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Measuring the Effects of Surface Features on the Atmospheric Boundary Layer with Instrumented Aircraft

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ABSTRACT

The influence of mesoscale features (e.g., irrigation projects, desert regions, patches of forest, cities, etc.) on the atmosphere is difficult to determine unless the sensors are very numerous or highly mobile. An instrumented aircraft system permits such measurements and was used to determine the influence of lakes and reservoirs, irrigation, a group of forested hills, a small city, and an area of (dry land) nonirrigated agricultural land on the vertical and horizontal characteristics of the lowest layer of the atmosphere. Studies were conducted over portions of southern Alberta, and southern Idaho. Strong sensible heat advection was found to cause high evaporation from a small lake with the formation of a cool air layer which extended well beyond the lee side of the lake. The flux of water vapor over irrigated land was essentially double that over surrounding nonirrigated areas. A small city produced a heat island which delayed development of a temperature inversion for up to 9 h.

1. Introduction

Our present understanding of the behavior of the atmospheric boundary layer has been gained mainly from point measurements taken near the earth's surface with data usually obtained from tower installations. The alternative to numerous surface instrument sites is a single sensor system that moves rapidly as when mounted in an aircraft. This concept is not new and instrumented aircraft have been used to study many special features particularly of the upper atmosphere. The airplane has enormous capability and mobility to transport an instrument system rapidly over an area or throughout a volume of interest.

The advantages of a mobile system are obvious for the study of many boundary layer phenomena related to heat, water vapor and momentum exchange in agriculture, forestry, oceanography, hydrology, environmental studies, etc. Synchronous, multi-position data are desirable, and while a single-instrumented aircraft cannot be everywhere at once, its speed enables it to approach simultaneous measurements.

Using instruments in aircraft, however, does require special mounting and electrical precautions because of vibration and grounding. A number of reviews and reports of instrumented aircraft are available which give information on techniques and capabilities. Holmes (1972) presented a review of aircraft instrumentation and research and outlined in detail the aircraft system used in these studies.

During the summers of 1967–70 the Holmes aircraft instrument system was used to study some of the gross atmospheric conditions existing over several different mesoscale surfaces. Turbulence sensors and special instrumentation permitting the separation of aircraft motion from that of the atmosphere permitted the measurement of the fluctuations of temperature, water vapor and the three components of wind speed. Eddy-correlation techniques were used to compute the vertical fluxes of heat and water vapor from the fluctuation data. Holmes (1972) discusses the techniques and equations used to accomplish this and the verification of the methods.

2. Data sources

a. Lake Pakowki, Alberta

This is the remnant of a large Pleistocene glacial lake in southwest Alberta. It is shallow, nearly always turbid, high in alkali salts, and fluctuates widely in annual water level. The surrounding terrain is composed of flat, dryland farms and rangeland in all directions.

Fig. 1 shows differences in air temperatures taken 15 m above the surface of the lake and surrounding farm land; the cooled air was displaced over the lee portion of the lake and extended well into the agricultural area. Strong advection of heat caused high evaporation rates from the water. As a result, a layer of cooled air formed over the lake and a short distance downwind. Other data obtained with an aircraft over

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[1] Deceased.

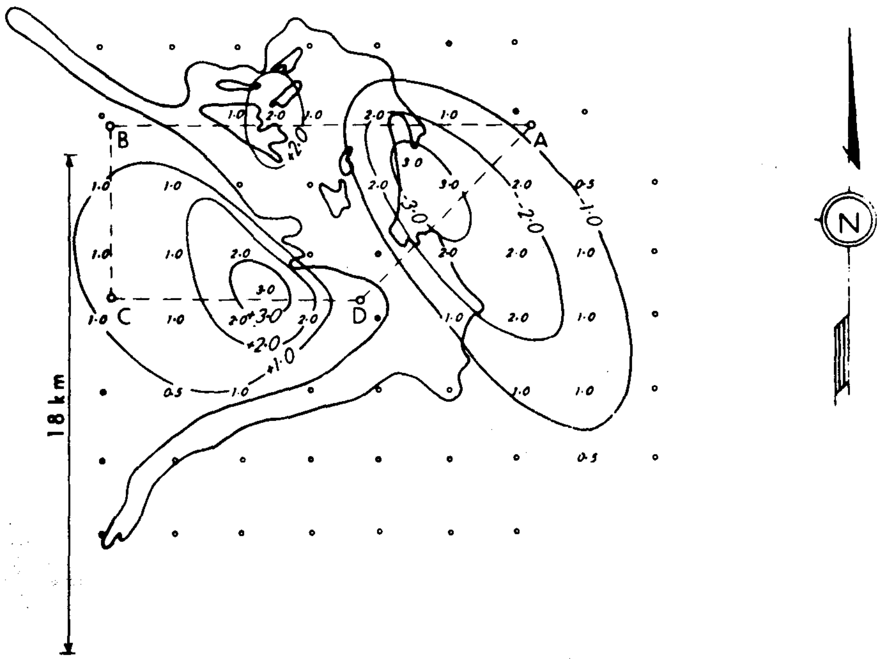

FIG. 1. Isotherms and temperature grid of average air temperature difference (°C) at 15 m above the surface near Lake Pakowki between positions indicated and ambient prairie air, 14–16 km upwind, 3 August 1967.

Lake Pakowki were reported in detail by Holmes (1969).

b. Lake Newell, Alberta

Lake Newell, located 150 mi north of Lake Pakowki, was created to contain irrigation water and drainage. Flights in this area at various altitudes showed a complex boundary layer with cooled and heated air existing over similar cool or hot terrain as shown in Fig. 2. At no time was there a consistent plume structure at any position. The atmosphere was "parcelized" and the data in Fig. 2 represent the average situation existing during the 2 h observation period. Other data for this terrain were reported by Holmes (1970).

c. St. Mary Reservoir

St. Mary Reservoir, near Cardston, Alberta and the Rocky Mountain foothills, is another irrigation reservoir. Fig. 3 shows temperature data taken at 15 m above the surface on a grid encompassing surrounding farm and rangeland. Here, too, air was cooled by passage over the lake. The cool air mixed with the warmer air and was carried somewhat downwind. Diffusion downwind quickly restored the original temperature structure of the overpassing atmosphere.

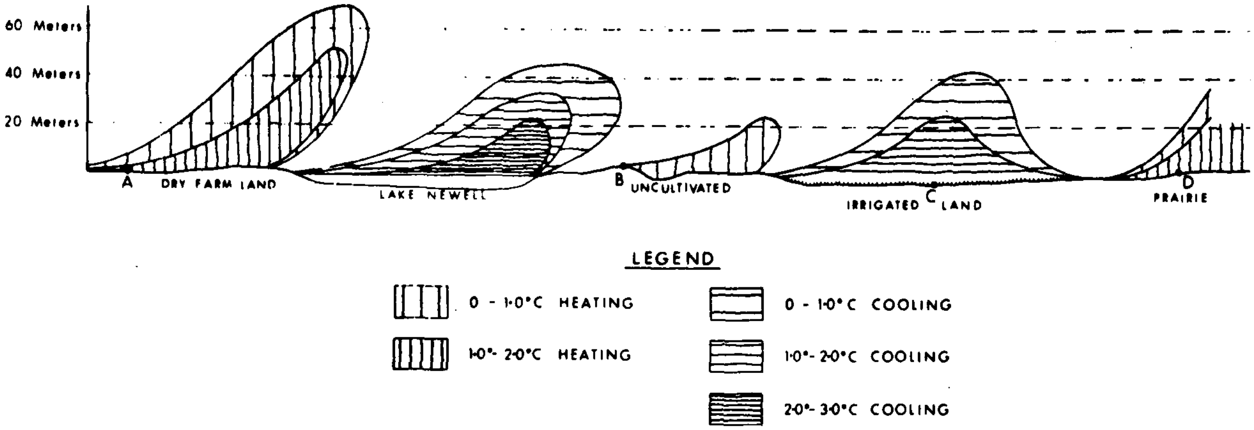

FIG. 2. Temperature profile of air temperature over ground tracks A, B, C, D, over area near Brooks, Alberta, 6 August 1968.

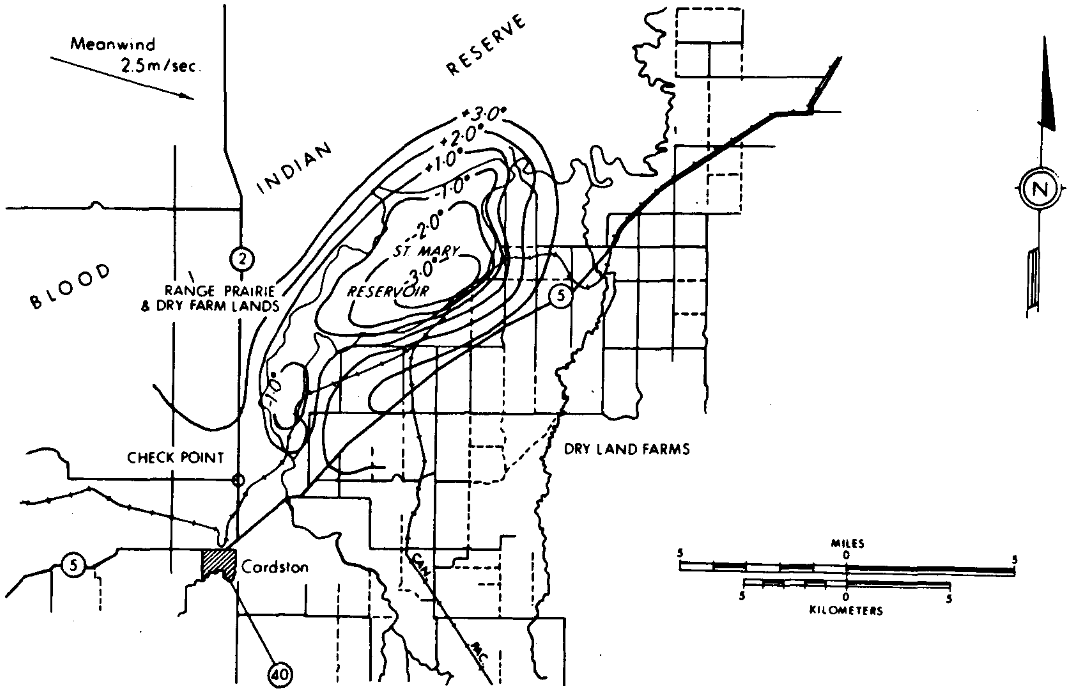

FIG. 3. Isotherms of average air temperature difference (°C) at 15 m above the surface of St. Mary Reservoir between positions indicated and ambient air over the Check Point, 14 August 1969.

Other data pointed to a strong cellular structure of "normal" and cooled air (Holmes, 1971).

d. Cypress Hills, Alberta

Near the southeast corner of Alberta a small group of hills stand 450–600 m above the surrounding grassy prairie. Cypress Hills, as they are called, are heavily forested on the slopes and have twice the rainfall of the surrounding prairie, presenting a definite oasis compared to the rest of southeastern Alberta. Fig. 4, a vertical transect through the atmosphere in a north–south direction, shows that at a given height above the terrain dewpoint temperatures were markedly higher over the forested region than over the grass.

Other flights were conducted to measure heat flux in the atmosphere over a portion of Cypress Hills. Data in Fig. 5 show lines of equal heat flux at the surface and at 50 and 100 m. The aircraft data were obtained at positions one to nine, at 50 and 100 m above the surface, with two 2 min runs at each altitude. The data show that a "negative-heat-oasis" was created by the western part of the hills.

e. Medicine Hat—Urban heat island

During August 1970 flights were conducted over Medicine Hat, a small city in southeastern Alberta. Residental areas spread from the coulee floor to the top and over the channel rim, with the business dis-

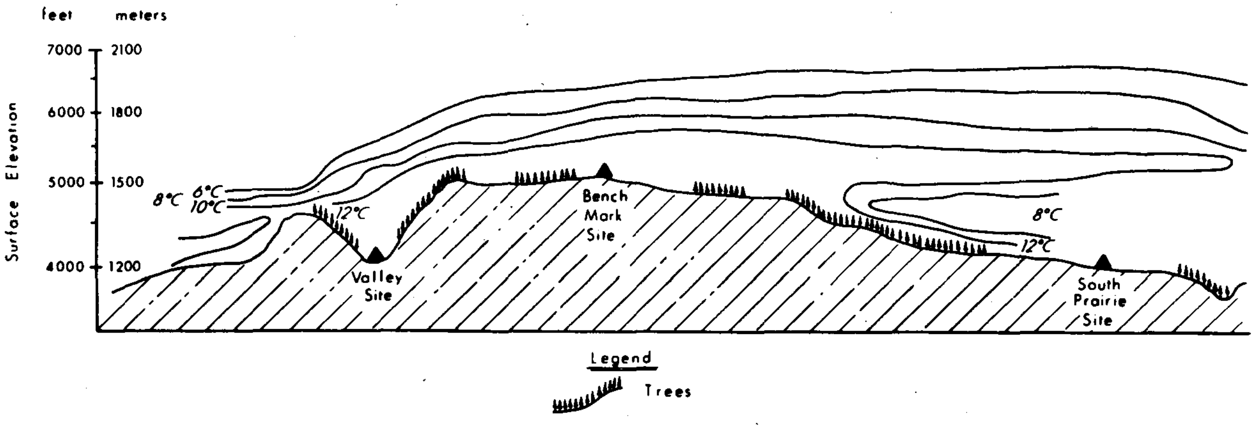

FIG. 4. Cypress Hills height-distance transect of dew-point temperature 1500–1650 MST 22 July 1970.

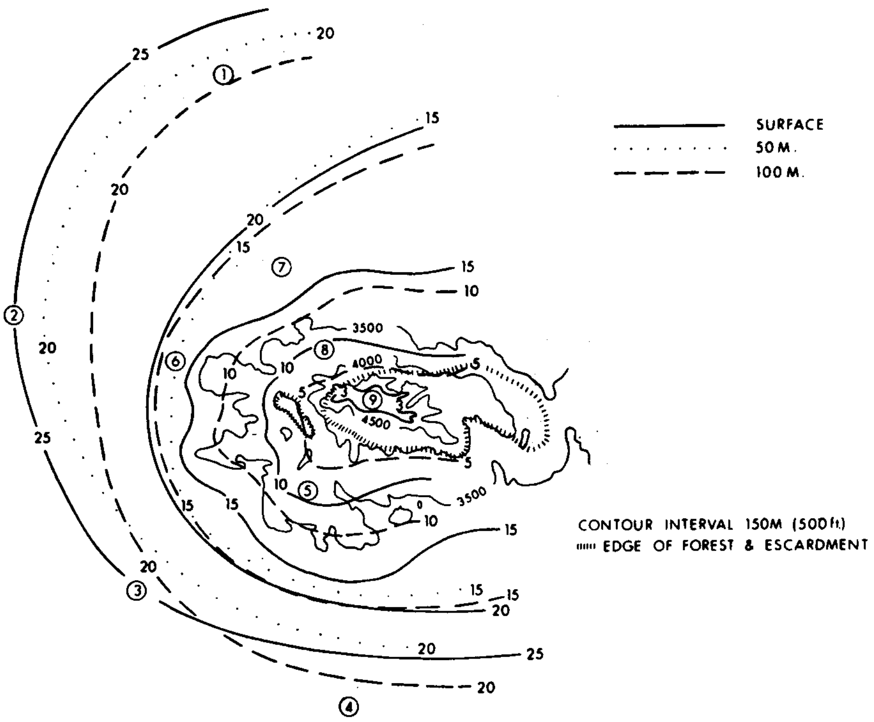

FIG. 5. Lines of equal heat flux (mW cm^{-2}) around Cypress Hills, Alberta, 1200–1500 MST 22 August 1970 at three elevations, based on surface and aircraft measurement at the nine locations indicated by circled numerals.

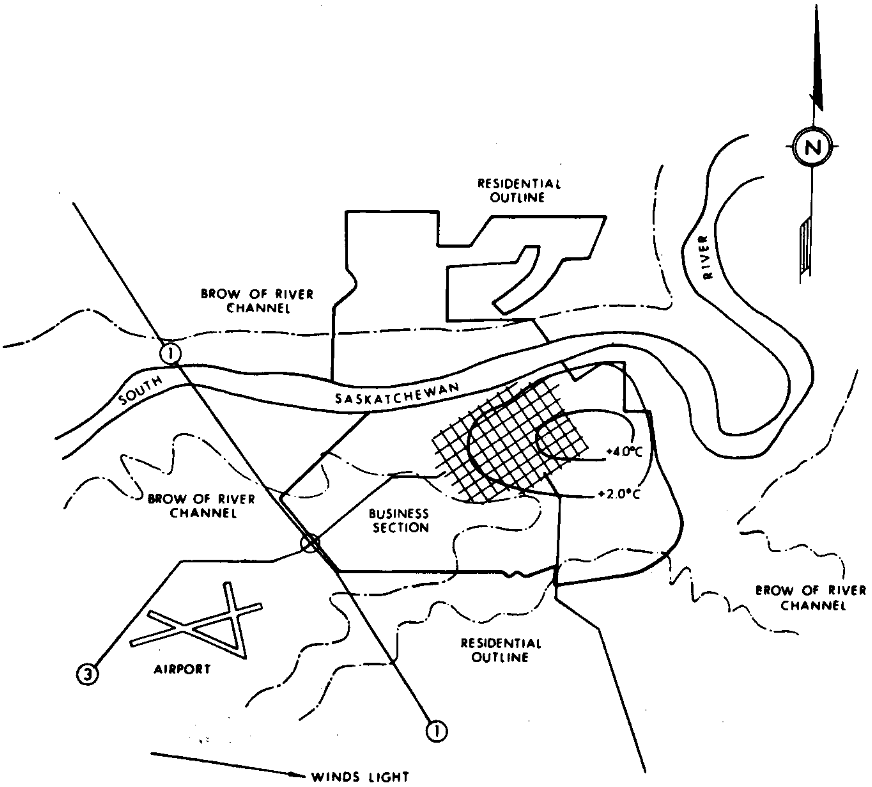

FIG. 6. Urban heat island over Medicine Hat, Alberta, 2200–2300 MST July 1970. Temperature isotherms are temperature differences between position indicated and that at same altitude over airport.

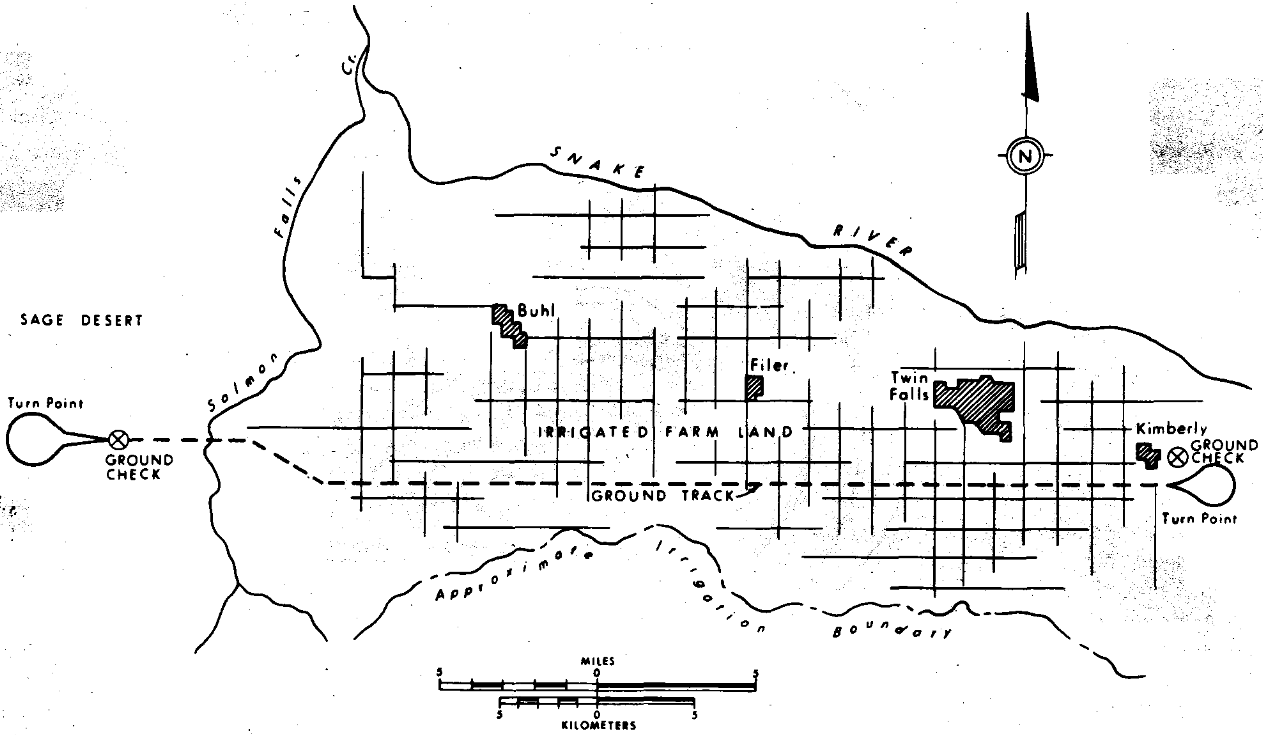

FIG. 7. Study area near Twin Falls, ID.

trict in the lowest part of the basin. Measurements of temperature were obtained at 150 m on a grid over the entire city. Some of the measurements (shown in Fig. 6) were obtained at night (2300 MST) and indicate higher temperatures over the business district than over other portions of the city. A strong tem-

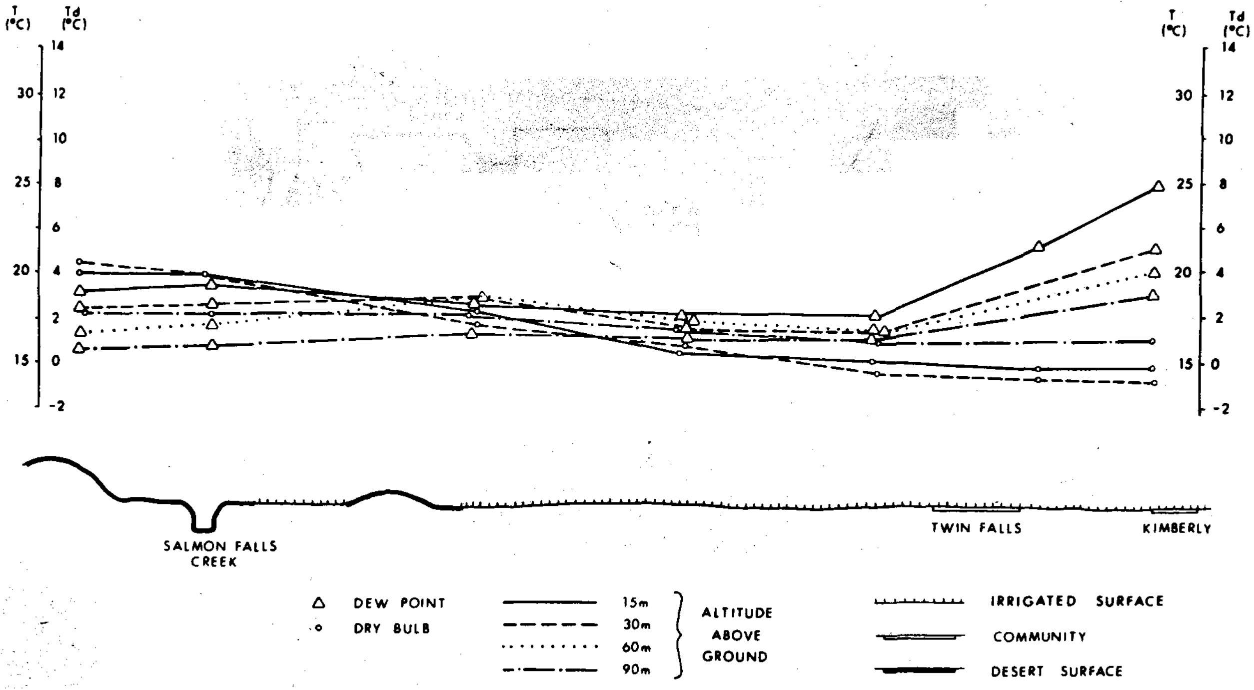

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FIG. 8. Profiles of air and dew-point temperatures over irrigated surface near Twin Falls, ID.

Table 1. Latent heat flux over agricultural land observed 14 July 1970 at 1400 MST at 15 m altitude near Lethbridge, Alberta.

Altitude (m)	Upwind (non-irrigated) (mW cm^{-2})	Center Project (irrigated) (mW cm^{-2})	Downwind (non-irrigated) (mW cm^{-2})
15	4.9	14.8	5.7

perature inversion developed over the airport and surrounding cultivated land by 1900 MST, but did not develop over the central portion of the city until 0400 MST, indicating an upward flux of heat from the heavily cemented business section.

f. Lethbridge–Irrigation area

Lethbridge, Alberta, is referred to as the "Irrigation Capital of Western Canada." While a considerable portion of the land is irrigated, it is concentrated in "pockets" with intermixed non-irrigated land. Flux measurements of water vapor were obtained with the aircraft system over an area upward from the general irrigated land, over the middle of an irrigated pocket, and downwind from the area over non-irrigated land. Since chart abstractions were used, only three values of water vapor flux were permitted. Measurements were made on two 2 min runs over the three described parts of the terrain. The latent heat flux from a lysimeter in the area near the flight position was 20 mW cm^{-2} compared with the 14.8 mW cm^{-2} observed with the aircraft at 15 m above the surface (see Table 1). These data show the pronounced influence of the irrigated pocket of land on the water vapor of the air at 15 m.

g. Idaho—Irrigated area

The irrigated land on the plains of the Snake River in southern Idaho shown in Fig. 7 forms a large oasis. Fig. 8 presents early morning data obtained over this area on a clear day with light westerly winds. At all altitudes the dewpoint temperature gradually increased downwind (easterly from the desert boundary) with a sharp increase toward the east side of the project. On the other hand, air temperature decreased with distance downwind. On the same day at 1600 MST, strong daytime heating was noted upwind over the desert with a rapid increase in dewpoint temperature downwind from the desert as shown in Fig. 9.

Data obtained during the morning runs indicated a definite breakup of the nocturnal temperature inversion. Some representative temperature profiles are shown in Fig. 10. Early in the morning the strong temperature inversion existed to a depth of $\sim$30 m above the ground. As solar heating progressed, convection cells originating from the surface began to penetrate the inversion layer. Traces of dewpoint temperature showed a marked "package" structure.

Other runs were conducted during August of the

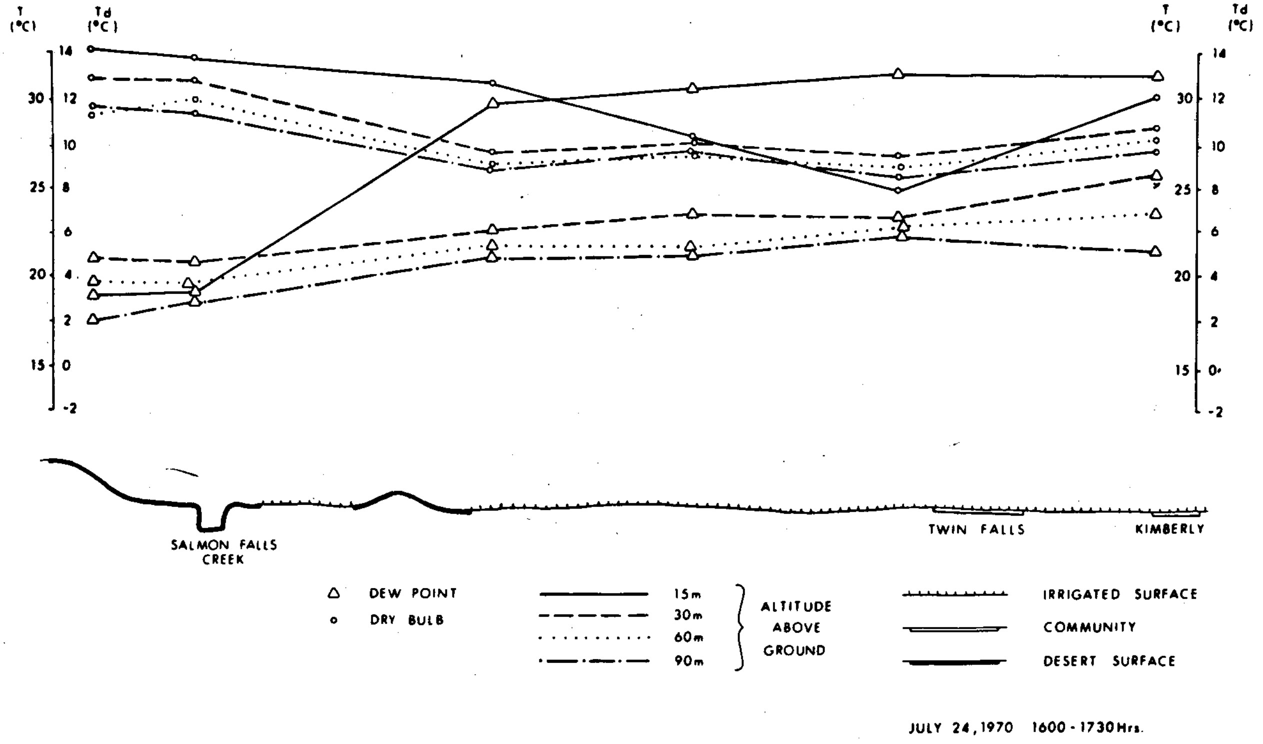

FIG. 9. As in Fig. 8.

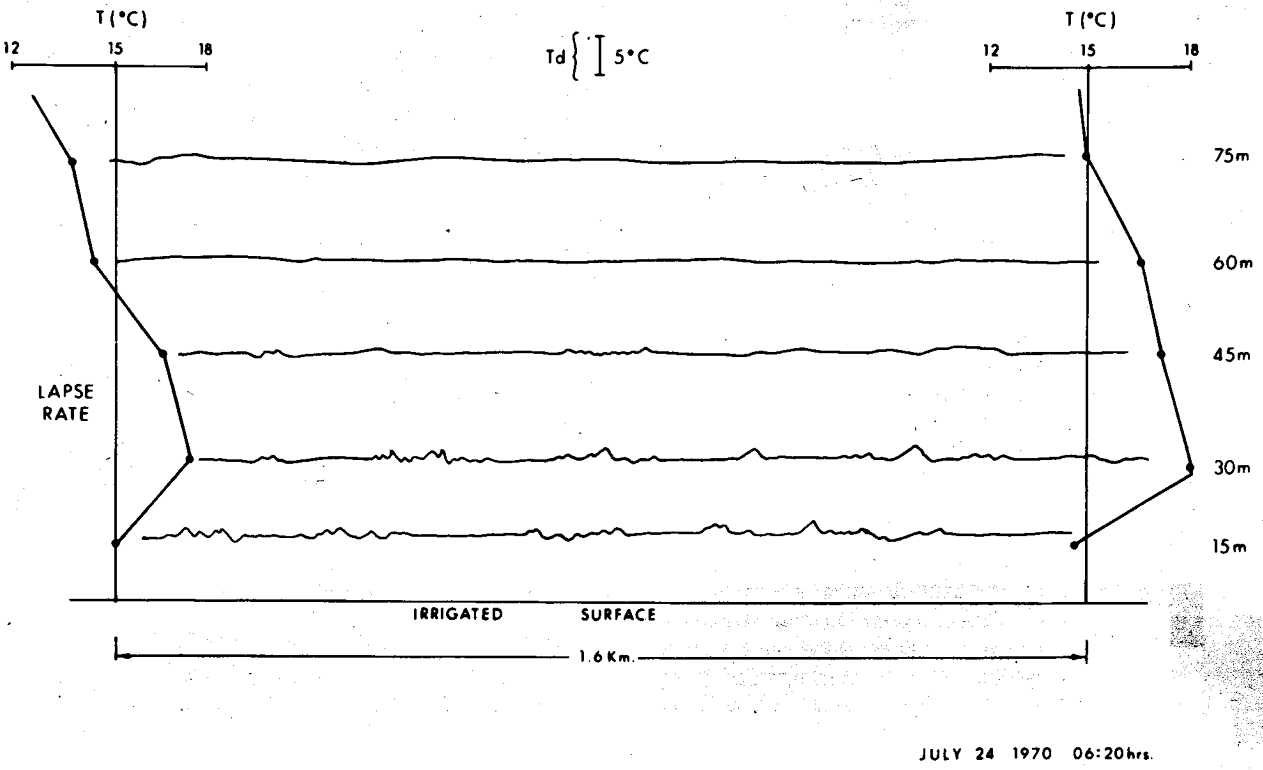

Fig. 10. Dewpoint temperature histories over a 1.6 km portion of runs at various altitudes near Twin Falls, ID.

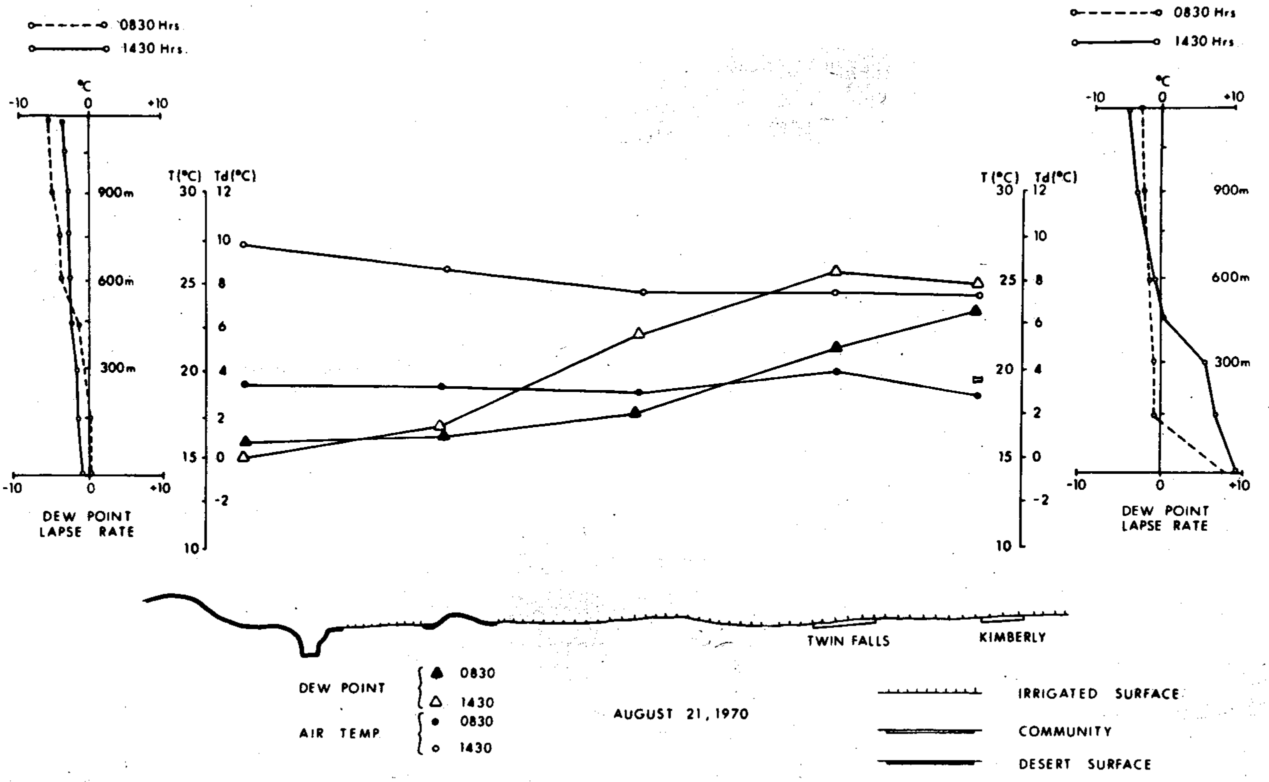

Fig. 11. Air and dew-point temperatures at 15 m altitude over irrigated surface near Twin Falls, ID, 0830 and 1430 MST.

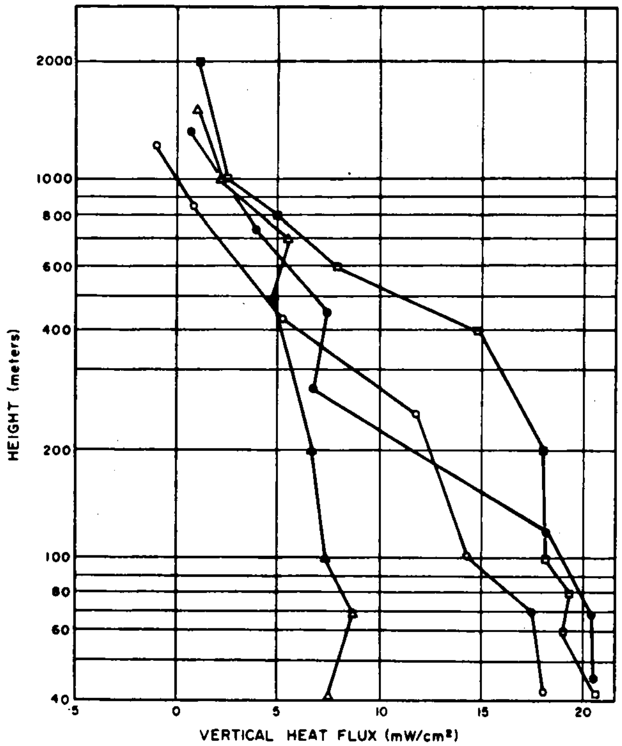

FIG. 12. Heat flux profiles in convection as measured by Telford and Warner (1964) (●) and Holmes (1972) (○) compared to profiles measured over Idaho sage desert (□) (see text) and over Idaho irrigated land (△) (see text).

same year. Fig. 11 presents dewpoint and air temperature data for positions upwind (desert) and downwind (Kimberly) of the border of the irrigated area during morning and afternoon periods on 21 August. Over the desert the dewpoint profile changed very little with time during the day even though air temperature increased considerably. On the other hand, the air mass downwind over the irrigated area contained significantly more water and the shape of the profile changed during the day. Early in the day the cool, moist air layer existed to a depth of ~50 m over the surface of the area near Kimberly. As the day progressed the depth of this air layer increased to ~500 m. The dewpoint temperature at 15 m changed only slightly at the two ends of the transect but increased significantly midway in response to high evaporation at the surface.

Extensive surface (2 m) measurements of temperature, humidity and wind speed were obtained for this same transect in 1972 and 1973 (Burman *et al.*, 1975). While the two sets of results show similar trends, the aircraft measurements extend the data up through the atmospheric boundary layer.

Existing models of vertical heat flux suggest that, under convective conditions, heat flux is positive near the surface and decreases with altitude to become negative at the top of the inversion layer. The sensible heat flux data in Fig. 12 obtained over the desert and irrigated areas in Idaho substantiate this view and are compared with data from Telford (1964) and Holmes (1972).

3. Summary

The results of these studies demonstrate the usefulness of an instrumented aircraft in measuring properties of the atmospheric boundary layer over several mesoscale surfaces. Further measurements obtained in time and space using such a system would greatly enhance our understanding of many mesoscale phenomena.

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