Polar Ozone Loss and the Tropical Tropopause Layer

Research based on meteorological fields from data assimilation systems

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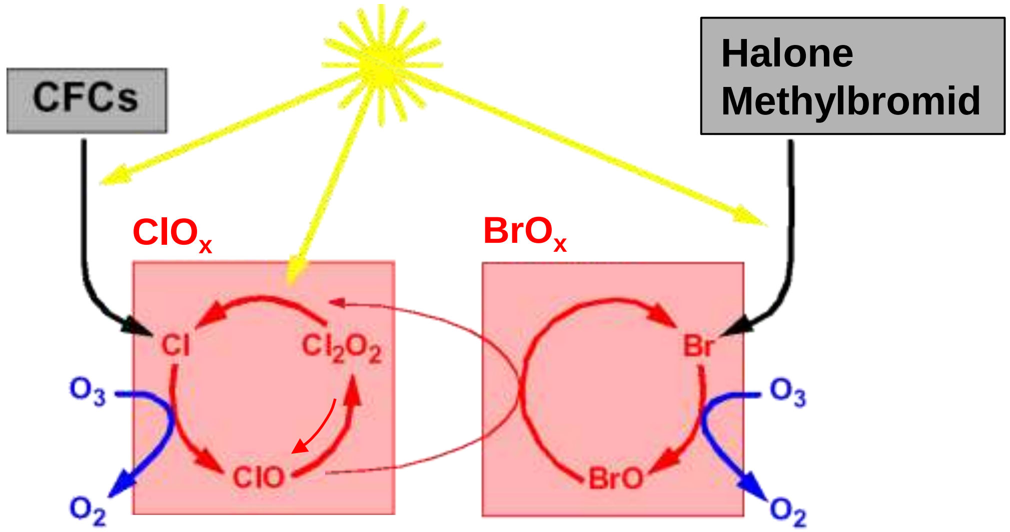
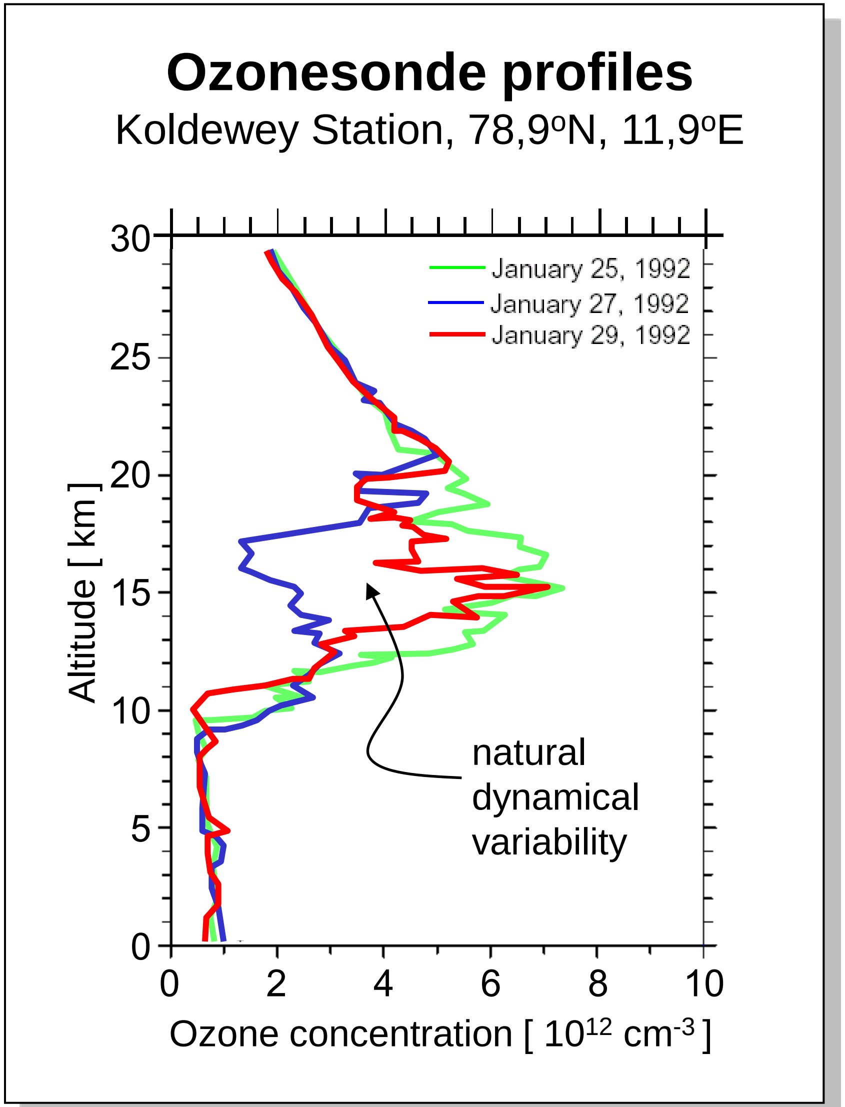
Polar ozone loss process



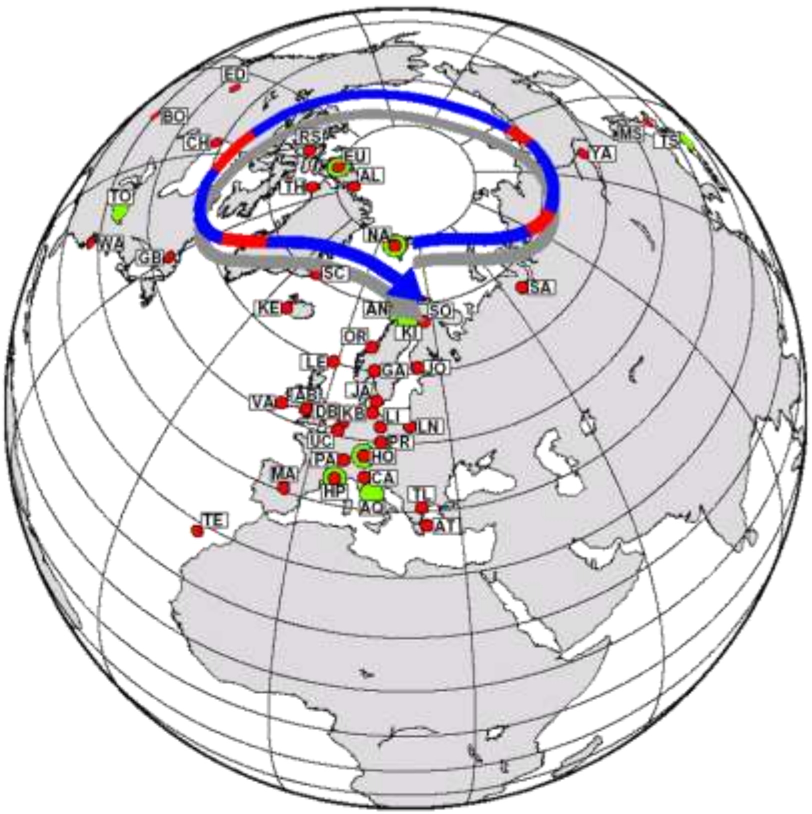
Ozonesondes

Ozonesonde launch in the Arctic

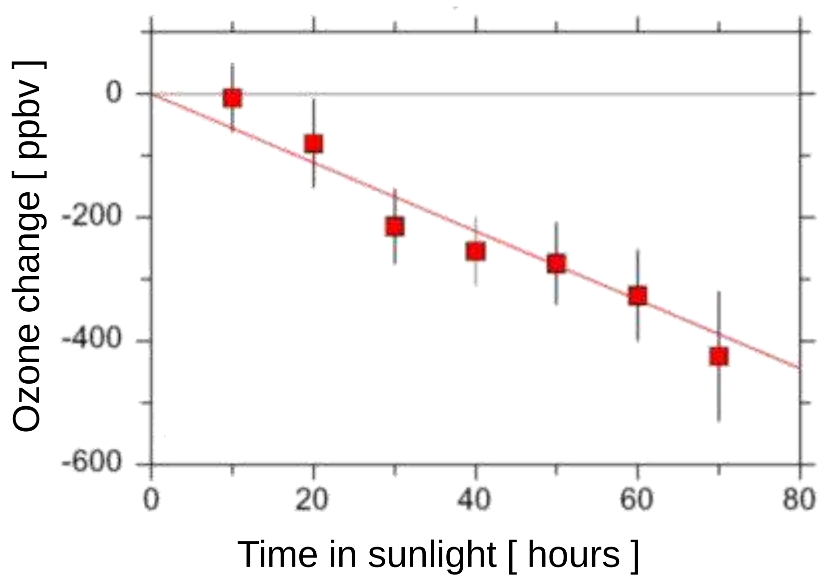


Rex et al., JGR, 1998

The Match project:
Lagrangian measurements of chemical ozone loss rates



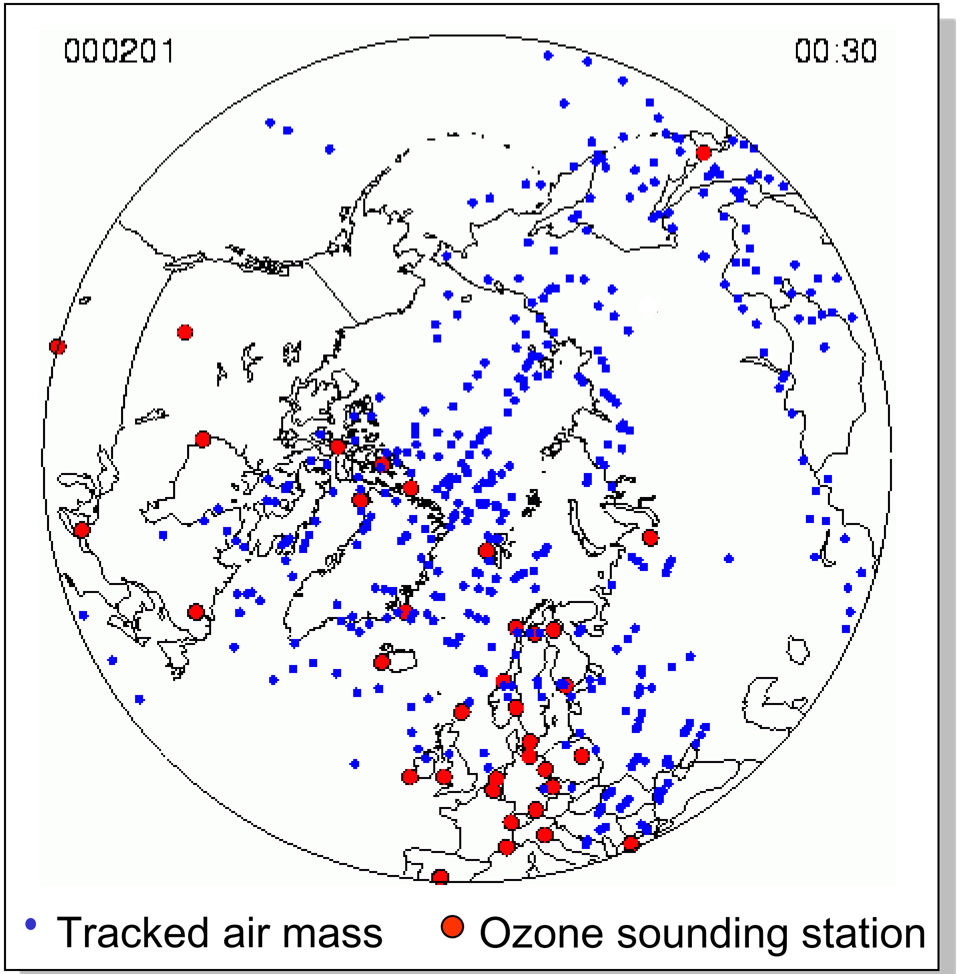
=> Chemical ozone loss rate



● Ozone sounding station ● Lidar station

Air mass trajectory (day/night)

The Match project



- International network of ~30 Stations operated by 17 nations.
- ~500-1200 ozonesonde launches per winter.
- 15 Arctic and 2 Antarctic campaigns since the early 1990s.

e.g.:
Von der Gathen, Rex et al., *Nature*, 1995
Rex, von der Gathen et al, *Nature*, 1997
Manney, Santee, Rex et al., *Nature*, 2011

Multiple Sensor approach for a System of three sensors (e.g. (A) ILAS II, (B) POAM III, and (C) sondes)

Standard Matches:

i Matches of Type A-A:

$\Delta O_3^{1} = -\, Lt_s^{1} + e^{1}$

⋮

$\Delta O_3^{i} = -\, Lt_s^{i} + e^{i}$

j Matches of Type B-B:

$\Delta O_3^{i+1} = -\, Lt_s^{i+1} + e^{i+1}$

⋮

$\Delta O_3^{i+j} = -\, Lt_s^{i+j} + e^{i+j}$

k Matches of Type C-C:

$\Delta O_3^{i+j+1} = -\, Lt_s^{i+j+1} + e^{i+j+1}$

⋮

$\Delta O_3^{i+j+k} = -\, Lt_s^{i+j+k} + e^{i+j+k}$

Mixed Matches:

l of Matches Type A

$\Delta O_3^{i+j+k+1} = Bias_B$ … $^{+k+l+1} + e^{i+j+k+l+1}$

⋮

$\Delta O_3^{i+j+k+l} = Bias_B$ … $^{j+k+l+m} + e^{i+j+k+l+m}$

n Matches of Type A

$\Delta O_3^{i+j+k+l+m+1} = Bi$ … $Lt_s^{i+j+k+l+m+n+1} + e^{i+j+k+l+m+n+1}$

⋮

$\Delta O_3^{i+j+k+l+m+n} = Bi$ … $Lt_s^{i+j+k+l+m+n+o} + e^{i+j+k+l+m+n+o}$

p Matches of Type B

$\Delta O_3^{i+\ldots+o+1} = Bias$ … $-\, Lt_s^{i+\ldots+p+1} + e^{i+\ldots+p+1}$

⋮

$\Delta O_3^{i+\ldots+p} = Bias_B - Bias_C -\, Lt_s^{i+\ldots+o+p} + e^{i+\ldots+p}$

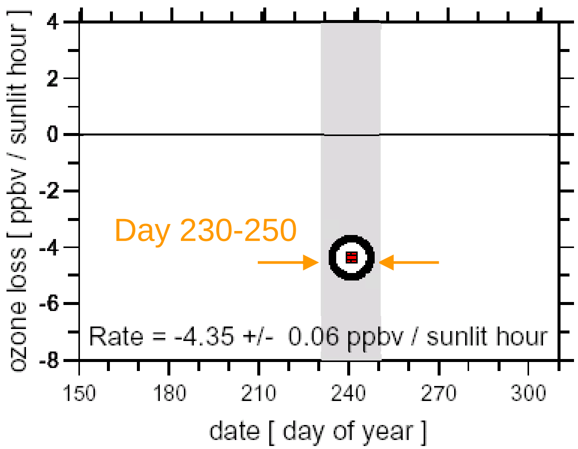
⋮

$\Delta O_3^{i+\ldots+p+q} = Bias_C - Bias_B -\, Lt_s^{i+\ldots+p+q} + e^{i+\ldots+p+q}$

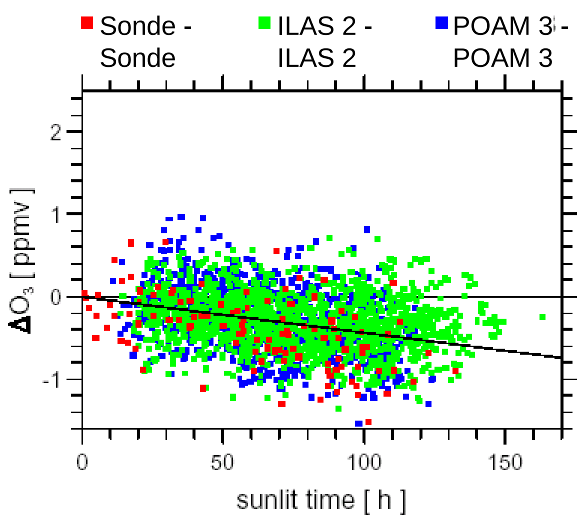
Caution: The errors in these ensembles of Matches are correlated. Covariance matrix is important for uncertainty estimates.
c.f. Lehman et al., 2005

- **i+j+k+l+m+n+o+p+q equations for the parameters L, $Bias_B$, and $Bias_C$, which can be determined simultaneously by a multivariate regression analysis**
- **Compared to standard Match: Ninefold increase in the number of equations for a threefold increase in the number of parameters**

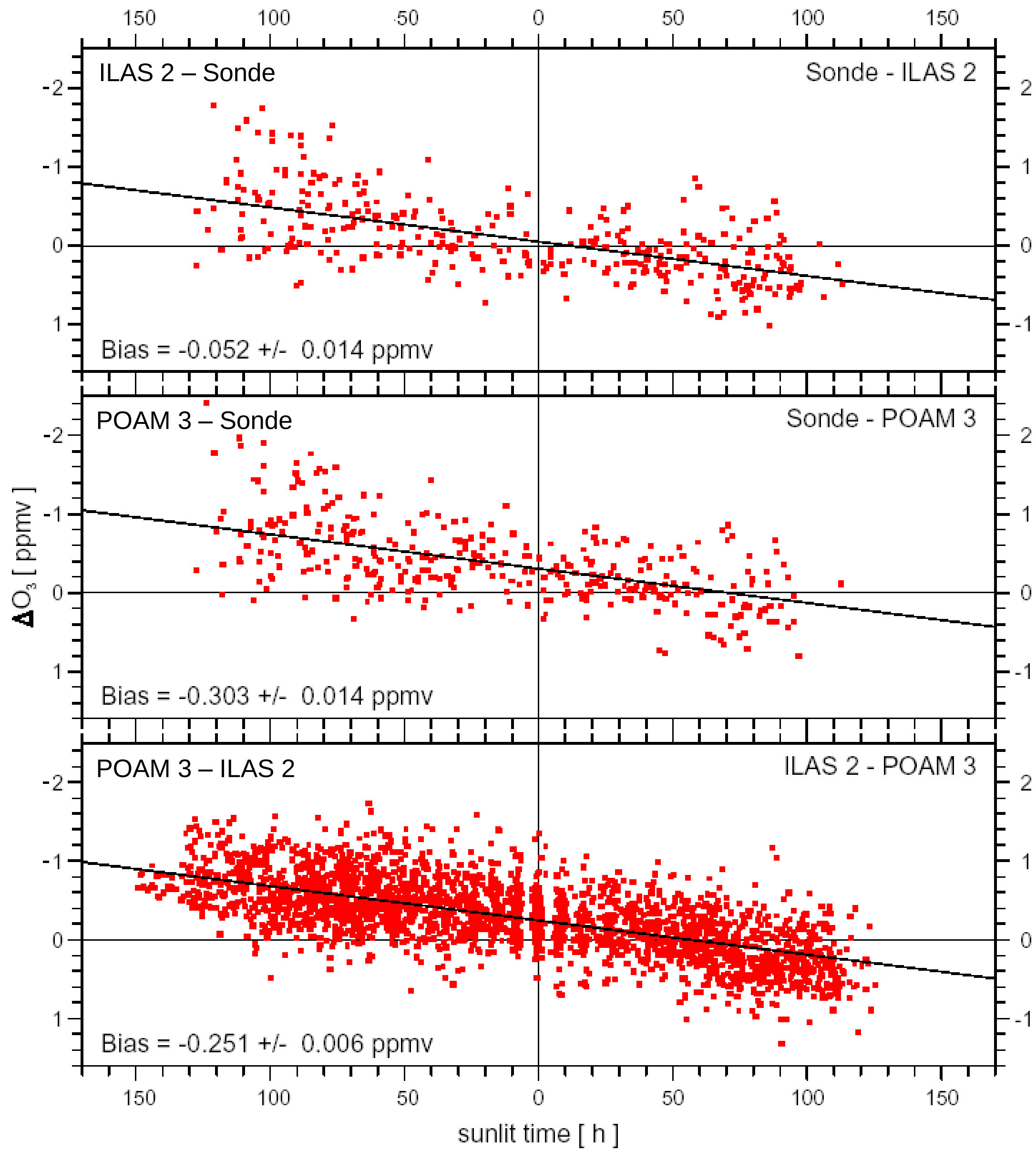
465 K - 485 K



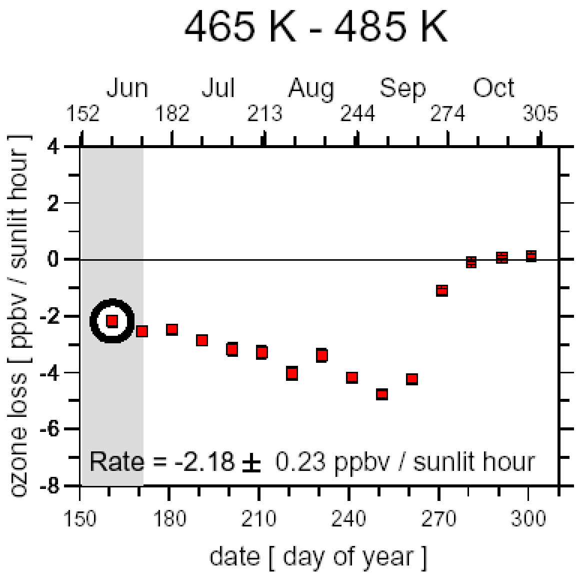
ozone loss [ppbv / sunlit hour]
4
2
0
-2
-4
-6
-8
Day 230-250
Rate = -4.35 +/- 0.06 ppbv / sunlit hour
150
180
210
240
270
300
date [day of year]

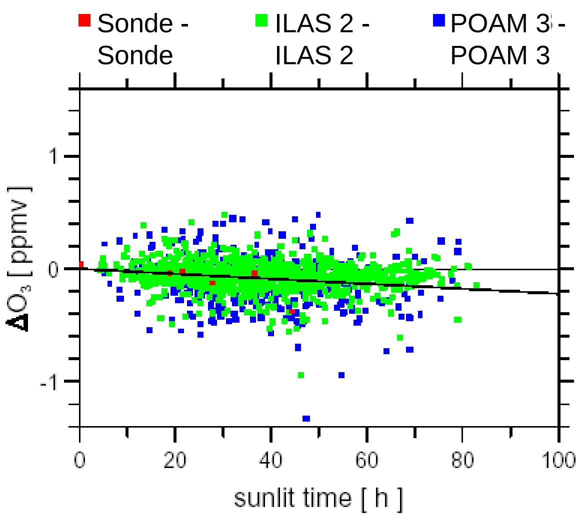


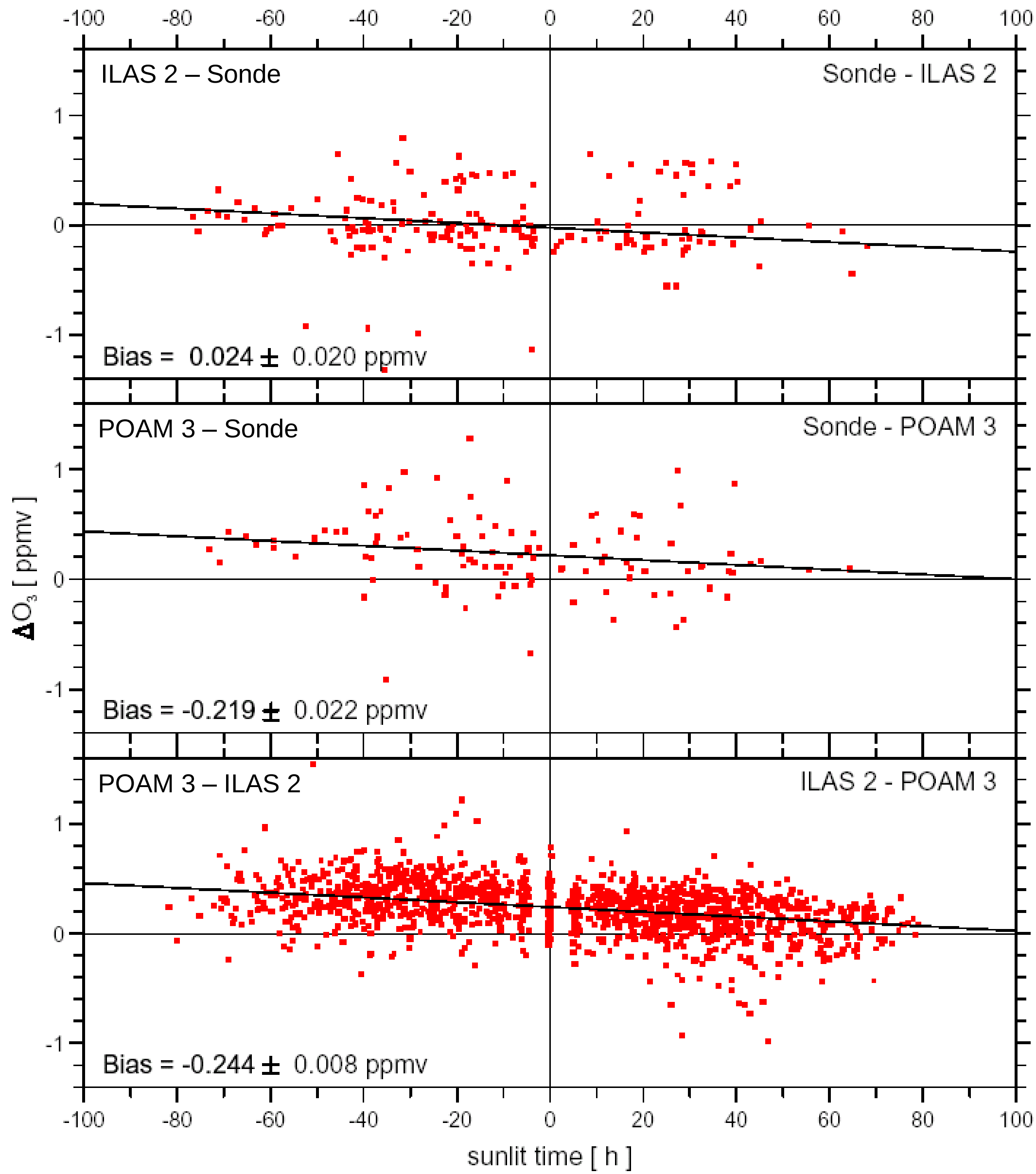
Sonde - Sonde
ILAS 2 - ILAS 2
POAM 3 - POAM 3
ΔO₃ [ppmv]
2
1
0
-1
0
50
100
150
sunlit time [h]

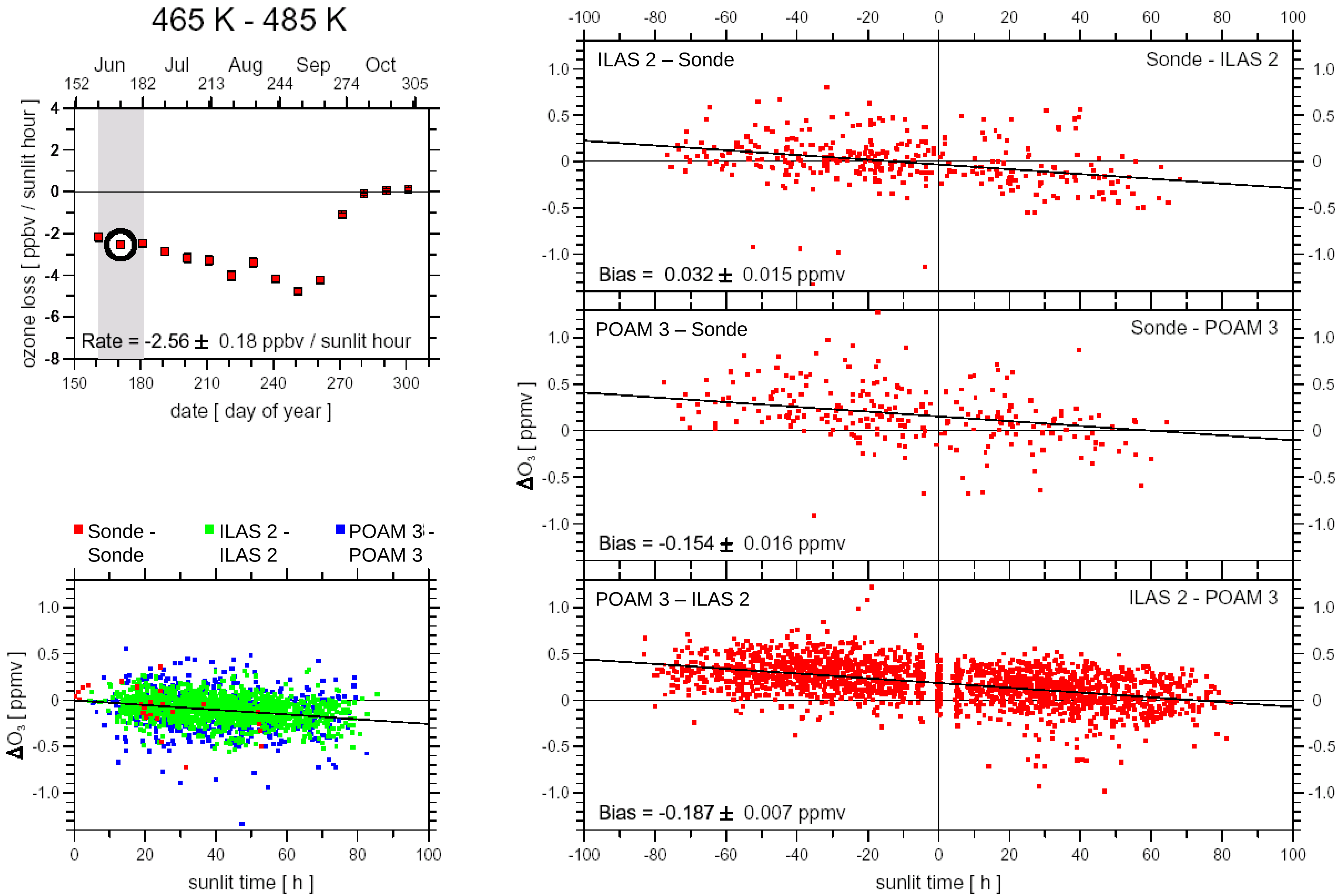


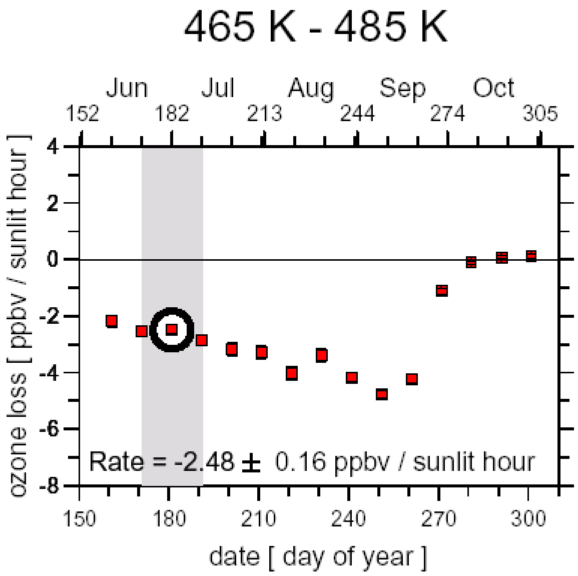
ILAS 2 – Sonde
Sonde - ILAS 2
Bias = -0.052 +/- 0.014 ppmv
POAM 3 – Sonde
Sonde - POAM 3
Bias = -0.303 +/- 0.014 ppmv
POAM 3 – ILAS 2
ILAS 2 - POAM 3
Bias = -0.251 +/- 0.006 ppmv
ΔO₃ [ppmv]
150
100
50
0
50
100
150
sunlit time [h]

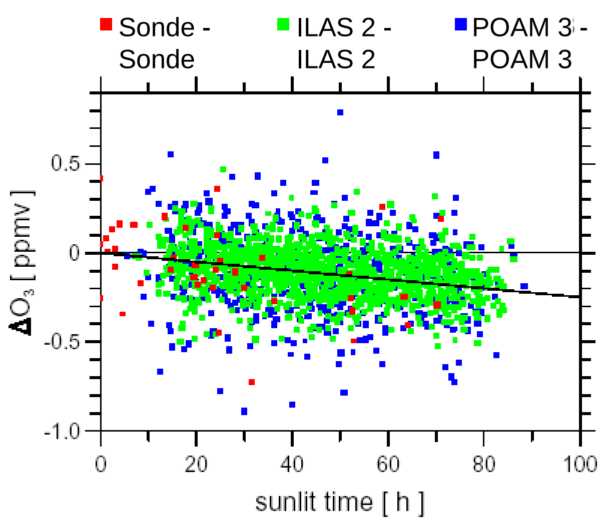

465 K - 485 K
Jun Jul Aug Sep Oct
152 182 213 244 274 305
ozone loss [ppbv / sunlit hour]
Rate = -2.18 ± 0.23 ppbv / sunlit hour
date [day of year]

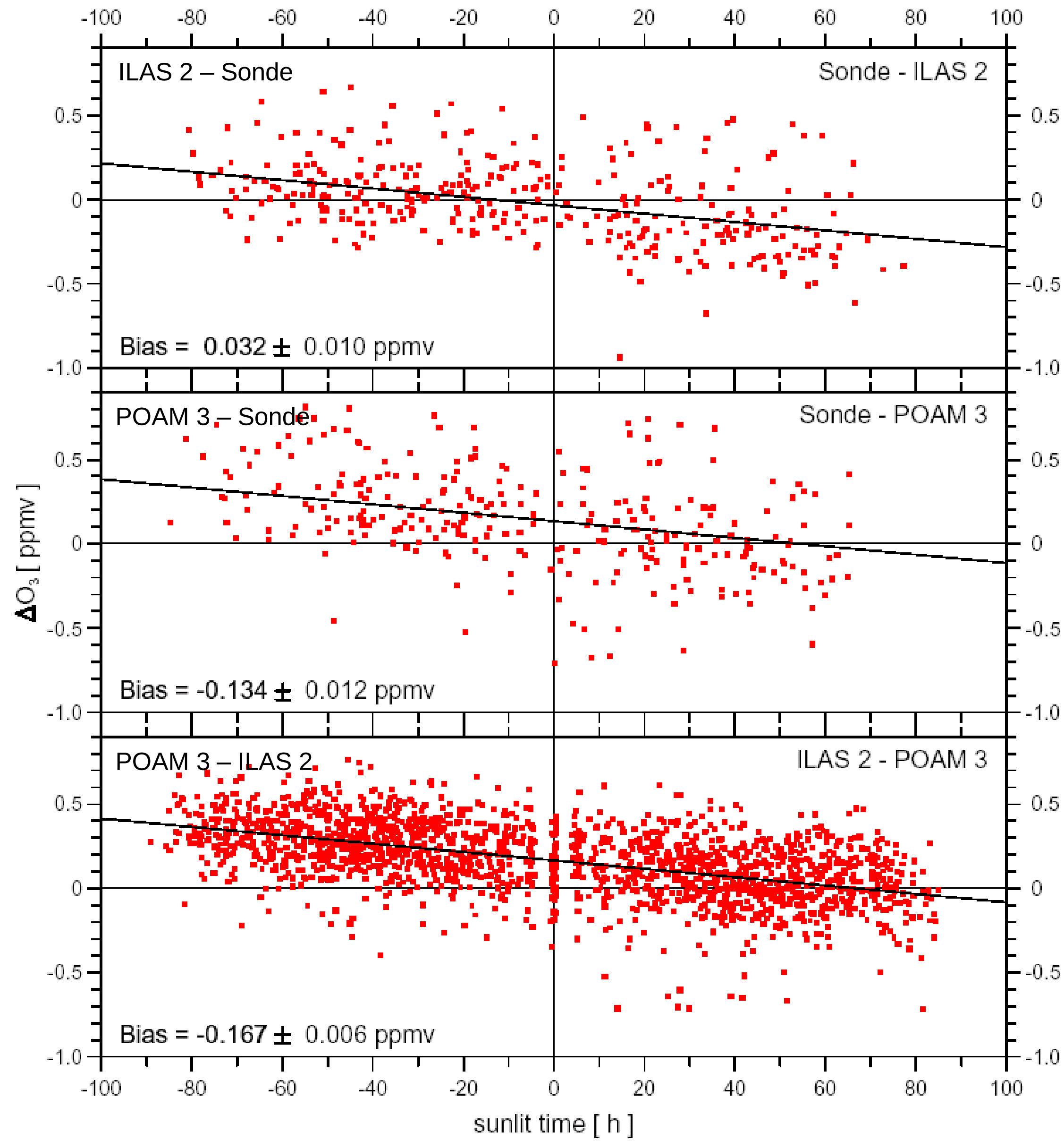

Sonde - Sonde
ILAS 2 - ILAS 2
POAM 3 - POAM 3
ΔO3 [ppmv]
sunlit time [h]

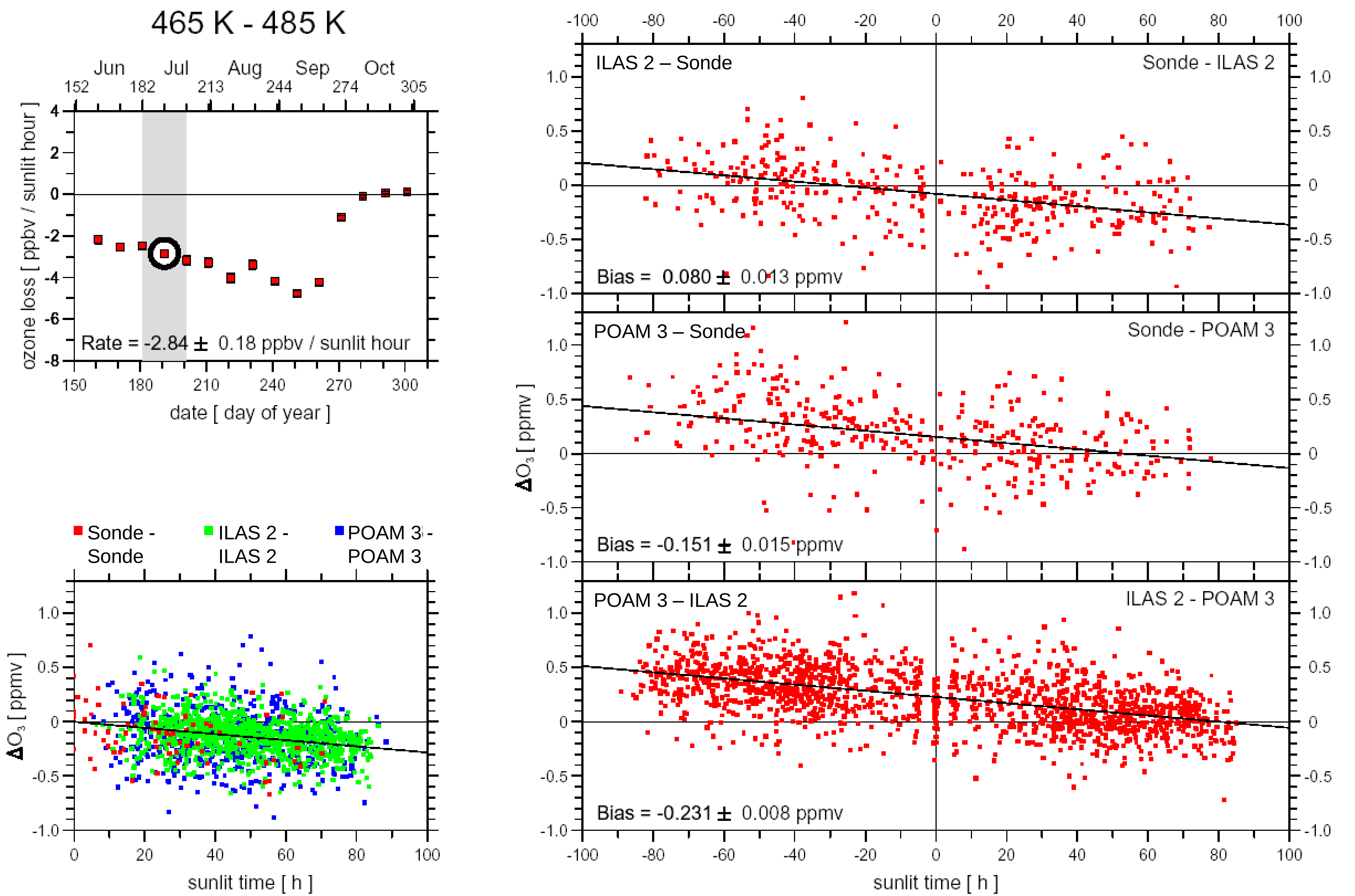

ILAS 2 – Sonde
Sonde - ILAS 2
Bias = 0.024 ± 0.020 ppmv
POAM 3 – Sonde
Sonde - POAM 3
Bias = -0.219 ± 0.022 ppmv
POAM 3 – ILAS 2
ILAS 2 - POAM 3
Bias = -0.244 ± 0.008 ppmv
ΔO3 [ppmv]
sunlit time [h]


465 K - 485 K
Jun
Jul
Aug
Sep
Oct
ozone loss [ppbv / sunlit hour]
Rate = -2.56 ± 0.18 ppbv / sunlit hour
date [day of year]
Sonde - Sonde
ILAS 2 - ILAS 2
POAM 3 - POAM 3
ΔO3 [ppmv]
sunlit time [h]
ILAS 2 – Sonde
Sonde - ILAS 2
Bias = 0.032 ± 0.015 ppmv
POAM 3 – Sonde
Sonde - POAM 3
Bias = -0.154 ± 0.016 ppmv
POAM 3 – ILAS 2
ILAS 2 - POAM 3
Bias = -0.187 ± 0.007 ppmv

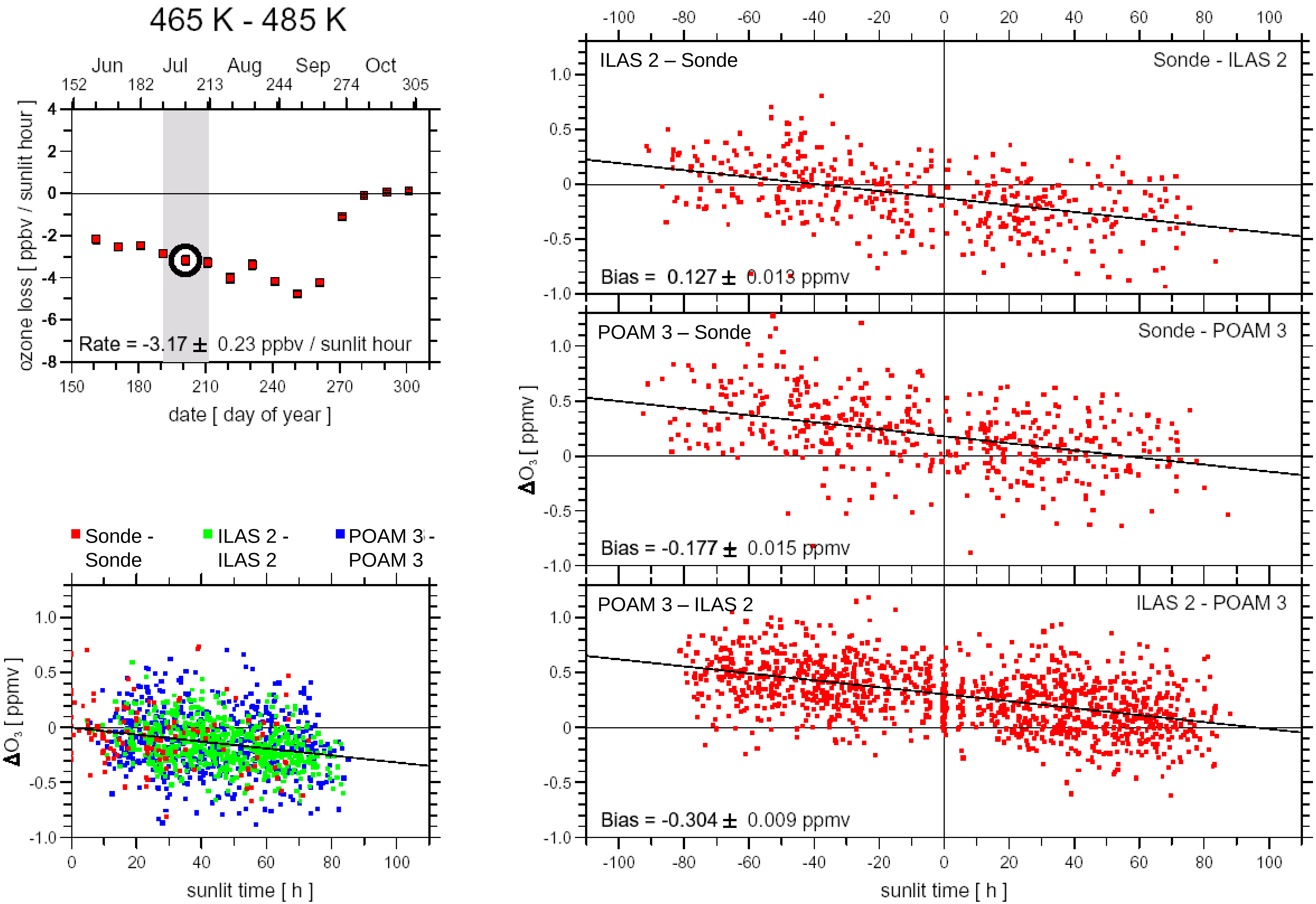

465 K - 485 K
Jun
Jul
Aug
Sep
Oct
152
182
213
244
274
305
ozone loss [ppbv / sunlit hour]
4
2
0
-2
-4
-6
-8
Rate = -2.48 ± 0.16 ppbv / sunlit hour
150
180
210
240
270
300
date [day of year]


Sonde - Sonde
ILAS 2 - ILAS 2
POAM 3 - POAM 3
ΔO3 [ppmv]
0.5
0
-0.5
-1.0
0
20
40
60
80
100
sunlit time [h]

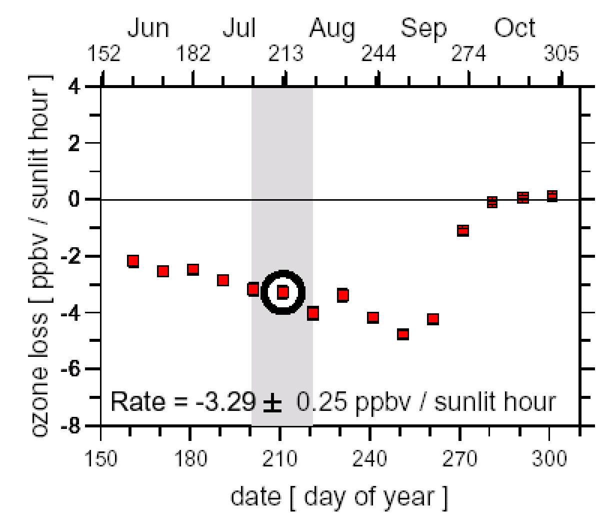

-100
-80
-60
-40
-20
0
20
40
60
80
100
ILAS 2 – Sonde
Sonde - ILAS 2
Bias = 0.032 ± 0.010 ppmv
POAM 3 – Sonde
Sonde - POAM 3
Bias = -0.134 ± 0.012 ppmv
POAM 3 – ILAS 2
ILAS 2 - POAM 3
Bias = -0.167 ± 0.006 ppmv
ΔO3 [ppmv]
0.5
0
-0.5
-1.0
sunlit time [h]

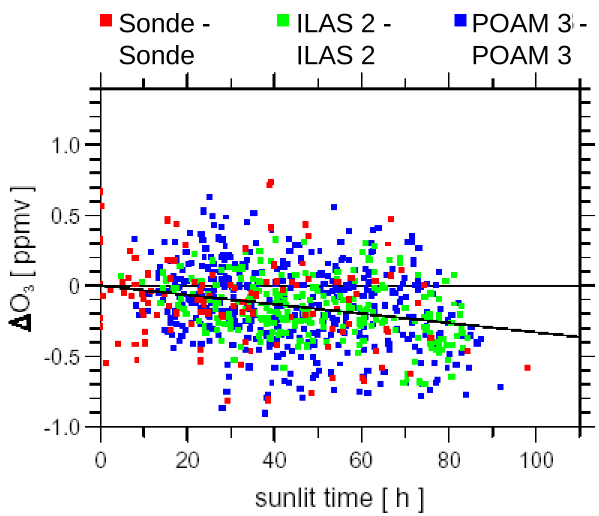


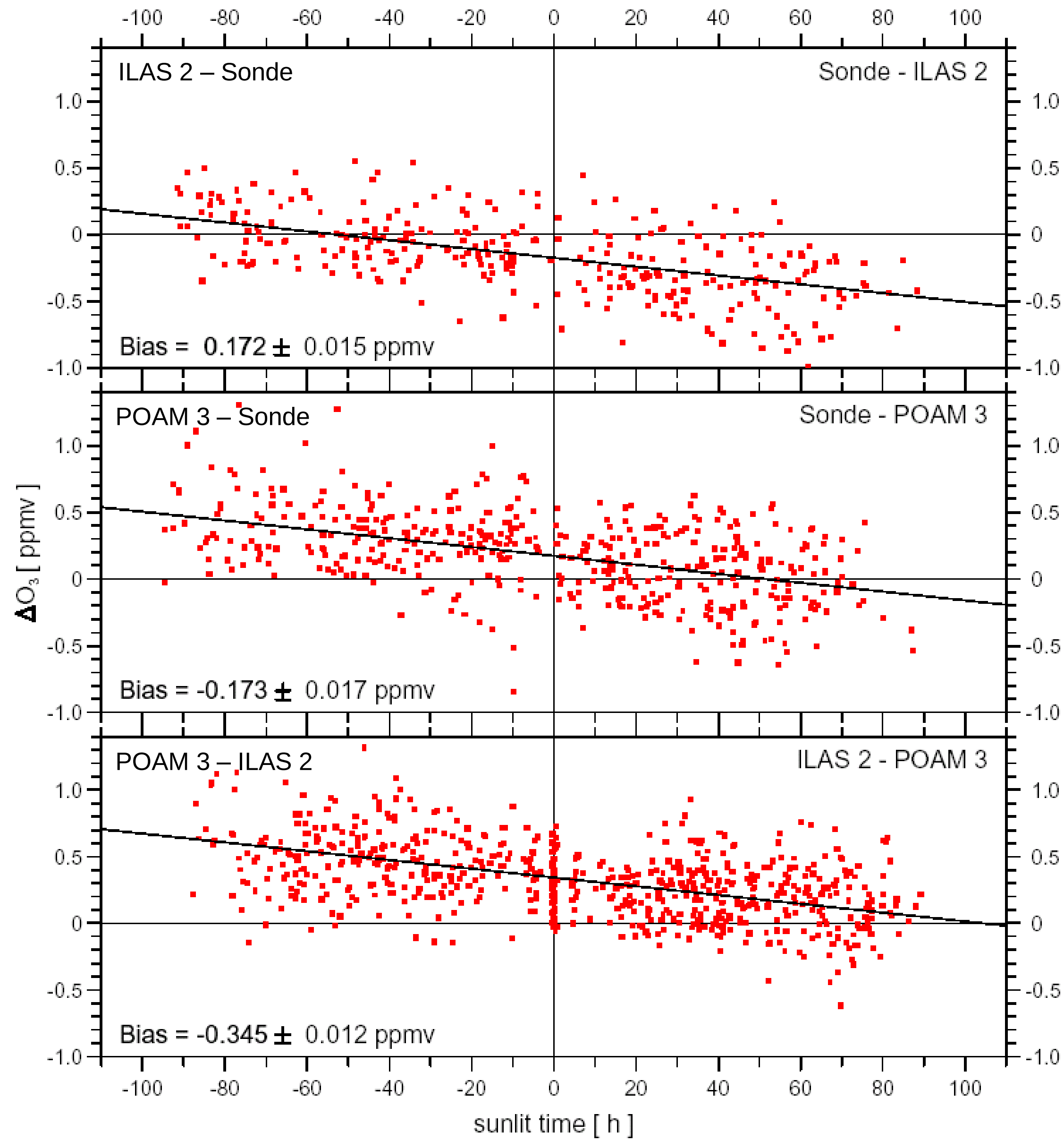
465 K - 485 K
Jun
Jul
Aug
Sep
Oct
ozone loss [ppbv / sunlit hour]
Rate = -2.84 ± 0.18 ppbv / sunlit hour
date [day of year]
Sonde - Sonde
ILAS 2 - ILAS 2
POAM 3 - POAM 3
ΔO_3 [ppmv]
sunlit time [h]
ILAS 2 – Sonde
Sonde - ILAS 2
Bias = 0.080 ± 0.013 ppmv
POAM 3 – Sonde
Sonde - POAM 3
Bias = -0.151 ± 0.015 ppmv
POAM 3 – ILAS 2
ILAS 2 - POAM 3
Bias = -0.231 ± 0.008 ppmv

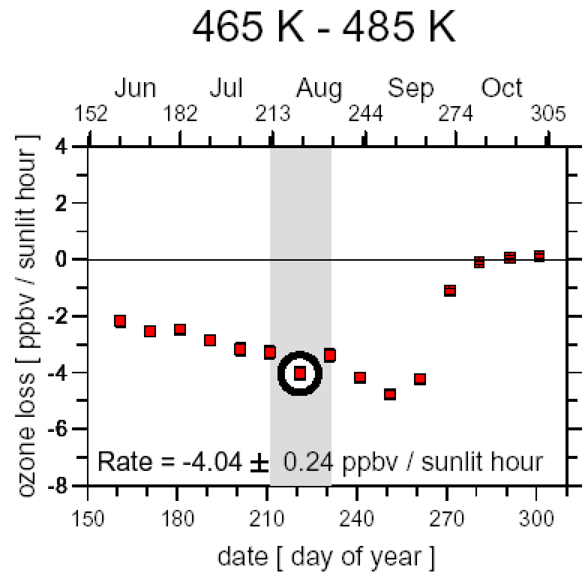

465 K - 485 K
Jun
Jul
Aug
Sep
Oct
152
182
213
244
274
305
ozone loss [ppbv / sunlit hour]
Rate = -3.17 ± 0.23 ppbv / sunlit hour
date [day of year]
Sonde - Sonde
ILAS 2 - ILAS 2
POAM 3 - POAM 3
ΔO3 [ppmv]
sunlit time [h]
ILAS 2 – Sonde
Sonde - ILAS 2
Bias = 0.127 ± 0.013 ppmv
POAM 3 – Sonde
Sonde - POAM 3
Bias = -0.177 ± 0.015 ppmv
POAM 3 – ILAS 2
ILAS 2 - POAM 3
Bias = -0.304 ± 0.009 ppmv

465 K - 485 K

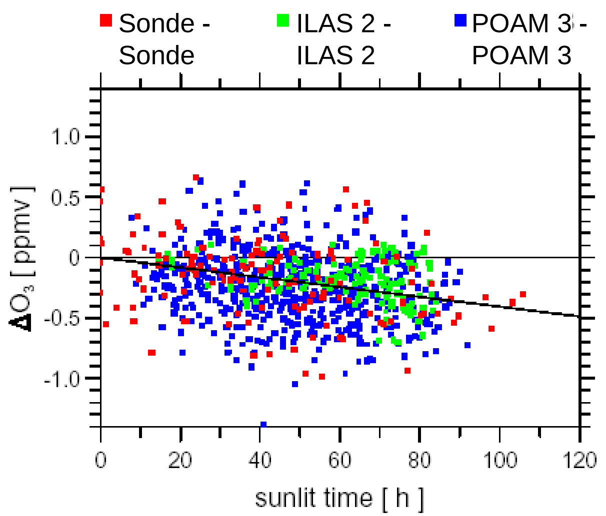

Jun
Jul
Aug
Sep
Oct
152
182
213
244
274
305
ozone loss [ppbv / sunlit hour]
Rate = -3.29 ± 0.25 ppbv / sunlit hour
date [day of year]


Sonde - Sonde
ILAS 2 - ILAS 2
POAM 3 - POAM 3
ΔO3 [ppmv]
sunlit time [h]

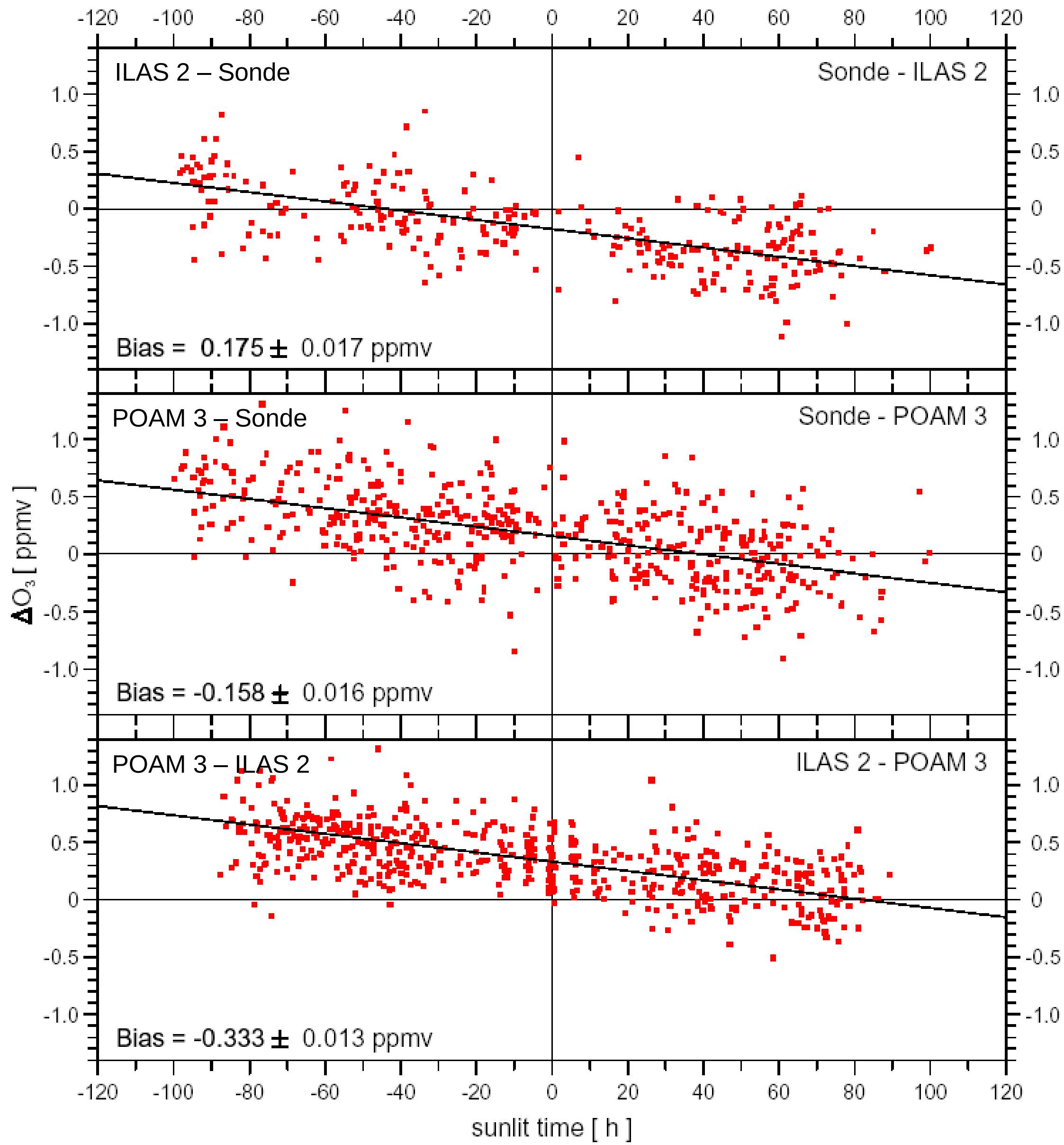

ILAS 2 – Sonde
Sonde - ILAS 2
Bias = 0.172 ± 0.015 ppmv
POAM 3 – Sonde
Sonde - POAM 3
Bias = -0.173 ± 0.017 ppmv
POAM 3 – ILAS 2
ILAS 2 - POAM 3
Bias = -0.345 ± 0.012 ppmv
ΔO3 [ppmv]
sunlit time [h]



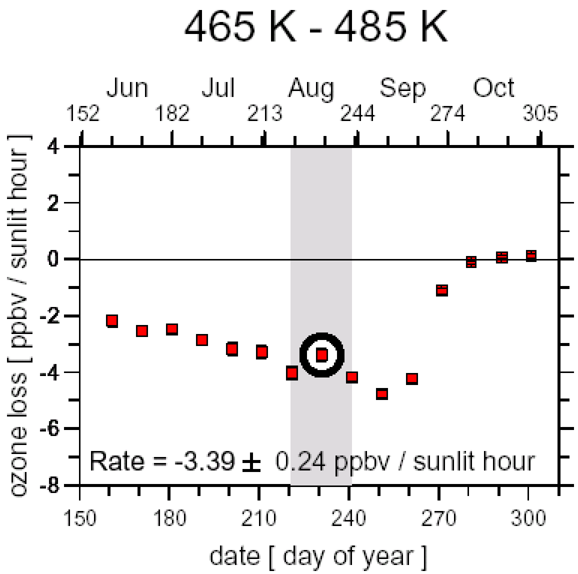
465 K - 485 K
Jun
Jul
Aug
Sep
Oct
ozone loss [ppbv / sunlit hour]
Rate = -4.04 ± 0.24 ppbv / sunlit hour
date [day of year]

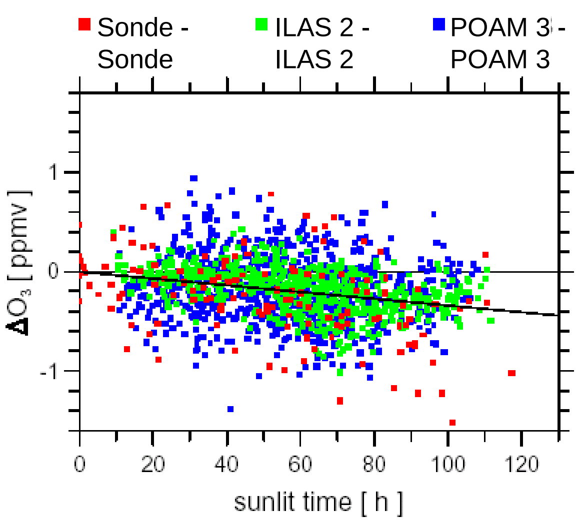


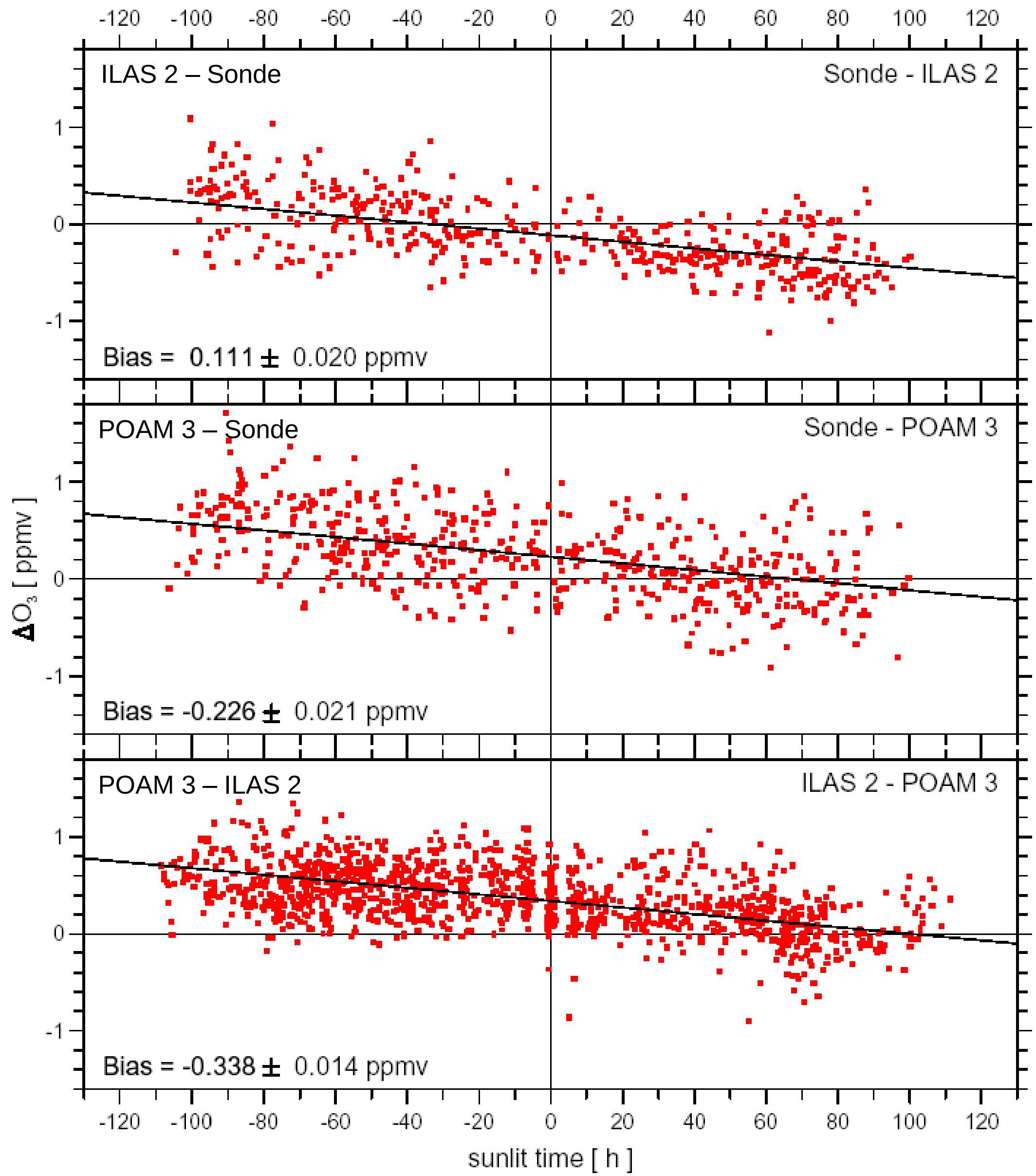
Sonde - Sonde
ILAS 2 - ILAS 2
POAM 3 - POAM 3
ΔO3 [ppmv]
sunlit time [h]

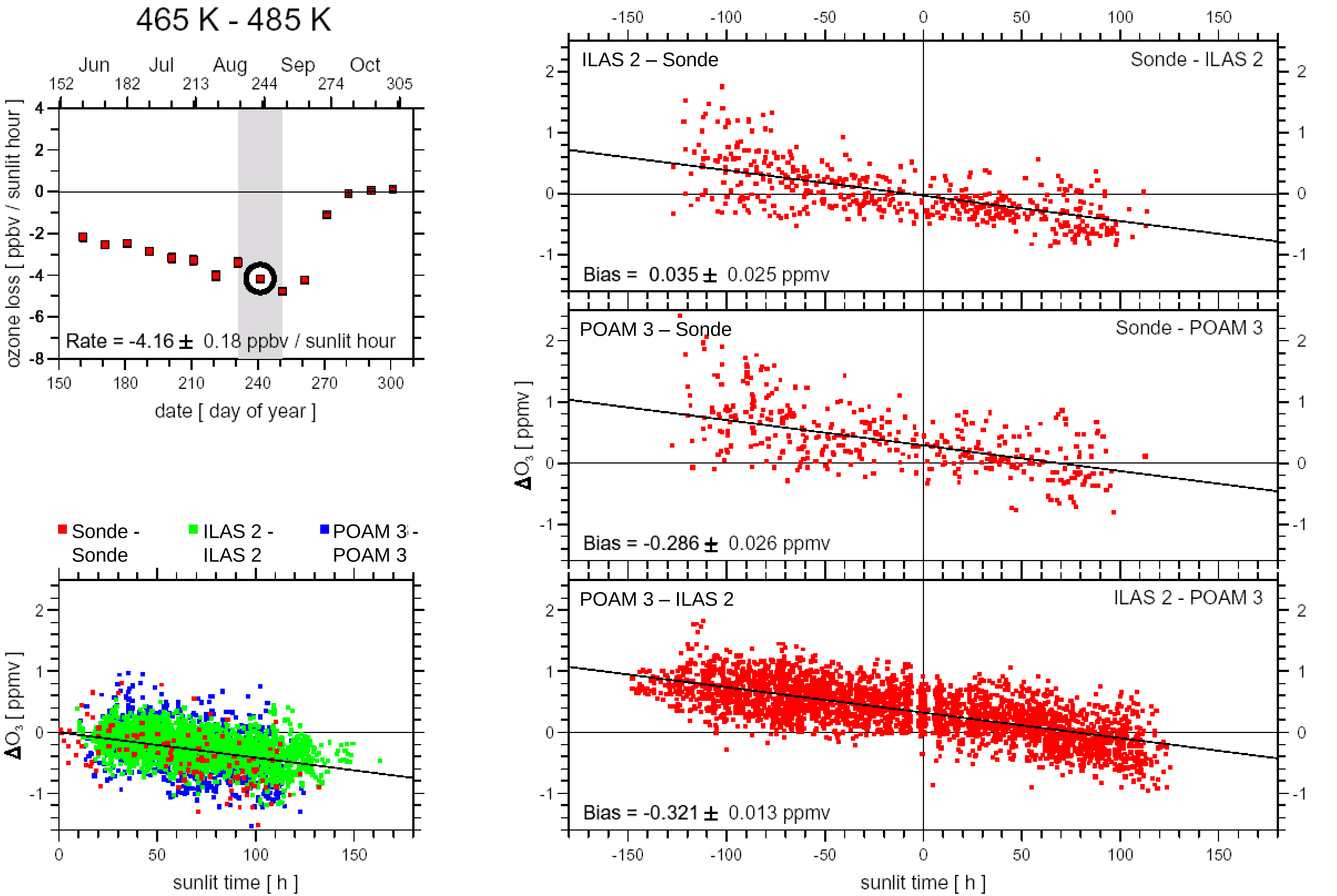


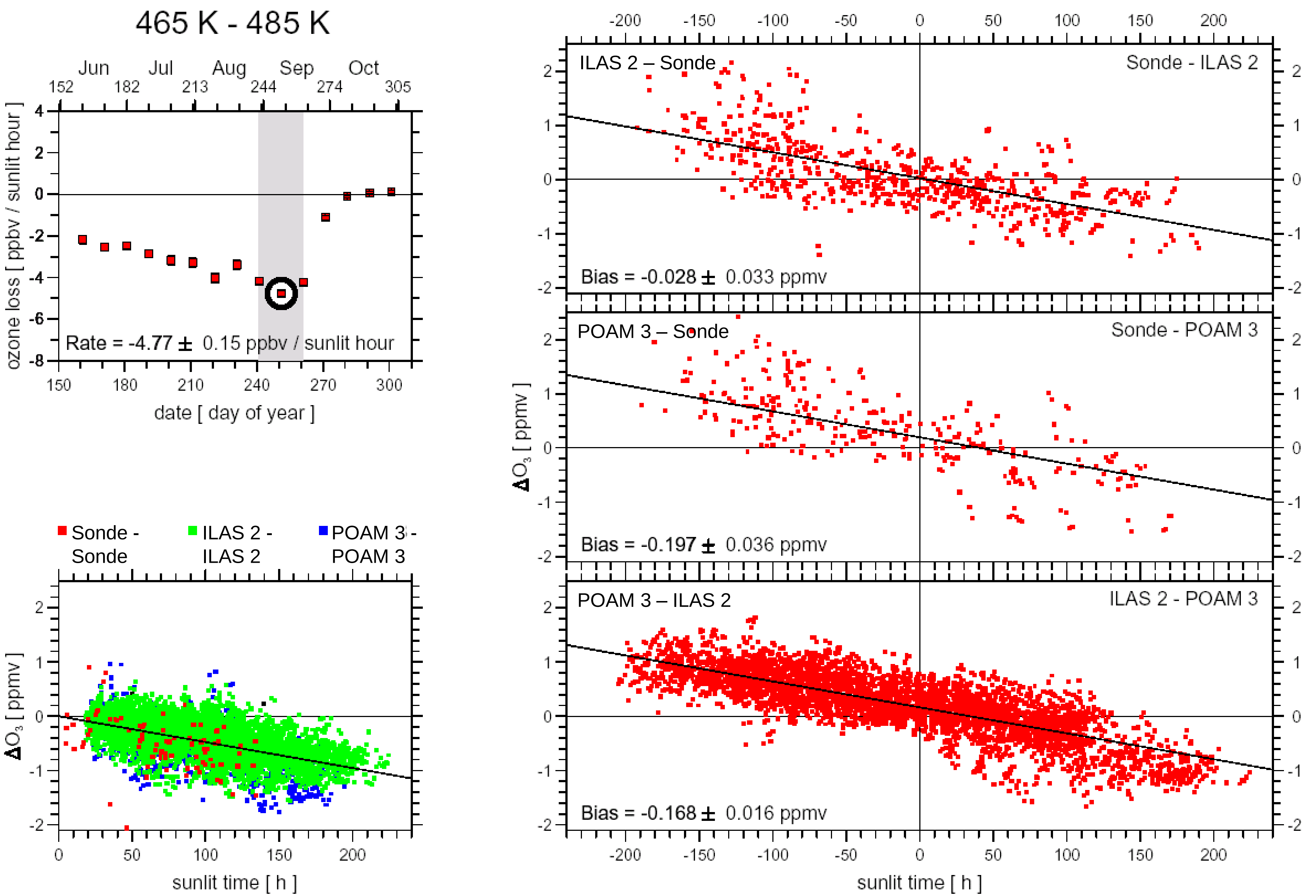
ILAS 2 – Sonde
Sonde - ILAS 2
Bias = 0.175 ± 0.017 ppmv
POAM 3 – Sonde
Sonde - POAM 3
Bias = -0.158 ± 0.016 ppmv
POAM 3 – ILAS 2
ILAS 2 - POAM 3
Bias = -0.333 ± 0.013 ppmv
ΔO3 [ppmv]
sunlit time [h]


465 K - 485 K
Jun Jul Aug Sep Oct
152 182 213 244 274 305
ozone loss [ppbv / sunlit hour]
Rate = -3.39 ± 0.24 ppbv / sunlit hour
date [day of year]

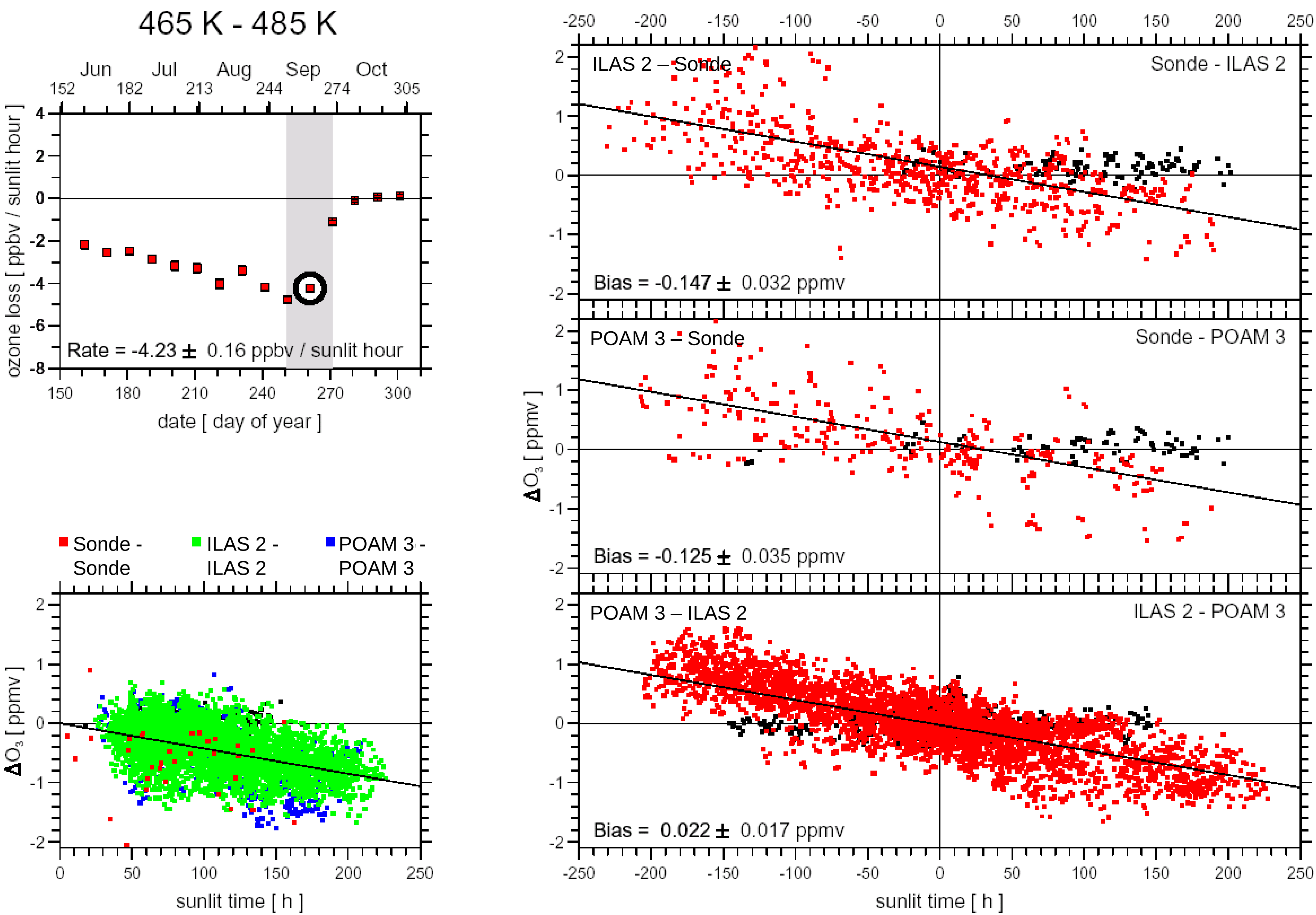

Sonde - Sonde
ILAS 2 - ILAS 2
POAM 3 - POAM 3
ΔO3 [ppmv]
sunlit time [h]

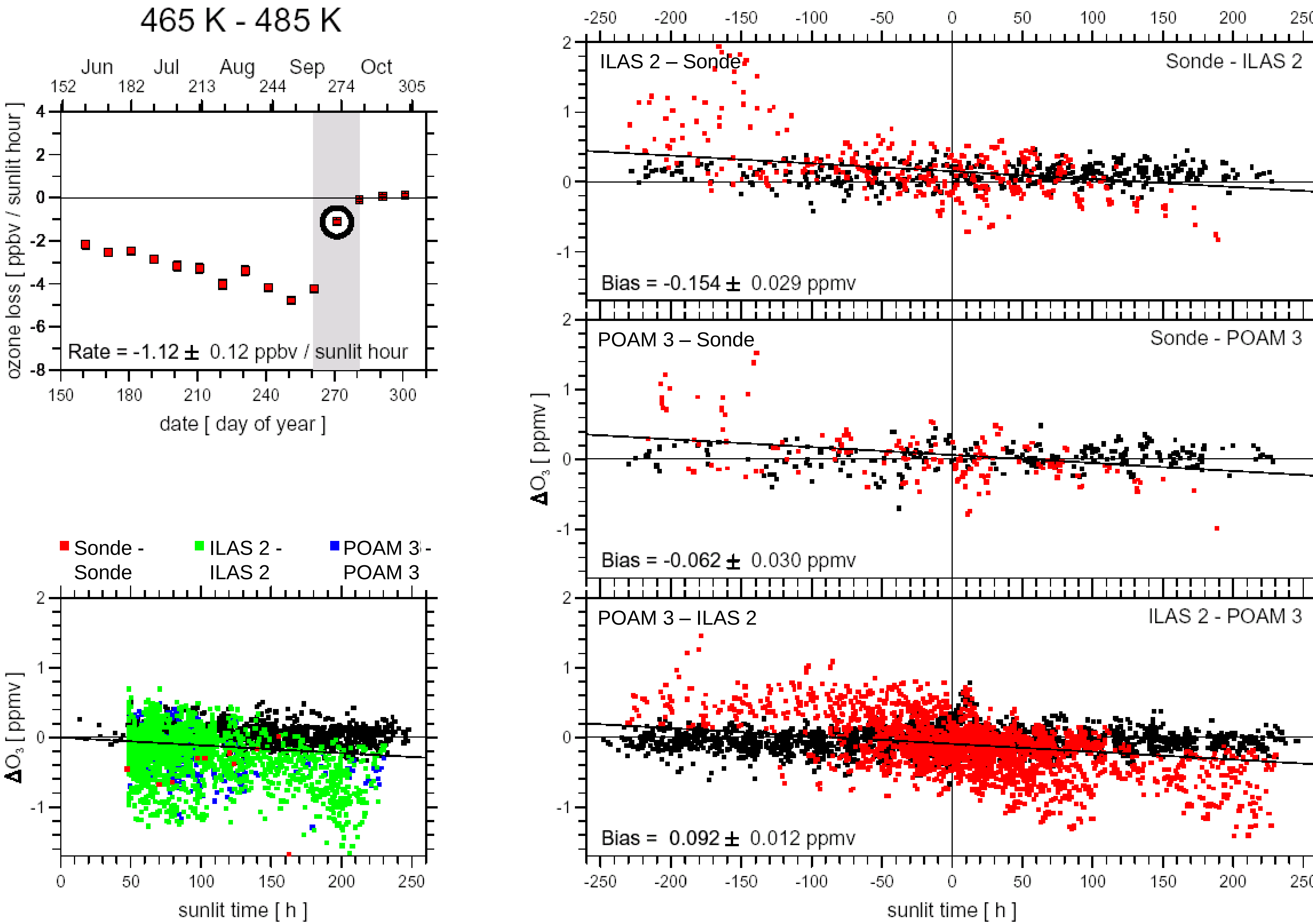

ILAS 2 – Sonde
Sonde - ILAS 2
Bias = 0.111 ± 0.020 ppmv
POAM 3 – Sonde
Sonde - POAM 3
Bias = -0.226 ± 0.021 ppmv
POAM 3 – ILAS 2
ILAS 2 - POAM 3
Bias = -0.338 ± 0.014 ppmv
ΔO3 [ppmv]
sunlit time [h]


465 K - 485 K
Jun
Jul
Aug
Sep
Oct
ozone loss [ppbv / sunlit hour]
Rate = -4.16 ± 0.18 ppbv / sunlit hour
date [day of year]
Sonde - Sonde
ILAS 2 - ILAS 2
POAM 3 - POAM 3
ΔO3 [ppmv]
sunlit time [h]
ILAS 2 – Sonde
Sonde - ILAS 2
Bias = 0.035 ± 0.025 ppmv
POAM 3 – Sonde
Sonde - POAM 3
Bias = -0.286 ± 0.026 ppmv
POAM 3 – ILAS 2
ILAS 2 - POAM 3
Bias = -0.321 ± 0.013 ppmv

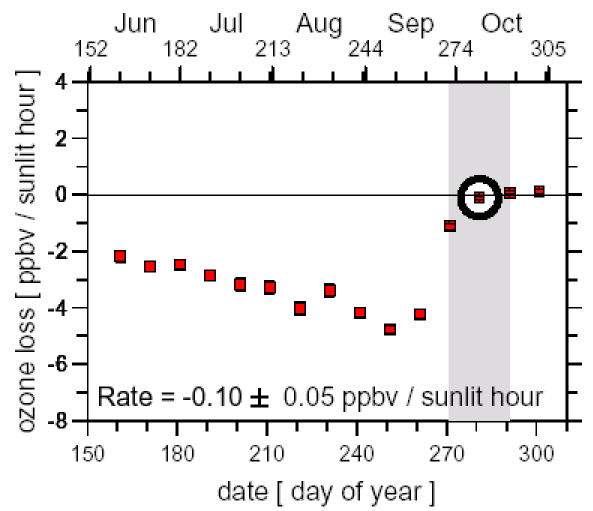


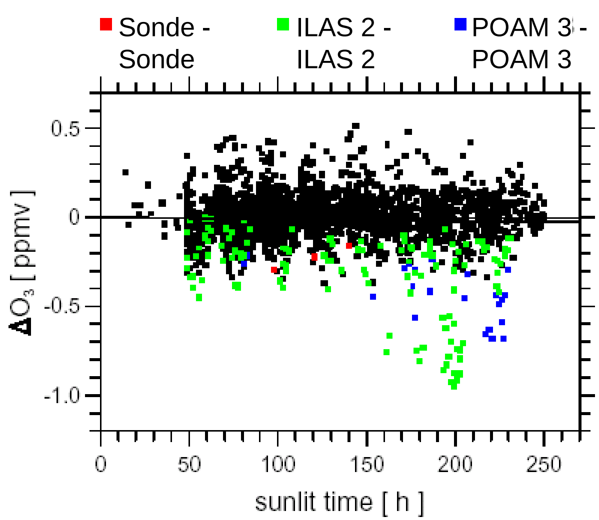
465 K - 485 K
Jun Jul Aug Sep Oct
152 182 213 244 274 305
ozone loss [ppbv / sunlit hour]
Rate = -4.77 ± 0.15 ppbv / sunlit hour
date [day of year]
Sonde - Sonde
ILAS 2 - ILAS 2
POAM 3 - POAM 3
ΔO3 [ppmv]
sunlit time [h]
ILAS 2 – Sonde
Sonde - ILAS 2
Bias = -0.028 ± 0.033 ppmv
POAM 3 – Sonde
Sonde - POAM 3
Bias = -0.197 ± 0.036 ppmv
POAM 3 – ILAS 2
ILAS 2 - POAM 3
Bias = -0.168 ± 0.016 ppmv

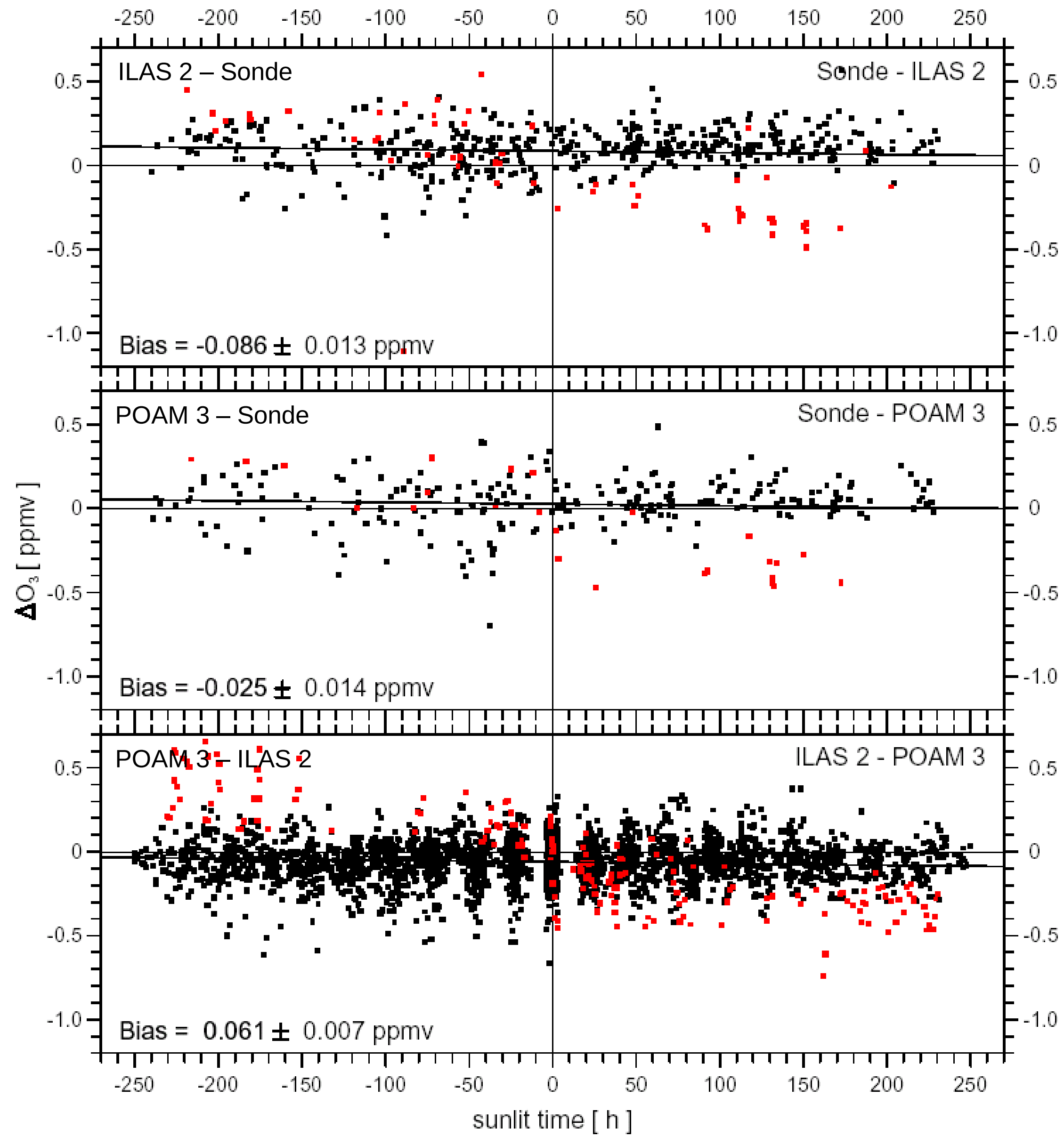

465 K - 485 K
Jun
Jul
Aug
Sep
Oct
ozone loss [ppbv / sunlit hour]
Rate = -4.23 ± 0.16 ppbv / sunlit hour
date [day of year]
Sonde - Sonde
ILAS 2 - ILAS 2
POAM 3 - POAM 3
ΔO3 [ppmv]
sunlit time [h]
ILAS 2 – Sonde
Sonde - ILAS 2
Bias = -0.147 ± 0.032 ppmv
POAM 3 – Sonde
Sonde - POAM 3
Bias = -0.125 ± 0.035 ppmv
POAM 3 – ILAS 2
ILAS 2 - POAM 3
Bias = 0.022 ± 0.017 ppmv
ΔO3 [ppmv]
sunlit time [h]


465 K - 485 K
Jun
Jul
Aug
Sep
Oct
ozone loss [ppbv / sunlit hour]
Rate = -1.12 ± 0.12 ppbv / sunlit hour
date [day of year]
Sonde - Sonde
ILAS 2 - ILAS 2
POAM 3 - POAM 3
ΔO3 [ppmv]
sunlit time [h]
ILAS 2 – Sonde
Sonde - ILAS 2
Bias = -0.154 ± 0.029 ppmv
POAM 3 – Sonde
Sonde - POAM 3
Bias = -0.062 ± 0.030 ppmv
POAM 3 – ILAS 2
ILAS 2 - POAM 3
Bias = 0.092 ± 0.012 ppmv

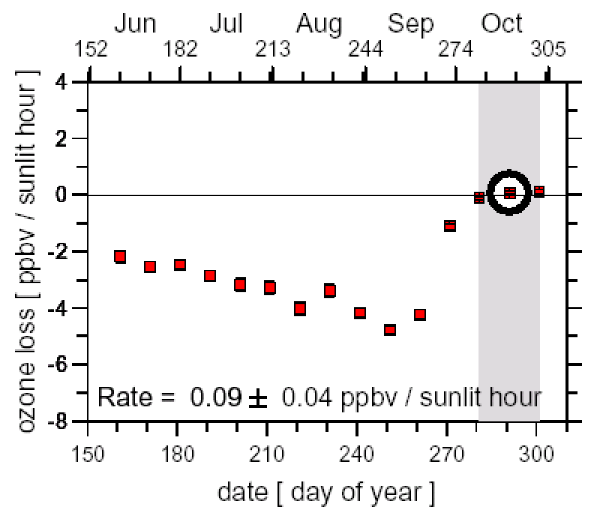
465 K - 485 K


Jun
Jul
Aug
Sep
Oct
ozone loss [ppbv / sunlit hour]
Rate = -0.10 ± 0.05 ppbv / sunlit hour
date [day of year]

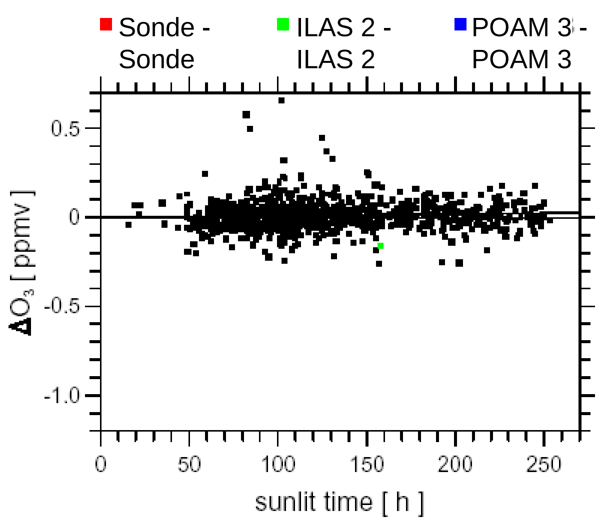

Sonde - Sonde
ILAS 2 - ILAS 2
POAM 3 - POAM 3
ΔO3 [ppmv]
sunlit time [h]


ILAS 2 – Sonde
Sonde - ILAS 2
Bias = -0.086 ± 0.013 ppmv
POAM 3 – Sonde
Sonde - POAM 3
Bias = -0.025 ± 0.014 ppmv
POAM 3 – ILAS 2
ILAS 2 - POAM 3
Bias = 0.061 ± 0.007 ppmv
ΔO3 [ppmv]
sunlit time [h]

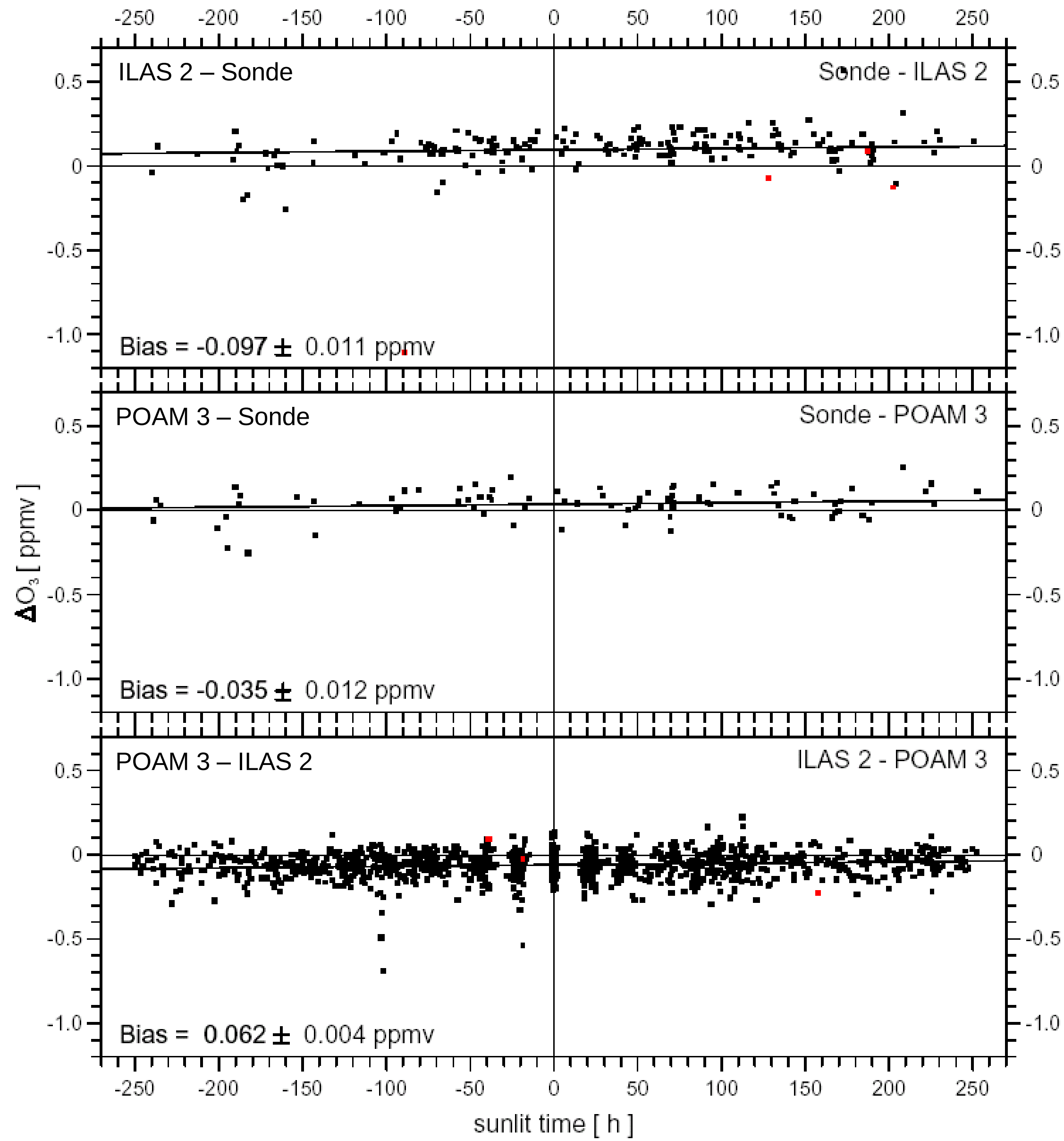
465 K - 485 K



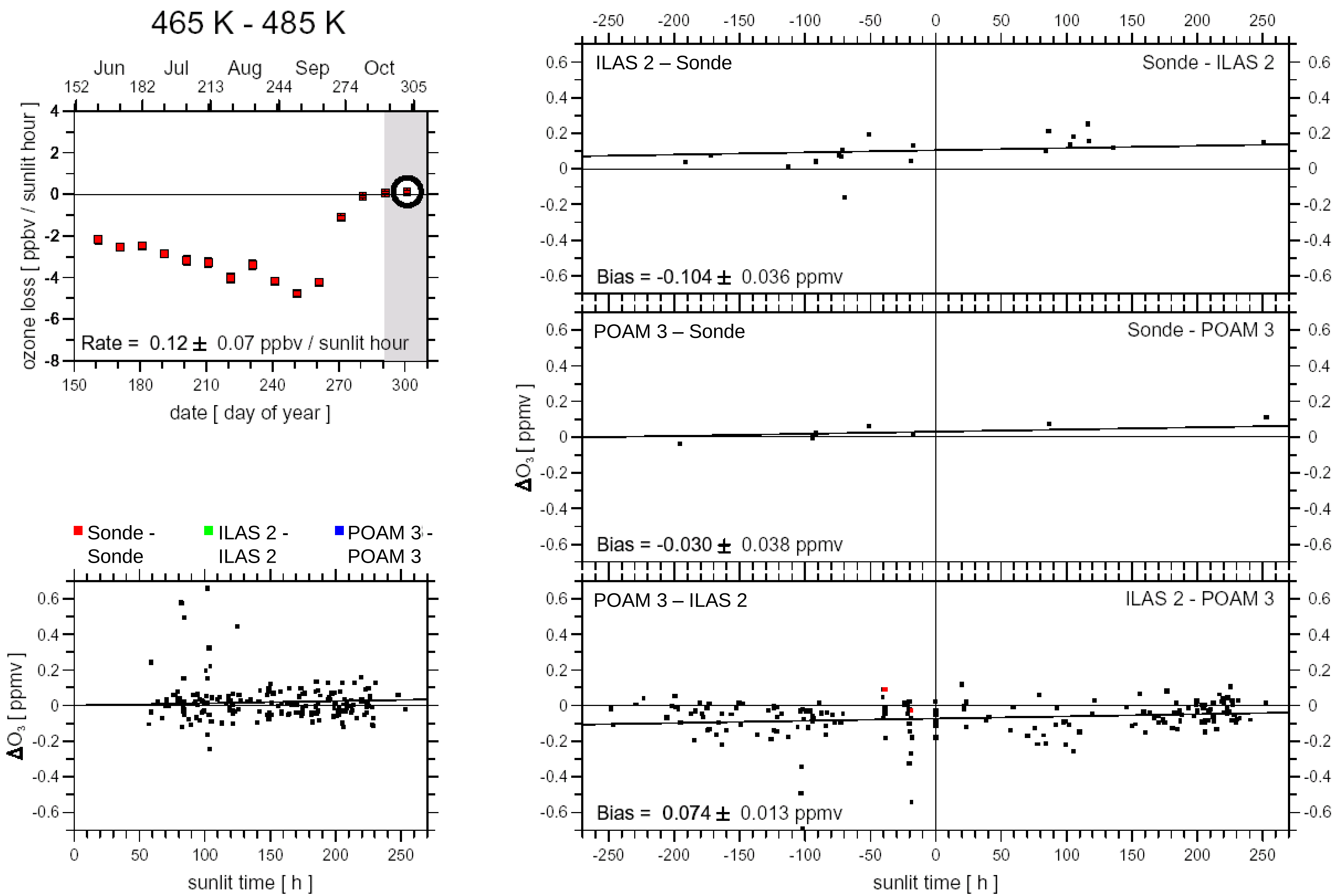
Jun
Jul
Aug
Sep
Oct
152
182
213
244
274
305
ozone loss [ppbv / sunlit hour]
4
2
0
-2
-4
-6
-8
Rate = 0.09 ± 0.04 ppbv / sunlit hour
150
180
210
240
270
300
date [day of year]



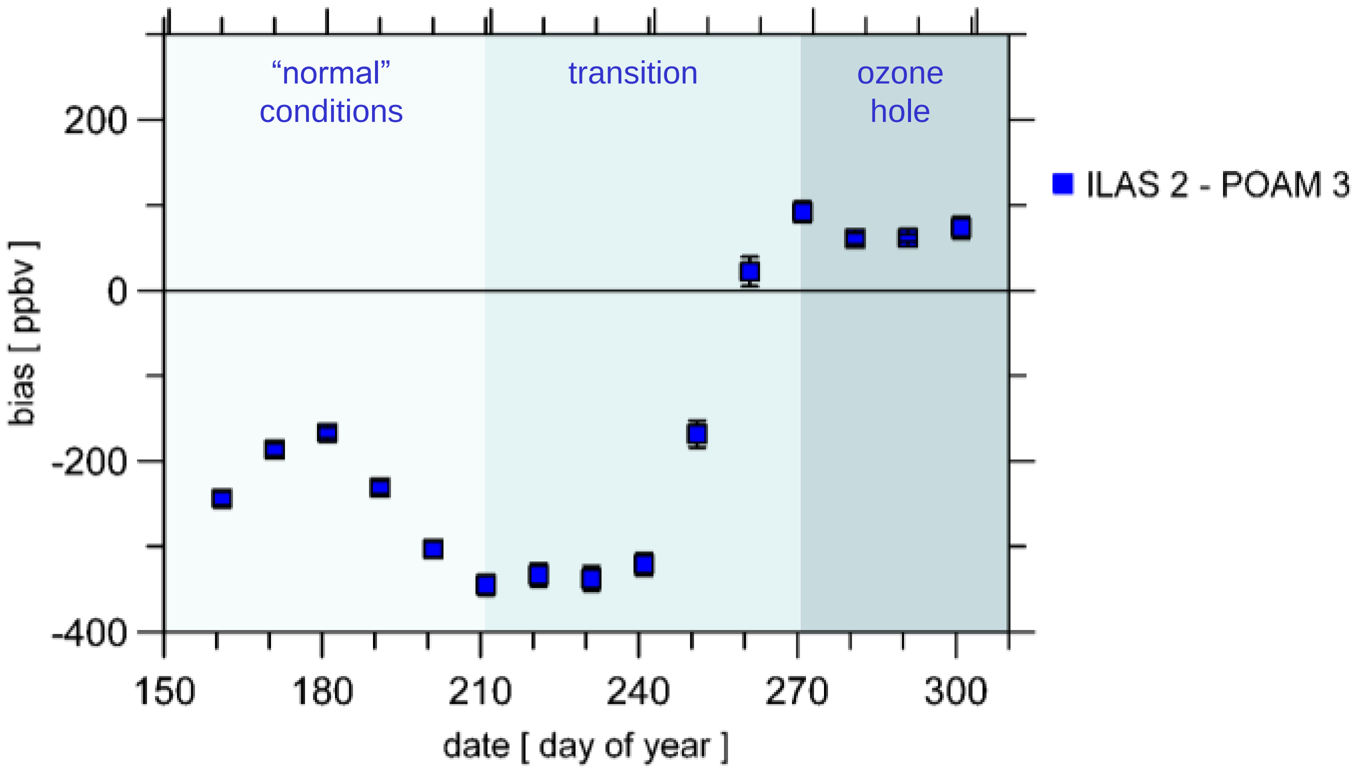
Sonde - Sonde
ILAS 2 - ILAS 2
POAM 3 - POAM 3
0.5
0
-0.5
-1.0
ΔO3 [ppmv]
0
50
100
150
200
250
sunlit time [h]



-250
-200
-150
-100
-50
0
50
100
150
200
250
ILAS 2 – Sonde
Sonde - ILAS 2
Bias = -0.097 ± 0.011 ppmv
POAM 3 – Sonde
Sonde - POAM 3
Bias = -0.035 ± 0.012 ppmv
POAM 3 – ILAS 2
ILAS 2 - POAM 3
Bias = 0.062 ± 0.004 ppmv
0.5
0
-0.5
-1.0
ΔO3 [ppmv]
sunlit time [h]

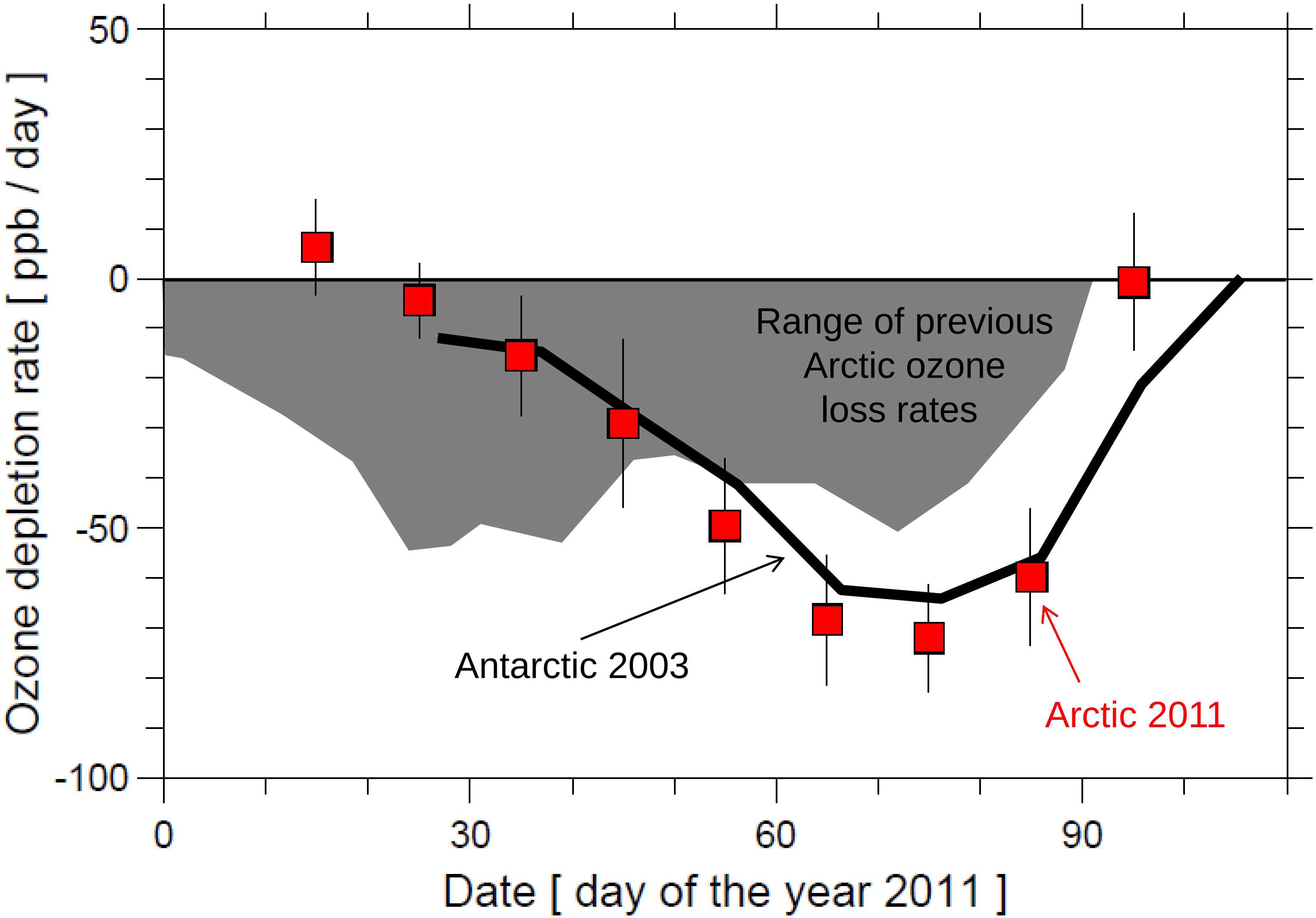

465 K - 485 K
Jun
Jul
Aug
Sep
Oct
152
182
213
244
274
305
ozone loss [ppbv / sunlit hour]
Rate = 0.12 ± 0.07 ppbv / sunlit hour
date [day of year]
Sonde - Sonde
ILAS 2 - ILAS 2
POAM 3 - POAM 3
ΔO3 [ppmv]
sunlit time [h]
ILAS 2 – Sonde
Sonde - ILAS 2
Bias = -0.104 ± 0.036 ppmv
POAM 3 – Sonde
Sonde - POAM 3
Bias = -0.030 ± 0.038 ppmv
POAM 3 – ILAS 2
ILAS 2 - POAM 3
Bias = 0.074 ± 0.013 ppmv
sunlit time [h]

Biases of ILAS2 versus POAM 3

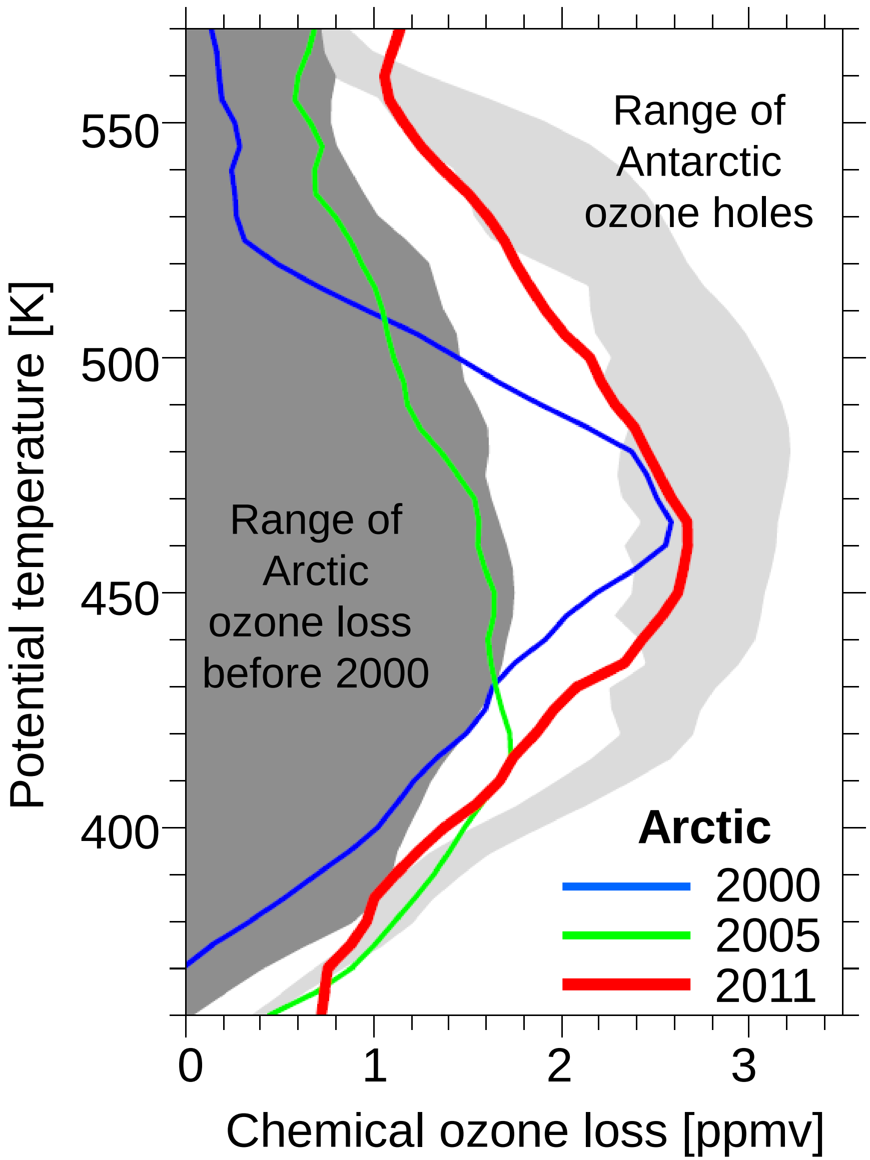


For background conditions ILAS II v1.4 is about 200-350 ppbv lower than POAM III. For very low ozone under ozone hole conditions it is about 50 ppbv higher.

Match: Chemical ozone loss rates @ eΘ~465K
(unmixed vortex air)

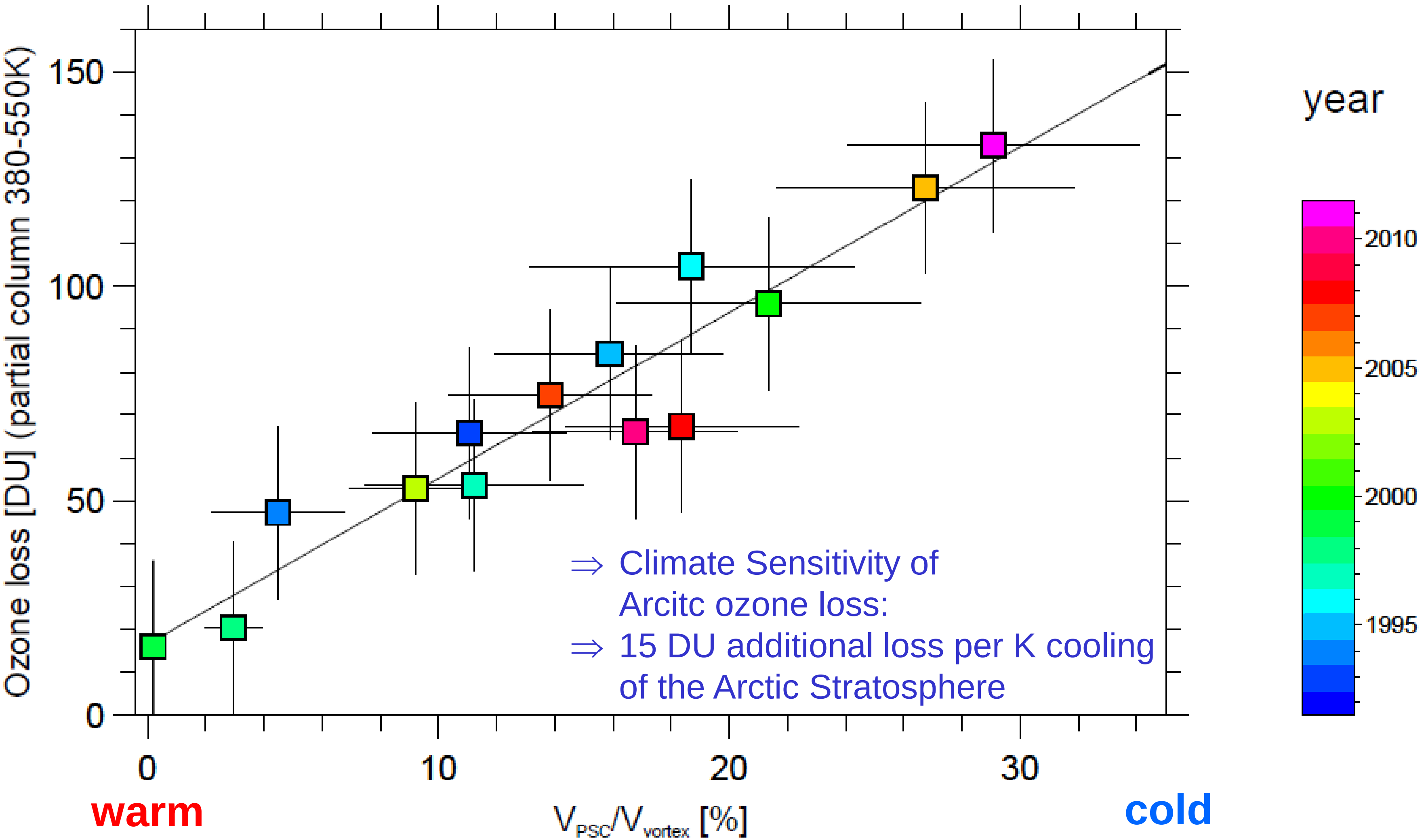


Ozone loss profiles



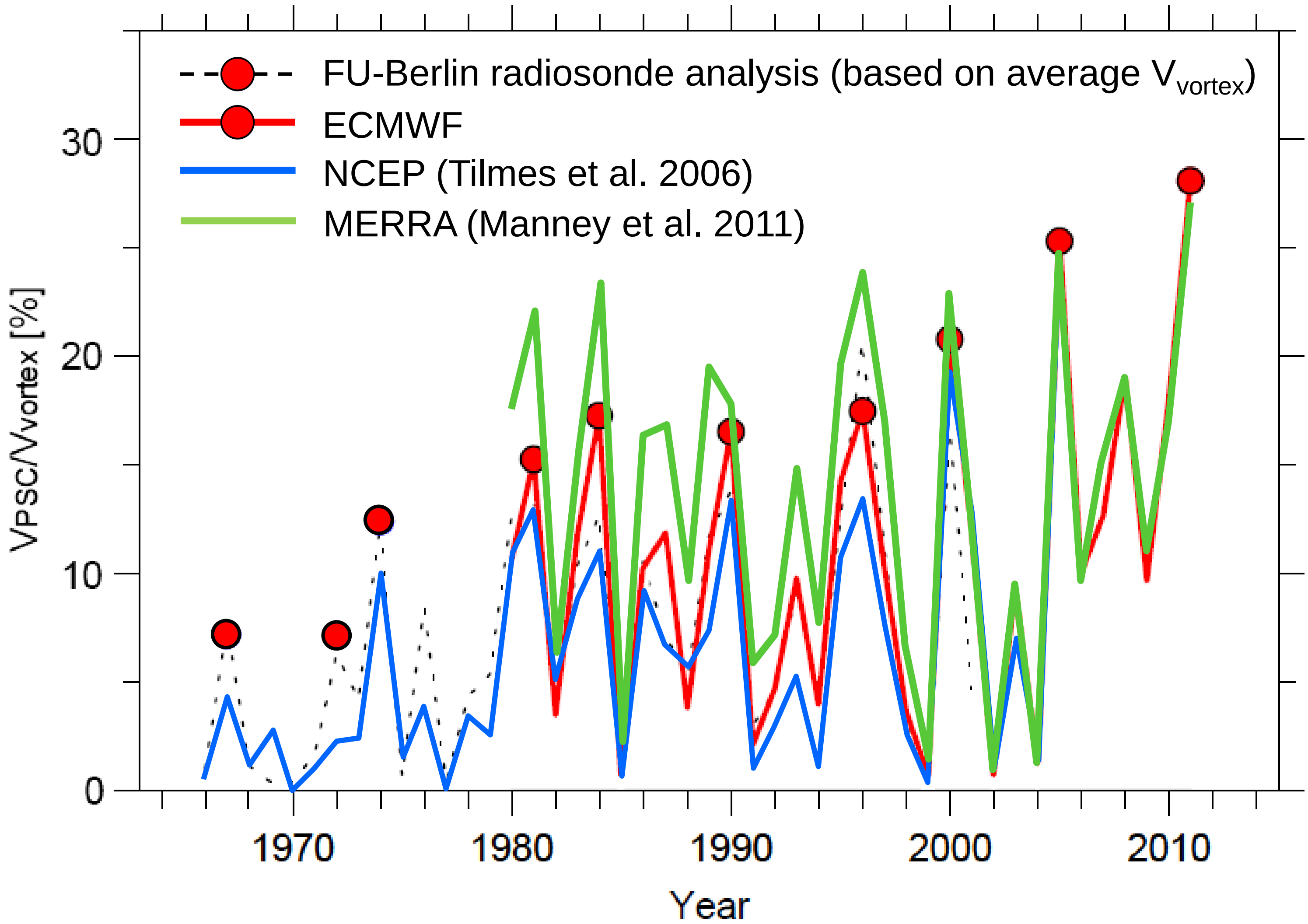
Manney, Santee,
Rex et al., Nature, 2011

Ozone loss versus PSC formation potential (V_{PSC})



Update of Rex et al., 2004; Rex et al., 2006; WMO 2007; WMO 2011

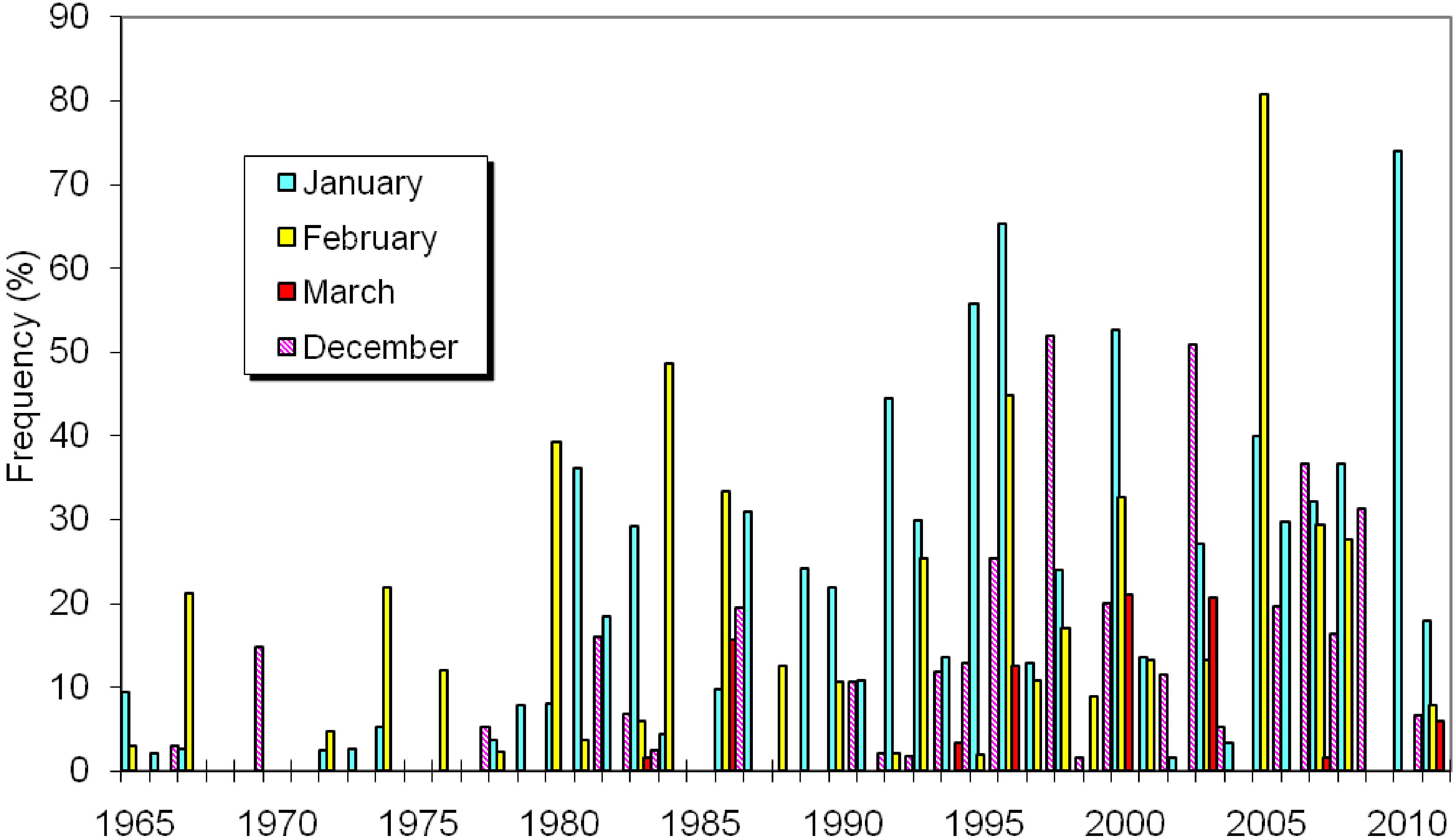
V_{PSC}/V_{Vortex}



Update of Rex et al., 2004; 2006; WMO 2007; 2011

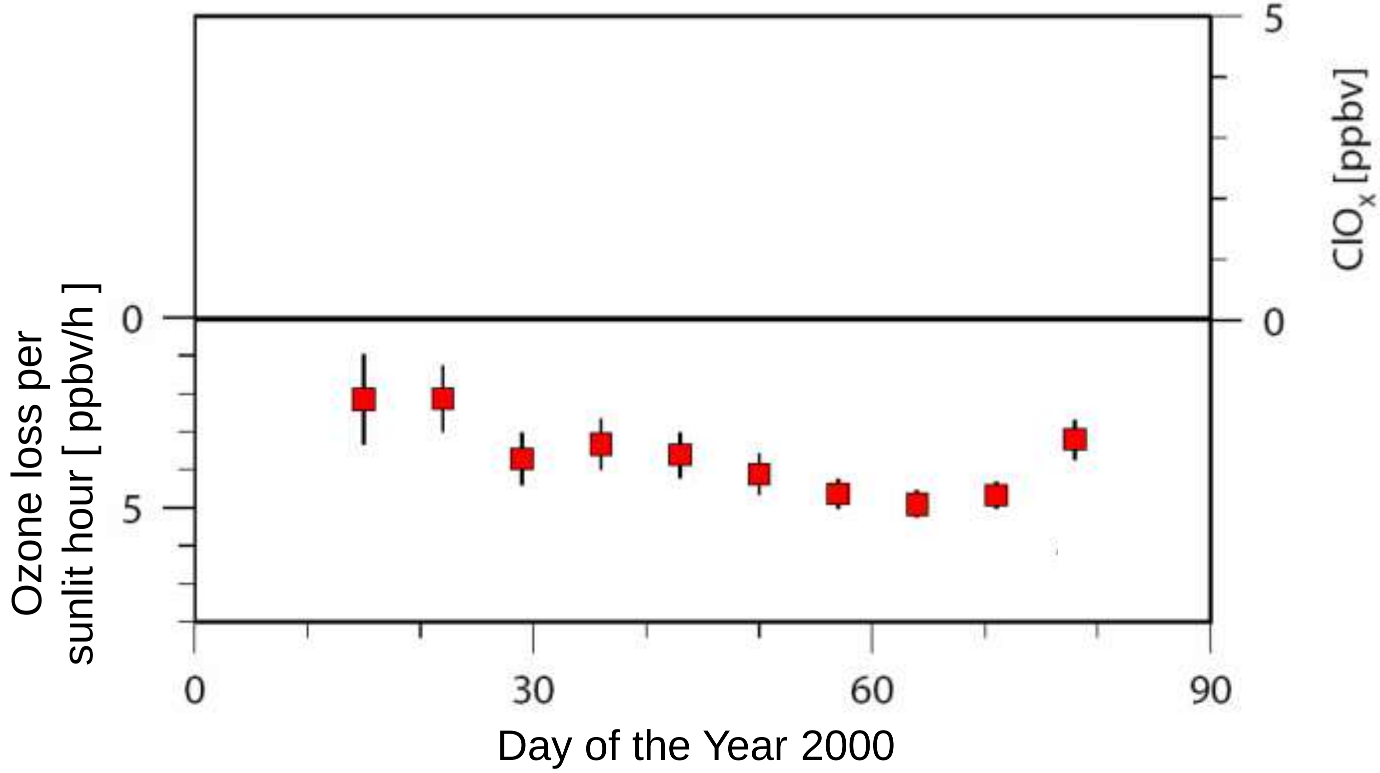
$T<T_{NAT}$ occurrence frequency over Sodankylä

50hPa, based on radiosonde data



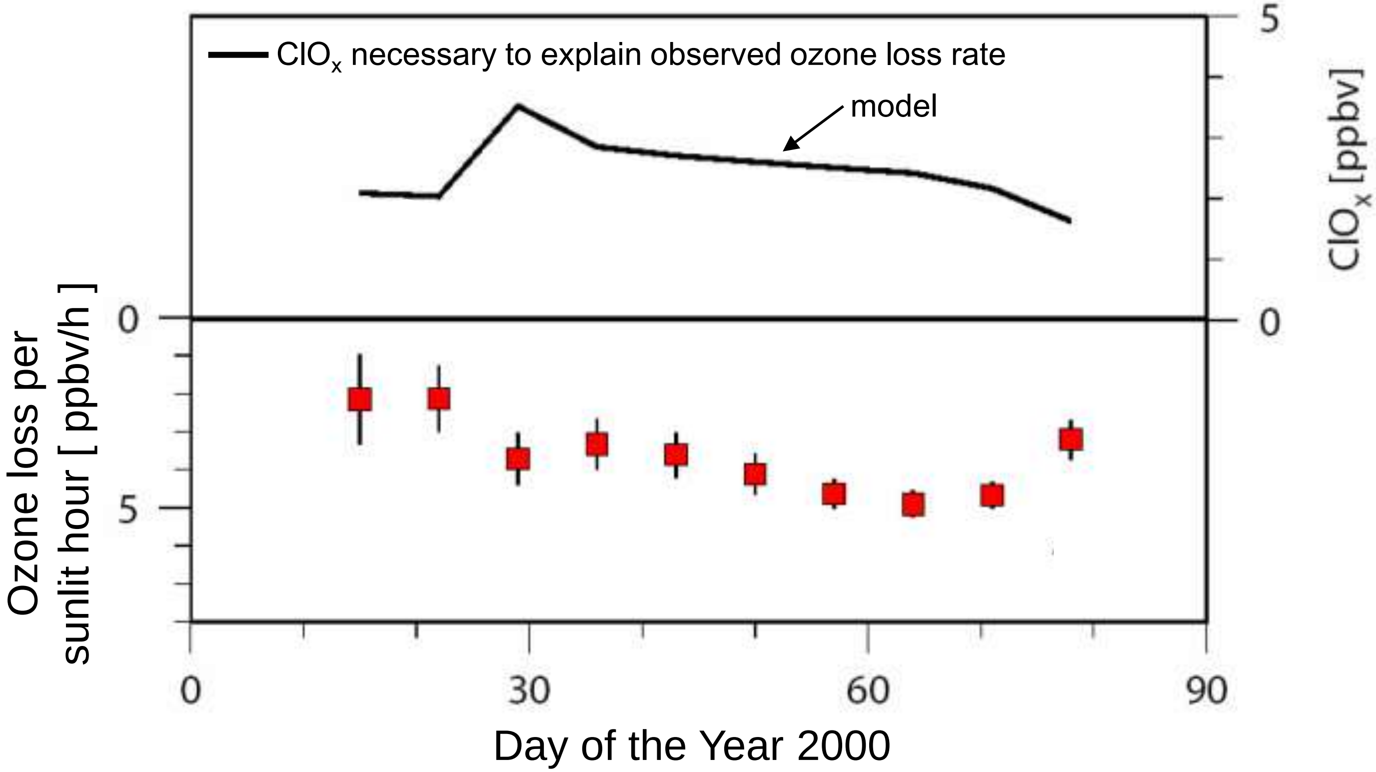
Rigel Kivi, FMI

Theoretical understanding of polar ozone loss process



Frieler et al., GRL 2006; WMO 2007

Theoretical understanding of polar ozone loss process



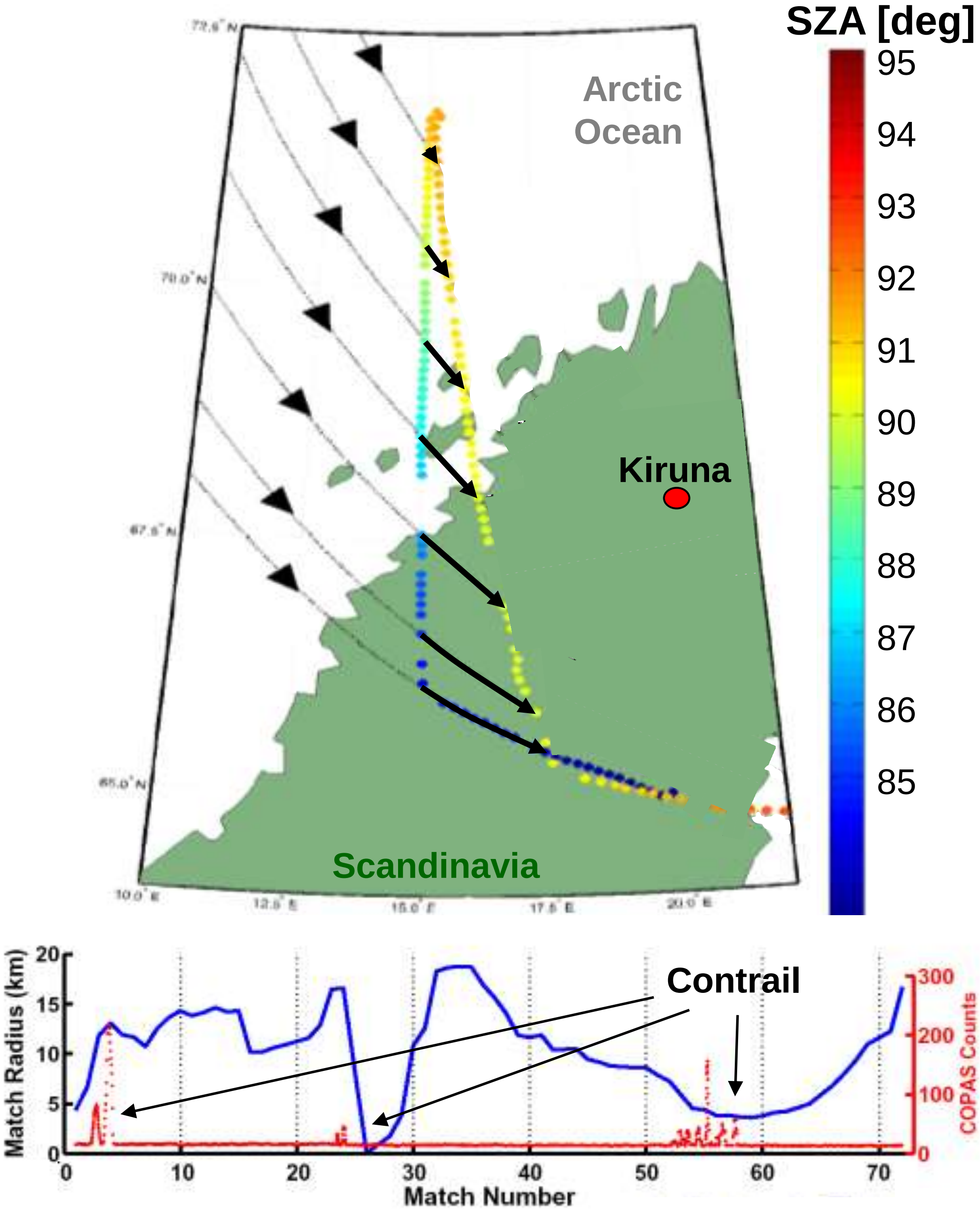
Frieler et al., GRL 2006; WMO 2006

Geophysika – 2003, 2010

Kiruna, March 2010

Lagrangian aircraft measurements:

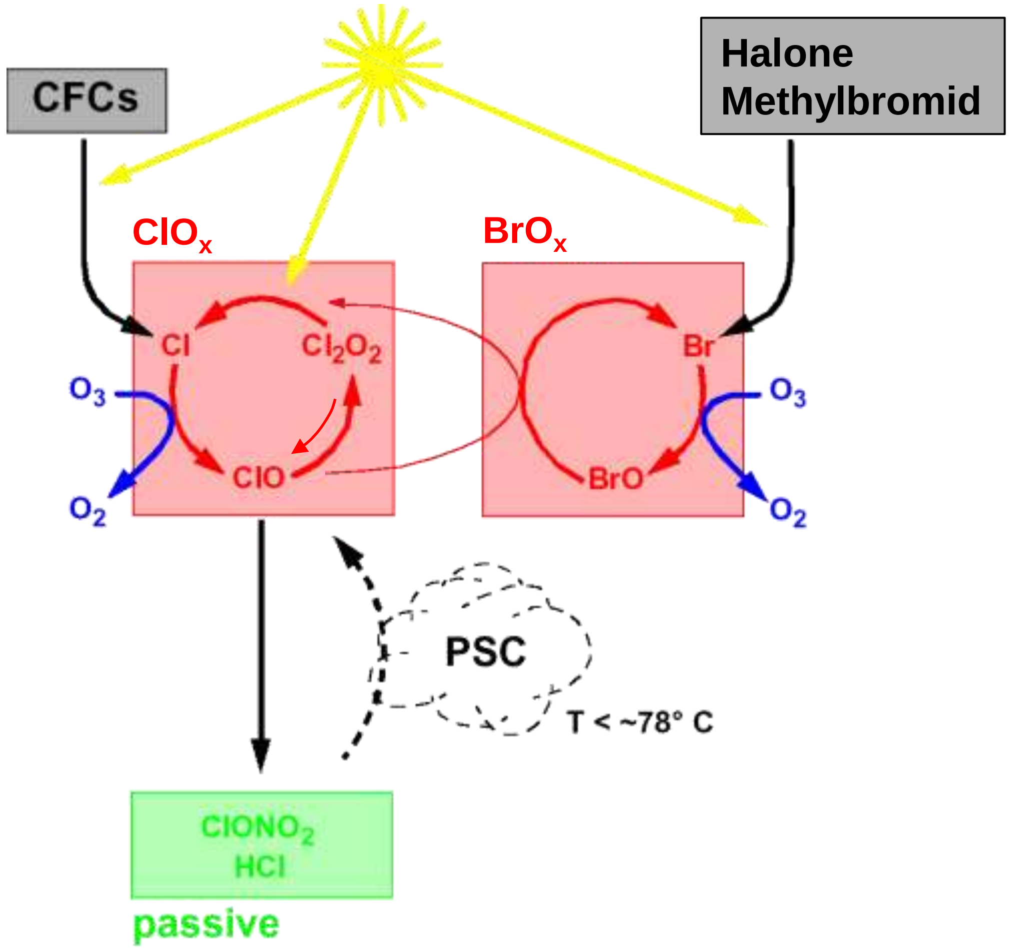
Self-Match-flights



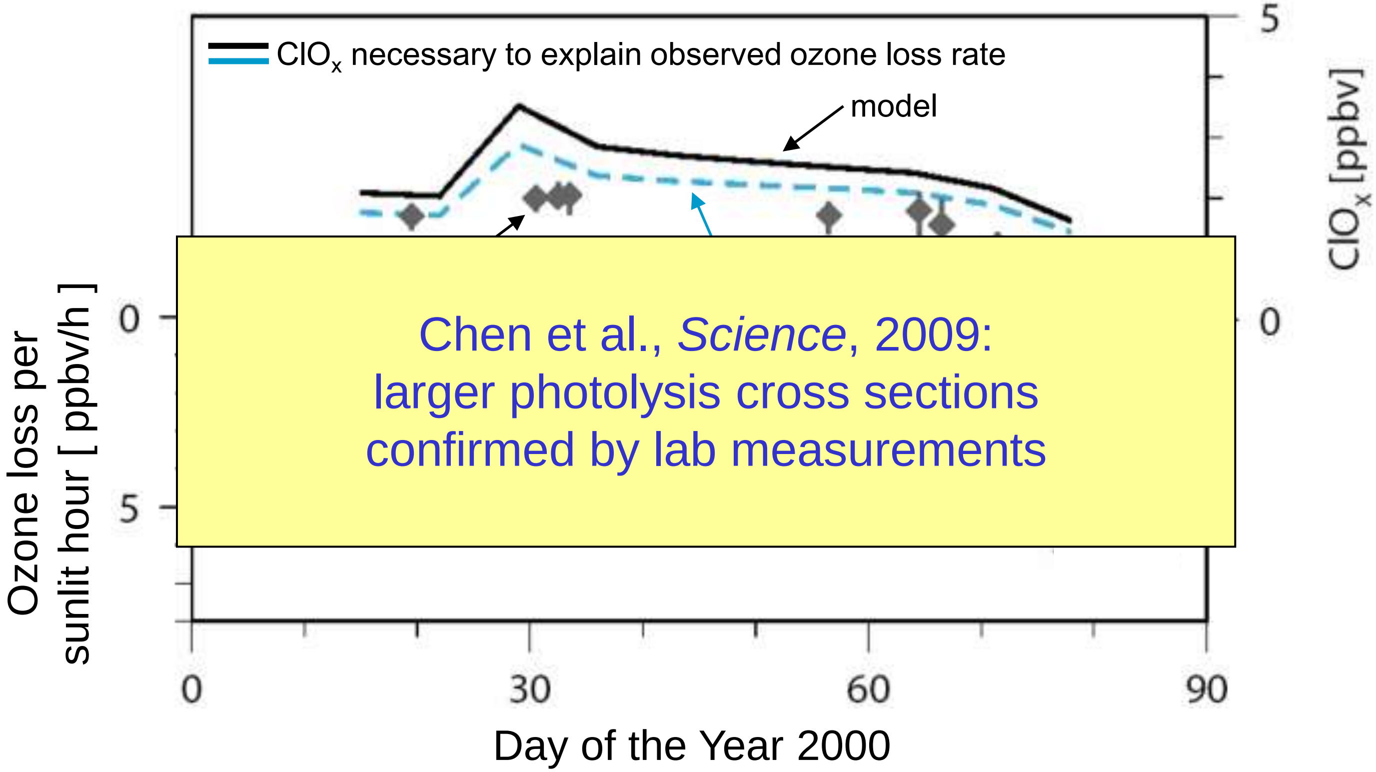
- Flight pattern designed to probe air masses before and after sunset/sunrise
- Success of flight planning confirmed by contrail encounter
- **EUPLEX:**
  - 1 Self-Match flight in 2003
- **RECONCILE: Jan-March 2010**
  - 3 Self-Match flights
  - 1 Match/Self-Match flight

Schofield et al., GRL, 2008

Polar ozone loss process

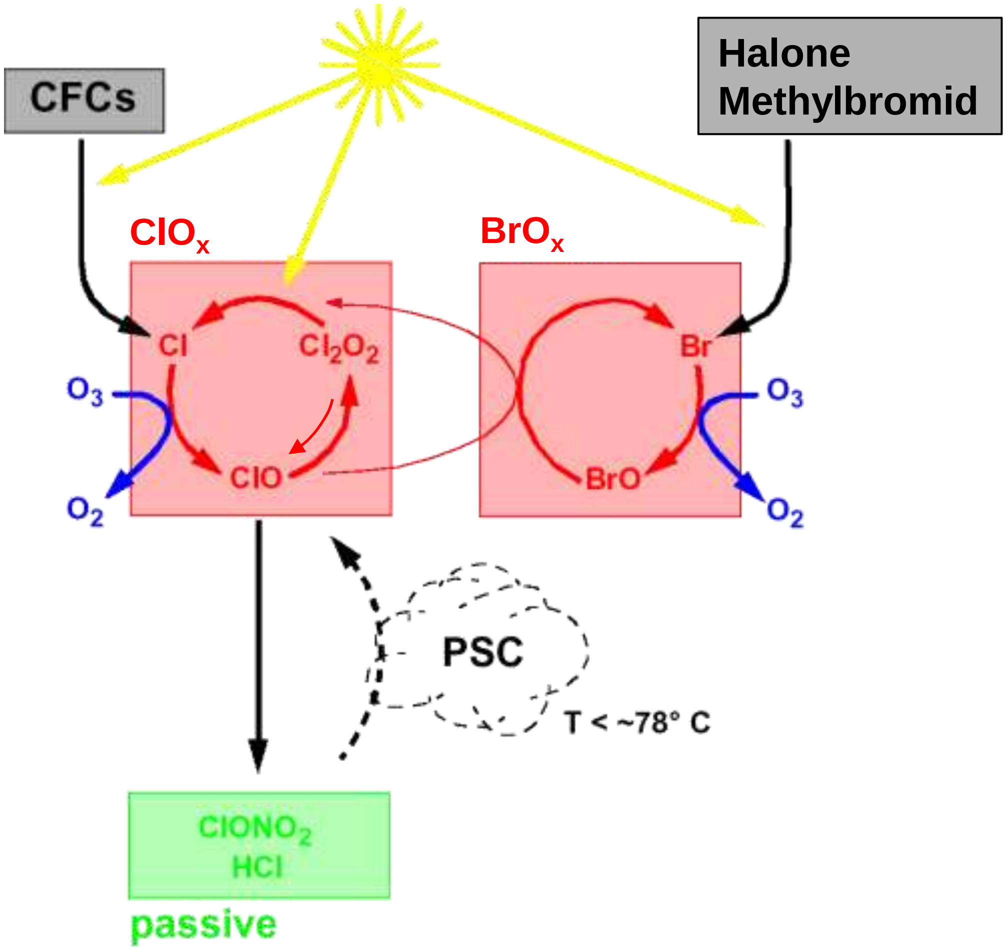


Theoretical understanding of polar ozone loss process

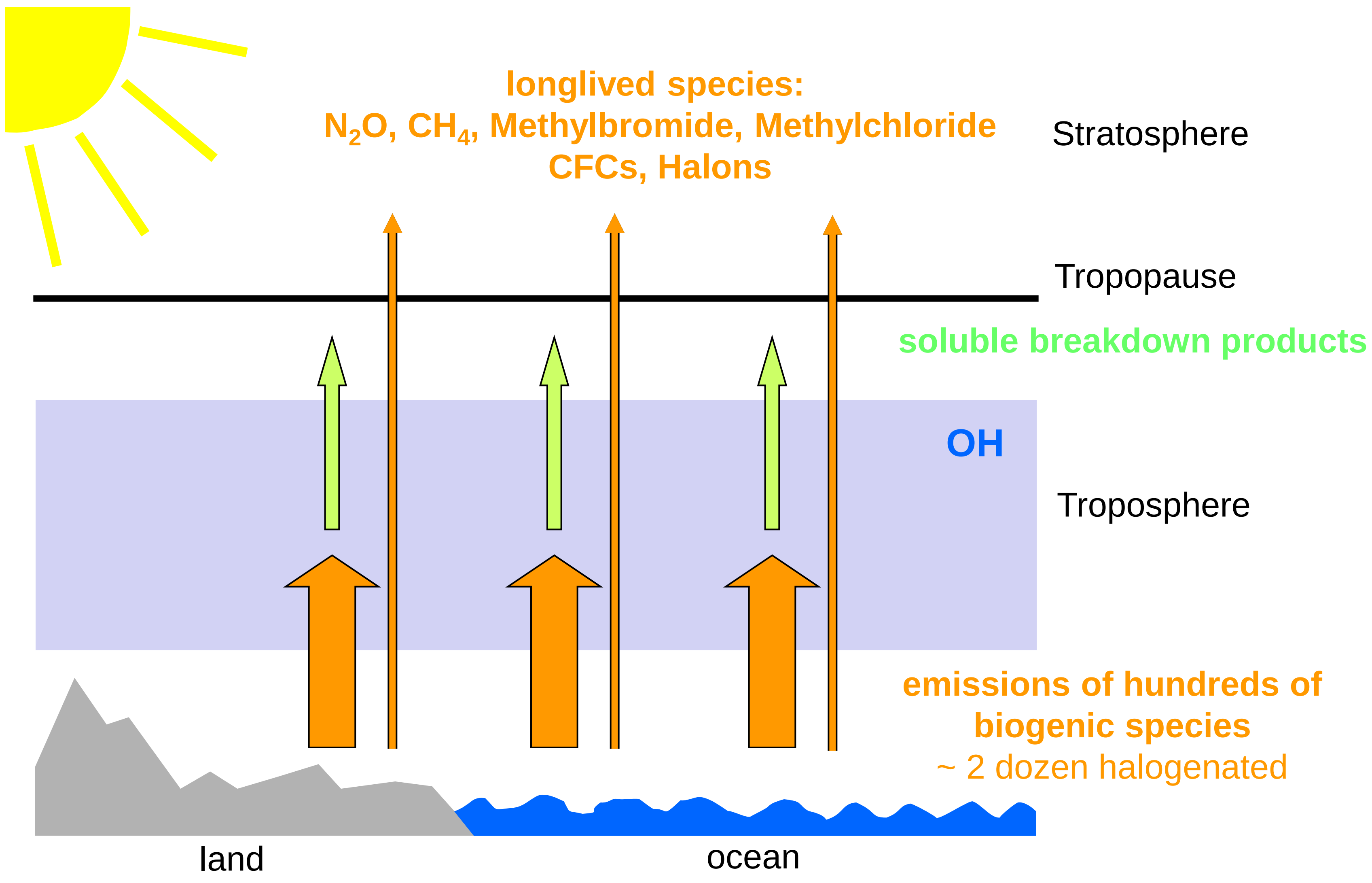


Update of Frieler et al., GRL 2006; WMO 2007

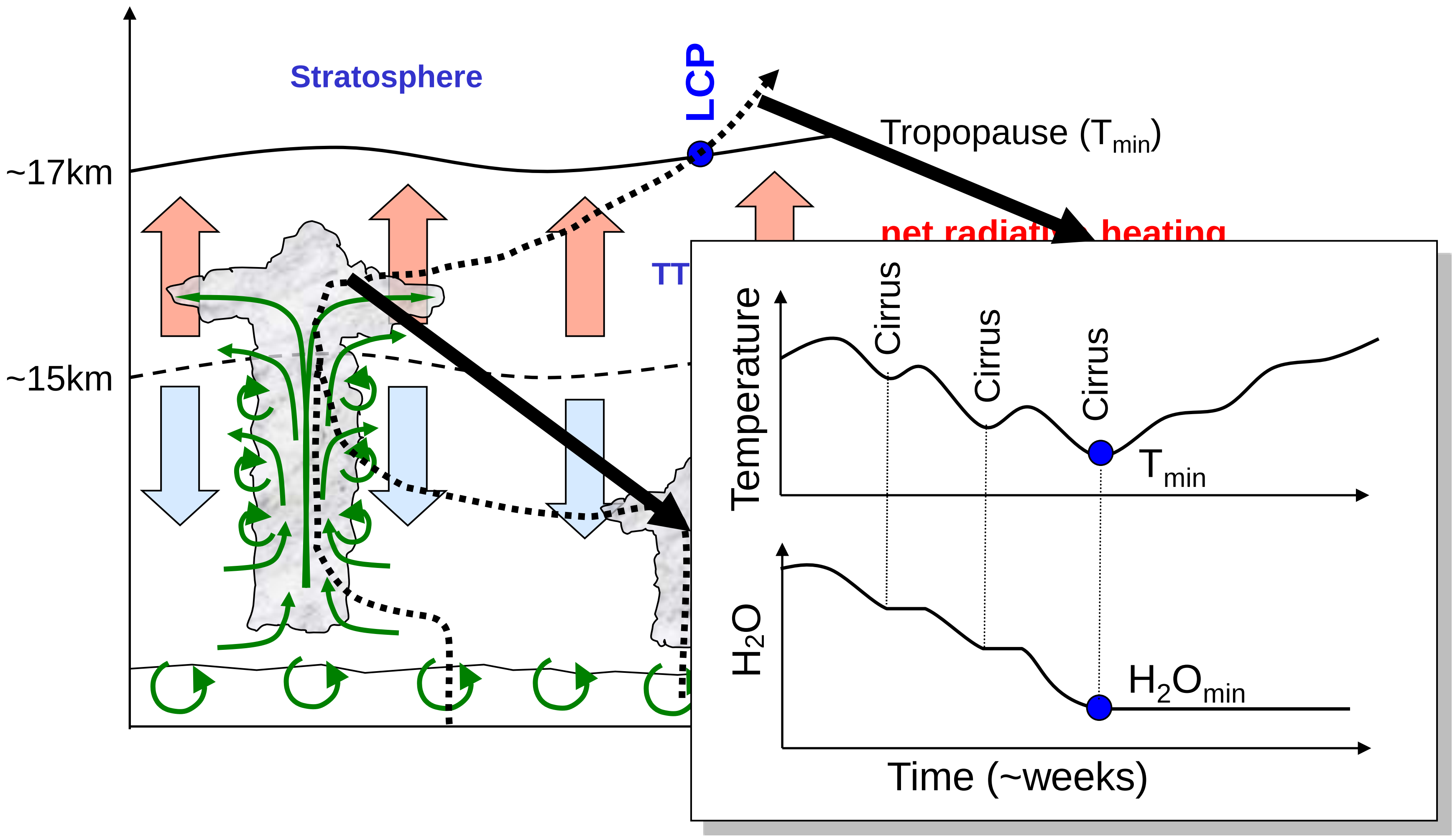
Polar ozone loss process



The „OH shield“



Transport into the Stratosphere



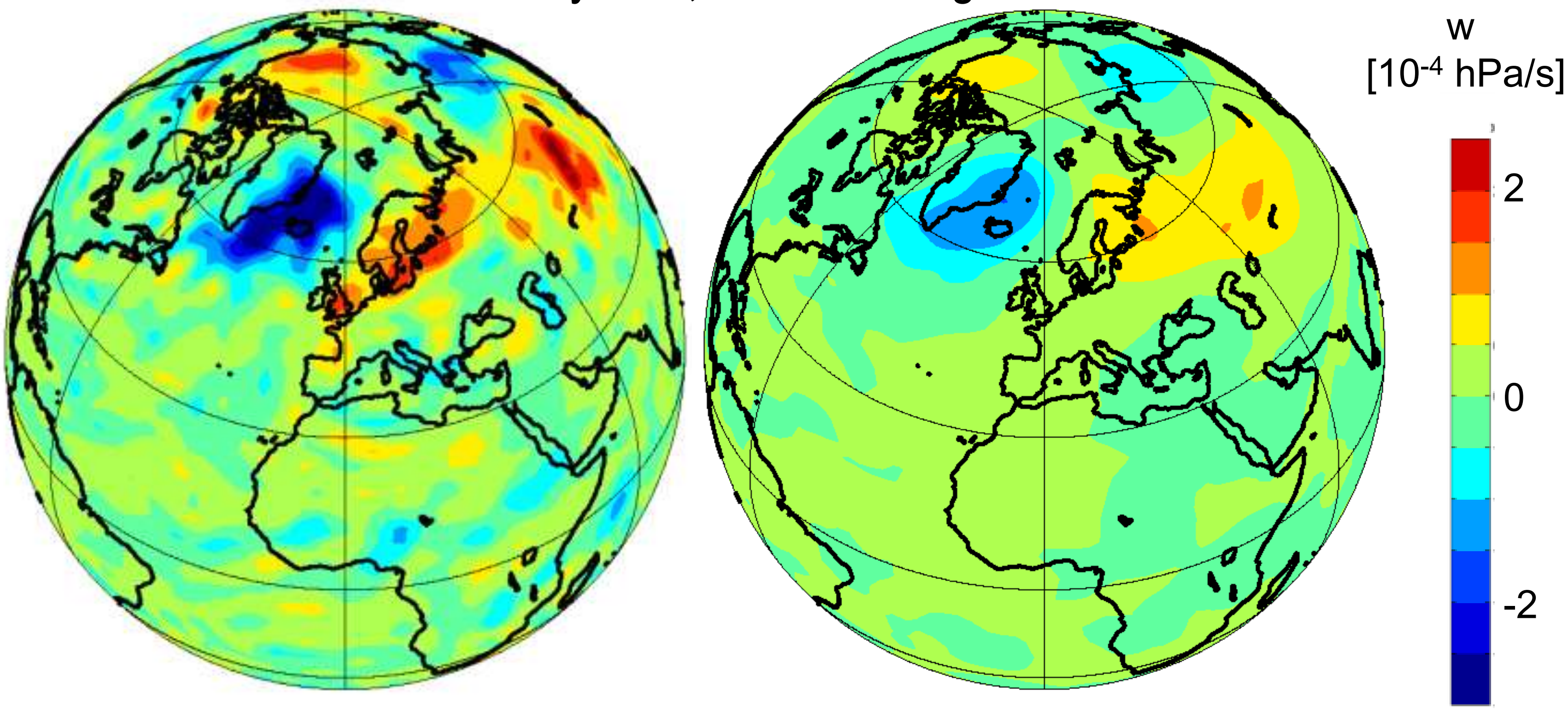
Thermodynamic vertical wind

w from the continuity equation for mass:

From the continuity equation for thermal energy follows:

$$w = (Q - \partial_t\theta - \frac{u}{a\cos\varphi}\partial_\lambda\theta - \frac{v}{a}\partial_\varphi\theta)/\partial_z\theta$$

1 January 2000, 24 hour average



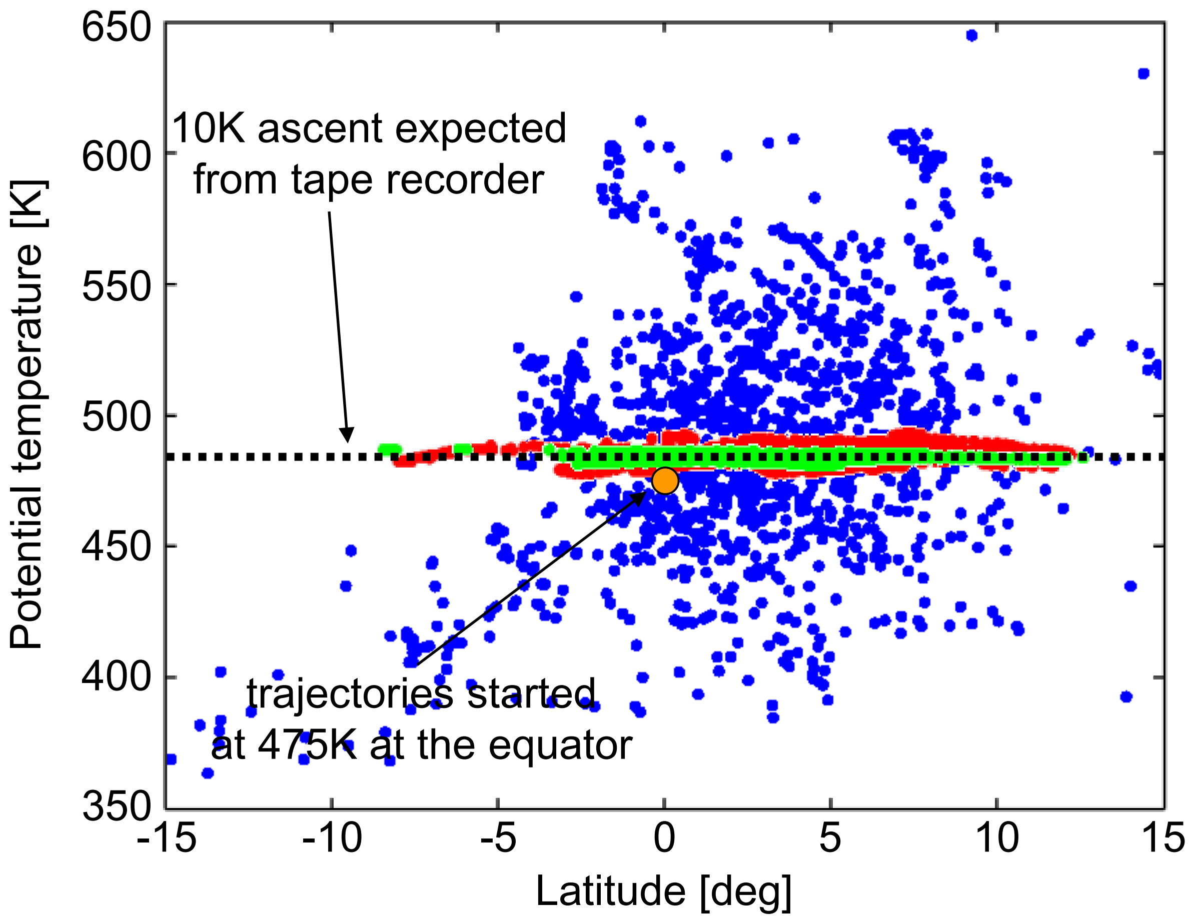
w-ECMWF

w-thermodynamic

Wohltmann and Rex, ACP, 2008

20 days lagrangian transport in ATLAS

starting 1 January 2000



Vertikal wind (w-ECMWF)

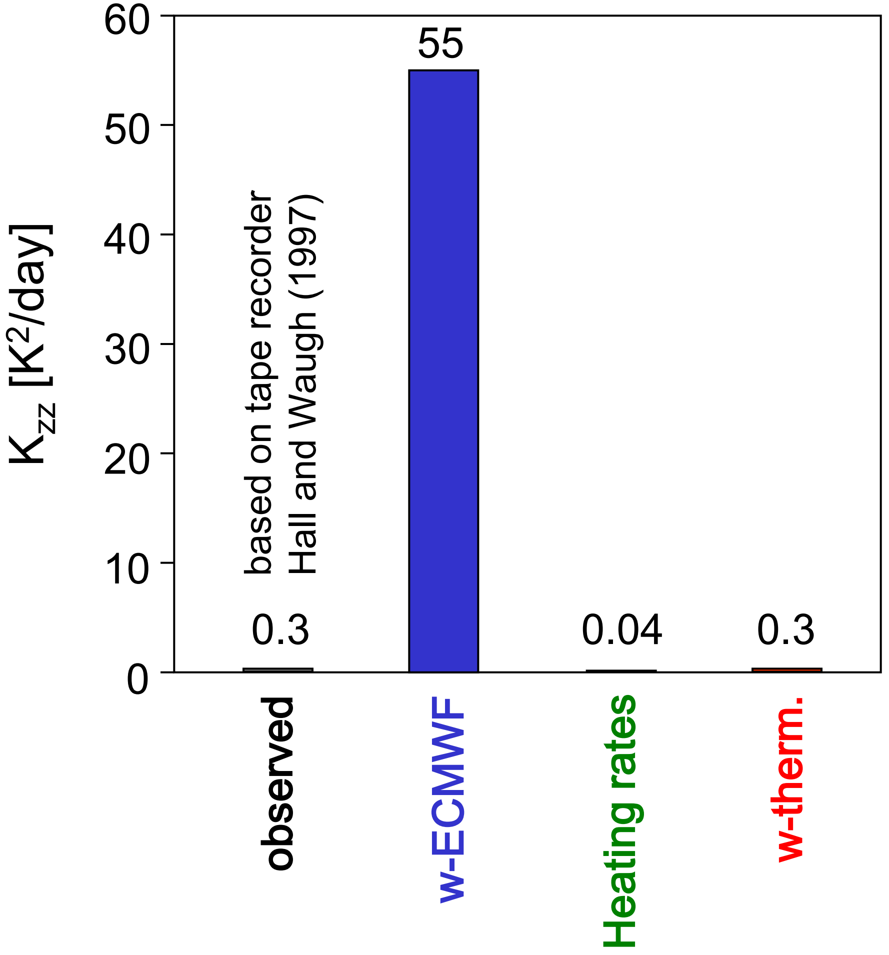
Heating rates (Q)

Thermodynamically balanced vertical wind (w-therm)

Wohltmann and Rex, ACPD, 2007

Vertical diffusion rate

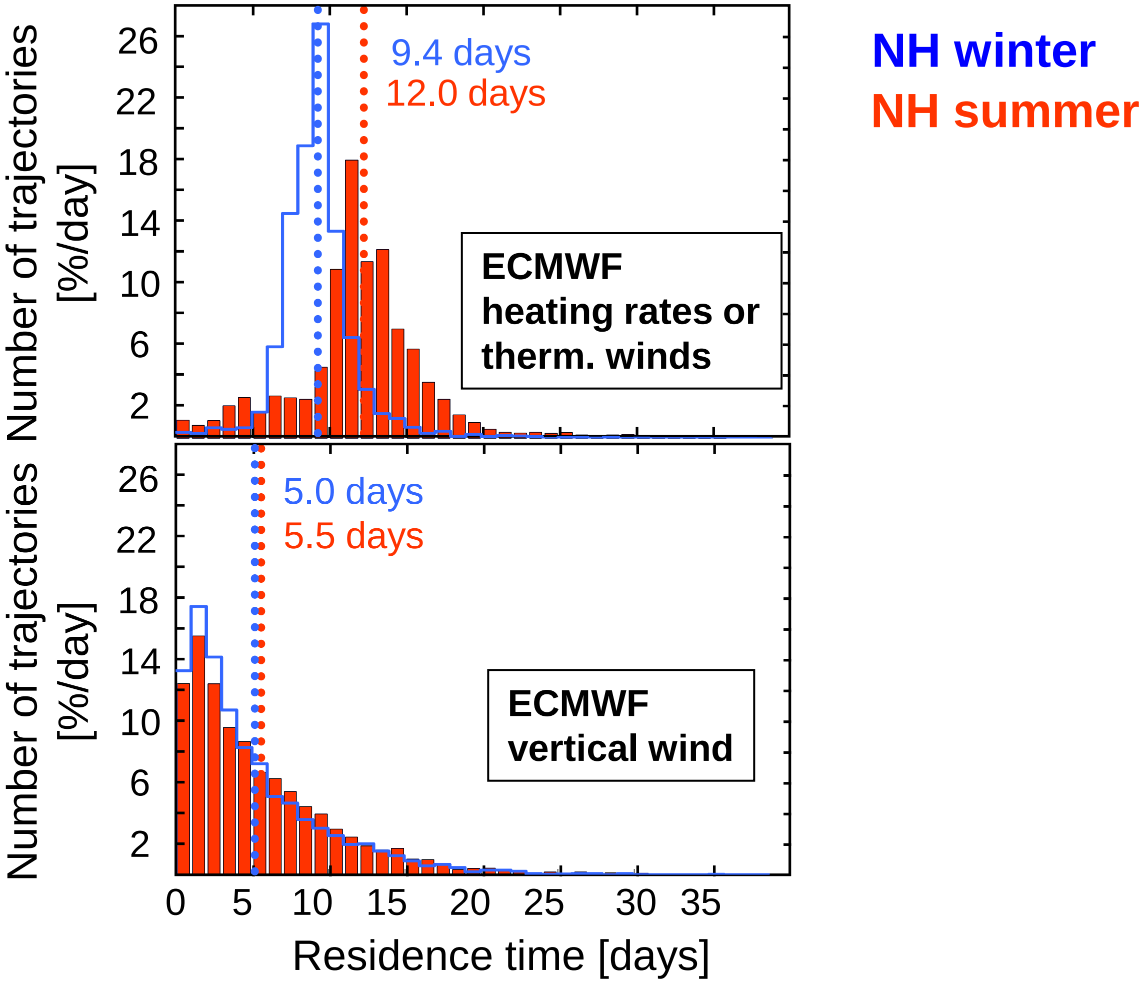
20 km altitude



Wohltmann and Rex, ACPD, 2007

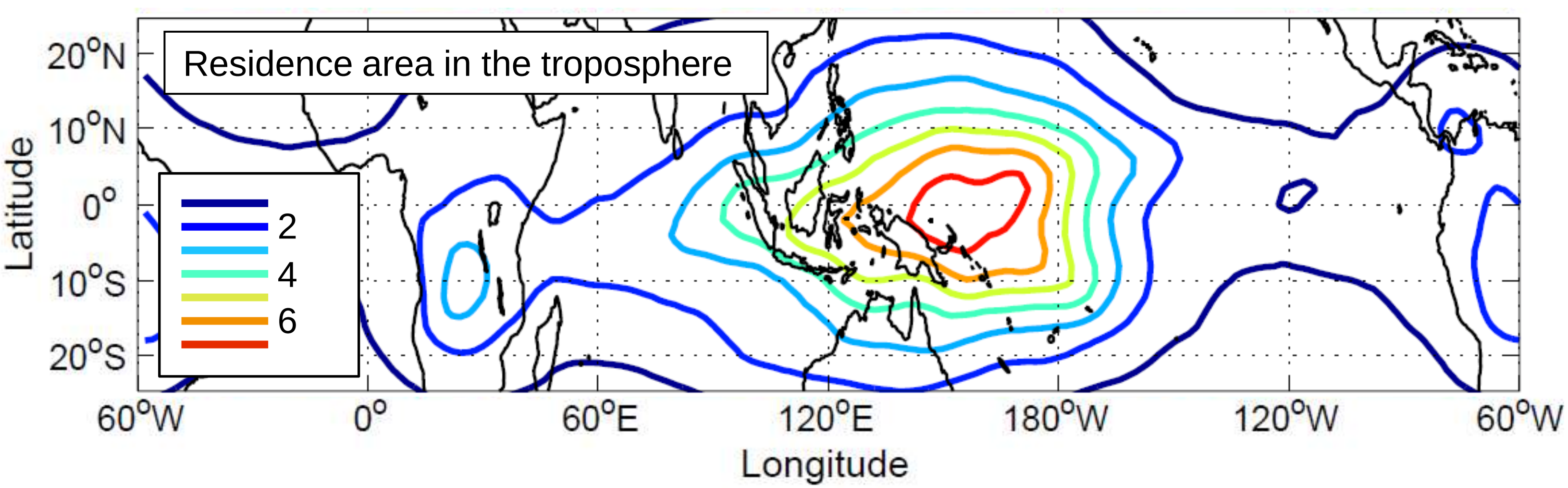
Residence time in upper TTL

(between 385-395 K)



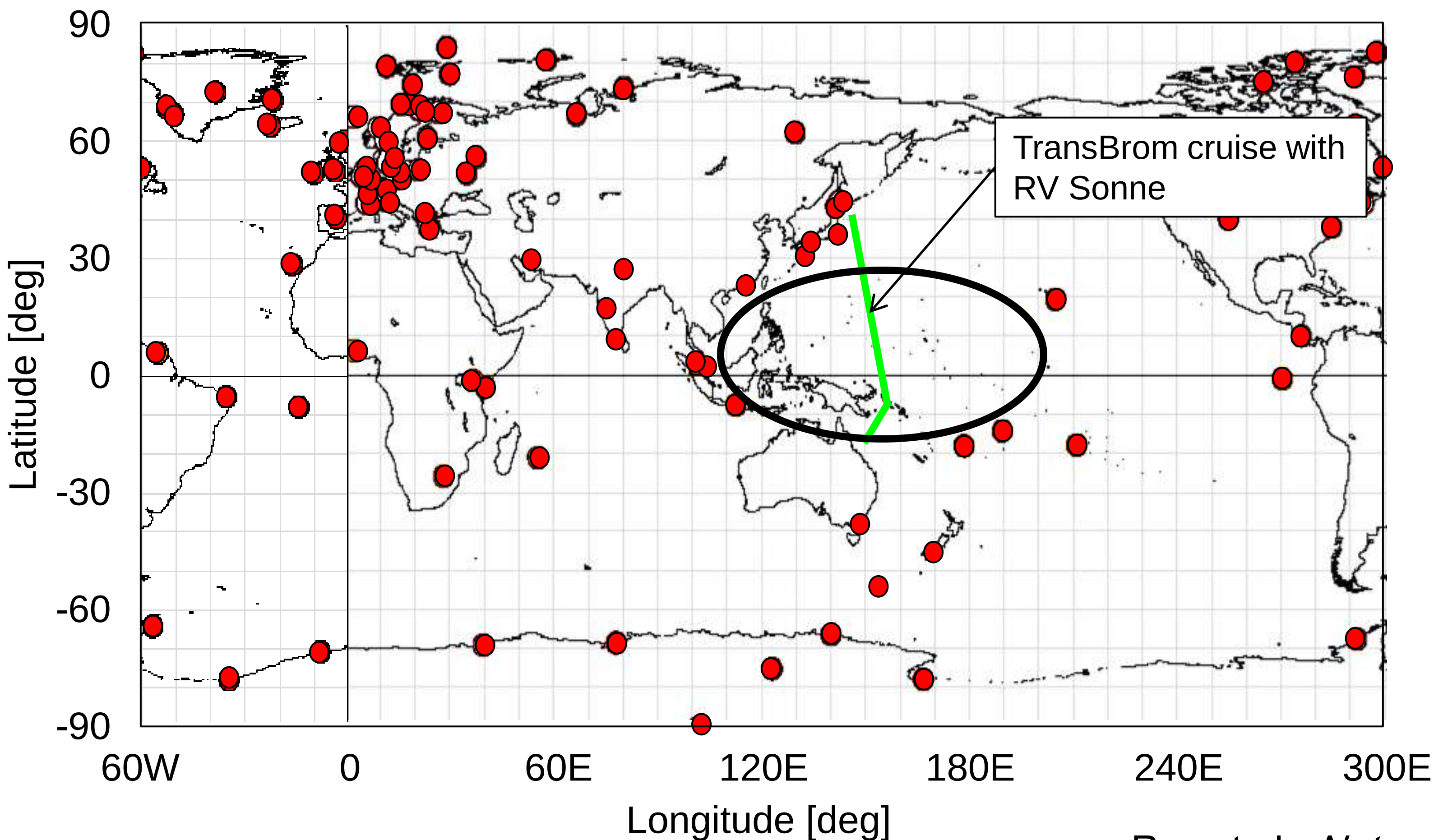
Geographic distribution of time spent in the troposphere for stratospheric air

During transport from the boundary layer to the LCP
Given relative to the tropical average
Based on ATLAS



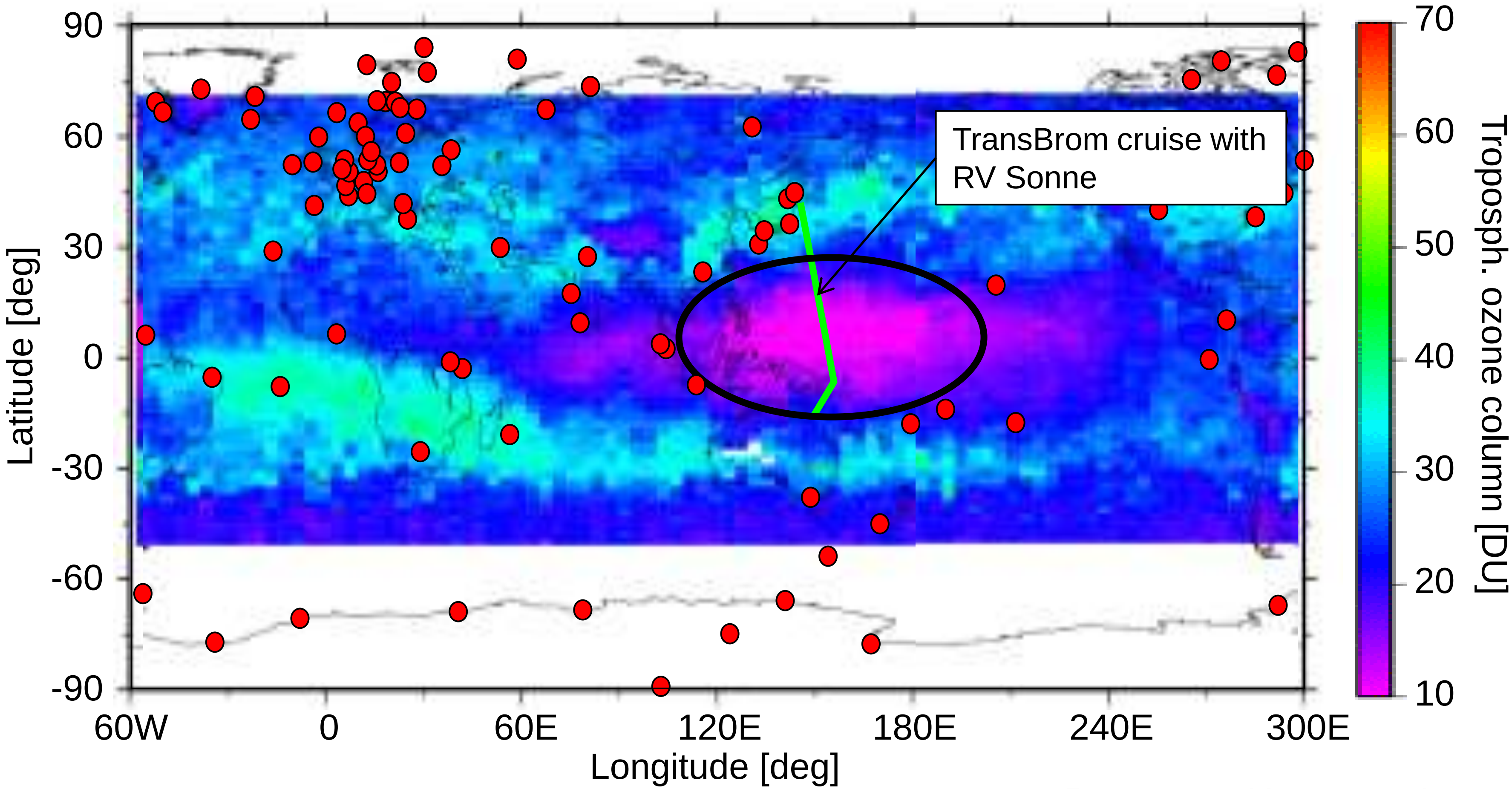
Rex et al., *Nature*, under review

Global ozonesonde station network



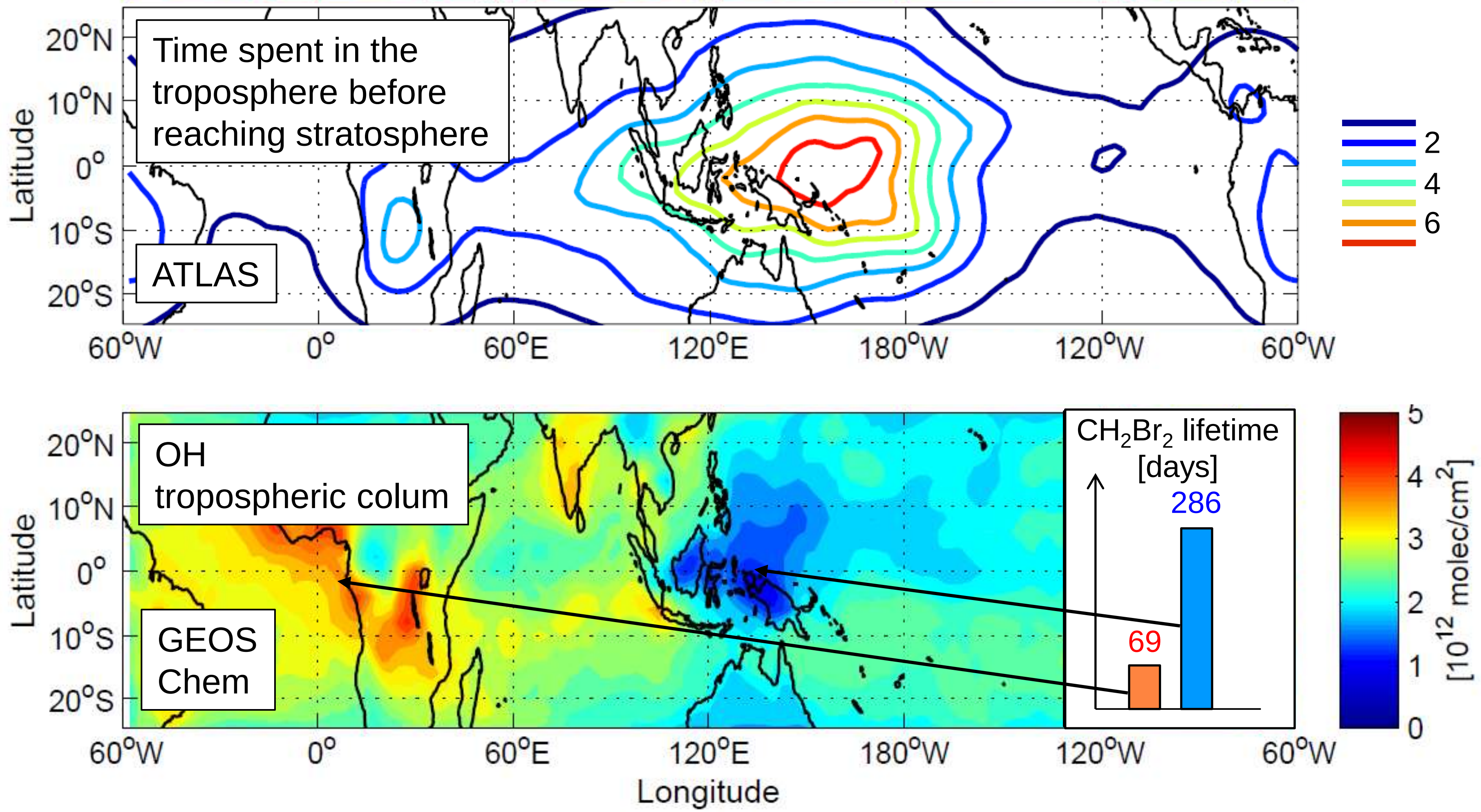
Rex et al., *Nature*, under review

TES tropospheric ozone column
October 2009

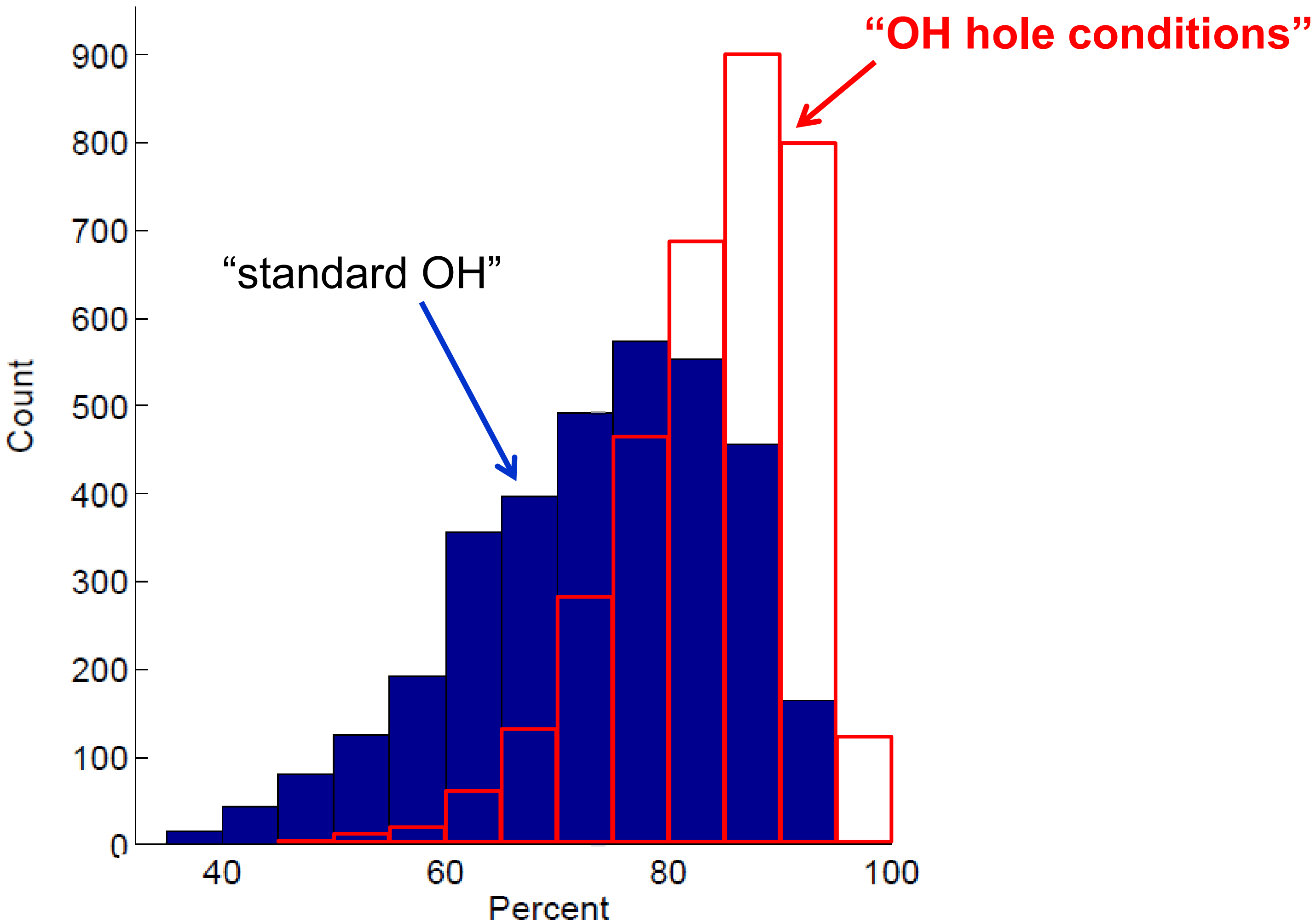


Rex et al., *Nature*, under review

Source region for stratospheric air OH distribution / SO_2 lifetimes

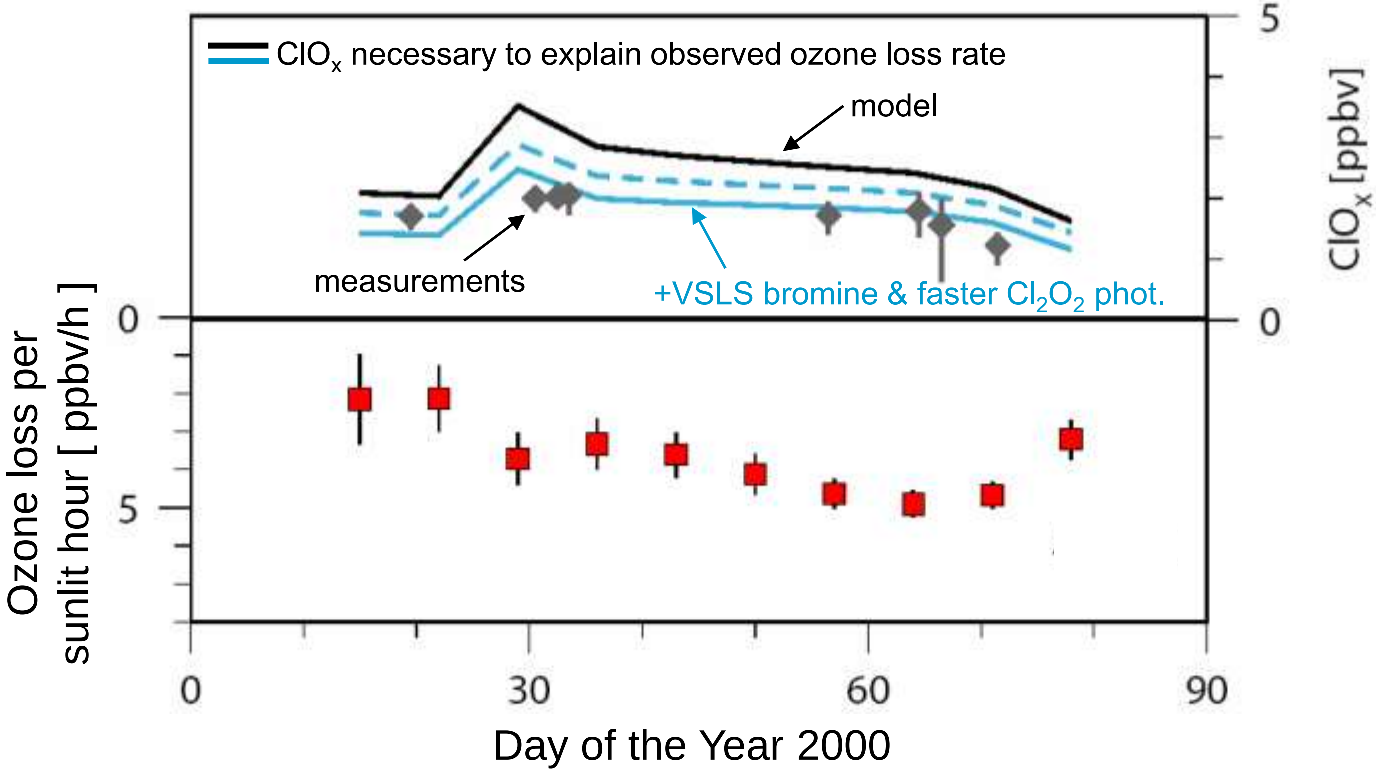


Fraction of CH_2Br_2 reaching the stratosphere



Rex et al., *Nature*, under review

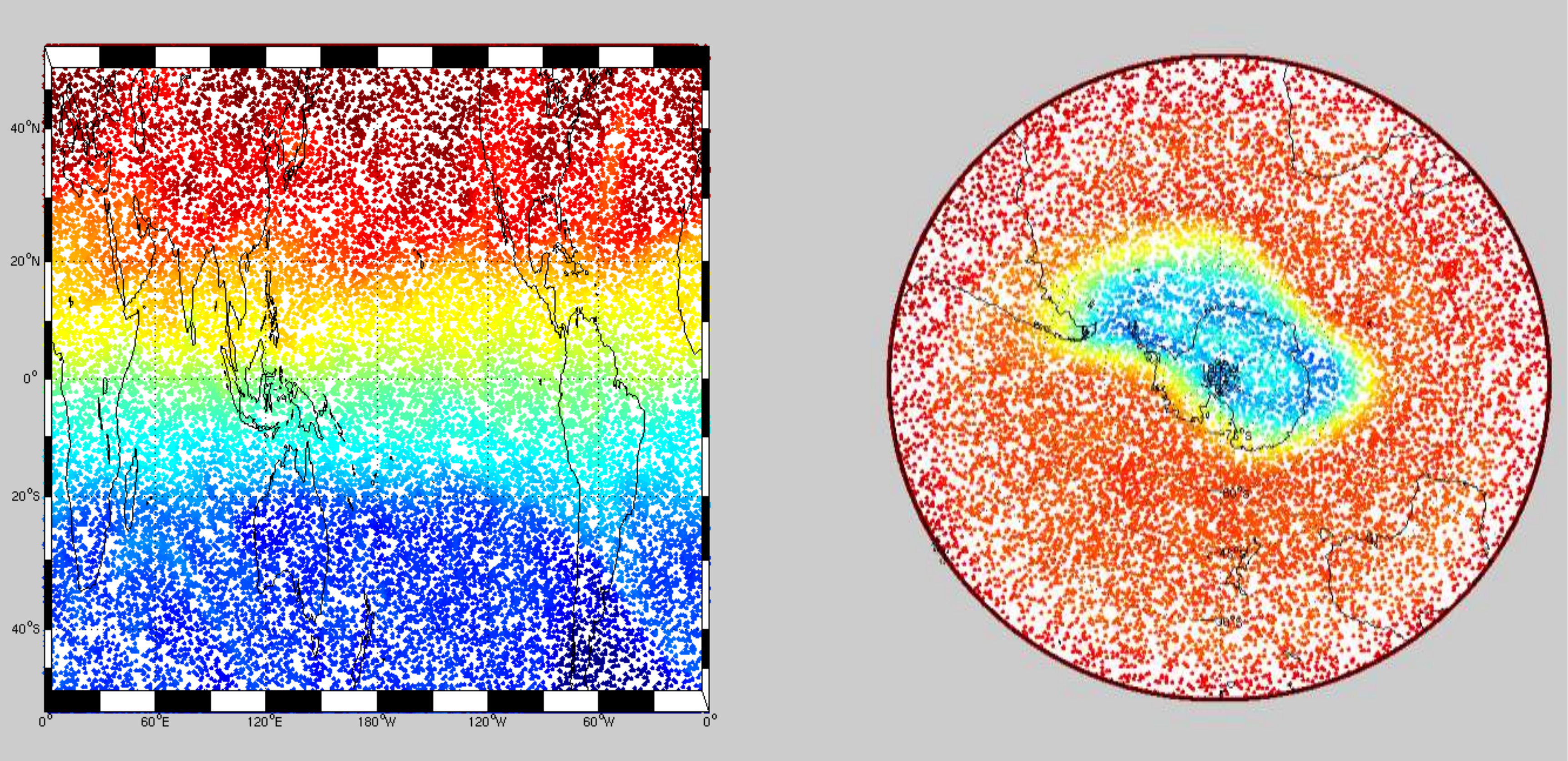
Theoretical understanding of polar ozone loss process



Update of Frieler et al., GRL 2006; WMO 2007

Lagrangesche Modellierung – ATLAS

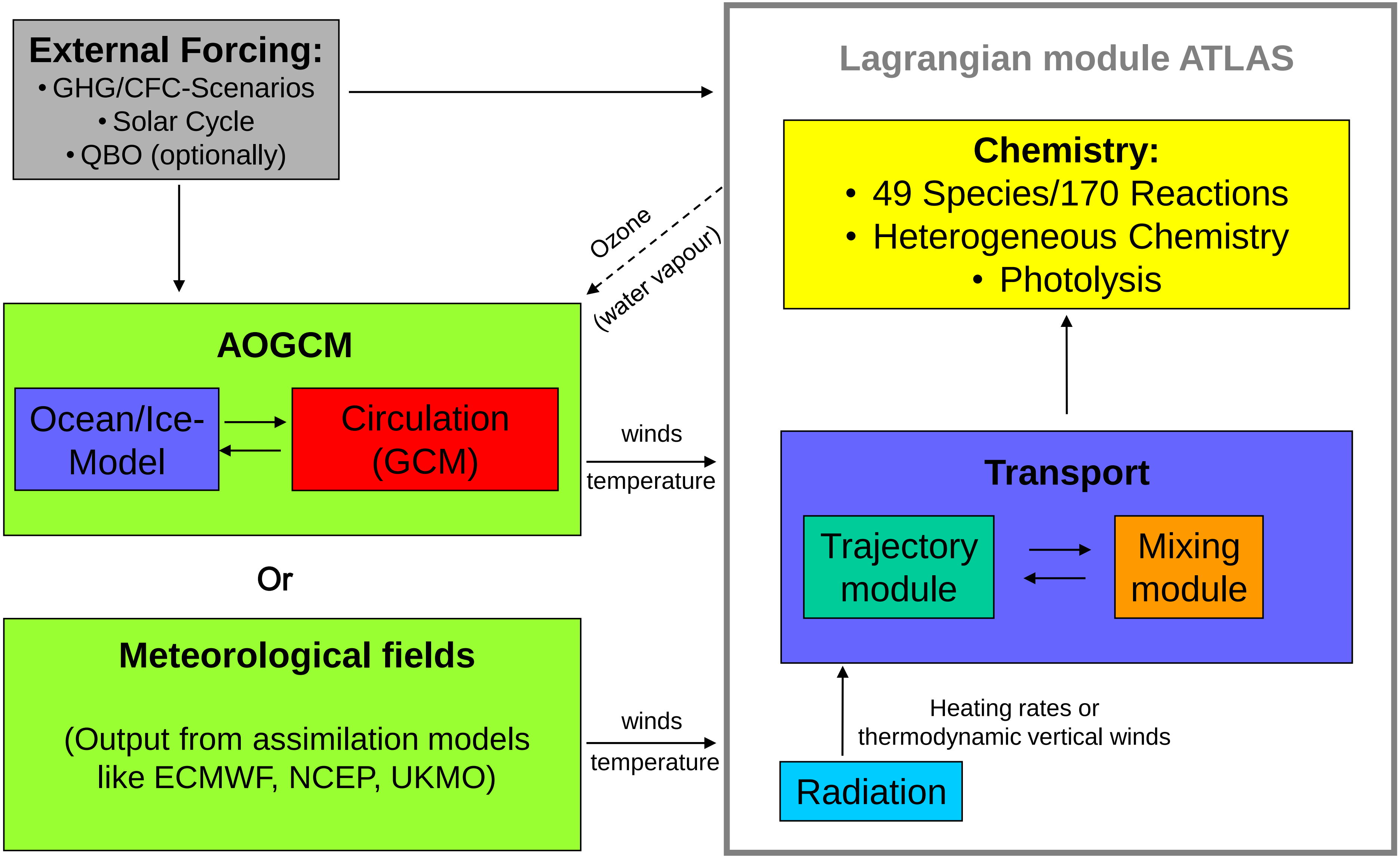
~20km altitude, 20 model days, dynamical tracer (PV), ~50km resolution run



- detailed homogeneous and heterogeneous chemistry
- Lagrangian particle sedimentation scheme
- no numerical diffusion, sophisticated 3d mixing scheme
- full parallel architecture – long integrations for climate runs feasible

Wohltmann & Rex, 2009; Wohltmann, Lehmann, and Rex, 2010

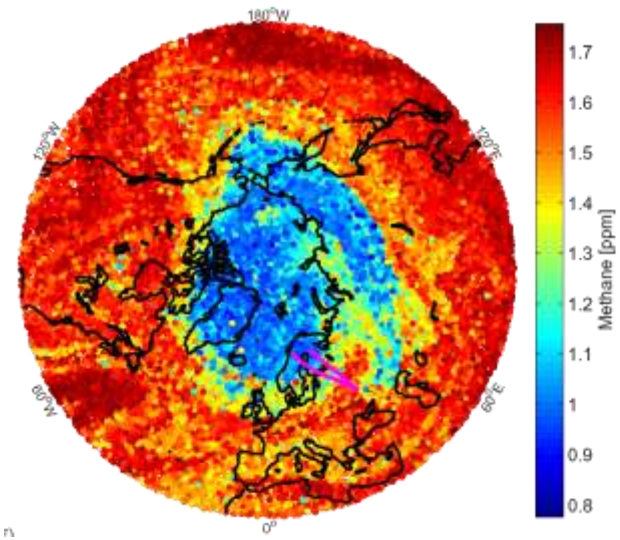
ATLAS – fully lagrangian chemistry-/transport modell



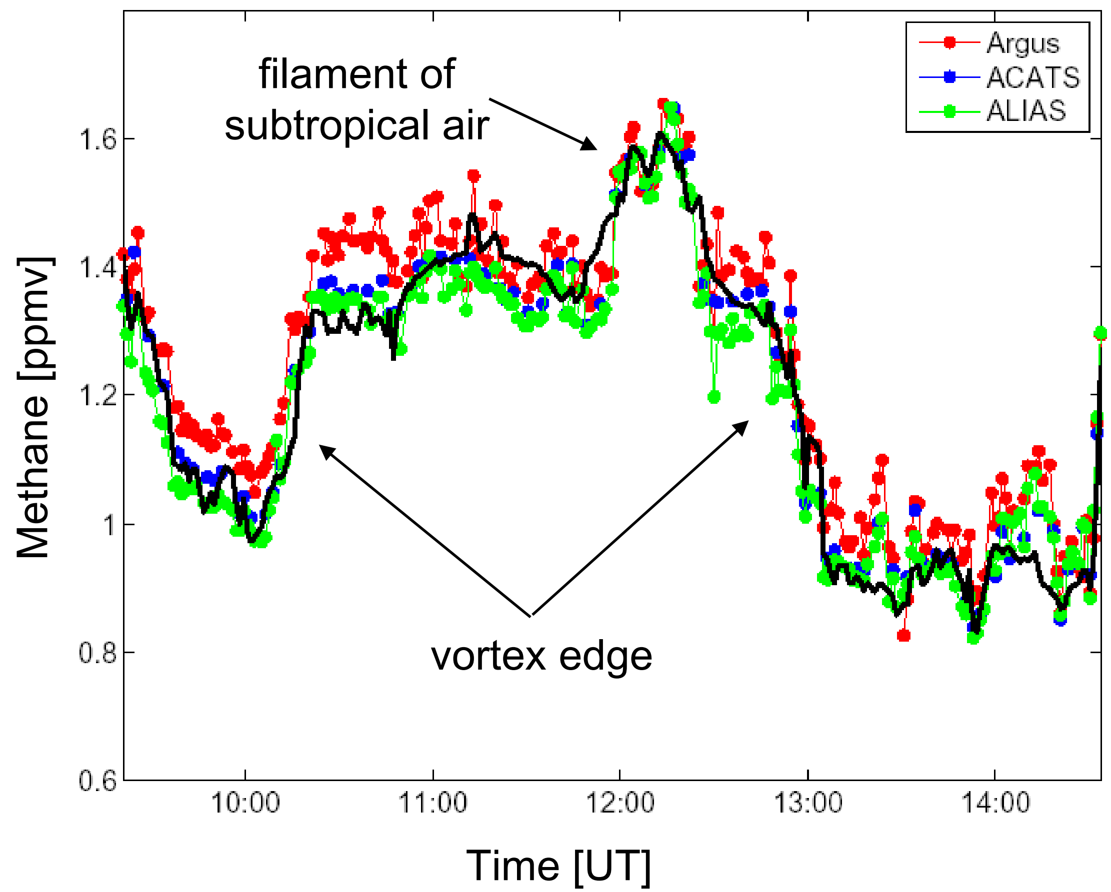
Wohltmann & Rex, 2009; Wohltmann, Lehmann, and Rex, 2010

ATLAS vs. SOLVE ER-2

27 January 2000



Methane

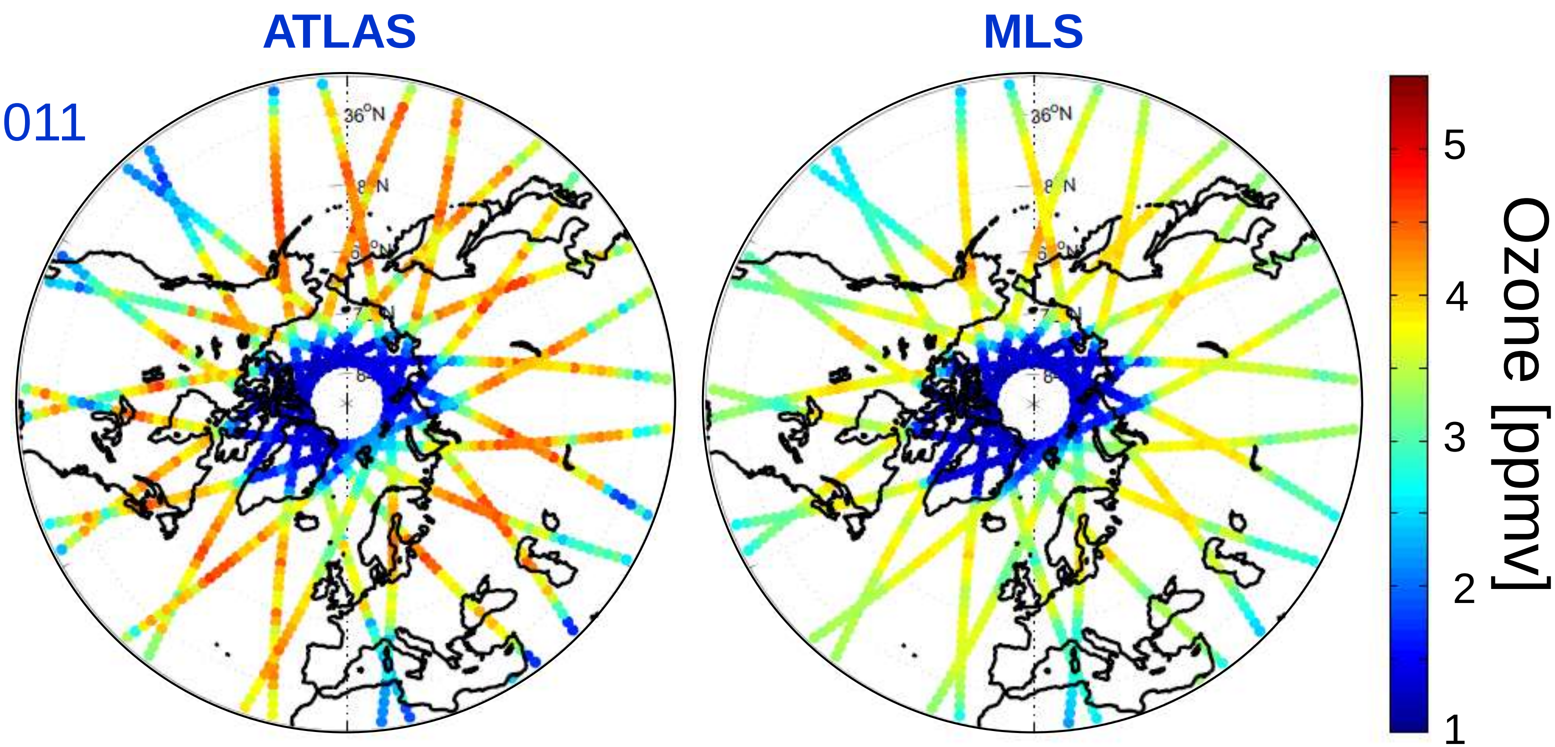


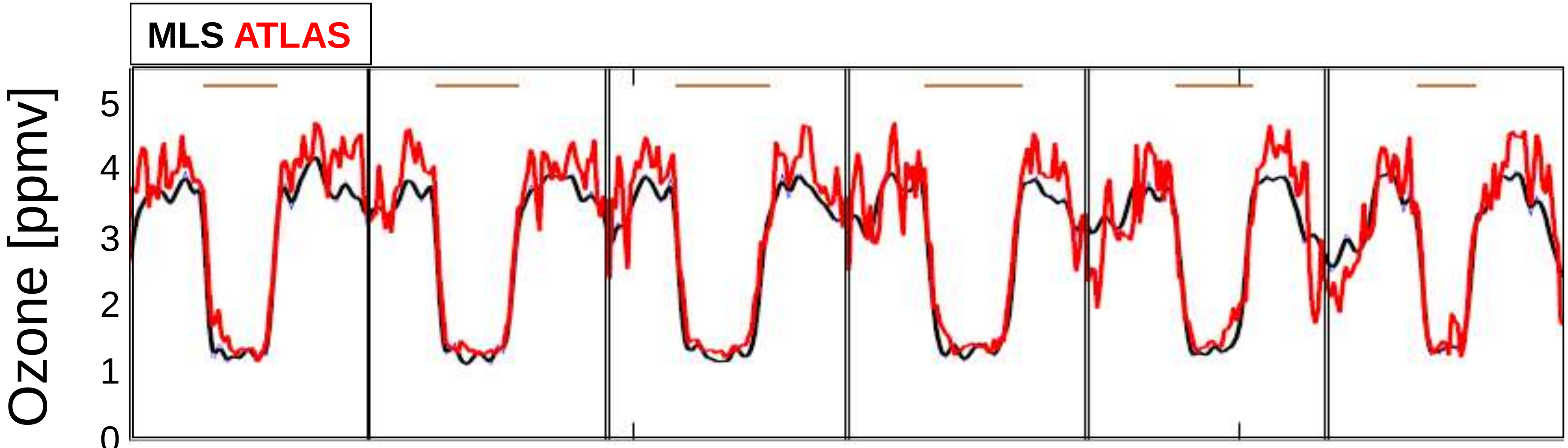
Wohltmann, Lehmann, and Rex, 2010

Ozone

16 March 2011

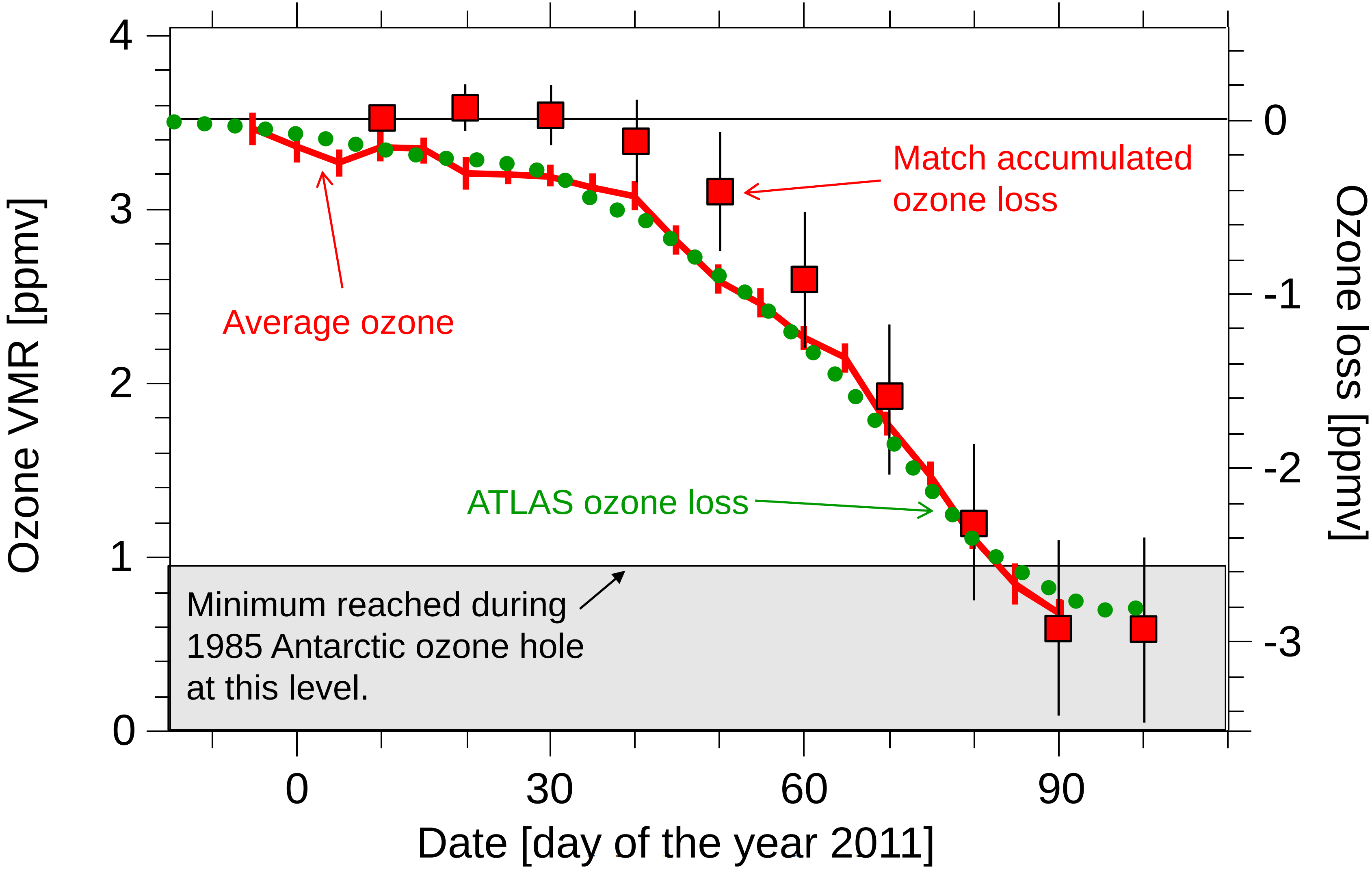
46 hPa





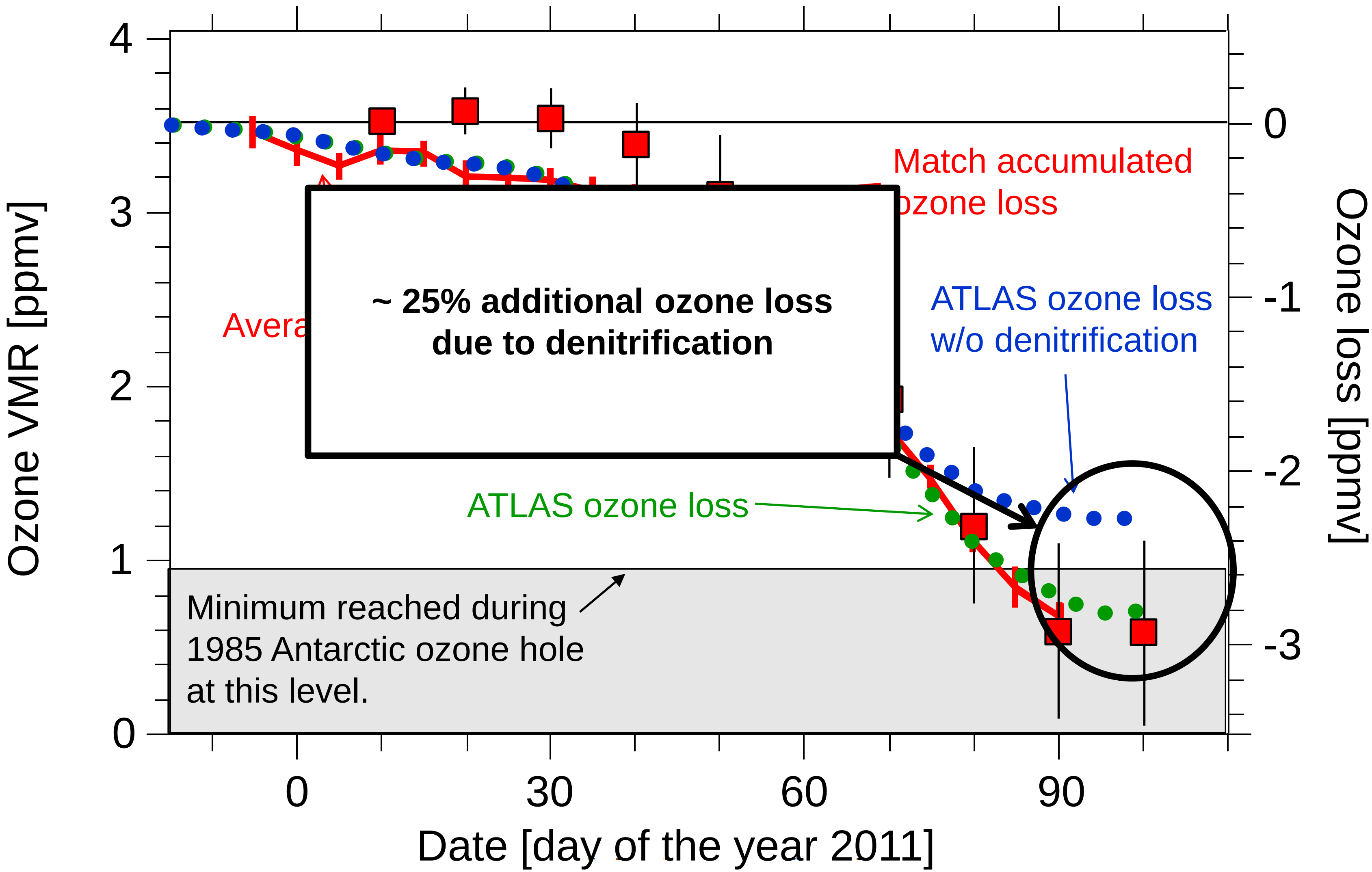
Ozone and ozone loss inside vortex @ eΘ=465K

(unmixed vortex air)



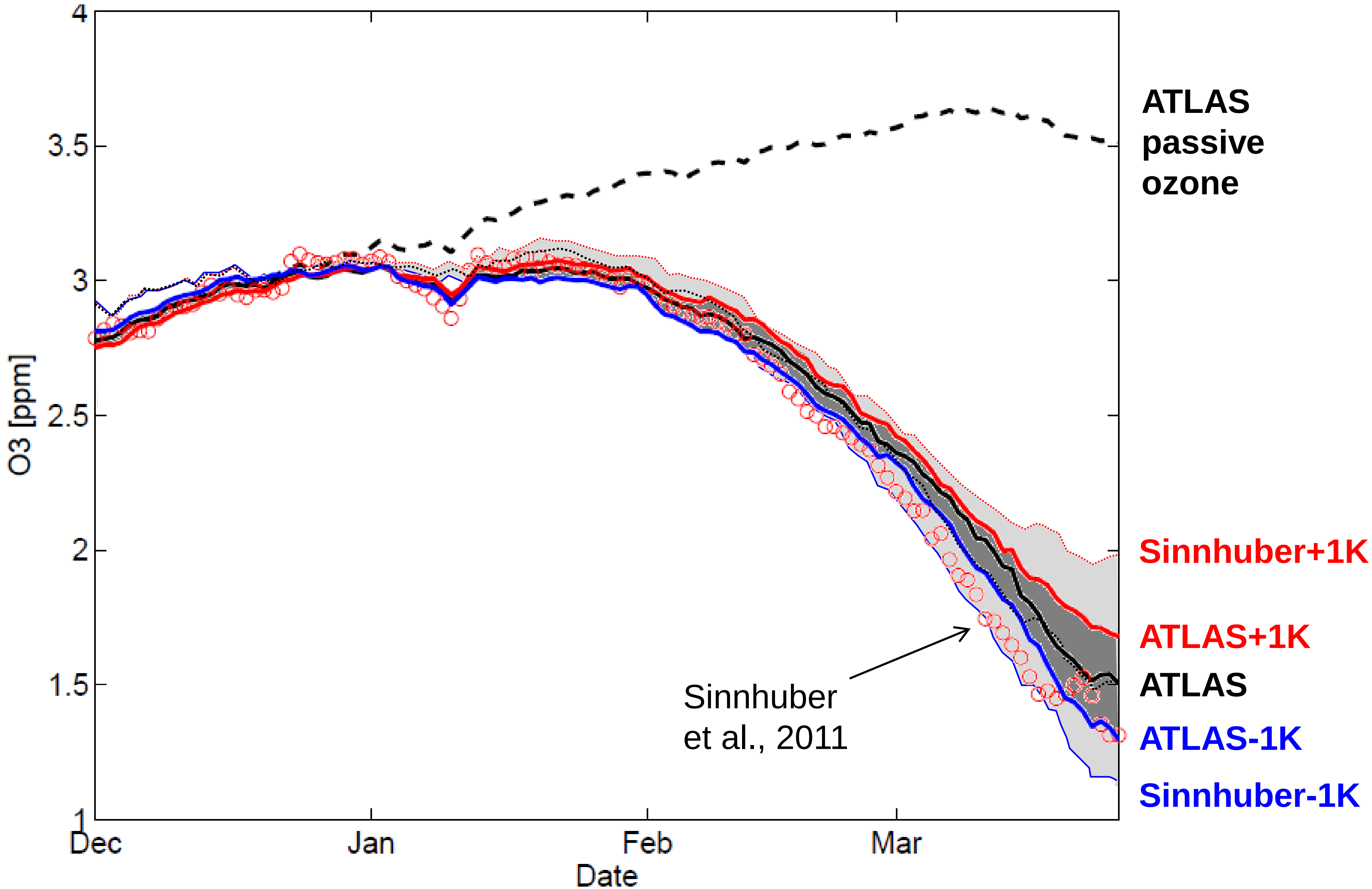
Ozone and ozone loss inside vortex @ eΘ=465K

(unmixed vortex air)



Ozone and passive ozone inside vortex @ fixed Θ=475K

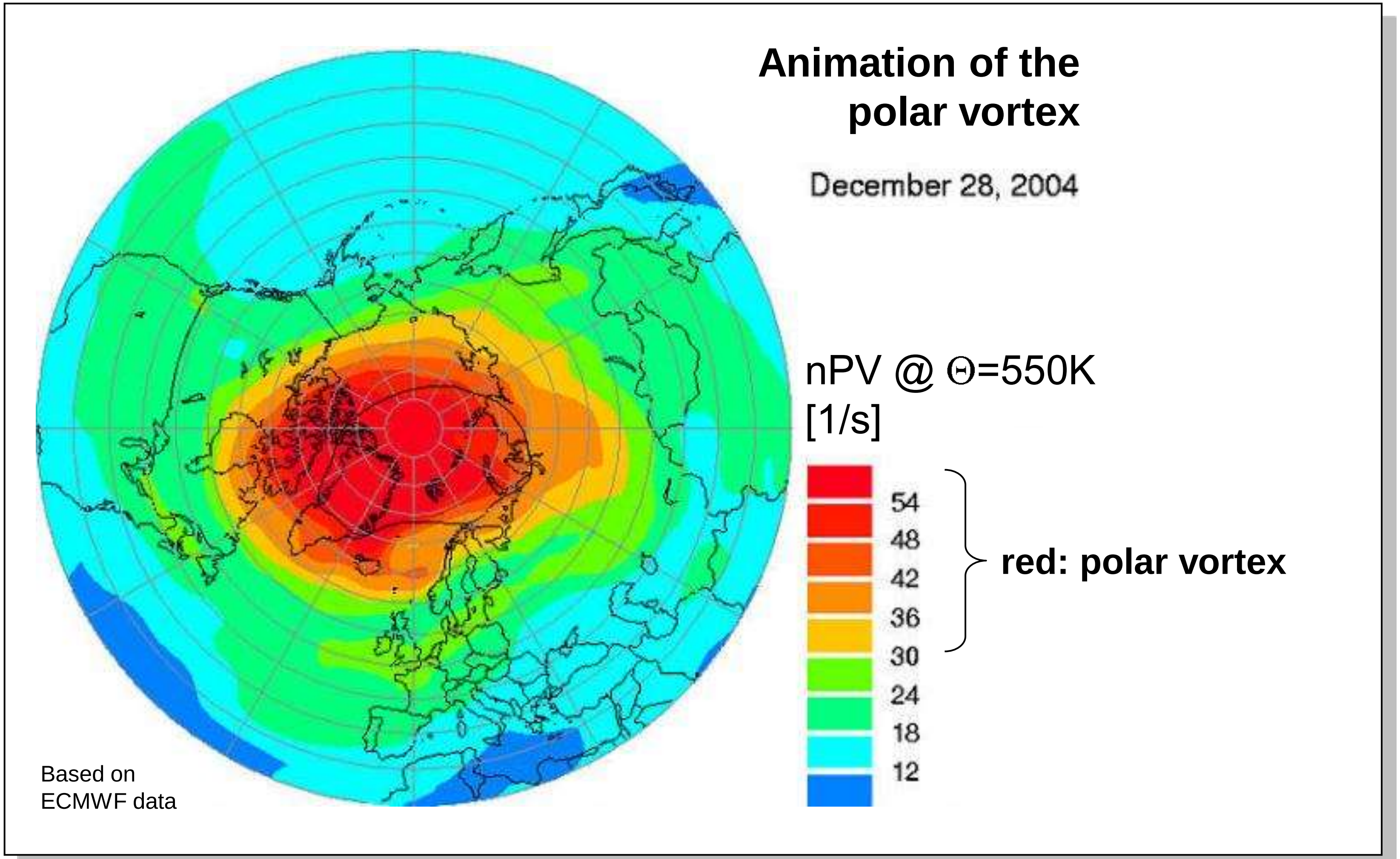
(full vortex average, including mixed areas)



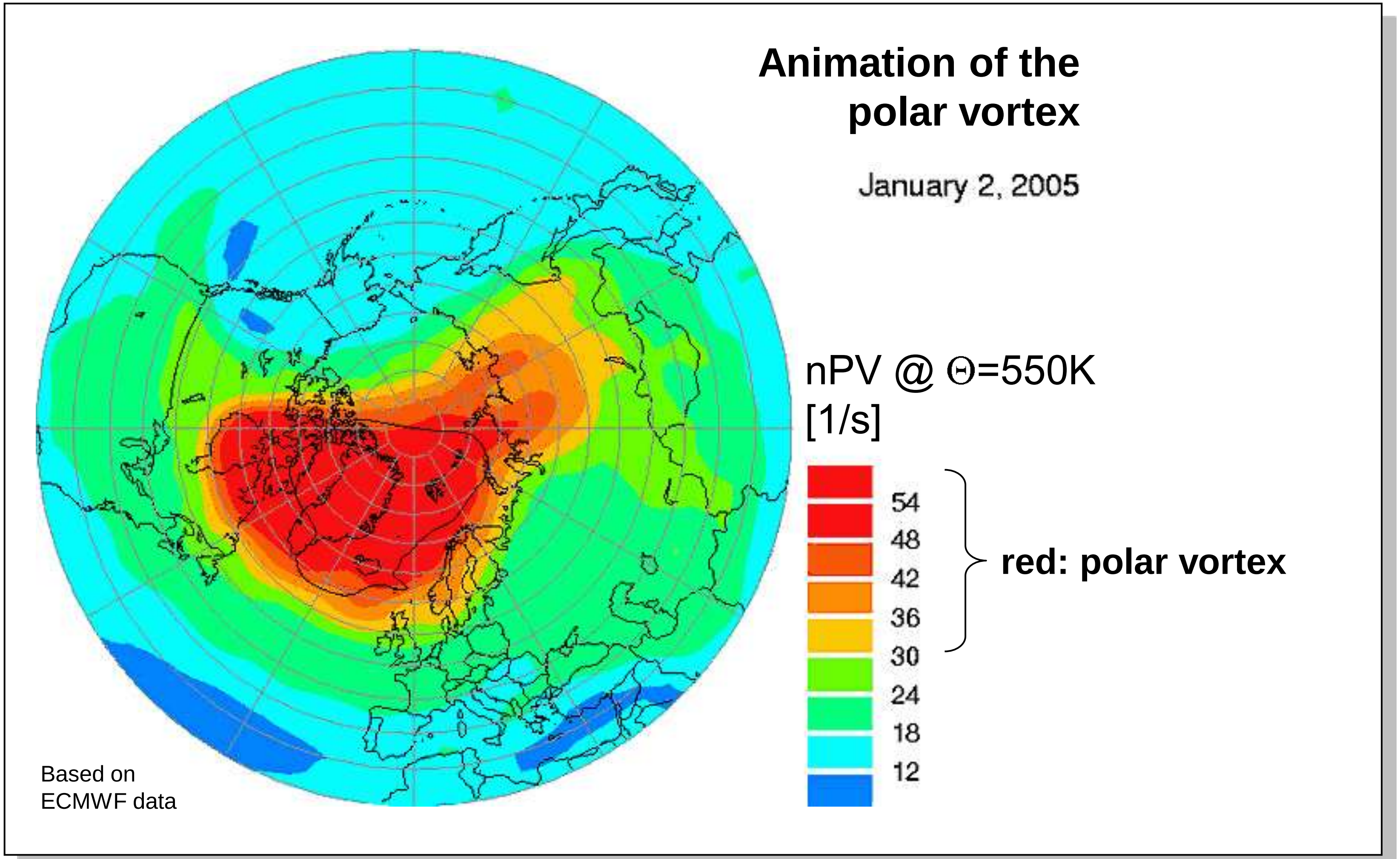
Conclusions

- Arctic ozone loss continues to get worse due to ozone/climate coupling.
- Processes at the tropical tropopause layer, particularly above the West Pacific, play an important role for the global ozone layer.
- A tropospheric ozone and OH hole exists over the tropical West Pacific. => Emissions from South East Asia and the tropical oceans there can play a larger role for the stratospheric composition.
- Data assimilation products are the basis for studies of stratospheric processes. These are particularly sensitive on uncertainties in:
    - The temperature fields in the polar lower stratopshere.
    - The vertical wind fields at the tropical tropopause.

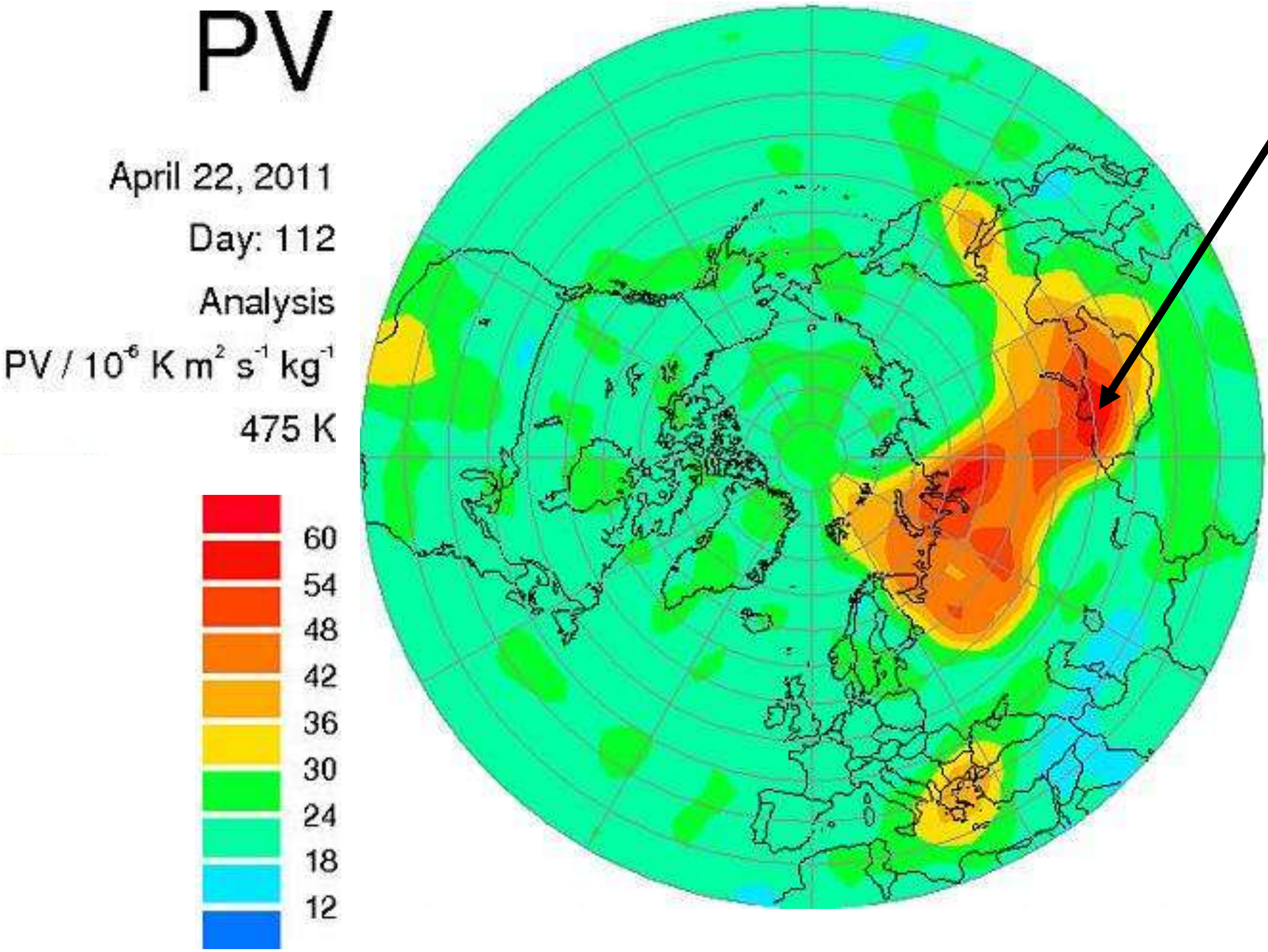
Typical movement of Arctic polar vortex



Typical movement of Arctic polar vortex



Impact on mid-latitude UV



UV-Index: 8.6

- Sunburn within minutes
- Long term average on April 22: 5.4
- 7 sigma deviation