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Supporting Information for

Assessment of an atmospheric transport model for annual inverse estimates of California greenhouse gas emissions

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Contents of this file

Text S1. CO Measurement Details

The CO measurements used in this study were made using sampling and analysis system that combine pumps, membrane (Nafion) air driers, and gas analyzers following methods described by *Andrews et al.* [2014] for WGC, or adapted for use at the other sites (SBC, CIT, ARV). In particular, while WGC employed a gas correlation spectrometer (Thermo Electron TE48-TC, the SBC, CIT, and ARV sites employed off-axis Integrated Cavity Output Spectroscopy (ICOS) (LGR Model 907-0015; Los Gatos Research Inc.). In addition, air handling and calibration methods differed across the sites. At two sites (WGC, SBC) air sampling is switched between the multiple heights (WGC: 30, 91, 483 m above ground level (magl), every 300 s; SBC: 27, and 58 magl, every 400 s) with measurements allowed to settle, and the last 120 seconds of each cycle used to quantify CO mixing ratios of the ambient air. For the analysis described below, we applied the 91m (WGC), and 58m (SBC) measurements for measurement model comparison. For other sites, measurements were made from single heights on those towers and switching was only applied for calibration.

The instrument offset and gain were measured periodically and corrected using different methods. At WGC, three National Oceanic and Atmospheric Administration (NOAA) primary standards were applied every six hours with separate target check measurements [*Andrews et al.,* 2014]. At SBC, the calibrations used three secondary gas standards tied to NOAA primary standards, with the offset and gain of the LGR instrument measured four hours using the “high and low” secondary standards and then checked with the third “target” standard at times midway between the “high-low” calibrations. At CIT, offset and gain were calibrated every three months using NOAA primaries and offset was calibrated using a secondary standard every 4.5 hr and checked for consistency using every other measurement. For the other two in-situ sites (ARV and STB), a “precision check” was performed every 23 hr using an un-calibrated secondary gas cylinder. For two sites (WGC and STR), CO was also measured in flask samples collected at 2200 GMT (1400 PST) and analyzed by NOAA's cooperative air sampling network. For SBC, and CIT, target check measurements typically showed RMS variations less than 1 ppb. Sites with infrequent (23 hr) precision checks (ARV) do not facilitate correction of diurnal variations in instrument offset due to temperature. Here, the residual observed RMS variation was ~ 3 ppb, depending on the time period.

Text S2. Assessment of WRF Boundary Layer and Land Surface Parameterizations

As described in Section 2.3, assessment of WRF boundary layer and land surface schemes were done using a combination of WRF parameterizations for the atmospheric boundary layer (MYNN2, MYJ, and YSU) and land surface (Noah and LSM) that differed by month. During April – September irrigation is prevalent in large portions of California's agricultural regions such as the Central Valley. Multiple studies have shown that the presence of irrigation can significantly alter the surface energy balance and influence boundary layer properties including the height of the boundary layer [*Kueppers et al.*, 2007; *Sacks et al.*, 2009; *Sorooshian et al.*, 2011; *Bagley and Miller*, 2015]. However, irrigation was absent in the version of the Noah land surface model used in this study, which contributed to poor representations of boundary layer height in Central California during the growing season (approximately April – September). This necessitated the use of the LSM land surface model (which simulates irrigation) at ARV where the observational CO footprint was strongly influenced by irrigated agricultural regions throughout California's Central Valley. Similarly, WGC is located in the Central Valley in a region of extensive irrigation. As shown in Figure S1, using Noah at this site led to higher than observed local boundary layer heights during the start of the growing season, with similar results during June - September. Due to this discrepancy we used LSM for June-August 2013 and April-May 2014. Finally, this suggests that future work in the Central Valley would benefit by the addition of an irrigation scheme to NOAH similar to methods used in prior studies [*Sorooshian et al.*, 2011; *Harding and Snyder*, 2012].

WRF-STILT simulations using the MYNN2 boundary layer scheme strongly underestimated CO at ARV and SBC sites during October-January (not shown). As discussed in Section 3.1, this period tended to be when WRF simulations had the largest errors in boundary layer winds and boundary layer height relative to observed meteorological conditions. Additionally, SBC and ARV are located in regions with extensive topography, with ARV being located at the southern end of a valley with topography that may have had a weak representation in WRF. Near SBC the MYNN2 boundary layer parameterization overpredicted surface wind speed, which led to an underprediction of CO at the tower (Figure S2). This was likely due to parcels moving too quickly over regions of high CO emissions to sample them realistically. Replacing MYNN2 with the YSU boundary layer scheme enabled a WRF parameterization designed to improve the representation of topographic effects. Using the YSU scheme with topographic effects at ARV and SBC improved the model representation of near surface wind speed, and correspondingly improved predictions of CO for ARV and SBC during November -January. Figure S2 shows the comparison between MYNN2 and YSU CO and surface wind speed for November – January at SBC. However, the YSU boundary layer scheme performed poorly relative to MYNN2 for CIT and WGC. This indicated that for regions with large heterogeneity such as California, a single model configuration is unlikely to be ideal for all seasons and locations. Table S2 gives the WRF boundary layer and land surface schemes found to best reproduce meteorological conditions and CO signals at each tower for each month, and were for this study.

Sites	December - February			March - May			June - August			March - May		
	Wind Speed	Wind Direction	z_i	Wind Speed	Wind Direction	z_i	Wind Speed	Wind Direction	z_i	Wind Speed	Wind Direction	z_i
Arvin (ARV)	.02 (2.48)	-4.9 (60.1)	31 (346)	-.12 (2.18)	0.9 (45.4)	38 (444)	.28 (1.44)	0.5 (44.6)	-103 (355)	-.18 (1.75)	3.8 (56.7)	176 (374)
Pasadena (CIT)	.07 (2.16)	-5.7 (75.7)	-282 (327)	.44 (2.00)	-5.4 (51.5)	-239 (346)	0.45 (1.07)	-9.7 (81.7)	-85 (142)	-.34 (1.89)	-3.8 (84.2)	-149 (289)
Madera (MAD)	.02 (2.48)	-4.9 (60.1)	31 (346)	.34 (1.94)	-3.7 (31.6)	224 (366)	-.20 (1.35)	1.9 (37.3)	160 (260)	-.44 (1.97)	9.4 (41.3)	95 (294)
Mt. Wilson (MTW)	.07 (2.16)	-5.7 (75.7)	-282 (327)	.44 (2.00)	-5.4 (51.5)	-239 (346)	0.45 (1.07)	-9.7 (81.7)	-85 (142)	-.34 (1.89)	-3.8 (84.2)	-149 (289)
Scripps, La Jolla (SIO)	-.28 (1.36)	-8.6 (46.4)	NA	-.22 (1.74)	4.6 (34.3)	NA	-.12 (1.25)	18.7 (34.0)	NA	-.51 (1.13)	-.8 (52.9)	NA
Sutter Buttes (STB)	.45 (2.84)	8.3 (60.3)	196 (262)	.58 (2.39)	.7 (41.5)	382 (528)	-.63 (2.38)	9.3 (51.4)	263 (225)	-.02 (2.42)	8.3 (56.1)	208 (337)
San Francisco (STR)	.64 (1.62)	-13.0 (44.0)	128 (330.3)	1.05 (1.56)	-4.6 (22.7)	122 (322)	.77 (1.27)	14.8 (17.1)	-34 (161)	.17 (1.24)	-4.1 (34.0)	16 (356)
Sunnyvale (SVL)	.64 (1.62)	-13.0 (44.0)	128 (330.3)	1.05 (1.56)	-4.6 (22.7)	122 (322)	.77 (1.27)	14.8 (17.1)	-34 (161)	.17 (1.24)	-4.1 (34.0)	16 (356)
Trinidad (THD)	-.19 (2.23)	-11.3 (73.9)	NA	-1.93 (2.92)	-3.4 (48.8)	NA	-.96 (2.73)	2.7 (48.2)	NA	-.78 (2.11)	-.8 (61.9)	NA
Tranquility (TRA)	.02 (2.48)	-4.9 (60.1)	31 (346)	.34 (1.94)	-3.7 (31.6)	224 (366)	-.20 (1.35)	1.9 (37.3)	160 (260)	-.44 (1.97)	9.4 (41.3)	95 (294)
Tuscan Buttes (TSB)	-.45 (2.64)	-11.8 (61.0)	NA	-.60 (2.44)	-10.9 (40.2)	NA	-.77 (1.70)	-2.2 (51.5)	NA	-.44 (2.44)	-4.2 (41.2)	NA
Victorville (VTR)	1.23 (2.34)	-7.0 (47.0)	-16.8 (359)	.61 (1.75)	-2.3 (35.4)	84 (500)	.05 (1.29)	4.0 (48.7)	64. (281)	.32 (1.98)	-5.3 (57.8)	195 (529)
Walnut Grove (WGC)	.92 (1.85)	2.3 (56.7)	42 (181)	1.0 (1.8)	3.6 (38.7)	140 (232)	-.21 (1.4)	8.0 (36.3)	105 (156)	.49 (1.72)	7.5 (43.3)	42 (261)
San Bernardino (SBC)	1.23 (2.34)	-7.0 (47.0)	-16.8 (359)	.61 (1.75)	-2.3 (35.4)	84 (500)	.05 (1.29)	4.0 (48.7)	64. (281)	.32 (1.98)	-5.3 (57.8)	195 (529)

Table S1. Mean seasonal meteorological model error (WRF - observation) for wind speed, wind direction, and boundary layer height (z_i) for each GHG tower shown in Figure 1. Values in parentheses are the seasonal standard deviation of the error and represent its random component. Sufficient representative z_i observations were not available for SIO, THD, and TSB.

	ARV	CIT	SBC	WGC
June	NA	MYNN2-Noah	MYNN2- Noah	MYNN2– LSM
Jul	NA	MYNN2- Noah	MYNN2- Noah	MYNN2 - LSM
Aug	NA	MYNN2- Noah	MYNN2- Noah	MYNN2 - LSM
Sep	NA	MYNN2- Noah	MYNN2- Noah	NA
Oct	MYNN2- Noah	MYNN2- Noah	MYNN2- Noah	MYNN2- Noah
Nov	YSU- Noah	MYNN2- Noah	YSU- Noah	MYNN2- Noah
Dec	YSU- Noah	MYNN2- Noah	YSU- Noah	MYNN2- Noah
Jan	YSU- Noah	MYNN2- Noah	YSU- Noah	MYNN2- Noah
Feb	MYNN2- Noah	MYNN2- Noah	MYNN2- Noah	MYNN2- Noah
Mar	MYNN2- Noah	MYNN2- Noah	MYNN2- Noah	MYNN2- Noah
Apr	MYNN2-LSM	MYNN2- Noah	MYNN2- Noah	MYNN2- LSM
May	MYNN2-LSM	MYNN2- Noah	MYNN2- Noah	MYNN2- LSM

Table S2. WRF-STILT Boundary layer – surface model combination used for predicting CO signal at ARV, CIT, SBC, and WGC for each month between June 2013 and May 2014. “NA“ indicates that CO observations were not available during that month.

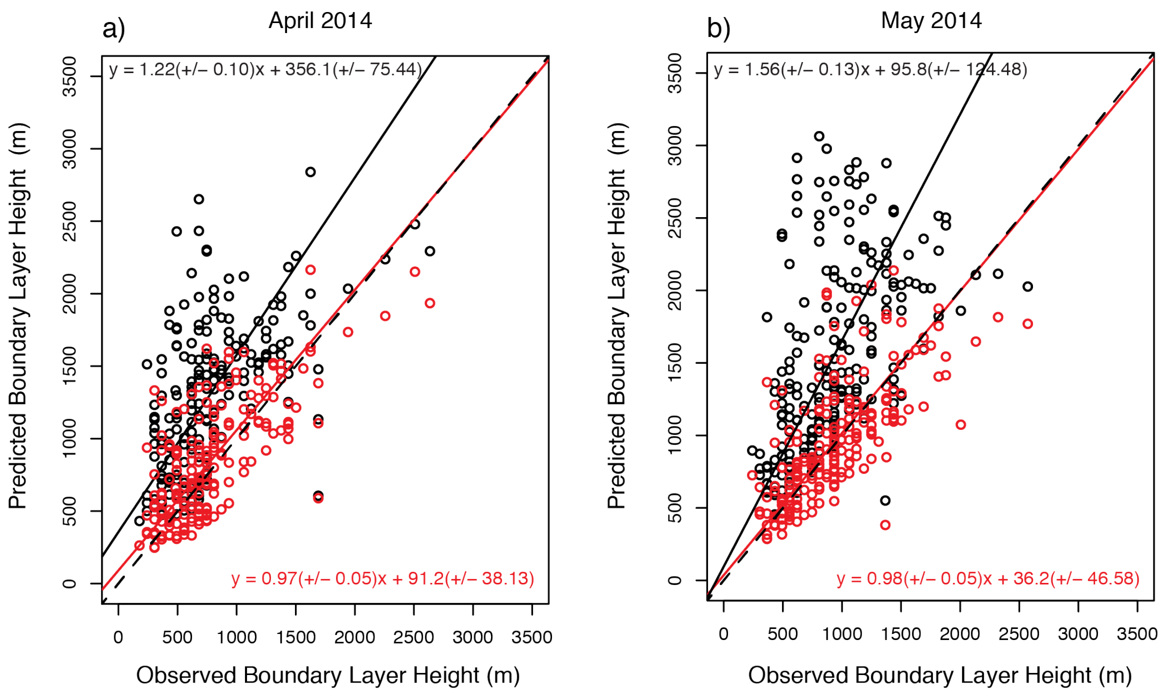

Figure S1. Scatterplot of predicted and observed boundary layer height at Sacramento profiler near WGC for April (left) and May (right) 2014. Red points represent results using the LSM land surface parameterization in WRF, and black points represent results from the Noah land surface parameterization in WRF. The dashed line indicates 1:1 correlation.

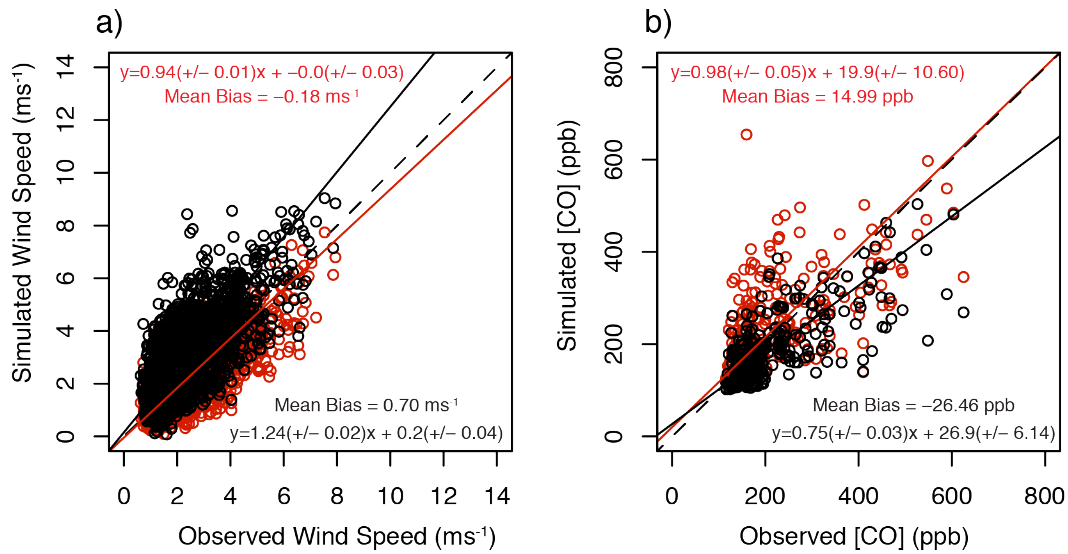

Figure S2. Daytime comparison at SBC between surface wind speeds (Left) and CO (Right) for November 2013 – January 2014 using YSU (red) and MYNN2 (black).