The Measurement of Air Pollution from Space

George H. Mount

Department of Civil and Environmental Engineering
and
Center for Environmental Research, Education, and Outreach

22 April 2010
ESRP 285

Iceland volcano – as seen from NASA OMI satellite in particulates and sulfur dioxide
What Pollutants Would You Want to Measure?

- EPA criteria pollutants – regulated in the US
  - nitrogen dioxide  \( \text{NO}_2 \)
  - sulfur dioxide  \( \text{SO}_2 \) - e.g. from the recent Iceland volcano
  - carbon monoxide  \( \text{CO} \)
  - ozone  \( \text{O}_3 \)
  - particulates (PM 2.5 µm & 10 µm)
  - lead (Pb)

- Air toxics (189 on EPA list)  [e.g. mercury]

- Greenhouse gases (e.g. \( \text{CO}_2, \text{CH}_4, \text{O}_3, \ldots \)) – science + carbon verification

- Compounds that control ozone in an urban airshed  - what are these?
Why Measure:  *Understand* the Problem to Develop Effective Controls

- In the face of increasing population in the US, emissions from mobile and stationary sources must be reduced to improve air quality

- These reductions must be based upon strategies which *correctly account for the physical and chemical realities of air pollutant behavior in the atmosphere*

- Satellites can provide *regional and global* coverage of air pollutants which is difficult with “point” instruments

- *verification of international emission agreements*
Ozone Air Quality, 1980 – 2007
(Based on Annual 4th Maximum 8-Hour Average)
National Trend based on 269 Sites

national trend in ozone

new ozone NAAQS: 0.075 ppm

1980 to 2007: 21% decrease in National Average

source: US EPA
Atmospheric Remote Sensing

• **astronomers**
  • use of a telescope to collect light from an extra-terrestrial source and analyse its spectrum
  • mid-1800s to present, atmospheric spectral lines drive them nuts
  • nice way to measure some atmospheric trace gases (e.g. CFCs)
• won’t talk about ground based methods - want global coverage

• **rockets and balloons - mainly upper atmosphere**
  • use of German rockets after WWII
  • use of sounding rockets continues to today
  • get about 10 minutes of time looking through/down at the atmosphere
  • balloons can give many hours of observation time

• **aircraft**
  • first serious studies began after WWII
  • continues today with many types of aircraft being used

• **satellite/space shuttle instruments**
  • first atmospheric measurements made in the late 1960s
  • first tropospheric measurements made from satellite in the 1970s
**Remote sensing from space**

- enables measurement on spatial and temporal scales that otherwise would not be possible
- enables global observation of the environment using **consistent** measuring tools giving uniformity of response

**Method**

- measurement of the electromagnetic spectrum
  - want to measure trace gas concentrations mainly in the boundary layer
- first air pollution measurements were made in the early 1980s
- first good air pollution measurements were made by the ESA GOME instrument launched in 1996
Structure of the Atmosphere
• need a **telescope** to look at the Earth – downwards, limb, sun through atmosphere
  • to collect light – need photons
  • to image the Earth surface onto the spectrograph over a wide field of view at high spatial resolution – need spatial resolution

• **spectrograph** to show spectral structure of the electromagnetic spectrum

• **imaging detector** which allows simultaneous detection of a large spectral region for each spatial resolution element over a wide swath of geography with high spatial resolution.
trace gases (e.g. O$_3$) are molecules, and

- each molecule has a *unique spectrum* that characterizes the quantum states of the molecule and the “pattern” of that molecular spectrum can be recognized in the atmospheric spectrum

- molecular spectra are located throughout the electromagnetic spectrum from the UV to the infrared to the microwave radio region – so in designing an instrument, you figure out what trace gases you want to measure and design for the spectral region those molecules show spectra
Laboratory Photoabsorption Cross Section of NO₂

Harder, Brault, Johnston and Mount, 1997
Spectroscopic Technique for Air Pollution Measurements

• basic physics
  
  • measurement of spectrum of light incident on the Earth (from Sun)
  • measurement of spectrum of reflected light from surface of Earth
    $= \text{Sun} + \text{atmospheric absorption}$
  
• ratio the two measurements $\to$
  • elimination of spectrum of the sun (to first order) – it is in both spectra
  • reveals absorption spectrum of molecules of interest - very small $< 1\%$

• all molecular spectra a piled on top of each other – need a complicated computer program to sort out the various patterns
The OMI (Ozone Monitoring Instrument) Project

• Dutch project (*not ESA or NASA*) started in 1996
• small US NASA team including WSU/LAR has been involved since inception
• planned as a follow-on to the NASA TOMS satellite instruments first launched in 1978, and gone through several evolutions
• **scientific objectives:**
  • study the evolution of stratospheric ozone (ozone hole and decadal trends)
  • measure air pollution from space
  • study the global effects of regional air pollution on the chemistry of the lower atmosphere

• measures the ultraviolet and visible light spectrum of the atmosphere in sunlight

• **OMI launched in July 2004 on the NASA Aura satellite, and is still working well**
trace gas measurements: observing the Earth’s backscattered uv/visible radiation

Sunlight passes through the atmosphere, reflects off clouds and the surface, and is scattered back into the instrument field of view. Molecular spectral absorption is proportional to the concentration of the gas doing the absorbing.
sky spectrum compared to laboratory NO$_2$ photoabsorption cross section
the correlation of the observed spectrum to NO$_2$ is clear
OMI – Ozone Monitoring Instrument

- UV and VIS Earth radiance backscatter instrument
- Wide 2600 km swath telescope yields daily global maps
- Urban scale resolution is best ever for air quality measurements from space (12 km x 13 km “zoom mode”, 13 km x 24 km “global mode”)
- Trace gases observed in troposphere with approximate sensitivity:
  - \( \text{O}_3 \): 1 ppbv
  - \( \text{CH}_2\text{O} \): few ppbv
  - \( \text{NO}_2 \): 1 ppbv
  - \( \text{SO}_2 \): few ppbv
  - \( \text{OClO} \)
  - \( \text{BrO} \)
  - aerosol optical depth
typical orbital coverage for sun synchronous satellite

OMI has a 2600 km swath – perpendicular to the orbit track
single pixel size for four satellite instruments
OMI pixel 12 km x 13 km superposed onto the Seattle airshed (zoom mode)
28 August 2007 OMI trop NO\textsubscript{2} images of the US
Transport of African Dust
Satellite Observations of Air Quality

Western Forest Fires Observed from SEAWiFS, TOMS (50km x 200km), and Terra/MOPITT (22km x 22km x 600km with mirror) (August 2000)

stolen from E. Hilsenrath
OMI “images” of the Iceland volcanic eruption – April 2010

Aerosol Index

0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0

ash/particulates

SO$_2$ column 15 km [DU]

0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0

sulfur dioxide
Are the concentrations correct ??

- Construct an innovative new instrument for measurement of trace gases

- Support Aura/OMI data validation

- WSU/LAR given funding in late 2004 to build this new instrument
  - Instrument observes the sun directly and the scattered sky at various azimuthal and elevation angles – ratio out sun → atmospheric gases
  - Instrument has been on field campaigns to PNNL, NASA GSFC, NASA JPL, Univ of Alabama, The Netherlands, Houston
  - planned for 2010: Pittsburgh and China
WSU MFDOAS instrument at NASA Goddard Space Flight Center in DC
May 2007

sky viewing port
sun viewing port
Okmok Volcanic Plume over Washington, 19 July 2008

SO₂ mass: 11.537 kt, Area: 172139 km², SO₂ max: 8.47 DU at lon: -119.78, lat: 47.18, 20:29 UTC
WSU MFDOAS SO\textsubscript{2} 

absolute error: \sim 0.2 \text{ DU}

4 days of data obtained before the cloud dissipated

Okmok plume 2008
SO₂
Okmok volcanic plume
17 - 21 July 2008
Pullman, WA
satellite data and air quality modeling in the Pacific NW

NOVEMBER, 2007 – Tropospheric Column NO₂

AIRPACT MODEL
www.airpact-3.wsu.edu

OMI

AIRPACT NO₂ Tropospheric Column - Monthly Average

OMI NO₂ Tropospheric Column - Monthly Average

Vertical Column Density (molec/cm² x 10¹⁵)
Good things about satellite air pollution measurements:

- global coverage with good spatial imaging footprint and a wide swath
- same instrument observes the entire globe - no need to piece things together
- uniformity of the measurement quality
- daily measurement
- cheap/measurement - Gb of data/day
- provide boundary conditions for modeling of airsheds – e.g. WSU AIRPACT-3 for PacNW
- provide direct comparison with regional airshed models

Bad things about satellite air pollution measurements:

- one measurement/day at a particular time (1350h for OMI) - loss of diurnal effects
- sunlit areas only (for Aura/OMI) - no night except for emissions instruments
- foot print is too big - limited by 7 km/s ground speed & measurement integration time
- expensive in total - OMI $60M, Aura $700M (5 instruments)
- will die in orbit – been taking data for 6 years and still going strong
- data often difficult to convert to concentrations in the troposphere
- can only do certain molecules - e.g. SO₂, NO₂
- must be clear to see the ground – clouds are a big problem
NASA Jet Propulsion Laboratory Orbiting Carbon Observatory

- proposed in 2001
- WSU involved since 2003
- launched into ocean in February 2009 – reflight under development now (2013 projected launch date)
- measures CO₂ from space - global coverage
- footprint ~ 10 km x 10 km
- accuracy 1 part per million in column CO₂ [385 ppm at ground]
- will measure and identify sources and sinks and changes over time
carbon emissions verification:

• what species would you measure?
• where would you want to look?
• what are instrument observation requirements?
  • very high spatial resolution so can resolve/distinguish point sources
  • global coverage – how often?
  • high sensitivity – what is the global natural variation of CO2?
• low cost
• long life
• high quality ground validation
Conclusions and Future

• satellite observations provide a critical new tool to:
  • validate models of air quality
  • provide boundary conditions for air quality modeling
  • provide global coverage of trace gases that affect health
  • identify global sources and sinks of trace gases
  • observe the evolution of air pollution in an urban airshed
  • understand the inter-relationships of trace gases in urban airsheds
  • verify international agreements concerning emissions – what problems do you see

• WSU/LAR received a grant to work with NASA Goddard Space Flight Center to develop an instrument to measure air pollution from geosynchronous orbit:
  • satellite remains stationary over a particular area of the Earth
  • 1 km spatial footprint
  • covers a spatial region (airshed) 450 km x 450 km
  • useful s/n in 5 minutes integration time over the entire airshed
  • flight in 2018

DOING THIS STUFF IS INCREDIBLE FUN !!!!!!!!!!!!!!!!!!!!!

all our work on this is funded by NASA
classes in environmental engineering of interest:

• CEE 401 – Climate Change Science and Engineering: eng aspects of climate change – spring 2011 first offering

• CEE 402 – Applied meteorology

• CEE 403 – Air quality management – fundamentals of air pollution from the perspective of an environmental manager

• CEE 404 – Sustainable engineering I

• CEE 405 – Sustainable engineering II

• CEE 415 – Environmental measurements – actual measurements of EPA criteria pollutants in Pullman – laboratory course

• CEE 456 – Sustainable Development of Water Resources

• CEE 174 – introductory meteorology – no longer offered