We will act with resolve and urgency to meet our shared multiple objectives of reducing greenhouse gas emissions, improving the global environment, enhancing energy security, and cutting air pollution in conjunction with our vigorous efforts to reduce poverty.

- G-8 Gleneagles Communiqué, July 2005

An energy policy is also an environmental policy is also an economic policy. They are not separate policies.

- William Rosenberg, Harvard University Belfer Center for Science and International Affairs
Space Applications to Monitor the Impact of Energy Generation and Use on Air Pollution

Symposium on Space Applications for Sustainable Development
Graz, Austria: 12-15 September 2006

Lawrence Friedl
NASA Applied Sciences Program
Science Mission Directorate

Extending the societal and economic benefits of Earth science research and technology …
Space Applications to Monitor the Impact of Energy Generation and Use on Air Pollution

Energy Technology Perspectives and Scenarios

Earth System Science and Observations
- Capabilities to measure and model pollutants
- Energy-related and other pollutants

Applications of Satellite Observations
- Air quality forecasting
- Long-range transport of pollutants
- Carbon management

Earth Science for Society: Opportunities and Data Access
- Group on Earth Observations
Global scenarios to illustrate potentials for different technologies in

- Power Generation
- Transport
- Buildings and Appliances
- Industry

Scenarios analyzed:
- Baseline Scenario
- Accelerated Technologies (ACT) under different policies
- TECH Plus
## Technology Assumptions

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Renewables</th>
<th>Nuclear</th>
<th>CCS</th>
<th>H₂ fuel cells</th>
<th>Advanced biofuels</th>
<th>End-use efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACT Map</td>
<td>Relatively optimistic across all technology areas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.0 % p.a. global improvement</td>
</tr>
<tr>
<td>ACT Low Renewables</td>
<td>Slower cost reductions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACT Low Nuclear</td>
<td>Lower public acceptance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACT No CCS</td>
<td>No CCS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACT Low Efficiency</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.7 % p.a. global improvement</td>
</tr>
<tr>
<td>TECH Plus</td>
<td>Stronger cost reductions</td>
<td>Stronger cost reductions &amp; technology improvements</td>
<td></td>
<td>Break-through for FC</td>
<td>Stronger cost reductions &amp; improved feedstock availability</td>
<td></td>
</tr>
</tbody>
</table>
Global CO2 Emissions 2003-2050

ACT Scenarios 2050

- Other
- Buildings
- Transport
- Industry
- Transformation
- Power Generation

Global CO2 Emissions 2003-2050

Mt CO2
Contribution of Technologies to CO2 Emissions *Reduction* - 2050

![Chart showing the contribution of various technologies to CO2 emissions reduction by 2050.](chart.png)

- **Map**: Energy efficiency, CCS, fuel mix, biofuels in transport, renewables, nuclear, hydrogen & fuel cells
- **Low Nuclear**: Energy efficiency, CCS, fuel mix, biofuels in transport, renewables, nuclear, hydrogen & fuel cells
- **Low Renewables**: Energy efficiency, CCS, fuel mix, biofuels in transport, renewables, nuclear, hydrogen & fuel cells
- **No CCS**: Energy efficiency, CCS, fuel mix, biofuels in transport, renewables, nuclear, hydrogen & fuel cells
- **Low Efficiency**: Energy efficiency, CCS, fuel mix, biofuels in transport, renewables, nuclear, hydrogen & fuel cells
- **TECH Plus**: Energy efficiency, CCS, fuel mix, biofuels in transport, renewables, nuclear, hydrogen & fuel cells

Mt CO2
CO2 Emissions Among OECD, Transition and Developing Countries

- OECD
- Transition economies
- Developing countries

Comparison of CO2 emissions across different scenarios:
- 2003: 10% OECD, 37% Developing countries
- Baseline 2030 (WEO 2005): 49% OECD, 9% Transition economies
- Baseline 2050: 55% OECD, 7% Transition economies
- ACT Map 2050: 35% OECD, 8% Developing countries
Most energy still comes from fossil fuels in 2050, and CO2 emissions can be returned to current levels by 2050.

Power generation can be substantially de-carbonised by 2050; growth in oil and electricity demand can be halved.

Improving end-use energy efficiency is top priority.

Collaboration among developed & less-developed countries is essential.

Improving end-use energy efficiency is top priority.

CCS is key for a sustainable energy future.

Other important technologies:
- Renewables, including biofuels
- Nuclear
- Efficient use of natural gas and coal

CO2 Storage – Need monitoring to manage risk of releases
Earth System Science & Observations

- Satellites & Models
- Energy-related & other pollutants
NASA Observing Spacecraft for Earth System Science Research
Observing Strategies for Atmospheric Composition

- Solar/Stellar Occultation
- Scattering
- Emission
- Nadir Sounding
- Limb Sounding
The Afternoon Constellation consists of 7 U.S. and international Earth Science satellites that fly within approximately 30 minutes of each other to enable coordinated science. The joint measurements provide an unprecedented sensor system for Earth observations.
The Afternoon Constellation observational “footprints” vary greatly

6x7 km POLDER

1.4 km Cloudsat

0.09 km CALIPSO

13.5 km AIRS IR; AMSU & HSB μ wave

0.5 km MODIS Band 3-7

5.3 x 8.5 km TES

Washington DC
USGS Map
Data Assimilation: Global to Local

Climate/Pollution Analysis

Satellite Products

Global Assimilation

Urban/Regional Prediction

Public Impact

NASA
Measurements & Capabilities
Emission Estimates for Particles
Significant Uncertainties

Important to remember – the lifetime of aerosols in the atmosphere is on the order of days, while that for CO2 is many decades

Courtesy of G.Carmichael, U.Iowa
OMI: SO$_2$ emissions from smelters and volcanoes

- Daily monitoring of SO$_2$ emissions is possible with OMI.
- The Peruvian copper smelters are among the world’s largest industrial point sources of SO$_2$.

Carn et al., in prep
Observations of a Volcanic Plume from the Eruption of Soufriere Hills, Montserrat, on May 20

CALIPSO: Space-based LIDAR of Aerosol Layer

CALIPSO Total Attenuated Backscatter 532 nm  7 June 2006

Volcanic plume

Aura/OMI Column SO₂
8 June 2006

CALIPSO Orbit Track
7 June 2006
OMI 13x24km resolution allows near real time mapping of NO$_2$. 

Aura/OMI and NO$_2$. 

November 12, 2004
Observing the Sabbath -- or -- Remote Sensing of Anthropogenic Sources

Day of week analysis helps to separate anthropogenic source types.

5-yr weekly average NO2 data from GOME

GOME Data from U of Heidelberg  Bierle Atmos. Chem. Phys. Discuss, 2003
Ozone & Carbon Monoxide

- Summer 05: Ozone and CO concentrations for JJA 2005.
- Fall 05: Ozone and CO concentrations for SON 2005.
- Winter 05-06: Ozone and CO concentrations for DJF 2005-06.

Color bars indicate concentration levels, with purple representing lower values and red representing higher values.
Aerosols: What can we do from satellites?  

**Occurrence**

*Monthly Global Aerosol Optical Depth Products*

---

**MISR Mid-vis AOD**
- Land & Water
- Bright Surfaces
- Globe ~ weekly
- ~ 10:30 AM
  [+ particle size & shape]

**MODIS Mid-vis AOD**
- Water & some Land
- Globe ~ every 2 days
- ~ 10:30 AM & 1:30 PM
  [+ fine/coarse mode ratio]
MODIS Visual (RGB) Level1B Image
25 June 2002

Data provided by NASA Goddard Space Flight Center.
Image processed by Battelle using MODIS HDF Look.
MODIS Aerosol Optical Depth
25 June 2002

Data provided by NASA Goddard Space Flight Center.
Image processed by Battelle using MODIS HDF Look.
Smoke from Alaskan/Yukon Fires
18 July 2004
PM2.5 Air Quality Forecasting

2004 Transport Event: MODIS Aerosol optical depth
Satellite & Ground Measurements

Baltimore, Maryland, USA

PM2.5 and MODIS AOD 20040703-20040831

- Hourly PM$_{2.5}$ concentration
- △ 24-Hour average PM2.5 concentration
- ⋅ 1-hour average PM2.5 concentration
- ⋄ MODIS AOD

Air Quality Index Categories for PM2.5

Good

Moderate

Unhealthy
Correlations between AOD and PM2.5 (hourly)

Engel-Cox, J. et al.
Carbon Management
CASA CQUEST
Decision Support Tool for Carbon Accounting

User Defined Profile
• Region of Interest
• Time Frame
• Biophysical
• Management
• Climate Scenario

NASA MODIS Products
NASA / NGA SRTM Elevation
Leaf Biomass
Cropland NPP

Inputs include continental-scale land cover, NDVI, FPAR, elevation, soils, and climate data ...

Outputs:
landscape-to continental scale predictive maps of above and below ground distributions of sequestered carbon for different climate scenarios

http://geo.arc.nasa.gov/website/cquestwebsite

Multi-scale Validation Information
Orbiting Carbon Observatory (OCO)

Science & Applications
- Space-based measurements of atmospheric CO$_2$
- Column average dry mole fraction
- Characterize carbon sources and sinks on regional scales and quantify their variability.
- OCO measurements are needed to:
  - Identify and bound CO$_2$ sources and sinks
  - Aid in understanding the global carbon budget
  - Study carbon management activities
  - Aid in verifying C emissions/sequestration reports

OCO Features
- High Resolution, 3-channel grating spectrometer
- Launch date: 2008
- Operational life: 2 years
Current in-situ network: Continental scales

OCO: Measuring CO$_2$ From Space

Monthly global source/sink estimates at regional to sub-regional scales

OCO will make global, space-based observations of atmospheric CO$_2$ with the precision, resolution, and coverage needed to monitor sources and sinks.
Data & Information:
Availability, Priorities, Opportunities
Group on Earth Observations:
Ministerial-level leadership for coordination of Earth observing systems
10-year implementation plan
Began August 2003

Integrate scientific capacity of organizations and observing systems to support nine societal benefit areas:
- Natural & Human Induced Disasters
- Water Resources Ecosystems
- Sustainable Agriculture & Desertification
- Energy Resources
- Climate Variability & Change
- Weather Information, Forecasting
- Human Health & Well-Being
- Oceans

Earth Observation Summit III
Feb. 2005

GEO involves:
65 nations
35+ international Organizations

GEO Secretariat at WMO in Geneva
GEO & “System of Systems” Architecture

GEOSS

Earth System Models
- Oceans
- Cryosphere
- Land
- Atmosphere
- Solid Earth
- Biosphere

Predictions
- High Performance Computing
- Communication
- Visualization

Earth Observation Systems
- Remotely-sensed
- In situ

Standards & Interoperability

Decision Support
- Assessment
- Decision Support Systems

Policy Decisions

Management Decisions

Ongoing feedback to optimize value and reduce gaps
GEO-NETCast

What?
GEO-NETCast is a near real-time data dissemination system.

Environmental *in situ*, airborne, and space-based observations, products, and services in standard formats.

Built on existing dissemination systems with data collection hubs around the globe.

Use of standard, multicast, dissemination protocols (e.g., Digital Video Broadcast – DVB) to encapsulate products of any format.

Sample Data Products

Radiation fluxes

Land surface type, albedo, temperature

Cloud Analysis and Cloud Mask

Ocean surface wind speed

Chlorophyll concentration

Normalized Differential Vegetation Index

Volcanic ash imagery and advisories

Fire and smoke analysis

Snow cover, depth, and water content
# Sources of Information

## Sensor Site
Moderate Resolution Imaging Spectroradiometer (MODIS)  
http://modis-atmos.gsfc.nasa.gov/  
http://rapidfire.sci.gsfc.nasa.gov/  
http://eosdb.ssec.wisc.edu/modisdirect/

## Data Sites
NASA Goddard Space Flight Center DAAC  
http://daac.gsfc.nasa.gov/  
NASA Langley Atmospheric Sciences Data Center  
http://eosweb.larc.nasa.gov/  
NASA Level 1 and Atmosphere Archive and Distribution Center  
https://ladsweb.nascom.nasa.gov:8300/

## Imagery Sites
U.S. Air Quality ("Smog Blog")  
http://alg.umbc.edu/usaq/  
NASA Earth Observatory  
http://earthobservatory.nasa.gov/  
NASA Visible Earth  
http://visibleearth.nasa.gov/  
NOAA Operational Significant Event Imagery  
http://www.osei.noaa.gov/  
US Interagency Air Quality Forecasting Support  
http://idea.ssec.wisc.edu/
Typical Receiver Station Configuration

- Dedicated personal computer (~ $1000)
- Satellite antenna dish (1-3 m) (~ $300-1200)
- DTH receiver card or box (~ $200)

Data analysis and processing should be done on separate computer(s)
Proposed Additional Coverage

Americas: US/NOAA

Asia: China
Science for Society:

*Convention on Long-range Transboundary Air Pollution*
## Convention on Long Range Transboundary Air Pollution (LRTAP)

1979 Agreement;
49 countries signed and ratified

Primarily Europe, Canada, USA, and Former Soviet Republics

Asia, Middle East, northern Africa, and central America are not currently included in LRTAP

Southern Hemisphere not included (different pollution issues – less industrial, more biomass burning)

### Protocols:

- Sulfur (1985, 1994)
- Nitrogen Oxides (1988)
- Persistent Organic Pollutants (1988)
- Heavy Metals (1998)
- Acidification, Eutrophication, and Ground-level Ozone (1999)

Typically, protocols set specific emission targets for pollutants and/or designate actions

LRTAP sets out fundamental principles to reduce air pollution, cooperate on research and monitoring, and information exchange

UN Economic Commission for Europe (UNECE) provides the Secretariat

Calls on parties to reduce transboundary air pollution using the best policies and strategies and best available technology which is economically feasible.

Intercontinental transport in Northern Hemisphere

Involves Northern Hemisphere countries who are not signatories to LRTAP

2005 – 2009: Assessment of the scientific evidence concerning hemispheric transport for use in international policy discussions and reviews of LRTAP protocols

Hemispheric approach will likely require information over oceans and regions with minimal ground-based monitors

Air Pollutants of Interest:
- Fine particles / PM
- Acidifying substances
- Persistent organic pollutants
- Ozone and precursors
- Mercury

http://www.htap.org/
HTAP Assessment Activities

Four Types of Experiments:

1. Sensitivity studies
   - North America, Europe, North Asia, South Asia
2. Tracer studies
3. Mixed activities
   - Climate change and variability issues
   - Short/long-term effects
   - Studies addressing disagreements from first two experiments
4. Source-receptor relationships

June 2005: Initial meeting
Jan. 2006: Model evaluation and intercomparison methodology
          http://aqm.jrc.it/HTAP
October 2006: Emissions Inventory and Projections Workshop
January 2007: Integrated Observations Workshop
March 2007: Interim assessment on O3 and PM
2007 & 2008: Additional workshops
2009: Assessment adds Hg and POPs
An energy policy is also an environmental policy is also an economic policy.

- William Rosenberg
Back-up Slides
Pre-industrial to present-day contributions to radiative forcing: 1750 to 2000

Global Mean Radiative Forcing (Wm⁻²)

1. Greenhouse Gases
   - Halocarbons
   - N₂O
   - CH₄
   - CO₂

2. Aerosols + Clouds
   - Tropospheric Ozone
   - Black Carbon from Fossil-Fuel Burning
   - Mineral Dust
   - Aviation Contrails Cirrus
   - Solar

3. Stratospheric Ozone
   - Sulfate
   - Organic Carbon from Fossil-Fuel Burning
   - Biomass Burning
   - Land Use (albedo only)

The height of a bar indicates a best estimate of the forcing, and the accompanying vertical line a likely range of values. Where no bar is present the vertical line only indicates the range in best estimates with no likelihood.

LEVEL OF SCIENTIFIC UNDERSTANDING
- High
- Medium
- Low
- Very low

- High
- Medium
- Medium
- Low
- Very low
- Very low
- Very low
- Very low
- Very low
- Very low
- Very low
- Very low
## CO₂ Storage

<table>
<thead>
<tr>
<th>Options</th>
<th>Risks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enhanced oil recovery</td>
<td>Leaks that cause local concentrations to exceed 2% can be harmful or fatal around 10%.</td>
</tr>
<tr>
<td>Depleted oil and gas reservoirs.</td>
<td>Leaks into fresh water aquifers could mobilize toxic metals, sulfate or chloride. Trace gases (H₂S, SO₂ or NO₂) could make this more likely.</td>
</tr>
<tr>
<td>Deep saline reservoirs.</td>
<td>Slow leaks could affect the climate for hundreds of years.</td>
</tr>
<tr>
<td>Deep unmineable coal seams.</td>
<td>Current evidence suggests that these risks would be minimal with well understood reservoirs, identification of abandoned wells and monitoring.</td>
</tr>
<tr>
<td>Coal-bed methane recovery.</td>
<td></td>
</tr>
<tr>
<td>Deep ocean storage not a suitable option.</td>
<td></td>
</tr>
</tbody>
</table>
Satellite / Sensor

Characteristics
Terra and Aqua

- NASA, Terra & Aqua
  - launched 1999, 2002
  - 705 km polar orbits, descending (10:30 a.m.) & ascending (1:30 p.m.)
- MODIS Sensor Characteristics
  - 36 spectral bands ranging from 0.41 to 14.385 µm
  - 2330 km swath width
  - Spatial resolutions: (250-1000m)
- MISR Sensor Characteristics
  - 4 spectral (0.446-0.867um)
  - 9 cameras
- CERES Sensor characteristics
  - Total shortwave <5 µm
  - Total longwave > 5 µm
EOS Aura

- Third of the big EOS platforms (Terra and Aqua are the other two)
- Orbit: Polar: 705 km, sun-synchronous, 98° inclination, ascending 1:45 PM equator crossing time. AURA follows AQUA in the same orbit by 15 minutes.
- Launched VAFB, July 15, 2004
- Six Year Spacecraft Life
- Main science objectives: stratospheric ozone recovery; air quality

OMI

HIRDLS

MLS

TES

OMI
• Tropospheric Emission Spectrometer
  • PI: R. Beer, JPL
  • Nadir and limb Fourier transform emission spectrometer
    • Limb mode, 2.3 km vert. res., vertical coverage 0-34 km
    • Nadir mode, 5.3x8.5 km
    • Spectral Coverage 3.3 - 15.4 µm
  • Tropospheric and stratospheric T, O$_3$, H$_2$O, CH$_4$, CO, HNO$_3$, NO$_2$
  • Aerosols, Temperature
  • Research Products (mostly limb)
    • H$_2$O$_2$, HDO, ethane, acetylene, formic acid, acetone, ethylene, nitric oxide, ammonia, HCN, SO$_2$, H$_2$S, SF$_6$, OCS, CFC’s, HCl, CCl$_4$, ClONO$_2$
OMI

Ozone Monitoring Instrument

- Joint Dutch-Finish Instrument with Dutch/Finish/U.S. Science Team
  - PI: P. Levelt, KNMI
- Nadir solar backscatter spectrometer
  - 280-500 nm
  - 13x24 km footprint
  - Swath width 2600 km
- Radicals: Column $O_3, NO_2, BrO, OCIO$
- $O_3$ profile ~ 5 km resolution
- Tracers: Column $SO_2, HCHO$
- Aerosols (smoke, dust and sulfates)
- Cloud top press., cloud coverage
- Surface UVB
- Tropospheric ozone residual (when combined with MLS or HIRDLS)
HIRDLS

High Resolution Dynamics Limb Sounder

- Joint UK-US instrument
  - Co-Pis: J. Gille, NCAR & U. of Col.; J. Barnett, Oxford
- Limb emission IR, high horizontal resolution scanner
  - 6.12 - 17.76 µm range
  - 1 km vertical, 500 km cross track
  - Swath 500-3,000 km wide, 6 positions
- Stratospheric radicals: O₃, NO₂
- Stratospheric Reservoirs: ClONO₂, HNO₃, N₂O₅
- Tracers: CFC-11, CFC-12, CH₄, H₂O, N₂O
- Temperature, Geopotential height
- Aerosols Extinction Coef. (4 channels)
- Upper tropospheric cirrus
Microwave Limb Sounder
- PI: J. Waters, JPL
- Microwave limb emission
  118 GHz - 2.5 THz
  - Vertical resolution 1.5-3 km, 3x200 km horizontal
- Data Products
  - Stratospheric Radicals: O₃, OH, HO₂, ClO, HOCl, BrO.
  - Stratospheric Reservoirs: HCl, HNO₃.
  - Tracers: N₂O, H₂O, SO₂, CO, HCN
  Upper tropospheric O₃, H₂O, Cirrus ice, HCN, and CO.
  - Temperature and geopotential height.