AEROSOLS, CLOUDS AND PRECIPITATION

RAL retreat
5 – 7 October 2005
Estes Park, Colorado
The aerosol/precip connection

• Aerosol environment has changed
  – CCN/sulfates are about 70% anthropogenic with strong variation in emissions geographically
  – Desert dust concentrations vary widely; appear to be important IN
• Clear anthropogenic effects (e.g., satellite evidence)
• Well known climate connections
  – Direct (reflect incoming solar radiation back to space)
  – Indirect (modify properties and lifetime of clouds)
• Linkage to precip understood in principle, but hard evidence is scanty and scattered; we lack quantitative/predictive skill
Motivation

- Worldwide water resource stresses
- Severe weather hazards
- New observational, computational, statistical technologies
- Operational programs with little scientific basis
- Population and demographic changes
- Inadvertent weather modification
  → similar physical processes!

“estimates of indirect forcing that include feedback to the liquid-water path and cloud amount from changes in cloud microphysics and precipitation efficiency range from -1.1W m\(^{-2}\) to -4.8W m\(^{-2}\)”
The Paradox

- Operational programs in more than 37 countries worldwide
- At least 69 programs in 11 U.S. states in 2001

- Limited funding supporting research as part of operational programs
- Impact of human activity on weather and climate recognized and heavily funded
Projects

- Current cloud physics and radar-upgrade projects
- Recent int’l projects involving equipment/software tech transfer, training, and outreach in the cloud physics/convective storm arena.

- Mexico: Radar upgrades for NAME, previous rainfall studies
- Burkina Faso: Upgrade radar infrastructure and training
- Italy and Greece: Upgrade radar infrastructure, observational project training
- Saudi Arabia and UAE: aerosol cloud interactions
- Indonesia: Infrastructure building and aerosol-cloud interactions
- Argentina: software upgrades for hail studies
Key Uncertainties

Cloud and precipitation microphysics issues
- Background concentration, sizes, and chemical composition of aerosols participating in cloud processes

Cloud dynamics issues
- Cloud-to-cloud and mesoscale interactions relating to updraft and downdraft structures and cloud evolution and lifetimes

Cloud modeling issues
- Combination of best cloud models with advanced observing systems in carefully designed field tests and experiments

Seeding-related issues
- Targeting of seeding agents, diffusion and transport of seeding material, and spread of seeding effects throughout the cloud volume
- Measurement capabilities and limitations of cell-tracking software, radar, and technologies to observe seeding effects
WEATHER MODIFICATION

Diagram showing the relationship between synoptic environment, mesoscale environment, cloud environment, water/ice nucleation, and precipitation (rain, snow, hail).
Microphysical processes in precipitation development

- **Wavelet Vapor**
- **Rain**
- **Cloud Water**
- **Cloud Ice**
- **Graupel Hail**
- **Snow**
- **Precipitation Fallout**

- **Conversion**
- **Collection**
- **Melting**
- **Freezing**
- **Autoconversion**
- **Collection**
- **Shedding**
- **Rimming**
- **Condensation**
- **Evaporation** during melting
- **Initiation**
- **Deposition**

**Additional Processes:**
- **Deposition/Condensation**
- **Evaporation/Condensation**
- **Deposition/Evaporation during melting**
- **Spattering**
- **Conversion**
- **Collection**
- **Collection**
- **Collection**
Aerosols That Affect Precipitation

Cloud Condensation Nuclei (CCN):
- Higher concentrations lead to reduced precipitation efficiency (next slide; also observed maritime/continental differences)

Ice Nuclei (IN):
- Ice formation is a complex process and the optimum concentration of ice nuclei depends on cloud conditions. Higher IN concentrations could increase or decrease precipitation, depending on conditions.

Giant / Ultragiant Aerosols (UGA, 10-100 µm):
- Embryos form first precipitation in cumulus clouds. Not clear how significant a role they play in overall precipitation formation.

Large CCN (around 1 µm):
- Play an important role in initiating the coalescence process.
Total aerosol, cloud condensation nuclei (CCN), and ice nuclei (IN) concentrations as a function of temperature.

- In order to enhance precipitation the concept of seeding is to seed with appropriate CCN or IN to make precipitation develop more efficiently.
Key Uncertainties
(Possible solutions)

Cloud and precipitation microphysics issues
• Background concentration, sizes, and chemical composition of aerosols participating in cloud processes (in-situ and satellite measurements, models)

Cloud dynamics issues
• Cloud-to-cloud and mesoscale interactions relating to updraft and downdraft structures and cloud evolution and lifetimes (Multi-parameter radar, models)

Cloud modeling issues
• Combination of best cloud models with advanced observing systems in carefully designed field tests and experiments (data assimilation, development of two-way interactive aerosol and microphysical parameterizations, land-surface interactions, upgraded and new parameterizations)
Main Points:

1. Aerosols Have Changed:
   - CCN: sulfate is about 70% anthropogenic, with emissions that have varied with location (e.g., peaking for the US about 1970 but increasing concentrations in some other parts of the world)
   - Desert dust concentrations fluctuate over a wide range but also show increases (factor of four to an order of magnitude). These have good ice nucleating ability, and are likely candidates for the ice nuclei that are of importance to precipitation formation.

2. Preliminary indications are that this could have changed precipitation processes in significant ways depending on the background pollution and aerosols in a specific region. These results apply both to inadvertent and advertent weather modification.
Main Points: (cont.)

3. Aerosol composition, concentrations and sizes also show great variations in one region during seasons and even on different days.
4. These changes affect precipitation processes.
5. A full understanding of precipitation processes will have to capture these effects.
6. Satellites can provide a first estimate and assimilated into models.
7. Aerosol chemical composition changes continuously in the atmosphere and also affect sizes and concentrations.

Measurements at Barbados of mineral dust concentrations. These and other observations indicate large variability, long-range transport, and factor-of-four increase from the late 60s to the early 80s. Higher concentrations are linked to drought conditions in the sub-Saharan region.

Some Comments on Hygroscopic Seeding

- Two methods: add giant/ultra-giant, or add large particles. Most experiments have used UGA, but recent experiments use flares that produce both.
- UGA produce embryos that grow to raindrops, but continued influence on the cloud will depend on breakup or some other mechanism to overcome the problem that each embryo otherwise produces one raindrop.
- Large CCN instead rely on acceleration of the production of drizzle which can occur in higher concentrations because the CCN are much smaller.
Supporting Observations:

SURROUNDED REGION

SEED?ED?

Measured in South Africa
Example Research Questions

- What is the **background aerosol concentration**:
  - in various places,
  - at different times of the year,
  - during different meteorological conditions?

- To what **extent** would weather modification operations be **dependent** on these background concentrations?
Aerosol and non-aerosol days classification for Mexican hygroscopic seeding data

- Typical non-aerosol day (<0.1 optical depth)
- Typical aerosol day (>0.1 optical depth)
MEXICO RANDOMIZED EXPERIMENT

ALL STORMS

Minutes From Decision

Not Seeded Storms

Seeded Storms
MEXICO RANDOMIZED EXPERIMENT
ONLY STORMS WITH REFLECTIVITY

Not Seeded Storms

Seeded Storms

Minutes From Decision

Log of Rain Mass > 0

0.0 1.5 3.0

-20 -15 -10 -5 0 5 10 15 20 25 30 35 40 45 50 55 60

Minutes From Decision

Log of Rain Mass > 0

0.0 1.5 3.0

-20 -15 -10 -5 0 5 10 15 20 25 30 35 40 45 50 55 60
CCN SUPERSATURATION SPECTRA AND ASSOCIATED PARTICLE TYPES FROM TEM/SEM IMAGES FROM BIOMASS SMOKE IN SOUTHERN AFRICA

CCN spectra at different altitudes in different layers of aerosols continuously changing composition, concentration, and size at the same location and time.
Aerosols and Composition (Saudi Arabia): In-situ measurements, satellites and models

Vertical measured size distribution of aerosols between .1 and 3 µm diameter

NAAPS (model and satellite) optical depth Sulfate, dust and biomass aerosols
Extremely high droplet concentrations during incursion of biomass smoke from Africa associated with drop in mean sizes of droplets

Daily microphysical measurements in clouds in Saudi Arabia during July and August 2004
COMBINED SATELLITE AND RADAR
UAE randomized seeding experiment
Randomized Experiment
Statistical Results
Microphysical Reasons for Negative Results

TITAN radar image

Droplet and ice concentrations

Particle images
Lake Matano

Lake Towuti

Watershed Area
2477 km$^2$
Sulawesi microphysical measurements

April 24 2005

Graphs and charts showing microphysical measurements including:
- Altitude [m] vs. SPP Total Conc
- LWC, Temp, Mean Diameter, MVD over time
- SPP Total Concentration [cm$^3$]
- Standard Deviation
- Mean diameter [μm]
- dN/dD [cm$^{-3}$•μm$^{-1}$] vs. Diameter [μm]
Aerosol-cloud interactions

India

CCN and aerosol conc.

Droplet conc.

Particle images
The Unified Aerosol Experiment-United Arab Emirates: UAE²
A Study of Arabian Gulf Aerosol Microphysics, Radiation, and Transport Phenomenology
NASA Rationale:
What We Knew Coming In

• Cross-roads of 4 sub-continents
• Bright Surface/Class two waters a challenge for satellites
• Very strong micro and mesoscale circulations
• Sea/land breeze excellent for testing models
• Unique environment for convective and stratus clouds
• Need “Pathfinder Mission” to study this region of the world
Dept. of Water Resources, Office of the President, United Arab Emirates
Droplet Measurement Technologies, Inc.
NASA et Propulsion Laboratory, Pasadena, CA.
National Center for Atmospheric Research, Boulder CO.
NASA Goddard Space Flight Center, Greenbelt MD.
Naval Research Laboratory, Monterey, CA
Naval Research Laboratory, Stennis, CA
North Carolina State University, Raleigh, NC
Oman Weather Service
Orsmond Aviation, South Africa.
Scripps Institution of Oceanography
South African Weather Agency
TNO Physics and Electronics Laboratory, The Hague, Netherlands
Universite de Shebrooke, Sherbrooke, Quebec, Canada
University of Alabama, Huntsville, AL
University of California, Davis, CA
University Corporation for Atmospheric Research
University of Hawaii, Honolulu HI
University of Lille, France
University of Maryland, Baltimore County, Baltimore MD
University of Maryland, College Park, MD
University of Muscat, Oman
University of Witwatersrand, South Africa
Warsaw University, Warsaw, Poland
EOS Spacecraft in orbit/
just in orbit

Aqua 5/02

ICESat 10/02

SORCE 01/04

Aura 07/04
Mission Support

**Satellites and Sensors**
- Aqua: MODIS
- ENVISAT: AATSR
- EO-1
- Meteosat 5
- NOAA-15/16/17: AVHRR
- SeaWiFS
- Terra: ASTER, CERES, MISR, MODIS
- TRMM
- Other various passive microwave systems

**Models**
- Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS™)
- Goddard/Georgia Tech Ozone Aerosol (GOCART)
- Mesoscale Model-5 (MM5) (2 platforms)
- NRL Aerosol Analysis and Prediction System (NAAPS)
- RT FDDA/MM-5
- WRF
Densest network of Sun photometers ever assembled
SeaWiFS, Sept. 1 2000
Arabian Gulf and Arabian Sea: A multitude of atmospheric phenomenon

- Dust
- Smoke+Dust
- Stratus
- Convection
- Class 2 Water
- Sea/Land Breeze
- Monsoonal flow/ Heat low

Kuwait Airport, Bandar Abbas, Iran, Bahrain Airport.
Satellite tracking of dust and pollution: Aug 30th
Dust and Pollution from Saudi Arabia and Iran

Aug. 28: Stagnant air in the central Gulf builds up pollution levels

Aug. 29: Air moves south towards UAE

Aug. 30: Humid air mass creates severe air quality episode in UAE
MISR/MODIS Plume Research Implications for Winds/Trajectory Modeling

The tracks of refinery plumes visible

TEM: soot particles, sulfate
TEM Aerosol Images from UAE

EDS analyses
Aggregation of NaCl particles

UAE

- Habshan: 150m alt.
- Zirku island: 120m alt.
- Also common: NaCl + (NH₄)₂SO₄
Real time Aerosol and Environmental Monitoring in the United Arab Emirates

Joint Dept of Water Resource Studies, NCAR, NASA, and NRL Development

An Example: September 12th, 2004

Step 1. MODIS images are taken twice a day over the world.

Step 2. From the 52 MODIS channels, atmospheric properties can be determined (e.g. aerosols/dust in air).

Step 3. Derived information from satellites are then fused with weather models.

Step 4. Based on monitoring such events, improved weather models are developed and improved.

Eventually, satellite data and observations will be assimilated directly into the models to provide an up to the minute assessment of aerosol and environmental conditions.

Sept. 12, 2004, had one of the best organized dust storms of 2004. This coincided with the UAE2 campaign.

Dust Concentration (µg m⁻³)
Evaluation component of a winter orographic cloud seeding project in Wyoming
Key Issues and Uncertainties

- Transport and dispersion of seeding material (targeting)
- Identifying spatial and temporal variations of SLW regions
- Identifying aerosol characteristics and ice nuclei background levels as well as in seeding plumes
- Demonstrating the increase of ice/snow from seeding (statistical design)
- Measuring precipitation
WRF Simulation of seeding releases
New Tools

1) New remote and in situ observational tools
   - e.g., Doppler lidar and airborne radars, MW radiometer, CPI, cell-tracking software

2) Cloud and precipitation physics modeling
   - e.g., focus on CCN, ice nucleation processes
INSTRUMENTED RESEARCH AIRCRAFT

Missions: chemistry and aerosol mapping, cloud penetrations, seeding trials

State parameters: $T$, $T_d$, $p$, TAS, Hdg, GPS position, derived winds

Trace gases: $\text{SO}_2$, $\text{O}_3$, $\text{NO}_{x/y}$

Aerosols: CN, CCN, PCASP, filter pack sampler

Cloud physics: FSSP, 2D-C, 2D-P, (HVPS), LWC
New Tools

3) Computation and **data assimilation** capabilities
   - rapid data processing
   - simulation of cloud and precipitation processes

4) Existing **field facilities** and new partnerships among research and operational groups
Summary

• Spatial and temporal changes in natural concentration, sizes, and chemical composition of aerosols change microphysical and precipitation processes
• Affects of seeding may widely differ from one situation to the other.
• These effects may mask seeding effects in the evaluation of experiments unless stratified by these conditions
• New tools available to stratify these results
Summary

Important Problem

• Water resource management
• Large societal investments
• Inadvertent weather modification effects

Opportunities

• New observing technologies
• Better models and computing
• Recent interesting research (Hygroscopic seeding, ship-track studies, Satellite studies, winter orographic seeding)

Establish programs with major emphasis on quantification of the effects of both advertent and inadvertent weather modification and include scientific community
New integrated approach needed to study effects of aerosols on precipitation patterns

- Combined observational, modeling and theoretical approach
- Observations: Surface and in-situ, satellites and multi-parameter radar
- Models: Two-way interactive development of pollution and natural aerosol transport, chemistry, physics, cloud microphysical and precipitation processes
- Theory: Aerosol physics and chemistry and interaction with cloud and precipitation processes.

ISSUE
The world is a complicated place. Take a look outside.