Interbasin Flux Measurements Using Simple Methods

Field study performed during DOE Vertical Transport and Mixing (VTMX) Campaign

Draft Final Report

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Prepared for

U.S. Department of Energy

DOE Contract Number
DE-FG03-99ER62845

January 5, 2005

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1.0 Introduction

The Vertical Transport and Mixing (VTMX) campaign (Doran, et al, 2002), sponsored by the U.S. Department of Energy, took place in the Salt Lake Valley during October, 2000. The purpose of VTMX was to further understanding of meteorological processes that govern vertical transport and mixing in complex terrain, particularly during nocturnal stable periods and their morning and evening transition periods. These meteorological processes were the subject of numerous sponsored studies during VTMX.

The Salt Lake (Salt Lake City) Basin and the Utah Basin to its south are separated by the Traverse Range. Near-surface airflow between the basins is channeled through the Jordan Narrows, also the channel for the Jordan River that flows from the Utah Basin into Salt Lake via the Salt Lake Basin. Jordan Narrows is thus a potentially significant corridor for pollutant transport between the two basins. This paper describes simple and direct pollutant (PM_{10}) measurements, with concurrent continuous meteorological monitoring, to characterize pollutant transport between the two basins via low-level stable nocturnal drainage flow, with an emphasis on its vertical variability when mixing is limited. The Jordan Narrows has similarities to other transport corridors where direct in-corridor monitoring of pollutant flux might enhance pollution forecasts during transport conditions. Thus our more general objective is to assess the usefulness of direct methods to characterize pollutant flux in similar environments.

2.0 VTMX Studies of Jordan Narrows Gap Flow

Gap flow, described by Whiteman (2000), occurs when pressure-driven channeled flow encounters a topographic restriction and is accelerated because of the Bernoulli effect. Gap flow through Jordan Narrows was the subject of several meteorological studies during VTMX. Pinto et al (2002) describe NCAR field measurements to characterize gap flow, including vertical boundary layer profiles collected just north of Jordan Narrows. NCAR measurements revealed a prominent low-level jet through the Jordan Gap. Zhong and Fast's (2003) discussion of high resolution model simulations of boundary layer development and thermal circulations over the Salt Lake basin during VTMX includes detailed description of Jordan Narrows gap flow within the Salt Lake Basin mesoscale context. It describes the observed low-level jet through the Jordan gap that "reverses direction diurnally in response to lake/land and mountain/valley thermal contrasts, usually reached a maximum speed of 6-10 m/s at a height between 100 to 200 m above ground and decreased rapidly to below 2 m/s at 1000 m". Chen et al (2004) also describe observed and simulated stably stratified flow through the Jordan Narrows gap during VTMX. Their simulations of developed flows near Jordan Narrows showed hydraulic jumps occurring 5 to 10 km downwind from the gap, not present during transition periods, where downslope flow converges with stable air in flatter terrain, resulting in narrow bands of upward motion on the order of 100's of meters deep. During fully developed drainage flow there were "even small regions where potential temperature isotherms are nearly vertical, and, hence, verge on instability." Such regions thus have potential for vertical mixing of transported and lingering inert surface pollutants during otherwise stable and stagnant nocturnal periods.

These and other VTMX studies consisted of various direct measurements of meteorological variables. Results from these studies yield important inferences for accumulation, transport, and mixing of atmospheric pollutants. The study described here used direct measurements of pollutant (PM_{10}) concentration, with surface meteorological measurements, to a) examine the usefulness of simple methods in air quality studies, and b) characterize channeled interbasin flux during VTMX.

2.0 Methods

2.1 Description of Study Area (Traverse Ridge)

Traverse Ridge forms a barrier between the Salt Lake Basin and the Utah Lake Basin except where it is cut by the Jordan River at the Jordan Narrows. Airflow between the two basins is well defined directionally and the Traverse Ridge provides a convenient and well-situated study area. Terrace-like elevation breaks along the ridgeline provide convenient locations for measurements that represent different elevation ranges of the ridgeline. Figure 1 shows the crest of the Traverse Ridge ridgeline, the length and width of which is taken as the "flux plane" for the purpose of our study.

Four sites were selected at different elevations of the Traverse Ridgeline. These were selected to represent different elevations of the Traverse Ridge "Flux Plane" depicted in Figure 1. The Jordan Narrows Pump Station site (PUMG) was located at the bottom of Jordan Narrows and represents flow and transport conditions at the lowest 75 m of the flux plane. The Camp Williams Turbine Site (TURG) was located just above the Jordan Narrows near the Wind Turbine at the Utah National Guard's Camp Williams. The Traverse Ridge Airpark Site (AIPG) was located on the terrace area just above and to the east of Highway 89. The AIPG site was collocated with a meteorological monitoring station operated by Utah State University. The PacificCorp Communications site (COMG) was located at a communications facility overlooking the Airpark. Meteorological data most representative of higher elevations of the Traverse Ridge were collected during VTMX at the TRAV site, also operated by USU. Figure 2 is a photograph of the eastern half of Traverse Ridge taken from the TURG site and shows the locations of the AIPG and COMG sites. The terraced nature of the ridgeline is evident in this photograph. A view of the Pump Station (PUMG) from the TURG site is shown in Figure 3. Figure 4 shows the relative elevations of monitoring sites along the Traverse Ridge ridgeline. Assumed areal dimensions for the flux plane section represented by each monitoring site are given in Table 1.

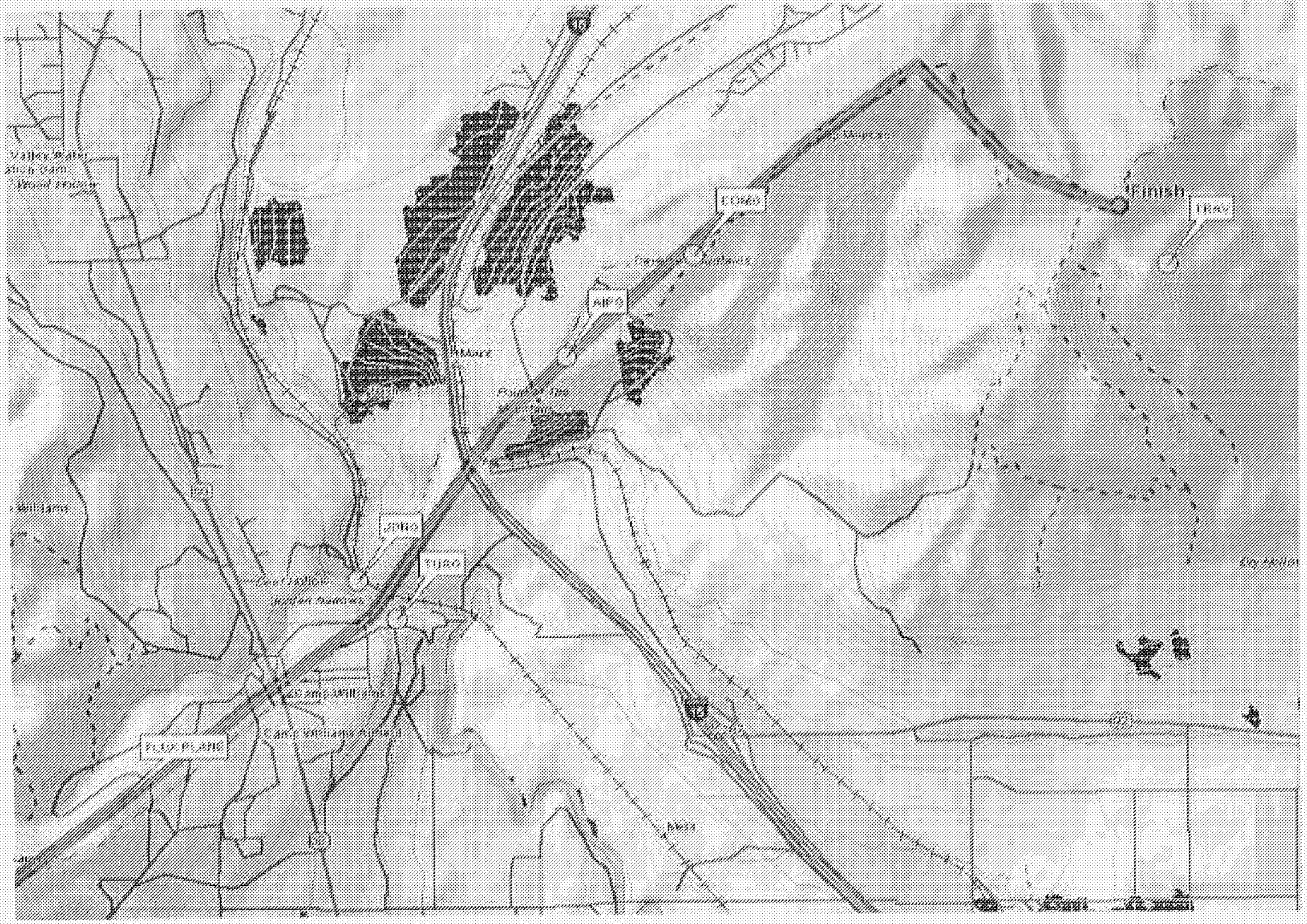

Figure 1. Flux Plane and Locations of Monitoring Sites.

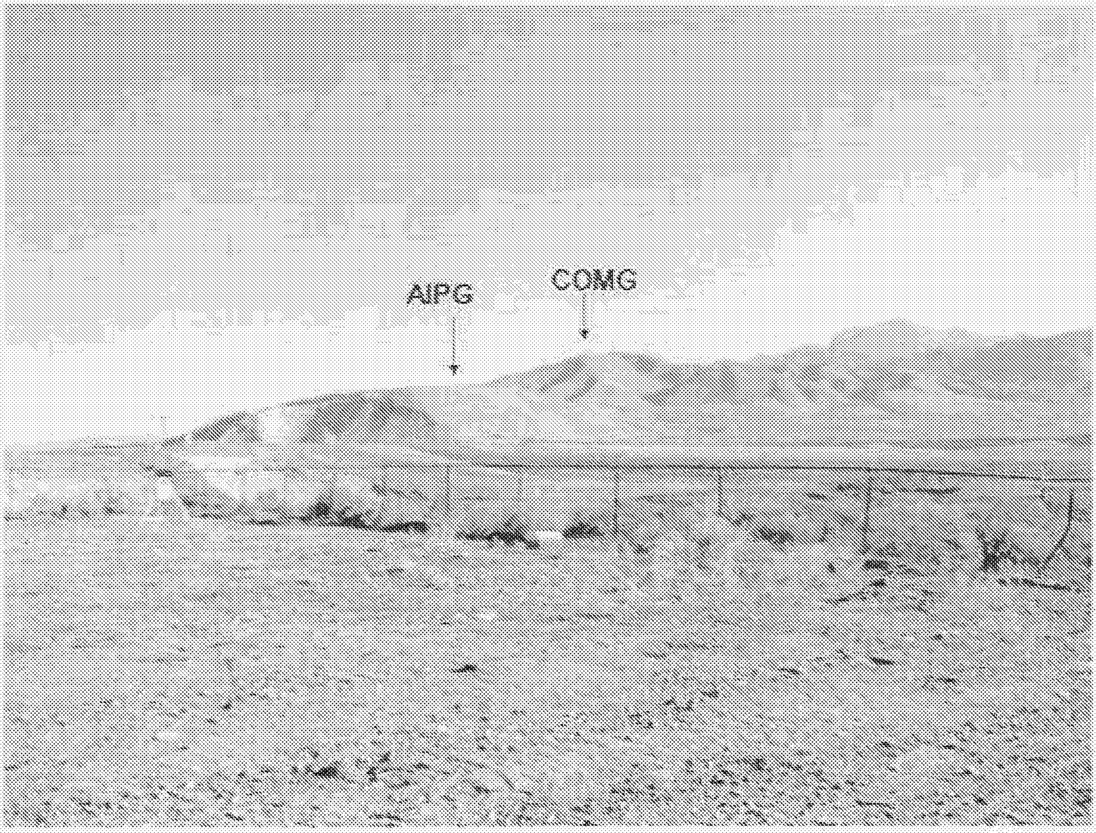

Figure 2. AIPG and COMG viewed from TURG.

Figure 3. PUMG viewed from TURG.

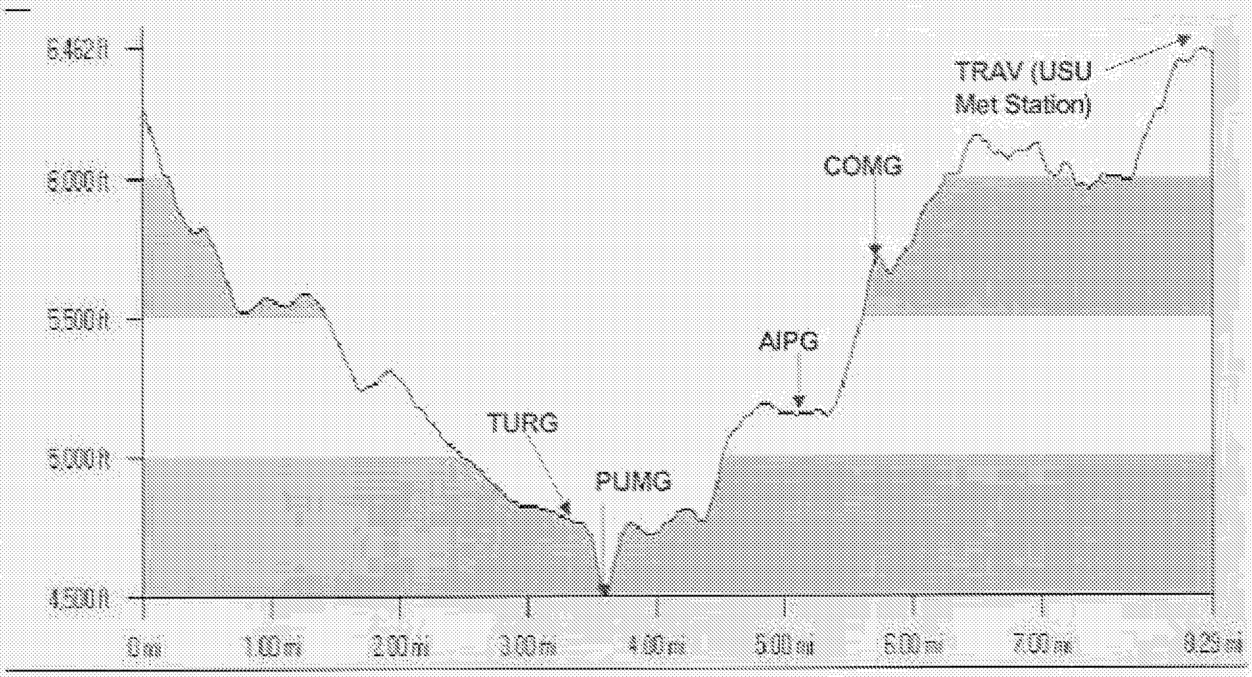

Figure 4. Relative Monitoring Site Elevations

Site	Height (m)	Width (m)	Area (m^2)
PUMG	75	210	16,000
TURG	140	2,600	364,000
AIPG	180	6,330	1,139,000
COMG	230	11,000	2,530,000

Table 1. Flux Plane Section Dimensions

2.2 Measurement Methods

2.2.1 PM_{10}

Particulate light scattering (PM_{scat}) data were collected using DustTrak portable aerosol monitors. The DustTrak is a relatively inexpensive, portable, battery operated laser-photometer that measures the light scattered by particles. It measures particle concentrations over periods of seconds to minutes and is traceable to a reference gravimetric method for PM_{10} concentrations using the National Institute of Standards and Technology (NIST) Ultra Fine Test Dust Reference Material (RM 8632), formerly known as the Arizona Fine Dust Standard. For this study, PM_{scat} measurements were used to represent PM_{10}, and are referred for convenience as PM_{10} even though it is not a true direct measurement of PM_{10} based on filter sampling methods such as the High Volume air sampler (Hivol). Dustrak samplers were enclosed in cooler boxes with a sample line collecting ambient air from outside the enclosure. Six-volt wet cell batteries provided the necessary power. The enclosure and sample line setup is shown in Figure 6. During monitoring, PM_{10} (i.e. PM_{scat}) data were collected as 10-minute averages and eventually archived as hourly averages taken from the 10-minute samples.

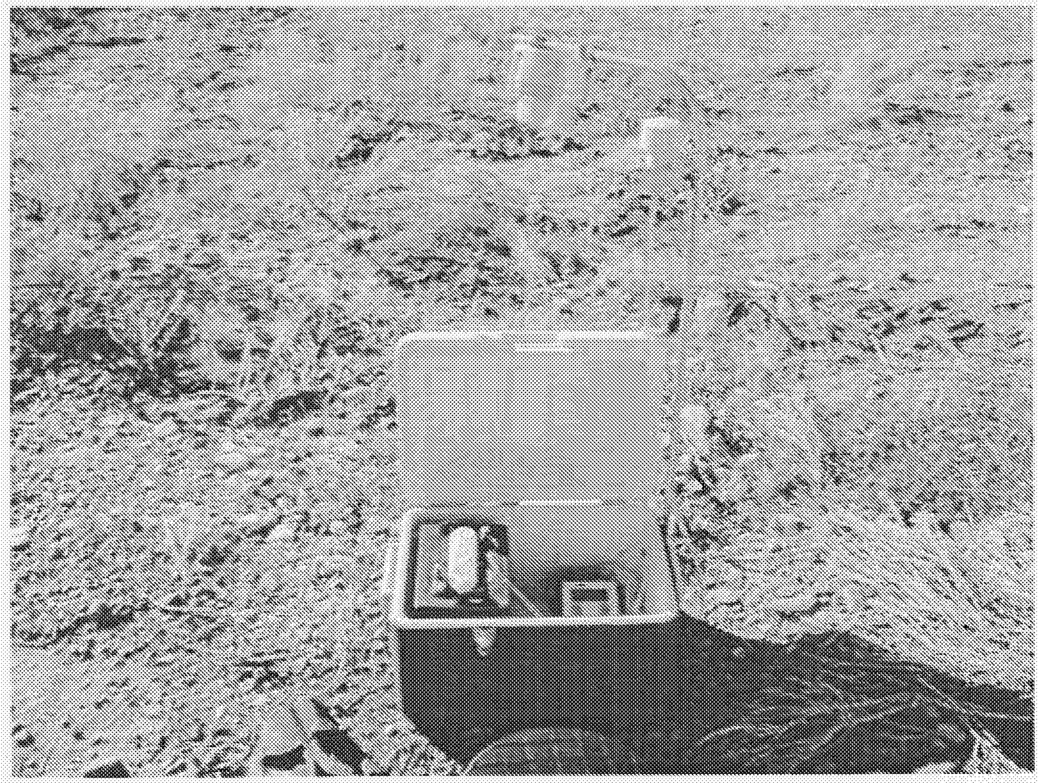

Figure 6. Dustrak Enclosure and Sample Line Setup.

2.2.2 Meteorology

Meteorological data (wind speed, wind direction, temperature) data were collected on 3m masts at the PUMG, TURG, AIPG, and TRAV sites. DRI installed instruments and collected data at PUMG and TURG. USU installed instruments and collected data at AIPG and TRAV.

2.2.3 PM_{10} Flux

For each hour, the flux of PM_{10} through the flux plane defined by Traverse Ridge was calculated as

$$F = WS * C$$

Where F is the hourly average Unit PM_{10} flux ($\mu g/m^2$-s), WS is hourly average wind speed (m/s), and C is the hourly average PM_{10} concentration ($\mu g/m^3$).

Figures 7a-d show wind roses for the VTMX campaign period October 2000 for the four sites. Wind directions have well-defined bimodal distributions that indicate flow either into or out of the Utah Lake Basin. The Total PM_{10} flux (g/s) between the Utah and Salt Lake Valleys was estimated by multiplying F by the corresponding flux plane area shown in Table 1, with positive flux arbitrarily defined as flow from the Utah Lake Basin into the Salt Lake Basin, and negative flux defined as the opposite flow.

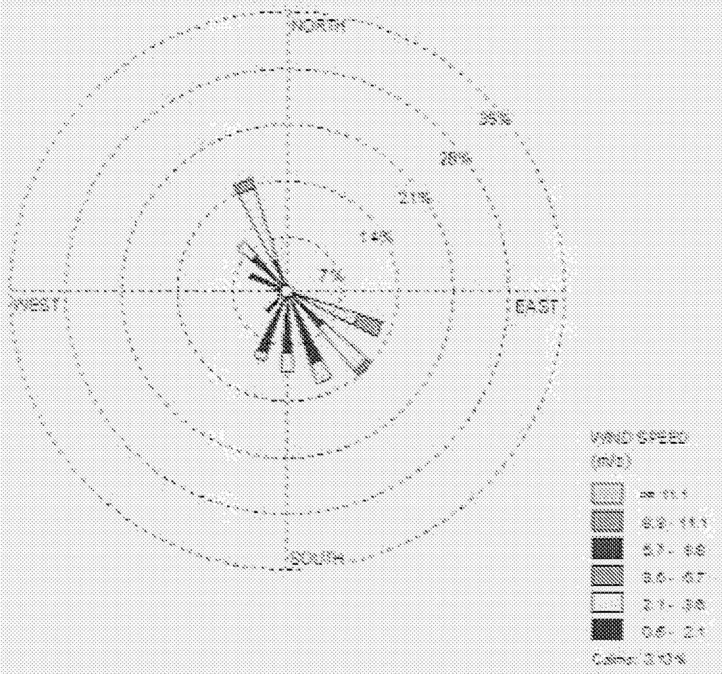

Figure 7a. PUMG Windrose, October, 2000

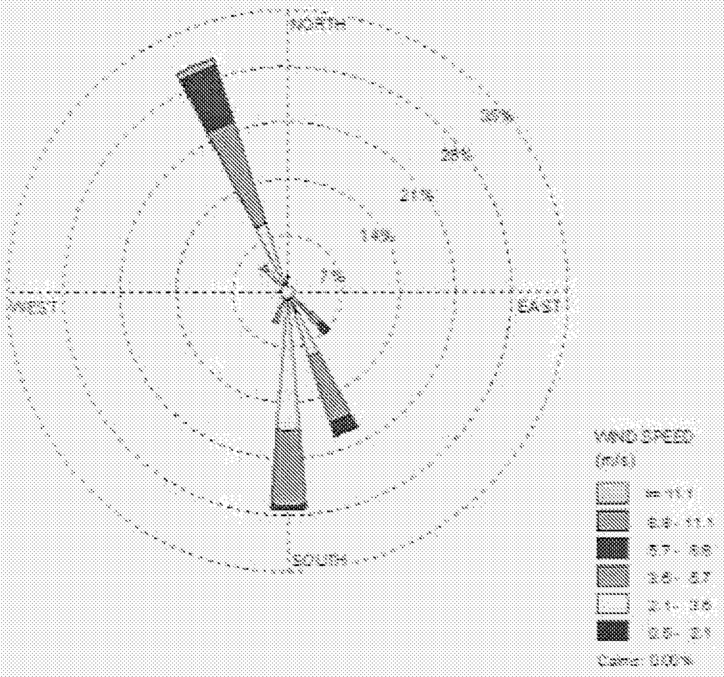

Figure 7b. TURG Windrose, October, 2000

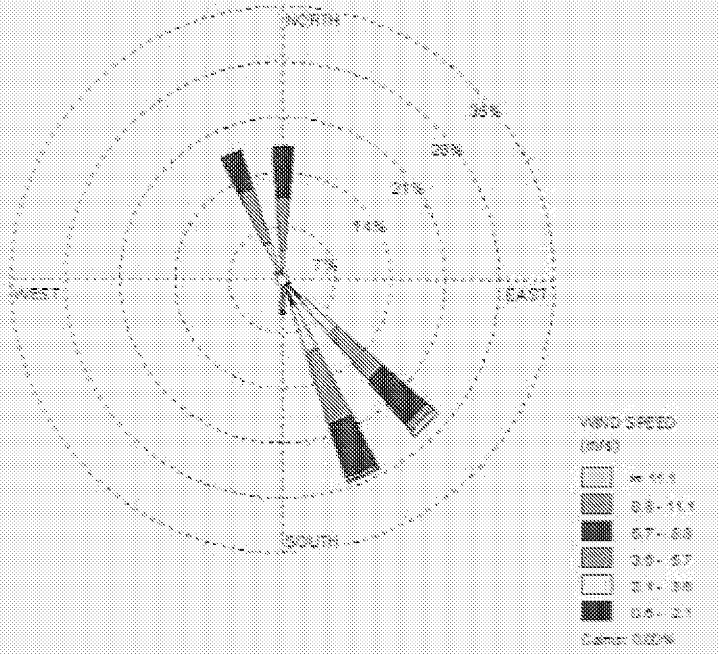

Figure 7c. AIPG Windrose, October, 2000

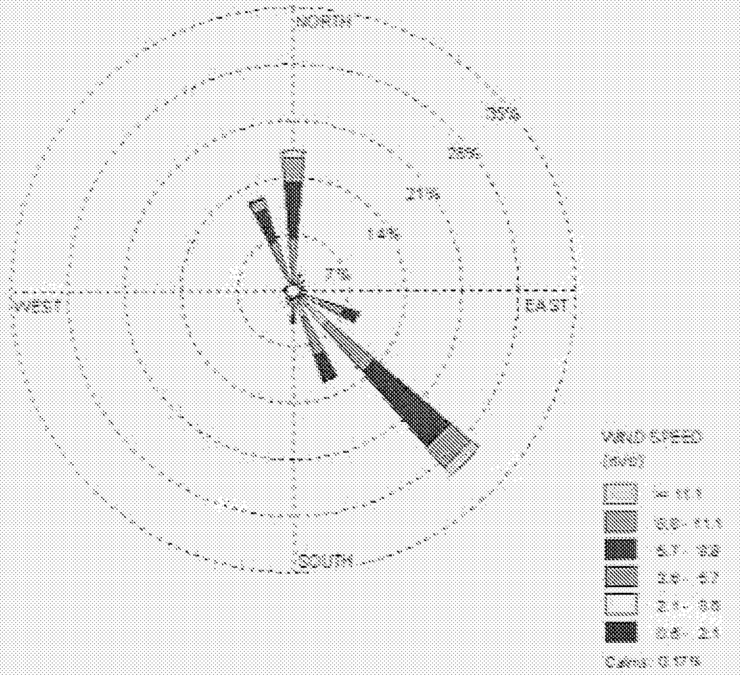

Figure 7d. COMG Windrose, October, 2000

2.2.4 Data Completeness

Valid data completeness and representation for the study period are shown in Figure 8. PM_{10} concentration data recovery was near complete for the period. PM_{10} flux data, with its dependence on wind data, was less complete, resulting in gaps in the record for complete and simultaneous flux data at all 4 levels. Best representation, including flux measurements at all 4 levels, is for the period generally between October 7 and October 12, which includes IOP 8, October 8-9.

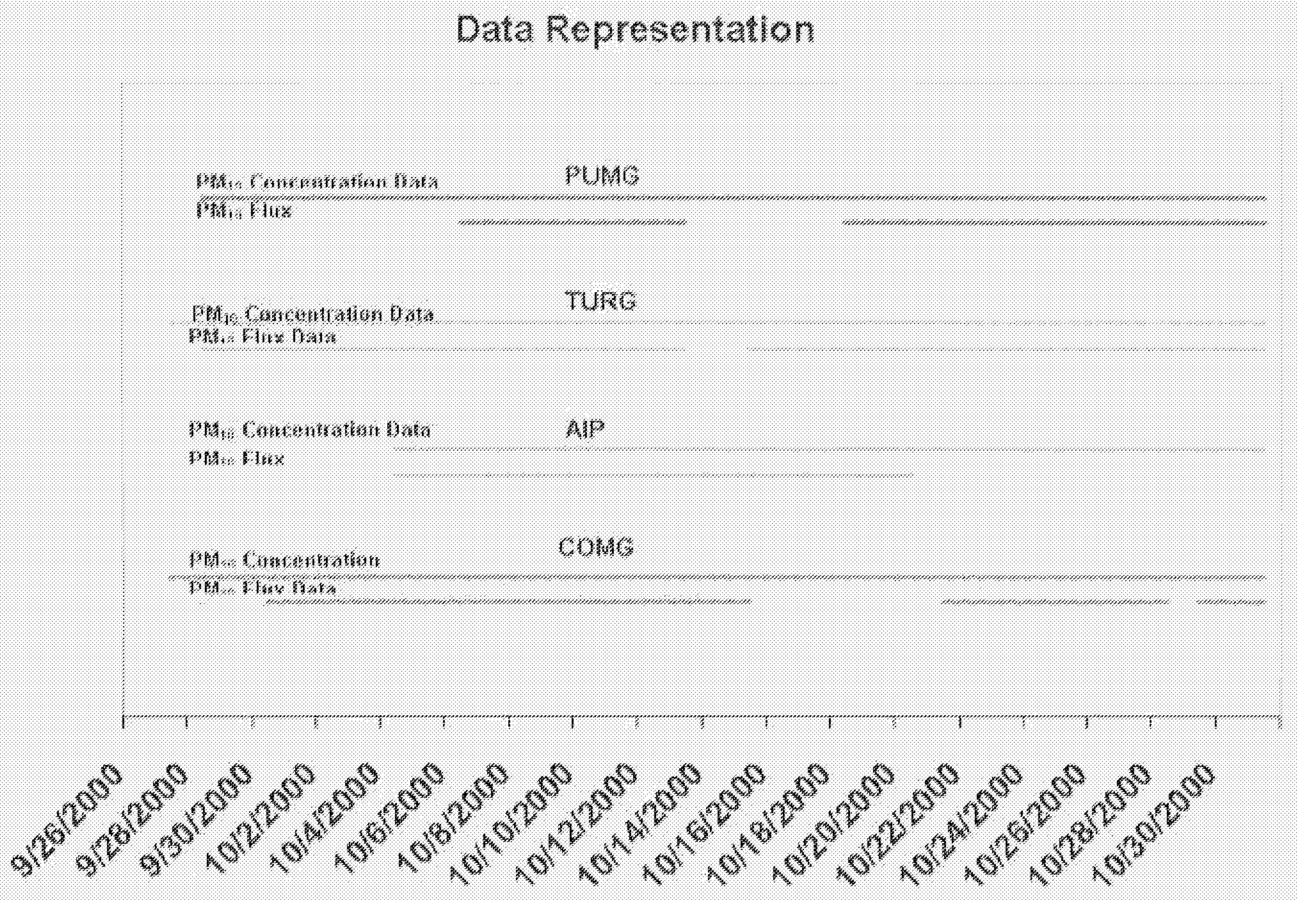

Figure 8. Data Representation for VTMX Study Period

3.0 Results

3.1 Average PM_{10} Concentrations and PM_{10} Flux During Study Period

Figures 8, 9, and 10 and 9 give 24 hour PM_{10} concentrations, unit area PM_{10} flux, and total PM_{10} flux at Traverse Ridge Dustrak sites for the VTMX study period. Note that there were no COMG data for October 16-19, no PUMG data for September 26 – October 5 and October 14 – 17, no AIPG data for October 21 – 30, and no TURG data for October 20. The most complete data representation is for October 7 – 12, which includes IOP's 3 (October 7-8) and 4 (October 8 – 9).

Figure 8 shows PM_{10} concentrations during VTMX for the 4 Dustrak monitoring stations along Traverse Ridge. During the periods with the best IOPs, October 8-9 and October 14-20, PM_{10} concentrations were higher than during non-IOP periods. Concentrations at PUMG and TURG, representative of the Jordan Narrows, were higher than concentrations at AIPG and much higher than at COMG, consistent with concurrent surface inversion and pollutant trapping conditions.

Figure 9 gives 24-hour average unit area PM_{10} flux, where positive bars represent flux into the Salt Lake Basin and negative bars represent flows out of the Salt Lake Basin. In general, and especially during IOP's, unit flux is generally lower at the lower level stations because of the lower wind speeds, even though PM_{10} concentrations are higher. The high positive flux at the COMG site during October 10-13 is a result of persistent high speed southeasterly flow associated with an upper-level trough during this non-IOP period. In contrast, around October 23 the 24-hour average unit area flux was generally negative (out of Salt Lake Basin), but was much higher at PUMG and TURG because of persistent northerly surface winds than at COMG where daytime northerly flow was balanced by nighttime return flow.

Figure 10 shows 24-hour average total PM_{10} flux. Although in general total flux in this plot is dominated by the upper portion of the flux plane represented by COMG because of the greater cross section area, note that during the period of complete data representation 10/7-12, which includes the IOP of 10/8-9, there is significant contribution from AIPG and TURG, indicating the potential importance of transport at lower elevations during stable surface inversion conditions.

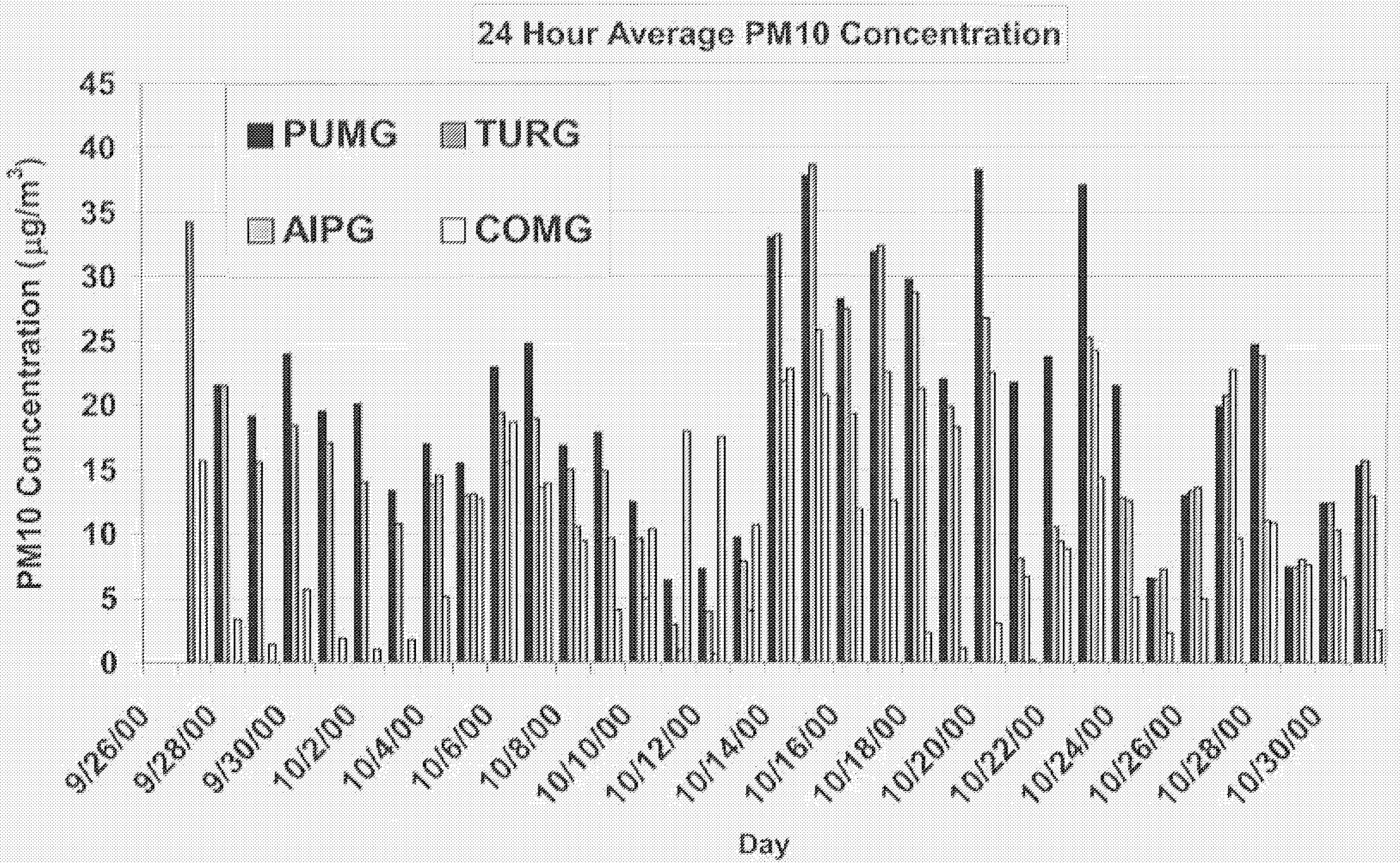

Figure 8. Twenty-four Hour PM_{10} Concentrations Duiring VTMX Study Period.

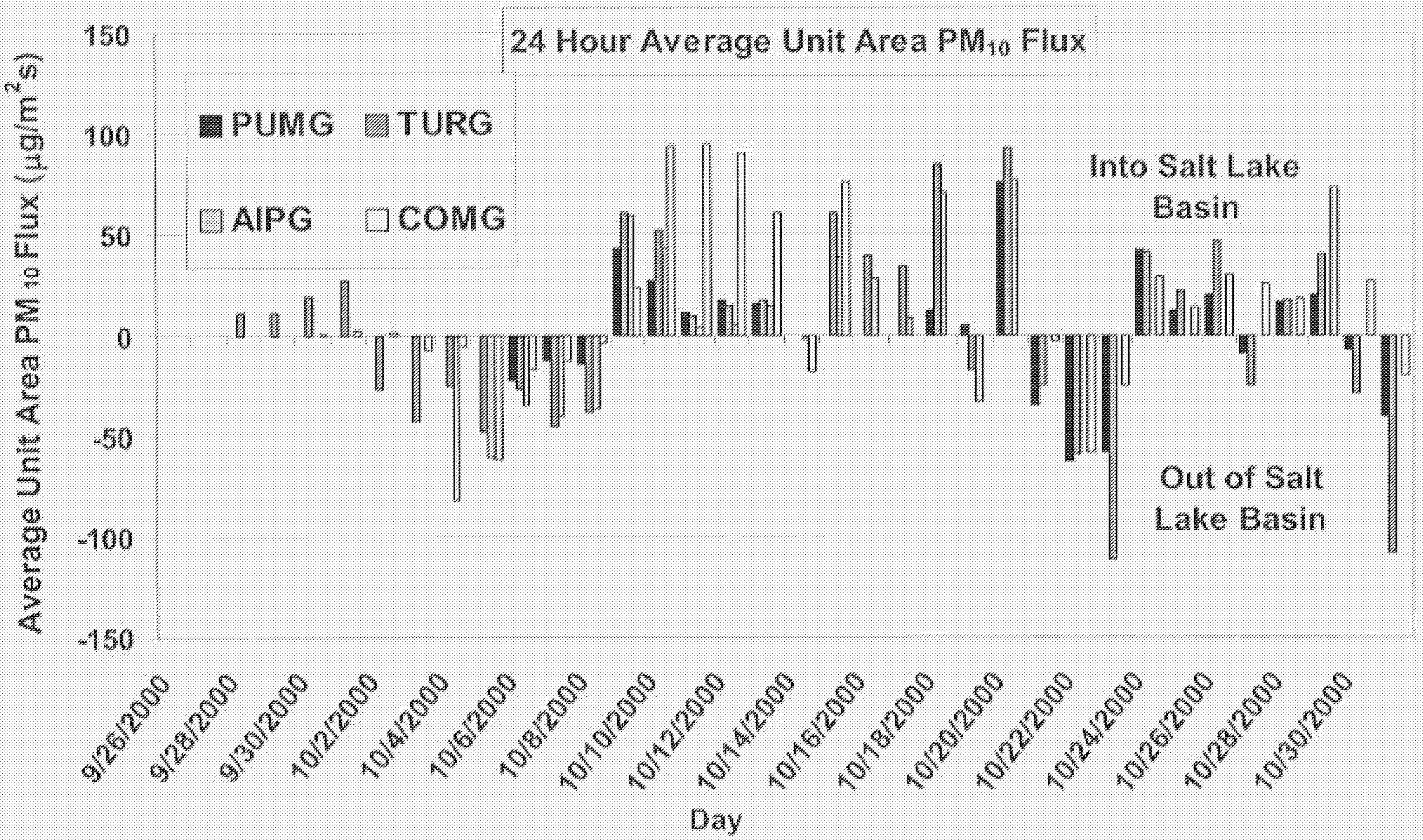

Figure 9. Twenty-Four Hour Average Unit Area PM_{10} Flux During VTMX Study Period.

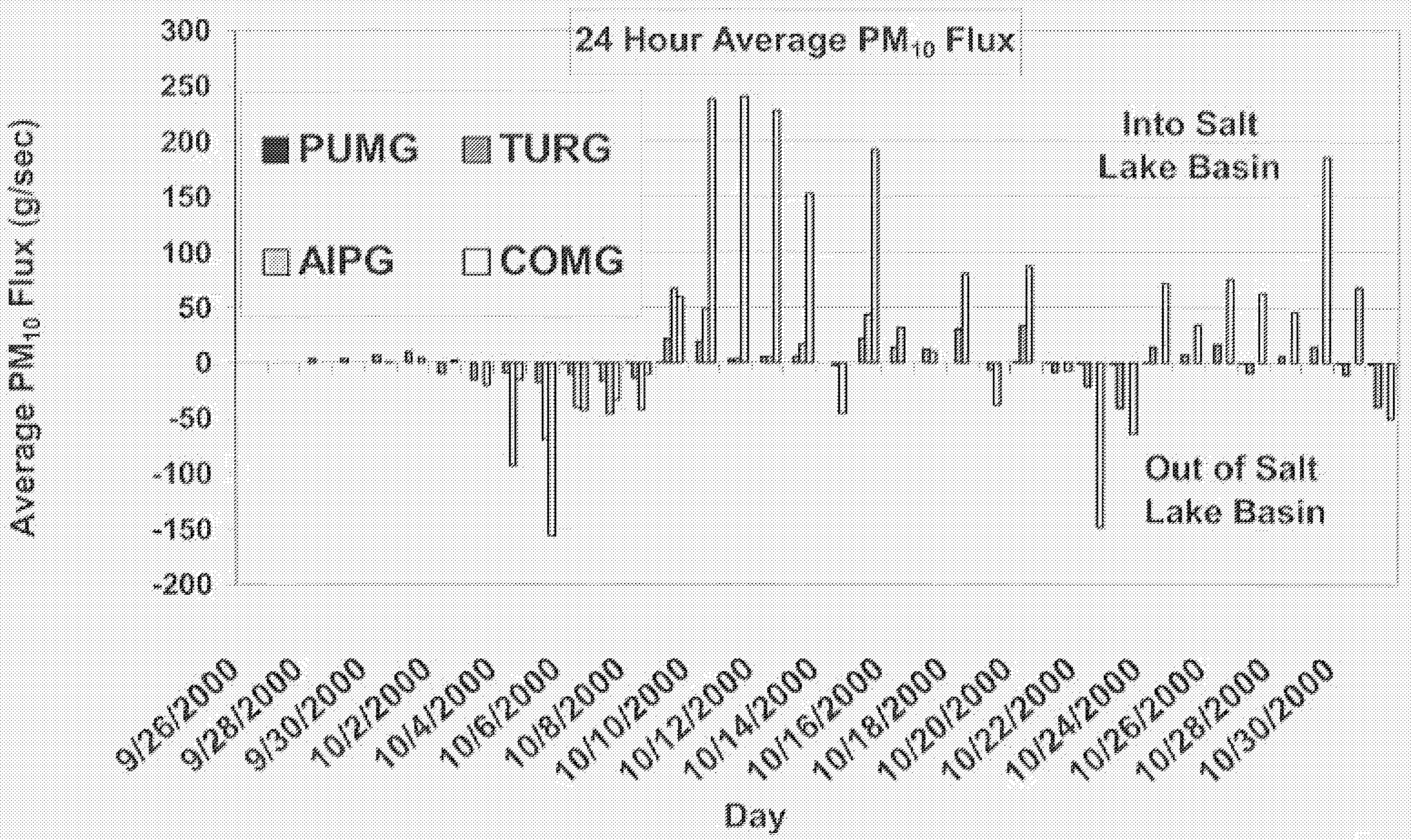

Figure 10. Twenty-Four Hour Average PM_{10} Flux During VTMX Study Period.

3.2 Selected IOPs

Detailed results from IOPs 4 (8-9 October), 7(17-18 October), and 8 (19-20 October) are presented here. Meteorological conditions during these IOPs are described in general by Doran et al (2002). IOPs 4 and 7 were characterized by clear skies, weak winds aloft, and a strong surface-based radiation inversion until 0500 LST. IOP 8 was one of the IOPs having well-developed drainage circulations, with a surface based inversion developed after sunset and persisting without significant interruption until sunrise. Valid flux data were collected at all four Jordan Narrows sites (PUMG, TURG, AIPG, and COMG) during IOP 4, at two sites, AIPG and TURG, during IOP 7, and at three sites, PUMG, TURG, and AIPG, during IOP 8. Detailed discussions of boundary layer evolution and structure over the VTMX study region during these IOPs are given by Chen et al (2004), Zhong and Fast (2002), and Pinto et al, (2002), including atmospheric profiles from a rawinsonde site 3 km NNW of PUMG, operated during VTMX by NCAR (Pinto et al, 2002). The NCAR site elevation is at the same elevation as the PUMG site elevation at the bottom of Jordan Narrows.

Figures 11-13 show results for these IOPs, from noon local time preceding the IOP until noon the following day. Each group of plots include potential temperature (degrees C) derived from temperature measurements using standard atmosphere extrapolation, PM_{10} concentration ($\mu g/m^3$), and unit area and total PM_{10} flux ($\mu g/m^2$-sec, g/sec) across the Traverse Ridge flux plane. Plots of potential temperature at the Jordan Gap sites indicate stable stratification setting up at lower levels (AIPG and lower) at 1800 to 2200 LST, and persisting until around 0800 LST the following morning, consistent with the nocturnal surface inversion conditions during IOPs.

PM_{10} concentration plots show significantly higher concentrations at the low elevation sites, with nighttime values at PUMG and TURG typically twice those at AIPG and much higher than at COMG. This is especially true during IOPs 7 and 8, when PM_{10} concentrations near the bottom of Jordan Narrows averaged 30 to 40 $\mu g/m^3$. Though well below the National and Utah 24-hour standard of 150 $\mu g/m^3$ it poses the possibility that gap flow acceleration through Jordan Narrows may provide a channel for pollutant transport into Salt Lake Basin via low level nocturnal drainage flow. Plots of calculated nighttime unit area PM_{10} flux into Salt Lake Basin show nearly equivalent values at the lower elevation sites, AIPG and below, for IOPs 4 and 8. The IOP7 plot, with AIPG and TURG only, suggest significantly higher unit area flux at TURG than AIPG. More significantly, the plots of total PM10 flux, calculated with the assumption of uniformity across vertical sections of the flux plane, show nocturnal transport into Salt Lake Basin at middle Jordan Narrows elevations, exemplified by the AIPG and TURG sites, that is much greater than that at the bottom site, PUMG, during IOPs 4 and 8. (Flux calculations were not available for PUMG for IOP7). TURG is 67m higher than the river level site PUMG. AIPG is 195m higher than PUMG. TURG is thus near or above a typical tens of meters extremely stable nighttime surface layer depth near the Jordan Narrows gap, while AIPG is probably above. Noteworthy in this regard, stratified flow simulations show that a lee side hydraulic jump can convert this shallow layer to a less stable and deeper layer a few km downwind from the gap (Chen et al, 2004). The resultant vertical mixing could occur over a depth that extends from the surface up to or above the AIPG elevation in any case.

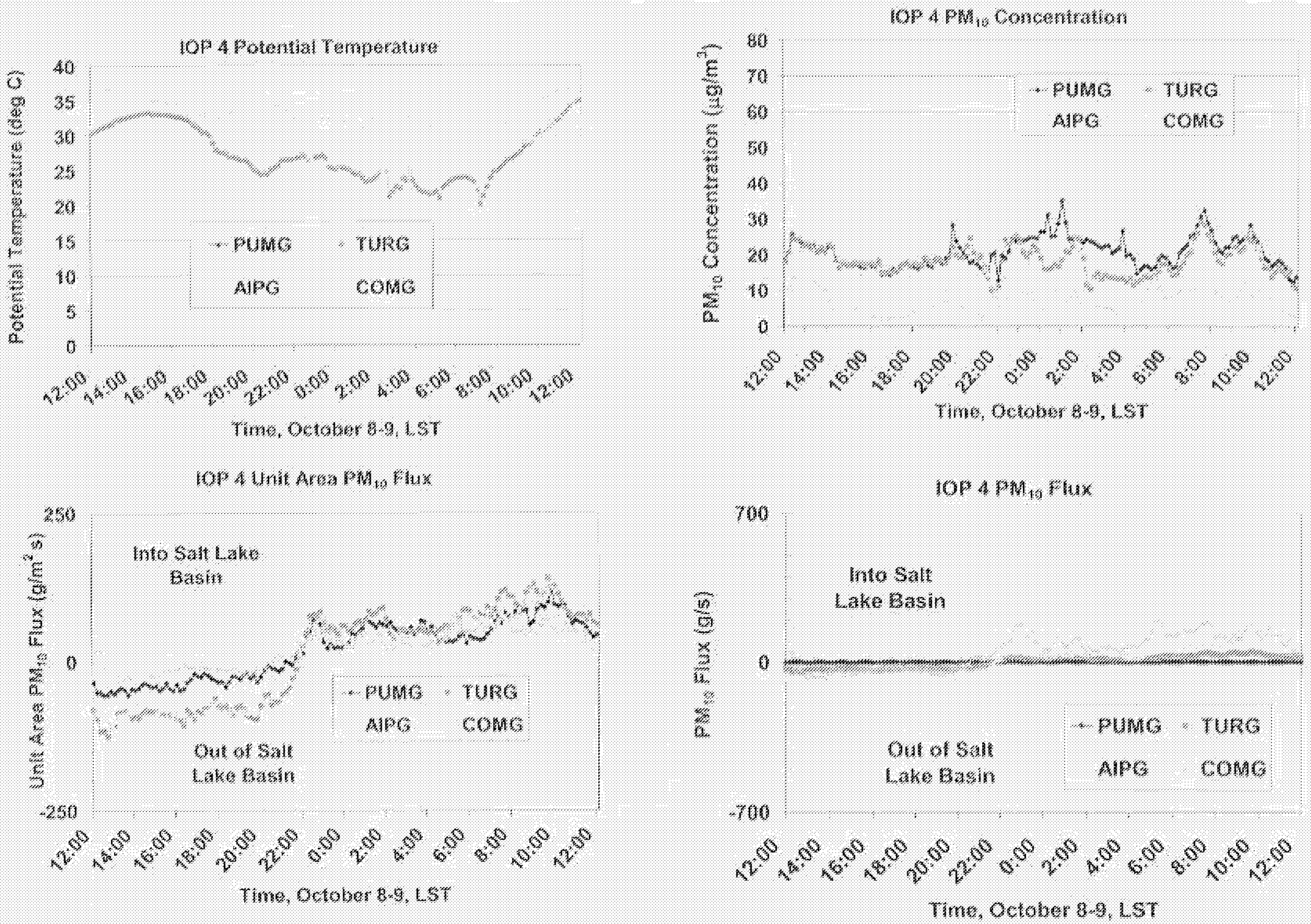

Figure 11. Potential Temperature, PM_{10} Concentration, Unit Area PM_{10} Flux, Total PM_{10} Flux During IOP 4.

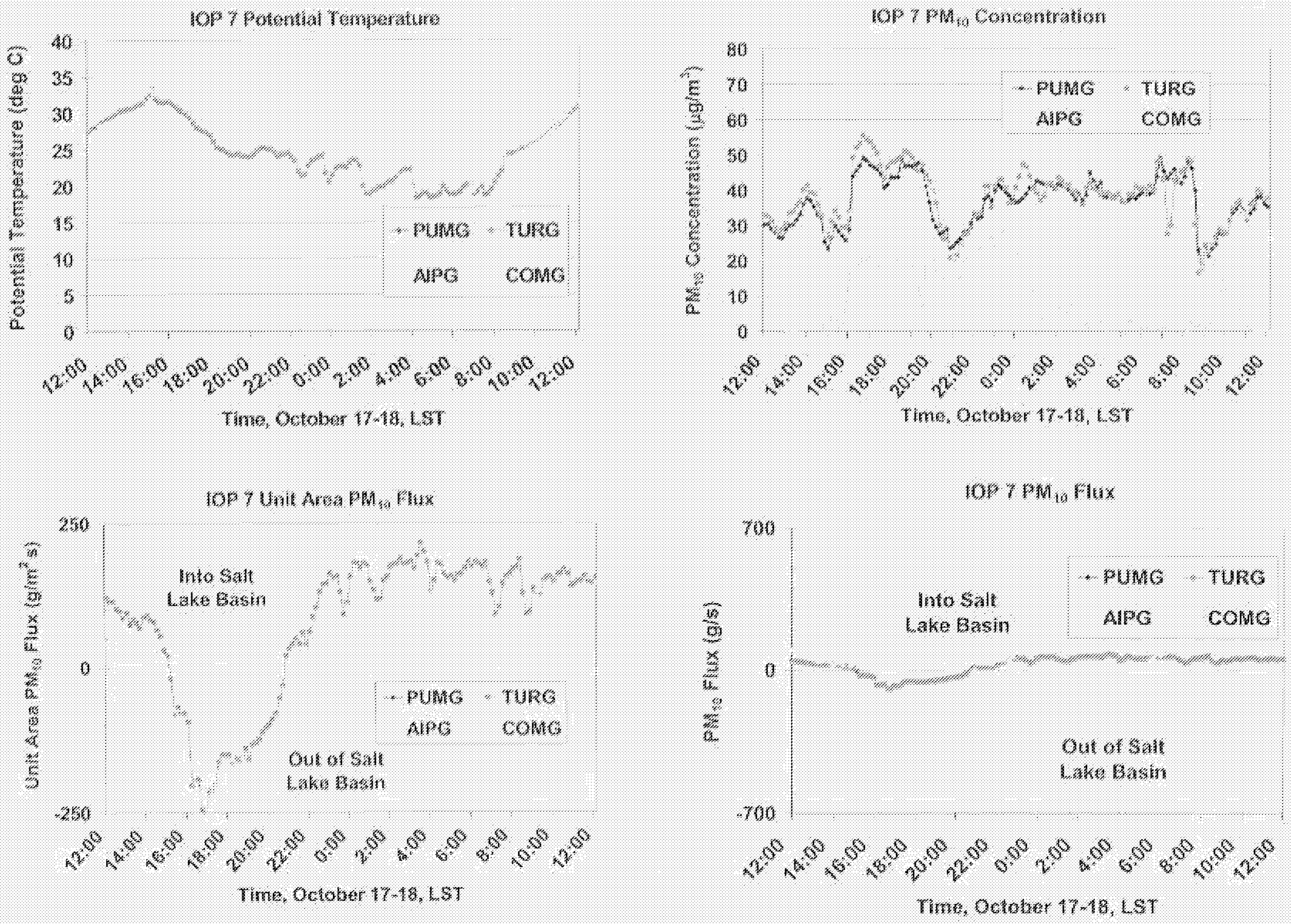

Figure 12. Potential Temperature, PM$_{10}$ Concentration, Unit Area PM$_{10}$ Flux, Total PM$_{10}$ Flux During IOP 7.

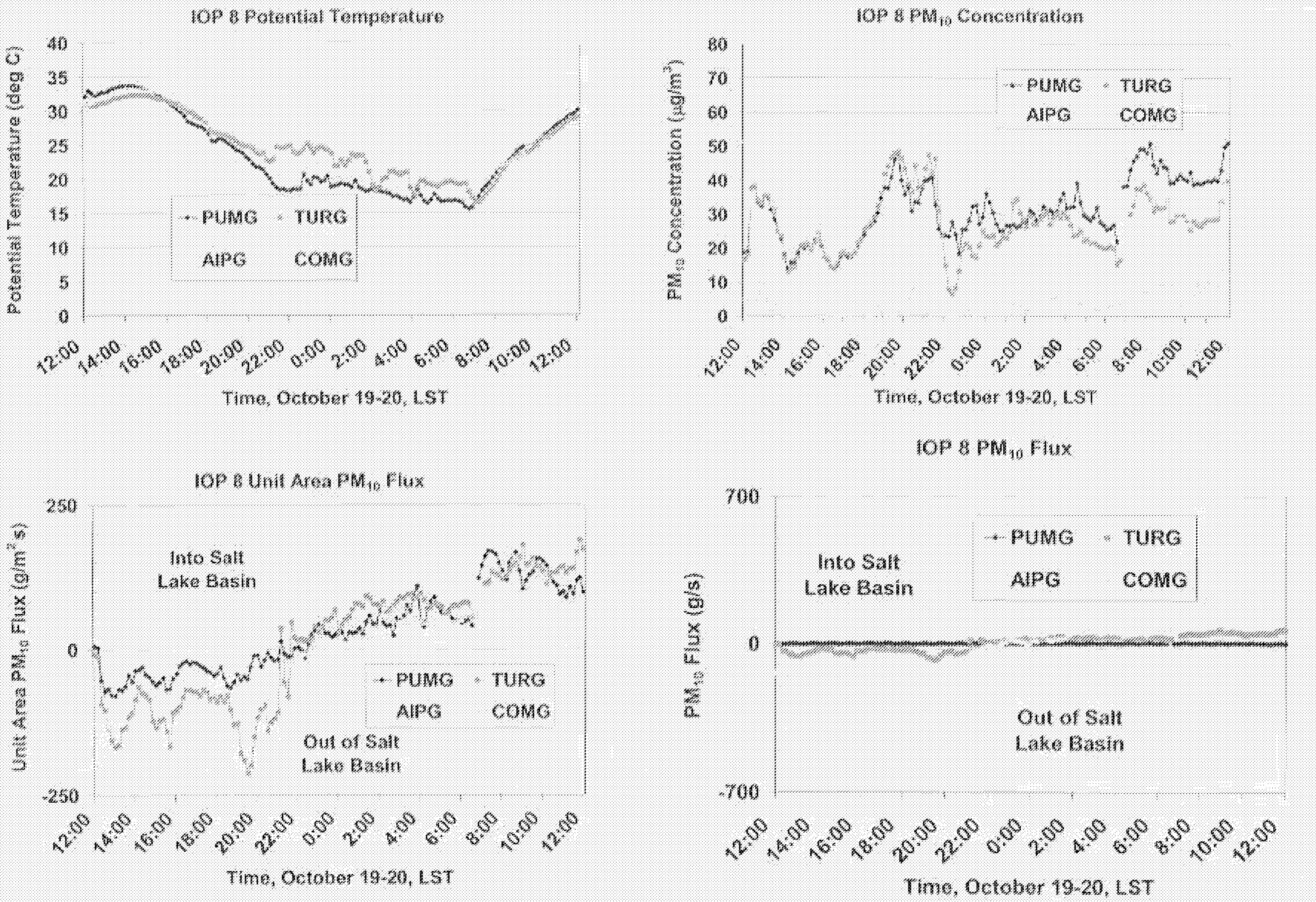

Figure 13. Potential Temperature, PM$_{10}$ Concentration, Unit Area PM$_{10}$ Flux, Total PM$_{10}$ Flux During IOP 8.

4.0 Conclusions

PM_{10} flux calculations in the vicinity of Jordan Narrows during stably stratified periods show significant interbasin flux at intermediate locations, TURG and AIPG. This is especially obvious during IOP4, with the most complete data representation.

Although PM_{10} concentrations are as high or higher at the bottom site, PUMG, concurrent meteorological data do not in general indicate significant interbasin transport at that level.

The simple methodology described here is potentially useful for monitoring interbasin flux through well-defined transport corridors. Flux monitoring may enable accurate forecasts of occurrence and timing of transport contributions to air pollution episodes in adjacent air basins. Application of the methodology can be refined with longer term monitoring during a variety of meteorological conditions.

5.0 References

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