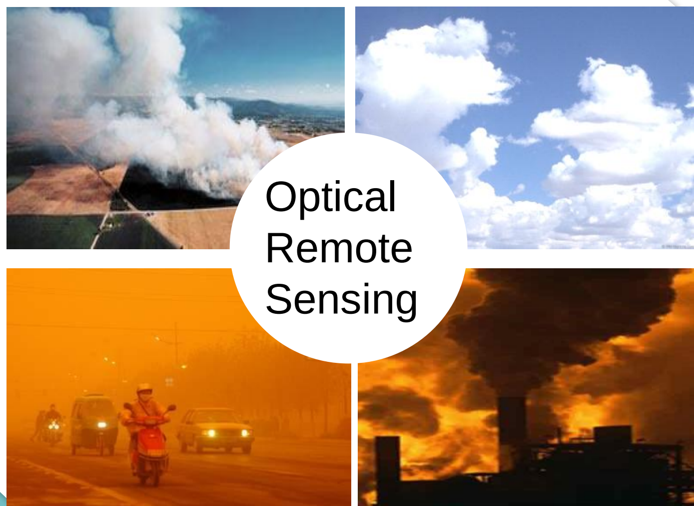
Optical remote sensing of atmospheric trace gases and aerosol



Young J. Kim, Jihyo Chong

Advanced Environmental Monitoring Research Center
School of Environmental Science and Engineering
Gwangju Institute of Science and Technology(GIST)

21 October 2010

Outline

- Introduction
- DOAS principle and methods
- Examples of measurements
  - I. MAX-DOAS measurements of ClO, SO_2, and NO_2
  - II. Imaging DOAS measurements of NO_2
  - III. MAX-DOAS measurement of Aerosol
  - IV. Satellite measurement of NO_2 and SO_2
- Summary

INTRODUCTION

Effects of Atmospheric Aerosols

1. **Human health** : Adverse effects on respiratory and cardiovascular systems
2. **Air quality** : a criteria pollutant, impairment of visibility [**Kim and Kim, 2003**]
3. **Climate change** : radiative forcing by direct and indirect effects, precipitation

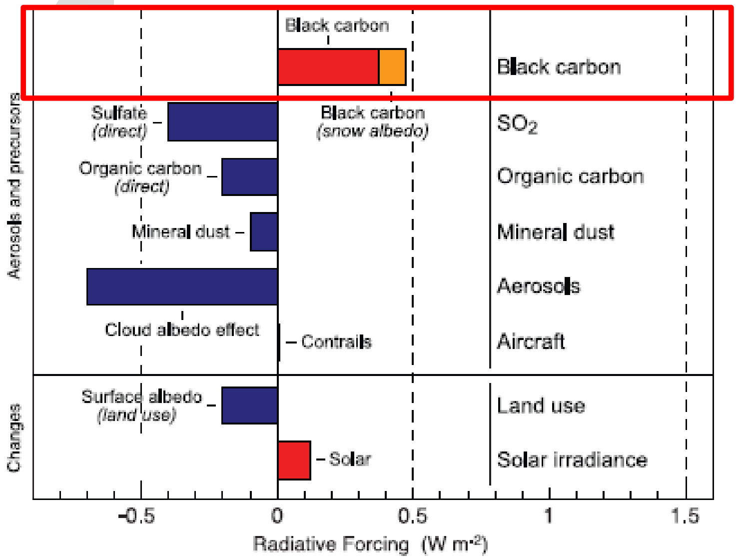
An Integrated Approach for Effective Monitoring of Atmospheric Environment at GIST/ADEMRC

- **Multi-wavelength Raman LIDAR** : **aerosol vertical profile, LIDAR ratio, extinction coeff.**
- **Sunphotometer** : **column aerosol optical depth aerosol size distribution**
- **Satellite retrieval** : **spectral aerosol optical depth**

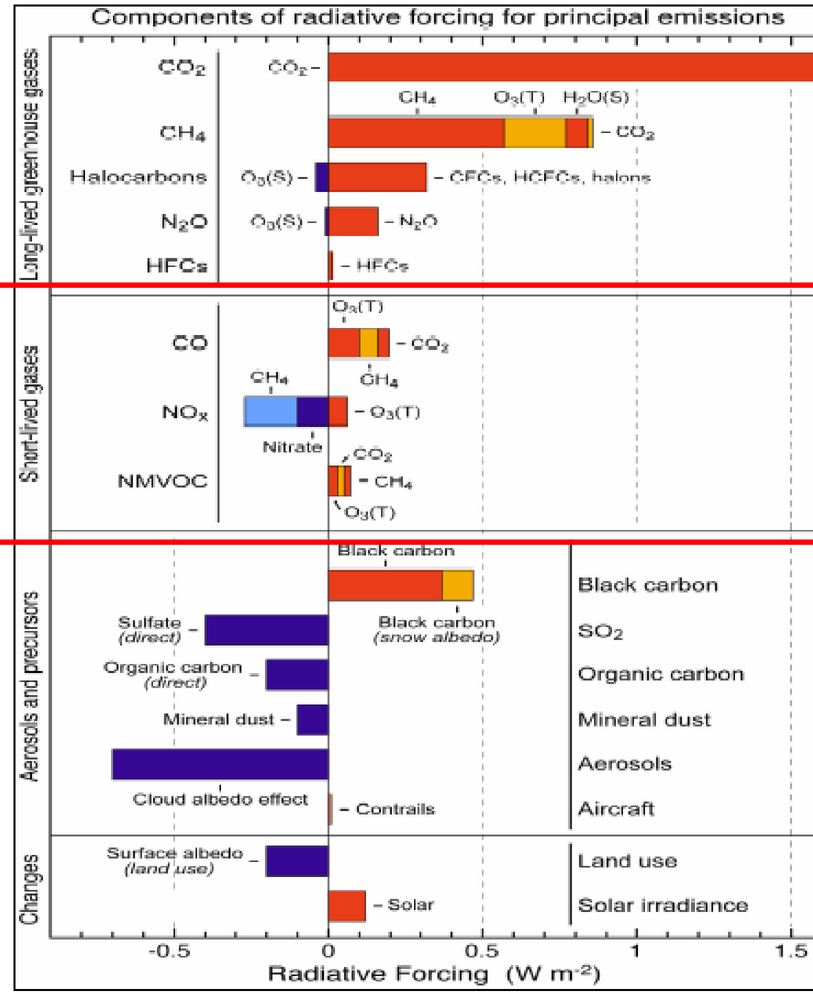
→

Better characterization of physical and optical properties of atmospheric aerosol

SLCFs* mater as much as CO2



[IPCC, 2007]

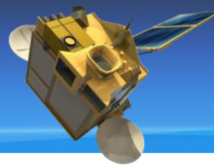


BC responsible for 50% or nearly 1.0º C of the 1.9º C temperature increase in the Arctic from 1890 to 2007 (Shindell, Faluvegi 2009)

*Short-lived Climate Forcers

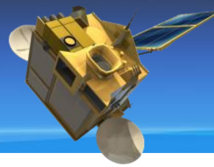
[Witherspoon, EPA SLCF Workshop, 2010]

Greenhouse Gases vs Aerosol



Greenhouse gases (GHG)	Aerosols
Greenhouse effect	Whitehouse effect Global dimming
Warming (+)	Cooling (−) sulfate Warming (+) black carbon
global distribution	localized
several to hundreds years	5~7 days
Low Uncertainty	Moderate to High Uncertainty

Greenhouse Gases vs. Aerosol



"There is little disagreement that the rise of aerosols since pre-industrial times has led to both a substantial reduction in solar radiation at the surface and increased solar heating of the atmosphere itself. But global models disagree as to the magnitude of these effects."

Nine different global climate models	
Greenhouse Gases (GHGs)	$+1.66 \pm 0.17$ W/m^{-2}
Aerosols	-0.22 ± 0.16 W/m^{-2} ($+0.04 \sim -0.41$ W/m^{-2})

(Seinfield, *Nature Geoscience*, 2008)

Considering near-term climate impacts as an additional effect of air pollutants

IIASA

- Near-term forcing of air pollutants
  - Warming: BC, O_3 (i.e., CH_4, CO, NO_x, VOC)
  - Cooling: SO_2, OC

  - accelerates or delays ongoing climate change at the regional scale,
  - changes regional weather circulation and precipitation patterns.

- Accelerated melting of Arctic ice and glaciers through deposition of (black) carbon

could be considered as an additional effect of air pollutants (on top of their health and ecosystems impacts)

(M. Ammann, 2010)

SLCF

- Health impacts of SLCF are important and immediate
  - Should be integral element of climate policy considerations
- Black carbon reductions would benefit both health and climate
  - Directionality is known even if magnitude is uncertain
  - Of the ways to improve PM air quality, reductions in black carbon are likely the best for climate
- O3 precursor reductions would also benefit health and climate
  - Of the ways to improve ozone air quality, reducing methane, CO, VOCs (in that order) are likely best for climate
- Eventual strategies will need to consider health, climate, and other effects.
  - Need integrated management view

Transboundary pollution in East Asia

Long-range transboundary transport of air pollutants in Northeast Asia (source-receptor regions)

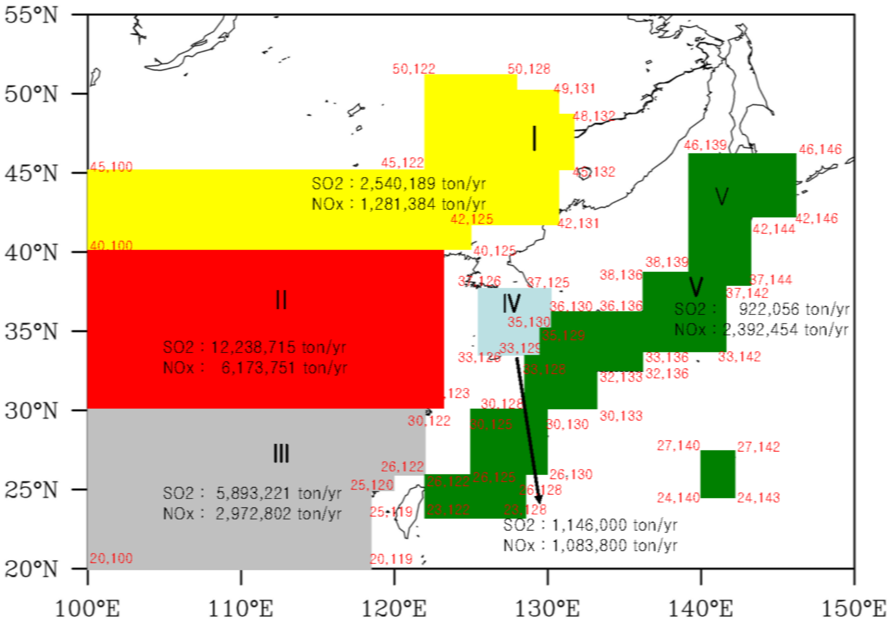
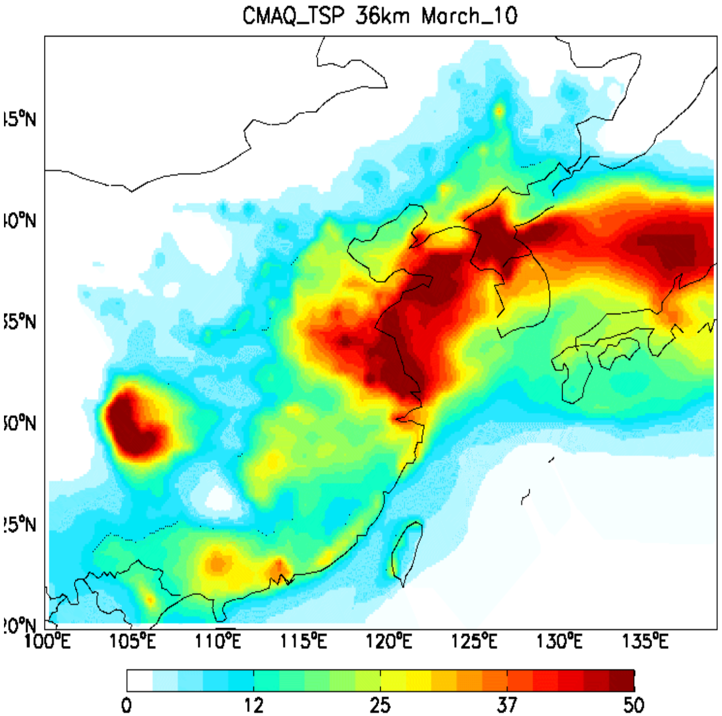
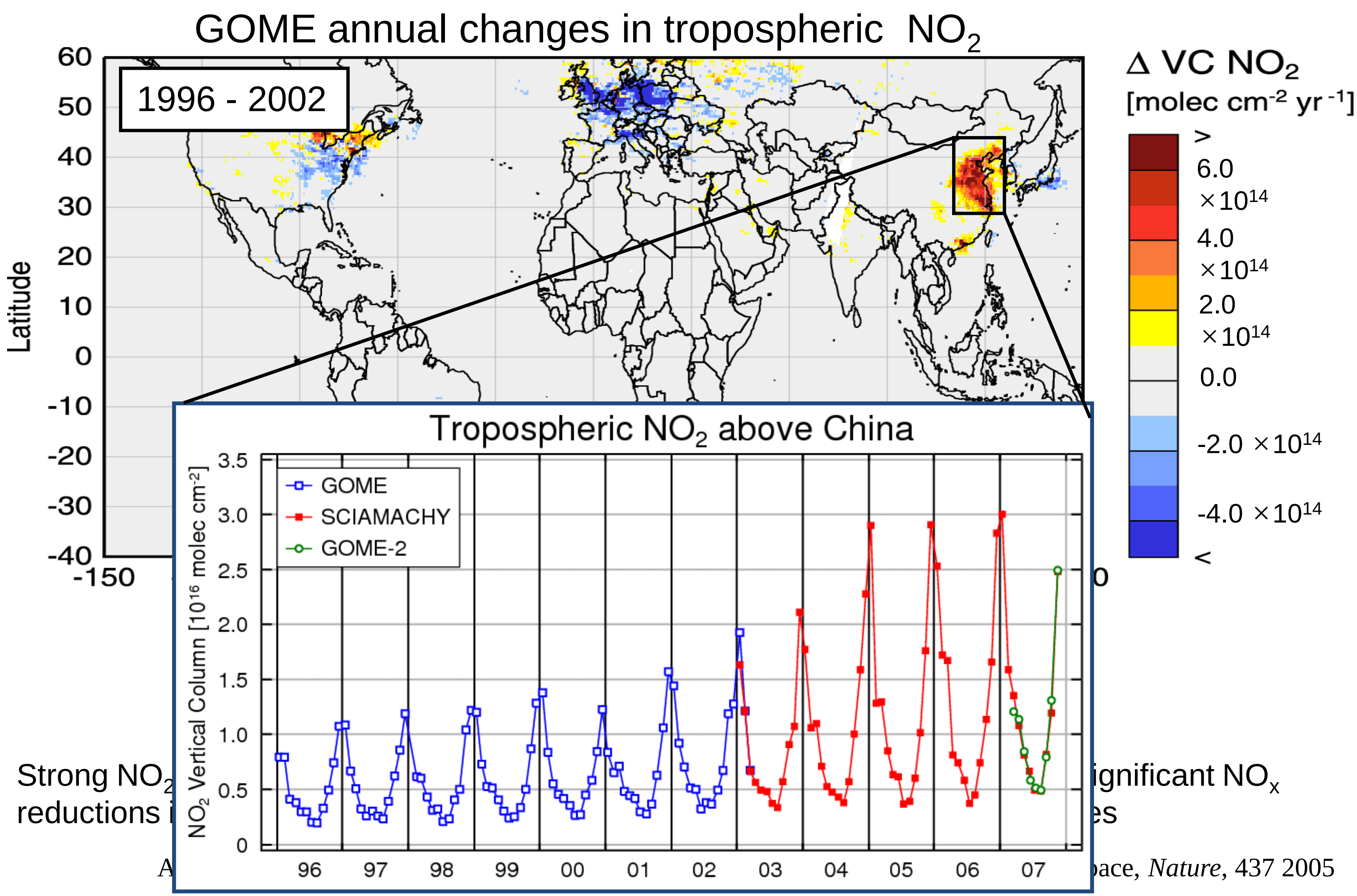


Fig. 8. Total emission amounts of SO_2 and NOx for each source/receptor region.



[*LTP project*, 2007]

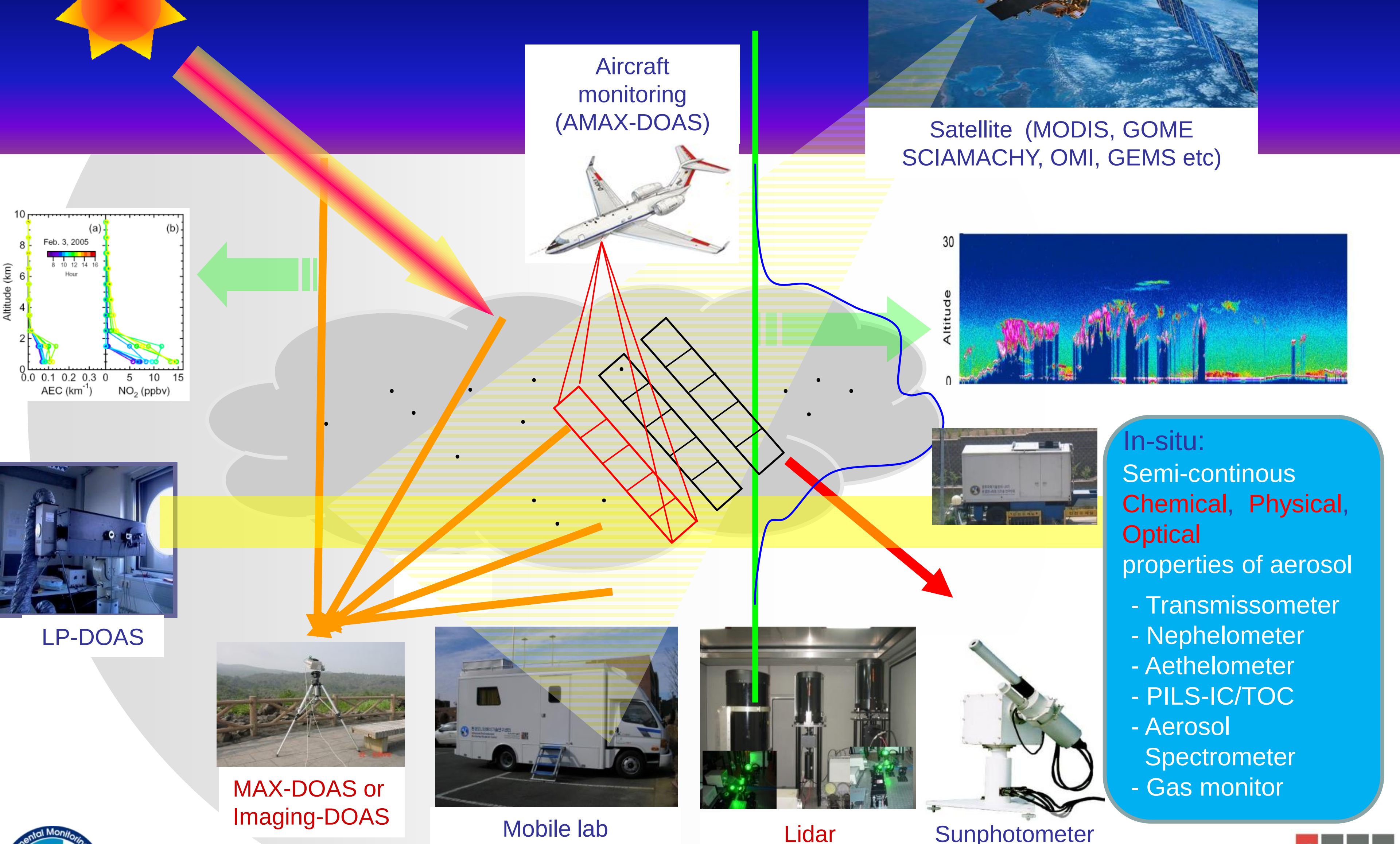
Satellite Retrieval of Tropospheric NO_2 column



- Strong NO_2 … ignificant NO_x
- reductions i … es

A … pace, *Nature*, 437 2005

Integrated Diagnostics of Atmospheric Environment



Differential Optical Absorption Spectroscopy (DOAS)

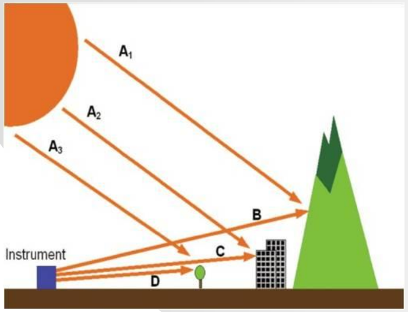
- DOAS technique is 30 years old …
- Many applications have been demonstrated and used, but research is still ongoing on many aspects

Active long-path DOAS

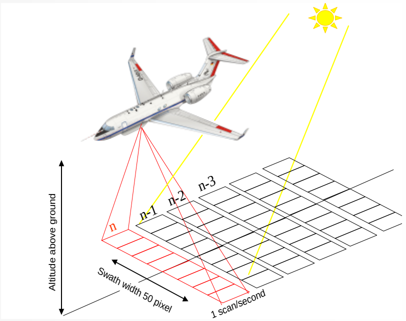
Passive MAX-DOAS

Passive Imaging DOAS

Passive ToTal*-DOAS



Airborne Multi-Axis DOAS



DOAS from space
(GOME, SCIAMACHY, OMI, and GEMS)

*Topographic Target Light scattering

DOAS principle

Remove by high-pass filtering

Lambert-Beer's Law:

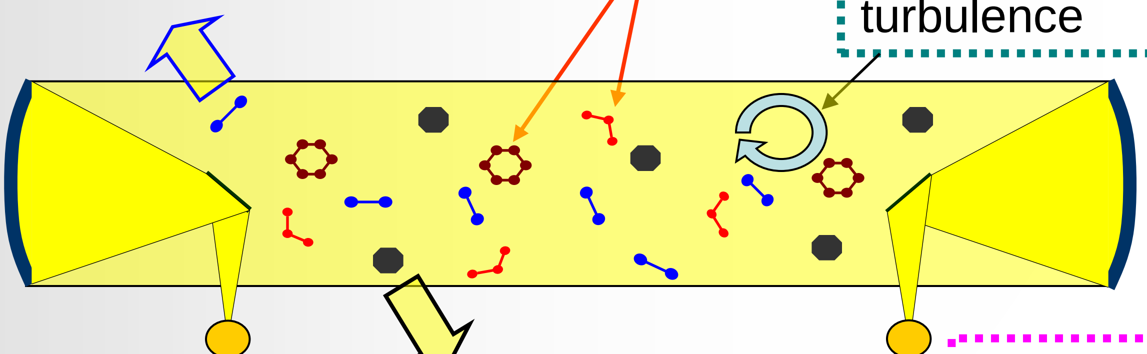
$$I(\lambda) = I_0(\lambda)\cdot e^{-[\Sigma\sigma'_i(\lambda)\cdot c_i\cdot L + (\sigma_{bi}\cdot c_i + \varepsilon_{Ray}(\lambda) + \varepsilon_{Mie}(\lambda))\cdot L]} \cdot T(\lambda))$$

narrow- ***wide*** ***band extinction***

Trace gas absorption
absorption cross section $\sigma_i(\lambda)$

Rayleigh scattering
$\sim \lambda^{-4}$

turbulence



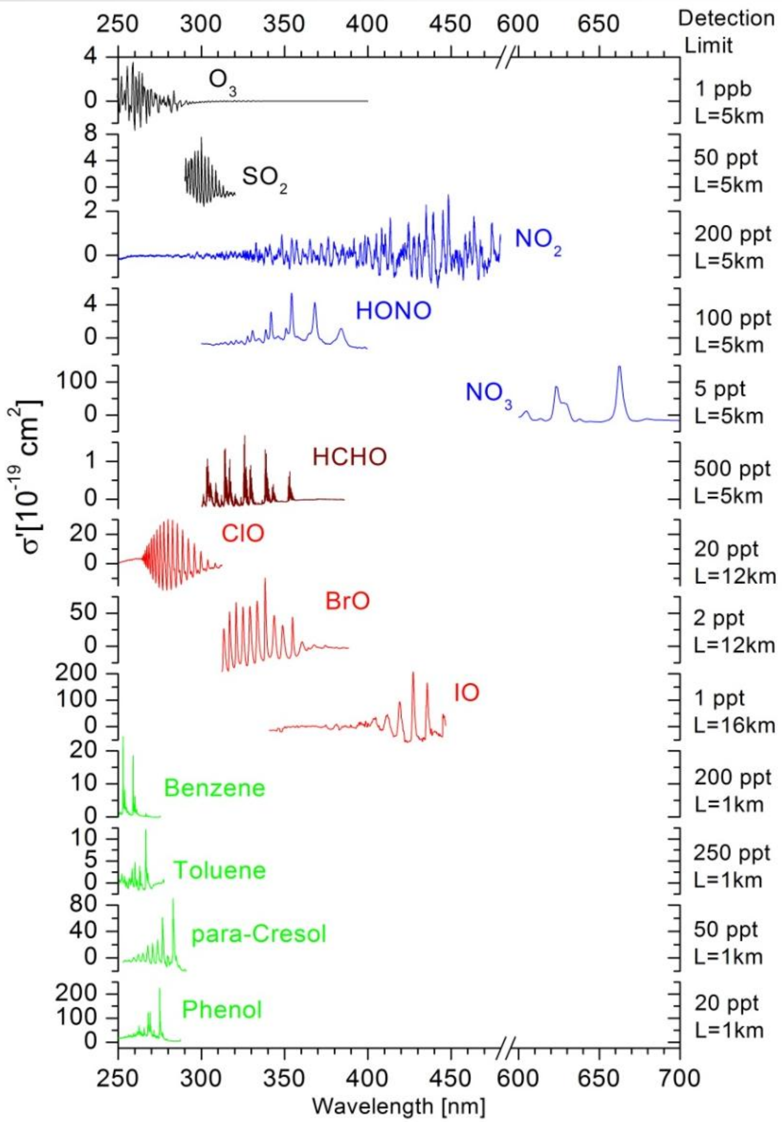
Lamp $I_0(\lambda)$

Mie Scattering
$\sim\lambda^{-(1\ldots3)}$

Detector $I(\lambda)$

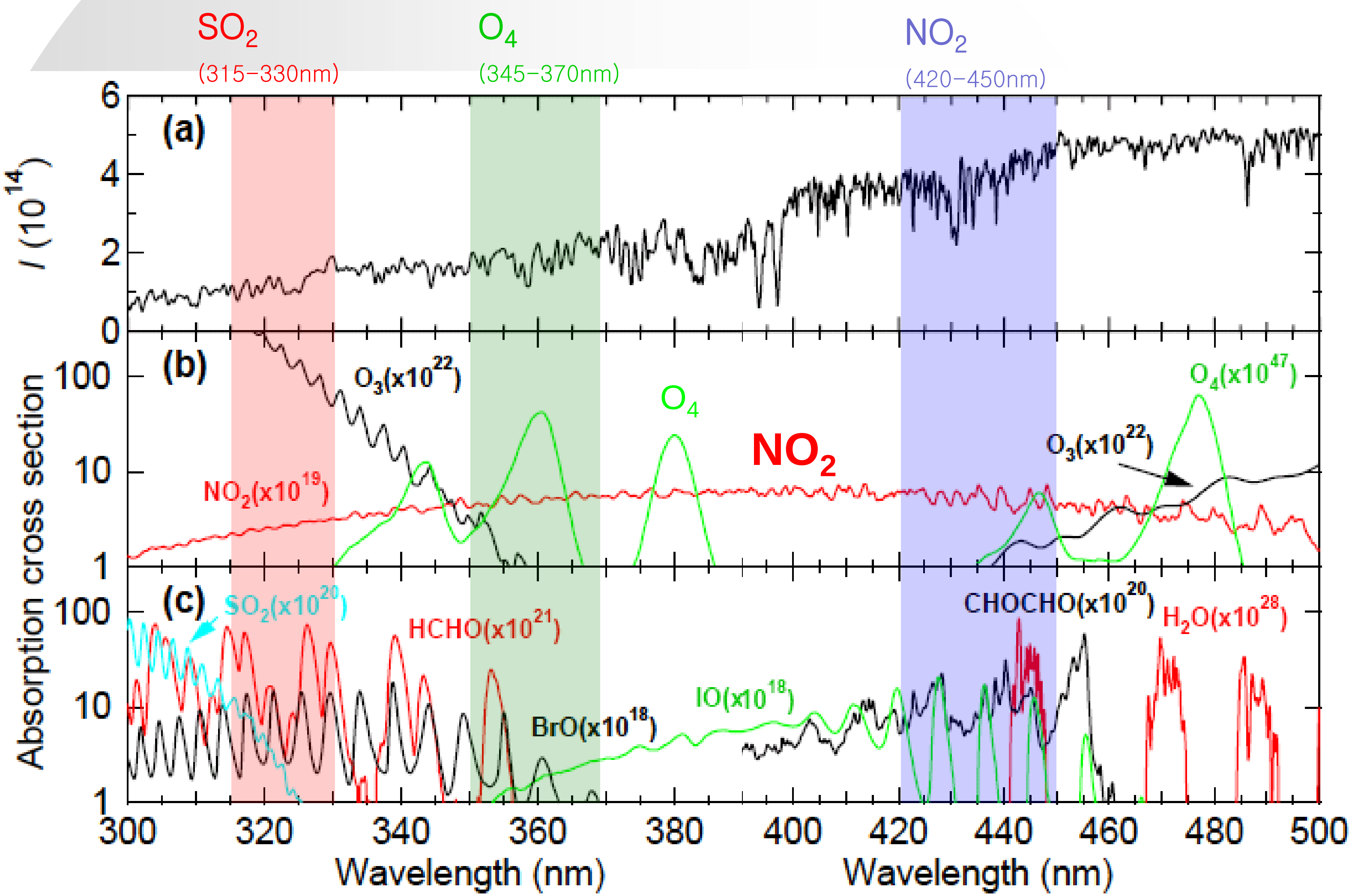
[Platt, 1994]

Absorption cross-sections in UV-Vis range



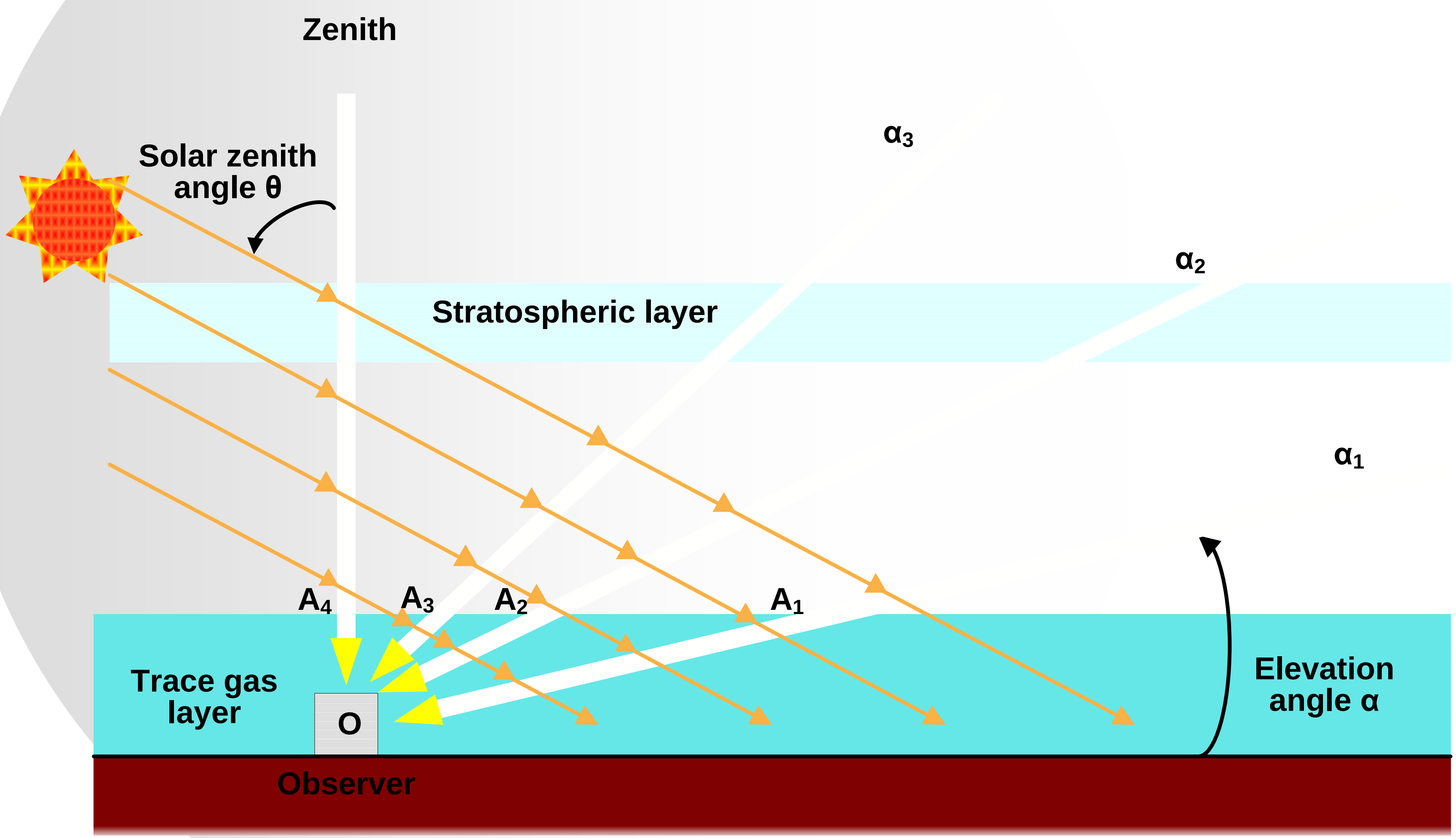
[IUP, Univ. Heidelberg, Germany (http://www.iup.uni-heidelberg.de)]

Absorption cross-sections in UV-Vis range



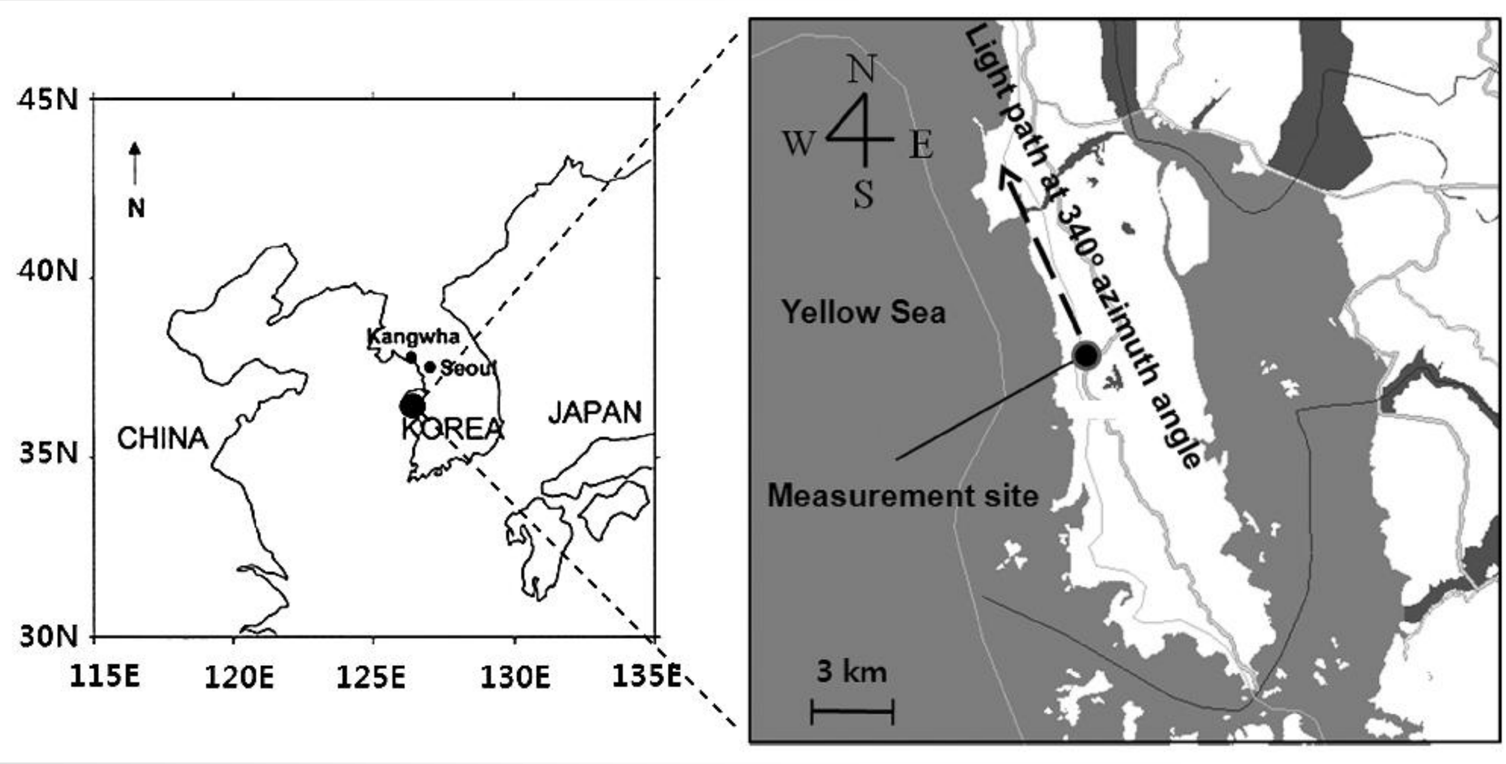
(*Courtesy of H. Irie*)

Multi-Axis DOAS (MAX-DOAS) viewing geometry



[Hoenninger, 2002]

Ⅰ. MAX-DOAS measurements of ClO, SO_2 and NO_2 at Anmyeon Island (Korea GAW site)



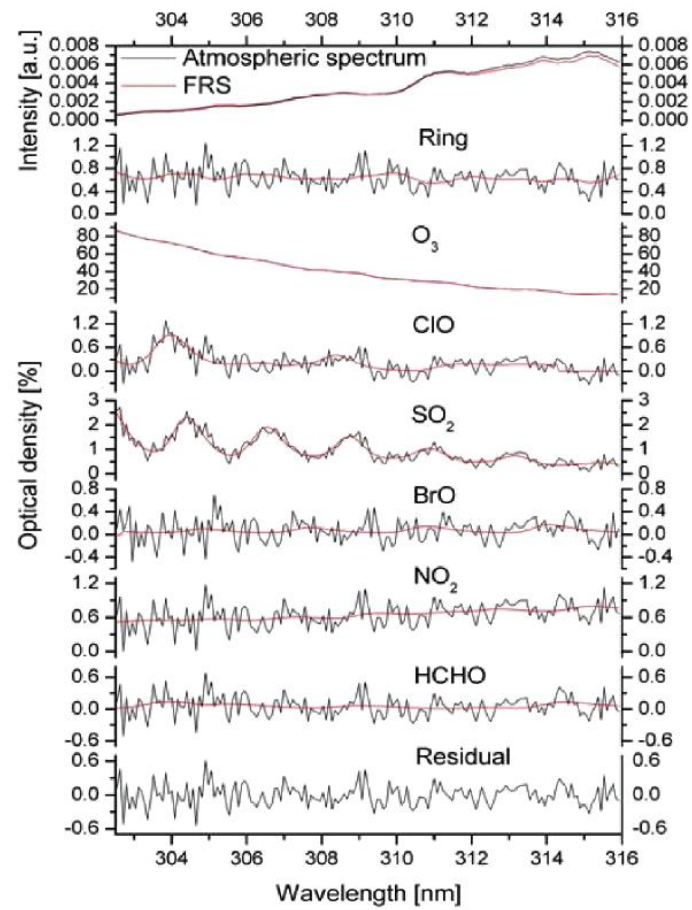
Site: The Korea Global Atmosphere Watch Observatory (KGAWO) (36.54° N, 127.12° E), Anmyeon Island
Period: 27 May ~ 9 June 2005.

[Lee, C. et al., 2008]

Ⅰ. Analysis

Specifications for the MAX-DOAS spectrum evaluation for ClO, NO_2, and SO_2

Molecule	Wavelength range, nm	Polynomial order	Cross-sections included in the fitting procedure
ClO	302.5–316	3	ClO, BrO, SO_2, HCHO, NO_2, O_3, Ring, FRS
SO_2	303.5–316	3	ClO, SO_2, BrO, NO_2, O_3, Ring, FRS
NO_2	399–418	3	NO_2, O_4, O_3, Ring, FRS

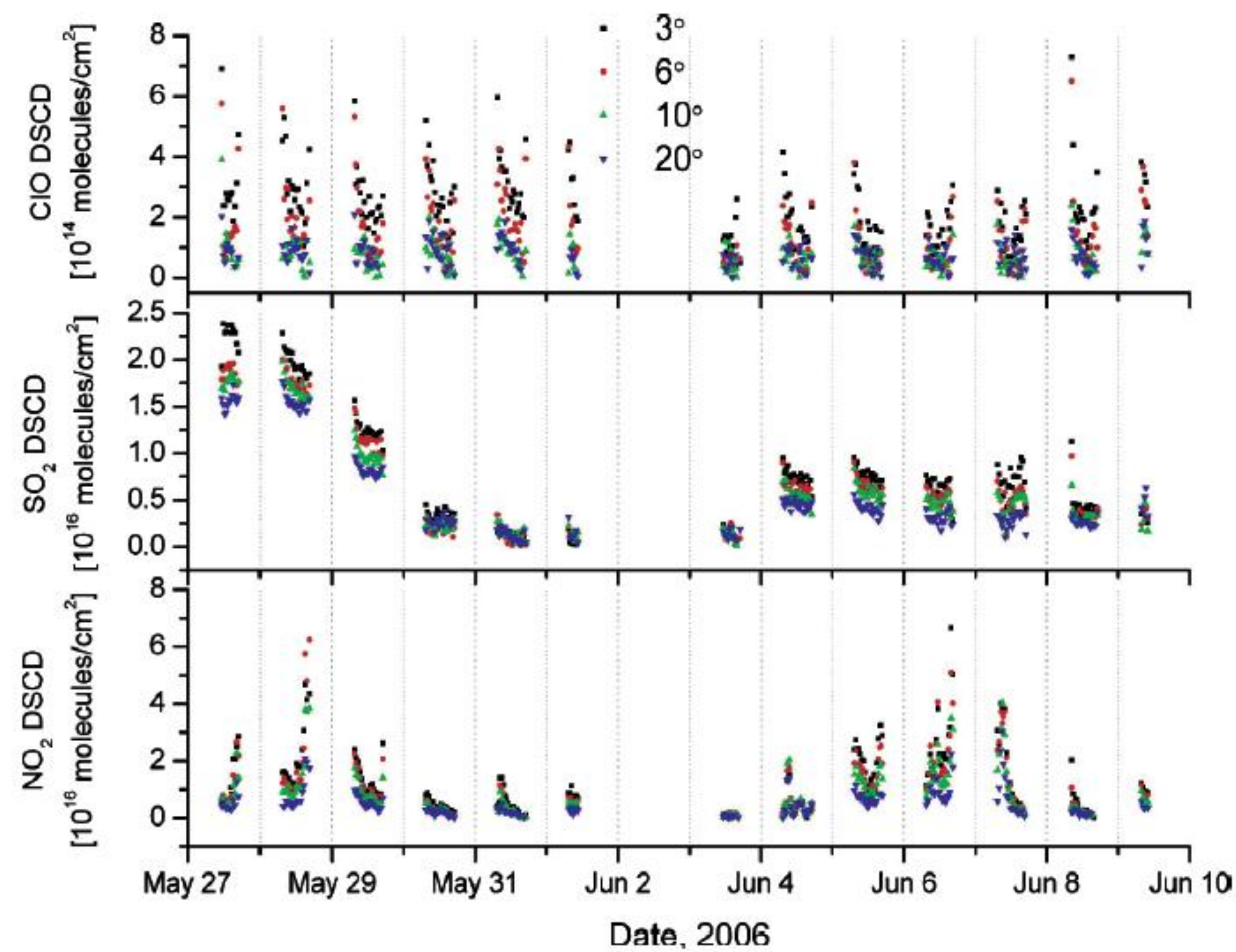


An evaluation example of a ClO SCD from the MAX-DOAS spectrum taken at a 3° elevation angle at 16:12 on 5 June 2005 (LT)

[Lee, C. et al., 2008]

➢Examples of measurements

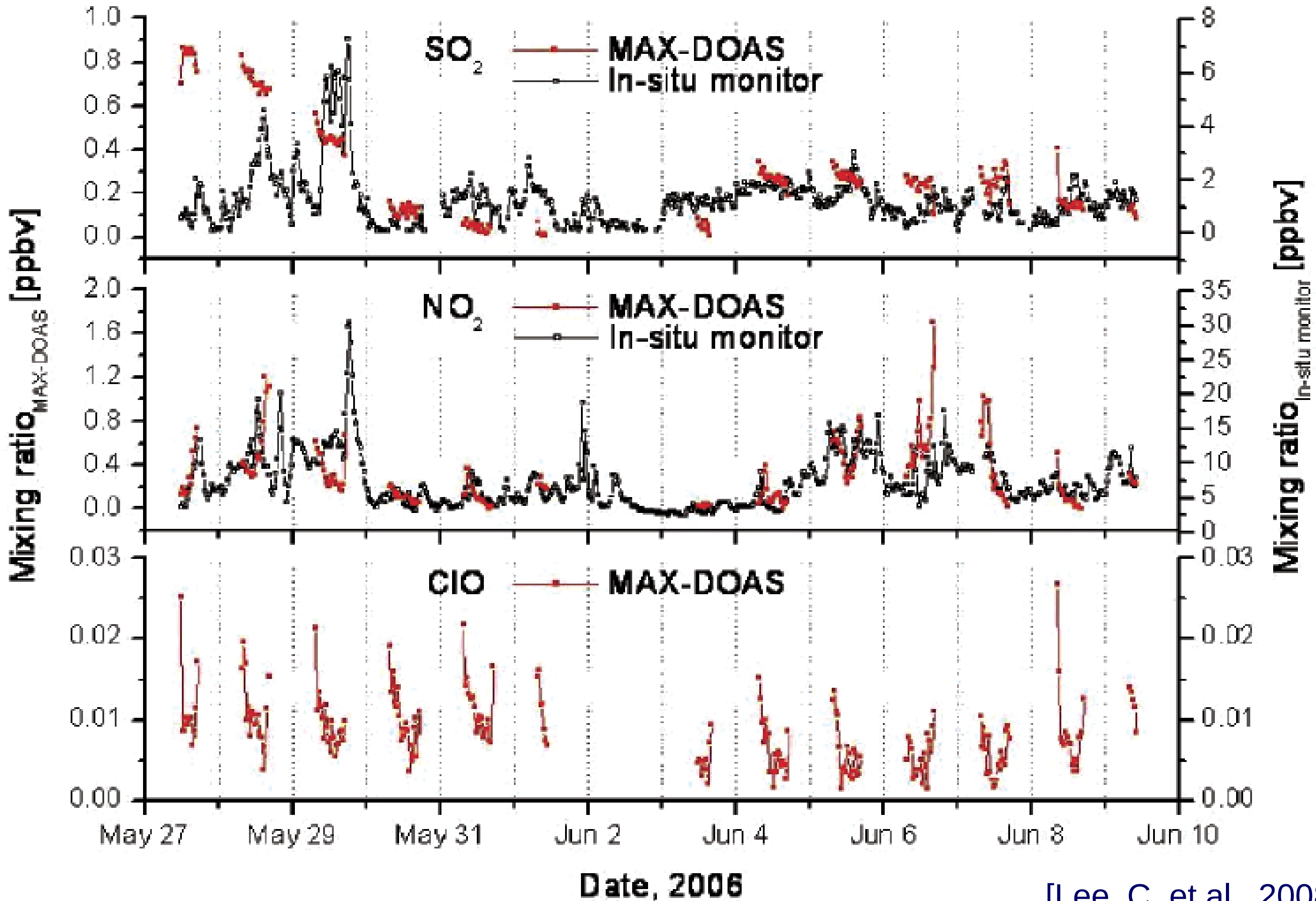
Ⅰ. ClO, SO_2 and NO_2 differential slant column densities (DSCD)



[Lee, C. et al., 2008]

➢Examples of measurements

Ⅰ. Mixing ratios of SO_2, NO_2, and ClO determined by the MAX-DOAS and in situ monitors.

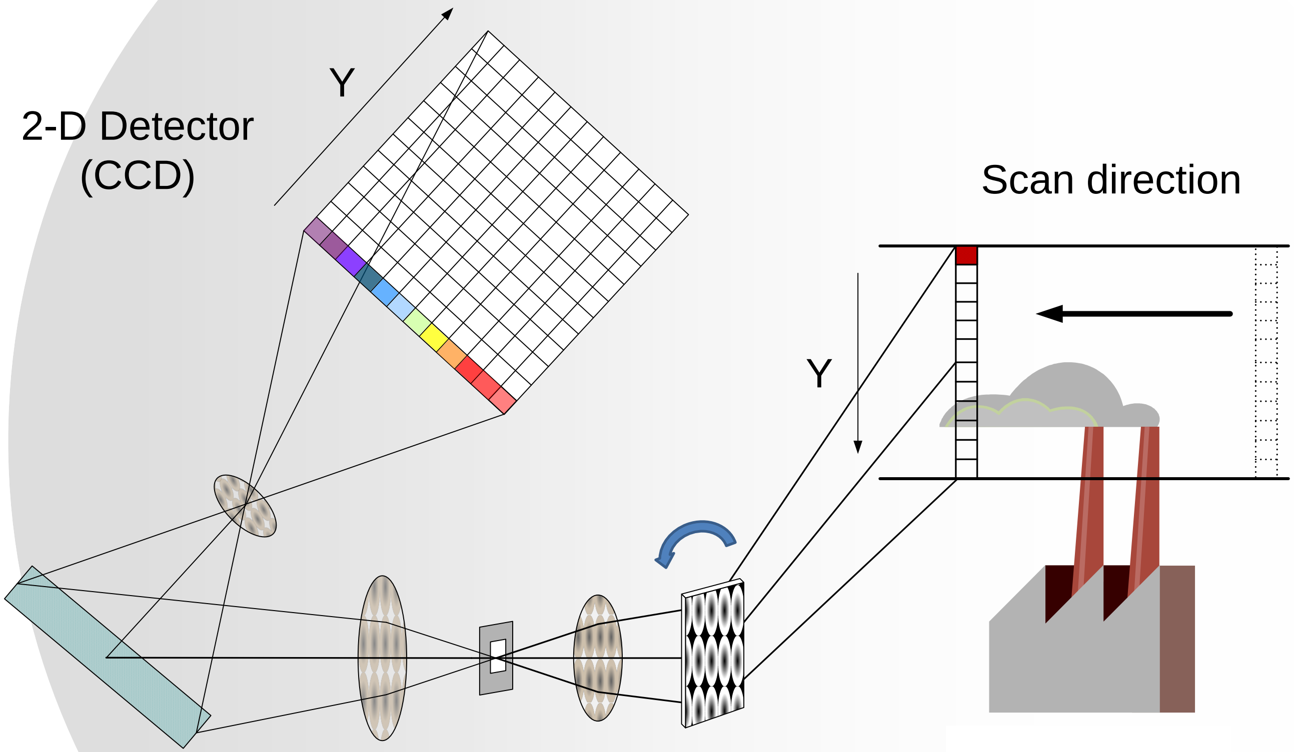


[Lee, C. et al., 2008]

Ⅰ. Summary

- ClO, SO_2 and NO_2 have been directly observed in the mid-latitude coastal boundary layer by the MAX-DOAS technique.
- The diurnal behavior of ClO was consistent with a source based on the heterogeneous processing of sea-salt aerosol. (ClO level was as high as ~27 pptv (with a mean of 8.4 pptv)
- Mean SO_2 and NO_2 levels observed during the measurement period were 296 (±233) and 305 (±284) ppbv, respectively.
- High SO_2 and NO_2 concentrations measured during the two event periods might have an effect on atmospheric halogen chemistry through reactive halogen release processes by the attack of strong acids on sea-salt aerosols, and through reducing processes by the reaction of ClO with NO_2.

Imaging DOAS viewing geometry



Pushbroom type I-DOAS

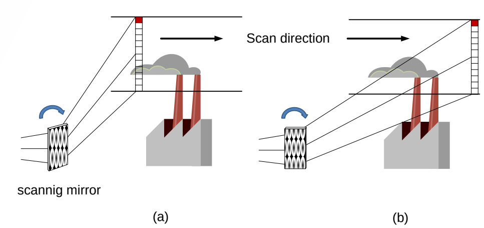
Slant line scanning

Field of view

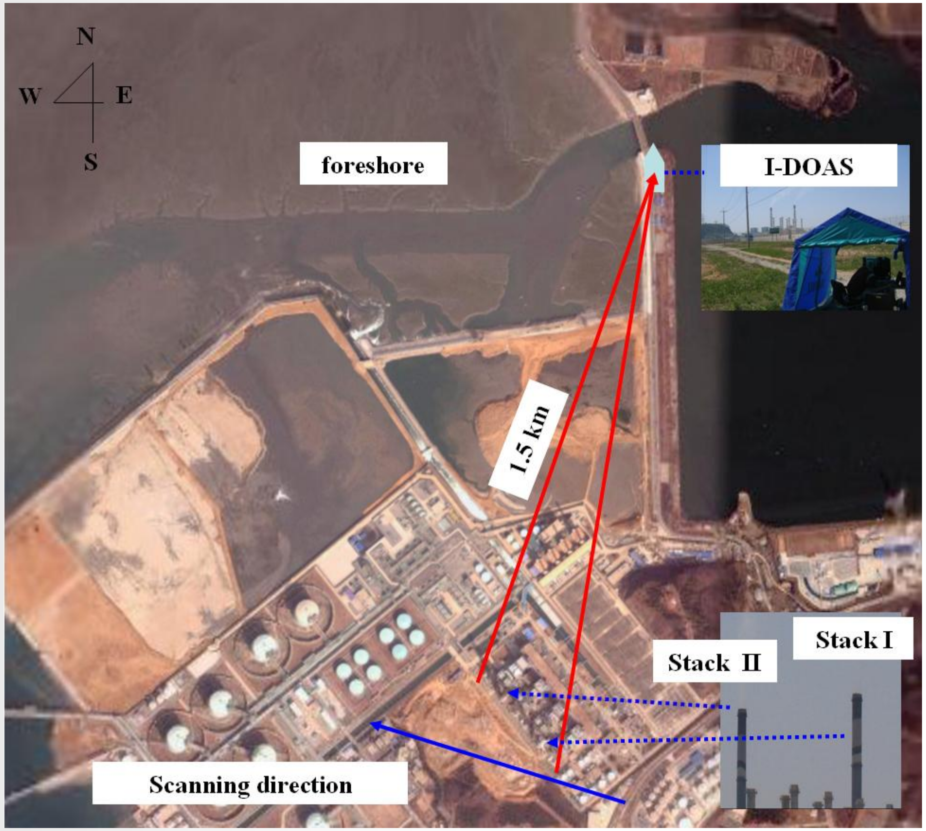
Superficial scanning

Scanning mirror

Volume scanning (Scanning mirror)



Ⅱ. Imaging DOAS measurements of NO_2



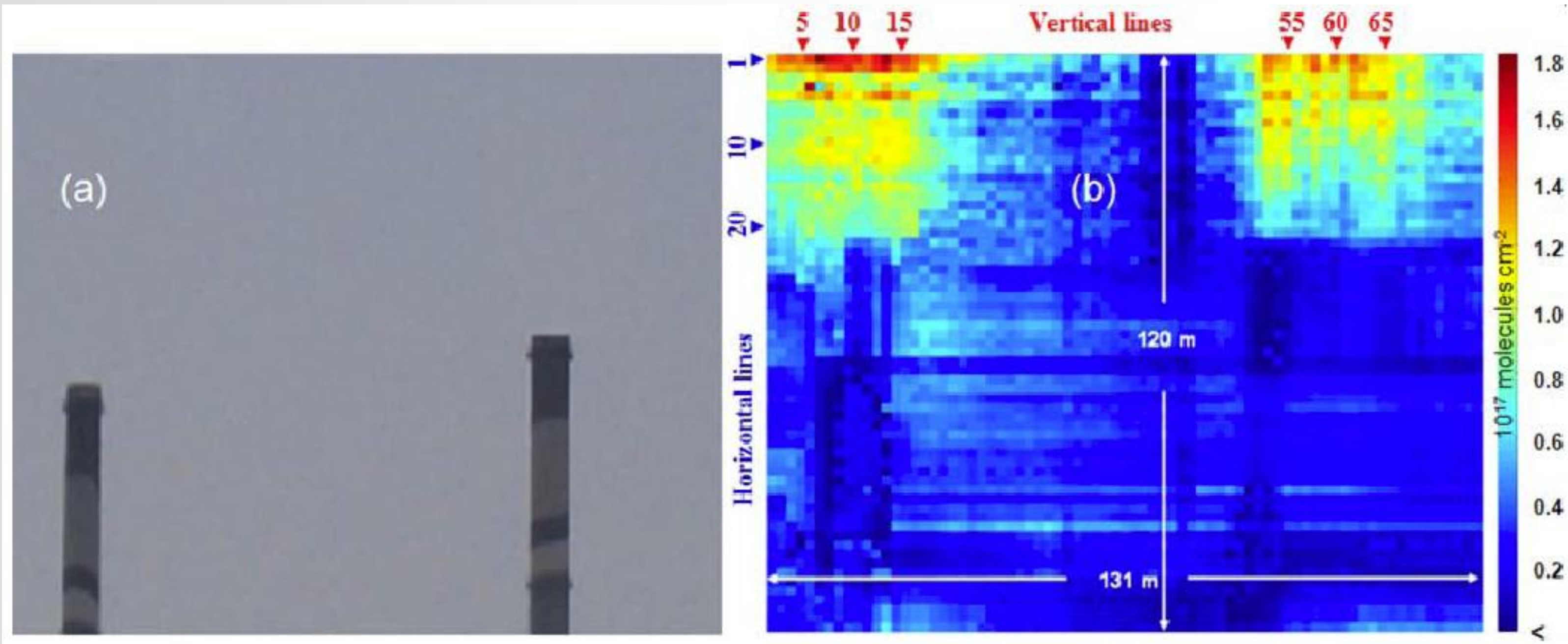
Site: the rooftop of a local agricultural administration facility at a distance of 1.7 km north from the Pyeongtaek thermal power plant (37.00° N,126.47° E)

Period: 15 September, 2005

[Lee, H. et al., 2009]

Ⅱ. NO_2 distribution in the power plant plume

The measurement was taken 1.7 km north of the stacks of the Pyeongtaek Power Plant between 9:15 A.M. and 9:37 A.M. on 15 September 2005



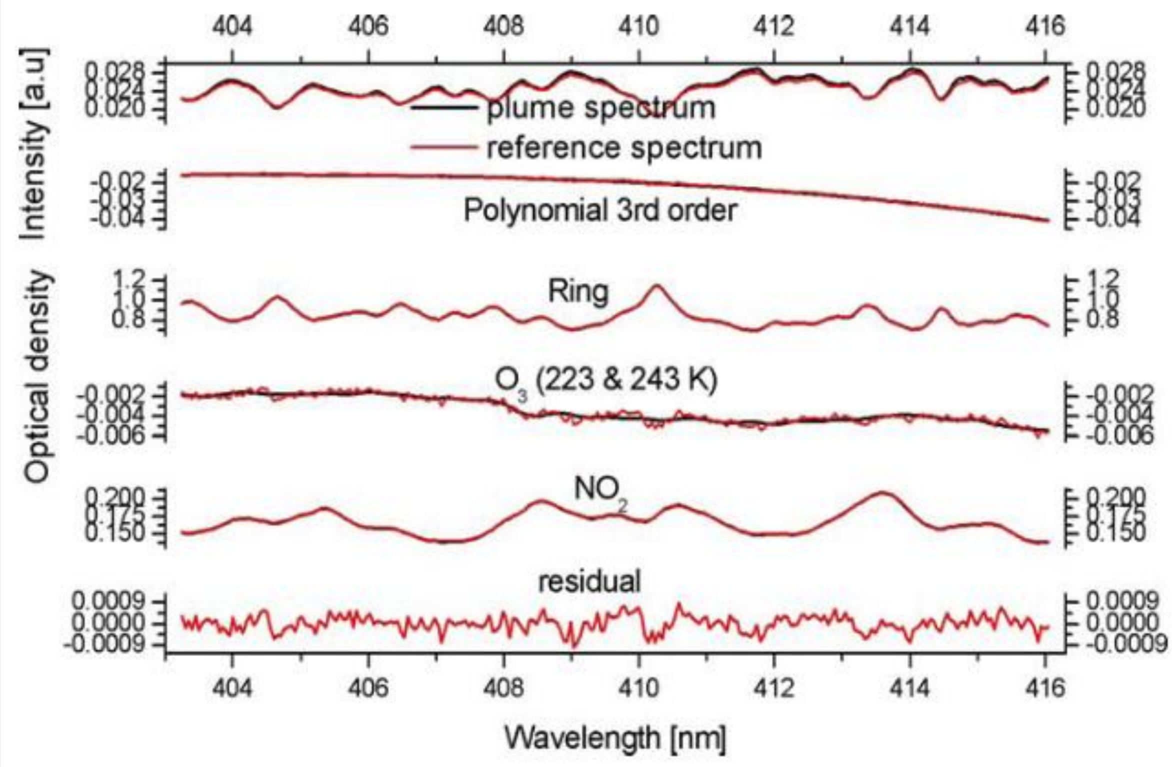
(a) is invisible in the RGB color photograph (b) is visualization of the distribution of NO_2

-Background SCD
:~0.2×10^{17} molecules cm^{-2}

-Max. SCD observed 45 m above the 1st stack exit
:1.8×10^{17} molecules cm^{-2}

[Lee, H. et al., 2009]

Ⅱ. Analysis

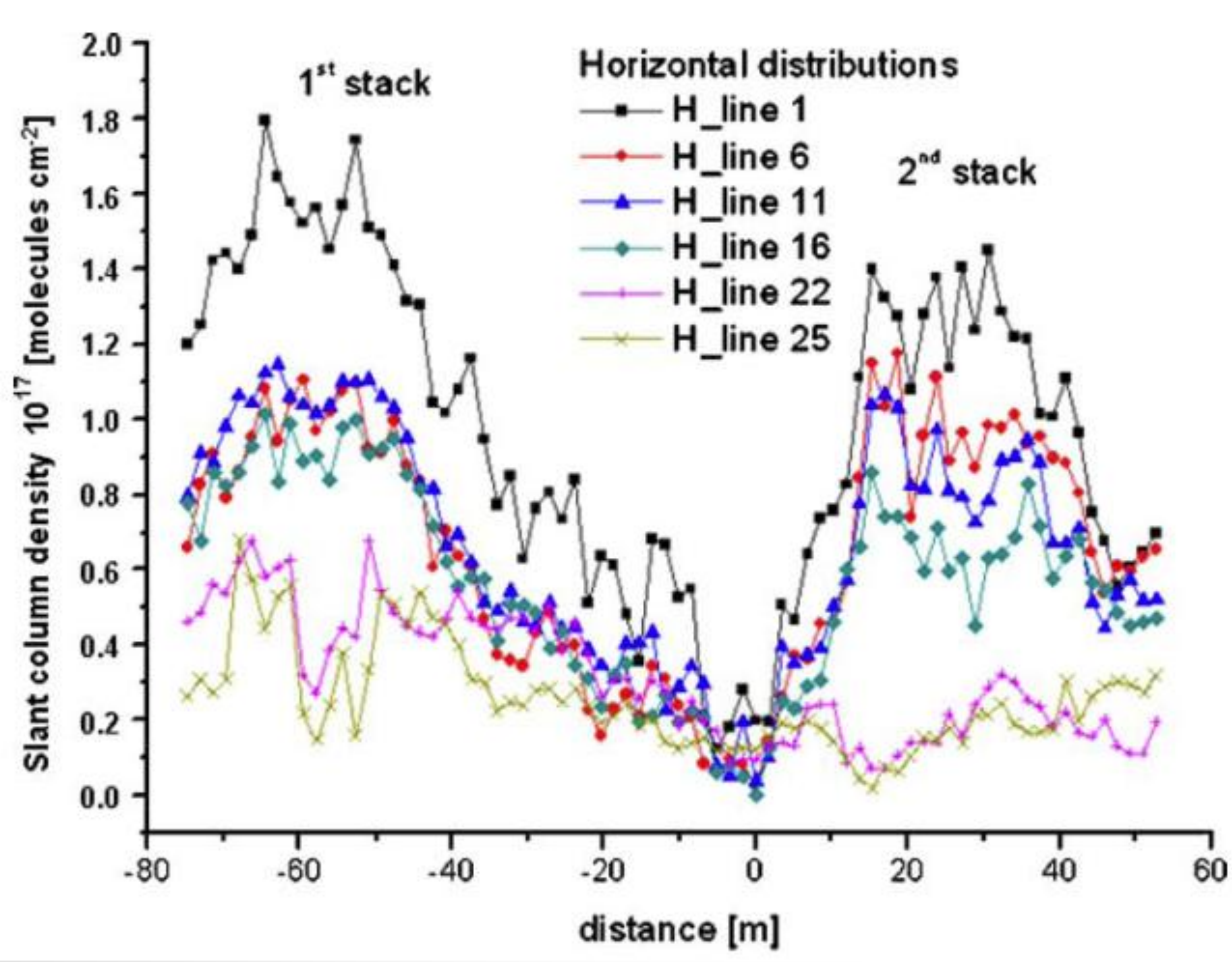


Molecule	Wavelength range (bands[a])	Polynomial order	Cross-sections included in fitting routine
NO_2	309.5 - 417 nm	3	NO_2, O_3, FRS, Ring

[Lee, H. et al., 2009]

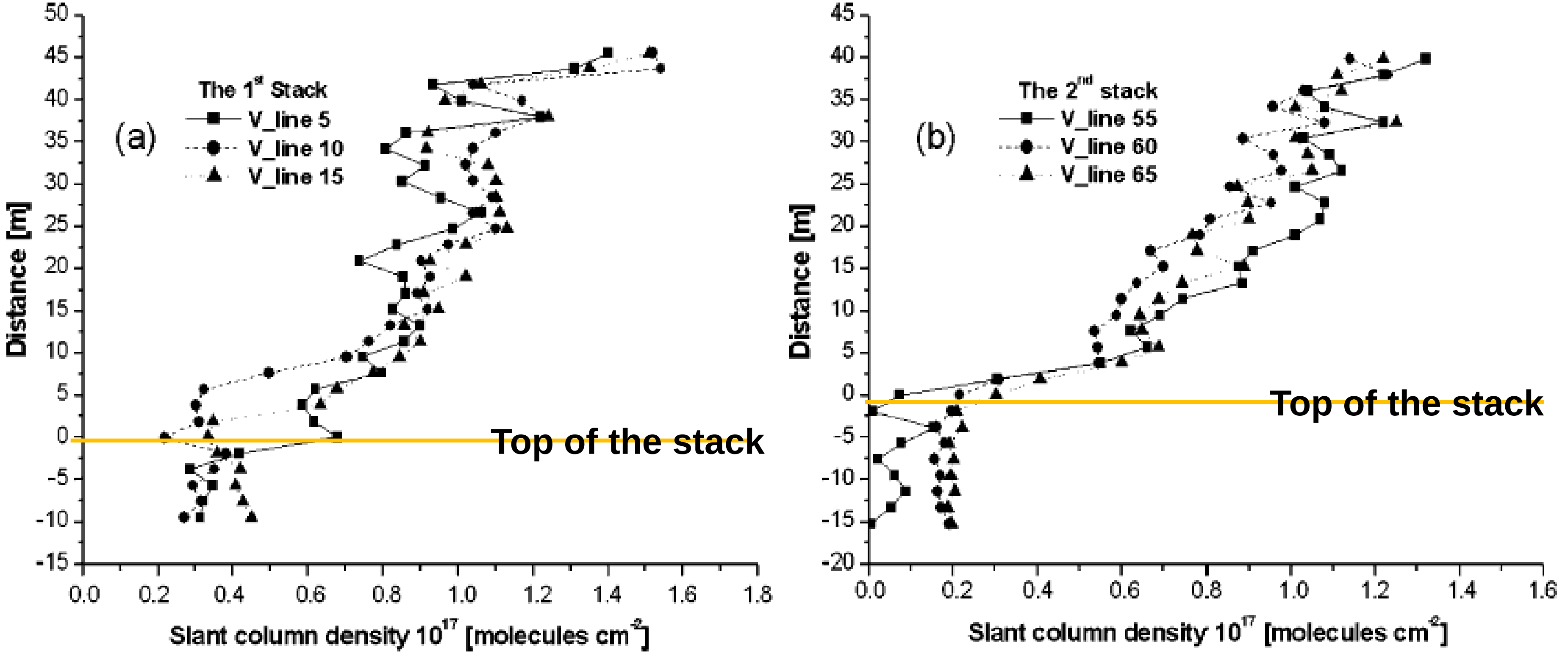
➢Examples of measurements

Ⅱ. Horizontal NO_2 slant column density (SCD)



[Lee, H. et al., 2009]

Ⅱ. Vertical NO_2 slant column density distributions above stacks

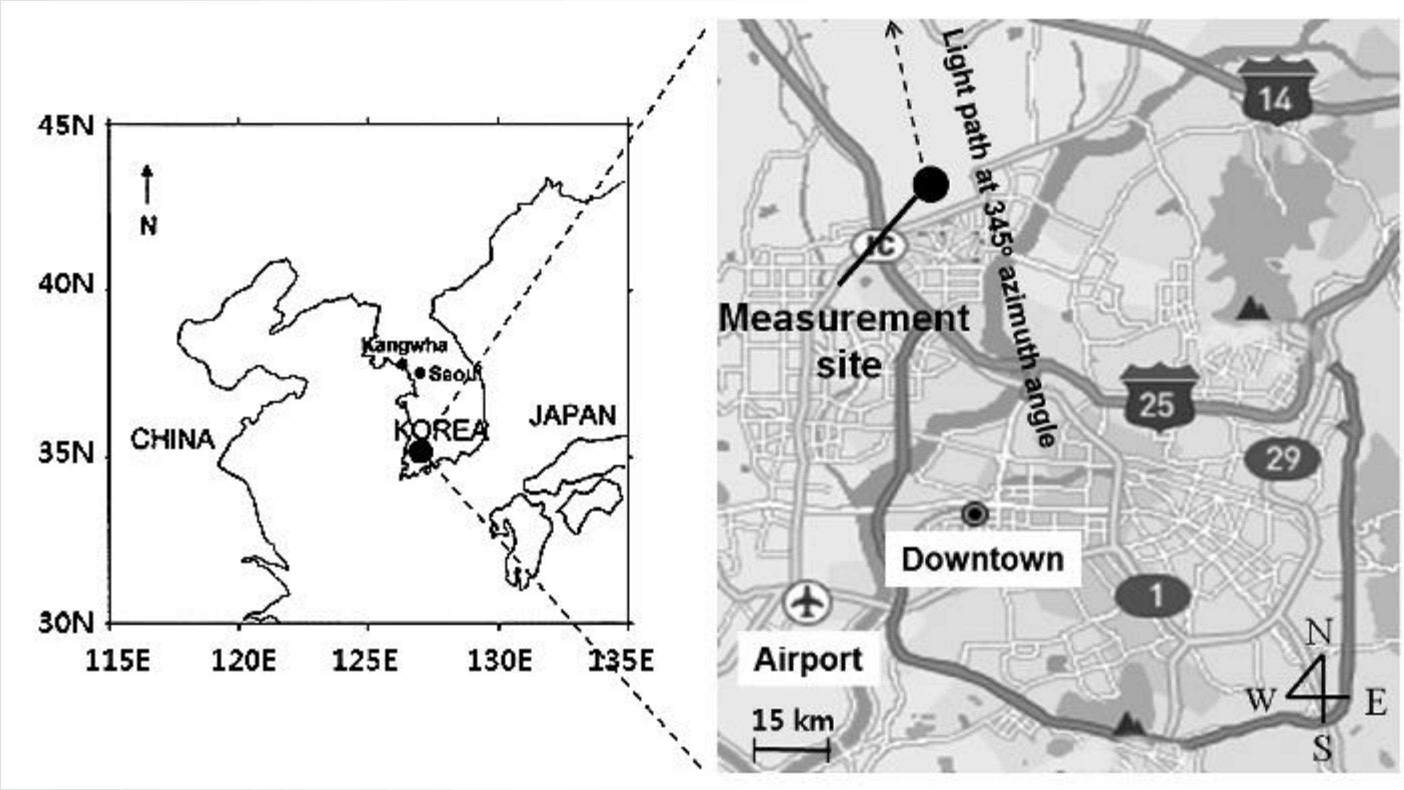


[Lee, H. et al., 2009]

Ⅱ. Summary

- This study is the first to measure the vertical NO_2 gradient in the 40–45 m above the exits of power plant stacks with a high spatial resolution of 1.9 (vertical)×1.7 m (horizontal).
- Rates of NO_2 increase within two rising plumes were directly obtained using the I-DOAS technique, revealing rates of 60 and 70 ppb s^{-1}, corresponding to 6 and 7 ppb m^{-1}, respectively.
- The obtained rates of NO_2 increase are only applicable to areas close to the stack.

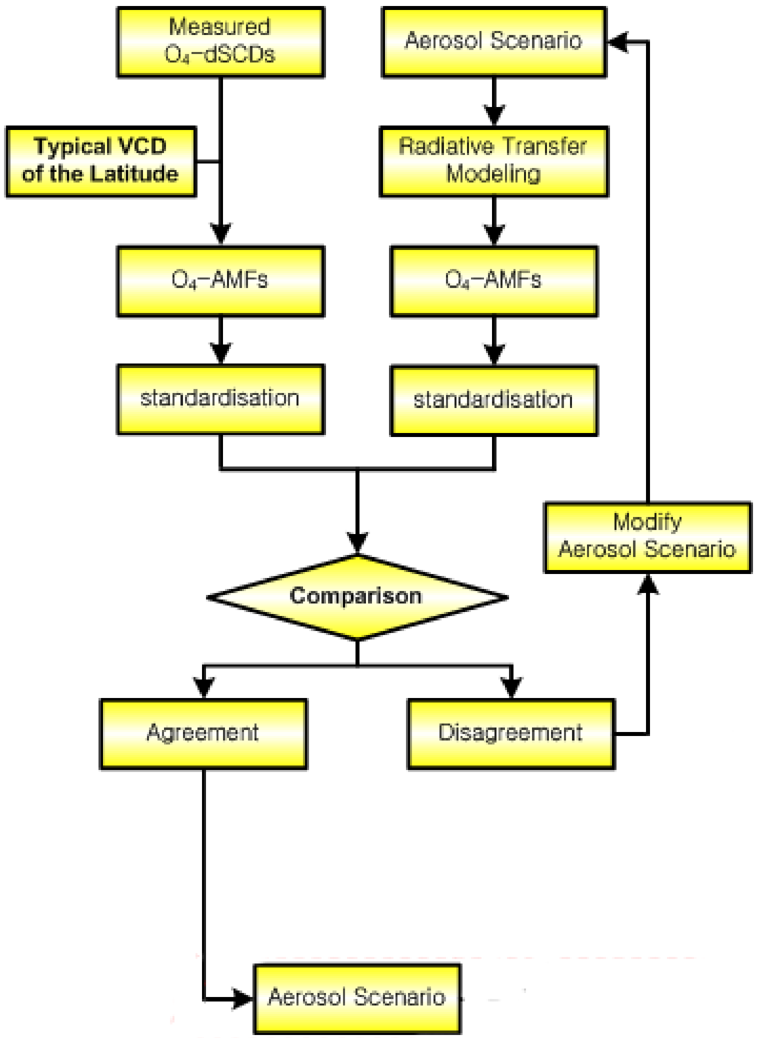
Ⅲ. MAX-DOAS measurement of Aerosol



Site: Gwangju (35.11 N, 126.54E)
Period: 27 February - 18 May 2008 ,
a period that includes two severe Asian dust storm days

[Lee, H. et al., 2009]

Ⅲ. Aerosol Retrieval Algorithm



1.Obtain O_4 DSCDs from MAX-DOAS measurement data

2.Calculate O_4 AMFs with known vertical O_4 column density at various elevation angles.

3.Vary aerosol profile as an input for RTM until simulated O4 matches with those observed at all elevation angles.

4.An optimized aerosol profile is obtained from the agreement for all elevation angles.

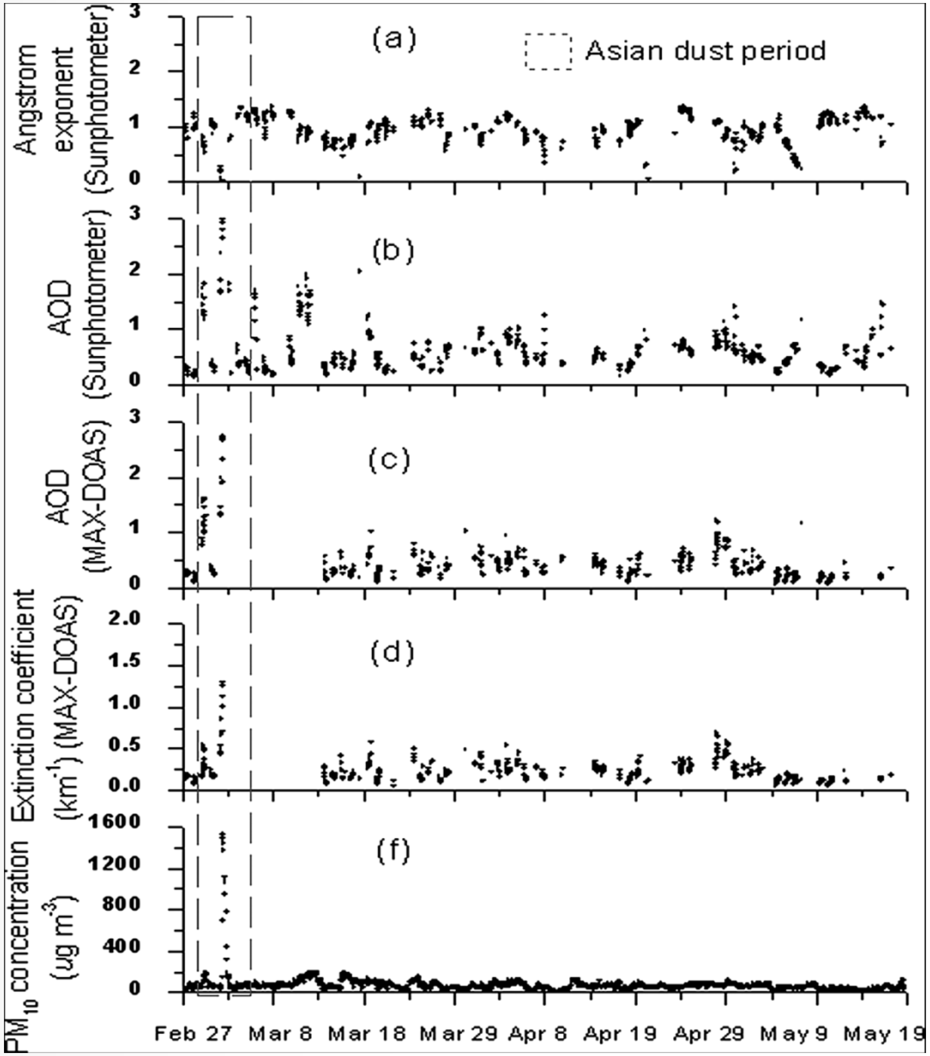
[Sinreich et al., 2005]

Ⅲ. Temporal variations of measured aerosol quantities

as low as 0.54 on 29 February
0.01 on 2 March

Note: Low A° exponent values on those two days suggest that the aerosol mostly consisted of coarse particles

PM10 concentrations range
from 37 to 1521 *μg* m^{-3}
on 2 March
from 45 to 185 *μgm*$^{-3}$
on 29 February

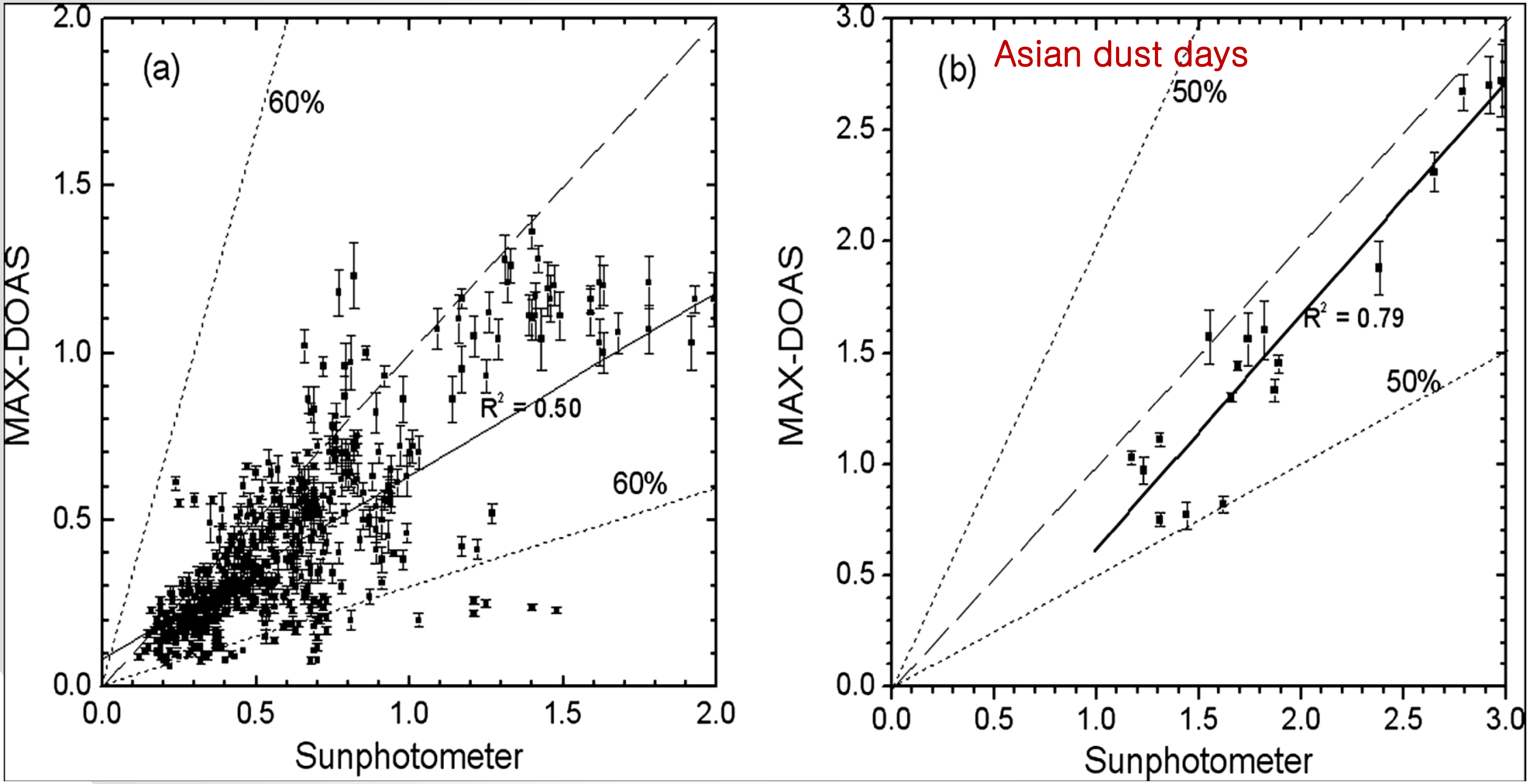


[Lee, H. et al., 2009]

Ⅲ. MAX-DOAS vs. Sunphotometer

(27 February–18 May 2008, except the two Asian dust days on 29 February 29 and 2 March)

(on 29 February 29 and 2 March)



[Lee, H. et al., 2009]

Ⅲ. Summary

- Retrieved AODs and AECs at the 0–1 km layer were validated by comparison with collocated sunphotometer data and surface PM10 concentrations measured by a beta gauge sampler.
- Scatter of the correlation is within 50% on the two Asian dust days.
- Much less correlation was also observed between the surface PM10 and AEC at 0.5 km above ground level on the Asian dust days than that obtained during the non episodic days.
- As investigated in recent studies (Irie et al. 2008a, 2009; Lee et al. 2009), several factors can cause uncertainties involved in MAX-DOAS measurements including a priori values, constants such as single scattering albedo, and fixed surface albedo, as well as atmospheric conditions such as fogs and clouds at lower altitudes.

Summary (1)

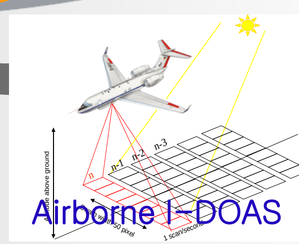
- Optical remote sensing techniques have been preferred for measurements of atmospheric trace gases and aerosol.
- DOAS has been used as a powerful tool for ground-based optical remote sensing of atmospheric trace species (e.g., SO_2, NO_2, O_3, HCHO, BrO, ClO, and VOCs) and aerosol.
- The more recently developed Imaging DOAS technique provides information on the spatially resolved two dimensional distributions of trace gases.
- DOAS technique has been applied as an alternative tool for the detection of atmospheric aerosols.
- The satellite remote sensing approach associated with the spectral DOAS fit technique has been successfully employed for the measurements of tropospheric trace gases on global and regional scales.

Summary (2)

Ground-based Max-DOAS

Optical remote sensing of atmospheric trace gases and aerosol

Airborne MAX-DOAS or Imaging-DOAS



Satellite observations

Thank you!

E-mail: yjkim@gist.ac.kr

➢Examples of measurements

IV. Major Satellite Sensors for the Trace Gas Measurements

TOMS (1978 – 2008)

❖ Total Ozone Mapping Spectrometer
- onboard Nibus, Adeos, Earth Probe
- O_3 (additionally SO_2)

GOME (1995 – 2003)

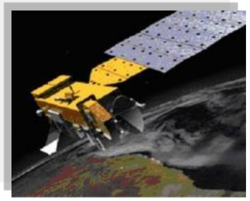
❖ Global Ozone Monitoring Experiment
- onboard ERS-2
- O_3, NO_2, OClO, BrO, HCHO, SO_2, H_2O, etc.

SCIAMACHY (2002 –)

❖ SCanning Imaging Absorption spetroMeter for Atmospheric CHartographY
- onboard ENVISAT
- O_3, NO_2, OClO, BrO, HCHO, SO_2, H_2O, CO, CO .

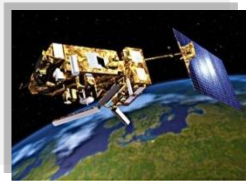
OMI (2004 –)

❖ Ozone Monitoring Instrument
- onboard EOS-Aura
- O_3, NO_2, OClO, BrO, HCHO, SO_2, H_2O, etc.



GOME-2 (2006 –)

❖ GOME-2
- onboard MetOp
- O_3, NO_2, OClO, BrO, HCHO, SO_2, H_2O, etc.



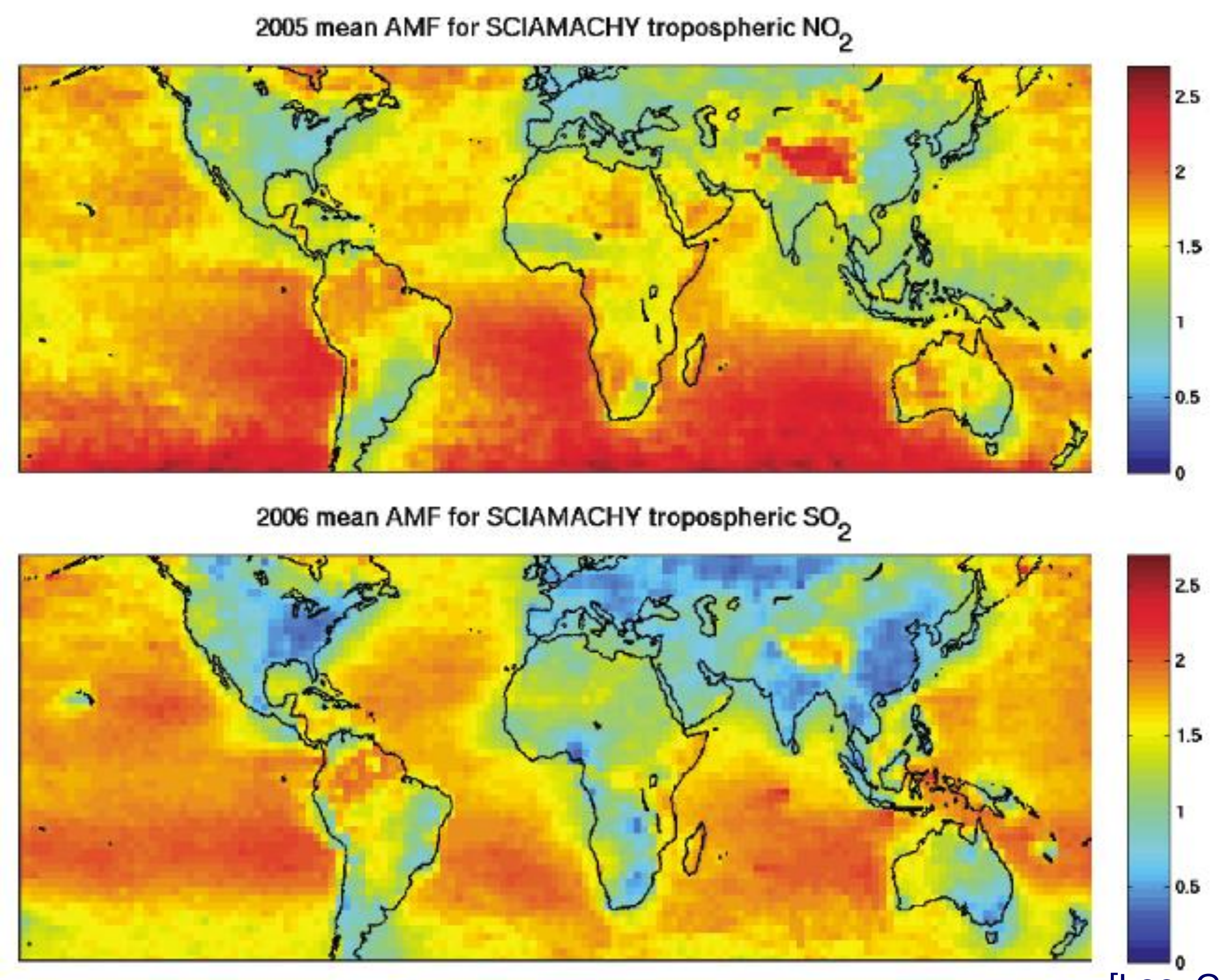
IV. Major satellite instruments for remote sensing

Instrument	Satellite platform	Measurement period	Equator crossing time (local time)	Spectral range (μm)	Spectral resolution (nm)	Spatial resolution, Nadir (km)	Global coverage (days)
GOME[a]	ERS-2	1995–2003[b]	10:30	0.23–0.79	0.2–0.4	320 × 40	3
SCIAMACHY[c]	Envisat	2002	10:00	0.23–2.3	0.25–0.4	60 × 30	6
OMI[d]	EOS-Aura	2004	13:30	0.27–0.50	0.5	24 × 13	1
GOME-2	MetOp	2006	09:30	0.24–0.79	0.26–0.51	80 × 40	1.5

[a] Global Ozone Monitoring Experiment.
[b] Operating at reduced coverage since June 2003.
[c] SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY.
[d] Ozone Monitoring Instrument.

[Lee, C. et al., 2009]

IV. Air mass factor (AMF) for conversion of tropospheric slant columns to tropospheric vertical columns



$$VC = \frac{SC}{AMF}$$

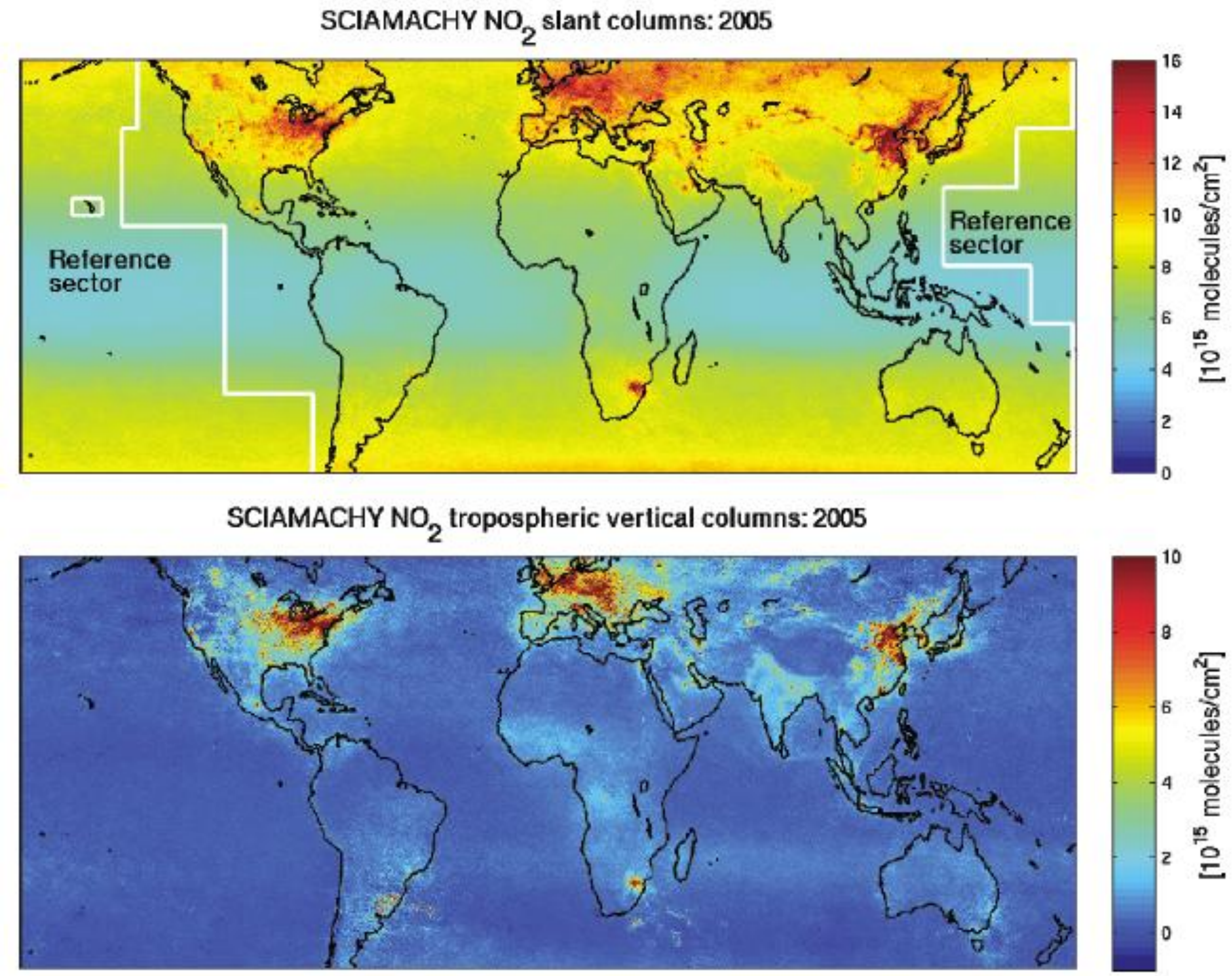
[Lee, C. et al., 2009]

IV. Specifications of NO_2 and SO_2 retrievals for SCIAMACHY data

Species	Wavelength range (nm)	Polynomial order	Cross-sections included in the fit
NO_2	426–450	3	NO_2 at 243 K (Vandaele et al. 2002) O_3 at 223 and 243 K (Bogumil et al. 2003) H_2O at 296 K (Rothman et al. 2005) O_2-O_2 at 296 K (Greenblatt et al. 1990) Ring (Chance and Spurr 1997)
SO_2	315–327	4	SO_2 at 295 K (Vandaele et al. 1994) O_3 at 223 and 243 K (Bogumil et al. 2003) Ring (Vountas et al. 1998) Undersampling Polarization dependency

[Lee, C. et al., 2009]

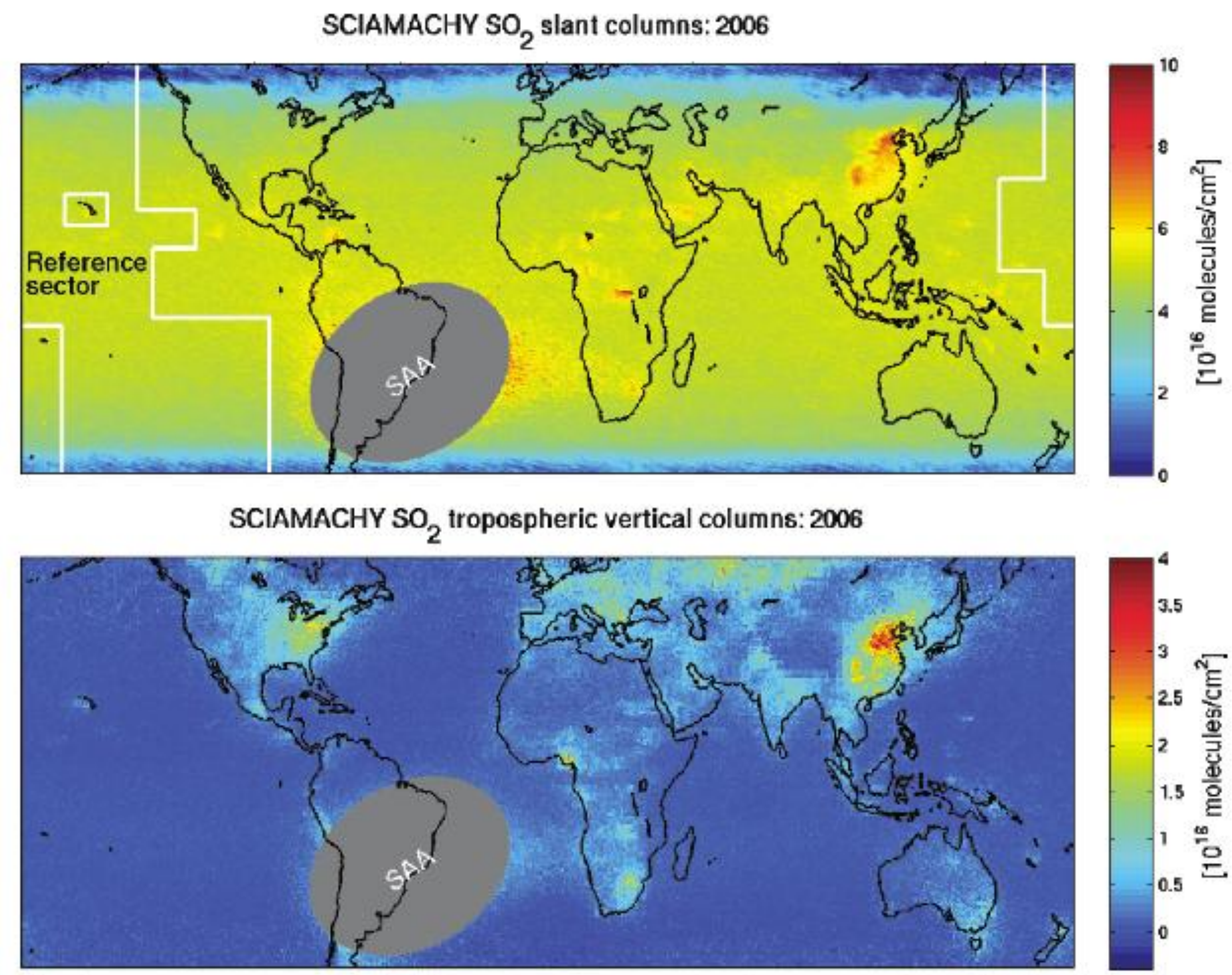
IV. NO_2 slant column and tropospheric vertical columns retrieved from SCIAMACHY



[Lee, C. et al., 2009]

➢Examples of measurements

IV. SO_2 slant column and tropospheric vertical columns retrieved from SCIAMACHY.



[Lee, C. et al., 2009]

IV. Summary

- Global mapping of trace gases from space provides critical information for constraining their emissions and improving our understanding of tropospheric chemistry.
- The retrievals of NO_2 and SO_2 in the troposphere and the AMF calculation to convert slant columns to vertical columns were presented.
- Satellite remote sensing has been successfully applied to measurements of trace gases in the troposphere.
- Satellite measurements of trace gases in the atmosphere are a crucial step forward for real time monitoring of air quality and forecasting such as hazard warning on a global scale.