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AIRBORNE ENERGY AND TRACE SPECIES FLUX MEASUREMENTS OVER LAKE MICHIGAN, JULY 22-26, 1991

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Airborne Energy and Trace Species Flux Measurements Over Lake Michigan July 22-26, 1991

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ABSTRACT

In support of the Environmental Protection Agency's (EPA) Lake Michigan Urban Air Toxics Study (LMUATS) conducted near the Chicago metropolitan area, airborne mass, momentum, and energy flux measurements were collected by the National Oceanic and Atmospheric Administration's Atmospheric Turbulence and Diffusion Division (NOAA-ATDD) on July 22 through 26, 1991 over the southern end of Lake Michigan. During 18 flight hours, fluxes were measured over 41 horizontal transects and 15 vertical profiles were obtained. All of the data were collected during the daytime over water at altitudes of 8 to 80 meters. Boundary layers conditions varied widely during the experiment due to influences from anomalous wind patterns and frontal passages.

This report describes the measurement method, scope, and some recommendations for the airborne Mobile Flux Platform (MFP) data collected on July 22-26, 1991. Flux eddy diffusivity (or K value) calculations are the focus of the report. These calculations are limited to sensible and latent heat fluxes. Although observations of CO_2 and O_3 flux were made by the MFP, the unavailability of simultaneously measured surface data collected by an outside source made calculation of K values impossible. However, sensible and latent heat flux eddy diffusivity calculations revealed that reasonable estimates of K values were obtained using the MFP. Thus, good estimates of toxic fluxes seem possible for future efforts if K value measurements are coupled with simultaneous, multiple-location, measurements of flux gradients.

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1.0 INTRODUCTION

Past measurements of toxic contaminants in the Great Lakes have suggested that direct atmospheric deposition constitutes a significant source of pollution. In an effort to monitor the problem, the U. S. Environmental Protection Agency (EPA) and Environment Canada have been modifying existing acid rain models for use with toxic contaminants. Current knowledge of pollutant sources and deposition rates to the Great Lakes ecosystem is insufficient to allow adequate performance of the models. Similarly, this same lack of information has prevented proper compliance with Annex 15 of the Great Lakes Water Quality Agreement. To fulfill these needs, calls for a comprehensive research program to study the Great Lakes ecosystem have been made. Such a program should include components of measurement, analysis, and modelling/integration.

As a result of the aforementioned goals, the EPA's Lake Michigan Urban Air Toxics Study (LMUATS) was conducted during the summer of 1991. As part of the experiment, the National Oceanic and Atmospheric Administration's Atmospheric Turbulence and Diffusion Division (NOAA-ATDD) collected data on trends of mean concentration and fluxes over Lake Michigan via airplane. NOAA-ATDD's Mobile Flux Platform (MFP), mounted on a small, light-weight aircraft, collected the measurements. Data collected provided an initial exploration of the potential use of airborne mean concentration and flux measurements to determine the flow of toxic contaminants to and from portions of the Great Lakes ecosystem. Specifically, NOAA-ATDD's mission was designed to attempt an accurate assessment of flux eddy diffusivities (K values). K values essentially quantify the ability of a specific portion of the atmosphere to transport particular flux quantities. Given successful data collection, K value measurements can be coupled with measurements of flux gradients in order to calculate estimate the quantity of toxics transported to and/or from the ecosystem.

This report describes data collected by the aircraft-mounted MFP only. Due to the unavailability of data from an outside source (University of Michigan), a planned comparison and joint analysis of NOAA-ATDD MFP data and simultaneously measured University of Michigan shipboard data have not been included. This report does not constitute a comprehensive analysis of the data presented. Consequently, any conclusions presented herein should not be interpreted as final or all-conclusive.

2.0 THE STUDY AREA

2.1 Site Description

The lower portion of Lake Michigan was selected as a subject of study because of its proximity to a major source of pollution (the Chicago metropolitan area). The MFP collected data during 41 horizontal transects flown over three relatively well-defined routes over the lake. These included: (1) a North-South flight path running roughly parallel to

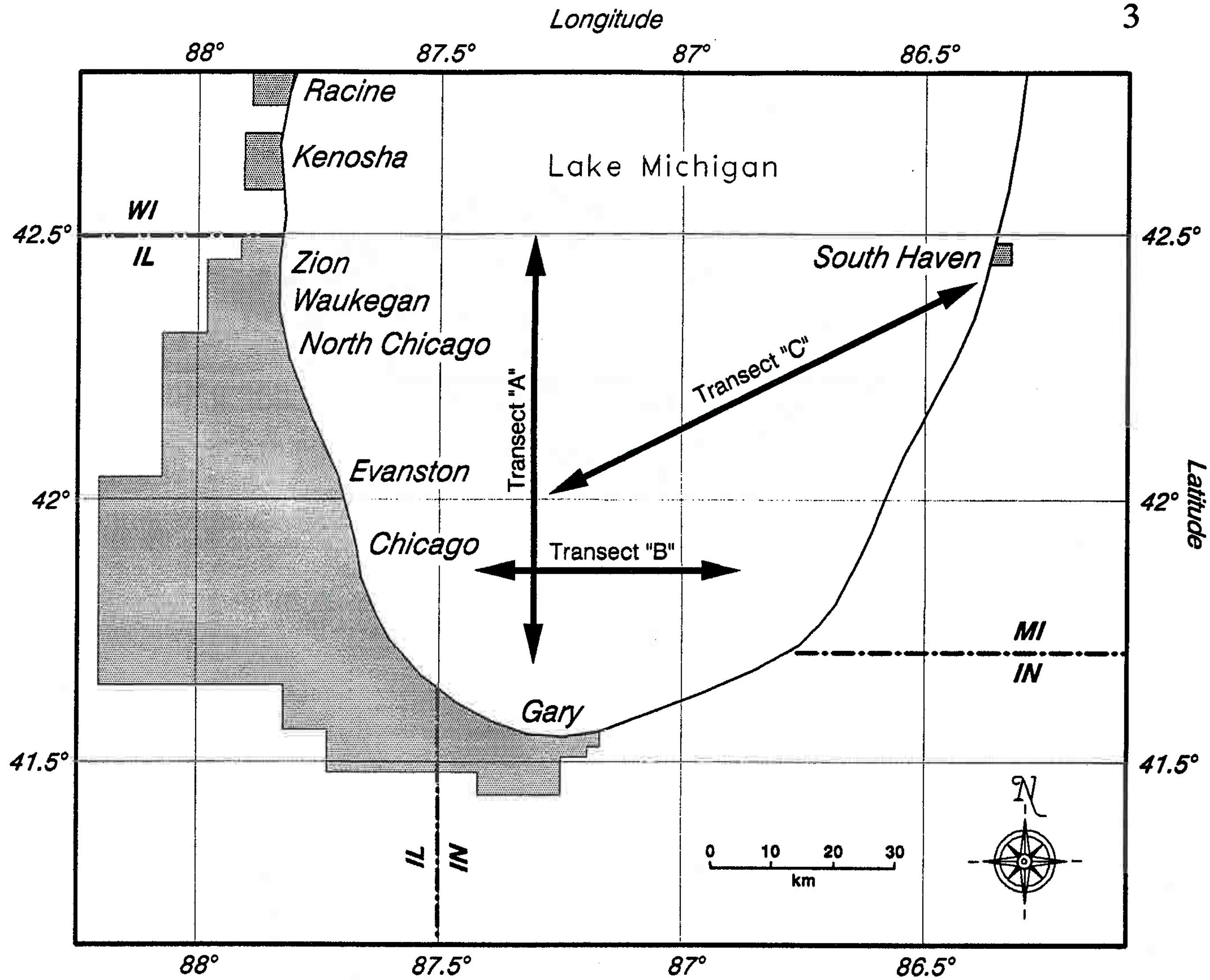

Figure 1. The experimental area used by the Mobile Flux Platform (MFP) on July22-26, 1991 during the Lake Michigan Urban Air Toxics Study (LMUATS). Shaded zones indicate urban areas. Each of the 41 horizontal transects flown during the experiment followed one of the indicated paths (Transect "A", "B", or "C"). These data collection paths averaged 65 km.

the Chicago metropolitan shore line, (2) an East-West flight path extending across the southern extremity of the lake, and (3) a diagonal Southwest-Northeast flight path extending from about the center of flight path (1) to near South Haven, Michigan.
Figure 1 shows the study area along with the associated urban areas and flight routes. Note that land areas adjacent to the western shoreline of Lake Michigan are heavily urbanized; however, land areas adjacent to the eastern shoreline are much less so. Consequently, regional winds having strong westerly components should tend to increase concentrations of urban toxics over the lake. Figure 2 provides a topographical perspective of the study area, with North rotated 45° to the left of vertical.

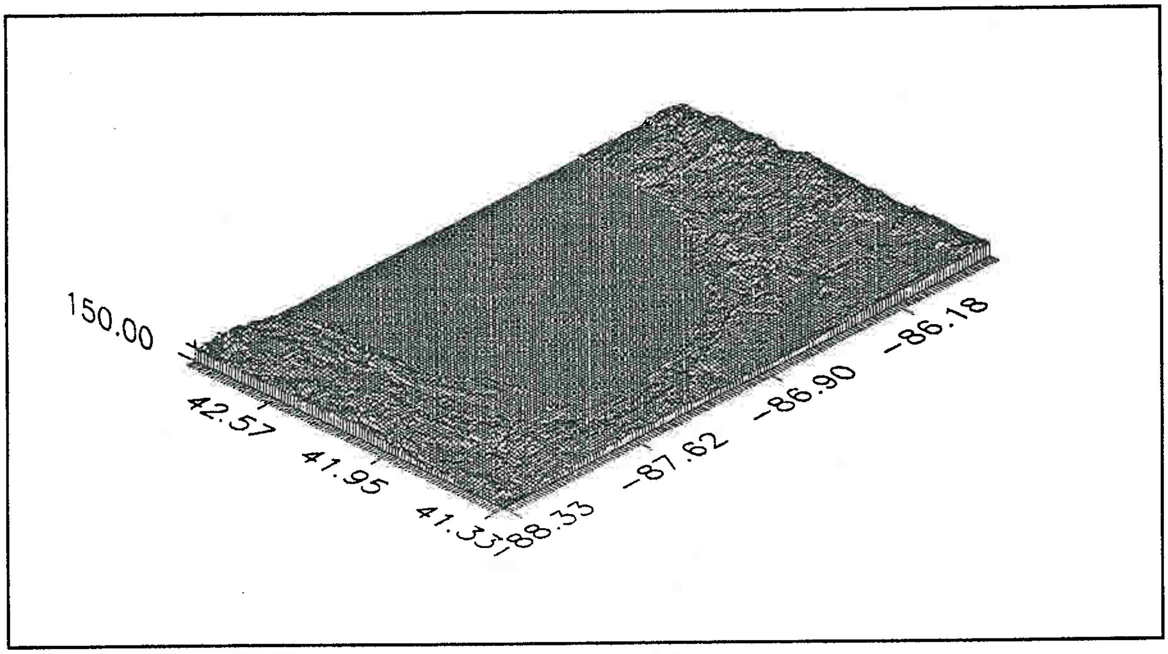

Figure 2. Topographic view of the study area. North is 45° left of vertical. Numbers along the lower borders of the figure indicate latitude and longitude.

2.2 Summary of Synoptic Weather Conditions

The following summaries assess overall regional weather conditions during each day of the experiment. It is important to note that specific measurements from the airborne MFP may vary significantly from the general conditions described here. The lake itself can modify ambient weather conditions significantly. For an overview of data measured by the MFP, see the Appendices.

July 22: The data collection period (12:30-14:36 CST) was characterized by a hot, southwesterly wind flow. Daily maximum temperatures along the west and south shorelines of the study area reached 38.5°C. As a result of the ambient flow, a strong temperature inversion developed over the much cooler lake surface. The lake to land breeze that would be expected during this period appears to have been disrupted. Synoptic weather maps suggest that the study area was positioned between an exiting warm front and an approaching cold front. Thunderstorms and rainshowers were approaching the region from the northwest.

July 23: The data collection period (07:38-14:42 CST) was characterized by a light northwesterly wind flow which gradually weakened as the day progressed. Temperatures were cooler since the cold front had exited the study area before the start of measurements. Pressure gradients were weaker in the afternoon, suggesting better establishment of a lake to land breeze.

July 24: The data collection period (07:54-14:14 CST) was characterized by a light westerly wind flow. An especially weak pressure gradient during the afternoon suggests that the lake to land breeze may have been well established.

July 25: The data collection period (08:01-16:10 CST) was characterized by a light northerly flow. Maximum temperatures along the shoreline were influenced by a cold front passage during the night of July 24-25; however, they seem further influenced by a lake breeze. Shoreline maximum temperatures were about 21-22°C. A weak pressure gradient also suggests the strong establishment of a lake to land breeze. Weak high pressure dominated the region.

July 26: The data collection period (07:55-08:09 CST) was characterized by calm conditions and a weak pressure gradient. Ambient temperatures were near 15°C. Weak high pressure continued to dominate the region.

3.0 MEASUREMENT SYSTEM DESCRIPTION

The airplane used to carry the NOAA-ATDD MFP measured mean and turbulent flux parameters. These are listed in Table 1. The MFP is designed for use as a high precision turbulent boundary layer research tool and is easily adaptable to other instrumentation. Additional flux instrumentation for NO, NO_2, and CH_4 is under development. Specifications of the MFP's instrumentation and use are given in following sections.

Table 1. Parameters Measured By the ATDD Mobile Flux Platform (MFP).

Mean Parameters	Turbulent Flux Parameters
Winds (U, V, W)	Momentum
Position (X, Y, Z)	Specific Heat
Temperature, Dew Point	Latent Heat
H_2O, CO_2, O_3	CO_2
Radiation, Surface Temp.	O_3

3.1 Airplane Description

A variant of the Rutan "Long-EZ", a two passenger high-performance airplane, was used to carry the MFP (see Figure 3). Aerodynamic characteristics of the Long-EZ are well suited for long-duration high-fidelity turbulent flux measurements. The "pusher" configuration leaves the front of the airframe free of propeller-induced disturbance, engine vibration, and exhaust. The small, light-weight, laminar-flow airframe has an equivalent "flat plate" drag area of only 0.2 m^2. The nose of the aircraft has especially small flow disturbance, and is ideal for measurement of winds, temperature, and trace chemical species using a turbulence probe developed at NOAA-ATDD (Crawford and Dobosy, 1992). The canard design of the aircraft results in a very low stall speed and little or no spin problems. The plane has superior pitch stability in turbulent conditions. These factors, combined with low wing loading, allow for safe, low-speed (50 m/s), and low-level (10 to 20 m AGL) turbulence measurements within the boundary layer, an impossible venture for instrumented aircraft in the past.

Table 2 lists the Long-EZ aircraft's specifications and performance characteristics. Since the airplane has a transit speed of 90 m/s and a range exceeding 3,300 km, experimental measurements almost anywhere in the world are possible. The airplane is IFR-equipped (including weather radar), and has a ceiling exceeding 9 km AMSL. The airframe structure is of fiber composite construction, conforming to the +9 to -6 G-load requirements of an aerobatic class airframe. The fatigue-resistant and high-strength characteristics of the aircraft allow for safe operation even in high levels of thermal or mechanical turbulence. To enhance flight safety, a ballistically-deployed parachute system, opening in 1.4 s, allows emergency recovery of the pilot, airplane, and instrumentation.

Table 2. NOAA/Long-EZ/N3R Airplane Specifications.

Specifications		Performance	
Type Certificate	Experimental	Stalling Speed	27 m/s
Powerplant	Lyc-O-320 160 HP	Maximum Speed	93 m/s
Electrical	65 amp 12VDC	Ceiling	9000 m
Empty Weight	430 kg (950 lb)	Range	3300 km
Gross Weight	725 kg (1,600 lb)	Endurance	10 to 18 hr
Fuel Capacity	200 kg (435 lb)	Fuel Use	8.2 to 19 kg/hr
Wing Area	9.3 m^2	Flow Blockage	1/5 m^2

Figure 3. The Long-EZ airplane used to carry the Mobile Flux Platform (MFP).

3.2 Eddy Correlation Technique

Measurements of turbulent mass, momentum, and energy flux were obtained using the eddy correlation technique. This method is a direct measure of turbulent air-surface exchange. On a fixed platform, such as a tower, the surface exchange of a species ϕ is given by

$$F_{\phi} \equiv \overline{(\rho w)'\phi'} = \overline{(\rho w)\phi} - \overline{\rho w}\,\overline{\phi} \qquad (1)$$

where ϕ is the mixing ratio of the species of interest, w is the vertical wind component, and ρ is the total air density (the sum of the dry air and water vapor densities). The overbars indicate an average of the quantity over a large enough time (or space) to adequately sample all relevent scales. Primes denote a deviation from the averaged values.

The eddy correlation technique takes a sample from the mass, momentum, and energy patterns of a flow and determines the average flux as a covariance. The averaging time or space must be selected carefully so that the desired turbulent features can be sampled by the data. Selecting either too large or too small a size could result in an inproper sampling of either large scale or small scale eddies. For the Lake Michigan measurements, data were sampled over averaging lengths of 3 km.

In order to compare measured airplane fluxes to those at the surface, flux divergence below the airplane must be considered. As the altitude of a flux measuring device increases, the effect of flux divergence also tends to increase. As a result, the effect of flux divergence on airplane-mounted instruments (flying at 8 to 80 m) is greater than would be expected for tower- or ship-based instruments located within a few m of the surface. Relevent factors for a quantity whose flux is being measured include atmospheric storage and mean transport, both horizontal and vertical. The relative importance of these factors varies with surface inhomogeneities (such as varying water surface temperature, etc.) and may result in organized flows and gradients of temperature, trace gases, and the like.

On a moving platform such as an airplane, covariance flux measurements should be corrected for flight speed variation. This factor results from the correlation between airplane speed and local vertical velocity. When an airplane enters an updraft, the autopilot (or pilot) maintains constant altitude by decreasing attack angle. As the airplane pitches over, it accelerates. The result is a faster transit through up-drafts than down-drafts, biasing the simple time covariances. Theoretically correct distance-based covariance fluxes, based on the assumption dx = S dt (where S = airplane speed), are determined as follows:

$$F = \frac{\overline{w\Phi S}}{\overline{S}} - \frac{\overline{wS}\;\overline{\Phi S}}{\overline{S}^{2}} \qquad (2)$$

The authors are not aware of the application of this correction technique in other similar aircraft measurements. This correction is particularly important for small airplanes (having small inertia) and when thermal turbulence becomes more organized. The importance of the correction was first noted during the MFP's participation in the 1991 Boardman ARM Regional Flux Experiment (a Department of Energy program).

3.3 Velocity and Temperature Measurements

Three-dimensional wind component and temperature measurements were obtained with a sensitive fast-response turbulence probe (Crawford and Dobosy, 1992). The velocity vector at the probe is obtained by adding the velocity $\mathbf{V}_a$ of the air relative to the probe to the velocity $\mathbf{V}_p$ of the probe. This gives the velocity $\mathbf{V}$ relative to earth:

$$\mathbf{V} = \mathbf{V}_p + \mathbf{V}_a \qquad (3)$$

The algorithm used to determine the probe velocity vector ($\mathbf{V}_p$) uses input from accelerometers to obtain high frequency contributions (Crawford *et al.* 1990). Input from a Global Positioning System (GPS, Dobosy and Crawford, 1992) was used to obtain low frequency contributions (LORAN was used during infrequent periods when GPS was not available). The velocity vector relative to the probe ($\mathbf{V}_a$) is computed from pressure differences observed on the probe. The probe is unique in that it co-locates the sensors (acceleration, pressure, and temperature) needed for accurate high frequency measurements of wind and temperature. The probe is mounted axi-symmetrically on the airplane.

Sensors used in the algorithm for air motion computation are summarized in Table 3.

Table 3. NOAA-ATDD/Long-EZ/N3R Turbulence, Wind, and Position Instrumentation Specifications.

Variable	Location	Range	Resolution	Sensor
Acceleration[1] Sensors				
X	P[2] & CG[5]	± 1g	.0005g	SenSym-SXL02G
Y	P & CG	± 1g	.0005g	SenSym-SXL02G
Z	P & CG	+2/-1g	.001g	SenSym-SXL02G
Pressure Sensors				
Dynamic	P	0-24 mb	.005 mb	MS[3]-160PC01D37
Yaw	P	± 12 mb	.005 mb	MS-160PC01D36
Pitch	P	± 12 mb	.005 mb	MS-160PC01D36
Static	P	700-100 mb	.04 mb	Setra System
Delta Static	P	± 12 mb	.005 mb	MS-160PC01D36
Gyros[4]				
Pitch	CG	± 83 deg	.15 deg	Honeywell JG7044A-35
Roll	CG	± 175 deg	.15 deg	
Yaw	CG	± 6 deg/s	.05 deg/s	Honeywell-GG13A
Position				
Lat/Lng	CG	Limited	± 100 m	LORAN
Lat/Lng	CG	Global	± 25 m	Global Pos Sys
Altitude	CG	Global	± 25 m	Global Pos Sys
Altitude	CG	Global	5%	Radar
Heading	P	0-360 deg	0.1 deg	KVH IND/MC201

Notes:

1. NOAA-ATDD designed and fabricated support circuitry for these transducers.
2. Probe
3. Micro Switch, a Honeywell Division
4. NOAA-ATDD R&D is developing a more accurate non-gyro approach.
5. Center of gravity

3.4 Chemical Species Measurement

Table 4 provides specific information on the MFP chemical sensors. The fast response H_2O/CO_2 sensor is a 20 cm open-path infrared analyzer described by Auble and Meyers (1992). Noise levels for H_2O and CO_2 concentrations are less than 10 mg/m^3 and 300 μg/m^3 RMS, respectively (for frequencies between 0.005 and 10 Hz). The fast O_3 sensor design follows that of Ray *et al.* (1986). The detection principle is ozone chemiluminescence with eosin Y dye dissolved in a fluid carrier. Sensitivity was enhanced by use of a 50% ethylene glycol, 40% ethanol, and 10% water carrier. Additional slow-response sensors included: net and short wave radiation; dew point and surface infrared temperature, H_2O/CO_2 (LI-COR, Inc.), and O_3 (DASIBI 300AH) gas analyzers.

Table 4. NOAA-ATDD/Long-EZ/N3R Chemical-Radiation-Temperature Specifications.

Variable	Use	Range	Resolution	Sensor
		Chemical Sensors		
H_2O	Mean	40°C Dewpoint	<1%	LI-COR LI-6262
H_2O	Flux	3 to 20 gm/m^3	4 mg/m^3	NOAA-ATDD Design
CO_2	Mean	0 to 3000 PPM	±1 PPM	LI-COR LI-6262
CO_2	Flux	200-500 PPM	±0.1 PPM	NOAA-ATDD Design
O_3	Mean	0 - 500 PPB	±0.3 PPB	DASIBI 1003AH
O_3	Flux	0 - 200 PPB	±.05 PPB	NOAA-ATDD Design
		Radiation		
Net	Mean	0 - 1200 W	±¼ W	Rad.Ene.Bal.Sys Q*6
Short Wave	Mean	0 - 1300 W	±¼ W	LI-COR LI-200s
		Temperature Sensors		
T	Mean	-7/+65°C	±0.02°C	Hy-Cal BA-507-B
T'	Flux	±15°C	±0.005°C	Thermistor
H_2O	Mean	-40 to +60°C	±0.25°C	EG&G chilled mirror
Sfc IR T	Mean	-30 to +100°C	±0.1°C	Everest Mod 4000

3.5 Data Processing

Fast response analog signal data were first conditioned with 10 Hz low-pass anti-aliasing four-pole Butterworth filters before being converted to 90 Hz digital signals. The 90 Hz digital signal was passed through a three-point Hanning filter, subsampled at 30 Hz, and written to disk for post processing. Slow response analog signal data was also digitized at 90 Hz but instead was passed through a two stage digital filter before being subsampled at 1 Hz for recording. The first stage was a three-point centered average, subsampled at 30 Hz. The second stage was a 60 point triangle filter rejecting frequencies above 1 Hz.

Heat, momentum, water vapor, CO_2, and O_3 fluxes were computed during post processing using covariance computation techniques [Equation (2)] with means removed but no trend removed. Future efforts may need to explore various trend removal techniques if large time trends become a problem. The 5 s path average fluxes were derived from 60 s covariance data segments. At the 50 ms^{-1} sampling speed, this allows variations up to scales of 3 km to contribute to the covariance. Larger-scale variability should be unimportant at such a low flight altitude. As outlined by Webb *et al.* (1980), necessary data corrections for pressure, temperature, and water vapor fluctuations can be eliminated by converting sensor outputs to mixing ratios (*i.e.*, the species mass density divided by the mass of dry air).

In covariance computations, lag or phase errors between the w' time series and that of any species of interest must be removed. Use of fast sensors and identical low-pass filters mitigates these problems. Still, phase differences are created by imperfect sensors and spatial separation. The distance from the probe to any non-colocated sensor will introduce a phase lag proportional to that distance divided by the air speed. The H_2O/CO_2 sensor is about 1 m behind the probe while the O_3 sensor is back about 3 m. Thus, at a 50 m/s flight speed, the expected lags are 1/50 and 3/50 s respectively. Experimentally, lags are precisely determined from the cross-correlation, or cross-correlogram of the two time series. Only the O_3 signal required a time lag adjustment.

4.0 EXPERIMENT DESCRIPTION

4.1 Background

Toxic air-surface exchange to a water body such as Lake Michigan is highly complex. Large-scale horizontal trends of deposition and/or outgassing, the characteristics of the water-air interface, chemistry/fluid dynamics within the lake, and seasonal variations are just a few considerations contributing to the complexity of the problem. Additionally, direct measurement of toxic chemical eddy-flux air to lake surface exchange is often impossible due to the unavailability of many of the required fast-response chemical sensors. However, using inferential methods, the desired toxic fluxes can be estimated. Inferential methods can generally be classified into two categories: ratio and bulk transport methods.

Using ratio methods, fluxes of toxic contaminants can be accurately determined by measuring the atmospheric vertical gradient of the toxic of interest while at the same time observing the gradient and eddy flux of a surrogate species such as O_3 or CO_2. The toxic flux can then be inferred by multiplying the ratio of gradients by the surrogate species' flux. For conservative species, the accuracy of this method is directly related to the accuracy of measured gradients and the surrogate flux. Since vertical gradient measurement is difficult and the determination of gradient toxic concentrations is costly, the ratio method is not generally practical at present.

When measuring the transport of toxics, bulk methods are less accurate because they incorporate physical processes influencing transport at the lake interface and within the lake. However, the accuracy of bulk methods can be improved by estimating the bulk transport coefficient from direct measurements of a similar surrogate species. Furthermore, an advantage of the method is that measurement results can be incorporated as parameterizations within an assessment model. The method can be generalized as follows:

$$\overline{-w'\phi'} = C_\phi \, U_{10} \, (\phi_{10} - \phi_s) \qquad (4)$$

The net flux, to or from the surface, is equal to the product of the bulk transport coefficient, C_ϕ, the wind speed at 10 m, U_{10}, and the gradient from 10 m to the surface, $(\phi_{10}-\phi_s)$. The empirical C_ϕ bulk transport coefficient embodies nearly all the physical processes controlling transport. Influences of atmospheric stability parameters and physical/chemical surface reactions are two more important factors controlling C_ϕ. U_{10} parameterizes shearing generated turbulence. The gradient, $(\phi_{10}-\phi_s)$, parameterizes "thermodynamic" potential forcing the exchange.

Flux parameters measurable with the NOAA-ATDD MFP system are useful for inferring C_ϕ values for toxic fluxes. The airborne MFP used in this study measured fluxes of momentum, heat, H_2O, CO_2, and O_3. Therefore, from Equation (3), C_ϕ values for the desired toxic fluxes can be defined. Differences in various C_ϕ values are primarily controlled by physical/chemical-based microlayer phenomena which are mostly a function of the character of the exchanging material. Table 5 lists various fluxes measured by the MFP and peculiarities of surface gradient and reaction related to each.

In order to adequately parameterize turbulent flux, it is often useful approximate equations such as (4) above using the gradients of mean variables (such as temperature, humidity, and wind) in combination with a scalar coefficient that describes the extent that atmospheric processes will allow the physical transport of a given chemical species or a physical property (such as temperature, momentum, etc.). This technique is usual called gradient transport theory or K theory. Using such an approximation, Equation (4) becomes:

$$-w'\Phi' = K_H \left(\frac{\partial \Phi}{dz}\right) \quad (5)$$

where K_H replaces the terms C_ϕ and U_{10} and represents sensible flux eddy diffusivity. Such coefficients are normally refered to as K values.

In order to accomplish the primary goal of the experiment (the calculation of K values), it was necessary to substitute finite flux gradients for the actual continuous gradients. The resulting K values, which were calculated for measurable parameters, should be useful for estimation of coincident toxic flux gradients when coupled with accurate flux gradient information. This would allow identification of some of the temporal and spatial characteristics of toxic deposition within portions of the Great Lakes ecosystem. Actual equations used for calculating K_H (sensible heat) and K_{LH} (latent heat) values are defined in Equations (5) and (6) below:

$$K_H = H\left(\frac{z_1 - z_2}{T_1 - T_2}\right) \quad (6)$$

$$K_{LH} = LH\left(\frac{z_1 - z_2}{Q_1 - Q_2}\right) \quad (7)$$

where,

H = w'T' (path-avg. heat flux defined by vertical wind speed and temperature)
LH = e'w' (path-avg. latent heat flux defined by water vapor content and temperature)
z_n = altitude (m)
T_n = potential temperature (C°) at the given altitude
Q_n = water vapor mixing ratio (g/g) at the given altitude

Variables denoted with a "1" subscript represent measurement values from the higher of two coincident flight paths. When K values were computed for gradients between a single flight altitude and the surface, Q_2 (saturation mixing ratio at the surface) was computed from its function of T_2, the surface temperature. In order to obtain values having proper units, K_H values were divided by factors of air density and the specific heat of moist air. K_{LH} values were adjusted similarly using factors of air density and latent heat of vaporization.

Table 5. Fluxes measured by the MFP with associated surface gradient and reaction peculiarities.

ϕ	$(\phi_{10}-\phi_s)$	SURFACE REACTION
Momentum, U*	U_{10} - 0	none, U_s=0
Heat, H	T_{10} - T_s	evaporation cooling may effect T_s
Moisture, LE	q_{10} - $f(T_s)$	q_s is a function of T_s
CO_2	CO_2 - pCO_2	chemically and physically complex soluble gas
O_3	O_3 - 0	nearly insoluble

4.2 Procedures

During July 22-26, 1991, the MFP measured fluxes of momentum, heat, moisture, CO_2, and O_3 over Lake Michigan. Measurements were collected along 41 horizontal transects over the flight paths outlined in Figure 1 (see Sec. 2). Average transect length was 65 km. In addition to the horizontal transects, 15 vertical profiles were obtained on each day of the experiment. Vertical profiles measured conditions from near the surface to altitudes of 1-2 km. All MFP flight transects conducted during the experiment are listed in Table 6.

Horizontal transects were generally flown in pairs. Each transect within a pair was flown at a different altitude from the other. Flight altitudes were typically about 25 or 70 m above the water surface. This method of data collection was intended to test the validity of vertical flux gradient measurement between two altitudes above the surface. Similarly, the inference of surface temperature and humidity from the MFP's surface infrared temperature sensor would test the ability of the instruments to measure vertical flux gradients between the surface and a given flight altitude. However, measurement of vertical flux gradients for CO_2 and O_3 would require a near-surface flux measurement system separate from the MFP.

In conjunction with the MFP measurements during July 22-26, 1991, a University of Michigan vessel known as the *Laurenthian* measured fluxes from instruments located on the bow of the ship. A number of the NOAA-ATDD measurements included flyovers of the *Laurenthian*. Intercomparisons between the airborne and ship data sets were planned, but the unavailability of the *Laurenthian*'s data set made the task impossible at this writing. Consequently, K value measurements for vertical flux gradients are limited to those for sensible and latent heat fluxes.

Table 6. MFP data collection flights during July 22-26, 1991.

22 July 1991		
Flight Type	Time (CST)	Distance, Heading, Altitude
Flux Transects (4)	12:55-13:12 13:14-13:36 13:37-13:57 13:59-14:21	61 km at 359°, 74 m AGL 64 km at 183°, 25 m AGL 67 km at 359°, 25 m AGL 70 km at 180°, 64 m AGL
Profiles (2)	12:30-12:55 14:21-14:36	38 km at 264°, 6-2159 m AGL 43 km at 82°, 7-1096 m AGL
23 July 1991		
Flight Type	Time (CST)	Distance, Heading, Altitude
Flux Transects (14)	07:58-08:30 08:36-09:06 09:08-09:27 09:29-09:51 09:54-10:07 11:45-12:01 12:04-12:29 12:32-12:44 12:47-13:15 13:17-13:45 13:48-14:06 14:07-14:22	100 km at 63°, 65 m AGL 98 km at 242°, 34 m AGL 53 km at 0°, 28 m AGL 84 km at 180°, 71 m AGL 37 km at 0°, 28 m AGL 51 km at 2°, 22 m AGL 92 km at 181°, 72 m AGL 39 km at 359°, 28 m AGL 97 km at 63°, 71 m AGL 97 km at 241°, 27 m AGL 55 km at 2°, 66 m AGL 54 km at 179°, 22 m AGL
Profiles (4)	07:38-07:56 10:09-10:28 11:27-11:45 14:25-14:42	50 km at 307°, 12-1660 m AGL 61 km at 128°, 10-1478 m AGL 51 km at 308°, 15-1674 m AGL 55 km at 128°, 13-1675 m AGL

24 July 1991		
Flight Type	**Time (CST)**	**Distance, Heading, Altitude**
Flux Transects (11)	08:19-08:35	56 km at 87°, 24 m AGL
	08:37-08:55	55 km at 270°, 71 m AGL
	08:57-09:21	78 km at 0°, 24 m AGL
	09:50-10:06	57 km at 87°, 68 m AGL
	10:07-10:26	56 km at 268°, 25 m AGL
	12:07-12:26	59 km at 86°, 26 m AGL
	12:27-12:44	56 km at 268°, 72 m AGL
	12:47-13:09	77 km at 0°, 26 m AGL
	13:12-13:37	76 km at 179°, 66 m AGL
	13:39-13:56	54 km at 87°, 68 m AGL
	13:58-14:14	53 km at 268°, 28 m AGL
Profiles (4)	07:54-08:15	45 km at 273°, 7-1599 m AGL
	10:27-10:36	30 km at 101°, 8-1652 m AGL
	11:44-12:06	50 km at 273°, 13-1664 m AGL
	14:14-14:28	38 km at 98°, 8-1650 m AGL

25 July 1991		
Flight Type	**Time (CST)**	**Distance, Heading, Altitude**
Flux Transects (14)	08:22-08:39	57 km at 88°, 33 m AGL
	08:40-08:57	54 km at 269°, 75 m AGL
	09:00-09:26	79 km at 0°, 27 m AGL
	09:28-09:49	75 km at 178°, 73 m AGL
	09:51-10:09	54 km at 87°, 71 m AGL
	10:10-10:27	56 km at 266°, 28 m AGL
	11:51-12:09	57 km at 86°, 25 m AGL
	12:10-12:27	54 km at 267°, 68 m AGL
	12:30-12:56	79 km at 359°, 29 m AGL
	12:57-13:18	78 km at 180°, 62 m AGL
	13:21-13:38	56 km at 87°, 65 m AGL
	15:19-15:37	54 km at 88°, 31 m AGL
	15:38-15:52	53 km at 269°, 83 m AGL
	15:54-16:10	55 km at 87°, 72 m AGL
Profiles (4)	08:01-08:21	49 km at 274°, 7-1586 m AGL
	11:35-11:50	47 km at 276°, 1-923 m AGL
	13:57-14:10	45 km at 100°, 13-1517 m AGL
	15:00-15:19	48 km at 275°, 13-961 m AGL

26 July 1991		
Flight Type	**Time (CST)**	**Distance, Heading, Altitude**
Profiles (1)	07:55-08:09	48 km at 273°, 19-1075 m AGL

5.0 OBSERVATIONS

A number of internal boundary layers were evident from the MFP-collected data set. Significant horizontal gradients of water vapor, CO_2, and O_3 were revealed. Several of the gradients appeared to be associated with the Chicago metropolitan area; others, however, proved less explainable. Some interesting variations in vertical winds and surface temperatures were noted. A particularly good example of this occurred during the flight on July 22, 1991 at 13:59-14:21. Plots of the MFP-collected data are located in the Appendices.

K values computed for gradients of vertical fluxes between pairs of horizontal transects proved largely disappointing. The inaccuracy of these estimates can probably be attributed to the presence of significant horizontal gradients as noted above. In contrast to the flight-pair comparisons, K value estimates using the surface infrared temperature sensor yielded very acceptable values. This occurred despite the fact that these computations could be vulnerable to inaccuracies in the sensor. However, it is noteworthy that the surface-inferred computations were not subject to errors introduced by horizontal gradients. This seems to result from the fact that surface measurements were collected simultaneously with corresponding flight altitude data.

A significant portion of the experiment took place during periods of temperature inversion. During these periods, K value calculations would, by definition, be irrelevant. This results from the fact that vertical fluxes are generally small in stable boundary layers. Thus, K values provided in this report are listed only for those times having valid vertical flux gradient conditions.

Although the experiment revealed that the pairing of coincident flight paths at different altitudes would need modifications in order to yield viable results, the remaining surface to single flight altitude measurements indicated that the MFP can be used to obtain accurate estimates of toxic vertical fluxes. Noting that K values tend to be highly variable, the consistency of values resulting from the MFP's surface to flight path comparison are very promising. The addition of simultaneously measured surface values of CO_2 and O_3 from the *Laurenthian* might have added a great deal to more to these findings.

K values measured during valid meteorological conditions are presented in Table 7. A greater number of valid K_{LH} values than K_H values is a result of the decreased sensitivity of K_{LH} value computations to temperature inversions. Data collected on July 22, 1991 represent a particularly troublesome day for K value measurement due to a strong inversion caused by a hot Southwesterly flow. July 25, 1991 yielded the best K value calculations since that date was characterized by relatively large negative temperature gradients between the lake and flight altitudes.

Table 7. K values calculated during valid meteorological conditions from MFP data collected over Lake Michigan, July 22-26, 1991. The K values listed are derived from comparisons of surface-inferred and flight altitude measurements.

K Values Calculated from Comparisons of Surface-inferred and Flight Altitude Measurements

Date	Start Time (CST)	K_H Value (m^2/s)	K_{LH} Value (m^2/s)	z Thickness (m)	Temperature Gradient SFC to z_1 (C°)
072291	12:55		0.0432	67.1	+7.31
	13:14		0.0060	27.3	+6.74
	13:37		0.1297	28.1	+6.67
	13:58		0.1025	63.7	+8.07
072391	07:58		0.4778	47.8	+0.38
	08:36		0.1995	19.6	+0.32
	09:07	1.1365	0.0804	7.78	-0.06
	09:29		0.4016	47.54	+0.52
	09:54	0.2735	0.0914	10.0	-0.33
	11:44	0.0006	0.0582	8.77	+0.54
	12:03		0.3755	53.2	+1.13
	12:32		0.0831	14.0	+0.53
	12:46		0.4556	53.9	+1.25
	13:16		0.1547	17.0	+0.88
	13:48	0.0279	0.3066	53.6	+1.76
	14:07		0.1167	14.6	+1.30
072491	08:19	0.1206	0.0482	7.0	-1.23
	08:36	1.7513	0.2750	48.4	-0.21
	08:57	0.3501	0.0514	7.7	-0.20
	09:23		0.2138	56.1	+0.81
	09:49		0.1849	46.8	+0.15
	10:07	0.3292	0.0470	10.0	-0.20
	12:07	0.4239	0.0722	19.4	-0.21
	12:26		0.2136	62.3	+0.54
	12:46		0.1210	24.3	+1.17
	13:12		0.2687	60.5	+1.83
	12:39		0.2224	59.6	+1.24
	12:57		0.0883	25.3	+1.04

K K Values Calculated from Comparisons of Surface-inferred and Flight Altitude Measurements (continued)

Date	Start Time (CST)	K_H Value (m^2/s)	K_{LH} Value (m^2/s)	z Thickness (m)	Temperature Gradient SFC to z_i (C°)
072591	08:21	0.4273	0.1994	27.0	-2.37
	08:40	0.9518	0.3903	63.5	-1.65
	08:59	0.1878	0.1194	16.7	-1.78
	09:27	1.3031	0.3591	56.6	-0.97
	09:51	0.9610	0.3640	56.8	-1.78
	10:10	0.2449	0.1461	17.7	-2.27
	11:51	0.0842	0.0637	7.8	-2.77
	12:10	0.6785	0.3340	47.6	-2.02
	12:29	0.1213	0.0771	10.0	-1.85
	12:57	0.6873	0.2363	39.5	-1.42
	13:20	0.4735	0.2727	42.8	-2.06
	13:41	0.2024	0.1073	11.0	-2.41
	15:19	0.1956	0.1372	13.5	-2.51
	15:37	1.2738	0.4805	60.2	-1.84
	15:53	0.6738	0.4069	50.5	-1.97

Data collected by the airborne MFP are available for review in the form of optional appendices containing the plotted data. Path-average data from which K values were calculated are also available on floppy disk (5 s overlapping path averages). Table 8 describes the contents of the appendices. Requests for either data set along with other questions may be directed to:

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Table 8. Listing of data plotted in the optional appendices.

Data Plotted in the Optional Appendices	
Appendix	Plotted Data
"A"	Horizontal Transects
"B"	Surface and Airborne Temp.
"C"	Mean Water Vapor (EG&G, ATDD, LI-COR)
"D"	Mean Ozone and Carbon Dioxide (Dasibi O_3, LI-COR CO_2)
"E"	Momentum Fluxes and Mean Winds (u'w', v'w', mean u, mean v, u^*
"F"	Ozone and Carbon Dioxide Flux (O_3'w', CO_2'w')
"G"	Heat Budget (Pyranometer, Net Radiation, Sensible Heat, Latent Heat, and Surface Temp.
"H"	Vertical Wind and Altimeter (Mean w, radar altimeter, adjusted P-altimeter)
"I"	Power Spectra (w,u)
"J"	Power Spectra (w,v)
"K"	Power Spectra (w,Ta)
"L"	Power Spectra (w,e')
"M"	Power Spectra (W,O_3)
"N"	Power Spectra (W,CO_2)

6.0 RECOMMENDATIONS

The data reveal that the NOAA-ATDD MFP and similar systems are viable tools for the estimation of toxic flux gradients. It is important to realize, however, that these systems cannot presently measure flux gradients simultaneously over an entire ecosystem. Consequently, the use of a point measurement from a single experiment as a representation of a large ecosystem such as Lake Michigan would be not be advisable. Better representativeness could be achieved by conducting several experiments over different regions of the lake. Only after extensive background information has been obtained can an acceptable understanding of the overall ecosystem be achieved. Finally, a model could be adapted or developed which could use relevant meteorological measurements to estimate deposition rates to the ecosystem.

It is also important to note that K values provide only half of the desired equation. An adequate calculation of flux bulk transport must include measurements of flux gradients as well as K values. Clearly, this goal must be achieved using simultaneous sampling by at least two flux platforms. Such a procedure is necessitated due to the highly variable nature of temperature, moisture, and chemical species gradients.

Given simultaneous sampling, estimation of toxic flux gradients could be accomplished using chemical surrogates such as CO_2 and O_3. These two gases represent extremes in chemical character (i.e. CO_2 is very soluble and O_3 nearly nonsoluble. Thus, the behavior of the two chemicals could identify important parameterizations about the behavior of soluble or insoluble toxic species of interest. Additionally, CO_2 and O_3 are gases that are measurable with the MFP.

Boundary layer stability should be considered in future experiments. The stability of the near-surface layer has a profound effect on the deposition and outgassing of toxic materials to and from the surface. A significant portion of the experiment revealed very stable boundary layers near the lake surface. Not surprisingly, climatological statistics suggest that stable boundary layers are a synoptic, diurnal, and seasonal companion of the lake. Since stable boundary layers may significant reduce the transfer of toxics to and from the lake, their effect on these processes must be quantified.

Future experiments should better differentiate between data collected near and far from the shoreline. Boundary layer processes are more complex and less understood near a shoreline; thus, initial measurements should concentrate on understanding of processes in the middle of the lake, where boundary layers have reached better equilibrium. Once an understanding of mid-lake processes is available, focus can shift to near-shore studies.

Background meteorological and chemical variables over the entire lake need to be better understood before specific gradients can be attributed to a particular urban area. For example, it was obvious during the experiment that Lake Michigan possesses a large but gradual North-South horizontal gradient for an undetermined set of chemical species. Measurements over the entire North-South length of the lake may be necessary to separate these gradients from those resulting from the Chicago metropolitan area. Other considerations include transport of toxics by the lake, and levels of outgassing in non-urban areas of the lake.

Deposition of toxics to terrestrial and marine ecosystems is a highly complex species-dependent problem. By seeking a careful understanding of the parameters involved in flux exchange rates, the EPA's efforts to assess toxic deposition can be realized. Close collaboration with scientists involved in micrometeorological and flux research would be a significant factor toward facilitating these goals.

7.0 REFERENCES

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