PM monitoring from space

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Motivation

- Exposure to particulate pollution impacts human health:
  - respiratory and cardiovascular morbidity, such as aggravation of asthma, respiratory symptoms and an increase in hospital admissions

Guidelines

$PM_{2.5}$:	**10 μg/m^3 annual mean** **25 μg/m^3 24-hour mean**
PM_{10}:	**20 μg/m^3 annual mean** **50 μg/m^3 24-hour mean**

WHO 2005

Motivation

- Knowledge of the concentration of aerosol particles with diameters smaller than 2.5 μm (PM2.5) is needed to maintain air quality standards and to restrict emissions of anthropogenic aerosols
- Epidemiologic and health impact studies of PM2.5 are limited by the lack of monitoring data, especially in developing countries.
- Satellite observations offer valuable global information about PM2.5 concentrations.

Motivation

WHOair quality guidelines and interim targets for particulate matter: annual mean concentrations[a]

	PM_{10} ($\mu g/m^3$)	$PM_{2.5}$ ($\mu g/m^3$)	Basis for the selected level
Iinterim target-1 (IT-1)	70	35	These levels are associated with about a 15% higher long-term mortality risk relative to the AQG level.
Interim target-2 (IT-2)	50	25	In addition to other health benefits, these levels lower the risk of premature mortality by approximately 6% [2–11%] relative to theIT-1 level.
Interim target-3 (IT-3)	30	15	In addition to other health benefits, these levels reduce the mortality risk by approximately 6% [2-11%] relative to the -IT-2 level.
Air quality guideline (AQG)	**20**	**10**	These are the lowest levels at which total, cardiopulmonary and lung cancer mortality have been shown to increase with more than 95% confidence in response to long-term exposure to $PM_{2.5}$.

WHO 2005

Motivation

WHO air quality guidelines and interim targets for particulate matter: 24-hour concentrations[a]

	PM_{10} ($\mu g/m^3$)	$PM_{2.5}$ ($\mu g/m^3$)	Basis for the selected level
Interim target-1 (IT-1)	150	75	Based on published risk coefficients from multi-centre studies and meta-analyses (about 5% increase of short-term mortality over the AQG value).
Interim target-2 (IT-2)	100	50	Based on published risk coefficients from multi-centre studies and meta-analyses (about 2.5% increase of short-term mortality over the AQG value).
Interim target-3 (IT-3)*	75	37.5	Based on published risk coefficients from multi-centre studies and meta-analyses (about 1.2% increase in short-term mortality over the AQG value).
Air quality guideline (AQG)	**50**	**25**	Based on relationship between 24-hour and annual PM levels.

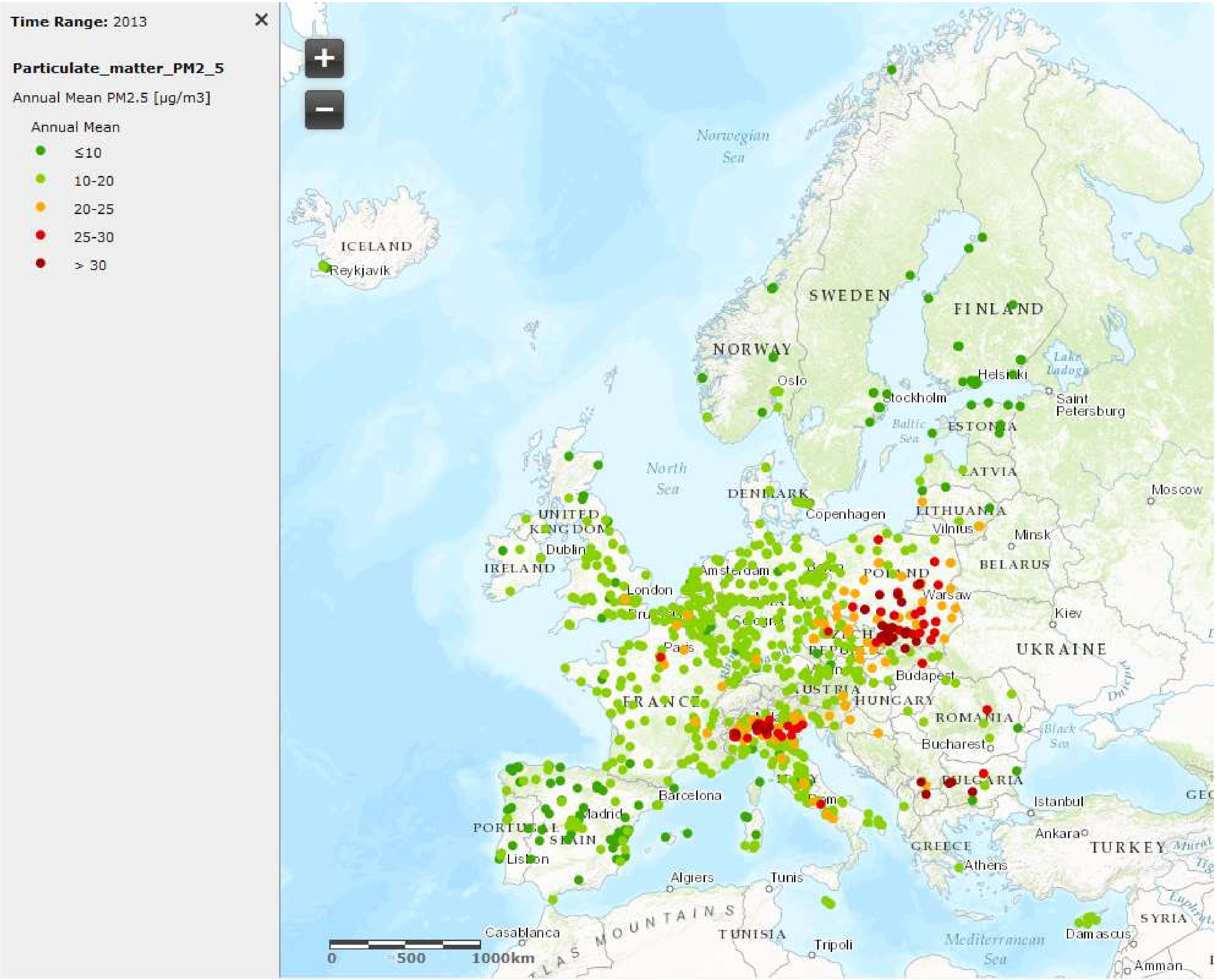
WHO 2005

Motivation

Index Values	Category	Cautionary Statements	$PM_{2.5}$ ($\mu g\ m^{-3}$)	PM_{10} ($\mu g\ m^{-3}$)
0–50	Good	None	0–15.4	0–54
51–100	Moderate	Unusually sensitive people should consider reducing prolonged or heavy exertion	15.5–40.4	55–154
101–150	Unhealthy for sensitive groups	Sensitive groups should reduce prolonged or heavy exertion	40.5–65.4	155–254
151–200	Unhealthy	Sensitive groups should avoid prolonged or heavy exertion; everyone else should reduce prolonged or heavy exertion	65.5–150.4	255–354
201–300	Very unhealthy	Sensitive groups should avoid all physical activity outdoors; everyone else should avoid prolonged or heavy exertion	150.5–250.4	355–424

TABLE 1. The U.S. EPA Air Quality Index for Particulate Matter.

Source: US EPA, 1997



http://www.eea.europa.eu/themes/air/interactive/pm2_5

Real-time air quality measurements (yesterday evening)

http://aqicn.org/map/world/#@g/14.1048/10.5469/3z

Motivation

- **In-situ measurements** provide observations of PM2.5 with **high temporal resolution** but only at **selected sites**
- **Satellite observations** of aerosol optical thickness (AOT) allow for **wide spatial coverage** but are **only available during times of satellite overpasses** (generally between 0900 and 1300 local time)
- Combining the two allows for a more comprehensive monitoring of air quality, especially in remote regions
- Previous studies suggest a **linear relationship** between aerosol load (PM2.5) and aerosol optical properties (extinction coefficient and AOT)

AOT and PM

2.1. AOD-PM Relation

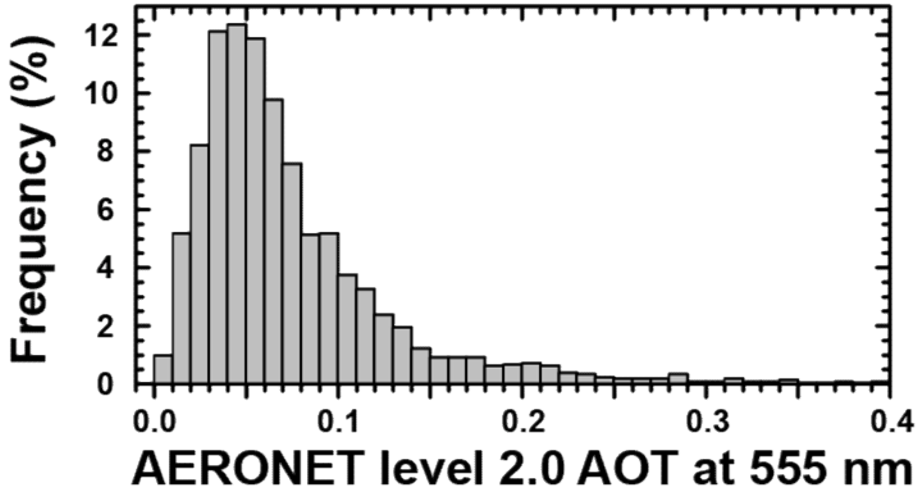
[5] AOD, τ, and total column aerosol mass loading Ω are related by:

$$\Omega = \frac{4}{3}\frac{\rho r_{eff}\tau}{Q_e} \qquad (2)$$

where ρ is the aerosol mass density at ambient relative humidity, r_{eff} is the column averaged effective radius (defined as the ratio of the third to second moment of an aerosol size distribution at ambient relative humidity), and Q_e is the column averaged extinction efficiency.

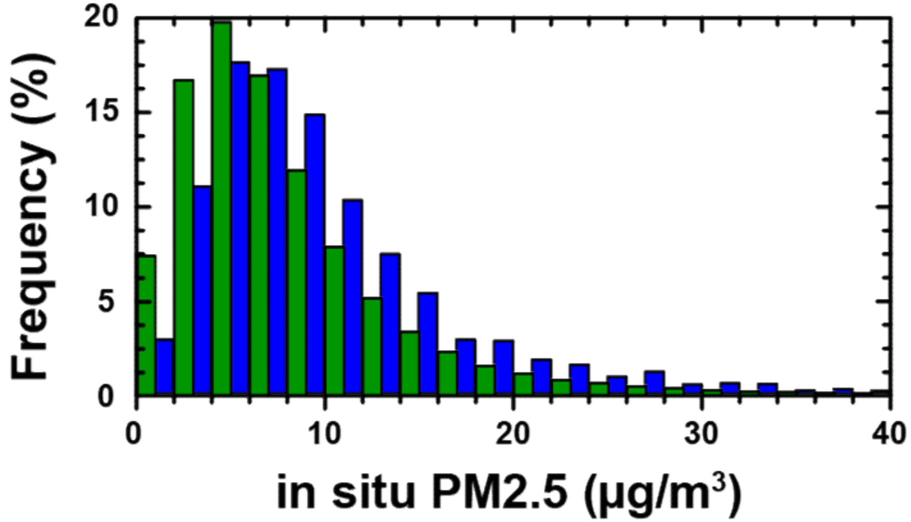
AOT and PM

AOT



daily means from AERONET measurements at Swedish sites between 1999 and 2012
n = 2042
mean: 0.076 ± 0.064
median: 0.059
range: 0.005 - 0.944

PM2.5



all hourly measurements between 2000 and 2012
N = 339231
mean: 7.99 ± 6.62
median: 6.47
range: 0.00 - 450.30

values related to MODIS overpasses
N = 8295
mean: 10.02 ± 7.90
median: 8.19
range: 0.06 - 226.83

Initial approach: direct link

Intercomparison between satellite-derived aerosol optical thickness and $PM_{2.5}$ mass: Implications for air quality studies

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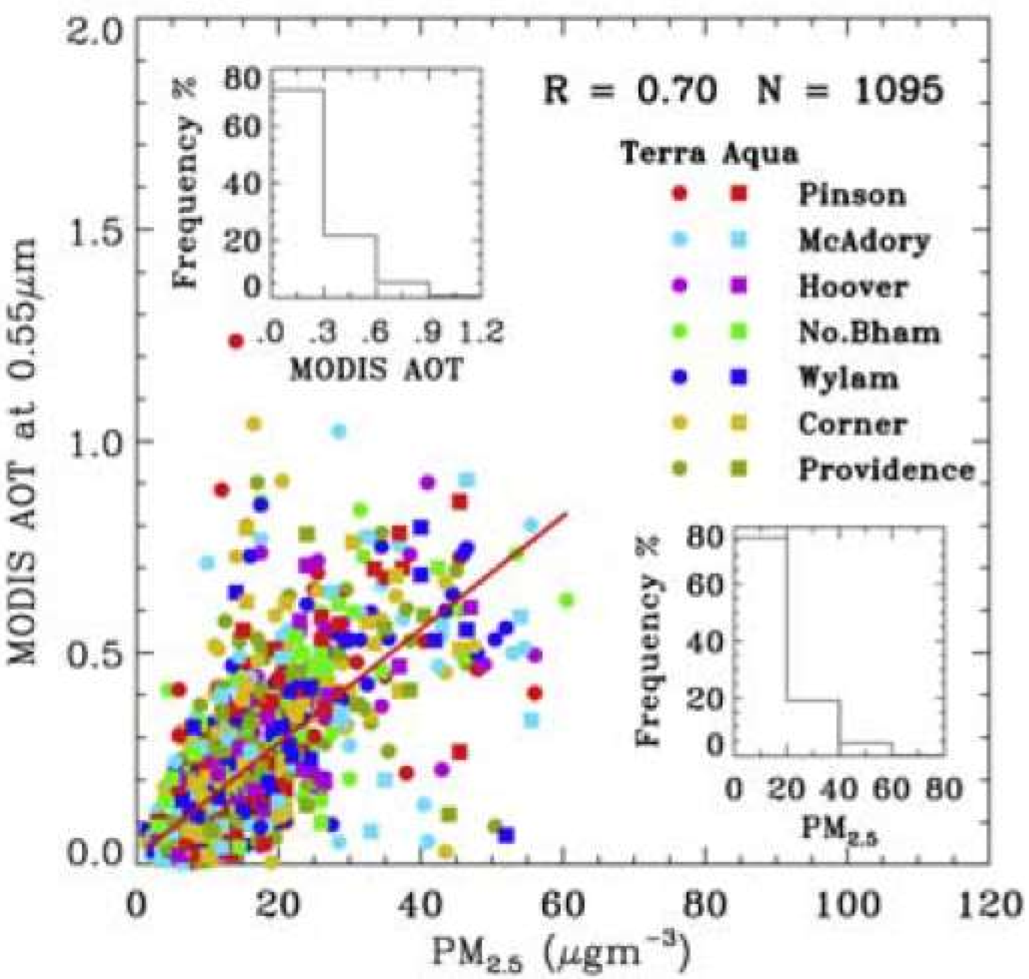
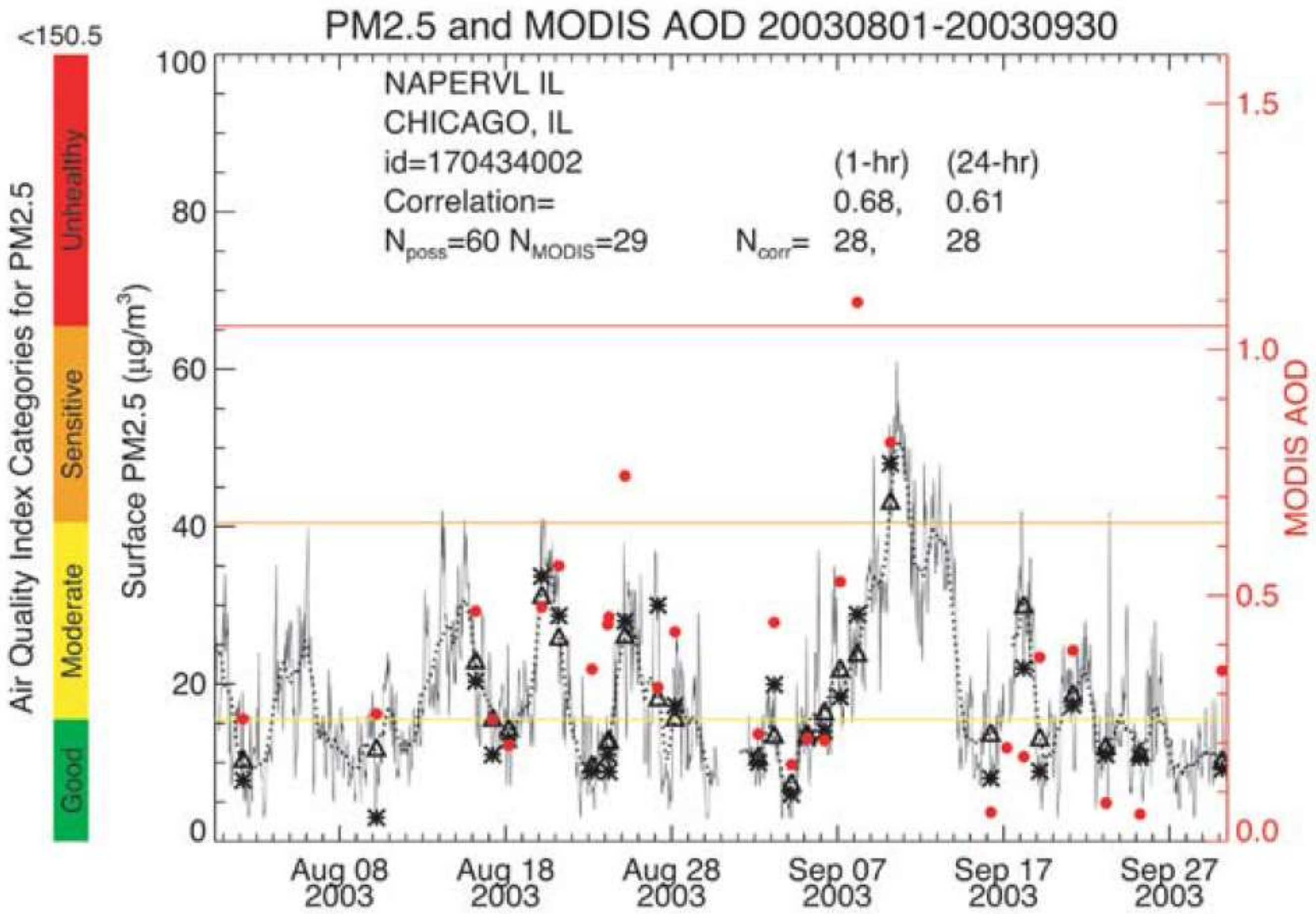
- Link (binned) MODIS AOT to hourly surface PM2.5
- good correlation (R = 0.7) between the satellite-derived AOT and PM2.5: most of the aerosols are in the well-mixed lower boundary layer during the satellite overpass times
- excellent agreement between monthly mean PM2.5 and MODIS AOT (R > 0.9)

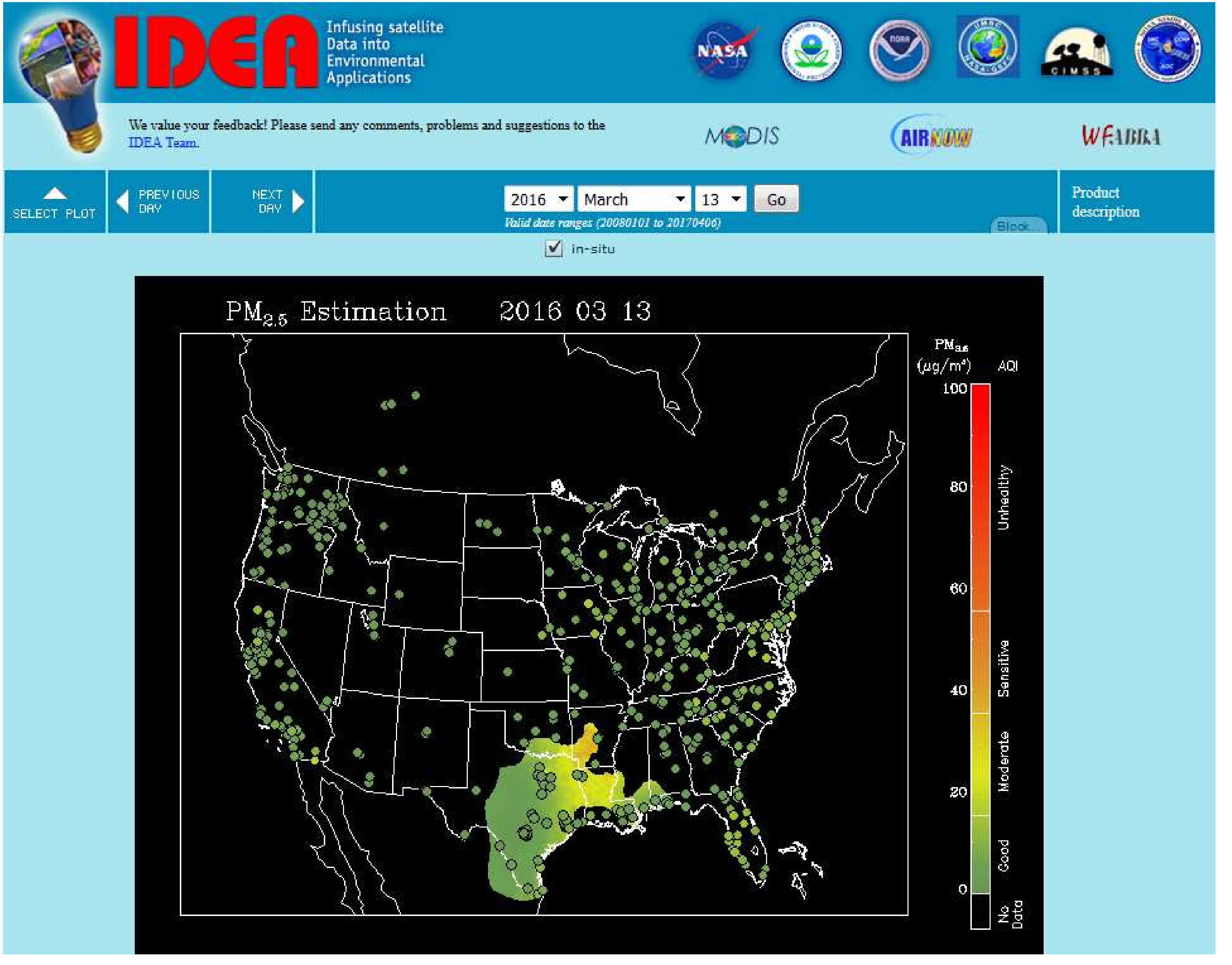


Initial approach: direct link



- MODIS AOT can be used quantitatively to estimate U.S. EPA air quality categories with an accuracy of more than 90% in cloud-free conditions.

Al-Saadi et al., BAMS 2005

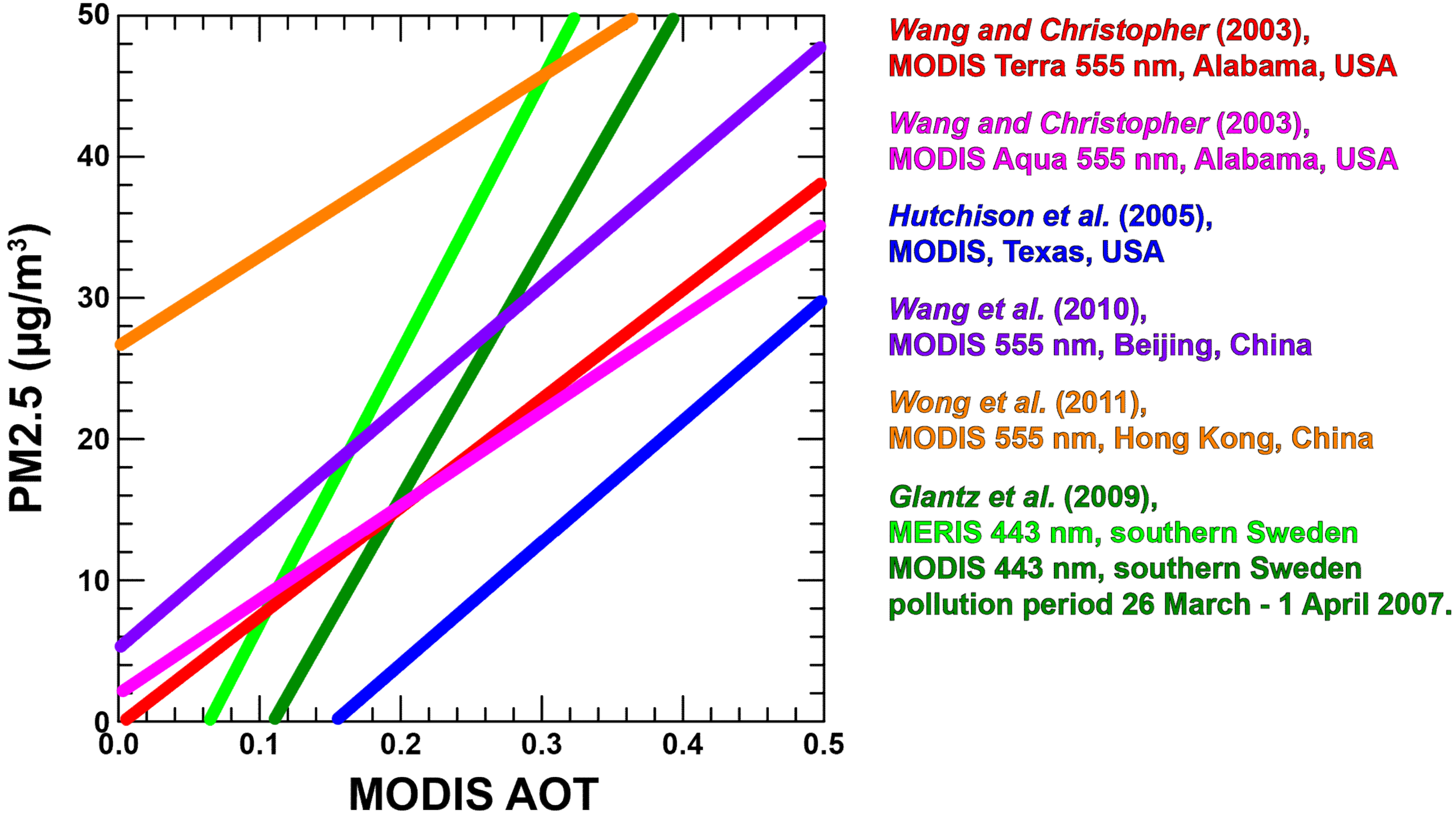


https://www.star.nesdis.noaa.gov/smcd/spb/aq/index.php?product_id=3

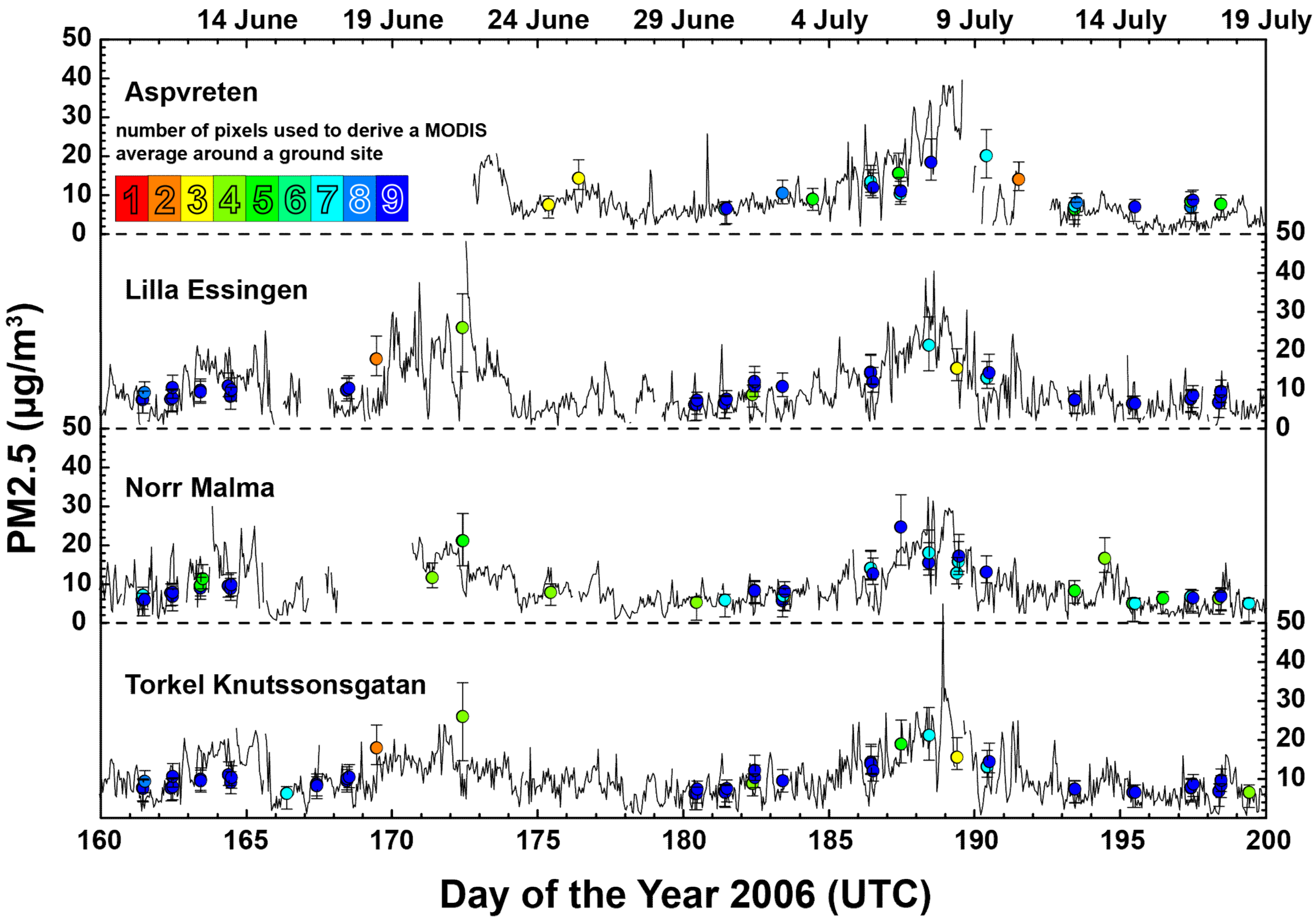
Error sources

- Aerosol hygroscopicity / Regional differences:
  - AOT-to-PM2.5 relationships refer to general conditions in a region and will fail if conditions change or when applied to another region. They are often dominated by linking very high PM concentrations to high AOT
- Aerosol layering
  - Aerosol inhomogeneity violates the assumptions about linking AOT and PM
- Cloudiness / representativeness
  - Spaceborne PM2.5 observations are biased towards fair-weather conditions and depend on underlying surface

Regional differences

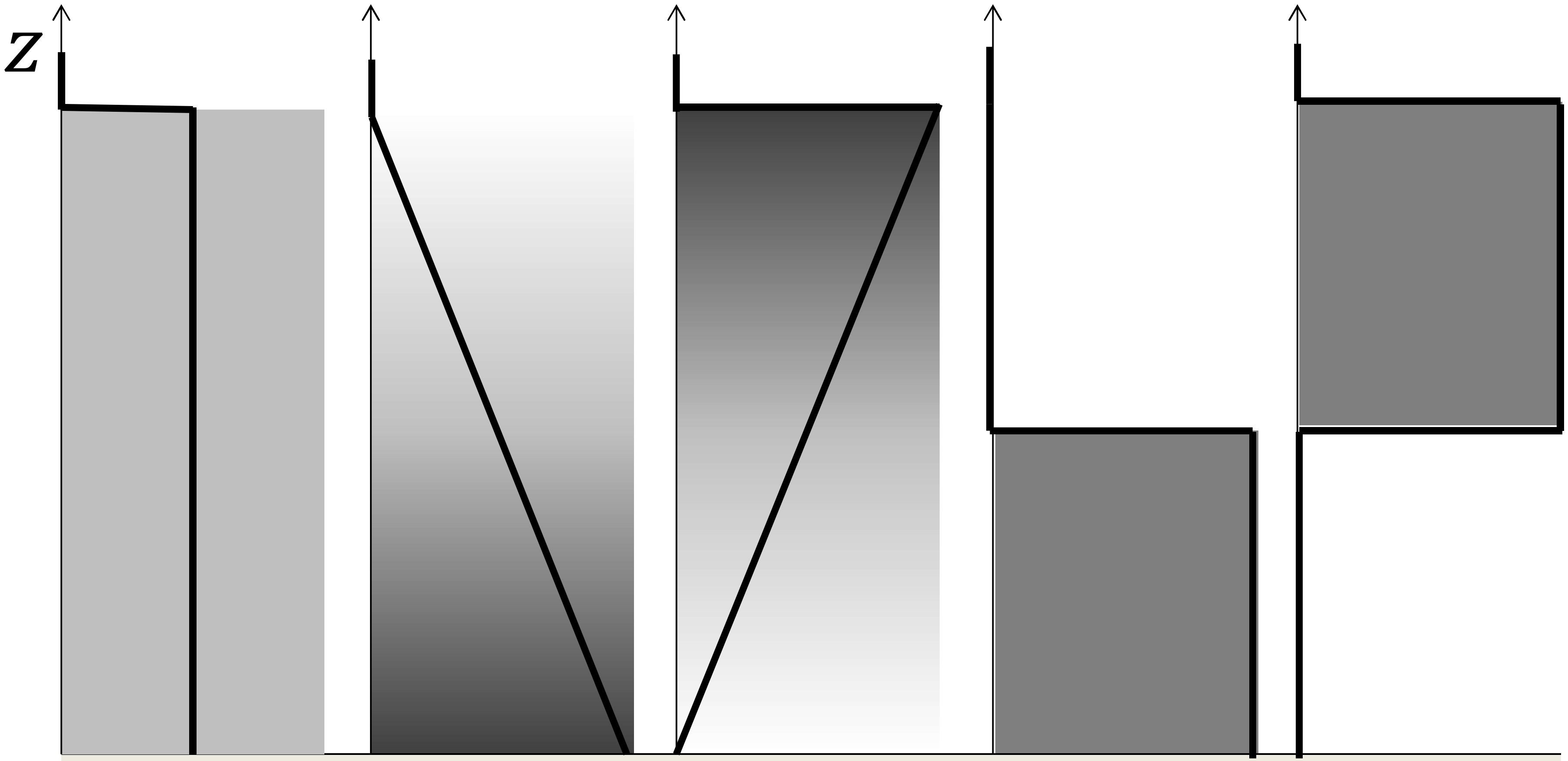


Works also under low PM conditions



MODIS-derived PM2.5 follows the observation at the ground site also for cases with few available pixels

Aerosol layering



$$\tau_1 = \tau_2 = \tau_3 = \tau_4 = \tau_5$$

$$\alpha_1(z) \neq \alpha_2(z) \neq \alpha_3(z) \neq \alpha_4(z) \neq \alpha_5(z)$$

Improved approach: involve model data

Estimating ground-level $PM_{2.5}$ using aerosol optical depth determined from satellite remote sensing

Aaron van Donkelaar,[1] Randall V. Martin,[1,2] and Rokjin J. Park[3]

Received 15 December 2005; revised 9 May 2006; accepted 25 July 2006; published 2 November 2006.

- Models can be used to obtain localized and seasonally resolved relationships and to address the effect of aerosol layering
- A global chemical transport model (GEOS-CHEM) is used to simulate the factors affecting the relation between AOD and PM2.5

$$Estimated\ PM_{2.5} = \frac{Model\ surface\ aerosol\ concentration}{Model\ AOD} \times Retrieved\ AOD$$

- The relative vertical profile of aerosol extinction is the most important factor affecting the spatial relationship between satellite and surface measurements of PM2.5

Improved approach: involve model data

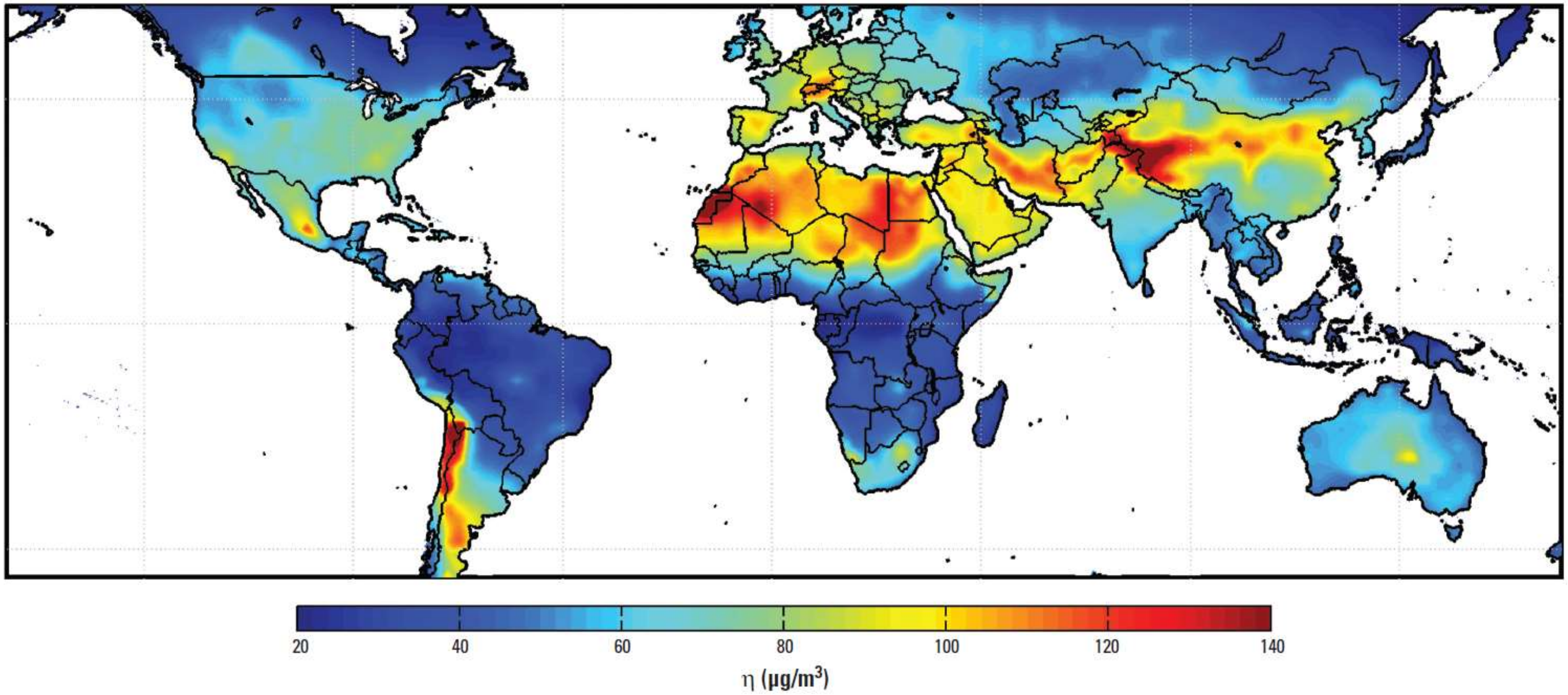


Figure 2. Annual mean η (ratio of $PM_{2.5}$ to AOD) for 35% relative humidity. White space indicates water.

Van Donkelaar et al., EHP 2010

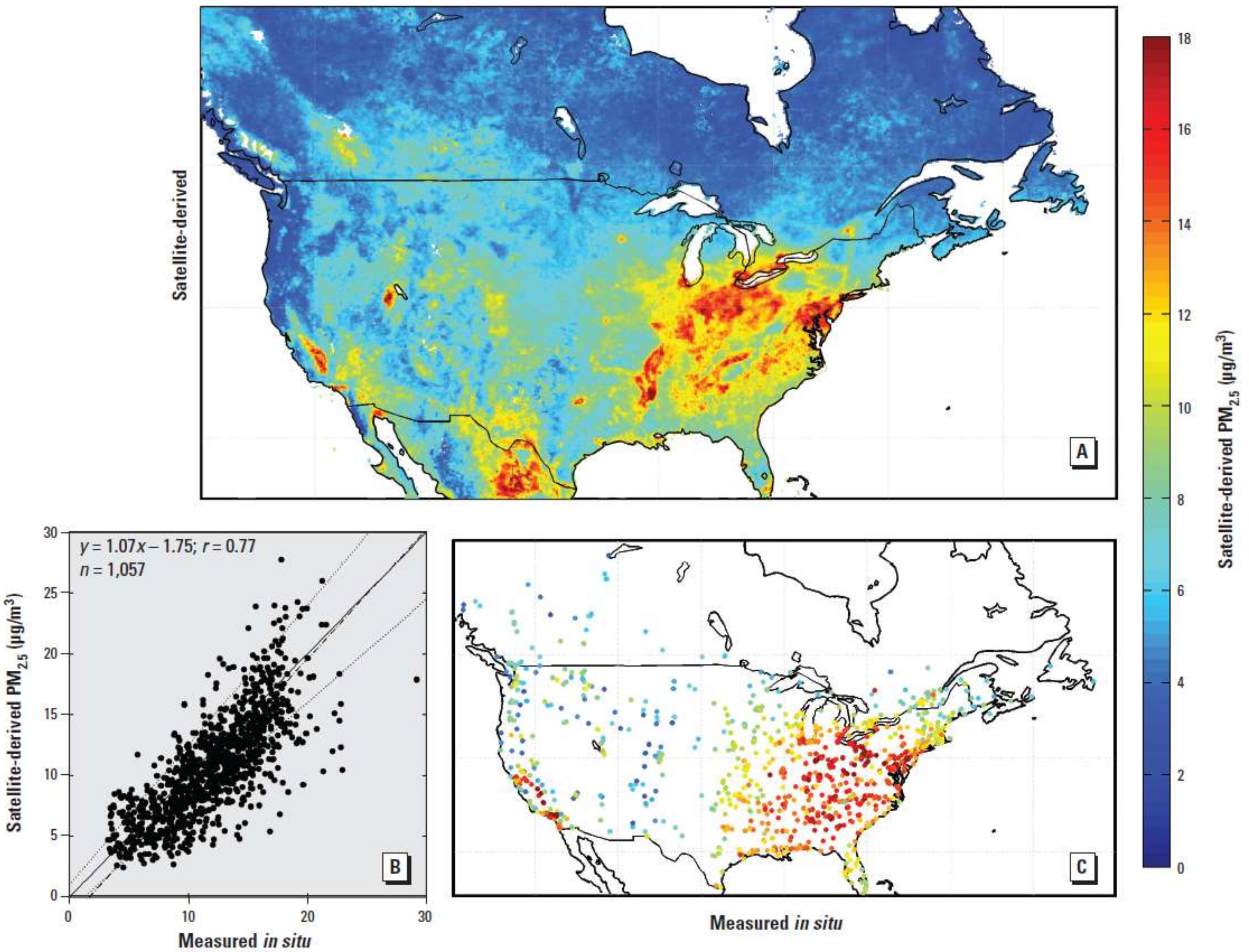


Figure 3. Satellite-derived $PM_{2.5}$ and comparison with surface measurements. (*A*) Mean satellite-derived $PM_{2.5}$ between 2001 and 2006; white space denotes water or < 50 AOD measurements. (*B*) Average coincident values of both measured and satellite-estimated $PM_{2.5}$. The solid black line denotes unity; thin dotted lines show uncertainty of ± (1 $\mu g/m^3$ + 15%); and the dashed line represents the best fit (Hirsh and Gilroy 1984). (*C*) Positions and mean values of coincidently measured surface sites.

Van Donkelaar et al., EHP 2010

Improved approach: involve model data

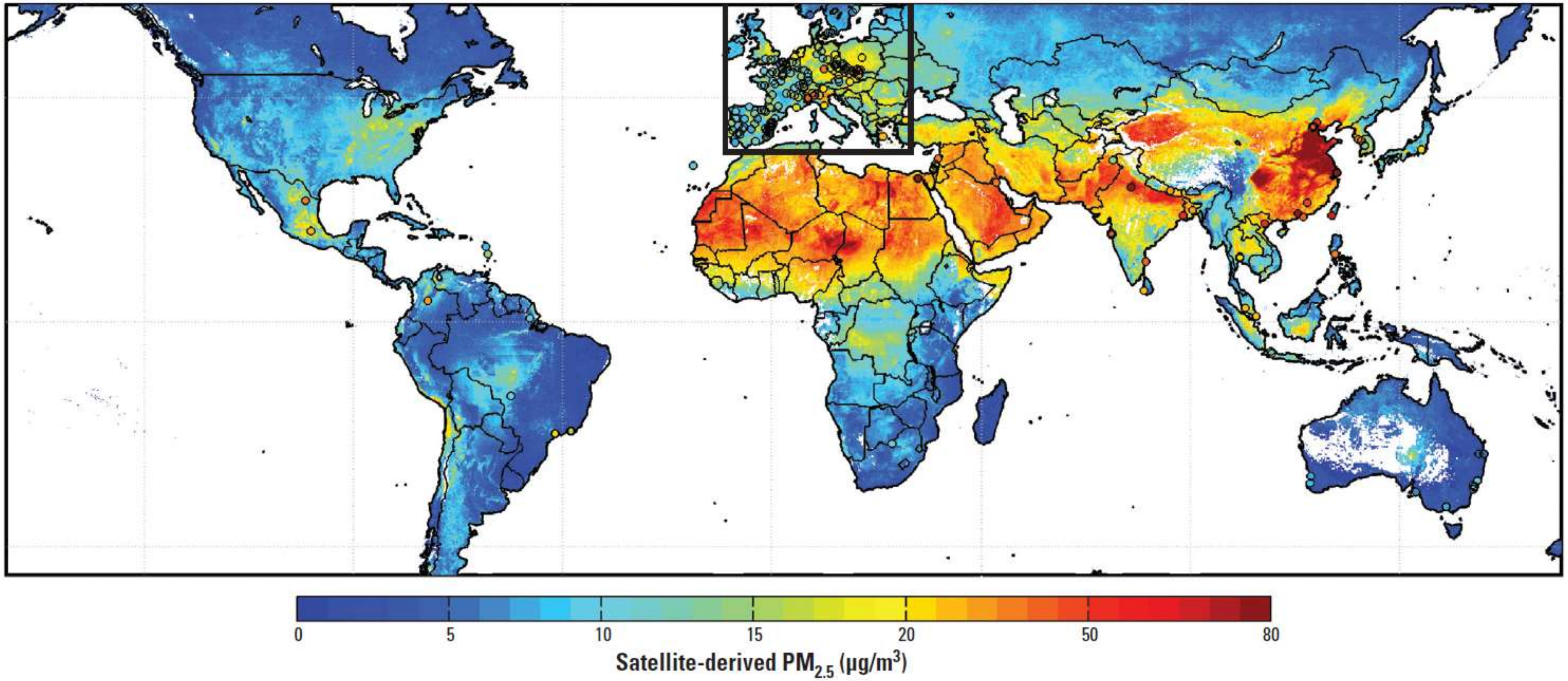


Figure 4. Global satellite-derived $PM_{2.5}$ averaged over 2001–2006. White space indicates water or locations containing < 50 measurements. Circles correspond to values and locations of comparison sites outside Canada and the United States; the black box outlines European sites.

Derive information on PM exposure needed for epidemiological studies

Van Donkelaar et al., EHP 2010

Improved approach: involve model data

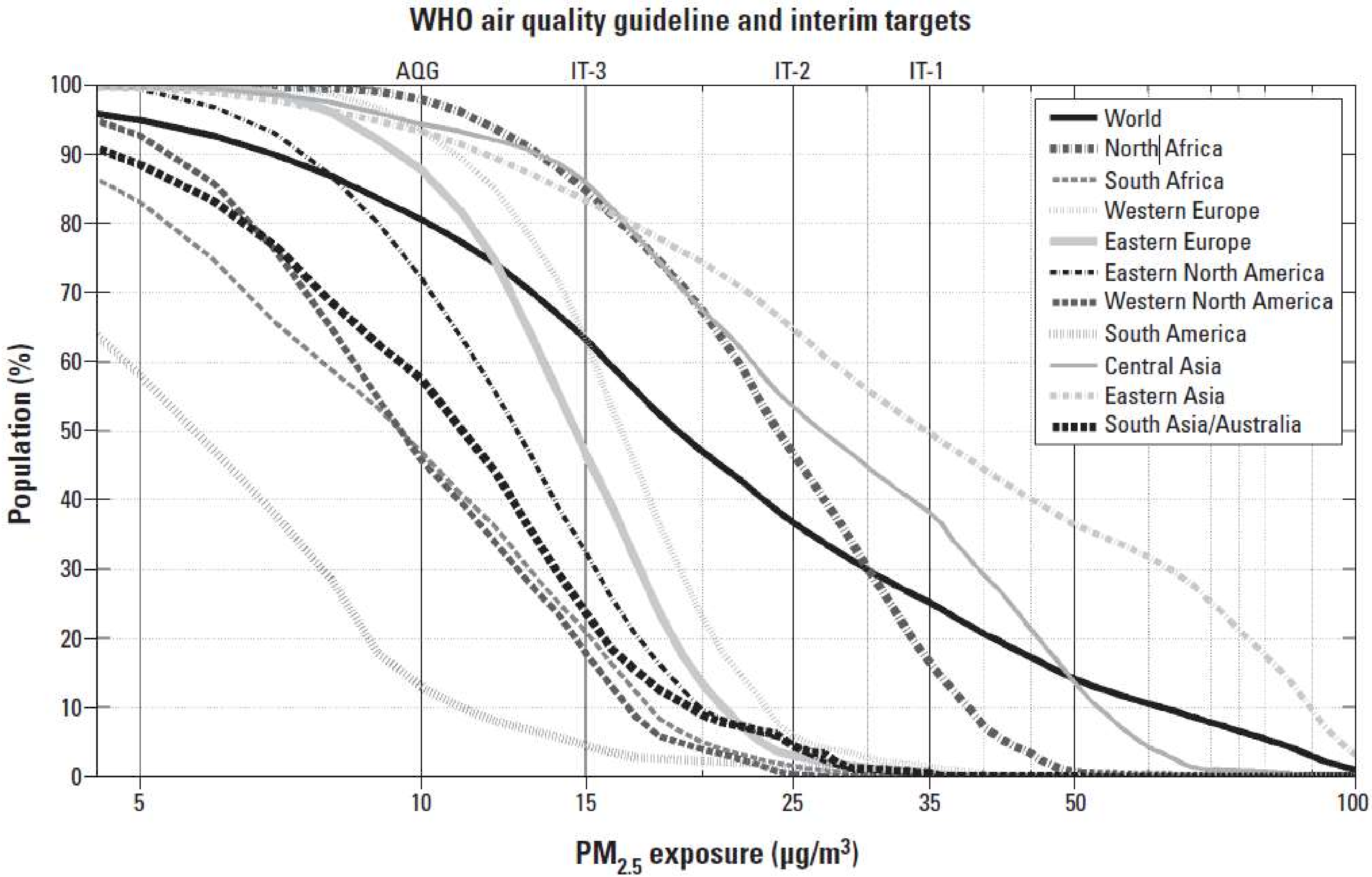
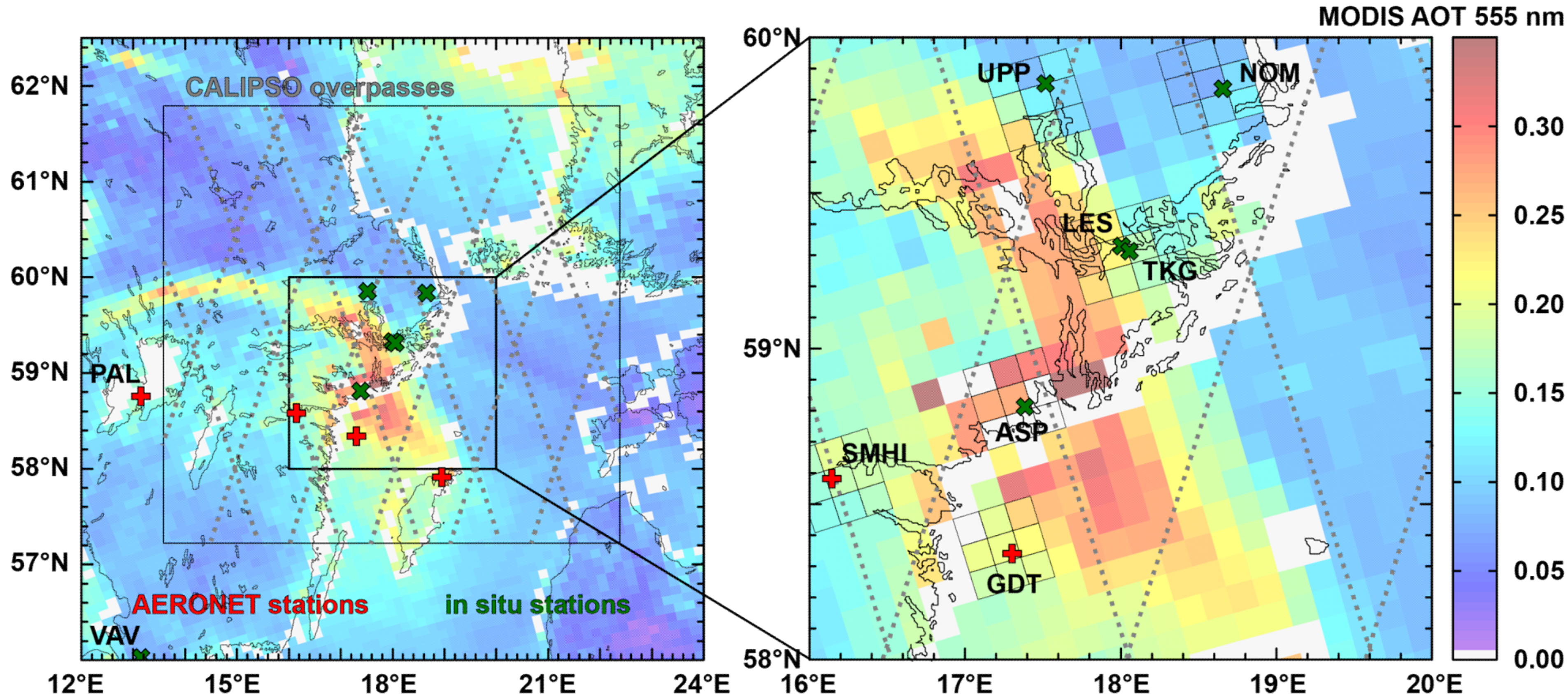


Figure 8. Cumulative distribution of regional, annual mean $PM_{2.5}$ estimated from satellite-derived $PM_{2.5}$ at a resolution of 0.1° × 0.1° for 2001–2006. The top axis identifies WHO AQG and Interim Target (IT) associated with each concentration level. Regions are outlined in Figure 6.

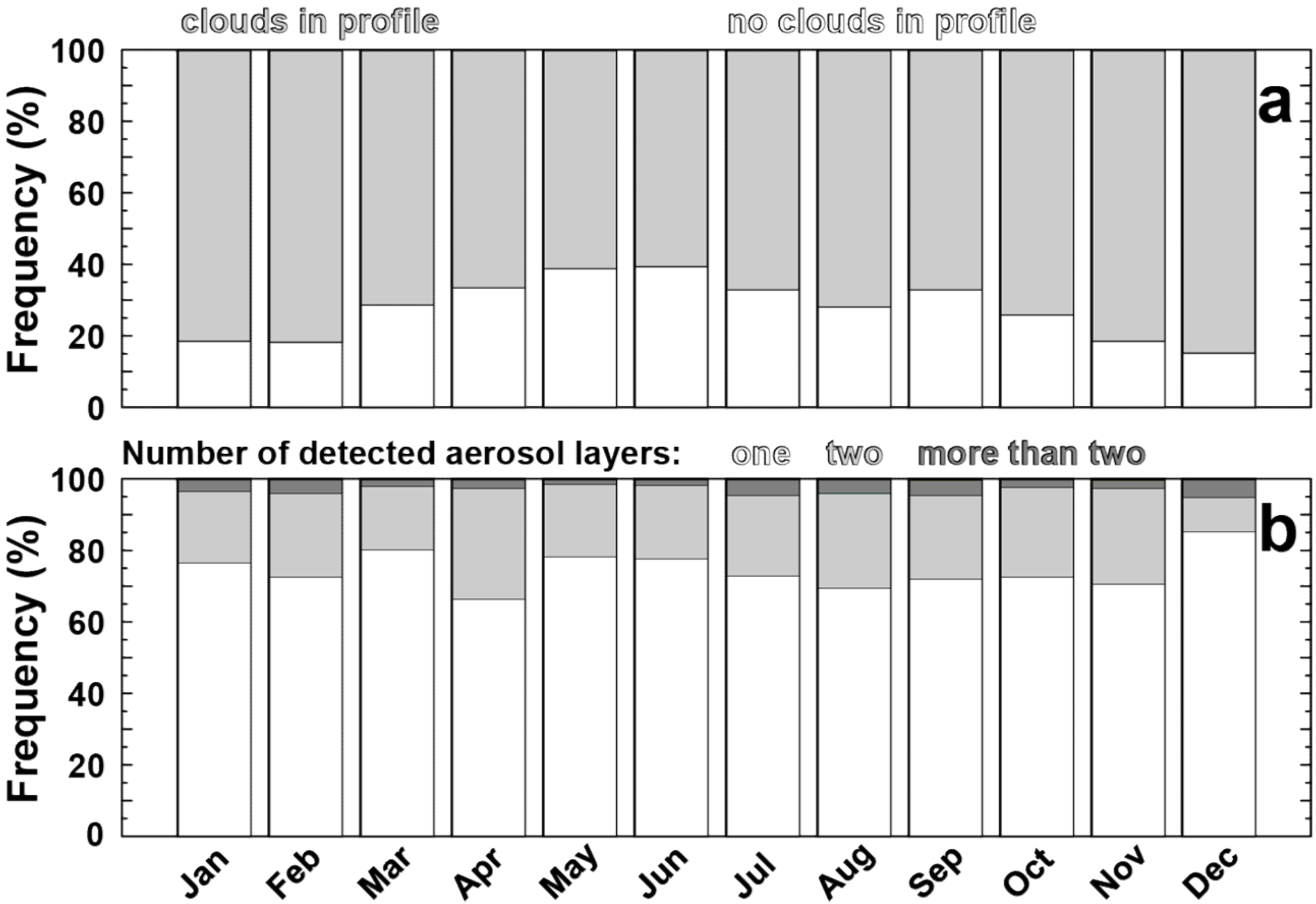
Van Donkelaar et al., EHP 2010

Representativeness

Clouds are the main obstacle in retrieving AOT with spaceborne sensors



Representativeness



What can be done?

- geostationary sensors allow for better temporal resolution (but might not provide information for reliable AOT retrievals, yet)

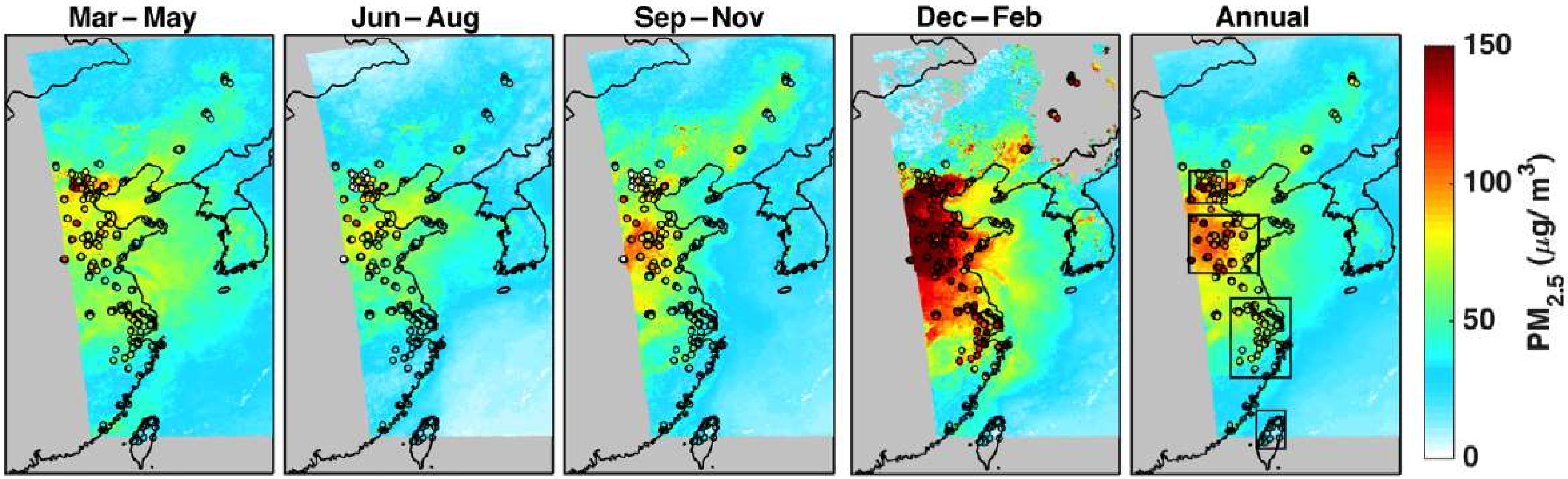


Figure 3. Seasonal and annual distribution of $PM_{2.5}$ concentrations at 6 km by 6 km resolution over East Asia for 2013. The background color indicates averages of GOCI-derived daily surface $PM_{2.5}$ concentrations. Filled circles represent averages of daily ground-based measurements of $PM_{2.5}$. Gray denotes missing values. Boxes in the annual map denote regions used for monthly comparisons in Fig. 5 from top to bottom: Beijing and surrounding areas, Shandong and surrounding regions, Shanghai and surrounding areas and northern Taiwan.

Xu et al., ACP 2015

What can be done?

- Dedicated programs to better understand the connection between aerosol optical properties and air quality
  - Establish ground-based networks to investigate the connection between surface PM2.5 and AOT: SPARTAN (Surface PARTiculate mAtter Network); nephelometer and filter sampler at AERONET sites
  - DISCOVER-AQ (Deriving Information on Surface conditions from Column and Vertically Resolved Observations Relevant to Air Quality, https://discover-aq.larc.nasa.gov/)