2.8 CARBON DIOXIDE TRANSPORT OVER COMPLEX TERRAIN

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1. INTRODUCTION

To understand regional sources and sinks of carbon dioxide, nocturnal CO_2 transport is one of the major issues that needs to be addressed (Sun et al. 1998). The importance of the horizontal transport of CO_2 has been investigated in the literature recently (Aubinet et al. 2003; Kominami et al. 2003; Staebler and Fitzjarrald 2004). Characteristics of the nocturnal and morning transition wind, turbulence, and temperature fields in a valley was studied extensively during several series of Atmosperic Studies in Complex Terrains (ASCOT) during 1980's (e.g. Clements et al. 1989). CO_2 transport over complex terrain is particularly important in regional carbon sequestration, especially over the western U.S. Schimel et al. (2002) found that 70% of the western U.S. carbon sink occurs at elevations above 750 m, an elevation range in which 50-85% of land is dominated by hilly or mountainous topography. During September 2002, we conducted a pilot experiment at the Niwot Ridge AmeriFlux site to focus on nocturnal transport of CO_2 over complex terrain. In this study, we report some of results on the issue.

2. OBSERVATIONS

The Niwot Ridge AmeriFlux tower site has been operational since 1998 (Monson et al. 2002; Turnipseed et al. 2002; Scott-Denton et al. 2003; Turnipseed et al. 2003; Anderson et al. 2004). The site is on the east of the continental divide with a west-east slope of 5-7 % at the elevation of 3050 m. It is surrounded with a subalpine forest that consists of subalpine fir (Abies lasiocarpa), Engelmann spruce (Picea engelmanii, lodgepole pine (Pinus contorta). The typical tree height is 11.4 m.

The Niwot Ridge AmeriFlux tower site consists of 6 towers (Fig.1). University of Colorado (CU) operates two towers: a 27-m scaffolding tower and a 6-m triangle tower, which are 4m apart. There are 6 levels of CO_2 concentration measurements (0.5 m, 1 m, 2 m, 5 m, 10 m, and 21 m, LiCor-6251); 3 levels of temperature and relative humidity measurements (2 m, 8 m, and 21 m, Vaisala); 7 levels of wind measurements (1 m, CSAT; 2.5 m CSAT; 6 m 2-D Handar; 9 m 2-D Handar; 16 m RM Young Vane; 21.5 m CSAT; and 25 m RM Young Vane); 1 level of pressure measurement (13 m), incoming and outgoing longwave and shortwave radiation measurements at 25 m, net radiation at 25 m (Kipp and Zonen), PAR at 25 m, precipitation at 10.5 m, and leaf wetness at 10 m. Turbulence is measured using the eddy correlation method at 2.5 m and 21.5 m, which includes sensible and latent (Krypton at 21 m and LiCor-7500 at 2.5 m) heat fluxes, momentum flux, and CO_2 flux. The CO_2 flux is measured with CSAT sonic anemometer and LiCor-6262 at 21 m, and CSAT sonic anemometer and LiCor-7500 at 2.5 m.

The other four towers were operated by USGS: a 33-m tower, a 8-m tower, and two 6-m towers (north and south towers). The 33-m and 8-m towers are about 4 m apart. Between the 33-m and the 8-m towers, there are 2 level of CO_2 flux measurements (Licor-6262 at 33 m, and NOAA IRGA at 2 m), 2 levels of moisture flux measurements (Krypton at 33 m and NOAA IRGA at 2 m), 5 levels of CO_2 concentration measurements (1 m, 2 m, 3 m, 6 m, 10 m, and 33 m), 5 levels of wind measurements (2-D Handar at 1 m, 2 m, 3 m, 6 m, and 10 m; cup and vane and CSAT-3 at 33 m), 3 levels of temperature and humidity measurements (2 m, 10 m, and 33 m), and net radiation and incoming shortwave at 33 m. Two levels of CO_2 concentration measurements (1 m and 6 m) are at both the north and south towers. In addition, there are 2 levels of wind measurements at the south tower (2-D Handar at 1 m and 6 m). Similar to CU tower, the CO_2 concentration is measured by a LiCor-7000, and the CO_2 flux is measured by the CSAT-3 sonic anemometer and LiCor-6262.

During the Niwot Ridge pilot experiment conducted in September, 2002, four additional 10-m towers were deployed at the Niwot Ridge AmeriFlux tower site by NCAR/ATD (Fig.1). Tower s2 was a scaffolding tower, and the rest of the towers were the triangle towers. On

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corresponding author address: Jielun Sun, National Center for Atmospheric Research, P. O. Box 3000, Boulder, CO 80307-3000; *email*: jsun@ucar.edu the three towers (s1, s2, and s3), there were 4 levels of CO_2 concentration measurements (1 m, 3 m, 6 m, and 10 m), 3 levels of wind measurements (s1 and s3: 1 m, 3 m, and 6 m; s2: 1 m, 6 m, 10 m) with 3-D sonic anemometers (CSAT and ATI), 2 to 3 levels of fast water vapor measurements with Krypton (s1 and s3: 1 m and 6 m, s2: 1 m, 6 m, and 10 m), and 2 to 4 levels of Vaisala temperature/relative humidity measurements (s1 and s3: 1 m and 6 m; s2: 1 m, 3 m, 6 m, and 10 m). On the central tower, there were 3 levels of CO_2 concentration measurements (1 m, 3 m, and 6 m). To compare the CO_2 concentration measurement from CU, USGS, and NCAR, we co-located CO_2 measurements at the USGS north tower (1 m), and the CU 27-m (1 m).

The CO_2 concentration at the four additional towers was measured by using a system called HYDRA, designed and assembled by Tony Delany at NCAR/ATD (Burns et al. 2004). It has 18 CO_2 inlets to two Licor-7000 CO_2/H_2O analyzers. Three calibration gases were used for CO_2 measurement accuracy.

To monitor temporal variations between the HYDRA, the CU CO_2 system, and the USGS CO_2 system, each HYDRA Licor-7000 had a co-located CO_2 inlet at 1 m on tower s2; a HYDRA inlet was also co-located with the CU CO_2 system at 1 m on the CU tower, and a HYDRA inlet was also co-located with the USGS CO_2 system at 1 m on the USGS north tower. We assume that the CO_2 readings from different systems should be the same from the co-located inlets, and the differences between the HYDRA and the CU system, and between the HYDRA and the USGS system are used to calibrate the USGS and CU systems for all their measurements.

3. NOCTURNAL CO2 TRANSFPORT BY DRAINAGE FLOW

By compositing the CO_2 concentration at 1 m at each tower during the entire pilot experiment, we investigated the spatial variation of the CO_2 concentration at 1 m in the area. We found that on average, the CO_2 concentration was high along the Como creek, not along the main east-west orientated slope. The CO_2 concentration did increase downs the main slope in the morning before the convective boundary layer started form and in the evening as the stable boundary layer started to develop (Fig.2). However, this pattern changed at 6 m, where the CO_2 concentration increased down the main slope (Fig.3). The comparison of Figs.2 and 3 indicates that the drainage flow along the Como creek was less than 6 m deep.

Since the drainage flow depends on stability of the air, turbulence generated by wind shear mixes the air in the vertical, which brings warm air down and rich CO_2 air up. On Julian day 267 (24 September), a wind gust prop-

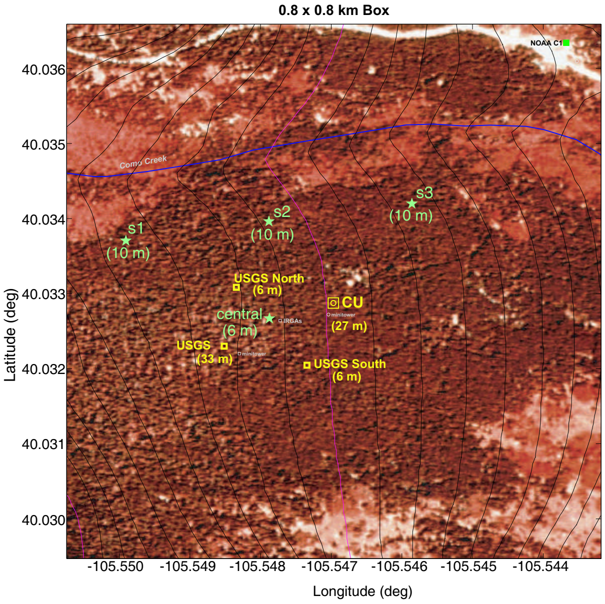

Figure 1: The area satellite map with topographic contours and the towers at the Niwot Ridge AmeriFlux site. The green and yellow symbols represent the pilot experiment and the AmeriFlux tower facilities, respectively. The tower heights are listed on the map. The Como creek is the thin blue line running from west to east about 40.035 deg latitude.

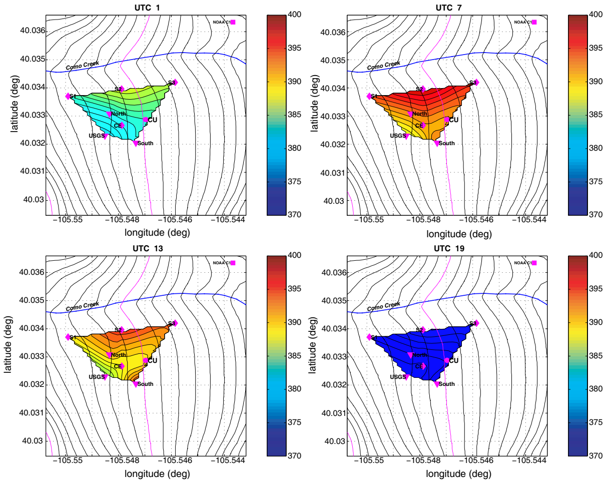

Figure 2: Composite spatial distributions of CO_2 concentration at 1 m during the pilot experiment at selected hours.

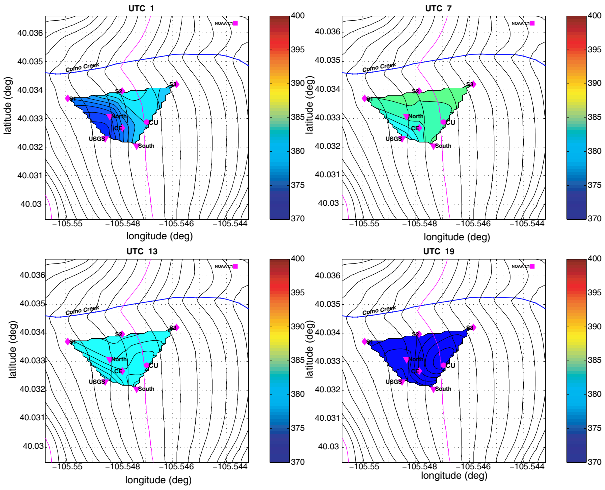

Figure 3: Composite spatial distributions of CO_2 concentration at 6 m during the pilot experiment at selected hours.

agated downward and eastward as shown from the vertical velocity measured at towers s1, s2, and s3 (Fig.4). The spatial pattern of the high CO_2 concentration along the Como creek at 1 m was destroyed right after the passage of the wind gust, the CO_2 concentration was reduced, and the relative high CO_2 concentration was shifted to increase down the main slope.

The wind-dependence of the CO_2 concentration can be also seen from Fig.5 for two different nights, during which the wind speed and wind direction changed, respectively (Fig.5). As the wind speed increased at around 5 UTC (Julian day 251.2), the CO_2 concentration at 1 m dropped at all the towers. As the wind direction oscillated from east to west on Julian day 252, the CO_2 concentration at 1 m oscillated at all the towers.

4. SUMMARY

The drainage flow is important in the CO_2 transport at night especially when wind is weak and the canopy layer is stable. Under very stable conditions, the high CO_2 flows to local low-ground, such as the Como creek due to the local drainage flow, which is less than 6 m deep. At the 6 m above the ground, the regional drainage flow dominates the CO_2 transport, and CO_2 is transported to the regional low ground. The local drainage flow is sensitive to turbulent mixing associated with local wind shear. Wind gusts can mix up the high CO_2 within the local low ground, while the regional drainage flow may survive.

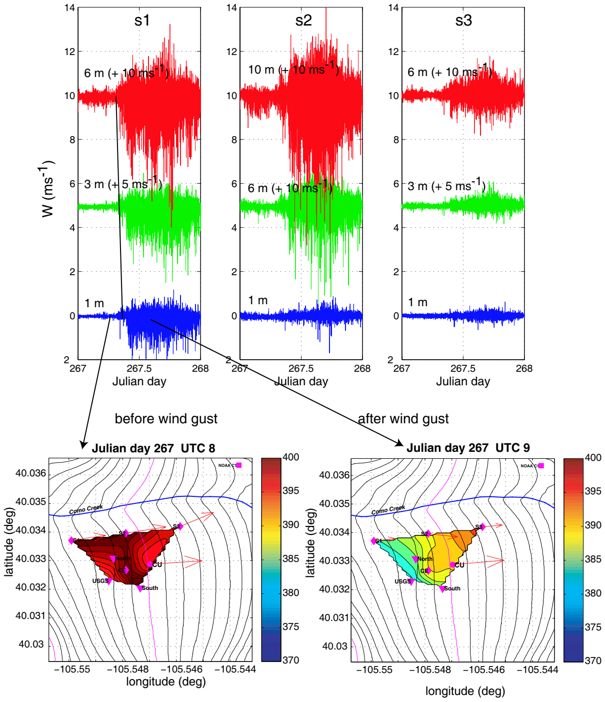

Figure 4: The wind gust shown as large vertical velocity oscillations at the various heights at towers s1, s2, and s3, and the CO_2 concentration map at 1 m before and after the wind gust. To better view the wind gust propagation, the vertical velocity measurements were plotted with constant shifts at each level.

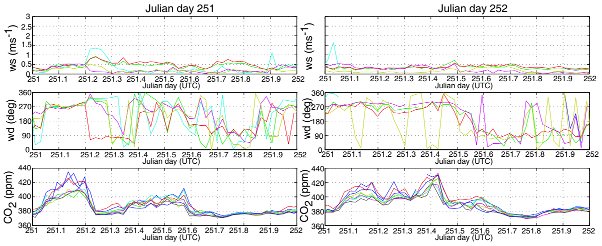

Figure 5: The time series of wind speed (top panels), wind direction (middle panels) and CO_2 concentration (bottom panels) at 1m at all the towers for Julian day 251 (left panels) and Julian day 252 (right panels).

Acknowledgements

NCAR is sponsored in part by the National Science Foundation. The research is sponsored by the NCAR director opportunity fund and the NCAR Biogeoscience Initiative fund.

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