Aerosol Particles and Climate Change on Earth:
How coordinated measurements from aircraft, satellites, and surfaces are helping to reduce uncertainties

Phil Russell, NASA Ames Research Center

Global Average Surface Temperature Change

NASA Ames Director’s Colloquium, 23 June 2009
Simulated and observed Earth surface temperature change, 1880-2005

Hansen et al. Science 2005

Stratospheric aerosol increase, decrease

Hansen et al. Science 2005
Simulated and observed Earth surface temperature change, 1880-2005

Hansen et al. Science 2005

Stratospheric aerosol increase, decrease

Tropospheric aerosol increase, moderation

Hansen et al. Science 2005
Simulated and observed Earth surface temperature change, 1880-2005

Message: These tiny aerosol particles are powerful.
- They can modulate, and sometimes even reverse, greenhouse warming (temporarily)
Aerosol Particles And Climate Change on Earth:
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Phil Russell, NASA Ames Research Center
Aerosol Particles
And Climate Change on Earth:
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Aerosol Particles
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Phil Russell, NASA Ames Research Center
MISR on NASA’s Terra satellite
MODIS on Terra

P. Russell, NASA Ames Director's Colloquium, 23 Jun 2009
What is Radiative Forcing?

A change in average net radiation at the top of the troposphere...

It perturbs the balance between incoming and outgoing radiation.

Radiative Forcing (RF) - ∆ 1750 to 2005 [unmodified] - Global average - Tropopause or TOA

Direct Radiative Effect (DRE) - Current, any aerosol - TOA, surface, within atmos, ...

P. Russell, NASA Ames Director's Colloquium, 23 Jun 2009
Sahara Dust, NW Africa & Canary Islands
FIGURE 11.9 Saharan dust storm of July 24, 2003, showing dust cloud over the Atlantic Ocean and Canary Islands off northwest Africa, as captured by NASA's MODIS instrument on the Terra satellite. Earlier, USSR cosmonaut Vladimir Kovalyonok had observed, "As an orange cloud formed as a result of a dust storm over the Sahara and, caught up by air currents, reached the Philippines and settled there with rain, I understood that we are all sailing in the same boat." SOURCE: Image courtesy of NASA.
Atlantic Coast of N America
Atlantic Coast of N America

Smoke from Alaska wildfires

MODIS on Aqua
21 Jul 2004

P. Russell, NASA Ames Director's Colloquium, 23 Jun 2009
Smoke from Alaska wildfires

MODIS on Terra
19 Jul 2004

MODIS on Aqua
21 Jul 2004
Atlantic Coast of N America
Smoke from Alaskan wildfires
MODIS on Aqua, 21 Jul 2004
Radiative Forcing of Climate

What is Radiative Forcing?
A change in average net radiation at the top of the troposphere...

Kiehl & Trenberth, BAMS, 1997
(A) Forcings used to drive climate simulations.

(B) Simulated and observed surface temperature change.

Hansen et al. *Science* 2005
Volcanic Emissions
Urban Pollution
Desert Dust
Biomass Smoke

Pinatubo eruption, 1991
Interpretation of the Polarization of Venus

JAMES E. HANSEN
Goddard Institute for Space Studies, New York, N. Y. 10025

J. W. HOVENIER
Dept. of Physics and Astronomy, Free University, Amsterdam, Netherlands
(Manuscript received 20 November 1973, in revised form 15 January 1974)

ABSTRACT

The linear polarization of sunlight reflected by Venus is analyzed by comparing observations with extensive multiple scattering computations. The analysis establishes that Venus is veiled by a cloud or haze layer of spherical particles. The refractive index of the particles is 1.44±0.015 at λ=0.55 μm with a normal dispersion, the refractive index decreasing from 1.46±0.015 at λ=0.365 μm to 1.43±0.015 at λ=0.99 μm. The cloud particles have a narrow size distribution with a mean radius of ~1 μm; specifically, the effective radius of the size distribution is 1.05±0.10 μm and the effective variance is 0.07±0.02. The particles exist at a high level in the atmosphere, with the optical thickness unity occurring where the pressure is about 50 mb.

The particle properties deduced from the polarization eliminate all but one of the cloud compositions which have been proposed for Venus. A concentrated solution of sulfuric acid (H₂SO₄·H₂O) provides good agreement with the polarization data.
Clouds of Venus, Polarimetry, & Their Dual Relevance to Earth’s Climate

JAMES E. HANSEN AND J. W. HOVENIER

Interpretation of the Polarization of Venus

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ABSTRACT

The linear polarization of sunlight reflected by Venus is analyzed by comparing observations with extensive multiple scattering computations. The analysis establishes that Venus is veiled by a cloud or haze layer of spherical particles. The refractive index of the particles is $1.44 \pm 0.015$ at $\lambda = 0.55 \mu m$ with a normal dispersion, the refractive index decreasing from $1.46 \pm 0.015$ at $\lambda = 0.365 \mu m$ to $1.43 \pm 0.015$ at $\lambda = 0.99 \mu m$. The cloud particles have a narrow size distribution with a mean radius of $\sim 1 \mu m$; specifically, the effective radius of the size distribution is $1.05 \pm 0.10 \mu m$ and the effective variance is $0.07 \pm 0.02$. The particles exist at a high level in the atmosphere, with the optical thickness unity occurring where the pressure is about 1 bar.

The particle properties deduced from the polarization eliminate all but one of the cloud compositions which have been proposed for Venus. A concentrated solution of sulfurous acid ($H_2SO_4\cdot H_2O$) provides good agreement with the polarization data.

17 proposed compositions before H&H polarimetric analysis

unknown. Many possible compositions have been suggested in the literature, including water, H$_2$O ice, solid CO$_2$, carbon suboxide (C$_2$O$_2$; Sinton, 1953; Kuiper, 1957; Harteck et al., 1963), hydrated ferrous chloride (FeCl$_2$$\cdot$2H$_2$O; Kuiper, 1969), NaCl (Hunten, 1968), formaldehyde (H$_2$C=O; Wildt, 1940), hydrocarbons (Velikovsky, 1950; Hoyle, 1955; Kaplan, 1963), hydrocarbon-amide polymers (Robbins, 1964), polywater (Donahue, 1970), ammonium nitride (NH$_4$$\cdot$NO$_2$; Dauwillier, 1956), calcium and magnesium carbonates (Opik, 1961), NH$_4$Cl (Lewis, 1968; Hunten and Goody, 1969), mercury and mercury compounds (Lewis, 1969; Rasool, 1970) and aqueous solutions of hydrochloric acid (HCl$\cdot$H$_2$O; Lewis, 1972; Hapke, 1972) and sulfuric acid (H$_2$SO$_4$$\cdot$H$_2$O; Sill, 1972; Young
(A) Forcings used to drive climate simulations.

(B) Simulated and observed surface temperature change.

Hansen et al. Science 2005
This talk focuses on the Uncertainty in Radiative Forcing, $\delta RF$
Structure of Talk

STARS, 1975

TARFOX, 1996

ACE-2, 1997

INTEX-B, 2006

ARCTAS, 2008

CLIMATE CHANGE 2001
The Scientific Basis

SAFARI 2000

ACE-Asia, 2001

INTEX-A, 2004

AR4

P. Russell, NASA Ames Director's Colloquium, 23 Jun 2009
A Chain of Field Experiments Measuring Aerosols & Their Effects on Atmospheric Radiation


TARFOX PRiDE ACE-Asia ACE-2 SAFARI ICARTT MILAGRO

CLAMS ADAM EVE INTEX

AIOP -A -B

AR4 TAR

Models frozen Simulations complete Published

Models frozen Simulations complete Published

P. Russell, NASA Ames Director's Colloquium, 23 Jun 2009
A Chain of Field Experiments Measuring Aerosols & Their Effects on Atmospheric Radiation


TARFOX
ACE-2
ADAM
EVE
INTEX-B
SAFARI
PRiDE

ARCTAS, 2008
AIOP, 2003 ALIVE, 2005
ACE-Asia, 2001
CLAMS, 2001
INTEX-A, 2004
SOLVE II, 2003

MISR Aerosol Optical Depth (558 nm), March 2006

Optical depth (Band 3, 558 nm)

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0


TARFOX PRiDE ACE-Asia ICARTT MILAGRO

ACE-2 SAFARI CLAMS AIOP

SOLVE II INTEX

AR4
Atmospheric Aerosol Properties and Climate Impacts

COORDINATING LEAD AUTHOR:
Mian Chin, NASA Goddard Space Flight Center

LEAD AND CONTRIBUTING AUTHORS:
Ralph A. Kahn, Lorraine A. Remer, Hongbin Yu, NASA GSFC;
David Rind, NASA GISS;
Graham Feingold, NOAA ESRL; Patricia K. Quinn, NOAA PMEL;
Stephen E. Schwartz, DOE BNL; David G. Streets, DOE ANL;
Philip DeCola, Rangasayi Halthore, NASA HQ

January 2009
1996:
What is Radiative Forcing?
A change in average net radiation at the top of the troposphere….

[It] perturbs the balance between incoming and outgoing radiation.

2007 (AR4):
[unmodified]
Radiative Forcing (RF)
- $\Delta$ 1750 to 2005 [for aer $\approx$ Anthro]
- Global average
- Tropopause or TOA
Direct Radiative Effect (DRE)
- Current, any aerosol
- TOA, surface, within atmos, …

P. Russell, NASA Ames Director's Colloquium, 23 Jun 2009
Global and annual mean radiative forcing (1750 to present)

- Halocarbons
- N₂O
- CH₄
- CO₂
- Trop. O₃
- Strat. O₃
- FF (bc)
- FF (oc)
- Mineral dust
- Aviation-induced
- Contrails
- Cirrus
- Land-use (albedo)
- Trop. aerosol indirect effect (1st type)

Level of scientific understanding (LOSU)
IPCC 2007: We’ve turned it on it’s side. Why?

[Haywood & Schulz, Kaufman Symposium]
The main reason for better quantification:

1) aerosol direct effect,
2) aerosol indirect effect

IPCC TAR:
Mean = 0.36 Wm$^{-2}$
Median = 0.64 Wm$^{-2}$
P(RF$<0$) = 28.4%

IPCC AR4:
Mean = 1.47 Wm$^{-2}$
Median = 1.50 Wm$^{-2}$
P(RF$<0$) = 0.4%

Haywood and Schulz, GRL 2007
Does this smaller $\delta$RF reflect this tapestry of field programs?

STARS, 1975

TARFOX, 1996

ACE-2, 1997

CLIMATE CHANGE 2001
The Scientific Basis

SAFARI 2000

ACE-Asia, 2001

CLIMATE CHANGE 2007
The Physical Science Basis

INTEX-A, 2004

AR4

INTEX-B 2006

ARCTAS 2008

P. Russell, NASA Ames Director's Colloquium, 23 Jun 2009
### Aerosol Direct Radiative Forcing

<table>
<thead>
<tr>
<th>Models published since TAR</th>
<th>Radiative Forcing (W m(^{-2}))</th>
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</thead>
<tbody>
<tr>
<td><strong>Observation based</strong></td>
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<tr>
<td>Bellouin et al. (2005)</td>
<td>![Bar graph for Bellouin et al. (2005)]</td>
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**AeroCom models**

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** IPCC WG1, 2007 [AR4]**

### Figure 2.13

\[ \Delta 1750 \text{ to } 2005 \text{ [for aer } \cong \text{ Anthro]} \]
- Global average
- Tropopause or TOA
MODIS-Terra AOD (0.55 \(\mu m\))

January to March 2001

August to October 2001

AERONET sites

Lidar network sites:
- EARLINET
- ADNET
- MPLNET

IPCC WG1, 2007 [AR4]
Pollution in India

- Red - pollution and smoke
- Green - dust and salt

Dust from China

Saharan dust

Salt aerosol?

Pollution in India

Kaufman, Stockli & Earth Observatory
Pollution in India

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Kaufman, Stockli & Earth Observatory
Figure 2.13

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P. Russell, NASA Ames Director's Colloquium, 23 Jun 2009

IPCC WG1, 2007 [AR4]
What, then, is the role of field programs (like TARFOX, ..., ARCTAS) in reducing the uncertainty in Aerosol Radiative Forcing?

Improving satellite retrieval algorithms & models by:

1. Testing satellite data products (validation)
2. Determining actual aerosol properties
3. Determining the processes leading to #2
4. Measuring aerosol radiative effects & testing closure between measured radiation & aerosol optical & physiochemical properties
5. Testing models

P. Russell, NASA Ames Director’s Colloquium, 23 Jun 2009
AEROSOL PROPERTIES AND PROCESSES
A Path from Field and Laboratory Measurements to Global Climate Models

by Steven J. Ghan and Stephen E. Schwartz

The U.S. Department of Energy strategy for improving the treatment of aerosol properties and processes in global climate models involves building up from the microscale with observational validation at every step.
Table 1. Stages of research and model development necessary to examine aerosol influences on climate.

<table>
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<tr>
<th>Stage</th>
<th>Activity</th>
<th>Outcome</th>
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</thead>
<tbody>
<tr>
<td>1)</td>
<td>Conduct process research: Field and laboratory studies</td>
<td>Improved understanding of processes</td>
</tr>
<tr>
<td>2)</td>
<td>Develop <strong>0-D models (modules)</strong> representing processes; comparison with</td>
<td>Modules: Model based representation of understanding</td>
</tr>
<tr>
<td></td>
<td>process research studies</td>
<td></td>
</tr>
<tr>
<td>3)</td>
<td>Incorporate modules describing aerosol processes in regional to global</td>
<td>Evaluated aerosol model incorporating processes</td>
</tr>
<tr>
<td></td>
<td>aerosol models. Production runs. Assessment of accuracy of aerosol models</td>
<td></td>
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<tr>
<td>4)</td>
<td>Incorporate representation of aerosol processes in climate model;</td>
<td>Climate relevant runs; assessment of skill of climate model</td>
</tr>
<tr>
<td></td>
<td>production runs; comparison with observations</td>
<td>against present and/or prior climate</td>
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Ghan & Schwartz, *BAMS* 2007:

These **0-D models (modules)** are also used, refined, & often developed in the analysis of field program data. They get incorporated, not just into **climate models**, But also into **satellite retrieval algorithms**.

---

P. Russell, NASA Ames Director's Colloquium, 23 Jun 2009
What is the role of field programs in reducing the uncertainty in Aerosol Radiative Forcing?

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P. Russell, NASA Ames Director's Colloquium, 23 Jun 2009
A Chain of Field Experiments Measuring Aerosols & Their Effects on Atmospheric Radiation


TARFOX PRiDE ACE-Asia SAFARI CLAMS ADAM EVE ICARTT INTEX MILAGRO POLARCAT ARCTAS ISDAC

Models frozen Simulations complete Published Models frozen Simulations complete Published

Radiative flux closure & forcing efficiency

Radiative flux($\lambda$) closure & forcing efficiency($\lambda$)

P. Russell, SETI Institute, Mountain View, CA, 6 May 2009
Two instruments developed at NASA Ames for measuring aerosols and their radiative effects

Ames Airborne Tracking Sun-photometer (AATS)

Solar Spectral Flux Radiometer (SSFR)
Scientific Conclusions

1. The gradients (spatial variations) in AOD that occur frequently off the US East coast provide a natural laboratory for studying effects of aerosol particles on solar energy, and hence on climate.

2. For the average aerosol optical depth of ~0.5 in the 10 cases shown above, aerosols on average reduced the incident visible radiation (near midday) by the amount of energy it would take to power one 40 W light bulb for every square meter of ocean surface (0.5 x -80 W m\(^{-2}\) = -40 W m\(^{-2}\); see right frame above).
What is the role of field programs in reducing the uncertainty in Aerosol Radiative Forcing?

Improving satellite retrieval algorithms & models by:
1. Testing satellite data products (validation)
2. Determining actual aerosol properties
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A Chain of Field Experiments Measuring Aerosols & Their Effects on Atmospheric Radiation

SSA from radiative flux closure

SSA(\lambda) from radiative flux closure

SSA(\lambda) from radiative flux closure

SSA(\lambda) from radiative flux closure

P. Russell, NASA Ames Director's Colloquium, 23 Jun 2009
Downwelling Flux: $F\downarrow$

Upwelling Flux: $F\uparrow$

Net Flux: $F\downarrow - F\uparrow$

Flux Divergence (absorption):

$$(F\downarrow - F\uparrow)_{2000\text{m}} - (F\downarrow - F\uparrow)_{43\text{m}}$$

Fractional absorption:

$$\frac{[(F\downarrow - F\uparrow)_{2000\text{m}} - (F\downarrow - F\uparrow)_{43\text{m}}]}{F\downarrow_{2000\text{m}}}$$
Aerosol Single Scattering Albedo Spectrum

Derived from measured flux and AOD spectra.

Desirable features:

- Describes aerosol in its ambient state (incl volatiles like water, organics, nitrates)
- Wide $\lambda$ range: UV-Vis-SWIR
- Includes $\lambda$ range of OMI-UV, OMI-MW, MISR, MODIS, CALIPSO, HSRL, Glory ASP, RSP, POLDER, ...
- Coalbedo (1-SSA) varies by factor 4, $\lambda = 350$-900 nm

[ Bergstrom, Pilewskie, Schmid et al., JGR 2004 ]

P. Russell, NASA Ames Director’s Colloquium, 23 Jun 2009
SSA Spectra from 4 Experiments

Figure 3. The single scattering albedo for the cases presented in Figure 2, ICARTT, SAFARI, PRIDE, and ACE Asia.
Aerosol Absorption Optical Depth (AAOD) Spectra from 5 Experiments

AAOD = $K \lambda^{-\text{AAE}}$

Absorption Angstrom Exponent (AAE)

For Black Carbon, AAE = 1

Bergstrom et al., *ACP*, 2007
A Chain of Field Experiments Measuring Aerosols & Their Effects on Atmospheric Radiation

SSA from radiative flux closure

SSA(λ) from radiative flux closure

SSA(λ) from radiative flux closure

SSA(λ) from in situ

P. Russell, SETI Institute, Mountain View, CA, 6 May 2009
Wavelength dependence of absorption over Mexico is linked to both the organic carbon component (AMS - J, Jimenez, P. DeCarlo) and dust. Model and remote sensing implications for SSA etc.

Expected value for pure BC

Organic fraction of non-refractory mass

Absorption Angstrom Exponent

$\lambda = 470, 530, 660$ nm

Shortwave Enhancement due to dust

Trend due to OC mass fraction

Pollution

Dust

Shinozuka, Clarke et al., 2007
Significance: Both the radiometric and the in situ results indicate that knowledge of Absorption Angstrom Exponent, plus size (or Extinction or Scattering Angstrom Exponent) can be used to determine particle composition.

- This holds out the promise of determining aerosol composition from space, provided Absorption Angstrom Exponent can be determined from space.
- A future spacecraft, Glory, promises to do this. (more later)
ARCTAS: Arctic Research of the Composition of the Troposphere using Aircraft and Satellites

NASA’s contribution to the recent International Polar Year (IPY)

NASA P-3: Specially instrumented to study Aerosols, Radiation, & Trace Gases
## Ames Roles in ARCTAS Leadership

<table>
<thead>
<tr>
<th>Project Management</th>
<th>Institution</th>
<th>Position</th>
</tr>
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<tbody>
<tr>
<td>Jim Crawford</td>
<td>NASA Headquarters</td>
<td>Program Manager, Tropospheric Chemistry</td>
</tr>
<tr>
<td>Hal Maring</td>
<td>NASA Headquarters</td>
<td>Program Manager, Radiation Sciences</td>
</tr>
<tr>
<td>Daniel Jacob</td>
<td>Harvard University</td>
<td>Project Scientist</td>
</tr>
<tr>
<td><strong>Hanwant Singh</strong></td>
<td>NASA Ames Research Center</td>
<td>Project Scientist</td>
</tr>
<tr>
<td>Henry Fuelberg</td>
<td>Florida State University</td>
<td>Project Meteorologist/Forecaster</td>
</tr>
<tr>
<td>Jack Dibb</td>
<td>University of New Hampshire</td>
<td>Platform Scientist, DC-8</td>
</tr>
<tr>
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<td>NASA Ames Research Center</td>
<td>Platform Scientist, P-3</td>
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<td>NASA Langley Research Center</td>
<td>Platform Scientist, B-200</td>
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<tr>
<td>Kathy Thompson</td>
<td>Computer Sciences Corporation</td>
<td>Project Coordinator</td>
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ARCTAS: Arctic Research of the Composition of the Troposphere from Aircraft and Satellites

Why Study the Arctic Now?

Third IPY (2007-2008)

- **ARCTIC IS UNDERGOING RAPID CHANGE** - Rapid warming; receptor of mid-latitudes pollution; boreal forest fires increasing

- **POTENTIALLY LARGE RESPONSE & UNIQUE CHEMISTRY** - Melting of polar ice sheets, decrease of snow albedo from soot, halogen chemistry

- **UNIQUE OPPORTUNITY** - Large NASA satellite fleet; Interagency & international collaboration via POLARCAT & IPY
Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS)

A NASA contribution to IPY and the international POLARCAT initiative

http://cloud1.arc.nasa.gov/arctas

Conducted in spring and summer 2008 with the following foci:

1. Long-range transport of pollution to the Arctic (including arctic haze, tropospheric ozone, and persistent pollutants such as mercury)
2. Boreal forest fires (implications for atmospheric composition and climate)
3. Aerosol radiative forcing (from arctic haze, boreal fires, surface-deposited black carbon, and other perturbations)
4. Chemical processes (with focus on ozone, aerosols, mercury, and halogens)

April 2008: Fairbanks and Barrow, Alaska; Thule, Greenland
July 2008: Cold Lake, Alberta; Yellowknife, NW Territories

Partners: NASA, NOAA, DOE, NSF, Canada, France, Germany

Slide courtesy Jim Crawford, HQ Mgr TCP
P-3B in ARCTAS: Payload

Ames Airborne Tracking Sunphotometer (AATS-14)
- AOD
- Ext
- \( H_2O \) vapor

Solar Spectral Flux Radiometer (SSFR)
- Flux\( \uparrow, \downarrow \) (\( \lambda \)), albedo(\( \lambda \))

HiGEAR Aerosols & \( O_3 \)
- OPC & DMA dry size dist, volatility
- Tandem Volatility DMA
- Neph scat + PSAP abs
- Humidified Neph \( f(RH) \)
- Ultrafine & CN
- Time of Flight Mass Spec size resolved chemistry
- SP2 black carbon mass

AERO3X
- Cavity Ringdown ext (2\( \lambda \))
- Reciprocal Neph sca (2\( \lambda \), RH)
- Nenes CCN
- PVM cloud drop \( r_{eff} \), vol
- TECO \( O_3 \)

Cloud Absorption Radiometer (CAR)
- Radiance, BRDF

P-3 Data System (PDS):
- Nav, Flight, Met (P, T, RH, ...)

COBALT: CO

Broad-Band Radiometers (BBR)
- LW
- SW
- Flux\( \uparrow, \downarrow \), albedo

REVEAL & RTMM
Aerosol-Radiation Connections in ARCTAS

Example Science Results

- 1 Spring Flight (of 8 P-3B)
- 1 Summer Flight (of 13 P-3B)

(See also presentations at http://geo.arc.nasa.gov/sgg/ARCTAS/presentation/index.html and data archive at http://www-air.larc.nasa.gov/cgi-bin/arcstat-c)
Accomplishments:
1. Comparison with NOAA WP-3D under B-200
2. Radiation stack with NOAA WP-3D under B-200 (with sufficient AOD & no hi/mid clouds)
3. Cascade impactor sample during 1, 2 for Raman & SEM analysis
4. Radiation leg along CALIPSO track (before overpass)
5. Albedo & BRDF measurements at Elson Lagoon over surface-based albedo & snow collection measurements
6. Zero ozone over open leads N & W of Elson Lagoon (2x)
7. Overflights of special albedo sites F1, B3, G4(x2), B4, F4, L1 (with variety of cloud conditions)
8. Extra radiation legs along return to Fairbanks
Try to derive aerosol forcing efficiency from these radiation measurements... Enough AOD between flight levels???
20080415 – “Golden Day” (Spring)

20080415 - UTC=20.1
Absorptance between NASA and NOAA plane

NASA: 2919 m
NOAA: 5341 m
ground ~ 100 m

SZA = 59.96 deg

- UTC=20.1 BRDF
- UTC=20.1 isotropic correction
- UTC=20.05 BRDF

ssa=0.87
ssa=0.92

Jens Redemann, AATS-14
Rich Ferrare, HSRL

[Bierwirth, Schmidt et al., ARCTAS]
Aerosol-Radiation Connections in ARCTAS

Example Science Results

- 1 Spring Flight (of 8 P-3B)
- 1 Summer Flight (of 13 P-3B)

(See also presentations at http://geo.arc.nasa.gov/sgg/ARCTAS/presentation/index.html and data archive at http://www-air.larc.nasa.gov/cgi-bin/arcstat-c)
WHY COLD LAKE, WHY JULY?

Canadian fire climatology, 1980-2004

[Map of Canada showing forest fires and Cold Lake location]
What, then, is the role of field programs (like TARFOX, ..., ARCTAS) in reducing the uncertainty in Aerosol Radiative Forcing?

Improving satellite retrieval algorithms & models by:

1. Testing satellite data products (validation)
2. Determining actual aerosol properties
3. Determining the processes leading to #2
4. Measuring aerosol radiative effects & testing closure between measured radiation & aerosol optical & physiochemical properties
5. Testing models

P. Russell, NASA Ames Director's Colloquium, 23 Jun 2009
NRL COAMPS PREDICTED SMOKE FROM ATHABASKA FIRES (courtesy Jeff Reid)

18 Z 9 Jul 2008

Shaded Surface Tracer Mass Load (mg/m²)

GEOS5 - Weak Siberia biomass burning plume between 1-6 km in central Canada, Courtesy Mian Chin - Similar features in some other models.
Turnaround Point
NRL COAMPS PREDICTED SMOKE FROM ATHABASKA FIRES (courtesy Jeff Reid)
GEOS5 - Weak Siberia biomass burning plume between 1-6 km in central Canada, Courtesy Mian Chin - Similar features in some other models.
18 Z 9 Jul 2008
2019 Z 9 Jul 2008 from P-3 cockpit
2024 Z 9 Jul 2008 from P-3 cockpit
9 July 2008: B200 and P-3B underfly the CALIPSO track sampling smoke plume from boreal fires in northern Saskatchewan.
Typical maneuvers flown by P-3 in ARCTAS
To measure aerosols, CO, O3, & radiative effects
HSRL/In situ Aerosol Extinction Comparison

- Comparison of aerosol extinction derived from HSRL (B200) and in situ dry scattering (neph) + absorption (PSAP) measurements while P-3 spiraled up below B200 (in situ data courtesy of Tony Clarke)

Preliminary
**HSRL/AATS-14 Aerosol Optical Thickness (AOT) Comparison**

- Comparison of AOT derived from HSRL (B200) and derived from AATS-14 Airborne Sun Photometer (P-3B) while P-3B spiraled up below B200 (AATS14 data courtesy of Jens Redemann)

- Large variability in AOT associated with smoke plume
Good agreement in and above the smoke! CALIPSO slightly lower

Ferrare, Hostetler, Winker, Redemann, Clarke et al.

Preliminary
Typical maneuvers flown by P-3 in ARCTAS
To measure aerosols, CO, O3, & radiative effects
Comparison of AATS, OMI, and MODIS AOD spectra

7/9/2008 Low alt transect:19.515-19.712 UT z(ASL): 0.72+-0.05 km

Aerosol Optical Depth

Wavelength [microns]

OMI UV
OMI MW
MODIS
AATS-14

Preliminary

J. Redemann, J. Livingston, Torres, Veihelmann, Veefkind
ARCTAS Summary & Future

1. NASA’s contribution to IPY & International POLARCAT
2. Strong intercenter, university, interagency, & international collaboration.
3. P-3 data set links air, surface, & space measurements and addresses all P-3B goals
   - linking variations in atmospheric radiation to microphysics and chemistry of haze & smoke aerosols + Arctic surfaces.
   Needed for
   --reliable interpretations of satellite inversions
   --refining model products
   --assessing climate forcing in terms of emissions and/or mitigation strategies.
4. Ames lead roles in project science, project management, & platform science. Also A/C instruments.
5. Most analyses in early stages.
7. ARCTAS Special Sessions: AGU Fall 2009
The Future

- Satellites
- Aircraft
- Instruments
- Field campaigns
Clouds of Venus, Polarimetry, & Their Dual Relevance to Earth’s Climate

17 proposed compositions before H&H polarimetric analysis

unknown. Many possible compositions have been suggested in the literature, including water, $\text{H}_2\text{O}$ ice, solid CO$_2$ carbonate (C$_2$O$_2$), Sinton, 1953; Kuiper, 1957; Harteeck et al., 1963), hydrated ferrous chloride (FeCl$_2$·2H$_2$O; Kuiper, 1969), NaCl (Hunten, 1968), formaldehyde (CH$_2$O; Wildt, 1940), hydrocarbons (Velikovsky, 1950; Hoyle, 1955; Kaplan, 1963), hydrocarbon-amide polymers (Robbins, 1964), polywater (Donahue, 1970), ammonium nitride (NH$_4$NO$_2$; Dauvillier, 1956), calcium and magnesium carbonates (Opik, 1961), NH$_4$Cl (Lewis, 1968; Hunten and Goody, 1969), mercury and mercury compounds (Lewis, 1969; Rasool, 1970) and aqueous solutions of hydrochloric acid (HCl·nH$_2$O; Lewis, 1972; Hapke, 1972) and sulfuric acid (H$_2$SO$_4$·nH$_2$O; Sil, 1972; Young

Interpretation of the Polarization of Venus

JAMES E. HANSEN

Goddard Institute for Space Studies, New York, N. Y. 10025

J. W. HOVENIER

Dept. of Physics and Astronomy, Free University, Amsterdam, Netherlands

(Manuscript received 20 November 1973, in revised form 15 January 1974)

ABSTRACT

The linear polarization of sunlight reflected by Venus is analyzed by comparing observations with extensive multiple scattering computations. The analysis establishes that Venus is veiled by a cloud or haze layer of spherical particles. The refractive index of the particles is 1.44±0.015 at $\lambda=0.55 \mu$m with a normal dispersion, the refractive index decreasing from 1.46±0.015 at $\lambda=0.365 \mu$m to 1.43±0.015 at $\lambda=0.99 \mu$m. The cloud particles have a narrow size distribution with a mean radius of $\sim 1 \mu$m; specifically, the effective radius of the size distribution is 1.05±0.10 $\mu$m and the effective variance is 0.07±0.02. The particles exist at high levels in the atmosphere, with the optical thickness unity occurring where the pressure is about nb.

The particle properties deduced from the polarization eliminate all but one of the cloud compositions which have been proposed for Venus. A concentrated solution of sulfuric acid (H$_2$SO$_4$·H$_2$O) provides good agreement with the polarization data.

P. Russell, NASA Ames Director’s Colloquium, 23 Jun 2009
The A-Train with Glory

Glory Aerosol Polarimetry Sensor (APS) level-3 aerosol data products
(adapted from Mishchenko et al., 2007)

<table>
<thead>
<tr>
<th>Data product (fine and coarse modes)</th>
<th>Range</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column spectral* aerosol optical depth</td>
<td>0-5</td>
<td>0.02 over ocean 0.04 over land</td>
</tr>
<tr>
<td>Aerosol effective radius</td>
<td>0.05-5 µm</td>
<td>10%</td>
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<tr>
<td>Effective variance of aerosol size distribution</td>
<td>0-3</td>
<td>40%</td>
</tr>
<tr>
<td>Aerosol spectral* real refractive index</td>
<td>1.3-1.7</td>
<td>0.02</td>
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<tr>
<td>Aerosol spectral* single-scattering albedo</td>
<td>0-1</td>
<td>0.03</td>
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<tr>
<td>Aerosol morphology</td>
<td>Spherical aerosols, irregular dust particles, soot clusters</td>
<td>N/A</td>
</tr>
</tbody>
</table>

*At least in three spectral channels; relative accuracy better where AOD is larger (typically 410-865 nm).

Planned launch: No earlier than Oct 2009

P. Russell, SETI Institute, Mountain View, CA, 6 May 2009
The Future

- Satellites
- Aircraft
- Instruments
- Field campaigns
Earth Science “Decadal Survey”

Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond
Committee on Earth Science and Applications from Space: A Community Assessment and Strategy for the Future, National Research Council
<table>
<thead>
<tr>
<th>Tier 1</th>
<th>Tier 2</th>
<th>Tier 3</th>
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<td><strong>Timeframe 2010 - 2013, Missions listed by cost</strong></td>
<td><strong>Timeframe 2013 - 2016, Missions listed by cost</strong></td>
<td><strong>Timeframe 2016-2020, Missions listed by cost</strong></td>
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<td>Solar and Earth radiation, spectrally resolved forcing and response</td>
<td>Land surface composition for agriculture and mineral characterization</td>
<td>Land surface topography for landslide hazards and water runoff</td>
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<td>of the climate system</td>
<td>vegetation types for ecosystem health</td>
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<td>Hyperspectral spectrometer</td>
<td>Laser altimeter</td>
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<td>Day/night, all-latitude, all-season CO2 columns integrals for</td>
<td>High frequency, all-weather temperature and humidity soundings for</td>
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<td>and climate; vegetation structure for ecosystem health</td>
<td>climate emissions</td>
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<td>MW array spectrometer</td>
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<td>GRACE-II</td>
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<td>Atmospheric gas columns for air quality forecasts; ocean color for</td>
<td>High temporal resolution gravity fields for tracking large-scale</td>
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<td>coastal ecosystem health and climate emissions</td>
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<td>Snow accumulation for fresh water availability</td>
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<td>MW array spectrometer</td>
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<td>GRACE-II</td>
<td>3D-Winds (Demo)</td>
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<td>High temporal resolution gravity fields for tracking large-scale</td>
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<td>Tropospheric winds for weather forecasting and pollution transport</td>
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AEROSOL-CLOUD-ECOSYSTEMS (ACE)
Launch: 2013-2016  Mission Size: Large

Cloud and aerosol height

Organic material in surface ocean layers

Improved climate models
Prediction of local climate change

Aerosol and cloud types and properties

Ocean productivity
Ocean health

Air-quality models and forecasts
Candidate Sensor System for ACE from NAS

Passive sensors

Multiangle imaging spectropolarimeter (UV-SWIR): Global column-averaged aerosol amount, size distribution, absorption, particle shape, refractive index; some height sensitivity

Optical spectrometer (ORCA): Measurements of biomass growth rates, organic and non-organic suspended matter assessments, aerosol absorption and size sensitivity

IR Scanner: Measurements of cloud height using cloud top temperature

Active sensors

Next generation aerosol lidar: Vertical profiles of aerosol abundances and microphysical properties with across-swath capability and/or direct extinction-backscatter separability

Cloud profiling radar: Vertical profiles of droplet effective radius and vertical profile of water phase, cloud base and top height, precipitation rates

“Use or disclosure of these data is subject to the restriction on the title page of this document”
GEOSTATIONARY COASTAL AND AIR POLLUTION EVENTS (GEO-CAPE)

Launch: 2013-2016  Mission Size: Medium

- Identification of human versus natural sources of aerosols and ozone precursors
- Dynamics of coastal ecosystems, river plumes, and tidal fronts
- Observation of air pollution transport in North, Central, and South America
- Prediction of track of oil spills, fires, and releases from natural disasters
- Detection and tracking of waterborne hazardous materials
- Coastal health
- Forecasts of air quality
GLOBAL ATMOSPHERIC COMPOSITION MISSION (GACM)

Launch: 2016-2020    Mission Size: Large

- Vertical profile of ozone and key ozone precursors
- Global aerosol and air pollution transport and processes
- Sources of pollutants
- Identification of sources and sinks of harmful pollutants
- Forecasts of ozone and surface radiation
- Forecasts of dangerous pollution events
The Future

- Satellites
- Aircraft
- Instruments
- Field campaigns
Global Hawk Pacific (GloPac 2009)

- Ceiling: 65,000 ft
- Duration: >31 hr

P. Russell, NASA Ames Director's Colloquium, 23 Jun 2009
Global Hawk Pacific (GloPac 2009)

**ACAM** – Cross-track scanning spectrographs of NO₂, O₃, and aerosols

**AMS** – Multi-spectral scanner for upper tropospheric water vapor measurements

**CPL** – Backscatter LIDAR for hi-res profiling of clouds and aerosols

**MMS** – Science quality aircraft state variable measurements

**MPT** – Passive microwave radiometer measurements of O₂ thermal emissions

**MVIs** – Time-lapse nadir color digital imagery with georeferencing

**NMASS/FCAS** – Aerosol size and concentration measurements

**Ozone** – Dual-beam UV photometer for accurate O₃ measurements

**UCATS** – Dual gas chromatographs for N₂O, SF₆, H₂, CO₂, and CH₄ measurements

**UHSAS** – Ultra-high sensitivity aerosol spectrometer

**ULH** – In-situ hi-accuracy atmospheric water vapor measurements
Global Hawk Pacific (GloPac 2009)

Description

• 12 instruments will be installed on the Global Hawk aircraft for the GloPac missions
• Six long-duration, high-altitude missions will be flown over the Pacific Ocean and Arctic region
• From the Global Hawk Operations Center, located at NASA Dryden, scientists will communicate with their payloads and view real-time data during the missions
• Each flight will originate and end at NASA Dryden

Scientific Objectives

• First demonstration of the Global Hawk unmanned aircraft system (UAS) for NASA and NOAA Earth science research and applications
• Validation of instruments on-board the Aura satellite
• Exploration of trace gases, aerosols, and dynamics of remote upper troposphere/lower stratosphere (UT/LS) regions
• Sample polar vortex fragments and atmospheric rivers
• Risk reduction for future Global Hawk missions that will study hurricanes and atmospheric rivers
The Future

- Satellites
- Aircraft
- Instruments
- Field campaigns
A Closing Point re Instruments

• Airborne instruments need to keep pace with the advancing state of knowledge and improving satellite capabilities

• A new airborne instrument with AERONET-like capabilities and more is in development at Ames (in collaboration with Battelle at DOE’s PNNL)
4STAR: Spectrometer for Sky-Scanning, Sun-Tracking

Atmospheric Research

AERONET-like
- Phase function
- Size mode distributions
- \( n_{re}(\lambda), n_{im}(\lambda) \)
- Single-scattering albedo
- Asymmetry parameter
- Shape
- Hence aerosol type

Improve \( H_2O, O_3 \)
Add \( NO_2 \)
Thus improve AOD

Simultaneous spectra yield airborne profiles of aerosol type via Aeronet-like retrievals

AATS-14 like retrievals of column amount and profiles of aerosol, \( H_2O \) and \( O_3 \)

B. Schmid, DOE-ASP Meeting, Annapolis, MD, 27 Feb 2008
Spectrometer for Sky-Scanning, Sun-Tracking Atmospheric Research (4STAR)

- Fiber Optics Cable
- Motor Feedback Devices
- Elevation Motor
- Aircraft Skin
- Azimuth Motor
- Fiber Optics Rotating Joint

Optical Entrance

Sun Tracking, Sky Scanning Head

B. Schmid, DOE-ASP Meeting, Annapolis, MD, 27 Feb 2008
Summary & Conclusions

- Integrated air-space-ground field studies have made major contributions to the reduction in aerosol radiative forcing uncertainty documented in IPCC AR4 (2007).
- They have done this by improving satellite retrieval algorithms and aerosol modules of climate models.
- There is a continuing need for such studies, & the trend is to interagency-international collaboration (e.g., POLARCAT: NASA ARCTAS-NOAA ARCPAC).
- Continuing advances in instrumentation & validation are required to reduce the remaining unacceptably large uncertainties in Aerosol Radiative Forcing.

P. Russell, NASA Ames Director's Colloquium, 23 Jun 2009
End of Presentation

Remaining Slides are Backup