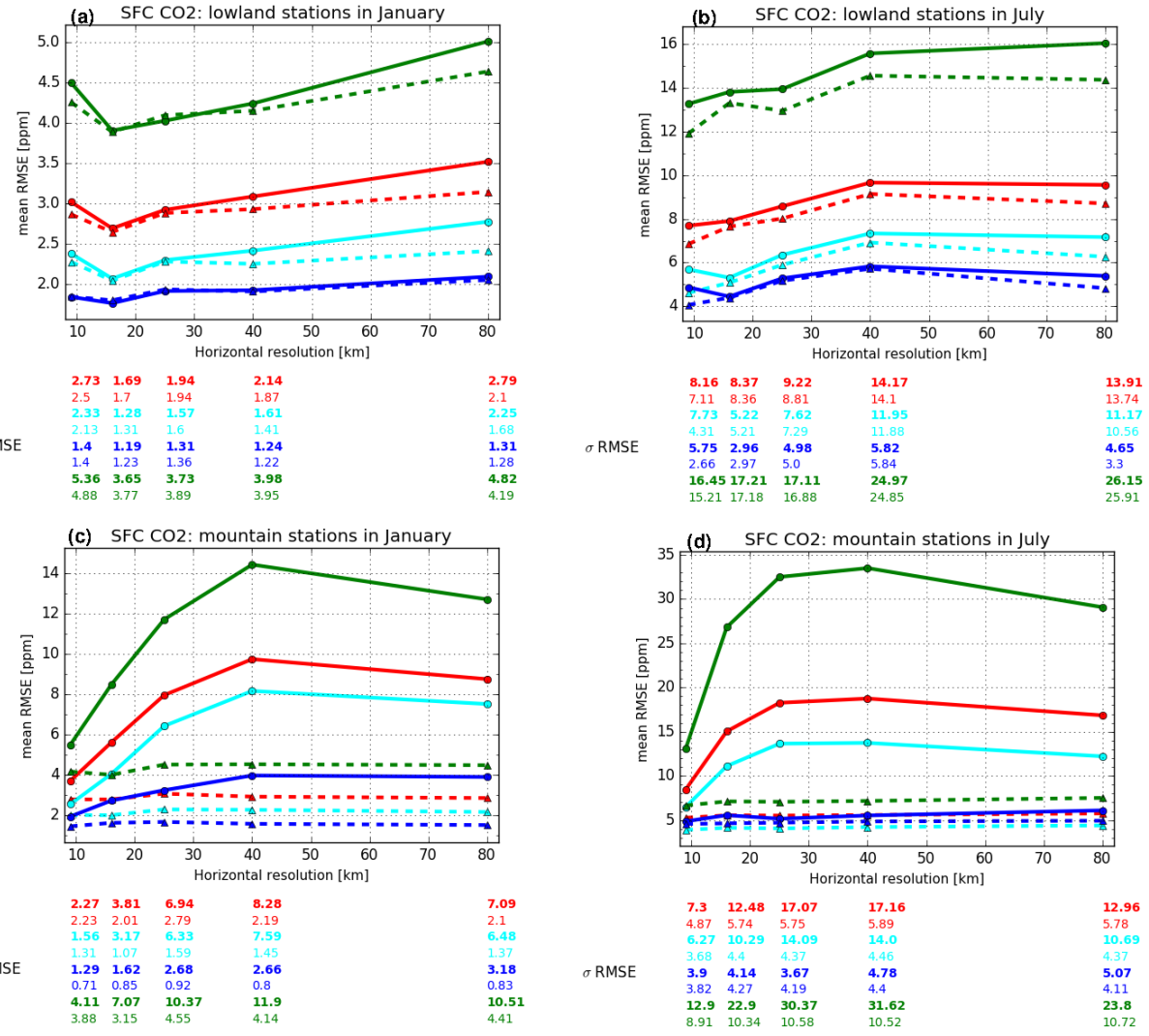
Modelling CO_2 weather – why horizontal resolution matters

A. Agustí-Panareda *et al.*



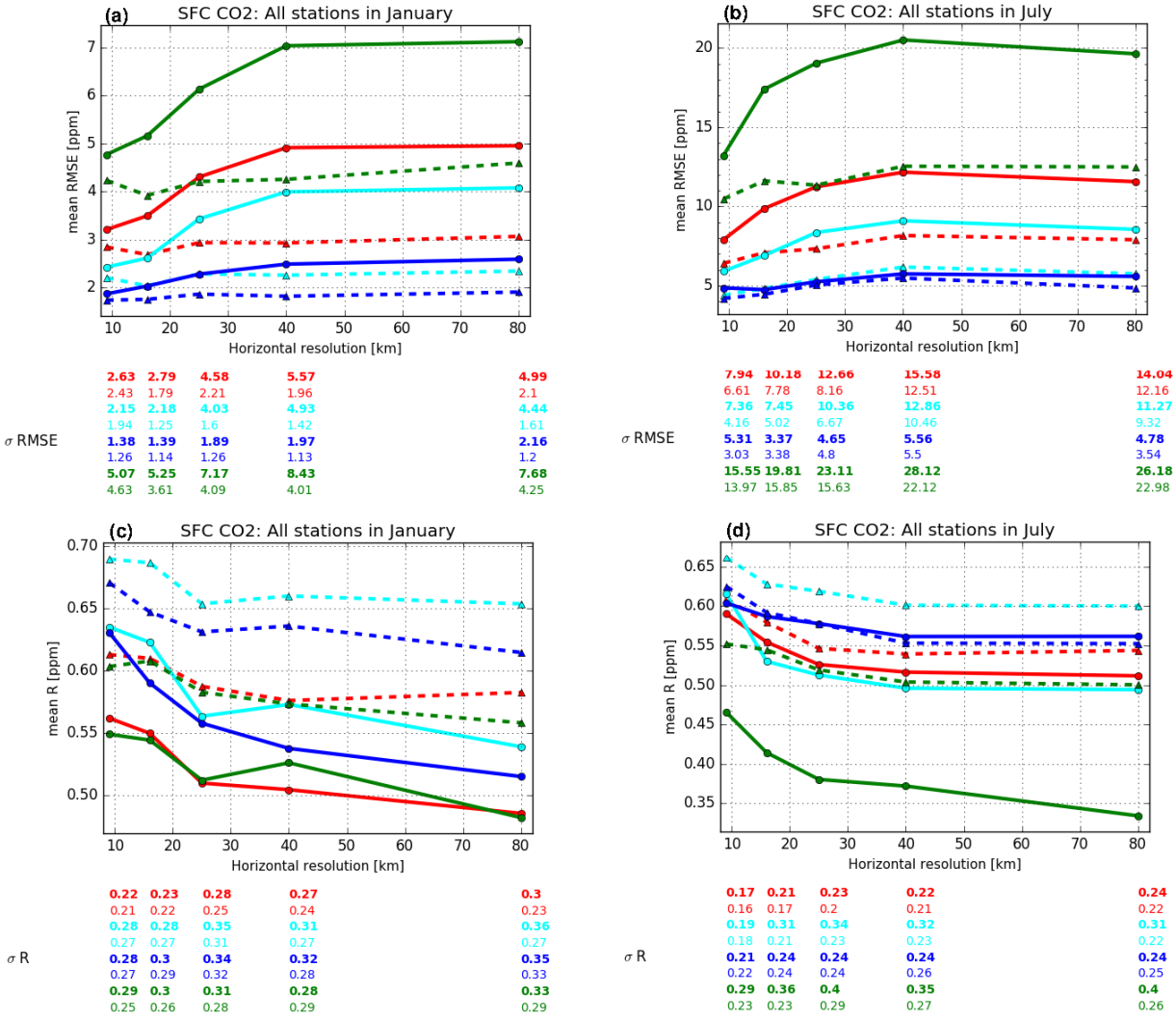
σ RMSE					
	2.73	**1.69**	**1.94**	**2.14**	**2.79**
	2.5	1.7	1.94	1.87	2.1
	2.33	**1.28**	**1.57**	**1.61**	**2.25**
	2.13	1.31	1.6	1.41	1.68
	1.4	**1.19**	**1.31**	**1.24**	**1.31**
	1.4	1.23	1.36	1.22	1.28
	5.36	**3.65**	**3.73**	**3.98**	**4.82**
	4.88	3.77	3.89	3.95	4.19

σ RMSE					
	8.16	**8.37**	**9.22**	**14.17**	**13.91**
	7.11	8.36	8.81	14.1	13.74
	7.73	**5.22**	**7.62**	**11.95**	**11.17**
	4.31	5.21	7.29	11.88	10.56
	5.75	**2.96**	**4.98**	**5.82**	**4.65**
	2.66	2.97	5.0	5.84	3.3
	16.45	**17.21**	**17.11**	**24.97**	**26.15**
	15.21	17.18	16.88	24.85	25.91

σ RMSE					
	2.27	**3.81**	**6.94**	**8.28**	**7.09**
	2.23	2.01	2.79	2.19	2.1
	1.56	**3.17**	**6.33**	**7.59**	**6.48**
	1.31	1.07	1.59	1.45	1.37
	1.29	**1.62**	**2.68**	**2.66**	**3.18**
	0.71	0.85	0.92	0.8	0.83
	4.11	**7.07**	**10.37**	**11.9**	**10.51**
	3.88	3.15	4.55	4.14	4.41

σ RMSE					
	7.3	**12.48**	**17.07**	**17.16**	**12.96**
	4.87	5.74	5.75	5.89	5.78
	6.27	**10.29**	**14.09**	**14.0**	**10.69**
	3.68	4.4	4.37	4.46	4.37
	3.9	**4.14**	**3.67**	**4.78**	**5.07**
	3.82	4.27	4.19	4.4	4.11
	12.9	**22.9**	**30.37**	**31.62**	**23.8**
	8.91	10.34	10.58	10.52	10.72

Figure S1. As in Fig. 6, using the different vertical sampling of the model with height above ground (solid lines) and height above mean sea level (dash lines). The standard deviation of the RMSE from each station is shown by the numbers below are in bold/non-bold for the height above ground/height above mean sea level. Note that different scales are used in each panel.



σ RMSE	**2.63**	**2.79**	**4.58**	**5.57**	**4.99**
	2.43	1.79	2.21	1.96	2.1
	2.15	**2.18**	**4.03**	**4.93**	**4.44**
	1.94	1.25	1.6	1.42	1.61
	1.38	**1.39**	**1.89**	**1.97**	**2.16**
	1.26	1.14	1.26	1.13	1.2
	5.07	**5.25**	**7.17**	**8.43**	**7.68**
	4.63	3.61	4.09	4.01	4.25

σ RMSE	**7.94**	**10.18**	**12.66**	**15.58**	**14.04**
	6.61	7.78	8.16	12.51	12.16
	7.36	**7.45**	**10.36**	**12.86**	**11.27**
	4.16	5.02	6.67	10.46	9.32
	5.31	**3.37**	**4.65**	**5.56**	**4.78**
	3.03	3.38	4.8	5.5	3.54
	15.55	**19.81**	**23.11**	**28.12**	**26.18**
	13.97	15.85	15.63	22.12	22.98

σ R	**0.22**	**0.23**	**0.28**	**0.27**	**0.3**
	0.21	0.22	0.25	0.24	0.23
	0.28	**0.28**	**0.35**	**0.31**	**0.36**
	0.27	0.27	0.31	0.27	0.27
	0.28	**0.3**	**0.34**	**0.32**	**0.35**
	0.27	0.29	0.32	0.28	0.33
	0.29	**0.3**	**0.31**	**0.28**	**0.33**
	0.25	0.26	0.28	0.29	0.29

σ R	**0.17**	**0.21**	**0.23**	**0.22**	**0.24**
	0.16	0.17	0.2	0.21	0.22
	0.19	**0.31**	**0.34**	**0.32**	**0.31**
	0.18	0.21	0.23	0.23	0.22
	0.21	**0.24**	**0.24**	**0.24**	**0.24**
	0.22	0.24	0.24	0.26	0.25
	0.29	**0.36**	**0.4**	**0.35**	**0.4**
	0.23	0.23	0.29	0.27	0.26

Figure S2. As in Fig. 5, using different vertical sampling of the model with height above ground (solid lines) and height above mean sea level (dash lines). The standard deviation of the RMSE from each station is shown by the numbers below are in bold/non-bold for the height above ground/height above mean sea level. Note that different scales are used in each panel.

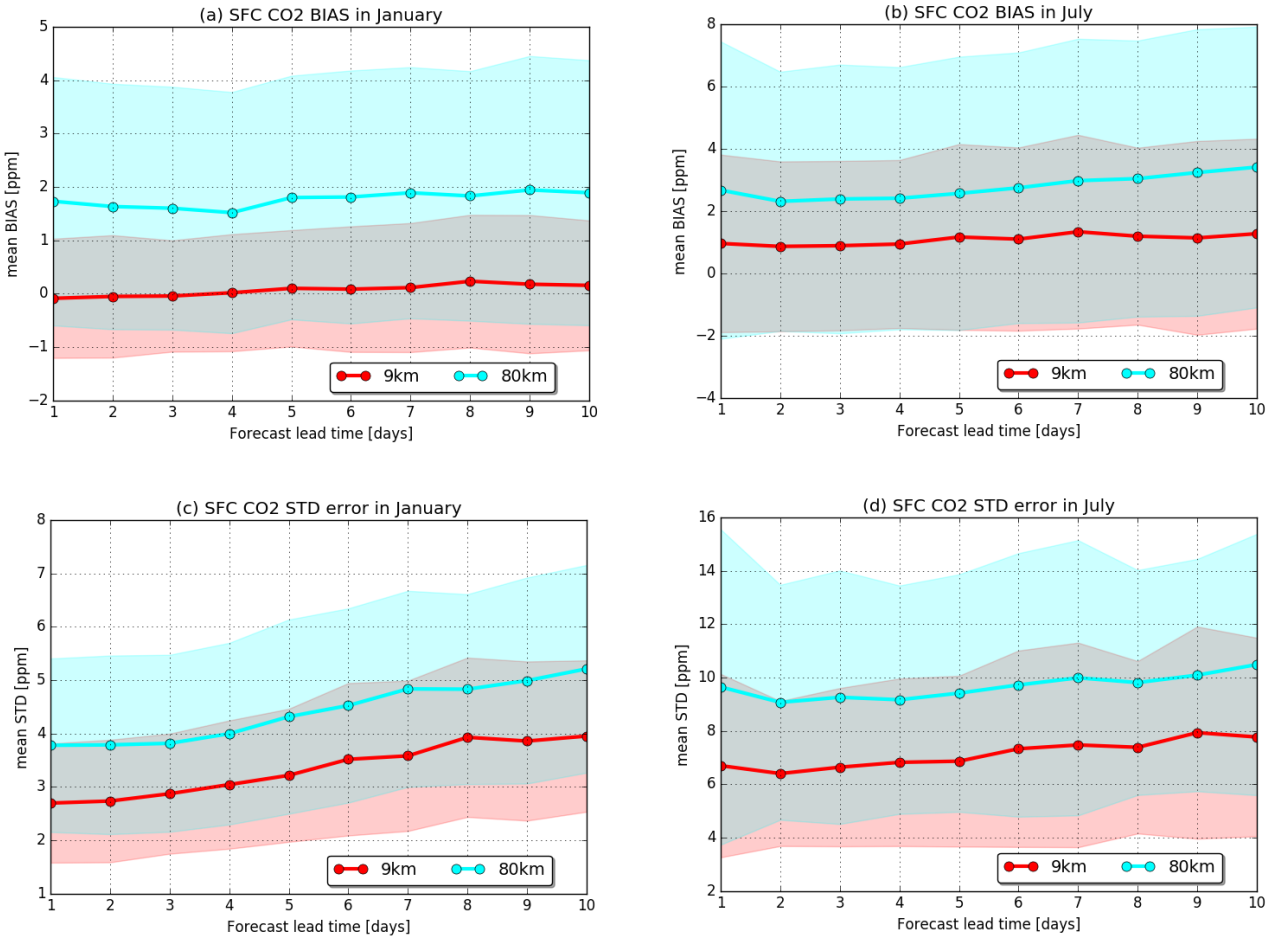


Figure S3. (a,b) Mean bias and (c,d) standard error of near-surface CO_2 at different forecast lead times for 9km-EXP (red) and 80km-EXP (blue) in (a,c,d) January and (b,d,f) July. The errors are computed with respect to continuous in situ surface measurements from 51 stations (see Tab A1). The error standard deviation between the different stations is shown with the shaded area. Note that different scales are used in each panel.

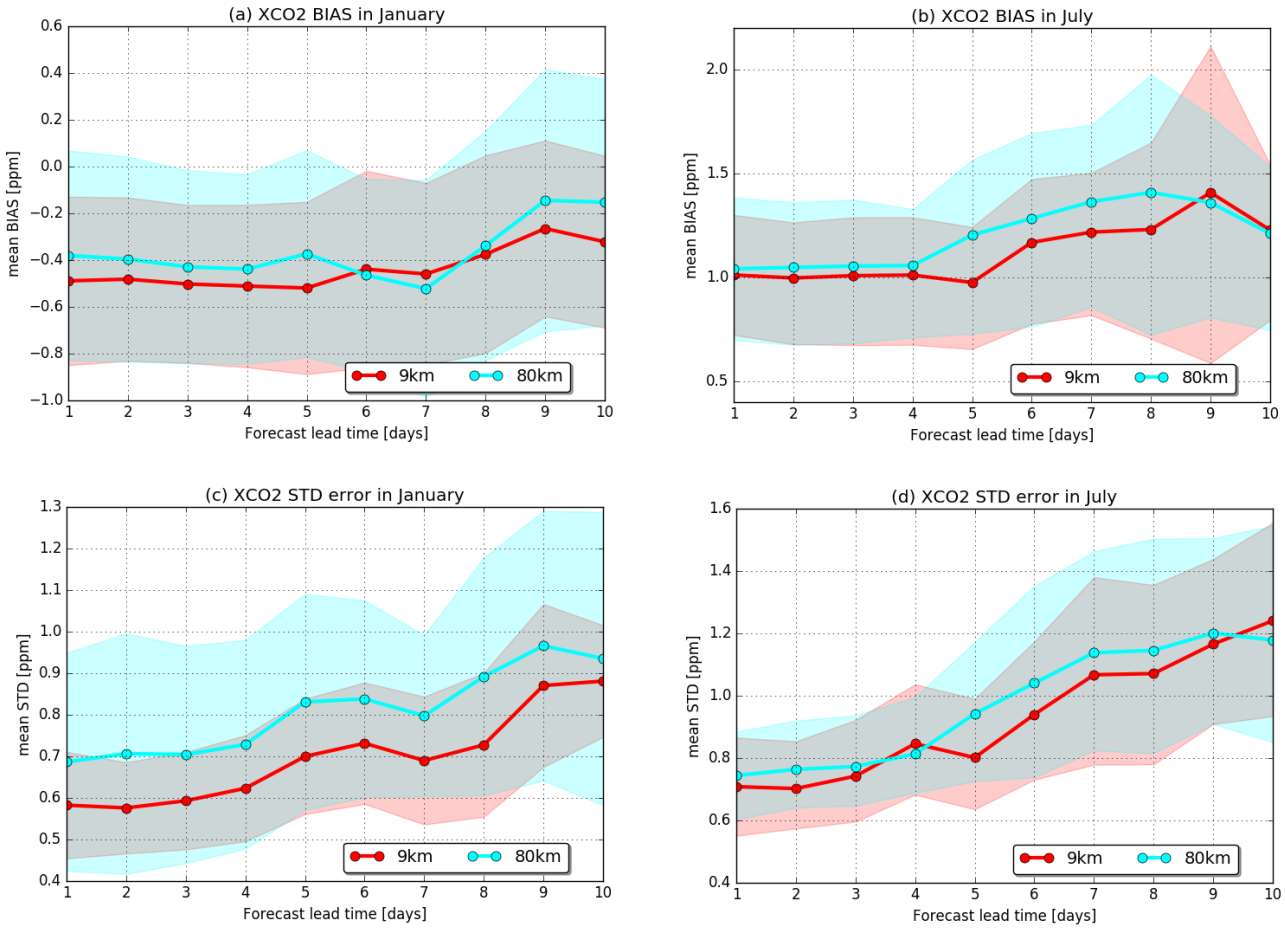


Figure S4. (a,b) Mean bias and (c,d) standard error of XCO_2 at different forecast lead times for 9km-EXP (red) and 80km-EXP (blue) in (a,c,d) January and (b,d,f) July. The errors are computed with respect to TCCON observations from 18 TCCON stations (see Tab. A2). The error standard deviation between the different stations is shown with the shaded area. Note that different scales are used in each panel.

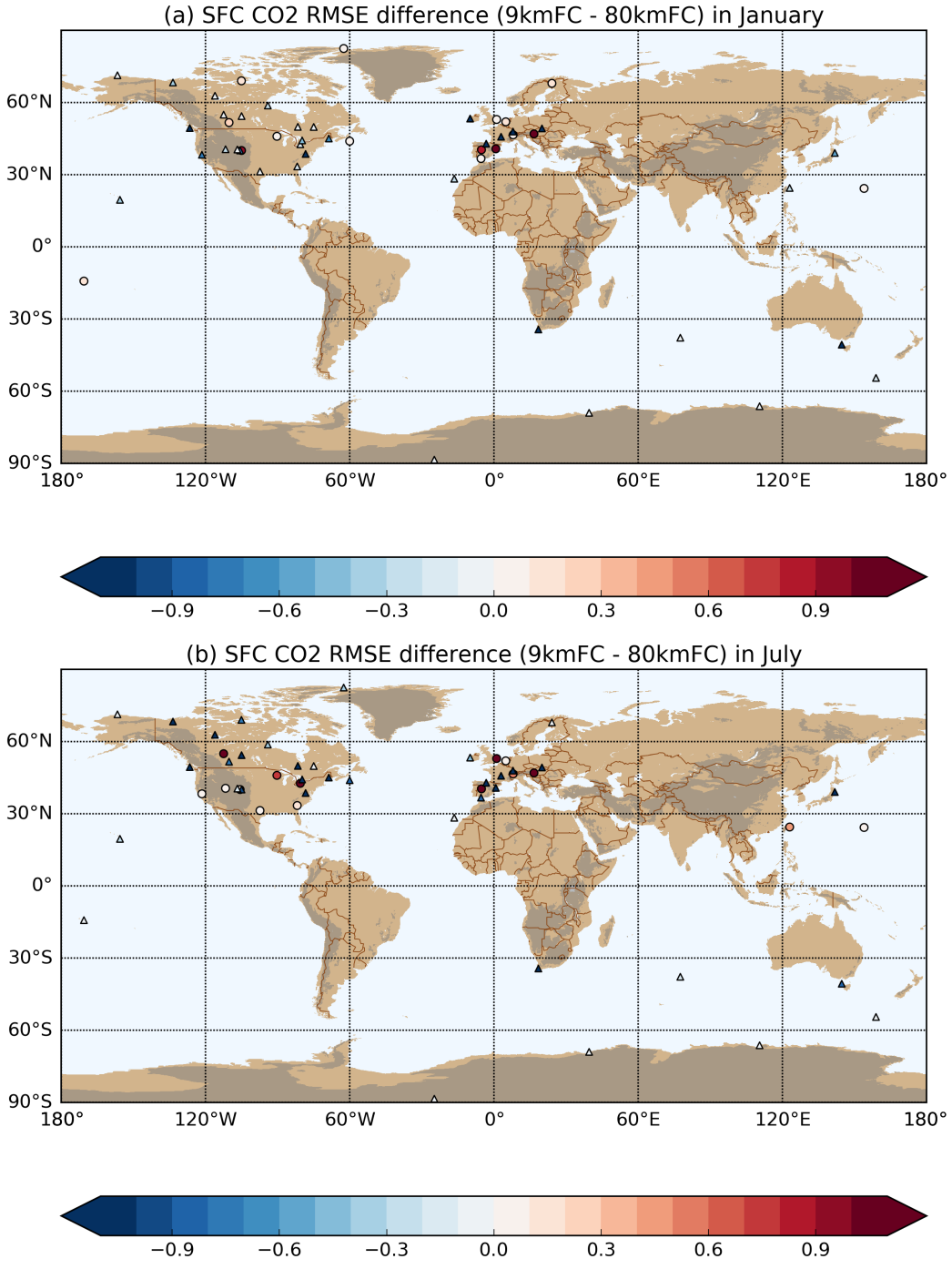


Figure S5. Difference in near-surface CO_2 RMSE [ppm] between highest and lowest resolution simulations (9km-EXP – 80km-EXP) in (a) January and (b) July at surface stations. Triangles indicate an RMSE reduction (blue colours) and circles an RMSE increase (red colours) as shown by the colour bar. Mountain regions with elevation > 1000 m above sea level are shaded in grey. The statistics for each station are listed Tabs S1 and S2 for January and July respectively.

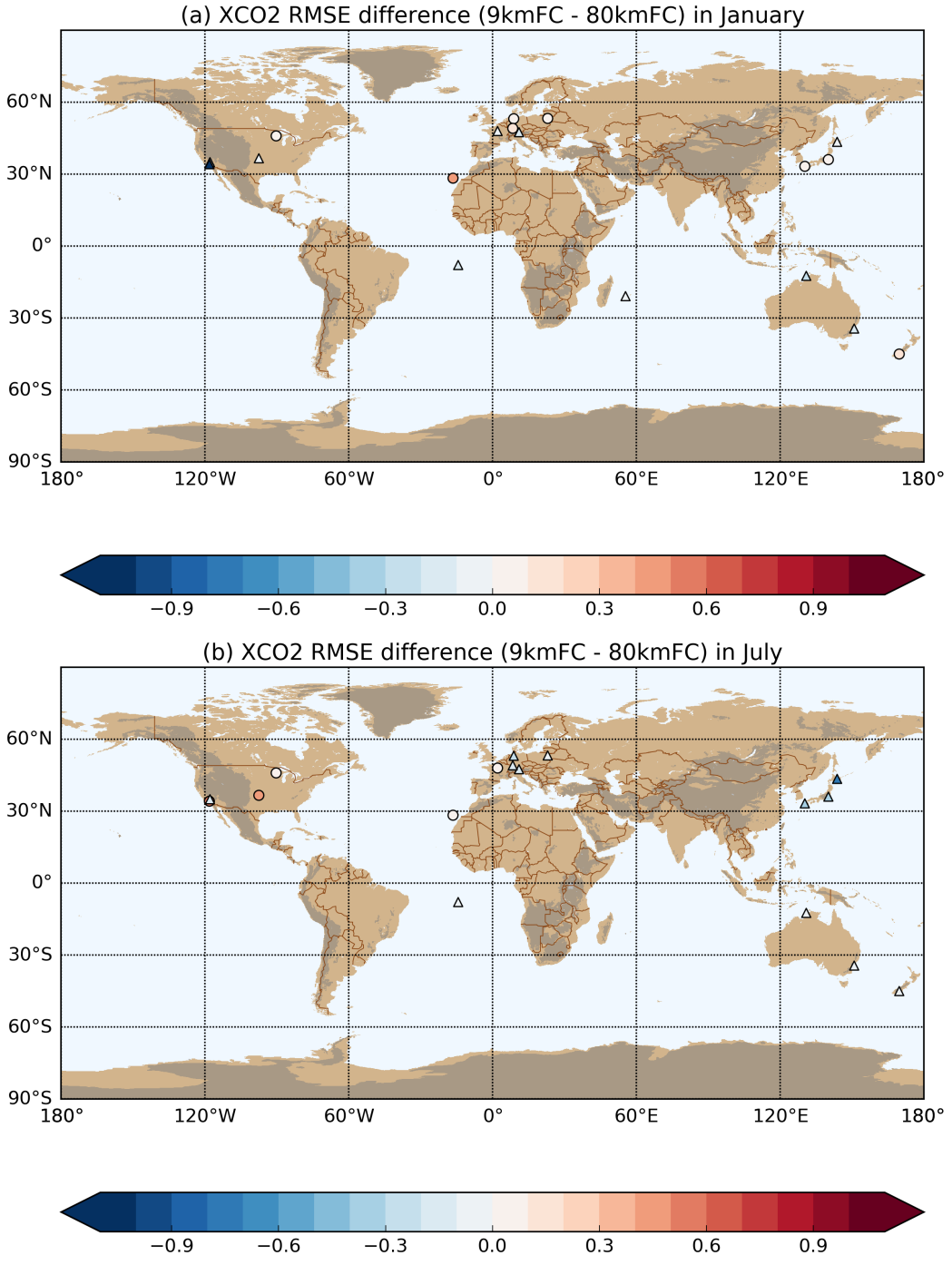


Figure S6. Difference in XCO_2 RMSE [ppm] between highest and lowest resolution simulations (9km-EXP – 80km-EXP) in (a) January and (b) July at TCCON stations. Mountain regions with elevation > 1000 m above sea level are shaded in grey. The statistics for each station are listed Tabs S3 and S4 for January and July respectively.

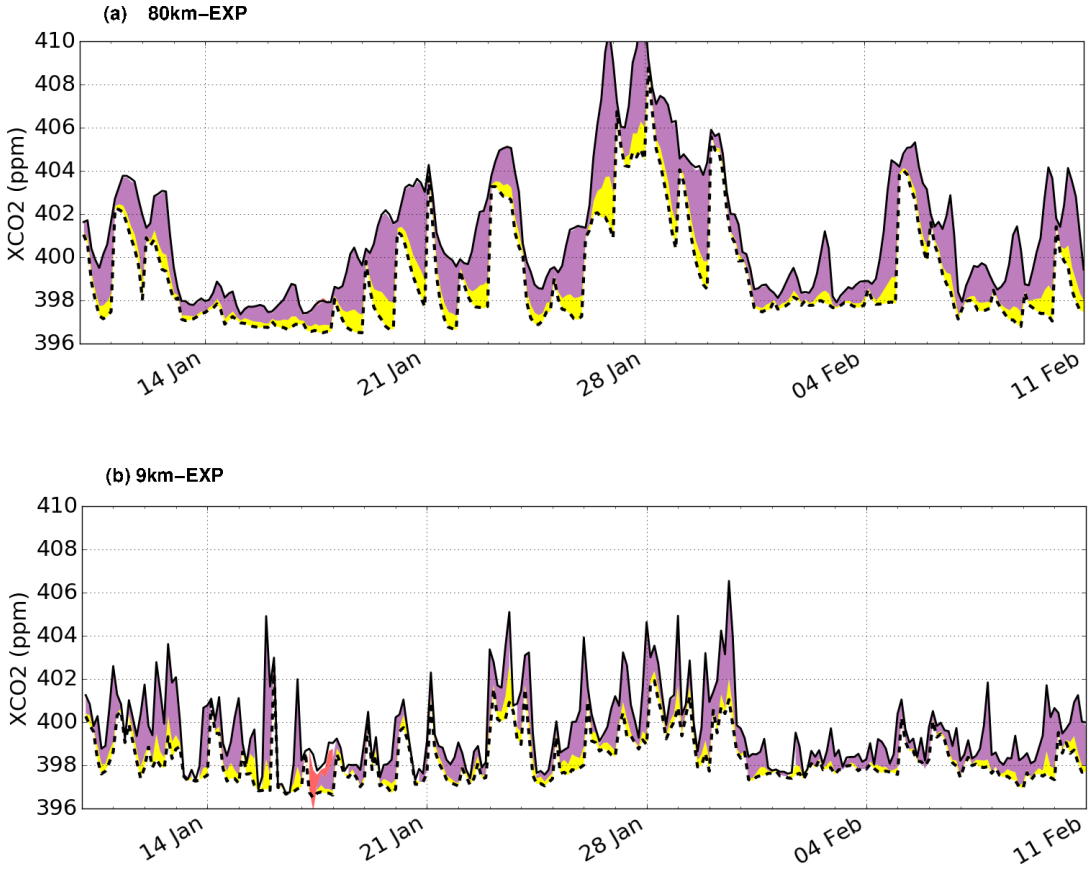


Figure S7. Modelled XCO_2 [ppm] from (a) 80km-EXP and (b) 9km-EXP simulations at the TCCON site of Pasadena (Tab.A2) responding to atmospheric transport and fluxes (solid line) and to only atmospheric transport (dash line). The XCO_2 enhancement associated with the different fluxes is coloured in purple (for anthropogenic emissions), yellow (for biogenic emissions) and red (for fires).

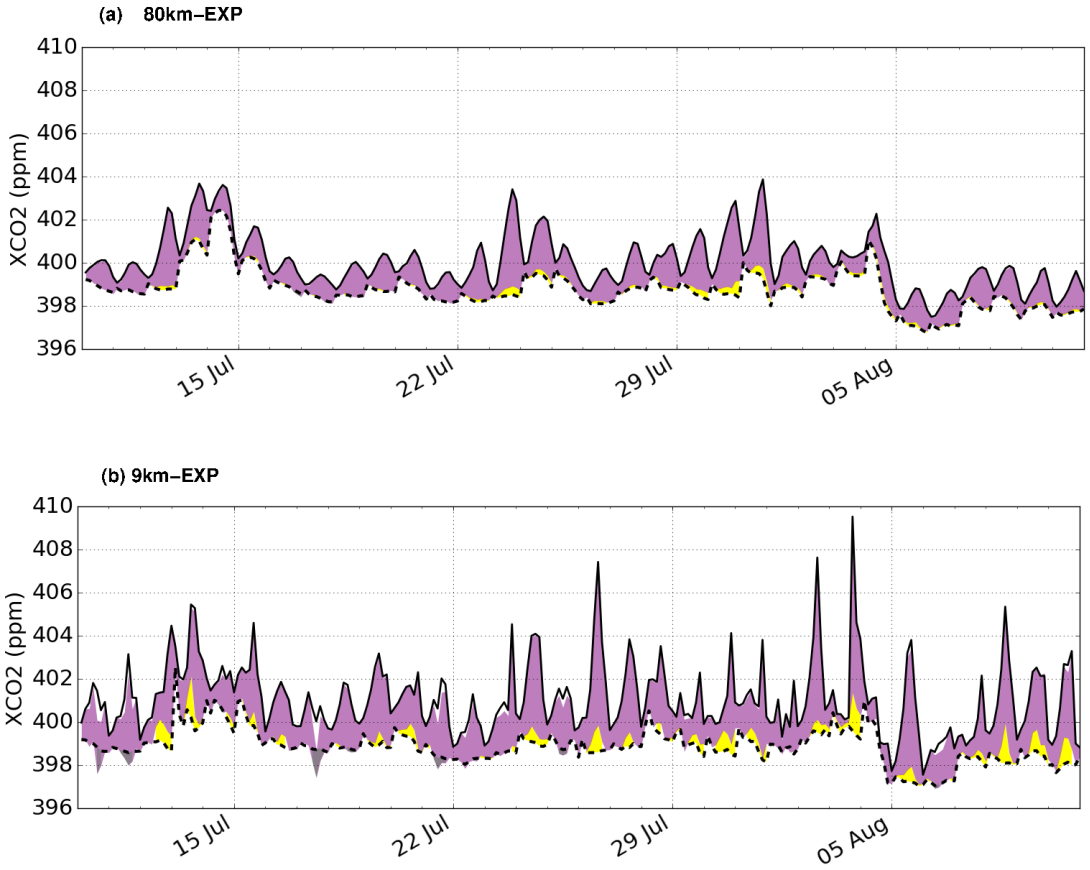


Figure S8. Same as Fig. S7 in July.

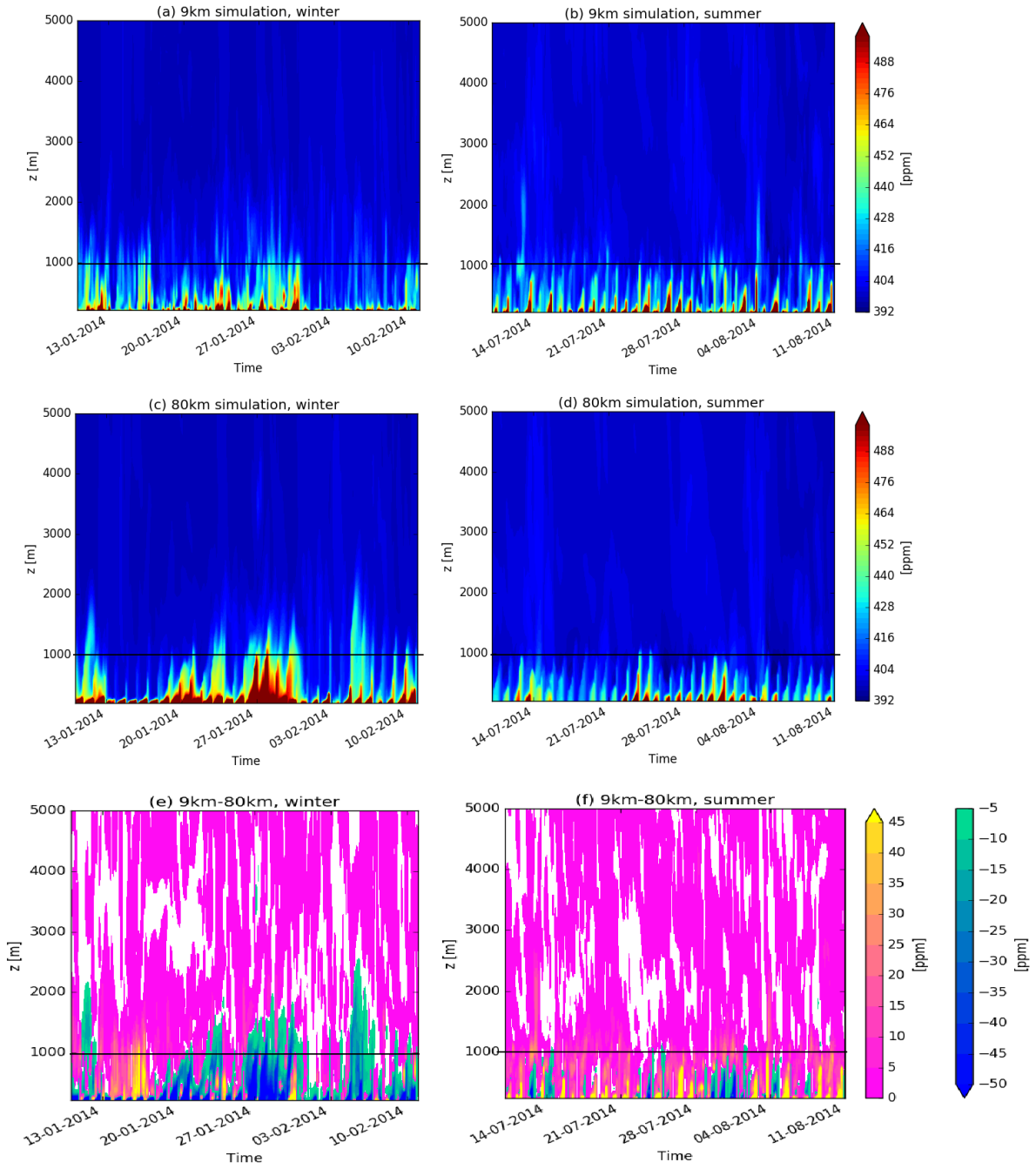


Figure S9. Modelled atmospheric CO_2 profile [ppm] showing 137 model levels at Pasadena from the 9-km resolution simulation and the 80-km resolution simulation. The horizontal black line shows the level approximately corresponding to 1000 m above the surface. In winter, the high CO_2 values are trapped below 1000 m in the boundary layer, except for certain synoptic episodes where boundary layer is ventilated as seen by high values (larger than 420 ppm) crossing the 1000 m line. While in summer the sea breeze circulation ventilates the boundary layer on a daily basis.

Table S1: January statistics of atmospheric CO_2 [ppm] from 9km-EXP and 80km-EXP simulations with respect to continuous in situ stations (surface and tower). The location and reference of each station can be found in Tab. A1.

Station	**Bias 9kmEXP**	**Bias 80kmEXP**	**STDerr 9kmEXP**	**STDerr 80kmEXP**	**RMSE 9kmEXP**	**RMSE 80kmEXP**	**N data**	**Δ RMSE 9kmEXP-80kmEXP**
brw	-1.45	-1.55	1.19	1.14	1.88	1.92	727	-0.04
mlo	-0.35	0.68	0.78	1.05	0.85	1.25	736	-0.4
smo	-1.10	-0.81	0.93	0.97	1.44	1.26	683	0.18
spo	-1.10	-1.10	0.18	0.19	1.12	1.12	736	0.0
amt-107magl	0.01	-0.50	2.68	2.77	2.68	2.81	741	-0.13
bao-300magl	0.34	-2.20	9.43	8.19	9.43	8.48	760	0.95
lef-396magl	-0.78	-0.49	1.47	1.51	1.67	1.59	765	0.08
sct-305magl	-0.13	0.42	3.61	3.83	3.62	3.85	762	-0.23
snp-17magl	3.05	9.66	3.97	10.87	5.01	14.54	768	-9.53
wgc-483magl	-0.58	-0.60	4.92	5.71	4.95	5.74	768	-0.79
wkt-457magl	0.06	0.22	2.34	2.38	2.34	2.39	733	-0.05
izo	0.01	0.63	2.80	0.98	2.80	1.16	722	1.64
alt	-2.14	-2.09	0.61	0.61	2.23	2.18	679	0.05
bck	0.93	1.21	1.45	1.37	1.73	1.83	768	-0.1
cby	-1.51	-1.30	0.58	0.56	1.62	1.42	298	0.2
chl	0.50	0.68	1.70	1.91	1.77	2.02	465	-0.25
cps	-0.58	0.06	1.32	1.49	1.44	1.49	697	-0.05
egb	-1.13	-1.66	5.14	5.33	5.26	5.58	726	-0.32
esp	1.01	4.43	3.71	4.93	3.84	6.62	753	-2.78
est	-1.20	-1.08	2.09	1.93	2.41	2.21	762	0.2
etl	-0.67	-0.17	1.53	1.71	1.68	1.72	695	-0.04
fsd	-0.73	-0.40	1.24	1.29	1.44	1.35	768	0.09
inu	0.50	0.36	2.04	2.45	2.11	2.47	702	-0.36
llb	-1.77	-1.59	3.19	3.32	3.65	3.69	699	-0.04
tpd	-0.01	0.81	3.11	3.20	3.11	3.30	768	-0.19
wsa	-1.24	-0.82	1.22	1.43	1.74	1.65	766	0.09
mnm	-0.34	-0.25	0.77	0.71	0.84	0.76	680	0.08
ryo	3.05	3.88	4.99	6.05	5.84	7.19	432	-1.35

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Table S1 – continued from previous page

Station	Bias 9kmEXP	Bias 80kmEXP	STDerr 9kmEXP	STDerr 80kmEXP	RMSE 9kmEXP	RMSE 80kmEXP	N data	Δ RMSE 9kmEXP-80kmEXP
yon	-0.40	-0.62	1.22	1.43	1.28	1.56	579	-0.28
hdp	1.48	16.83	2.73	10.25	3.10	19.71	668	-16.61
nwr	0.76	1.56	1.45	3.40	1.64	3.74	730	-2.1
spl	2.28	2.72	3.23	3.50	3.95	4.43	682	-0.48
syo	-1.09	-1.15	0.14	0.15	1.10	1.16	32	-0.06
cpt-marine	-1.11	1.86	0.60	6.02	1.26	6.30	618	-5.04
ams	-1.20	-1.27	0.26	0.27	1.22	1.30	116	-0.08
mhd	-1.11	2.34	4.75	1.03	1.52	5.30	759	-3.78
puy	2.39	6.11	3.91	8.29	4.58	10.30	752	-5.72
ces-200magl	-2.39	-1.27	4.41	4.71	5.02	4.88	679	0.14
wao	-0.68	-0.01	3.24	3.26	3.31	3.26	92	0.05
ssl	3.21	18.72	4.87	15.00	5.83	23.99	739	-18.16
hun-115magl	-6.58	-2.68	5.52	5.64	8.59	6.24	751	2.35
pal-nonlocal	-0.89	0.32	2.13	3.44	2.31	3.46	595	-1.15
jfj	0.08	12.47	2.53	9.29	2.53	15.55	720	-13.02
kas	0.67	8.45	4.39	6.57	4.44	10.71	503	-6.27
cgo	-0.69	-1.39	2.46	4.25	2.56	4.47	768	-1.91
mqa	-1.11	-1.26	0.65	0.66	1.29	1.43	618	-0.14
cya	-1.14	-1.14	0.36	0.36	1.19	1.19	693	0.0
ara	-0.90	-0.41	4.82	6.63	4.90	6.65	585	-1.75
dec	11.13	7.43	11.42	7.31	15.95	10.42	588	5.53
gic	-1.88	1.69	5.28	4.43	5.60	4.74	765	0.86
vac	-0.13	1.82	1.10	1.82	1.10	2.28	161	-1.82
sgc	1.31	10.31	5.61	9.62	5.76	14.10	652	-8.34

Table S2: July statistics of atmospheric CO_2 [ppm] from 9km-EXP and 80km-EXP simulations with respect to continuous in situ stations (surface and tower). The location and reference of each station can be found in Tab. A1.

Station	**Bias 9kmEXP**	**Bias 80kmEXP**	**STDerr 9kmEXP**	**STDerr 80kmEXP**	**RMSE 9kmEXP**	**RMSE 80kmEXP**	**N data**	**Δ RMSE 9kmEXP-80kmEXP**
brw	-0.85	-0.68	2.06	2.20	2.23	2.31	738	-0.08
mlo	0.83	-0.52	1.22	1.60	1.47	1.68	612	-0.21
smo	-0.26	-0.34	0.80	0.87	0.84	0.93	695	-0.09
spo	-0.83	-0.88	0.16	0.15	0.85	0.89	737	-0.04
amt-107magl	2.60	-0.94	8.24	7.95	8.64	8.00	768	0.64
bao-300magl	1.05	-1.43	5.69	6.55	5.79	6.70	743	-0.91
lef-396magl	3.88	2.53	6.22	6.05	7.33	6.56	744	0.77
sct-305magl	3.90	4.21	7.82	7.31	8.73	8.43	767	0.3
snp-17magl	24.15	37.81	16.55	30.11	29.28	48.33	768	-19.05
wgc-483magl	1.57	1.37	2.75	2.81	3.17	3.13	384	0.04
wkt-457magl	4.75	4.90	4.32	3.93	6.42	6.28	666	0.14
izo	4.65	-1.84	3.82	2.22	6.01	2.88	746	3.13
alt	-0.93	-1.36	1.05	1.17	1.40	1.80	623	-0.4
bck	10.36	34.84	38.58	79.33	39.95	86.65	757	-46.7
cby	-0.67	-1.83	3.07	3.50	3.15	3.95	754	-0.8
chl	-0.09	-0.77	4.45	4.61	4.45	4.67	768	-0.22
cps	-2.98	-3.85	7.03	7.52	7.64	8.45	760	-0.81
egb	-1.24	-6.52	13.31	15.61	13.37	16.92	632	-3.55
esp	0.28	-6.53	5.69	10.09	5.70	12.01	318	-6.31
est	0.35	0.50	8.62	9.37	8.63	9.38	79	-0.75
etl	-3.59	-4.90	7.02	7.48	7.88	8.94	549	-1.06
fsd	-3.51	-4.59	8.96	9.23	9.62	10.31	768	-0.69
inu	-1.40	-2.54	3.98	5.07	4.22	5.67	765	-1.45
llb	-10.09	-7.88	14.30	13.39	17.50	15.53	352	1.97
tpd	-1.20	-2.44	14.31	13.12	14.37	13.34	767	1.03
wsa	0.95	0.41	4.66	5.60	4.76	5.62	768	-0.86
mnm	0.33	0.27	0.98	0.97	1.04	1.00	647	0.04
ryo	18.51	10.77	27.89	17.28	33.48	20.36	170	13.12

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Table S2 – continued from previous page

Station	Bias 9kmEXP	Bias 80kmEXP	STDerr 9kmEXP	STDerr 80kmEXP	RMSE 9kmEXP	RMSE 80kmEXP	N data	Δ RMSE 9kmEXP-80kmEXP
yon	0.61	0.26	1.98	1.58	2.07	1.60	522	0.47
hdp	4.11	27.16	4.36	25.67	5.99	37.37	551	-31.38
nwr	3.63	11.03	3.68	15.20	5.17	18.78	399	-13.61
spl	8.73	20.16	6.34	16.93	10.79	26.32	493	-15.53
syo	-0.92	-0.97	0.14	0.13	0.93	0.98	32	-0.05
cpt-36-marine	-0.12	-0.82	0.93	5.91	0.94	5.97	536	-5.03
ams	-0.90	-1.03	0.28	0.29	0.94	1.07	306	-0.13
mhd	-2.27	-0.40	5.63	6.52	6.07	6.53	703	-0.46
puy	0.75	4.88	7.19	12.36	7.23	13.29	752	-6.06
ces-200magl	-3.49	-2.93	7.76	7.97	8.51	8.50	668	0.01
wao	-4.01	-3.44	8.33	7.12	9.24	7.91	568	1.33
ssl	-0.11	9.63	8.99	18.56	8.99	20.91	761	-11.92
hun-115magl	-6.61	-5.61	7.87	7.43	10.28	9.32	768	0.96
pal-nonlocal	2.03	4.40	6.13	10.86	6.45	11.72	345	-5.27
jfj	-5.23	-5.48	3.60	10.60	6.35	11.93	109	-5.58
kas	-1.01	7.42	4.17	15.93	4.29	17.57	558	-13.28
cgo	-0.55	-0.41	1.56	2.42	1.66	2.45	758	-0.79
mqa	-0.84	-0.94	0.40	0.40	0.93	1.02	692	-0.09
cya	-0.95	-1.01	0.29	0.29	0.99	1.05	760	-0.06
dec	7.78	11.01	10.37	11.97	12.96	16.26	619	-3.3
gic	-10.88	-6.14	17.13	14.08	20.30	15.36	147	4.94
vac	2.85	6.98	5.22	12.04	5.95	13.91	764	-7.96
sgc	5.74	14.61	5.71	12.54	8.09	19.25	719	-11.16

Table S3: January statistics of XCO_2 [ppm] from 9km-EXP and 80km-EXP simulations with respect to TCCON stations. The location of the station and their associated reference are provided in Tab A2.

Station	**Bias 9kmEXP**	**Bias 80kmEXP**	**STDerr 9kmEXP**	**STDerr 80kmEXP**	**RMSE 9kmEXP**	**RMSE 80kmEXP**	**N data**	**Δ RMSE 9kmEXP-80kmEXP**
ascension01	0.69	0.89	0.71	0.72	0.99	1.15	153	-0.16
bialystok01	-1.28	-1.20	0.29	0.33	1.32	1.24	15	0.08
bremen01	0.22	0.12	0.73	0.70	0.77	0.71	8	-0.06
darwin01	-1.04	-1.17	0.49	0.76	1.15	1.39	34	-0.24
edwards01	0.42	0.05	0.47	0.64	0.63	0.65	191	-0.02
garmisch01	-0.53	-0.73	0.55	0.60	0.76	0.94	33	-0.18
izana01	-0.85	-0.36	0.39	0.29	0.93	0.46	18	0.47
karlsruhe01	0.11	-0.12	0.69	0.54	0.70	0.55	33	0.15
lamont01	-0.98	-1.03	0.64	0.66	1.17	1.22	129	-0.05
lauder02	-1.00	-0.77	0.55	0.56	1.14	0.95	104	0.19
orleans01	-0.25	-0.26	0.45	0.48	0.52	0.54	67	-0.02
parkfalls01	-1.42	-1.38	0.37	0.36	1.46	1.42	28	0.04
pasadena01	0.32	2.03	1.24	2.68	1.28	3.36	160	-2.08
reunion01	-0.10	0.01	0.34	0.36	0.35	0.36	150	-0.01
rikubetsu01	-1.74	-1.74	0.14	0.17	1.74	1.75	21	-0.01
saga01	-1.30	-1.36	0.78	0.64	1.52	1.50	30	0.02
tsukuba02	0.37	0.36	1.02	0.97	1.08	1.03	111	0.05
wollongong01	-0.45	-0.19	0.63	0.89	0.78	0.91	157	-0.13

Table S4: July statistics of XCO_2 [ppm] from 9km-EXP and 80km-EXP simulations with respect to TCCON stations. The location of the station and their associated DOI are provided in Tab A2.

Station	**Bias 9kmEXP**	**Bias 80kmEXP**	**STDerr 9kmEXP**	**STDerr 80kmEXP**	**RMSE 9kmEXP**	**RMSE 80kmEXP**	**N data**	**Δ RMSE 9kmEXP-80kmEXP**
ascension01	0.08	0.18	0.45	0.47	0.46	0.51	158	-0.05
bialystok01	0.97	1.01	1.06	1.17	1.44	1.54	68	-0.1
bremen01	1.18	1.36	0.67	0.77	1.36	1.57	44	-0.21
darwin01	1.54	1.55	0.33	0.35	1.58	1.59	264	-0.01
edwards01	1.28	1.40	0.76	0.79	1.49	1.61	316	-0.12
garmisch01	0.92	1.03	0.66	0.74	1.14	1.27	90	-0.13
izana01	0.45	0.11	0.36	0.49	0.58	0.50	43	0.08
karlsruhe01	1.25	1.44	0.77	0.81	1.47	1.65	90	-0.18
lamont01	2.00	1.48	1.32	1.25	2.40	1.94	299	0.46
lauder02	0.10	0.11	0.27	0.31	0.29	0.33	86	-0.04
orleans01	1.38	1.36	0.66	0.66	1.53	1.51	16	0.02
parkfalls01	0.56	0.49	1.09	1.07	1.23	1.18	168	0.05
pasadena01	1.23	0.57	1.30	1.09	1.79	1.23	302	0.56
reunion01	0.81	0.79	0.33	0.36	0.87	0.87	136	0.0
rikubetsu01	2.21	2.92	0.55	0.64	2.27	2.99	9	-0.72
saga01	0.80	1.20	0.57	0.66	0.98	1.37	30	-0.39
tsukuba02	1.21	1.52	0.95	1.06	1.54	1.85	120	-0.31
wollongong01	0.23	0.22	0.64	0.69	0.68	0.73	96	-0.05