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A frost-point hygrometer has been installed on the NASA C141 Flying Observatory to measure water vapor in the upper troposphere and lower stratosphere. Measurements were made during two flights in June 1974 in the region of the subtropical high-pressure cell over the eastern Pacific Ocean at an upper tropospheric pressure height of 180 mb.

The relative humidity in the region was found to be high, implying that the subsidence characterizing the lower tropospheric level of the subtropical high is weak (continued)

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or nonexistent at the 180-mb level in early summer. Saturation of the level at times due to vertical oscillations seems likely.

CONTENTS

WATER VAPOR MEASUREMENTS OVER THE EASTERN PACIFIC OCEAN AT THE 180-MILLIBAR PRESSURE LEVEL

INTRODUCTION

Water vapor is important in the radiation and energy budget of the earth and atmosphere and in the chemistry of the stratosphere. The concentration of water vapor and its geographical and temporal variation in the natural stratosphere must be known for the modeling of stratospheric behavior and the assessment of the effects of aircraft emissions.

Water vapor concentration in the lower troposphere is routinely measured by the meteorological networks of the world, but measurements in the upper troposphere and stratosphere are few. Early measurements produced more controversy than agreement over the amount and distribution of water vapor in the stratosphere; and it is only in recent years that there have been enough quality observations from independently conducted programs for the scientific community to place reasonable bounds on the real concentration and variability of stratospheric water vapor. The recent observations and the present state of knowledge of stratospheric water vapor distribution are summarized by Mastenbrook [1].

The available data allow for a general assessment of the latitudinal gradient, seasonal variation, and long-term trends; but little can be said about variation over periods of hours, days or weeks, or about the horizontal space variation. Space variation can best be determined by instrumented aircraft which can traverse large areas within a few hours. A frost-point hygrometer has been installed on the NASA C141 Flying Observatory to study time and space variation in the high troposphere and stratosphere.

INSTRUMENTATION

The hygrometer installed on the NASA C141 is an adaptation of the NRL balloon-borne hygrometer which has been successfully used for over a decade to measure the vertical distribution of water vapor to a height of 30 km [2-4].

The hygrometer utilizes an optical-electronic-thermo servo loop to continuously control the temperature of a mirror to maintain a frost deposit in equilibrium with the partial pressure of water vapor. The mirror is cryogenically cooled using liquid nitrogen and is heated using a peripheral induction heater to provide frost-point temperature measurements ranging from $-100°$ to $+30°$ C. A bead thermistor embedded in the mirror surface provides the measure of mirror temperature which, under control conditions, is the frost-point temperature. The system response time to a change in frost-point temperature is 20 s at $-72°$ C frost point.

Note: Manuscript submitted November 22, 1974.

The sensor is mounted on a plate covering a fuselage port 20 ft from the nose of the aircraft and couples directly to air intake and exhaust ports. The air intake probe is a modified Rosemount pitot-static probe which locates the air-intake 9 in. away from the fuselage and outside the boundary layer. Heaters in the probe prevent icing of the inlet tube.

The inlet and exhaust ports are connected to the sensor cavity through valves which are adjusted in flight to equalize cavity pressure and atmospheric pressure. When the two pressures are equal, the frost-point temperature within the cavity is also the frost-point temperature of the ambient atmosphere. Static pressure measured within the cavity is compared with atmospheric pressure as measured by the aircraft altimeter to make the pressure adjustment.

To measure the very low water vapor concentrations of the stratosphere, we must take precautions to avoid water vapor contamination of the air sample. The forward location of the air intake probe prevents contamination from the skin of the aircraft, and the close coupling of the sensor to the probe and the use of stainless steel for the probe, sensor cavity and associated plumbing, minimize the internal sources of contamination. Finally, the contamination which cannot be avoided is diluted to a level of insignificance by using a high volume sample flow rate of approximately 0.2 m^3/min. The components of the aircraft hygrometer, consisting of the sensor unit, probe, and control equipment, are shown in Fig. 1. The configuration of the equipment within the aircraft is shown in Fig. 2.

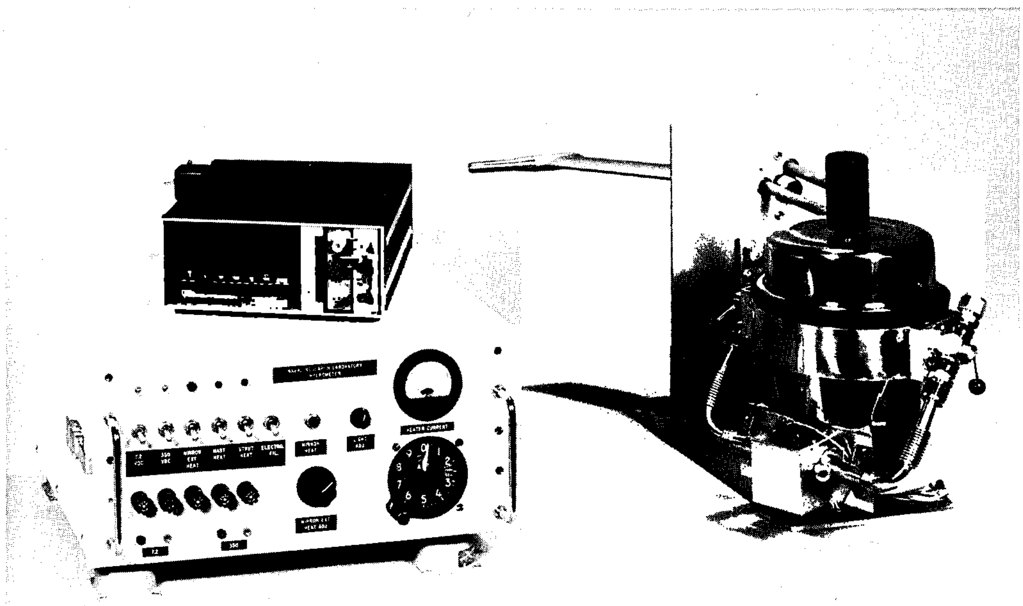

Fig. 1 — Components of the frost-point hygrometer installed on the NASA C141 aircraft; sensor unit and air intake probe (right), control equipment (left)

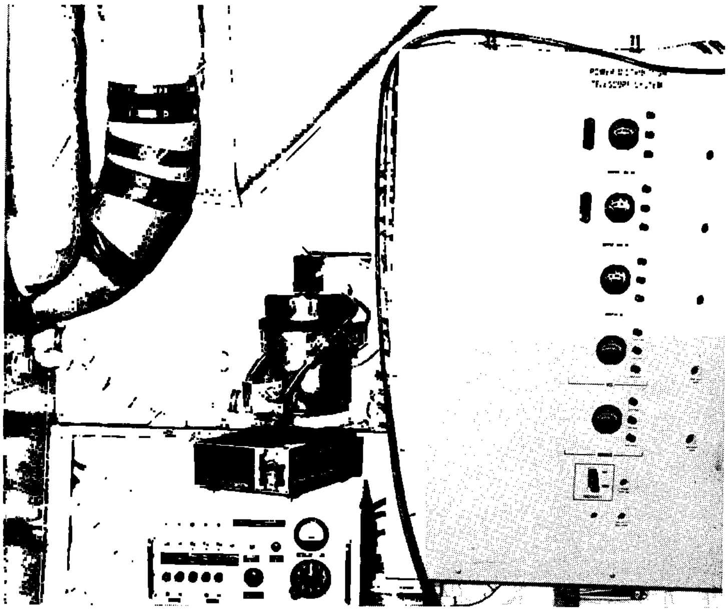

Fig. 2 — Frost-point hygrometer installed on the NASA C141 aircraft

The principal measurement is the resistance of the thermistor embedded in the mirror of the hygrometer sensor. The measured resistance is displayed on a digital meter and is transferred to the aircraft computer system. Measurements are averaged over a selected time span, and the averages are used to compute the frost-point temperature and the water-vapor mass mixing ratio. The data and computer outputs are stored on magnetic tape. A line printer aboard the aircraft provides a real-time display of selected computations.

OBSERVATIONS

The first measurements in the atmosphere were made during a flight over the eastern Pacific Ocean on June 5, 1974. The aircraft flew a rectangular pattern by flying south from to 30° N latitude, west to 130° W longitude, north to 36° N latitude, and then east to the starting point (Moffett Field). Approximately 4 hr of flight time were at the 180-mb pressure level as determined by a pressure altimeter, or at an indicated altitude of 41,000 ft, assuming a standard atmosphere. The real altitude of the 180-mb pressure level was 42,430 ft over Oakland as determined from the meteorological sounding.

The weather pattern showed a well-defined jetstream 500 mi north-northeast of Moffett Field. South of the jetstream at Oakland, the tropopause pressure height was 160 mb, while north of the jetstream at Spokane, the tropopause pressure height was 300 mb. The aircraft flying at the 180-mb pressure level would thus be in the stratosphere when flying north of the jetstream and in the upper troposphere when south of the jetstream. During this flight, the aircraft was in the troposphere flying south of the jetstream at all times and was in a region dominated by the subtropical high pressure cell of the eastern Pacific Ocean.

The primary objective of the first flight was to observe the performance of the hygrometer under flight conditions. Data interfacing with the on-board computer had not been completed at this time, and data were recorded manually at 1-min intervals. The continuous performance of the hygrometer was observed by monitoring a digital display of the resistance of the thermistor embedded in the mirror surface. Periodically the automatic control was upset by partially or completely clearing the condensate from the mirror; the recovery of the instrument to a control condition was then observed. The instrument performed well in flight with response times consistent with laboratory observations; there was no evidence of electrical interference from aircraft systems. At all stages of flight, there were ample reserves of heating and cooling to control the mirror temperature. Cavity pressure was readily adjusted to ambient air pressure by using the valves controlling the inlet and exhaust flows of the air sample. Suction at the exhaust port was found to be weak compared with the inlet ram pressure, which was easily corrected by reconstructing the exhaust port.

The flight provided an opportunity for the in situ measurement of water vapor in an upper tropospheric region of meteorological interest for which there are little or no prior data. The path of the 4-hr flight, which began at 0700 GMT, and the weather features for the 200-mb pressure surface are shown in Fig. 3. The observed frost-point temperatures averaged over 15-min intervals and the winds obtained from the navigation system appear at the place of observation along the flight path. The 200-mb surface analysis shows the height contours, position of the jetstream, and the temperature and winds for several locations. On the first leg of the flight, the aircraft traversed the subtropical high-pressure cell from north to south. The aircraft followed a westward course for 500 mi turned north, and then northeast to cross the subtropical high-pressure cell again from south to north.

The averaged frost-point temperatures over the course of the flight between 30° and 36° N latitudes ranged between −63.1° and 65.1° C, which correspond to water vapor to air mass mixing rations of 23.4 ppm and 16.0 ppm. These concentrations for the eastern Pacific Ocean do not differ substantially from an average concentration of 16.0 ppm at the 180-mb level for the month of June over Washington, D.C. (39° N latitude) as determined from 6 yr of vertical water vapor soundings [3].

The measurements expressed in terms of relative humidity allow for an assessment of the subsidence characteristics of the subtropical high-pressure cell at high tropospheric levels. The subtropical high-pressure cell of the eastern Pacific Ocean is know to be a region of strong subsidence with the relative humidity generally less than 20% in the lower tropospheric layers above the marine layer. The low relative humidity is maintained by a steady subsidence and warming of the air, which increases the capacity of the air to hold water vapor and decreases the relative humidity. The descent of dry air counters the upward flux of moisture from the surface layers. By examining the humidity at the 180-mb level, we can determine whether the strong subsidence characterizing the lower tropospheric level is also present at the higher tropospheric levels.

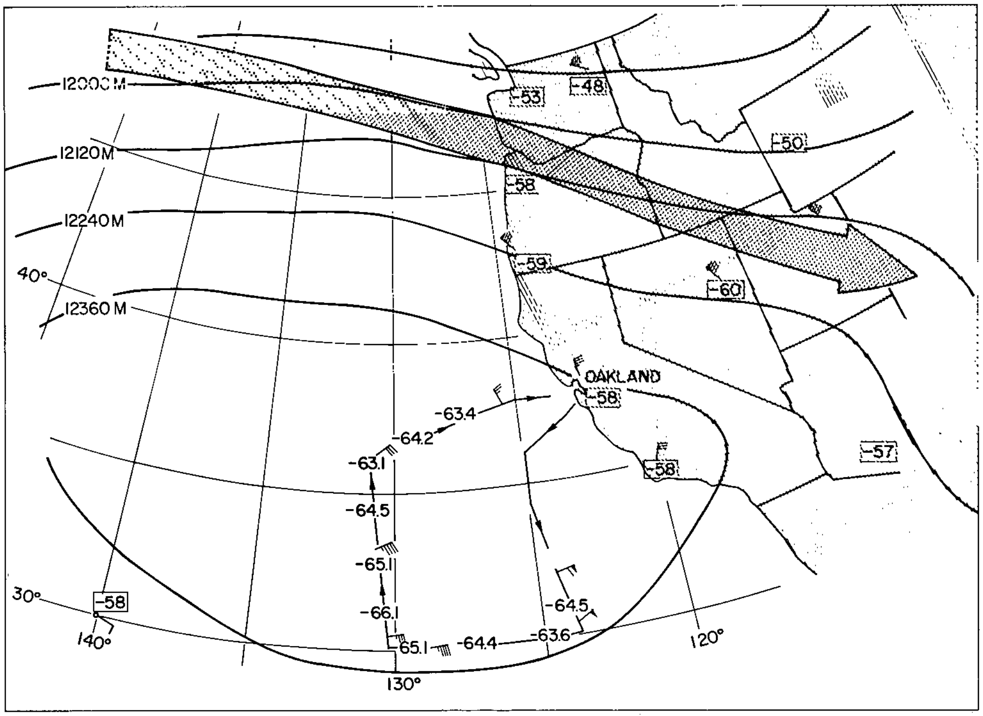

Fig. 3 — The observed frost-point temperatures (Centigrade and averaged over 15-min intervals) and winds at a pressure height of 180 mb along the flight path for the flight of June 5, 1974, and the June 5th, 1200 GMT analysis of weather features for the 200-mb pressure surface consisting of height contours (meters), position of the atmospheric jetstream (hatched band), winds, and temperatures for selected stations.

The humidity is determined by the ratio of vapor pressures at frost point and air temperatures. The ambient air temperature was not measured along the flight path; however the 200-mb weather analysis indicates that a single temperature would be applicable to the region of measurement. The temperature at the flight level as determined from the Oakland meteorological sounding was −63.1°C. Using this value for the air temperature and the averaged frost-point temperature along the flight path, we found the relative humidities to range from 65 to 100%.

The observed relative humidities are much higher than the humidity associated with the subsidence of the subtropical high in the lower troposphere, and a persistent strong subsidence condition is not indicated at the 180-mb level. The range is more typical of the average atmosphere where the humidity reflects the oscillatory fluctuations of the vertical motion of the atmosphere due to changing synoptic conditions and the mean vertical motion is of small magnitude. Under these conditions, ascending motions measured in hours lower the air temperature and increase the relative humidity, occasionally saturating the region of ascent. Descending motion, however, raises the air temperature and decreases the relative humidity. The effect is a fluctuating relative humidity about a mean value with the mean value determined more by the amplitude of the vertical oscillation than by the mean vertical motion.

A second flight of 9 hr was made on June 7, 1974, departing Moffett Field at 0430 GMT. The aircraft ascended to an altitude of 40,400 ft (200 mb pressure level) while flying northeast toward the core of the jetstream. The aircraft turned 50 mi south of the core of the jetstream in northern Nevada and flew southwestward to Los Angeles. It increased altitude to 42,500 ft (180-mb pressure level) at Los Angeles and flew northward along the coast to Oregon, south to 32° N latitude, west 700 mi, and finally northeast to return to Moffett Field. Figure 4 shows the flight pattern and the 200-mb analysis of weather features. The frost-point temperatures and winds measured along the flight path appear in Fig. 5.

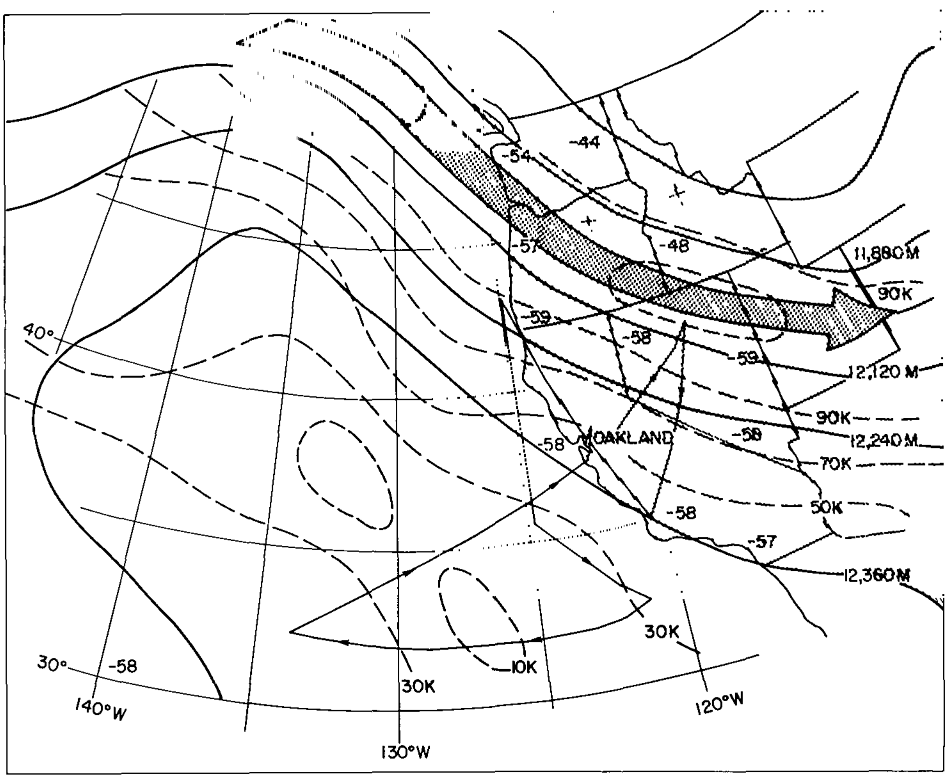

Fig. 4 — Path of the flight of June 7, 1974, and the June 7th, 1200 GMT analysis of weather features for the 200-mb pressure surface consisting of height contours (meters), isotachs (knots), temperatures (°C) for selected stations, and position of the atmospheric jetstream (hatched band)

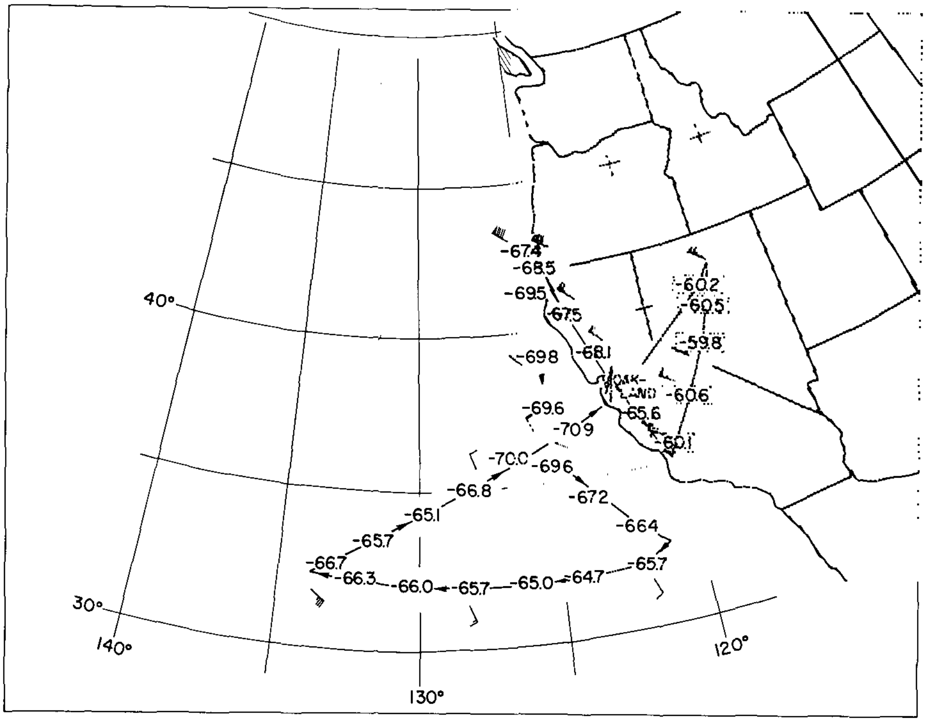

Fig. 5 — Observed frost-point temperatures (15-min averages) and winds (knots) along the path of the flight of June 7, 1974. The boxed temperatures are for a pressure height of 200 mb; all other temperatures are for the 180-mb pressure height.

Data collection began during the flight from Nevada to Los Angeles when the aircraft was flying along the 200-mb surface. The observed frost-point temperatures ranged from 2 to 3 degrees colder than the air temperature in a relative humidity range of 67% to 76%. The remainder of the flight was at a pressure height of 180 mb.

The lowest frost-point temperatures were encountered over the ocean during the south-bound leg of the flight from Oregon to 35°N latitude when frost-point temperatures ranged from −68.5° to −70.9° C. These temperatures correspond to a mixing ratio range of 11.3 ppm to 7.9 ppm. The air temperature at the flight level over Oakland was used to compute the relative humidity range of 41% to 29%. South of 35°N latitude the observed frost-point temperatures increased as the aircraft passed out of the westerly wind circulation and into the easterly flow. During the westward leg of the flight at 32° N latitude, the frost point ranged between −66.3 and −64.7° C (relative humidity 57 to 71%, mixing ratio 15.5 ppm to 19.5 ppm). The final leg of the flight crossed the high-pressure ridge again in a northwesterly direction. The frost-point temperatures remained high while flying south of the ridge. When the aircraft crossed the ridge and entered the circulation of the westerlies to the north, the frost-point temperature was again found to be lower.

CONCLUSIONS

The two flights at the 180-mb level in the region of the subtropical high-pressure cell over the eastern Pacific provided measurements of the water vapor concentration which allow for an assessment of the subsidence characteristics of the cell at a high tropospheric level.

The region south of the high-pressure ridge in the easterly wind circulation was found to have a high relative humidity during both flights, and a dominant, strong subsidence condition for the region was not evident. This is in contrast to the very strong subsidence that characterizes the lower tropospheric levels of the subtropical high-pressure cell.

North of the high-pressure ridge the relative humidity in the westerly wind circulation was high during the first flight and low during the second flight. The high relative humidity again suggests that a strong net subsidence is not a dominant feature which determines the relative humidity of the region, and that the large variations between flights indicate large relative humidity fluctuations caused by vertical oscillations in the atmosphere.

The observations suggest that the subtopical high-pressure cell over the eastern Pacific Ocean in early summer is characterized by weak subsidence or no subsidence at the 180-mb level and by a high relative humidity. Saturation of the air can easily occur during periods of strong ascending motion, which is most likely north of the ridge in the westerly wind circulation.

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