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The NASA Spring 1984 Stratosphere-Troposphere Exchange Experiment: Science Objectives and Operations

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We present an overview of the first experiment of the Stratosphere-Troposphere Exchange Project (STEP), conducted in spring 1984 over the southwestern United States. The objective was to identify modes of transport during large-scale cyclogenesis, both (1) within the stratosphere, from the anticyclonic to the cyclonic side of the jet, and (2) from the troposphere to the stratosphere. The primary platform was the NASA U-2 high-altitude research aircraft, supported by the regular twice-daily radiosonde network. Measurements included temperature, pressure, horizontal wind, ozone, cosmogenic radionuclides, water vapor, and condensation nuclei. U-2 flights were made on 4 days. On 3 days the flight path was in a vertical plane orthogonal to the jet stream flow, extending from the anticyclonic side of the jet, across it, and into the cyclonic vortex. The other flight was directed at processes associated with the upper level cirrus outflow from a tropical vortex. Aircraft direction was performed using analysis of NMC prognostications, commercial diagnostics and predictions, radiosonde data, and satellite infrared imagery. The cross-jet flight most intensively analyzed (April 20–21, 1984) was coordinated with simultaneous flights in the troposphere and lower stratosphere made by the NASA CV-990 and Electra as a part of the Global Tropospheric Experiment. This paper briefly reviews the U-2 instrument payload, shows the flight paths of April 20–21 and May 6 in relation to the respective meteorological situations, and reviews the procedures used to predict large-scale cyclogenesis and associated tropopause folding and to direct the aircraft. The following papers report the measurement data and interpret the results in terms of reversible and irreversible cross-jet transport mechanisms.

Introduction

The Stratosphere-Troposphere Exchange Project (STEP) has two broad goals: (1) investigate the mechanisms and rates of irreversible transfer of mass, trace gases, and aerosols from troposphere to stratosphere and within the lower stratosphere; and (2) explain the observed extreme dryness of the stratosphere. This and the following series of papers report on the first of STEP's field experiments, conducted in spring 1984 [*Holton et al.*, 1984]. The objective of the spring 1984 experiment was a part of STEP's first goal.

Specifically, the main objective of the spring 1984 experiment was to study intrastratospheric transport with the aid of high-resolution measurements of meteorological variables and trace constituents. Of particular interest was identifying modes of transport from the anticyclonic to the cyclonic side of stratospheric jets. Also studied was transport from upper troposphere to lower stratosphere and its role in maintaining gradients in that region. The experimental focus was the disturbed stratosphere during large-scale cyclogenesis, when wave transports were assumed to be effective and identifiable by nonlinear spatial distributions of tracers and by their respective correlations. The approach was to make measurements in the stratosphere of tracers of stratospheric and tropospheric origin and to analyze the resulting tracer distributions for evidence of different modes of transport.

Platforms and Measurements

Both the twice-daily radiosondes and the NASA U-2 were used to supply the measurements analyzed for evidence of transport. The U-2 instrument configuration is shown in Figure 1. The U-2 and radiosonde measurements can be usefully grouped as follows: Meteorological variables: (1) low resolution: radiosonde temperature, pressure, and winds; and (2) high resolution: U-2 temperature, pressure, and horizontal winds [*Chan et al.*, this issue]. Tracers: (1) low resolution, stratospheric: potential vorticity (computed by combining radiosonde temperature, pressure, and winds with appropriately filtered U-2 temperatures [see *Danielsen et al.*, 1987; *Danielsen et al.*, this issue]; and cosmogenic radionuclides, ^{7}Be and ^{32}P, measured by analysis of U-2 filter samples [*Kritz et al.*, this issue] and designed to provide evidence of large-scale transports; (2) high resolution stratospheric: ozone mixing ratio determined by an ultraviolet photometer on the U-2 [*Danielsen et al.*, this issue]; and (3) high resolution tropospheric: water vapor, with a required sensitivity of about 1 part per million by volume (ppmv), provided by a Lyman alpha hygrometer designed and built especially for the U-2 [*Danielsen et al.*, this issue]; and condensation nuclei, obtained with a high-supersaturation counter also designed and built for U-2 operations [*Wilson et al.*, this issue].

All U-2 measurements designated high resolution were made at a frequency of 0.2 Hz or greater, so as to resolve small-scale features and correlations among the tracers. At the U-2 cruising speed of 200 m s^{-1}, 0.2 Hz corresponds to a spatial scale of 1 km.

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Experimental Approach

Flights were directed into four cases of cyclogenesis in spring 1984: The first flight, on April 20, 1984, sampled an occurrence of large-scale cyclogenesis that produced a well-defined tropopause fold. Figure 2 shows contours of the Montgomery stream function [*Dutton*, 1986, pp. 244–247] on the 310 K potential temperature surface. In this figure the

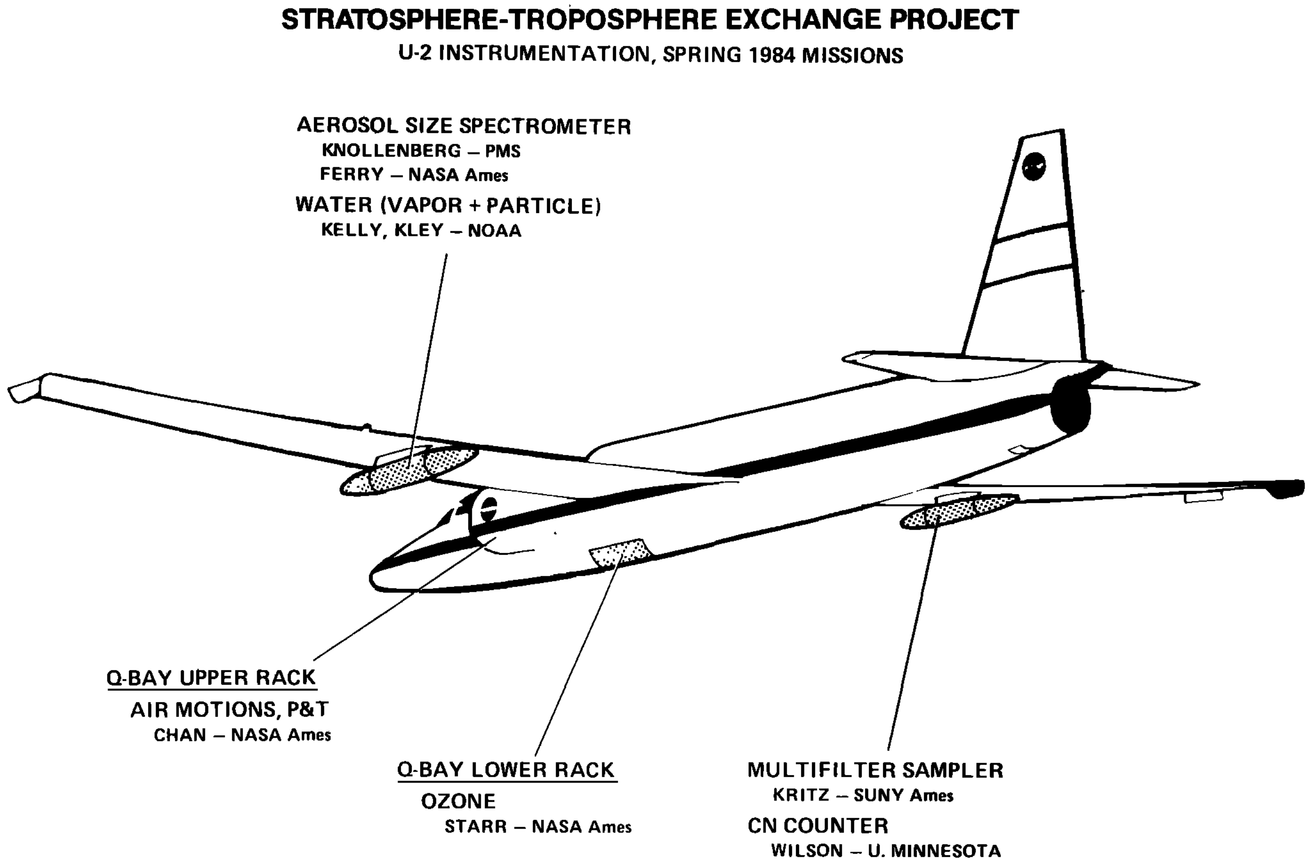

Fig. 1. U-2 instrumentation for the spring 1984 Stratosphere-Troposphere Exchange Project flights. Instrument malfunctions prevented collection of aerosol size spectrometer data. All other instruments produced data as described in the text.

locus of the jet stream is given by the regions where the Montgomery stream function contours are most closely packed. That is, the jet stream crosses the west coast of North America at about 43°N and sweeps south-southeastward toward the Gulf of California but curves eastward before reaching the gulf. Thus as the jet crosses over eastern California and Arizona, anticyclonic air is to the southwest and south of the jet and cyclonic air to the northeast and north.

As can be seen from Figures 2, 3, and 4, the U-2 flights were made in a vertical plane orthogonal to the flow, extending across the jet from the anticyclonic side and into the center of the cyclonic vortex. The U-2 paths were chosen orthogonal to the flow so as to maximize the variability of tracers encountered and to yield the most accurate measurements of shear vorticity. The U-2 flight legs shown in Figure 3 are about 600 km long; overall flight duration for the horizontal and vertical legs on April 20–21 was about 5 hours.

Also, as shown in Figure 3, the U-2 flight of April 20 was coordinated with flights, at lower elevations in the stratosphere and across the anticipated tropopause fold in the upper troposphere, of CV-990 and Electra aircraft [*McNeal et al.*, 1983]. As described by *Danielsen et al.* [1987] and *Browell et al.* [1987], the coordinated flights were used to provide values of potential vorticity, ozone, and carbon monoxide at the lower-aircraft heights, as well as vertical cross sections of ozone and aerosols below the Electra. *Hipskind et al.* [1987] describe the correlations between ozone and carbon monoxide found in those measurements.

For the second U-2 flight day, April 24, both the meteorological situation and the flight path were similar to those on April 20. The jet location was similar to that shown in Figure 2 and the U-2 sampled above the jet and primarily on the cyclonic side.

The third U-2 flight, on May 5, was directed south, offshore of Baja California. The goal was to penetrate the cirrus outflow from a tropical vortex southwest of Baja and study its properties.

The fourth U-2 flight, on May 6, was similar to the first two in being directed in a plane over the jet and perpendicular to its flow. Figure 4 depicts the geopotential height field at 150 mb for 1200 UTC on that day. In contrast to the flow on April 20 shown in Figure 2, on this day the jet stream core was farther to the north, and the U-2 flight legs were directed so as to sample equally on the anticyclonic and cyclonic sides of the jet. In contrast, the first two flights sampled more toward the anticyclonic side.

OPERATIONS

The scientific objectives described above led to two operational objectives for the April 20 flights: (1) predict the large-scale cyclogenesis associated with tropopause folding and (2) direct the three aircraft to sample a plane perpendicular to the jet, such that the U-2 would sample four altitudes

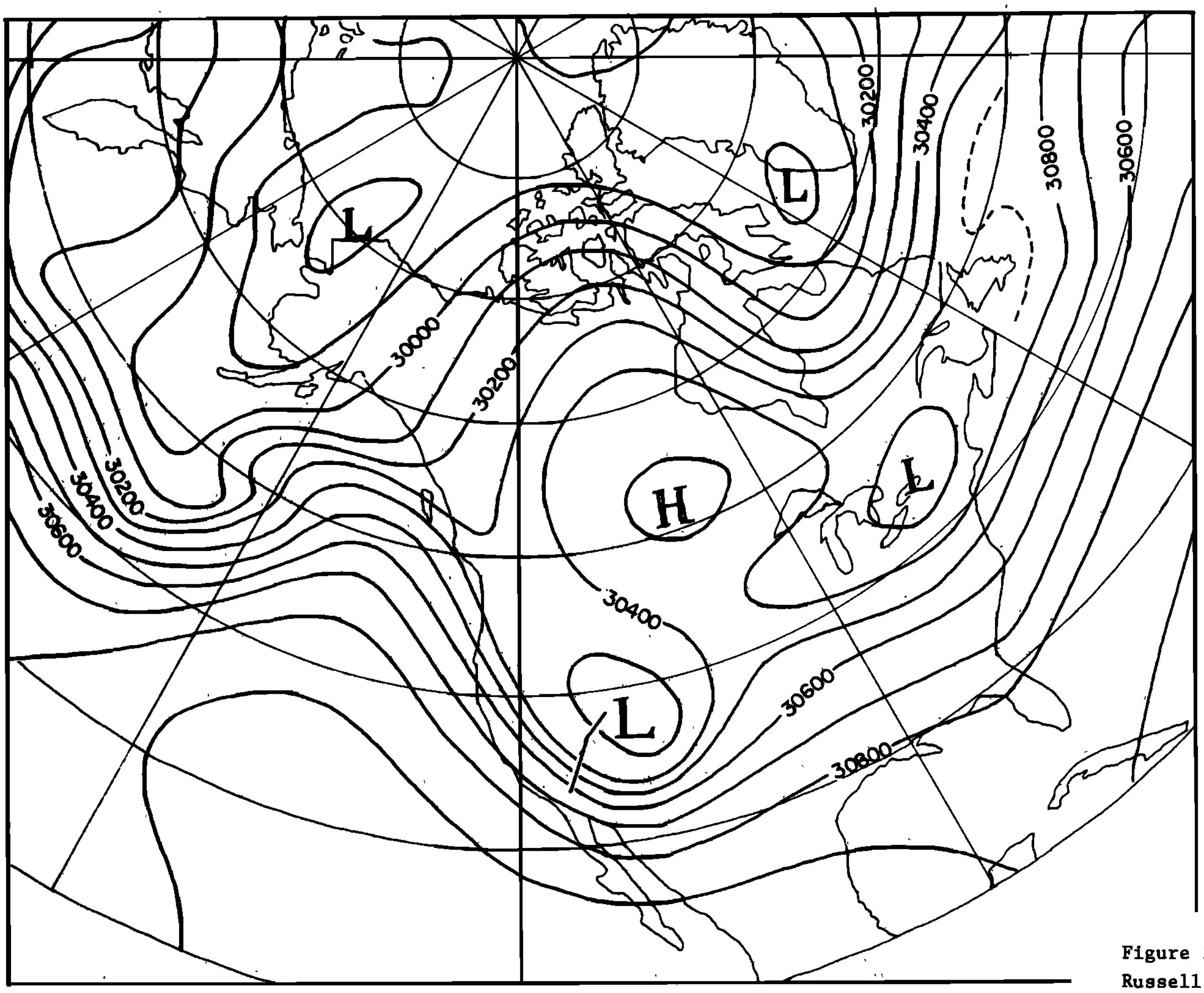

Figure 2
Russell et al.

Fig. 2. Montgomery stream function analysis for the 310 K potential temperature surface, April 20, 1984. Contour interval 10^6 ergs s^{-1}. U-2 flight track indicated by solid line.

above the jet; the CV-990 would sample the lower stratosphere and through the fold; and the Electra would sample the upper troposphere and the fold, while mapping the sample plane with the downward looking lidar. The three later flights, April 24, May 5, and May 6, made use of the U-2 only.

To achieve these objectives, the following suite of prediction tools was assembled: (1) National Meteorological Center (NMC) 500-mb prognostications (36, 48, 60, 70, and 90 hours, used to identify times when cyclogenesis was highly probable over the western United States and also to discriminate between cyclogenesis to the east and to the west of the Cascade-Sierra Nevada mountain barrier); (2) diagnostics and 36-hour predictions (from a commercial supplier, plotted and contoured especially for this experiment); (3) radiosonde data (used to plot soundings, cross sections, and isentropic maps); and (4) geosynchronous satellite infrared (IR) imagery.

The IR images were displayed on a digital weather information processing system (DWIPS) made by Information Processing Systems, Incorporated. The video display included both individual photos and sequential loops. Major use was made of the IR photos in the 6.7-micron water vapor channel of the GOES satellite. Normally, these images are transmitted every 6 hours. However, by special arrangements they were sent every 3 hours during portions of this experiment.

Predictions were developed through the night, as the data arrived. The predictions included whether a tropopause fold would occur and, if so, where the fold and the jet would be located. On the basis of the prediction, flight plans were developed for all three aircraft. Pilots and experimenters were briefed near dawn. Later in the day the project scientist, pilots, and experimenters conferred on data from previous flights. The prediction process was then repeated on the following night.

SUMMARY

U-2 flights were conducted on 3 days (April 20 and 24, and May 6, 1984) to study cross-jet transfer and on 1 day (May 5) to study processes associated with cirrus outflow from a tropical vortex. On the day analyzed most thoroughly (April 20), the U-2 flights above the jet were supplemented by CV-990 flights in the lower stratosphere and through the tropopause fold and by Electra flights in the upper troposphere and fold [*Danielsen et al.*, 1987]. U-2 measurements included temperature, pressure, horizontal wind, ozone,

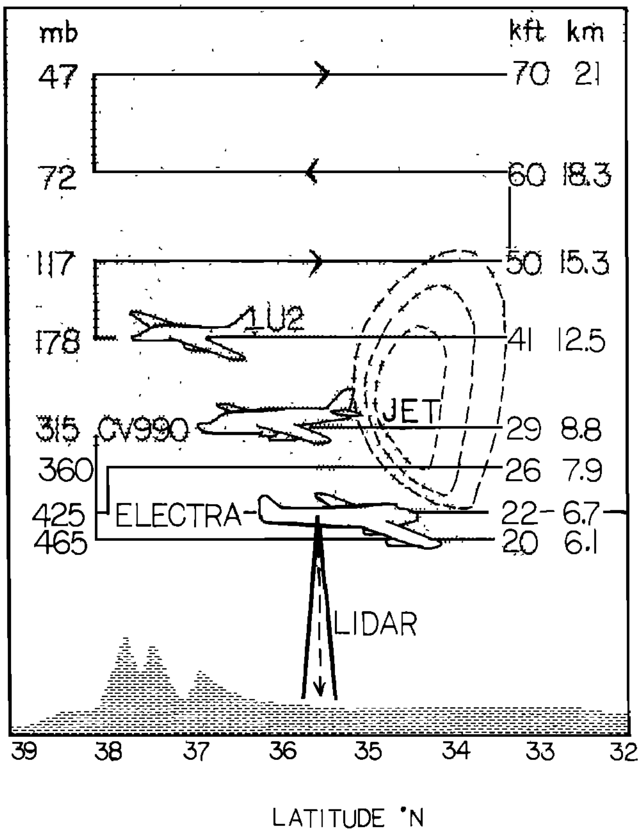

Fig. 3. Schematic vertical cross section of flight paths and meteorological features, April 20, 1984.

cosmogenic radionuclides, water vapor, and condensation nuclei. The U-2 measurements were supplemented by temperature, pressure, and wind data from the regular, twice-daily radiosonde network.

Predictions were developed and the aircraft directed, using NMC 500-mbar (36 to 90 hours) prognostications, commercial diagnostics and 36-hour predictions, radiosonde data, and geosynchronous satellite infrared imagery [*Danielsen et al.*, 1987]. On the flights studying cross-jet transfer, the U-2 was directed to fly in a plane perpendicular to the jet, sampling several altitudes above it and extending from its anticyclonic to its cyclonic side. The goal was to make high- and low-resolution measurents of tracers of stratospheric and tropospheric origin and to analyze the resulting tracer distributions for evidence of different modes of transport.

The following series of papers describe the measurements acquired during the U-2 flights, the meteorological situation inferred from the U-2 and supporting data, and the derived implications regarding irreversible cross-jet transport in the lower stratosphere.

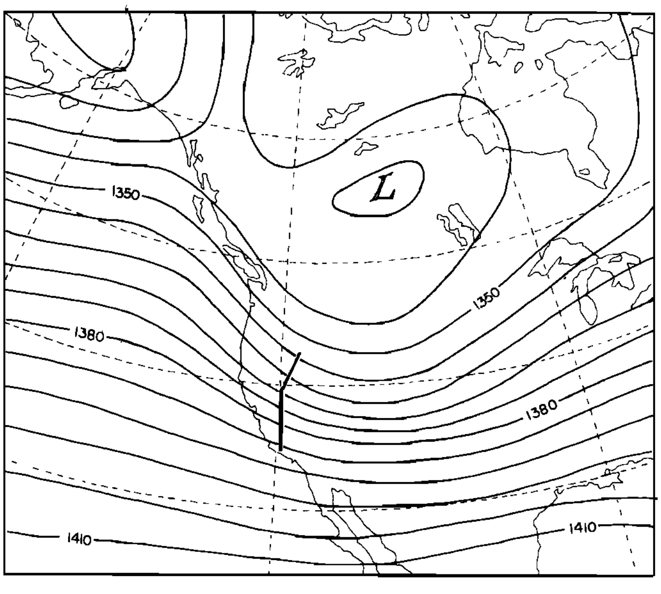

Fig. 4. Geopotential height (in dekameters) on the 150-mbar pressure surface for 1200 UTC, May 6, 1984. U-2 flight track indicated by solid line.

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