# The Spatial and Temporal Variations of the Turbulent Fluxes of Heat, Momentum and Water Vapor over Lake Ontario

B. R. BEAN, C. B. EMMANUEL, R. O. GILMER AND R. E. MCGAVIN

*Environmental Research Laboratories, NOAA, Boulder, Colo. 80302*

(Manuscript received 29 May 1974, in revised form 12 February 1975)

ABSTRACT

During the 1972 IFYGL "alert" periods, the NOAA/RFF/DC-6 gust probe instrumented aircraft was used to record time series of wind, temperature and water vapor at heights ranging from 18 to 300 m above the surface of Lake Ontario. The time series records show great variability. This is especially the case for evaporation when, in the fall, polar continental outbreaks move across the lake. In particular, such an outbreak of cold dry air moved across the lake at 12–15 m $s^{-1}$ on 9 October 1972. This resulted in a drop of the air temperature at 30 m above the lake from 12 to 6°C while the evaporation rate increased to more than 1 cm $day^{-1}$. This may be compared to the 0.5 cm $day^{-1}$ typical evaporation rate observed in the tropics during BOMEX. Furthermore, IR lake surface temperatures show cold regions (~5°C) along the north shore, presumably due to strong upwelling, while the center and south shore regions of the lake were of the order of 12–15°C. The turbulent flux quantities of momentum, heat and water vapor were obtained by the eddy correlation technique and their spectra were determined at several locations over the lake surface for 3 min sampling lengths. At the aircraft speed of 92 m $s^{-1}$ this represents a flight path of about 17 km. The spectra demonstrate the tendency for the peak value to march to longer wavelengths with increasing height.

## 1. Introduction

Because of the nature of the physical environment, the measurement of the fluxes of heat, momentum and water vapor above a large body of water has been extremely difficult to make. In recent years, however, use of properly instrumented aircraft has contributed much to our knowledge of the planetary marine and lake boundary layers (Bean *et al.*, 1972; Lenschow, 1974). This has become possible because of the availability of precise, fast-response sensors of wind gusts as well as sensors which sample the temperature and water vapor fields from mesoscale horizontal distances to scales of a few tens of meters within short periods of time, say, 3–10 min. This was the case during the 1972 United States-Canadian cooperative studies at Lake Ontario throughout the International Field Year for the Great Lakes (IFYGL). The extensive measurements that were taken during the IFYGL "alert" periods both from buoys and aircraft should be most useful in understanding the physical processes of the marine boundary layer, especially the spatial and temporal variations of the fluxes of heat, momentum and water vapor. In this paper we present our work on the direct measurement of these fluxes over Lake Ontario.

The platform used for our measurements was the highly instrumented NOAA/RFF/DC-6 aircraft (Fig. 1a), equipped with a gust probe system (Fig. 1b), a fast-response thermistor, a microwave refractometer, and a downward-pointing infrared (IR) system, as well as the normal in-flight measurement of standard meteorological parameters. The wind field measurements were made via the two vanes that are situated near the tip of the boom (Fig. 1b). Strain gauges are fixed to the vanes and record the force exerted by the air motion. At the very tip of the boom is a pitot tube which records air motion as small pressure fluctuations. The remaining instrumentation on the boom consists of a fast-response thermistor (for frequencies up to 20 Hz) for the recording of the air temperature fluctuations and a microwave cavity for the measurement of the short-term fluctuations of the radio refractive index (frequencies up to 100 Hz). However, all variables are low-pass filtered at 12.5 Hz to avoid contamination from mechanical vibration of the boom. The refractive index fluctuations are then translated into the short-term fluctuations of the water vapor density (Bean and Dutton, 1968). A downward pointing IR system was used for the measurement of the surface temperature of the lake.

The flight patterns were designed to give, for constant fetch (i.e., constant distance from the upwind shore), maximum coverage of the air field over the entire lake. Although true constant fetch was not realized in practice, every effort was made to maintain constant distance from the upwind shore consistent with the requirement that the gust probe be flown level and straight during a run. Measurements were made during intensive periods of approximately two weeks duration in May, June, August, October and November, 1972.

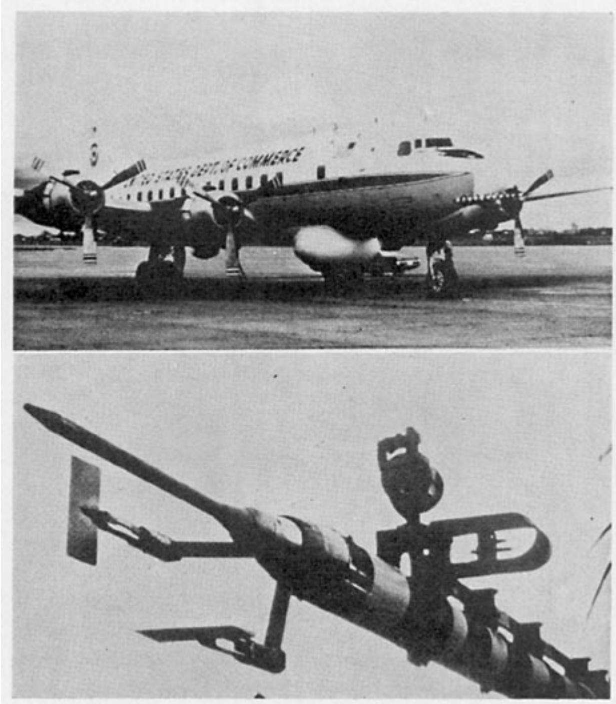

Fig. 1. The NOAA Research Flight Facility (RFF) DC-6 research aircraft (upper) and the gust probe system (lower).

Table 1 presents a summary of the pertinent results obtained during the IFYGL. Note that in May and June the lake surface temperature is much lower than the air temperature at 30 m. The fluxes of heat and water vapor are approximately zero for May, and small and negative for June. This implies that in June water vapor may be condensing onto the lake surface. It is interesting to note that the results shown in Table 1 agree well with the annual evaporation curve given by Derecki (1972) who finds that the lowest evaporation rate occurs in the spring (with condensation onto the lake surface during April, May and June) and the highest in the fall (September and October). In this discussion, evaporation from a water surface is defined as the amount of water vapor carried aloft from unit area per unit time; hence,

$$E = \text{Evaporation} = \rho_w w \quad [\text{g m}^{-2}\ \text{s}^{-1}], \tag{1}$$

where $\rho_w$ is the water vapor density (g m$^{-3}$) and $w$ the vertical wind (m s$^{-1}$). We report $E$ as equivalent depth of water evaporated per day, i.e., cm day$^{-1}$. The determination of the evaporation rate implies a time average of the product of $\rho_w$ and $w$. Consequently, we can express the instantaneous values of both of these quantities as composed of a mean value (denoted by an overbar) and a fluctuating quantity (denoted by a prime), i.e.,

$$\left.\begin{aligned} \rho_w &= \bar{\rho} + \rho_w' \\ w &= \bar{w} + w' \end{aligned}\right\}. \tag{2}$$

The evaporation may then be expressed as

$$E = \overline{\rho_w' w'} + \bar{\rho}_w \bar{w}, \tag{3}$$

where the first term on the right is the eddy flux. For sufficiently long averaging time, i.e., so that $\bar{w} \equiv 0$, then

$$E = \overline{\rho_w' w'}\ [\text{gm}^{-2}\text{s}^{-1}]. \tag{4}$$

A similar argument is used for the determination of the heat flux $(\overline{w'T'})$ and momentum flux $\overline{u'w'}$. Note that $w$ is the vertical velocity and $u$ the horizontal velocity measured along the longitudinal axis of the aircraft. As a practical restraint, 3 min legs were chosen to minimize variation in fetch with changing shoreline or in traversing the lake with the wind. All variables were linearly detrended over the 3 min period and the flux values calculated from the resultant data.

In this paper we discuss in some detail the results we have obtained from airborne measurements of the pertinent parameters over Lake Ontario. In particular, we focus our attention on the measurements during May and October, 1972. These were made at altitudes ranging from 18 to 300 m above the lake surface.

## 2. Measurements and data reduction

Although measurements were taken throughout the region above the lake, our main efforts at making a thorough investigation of the boundary layer were concentrated near the central portion, primarily along a line running from Cobourg to Sodus Bay. Flights were made at several heights above the lake surface both along and across the prevailing wind field as shown in Fig. 2.

From the original data tapes the calibrated and detrended time series records were constructed at a rate of 50 samples per second. From these records, 3 min time segments were chosen for analysis: mean values of the three components of the wind field ($u$, $v$, $w$), temperature ($T$), and water vapor density ($\rho_w$) as well as their flux quantities were determined. In this context $v$ is always the component of the wind normal to the flight path. For the spectrum analysis of these records the sample rate was reduced to 25 samples per second by averaging consecutive pairs of samples. The aircraft acts as an Eulerian reference

Table 1. IFYGL average values. All data at 30 m above the lake surface.

| | $T_s$ (°C) | $T_a$ (°C) | $\overline{\rho_w' w'}$ (cm day$^{-1}$) | $\overline{w'T'}$ (K m s$^{-1}$) |
|---|---|---|---|---|
| May | 2 | 10 | ∼0* | ∼0* |
| June | 9 | 17 | −0.01 | −0.01 |
| August | 19 | 18 | 0.04 | ∼0 |
| October | 14 | 12 | 0.32 | 0.02 |
| November | 6 | 0 | 0.20 | 0.04 |

* These values are probably slightly negative as we were not able to determine such small negative values during the May alert period; we were equipped to do so from June onward.

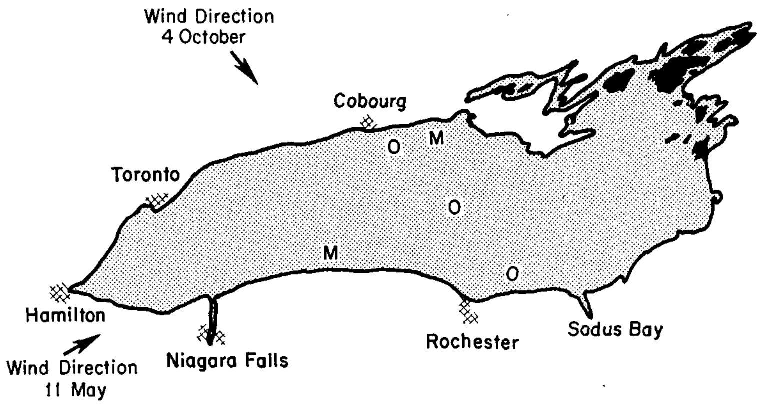


FIG. 2. Lake Ontario with indicated regions of intensive measurements during May (M) and October (O).

system in which the flow moves past the sensor at the true air speed of the aircraft. In this fashion, contributions to the flux quantities from wavelengths much longer than those normally measured from fixed platforms can be measured in a comparatively short period of time. The fixed vane gust probe, which is referenced to an inertially stabilized platform, measures the turbulent fluctuations $w'$ of the vertical wind; the microwave refractometer measures refractivity which is used to calculate turbulent water vapor fluctuations $\rho_w'$. As a result, one may estimate the eddy correlation of water vapor flux, $\overline{w'\rho_w'}$, with relative ease. The horizontal resolution of the gust probe system was from about 8.4 m (the low-pass filter cutoff) to about 8.4 km (half the flight path length equivalent to a 3 min run).

Grossman and Bean (1973) present a detailed error analysis on the airborne gust probe system. This error analysis is rather long and detailed; it is sufficient for the present to note that the expected errors from all sources in the flux values reported here are never greater than 10%.

## 3. The time series records

### *a. 11 May 1972*

Fig. 3 presents the time series records for the turbulent fluctuating components of the wind ($u'$, $v'$, $w'$),

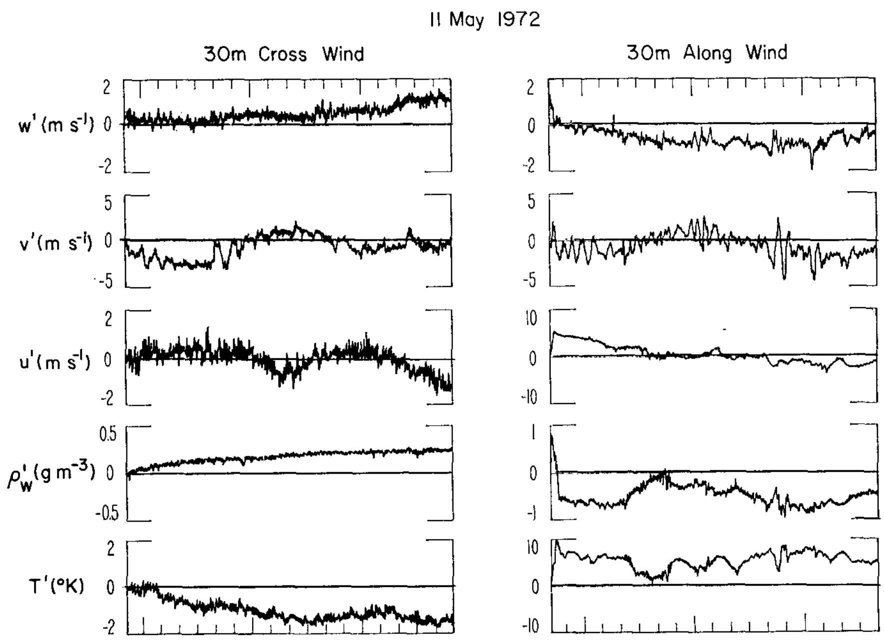


FIG. 3. Time series records for the fluctuating components of the wind ($u'$,$v'$,$w'$), the water vapor density ($\rho_w'$), and the temperature ($T'$) at 30 m for cross- and alongwind flights. The abscissa represents time with each "tick" mark equivalent to 10 s.

TABLE 2. Statistics for each 3 min time segment on 11 May 1972.

| Level (m) | $\overline{u'w'}$ ($m^2 s^{-1}$) | $\overline{w'T'}$ ($m^2$ K $s^{-1}$) | $\overline{\rho_w' w'}$ (cm $day^{-1}$) |
|---|---|---|---|
| 30 | −0.10 | 0.01 | 0.00 |
| 90 | 0.08 | 0.02 | −0.02 |
| 150 | −0.00 | −0.01 | 0.04 |
| 300 | −0.12 | −0.02 | −0.03 |
| 18 | −0.05 | −0.02 | 0.04 |
| 30 | 0.50 | 0.10 | 0.05 |
| 90 | −0.08 | −0.03 | 0.10 |
| 150 | −0.40 | −0.01 | −0.00 |
| 30 | −0.03 | −0.02 | −0.03 |
| 150 | −0.82 | 1.01 | −1.27 |

the water vapor density ($\rho_w'$), and temperature, ($T'$), at 30 m for both cross- and alongwind flights approximately 10 km south of the north shore of the lake.

In these and subsequent figures, the mean subtracted from each data point is the average of the first record of each 3 min sample (which consists of 280 records). This should explain the apparent trend in the data. In the analysis, however, the data were properly detrended as indicated in the previous section. Table 2 summarizes the pertinent statistics for each 3 min time segment.

In general, this particular day exhibited small negative heat, water vapor and momentum flux; the only exception were those values obtained on the flight path shown in Fig. 4. This particular flight, however, exhibits a structure reminiscent of that found on measurements taken when instabilities of the Kelvin-Helmholtz type are present (Woods, 1969; Browning, 1971; Emmanuel, 1973). Note the general appearance of the wave-induced fluctuations in all the quantities. Those pertaining to $w'$ have an average descending motion of ~8.75 s which corresponds to a horizontal scale of ~814 m at the aircraft speed of 92 m $s^{-1}$. The ascending portion takes place in ~14.3 s which corresponds to ~1330 m. At the same time, $\rho_w'$ and $T'$ exhibit high (negative) correlation. Also, a slight lag is found between the minima in $T'$ and $u'$. Furthermore, the broad maximum values of $\rho_w'$ and minimum values in $T'$ and $u'$ compared to the saw-tooth structure of $w'$ suggest the aircraft was traversing a region of breaking waves. In addition, during this time the aircraft experienced three to four "bumps." The surface temperature of the lake did not vary by more than 0.1°C and was much less than the air temperature at 30 m, so we may exclude the possibility of thermal plumes. In fact, strong positive temperature gradients persisted during the day over the entire lake. On the average the surface temperature was approximately 2°C while the temperature at 30 m was in the neighborhood of 10°C and at 90 m it was 14°C. The mean temperature was nearly constant between 90 and 300 m.

*b. 9–10 October 1972*

October 9 was the first day in the IFYGL "evaporation year" that a cold polar continental outbreak moved

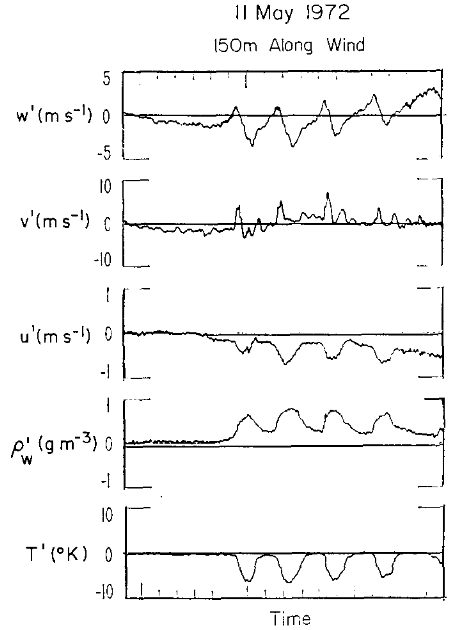


FIG. 4. As in Fig. 3 except for an alongwind flight at 150 m.

over the lake. During the day the winds were steady over the entire lake blowing out of the northwest at about 12 m $s^{-1}$ at an altitude of 30 m. The continuous and strong winds had a pronounced effect on both the surface temperature distribution of the lake and the temperature at 30 m. Fig. 5 gives the surface temperature distribution obtained on two flight paths from Cobourg to Sodus Bay and back to Cobourg. Bathymetric maps indicate that there is a sharp increase in the depth of the lake approximately 10 km SSE of Cobourg. The induced wind drag on the lake sürface due to the persistently strong winds resulted in considerable upwelling currents from the north shore to

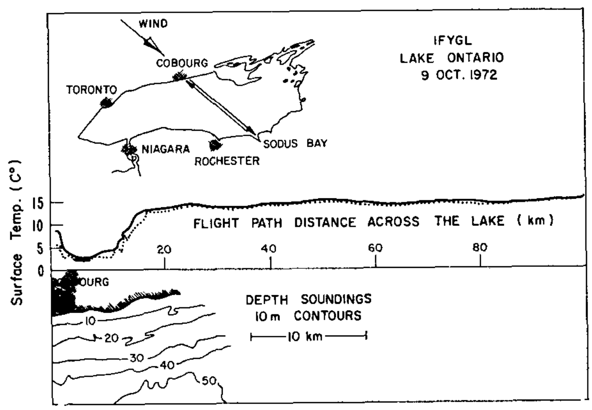


FIG. 5. Surface temperature distribution obtained via the IR system made on 9 October 1972 during two traverses across the lake at 90 m (solid line) and 150 m (dotted line). Also shown is the depth of the lake in the vicinity of Cobourg, Canada, where the surface temperature was lowest.

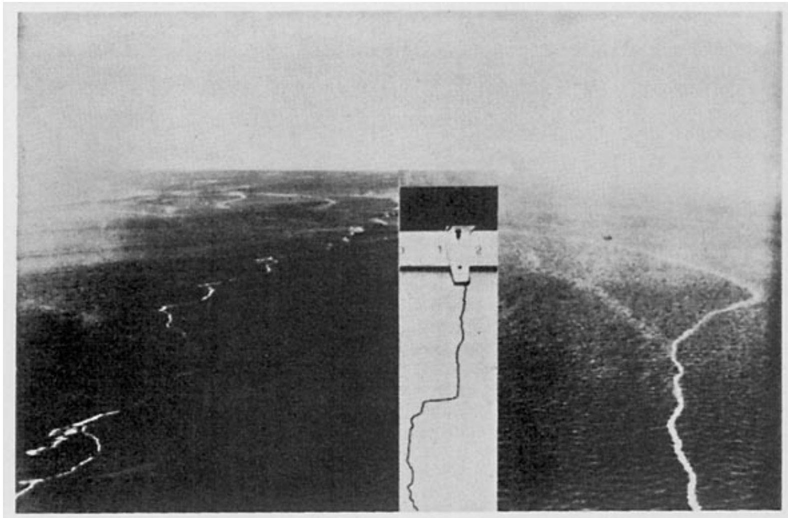

FIG. 6. The convergence zone separating the cold and warm water masses along with the IR surface temperature gradient corresponding to the photo on the right.

about 5–10 km offshore. Fig. 6 shows the white convergence zone separating the cold and warm masses of water as observed on the following day, 10 October. Also shown on the figure is the surface IR temperature trace as the aircraft crossed the white "streak."

As in the case for the May data, the original time series records were used to extract the time series of the turbulent fluctuating quantities of the three components of the wind, temperature and water vapor density. This was accomplished by removing the mean values for each time segment and also any linear trends present over the 3 min runs. These are shown in Fig. 7 for crosswind flights made at 30 m.

Table 3 summarizes the statistics for each 3 min time segment for each altitude flown.

Fig. 8 presents the flux statistics obtained throughout the day on flights made at 90 m above the lake surface. Direct comparison with the flux values obtained in May, which was a quiet day, shows that 9 October was a rather active day. In May all flux values were small or negative, and in the case of evaporation we apparently have condensation onto the lake surface. In

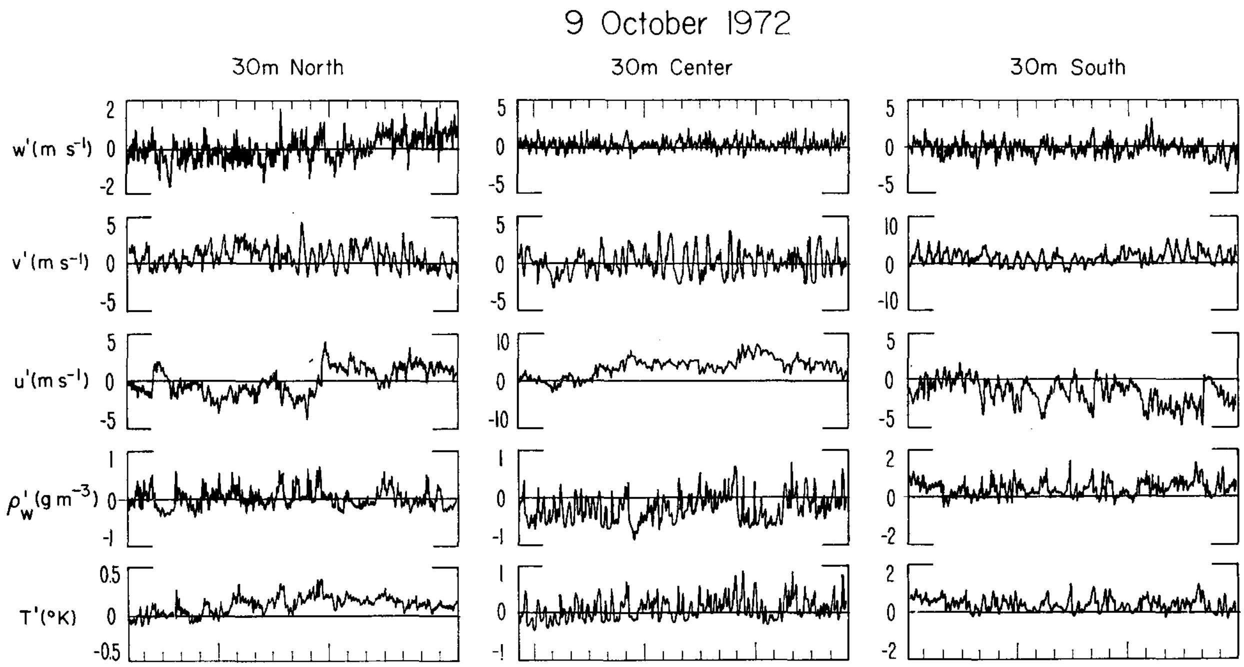


FIG. 7. Time series records for the fluctuating components of the wind $(u',v',w')$, the water vapor density $(\rho_w')$, and the temperature $(T')$ at 30 m for crosswind flights. The abscissa represents time with each "tick" mark equivalent to 10 s.

TABLE 3. Mean flux values for 9 October 1972. All flights normal to the wind.

| Location | Level (m) | $\overline{u'w'}$ ($m^2 s^{-2}$) | $\overline{w'T'}$ ($m K s^{-1}$) | $\overline{w'\rho_w'}$ ($cm day^{-1}$) |
|---|---|---|---|---|
| | 30 | 0.09 | 0.01 | 0.48 |
| North | 90 | −0.67 | −0.02 | 0.55 |
| | 150 | −0.39 | 0.01 | 0.58 |
| | 30 | 0.02 | 0.08 | 0.92 |
| Center | 90 | −0.23 | 0.10 | 1.07 |
| | 150 | −0.30 | 0.06 | 0.60 |
| | 30 | −0.36 | 0.12 | 1.36 |
| South | 90 | 0.37 | 0.10 | 1.14 |
| | 150 | −0.24 | 0.10 | 1.29 |

October, however, a marked increase in evaporation is evident as measurements were made from north to south of the lake, perhaps due to building surf and resultant spray from white caps. Independent measurements of the turbulent fluxes made by McBean and Paterson (1975) on the same day, although not necessarily at the same location, height and time, agree well with those reported here.

## 4. Spectrum analysis

From the time series records of $u'$, $w'$, $T'$ and $\rho_w'$ the flux quantities were calculated via the eddy correlation technique. The resulting time series (of the product of $w'$ with each of the other variables), as well as those of $u'$, $w'$, $T'$ and $\rho_w'$, were spectrum-analyzed by means of a fast Fourier transform technique to gain further insight into the nature of the turbulent regions prevailing over the lake. The spectra were plotted in the following way: the frequency range $10^{-2}$ to 12.5 Hz was divided into 28 frequency band widths. The first seven points of the spectra are single-value points. The following points are block-averaged spectral estimates ranging from 2 points at the lower frequency range to 93 points at the high-frequency end. The averaged values are then plotted at the mid-point of each frequency band width. For convenience in the interpretation of the data, the spectral densities were multiplied by frequency (except for Fig. 9) so that area under the

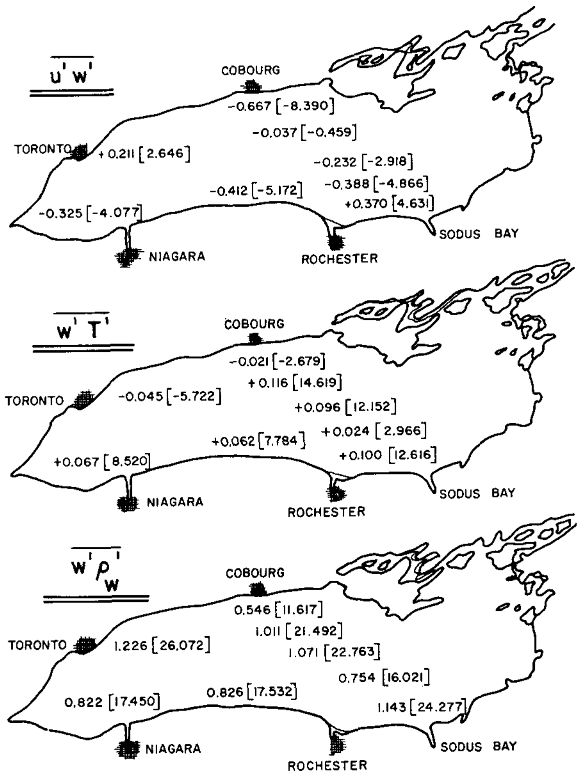


FIG. 8. The distribution of momentum, heat and water vapor fluxes at 90 m for 9 October 1972 (flight paths normal to the wind). Legend: $\overline{u'w'}$ [$m^2 s^{-2}$], $\overline{w'T'}$ [$m K s^{-1}$], $\overline{w'\rho_w'}$ [$cm day^{-1}$]. Quantities in brackets are in dyn $cm^{-2}$ for $\overline{u'w'}$ and mW $cm^{-2}$ for $\overline{w'T'}$ and $\overline{w'\rho_w'}$.

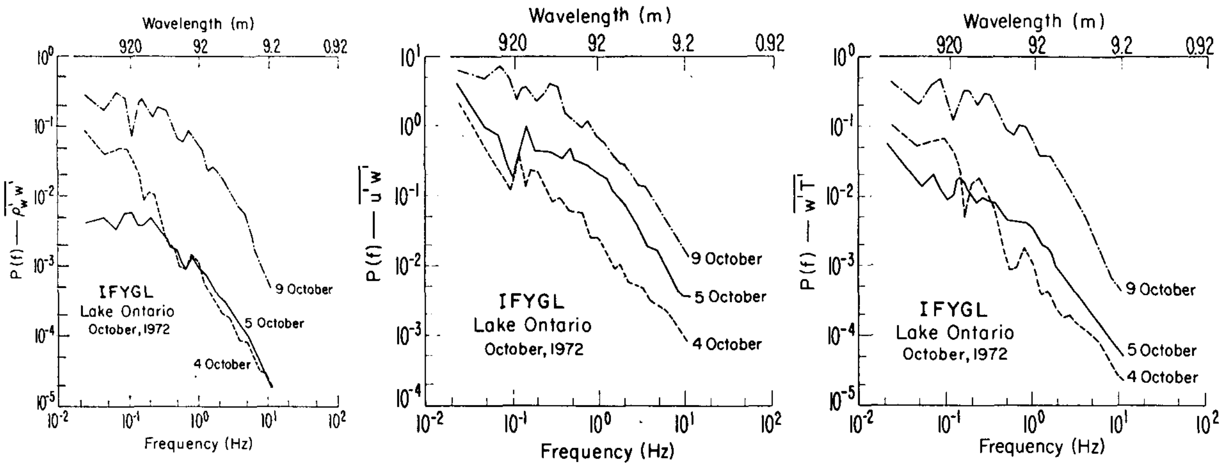


FIG. 9. Spectra of the fluxes of water vapor, momentum and heat at 30 m for crosswind flights. Units: $P(f)$—$\overline{\rho_w'w'}$ [$(g m^{-2} s^{-1})^2$ per unit bandwidth], $P(f)$—$\overline{u'w'}$ [$(m s^{-1})^2$ per unit bandwidth], $P(f)$—$\overline{w'T'}$ [$(K m s^{-1})^2$ per unit bandwidth].

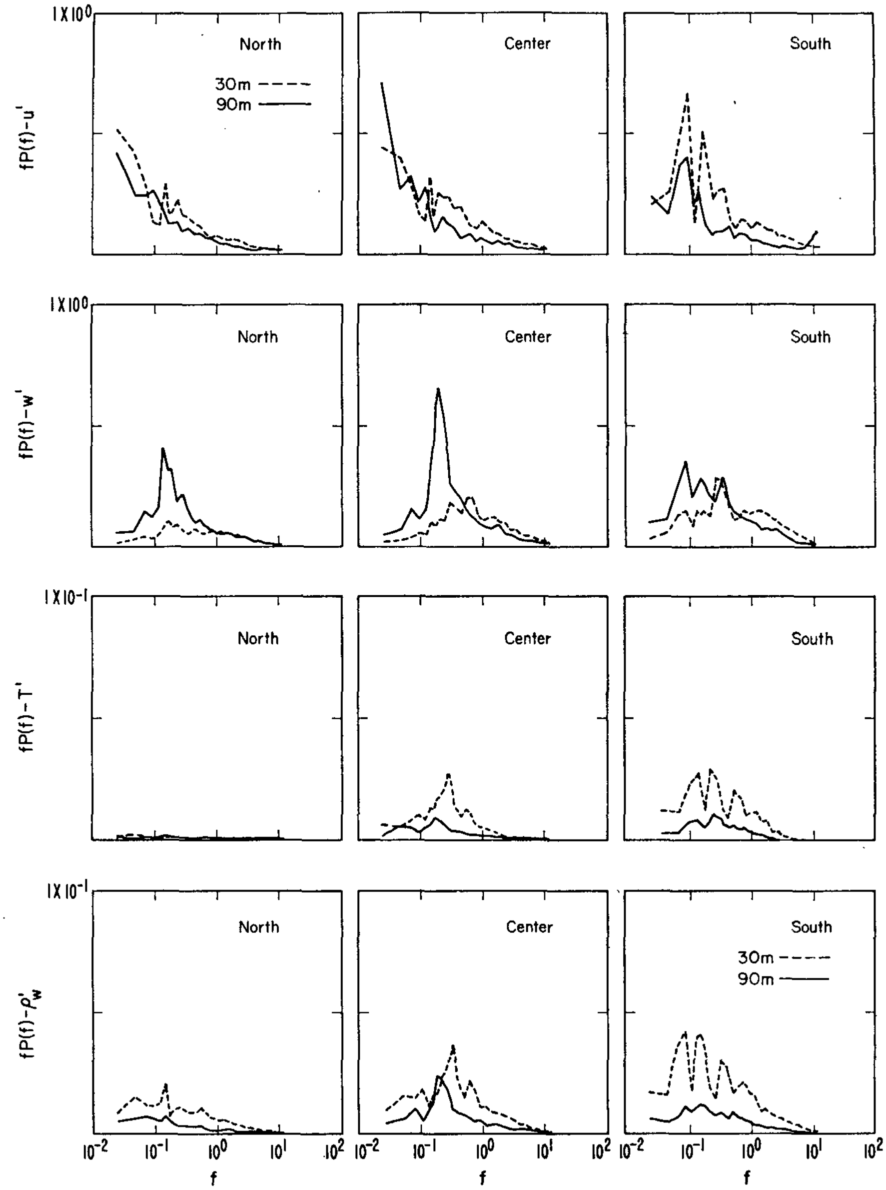


FIG. 10. Spectra of $u'$, $w'$, $T'$ and $\rho_w'$ obtained during flights normal to the wind at the north, center and south sides of the lake. The dotted line is for flights made at 30 m above the lake surface, the solid for 90 m. All flights were made on 9 October 1972. Units: $fP(f)$—$u'$, $w'$ [$m^2 s^{-2}$], $fP(f)$—$T$ [$(K)^2$], $fP(f)$—$\rho_w'$ [$g^2 m^{-6}$], $f$ [Hz].

curve is proportional to the energy when plotted with the linear ordinate $fP(f)$ and log $f$ as abscissa.

In early October and, in particular, on the 4th and 5th, the prevalent atmospheric conditions over the Lake Ontario basin were considered to be normal for this period of the year. Measurements taken on those days were analyzed and compared with those obtained on the 9th. In particular, the mean fluxes of heat, momentum and water vapor were found to be nearly an order of magnitude lower. Fig. 9 shows the spectral characteristics of the momentum, heat and water vapor fluxes. The abscissa, in addition to the frequency scale, is also shown as wavelength (length scale). This, of course, was accomplished by using the aircraft speed of 92 m $s^{-1}$ and, as a result, all our data are confined between wavelengths of 9.2 m and 4.5 km. Note that at all scales the spectral power for 9 October is nearly an order of magnitude higher than those for either 4 or 5 October.

### *a. 11 May 1972*

On 11 May 1972 several flights were made both parallel to and across the prevailing wind field at 10 km offshore along the north side of the lake. Spectral estimates of $u'$, $w'$, $T'$ and $\rho_w'$ as well as the spectra of the vertical flux show little energy present in the turbulent field over the lake surface. The flights were made at 18, 30 and 90 m. These results, although not shown here, are to be expected since the day was chosen because of its typical spring calmness over the entire area, and is to be compared with the very active conditions that prevailed on 9 October 1972.

### b. *9 October 1972*

Figs. 10 and 11 show the spectra of $u'$, $w'$, $T'$, $\rho_w'$ and $w'$ with each of the other variables. Note the increase in power at the center and south sides of the lake as compared to that at the north. This is evident at all three levels flown on this particular day. The results obtained by Bean *et al.* (1972) during BOMEX are confirmed here. The spectra demonstrate clearly the tendency for the peak value to change to lower frequencies (longer wavelengths) with increasing height. This, of course, implies that while the small-scale eddies contribute more to the flux of water vapor near the surface, there is a tendency for this effect to be transferred to larger and larger eddies with increasing height.

Plotting the maximum wavelength of the spectra vs height on log-log paper one obtains a linear relationship with a slope of ~0.7 and intercept at the 10 m height of ~110 m, similar to the BOMEX results reported by Bean *et al.* (1972). In addition, the distinct features observed by these same authors in the spectra for along- and crosswind flights during BOMEX have also been observed over Lake Ontario. Consequently, their assertion that the spectra reveal an extraordinary organization of the clear air convection regime in the lower subcloud layer is reaffirmed here.

## 5. Conclusions

The results obtained during the "evaporation year" of IFYGL indicate that during the spring months there is apparent condensation onto the lake surface. This, of course, is due to the large temperature difference that exists between the surface temperature of the lake and the temperature of the overlying air. It was found that

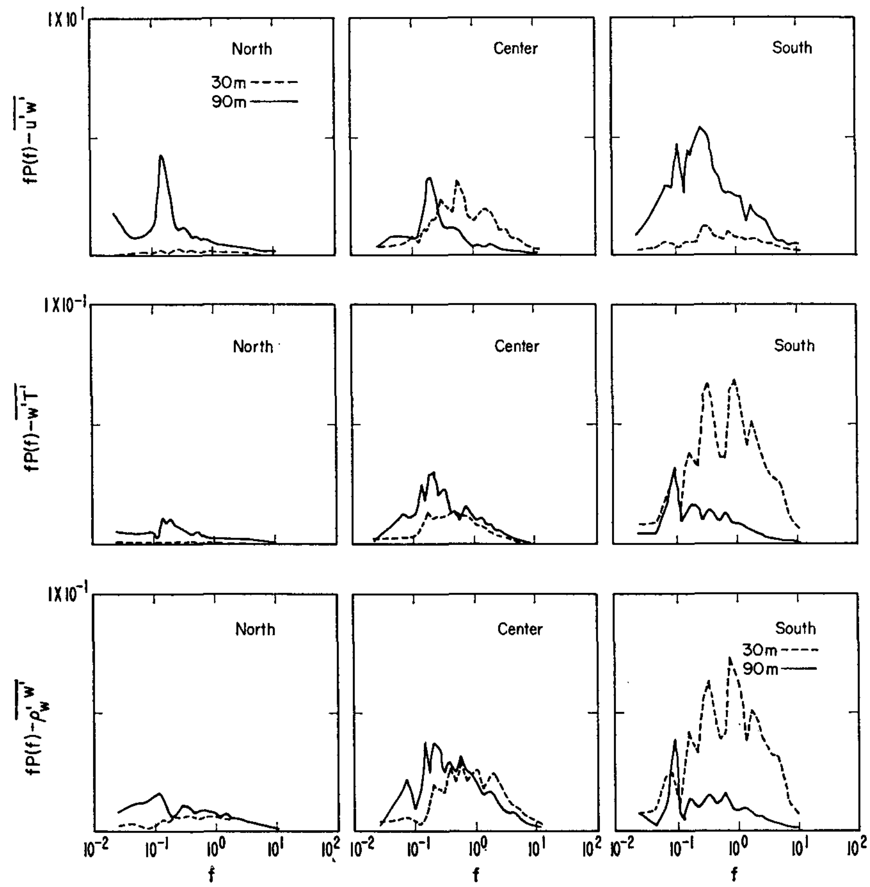


FIG. 11. Power spectra of the fluxes of water vapor, momentum and heat obtained during flights normal to the wind at the north, center and south sides of the lake. The dotted line is for flights made at 30 m above the lake surface, the solid for 90 m. All flights were made on 9 October 1972. Units: $fP(f)$—$\overline{u'w'}$ [$m^2 s^{-2}$], $fP(f)$—$\overline{w'T'}$ [$(K\, m\, s^{-1})^2$], $fP(f)$—$\overline{\rho_w'w'}$ [$(g\, m^{-2} s^{-1})^2$], $f$ [Hz].

for the months of May and June the surface temperature of the lake was about 8°C lower than the air temperature at 30 m above the lake surface. The month of August was characterized by a near-equilibrium temperature distribution between the lake surface and that of the air at 30 m. As a result, both the heat flux and evaporation rate were found to be very small. During October and November the lake surface temperature was found to be greater than that at 30 m. Both the heat flux and evaporation rate were found to be large and positive.

While the "normal" evaporation rate for October is near 0.3 cm day$^{-1}$, this rate almost quadruples during polar continental outbreaks. These are characterized by cold dry air moving down from Canada and accompanied by sustained high winds. On 9 October the winds were of the order of 12 m s$^{-1}$ over the entire area of the lake. The resultant evaporation rate (cm day$^{-1}$) at the 30 m level was 0.48 at the north side of the lake, 0.92 at the center, and 1.36 at the south side of the lake. The heat flux also increases from north to south at the 30 m level with the most dramatic increase being from north to center. While there is upward transfer of momentum at the north and center of the lake, the south is characterized by downward flow of momentum, again at the 30 m level.

The average annual precipitation falling into Lake Ontario is about 80 cm, being nearly balanced by the evaporation of 70 cm. The months of October, November and December normally account for 42% of the annual evaporation while October accounts for 15% of the annual total. The event just described produced 2.50 cm of evaporation in a 60 h period to account for 23% of the monthly mean evaporation in only 8% of the month.

The polar continental outbreaks are also characterized by strong upwelling currents along the north shore of the lake. We found that at ~10 km offshore along the north side the surface temperature of the lake had the smallest value due to the upwelling of cold bottom water. This convergence zone was also found to correspond to a region in the lake bottom where there is a sharp increase in the depth of the lake.

Derecki (1972) finds that the maximum evaporation of ~11.4 cm (or ~0.38 cm day$^{-1}$) is in September and October; the evaporation rate is nearly 0.35 cm day$^{-1}$ for October (all these from surface measurements around the lake). We have found that at the 30 m level across the lake the evaporation rate is ~0.32 cm day$^{-1}$ for the month of October.

*Acknowledgments.* We acknowledge the valuable critique of the manuscript given by the reviewers.

## REFERENCES

Bean, B. R., and E. J. Dutton, 1968: *Radio Meteorology.* Dover Publ., 435 pp.

——, R. Gilmer, R. McGavin and C. Travis, 1972: An analysis of airborne measurements of vertical water vapor flux during BOMEX. *J. Atmos. Sci.*, **29**, 860–869.

Browning, K. A., 1971: Structure of the atmosphere in the vicinity of large-amplitude Kelvin-Helmholtz billows. *Quart. J. Roy. Meteor. Soc.*, **97**, 283–299.

Derecki, Jan A., 1972: An unknown quantity. *NOAA*, **2**, No. 3, U. S. Government Printing Office, 38–41.

Emmanuel, C. B., 1973: Richardson number profiles through shear instability wave regions observed in the lower planetary boundary layer. *Bound. Layer Meteor.*, **5**, 19–27.

Grossman, R., and B. Bean, 1973: An aircraft investigation of turbulence in the lower layers of a marine boundary layer. NOAA TR ERL 291, WMPO-4.

Lenschow, D. H., 1974: Model of the height variation of the turbulence kinetic energy budget in the unstable planetary boundary layer. *J. Atmos. Sci.*, **31**, 465–474.

McBean, G. A., and R. D. Paterson, 1975: Variations of the turbulent fluxes of momentum, heat and moisture over Lake Ontario. *J. Phys. Oceanogr.*, **5**, 523–531.

Woods, J. D., 1969: On Richardson's number as a criterion for laminar-turbulent-laminar transition in the ocean and atmosphere. *Radio Sci.*, 4, 1289–1298.