# Global Dimming & Anomalous Solar Absorption: New Studies with Unmanned Aircraft Systems

*V Ramanathan*
*Scripps Institution of Oceanography*

# Acknowledgements

1. My colleagues at Scripps: C Chung, C. Corrigan, Y.Feng, O Hadley, H. Nguyen, M V Ramana, G. Roberts, A Zhu

2. Colleagues: J Kuettner, W Collins, A Vogelmann

3. ABC-Asia science Team

4. Numerous coauthors

5. Funded by : NSF; Thanks to Jay Fein
NOAA; UNEP

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Clouds,
Chemistry and
Climate

*A NSF Science and Technology Center at the Scripps Institution of Oceanography, UCSD*

*An interdisciplinary, multi-institutional and multi-national collaborative effort on problems dealing with the environment*

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**Forschungszentrum Jülich (Govt)**
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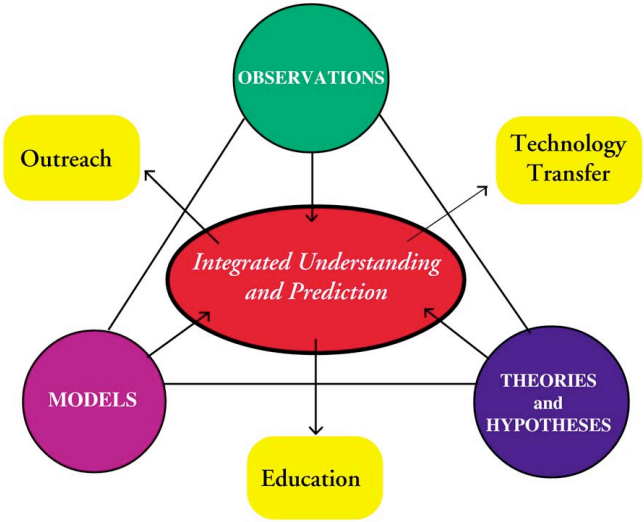


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*http://www-c4.ucsd.edu*

NATURE · VOL 351 · 2 MAY 1991



# Thermodynamic regulation of ocean warming by cirrus clouds deduced from observations of the 1987 El Niño

**V. Ramanathan & W. Collins**

Scripps Institution of Oceanography and California Space Institute, University of California at San Diego, La Jolla, California 92093, USA

studies[15,38]. For the hypothesis to become a validated theory, we need to establish the link between convection dynamics, large-scale moisture convergence into the warm regions and the brightness of those regions. Three-dimensional climate models in conjunction with detailed field and satellite observations can provide that link, but first the models must pass the test posed by the El Niño observations. □

Participating Institutions

***Lead Agency: NSF***

Aeromet, Inc., Tulsa
Center for Clouds, Chemistry and Climate
Colorado State University, Fort Collins
Forschungszentrum, Jülich
Harvard University, Boston
Max-Planck Institute for Chemistry, Mains
Max-Planck Institute for Meteorology, Hamburg
NASA-Ames Research Center, Moffet Field
National Center for Atmospheric Research, Boulder
NOAA-Environmental Research Laboratory, Boulder
University of Colorado, Boulder
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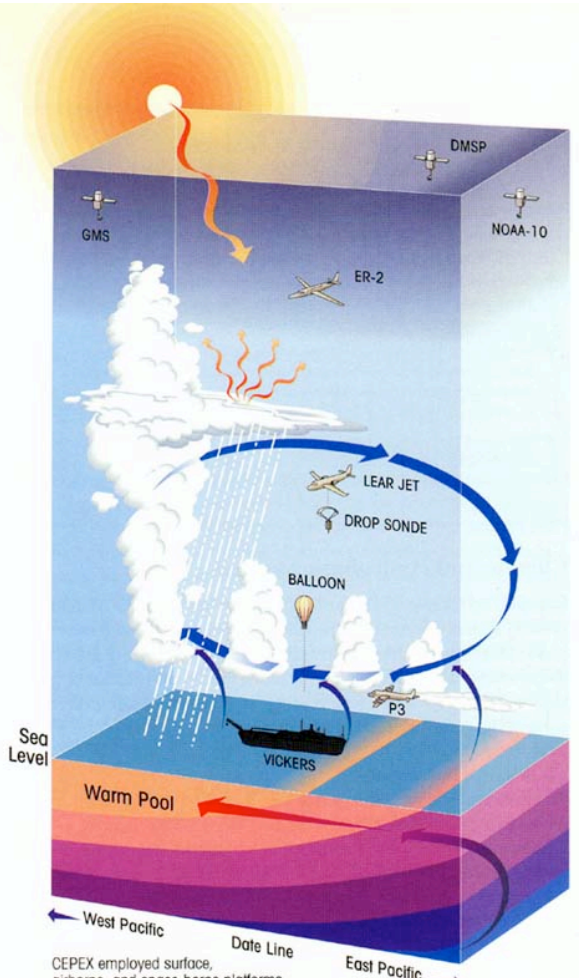
Los Alamos National Laboratory
Los Alamos, Institute of Geophysics and Planetary Phys
Oregon State University, Corvallis
Princeton University, Geophysical Fluid Dynamics Labc
State University of New York, Stoney Brook
University of California, Los Angeles
University of Chicago

"Under the Influence of clouds Yvonne Baskin *Discover*, September 1995, **16**(9), 62-69.

Ø "Looking at Clouds from both sides"San Union Tribune, California, December 9, 1992, Section, C1 and C6.

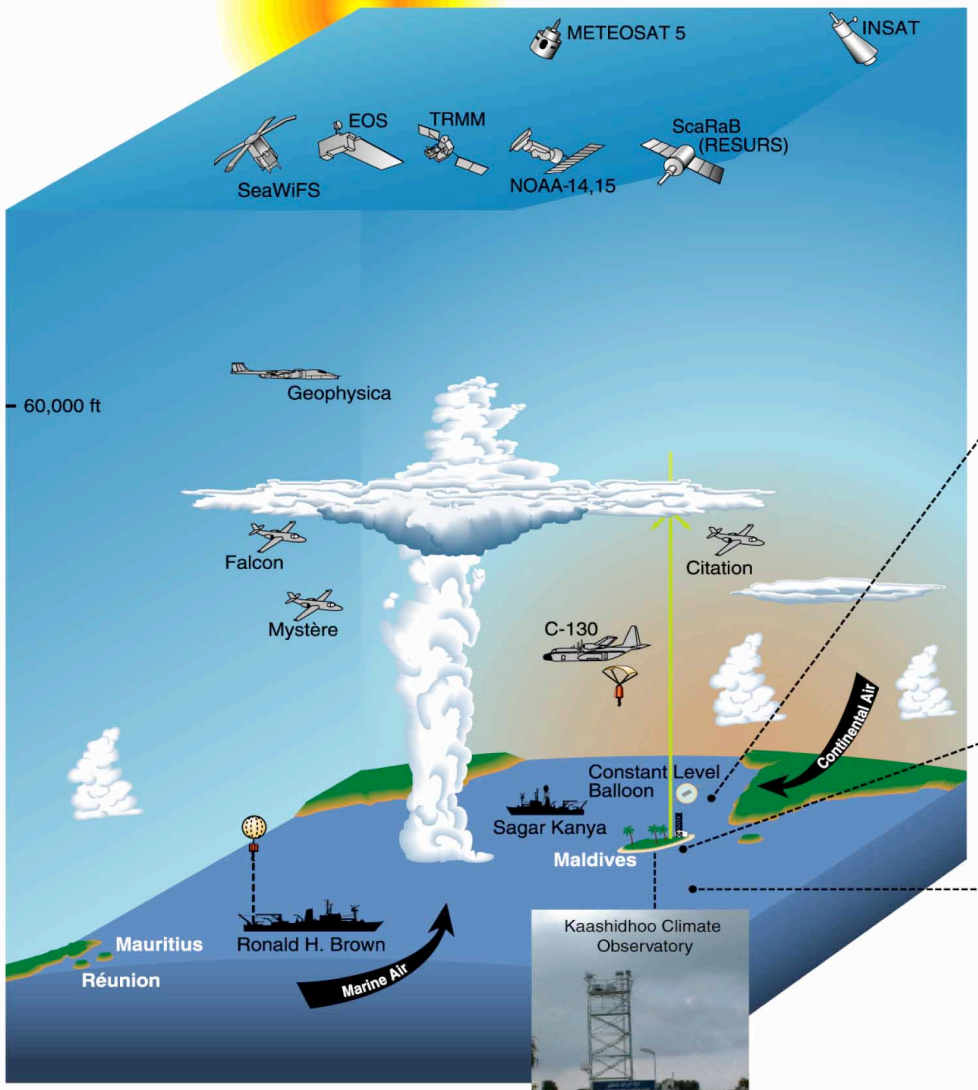


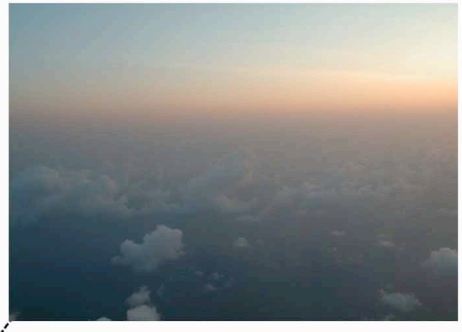

CEPEX employed surface, airborne, and space-borne platforms. The airborne platforms were NASA's ER-2, Aeromet's Learjet, the NOAA P–3, and the NCAR Electra. The surface platforms include the R/V Vickers, TOGA moorings (buoys), and upper-air stations on islands. Space-borne platforms are Sun-synchronous polar orbiters (NOAA–10 and DMSP) and geosynchronous monitoring satellites (GMS). Instruments on these platforms measure radiation fluxes, cirrus radiative and microphysical properties, vertical water-vapor distribution, evaporation from the sea surface, and precipitation.

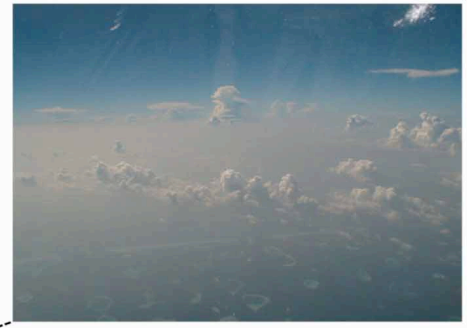
# ***Central Equatorial Pacific Experiment (CEPEX)***

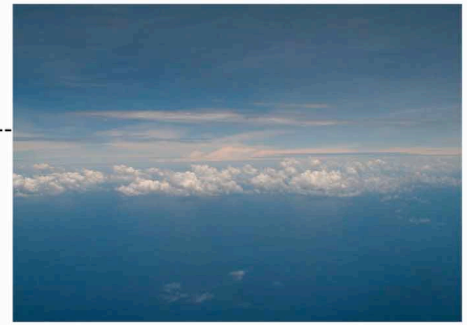
# Indian Ocean Experiment

## Why Brown Cloud?







Ramanathan et al, JGR, 2001

# MAC: Maldives Autonomous-UAV Campaign

## *The MAC Observing System*

Atmos. Chem. Phys. Discuss., 7, 11429–11463, 2007
www.atmos-chem-phys-discuss.net/7/11429/2007/


Atmospheric Chemistry and Physics Discussions

# Capturing vertical profiles of aerosols and black carbon over the Indian Ocean using autonomous unmanned aerial vehicles

C. E. Corrigan, G. C. Roberts, M. V. Ramana, D. Kim, and V. Ramanathan

QUARTERLY JOURNAL OF THE ROYAL METEOROLOGICAL SOCIETY
*Q. J. R. Meteorol. Soc.* **133**: 1913–1931 (2007)
Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/qj.172

RMetS
ROYAL METEOROLOGICAL SOCIETY

# Albedo, atmospheric solar absorption and heating rate measurements with stacked UAVs

M. V. Ramana,* V. Ramanathan, D. Kim, G. C. Roberts and C. E. Corrigan
*Center for Atmospheric Sciences, Scripps Institution of Oceanography, University of California at San Diego, La Jolla, USA*

**MOUNTAIN CAMP – MT WHITNEY**
(FROM A SKETCH BY T.MORAN)

UNITED STATES OF AMERICA,
WAR DEPARTMENT.

PROFESSIONAL PAPERS OF THE SIGNAL SERVICE.
No. XV.

# RESEARCHES ON SOLAR HEAT

AND

# ITS ABSORPTION BY THE EARTH'S ATMOSPHERE.

A REPORT OF THE MOUNT WHITNEY EXPEDITION.

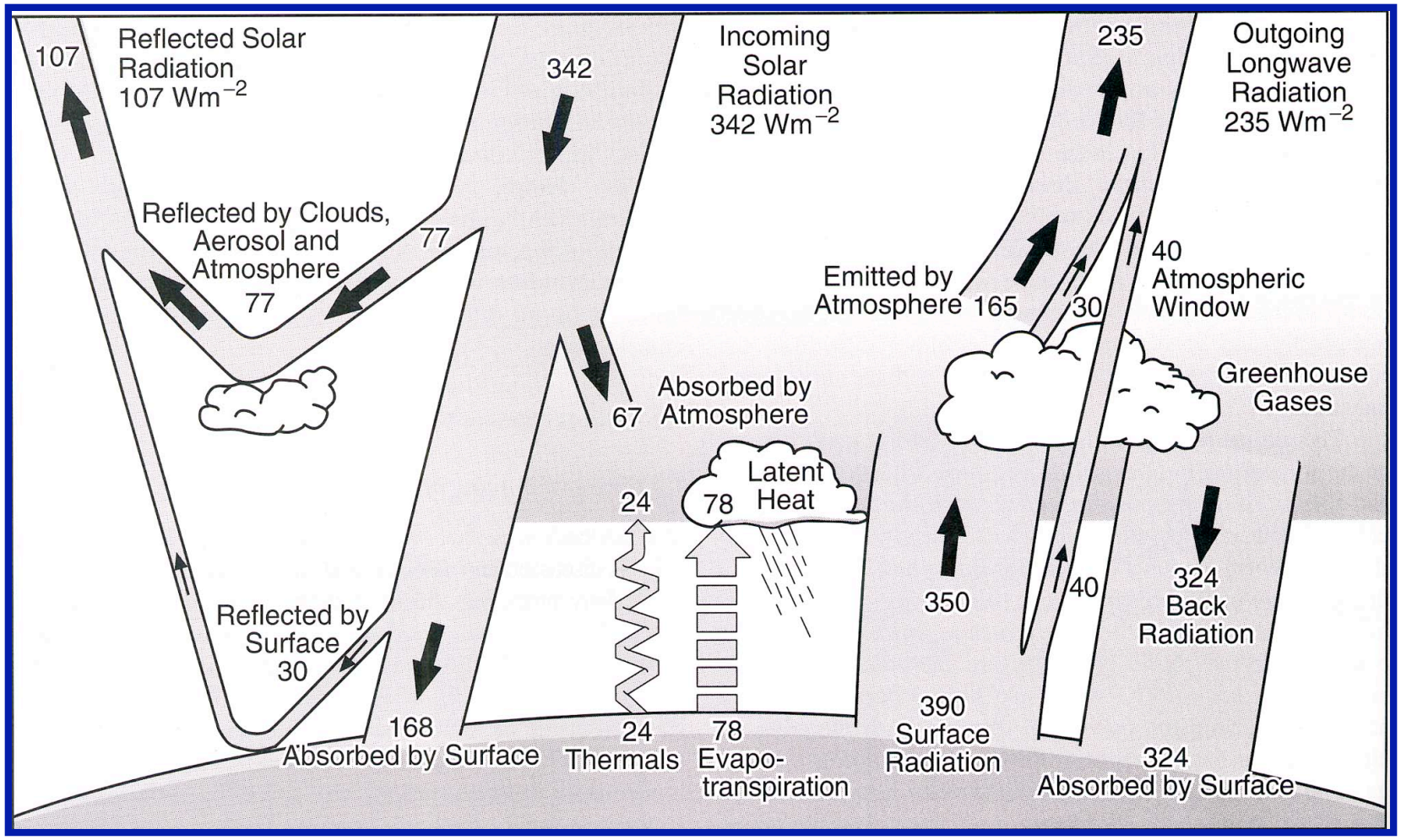
PREPARED UNDER THE DIRECTION OF
BRIG. AND BVT. MAJ. GEN. W. B. HAZEN,
CHIEF SIGNAL OFFICER OF THE ARMY.
BY
S. P. LANGLEY,
DIRECTOR OF THE ALLEGHENY OBSERVATORY, WITH THE APPROVAL OF ITS TRUSTEES.

PUBLISHED BY AUTHORITY OF THE SECRETARY OF WAR.

WASHINGTON:
GOVERNMENT PRINTING OFFICE.
1884.

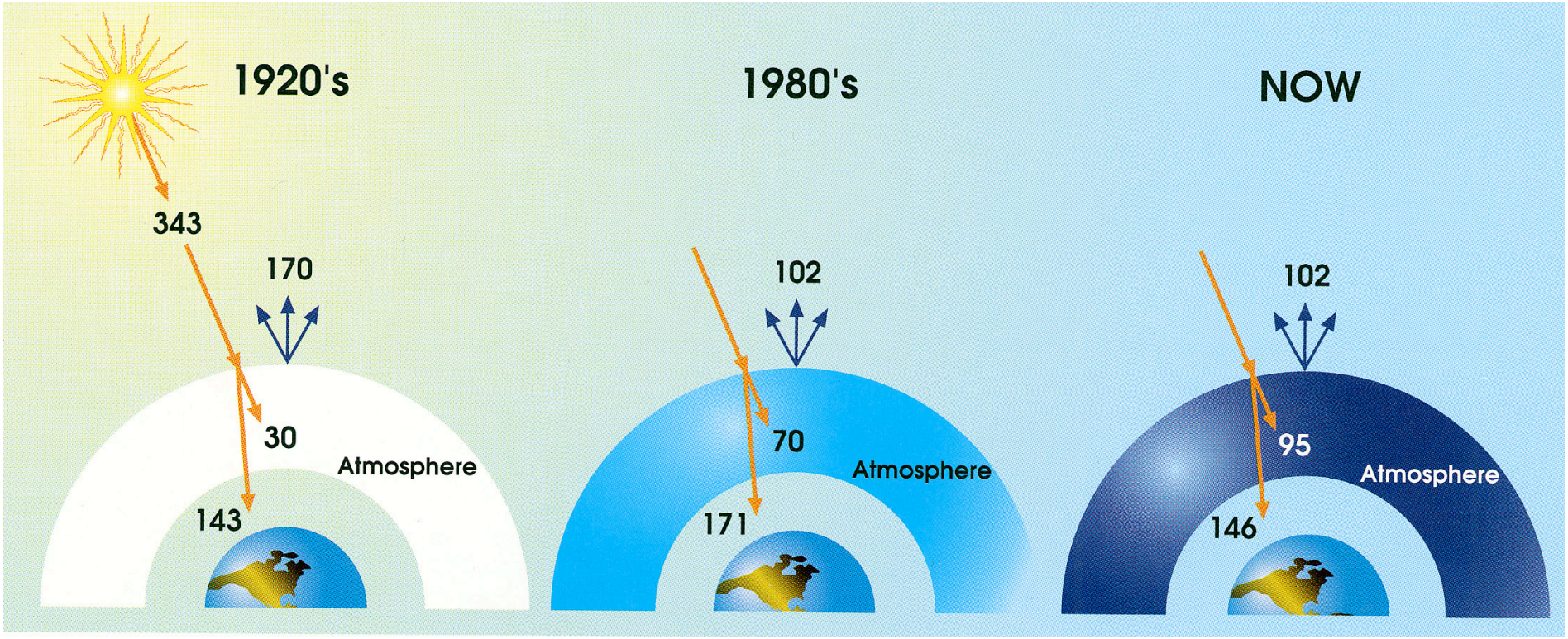
12535——No. XV

# IPCC; 2001.. Trenberth et al Chapter




Source: Climate Change, *IPCC*, 2001

**Ohmura and Gilgen; GEBA Data**




Stephens and Tsay, 1990

**Source: Ramanathan et al, Indian Ocean Experiment 1996**

# Warm Pool Heat Budget and Shortwave Cloud Forcing: A Missing Physics?

V. Ramanathan,* B. Subasilar, G. J. Zhang, W. Conant,
R. D. Cess, J. T. Kiehl, H. Grassl, L. Shi

Ship observations and ocean models indicate that heat export from the mixed layer of the western Pacific warm pool is small (<20 watts per square meter). This value was used to deduce the effect of clouds on the net solar radiation at the sea surface. The inferred magnitude of this shortwave cloud forcing was large ($\approx -100$ watts per square meter) and exceeded its observed value at the top of the atmosphere by a factor of about 1.5. This result implies that clouds (at least over the warm pool) reduce net solar radiation at the sea surface not only by reflecting a significant amount back to space, but also by trapping a large amount in the cloudy atmosphere, an inference that is at variance with most model results. The excess cloud absorption, if confirmed, has many climatic implications, including a significant reduction in the required tropics to extra-tropics heat transport in the oceans.

Source: V. Ramanathan et al., *Science*, 1995

# RAMANATHAN ET AL. (1995)
# TROPICAL PACIFIC WARM POOL

SW CRF(TOA) = -65 W $m^{-2}$

EXCESS ALL-SKY ABSORPTION
RELATIVE TO CLEAR SKIES = 35 W $m^{-2}$

SW CRF(SRF) = -100 W $m^{-2}$ (FROM RESIDUAL)

WALISER, COLLINS & ANDERSON (1996):
SW CRF(SRF) = -103 W $m^{-2}$ FROM IMET BUOYS

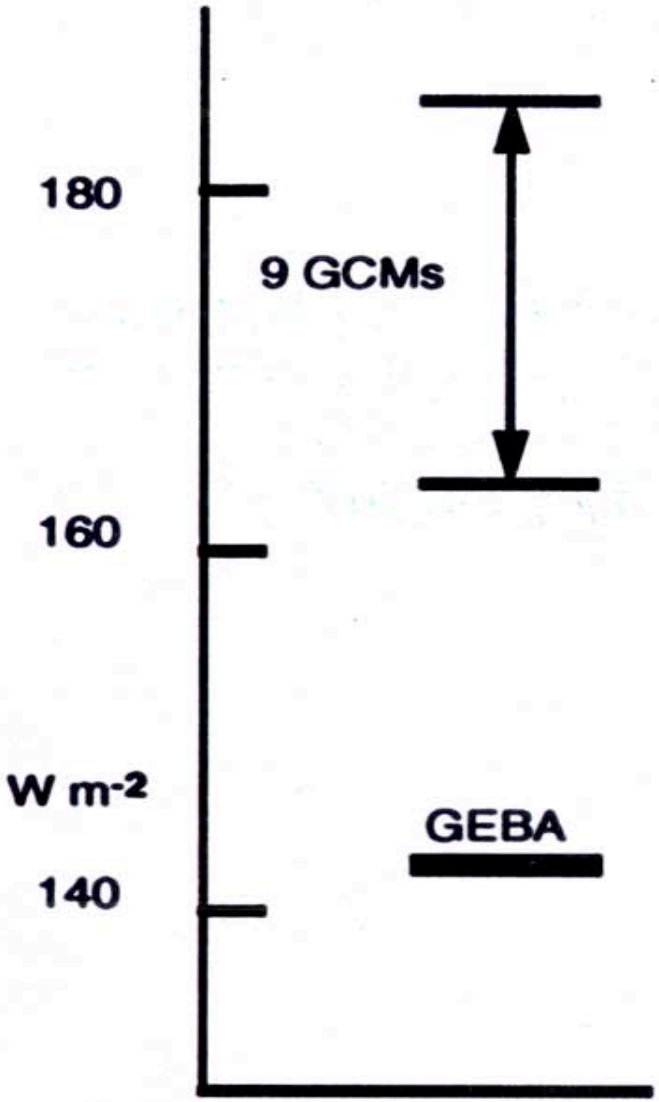
CONANT ET AL. (1996): RADIATION MODELS AGREE TO WITHIN 4 W $m^{-2}$ OF THE OBSERVED AVERAGE CLEAR-SKY OCEAN AND ATMOSPHERIC HEATING.

CHOW & ZHAO (1996): IMET BUOYS, 2 SHIPS & 2 ISLANDS
SW CRF(SRF) = -99 W $m^{-2}$ AND NO CLEAR-SKY OBSERVATIONAL-MODEL DISCREPANCY

## ABSORBED SOLAR RADIATION AT THE SURFACE

**Models Vs Pyranometer Observations**

**GLOBAL ANNUAL MEAN; Average Cloudy Skies**




**Ramanathan & Vogelmann, 1997**

# ARM-ARESÈ1 & 2

**Valero etal, 2003**

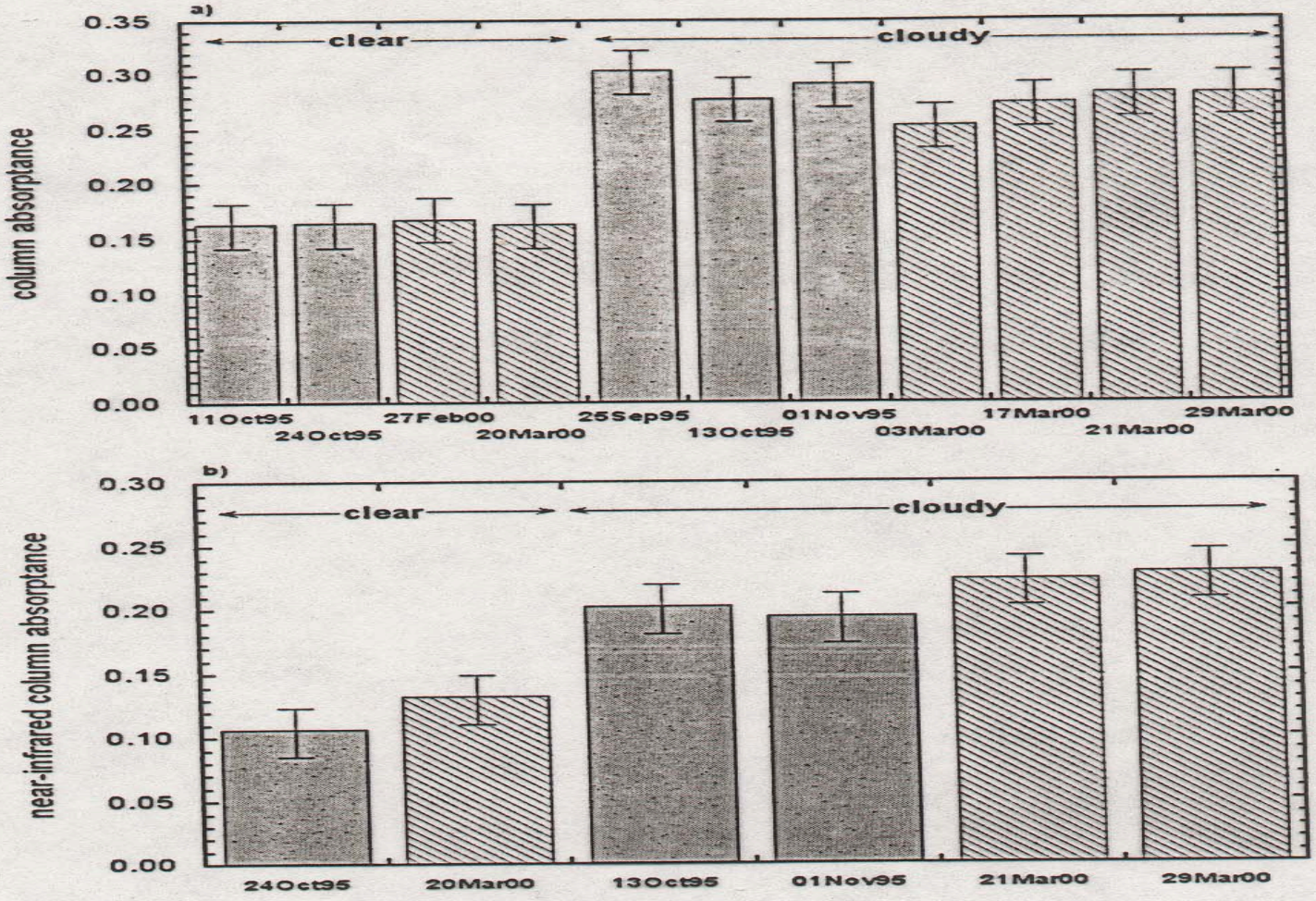
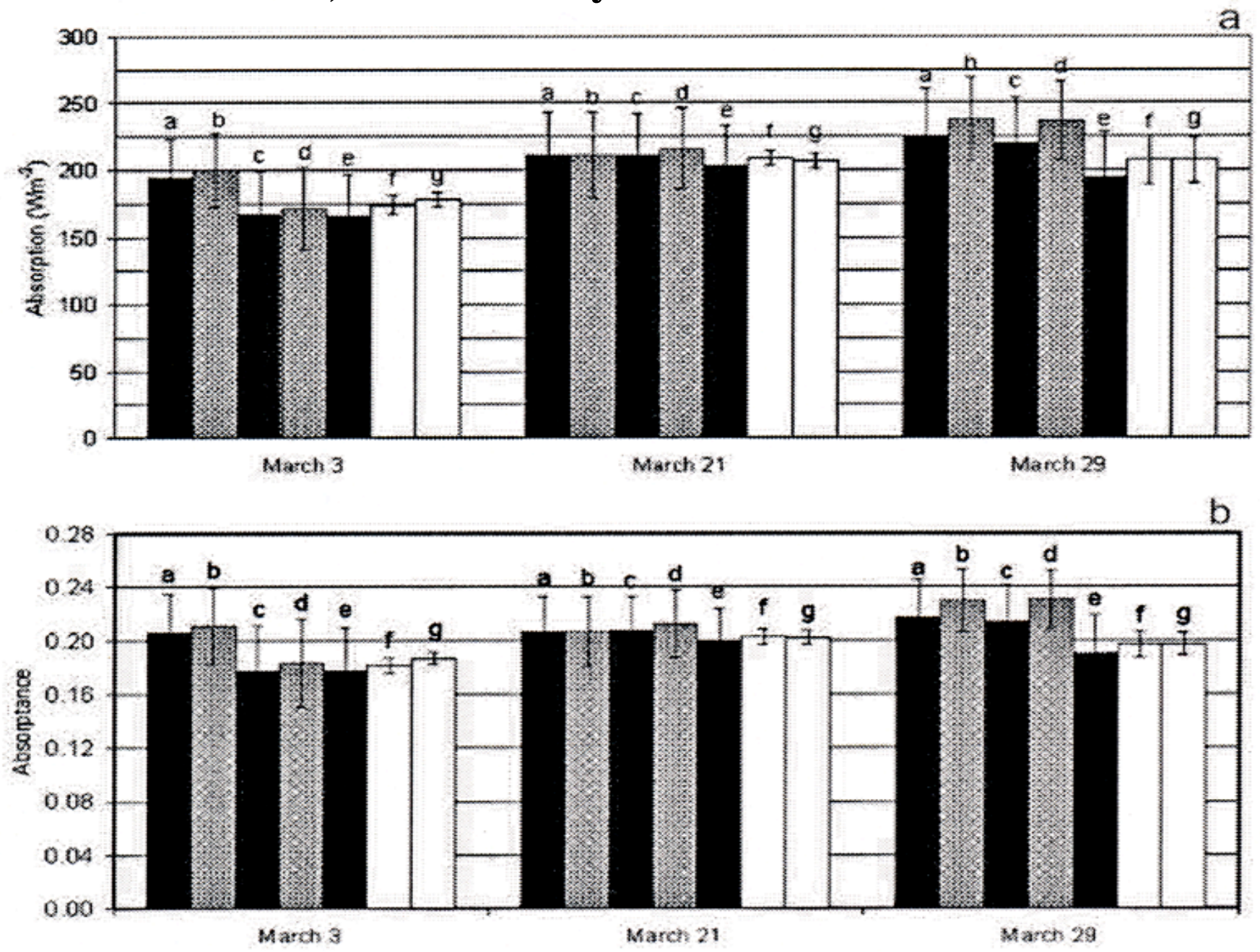



**Figure 13.** Values of absorptance from ARESE I (gray) and ARESE II (hatched) are compared, after being converted to whole-column values using model estimates for the absorptance between 13 km and TOA or 7 km and TOA. Total solar results are in (a), and near-infrared results in (b). (See Figure 11 caption regarding error bars.)

# Ackerman et al, 2003: Cloudy Skies



# 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)***

***Advisory Team:***

***D. Fahey, J. Fein, C. Jennison, J. Kuettner***



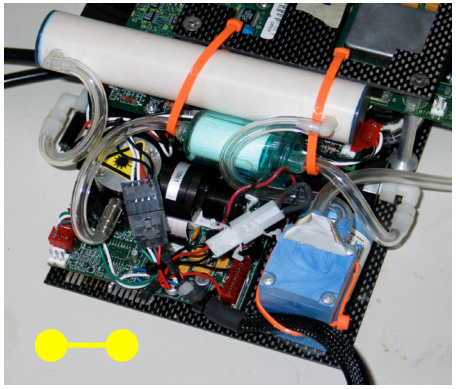
***Funding Agencies: NSF/NOAA/NASA/Vetlesen/Alderson***

# 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

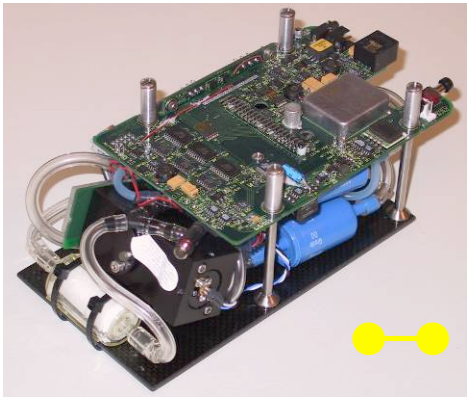

# Miniaturized Instruments for UAV

**Roberts, Ramana and Corrigan**



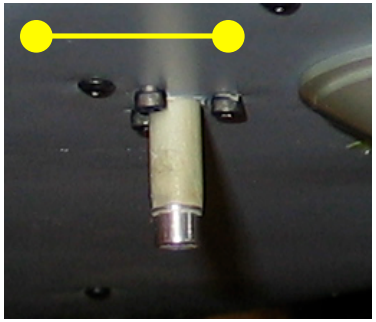
*Optical Particle Counter (580 g)*
→ $N_{OPC}$; $0.3 < D_p < 3$ μm

[=] 1 inch

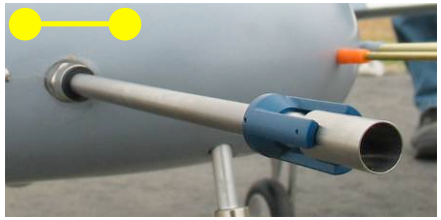


*Condensation Particle Counter (870 g)* → $N_{CN}$; $D_p > 10$ nm

*Aethalometer (820 g)*
→ absorbing aerosol

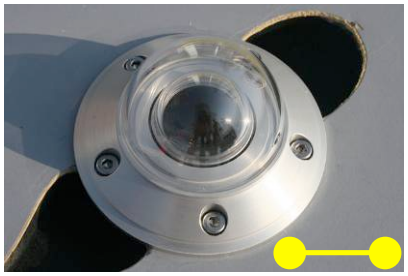


*T/RH probe (50 g)*
→ Temperature & RH

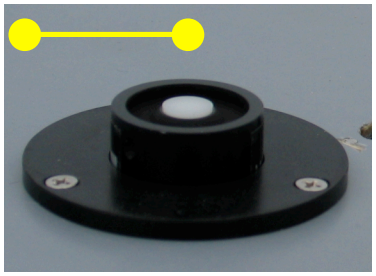


*Aerosol inlet & splitter (150 g)*
→ unbiased aerosol sampling

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

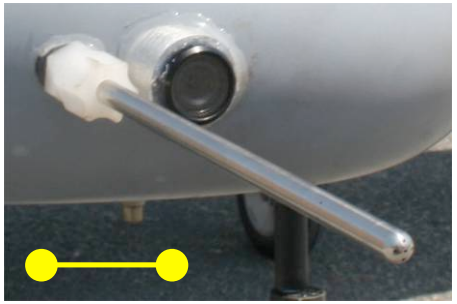


*Pyranometer (190 g)*
→ irradiance 0.3 – 2.8 μm



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

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



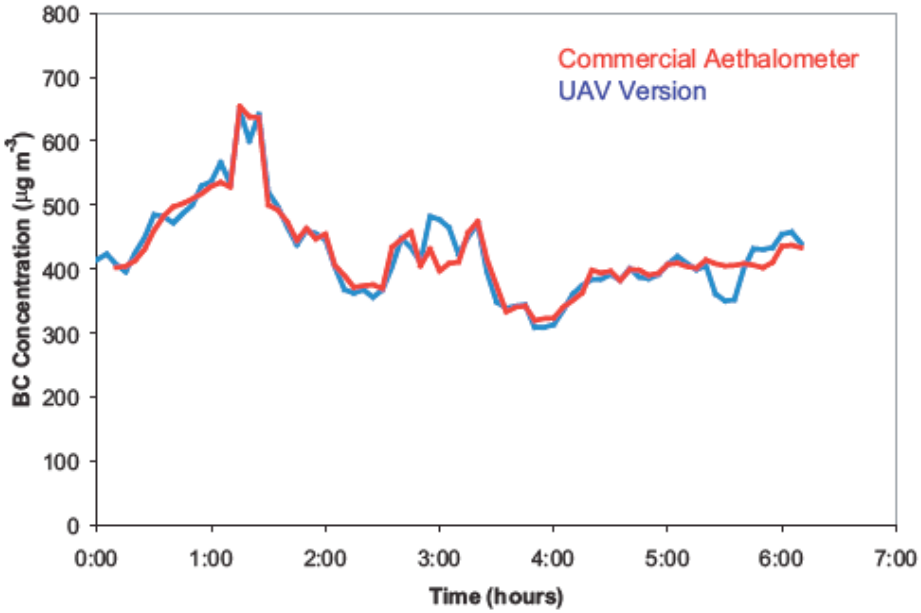
*Video camera (280 g)*
→ cloud targeting

# *Necessary to Shrink Instruments*

***Lead Inst scientist for black carbon: C. Corrigan***

UAV version

Commercial

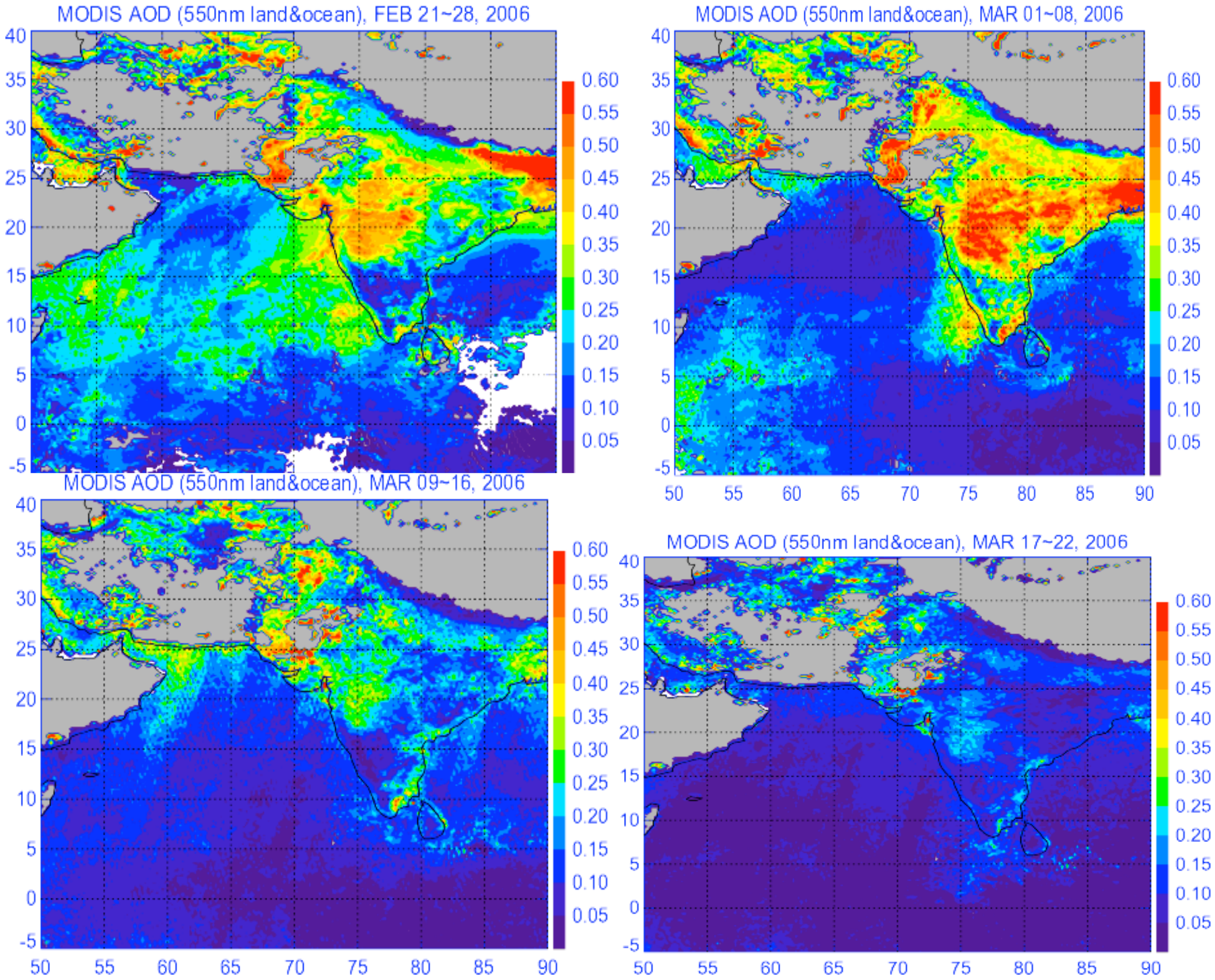
# The Maldives Autonomous Unmanned Aerial Vehicle Campaign (MAC)

06 March - 01 April, 2006


# *Warming Trends in Asia amplified by brown cloud solar absorption*

*Ramanathan, Ramana, Roberts, Corrigan, Chung and Winker, Nature, **448**, 575-578, 2007.*


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


MODIS AOD (550nm land&ocean), FEB 21~28, 2006
MODIS AOD (550nm land&ocean), MAR 01~08, 2006
MODIS AOD (550nm land&ocean), MAR 09~16, 2006
MODIS AOD (550nm land&ocean), MAR 17~22, 2006
40
35
30
25
20
15
10
5
0
-5
50
55
60
65
70
75
80
85
90
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05

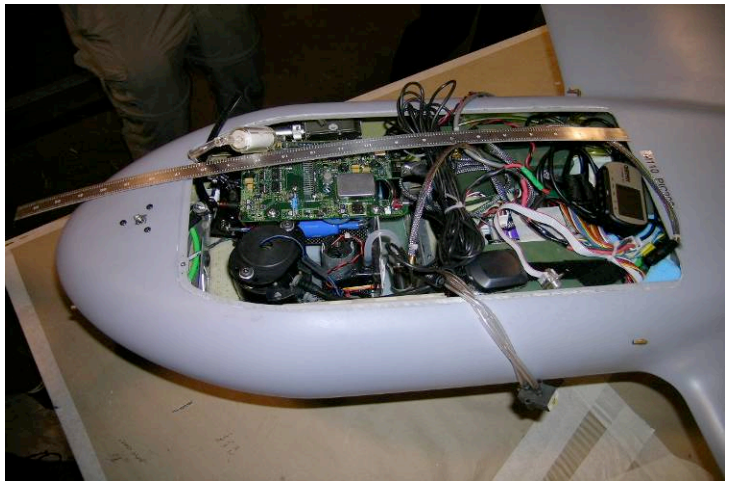
# Hanimaadhoo Island

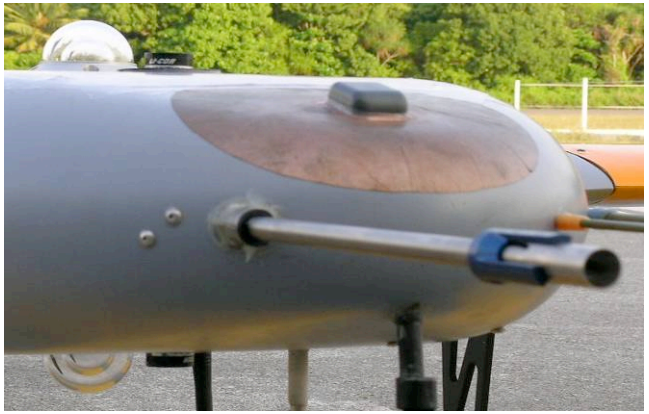
Maldives Climate Observatory - Hanimaadhoo (MCOH)

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

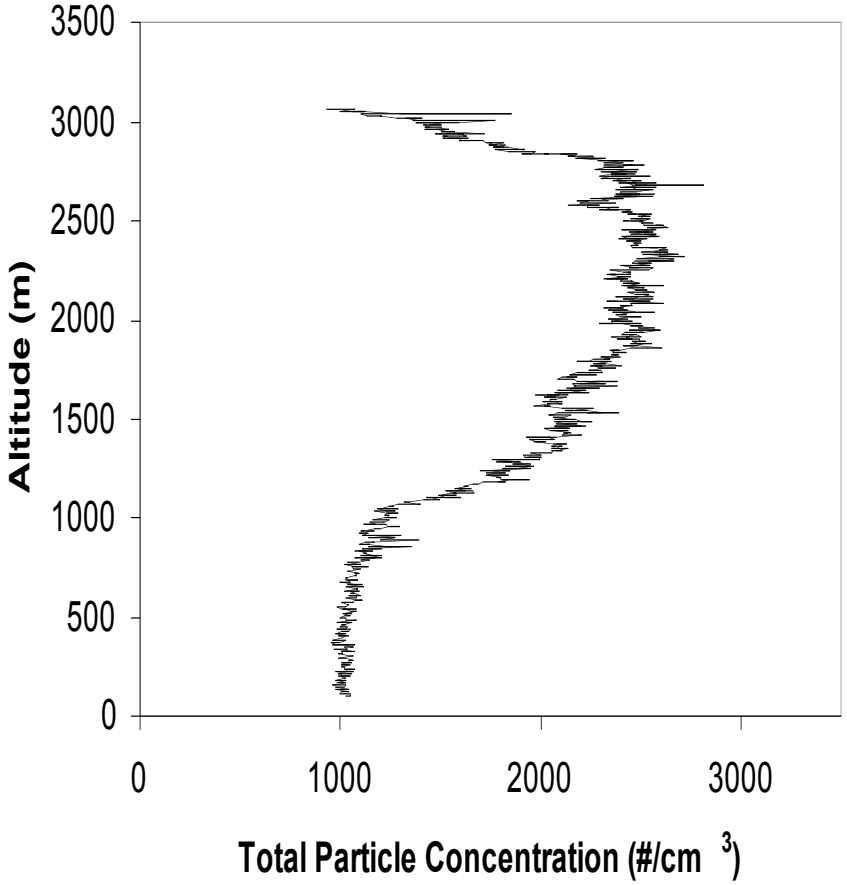
100 m below cloud

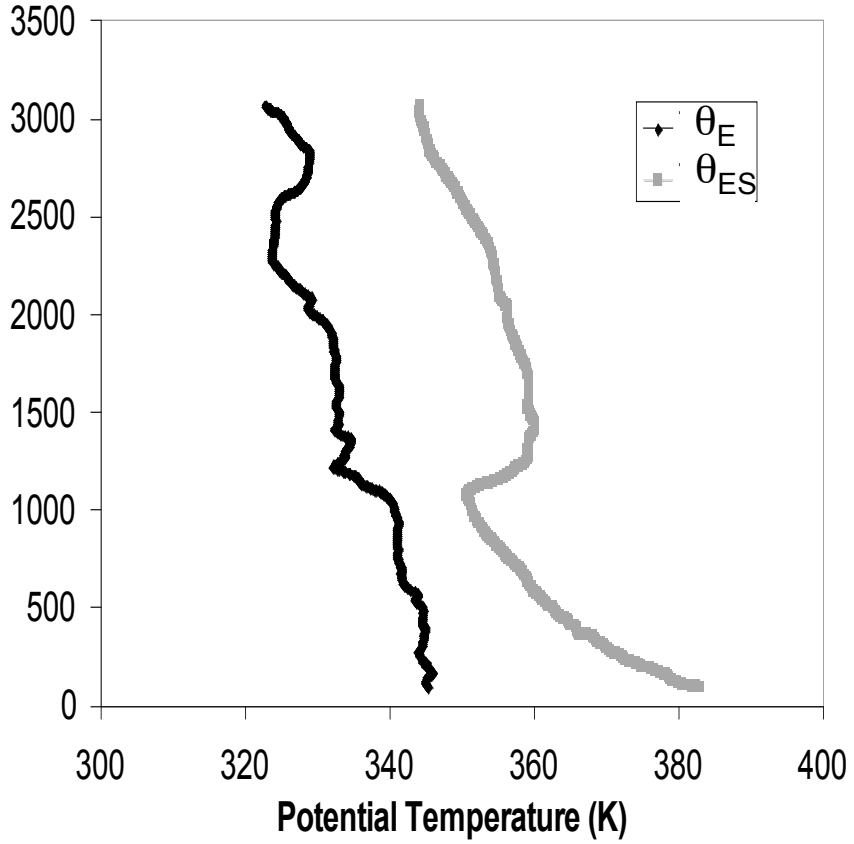
Surface observations

# 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

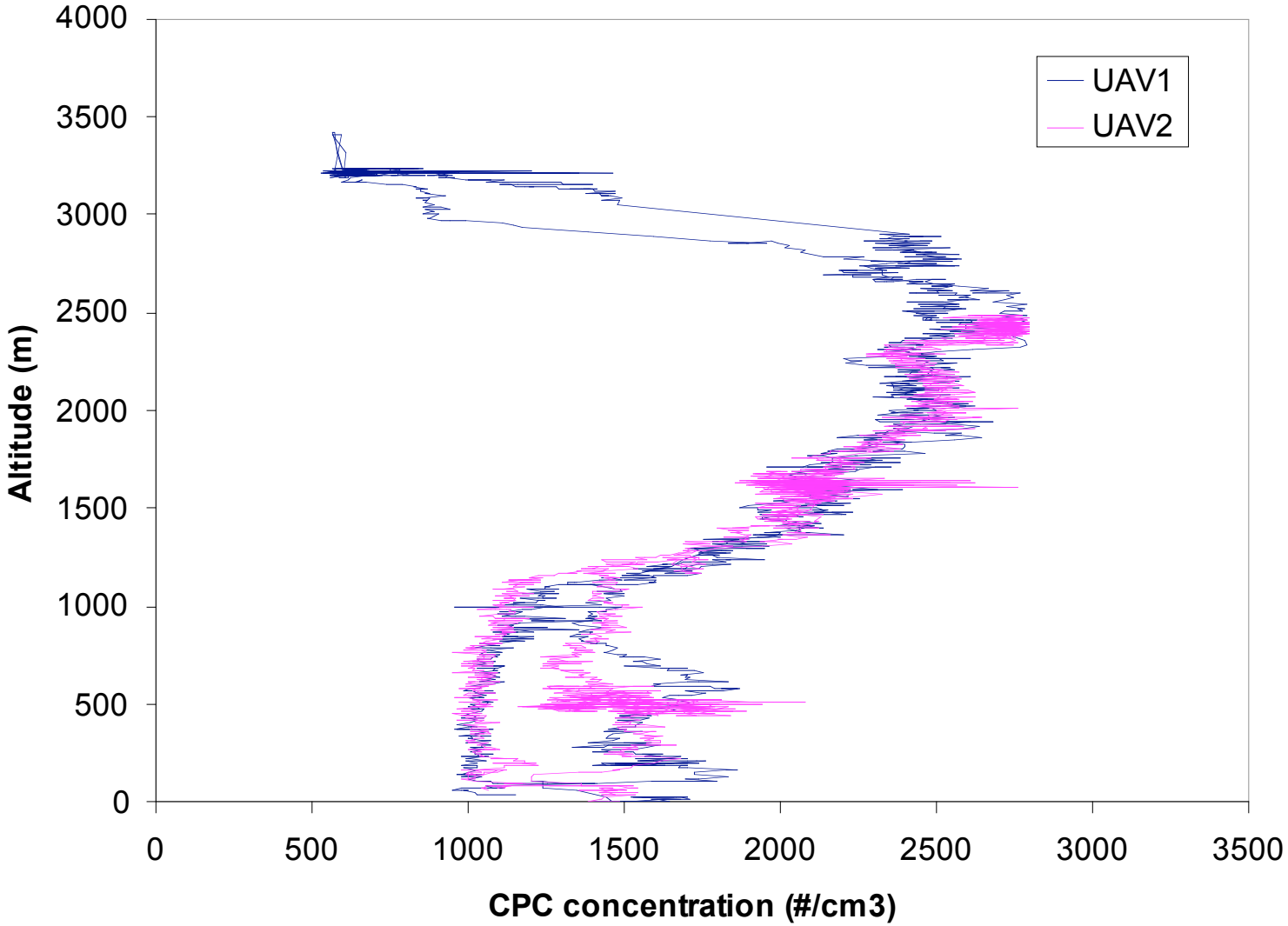
# Atmospheric Layers



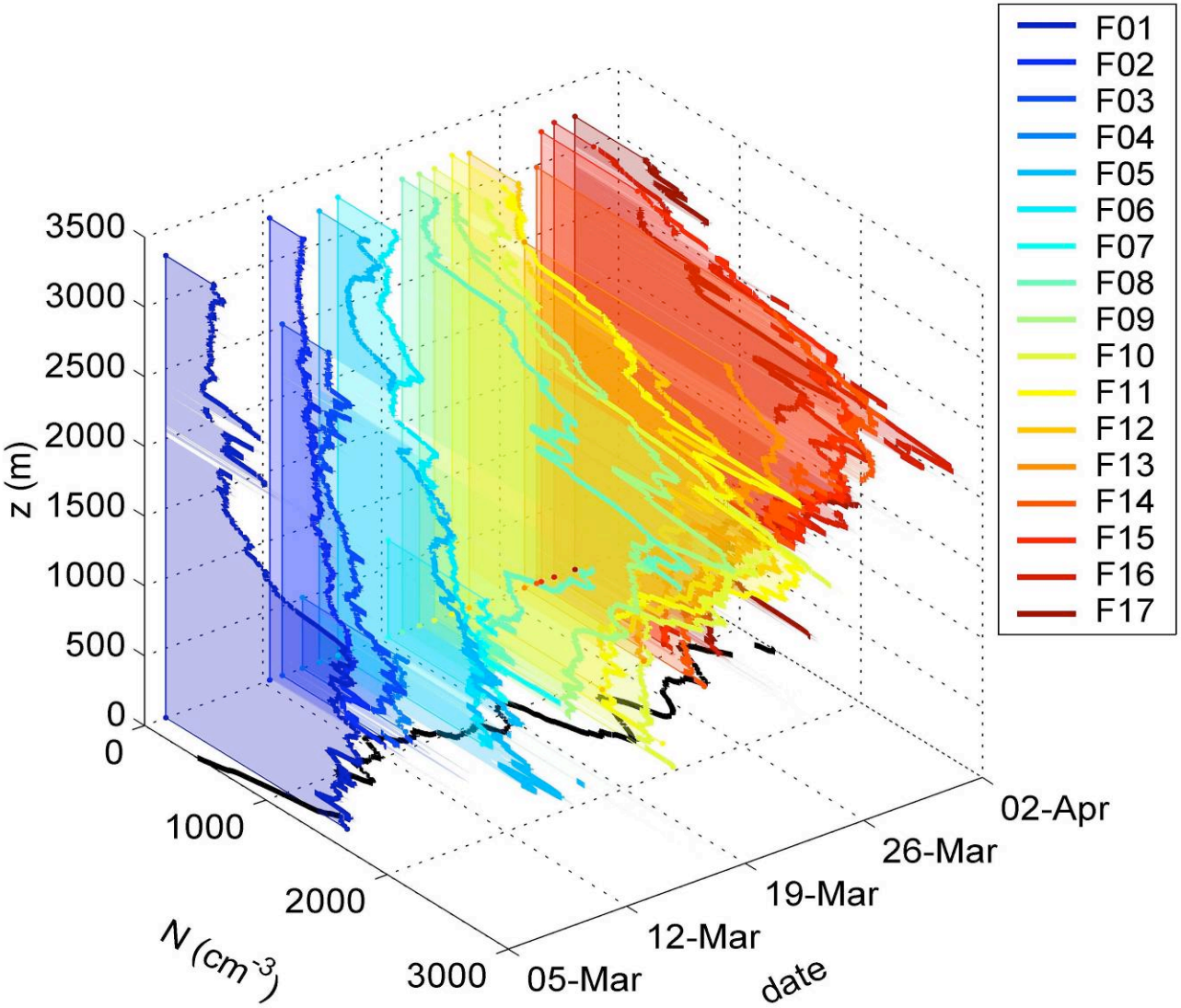

*Corrigan et al., 2007*

# Cross-platform Comparison of Total Particle Counter

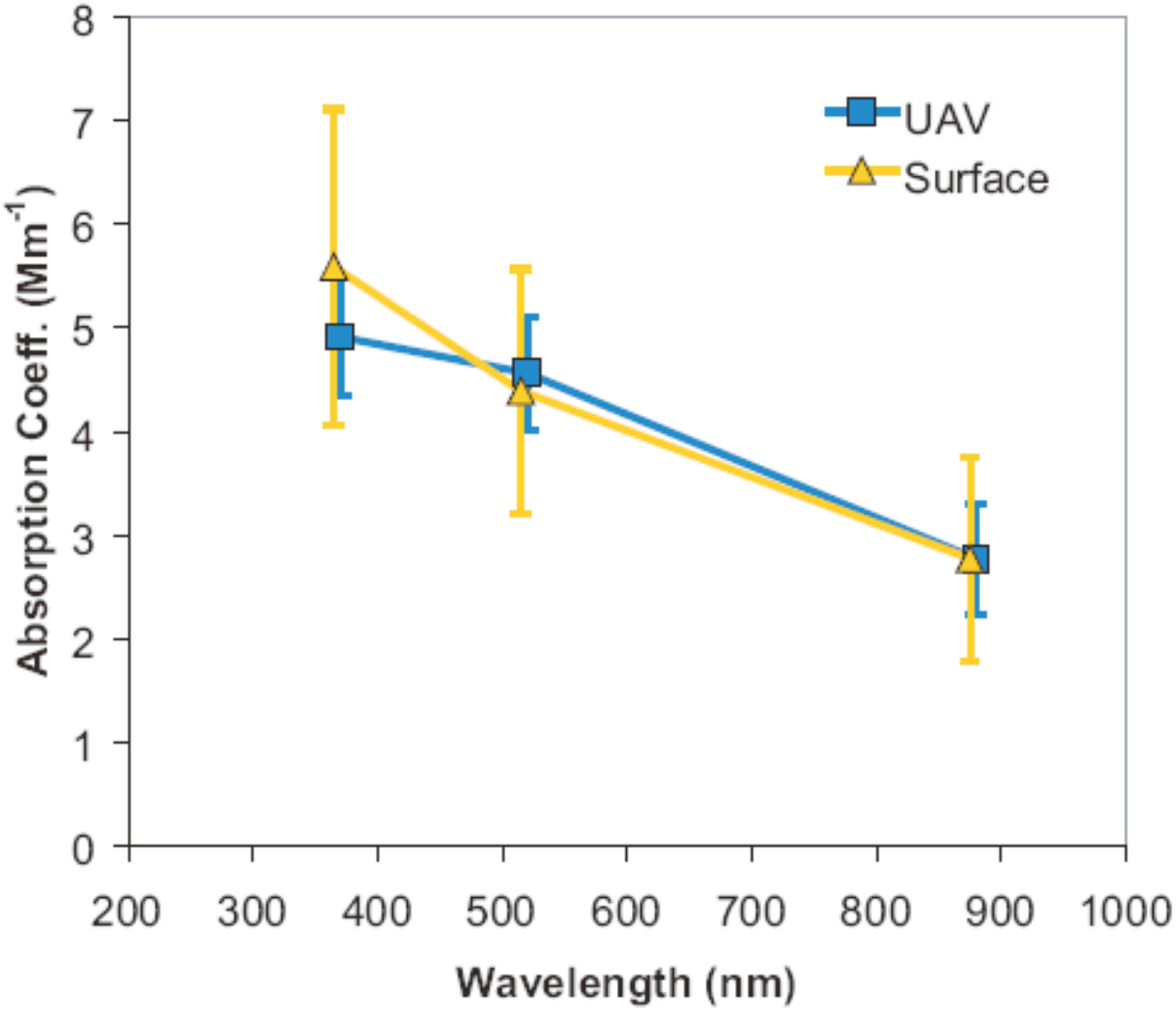



*Corrigan et al., 2007*

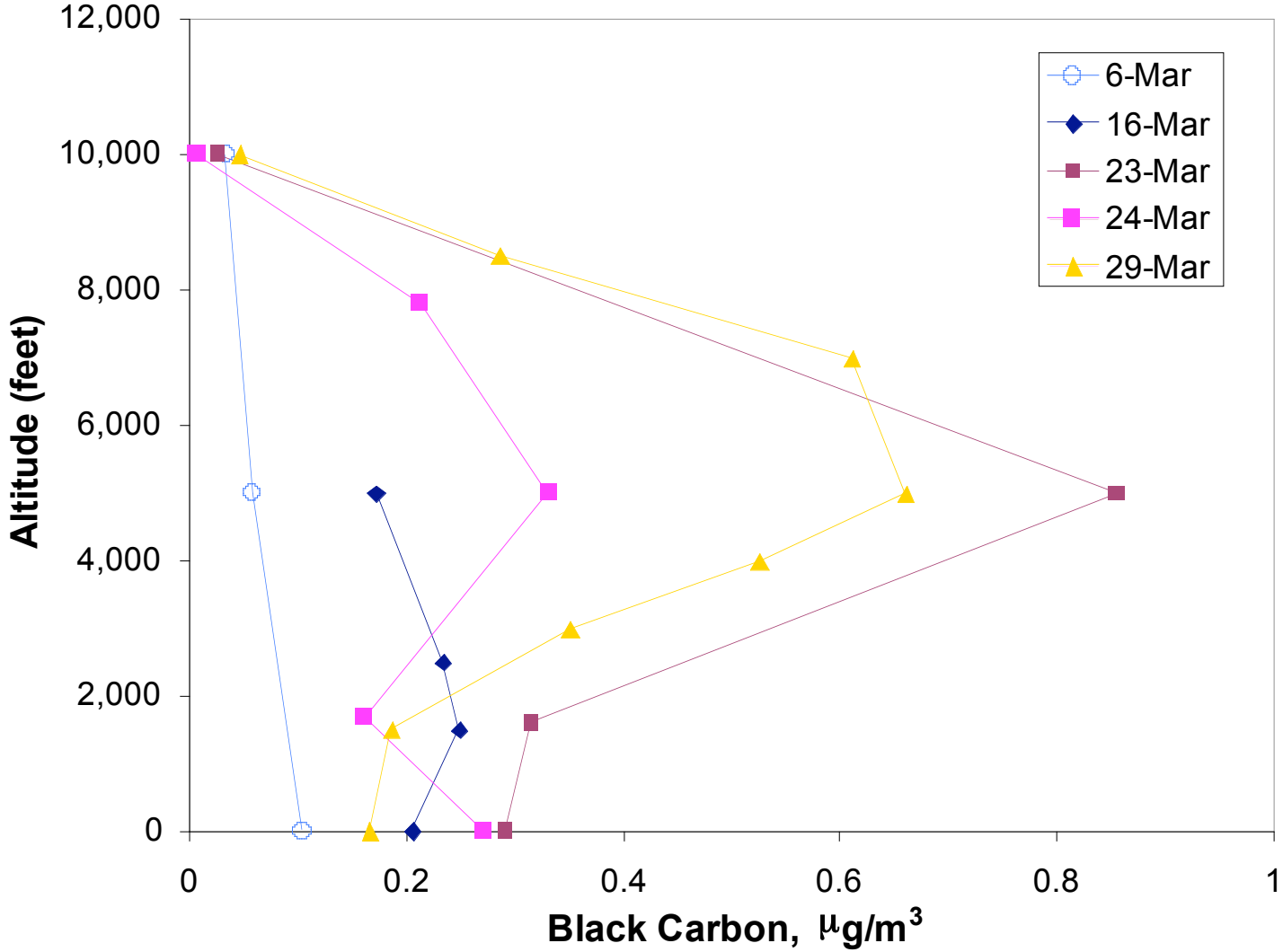
# Total Particle Concentration during MAC




*Corrigan et al., 2007*

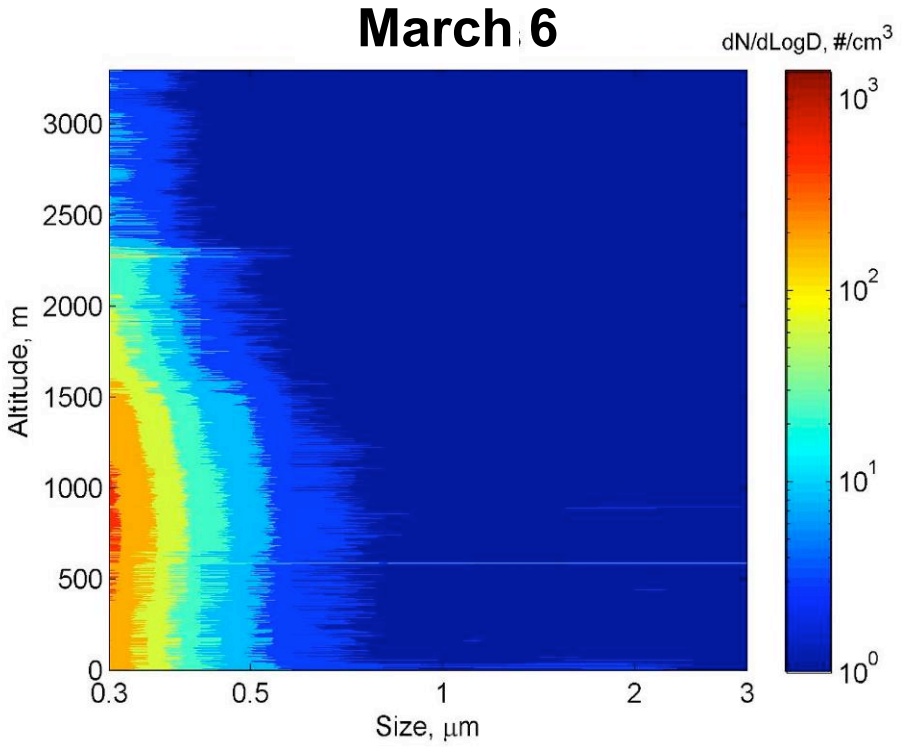

Absorption Coeff. (Mm-1)
Wavelength (nm)
UAV
Surface
0
1
2
3
4
5
6
7
8
200
300
400
500
600
700
800
900
1000

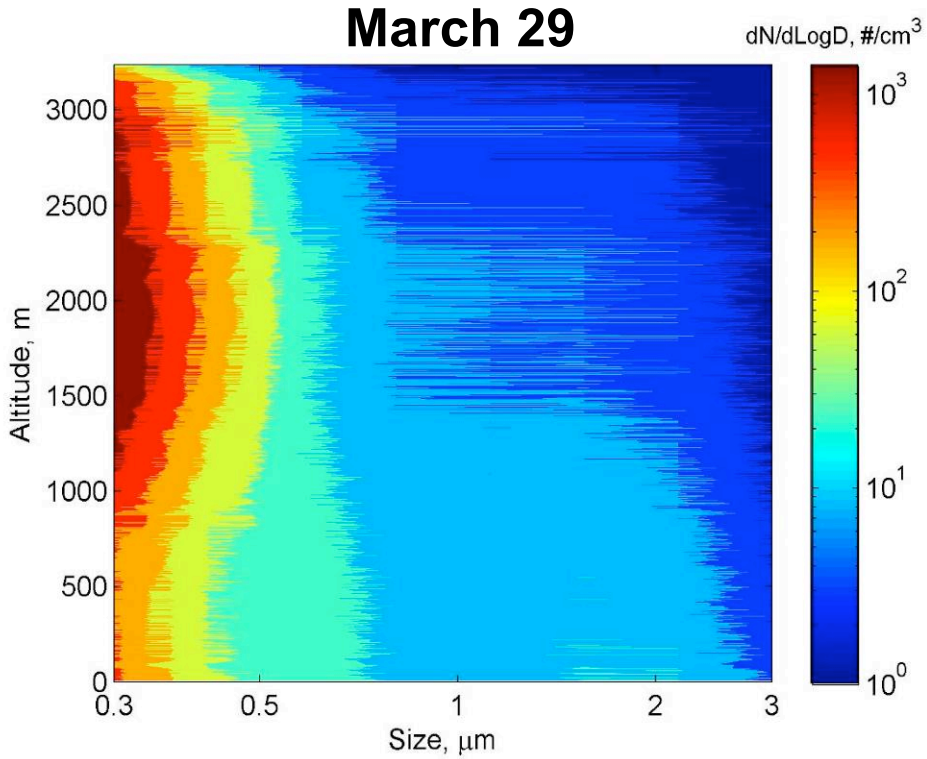
# Black Carbon Vertical Profiles during MAC




*Corrigan et al., 2007*

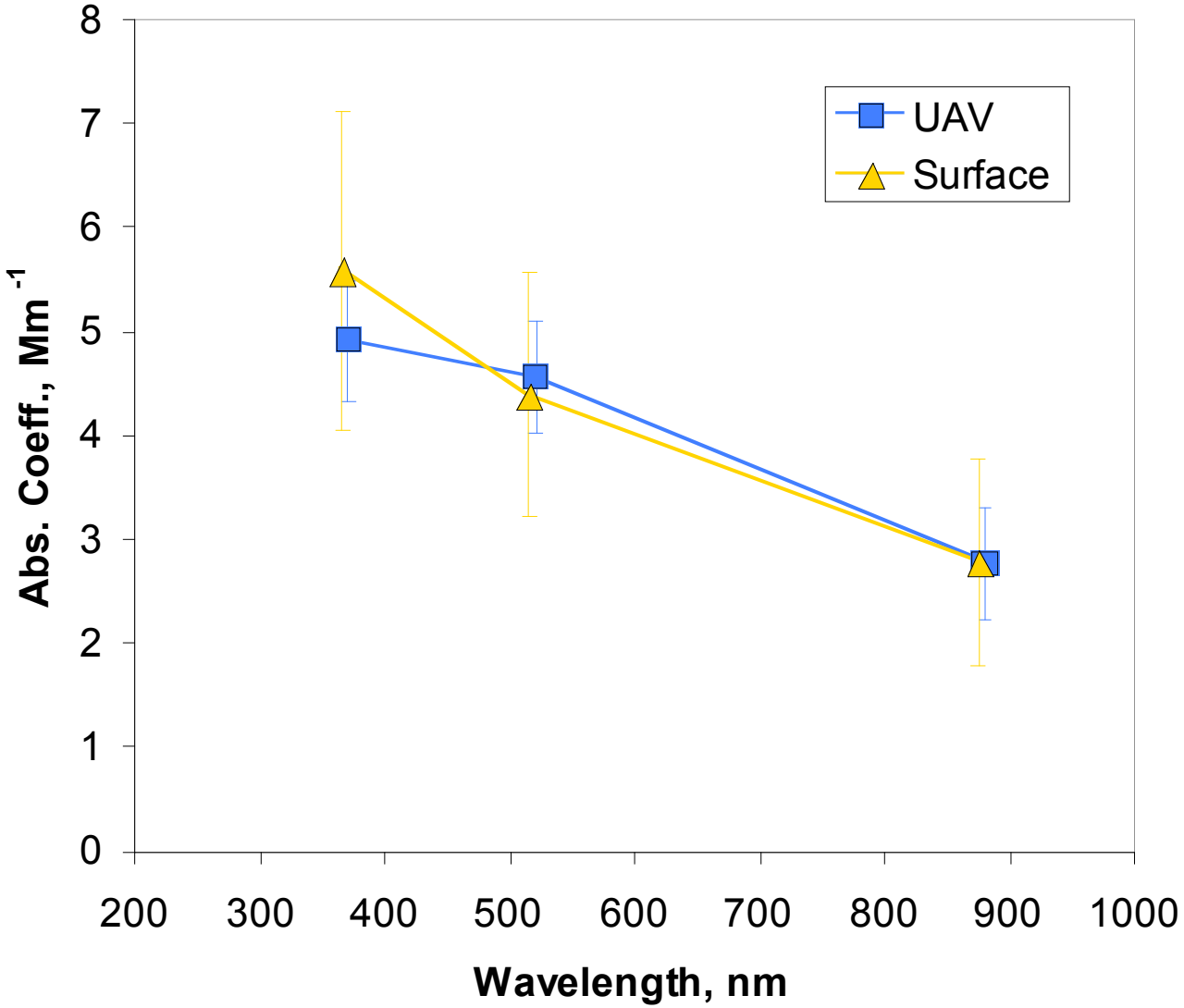
# Aerosol Size Distribution from Clean and Polluted Periods




*Corrigan et al., 2007*

# Surface and UAV Absorption Comparison (Aethalometer).




*Corrigan et al., 2007*

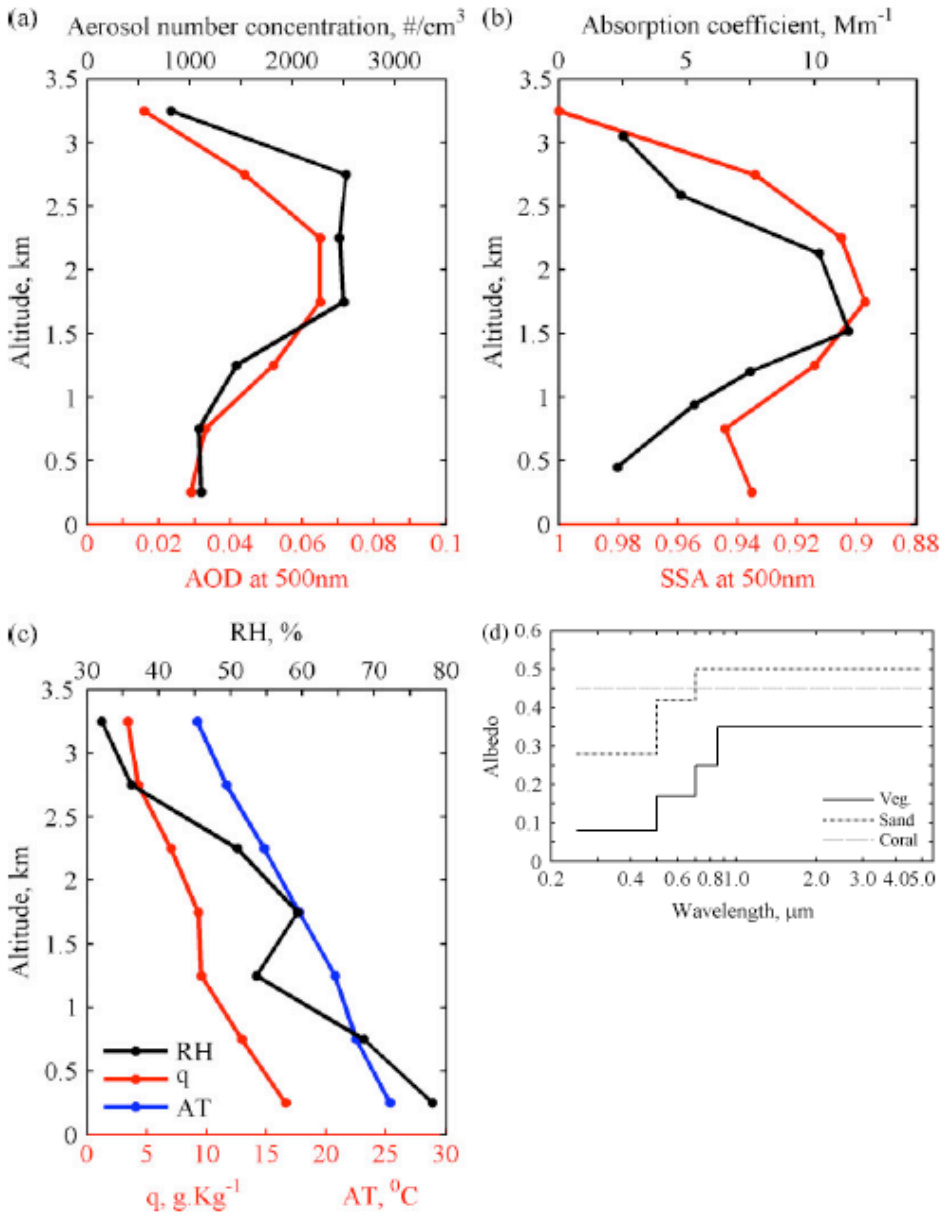



**Fig. 15.** ( tion photometer and AERONE by the cross symbol.

# *Validation with Ground Observations*

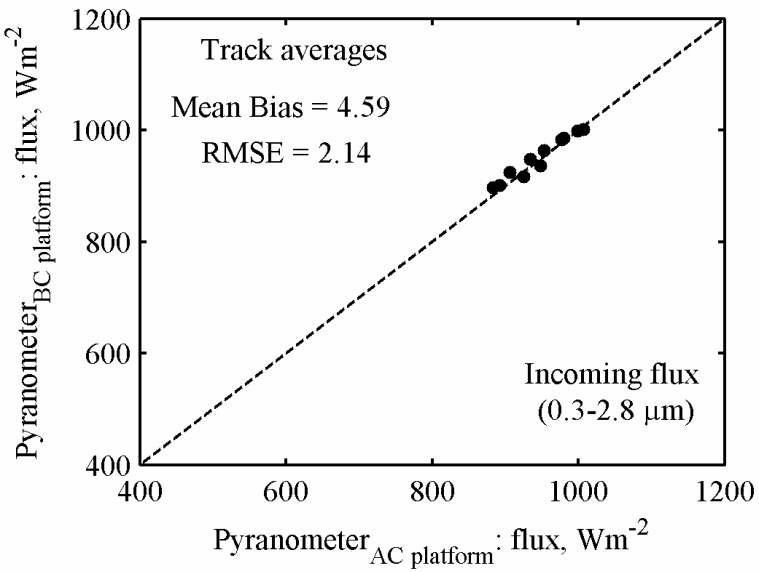
UAV-Pyranometer

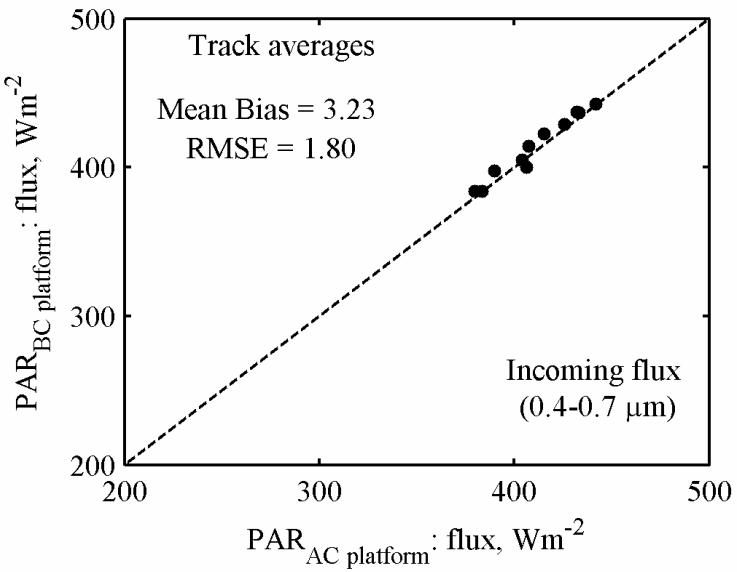
UAV - PAR

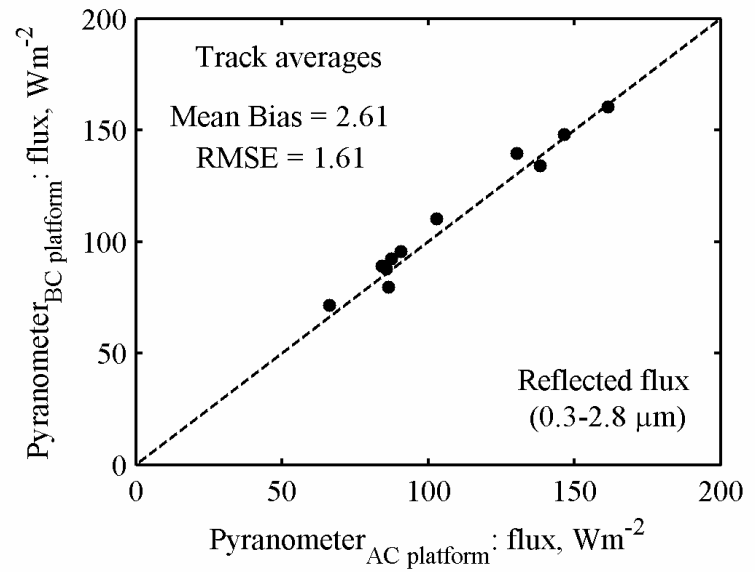
MCOH - PAR

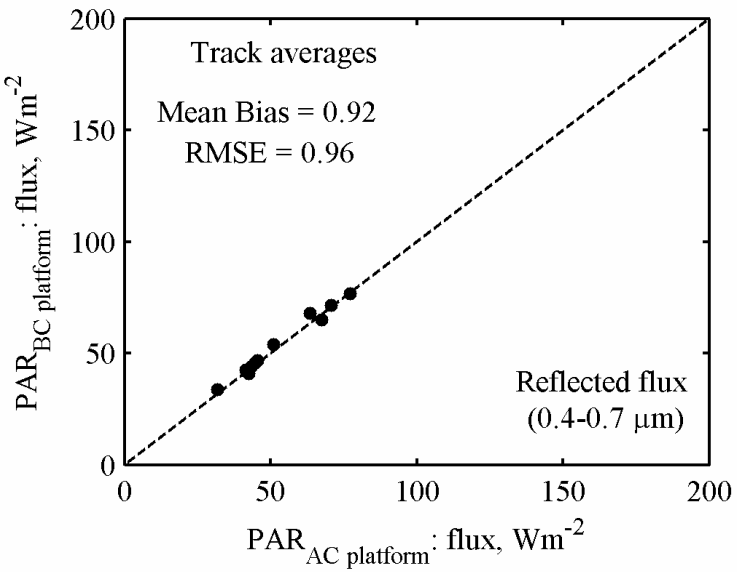
MCOH-Pyranometer

# *Wing tip to Wing tip comparison*



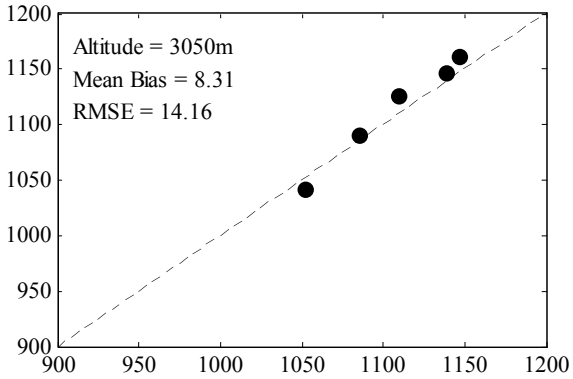



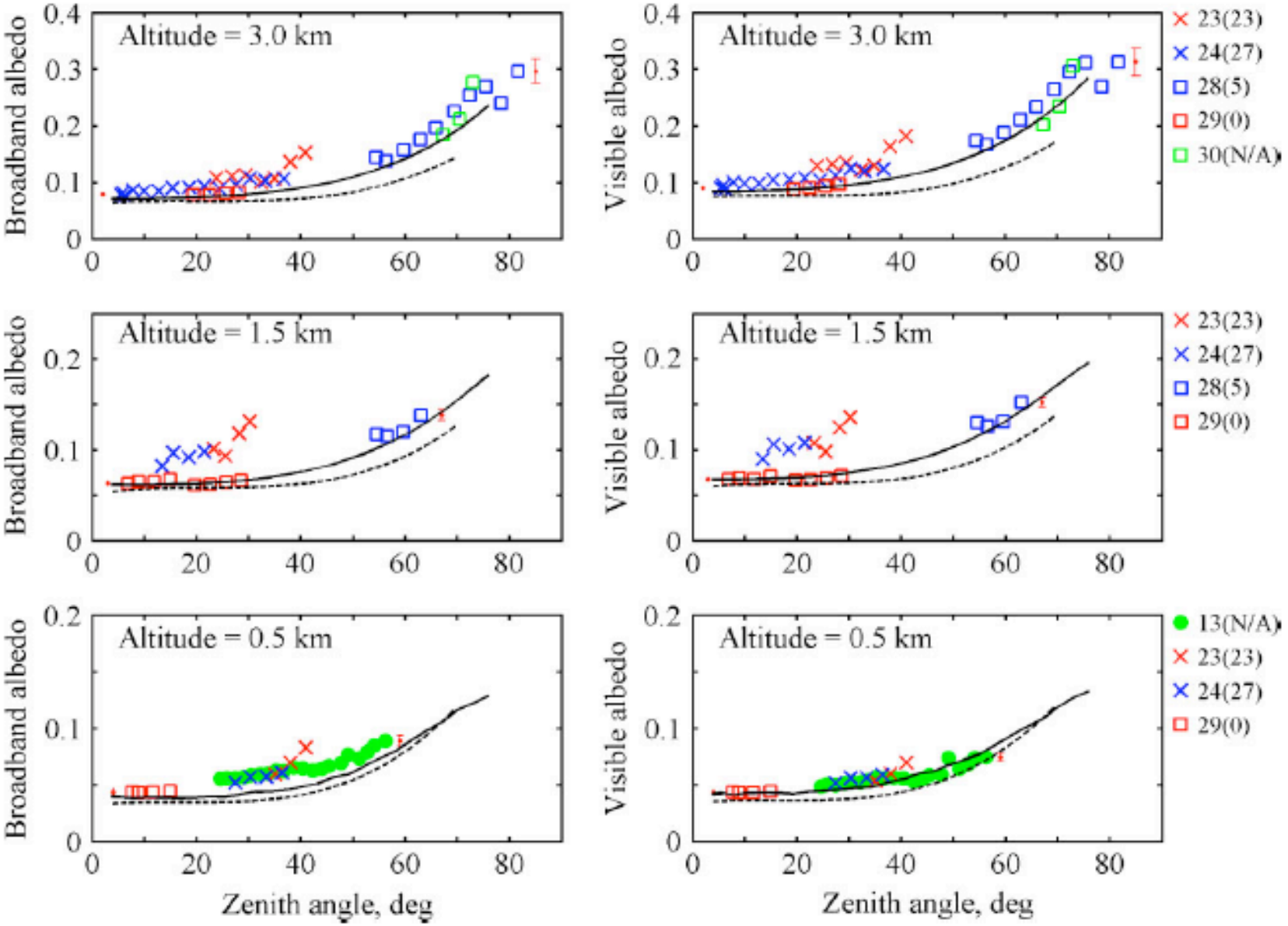




*Ramana et al., 2007*

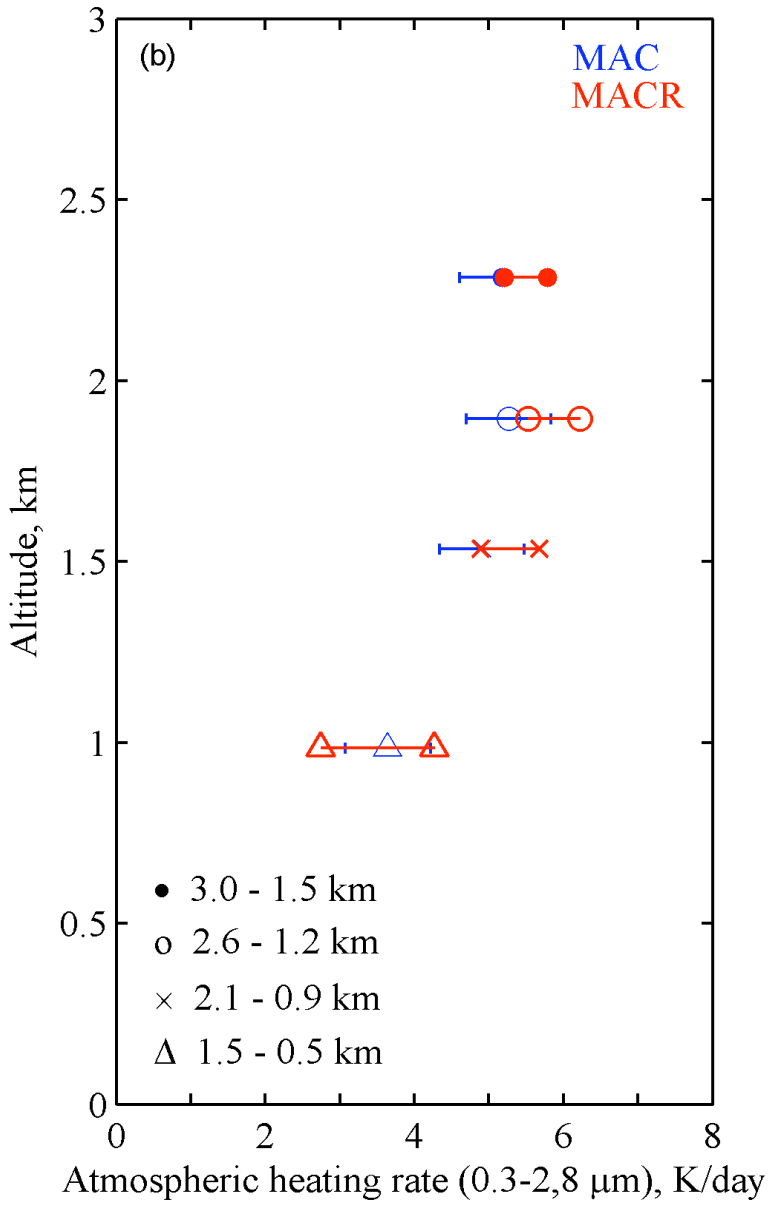
# *Incoming broadband flux comparison: MAC vs MACR (cloud-free day)*




*Ramana et al., 2007*

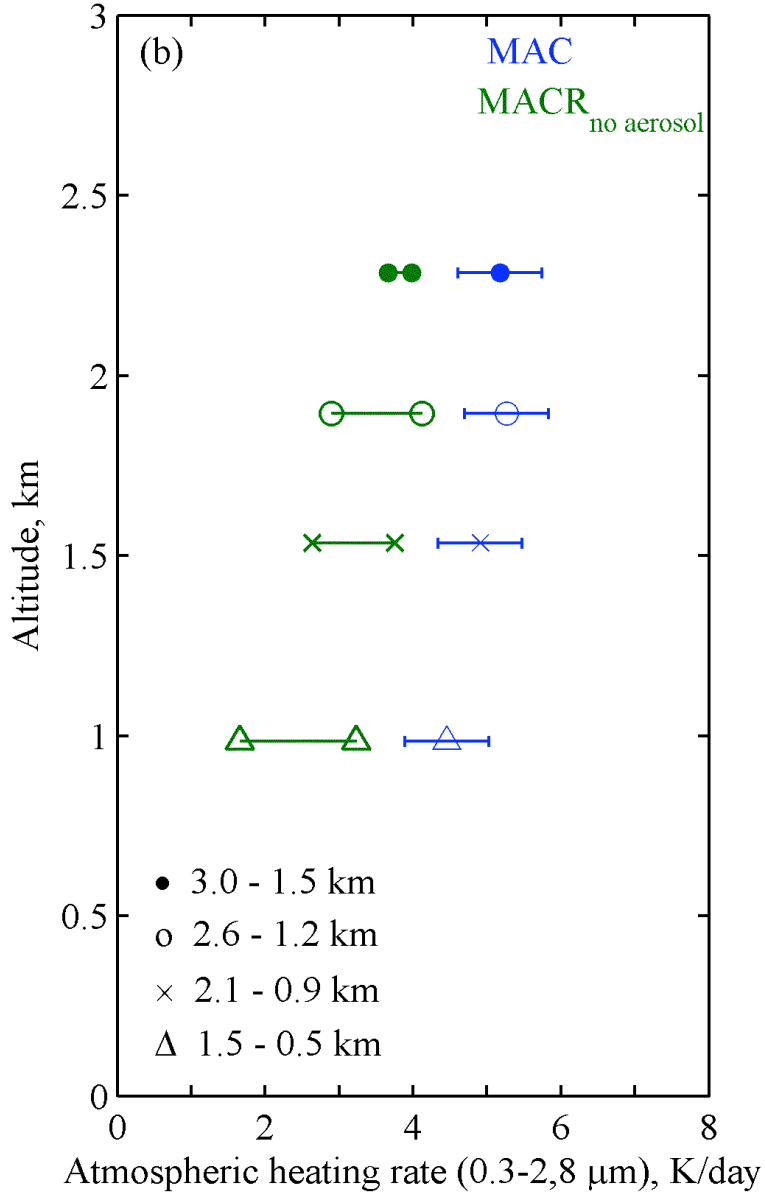

Altitude = 3.0 km
Broadband albedo
Visible albedo
Altitude = 1.5 km
Altitude = 0.5 km
Zenith angle, deg
23(23)
24(27)
28(5)
29(0)
30(N/A)
13(N/A)

# *Atmospheric Absorption and Heating rate : cloud-free day*



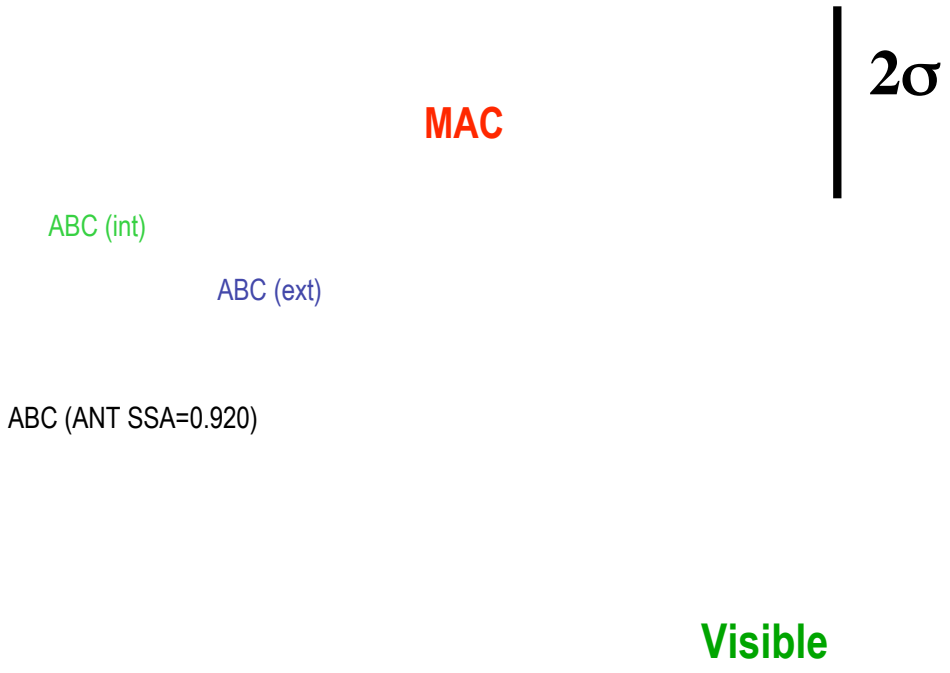

*Ramana et al., 2007*

# *Simulated Heating Rate without Aerosol*



# *Almost clear day*

Above Cloud (1500-3000m)
[Visible]: March 29, 2006



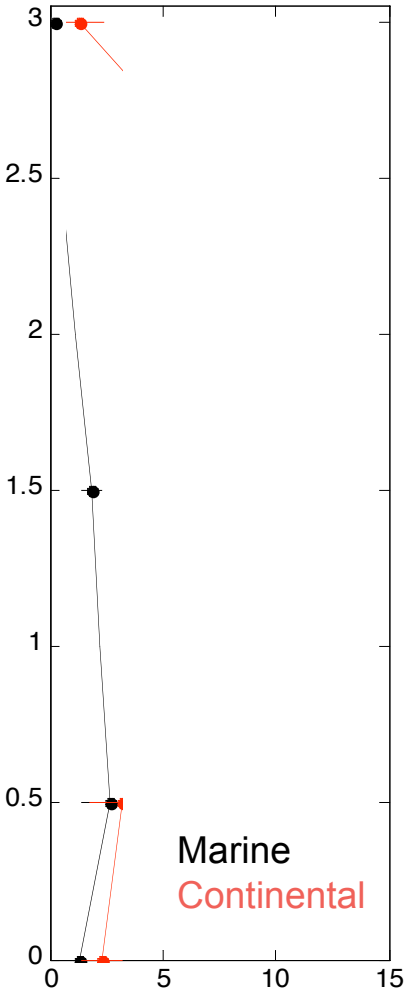

ABC (ANT SSA=0.920): vertically same SSA with AERONET SSA
ABC (ext): External mixture of Sulfate (30%)+Dust(97-99%)+BC(1-3%)
ABC (int): Internal mixture of Sulfate (30%)+Dust(97-99%)+BC(1-3%)

# 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*

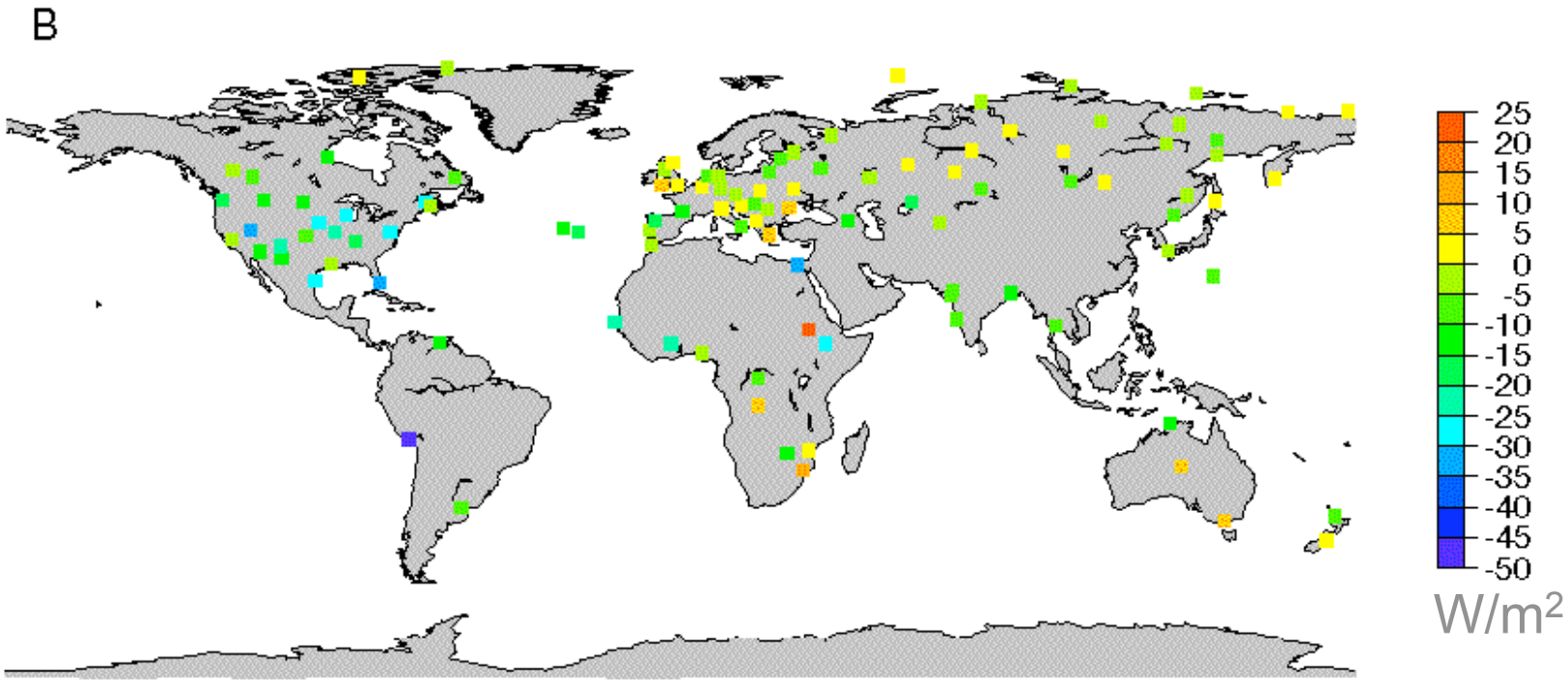



*Ramanathan et al., 2007*

# Global Dimming

Changes of Decadal Mean Surface Solar Radiation:
1981 - 1990 minus 1961-1970 (Liepert, *GRL*, 2002)

$\Delta F = -7 W/m^2 \approx -4\%$



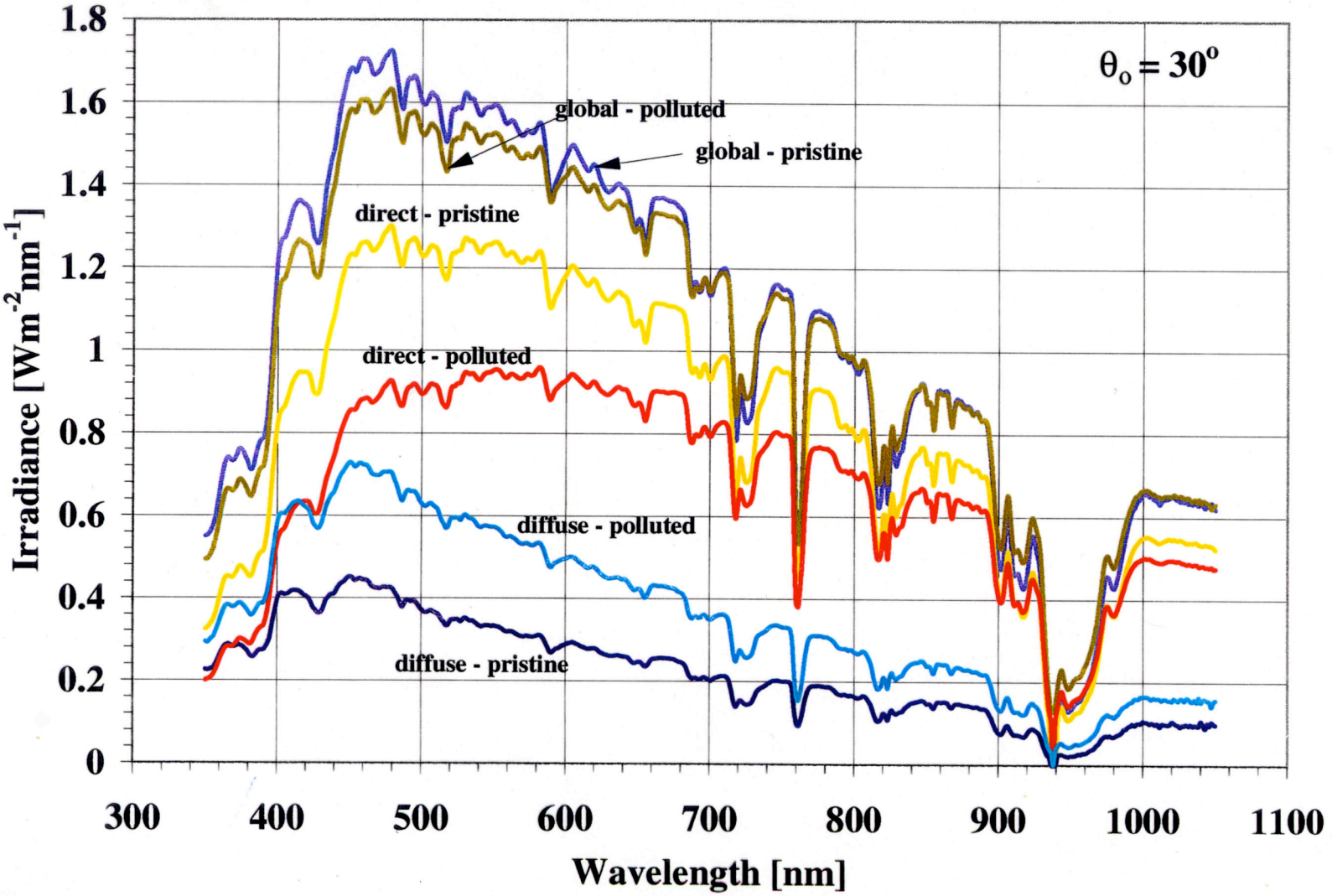
# Is there Direct Evidence for the Dimming and its Causal Factors?

- The Indian Ocean Experiment Provided Direct Chemical, Microphysical and Radaiometric Evidence that absorbing aerosols can lead to 10 to 15% reduction in seasonal averaged solar radiation at the surface over a large area, as large as the entire Arabian sea, Bay of Bengal and the S. Asian Region an area as large as USA;

**Satheesh and Ramanathan, 2000;**
**Ramanathan et al, 2001;**
**over 100 papers and two special volumes in JGR**

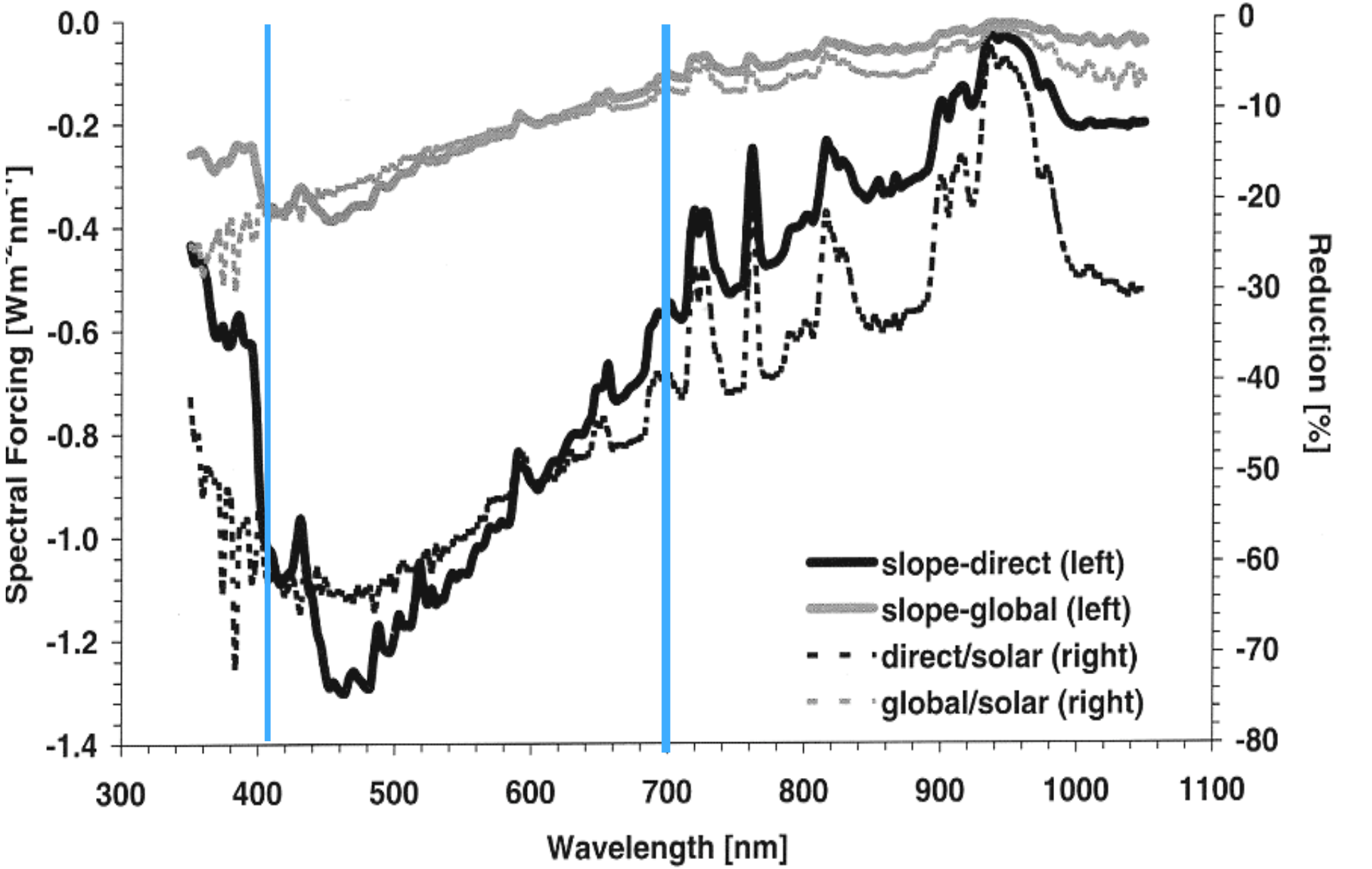
# Direct Evidence

Ref: Meywerk and Ramanathan, 1999; 2004



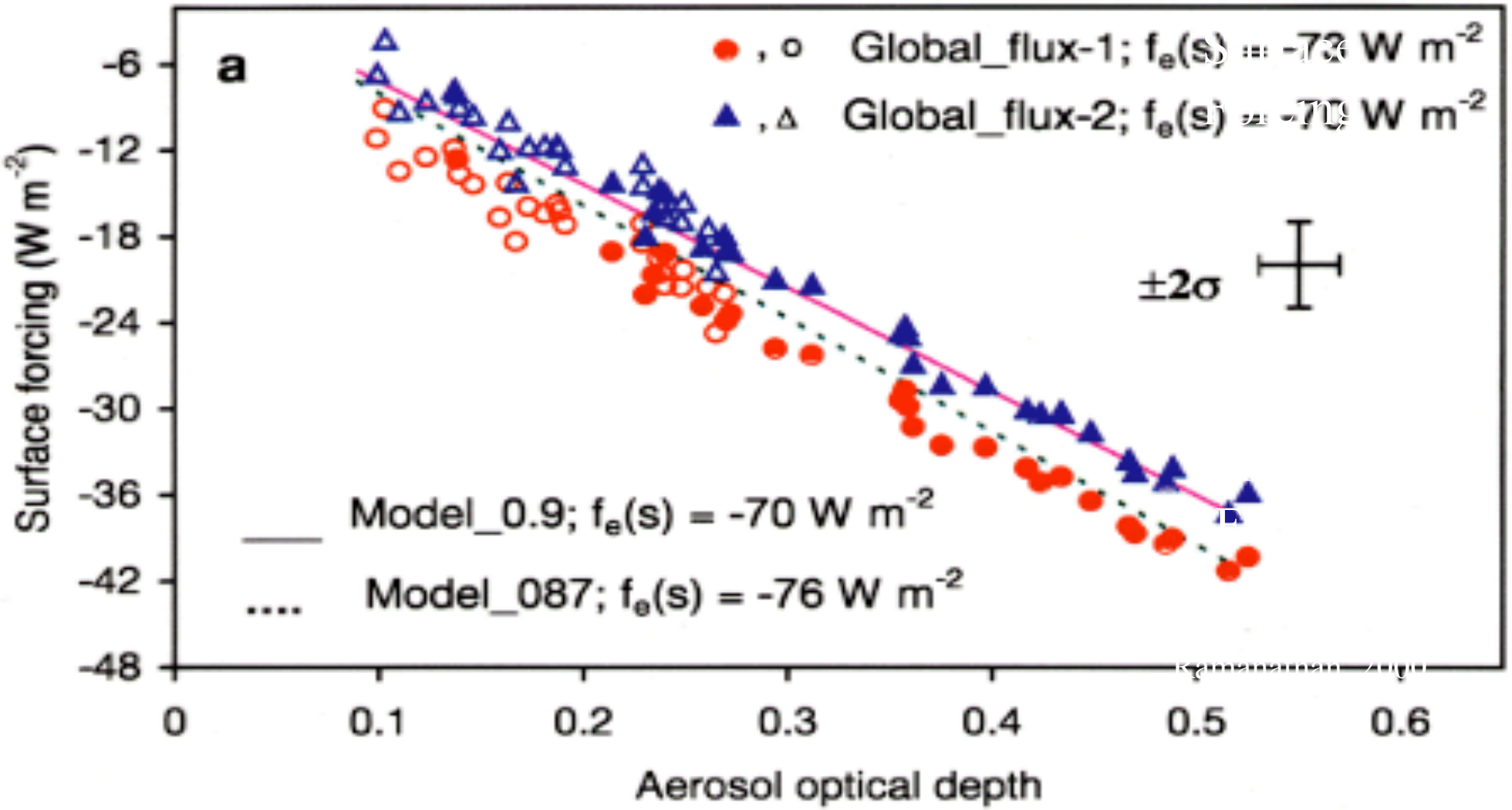
# Spectral Radiative Forcing

# Meywerk & Ram, 2003



# Direct observations: Clear-sky Forcing Efficiency

**Satheesh and Ramanathan, Nature 2000**



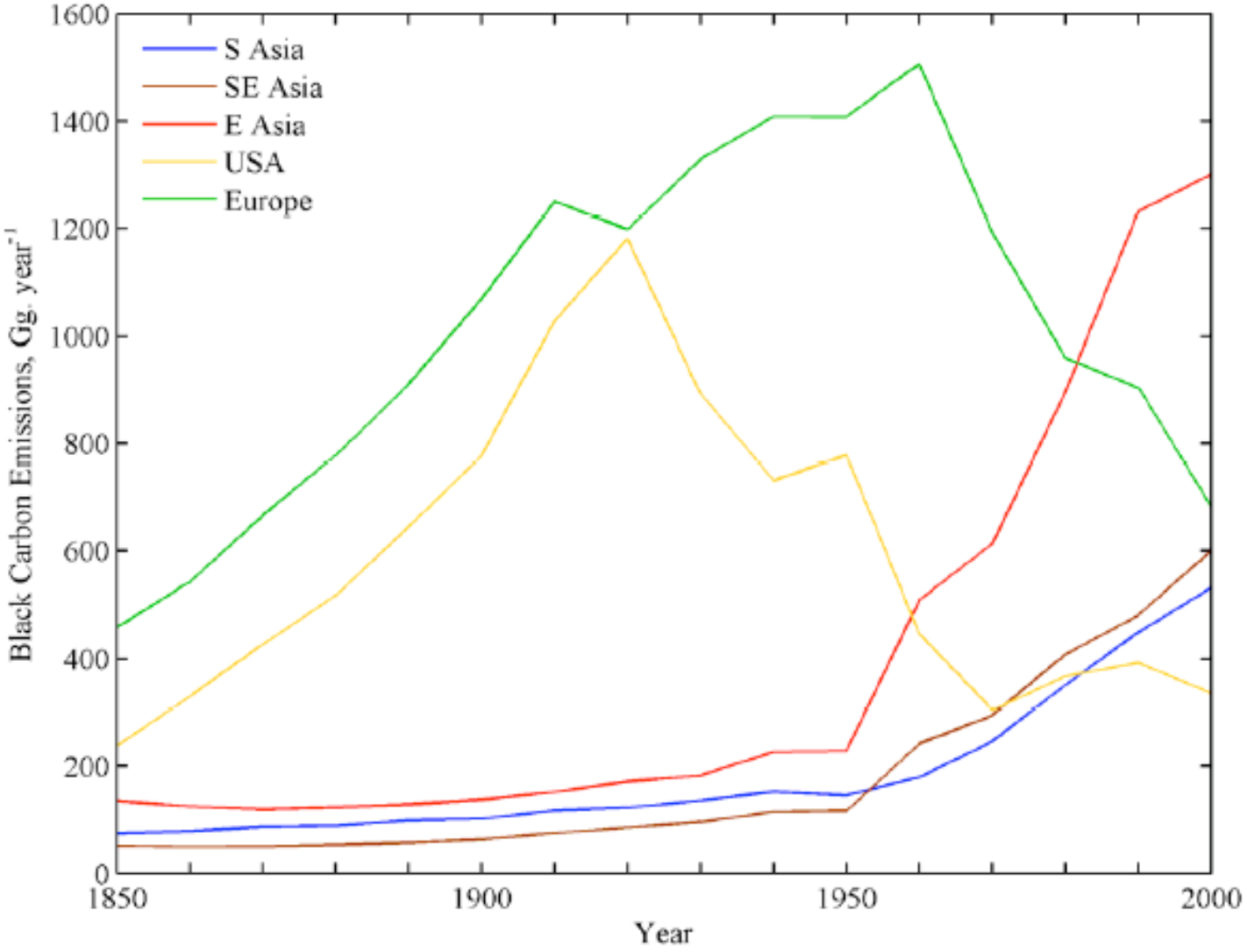
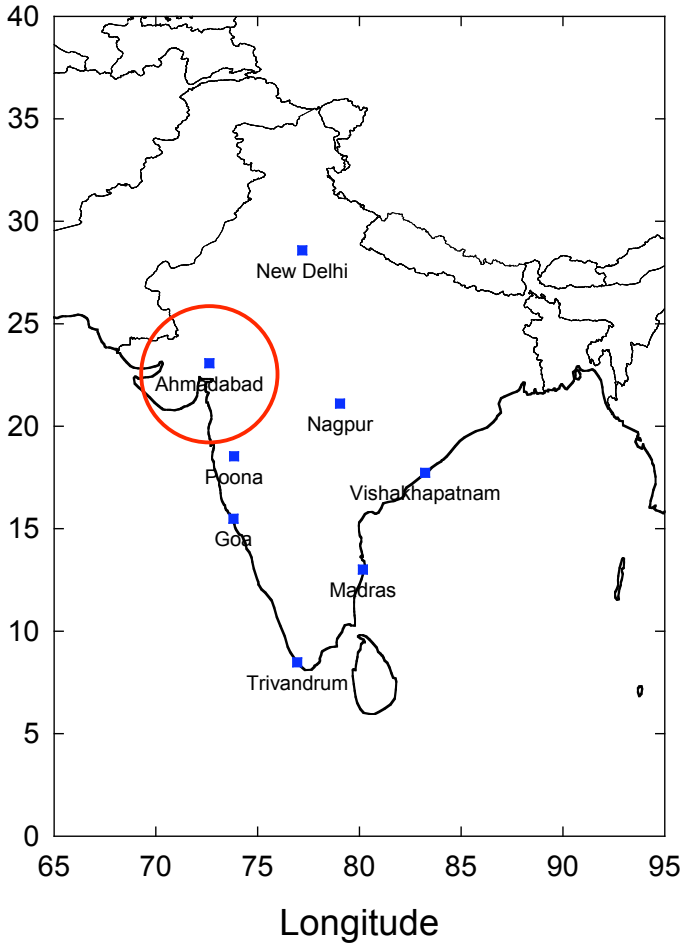
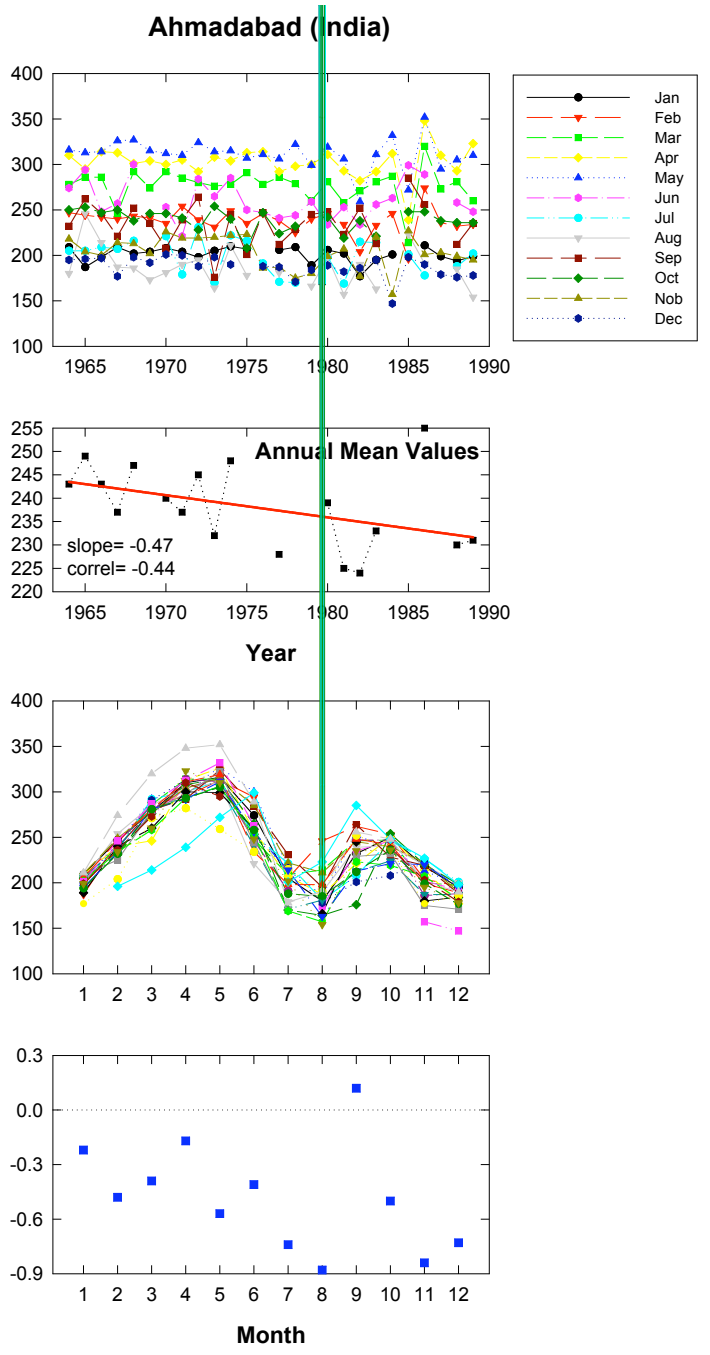



**Figure 2.19** Black carbon emissions for 1998 (Source: Bond *et al.,* 2004).

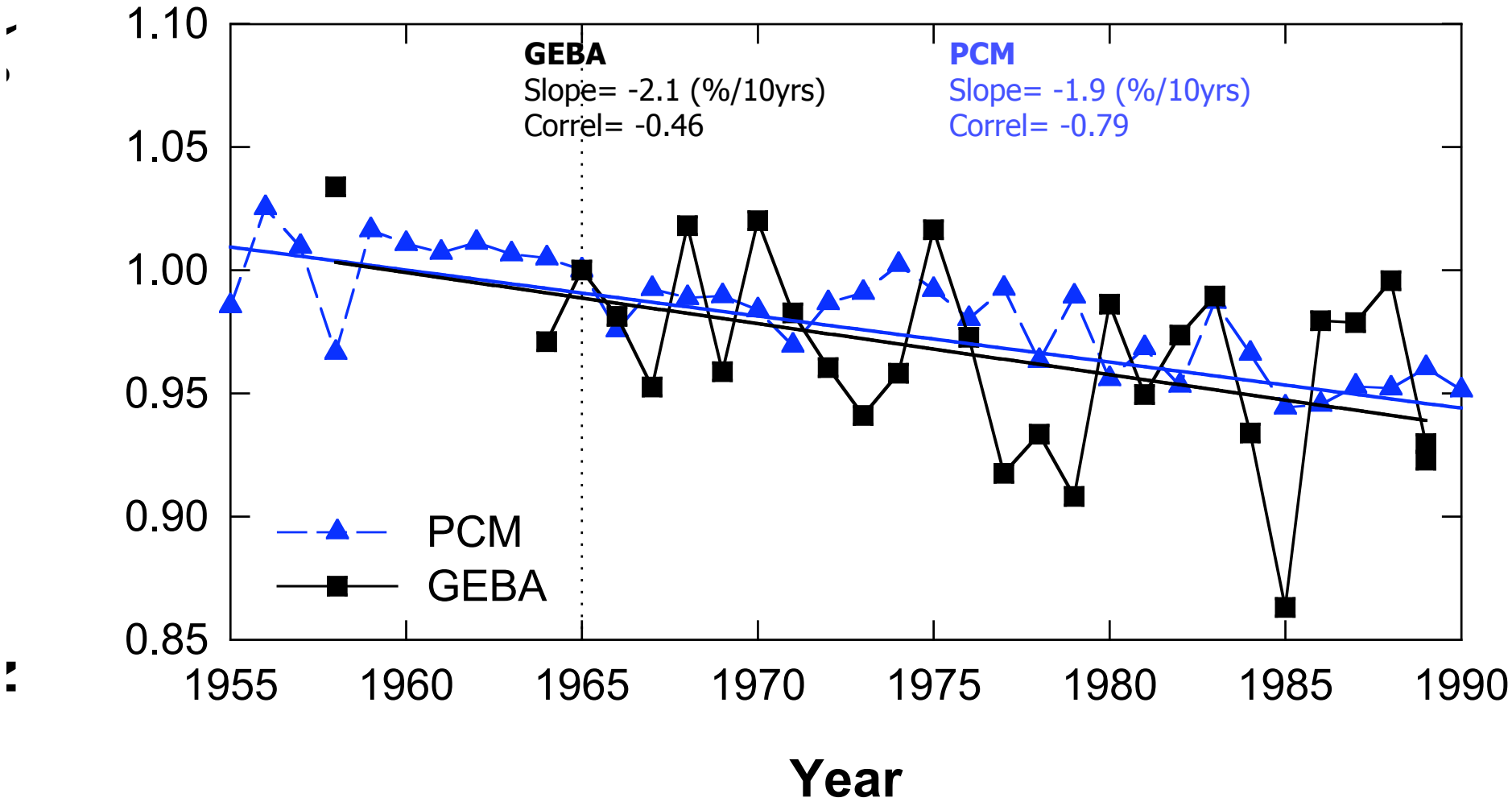
# India


New Delhi
Ahmadabad
Nagpur
Poona
Vishakhapatnam
Goa
Madras
Trivandrum
Longitude


Ahmadabad (India)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nob
Dec
Annual Mean Values
slope= -0.47
correl= -0.44
Year
Month

# GEBA and PCM Estimated Trends in Surface Solar Radiation: March.

***All values were Normalized with 1965 Values; For West Coast Only***



Wild et al, 1995

**ABSORBED SOLAR RADIATION AT THE SURFACE**

**Models Vs Pyranometer Observations**

**GLOBAL ANNUAL MEAN; Average Cloudy Skies**

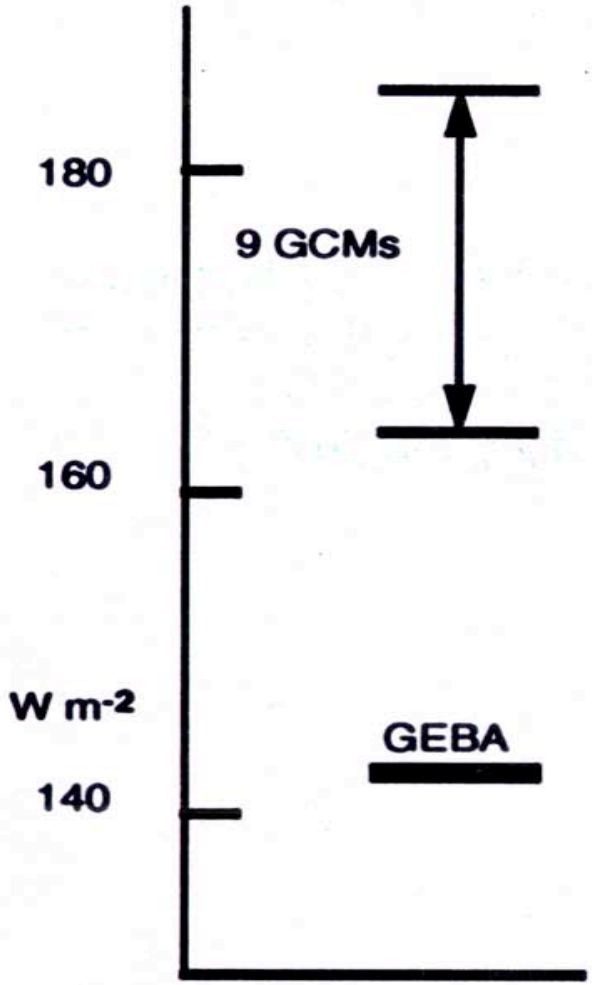
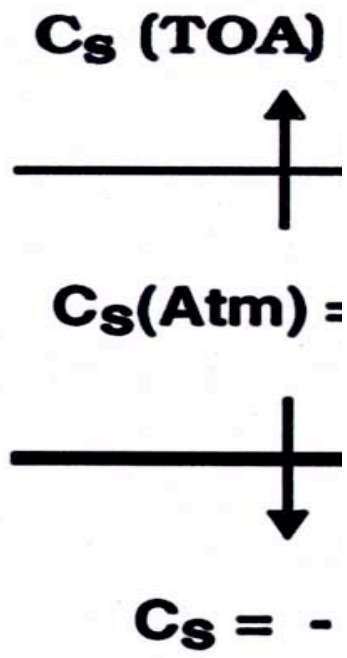


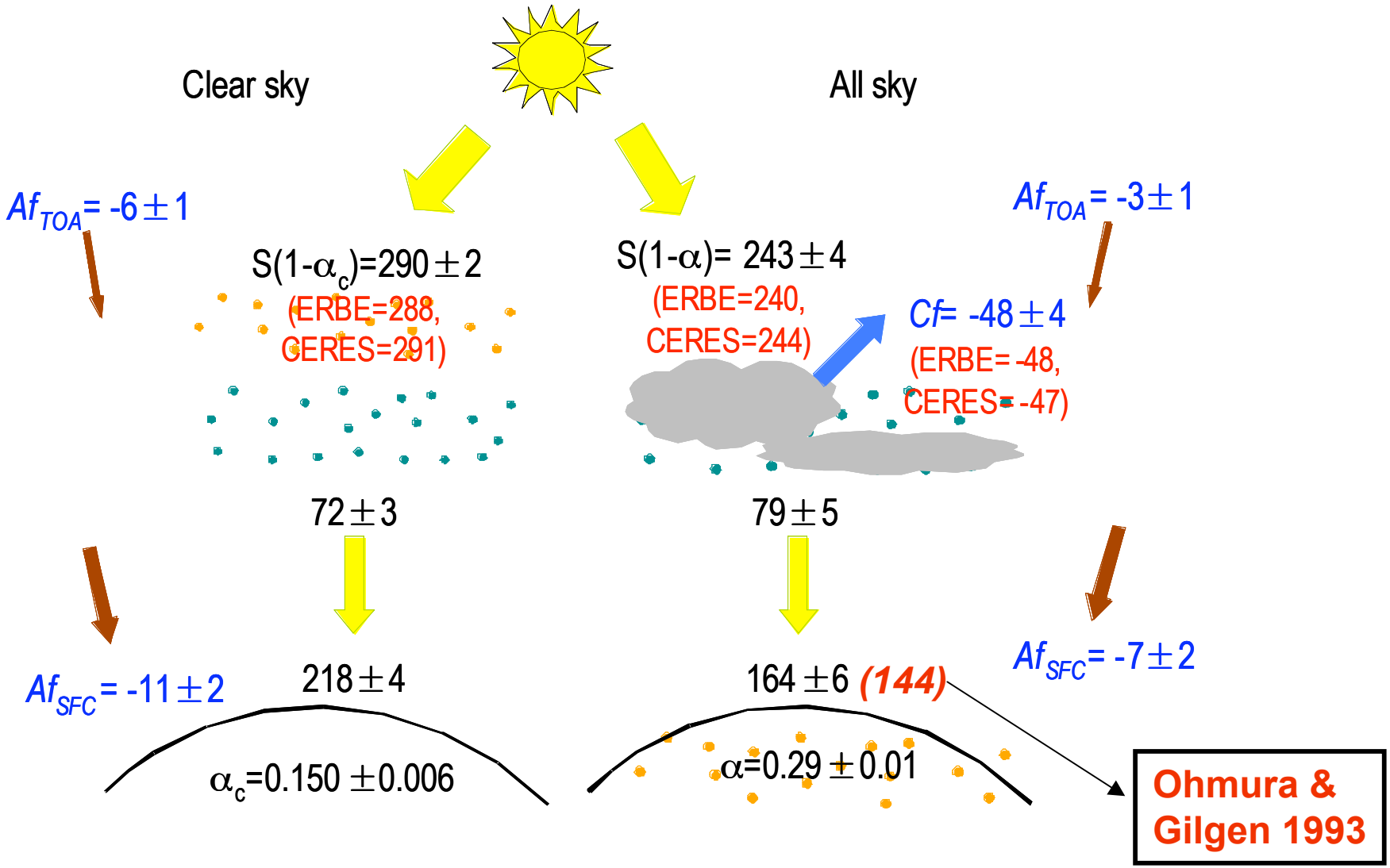

Figure 4. Comparison of the global annual mean shortwave absorbed at the surface as estimated from models and observations. The arrow indicates the range of values computed by nine general circulating models (GCMs). Observations are

Tropical Western
Ramanathan



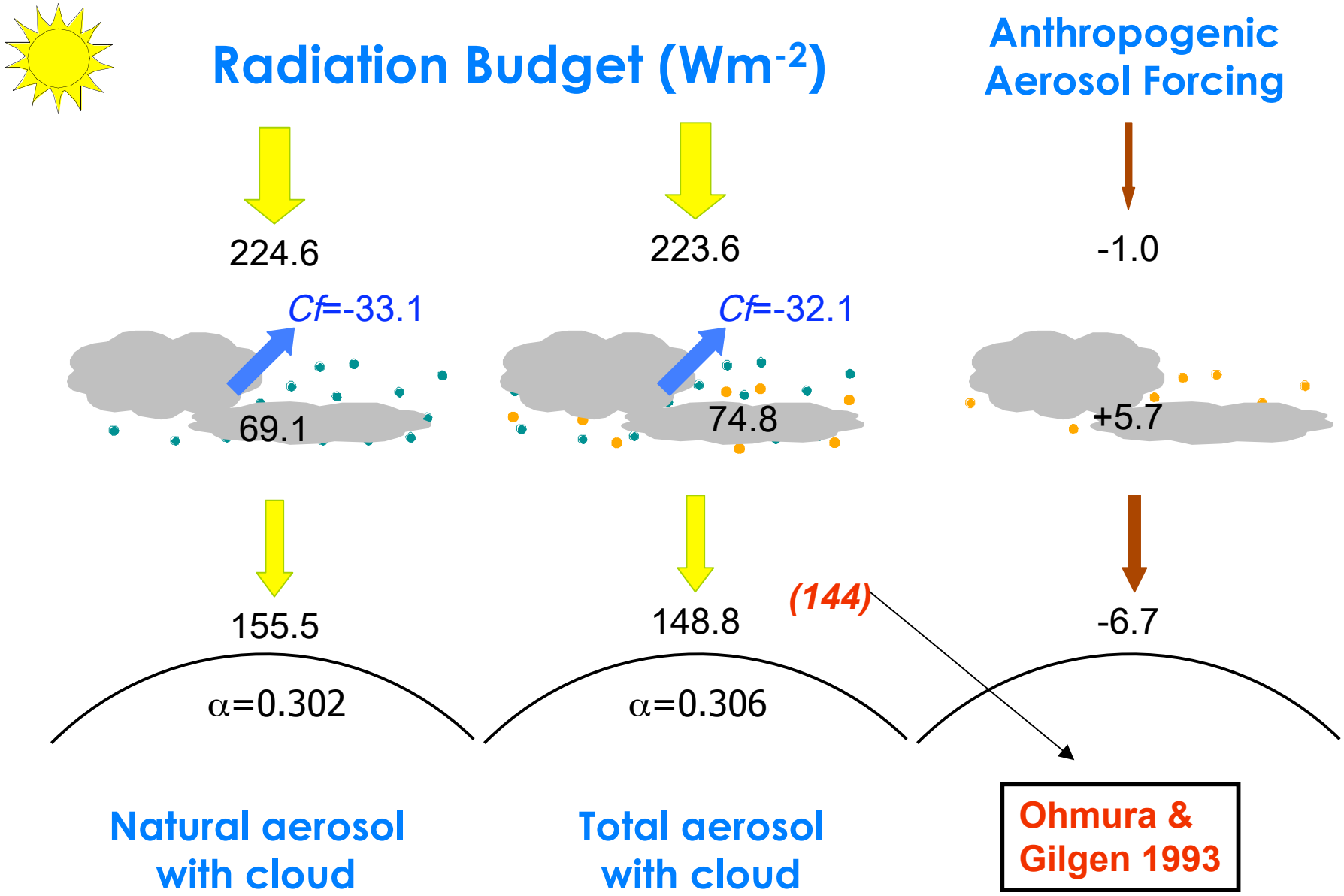

Units: W m-2

Figure 5. Excess al
presented. Cs is t
average cloudy sky
respectively, the TC
plus atmospheric co
The warm pool unc
global values, the T
TOA cloud forcing i

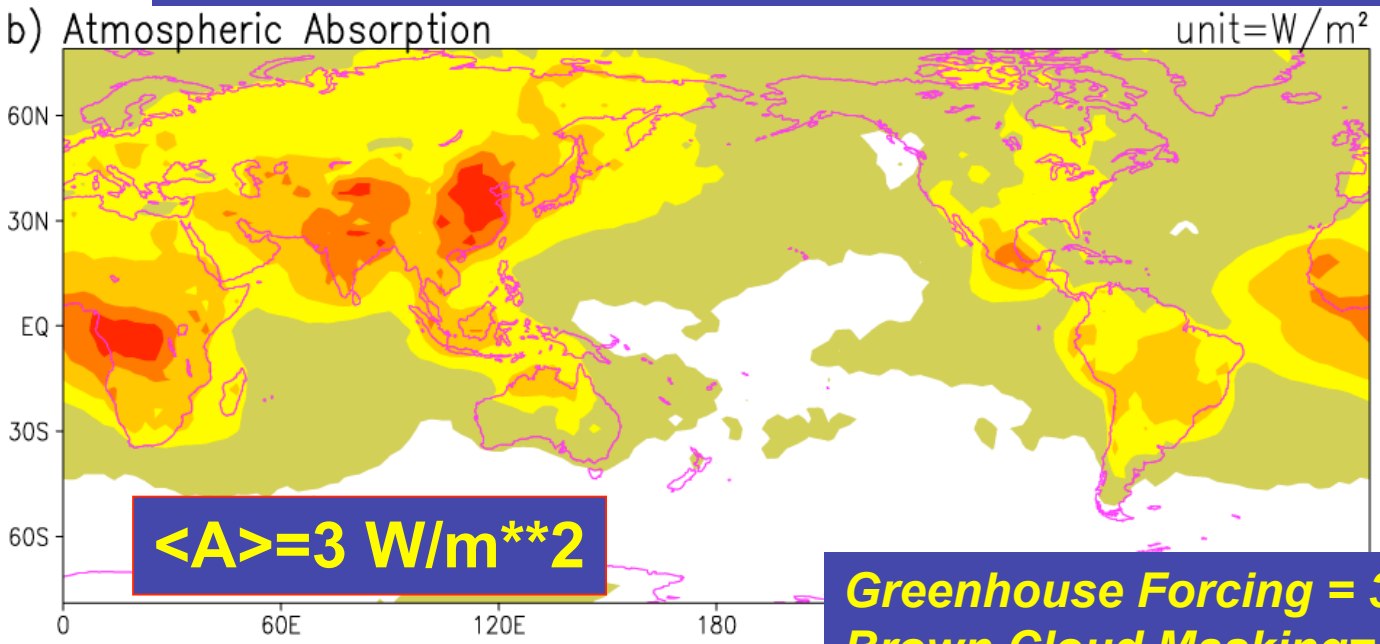



***Revised Solar Radiation Budget : Kim and Ramanathan, JGR, 2008***

# NH Land mean solar radiative fluxes: Cloudy sky



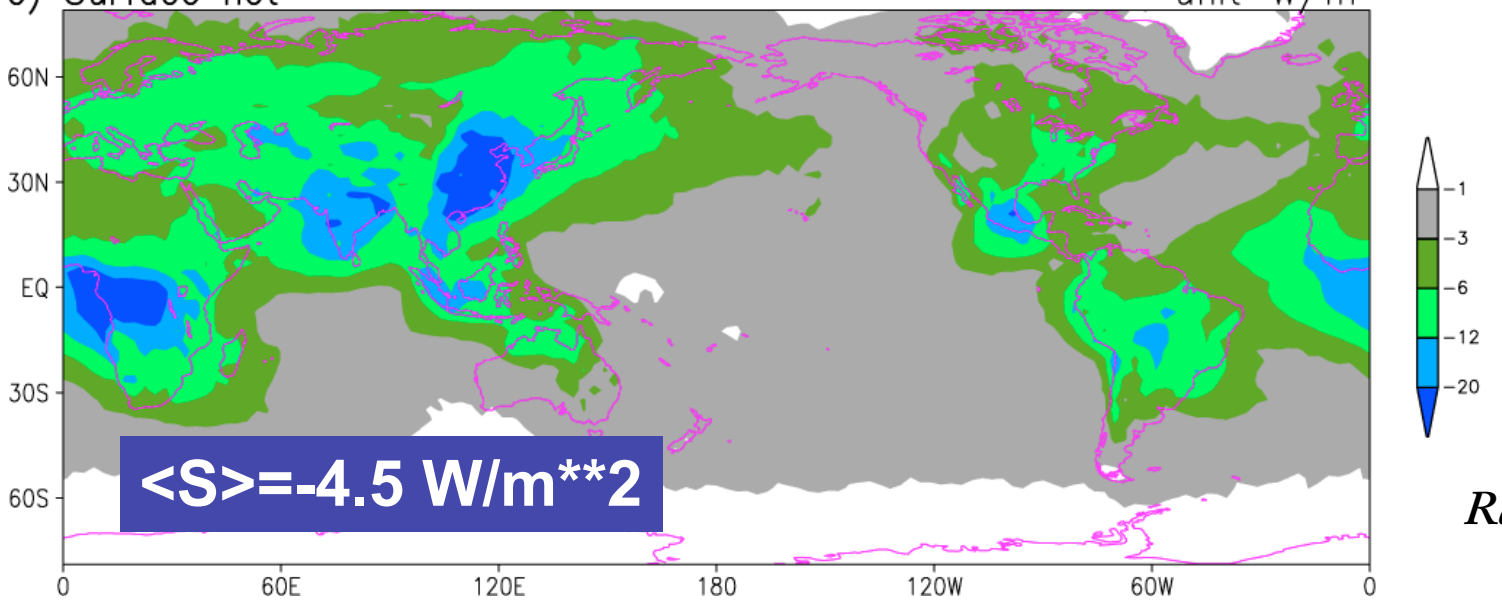
# Surface Dimming & Atmospheric Heating by Brown Clouds: 2000-2003




<A>=3 W/m**2

Chung, Ramanathan, Kim, Podgorny,2005

*Greenhouse Forcing = 3 W/m**2*
*Brown Cloud Masking= -1.5 (+-50%) W/m**2*




<S>=-4.5 W/m**2

*Ramanathan 2007*

# Future Missions Planned by our Team

*1. Light Weight UAVs as Airborne Observatories*

***Profiling aerosol-chemistry-air pollution in California***

•CAPPS (funded by CEC) (2007- )

*2. Olympics Campaign*

***Definitive Measurements of Cloudy Sky Solar Absorption Indirect Effect of Aerosols***

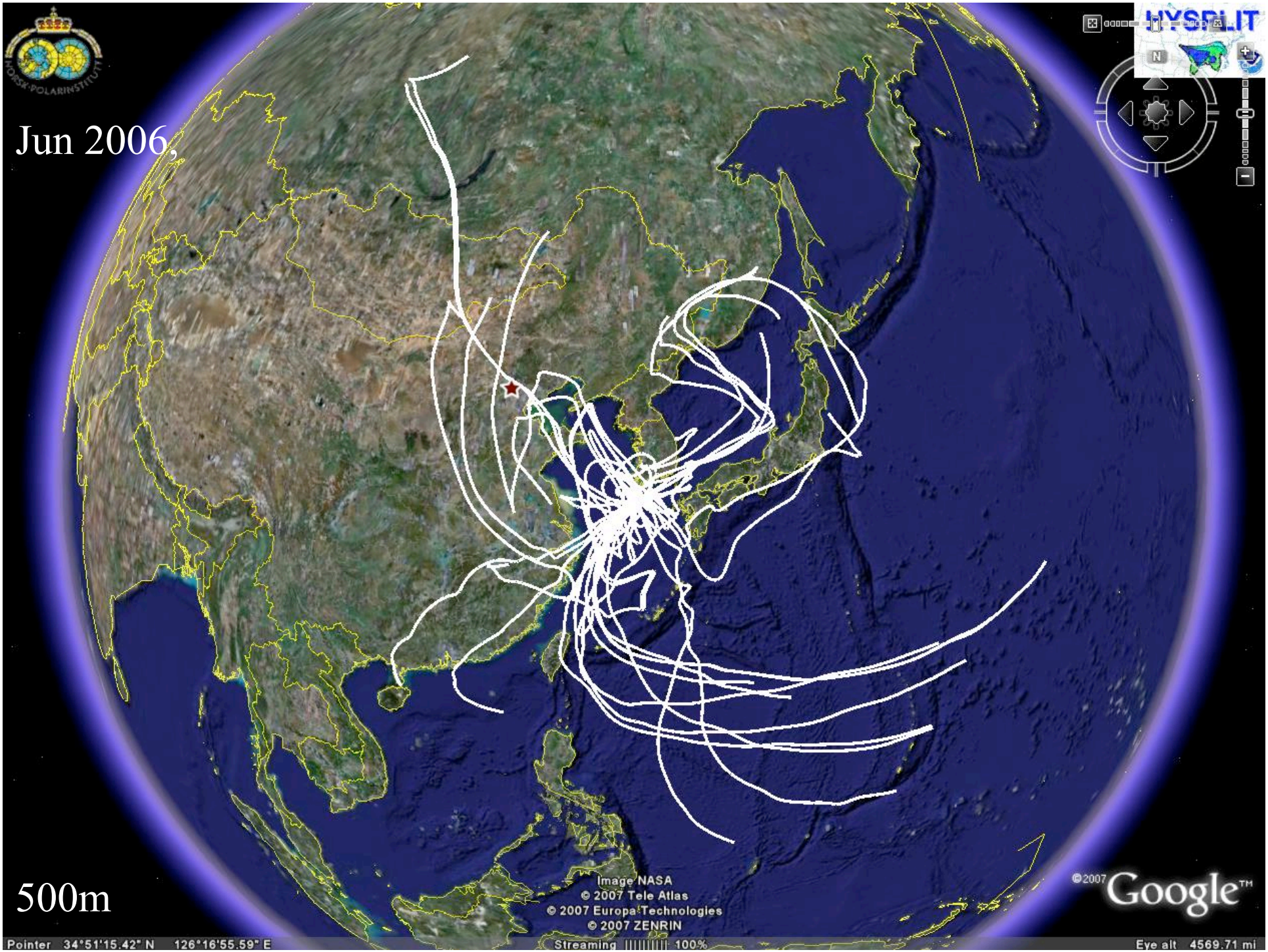
- ***Marine stratocumulus clouds (Pilot 2009; Campaign: 2010)***
- ***{ With M Ralph; G McFarquhar; Marshak; }***

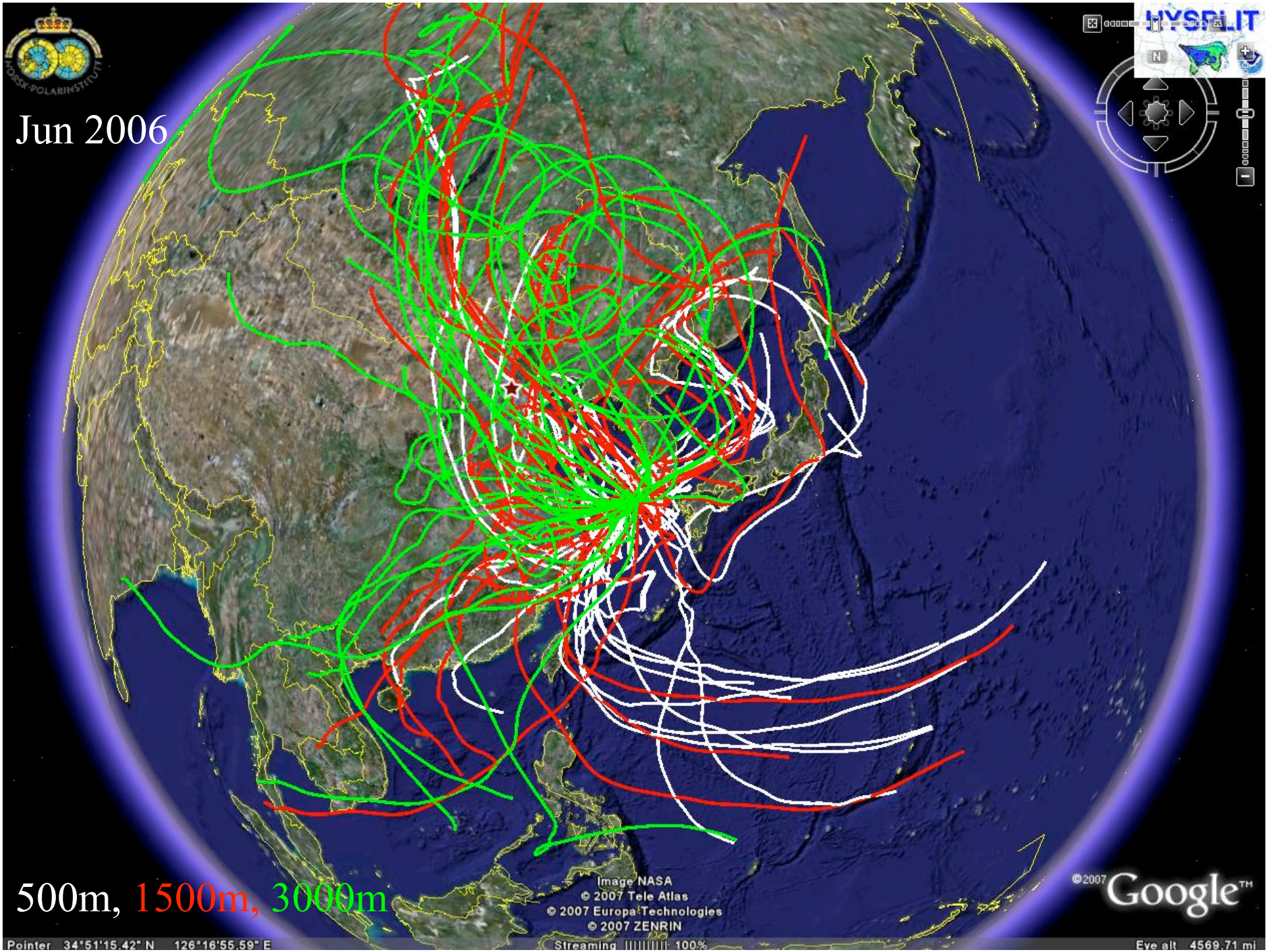
# Measurements for CAPPS

( Corrigan, Ramana, Lehmann, Nguyen, Ramanathan

- 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

Funded by CEC


Jun 2006,
500m
HYSPLIT
Image NASA
© 2007 Tele Atlas
© 2007 Europa Technologies
© 2007 ZENRIN
©2007 Google™
Pointer 34°51'15.42" N 126°16'55.59" E
Streaming 100%
Eye alt 4569.71 mi


Jun 2006
500m, 1500m, 3000m
HYSPLIT
Image NASA
© 2007 Tele Atlas
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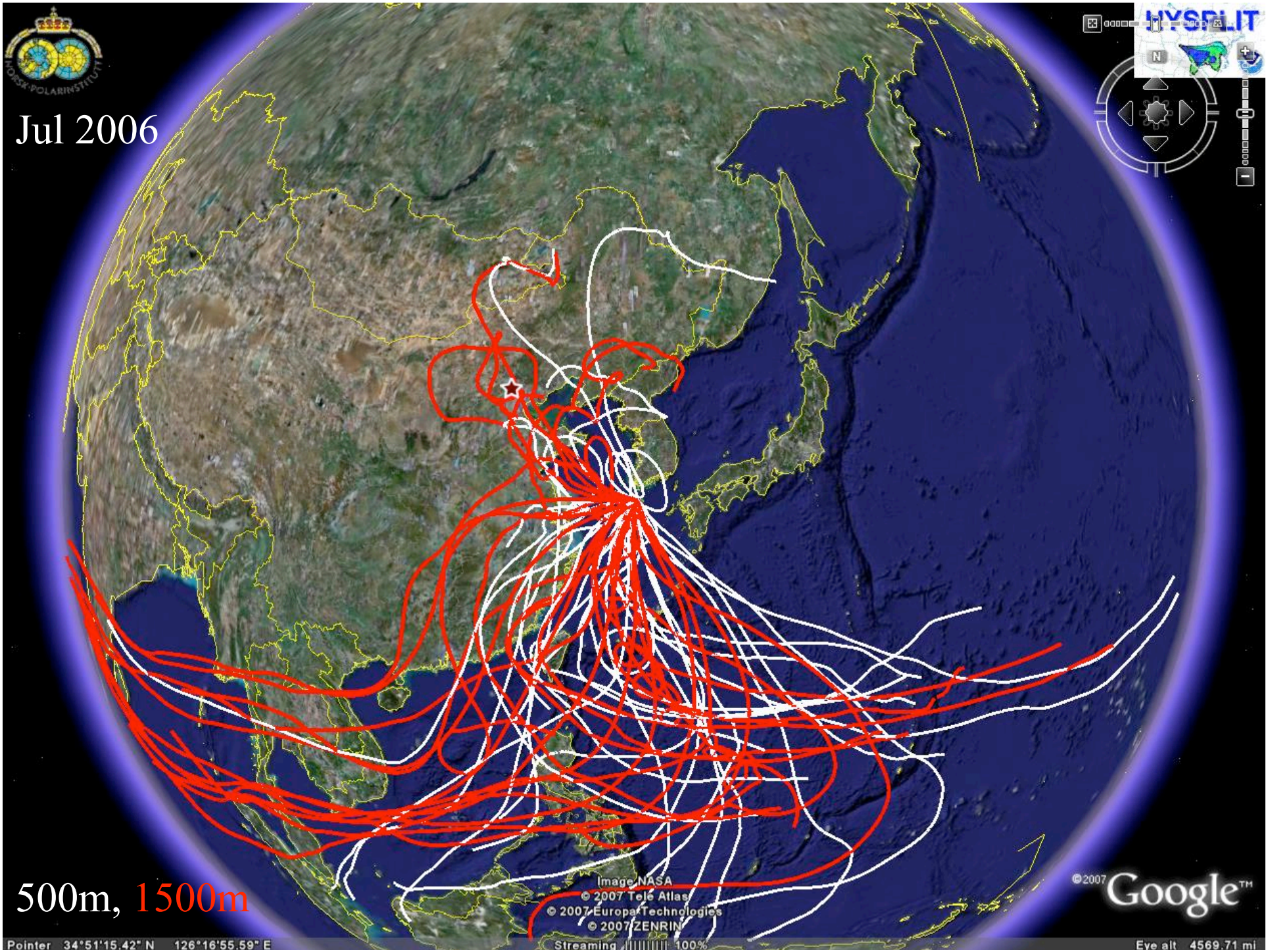
Pointer 34°51'15.42" N 126°16'55.59" E
Streaming 100%
Eye alt 4569.71 mi


Jul 2006
HYSPLIT
500m, 1500m
Image NASA
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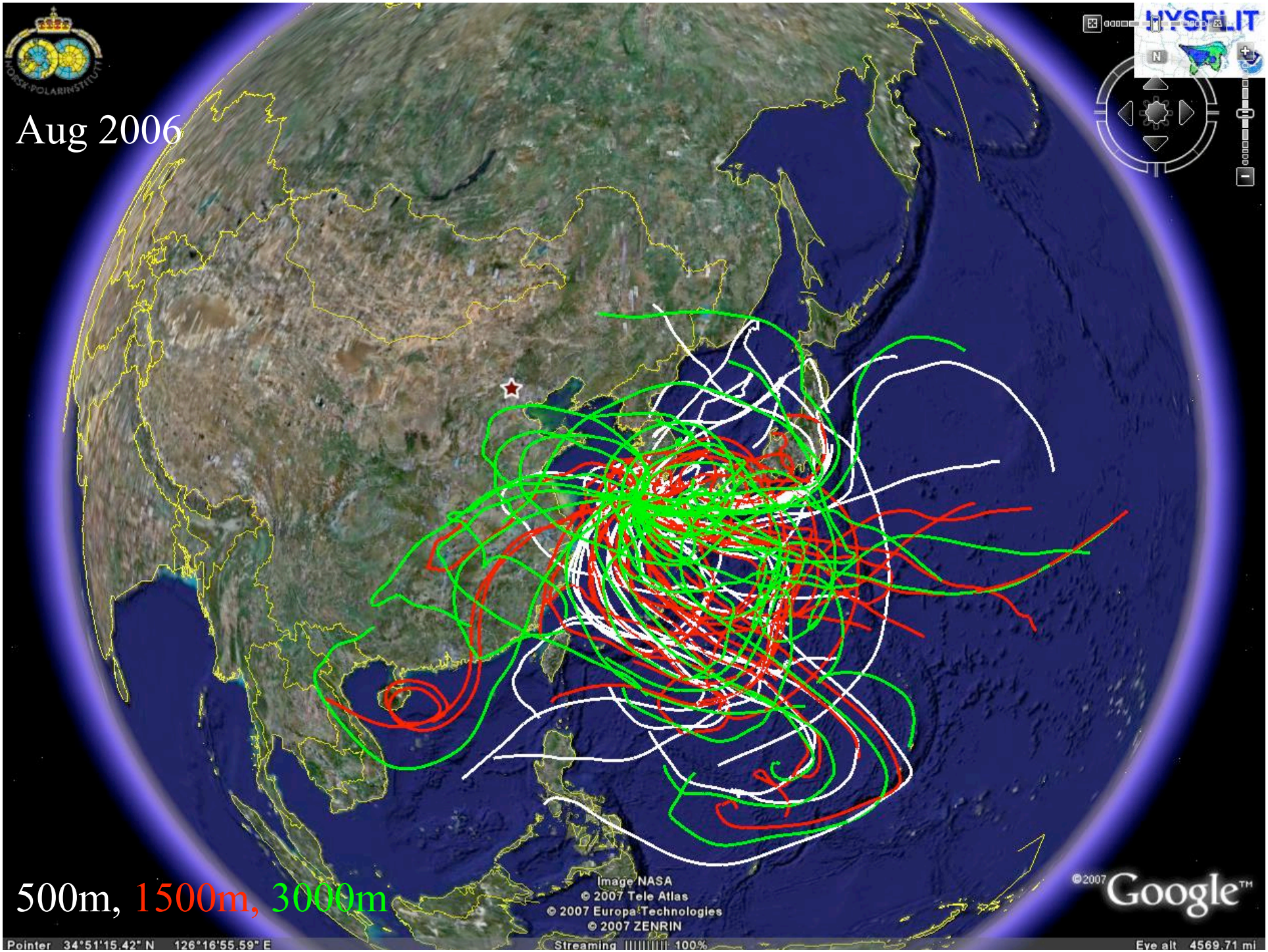
Pointer 34°51'15.42" N 126°16'55.59" E
Streaming 100%
Eye alt 4569.71 mi


Aug 2006
HYSPLIT
500m, 1500m, 3000m
Image NASA
© 2007 Tele Atlas
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© 2007 ZENRIN
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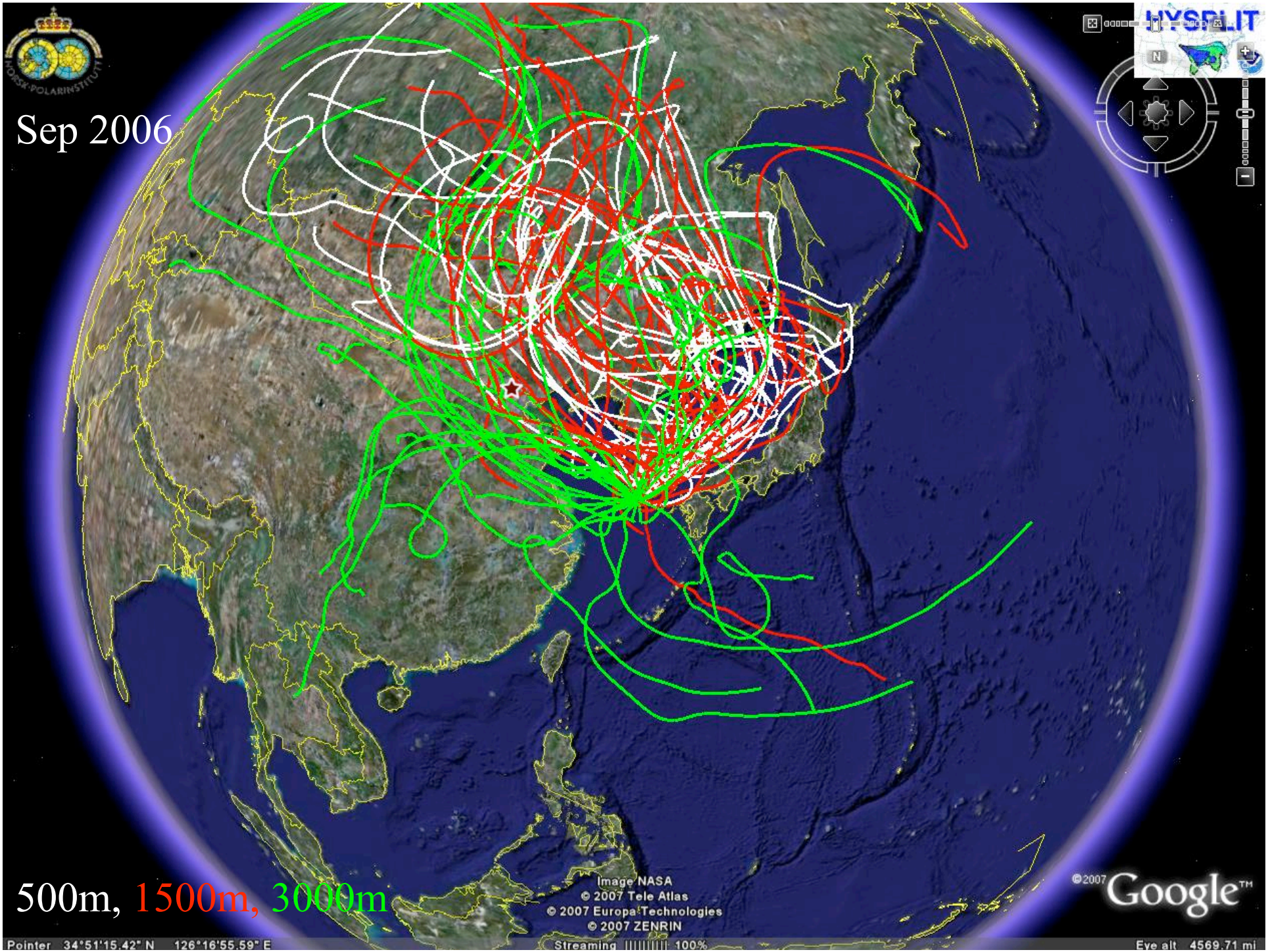
Pointer 34°51'15.42" N 126°16'55.59" E
Streaming 100%
Eye alt 4569.71 mi


Sep 2006
500m, 1500m, 3000m
HYSPLIT
Image NASA
© 2007 Tele Atlas
© 2007 Europa Technologies
© 2007 ZENRIN
©2007 Google™
Pointer 34°51'15.42" N 126°16'55.59" E
Streaming 100%
Eye alt 4569.71 mi

Thank You

1) NSF/ NOAA/NASA/Vetlesen/Alderson
2) Maldives Govt
3) Fahey/Fein/Koblinky/Kuettner/Maring/Yuhas
4) NASA-Dryden (Curry/Jennison)

Scripps Team: Hung/Roberts/Ramana/Corrigan/Kim/Li

ACR Team: Patterson/Mulligan/ Maldives Crew