JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 102, NO. D24, PAGES 29,155–29,166, DECEMBER 26, 1997

Lake-induced atmospheric circulations during BOREAS

Jielun Sun,[1] Donald H. Lenschow,[2] L. Mahrt,[3] Tim L. Crawford,[4]
Kenneth J. Davis,[2] Steve P. Oncley,[2] J. I. MacPherson,[5]
Qing Wang,[6] Ron J. Dobosy,[4] and R. L. Desjardins[7]

Abstract. Lake-induced atmospheric circulations over three lakes ranging from 3 to 10 km width are analyzed using data from three aircraft during the 1994 Boreal Ecosystem-Atmosphere Study (BOREAS). A well-defined divergent lake breeze circulation is observed over all three lakes during the day. Under light wind conditions, the lake breeze is not very sensitive to the water temperature, and the strength of the divergence over the lake decreases with increasing lake size. The boundary-layer development over the surrounding land can be very important for generating a horizontal pressure difference which drives the lake breeze. Diurnal and seasonal variations of lake breezes are investigated on the basis of repeated passes from the different aircraft at different altitudes from late spring to early fall of 1994. The lake breeze divergence increases with time during the day and reaches a maximum around 1300 LST. The latent heat flux over 10-km-wide Candle Lake increases steadily from spring to fall as the lake temperature increases. The latent heat flux over the land reaches a maximum during the summer due to evapotranspiration. The lake effect on area-averaged fluxes sometimes leads to a negative heat transfer coefficient for an averaging scale of several times the lake width.

1. Introduction

Atmospheric boundary layer flow can be strongly influenced by the spatially varying energy exchange between heterogeneous ground surfaces and overlying air. Lakes can lead to particularly strong variations in surface heat flux.

The summer daytime air over a lake typically is cooler and denser than the air overlying relatively warm adjacent land surfaces. As a result, a horizontal pressure gradient is generated by the air density difference which forces onshore flow, commonly called the lake breeze. Lake breeze studies have been reported for Lake Erie [*Biggs and Graves*, 1962], Lake Michigan [*Lyons*, 1972; *Keen and Lyons*, 1978], and Lake Ontario [*Estoque et al.*, 1976]. A commonly applied lake breeze index, $\sigma \equiv V^2/(c_p \Delta T)$, was introduced by *Biggs and Graves* [1962]. Here V is a characteristic wind speed such as the hourly-averaged speed between 1000 and 1600 LT, or the geostrophic wind from 1200 UT surface maps at an inland location, c_p is the specific heat of dry air, and ΔT is the difference between the maximum surface air temperature at the inland location and the mean water temperature.

The lake breeze and its related thermal internal boundary layer have also been studied with numerical models [*Segal and Pielke*, 1985; *Arritt*, 1987]. *Arritt* [1987] concluded that the exact lake surface temperature does not critically influence the characteristics of the lake breeze as long as the lake air temperature is cooler than the inland air temperature and that the lake breeze is most sensitive to depth of the internal boundary layer over the lake.

Rabin et al. [1990] and citations therein noted that lakes on scales of 1–10 km could induce cloud-free areas in a region of otherwise convective cloudiness associated with surface heating. They also noted that the minimum lake size required to affect the cloud pattern is proportional to the wind speed; on windier days, only the large lakes affect the cloud pattern. For small lakes the large-scale flow may essentially eliminate the horizontal gradient of air temperature due to rapid removal of air immediately above the lake. Furthermore, lake breezes associated with small lakes are more likely affected by background transient mesoscale circulations. *Arritt et al.* [1996] have also found cloud suppression associated with the lake breeze.

As part of the 1994 Boreal Ecosystem-Atmosphere Study (BOREAS), four aircraft flew over a region in Saskatchewan and Manitoba, Canada, containing numerous lakes [*Sellers et al.*, 1995]. The extensive data collected by the aircraft offer more detailed temporal and spatial observations of the flow above lakes than previously available. We examine the generation of the lake breeze, the strength of such circulations as a function of the large-scale flow and lake-land temperature contrast, and contrasts in vertical fluxes over the lake and the adjacent area.

The atmospheric data analyzed in this paper are from the aircraft flying repeatedly along the same flight track (section 2). The general characteristics of meteorological variables over the lake and the surrounding land are described in section 3. A new scaling argument for predicting the strength of the lake-induced atmospheric circulation is developed, and important factors on the generation of the lake breeze are discussed in section 4. Diurnal variation of the lake-induced atmospheric

---

[1] Program in Atmospheric and Oceanic Sciences, University of Colorado, Boulder.

[2] National Center for Atmospheric Research, Boulder, Colorado.

[3] College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis.

[4] Atmospheric Turbulence and Diffusion Division, NOAA ARL, Oak Ridge, Tennessee.

[5] National Research Council, Ottawa.

[6] Meteorology Department, Naval Postgraduate School, Monterey, California.

[7] Land Resources Research Centre, Agriculture Canada, Ottawa.

Paper number 97JD01114.
0148-0227/97/97JD-01114$09.00

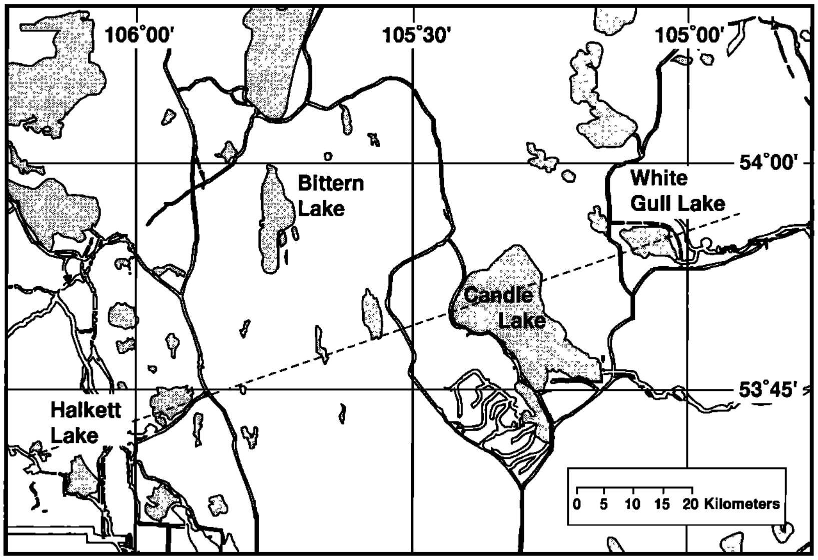


Figure 1. Schematic of Candle Lake flight track.

circulation is investigated in section 5. Seasonal variations of the lake breeze are examined in section 6. The influence of the lake on area-averaged fluxes is documented in section 7, and results are summarized in section 8.

2. Data Description

2.1. General Information

This study focuses on Candle Lake in the BOREAS southern study area (SSA), located 70 km northeast of Prince Albert, Saskatchewan, Canada. Candle Lake, surrounded by mixed canopies, is about 10 km across in the northeast-southwest direction and about 20 km in the northwest-southeast direction and is the largest lake in the SSA. In order to study the lake breeze for different sizes of lakes the data over White Gull Lake (5 km in diameter) and Halkett Lake (3 km in diameter) will be compared with those over Candle Lake. All three lakes are on the same flight track used by all aircraft (Figure 1). White Gull Lake is in a region of black spruce and mixed vegetation about 12 km NE of Candle Lake, and Halkett Lake is surrounded by aspen about 50 km SW of Candle Lake.

Measurements from the NOAA LongEZ, Canadian NRC Twin Otter [*MacPherson*, 1996], and NCAR Electra aircraft were used. Both the Twin Otter and the LongEZ flew at about 30 m above the surface, and the Electra flew at altitudes ranging from 100 m to 3 km above the surface. During the three intensive field campaigns, there were 13, 120, and 66 low-level legs over Candle Lake for the Twin Otter, LongEZ, and Electra, respectively, and 37 Electra flight legs higher than 100 m and within the boundary layer. The data cover between 0900 LST and 1700 LST from late May to mid-September. Wind components, air temperature, humidity, and CO_2 concentration are available at 25 s^{-1} on the Electra, 16 s^{-1} on the Twin Otter, and 40 s^{-1} on the LongEZ. In addition, the O_3 concentration was recorded on the Electra and the Twin Otter.

In order to document the land-lake surface temperature contrasts, track segments over land about the width of the lake on both sides of the lake were selected. Fluxes over the lake and over the adjacent land segments were calculated using eddy correlation methods where the unweighted mean is computed over a window size equal to the lake width.

2.2. Data Comparisons Between Aircraft

The Electra flew a Barnes Engineering Model PRT5 radiometer during the first intensive field campaign (IFC-1) and both the PRT5 and a Heimann radiometer during IFC-2 and IFC-3. Surface radiation temperatures from the two radiometers show very good agreement. During IFC-1 the PRT5 sometimes failed due to instrument overheating.

During the three field campaigns in 1994 the Twin Otter and the Electra flew over Candle Lake on the same day on four occasions and the LongEZ and the Electra on nine occasions. In general, the Twin Otter and LongEZ Candle Lake radiation temperatures are about 1°C lower than the Electra. On the basis of the four intercomparison flights between the LongEZ and the Twin Otter the air temperature and the water vapor mixing ratio are, on the average, about 1.75°C and 1.2 g kg^{-1} higher on the Twin Otter. The latent heat flux compares well between the two, while the sensible heat flux appears to be 38 W m^{-2} higher from the LongEZ than the Twin Otter [*Kelly et al.*, 1996; *Dobosy et al.*, this issue]. No corrections to any of the aircraft data are made in this study.

3. General Characteristics of Meteorological Variables Around Candle Lake

Air temperature averaged over all the Candle Lake passes is about 0.7°C warmer over the land than over the lake at the 30 m level and about 0.3°C warmer at the 100 m level (Figure 2 and Table 1). The variation of the air temperature over both the land and the lake follows the variation of the ground temperature (Figure 2). Because of the stably stratified flow over the cool, smooth lake and the unstably stratified flow over the warm, rough land surface, the fluctuations of wind components, air temperature, humidity, and CO_2 and O_3 concentration are smaller over the lake than over the land (Table 3). Sensible heat, latent heat, momentum, carbon dioxide, and ozone fluxes averaged over all the Candle Lake passes are much smaller over Candle Lake than over the land (Table 2).

The standard deviations of the pass-averaged variables in Table 1 and fluxes between the passes in Table 2 include diurnal and day-to-day variations and flux random sampling errors from each pass (sections 5 and 6). The influence of cold front passages on surface radiation temperature and air temperature is evident in Figure 2b.

The sensible heat flux averaged over all the Candle Lake passes is weak downward over the lake and strong upward over the land, which is also found by *McDermott and Kelly* [1995]. The moisture flux is upward over both the lake and the land. The CO_2 and O_3 fluxes are downward over both the land and the lake at the 100 m level but upward over the lake at the 30 m level (Figure 3). The negative skewness of the vertical velocity at 30 m over the lake (Table 3) implies that the strongest vertical motions are downdrafts. This suggests that the main turbulence source over the lake is above 30 m. Combining the skewness of the vertical wind component in Table 3 and the vertical flux convergence in Table 2, we infer that the O_3 and CO_2 sinks are between 30 m and 100 m over the lake and below 30 m over the land; the heat source is above 30 m over the lake and below 30 m over the land; and the moisture source is from the surface (Figure 3). The sinks and sources are the advection of warm, dry, and low CO_2 and O_3 air from land over the lake between 30 m and 100 m.

The specific humidity is about the same over the land as over the lake except sometimes in the morning (section 5) when it is higher over the lake. Carbon dioxide and ozone concentrations are, respectively, about 2 ppmv and 0.3 ppbv higher over the lake than over the land at the 30 m level due to the uptake of the carbon dioxide by the vegetation and ozone deposition to leaf and ground surfaces. The strong downward entrainment of ozone-rich air from the overlying free atmosphere makes the ozone concentration at the 100 m level higher over the land than over the lake even though downward vertical motion associated with the lake breeze may bring down ozone-rich air over the lake.

4. Lake-Induced Atmospheric Circulation

4.1. Scale Analysis

The horizontal pressure difference (ΔP) generated by the thermal contrast between the lake and the land can be estimated by combining the hydrostatic equation and the horizontal equation of motion (neglecting the Coriolis term) along the direction of flight at aircraft flight level z_1:

$$\Delta P = \Delta \int_{z_1}^{z_2} \rho g \, dz = \Delta \rho g H \simeq -\rho_0 g H \Delta T / T_0 \qquad (1)$$

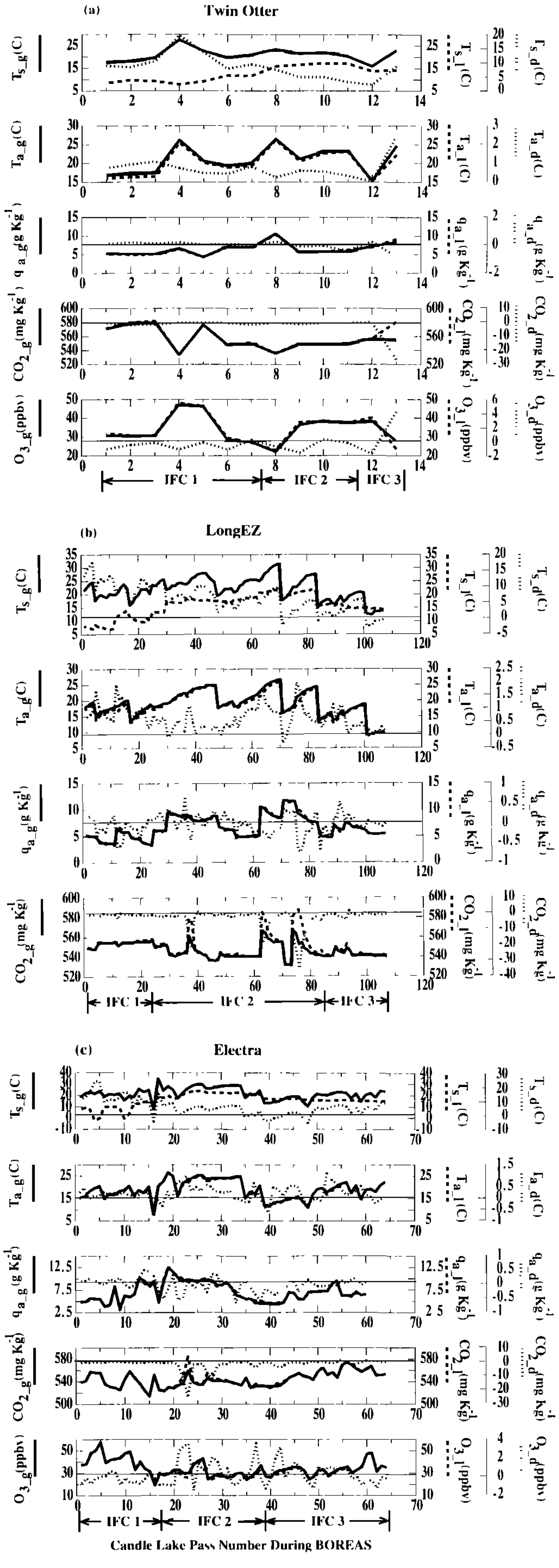


Figure 2. (opposite) Mean surface radiation temperature (T_s), air temperature (T_a), specific humidity (q_a), and CO_2 and O_3 concentrations over both the land (solid lines, subscript g) and Candle Lake (dashed lines, subscript l) for (a) the Twin Otter, (b) the LongEZ except for O_3, and (c) the Electra except for CO_2 for all the Candle Lake passes. The difference between the variables over the land and over the lake (dotted lines, subscript d) is also plotted. The abscissa is the Candle Lake pass number for all passes during the 1994 BOREAS campaigns. The surface radiation temperatures from pass numbers 4, 5, and 10 from the Electra are low due to instrument overheating. The thin horizontal line is the zero difference line.

Table 1. Mean Variables and Standard Deviations of Mean Variable Between Passes (in Parentheses) for All Candle Lake Passes

	Twin Otter (at 30 m)		LongEZ (at 30 m)		Electra (at 100 m)	
Variables	Land	Lake	Land	Lake	Land	Lake
T_a	20.92	20.18	19.54	18.87	19.00	18.73
(C)	(3.67)	(3.61)	(3.50)	(3.49)	(4.12)	(4.06)
q_a	6.50	6.49	6.79	6.82	7.09	7.11
(g kg^{-1})	(1.66)	(1.71)	(2.13)	(2.11)	(2.14)	(2.12)
CO_2	365.9	367.7	359.3	362.0	357.9	358.8
(ppmv)	(10.24)	(11.28)	(5.14)	(7.70)	(8.68)	(2.5)
O_3	33.96	34.21			34.17	33.87
(ppbv)	(7.44)	(7.96)			(7.43)	(7.69)

$$U\Delta U/L \simeq -(1/\rho_0)\Delta P/L. \qquad (2)$$

Here Δ represents the horizontal variation across a lake with width L along the flight track, z_2 is the top of the lake-influenced internal boundary layer at which level the air temperatures over the lake and surrounding land are equal, $H = z_2 - z_1$ is the depth of the lake-induced internal boundary layer above the aircraft flight level, and $\Delta\rho$ and ΔT are the vertically integrated horizontal density and temperature variations, respectively. The subscript 0 represents a reference state. The variables P, T, and U are pressure, air temperature, and wind speed along the direction of flight, respectively, and g is gravity. The state equation

$$P = \rho R T_v \simeq \rho R T \qquad (3)$$

is used in the derivation of (1) together with the assumption that the density variation is dominated by the temperature variation

$$\Delta\rho/\rho_0 \simeq -\Delta T/T_0. \qquad (4)$$

Combining (1) and (2),

$$\Delta U/L \simeq \frac{gH\Delta T}{LT_0U}. \qquad (5)$$

Here $\Delta U/L$ is the contribution to the divergence of the flow over the lake along the flight track. Equation (5) indicates that for a fixed lake size, the divergent flow increases with the vertically integrated horizontal air temperature difference and the depth of the air modified by the cool lake and decreases with ambient wind speed.

4.2. Correlations Among Lake Breeze, Air Temperature and Ambient Wind

The divergence over Candle Lake is estimated from the least squares linear slope of the along-flight-track wind component as a function of distance across the lake. The ambient wind speed U along the flight track is averaged over the land on both sides of the lake. The scatter in Figure 4 probably reflects the importance of the missing variable H, the internal boundary layer depth [see also *Arritt*, 1987]. *Arritt et al.* [1996] have observed lake breeze circulations 250–300 m deep around 1445 EDT with wind speeds of 5 m s^{-1} over Lake Okeechobee, about 40 km in diameter. The cool air over Candle Lake can sometimes be observed even at the 700 m Electra flight level. The variation in H can be caused by variations in large-scale flow, lake-land surface temperature difference, and the diurnal and day-to-day variation of the stratification of the internal boundary layer. The scatter in Figure 4 may also be due to the fact that the divergence along the flight track is estimated with the wind component directly over the lake although the aircraft sometimes flew above the lake-modified air for part of the lake transverse, particularly under strong wind conditions. Under this situation the divergence is displaced and occurs only over that part of the lake where the lake air is not completely replaced by the advected land air. Because of lack of temperature profiles over the lake the replacement of the vertically integrated temperature difference ΔT with the temperature difference at the aircraft level is another source of the scatter in Figure 4.

The traditional lake breeze index, σ in Table 4, is estimated for each Candle Lake pass using the total ambient wind veloc-

Table 2. Average Fluxes and Standard Deviations of Fluxes (in Parentheses) Over Land and Over Candle Lake for all Candle Lake Passes

	Twin Otter (at 30 m)		LongEZ (at 30 m)		Electra (at 100 m)	
Fluxes	Land	Lake	Land	Lake	Land	Lake
Sensible heat flux	174.3	−15.8	110.72	−6.2	105.3	−1.83
(W m^{-2})	(41.4)	(24.2)	(43.3)	(28.5)	(59.4)	(33.6)
Latent heat flux	202.4	26.3	140.8	42.3	159.2	49.86
(W m^{-2})	(55.4)	(43.5)	(65.2)	(62.1)	(76.1)	(58.92)
Friction velocity u_*	0.39	0.08	0.38	0.15	0.28	0.12
(m s^{-1})	(0.26)	(0.1)	(0.22)	(0.15)	(0.16)	(0.11)
Carbon dioxide flux	−0.11	0.01	−0.04	0.003	−0.03	−0.01
(m s^{-1} ppmv)	(0.04)	(0.02)	(0.06)	(0.1)	(0.06)	(0.09)
Ozone flux	−0.17	0.003			−0.18	−0.007
(ppbv m s^{-1})	(0.05)	(0.023)			(0.09)	(0.11)

Table 3. Standard Deviation σ and Skewness S of Variables From Each Pass Averaged Over All Flight Legs Over Land and Over Candle Lake

	Twin Otter		LongEZ		Electra	
Statistics	Land	Lake	Land	Lake	Land	Lake
$\sigma(w)$ (m s^{-1})	0.82	0.29	0.95	0.49	0.89	0.51
S(w) (m^3 s^{-3})	0.3	−0.31	0.16	−0.06	0.41	0.16
σ(u) (m s^{-1})	1.76	1.31	1.73	1.37	1.39	1.14
σ(v) (m s^{-1})	1.6	1.0	2.07	1.52	1.29	1.02
$\sigma(T_a)$ (C)	0.39	0.26	0.39	0.33	0.28	0.25
$S(T_a)$ (C^3)	0.27	0.075	0.41	0.31	0.49	0.4
$\sigma(q_a)$ (g Kg^{-1})	0.25	0.23	0.27	0.27	0.26	0.24
$S(q_a)$ (g_3 Kg^{-3})	0.20	0.45	0.13	0.45	0.23	0.34
$\sigma(CO_2)$ (ppmv)	0.80	0.62	0.97	1.38	0.44	0.58
$S(CO_2)$ ($ppmv^3$)	−0.08	−0.01	−0.01	0.01	−0.02	−0.01
$\sigma(O_3)$ (ppbv)	0.97	0.72			1.1	0.99
$S(O_3)$ ($ppbv^3$)	−0.2	0.09			0.1	0.15

ity over the land and the difference between the air temperature over the land and the lake surface radiation temperature. The linear correlation coefficients between the divergence over the lake and the lake breeze index, ΔT, U, and $\Delta T/U$ in Table 4, indicate that the divergence is best correlated with the ambient wind at 30 m altitude and with the air temperature difference at 100 m altitude. The strength of the advection can modify the air temperature difference and vertical mixing over the lake very effectively at the lower level, while the air temperature difference at 100 m is more correlated with the vertical development of the thermal influence of the lake. The net observed effect is that the column of the cool air over the lake grows during the increase of the vertical mixing in the morning. The deepening of the internal boundary layer over the lake strengthens the horizontal pressure gradient which leads to strong divergent flow over the lake even if the horizontal temperature difference at lower levels does not increase.

To interpret the relationship between the lake breeze circulation and the strength of the large-scale flow, one must recognize several competing influences. The significant wind can tilt the internal boundary layer over the lake at the upper level and reduce the air temperature difference at the lower level. These influences act to reduce the generation of lake breeze flow and lead to a general negative correlation between the lake breeze divergence and the speed of the large-scale flow. However, the depth of the stable layer over the lake, H, may

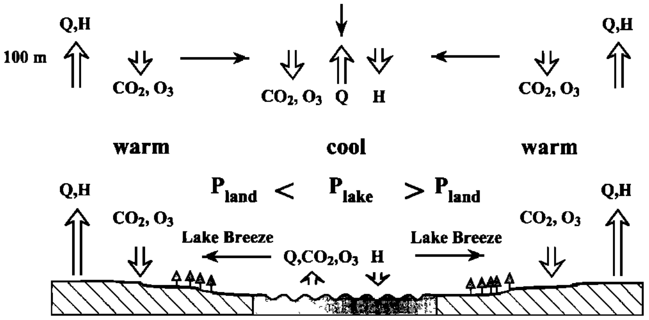


Figure 3. Schematic diagram of the fluxes and airflows around Candle Lake. The solid arrow and the open arrow represent the airflow and the flux, respectively.

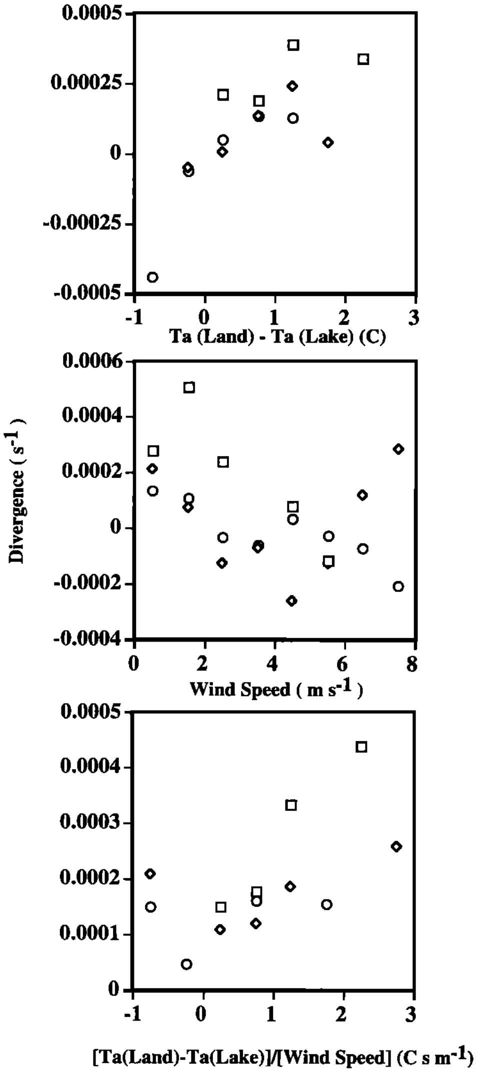


Figure 4. Along-flight-path component of the divergent flow over Candle Lake as a function of the air temperature (T_a) difference between the land and lake areas (top), wind speed along the flight track (middle), and their ratio (bottom). Each point represents bin averages over an interval along x axis. Squares, Twin Otter; diamonds, LongEZ; circles, Electra.

Table 4. Linear Correlation Coefficients Between Divergence and Other Parameters

Parameters	Linear Correlation Coefficients Twin Otter	LongEZ	Electra
Lake breeze index (σ)	−0.39	−0.33	−0.09
ΔT	0.18	0.25	0.47
U	−0.67	−0.36	−0.33
$\Delta T/U$	0.29	0.27	0.14

increase with wind speed due to shear-induced mixing. This secondary effect of the strength of the large-scale flow acts to increase the strength of the lake breeze circulation since the cool internal boundary layer over the lake is deepened.

4.3. Upper Level Circulation Induced by Lake Breeze

The downward air motion induced by the low-level divergence is seen on the August 31, 1994, Electra flight where the difference between the vertical wind component over the land and over the lake increases with height (Table 5). This downward motion is associated with the vertical change of sign of the horizontal temperature difference ΔT. The air is cooler over the lake than over the land at lower levels and warmer at higher levels. These results suggest adiabatic warming associated with downward motion over the lake.

The strong vertical mixing and development of a well-mixed boundary layer over land during the morning rapid transition period can also cool the air at higher levels [*Lenschow et al.*, 1979; *Ehret et al.*, 1996]. As a result, the air over the lake above the nocturnal inversion layer can be warmer than the rapidly vertically mixed air over the land. However, all the higher-level Electra flights are close to local noon; therefore the warmer air over the lake at higher levels is likely to be due to adiabatic warming associated with the downward circulation over the lake.

The standard deviation of the vertical motion is smaller over the lake than over the land (Table 5), including the levels where the air temperature is warmer over the lake than over the land. The difference of the standard deviation of the air temperature between the land and the lake, however, changes in the vertical. The standard deviation of the air temperature is smaller within the lake-modified cool air at the lower level over the lake and becomes larger when the air temperature is warmer over the lake than over the land at the higher level. The higher standard deviation of the air temperature over the lake at 1600 m (Table 5) is apparently associated with stable temperature stratification and residual turbulence at the upper level over the lake.

Pressure adjustments resulting from subsidence and consequent adiabatic warming in the presence of stable stratification within or at the top of the internal boundary layer can act as a negative feedback to the lake-induced circulation. The adiabatic warming due to the subsidence over the lake acts to limit the generation of surface high pressure over the lake. Since this effect preferentially inhibits the development of circulations driven by small-scale surface heterogeneity [*Smith and Mahrt*, 1981], it more effectively reduces the influence of small lakes and is probably important on the scale of Candle Lake. This negative feedback appears to contribute to the preferred sea breeze scale found in the analysis of *Rotunno* [1983] and *Dalu et al.* [1991]. Therefore the pressure over the lake is the balance between the lowering of pressure caused by the adiabatic warming and the increasing pressure caused by the cool lake-modified air associated with the weak downward heat flux into the layer just above the lake.

4.4. Influence of Boundary Layer Development on Lake Breeze

The development of the low-level divergent flow over the lake depends on the depth of the layer in which the air temperature over the lake is substantially different from the air temperature over the land. This depth can be associated with the development of the internal boundary layer over the lake or the growth of the heated boundary layer over the land. As an example, on May 25, 1994, when the ambient wind was weak (about 1 m s^{-1}), the divergence is about 2 and 2.4 times, respectively, stronger over White Gull Lake and Halkett Lake than over Candle Lake (Figure 5). The strength of the divergence can be easily seen from the strong gradient of the along-flight-track wind across the lake shown in Figure 5. The air temperature at 30 m over all three lakes is about the same even though the water temperature of the shallower White Gull and Halkett Lakes is about 5°C warmer than Candle Lake. The similar air temperature between large and small lakes may be due to the weak vertical mixing in the stable layer over the lake and less influence from the land under the weak wind condition. The above observations imply that the internal boundary layer depths over the three lakes are roughly the same because of the cancelation of the lake size on both sides of (5). The divergence apparently decreases with increasing lake size under this weak wind condition. The results also indicate that the development of the boundary layer over the land may play an active role in the buildup of the horizontal land-lake pressure difference. The cold lake simply maintains the overlying cool

Table 5. Standard Deviation σ and Skewness S of Air Temperature and Vertical Motion Over Land and Over Lake and Air Temperature Difference Between Land and Lake From Electra on August 31, 1994

		T_a (C)					w (m s^{-1})			
		Land		Lake			Land		Lake	
Level (m)	ΔT_a	$\sigma(T_a)$	$S(T_a)$	$\sigma(T_a)$	$S(T_a)$	Δw	$\sigma(w)$	$S(w)$	$\sigma(w)$	$S(w)$
100	0.46	0.27	0.49	0.14	0.4	0.12	1.06	0.43	0.43	0.032
530	0.17	0.14	0.39	0.12	0.29	0.18	1.48	0.42	0.55	−0.41
1200	−0.04	0.18	1.84	0.24	1.35	0.13	0.94	1.01	0.43	0.03
1600	−0.35	0.13	2.11	0.35	1.31	0.29	0.98	0.45	0.84	0.43

air because of inefficient horizontal and vertical mixing with weak large-scale flow.

The observed lake breezes over White Gull and Halkett Lakes also imply that the exact water temperature of the lake is not crucial for the lake breeze but rather it is the contrast between the boundary layer development over the warm land surrounding the lake and the stable cool air over the lake. This is consistent with the results of *Segal and Pielke* [1985] and *Arritt* [1987]. The size of the lake for which the divergent flow can be observed appears to be controlled by the ambient wind and the stability of the air over the lake since both factors can affect the warm-up of the lake-modified air.

5. Diurnal Variation of Lake-Induced Atmospheric Circulation

The traditional lake breeze index (σ) is defined in terms of the daily maximum air temperature and the hourly averaged wind in the morning. Therefore it cannot be used to characterize the diurnal variation of the lake breeze. BOREAS 1994 contains 1 Twin Otter and 16 LongEZ at 30-m-level and 10 100-m-level Electra Candle Lake missions with at least 3 repeated passes. On the basis of these repeated passes the diurnal variation of the lake-induced atmospheric circulation can be summarized. As a representative example, the diurnal variation of the lake breeze on May 31, 1994, is shown in Figure 6.

Apparently, because of inertia the nocturnal land breeze continues in the morning even after the air over the land becomes warmer than the air over the lake. The land breeze is seen as the convergent flow at 30 m and the divergent flow at 1000 m over Candle Lake in Figure 6. As the air is heated by the warm land surface, the flow over the lake gradually changes from the land breeze to the lake breeze. At 1230 LST the divergent and convergent flow over the lake is seen at 30 m and at 100 m, respectively. The observation of convergence at the higher level over the lake is consistent with the existence of the downward adiabatic warming described in section 4. The divergence generally increases in the morning, reaches a maximum around 13 LST, then decreases in the afternoon. This

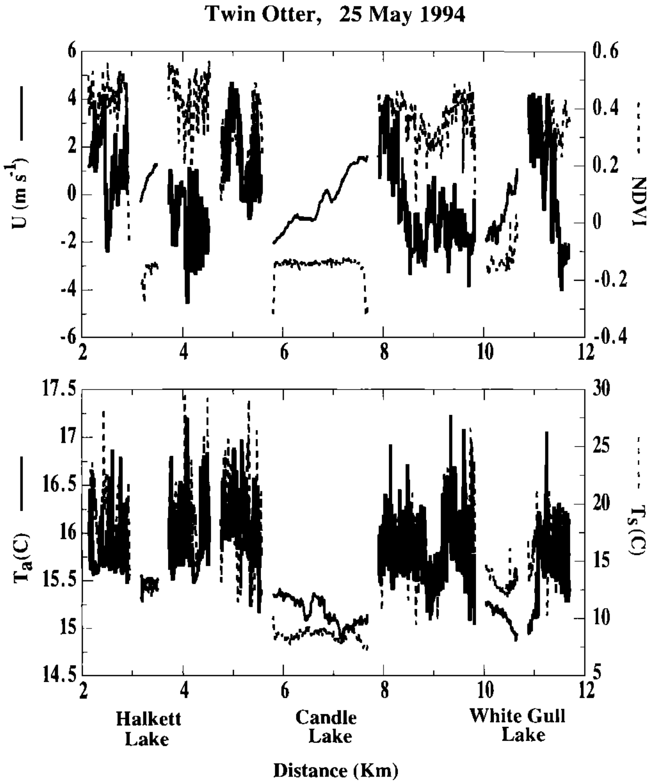


Figure 5. The Twin Otter pass along the flight track over Halkett Lake, Candle Lake, and White Gull Lake on May 25, 1994. As in equation (2), here U is the wind component along the flight track, positive toward northeast. NDVI is the normalized difference of vegetation index. The variables over the land, 5 km upstream and 5 km downstream from each lake, are also plotted for comparison.

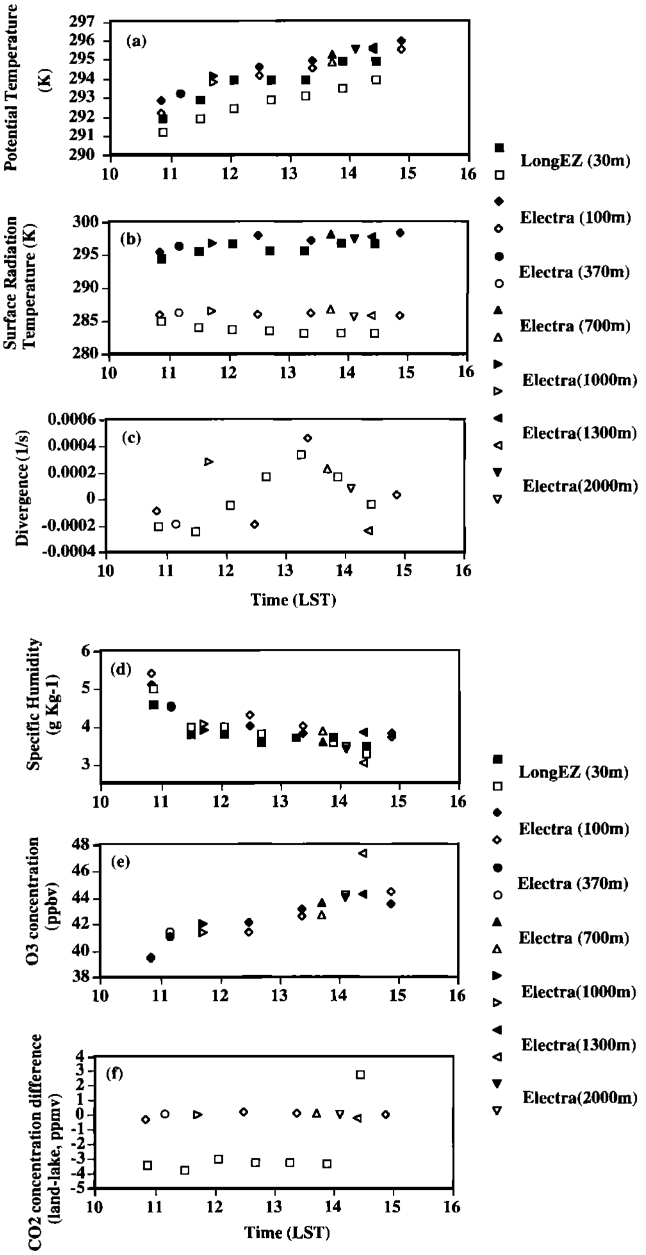
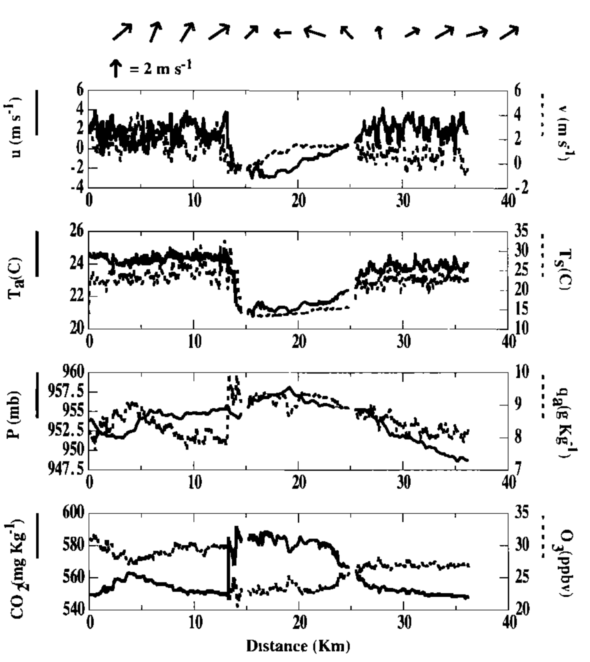


Figure 6. Diurnal variations of (a) air temperature, (b) surface radiation temperature, (c) the divergence over Candle Lake, (d) specific humidity both over the land (solid symbols) and over the Candle Lake (open symbols), (e) O_3 concentrations, and (f) the difference of the CO_2 concentration over the land and over the lake on May 31, 1994.

(a) Twin Otter, 17 September 1994



(b) Twin Otter, 17 September 1994

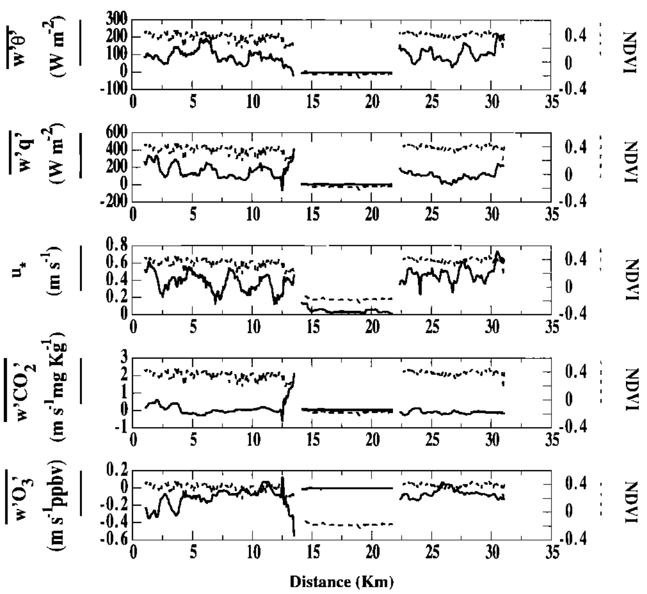


Figure 7. The Twin Otter flight over Candle Lake around noon on September 17, 1994; (a) mean variables (zonal and meridional wind components u and v, air temperature T_a, surface radiation temperature T_s, pressure P, specific humidity q_a, CO_2, and O_3 concentrations), (b) fluxes. The reference point 0 km along the flight track is arbitrarily chosen as the west end of the land on the west side of Candle Lake.

variation of the divergence is consistent with the observations at Lake Okeechobee [*Arritt et al.*, 1996].

The divergence increase in the morning occurs even when the horizontal air temperature difference at 30 m decreases with time. In the early morning the layer of warm air over the land is too shallow to create a significant horizontal pressure gradient and there is no lake breeze to oppose the warm air advection from the land. Gradually, the rate of warming over the land decreases with time due to increasing depth of the vertical mixing. At the same time, the cool lake air is warmed due to both advection and downward mixing of the warm air. As a result, the land-lake air temperature difference decreases at the lower level. However, the warm layer over the land deepens, the vertically integrated land-lake air temperature difference increases as does the internal boundary layer depth H. Therefore the divergence at the lower level increases steadily in the morning. This example further explains the relatively poor correlation between the divergence and the low-level air temperature difference between the land and the lake areas discussed in section 4.

As the horizontal divergence becomes established over the lake, the advection of the warm land air over the lake surface is opposed by the divergent lake breeze. The mixing between the cool lake air and the warm land air is reduced, and ΔT starts to increase at the 30 m level. This increase of the air temperature difference is commonly observed in the early afternoon.

Specific humidity and CO_2 concentration are generally higher over the lake than over the land in the morning (Figure 6). A Twin Otter pass around noon over Candle Lake under the light wind condition shows a sharp drop of specific humidity as well as CO_2 and O_3 concentrations at the west end of the lake (Figure 7). The sharp front is the result of easterly moving dry land air with low CO_2 and high O_3 and the westerly moving onshore lake breeze with high humidity and CO_2 and low O_3 lake-modified air.

The high CO_2 and humidity and low O_3 concentration over the lake may be related to the remnants of the nocturnal air, which has high CO_2 concentration from the land respiration, high moisture due to evaporation, and low O_3 due to ozone deposition on leaves and the ground surface. This air is transported horizontally and retained in the stable nocturnal boundary layer over the lake. If the lake water is warmer than the surrounding land at night, then the unstable air over the lake may help distribute the high CO_2 and water vapor and low O_3 air into higher levels over the lake [*Sun et al.*, 1997]. Nevertheless, only small fluxes are observed over Candle Lake during the aircraft passes when higher CO_2 and moisture and lower O_3 over the lake are observed (Figure 7). The high humidity over the lake in the morning may also be related to the weak upward moisture flux being confined to a thin stratified layer over the lake surface.

Both humidity and CO_2 decrease, and O_3 increases over both the land and the lake during the day. These variations are caused by the plant uptake of CO_2, possible photochemical production of ozone, and entrainment and downward mixing of dry and O_3-rich air. The air is sometimes drier over the lake than over the land in the early afternoon because of the mean downward motion at the higher levels over the lake (section 4) and partly by less evaporation over the cool lake compared with the large midday evapotranspiration over the land. As a part of the lake breeze circulation, the convergent flow associated with the subsiding warmer, drier air with higher ozone concentration is seen at 1420 LST at 1300 m in Figure 6. The CO_2 concentration above 100 m is about the same over the lake as over the land during the day (Figure 6). The sharp increase of the CO_2 concentration over the land at 1430 LST at 30 m in Figure 6 may be related to partial stomatal closure due to development of clouds.

The large heat capacity of the lake water delays boundary layer development over the lake. Since the airplane flights do not occur before midmorning, the transition between nocturnal and daytime boundary layer cannot be observed over the land but can be observed over the lake. As a result, the variations of CO_2 and O_3 concentrations between flight passes are larger over the lake than those over the land (Table 1, section 3).

Horizontal asymmetry of specific humidity, CO_2 and O_3 concentrations due to the mean wind can be seen in the September 17 case, shown in Figure 7. The concentration of water vapor, CO_2, and O_3 are higher downstream from the lake than upstream because of the advection of moist, CO_2- and O_3-rich air by the westerly ambient wind. The asymmetry is not very clear for many of the other cases since the concentration differences between over the lake and over the land are typically small during the day.

6. Seasonal Variations

The lake temperature is about 10°C colder than the typical midday land temperature at the end of May (Figure 2). The lake temperature increases slowly from spring to summer and decreases slowly in late summer. The slow variation of the lake temperature is due to the large heat capacity of the water (Figure 2, section 3). As a result, the moisture flux over Candle Lake increases steadily with time during the three IFCs (Figure 8). Following the slow seasonal variation of the lake temperature, the air-lake temperature difference decreases with time from spring through fall since the air temperature over the lake is more controlled by the advection from the land (Figure 2, section 3). That is, the climatological stability of the boundary layer over the lake changes from stable in the spring to unstable in the fall, with occasional disruptions by cold-front passages. The seasonal trend for the weak sensible heat flux is not apparent due to the limited number of flight missions with more than three repeated passes required for Figure 8 in order to reduce random sampling errors in the fluxes.

Associated with the full development of leaves, canopy stomata release more water vapor and take more CO_2 and O_3 during the summer, which leads to a larger upward moisture flux and large downward CO_2 and O_3 fluxes (Figure 8). However, the soil temperature dependence of the respiration may balance the decrease of the CO_2 concentration. As a result, the seasonal variation of the CO_2 flux is not well defined (not shown).

Since the lake cools slowly at night, the lake temperature is warmer than the land in the early morning for many of the days after the end of July. However, for most of the cases, the upward heat and moisture fluxes during the daytime are larger over the land than over the lake even when the lake temperature is warmer than the land surface radiation temperature [*Lenschow et al.*, 1996]. *Sun and Mahrt* [1995] have found that the spatially averaged surface radiation temperature over the land during BOREAS can be strongly influenced by the shaded cool ground surfaces, while the heat flux is dominated by the sunny canopy top. As a result, the heat flux can be upward even though the averaged surface radiation temperature may be cooler than the air temperature. The fraction of shaded ground surface is particularly large in the morning when the Sun angle is low. Therefore the sunny canopy top over the land leads to upward heat flux although the averaged surface radiation temperature is lower over the land than over the lake.

However, some special cases are observed where the fluxes over the lake are larger than those over the land. For example, on September 3, 1994, the land surface was about 6°C colder than the lake temperature in the middle of the day with heavy cloud cover (Figure 9). For this case, the specific humidity and air temperature are higher over the lake than over the land. The sensible and latent heat fluxes over the lake are, respectively, about two and four times larger than those over the land due to the cool land air over the warm water. The momentum, CO_2, and O_3 fluxes are about the same over both surfaces.

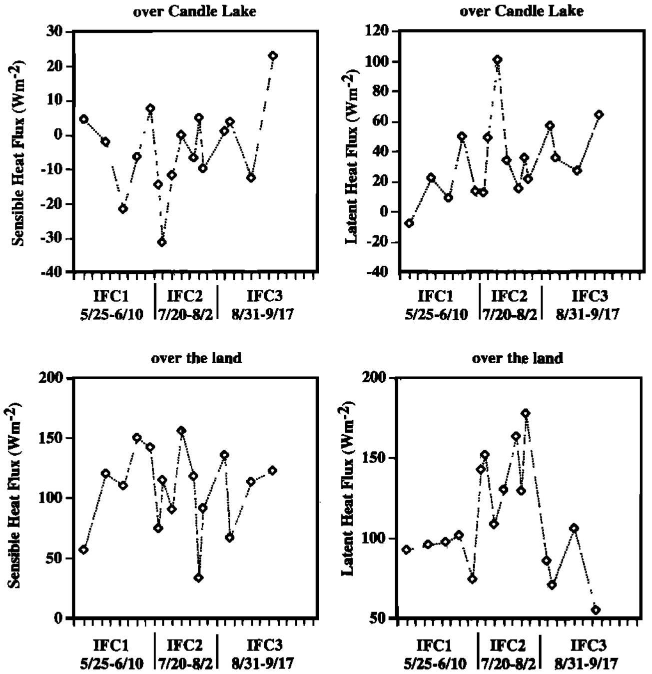


Figure 8. Seasonal variations of sensible heat (top left) and latent heat (top right) fluxes over Candle Lake and sensible heat (bottom left) and latent heat (bottom right) fluxes over land based on LongEZ observations. The increment between ticks on the x axis represents a 2-day period. The dates of the intensive field campaigns are indicated in the abscissa.

7. Fluxes As Function of Flux Averaging Scales

Applying the bulk formulae for fluxes over heterogeneous surfaces is problematical [*Mahrt and Sun*, 1995a, b]. The bulk formulae are developed for calculation of turbulent fluxes based on local mean variables. These relationships between the fluxes and the local mean variables may not be the same as the relationship between the area-averaged fluxes and the area-averaged mean variables. With surface heterogeneity, the relationship between the grid-averaged fluxes and the grid-averaged air-ground temperature and humidity differences and wind speed in numerical models depends on the grid size [*Mahrt and Sun*, 1995a, b]. The required transfer coefficients in the bulk formula may not follow surface similarity theory.

In order to examine the grid size dependence of the bulk relationship in the presence of lakes the transfer coefficient is examined in this section as a function of the averaging grid size, as simulated by choosing sections of aircraft record of different lengths. The fluxes and the mean variables required in the bulk formula are averaged over lengths of L, $2L$, $\cdots$, along flight tracks, where L is the lake width. For an averaging width of L the area covers Candle Lake only. For the width of $2L$ the area covers the lake and the adjacent land along the flight track. As the averaging window width increases, the per-

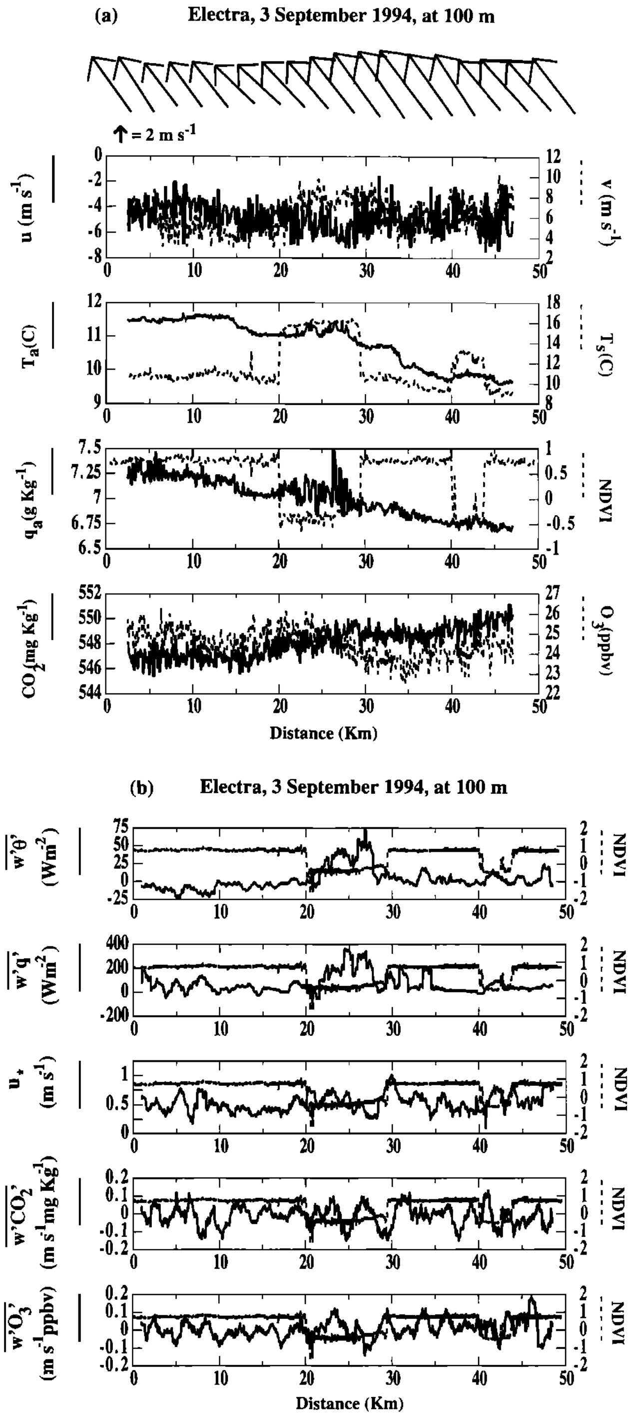


Figure 9. (a) Electra zonal and meridional wind components u and v, air (T_a), and surface temperatures (T_s), specific humidity (q_a), NDVI (normalized difference of vegetation index), CO_2 and O_3 concentrations over Candle Lake at an altitude of 100 m on September 3, 1994. Candle Lake is the low NDVI area in the center. The low NDVI area at 40 km corresponds to White Gull Lake. (b) Sensible and latent heat, momentum (expressed as friction velocity), carbon dioxide, and ozone fluxes across Candle Lake.

centage of the lake in the averaging area decreases. In this approach, averaging along the flight track is assumed to be equivalent to averaging across a grid area. To exclude mesoscale fluxes, the turbulence is calculated as perturbations from unweighted means with a fixed averaging width of 1.2 km. The cutoff length of 1.2 km captures most of the turbulent flux based on arguments similar to those presented by *Sun et al.* [1996]. The wind is vector averaged as in numerical models

$$V = (\overline{v_x}^2 + \overline{v_y}^2)^{1/2}. \tag{6}$$

Here v_x and v_y are the wind components in the zonal and meridional directions, and the overbar represents the spatial averaging. Transfer coefficients are calculated from the fluxes, air-ground differences, and wind components which are averaged over repeated passes during a given flight.

As an example, the lake effect on the area-averaged flux from the LongEZ on May 26, 1994, is shown in Figure 10. When the grid size covers only the lake, the grid area is homogeneous, the air over Candle Lake is stable with weak downward sensible heat at the aircraft flight level of 30 m; the air is warmer than the lake water and the airwater temperature difference is small. As the averaging window increases to include more warm land surfaces, the fluxes and the grid-averaged variables are dominated by strong upward sensible heat, latent heat, and momentum fluxes and large air-ground differences. Therefore as the averaging scale increases from 100% lake to almost 100% of the land, where the lake effect becomes negligible, the averaged sensible heat flux and the mean air-ground temperature difference change signs from

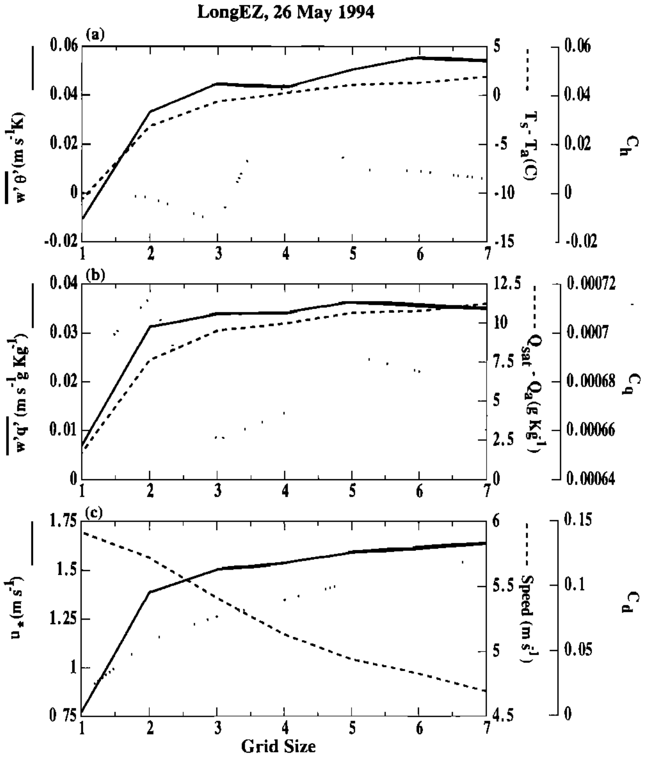


Figure 10. (a) Sensible heat flux, the difference between air and surface radiation temperatures, and observed heat transfer coefficient as a function of averaging scale; (b) moisture flux, the difference between specific humidity and the saturated specific humidity using surface radiation temperature, and observed moisture transfer coefficient; (c) momentum flux, wind speed, and observed drag coefficient. All the variables are averaged from four repeated passes, and the abscissa represents the averaging scale equal to L, $2L$, $3L$, $\cdots$, where L is the lake width.

negative to positive at some intermediate averaging lengths. This intermediate averaging length corresponds to the grid area where both lake and land are important and is several times the lake width. However, the increase of the sensible heat flux with averaging scale can be faster or slower than the increase of the air-temperature difference with averaging scale. As a result, the transfer coefficient must become negative at some grid sizes in order to use the bulk formula to obtain the measured sensible heat flux. The dramatic variation of the exchange coefficient for heat happens only when the heat flux is downward over the lake and the air is warmer than the lake. The exchange coefficients for moisture and momentum generally increase steadily with averaging scale.

In addition to the averaging problem in the sensible heat flux, the grid-averaged wind speed based on (6) decreases with averaging scale [*Mahrt and Sun*, 1995a, b]. If the grid just covers the lake, the divergence from the lake breeze leads to a very small grid-averaged wind speed. As the grid averaging scale increases to include the land surface, the vector-averaged wind speed is closer to the ambient large-scale wind. Therefore the area-averaged wind speed may increase as the percentage of the land surface in the grid increases. Because of the restriction of the observations to a single flight track, the cancelation for the averaging scale equal to the lake width in Figure 10 is limited only to the direction of the flight track. As the averaging scale continues to increase, the area-averaged wind speed decreases due to random fluctuations of the wind direction. This problem is not related to lakes specifically but more to area averaging in general. Therefore the exchange coefficients may increase with averaging scale unless the fluxes and the air-ground differences depend significantly on grid size.

The problems related to the area averaging can be complicated if a grid size covers several lakes, which could happen with grid areas in the BOREAS study area. The example in Figure 10 shows typical difficulties with scaling up in cases of strong heterogeneity associated with lakes. In situations where lakes dominate the surface heterogeneity, the mosaic approach in numerical modeling [*Wetzel and Chang*, 1988; *Avissar and Pielke*, 1989; *Claussen*, 1991; *Ducoudré et al.*, 1993; *Huang and Lyons*, 1995] may be suitable for solving the area-averaging problems.

8. Summary

The above study has shown that cool lakes, here ranging from 3 to 10 km in width, can generate well-defined lake breezes on days with weak large-scale flow. As a part of the lake breeze circulation, downward motion of warm, dry air, and high ozone concentration is observed at 1000 m over Candle Lake. The turbulence is weak over Candle Lake than over the surrounding land even at the 1000 m level.

The divergence of the lake breeze circulation is negatively correlated with the wind speed. Under weak wind conditions, the lake divergence decreases with increasing lake size and is not sensitive to the lake water temperature. The air temperature over three different sized lakes is about the same since the timescale of the vertical mixing in the stratified air over the lake is longer than the timescale of the land-air advection. The lake breeze is sensitive to the relative horizontal difference in the boundary layer development and column air temperature between the lake and the land, not the air temperature difference at lower levels. The rapid boundary layer deepening over the warm land contributes to the horizontal difference of the column air temperature which leads to a horizontal pressure difference that drives the lake breeze circulation.

The lake breeze strongly depends on the diurnal development of the difference between the boundary layers over the land and over the lake. In the morning the residual land breeze is commonly observed even as the air first becomes warmer over the land than over the lake. The carbon dioxide and water vapor concentrations can be higher over Candle Lake than over the land in the morning due to retention of nocturnal air over the lake and the much larger vertical mixing over the land. As the air over the land continues to warm, the horizontal pressure gradient increases. This pressure gradient drives the divergence over the lake which reaches maximum values around 1300 LST.

The vertical turbulent fluxes are much smaller over the lake than over the land. Weak downward sensible heat flux is observed at the 30- and 100-m flight levels. As the lake warms up from spring to fall, the latent heat flux over the lake increases steadily, while over the land, the latent heat flux peaks during the summer season due to transpiration.

The area-averaged fluxes strongly depend on the averaging length when significant land-lake contrast occurs in the averaging area. For a grid size several times the lake width, the exchange coefficient for heat in the bulk formula must be negative to predict the correct grid-averaged heat flux. The negative exchange coefficient occurs when the sensible heat flux and the air-ground temperature differences are dominated by the different surface types.

Numerous lakes in BOREAS influence not only the flow through land and lake breezes, which also induce local changes in cloud cover, but also the area-averaged fluxes. In the BOREAS southern and northern study areas, lakes cover about 10% and 20% of the study areas, respectively. If we assume the upward sensible heat flux over the land and downward over Candle Lake on May 26, 1994 (Figure 10), to represent lake and the land areas in BOREAS, respectively, the area-averaged sensible heat flux over boreal forest is estimated to be 12–24% lower than if the area were covered by forest. However, a more accurate estimate of the area-averaged heat flux over the BOREAS area requires more information on the spatial variation of the surface fluxes over the boreal forest. Besides the surface type, the sensible heat flux can depend on the depth and turbidity of the lake. For example, the sensible and latent heat fluxes over White Gull Lake are found to be higher than those over Candle and Halkett Lakes since this lake is shallow and turbid.

Acknowledgments. Jielun Sun and Larry Mahrt were supported by NASA grant NAG 5-2300. Donald H. Lenschow, Steve Oncley, Qing Wang, and K. J. Davis were sponsored by NASA grant PO S-12857-F. Qing Wang and K. J. Davis's participation was also supported in part by NCAR's Advanced Study Program. The NOAA LongEZ observations, operated by Tim Crawford and Ron Dobosy, were completed under BOREAS program funding. Funding for Twin Otter operations in BOREAS was provided by the National Research Council of Canada, Agriculture Canada, and the Natural Sciences and Engineering Research Council of Canada. Discussions with Ray Arritt were greatly appreciated The National Center for Atmospheric Research is supported by the National Science Foundation.

References

Arritt, R. W., The effect of water surface temperature on lake breezes and thermal internal boundary layers, *Boundary Layer Meteorol.*, *40*, 101–125, 1987.

Arritt, R. W., M. Segal, M. Leuthold, C. J. Anderson, and R. W. Turner, An observational study of the Lake Okeechobee lake breeze and its effect on deep convection, paper presented at the Conference on Coastal Oceanic and Atmospheric Prediction, Am. Meteorol. Soc., Atlanta, Ga., 28 January–2 February 1996, 1996.

Avissar, R., and R. A. Pielke, A parameterization of heterogeneous land surfaces for atmospheric numerical models and its impact on regional meteorology, *Mon. Weather Rev.*, *117*, 2113–2136, 1989.

Biggs, W. G., and M. E. Graves, A lake breeze index, *J. Appl. Meteorol.*, *1*, 474–480, 1962.

Claussen, M., Estimation of areally-averaged surface fluxes, *Boundary Layer Meteorol.*, *54*, 387–410, 1991.

Dalu, G. A., R. A. Pielke, R. Avissar, G. Kallos, M. Baldi, and A. Guerrini, Linear impact of thermal inhomogeneities on mesoscale atmospheric flow with zero synoptic wind, *Ann. Geophys.*, *9*, 641–647, 1991.

Dobosy, R. J., T. L. Crawford, J. I. MacPherson, R. Desjardins, R. D. Kelly, S. P. Oncley, and D. H. Lenschow, Intercomparison among the four flux aircraft at BOREAS in 1994, *J. Geophys. Res.*, this issue.

Ducoudré, N. I., K. Laval, and A. Perrier, SECHIBA, a new set of parameterizations of the hydrologic exchanges at the land/atmosphere interface within the LMD atmospheric general circulation model, *J. Clim.*, *6*, 248–273, 1993.

Ehret, G., A. Giez, C. Kiemle, K. J. Davis, D. H. Lenschow, S. P. Oncley, and R. D. Kelly, Airborne water vapor DIAL and in situ observations of a sea-land interface, *Contrib. Atmos. Phys.*, *69*, 215–228, 1996.

Estoque, M. A., J. Gross, and H. W. Lai, A lake breeze over southern Lake Ontario, *Mon Weather Rev.*, *104*, 386–396, 1976.

Huang, X., and T. J. Lyons, The simulation of surface heat fluxes in a land surface-atmosphere model, *J. Appl. Meteorol.*, *34*, 1099–1111, 1995.

Keen C. S., and W. A. Lyons, Lake/land breeze circulations on the western shore of Lake Michigan, *J. Appl. Meteorol.*, *17*, 1843–1855, 1978.

Kelly, R. D., J. I. MacPherson, R. J. Dobosy, and T. L. Crawford, BOREAS 1994 intercomparison among three flux aircraft, paper presented at the 22nd Conference on Agricultural and Forest Meteorology With Symposium on Fire and Forest Meteorology, Am. Meteorol. Soc., Atlanta, Ga., Jan. 28–Feb. 2, 1996.

Lenschow, D. H., B. B. Stankov, and L. Mahrt, The rapid morning boundary layer transition, *J. Atmos. Soc.*, *36*, 2108–2124, 1979.

Lenschow, D. H., Q. Wang, S. P. Oncley, K. J. Davis, and J. Mann, Lake-induced modification of the boundary layer over the boreal forest, paper presented at the 22nd Conference on Agricultural and Forest Meteorology With Symposium on Fire and Forest Meteorology, Am. Meteorol. Soc., Atlanta, Ga., Jan. 28–Feb. 2, 1996.

Lyons, W. A., The climatology and prediction of the Chicago lake breeze, *J. Appl. Meteorol.*, *11*, 1259–1270, 1972.

MacPherson, J. I., NRC Twin Otter operations in BOREAS 1994, *NRC Rep. LTR-FR-129*, *Natl. Res. Counc. of Can.*, Ottawa, Can., 1996.

Mahrt, L., and J. Sun, Multiple velocity scales in the bulk aerodynamic relationship for spatially averaged fluxes, *Mon. Weather Rev.*, *123*, 3032–3041, 1995a.

Mahrt, L., and J. Sun, Dependence of exchange coefficients on averaging scale or grid size, *Q. J. R. Meteorol. Soc.*, *121*, 1835–1852, 1995b.

McDermott, M. L., and R. D. Kelly, Fluxes over a heterogeneous forest, paper presented at the 11th Symposium on Boundary Layers and Turbulence, Am. Meteorol. Soc., Charlotte, N. C., March 27–31, 1995.

Rabin, M. S., S. Stadler, P. J. Wetzel, D. J. Stensrud, and M. Gregory, Observed effects of landscape variability on convective clouds, *Bull. Am. Meteorol. Soc.*, *71*, 272–280, 1990.

Rotunno, R., On the linear theory of land and sea breeze, *J. Atmos. Soc.*, *40*, 1999–2009, 1983.

Segal, M., and R. A. Pielke, The effect of water temperature and synoptic winds on the development of surface flows over narrow, elongated water bodies, *J. Geophys. Res.*, *90*, 4907–4910, 1985.

Sellers, P., et al., The Boreal Ecosystem-Atmosphere Study (BOREAS): An overview and early results from the 1994 field year, *Bull. Am. Meteorol. Soc.*, *76*, 1549–1577, 1995.

Smith, B., and L. Mahrt, A study of boundary layer pressure adjustments, *J. Atmos. Soc.*, *38*, 334–346, 1981.

Sun, J., and L. Mahrt, Relationship of surface heat flux to microscale temperature variations: Application to BOREAS, *Boundary Layer Meteorol.*, *76*, 291–301, 1995.

Sun, J., L. Mahrt, S. K. Esbensen, J. F. Howell, C. M. Greb, R. Grossman, and M. A. LeMone, Scale dependence of air-sea fluxes over the western equatorial Pacific, *J. Atmos. Soc.*, *53*, 2997–3012, 1996.

Sun, J., R. Desjardins, and L. Mahrt, The influence of lakes on atmospheric transport carbon dioxide in BOREAS, paper presented at the Special Symposium on Boundary Layer and Turbulence, Am. Meteorol. Soc., Long Beach, Calif., Feb. 2–7, 1997.

Wetzel, P. J., and J. T. Chang, Evapotranspiration from non-uniform surfaces: A first approach for short-term numerical weather prediction, *Mon. Weather Rev.*, *116*, 600–621, 1988.

J. Sun, Program in Atmospheric and Oceanic Sciences, University of Colorado, Boulder, CO 80309-0311. (e-mail: jls@monsoon.colorado.edu)

K. J. Davis, D. H. Lenschow, and S. P. Oncley, National Center for Atmospheric Research, Boulder, CO 80307-3000.

L. Mahrt, College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331.

T. L. Crawford and R. J. Dobosy, Atmospheric Turbulence and Diffusion Division, NOAA ARL, Oak Ridge, TN 37830.

J. I. MacPherson, National Research Council, Ottawa, Ontario, K1A036, Canada.

Q. Wang, Meteorology Department, Code MR/Qg, Naval Postgraduate School, Monterey, CA 93943-5114.

R. L. Desjardins, Land Resources Research Centre, Agriculture Canada, Ottawa, ON, K1A 0C6, Canada.

(Received March 28, 1996; revised February 15, 1997;
accepted March 3, 1997.)