



Supplement of

Multi-dimensional satellite observations of aerosol properties and aerosol types over three major urban clusters in eastern China

Yuqin Liu et al.

Correspondence to: Tao Lin (tlin@iue.ac.cn) and Jiahua Zhang (zhangjh@radi.ac.cn)

The copyright of individual parts of the supplement might differ from the article licence.

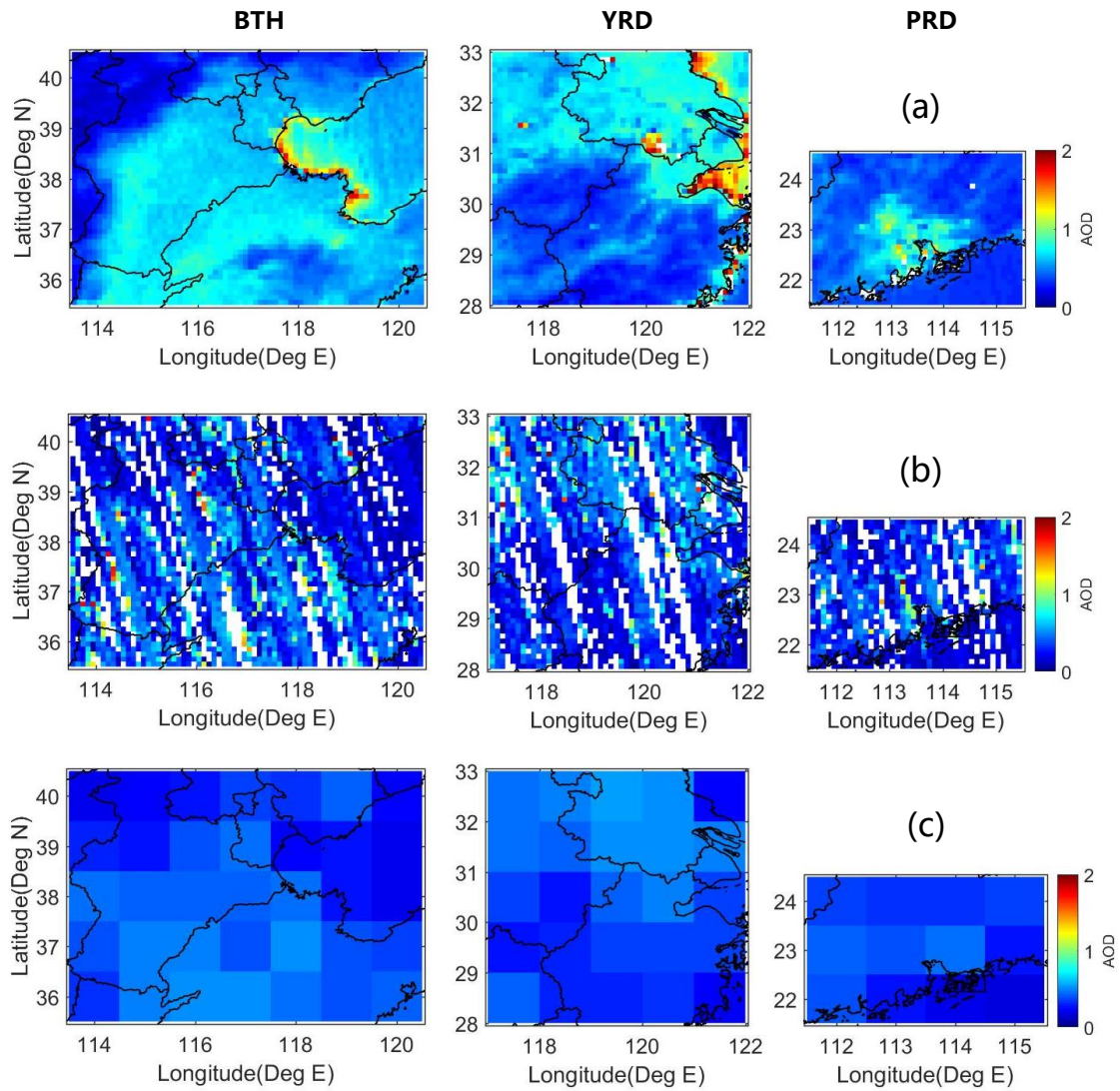


Figure S1. Spatial distributions of annually averaged (a) MODIS AOD, plotted with a spatial resolution of $0.1^\circ \times 0.1^\circ$, (b) CALIOP AOD, spatial resolution $0.1^\circ \times 0.1^\circ$ and (c) CALIOP AOD, spatial resolution $1^\circ \times 1^\circ$, during the period from 2007 to 2020 over the BTH (left), YRD (middle), and PRD (right). Note that the MODIS AOD is at 550 nm, whereas the CALIOP AOD is at a slightly smaller wavelength (532 nm). Also, there is a large difference in spatial coverage, with a MODIS swath width of 2330 km providing daily coverage in 1-2 days, as compared to the CALIOP footprint of 70m.

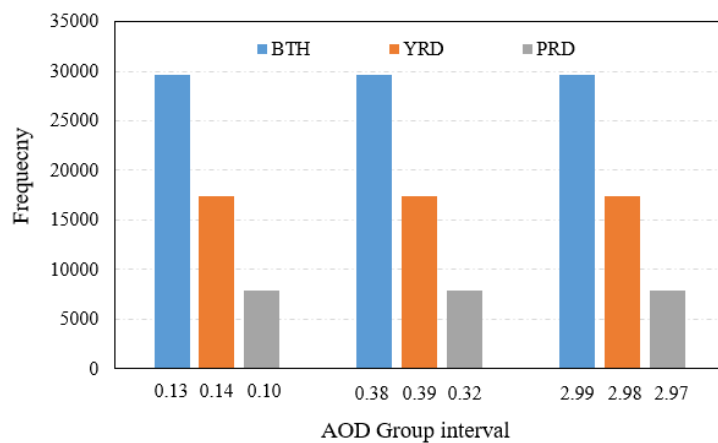


Figure S2. Histogram of number of CALIOP AOD values in each study area assigned to the AOD categories used to discriminate between moderately polluted (left), polluted (middle) and heavily polluted (right) during the period from 2007 to 2020 over the BTH, YRD and PRD. The AOD values along the x-axis are the maximum values for the different cases. The AOD ranges are provided in Table S10 and were selected such that the profiles over each region were divided into three equally sized subsets.

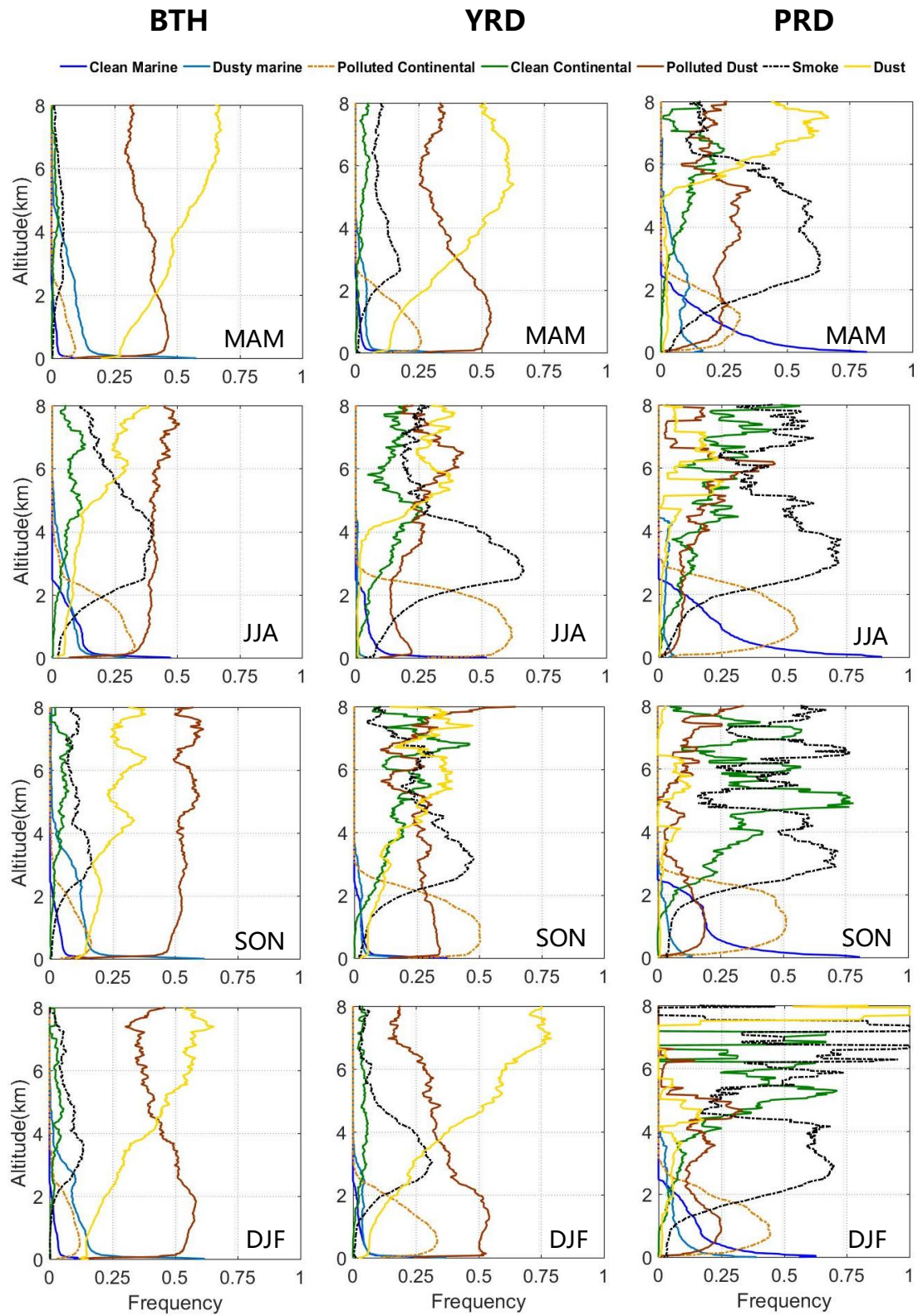


Figure S3. Vertical distributions of the nighttime frequency of occurrences for different CALIOP aerosol types (see legend at the top), derived using the Layer_FO approach, by season over the BTH (left), YRD (middle) and PRD (right), averaged over the years 2007-2020.

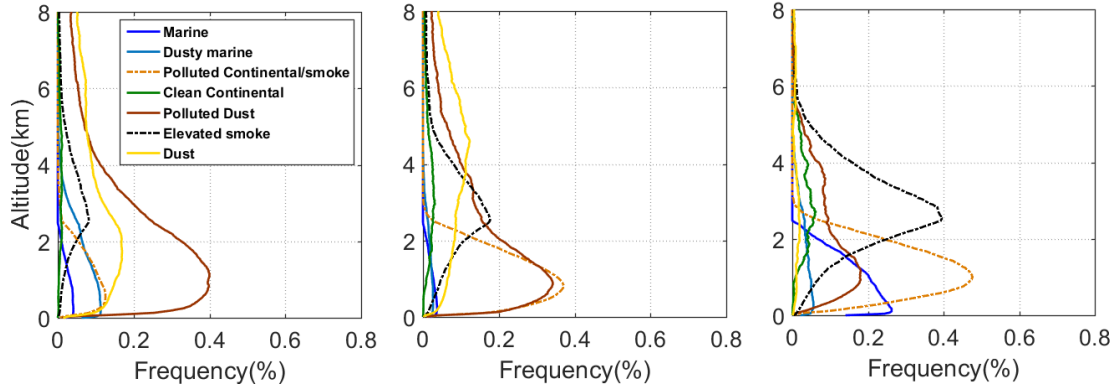


Figure S4. Annual mean vertical distribution of the nighttime frequency of occurrences for different CALIOP aerosol types (see legend), derived using the All_FO approach, over the BTH (left), YRD (middle) and PRD (right), averaged over the years 2007-2020.

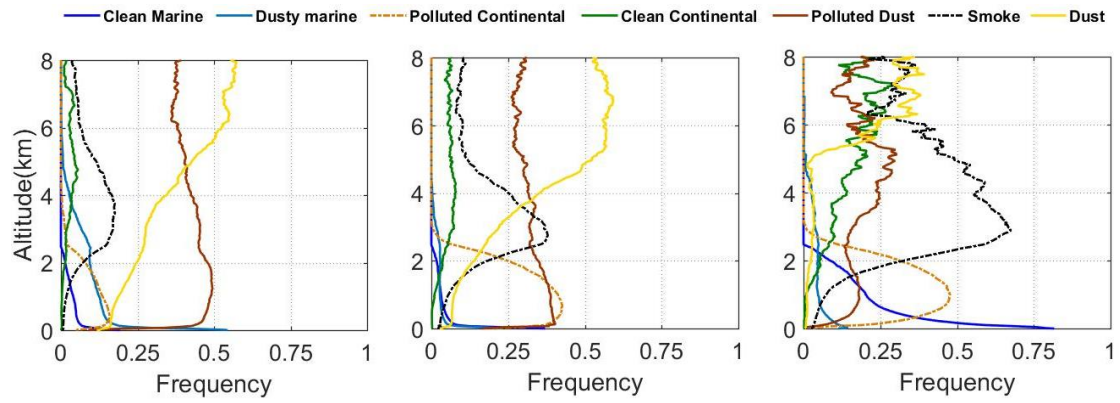


Figure S5. Annual mean vertical distributions of the nighttime frequency of occurrences for different CALIOP aerosol types (see legend at the top), derived using the Layer_FO approach, over the BTH (left), YRD (middle) and PRD (right), averaged over the years 2007-2020.

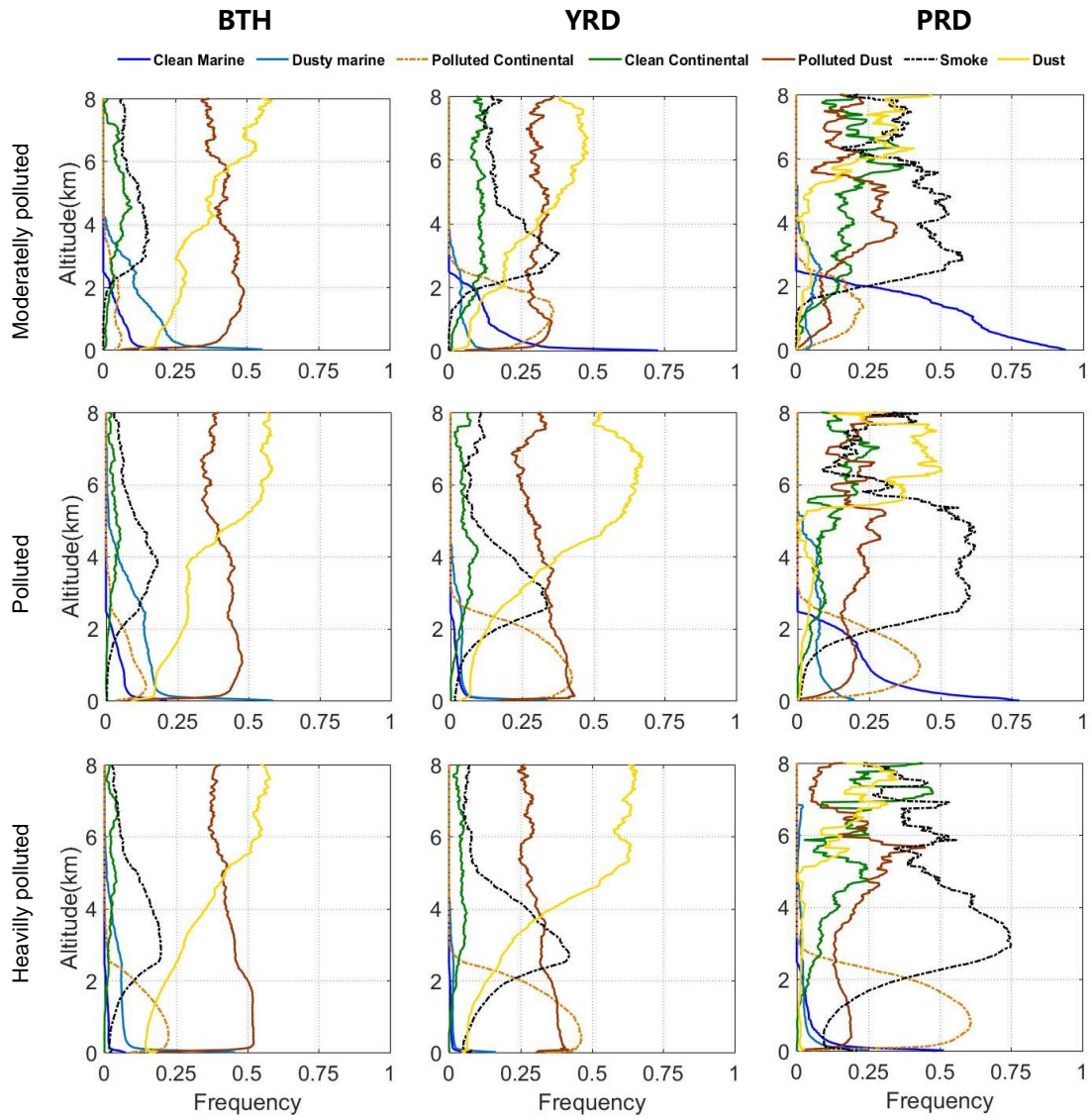


Figure S6. Vertical distribution of the nighttime frequency of occurrences for different CALIOP aerosol types (see legend at the top), derived using the Layer_FO approach, averaged over the years 2007-2020 and grouped in different CALIOP AOD ranges for moderately polluted (top), polluted (middle) and heavily polluted (bottom) conditions (see caption), over the BTH (left), YRD (middle) and PRD (right).

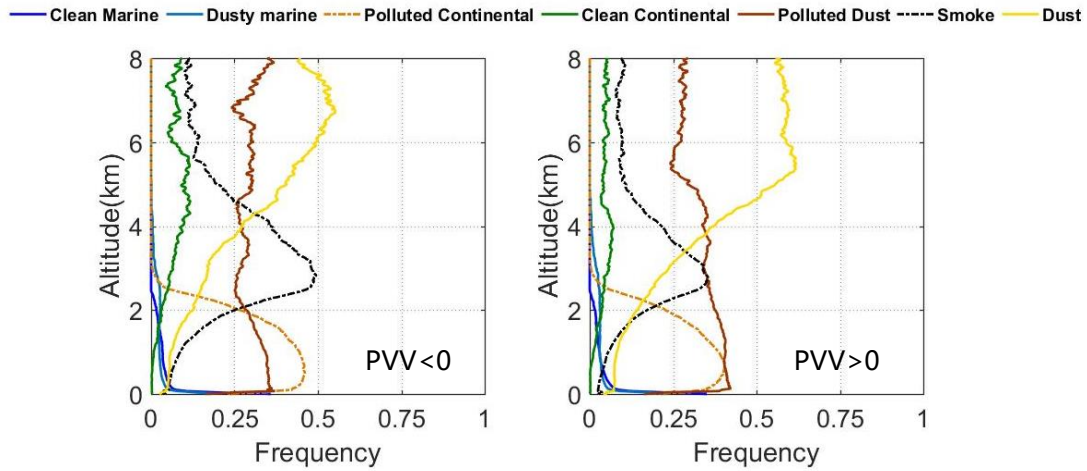


Figure S7. Vertical distributions of the nighttime frequency of occurrences for different aerosol types (see legend at the top), derived using the Layer_FO approach with nighttime data over the YRD, averaged over the years 2007-2020. The profiles are stratified by pressure vertical velocity (PVV), as a measure for the strength of vertical mixing (see text), at 750 hPa: i.e. for PVV<0 (left) and for PVV>0 (right).

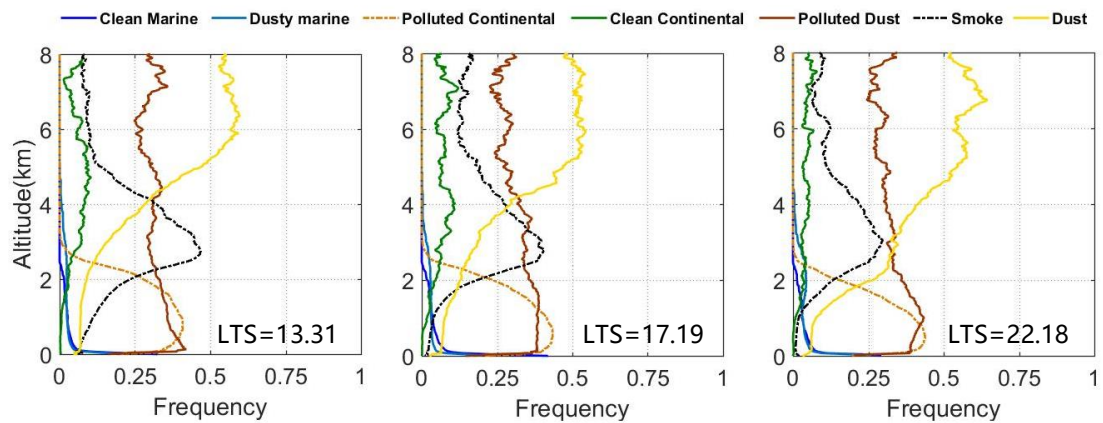


Figure S8. Vertical distributions of the nighttime frequency of occurrences for different aerosol types (see legend at the top), derived using the Layer_FO approach with nighttime data over the YRD, averaged over the years 2007-2020. The profiles are stratified by unstable atmosphere (left), neutral stable atmosphere (middle) and stable atmosphere (right). See text for further explanation.

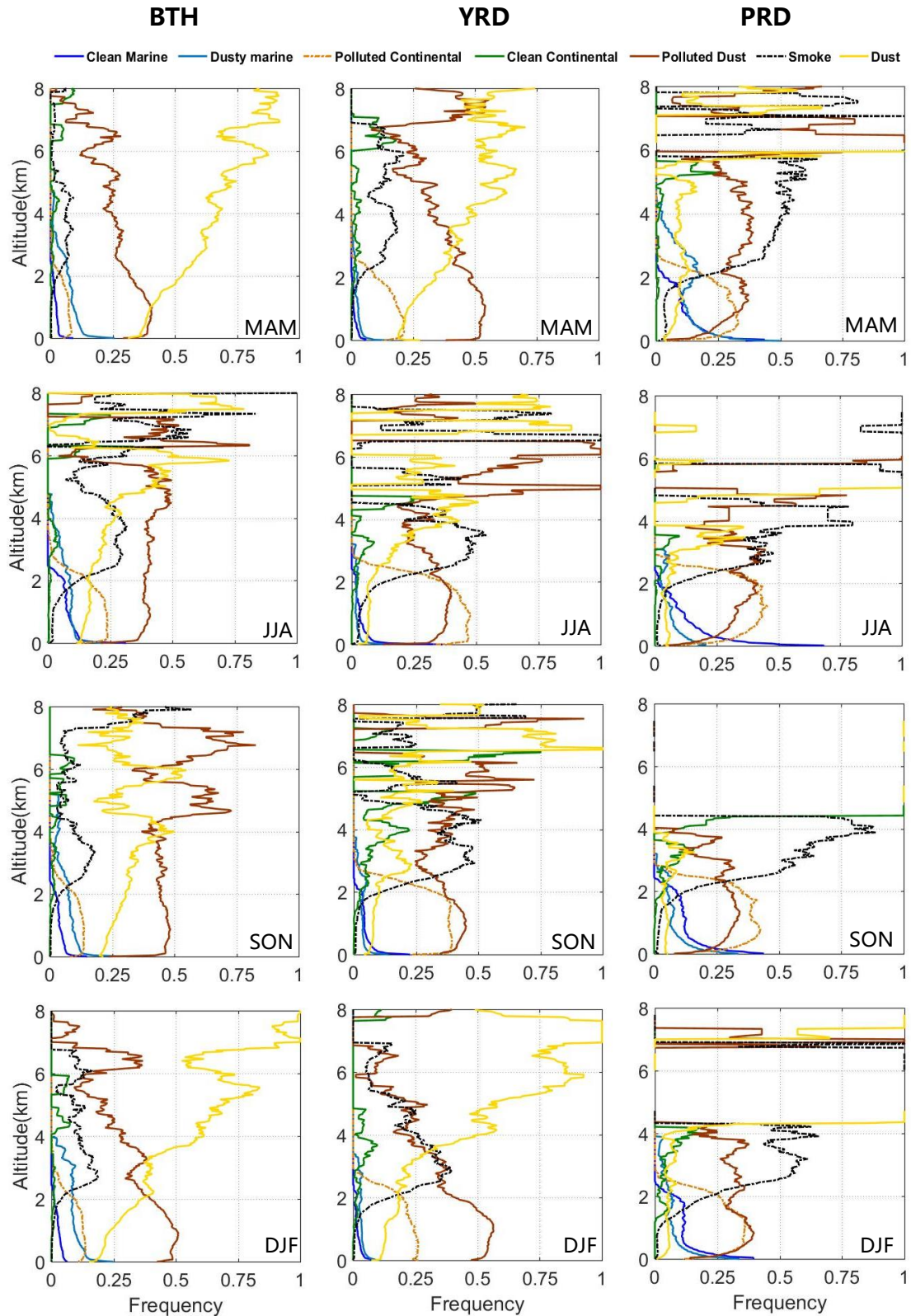


Figure S9. Daytime vertical distribution of the frequency of occurrences for different CALIOP aerosol types (see legend at the top), derived using the Layer_FO approach, by season over the BTH (left), YRD (middle) and PRD (right), averaged over the years 2007-2020.

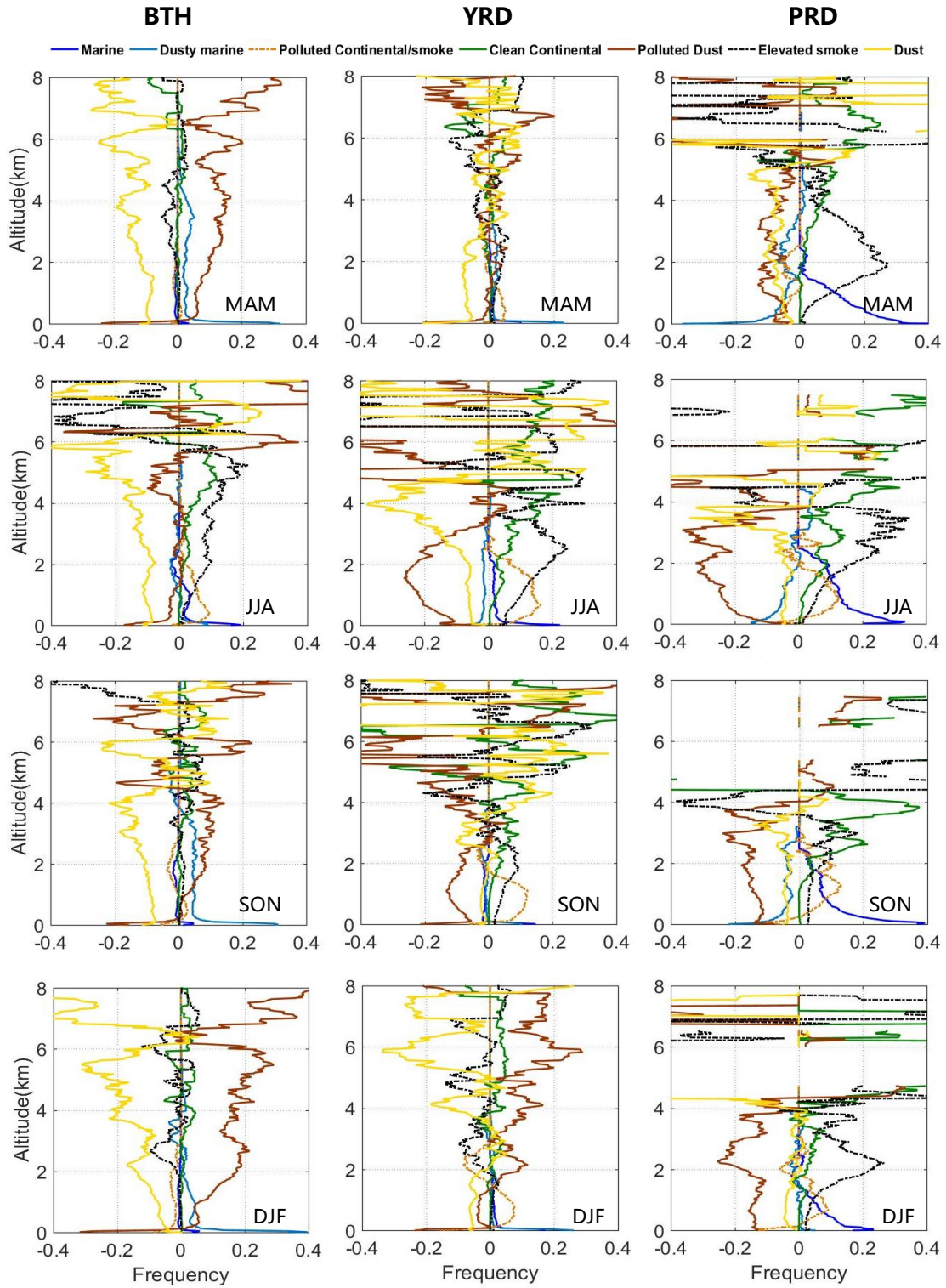


Figure S10. Differences between nighttime and daytime vertical distributions of the frequency of occurrences for CALIOP-derived aerosol types (see legend at the top), derived using the Layer_FO approach (nighttime minus daytime measurements) by season over the BTH (left), YRD (middle) and PRD (right), averaged over the years 2007-2020.

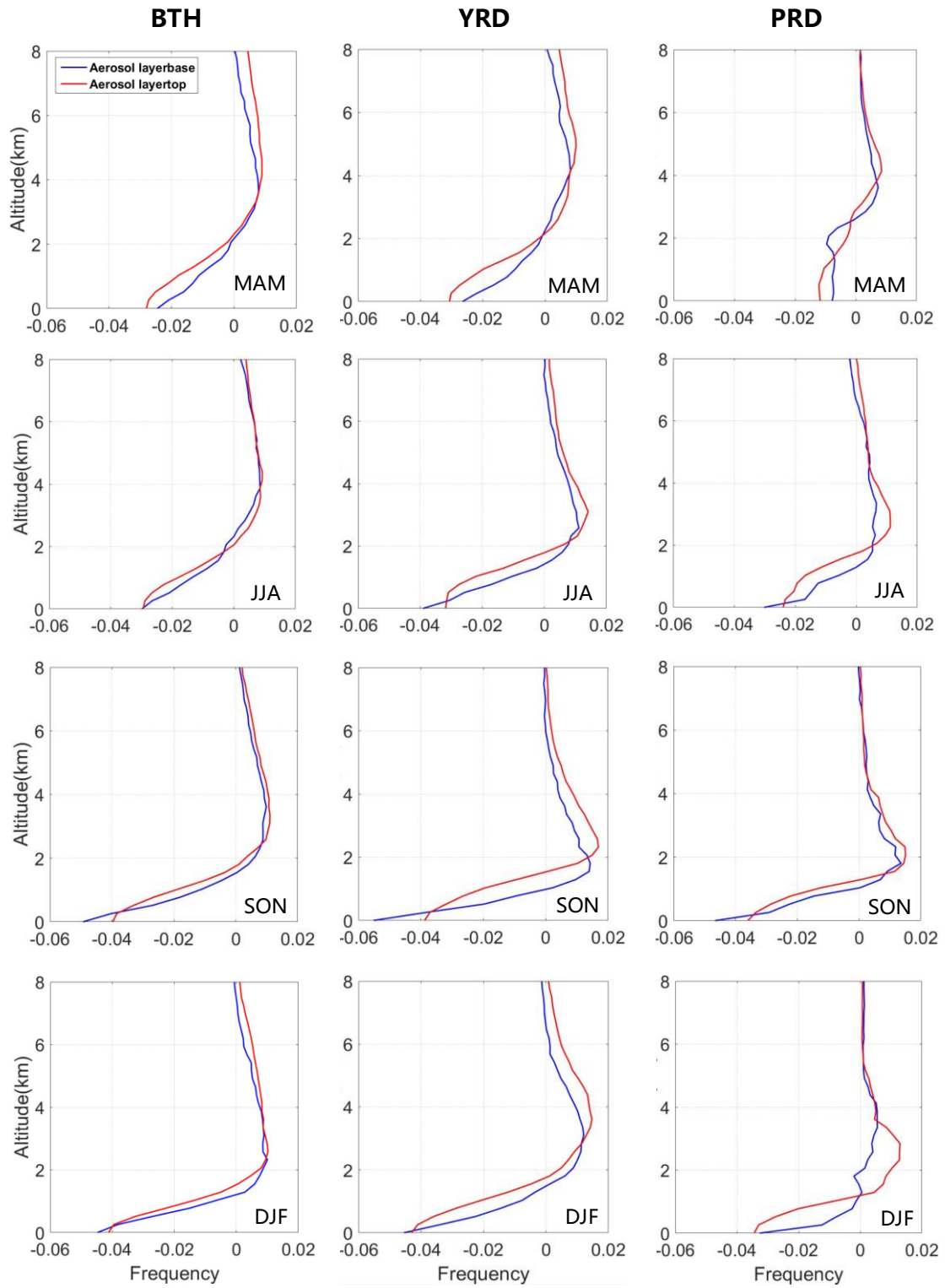


Figure S11. Night/day difference (nighttime minus daytime measurements) of the vertical distributions of the frequency of occurrences of aerosol layer top and base by season over the BTH (left), YRD (middle) and PRD (right), averaged over the years 2007 to 2020.

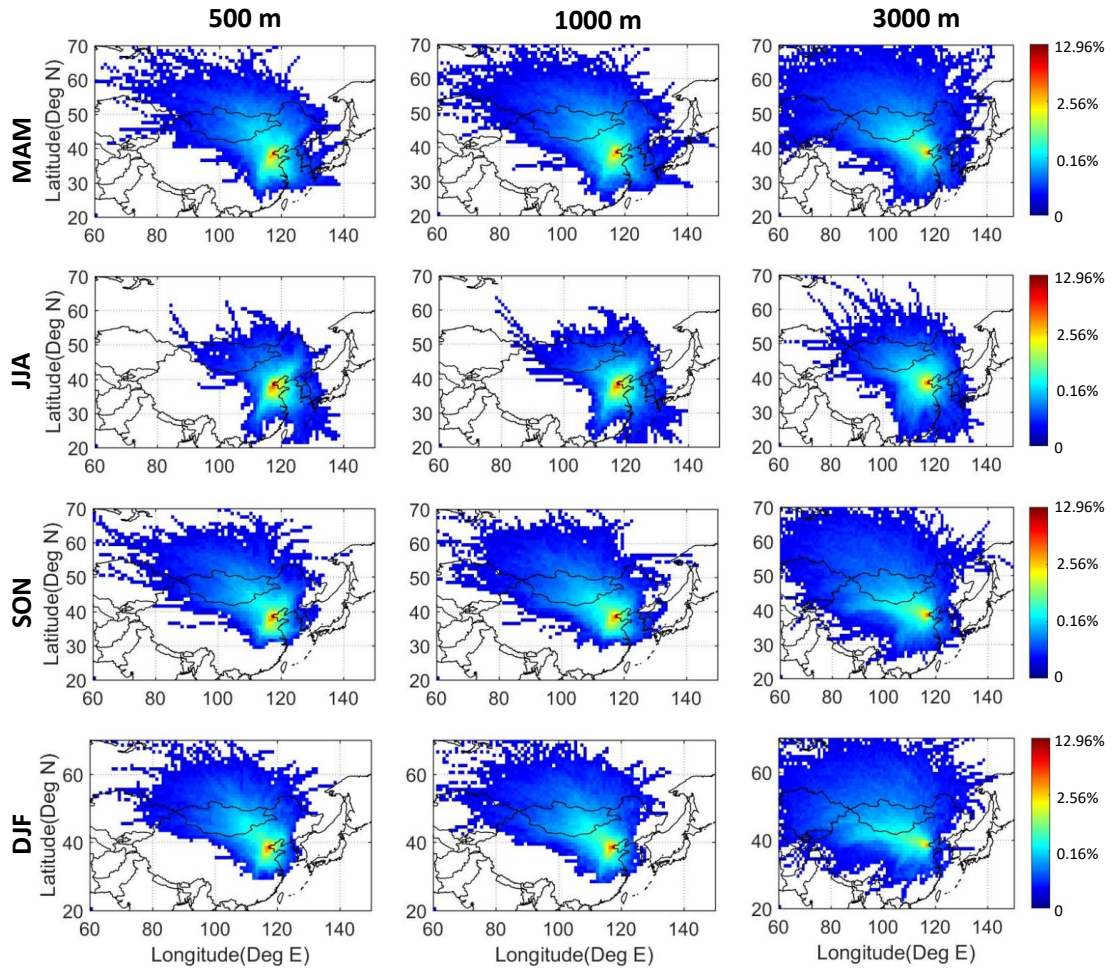


Figure S12. 48-h backward air mass trajectories calculated for arrival at the BTH (Sect. 2.2.4) at heights of 500 m (left column), 1000 m (middle column) and 3000 m (right column) above the surface, at 00:00 UTC, for every day in the period 2007-2020. The air mass trajectories were grouped by season: spring (MAM), summer (JJA), autumn (SON), and winter (DJF) (top to bottom rows) The density was color coded as shown in the color bar to the right. Trajectories were calculated using GDAS Meteorological data.

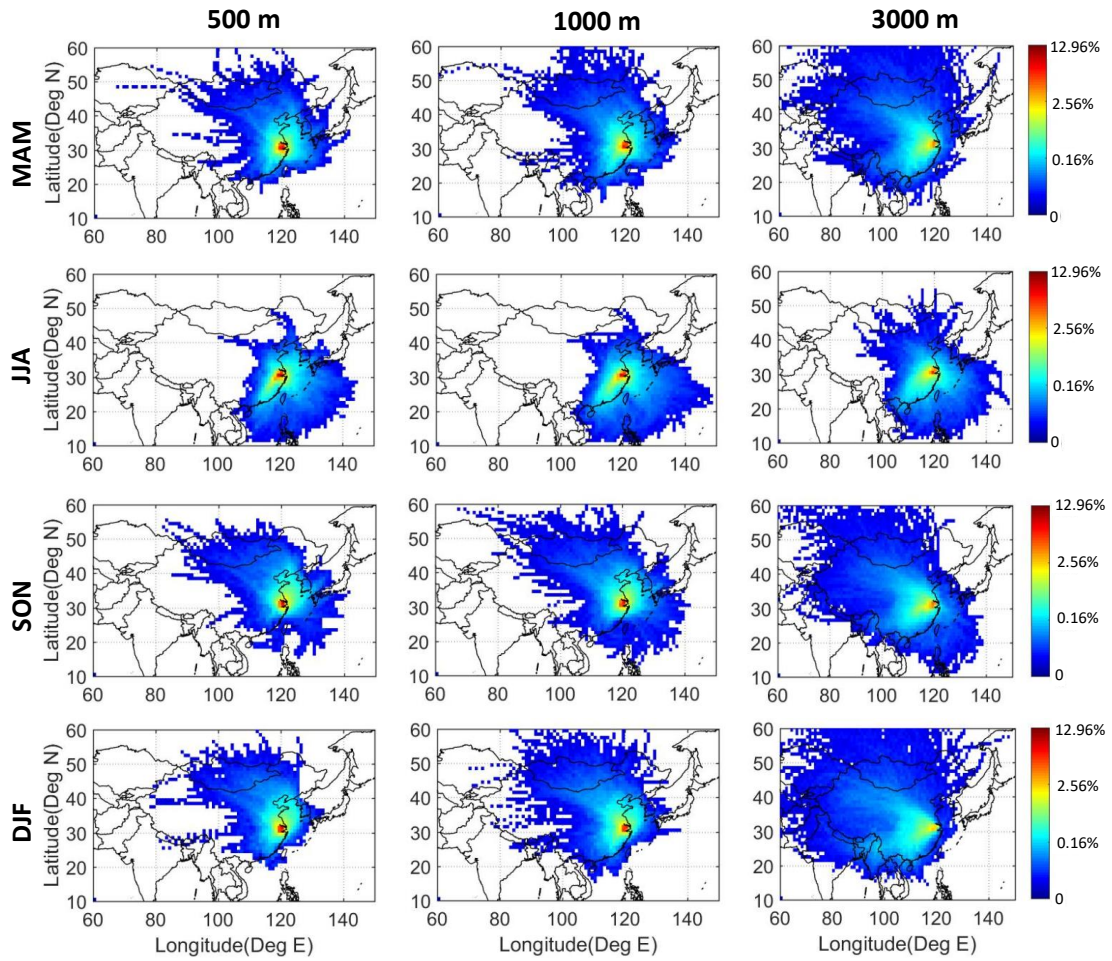


Figure S13. 48-h backward air mass trajectories calculated for arrival at the YRD (Sect. 2.2.4) at heights of 500 m (left column), 1000 m (middle column) and 3000 m (right column) above the surface, at 00:00 UTC, for every day in the period 2007-2020. The air mass trajectories were grouped by season: spring (MAM), summer (JJA), autumn (SON), and winter (DJF) (top to bottom rows) The density was color coded as shown in the color bar to the right. Trajectories were calculated using GDAS Meteorological data.

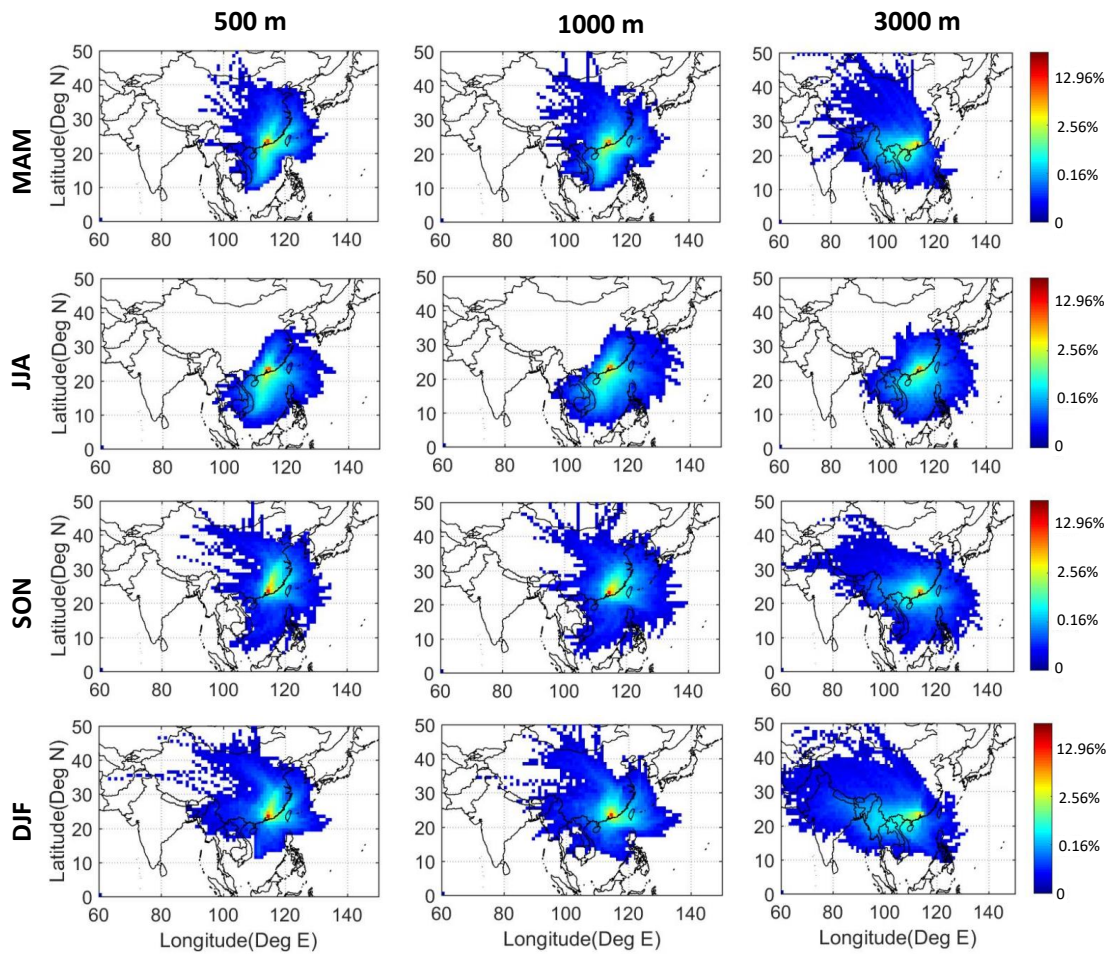


Figure S14. 48-h backward air mass trajectories calculated for arrival at the PRD (Sect. 2.2.4) at heights of 500 m (left column), 1000 m (middle column) and 3000 m (right column) above the surface, at 00:00 UTC, for every day in the period 2007-2020. The air mass trajectories were grouped by season: spring (MAM), summer (JJA), autumn (SON), and winter (DJF) (top to bottom rows) The density was color coded as shown in the color bar to the right. Trajectories were calculated using GDAS Meteorological data.

Table S1. Annual mean values of the MODIS AOD at 550 nm over the BTH, YRD and PRD for each year during the period from 2007 to 2020, together with the mean and median AOD averaged over the whole study period, as well as the minimum and maximum values and the standard deviations over each area.

Year	BTH	YRD	PRD
2007	0.60	0.63	0.52
2008	0.61	0.62	0.44
2009	0.56	0.60	0.49
2010	0.62	0.61	0.46
2011	0.64	0.68	0.45
2012	0.66	0.59	0.52
2013	0.61	0.55	0.45
2014	0.63	0.60	0.46
2015	0.57	0.56	0.36
2016	0.52	0.49	0.28
2017	0.47	0.46	0.34
2018	0.49	0.43	0.30
2019	0.46	0.43	0.32
2020	0.45	0.41	0.29
Min	0.45	0.41	0.28
Median	0.59	0.58	0.44
Max	0.66	0.68	0.52
Mean	0.56	0.55	0.41
Std. Dev.	0.07	0.09	0.09

Table S2. Seasonal mean values of the MODIS AOD at 550 nm over the BTH, YRD and PRD for each year during the period from 2007 to 2020, together with the seasonal mean and median AOD averaged over the whole study period, as well as the minimum and maximum values and the standard deviations for each season over the three areas.

Year \ Season	BTH				YRD				PRD			
	Spr	Sum	Aut	Win	Spr	Sum	Aut	Win	Spr	Sum	Aut	Win
2007	0.65	0.87	0.45	0.53	0.77	0.72	0.53	0.52	0.53	0.28	0.56	0.52
2008	0.75	0.83	0.46	0.53	0.70	0.80	0.53	0.51	0.71	0.40	0.36	0.38
2009	0.63	0.57	0.51	0.54	0.59	0.87	0.52	0.52	0.60	0.36	0.47	0.50
2010	0.61	0.94	0.49	0.56	0.74	0.75	0.58	0.46	0.73	0.26	0.45	0.38
2011	0.59	0.89	0.54	0.62	0.77	0.80	0.53	0.64	0.62	0.37	0.40	0.44
2012	0.72	0.77	0.48	0.72	0.68	0.72	0.50	0.53	0.74	0.43	0.51	0.39
2013	0.68	0.72	0.53	0.54	0.65	0.48	0.46	0.62	0.65	0.21	0.41	0.48
2014	0.69	0.79	0.49	0.59	0.70	0.83	0.44	0.59	0.76	0.47	0.46	0.42
2015	0.65	0.72	0.47	0.48	0.65	0.52	0.47	0.62	0.50	0.36	0.29	0.36
2016	0.55	0.62	0.51	0.46	0.61	0.50	0.36	0.46	0.45	0.26	0.29	0.23
2017	0.46	0.67	0.39	0.43	0.53	0.50	0.35	0.48	0.46	0.25	0.32	0.32
2018	0.65	0.50	0.38	0.45	0.54	0.44	0.35	0.34	0.39	0.30	0.24	0.28
2019	0.47	0.51	0.42	0.49	0.51	0.53	0.35	0.41	0.65	0.35	0.30	0.27
2020	0.47	0.52	0.40	0.44	0.52	0.43	0.29	0.42	0.48	0.15	0.21	0.29
Min	0.46	0.50	0.38	0.43	0.51	0.43	0.29	0.34	0.39	0.15	0.21	0.23
Median	0.64	0.72	0.47	0.53	0.65	0.62	0.47	0.52	0.61	0.33	0.38	0.38
Max	0.75	0.94	0.54	0.72	0.77	0.87	0.58	0.64	0.76	0.47	0.56	0.52
Mean	0.61	0.71	0.46	0.53	0.64	0.64	0.45	0.51	0.59	0.32	0.37	0.38
Std. Dev.	0.09	0.15	0.05	0.08	0.09	0.16	0.09	0.09	0.12	0.09	0.11	0.09

Table S3. Monthly mean values of the MODIS AOD at 550 nm over the BTH for each year during the period from 2007 to 2020, together with the monthly mean and median AOD averaged over the whole study period, as well as the minimum and maximum values and the standard deviations over each area for each month.

		BTH											
Year	Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2007		0.48	0.68	0.77	0.65	0.58	0.98	0.86	0.76	0.46	0.40	0.49	0.41
2008		0.54	0.64	0.55	0.80	0.93	0.97	0.87	0.62	0.59	0.47	0.35	0.40
2009		0.50	0.74	0.57	0.70	0.60	0.53	0.67	0.56	0.52	0.43	0.66	0.46
2010		0.62	0.73	0.54	0.65	0.62	1.13	0.89	0.70	0.55	0.49	0.45	0.44
2011		0.42	1.03	0.45	0.67	0.69	0.89	0.97	0.78	0.52	0.57	0.52	0.50
2012		0.74	0.84	0.62	0.67	0.85	0.97	0.75	0.48	0.50	0.51	0.42	0.49
2013		0.87	0.79	0.69	0.68	0.66	0.96	0.55	0.65	0.55	0.65	0.38	0.36
2014		0.64	1.22	0.68	0.77	0.62	0.72	0.89	0.72	0.57	0.53	0.39	0.31
2015		0.43	0.49	0.69	0.68	0.59	0.71	0.82	0.62	0.54	0.44	0.40	0.52
2016		0.55	0.35	0.55	0.62	0.46	0.68	0.71	0.44	0.49	0.54	0.49	0.50
2017		0.59	0.48	0.47	0.35	0.53	0.76	0.70	0.49	0.43	0.48	0.31	0.30
2018		0.49	0.54	0.76	0.65	0.50	0.48	0.65	0.44	0.26	0.37	0.48	0.30
2019		0.51	0.79	0.41	0.56	0.46	0.63	0.52	0.33	0.40	0.51	0.33	0.33
2020		0.58	0.51	0.40	0.49	0.53	0.61	0.42	0.45	0.31	0.40	0.45	0.31
Min		0.42	0.35	0.40	0.35	0.46	0.48	0.42	0.33	0.26	0.37	0.31	0.30
Median		0.54	0.71	0.56	0.66	0.59	0.74	0.73	0.59	0.51	0.49	0.43	0.40
Max		0.87	1.22	0.77	0.80	0.93	1.13	0.97	0.78	0.59	0.65	0.66	0.52
Mean		0.57	0.70	0.58	0.64	0.61	0.79	0.73	0.57	0.48	0.49	0.44	0.40
Std. Dev.		0.12	0.23	0.12	0.11	0.14	0.20	0.16	0.14	0.10	0.08	0.09	0.08

Table S4. Monthly mean values of the MODIS AOD at 550 nm over the YRD for each year during the period from 2007 to 2020, together with the monthly mean and median AOD averaged over the whole study period, as well as the minimum and maximum values and the standard deviations over each area for each month.

		YRD											
Year	Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2007		0.49	0.55	0.73	0.72	0.84	0.87	0.73	0.63	0.58	0.53	0.51	0.48
2008		0.66	0.74	0.60	0.78	0.76	1.17	0.63	0.75	0.93	0.47	0.41	0.36
2009		0.45	0.58	0.50	0.67	0.54	1.00	0.61	0.83	0.75	0.53	0.40	0.53
2010		0.63	0.46	0.77	0.80	0.64	1.01	0.89	0.54	0.54	0.55	0.59	0.40
2011		0.53	0.75	0.72	0.83	0.73	0.84	0.85	0.69	0.55	0.56	0.51	0.51
2012		0.62	0.53	0.70	0.66	0.68	1.13	0.44	0.41	0.69	0.45	0.50	0.48
2013		0.72	0.62	0.68	0.64	0.64	0.77	0.40	0.45	0.44	0.39	0.53	0.58
2014		0.69	0.71	0.67	0.73	0.74	1.00	0.63	0.67	0.55	0.43	0.44	0.39
2015		0.56	0.74	0.70	0.65	0.58	0.72	0.59	0.40	0.58	0.43	0.53	0.55
2016		0.47	0.48	0.63	0.73	0.48	0.57	0.45	0.49	0.44	0.26	0.30	0.44
2017		0.39	0.56	0.61	0.52	0.48	0.92	0.44	0.43	0.30	0.34	0.38	0.45
2018		0.35	0.34	0.58	0.50	0.55	0.53	0.34	0.43	0.38	0.37	0.31	0.34
2019		0.44	0.43	0.55	0.56	0.43	0.58	0.56	0.47	0.32	0.41	0.33	0.40
2020		0.53	0.37	0.49	0.56	0.48	0.68	0.66	0.28	0.41	0.27	0.26	0.51
Min		0.35	0.34	0.49	0.50	0.43	0.53	0.34	0.28	0.30	0.26	0.26	0.34
Median		0.53	0.56	0.65	0.67	0.61	0.85	0.60	0.48	0.54	0.43	0.43	0.46
Max		0.72	0.75	0.77	0.83	0.84	1.17	0.89	0.83	0.93	0.56	0.59	0.58
Mean		0.54	0.56	0.64	0.67	0.61	0.84	0.59	0.53	0.53	0.43	0.43	0.46
Std. Dev.		0.11	0.14	0.09	0.10	0.12	0.21	0.16	0.16	0.17	0.10	0.10	0.07

Table S5. Monthly mean values of the MODIS AOD at 550 nm over the PRD for each year during the period from 2007 to 2020, together with the monthly mean and median AOD averaged over the whole study period, as well as the minimum and maximum values and the standard deviations over each area for each month.

		PRD											
Year	Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2007		0.47	0.52	0.85	0.53	0.45	0.34	0.23	0.34	0.57	0.65	0.49	0.56
2008		0.41	0.48	0.76	0.60	0.65	0.33	0.47	0.33	0.52	0.42	0.29	0.35
2009		0.42	0.59	0.58	0.80	0.44	0.39	0.19	0.45	0.57	0.56	0.32	0.57
2010		0.46	0.51	0.85	0.64	0.48	0.60	0.18	0.28	0.56	0.35	0.45	0.35
2011		0.47	0.46	0.67	0.72	0.46	0.55	0.33	0.31	0.52	0.40	0.32	0.42
2012		0.44	0.62	0.88	0.64	0.36	0.50	0.26	0.52	0.34	0.65	0.32	0.31
2013		0.47	0.32	0.65	0.77	0.34	0.22	0.16	0.24	0.37	0.49	0.30	0.50
2014		0.54	0.26	0.75	0.90	0.34	0.61	0.32	0.45	0.30	0.51	0.42	0.27
2015		0.34	0.55	0.88	0.45	0.32	0.18	0.37	0.43	0.42	0.29	0.21	0.25
2016		0.27	0.24	0.44	0.87	0.30	0.20	0.23	0.36	0.37	0.30	0.24	0.22
2017		0.30	0.38	0.50	0.44	0.44	0.17	0.30	0.25	0.28	0.36	0.30	0.31
2018		0.26	0.44	0.41	0.49	0.18	0.30	0.26	0.36	0.27	0.26	0.20	0.16
2019		0.33	0.38	0.71	0.60	0.49	0.25	0.28	0.40	0.30	0.36	0.27	0.23
2020		0.29	0.39	0.56	0.49	0.30	0.13	0.15	0.17	0.34	0.21	0.19	0.24
Min		0.26	0.24	0.41	0.44	0.18	0.13	0.15	0.17	0.27	0.21	0.19	0.16
Median		0.42	0.45	0.69	0.62	0.40	0.32	0.26	0.35	0.37	0.38	0.30	0.31
Max		0.54	0.62	0.88	0.90	0.65	0.61	0.47	0.52	0.57	0.65	0.49	0.57
Mean		0.39	0.44	0.68	0.64	0.40	0.34	0.27	0.35	0.41	0.41	0.31	0.34
Std. Dev.		0.09	0.12	0.16	0.15	0.12	0.16	0.09	0.10	0.12	0.14	0.09	0.13

Table S6. The total number of MODIS overpasses over the BTH during each month in the period from 2007-2020.

BTH													
Year \ Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
2007	55	55	57	54	54	56	59	57	55	55	53	64	
2008	56	57	54	55	55	57	55	55	54	59	57	66	
2009	56	55	56	55	57	55	52	57	58	56	54	65	
2010	53	54	58	55	54	52	58	56	55	56	56	65	
2011	56	56	54	58	56	55	55	56	57	57	56	66	
2012	55	57	55	57	56	55	54	57	57	55	55	67	
2013	57	56	55	56	57	55	55	56	56	57	53	64	
2014	59	58	55	55	55	57	55	56	54	57	55	65	
2015	54	54	56	55	55	54	58	54	56	55	56	67	
2016	56	53	56	54	59	56	55	55	55	57	57	65	
2017	54	57	55	58	56	56	53	55	54	55	56	65	
2018	57	55	56	57	56	54	56	56	55	57	57	64	
2019	57	55	58	55	56	55	57	57	57	56	57	65	
2020	55	56	55	56	55	57	57	36	46	56	55	69	

Table S7. The total number of MODIS overpasses over the YRD during each month in the period from 2007-2020.

YRD													
Year \ Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
2007	48	46	52	48	46	48	47	47	47	47	47	51	
2008	47	47	48	47	49	50	47	49	51	49	47	56	
2009	48	48	47	49	48	49	45	48	50	47	47	58	
2010	46	47	48	51	49	48	49	47	50	51	49	58	
2011	52	49	46	48	50	47	45	45	50	50	47	53	
2012	48	49	46	52	51	46	47	48	49	47	47	59	
2013	48	46	50	51	52	51	49	48	48	48	48	55	
2014	52	49	48	49	49	50	49	47	48	48	51	56	
2015	49	50	48	50	49	47	50	49	46	48	49	58	
2016	46	45	50	50	55	50	48	45	45	49	46	53	
2017	49	48	50	48	49	49	47	45	49	48	48	57	
2018	49	49	46	49	51	50	50	49	49	48	48	55	
2019	47	49	50	51	45	49	47	49	49	50	49	56	
2020	49	47	46	48	48	49	48	33	40	47	48	61	

Table S8. The total number of MODIS overpasses over the PRD during each month in the period from 2007-2020.

		PRD											
Year \ Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
2007	38	41	41	39	40	38	38	39	40	38	40	45	
2008	39	39	40	38	38	36	39	38	40	36	37	49	
2009	39	39	38	38	38	38	39	38	34	40	39	43	
2010	39	39	35	36	36	40	37	37	39	40	40	46	
2011	40	38	42	38	38	37	40	38	36	37	38	47	
2012	38	40	37	37	37	40	40	37	38	38	39	48	
2013	39	38	39	37	37	38	40	39	38	39	40	47	
2014	36	38	39	39	41	38	38	40	38	39	41	46	
2015	37	40	40	38	38	40	36	39	36	37	38	41	
2016	37	39	35	40	39	38	38	40	38	39	39	48	
2017	37	38	38	38	37	36	38	39	38	38	36	44	
2018	39	37	39	38	35	39	39	40	40	38	37	43	
2019	39	38	39	38	40	38	37	36	38	36	37	44	
2020	37	37	40	40	40	38	38	26	30	38	38	44	

Table S9. Statistical information on the averaged MODIS and CALIOP AOD, plotted with a spatial resolution of 0.1° by 0.1° over the BTH, YRD and PRD, in Figure S1.

		MODIS			CALIOP		
		BTH	YRD	PRD	BTH	YRD	PRD
AOD	Mean	0.56	0.55	0.41	0.38	0.40	0.33
	Std	0.52	0.38	0.28	0.36	0.34	0.30
	Min	0.00	0.00	0.00	0.0012	0.0015	0.0016
	Max	3.00	3.00	2.98	2.92	2.79	2.85
	Median	0.41	0.46	0.34	0.26	0.31	0.24
Nr of overpasses		9466	8202	6512	1682	1162	875

Table S10. AOD categories use to sub-divide the CALIOP observation in equally sized subsets for moderately polluted, polluted and heavily polluted conditions, based on the CALIOP AOD values over the three study regions. For each condition, the mean value and the range (minimum, maximum value) are shown together with the number of overpasses. All data in the period from 2007 to 2020 are included.

CALIOP				
AOD		BTH	YRD	PRD
Moderately polluted	Mean	0.06	0.06	0.04
	Min	0.0003	0.0002	0.0005
	Max	0.13	0.14	0.10
	nr of overpasses	1440	1014	689
Polluted	Mean	0.24	0.26	0.19
	Min	0.13	0.14	0.10
	Max	0.38	0.40	0.32
	nr of overpasses	1442	923	669
Heavily polluted	Mean	0.79	0.76	0.69
	Min	0.38	0.40	0.32
	Max	2.99	2.98	2.97
	nr of overpasses	1231	813	615