Autonomous Unmanned Aerial Vehicles as a Tool for Measuring Cloud-Aerosol-Radiation- Chemistry

Scripps Institution of Oceanography

V Ramanathan, Craig Corrigan, D Kim, H Nguyen, M Ramana, Greg Roberts

ARM Aerial Vehicle Program science team meeting, Monterey; March 29, 2007

Outline

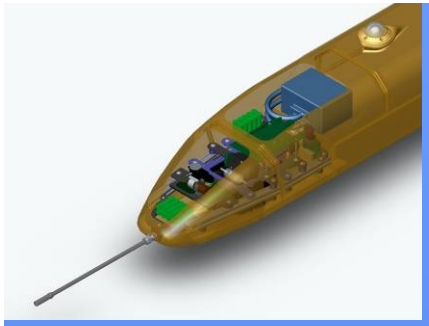
- Introduction
- MAC Campaign
- Radiation Results
- Aerosol Results
- Future Missions and Collaborations
  - Possible Experiment with DOE

Advantages of Using Lightweight AUAVs

- Complement manned aircraft missions
- Inexpensive, routine operation
- Fly coordinated missions with multiple aircraft
- Can fly in risky environments
- Can operate from remote locations (ships, islands, etc.)

ACR Manta

Weight - 23 kg (takeoff)
Wingspan - 2.7 meters
Cruise velocity - 35 m/s
Payload - 5 kg
Flight duration - 5+ hours
Manual or Catapult Launch
Autonomous GPS flight
Satellite communication link



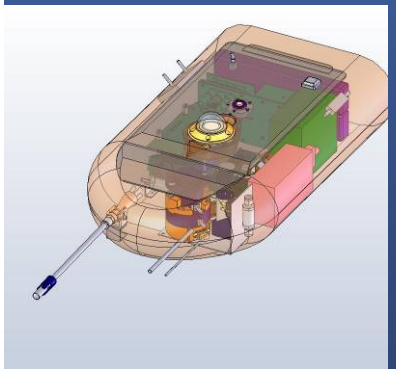
Scripps Payload Design & Integration

2003 – 2004

Initial development *Jan. – May '03*	Seattle, WA *Sept. '03*	El Mirage, CA *Dec. '03*	Seattle, WA *July '04*	El Mirage, CA *Sept. '04*	MALDIVES *Oct. '04*

2005 – 2006

Tucson, AZ *May '05*	Tucson, AZ *July '05*	Yuma, AZ *Aug. '05*	El Centro, CA *Nov. '05*	MALDIVES *Mar. '06*

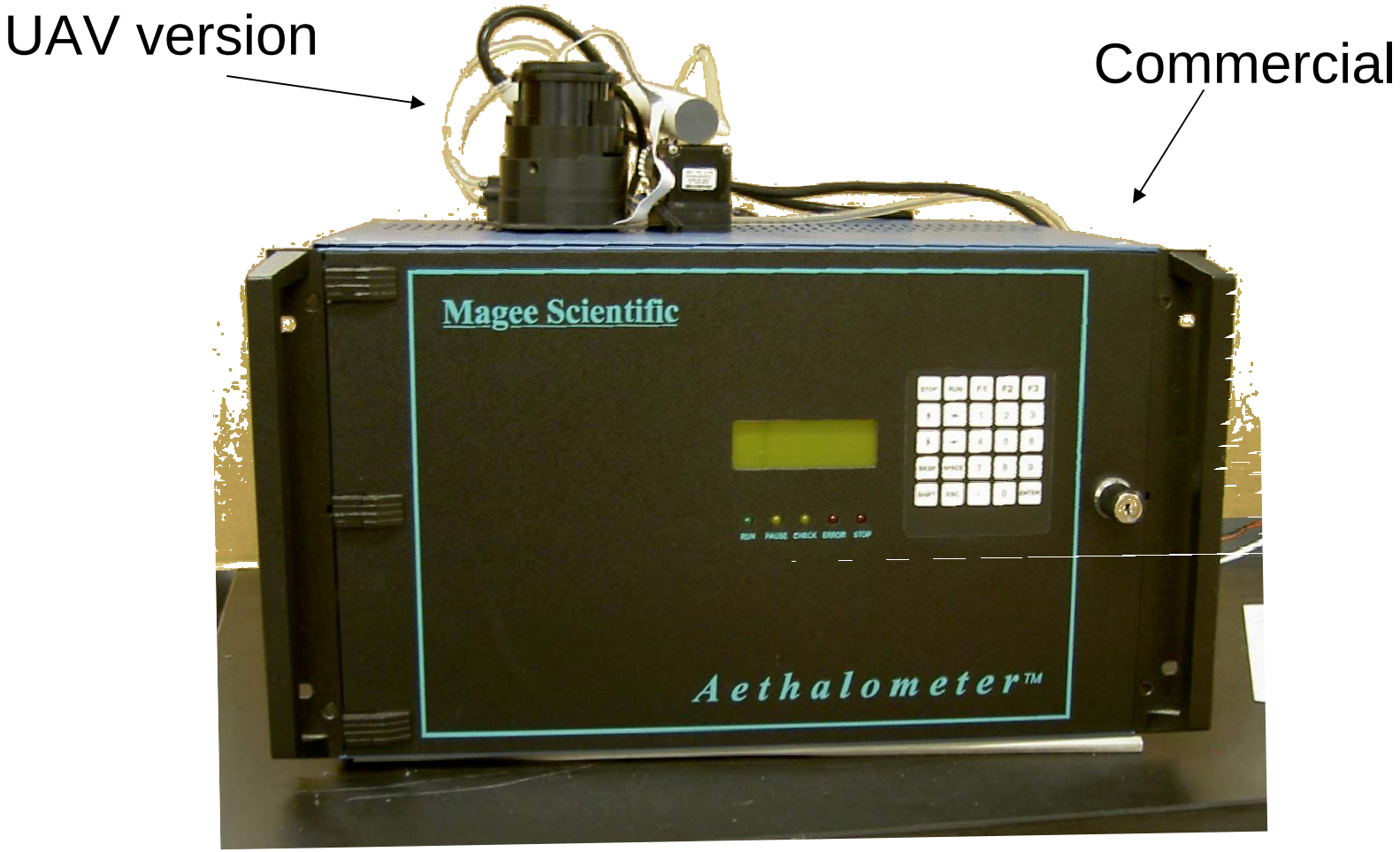


Test Flights

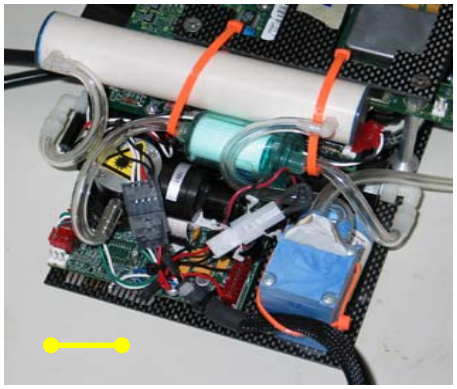
Instrumented Flights

Experiments

Necessary to Shrink Instruments

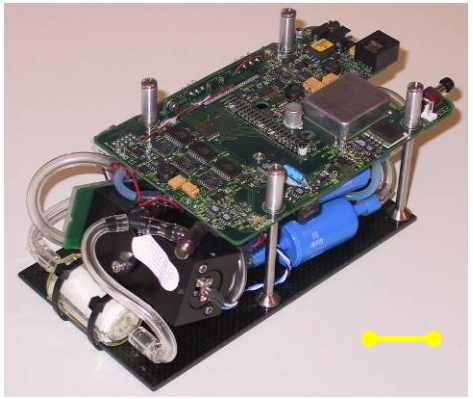


Miniaturized Instruments for UAV



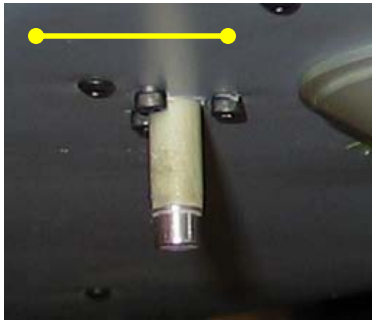
Optical Particle Counter (580 g)
→ N_{OPC}; 0.3 < D_p < 3 μm

[=] 1 inch



Condensation Particle Counter (870 g) → N_{CN}; D_p > 10 nm

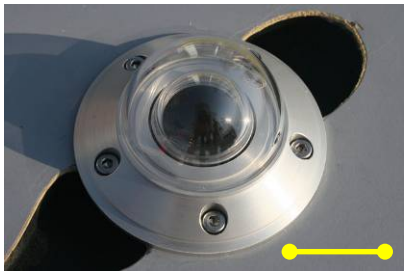
Aethalometer (820 g)
→ absorbing aerosol



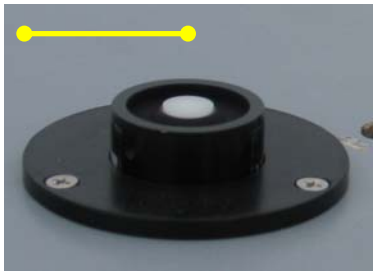
T/RH probe (50 g)
→ Temperature & RH

Aerosol inlet & splitter (150 g)
→ unbiased aerosol sampling

Cloud Droplet Spectrometer (1.4 kg) → distr. 1 < D < 50 μm

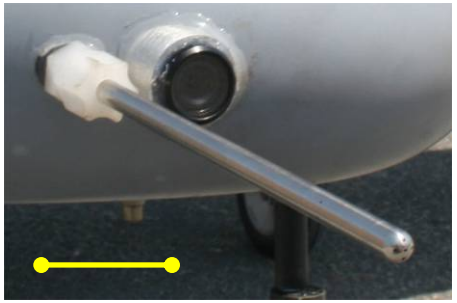


Pyranometer (190 g)
→ irradiance 0.3 – 2.8 μm



PAR radiometer (45 g)
→ irradiance 400 – 700 nm

LWC probe (450 g)
→ Cloud water (g m^{-3})



Video camera (280 g)
→ cloud targeting

The Maldives Autonomous Unmanned Aerial Vehicle Campaign (MAC)

06 March - 01 April, 2006

The Maldives Autonomous Unmanned Aerial Vehicle Campaign (MAC)

06 March - 01 April, 2006

Science Team: Scripps Institution of Oceanography

V. Ramanathan *(PI)*
H. Nguyen *(Mission Director)*
C. Corrigan *(Aerosols)*
M.V. Ramana *(Radiation)*
G. Roberts *(Lead Instrument Scientist)*

Flight Team: Advanced Ceramic Research

A. Mulligan *(Project Director)*
M. Patterson *(Project Manager)*
L. Wardell *(Project Leader)*
P. Corcoran *(Pilot-in-Command)*
E. Hooper *(Pilot)*
R .A.G. Pineda *(Pilot)*

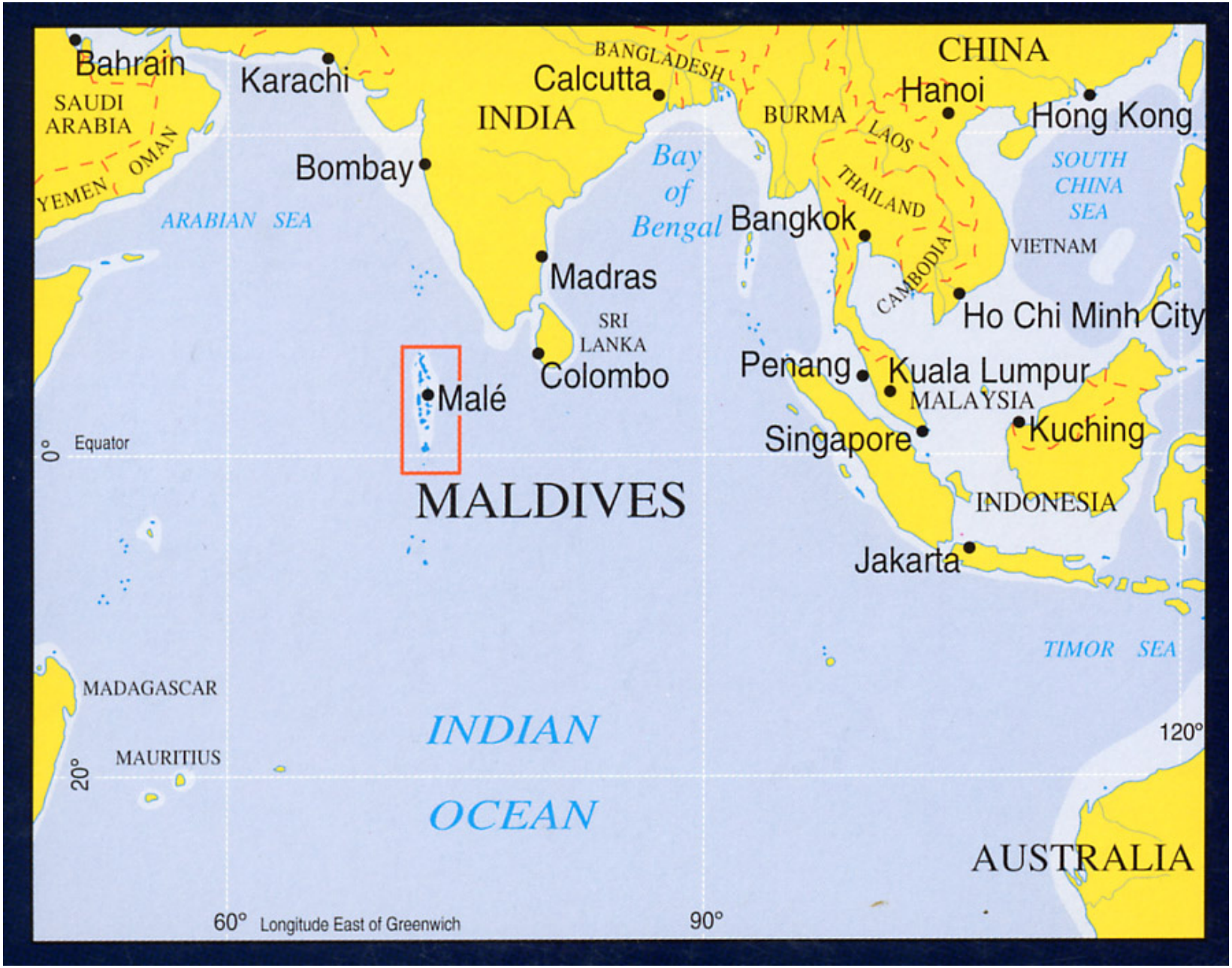
NSF/NOAA/NASA/Vetlesen/Alderson

Maldives AUAV Campaign (MAC) Objectives

1. Technology demonstration
2. Vertical profiles of aerosols, clouds and radiation fluxes
3. Direct measurement of solar absorption and heating rates in the atmosphere
4. Linking aerosols with atmospheric solar absorption and cloud microphysical properties
5. *Required stacked flight missions to observe atmospheric layers and clouds simultaneously from above, below, and within*.

MAC Papers Communicated

1. *Capturing Vertical Profiles of Aerosols and Black Carbon over the Indian Ocean Using Autonomous Unmanned Aerial Vehicles* (Corrigan et al., submitted GRL)
2. *Albedo, Atmospheric Solar Absorption, and Atmospheric Heating Rate Measurements with Lightweight Autonomous Stacked UAVs* (Ramana et al., submitted QJRMS)
3. *Stacked UAVs Link Large Solar Heating by Brown Clouds with Retreat of Himalayan Glaciers (Ramanathan et al., submitted to Nature)*
4. *Direct observations of aerosol-cloud interactions using UAVs as new tools in atmospheric sciences (Roberts et al., to be submitted to Science)*
5. *Instrument Development Technical Paper (Roberts et al., in preparation.)*


Bahrain
Karachi
Calcutta
BANGLADESH
CHINA
Hanoi
Hong Kong
SAUDI ARABIA
INDIA
BURMA
LAOS
YEMEN
OMAN
Bombay
Bay of Bengal
THAILAND
SOUTH CHINA SEA
ARABIAN SEA
Bangkok
VIETNAM
CAMBODIA
Madras
Ho Chi Minh City
SRI LANKA
Penang
Kuala Lumpur
Colombo
MALAYSIA
Malé
Singapore
Kuching
0° Equator
MALDIVES
INDONESIA
Jakarta
TIMOR SEA
MADAGASCAR
INDIAN
120°
MAURITIUS
20°
OCEAN
AUSTRALIA
60° Longitude East of Greenwich
90°

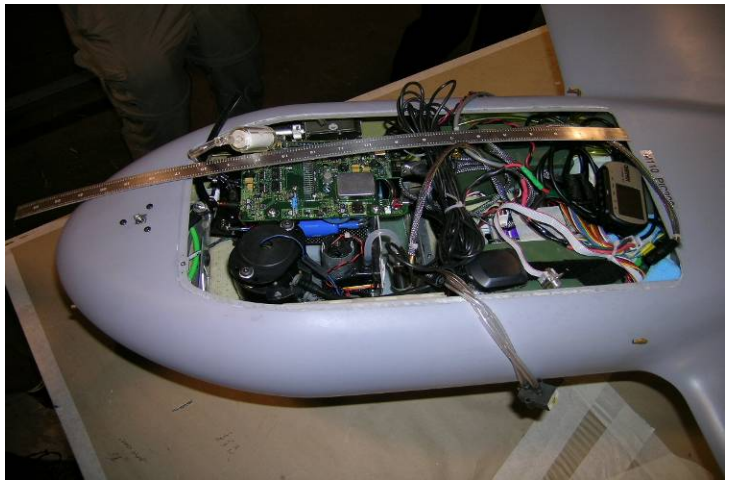
Hanimaadhoo Island

Maldives Climate Observatory - Hanimaadhoo (MCOH)

Project Atmospheric Brown Cloud

MAC Lightweight Instrumentation

Instruments	Above Cloud	In-Cloud	Below Cloud
Aerosol			
Total particle concentration	√		√
Size distribution	√		√
Black carbon and absorption	√		√
Radiation			
Up/Down Pyranometer	√		√
UP/Down PAR	√		√
Clouds			
Cloud droplet probe		√	
Liquid water content probe		√	
Meteorology			
Temperature		√	
Relative Humidity			
Pressure	√	√	√
Aerosol inlet system	√		√
Data Acquisition system	√	√	√
Video Camera + Downlink		√	
Miscellaneous + Batteries	√	√	√
Total weight	**5.4 kg**	**5.3 kg**	**3.9 kg**



MAC Stacked UAV Flight Configuration

3 km asl

In cloud

100 m below cloud

Surface observations

Validation with Ground Observations

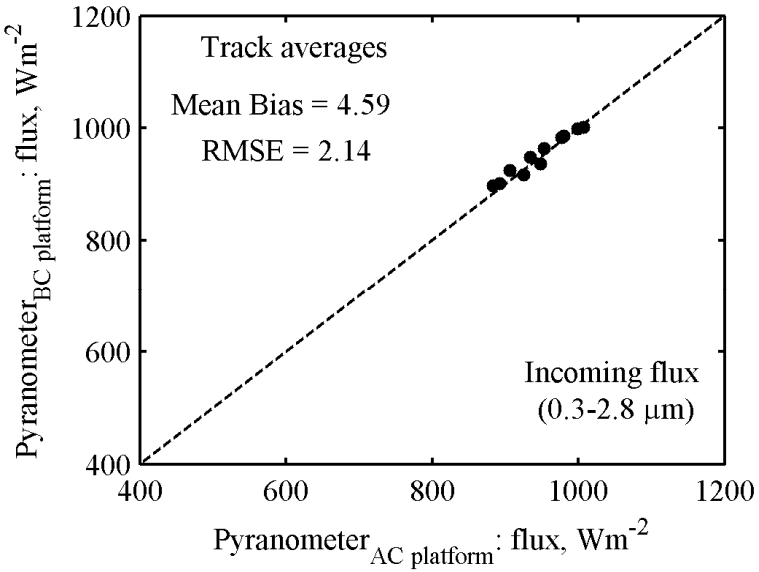
UAV-Pyranometer

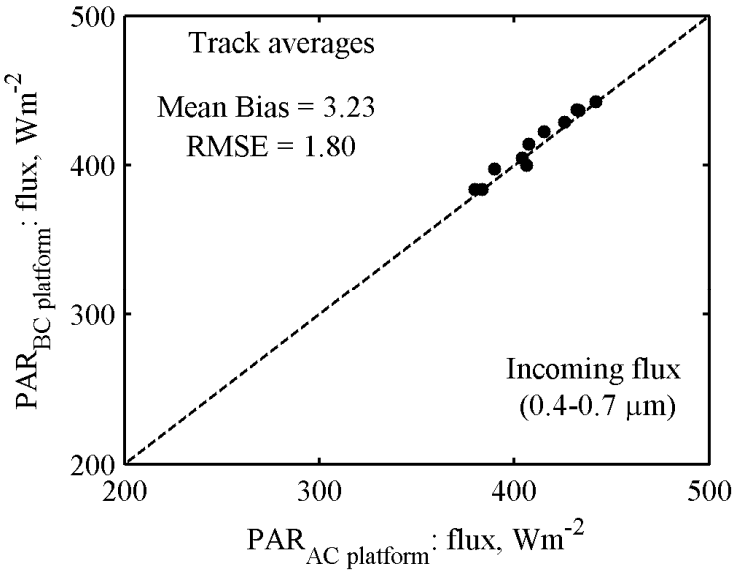
UAV - PAR

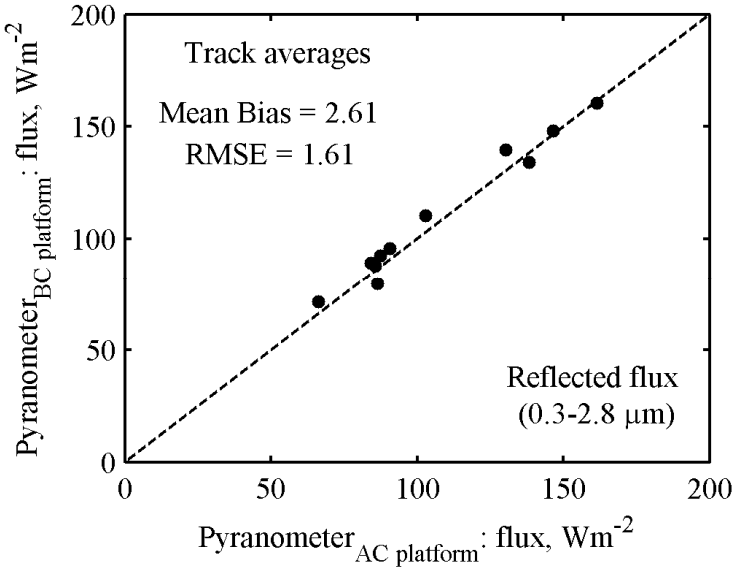
MCOH - PAR

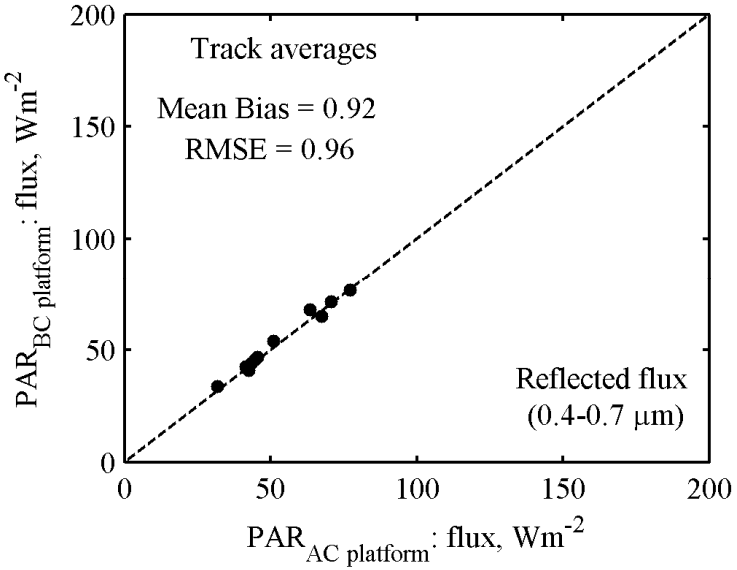
MCOH-Pyranometer

Wing tip to Wing tip comparison



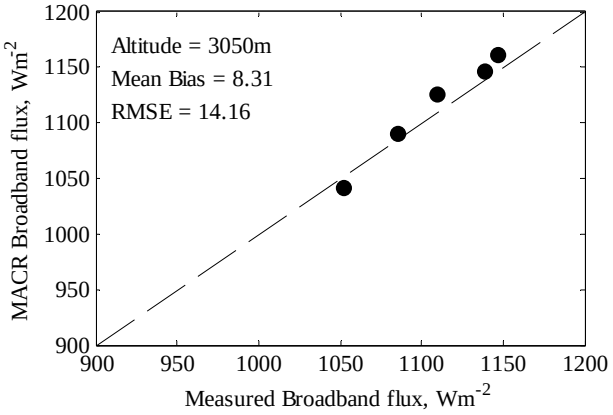


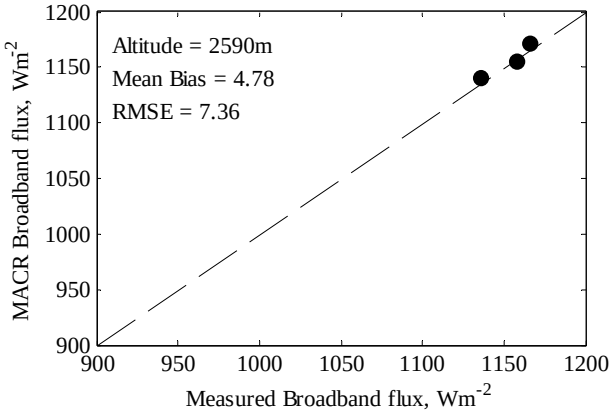


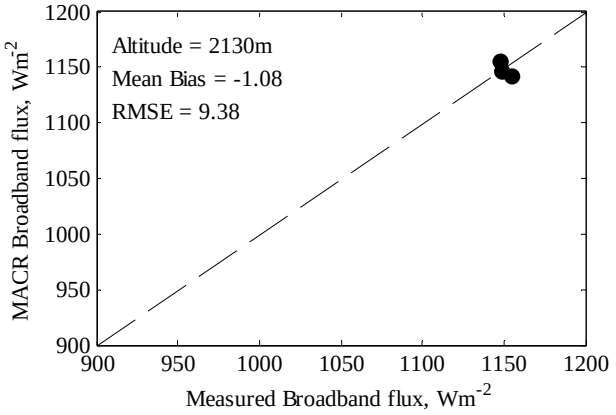


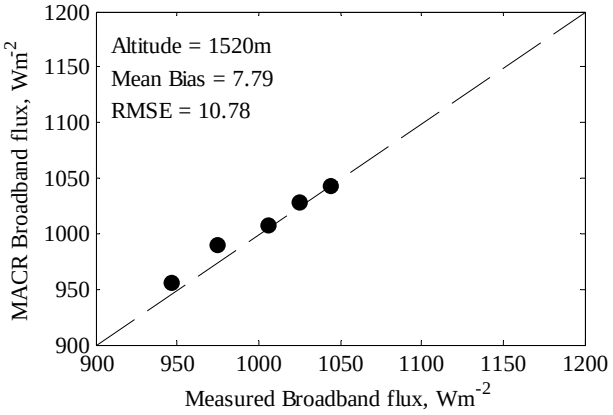
Ramana et al., 2007

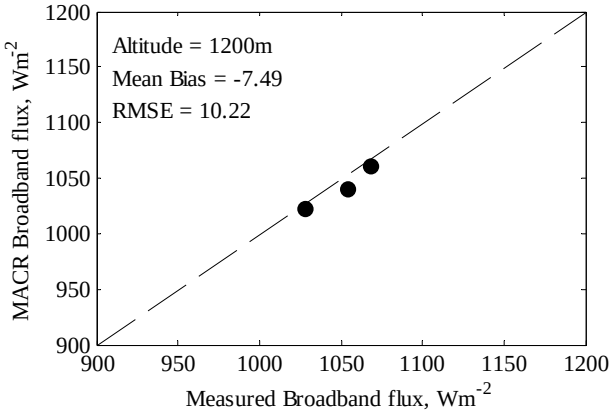
Incoming broadband flux comparison: MAC vs MACR (cloud-free day)

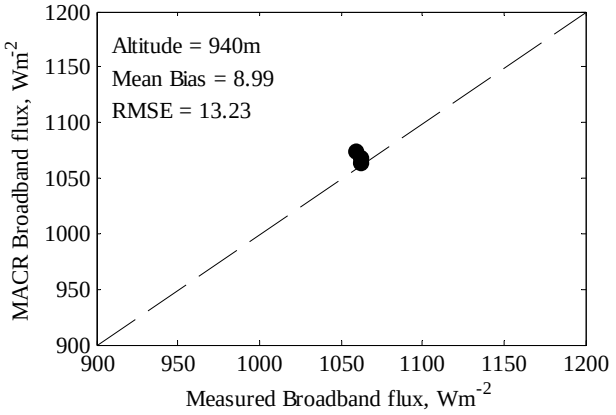






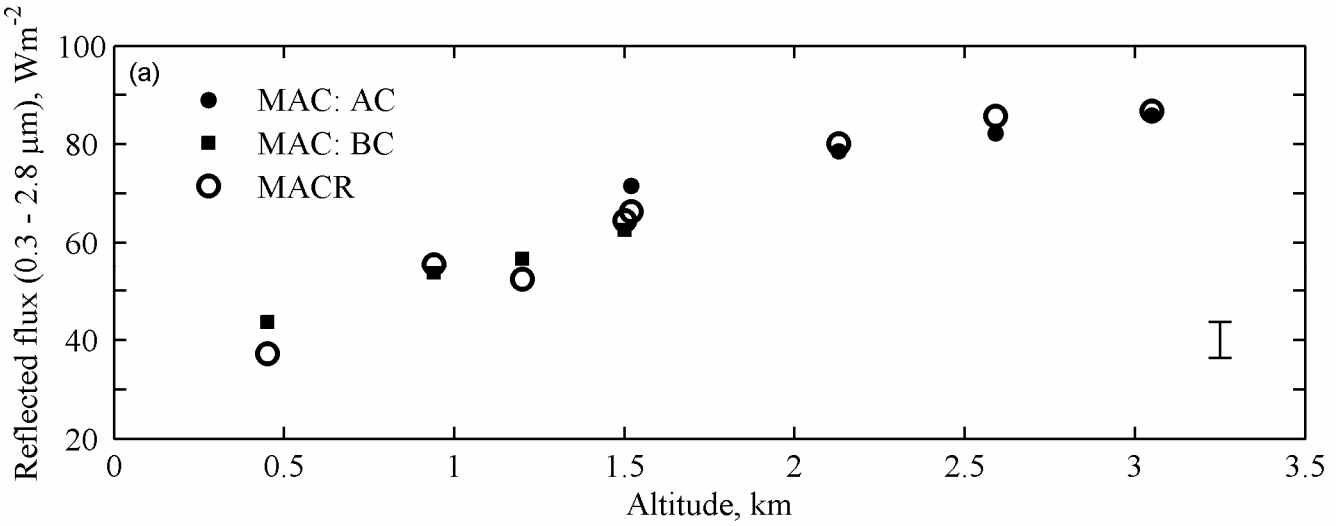




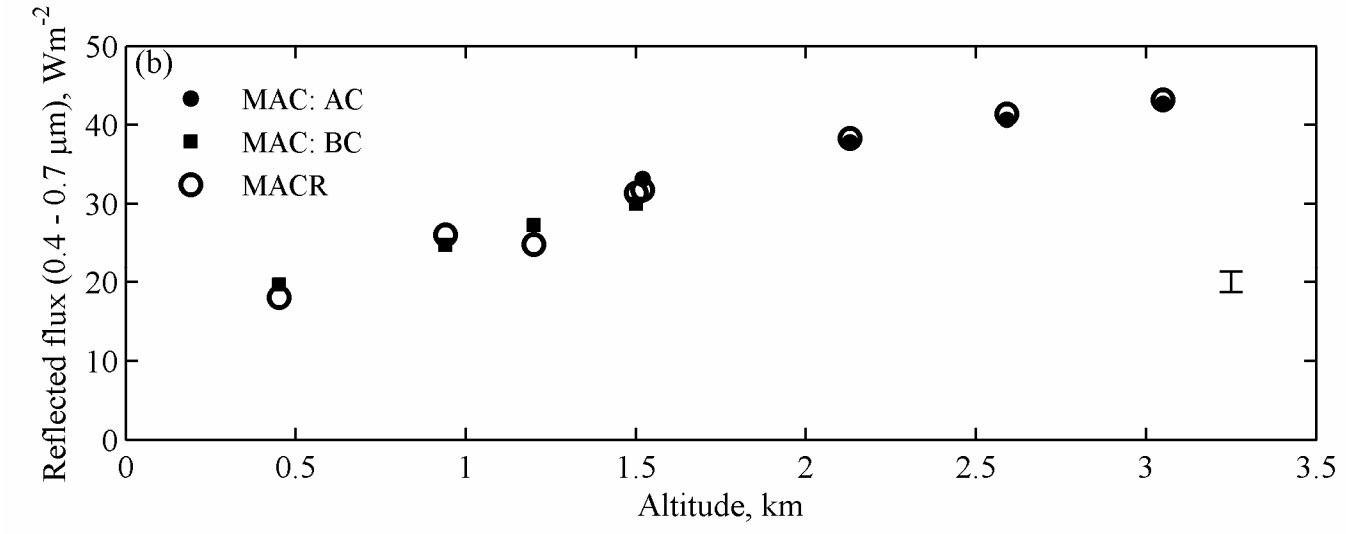


Ramana et al., 2007

Reflected flux comparison: MAC vs MACR (cloud-free day)



Broadband

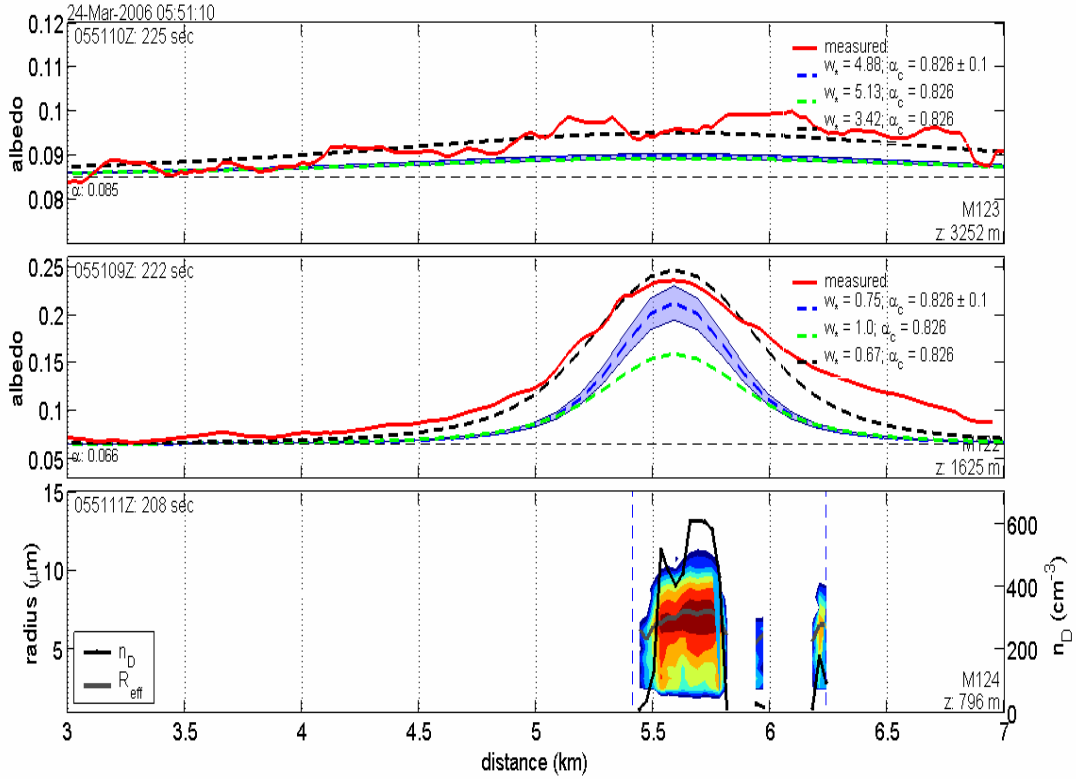


Visible

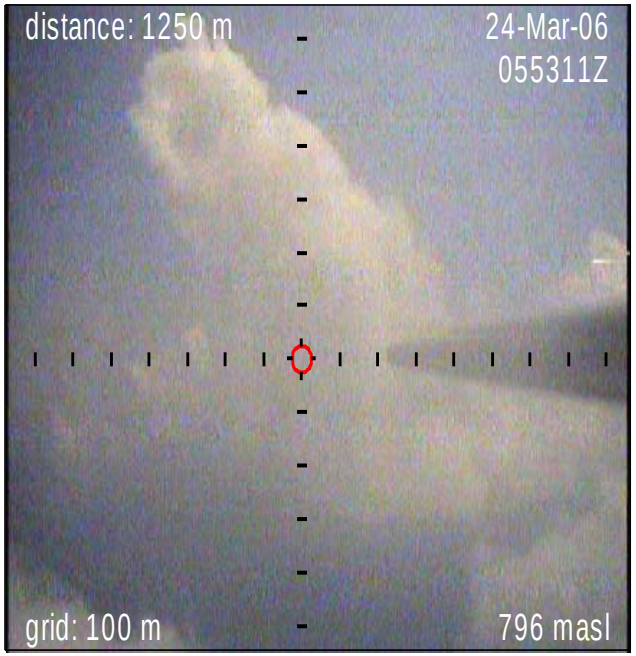
Ramana et al., 2007

Simultaneous observations of clouds and radiometric fluxes

a.

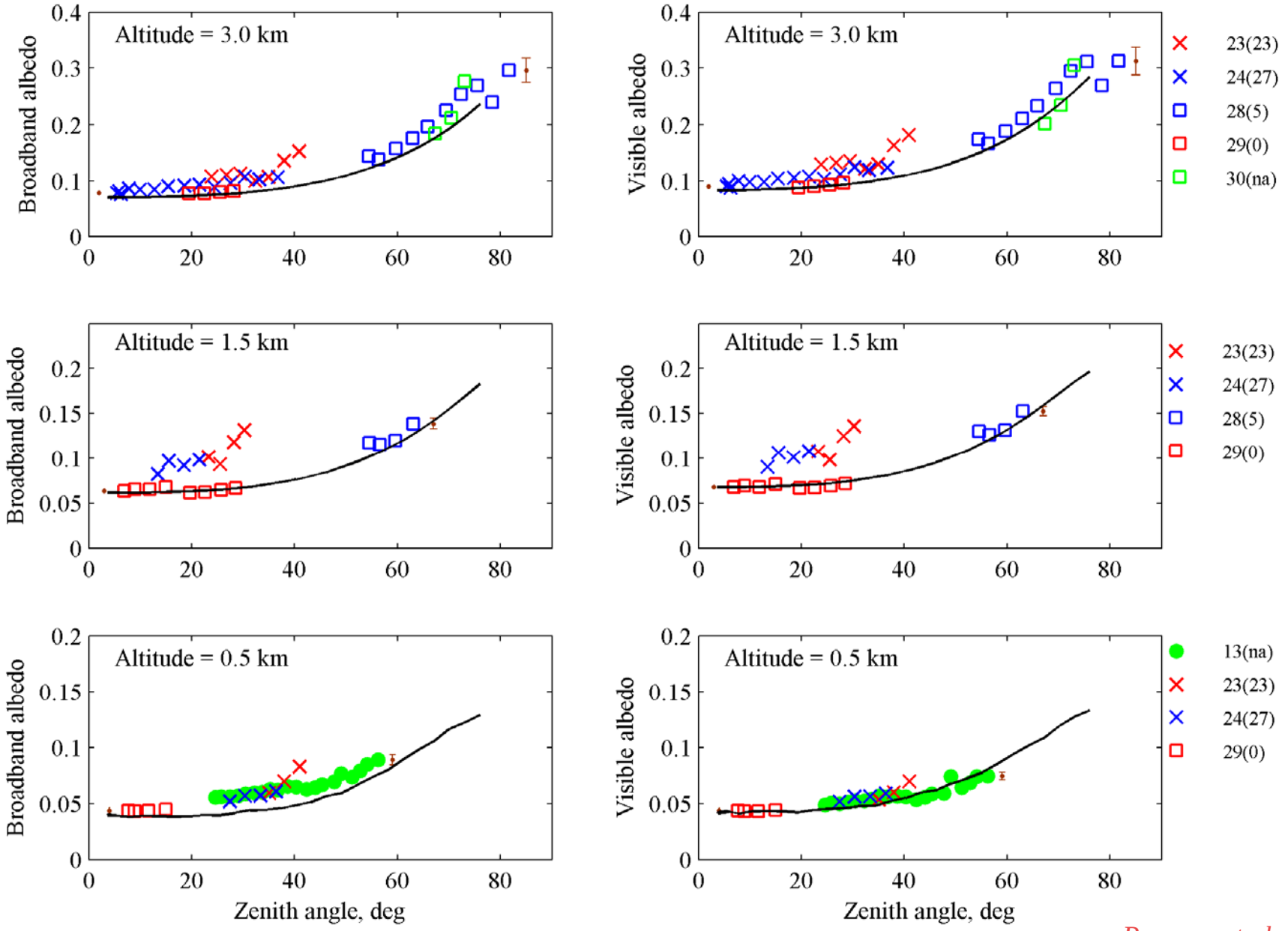


b.



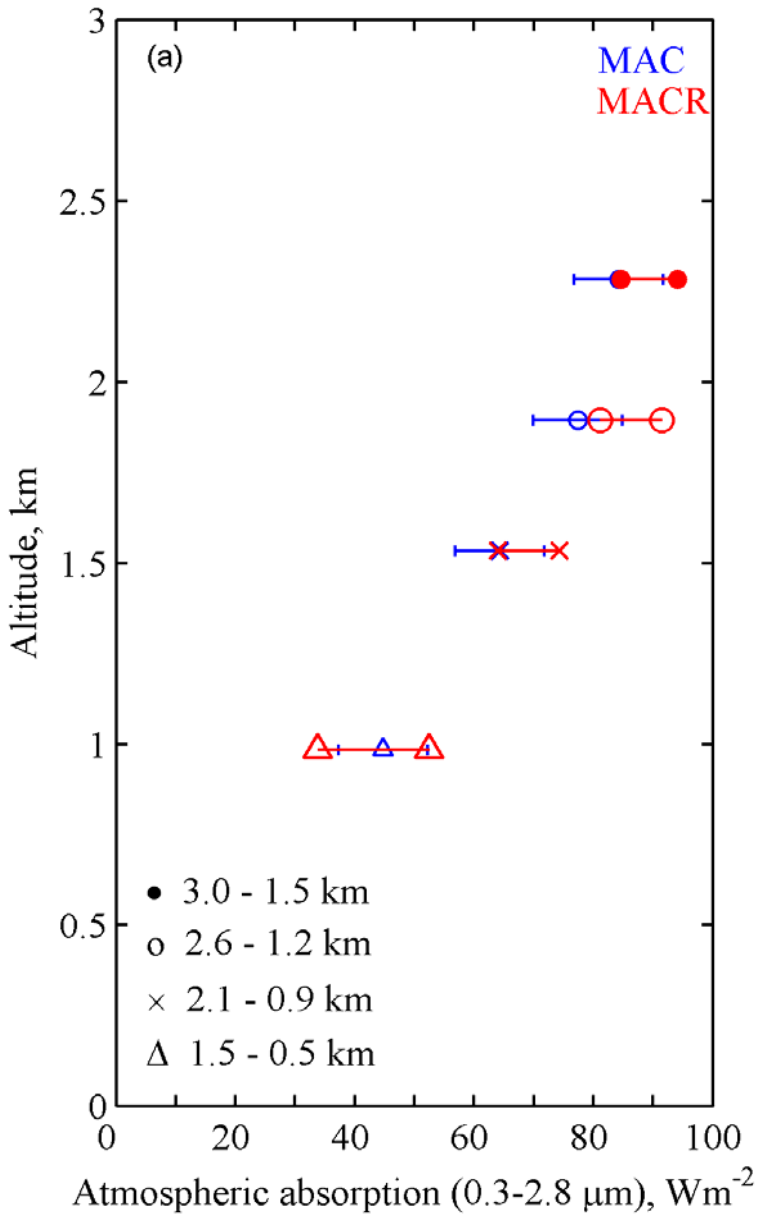
Roberts et al., 2007

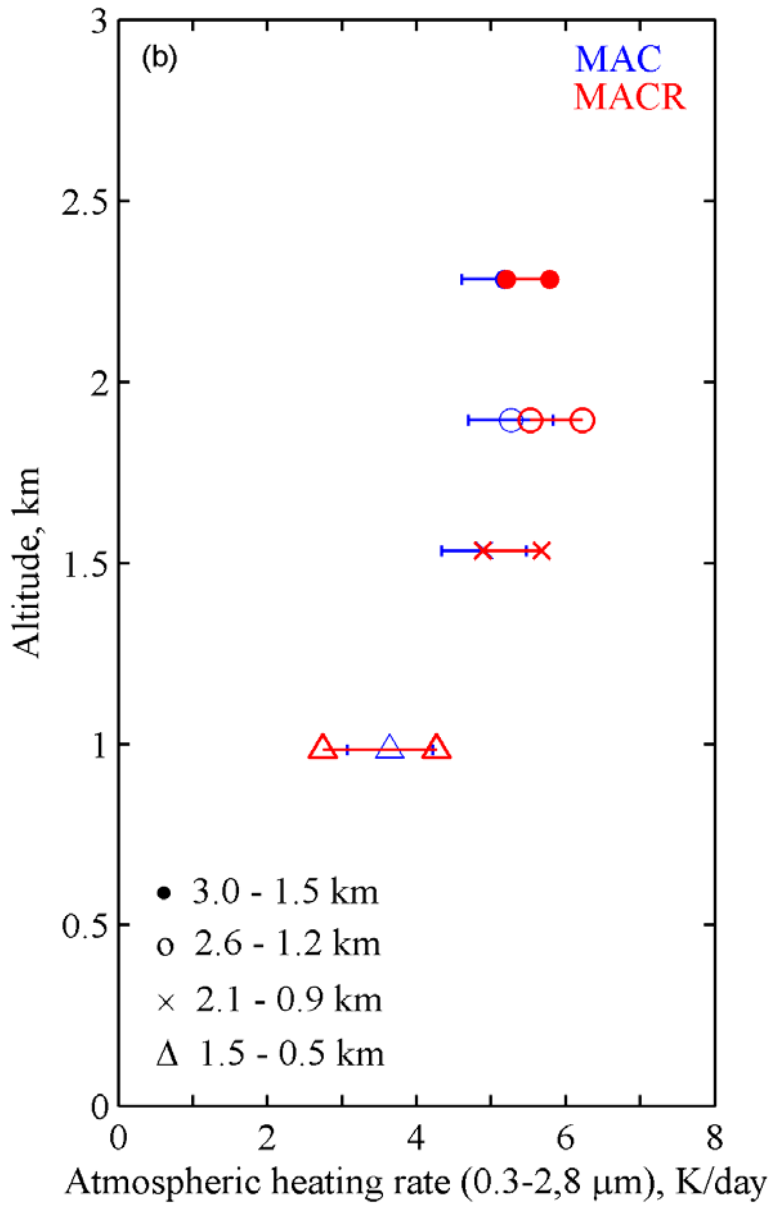
Albedo: Broadband & Visible (near cloud-free days)



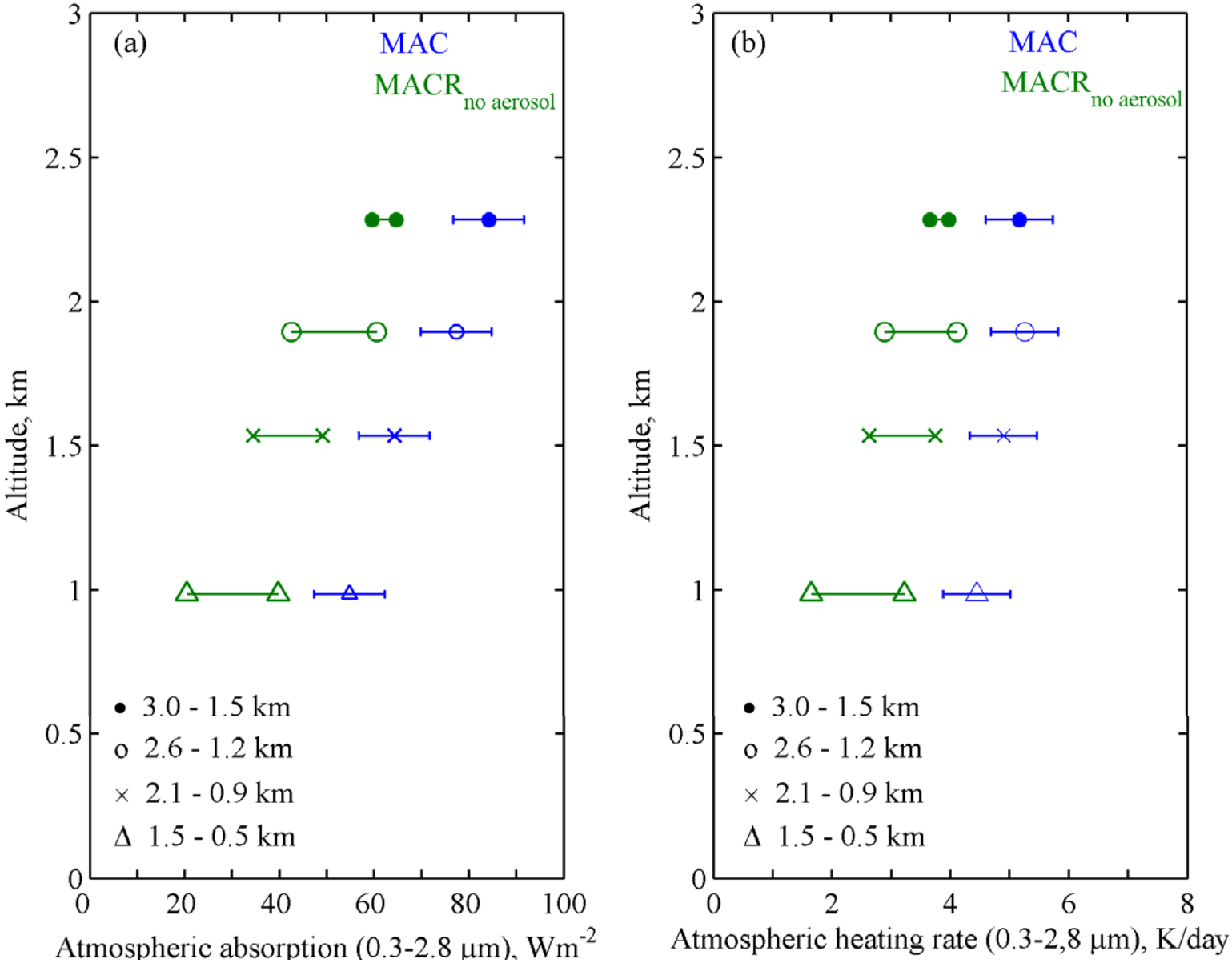
Ramana et al., 2007

Atmospheric Absorption and Heating rate : cloud-free day





Ramana et al., 2007

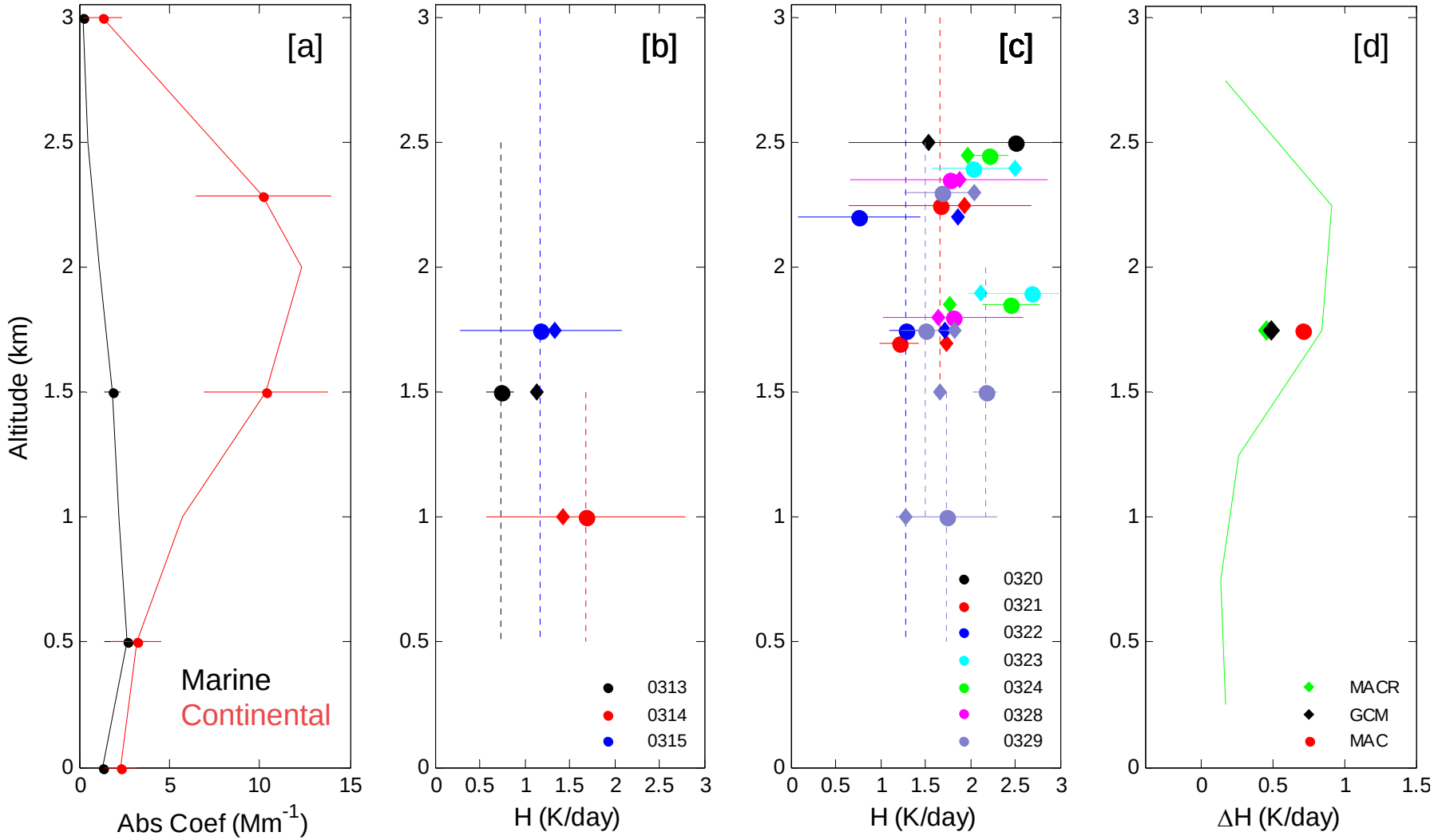

(a)
MAC
MACR no aerosol
Altitude, km
Atmospheric absorption (0.3-2.8 μm), Wm-2
• 3.0 - 1.5 km
o 2.6 - 1.2 km
× 2.1 - 0.9 km
Δ 1.5 - 0.5 km
(b)
MAC
MACR no aerosol
Altitude, km
Atmospheric heating rate (0.3-2,8 μm), K/day
• 3.0 - 1.5 km
o 2.6 - 1.2 km
× 2.1 - 0.9 km
Δ 1.5 - 0.5 km

Diurnal mean Atmospheric Absorption and Heating rates between 0.5-3.0 km *(cloud-free day)*

Spectral range	Absorption, Wm^{-2} 0.5 – 3.0 km			Heating rate, $K.Day^{-1}$ 0.5 – 3.0 km		
	MAC	MACR	MACR {without aerosols}	MAC	MACR	MACR {without aerosols}
Broadband (0.3-2.8µm)	41.2±7.5	45.4 ± 2	34.1	1.53±0.26	1.59±0.05	1.19
Visible (0.4-0.7 µm)	8.3 ± 4.7	7.2 ± 1	1.2	0.29±0.17	0.25±0.02	0.04

Ramana et al., 2007

Atmospheric Heating rate : during the MAC experiment



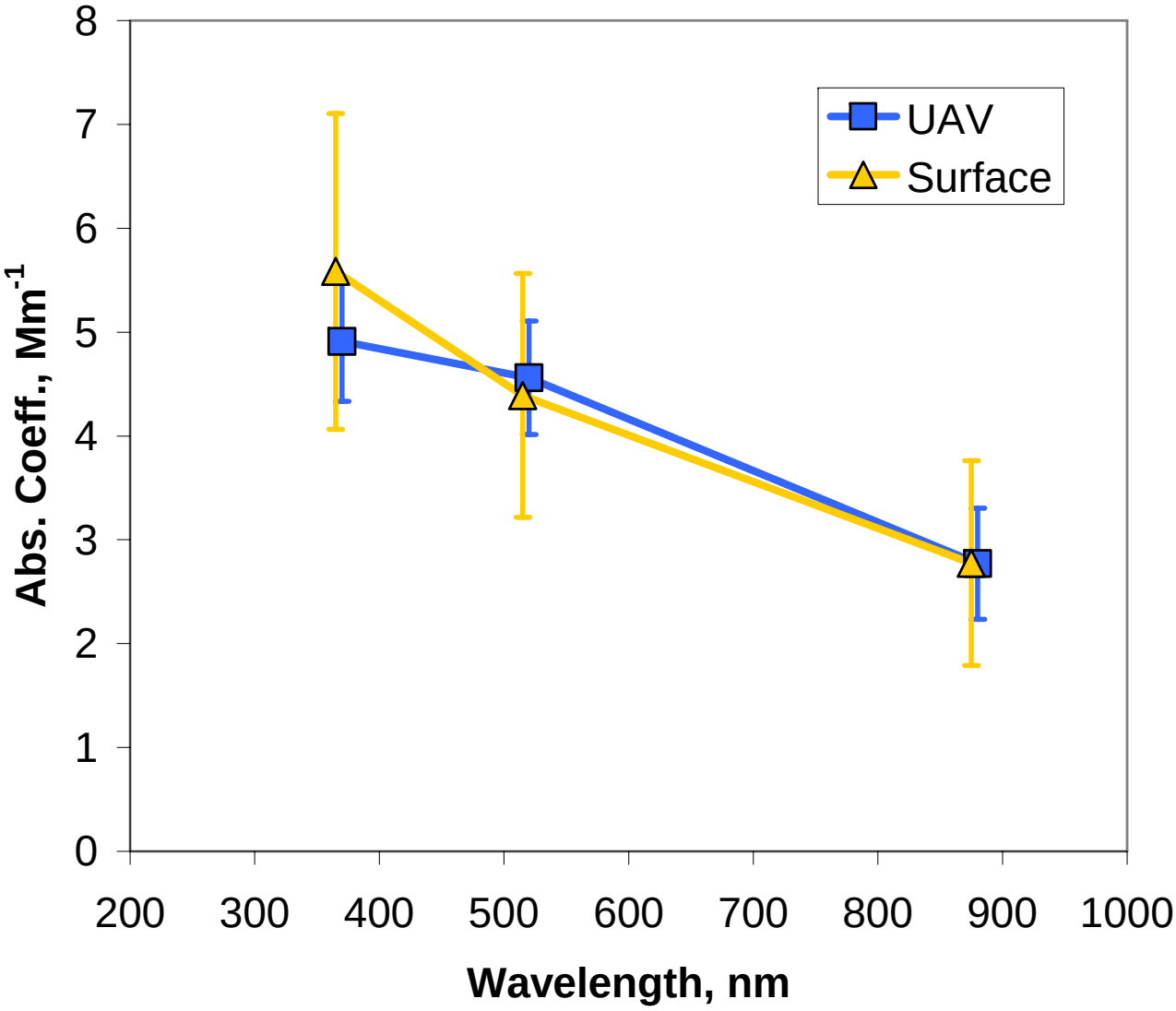
Ramanathan et al., 2007

MAC Results – Vertical Profiling

Methods for data quality assurance

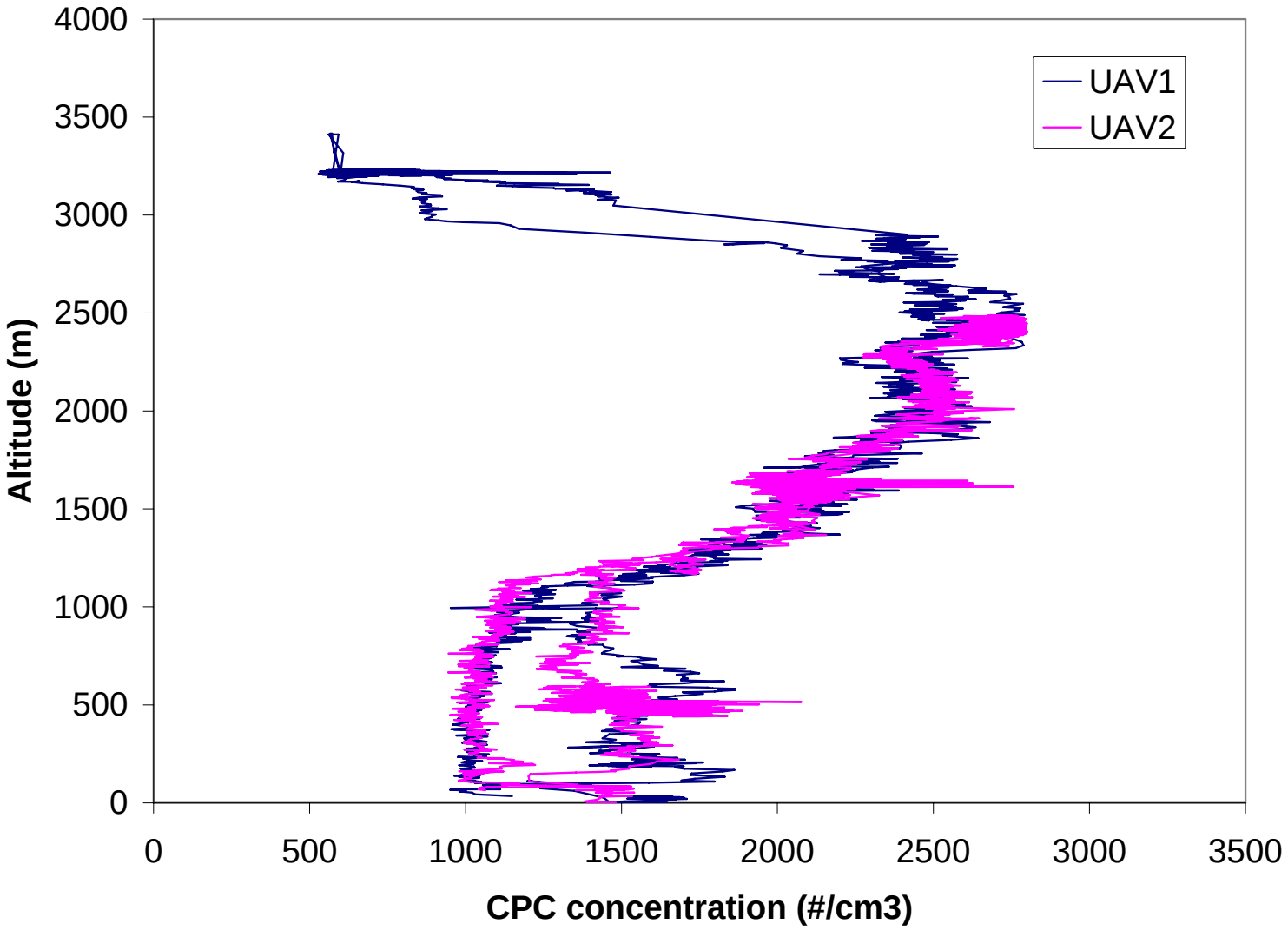
- Laboratory calibrations
- On-site calibration/comparison with established instruments (MCOH)
- Pre-flight readings
- Inter-plane comparison
- Fly-by of ground station

Surface and UAV Absorption Comparison (Aethalometer).



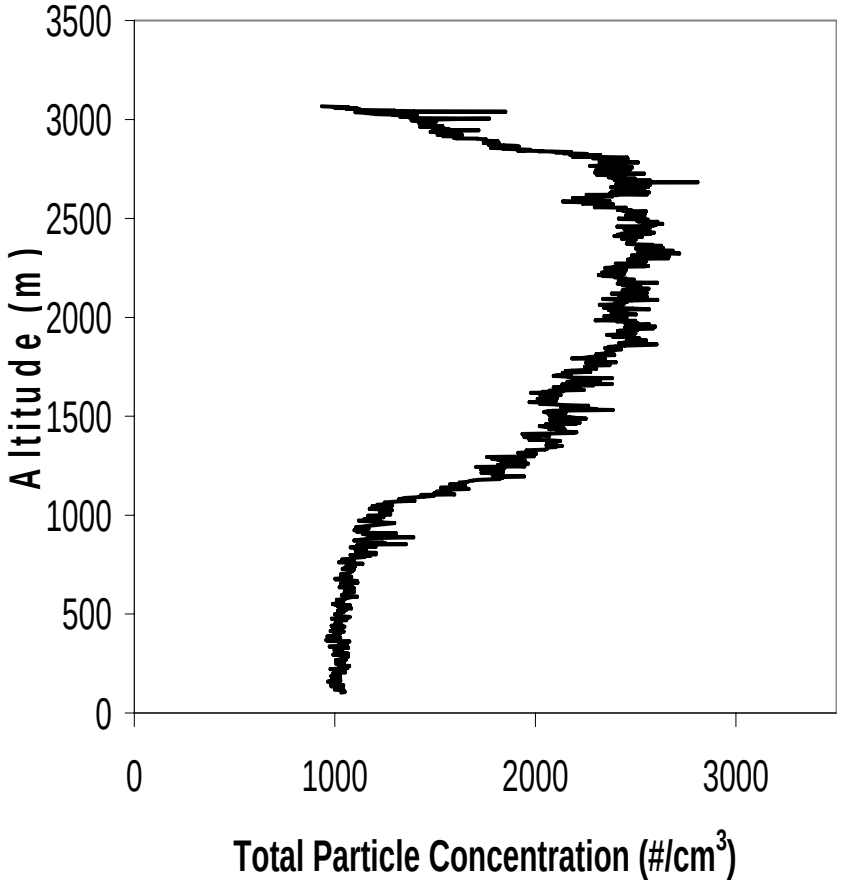
Corrigan et al., 2007

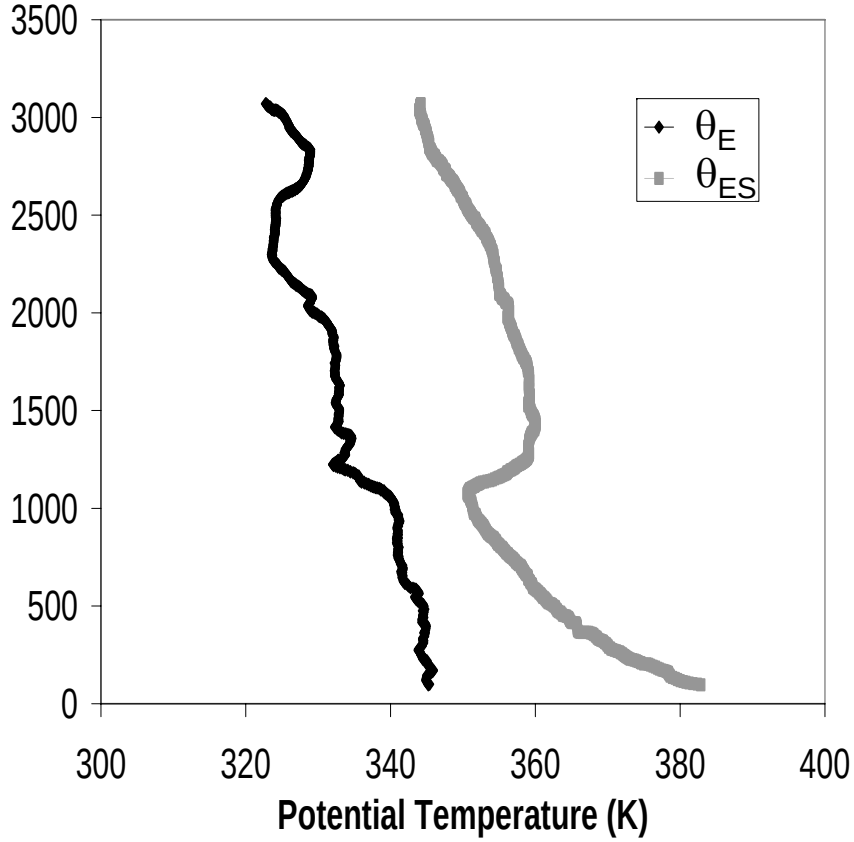
Cross-platform Comparison of Total Particle Counter



Corrigan et al., 2007

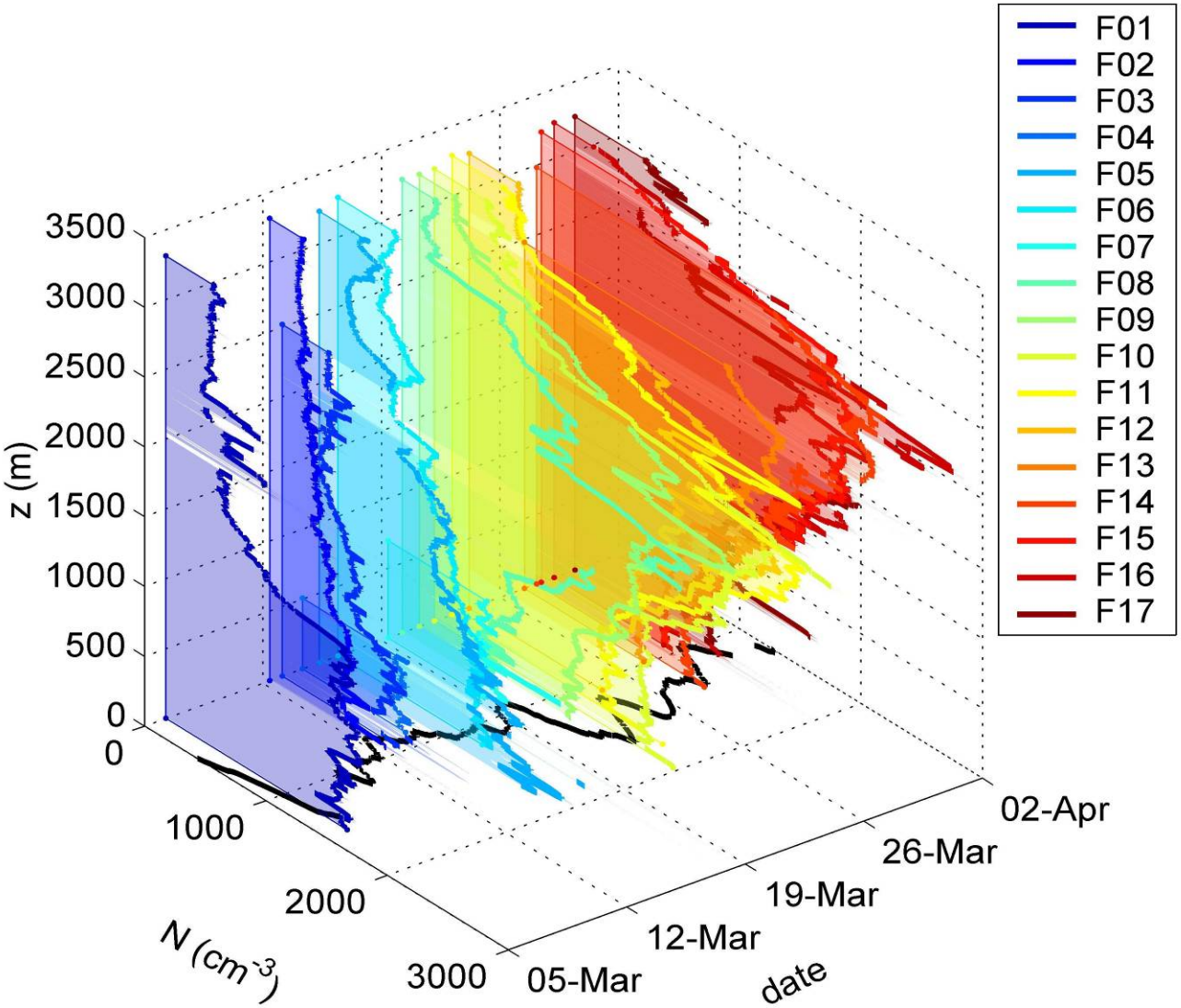
Atmospheric Layers





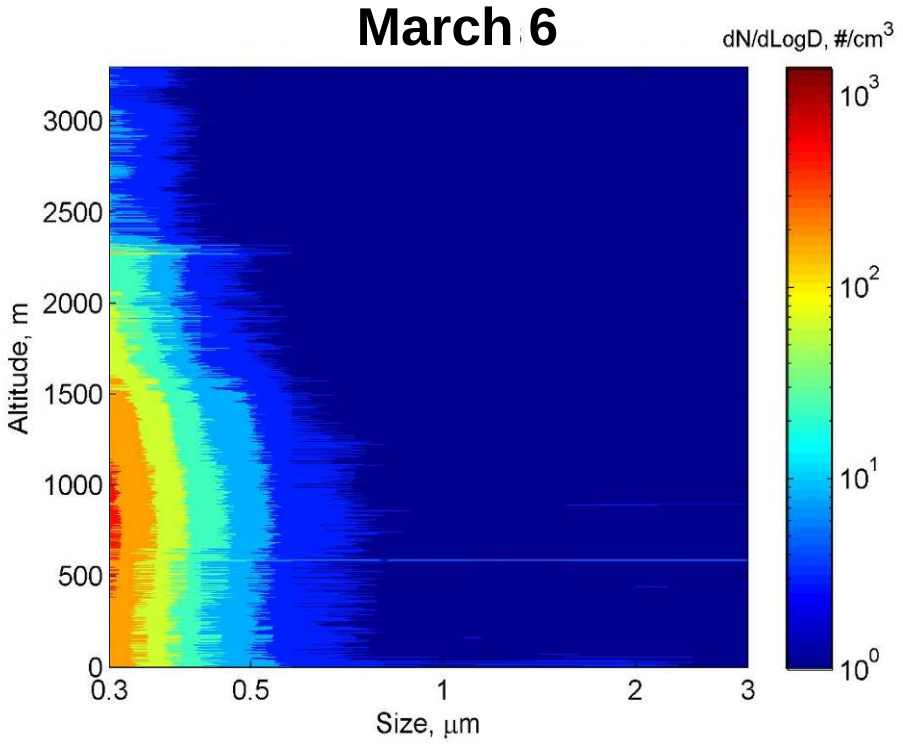
Corrigan et al., 2007

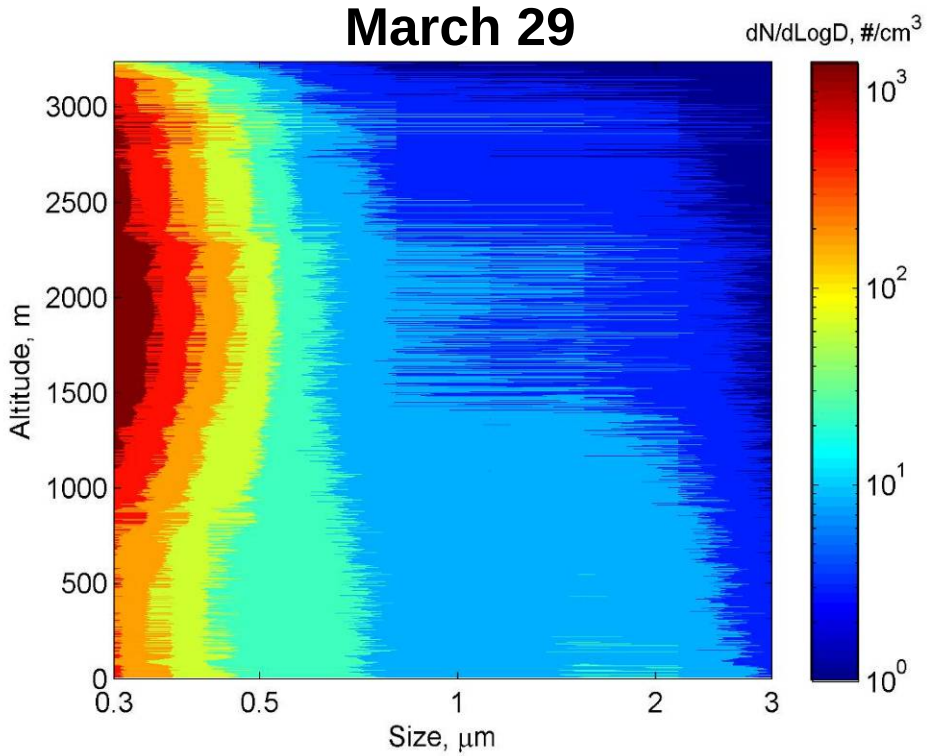
Total Particle Concentration during MAC



Corrigan et al., 2007

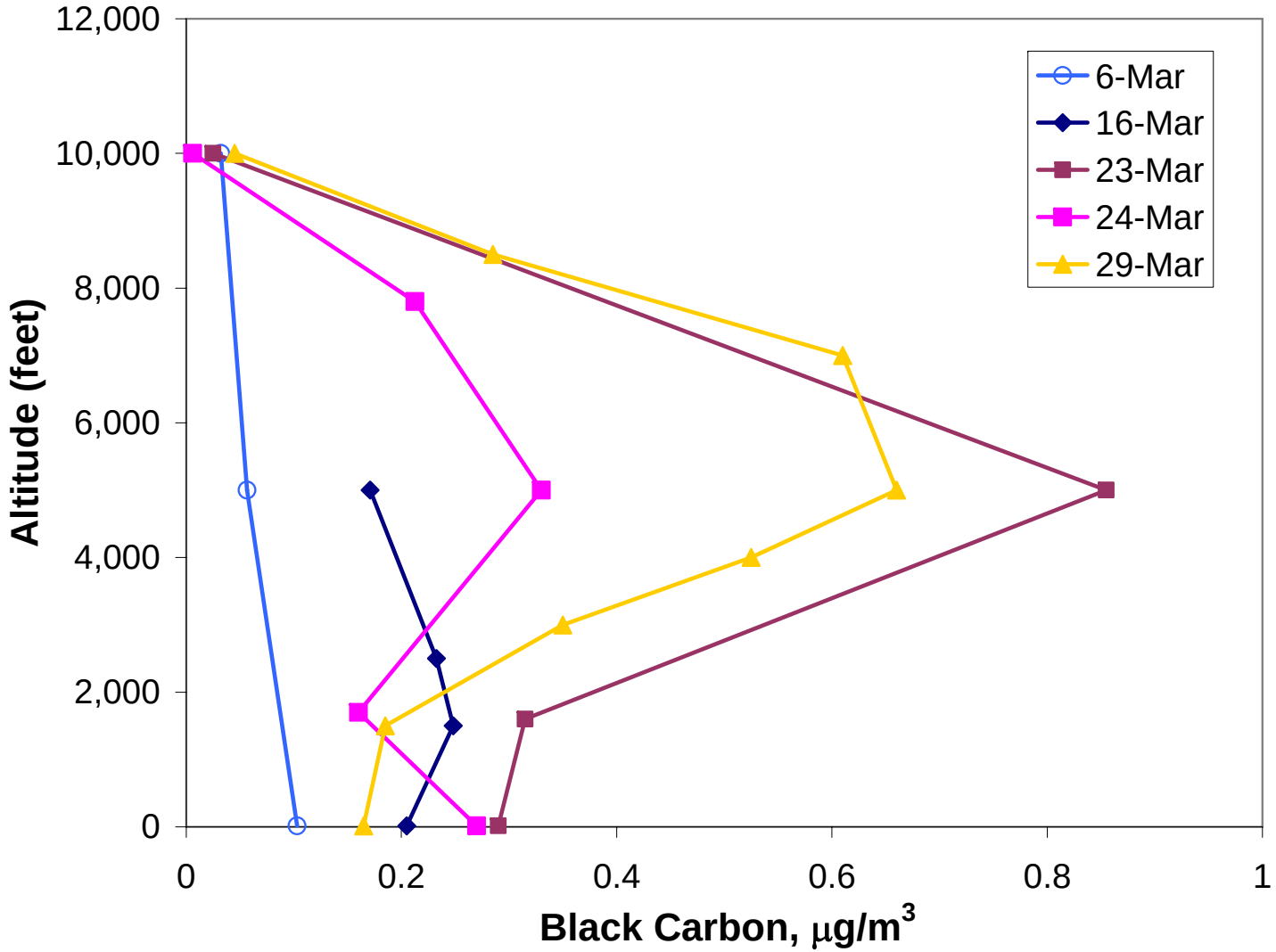
Aerosol Size Distribution from Clean and Polluted Periods





Corrigan et al., 2007

Black Carbon Vertical Profiles during MAC



Corrigan et al., 2007

Upcoming Projects

Future Missions Planned by our Team

Airborne observatories for profiling aerosol-chemistry-air pollution

•CAPPS (funded by CEC) (2007-)

Multi-UAV missions for aerosol-cloud-radiation

•Marine stratocumulus clouds (June ‘08?)

- Possible experiment with DOE

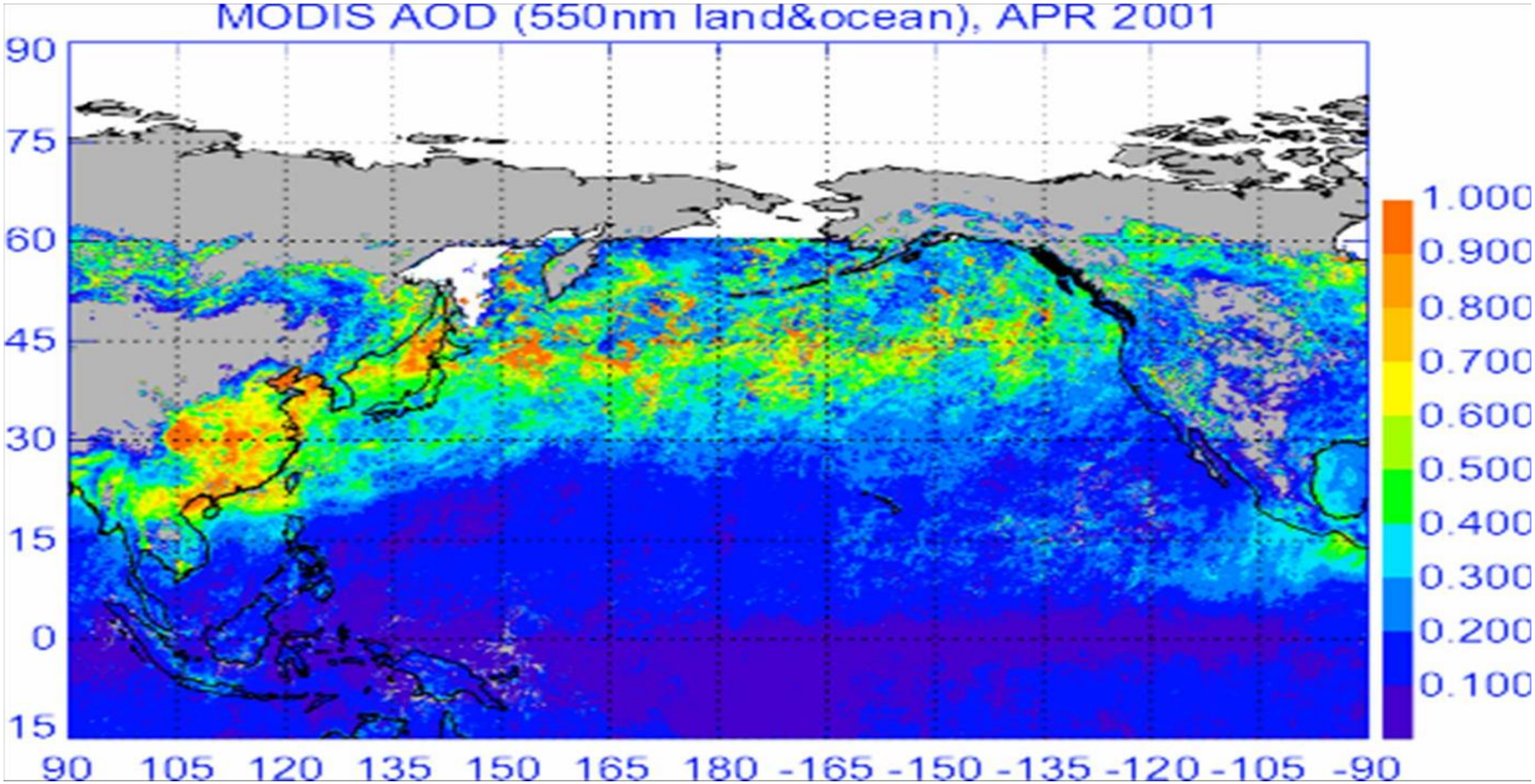
CAPPS

(California AUAV Air Pollution Profiling Study)

Funded by Calif. Energy Commission.

- Collect an annual record of aerosol, black carbon, ozone, NO_x and CO pollution concentrations from surface up to 12,000 feet asl.
- California generated pollution vs. long-range pollution from other regions.
- Look at the impact of pollution layers on radiative forcing to quantify the amount of solar dimming.

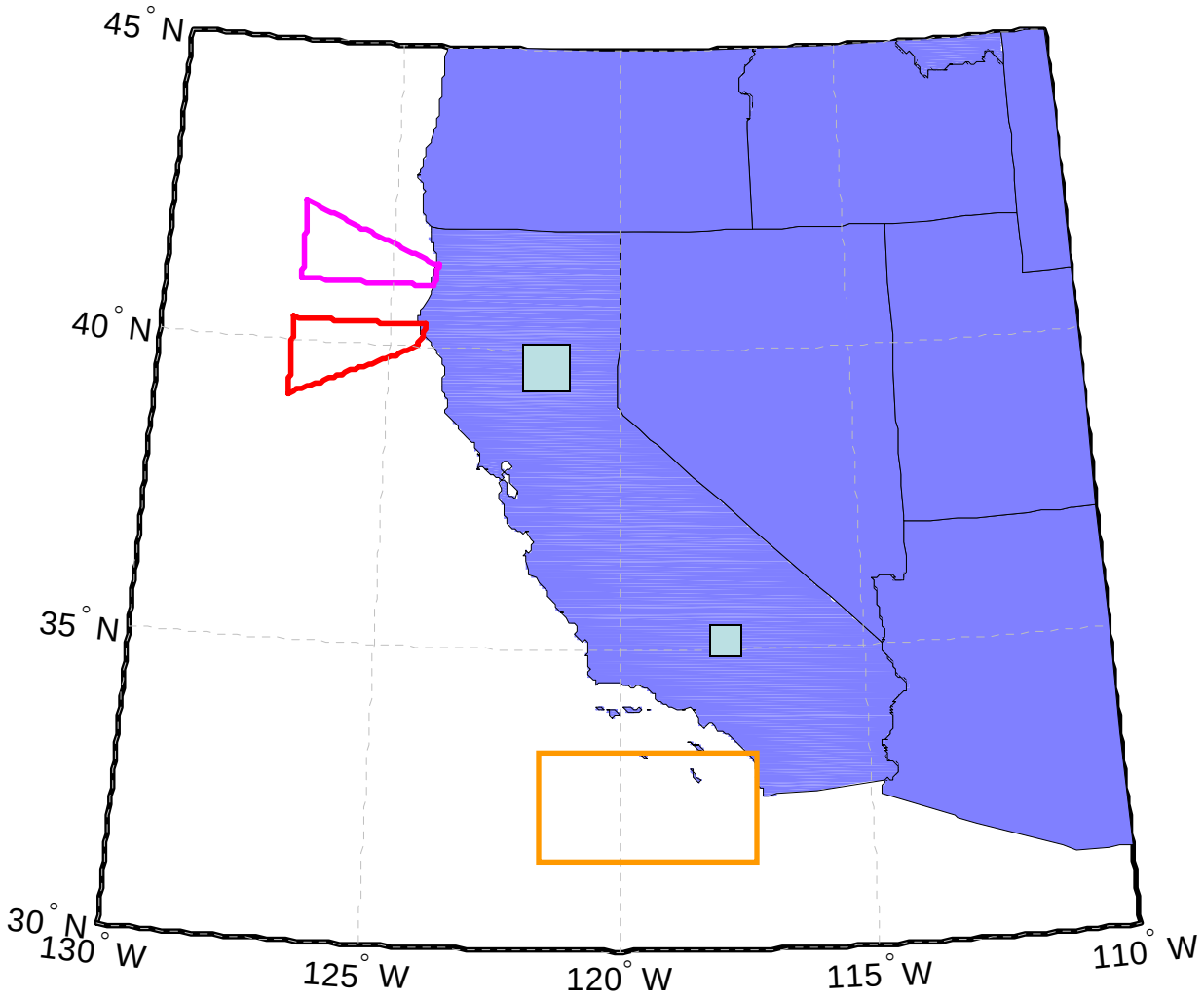
Asian particulate pollution transported to North America



Measurements for CAPPS

- Aerosol Number Concentration
- Aerosol Size Distribution (0.3 – 3 μm)
- Aerosol Absorption/Black Carbon Concentration
- Ozone
- CO
- NO_x/NO/NO_2
- Temperature, Pressure, Relative Humidity

Possible Flight Locations for CAPPS



Marine Stratocumulus Cloud (possible experiment with DOE ?)

Was discussed at ARM La Jolla Workshop by Wiscombe, Marshak, Barker, and Ramanathan.

A definitive experiment to investigate absorption in cloudy skies. Can we understand using known physics and chemistry?

- Atmospheric Absorption
- Albedo enhancement

- May-June, 2008/2009

Off the coast of San Diego

Cloud Absorption Experiment:

3 km asl

above cloud

In cloud

below cloud

Vertical Profiling

Planned Instrumentation

MAC instruments and the following:

- Spectro-radiometers
- Stabilizing platforms for radiometers
- LWC probe
- Improved absorption photometer
- Gas chemistry – CO, Ozone, NO_x
- CCN
- Gust Probe