Satellite Observations of Changes in Anthropogenic SO_2

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SO_2 in the Atmosphere

Sources of SO_2
- volcanoes (degassing, eruptions)
- DMS oxidation
- smelting of ores
- combustion of coal

Relevance of SO_2
- acid rain formation
- acidification of water bodies, release of aluminum
- smog
- aerosol formation (reflective)

Changes in atmospheric SO_2 levels can result from
- changes in emissions (e.g. pollution, volcanic activity)
- changes in air chemistry (e.g. OH concentration)
- changes in dynamics (e.g. frequency of frontal systems)
- any combination of the above

How to measure from Space?

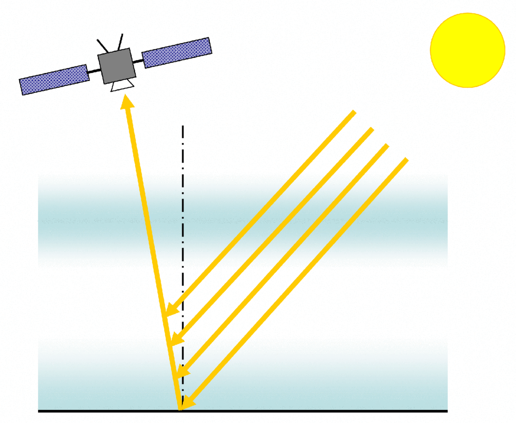

Fig 1: Cartoon of the measurement geometry. The light observed by the satellite is either reflected on the surface or scattered back from the atmosphere. Not all photons probe the lowest layers which reduces the sensitivity of the measurements, in particular in the UV where Rayleigh scattering is more effective, resulting in reduced sensitivity to SO_2

Measurement Technique:
- Differential Optical Absorption Spectroscopy on UV/visible sun light scattered back and reflected from the atmosphere and surface
- use of Lambert-Beer's law to determine the absorption along the effective light path
- use of radiative transfer simulations to determine the effective light path
- separation of tropospheric and stratospheric components by making assumptions on zonal homogeneity of the stratospheric fields

Instruments used:

GOME
- data from 9.95 - 6.2003
- 320 x 40 km^2 pixels
- global coverage 3 days
- 10:30 LT equator crossing

SCIAMACHY
- data since 8.2002
- 60 x 30 km^2 pixels
- global coverage 6 days
- 10:00 LT equator crossing

GOME-2
- data since 1.2007
- 80 x 40 km^2 pixels
- global coverage 1.5 days
- 09:30 LT equator crossing

SO_2 Results

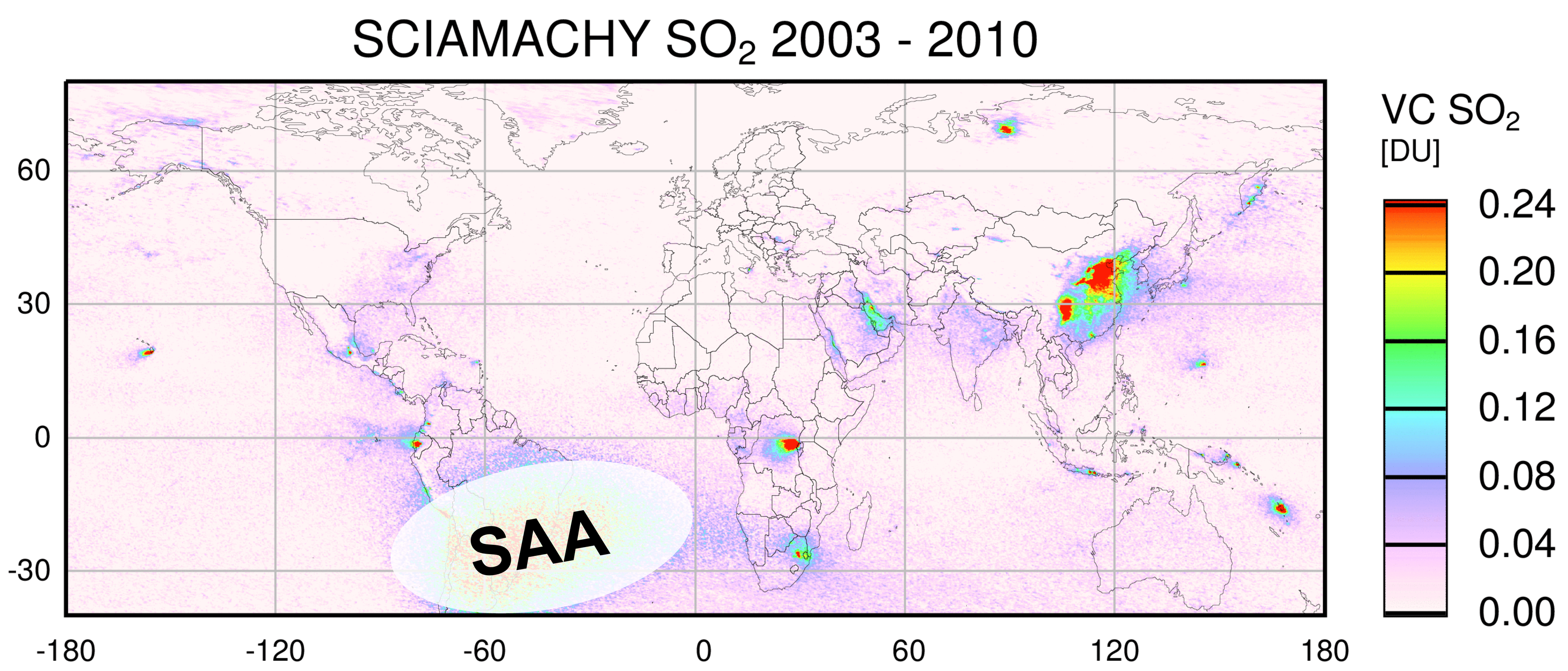

Fig.2: SCIAMACHY SO_2 columns averaged over the years 2003 - 2010. A stratospheric air mass factor was assumed resulting in strong underestimation of columns in the lower troposphere. Data in the Southern Atlantic Anomaly (SAA) region have much increased scatter. Four main regions of anthropogenic SO_2 signals are China, the South African Highvelt region, the Persian Gulf and the area around Norilsk. Smaller signals are also visible from some power plant regions in the US and Europe. Other SO_2 enhancements in Central and South America, Indonesia, Oceania, and Southern Italy are from volcanic emissions.

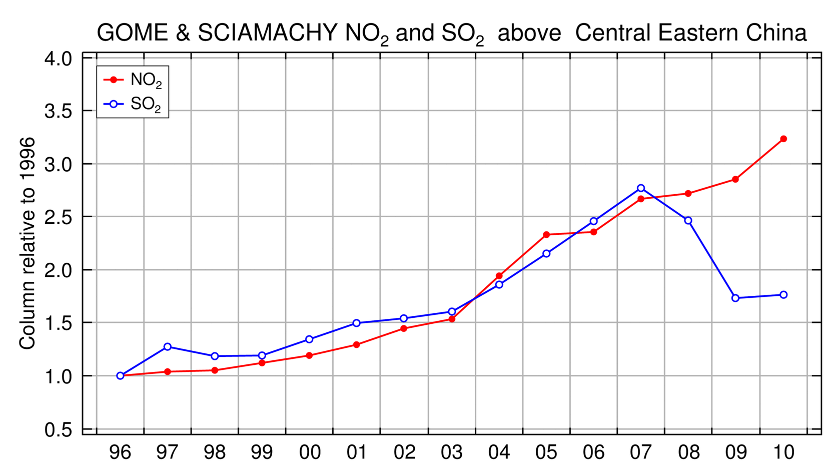

Fig.3: Relative changes of SO_2 and NO_2 columns over East Central China (30°N - 40°N, 110°E - 123°E)

Central East China
- large SO_2 increase since 1996
- parallel to increase in NO_2 columns until 2007
- source: mainly coal burning in power plants
- large decrease 2008 / 2009 as flue gas desulphurisation became mandatory
- no further reduction since as other SO_2 sources remain unregulated
- values remain above 2003 levels

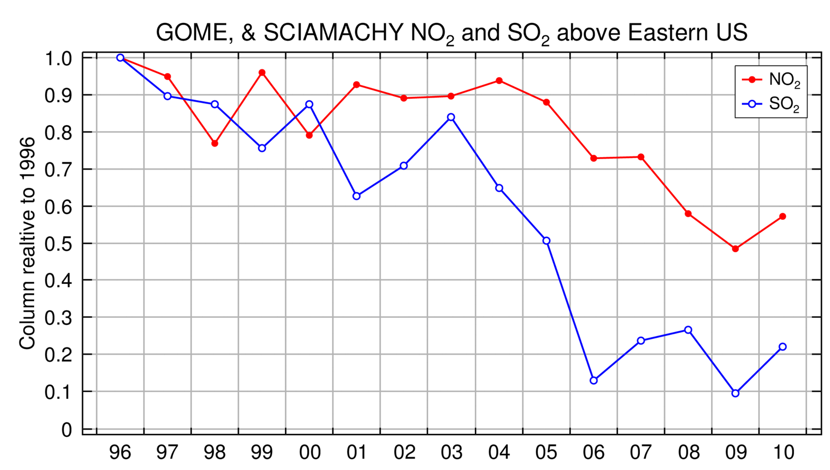

Fig.4: Relative changes of SO_2 and NO_2 columns over the Eastern US (38°N - 43°N, 84.5°W - 76°W)

Ohio River Valley (US)
- strong SO_2 decrease from 2003 to 2006
- parallel to decrease in NO_2 columns but much more pronounced
- source: mainly coal burning in power plants
- large decrease result of changes in EPA regulations
- SO_2 now very close to detection limit of SCIAMACHY
- August 2008 data excluded (volcanic interference)

Other Regions
For most other regions, the year-to-year variability is too large to reliably detect changes in anthropogenic SO_2 emission.

Problems and possible Solutions

- **Instrument Changes**
- any instrument may change over time introducing artificial changes
- long-term data sets rely on data from different sensors which may differ for several reasons:
  - instrument characteristics
  - spatial resolution differences
  - local time of measurement differences

=> *verification using overlapping time series (see Figure 5)*

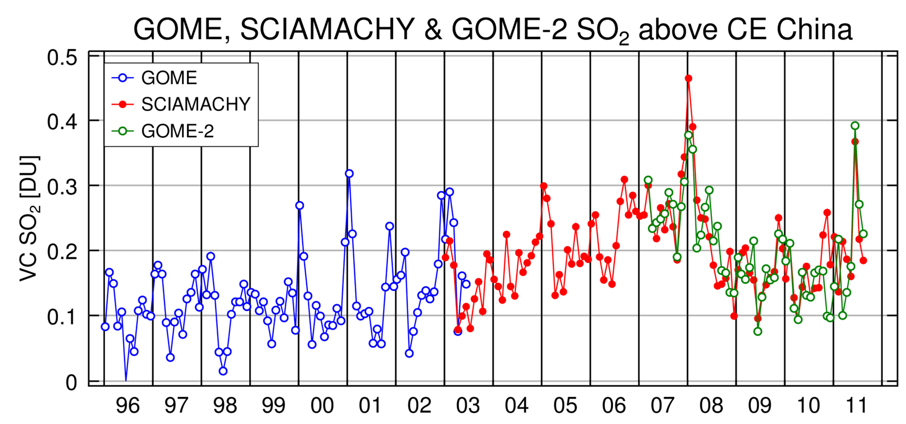

Fig. 5: Monthly averages of GOME, SCIAMACHY, and GOME-2 SO_2 above Central East China showing the agreement in the overlapping months in spite of differences in sampling and coverage. 2011 values are affected by volcanic SO_2.

Viewing Condition Changes
- over a longer time series, the observation conditions may change, e.g. through:
  - systematic cloud changes
  - changes in surface albedo (e.g. deforestation)
  - changes in aerosol loading, possibly linked to emission changes of SO_2 (e.g. in China)
  - changes in emission height (see figure 6)

=> *validation with external data needed*

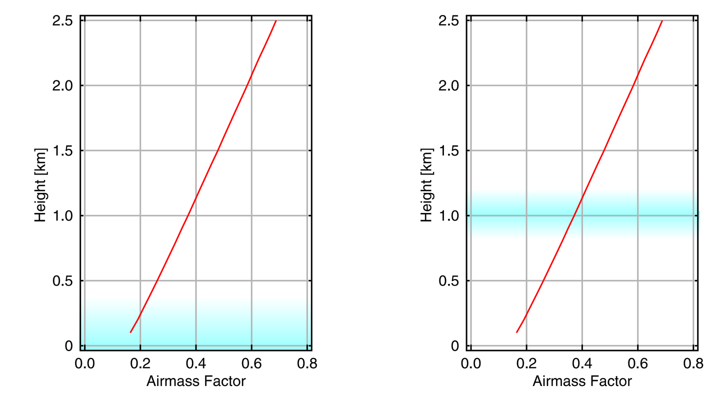

Fig. 6: Vertical sensitivity of SO_2 measurement and the effect of different emission types (domestic fires: low emission, power plants: high altitude emissions and possibly export into free troposphere). A change in emission type will lead to a signal change at the same emission strength if not accounted for.

Volcanic interference
- SO_2 is also emitted from volcanoes
- large eruptions can be identified and removed from time series
- SO_2 injected high in the atmosphere has increased life time and slowly decays
- transport to regions of anthropogenic emissions possible
- enhancement of anthropogenic signals cannot always be excluded

=> *careful screening of data is needed*

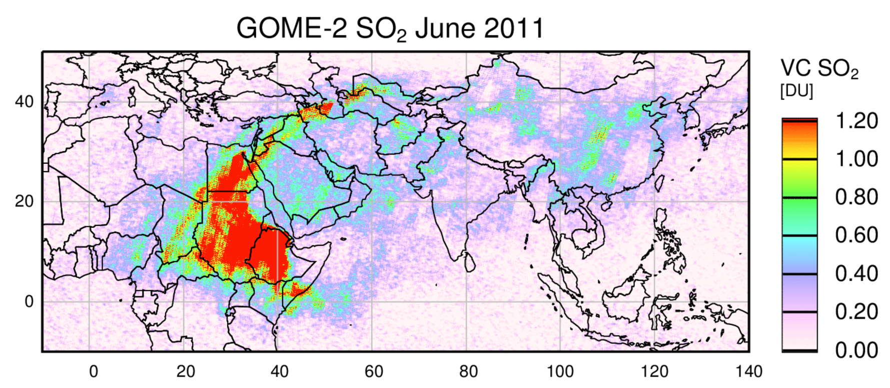

Fig.7: GOME-2 SO_2 columns for June 2011. The high values are the result of SO_2 from the eruption of the Nabor volcano in Eritrea and affect a very large region including China. Note the difference in scale compared to Fig. 2.

Conclusions

- UV/visible satellite measurements of SO_2 provide valuable long-term data sets
- the data can be used to monitor emission changes
- examples are increases and subsequent reductions in anthropogenic emissions of SO_2 in China, reductions in SO_2 emissions from power plants in the US
- use of multi-sensor time series necessitates careful instrument cross-verification but also provides cross-validation opportunities
- possible changes in observation conditions (e.g. changes in SO_2 vertical profile) have to be considered

Acknowledgements

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