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Supplement of

Quantifying the drivers of surface ozone anomalies in the urban areas over the Qinghai-Tibet Plateau

Hao Yin et al.

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Table S1. Diurnal and seasonal cycles (units: μg/m^3) of surface ozone in each city over the QTP.

City	Diurnal cycle		Seasonal cycle		Interannual trend
	Maximum	Minimum	Maximum	Minimum	(μg/m^3·yr^{-1})
Ngari	86.08 ± 22.29 (18:00)	43.07 ± 20.21 (9:00)	107.55 ± 38.43 (June)	51.84 ± 24.72 (December)	7.55 ± 1.61
Shigatse	93.43 ± 14.43 (17:00)	33.92 ± 28.16 (9:00)	110.96 ± 25.60 (May)	53.31 ± 32.82 (September)	0.37 ± 0.12
Lhasa	95.92 ± 15.59 (17:00)	37.14 ± 18.39 (9:00)	112.46 ± 28.92 (May)	53.76 ± 26.14 (December)	-1.62 ± 0.76
Shannan	93.91 ± 14.97 (17:00)	37.60 ± 17.23 (9:00)	107.84 ± 26.93 (April)	61.17 ± 23.54 (December)	1.51 ± 0.36
Naqu	66.86 ± 19.12 (16:00)	22.89 ± 15.55 (9:00)	71.39 ± 23.51 (May)	38.17 ± 22.29 (November)	3.23 ± 0.71
Nyingchi	73.12 ± 16.52 (15:00)	33.79 ± 18.35 (9:00)	91.50 ± 25.33 (April)	41.89 ± 22.29 (September)	0.10 ± 0.81
Qamdo	80.77 ± 15.48 (16:00)	29.31 ± 14.90 (9:00)	91.48 ± 22.29 (May)	41.53 ± 22.29 (December)	-2.43 ± 0.56
Diqing	57.77 ± 21.56 (15:00)	27.94 ± 14.34 (9:00)	79.78 ± 21.48 (March)	38.16 ± 19.83 (September)	5.31 ± 1.28
Haixi	100.36 ± 17.68 (16:00)	68.96 ± 18.27 (8:00)	110.95 ± 25.51 (July)	70.73 ± 16.81 (December)	1.36 ± 0.93
Guoluo	102.08 ± 15.14 (15:00)	53.25 ± 26.27 (8:00)	94.82 ± 34.55 (June)	60.45 ± 31.35 (December)	-2.36 ± 0.81
Xining	82.95 ± 21.15 (16:00)	20.73 ± 15.30 (8:00)	80.23 ± 27.73 (August)	29.21 ± 19.03 (December)	1.83 ± 0.56
Aba	67.50 ± 14.19 (16:00)	14.84 ± 10.77 (8:00)	71.25 ± 26.53 (April)	31.30 ± 22.39 (September)	1.86 ± 0.21

Table S2. The drivers of surface ozone nonattainment events from 2015 to 2020 in each city over the QTP.

City	Number of nonattainment day											
	Anthropogenic-dominated						Meteorology-dominated					
	2015	2016	2017	2018	2019	2020	2015	2016	2017	2018	2019	2020
Ngari	0	0	0	0	0	0	0	0	8	9	0	0
Shigatse	0	0	0	0	0	0	0	5	3	4	5	2
Lhasa	0	0	1	0	0	0	10	20	1	5	0	0
Shannan	0	0	2	0	0	0	0	2	10	10	2	3
Naqu	0	0	0	0	0	0	0	0	0	0	0	0
Nyingchi	0	0	0	0	0	0	0	0	1	0	0	0
Qamdo	0	0	0	0	0	0	0	2	0	0	0	0
Diqing	0	0	0	0	0	0	0	0	0	0	0	0
Haixi	2	0	0	0	1	0	12	0	0	0	15	2
Guoluo	0	0	0	0	0	0	3	0	3	3	0	0
Xining	0	0	0	0	0	0	0	2	17	6	3	3
Aba	0	0	0	0	0	0	0	0	0	0	0	0

Table S3. Inter-annual trends (units: μg·m^{-3}·yr^{-1}) of surface ozone anomalies, $O_{3,emis}$ and $O_{3,meteos}$ in each city over the QTP fitted by the bootstrap resampling method.

City	Total	$O_{3,emis}$	$O_{3,meteos}$
Ngari	7.55 ± 1.61	7.23 ± 1.25	0.31 ± 0.37
Shigatse	0.37 ± 0.12	0.47 ± 0.16	-0.10 ± 0.16
Lhasa	-1.62 ± 0.76	-1.56 ± 0.88	-0.06 ± 0.38
Shannan	1.51 ± 0.36	1.73 ± 0.37	-0.22 ± 0.33
Naqu	3.23 ± 0.71	3.16 ± 0.79	0.07 ± 0.25
Nyingchi	0.10 ± 0.81	0.22 ± 0.65	-0.12 ± 0.71
Qamdo	-2.43 ± 0.56	-2.00 ± 0.38	-0.43 ± 0.39
Diqing	5.31 ± 1.28	5.40 ± 1.25	-0.09 ± 0.21
Haixi	1.36 ± 0.93	1.35 ± 0.75	0.01 ± 0.15
Guoluo	-2.36 ± 0.81	-2.05 ± 0.65	-0.31 ± 0.16
Xining	1.83 ± 0.56	1.85 ± 0.38	-0.02 ± 0.18
Aba	1.86 ± 0.21	2.25 ± 0.35	-0.39 ± 0.32

Table S4. Correlations of $O_{3,\ meteo}$ against each meteorological parameter anomalies from 2015 to 2020 over the QTP.

City	Correlations									
	$T_{surface}$	U_{10m}	V_{10m}	PBLH	TCC	Rain	Omega	SWGDN	RH_{2m}	TROPH
Ngari	0.78	0.25	0.40	0.58	-0.08	-0.19	0.31	0.75	-0.40	0.40
Shigatse	0.80	0.27	0.14	0.70	-0.09	-0.23	0.28	0.78	-0.29	0.14
Lhasa	0.83	0.23	-0.03	0.76	-0.12	-0.16	0.36	0.76	-0.20	0.23
Shannan	0.82	0.31	0.15	0.43	-0.18	-0.22	0.27	0.82	-0.26	0.41
Naqu	0.84	0.25	-0.12	0.81	-0.23	-0.31	0.77	0.77	-0.14	0.12
Nyingchi	0.85	-0.35	0.27	0.32	-0.10	-0.25	0.33	0.79	-0.16	0.17
Qamdo	0.81	0.39	-0.16	0.71	-0.15	-0.32	0.14	0.79	-0.18	0.16
Diqing	0.91	0.20	0.43	0.62	-0.06	-0.22	0.32	0.91	-0.21	0.43
Haixi	0.76	0.22	0.21	0.96	-0.21	-0.11	0.50	0.81	-0.40	0.21
Guoluo	0.83	-0.21	-0.12	0.72	-0.36	-0.18	0.56	0.73	-0.39	0.12
Xining	0.87	-0.39	0.27	0.62	-0.28	-0.14	0.26	0.75	-0.19	0.47
Aba	0.91	0.06	-0.15	0.78	-0.12	-0.22	0.35	0.78	-0.11	0.41

Table S5. Correlations of $O_{3,\ meteo}$ against each meteorological parameter anomalies in diurnal scale from 2015 to 2020 over the QTP.

City	Correlations									
	$T_{surface}$	U_{10m}	V_{10m}	PBLH	TCC	Rain	Omega	SWGDN	RH_{2m}	TROPH
Ngari	0.64	0.20	0.91	0.62	-0.16	-0.22	0.71	0.55	-0.21	0.43
Shigatse	0.72	0.22	0.73	0.76	-0.31	-0.31	0.23	0.53	-0.48	0.23
Lhasa	0.76	0.25	-0.82	0.81	-0.32	-0.51	0.57	0.64	-0.43	0.12
Shannan	0.73	0.35	0.38	0.58	-0.18	-0.09	0.53	0.60	-0.40	0.39
Naqu	0.74	-0.15	0.68	0.72	-0.10	-0.34	0.69	0.63	-0.34	0.37
Nyingchi	0.72	0.49	-0.79	0.71	-0.25	-0.32	0.64	0.64	-0.23	0.16
Qamdo	0.77	0.31	0.75	0.42	-0.22	-0.52	0.27	0.75	-0.10	0.32
Diqing	0.80	0.70	0.78	0.70	-0.19	-0.03	0.73	0.69	-0.29	0.14
Haixi	0.73	-0.60	0.27	0.63	-0.15	-0.56	0.76	0.89	-0.15	0.51
Guoluo	0.75	-0.21	-0.93	0.72	-0.16	-0.38	0.36	0.70	-0.49	0.12
Xining	0.89	-0.06	-0.96	0.78	-0.12	-0.21	0.35	0.91	-0.41	0.40
Aba	0.95	0.52	-0.33	0.96	-0.21	-0.32	0.80	0.72	-0.40	0.20

Table S6. Correlations of $O_{3,\ meteo}$ against each meteorological parameter anomalies in seasonal scale from 2015 to 2020 over the QTP.

City	Correlations									
	$T_{surface}$	U_{10m}	V_{10m}	PBLH	TCC	Rain	Omega	SWGDN	RH_{2m}	TROPH
Ngari	0.80	0.20	-0.05	0.68	-0.20	-0.21	0.64	0.57	-0.50	0.40
Shigatse	0.81	-0.34	0.21	0.77	-0.25	-0.26	0.58	0.92	-0.19	0.27
Lhasa	0.83	-0.45	-0.07	0.65	-0.22	-0.31	0.25	0.88	-0.32	0.38
Shannan	0.86	-0.20	-0.64	0.69	-0.33	-0.45	0.34	0.95	-0.57	0.62
Naqu	0.87	0.36	0.16	0.60	-0.29	-0.16	0.33	0.63	-0.38	0.61
Nyingchi	0.83	-0.09	-0.36	0.67	-0.21	-0.34	0.51	0.73	-0.11	0.26
Qamdo	0.83	-0.21	0.18	0.75	-0.31	-0.27	0.57	0.90	-0.15	0.28
Diqing	0.92	-0.14	0.23	0.70	-0.33	-0.06	0.58	0.84	-0.12	0.16
Haixi	0.87	-0.40	-0.76	0.90	-0.34	-0.28	0.69	0.64	-0.32	0.67
Guoluo	0.96	-0.21	-0.89	0.79	-0.21	-0.36	0.79	0.92	-0.64	0.46
Xining	0.83	0.27	-0.73	0.71	-0.36	-0.28	0.37	0.96	-0.35	0.59
Aba	0.92	-0.25	-0.66	0.95	-0.27	-0.32	0.87	0.72	-0.32	0.50

Table S7. Correlations of $O_{3,\ meteo}$ against each meteorological parameter anomalies in multi-year scale from 2015 to 2020 over the QTP.

City	Correlations									
	$T_{surface}$	U_{10m}	V_{10m}	PBLH	TCC	Rain	Omega	SWGDN	RH_{2m}	TROPH
Ngari	0.79	0.51	0.75	0.66	-0.29	-0.34	0.77	0.64	-0.43	0.39
Shigatse	0.82	-0.11	-0.11	0.76	-0.19	-0.18	0.53	0.71	-0.18	0.16
Lhasa	0.86	-0.30	-0.51	0.86	-0.37	-0.29	0.38	0.65	-0.53	0.33
Shannan	0.91	0.16	-0.16	0.81	-0.15	-0.11	0.29	0.75	-0.28	0.53
Naqu	0.82	-0.82	0.80	0.86	-0.29	-0.16	0.23	0.85	-0.46	0.56
Nyingchi	0.91	0.28	-0.97	0.98	-0.39	-0.17	0.66	0.84	-0.53	0.73
Qamdo	0.93	0.88	-0.88	0.85	-0.18	-0.25	0.72	0.86	-0.55	0.61
Diqing	0.90	-0.85	-0.90	0.95	-0.38	-0.23	0.61	0.92	-0.35	0.80
Haixi	0.84	-0.83	-0.51	0.81	-0.57	-0.29	0.63	0.78	-0.50	0.85
Guoluo	0.88	-0.79	-0.85	0.84	-0.36	-0.30	0.53	0.87	-0.34	0.52
Xining	0.80	-0.55	0.40	0.84	-0.20	-0.28	0.32	0.78	-0.39	0.64
Aba	0.92	-0.19	0.53	0.92	-0.10	-0.34	0.76	0.87	-0.40	0.49

Table S8. The correlations between each meteorological variable and ozone anomalies in each city over the QTP region during ozone nonattainment events.

City	Correlations									
	$T_{surface}$	U_{10m}	V_{10m}	PBLH	TCC	Rain	Omega	SWGDN	RH_{2m}	TROPH
Ngari	0.57	-0.45	-0.13	0.09	0.35	0.38	0.32	-0.25	-0.02	0.16
Shigatse	0.69	0.38	-0.02	0.29	-0.13	-0.37	0.31	-0.37	-0.36	0.23
Lhasa	0.51	0.35	-0.12	0.34	-0.15	-0.39	0.35	0.02	-0.36	0.18
Shannan	0.67	-0.22	-0.25	0.02	0.22	0.14	0.25	-0.04	-0.11	0.32
Naqu	NA[1]	NA	NA	NA	NA	NA	NA	NA	NA	NA
Nyingchi	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Qamdo	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Diqing	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Haixi	0.83	0.28	-0.08	0.40	0.10	0.23	0.22	-0.77	-0.38	0.30
Guoluo	0.52	-0.76	-0.34	0.15	0.39	-0.12	0.69	0.45	-0.34	0.33
Xining	0.69	-0.20	-0.37	0.34	0.35	0.45	0.36	0.08	-0.20	0.31
Aba	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

[1] In these cities, there is no ozone nonattainment events during 2015 to 2020, expected Qamdo. In Qamdo, the ozone nonattainment events are only in 2 days. Therefore, we cannot calculate the correlations between each meteorological variable and ozone anomalies in these cities.

Table S9. The anthropogenic emissions of monthly total NO_x from 2015 to 2020 at each city over the QTP. (Units: t)

City	1	2	3	4	5	6	7	8	9	10	11	12
Ngari	0.20	0.20	0.22	0.22	0.22	0.24	0.22	0.23	0.22	0.22	0.21	0.20
Shigatse	5.54	5.56	5.85	5.95	6.03	6.26	5.98	6.04	5.97	5.88	5.79	5.54
Lhasa	68.51	69.61	82.56	87.52	91.02	101.27	89.05	91.53	88.52	84.42	79.61	68.67
Shannan	8.09	8.23	9.89	10.52	10.96	12.28	10.71	11.03	10.64	10.12	9.52	8.11
Naqu	1.99	2.00	2.21	2.28	2.34	2.51	2.30	2.34	2.29	2.23	2.17	1.99
Nyingchi	1.32	1.35	1.70	1.83	1.93	2.21	1.87	1.94	1.86	1.75	1.62	1.32
Qamdo	5.53	5.54	5.75	5.82	5.87	6.04	5.84	5.88	5.83	5.77	5.70	5.53
Diqing	8.13	6.80	8.37	8.32	7.99	8.35	7.80	8.01	8.74	8.30	9.28	9.66
Haixi	38.72	31.92	34.47	36.21	30.08	30.65	29.77	27.37	29.65	37.99	36.50	35.51
Guoluo	5.39	4.63	5.39	6.43	5.77	5.91	6.23	6.93	6.25	6.56	7.60	7.64
Xining	11.16	10.72	11.80	12.70	12.42	12.68	12.66	12.88	13.51	13.50	13.75	13.20
Aba	0.73	0.65	0.63	0.62	0.62	0.62	0.61	0.61	0.61	0.61	0.62	0.66

Table S10. The anthropogenic emissions of monthly total VOCs from 2015 to 2020 at each city over the QTP. (Units: t)

City	1	2	3	4	5	6	7	8	9	10	11	12
Ngari	0.11	0.64	0.80	1.06	1.01	1.17	0.95	1.10	1.20	0.72	2.34	2.14
Shigatse	1.59	1.69	1.77	1.82	1.80	1.91	1.80	1.84	1.82	1.73	2.10	2.00
Lhasa	21.51	50.83	62.66	78.25	75.99	87.45	72.76	81.32	85.73	58.93	146.36	132.92
Shannan	2.52	9.46	11.93	15.41	14.75	17.19	13.99	15.97	17.14	10.89	31.98	29.05
Naqu	0.71	2.57	3.17	4.06	3.85	4.46	3.65	4.17	4.50	2.85	8.61	7.87
Nyingchi	0.40	0.42	0.50	0.54	0.55	0.63	0.54	0.56	0.54	0.51	0.54	0.46
Qamdo	1.56	1.62	1.68	1.74	1.73	1.82	1.75	1.77	1.75	1.69	1.86	1.80
Diqing	14.16	11.67	14.62	13.29	11.14	11.52	10.66	11.43	13.19	11.68	13.11	14.76
Haixi	20.92	18.03	19.89	23.61	20.91	21.78	23.23	25.17	22.23	23.54	27.21	27.30
Guoluo	10.08	8.64	9.54	11.59	10.27	10.73	11.51	12.54	10.84	11.45	13.14	13.29
Xining	14.64	13.50	13.57	13.00	11.60	11.92	12.29	12.77	12.29	13.20	16.58	16.50
Aba	1.77	1.20	1.07	1.02	1.06	1.10	1.05	1.04	1.07	1.06	1.10	1.39

Table S11. The anthropogenic emissions of annual total NO_x from 2015 to 2020 at each city over the QTP. (Units: t)

City	2015	2016	2017
Ngari	0.25	0.20	0.22
Shigatse	5.82	5.96	5.92
Lhasa	82.14	83.70	84.74
Shannan	9.79	10.06	10.18
Naqu	2.28	2.18	2.23
Nyingchi	1.67	1.74	1.76
Qamdo	5.85	5.73	5.69
Diqing	8.69	8.08	8.16
Haixi	37.55	30.73	31.54
Guoluo	6.02	6.10	6.26
Xining	13.17	12.41	12.16
Aba	0.66	0.62	0.61

Table S12. The anthropogenic emissions of monthly total VOCs from 2015 to 2020 at each city over the QTP. (Units: t)

City	2015	2016	2017
Ngari	1.16	1.11	1.18
Shigatse	1.68	1.82	1.79
Lhasa	77.16	79.70	81.82
Shannan	15.11	15.91	16.55
Naqu	4.51	4.22	4.38
Nyingchi	0.54	0.52	0.49
Qamdo	1.90	1.70	1.59
Diqing	12.66	12.40	12.75
Haixi	21.96	22.63	23.87
Guoluo	10.71	10.99	11.72
Xining	13.71	13.47	13.29
Aba	1.22	1.15	1.11

Table S13. The correlations between the monthly averaged anthropogenic contributions and NO_x and VOCs emissions by MEIC inventory.

City	$R_{NO_x-month}$	$R_{VOC-month}$	R_{NO_x-year}	$R_{VOC-year}$
Ngari	0.74	0.62	0.15	0.88
Shigatse	0.58	0.61	0.56	0.62
Lhasa	0.43	0.33	0.28	0.34
Shannan	0.35	0.65	0.94	0.98
Naqu	0.56	0.66	0.78	0.82
Nyingchi	0.65	0.61	-0.84	0.54
Qamdo	0.75	0.35	0.82	0.83
Diqing	0.66	0.55	-0.29	0.77
Haixizhou	0.81	0.39	0.92	-0.36
Guoluozhou	0.74	0.71	0.93	0.92
Xining	0.55	0.83	0.91	0.90
Abazhou	0.77	0.67	0.87	0.89

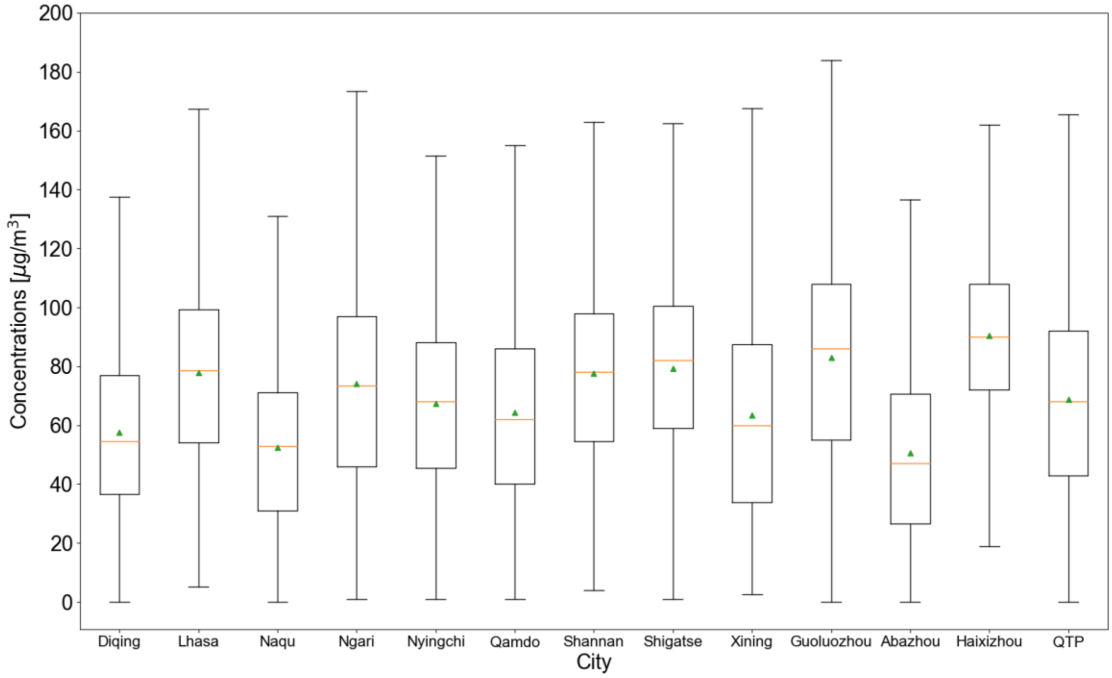

Figure S1. Boxplot of surface ozone (units: μg/m^3) from 2015 to 2020 in each city over the QTP. Lower and upper box boundaries represent 25th and 75th percentiles, respectively; line and triangle inside box represent median and mean, respectively; lower and upper error lines represent 1.5*IQR (interquartile range) below the third quartile and above the first quartile, respectively.

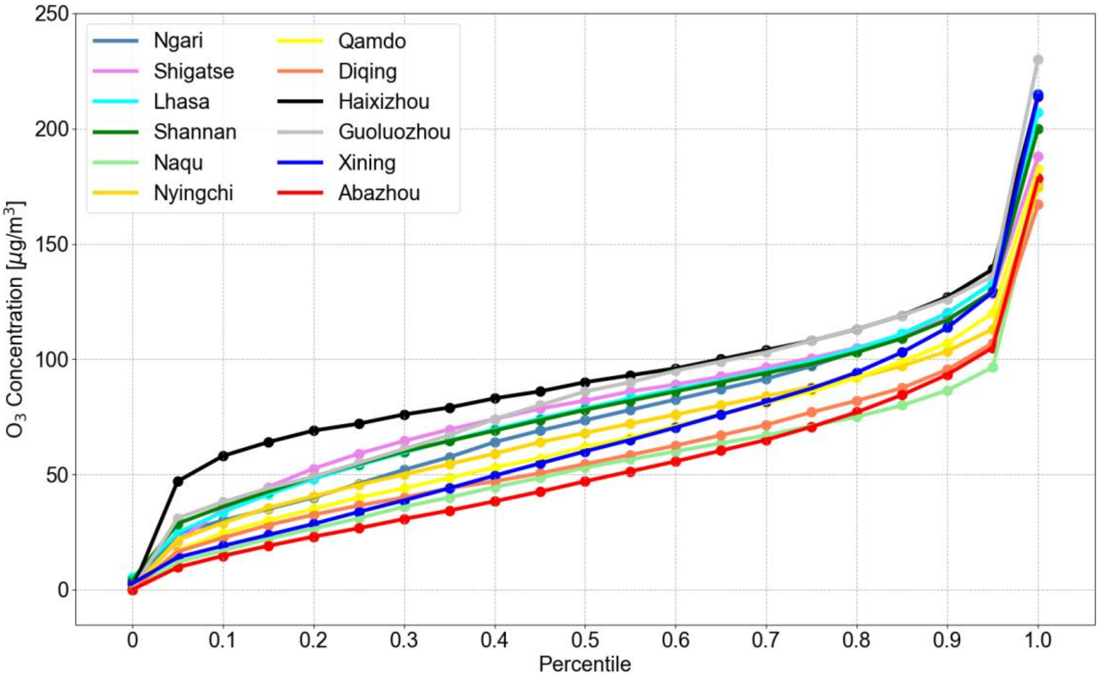

Figure S2. The percentile variation of surface ozone concentration (units: μg/m^3) in each city over the QTP from 2015 to 2020.

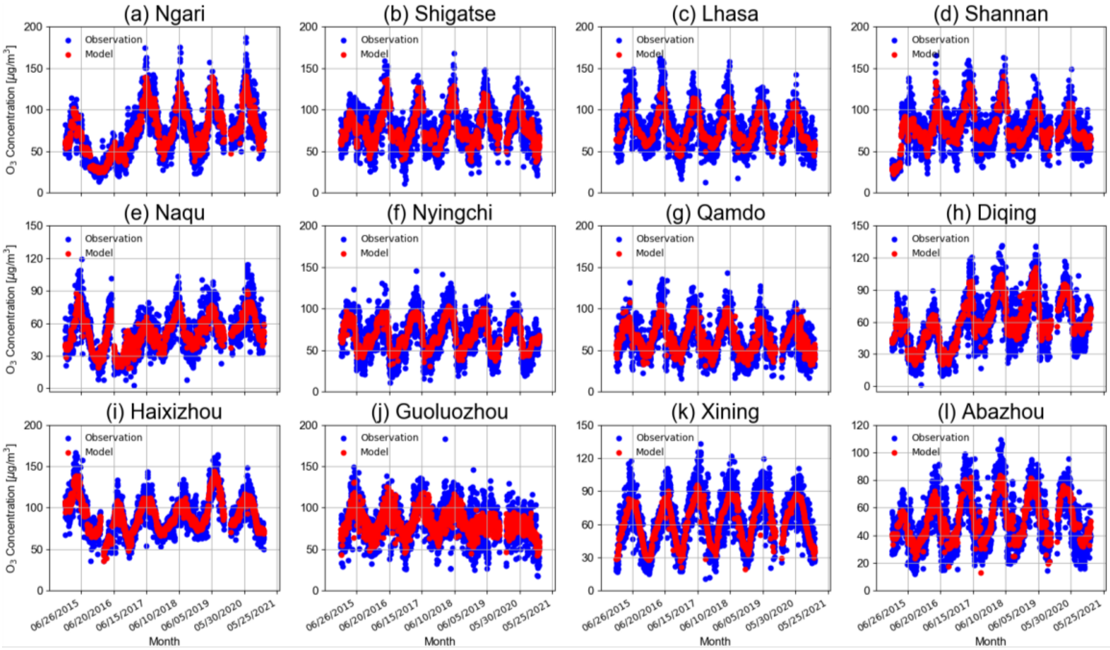

Figure S3. The time series of surface ozone observations and meteorological normalization data in each city over the QTP region from 2015 to 2020.

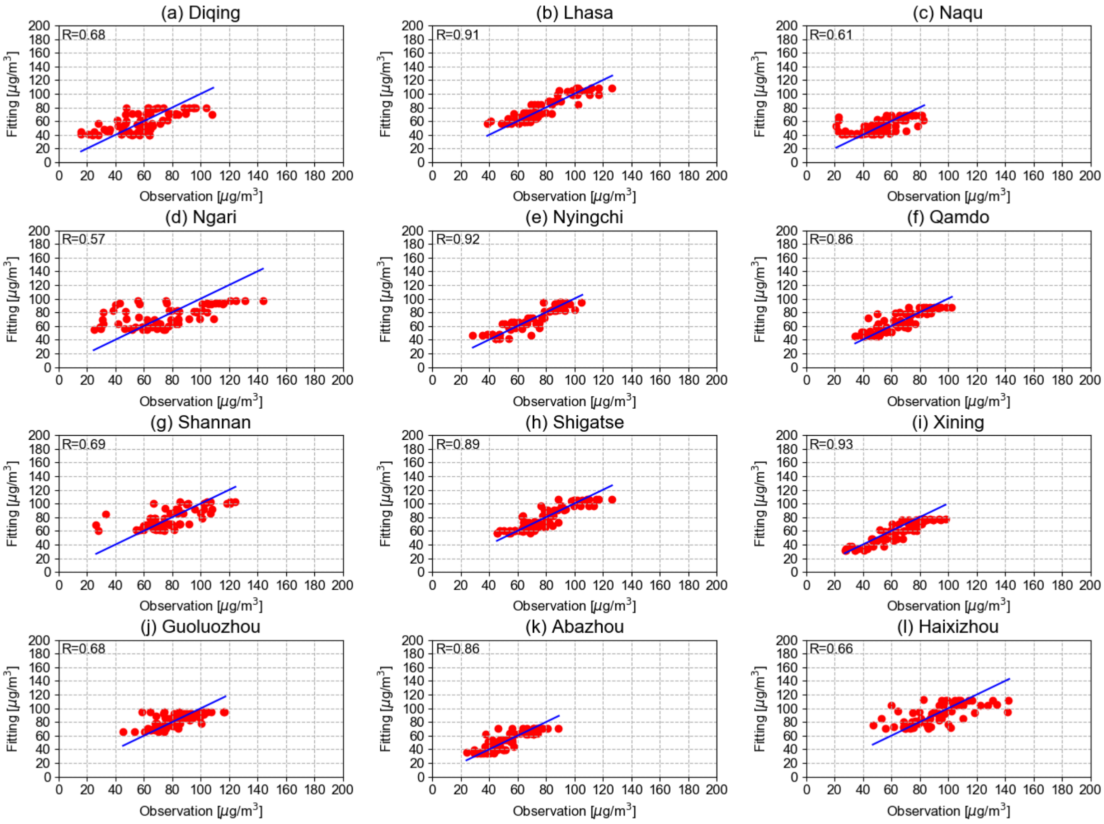

Figure S4. The comparisons of measured and fitted surface ozone concentrations in each city over the QTP region.

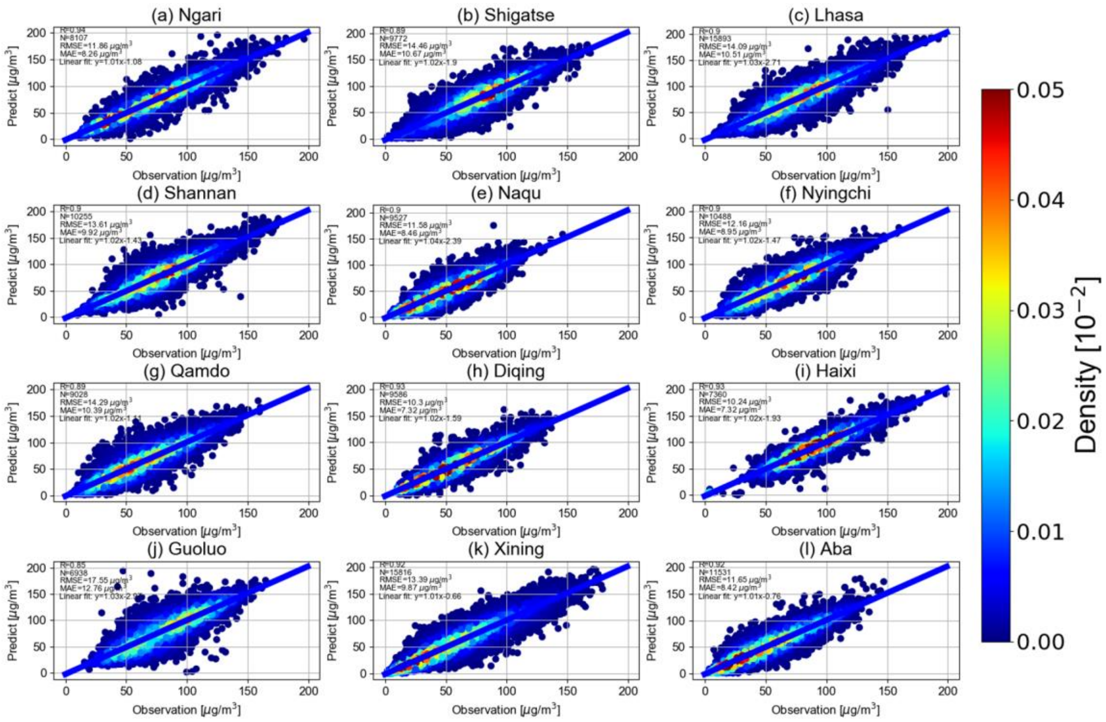

Figure S5. Performance of the RF model in predicting hourly surface ozone levels in each city over the QTP. The model was constructed with 70% training data and validated with the remaining 30% testing data. The plots show the comparisons between the model predictions and measurements for the 30% testing data in each city over the QTP. The blue lines are linear fitted curves of the respective scatter points. The colors represent probability distribution densities.

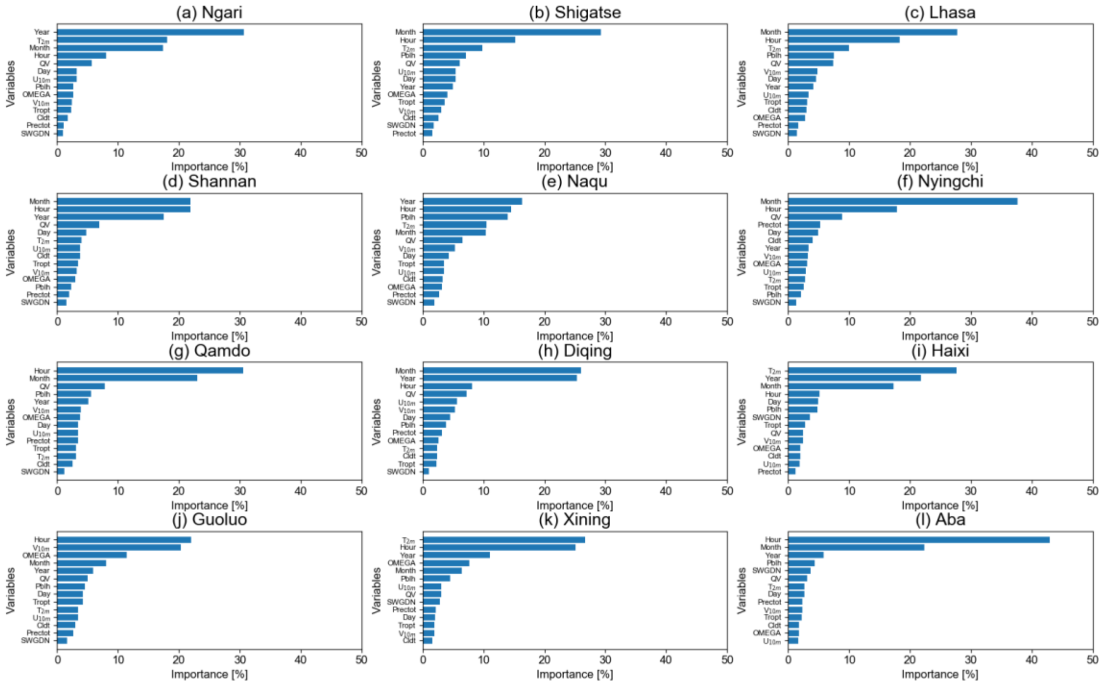

Figure S6. Importance scores (%) of each predictive variable, including Temperature (T_{2m}), Winds (U_{10m}, V_{10m}), Planetary boundary layer height (PBLH), Total cloud are fraction (CLDT), Rainfall (PRECTOT), Vertical pressure velocity (OMEGA), Surface incoming shortwave flux (SWGDN), Specific humidity (QV), Tropospheric layer Pressure (TROPT) and time information (Year, Month, Day and Hour), considered for predicting surface ozone levels in each city over the QTP using the RF model.