Draft for open comment

Tropospheric Ozone Assessment Report: Present-day distribution and trends of tropospheric ozone relevant to climate and global atmospheric chemistry model evaluation

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The Tropospheric Ozone Assessment Report (TOAR) is a current IGAC activity (http://www.igacproject.org/activities/TOAR) with a mission to provide the research community with an up-to-date scientific assessment of tropospheric ozone's global distribution and trends from the surface to the tropopause.

Guided by this mission, TOAR has two goals:

1) Produce the first tropospheric ozone assessment report based on the peer-reviewed literature and new analyses.

2) Generate easily accessible, documented data on ozone exposure and dose metrics at hundreds of measurement sites around the world (urban and non-urban), freely accessible for research on the global-scale impact of ozone on climate, human health and crop/ecosystem productivity.

The report is being written as a series of eight stand-alone publications to be submitted for peer-review to *Elementa: Science of the Anthropocene*, an open-access, non-profit science journal founded by five US research Universities and published by University of California Press (www.elementascience.org). Prior to submission each paper will be posted to the TOAR webpage (http://www.igacproject.org/activities/TOAR/OpenComments) for a 30-day open comment period. We invite members of the atmospheric and biological sciences communities as well as the general public to read the papers and provide comments if they wish to do so. The open comment period will last for 30 days for each paper, with the draft papers posted to the website as they become available.

To provide comments on this particular paper, please send an e-mail to lead author Audrey Gaudel: Audrey.Gaudel@colorado.edu

Table 2.4. Details of the TCO products discussed in this paper.

Product name and institution	**Horizontal resolution of gridded products**	**Horizontal coverage**	**Vertical range (tropopause definition)**	**Temporal resolution/time of day**	**Record length**
OMI/MLS *NASA GSFC*	1°x 1.25°	60°S - 60°N	Surface to tropopause (WMO 2 K km^{-1} lapse-rate)	Monthly/ Seasonal 13:45	2004 – 2016, continuing
GOME & OMI *Smithsonian Astrophysical Observatory (SAO)*	1°x 1.25°	60°S - 60°N	Surface to tropopause (WMO 2 K km^{-1} lapse-rate)	Monthly/Seasonal OMI: 13:45 GOME: 10:30	GOME: 1995 – 6/2003 OMI: 10/2004-2015, continuing
OMI-RAL *Rutherford Appleton Laboratory (RAL)*[1]	5°x 5°	60°S - 60°N	Surface-450hPa mole fraction and surface to tropopause column (WMO 2 K km^{-1} lapse rate)	Monthly/ Seasonal 13:45	1995- 2016, continuing
IASI-LISA *LISA*	Averaged over 0.25°x 0.25° grids	Regional (Asia)	Surface-6 and 6-12 km	Seasonal 9:30	2008-2014, continuing
IASI+GOME2 *LISA*	1°x 1°	Regional (Europe, Asia)	Surface to 3 km, and 3-9 km	Monthly/ seasonal 9:30	2009-2010
IASI - FORLI *Université Libre de Bruxelles and LATMOS/IPSL*	Averaged over 5°x 5° grids	90°S-90°N	Surface to tropopause (WMO 2 K km^{-1} lapse rate)	Seasonal 9:30	2008 – 2016, continuing
IASI - SOFRID *CNRS*	5°x 5°	80°S-80°N	Surface to tropopause (WMO 2 K km^{-1} lapse rate)	Seasonal 9:30	2008 – 2016, continuing
SCIAMACHY	Averaged over grids 1°x 1°, 2°x 2°, 5°x 5°	80°S-80°N	Tropopause to 60 km (blended tropopause)	Monthly 10:00	2002/08-2012/4
FTIR *NDACC*	Point location	Various sites around the world	Surface to 8 km a.s.l. in this analysis. Retrievals to 45 km are also possible	Monthly/ annual	Earliest data from 1995, continuing
Umkehr Umk04+stray light correction, NOAA processing	Point location	Various sites around the world	Surface to 250 hPa	Monthly/annual Morning and afternoon profiles, averaged profile during measurements between 70-90° SZA, latitude and season dependent time of measurements	Earliest data from 1956 at Arosa, Switzerland, continuing
TOST	5°x 5°	90°S-90°N	Surface to tropopause (WMO 2 K km^{-1} lapse rate)	Seasonal/annual	2008-2012

[1] *GOME-1, -2A and -2B data in preparation*

Table 4.1 Nighttime ozone trends at eight mountaintop sites for winter (DJF), spring (MAM), summer (JJA) and autumn (SON). Bold face indicates trend values that are statistically significant at p-value <0.05. Trend values in parentheses indicate the high and low trend values that bound the 95% confidence interval.

Site name *lat. long. alt.(m a.s.l.)*	Years with data		Trend, full record	p-value	Trend, 2000-2015	p-value
	1973-2015	DJF	**0.10 (0.03, 0.21)**	**0.01**	-0.05 (-0.63, 0.33)	0.69
Mauna Loa		MAM	0.10 (-0.04, 0.23)	0.15	**0.60 (0.09, 1.13)**	**0.04**
19.5°N, 155.6°W		JJA	**0.16 (0.09, 0.23)**	**0.00**	0.18 (-0.06, 0.40)	0.14
3397 m		SON	**0.24 (0.14, 0.34)**	**0.00**	-0.26 (-0.67, 0.29)	0.32
	1987 - 2015	DJF	**0.19 (0.09, 0.28)**	**0.01**	0.00 (-0.16, 0.29)	1.00
Izaña		MAM	**0.14 (0.02, 0.27)**	**0.03**	0.07 (-0.20, 0.29)	0.62
28.3°N, 16.5°W		JJA	0.14 (-0.02, 0.28)	0.07	0.12 (-0.24, 0.42)	0.69
2367 m		SON	**0.13 (0.02, 0.21)**	**0.02**	0.06 (-0.16, 0.26)	0.89
	1994 - 2015	DJF	**0.11 (0.01, 0.20)**	**0.04**	0.08 (-0.10, 0.23)	0.69
Mt. Waliguan		MAM	**0.20 (0.10, 0.32)**	**0.00**	0.18 (-0.03, 0.37)	0.06
36.3°N, 100.9°E		JJA	0.19 (-0.06, 0.37)	0.09	0.15 (-0.14, 0.48)	0.32
3810 m		SON	**0.32 (0.17, 0.36)**	**0.00**	**0.32 (0.15, 0.36)**	**0.00**
	2004 - 2015	DJF	too few data	-	too few data	-
Mt Bachelor		MAM	**0.64 (0.02, 1.24)**	**0.05**	**0.64 (0.02, 1.24)**	**0.05**
44.0°N, 121.7°W		JJA	0.77 (-0.11, 1.58)	0.09	0.77 (-0.11, 1.58)	0.09
2763 m		SON	**1.14 (0.41, 1.70)**	**0.01**	**1.14 (0.41, 1.70)**	**0.01**
	1975 - 2015	DJF	too few data	-	too few data	-
Whiteface Mt Summit		MAM	-0.07 (-0.24, 0.08)	0.29	too few data	-
44.4°N, 73.9°W		JJA	**-0.38 (-0.49, -0.22)**	**0.00**	**-0.71 (-1.61, -0.07)**	**0.02**
1483 m		SON	-0.04 (-0.11, 0.05)	0.38	-0.29 (-0.85, 0.12)	0.13
	1986 - 2015	DJF	**0.15 (0.04, 0.29)**	**0.01**	-0.07 (-0.21, 0.05)	0.26
Jungfraujoch		MAM	0.05 (-0.06, 0.19)	0.30	**-0.15 (-0.24, -0.01)**	**0.03**
46.5°N, 8.0°E		JJA	-0.05 (-0.16, 0.11)	0.42	-0.12 (-0.37, 0.17)	0.39
3580 m		SON	**0.13 (0.03, 0.23)**	**0.01**	0.03 (-0.09, 0.14)	0.56
	1978 - 2015	DJF	**0.31 (0.19, 0.42)**	**0.00**	-0.08 (-0.25, 0.05)	0.12
Zugspitze		MAM	**0.20 (0.04, 0.35)**	**0.01**	**-0.27 (-0.34 -0.13)**	**0.01**
47.4°N, 11.0°E		JJA	0.12 (-0.02, 0.28)	0.08	-0.20 (-0.49, 0.13)	0.30
2962 m		SON	**0.15 (0.07, 0.26)**	**0.00**	-0.07 (-0.31, 0.10)	0.44
	2000 - 2015	DJF	0.02 (-0.26, 0.45)	0.85	0.02 (-0.26, 0.45)	0.86
Summit		MAM	**-0.32 (-1.04, -0.05)**	**0.02**	**-0.32 (-1.04, -0.05)**	**0.02**
72.6°N, 38.5°W		JJA	too few data	-	too few data	-
3212 m		SON	-0.08 (-0.30, 0.14)	0.32	-0.08 (-0.30, 0.14)	0.32

Table 5.7 Multi-year mean tropospheric ozone burden (Tg) as measrued by ozonesondes and satellites. Also shown is the mean and standard deviation of TOB from the ACCMIP model ensemble for the year 2000 (Young et al., 2013). IASI-FORLI and IASI-SOFRID TOB values for their full latitude range are underestimates due to missing data during polar night.

	60° S – 60° N			Full latitude range		
	2000	2010-2014	2014-2016	2000	2010-2014	2014-2016
TOST		306	NA		337 90° S – 90° N	NA
OMI/MLS		281	285		-	-
OMI-SAO		305	303			
OMI-RAL		281	287			
IASI-FORLI		301	293		333 90° S – 90° N	324 90° S – 90° N
IASI-SOFRID		318	311		345 75° S – 75° N	338 75° S – 75° N
Mean (range), all six products		299 (281-318)				
Mean (range), five satellite products		297 (281-318)	296 (285-311)			
ACCMIP model ensemble	299 ± 21*			337 ± 23 90°S – 90°N		

* Personal communication from Paul Young, Lancaster University

Table 5.8 Availability of all data sets presented in TOAR-Climate.

In situ observations	
Surface ozone observations	The surface ozone values and trends shown in Figures 3.1.1, 3.1.2, 4.1.3 and 4.1.4 (as well as the figures themselves) can be downloaded from: Schultz, MG; Schröder, S; Lyapina, O et al. (2017): Tropospheric Ozone Assessment Report, links to datasets https://doi.pangaea.de/10.1594/PANGAEA.876108
TOST ozonesonde product	The global monthly gridded product is available from the World Ozone and Ultraviolet Radiation Data Centre (WOUDC): http://woudc.org/archive/products/ozone/vertical-ozone-profile/ozonesonde/1.0/tost/
IAGOS commercial aircraft	High resolution IAGOS observations can be downloaded from the IAGOS Data Portal: http://iagos.sedoo.fr/
Mauna Loa Observatory ozone and meteorology	Hourly ozone and meteorological data shown in Figure 4.1.1 are available from NOAA's Global Monitoring Division: https://www.esrl.noaa.gov/gmd/dv/ftpdata.html
Lauder, NZ ozonesondes	The ozonesonde data at Lauder are part of WOUDC and the Network for the Detection of Atmospheric Composition Change (NDACC) and are publicly available: http://woudc.org/data/explore.php, ftp://ftp.cpc.ncep.noaa.gov/ndacc/station/lauder/ames/o3sonde/.
Surface-based remote sensing	
Table Mountain lidar	Data used in this publication are archived with NDACC and are publicly available (see http://www.ndacc.org; Leblanc, 2016). For additional data or information please contact the authors. Leblanc, T.: TMO lidar data at NDACC database, available at: ftp://ftp.cpc.ncep.noaa.gov/ndacc/station/tmo/ames/lidar/, last access: 25 July 2016.
OHP ozonesondes and lidar	Data used in this publication are archived with NDACC and are publicly available: http://www.ndacc.org
FTIR	Profiles with 40-50 levels archived at NDACC database: http://www.ndsc.ncep.noaa.gov/data/ , https://www2.acom.ucar.edu/irwg
Umkehr	http://www.woudc.org/
Satellite products	
OMI/MLS	Monthly gridded data at 1°x1.25° resolution available from NASA Goddard Space Flight Center: https://acd-ext.gsfc.nasa.gov/Data_services/cloud_slice/
GOME and OMI from SAO	Monthly GOME gridded data are available at https://www.cfa.harvard.edu/~xliu/res/gmtrop.htm. Monthly gridded data at 1°x1.25° resolution are derived from OMI OMPROFOZ data. OMI OMPROFOZ data are available from Aura Validation Data Center, NASA Goddard Space Flight Center: https://avdc.gsfc.nasa.gov/index.php?site=1389025893&id=74
OMI-RAL	Archive under development
IASI-FORLI	http://cds-espri.ipsl.upmc.fr/etherTypo/index.php?id=1719&L=1
IASI-SOFRID	v1.5 ozone data are available online at http://thredds.sedoo.fr/iasi-sofrid-o3-co/

SCIAMACHY	Data are available from the Institute of Environmental Physics, University of Bremen on request
IASI LWRE	Archive under development
IASI-LISA	Data are available from the Laboratoire Interuniversitaire des Systèmes Atmosphériques (LISA, CNRS-UPEC-UPD) upon request. Contact: cuesta@lisa.u-pec.fr
IASI+GOME2, LISA	These data are now being produced routinely and will soon be available at http://www.aeris-data.fr. Until then, the data will be made available from the Laboratoire Interuniversitaire des Systèmes Atmosphériques (LISA, CNRS-UPEC-UPD) upon request. Contact: cuesta@lisa.u-pec.fr
TES	Ozone vertical profiles, total column, tropospheric column for single observations with 5km x 8km horizontal resolution (L2) and daily/monthly averaged, gridded (L3) products. Global observations for 2004-2009; Megacity and other regions of interest for 2010-present. available at: https://eosweb.larc.nasa.gov/project/tes/tes_table
TOR (Tropopsheric Ozone Residual satellite product)	Monthly gridded data at 1°x1.25° resolution available from NASA Langley Reseach Center: https://science.larc.nasa.gov/TOR/

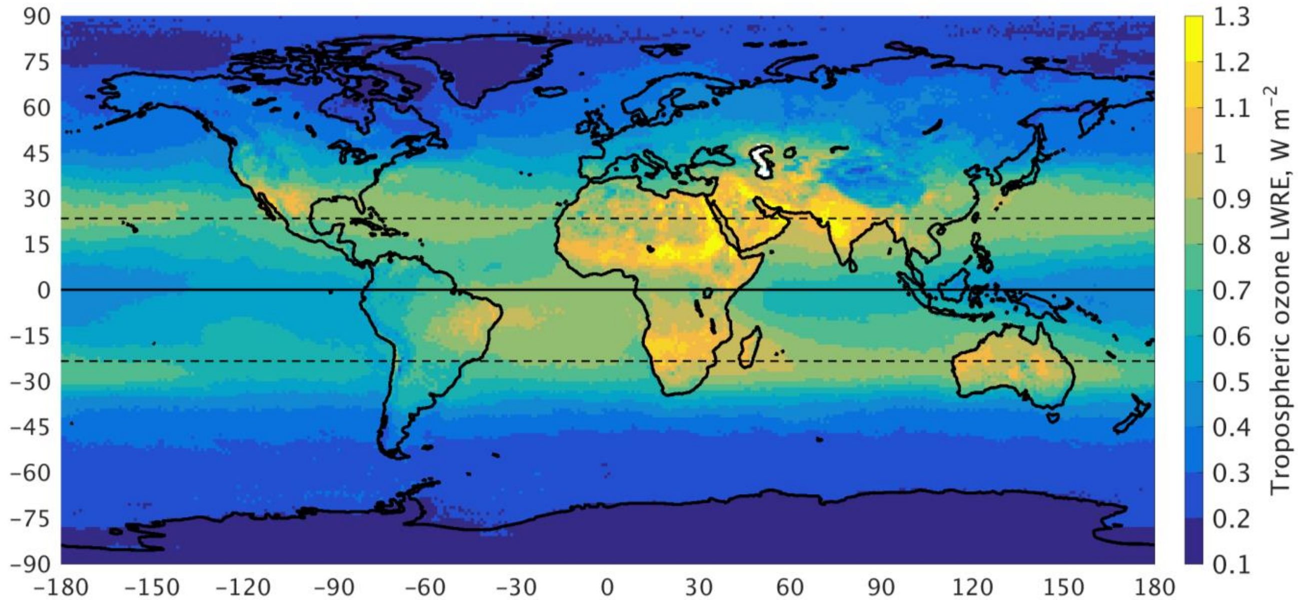


Figure 1.2 Clear-sky (cloud cover < 13%) ozone LWRE (W m^{-2}) as estimated from IASI measurements shows the present day greenhouse effect of tropospheric ozone. The spatial variability of LWRE is due to variations in tropospheric ozone, surface temperature, atmospheric temperature and water vapor. Data are averaged from December 2014 to November 2015 on a 1°x1° grid.

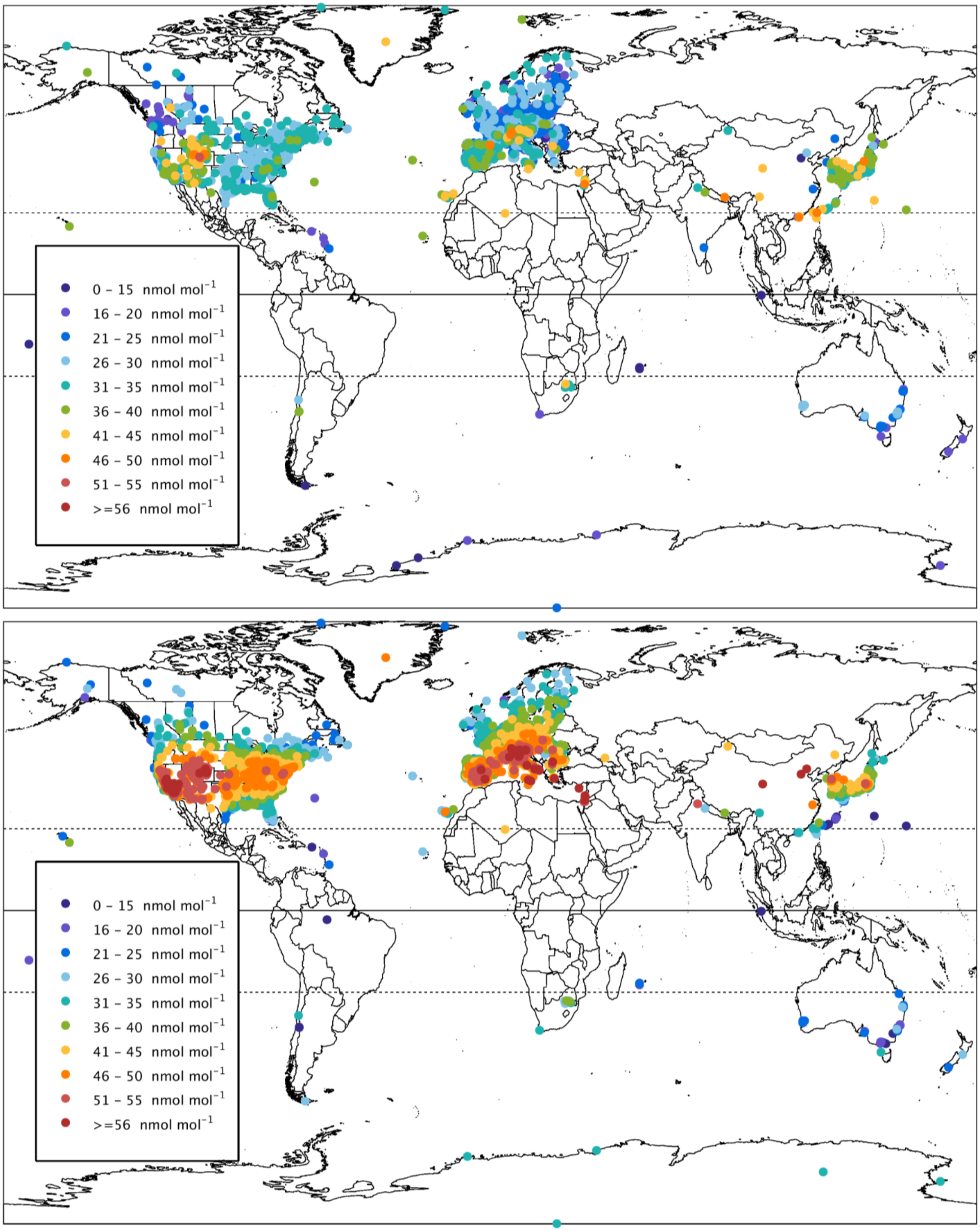
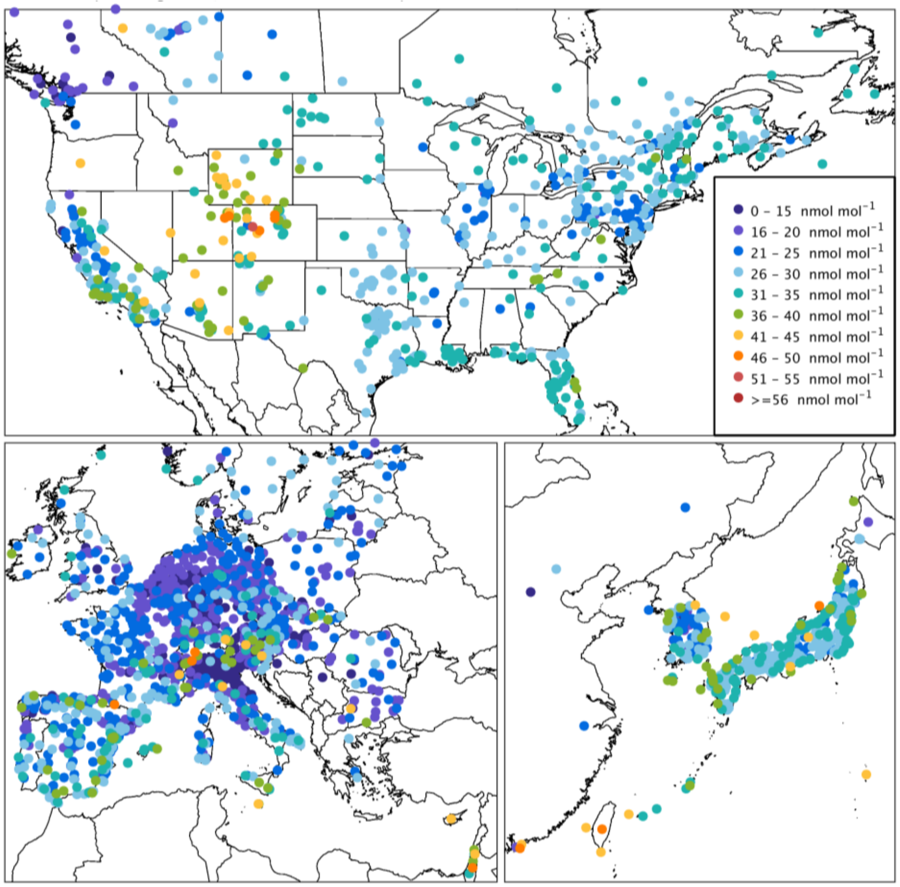
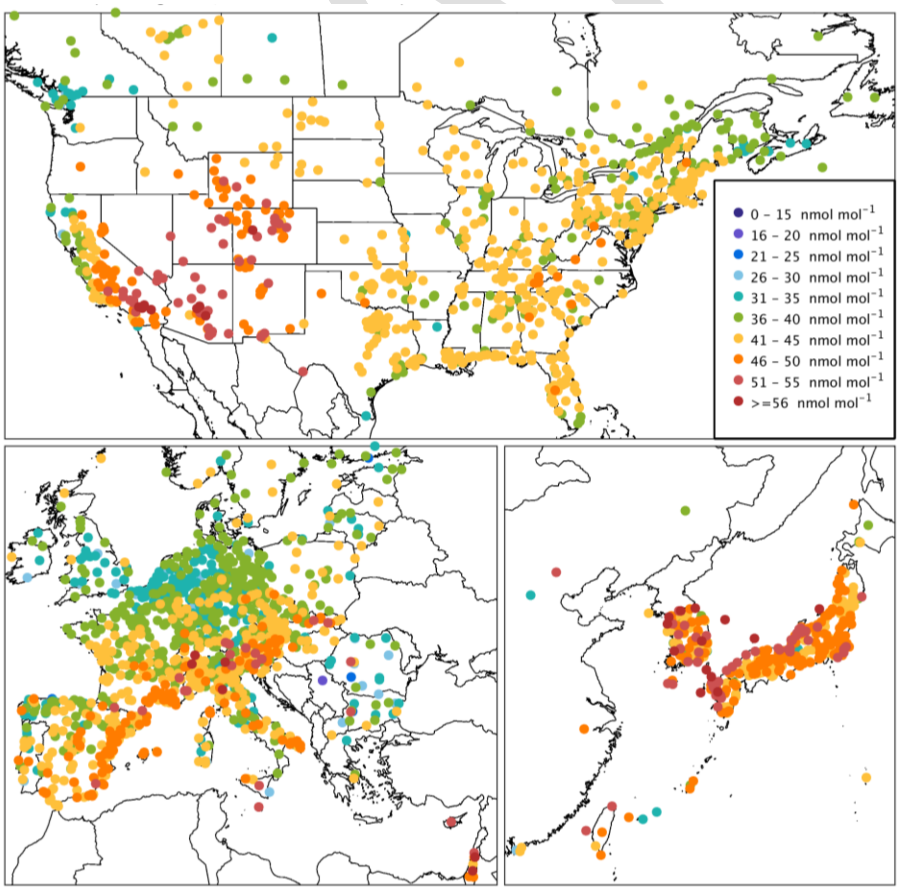


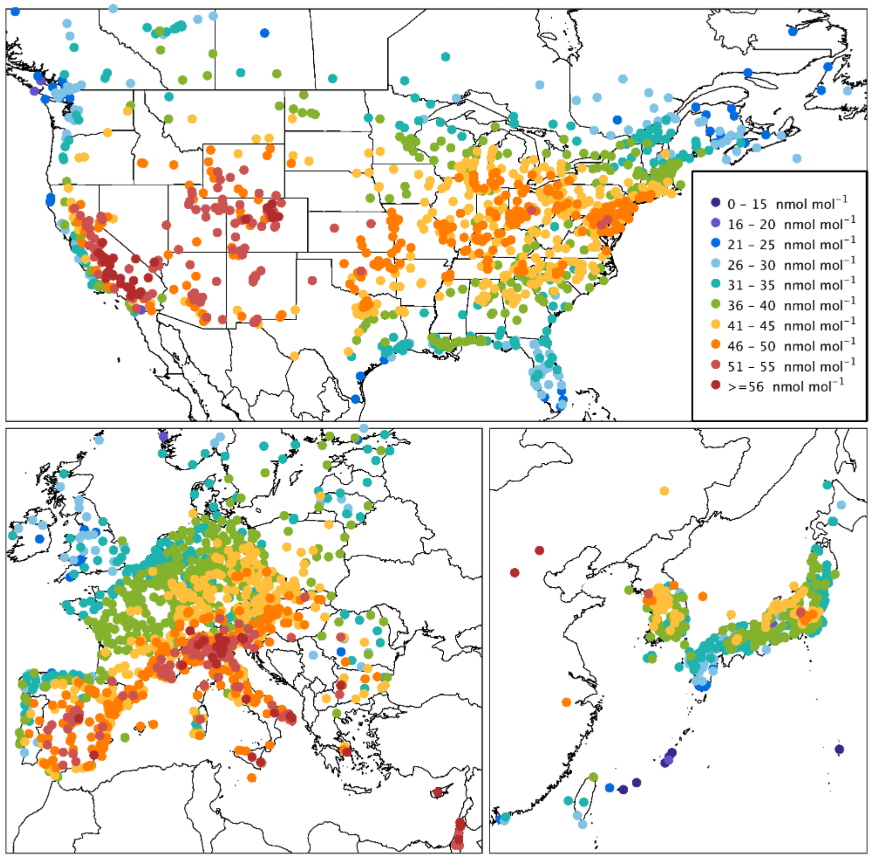
Figure 3.1.1 Daytime average ozone (nmol mol^{-1}) at 2702 non-urban surface sites in December-January-February (top) and 3136 non-urban sites in June-July-August (bottom) for the present-day period, 2010-2014.


0 – 15 nmol mol^{-1}
16 – 20 nmol mol^{-1}
21 – 25 nmol mol^{-1}
26 – 30 nmol mol^{-1}
31 – 35 nmol mol^{-1}
36 – 40 nmol mol^{-1}
41 – 45 nmol mol^{-1}
46 – 50 nmol mol^{-1}
51 – 55 nmol mol^{-1}
>=56 nmol mol^{-1}

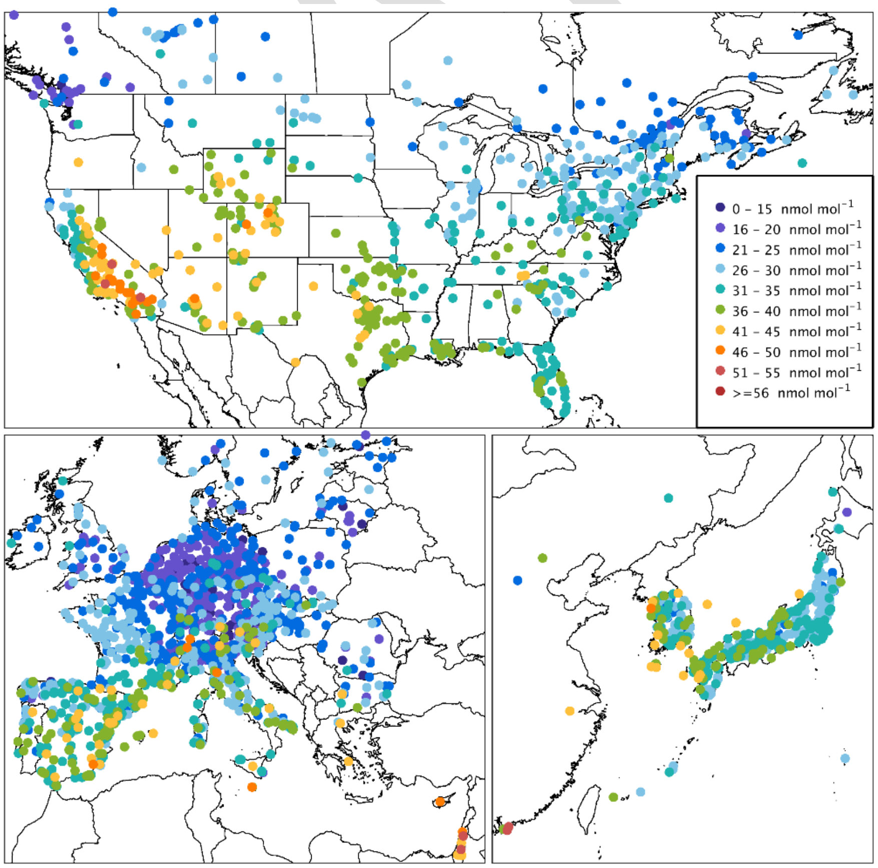
a


0 – 15 nmol mol^{-1}
16 – 20 nmol mol^{-1}
21 – 25 nmol mol^{-1}
26 – 30 nmol mol^{-1}
31 – 35 nmol mol^{-1}
36 – 40 nmol mol^{-1}
41 – 45 nmol mol^{-1}
46 – 50 nmol mol^{-1}
51 – 55 nmol mol^{-1}
>=56 nmol mol^{-1}

b



c



d

Figure 3.1.2 Daytime average ozone (nmol mol^{-1}) at all available non-urban surface sites for DJF (a), MAM (b), JJA (c) and SON (d), for the present-day period, 2010-2014. Panels (a) and (c) show the same data as Figure 3.1.1 (top and bottom, respectively), but focus on the three regions with dense surface networks.

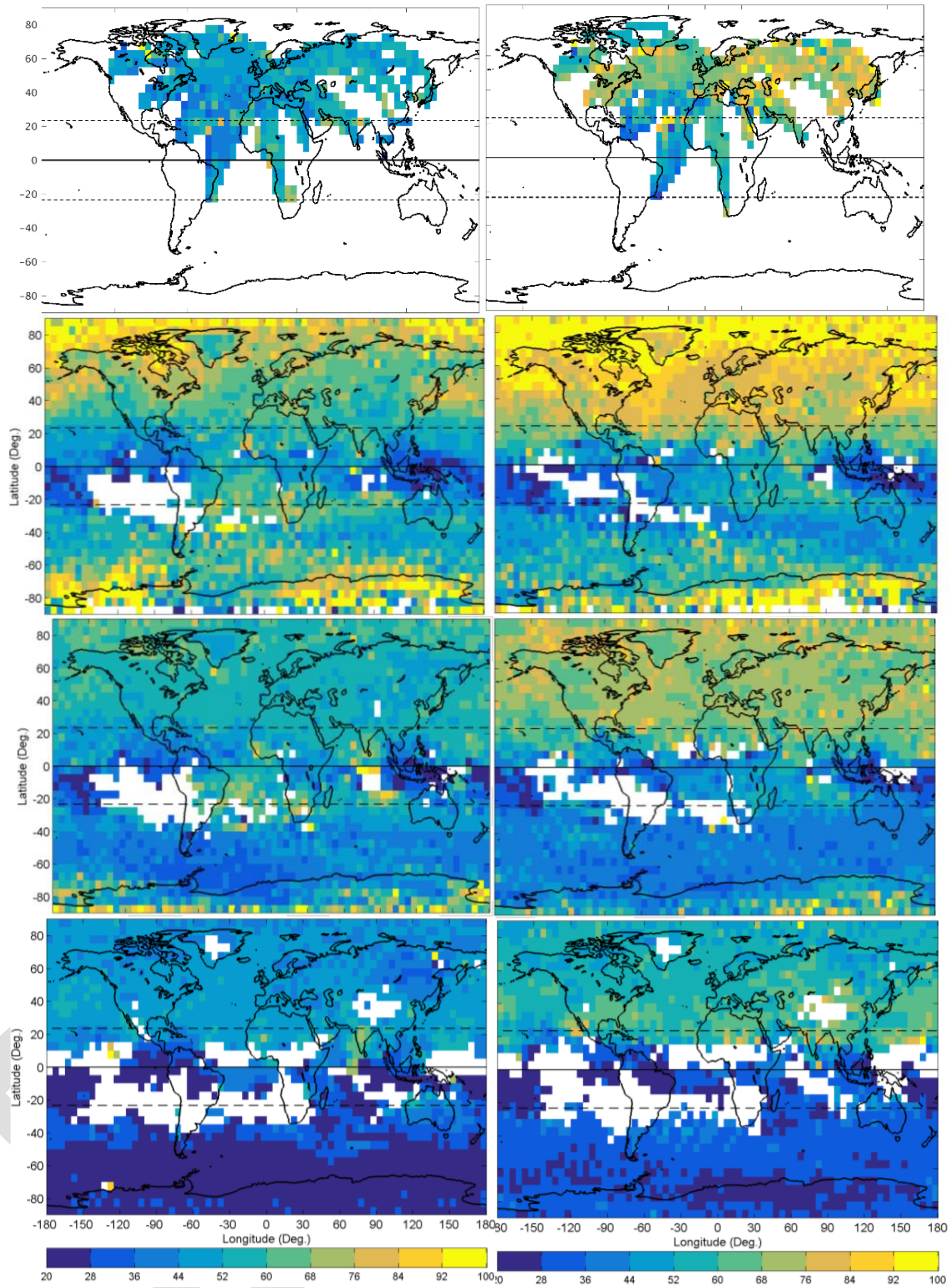


Figure 3.2.1 Mean ozone (nmol mol^{-1}) at four levels in the free troposphere as measured by IAGOS commercial aircraft (2009-2013) at 9-12 km (UT), but below the dynamical tropopause (top row), and as measured by ozonesondes (data from 2008-2012 spatially distributed using the TOST method) at 7-9 km (2nd row), 5-7 km (3rd row) and 2-3 km (bottom row). White areas indicate no data. Data are displayed seasonally for DJF (left) and MAM (right)…*figure continued on next page*.

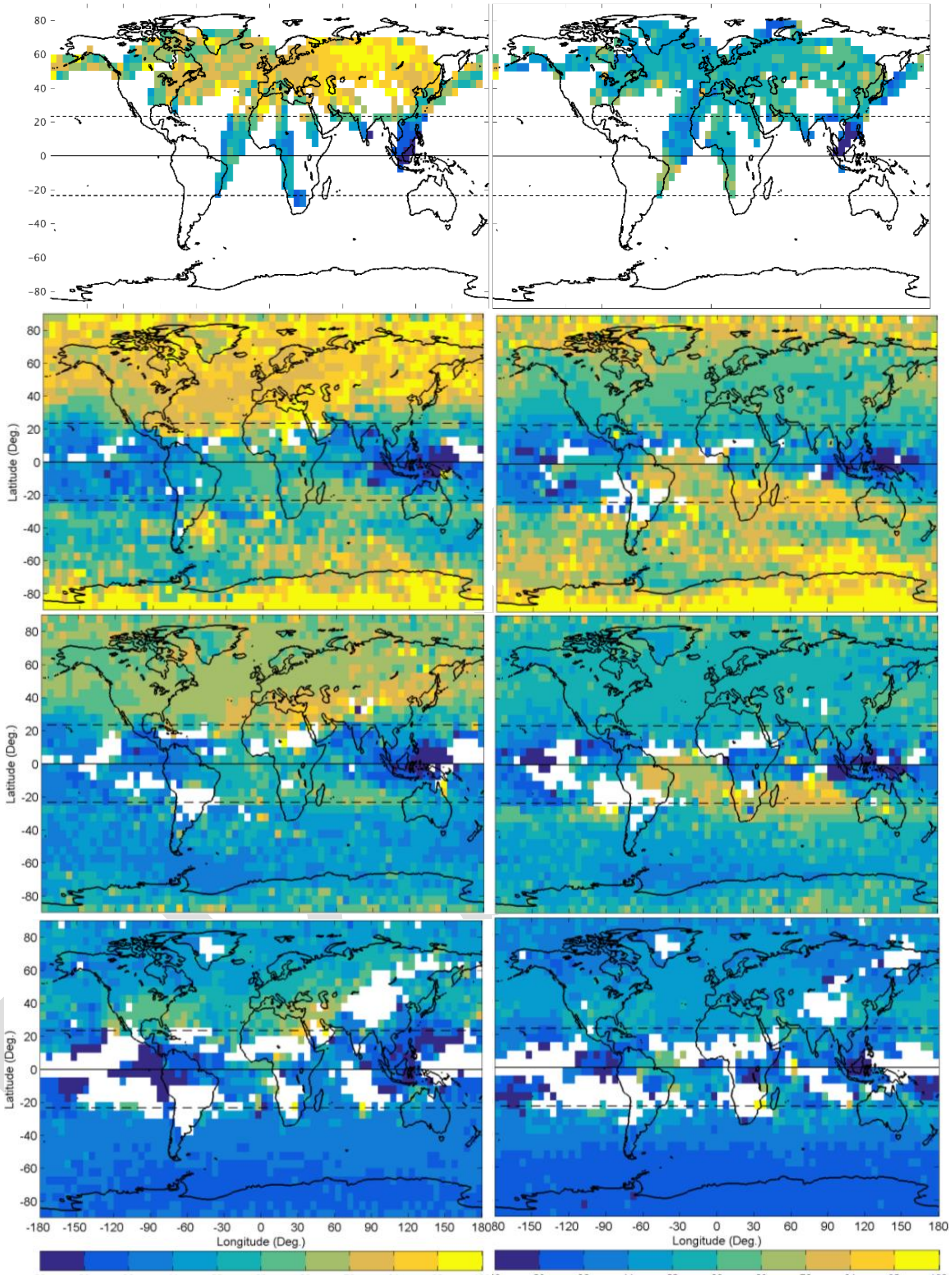


Figure 3.2.1 … continued: JJA (left) and SON (right).

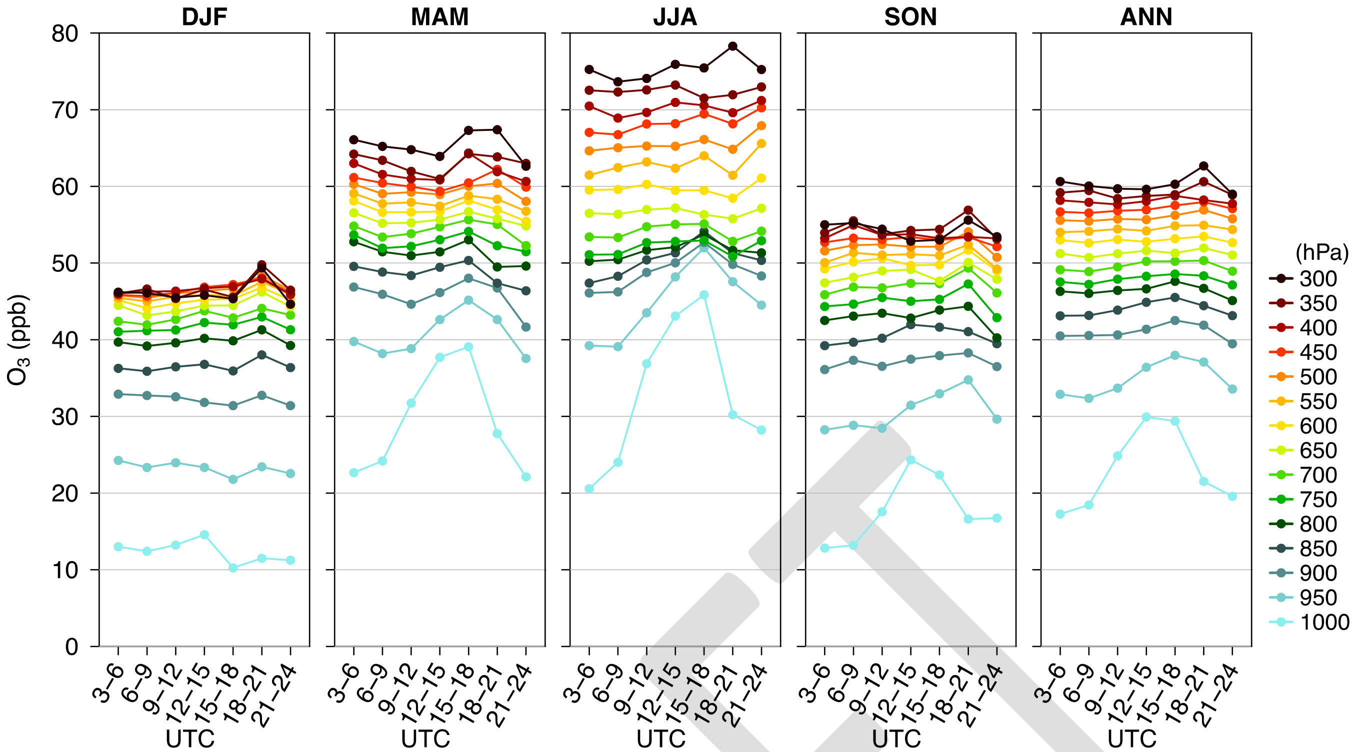


Figure 3.2.2 Diurnal variability of mean tropospheric ozone from the surface to the tropopause above Frankfurt between August 1994 and December 2012, by season and annually (ANN: annual). Reproduced with authorization from the authors of *Petetin et al.* (2016).

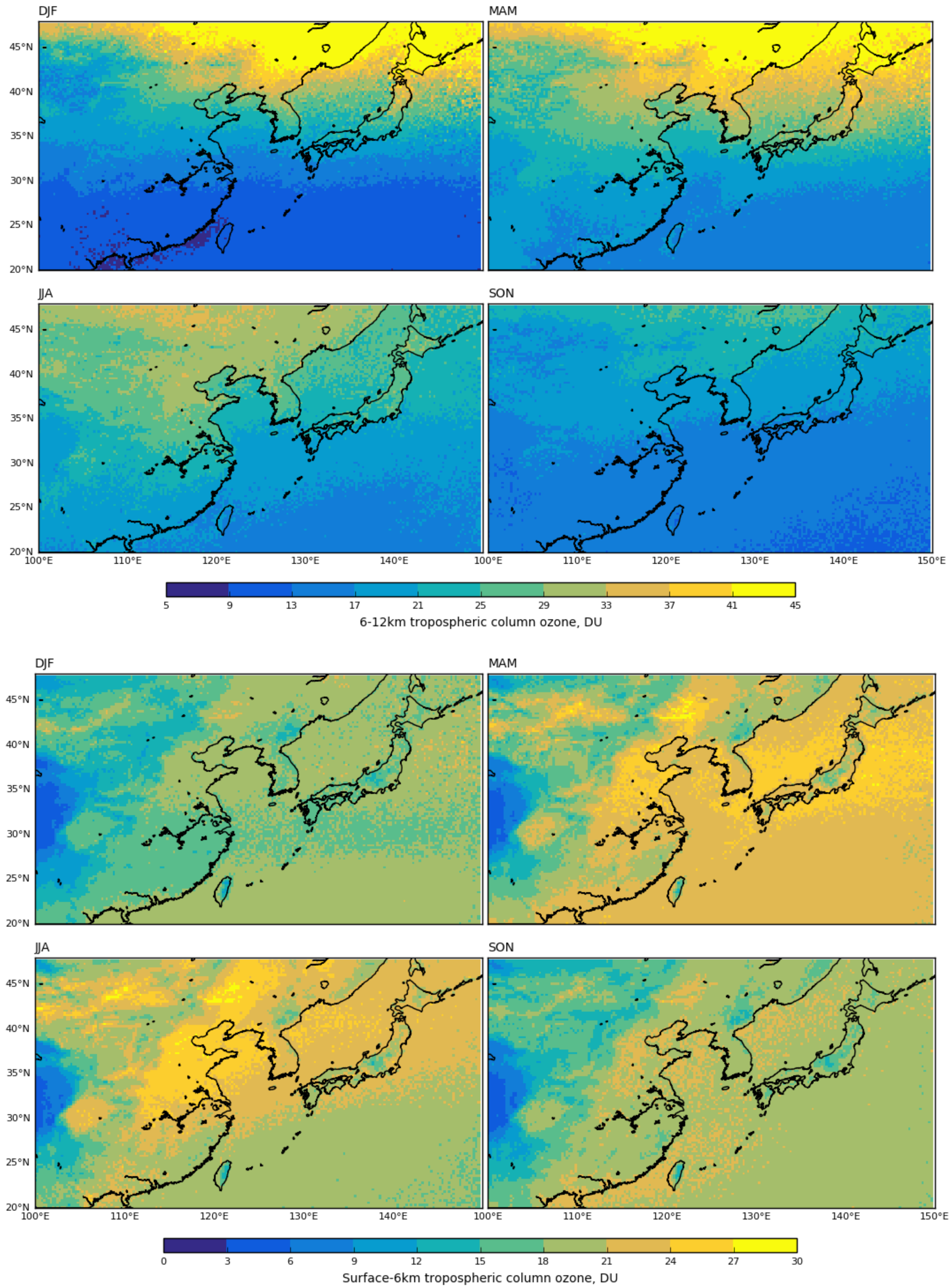


Figure 3.3.1 Seasonal 6-12 km (top) and surface-6 km (bottom) partial ozone columns (DU) over East Asia, according to the IASI-LISA (TP) product for 2010-2014.

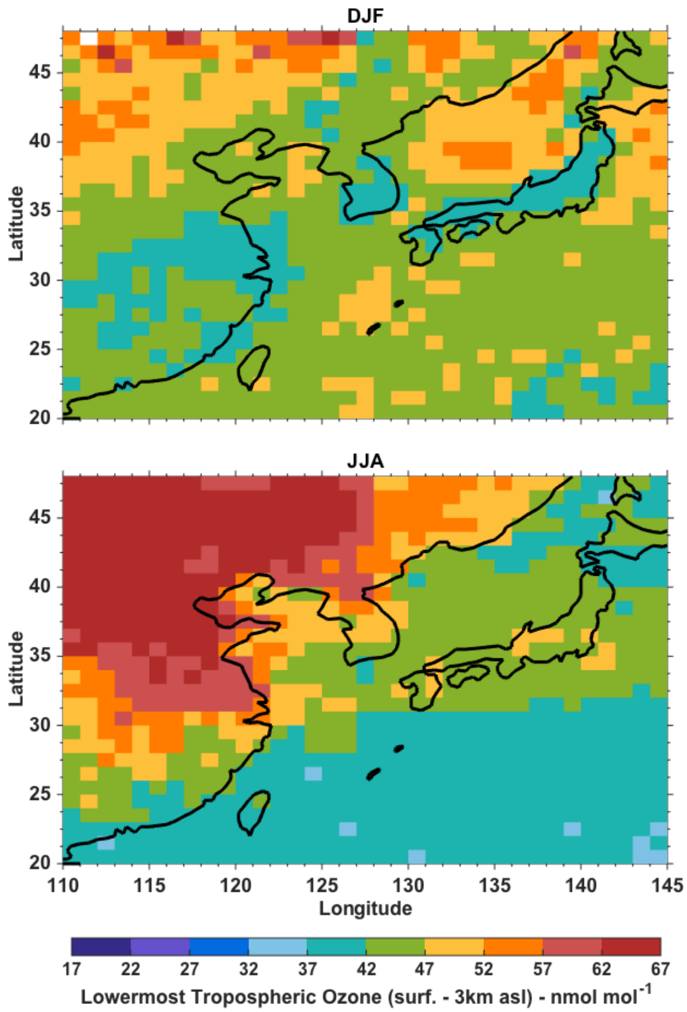


Figure 3.3.2 IASI+GOME2 (LISA) seasonal (2010) average ozone mole fraction (nmol mol^{-1}) over East Asia from the surface to 3 km. Horizontal resolution is 1° x 1°.

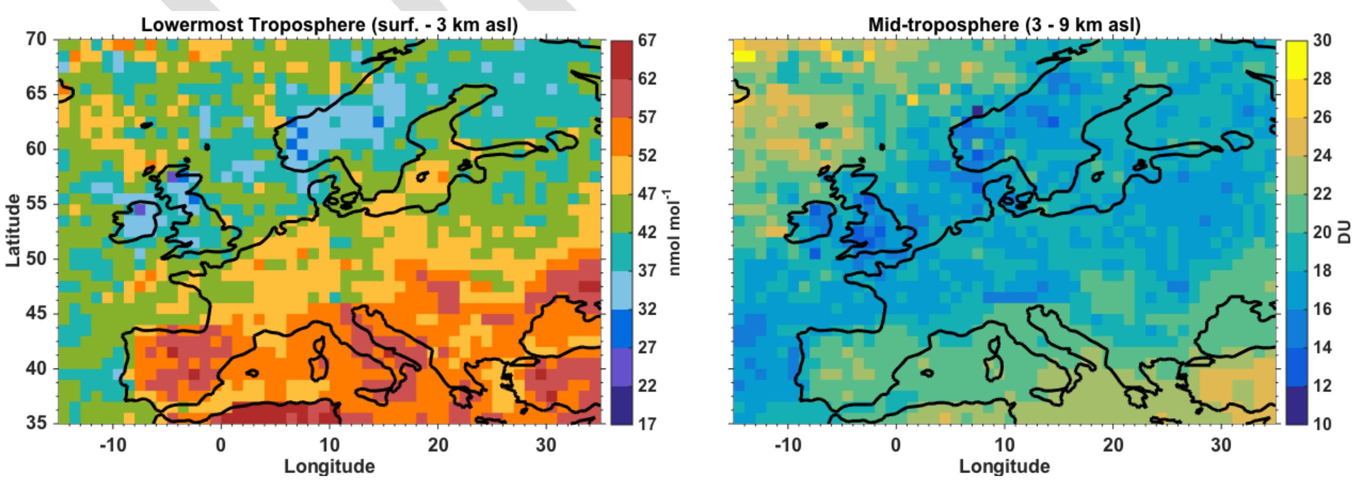


Figure 3.3.3 IASI+GOME2 (LISA) monthly average (August, 2009) mixing ratio (nmol mol^{-1}) from the surface to 3 km (left) and partial column ozone (DU) from 3 to 9 km (right) over Europe. Horizontal resolution is 0.5° x 0.5° and the data are smoothed using a horizontal moving average of 1.5°.

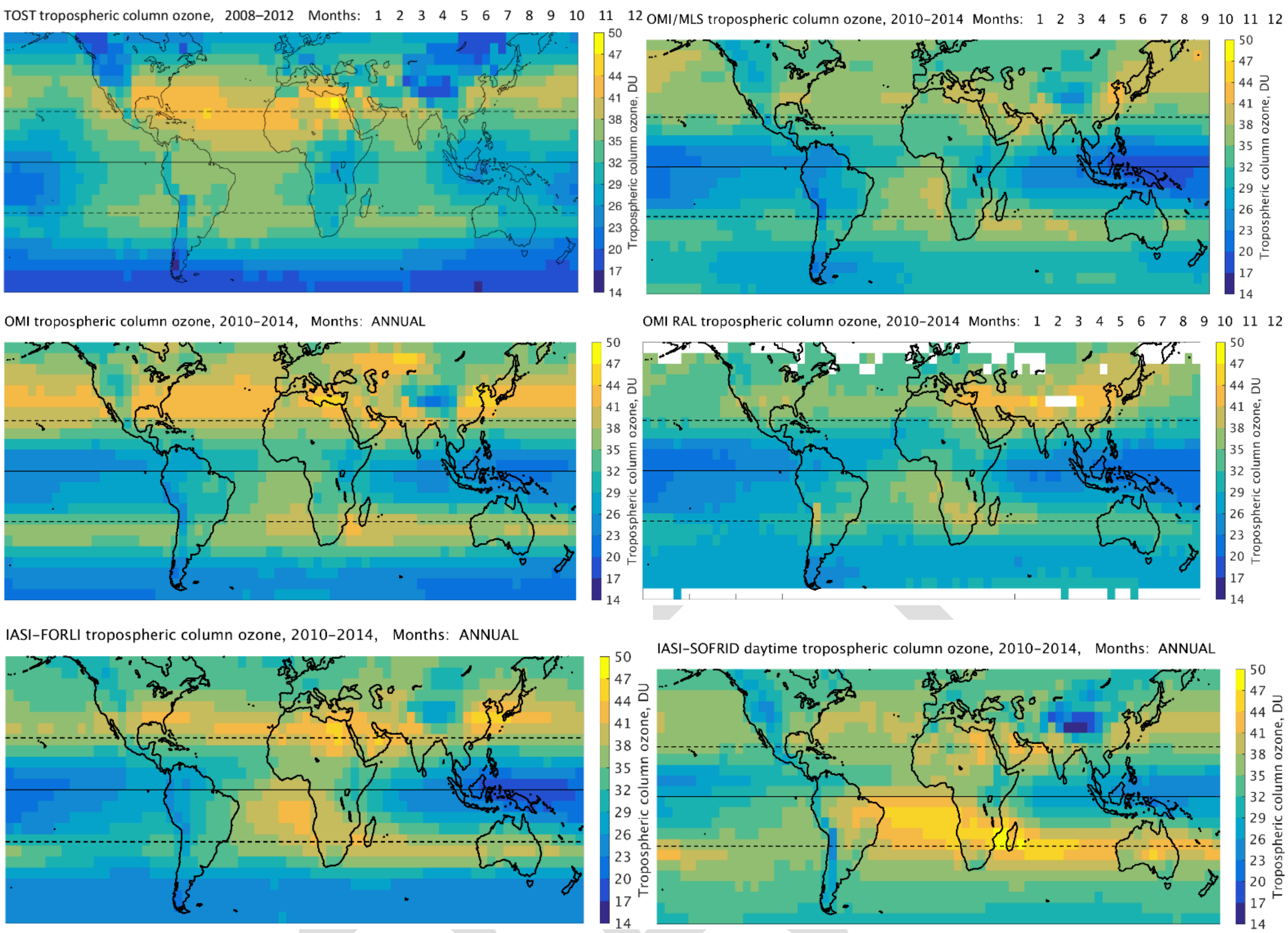


Figure 3.4.1 Annual mean tropospheric column ozone (DU) as measured by TOST (top left), OMI/MLS (top right, with + 2 DU offset to account for bias), OMI-SAO (middle left), OMI-RAL (middle right), IASI-FORLI (bottom left) and IASI-SOFRID (bottom right). The data are averaged over the period January 2010 through December 2014 and reported at 5°×5° horizontal resolution, except for TOST, which covers the period 2008-2012.

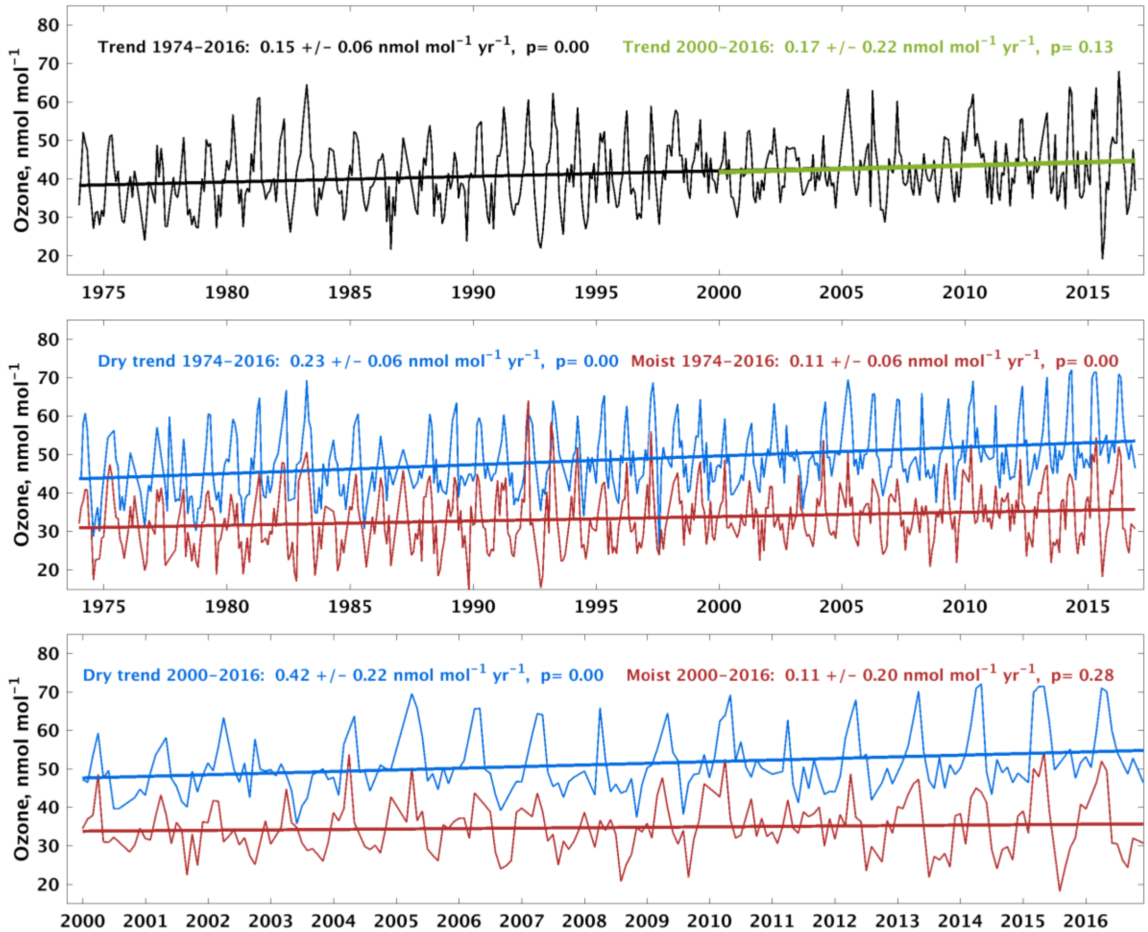


Figure 4.1.1 a) Nighttime monthly median ozone values at Mauna Loa Observatory calculated with all available data for months with at least 50% data availability, January 1974 – December 2016. b) Same as in a) but for data split into dry (dewpoint less than the climatological monthly 40th percentile) and moist (dewpoint greater than the climatological monthly 60th percentile) categories. A dry or moist category in any given month must have a sample size of at least 24 individual hourly nighttime observations. c) As in b) but for 2000-2016. Trends in this figure are based on least-squares linear regression fit through the monthly median values, and reported with 95% confidence intervals and p-values.

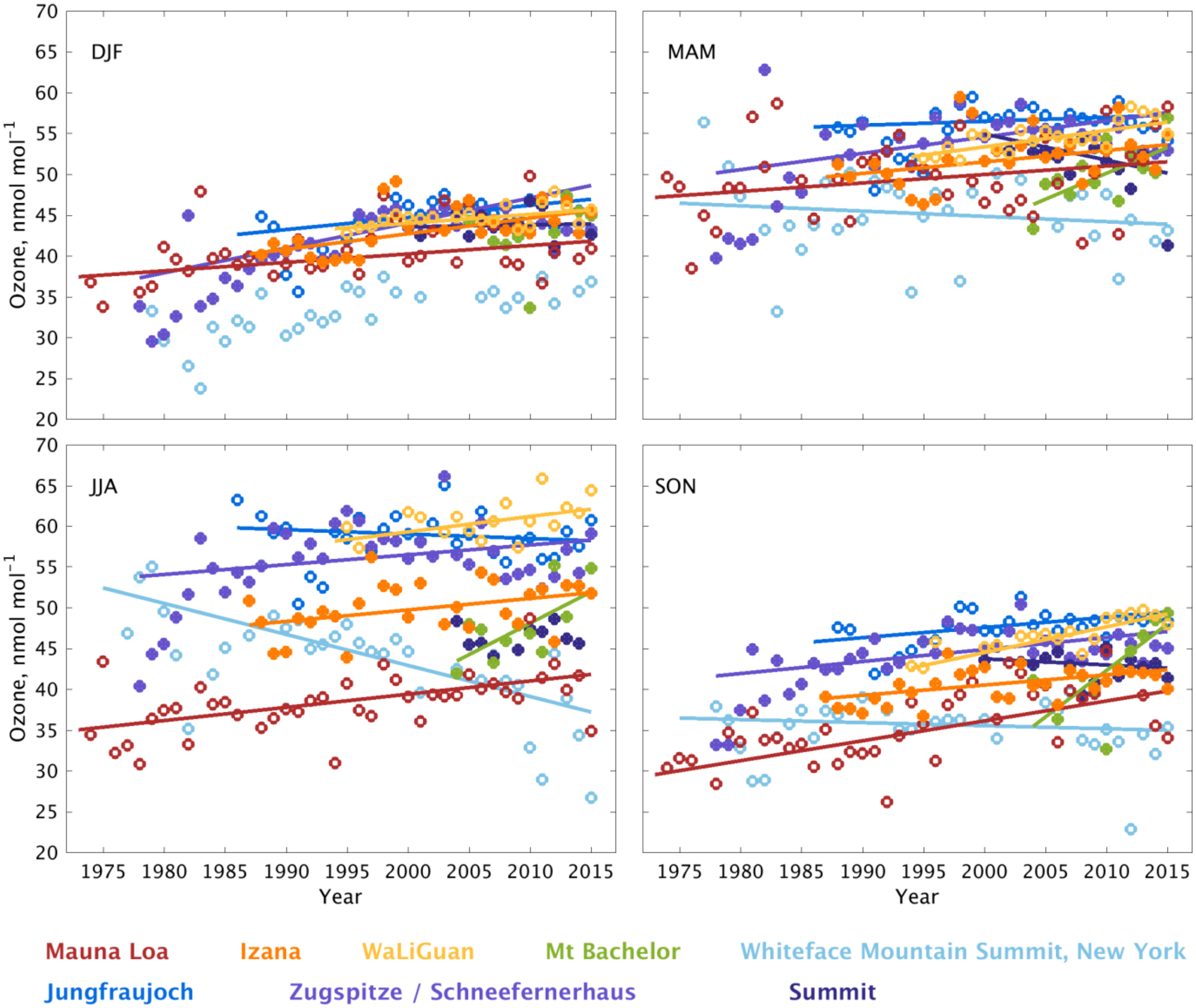


Figure 4.1.2 Nighttime ozone trends at eight Northern Hemisphere mountaintop sites by season. Trend values are given in Table 4.1.

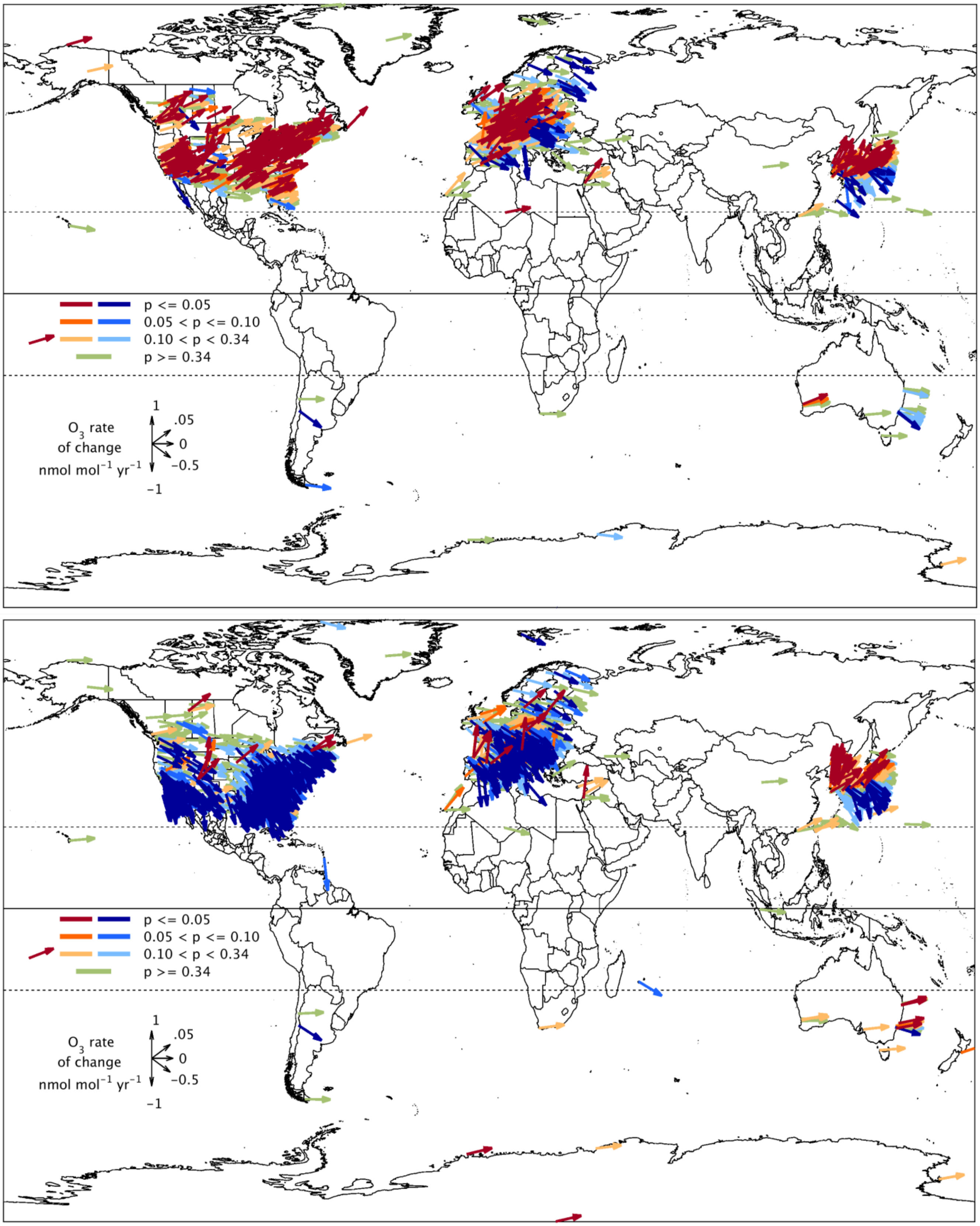
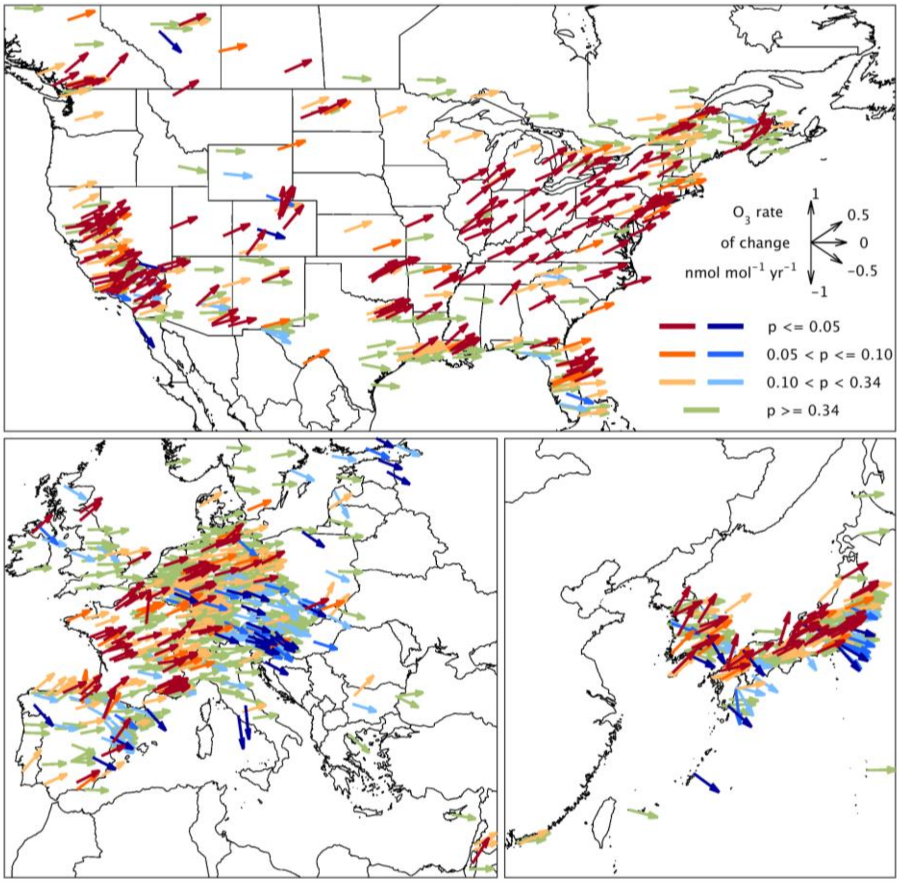
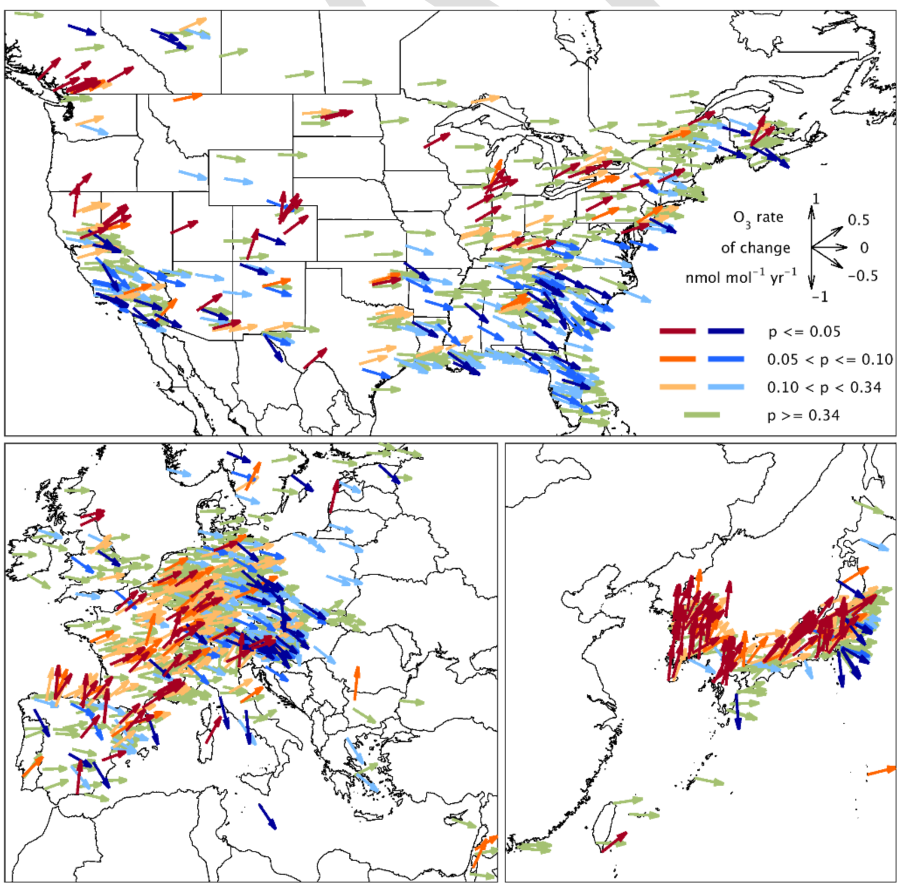


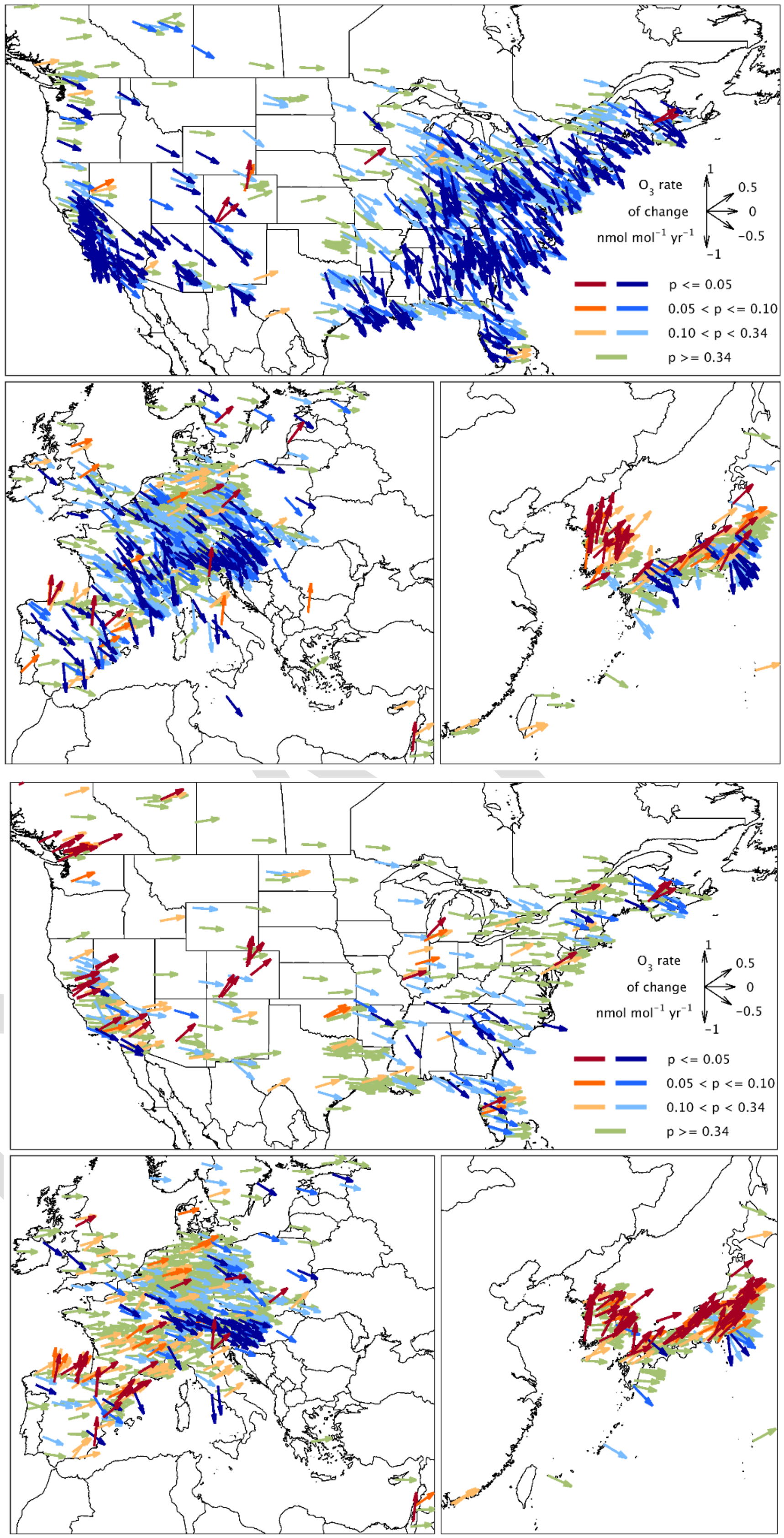
Figure 4.1.3 2000-2014 trends of daytime average ozone (nmol mol^{-1}) at 1375 non-urban sites in December-January-February (top) and 1784 non-urban sites in June-July-August (bottom). The number of available sites is greater in June-July-August because many US sites only operate in the warm season. Vector colors indicate the p-values on the linear trend for each site: blues indicate negative trends, oranges indicate positive trends and green indicates weak or no trend; lower p-values have greater color saturation.


O3 rate
of change
nmol mol−1 yr−1
1
0.5
0
−0.5
−1
p <= 0.05
0.05 < p <= 0.10
0.10 < p < 0.34
p >= 0.34

a.


O3 rate
of change
nmol mol−1 yr−1
1
0.5
0
−0.5
−1
p <= 0.05
0.05 < p <= 0.10
0.10 < p < 0.34
p >= 0.34

b.



c.

d.

Figure 4.1.4 Regional trends (2000-2014) of daytime average ozone (nmol mol^{-1} yr^{-1}) at all non-urban sites for Dec-Jan-Feb (a), Mar-Apr-May (b), Jun-Jul-Aug (c) and September-October-November (d). Vector colors indicate the p-Values on the linear trend for each site: blues indicate negative trends, oranges indicate positive trends and green indicates weak or no trend.

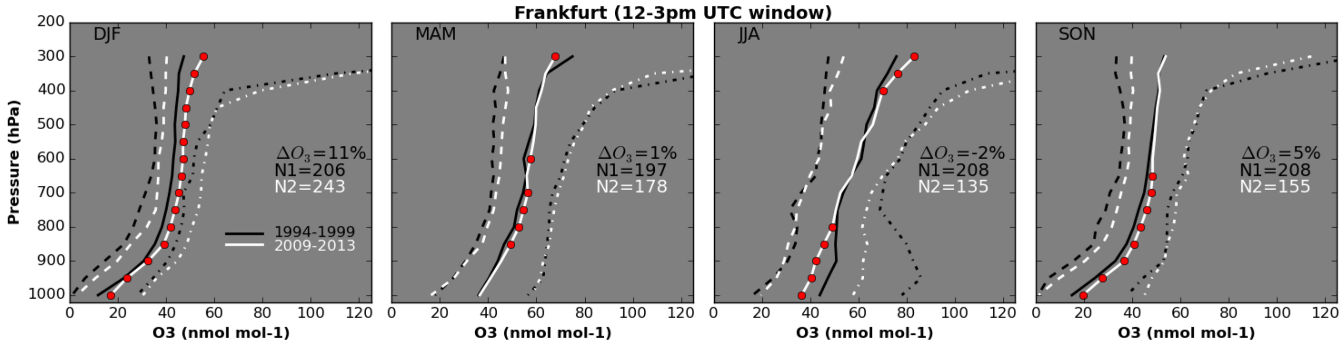


Figure 4.2.1 Seasonal changes of ozone above Frankfurt, Germany, based on MOZAIC/IAGOS aircraft profiles over the periods 1994-1999 (black lines) and 2009-2013 (white lines) for the 5th, 50th and 95th percentiles. Red dots indicate a statistically significant difference at that level between the two periods, based on a t-test and a 95% confidence interval. Percent changes of ozone are reported for the mass of ozone from the surface to 300 hPa.

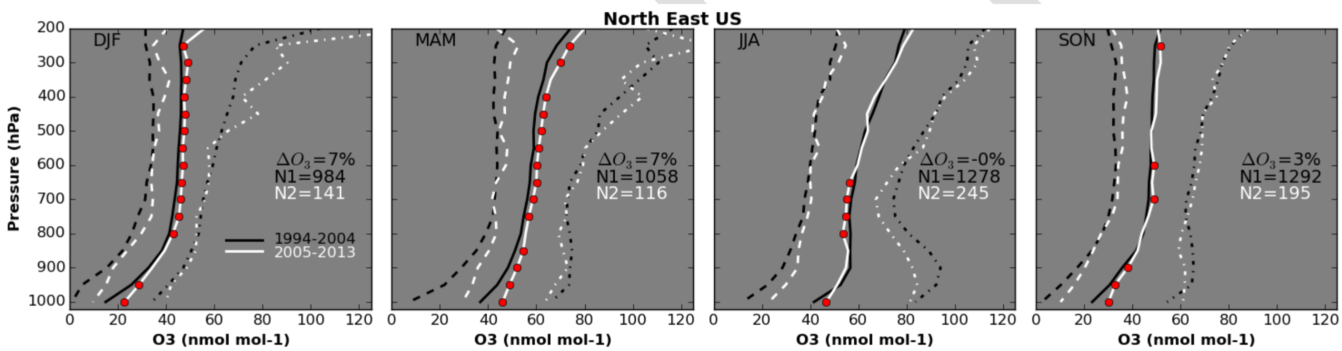


Figure 4.2.2 Seasonal change in the 5th, 50th and 95th ozone percentiles above the northeastern USA, based on MOZAIC/IAGOS aircraft profiles from 1994-2004 (black lines) to 2005-2013 (white lines) as measured by lidar. Red dots indicate a statistically significant difference at that level between the two periods, based on a t-test and a 95% confidence interval. ΔO_3 values refer to the change in tropospheric ozone mass between the two periods.

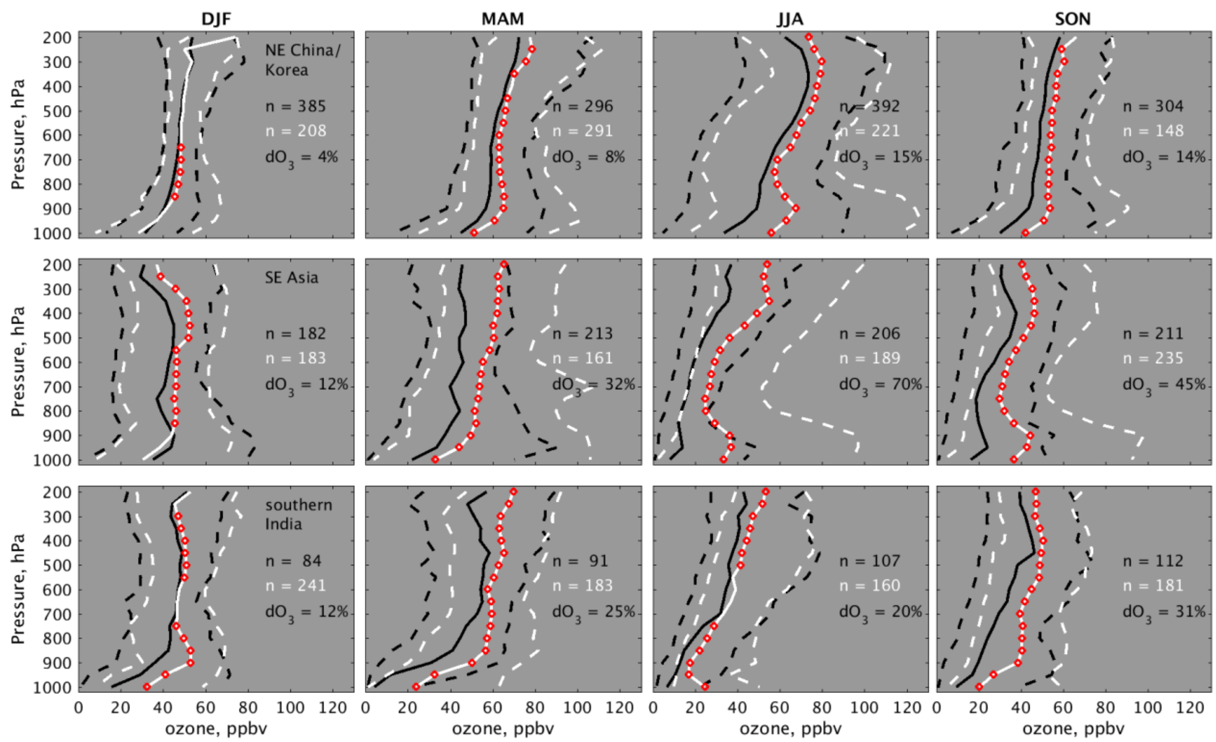


Figure 4.2.3 Ozone profiles above northeastern China (30°-43°N, 110°-129°E), Southeast Asia (10°-24°N, 93°-115°E), and south/central India (6°-24°N, 70°-89°E) based on observations from IAGOS commercial aircraft to and from several airports in each region. In addition, SE Asia includes ozonesonde profiles from the SHADOZ station in Hanoi, Vietnam. Shown are the 50th (solid lines) and 5th and 95th percentiles (dashed lines) for the periods 1994-2004 (black) and 2005-2014 (white). Layers in which there is a statistically significant ozone difference between the two time periods are indicated by red circles, based on a t-test and a 95% confidence interval. Each panel indicates the percent increase in the tropospheric ozone mass (1000-200 hPa) from the earlier to the later period, as well as the number (n) of vertical profiles associated with each region and time period. These results were first reported by *Zhang et al.* (2016).

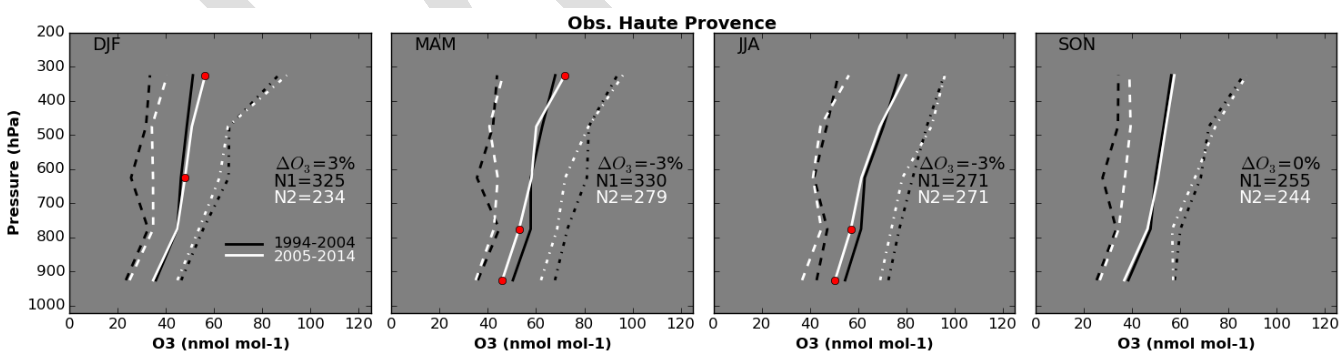


Figure 4.2.4 Seasonal change in the 5th, 50th and 95th ozone percentiles above Observatoire de Haute Provence, France, from 1994-2004 (black lines) to 2005-2014 (white lines) as measured by a combination of lidar and ozonesonde profiles. Red dots indicate a statistically significant difference at that level between the two periods, based on a t-test and a 95% confidence interval. ΔO_3 values refer to the change in tropospheric ozone mass between the two periods. An update to *Gaudel et al.* (2015).

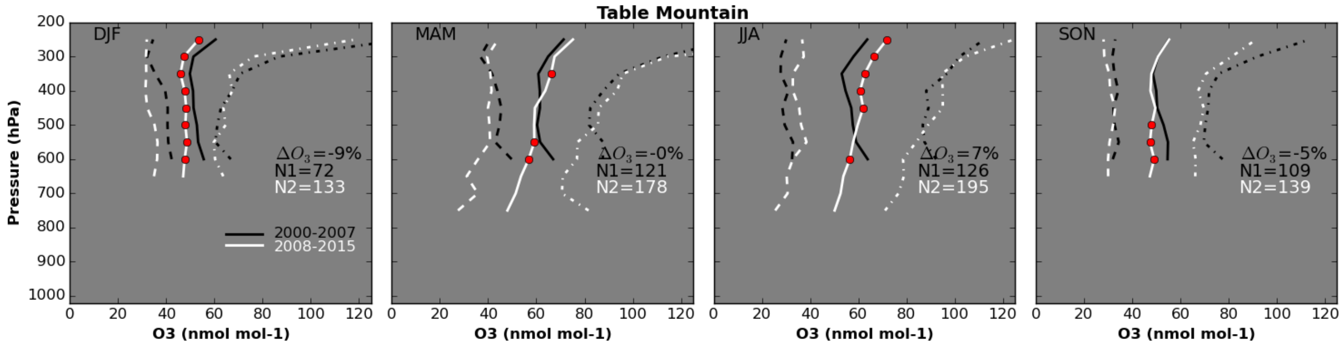


Figure 4.2.5 Seasonal change in the 5th, 50th and 95th ozone percentiles above Table Mountain, southern California, from 2000-2007 (black lines) to 2008-2015 (white lines) as measured by lidar. Red dots indicate a statistically significant difference at that level between the two periods, based on a t-test and a 95% confidence interval. ΔO_3 values refer to the change in tropospheric ozone mass between the two periods. An update to *Granados-Muñoz et al.* (2016).

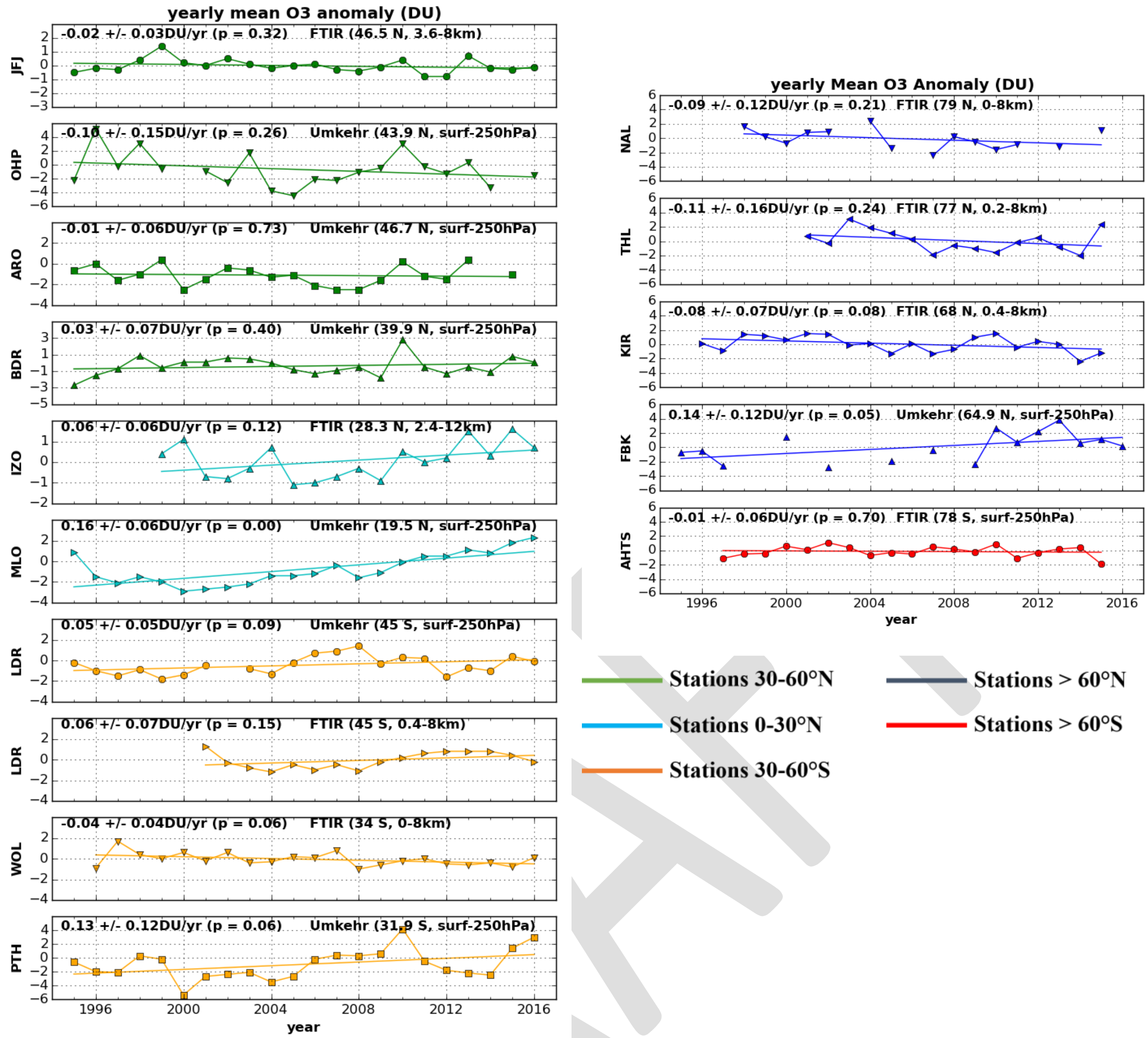


Figure 4.2.6 Trends of TCO anomalies (DU) measured by FTIR and Umkehr above thirteen stations: Jungfraujoch (JFJ), Observatoire de Haute Provence (OHP), Boulder (BDR), Izaña (IZO), Mauna Loa (MLO), Lauder (LDR), Wollongong (WOL), Perth (PTH), Ny-Ålesund (NAL), Thule (THL), Kiruna (KIR), Fairbanks (FBK) and Arrival Heights (AHTS). Colors indicate the latitude bands in which stations are located. Time series of TCO for latitude bands above 60°N or 60°S are shown in the right panel.