The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2018-26

Winter College on Optics in Environmental Science

2 - 18 February 2009

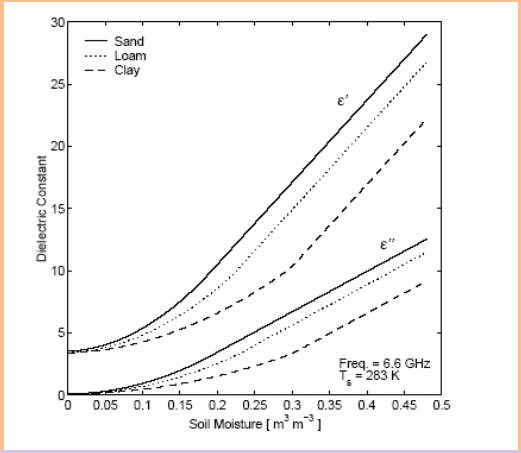
Optical Remote Sensing and applications in monitoring Earth and its surroundings

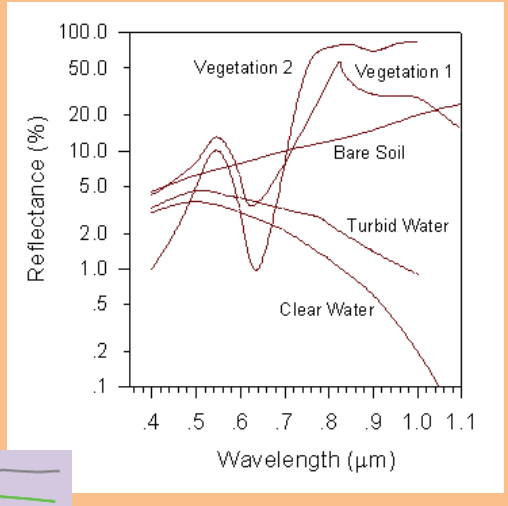
Singh R.P.
George Mason University
U.S.A.

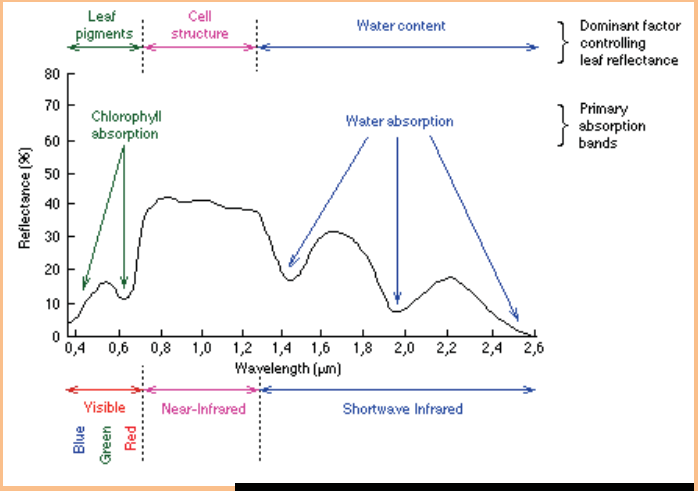
Winter College on "Optics in Environmental Science"

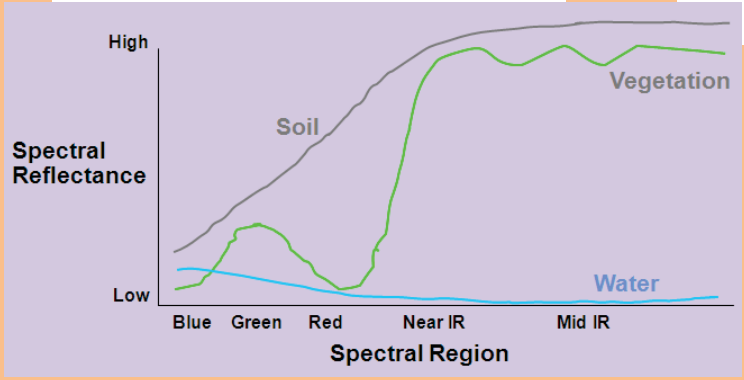
Optical Remote Sensing and Applications in Monitoring Earth and Its Surroundings

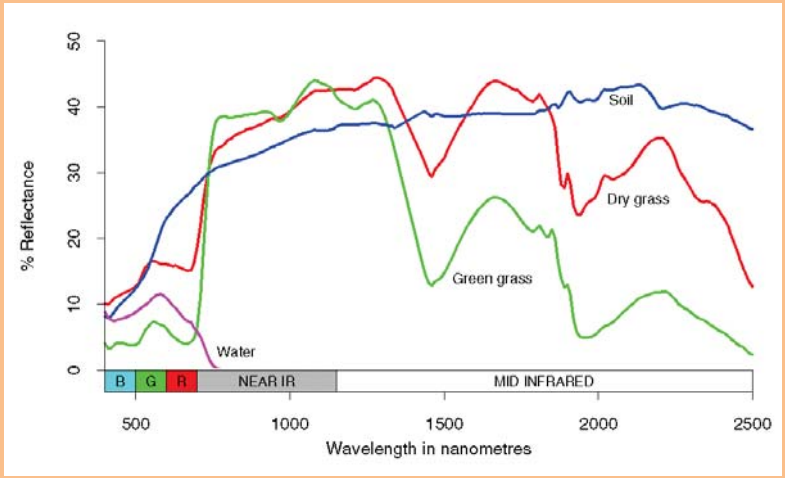
Ramesh P. Singh
Professor
Chapman University
Orange, CA, USA
rpiitkanpur@gmail.com

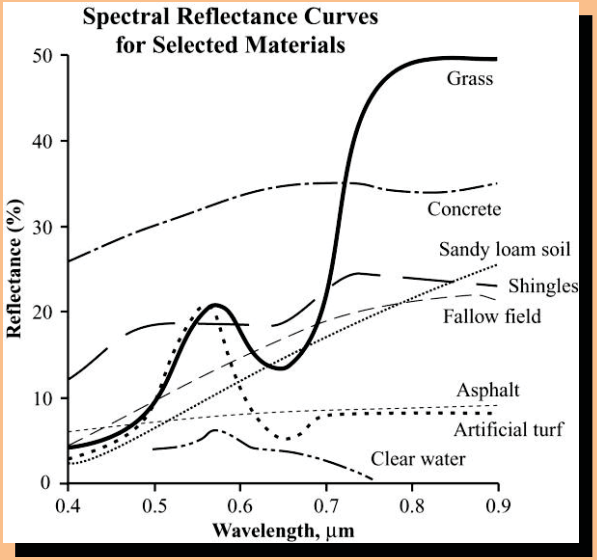

Sand
Loam
Clay
ε'
ε''
Freq. = 6.6 GHz
T_s = 283 K
Dielectric Constant
Soil Moisture [m³ m⁻³]

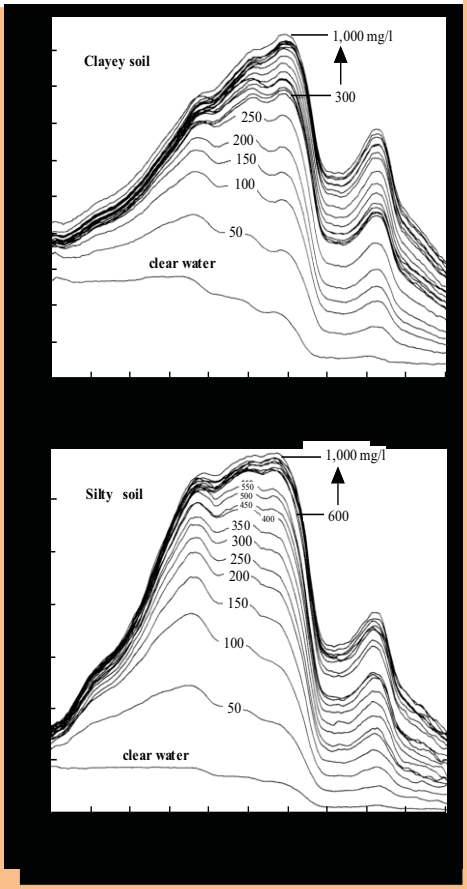

Vegetation 2
Vegetation 1
Bare Soil
Turbid Water
Clear Water
Reflectance (%)
Wavelength (μm)


Leaf pigments
Cell structure
Water content
Dominant factor controlling leaf reflectance
Chlorophyll absorption
Water absorption
Primary absorption bands
Reflectance (%)
Wavelength (μm)
Visible
Near-Infrared
Shortwave Infrared
Blue
Green
Red


High
Low
Spectral Reflectance
Soil
Vegetation
Water
Blue
Green
Red
Near IR
Mid IR
Spectral Region


% Reflectance
Soil
Dry grass
Green grass
Water
B
G
R
NEAR IR
MID INFRARED
Wavelength in nanometres

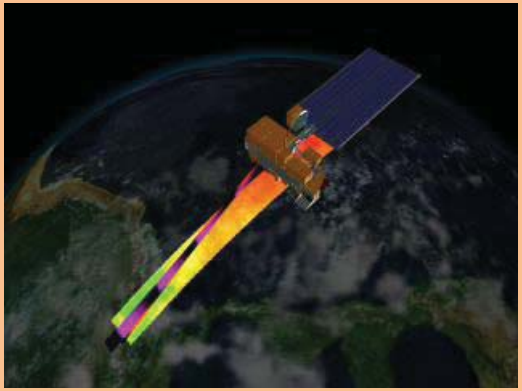

Spectral Reflectance Curves
for Selected Materials
Grass
Concrete
Sandy loam soil
Shingles
Fallow field
Asphalt
Artificial turf
Clear water
Reflectance (%)
Wavelength, μm


Clayey soil
1,000 mg/l
300
250
200
150
100
50
clear water
Silty soil
1,000 mg/l
600
550
500
450
400
350
300
250
200
150
100
50
clear water

Multi Sensor Data to understand Natural Hazards and Coupling Process

Satellites

- MODIS
- MISR
- AVHRR
- OMI AURA
- SPOT VEG
- SCIAMACHY
- IRS
- TOMS
- AIRS
- MOPITT
- TRMM
- ASTER
- LANDSAT
- CALIPSO
- CloudSat etc



- Aerosols
- Clouds
- Water Vapor
- Greenhouse and other gases
  CO, CO_2, NOx, SOx, CH_4
- Radiative Forcing
- Fog, Haze and Smog
- Vegetation
- Rainfall
- Drought
- Floods
- Hurricanes

Ground based

- Sun-photometer
  - CIMEL (AERONET)
- GPS
  - GPS Meteorology
- Automatic weather station
- Buoy
- Radio-sonde
- Survey

Models & other Data

- HYSPLIT
- ISCST3
- SBDART
- OPAC
- NCEP-CDC
- GPCP
- COLA

- **Earth - Land, Land cover, Ocean and Atmosphere**
- **Land cover – Forests, Vegetation, Water, Snow and laciers**
- **Earth Process – Plate motion**
- **Ocean - Ocean ecology, Harmful algal blooms, Ocean wave and wave height**
- **Snow - Characteristics and state of snow**
- **Glaciers - characteristics and movements**

Weather and Weather conditions

- Radio and Television News, using satellite Remote Sensing data

Natural Hazards –

- Earthquakes,
- Volcanoes,
- Landslides,
- Droughts,
- Floods,
- Forest Fire,
- Dust storms
- Cyclone/Hurricanes/Typhoons
- Oil spills
- Harmful algal blooms

Meteorological Parameters

- Rainfall
- Surface and Air temperature
- Surface Wind
- Water vapor
- Relative humidity
- CO, CO2, NOx, SO2, and other trace gases
- Ozone

Pollution

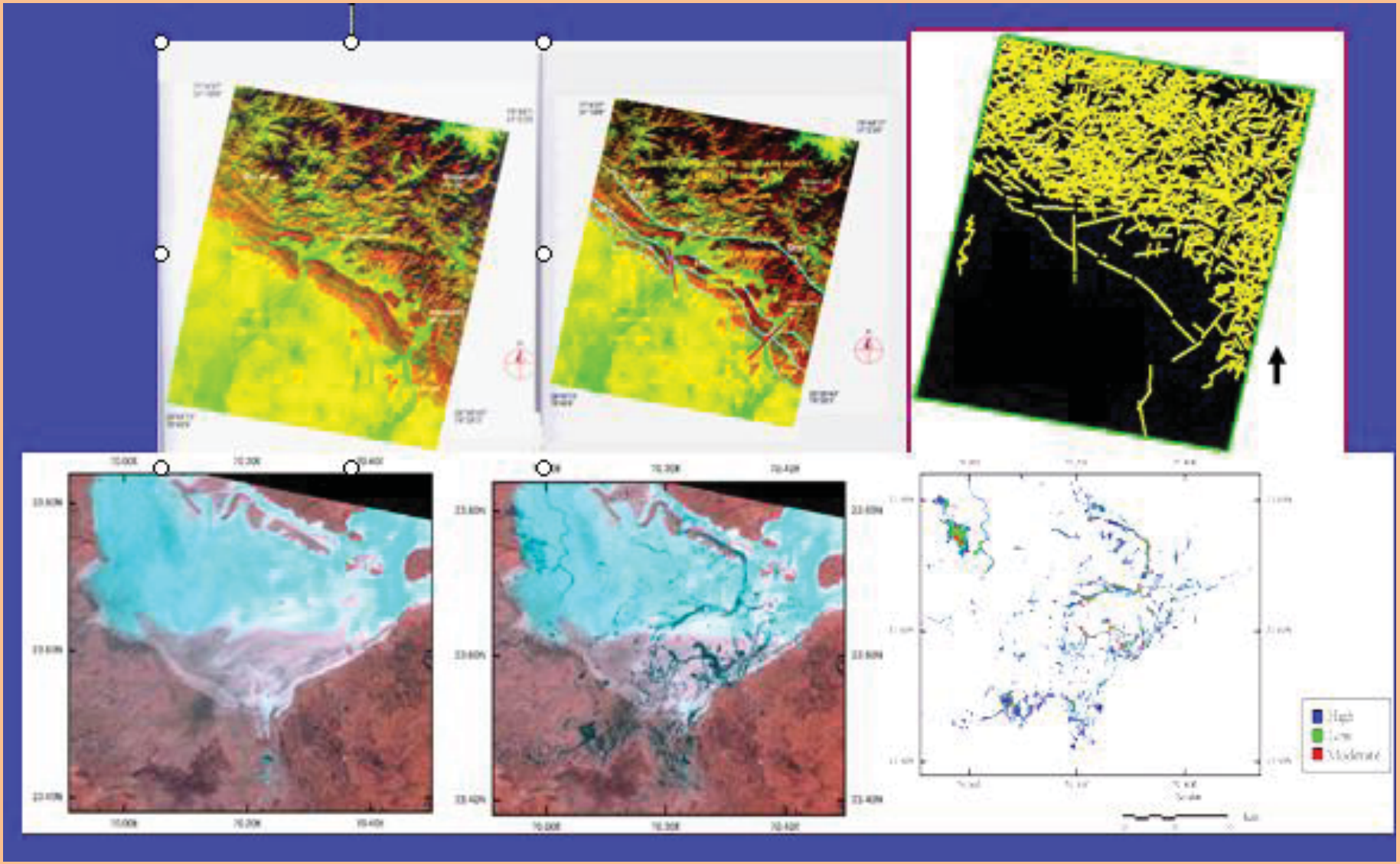
- Air Pollution
- Water Pollution
- Land contamination (soil characteristics)
- Snow contamination (due to dust)

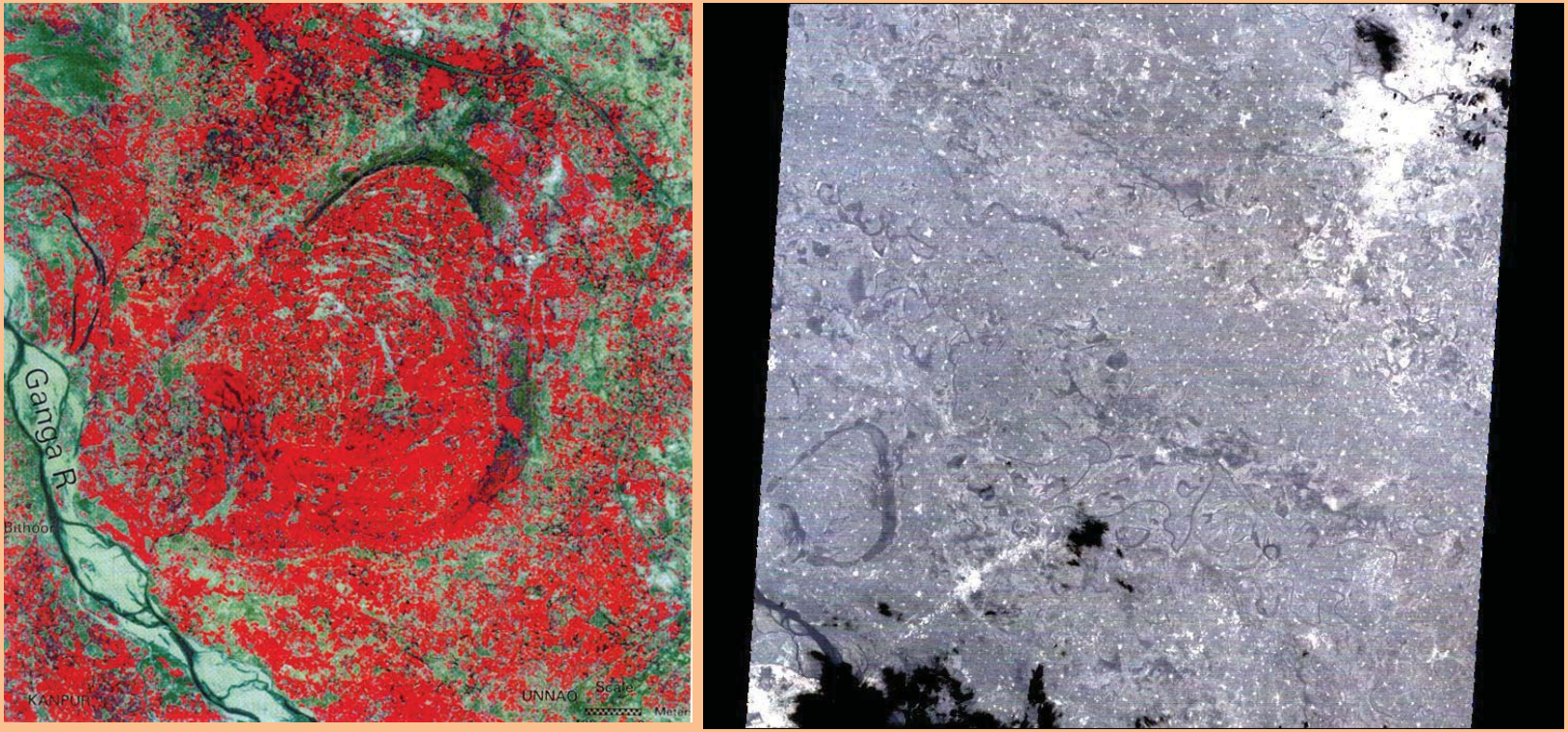
Agriculture applications

- Crop discrimination
- Crop Acreage estimation
- Crop yield
- Decision about irrigation
- Soil moisture
- Drought conditions

- Land Related applications
- Urban planning
- Maps
- Soil and Rocks, surface terrain
- Change detection studies

- Geological Applications

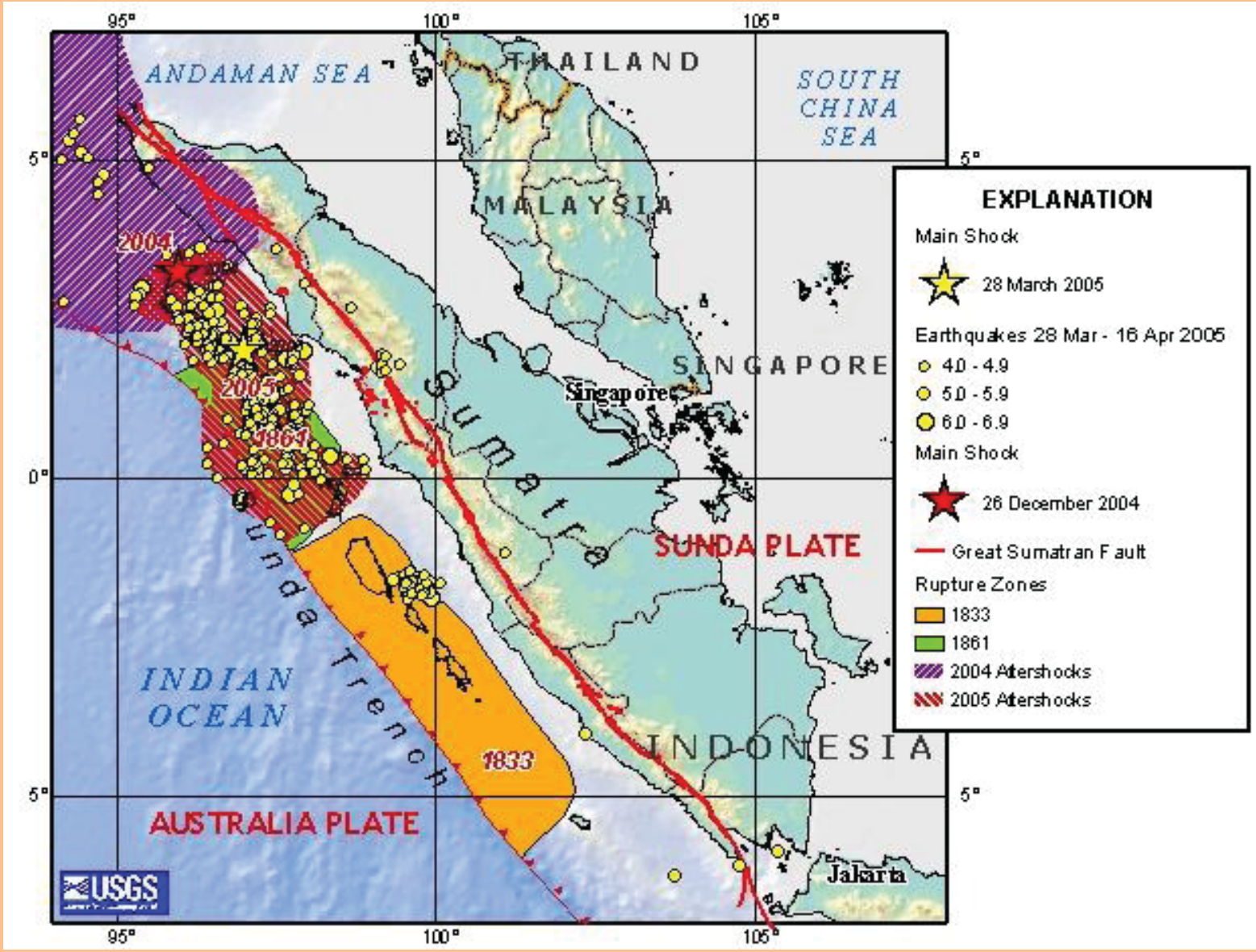




Satellite image showing the migration of river

Location of Epicenter

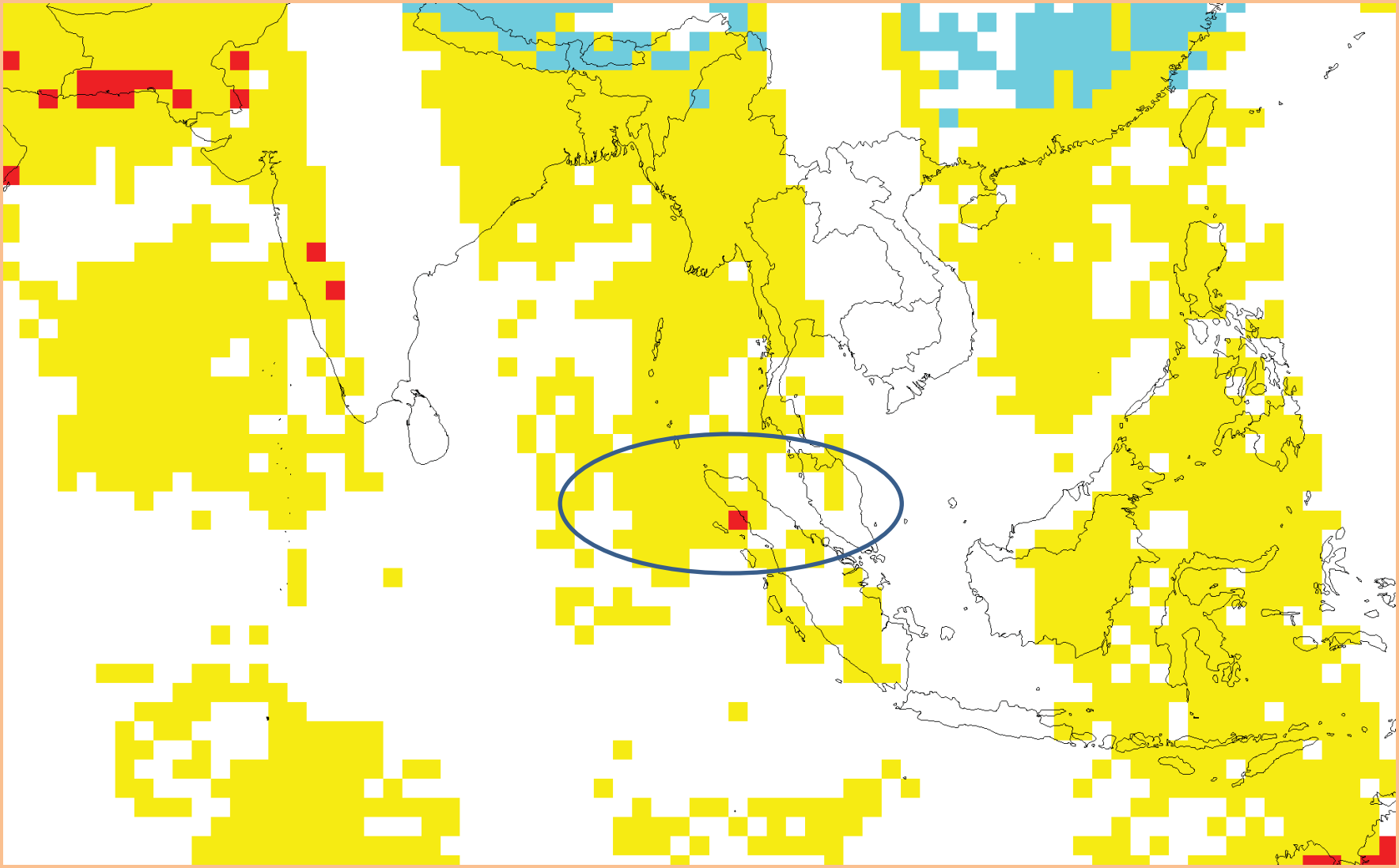
(Sumatra Earthquake; Dec 26, 2004 and March 28, 2005)

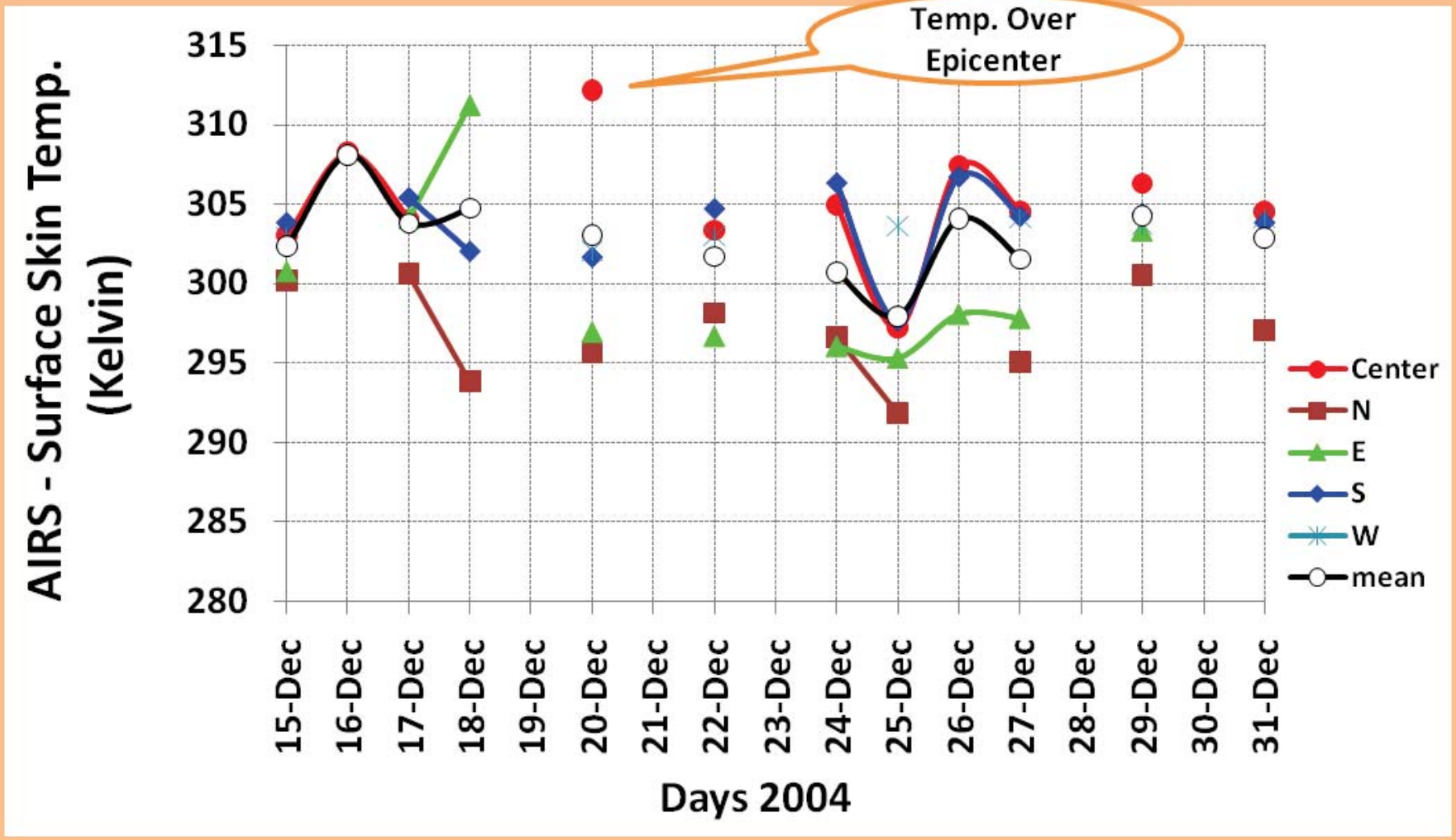


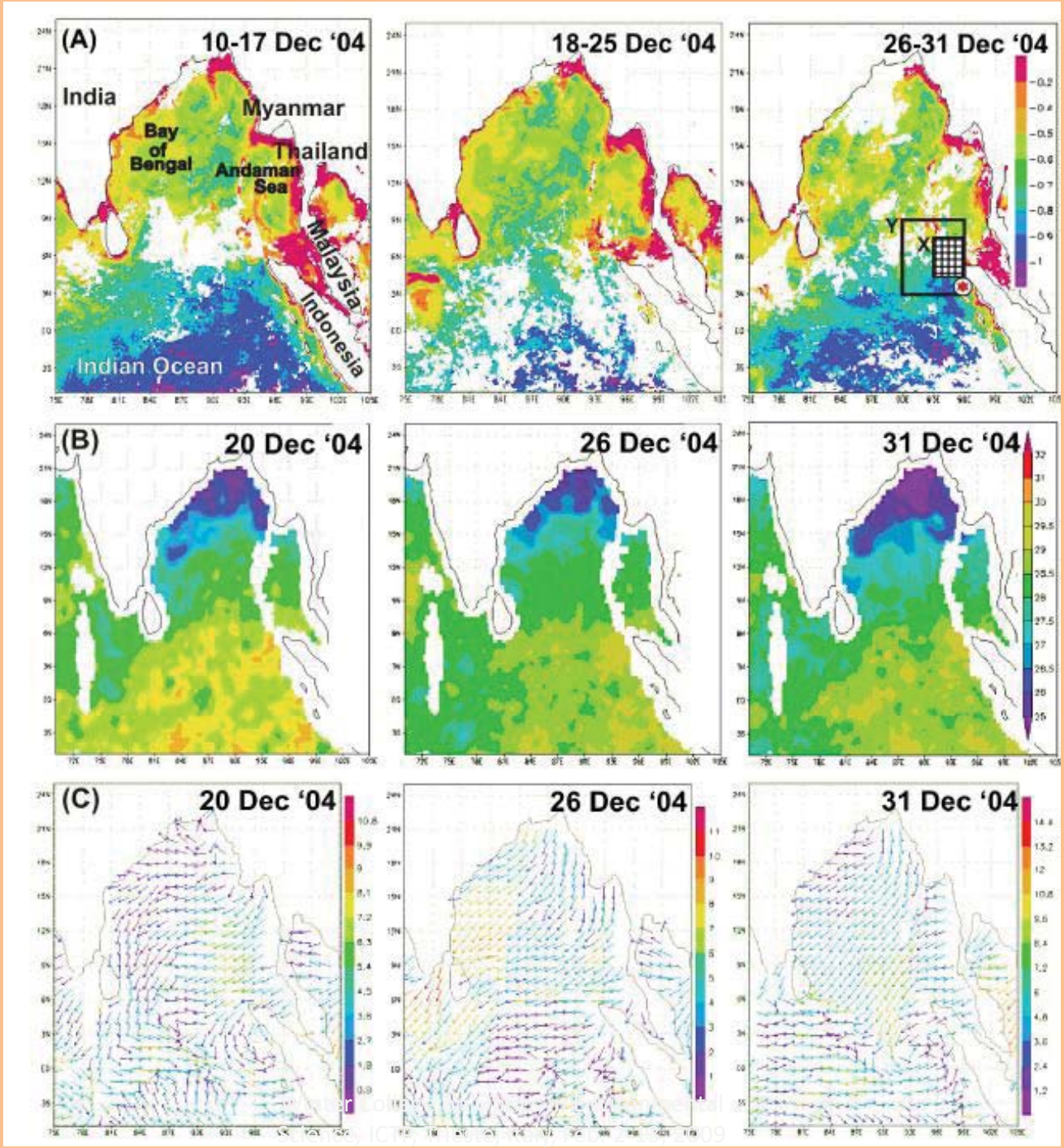
AIRS

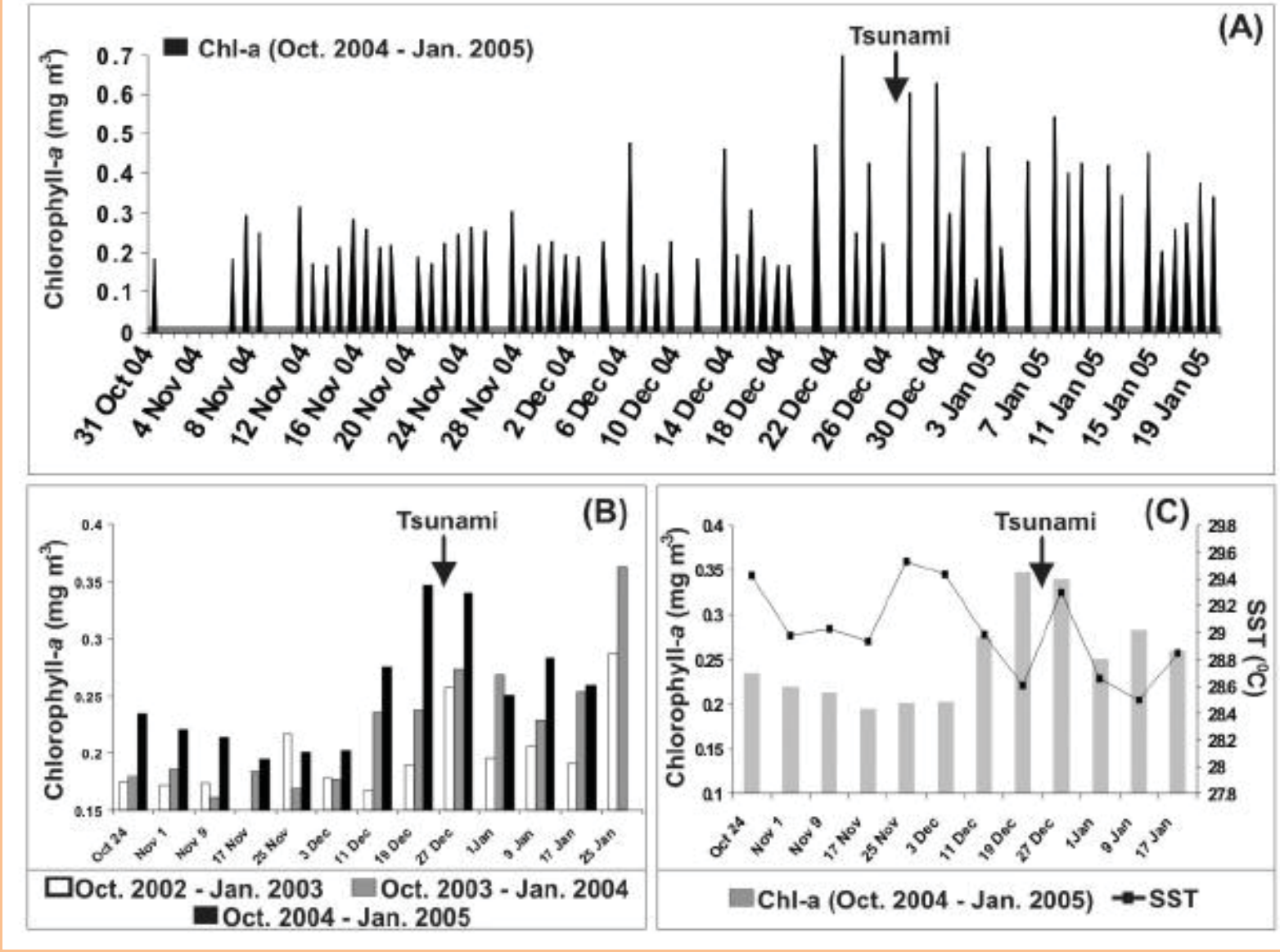
Surface Skin Temperature (Dec. 20, 2004)

High value exactly over epicenter!! of Sumatra earthquake on Dec 26, 2004




Temp. Over Epicenter
AIRS - Surface Skin Temp. (Kelvin)
315
310
305
300
295
290
285
280
15-Dec
16-Dec
17-Dec
18-Dec
19-Dec
20-Dec
21-Dec
22-Dec
23-Dec
24-Dec
25-Dec
26-Dec
27-Dec
28-Dec
29-Dec
30-Dec
31-Dec
Days 2004
Center
N
E
S
W
mean


(A)
10-17 Dec '04
India
Myanmar
Bay of Bengal
Thailand
Andaman Sea
Malaysia
Indonesia
Indian Ocean
18-25 Dec '04
26-31 Dec '04
Y
X
(B)
20 Dec '04
26 Dec '04
31 Dec '04
(C)
20 Dec '04
26 Dec '04
31 Dec '04

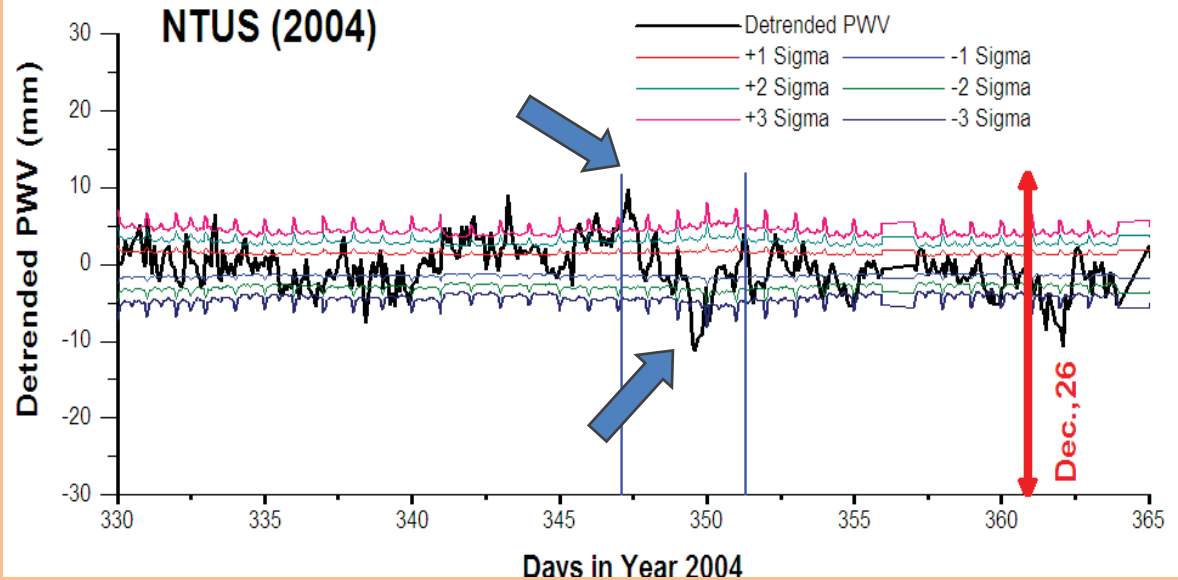


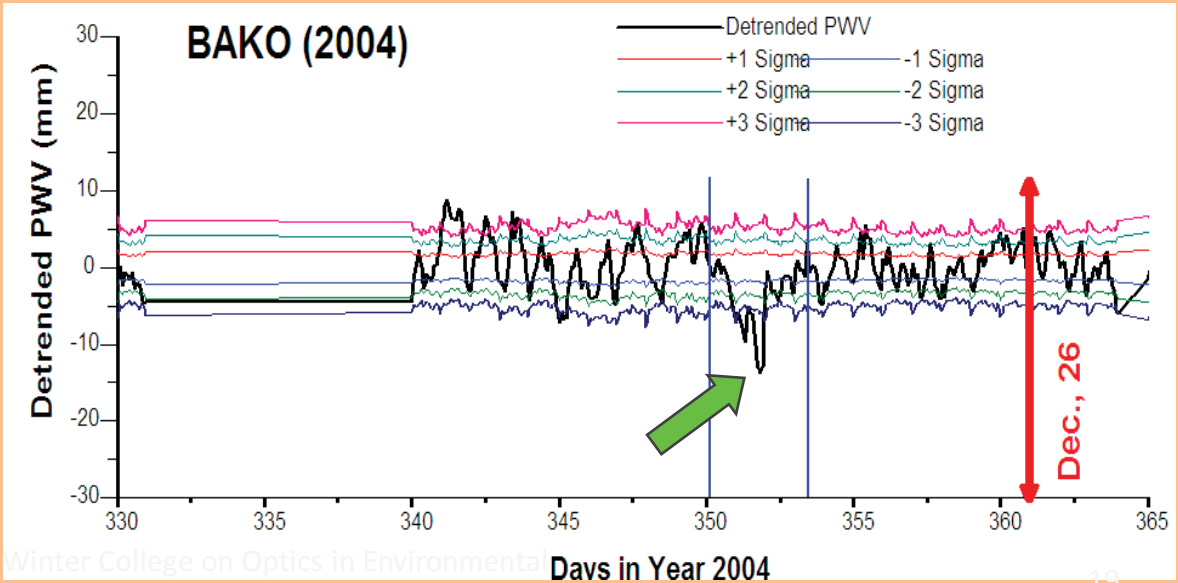
Tang et al., 2007

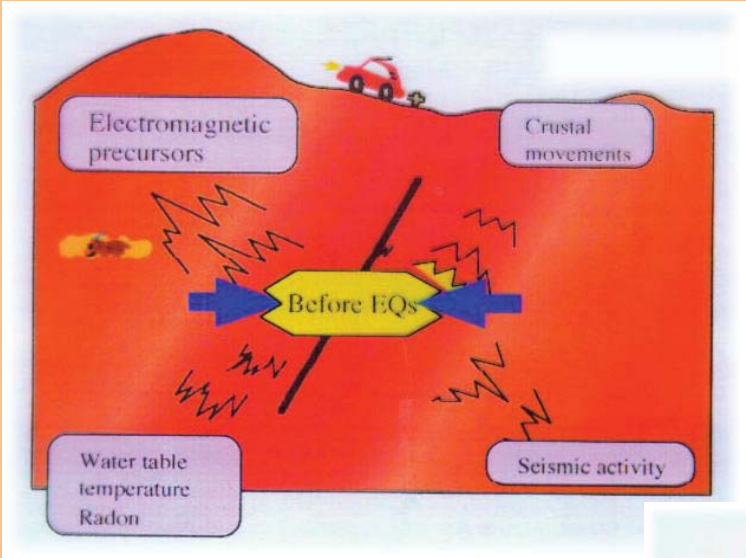
Sumatra Earthquake: Dec. 26, 2004

GPS Precipitable Water Vapor (mm): hourly

Singh et al. (2007)

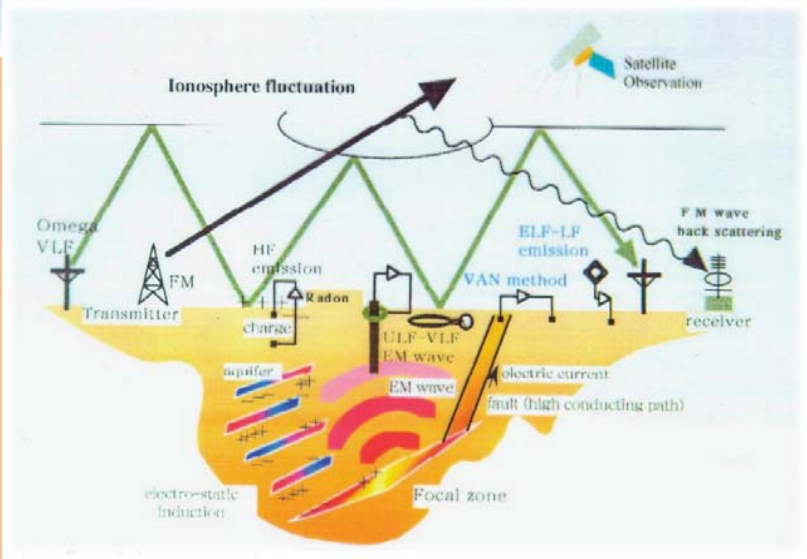






Possible earthquake precursors

Current studies of electromagnetic methods for short-term EQ prediction.



Earthquakes – Land and Ocean

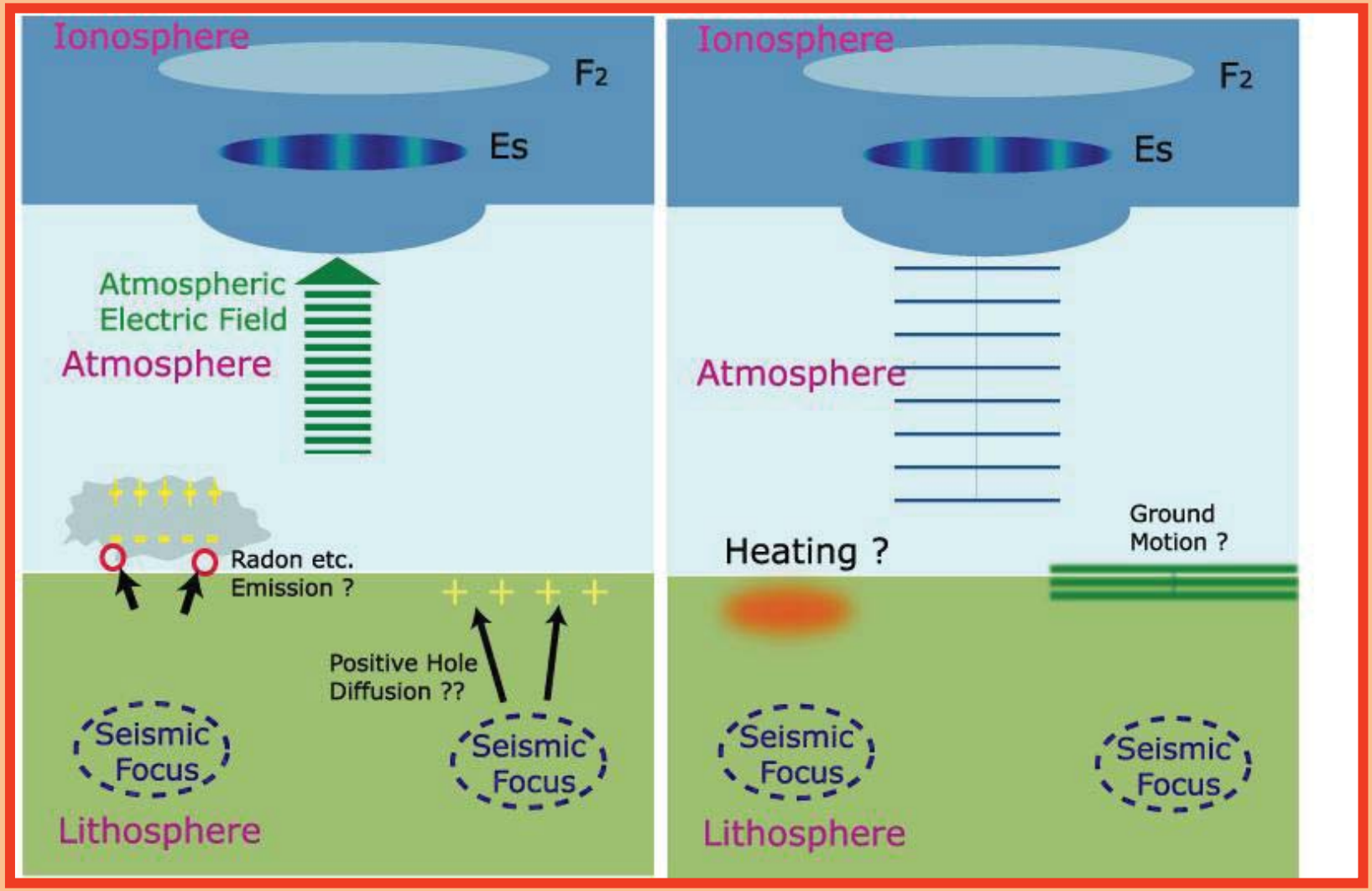
- Effect can be seen on the earth, ocean and atmosphere

  atmosphere is linkage between land and Ocean

- Ground monitoring – using Geophysical methods

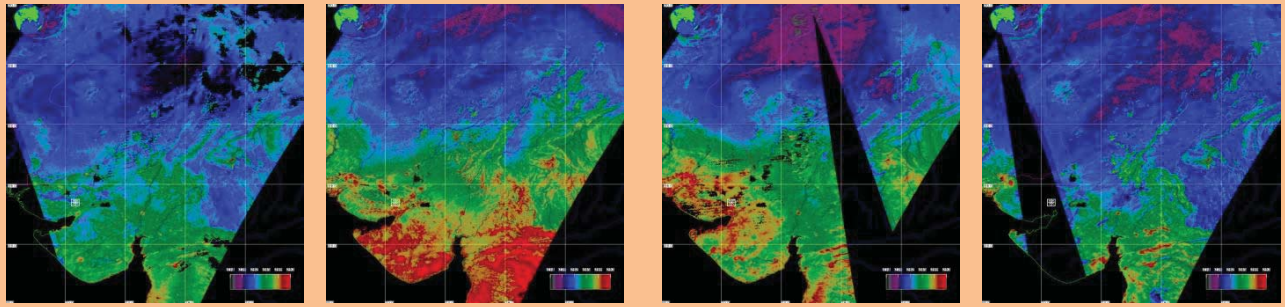
It was difficult to find complementary behavior

Lithosphere-Atmosphere-Ionosphere (LAI) Coupling

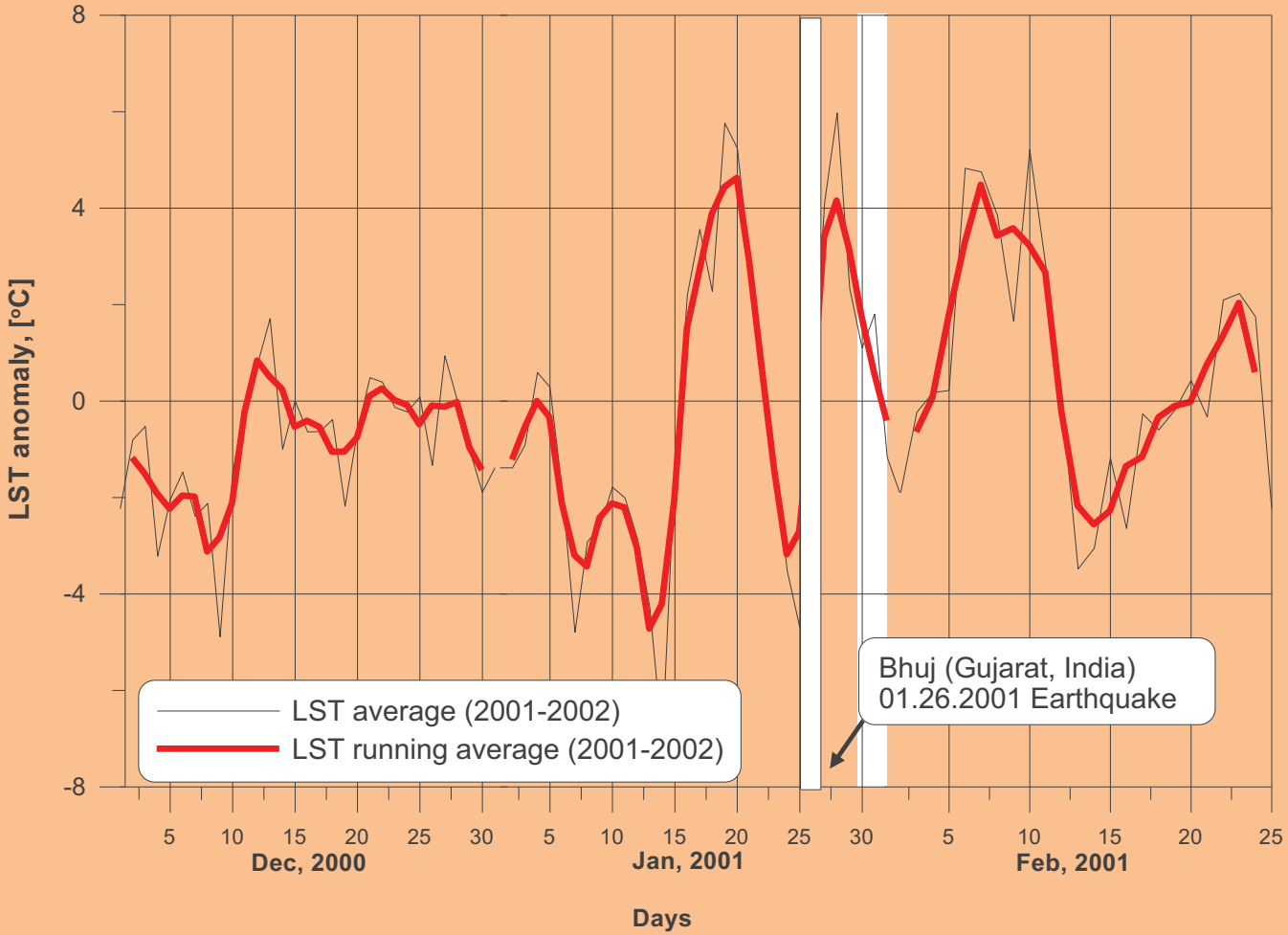


Kamogawa[2006, GRL]

b

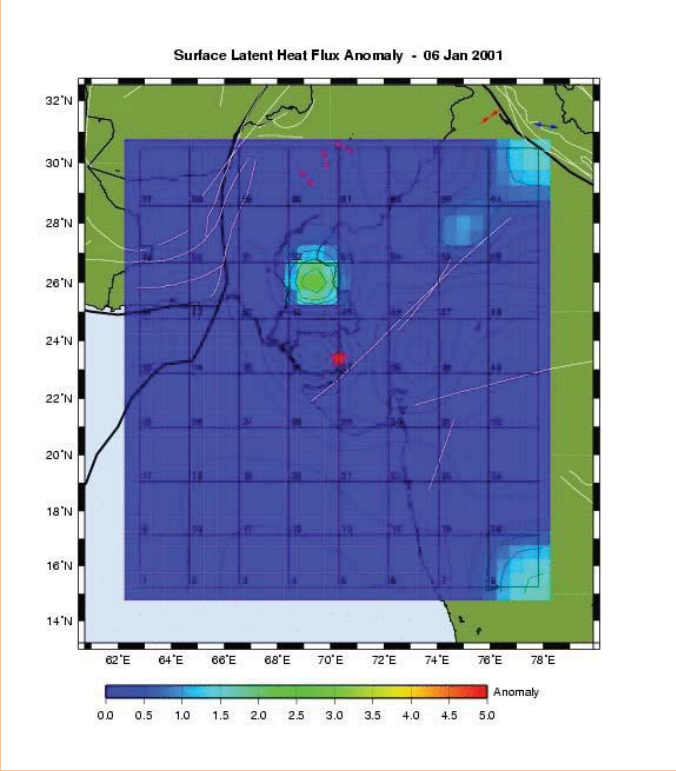


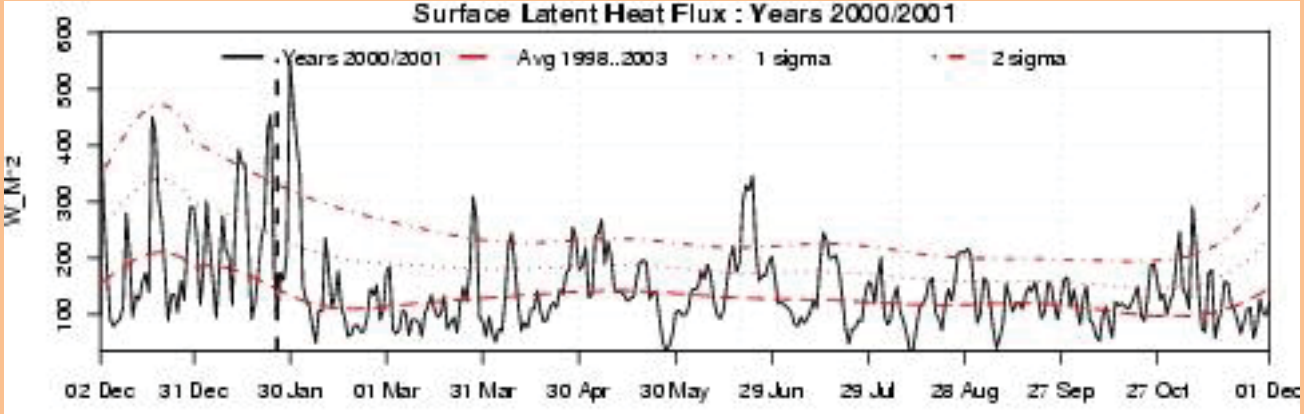
a



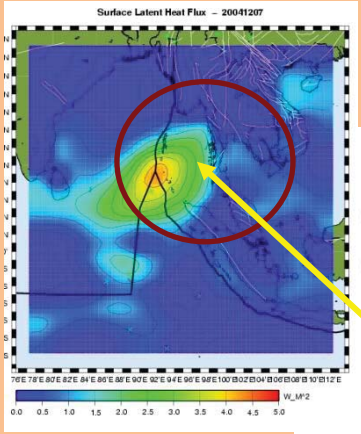
Ouzounov, 2004

M7.9 Bhuj, India, Jan 26, 2001

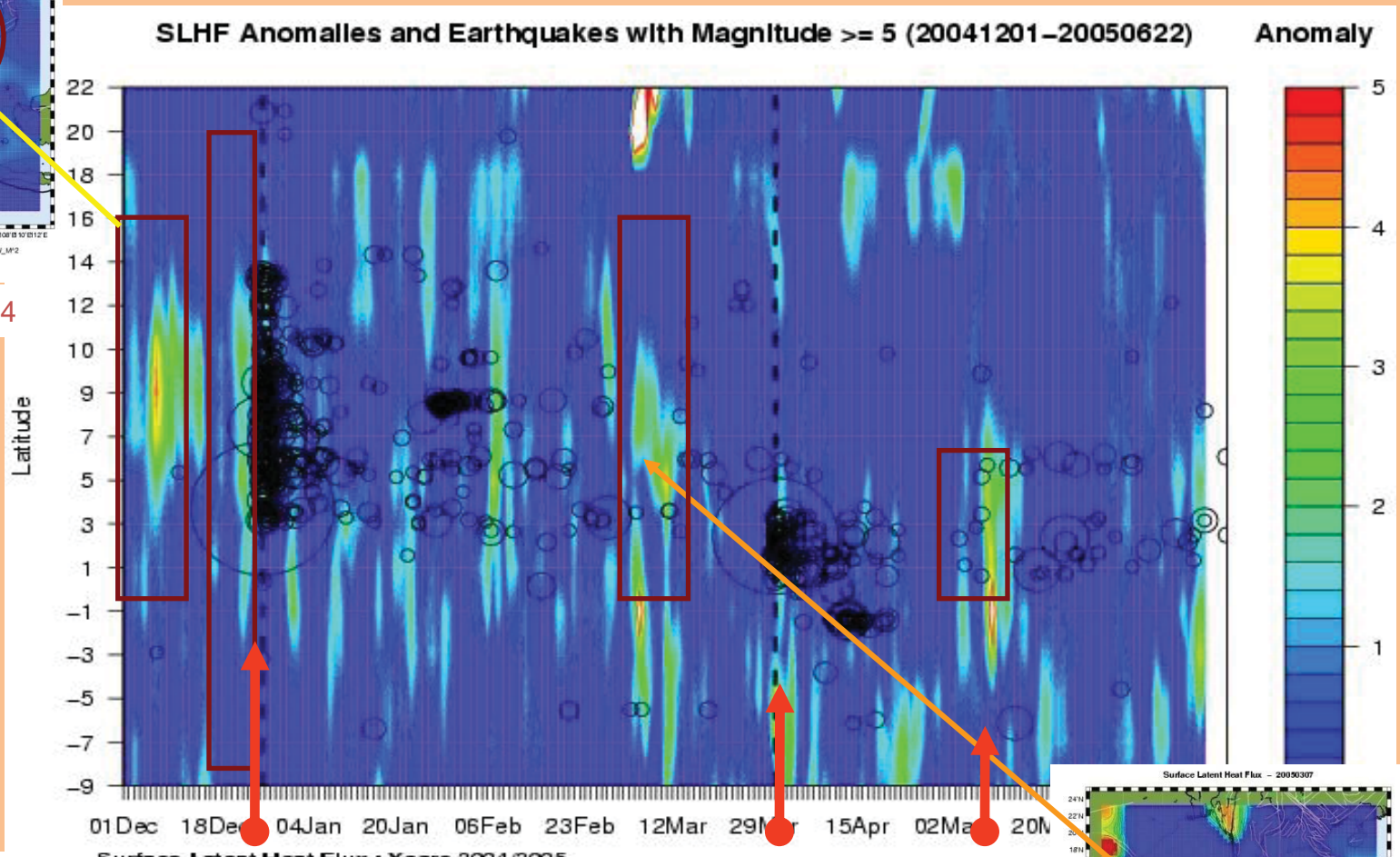


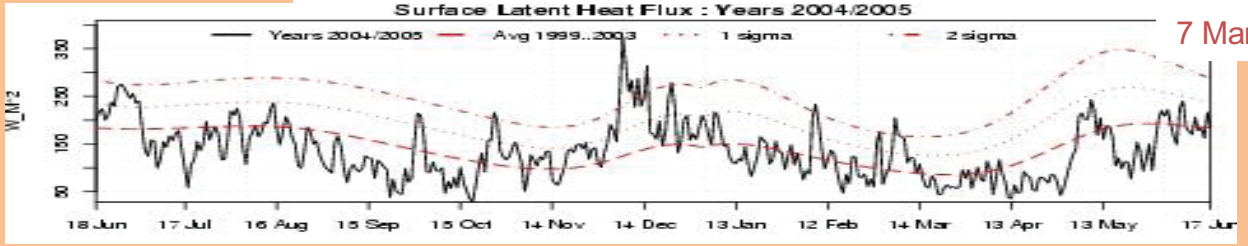


SLHF for Sumatra Dec, 2004 –June, 2005

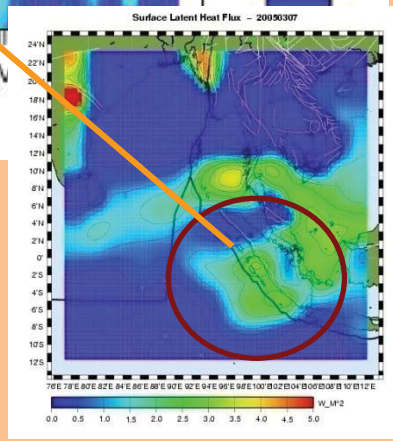


7 December 2004





7 March 2005

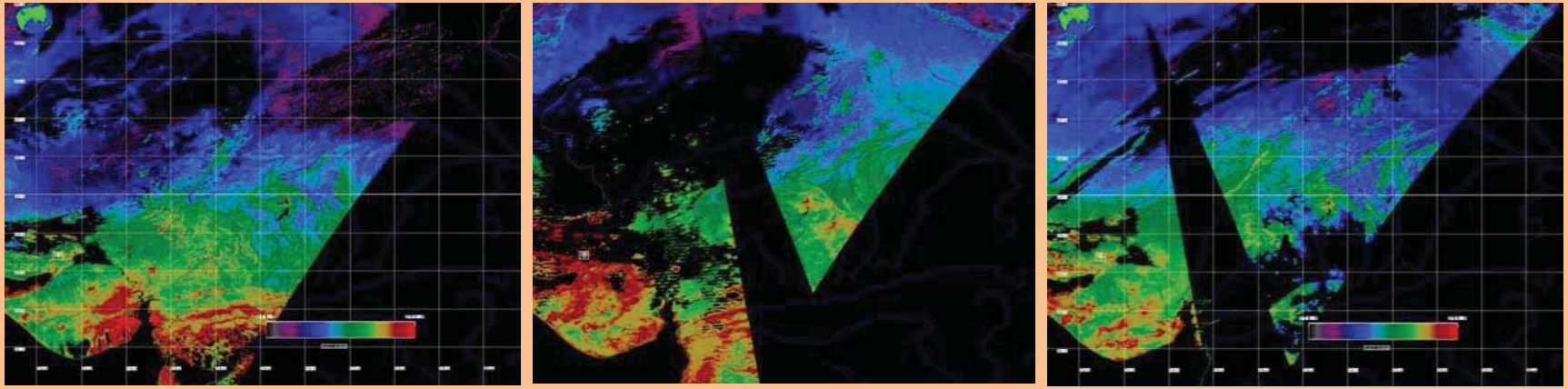


Singh et al., IJRS, 2007

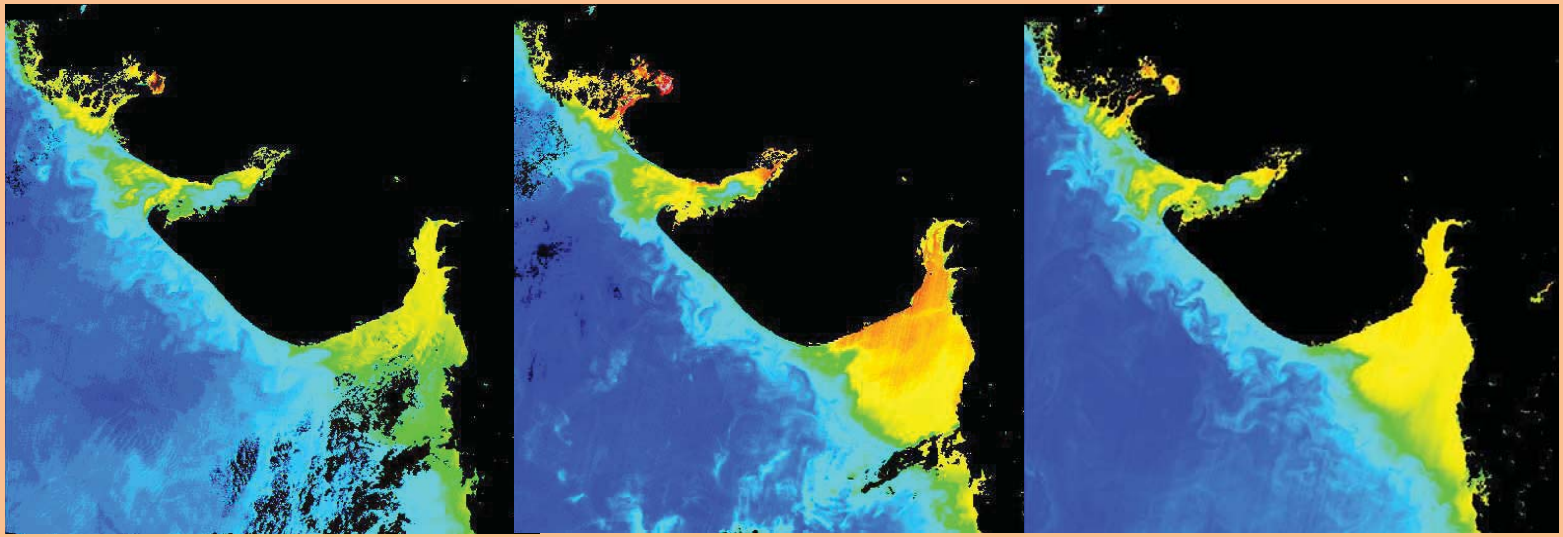
Pre-earthquake

Post-earthquake

Complementary Parameters



Jan 6, 2001 Jan 21, 2001 Jan 28, 2001



(a) January 18, 2001 (b) January 26, 2001 (c) February 3, 2001

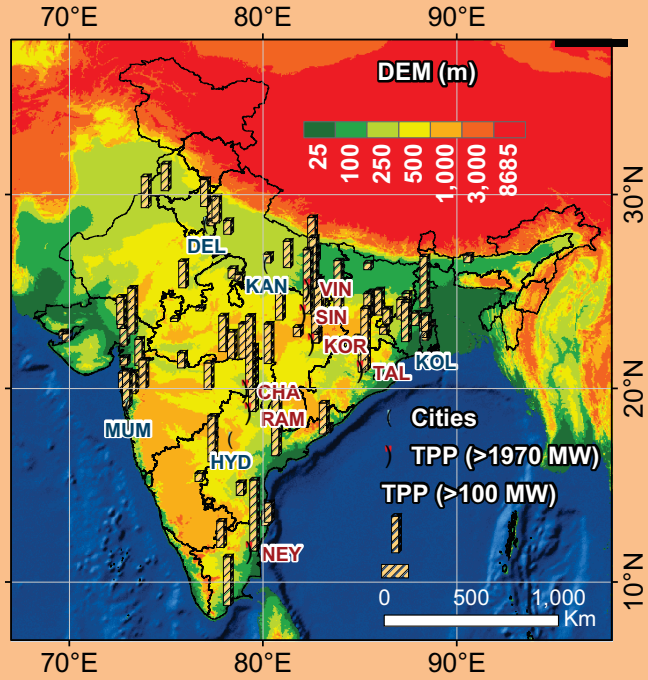
0.1 1 2 > 5 mg/m^3

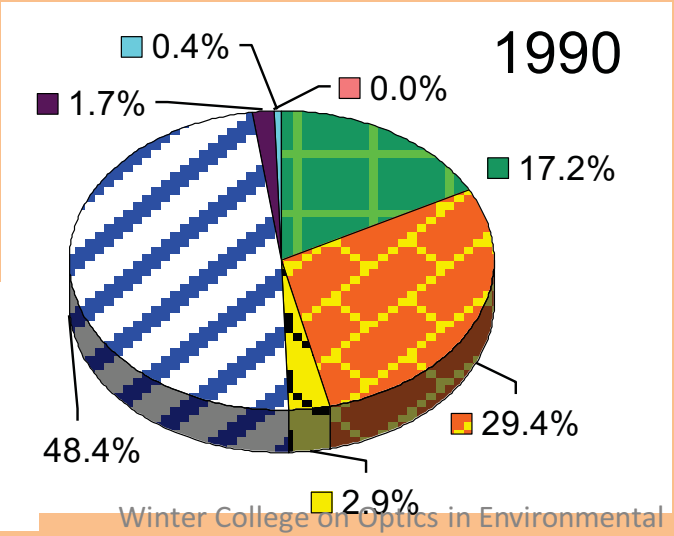
Singh et al., 2001, 2006

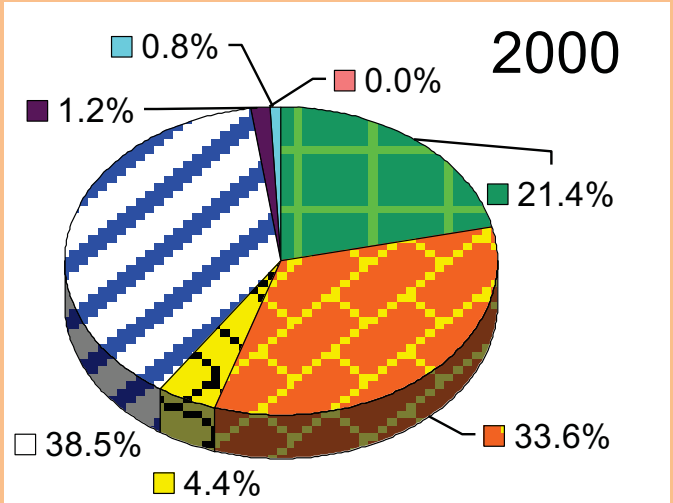
Atmospheric Pollution Associated with Power Plants

Growth in Energy Demand and Thermal Power Plants (TPP)

- *1980 to 2001*
  *Increase in energy consumption by **208%** (**4.16** to **12.8** quadrillion Btu).*
- *1990 to 2000*
  *Coal percent share has increased from **29.4% to 33.6%***
  *Share of biomass has declined by **9.9%***
- *India is fifth (in the year 2001) in the world in carbon emissions (**251** million metric tons of carbon equivalent).*



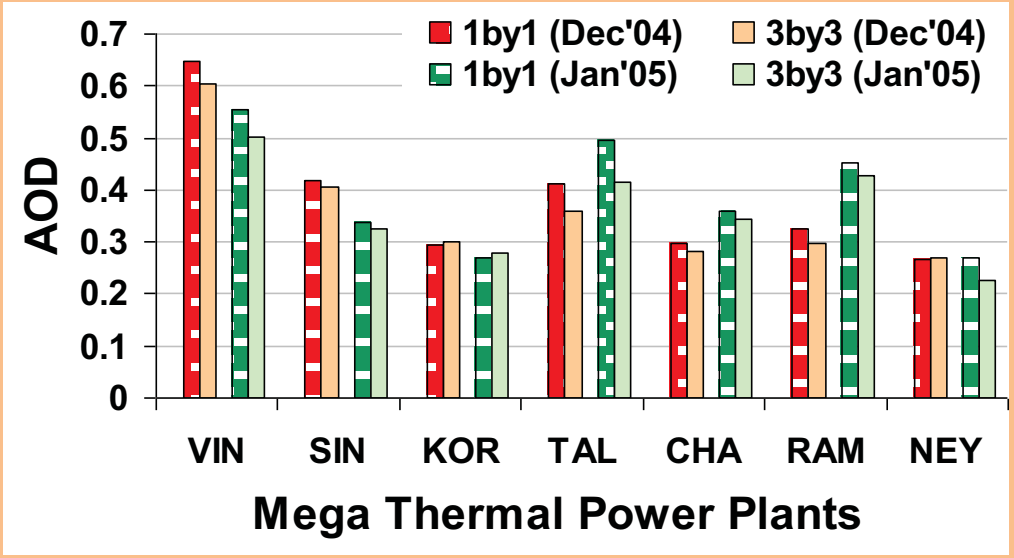


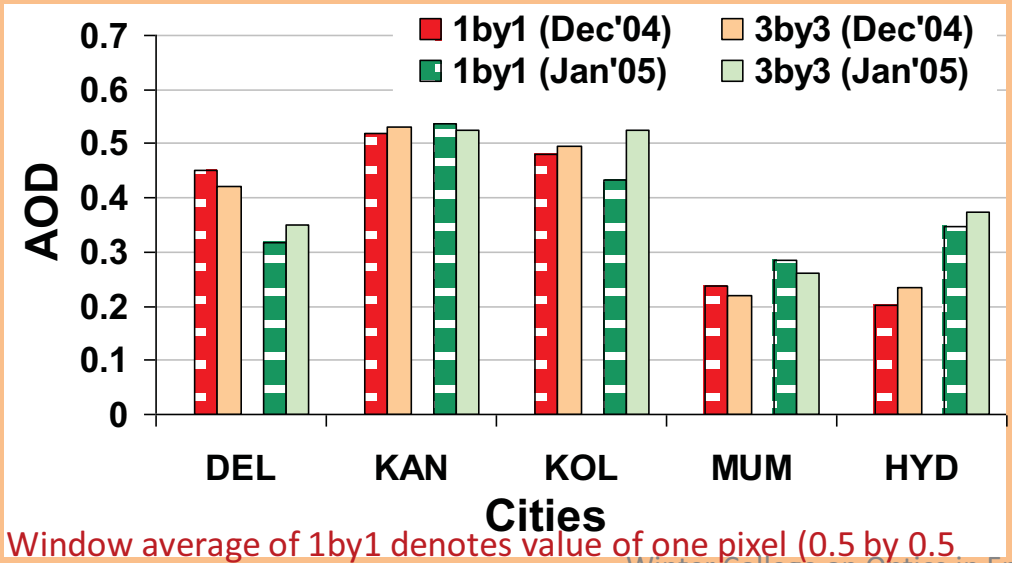


Petroleum
Coal
Natural gas
Biomass
Hydroelectric
Geothermal, solar, wind and wave
Nuclear

MISR (0.5 degree spatial resolution) AOD

over major cities and mega thermal power plants (>1970MW).





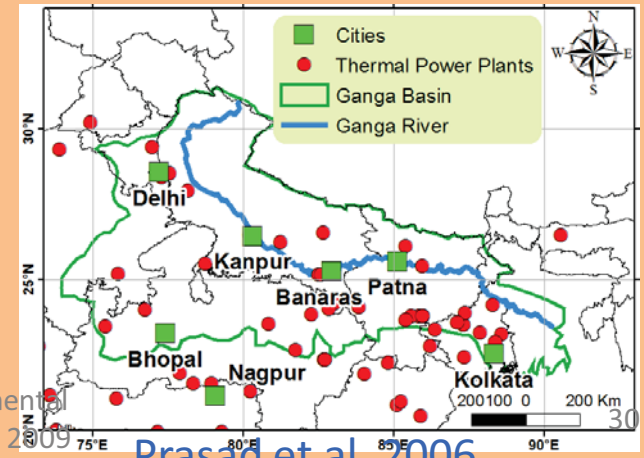
Window average of 1by1 denotes value of one pixel (0.5 by 0.5 degree) and 3by3 denotes average value for 1.5 by1.5 degree area.

AOD is significantly higher over major TPP compared to major cities.

AOD over Hyderabad is only 0.2027-0.3466 compared to that of 0.3266-0.4529 (December 2004-January 2005) over Ramagundam TPP.

AOD is higher over power plant locations compared to surroundings.

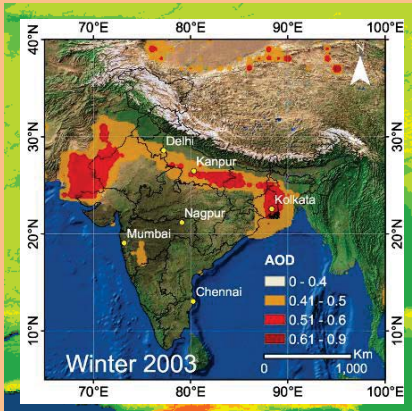
Notable exceptions here are Korba and Neyveli TPP. Neyveli TPP is close to sea and effect of sea aerosols is likely to play role in the observed deviation from trend.



Prasad et al. 2006

Thermal Power Plant Emissions in India: cause for Higher

Aerosol Loading during Winter Season over the Indo-Gangetic basin



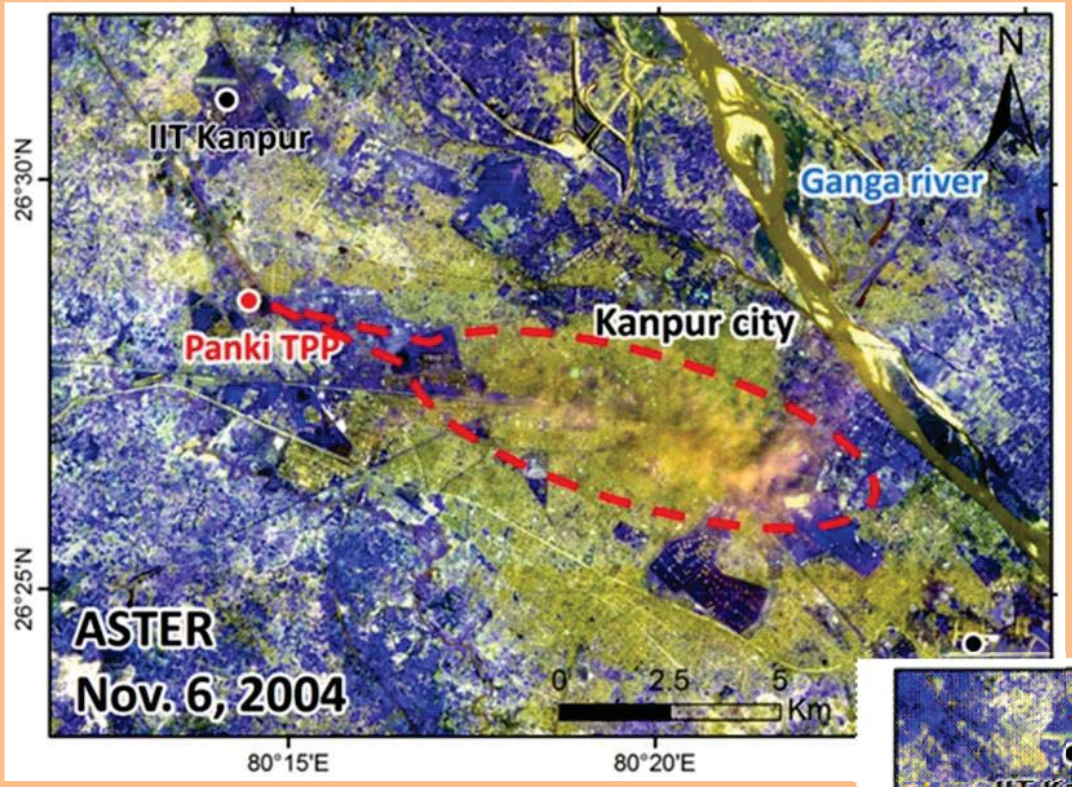
- Dense network of power plants in the eastern part of the Indo-Gangetic basin.
- During winter season, dense haze, fog and smog are seen over the IG basin.
- The light and dark green color show low topography of the IG basin, as a result pollutants are concentrated in the region especially during winter season.
- The point sources of pollutants are the emissions from the dense network of these coal based power plants.

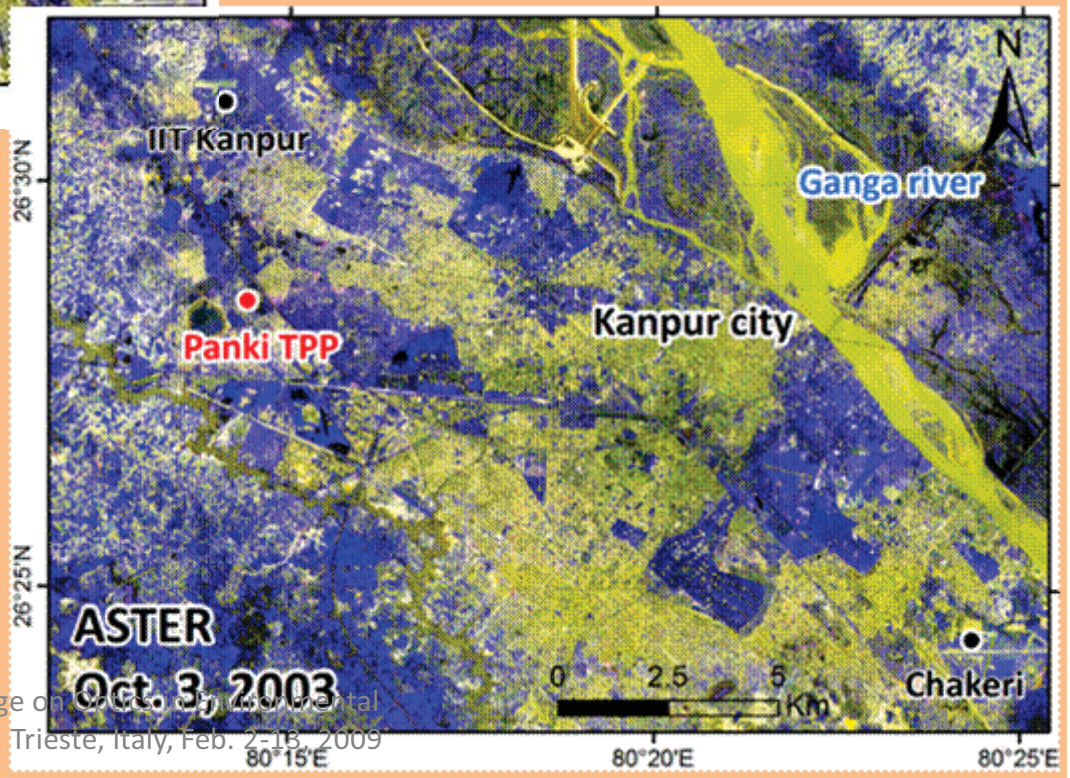
DEM (m)
0 - 25
26 - 100
101 - 250
251 - 500
501 - 1,000
1,001 - 3,000
> 3,001

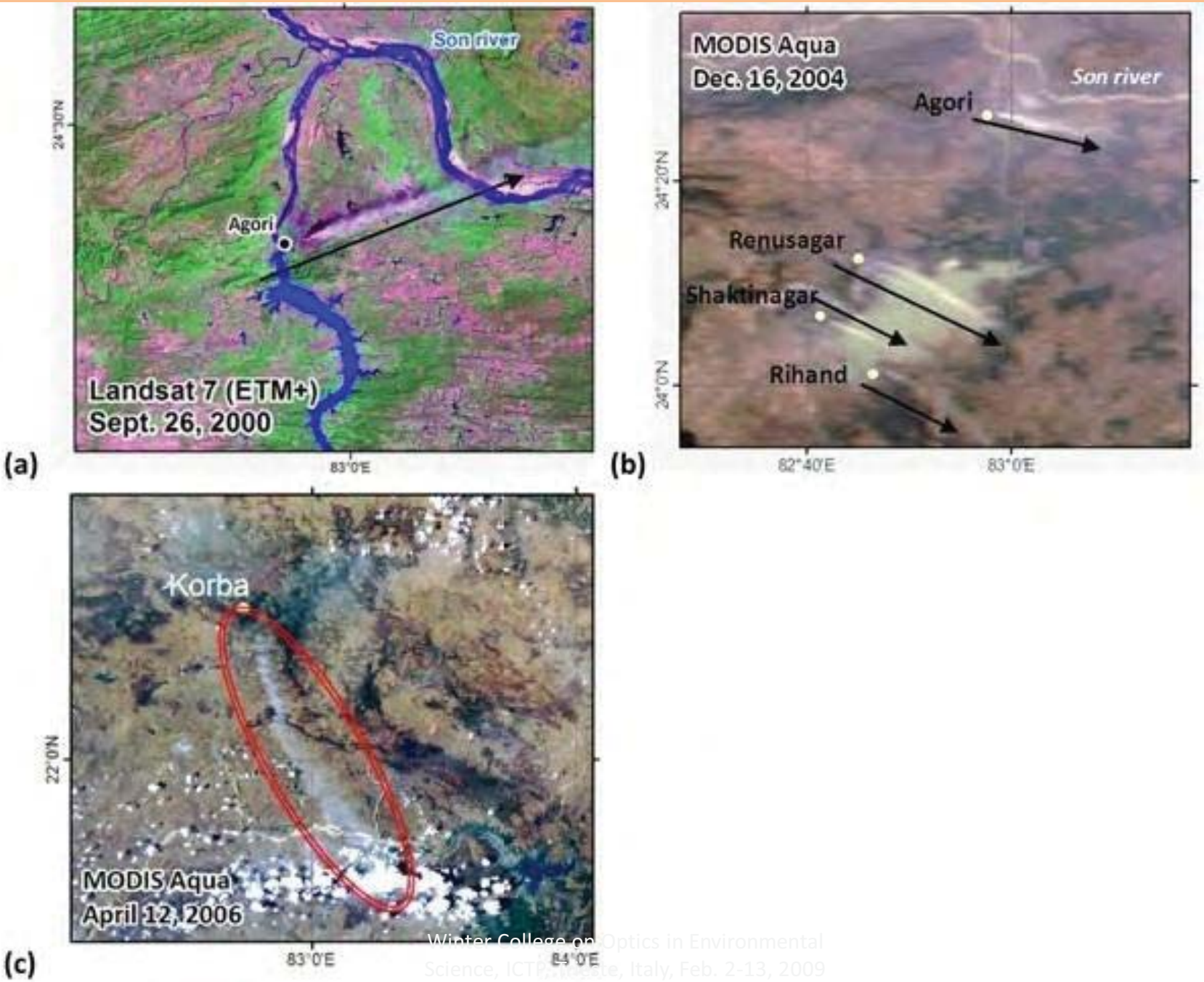
Location of cities, mega thermal power plants (TPP) (>1970MW) and all TPP >100MW in India.


2005 5 25

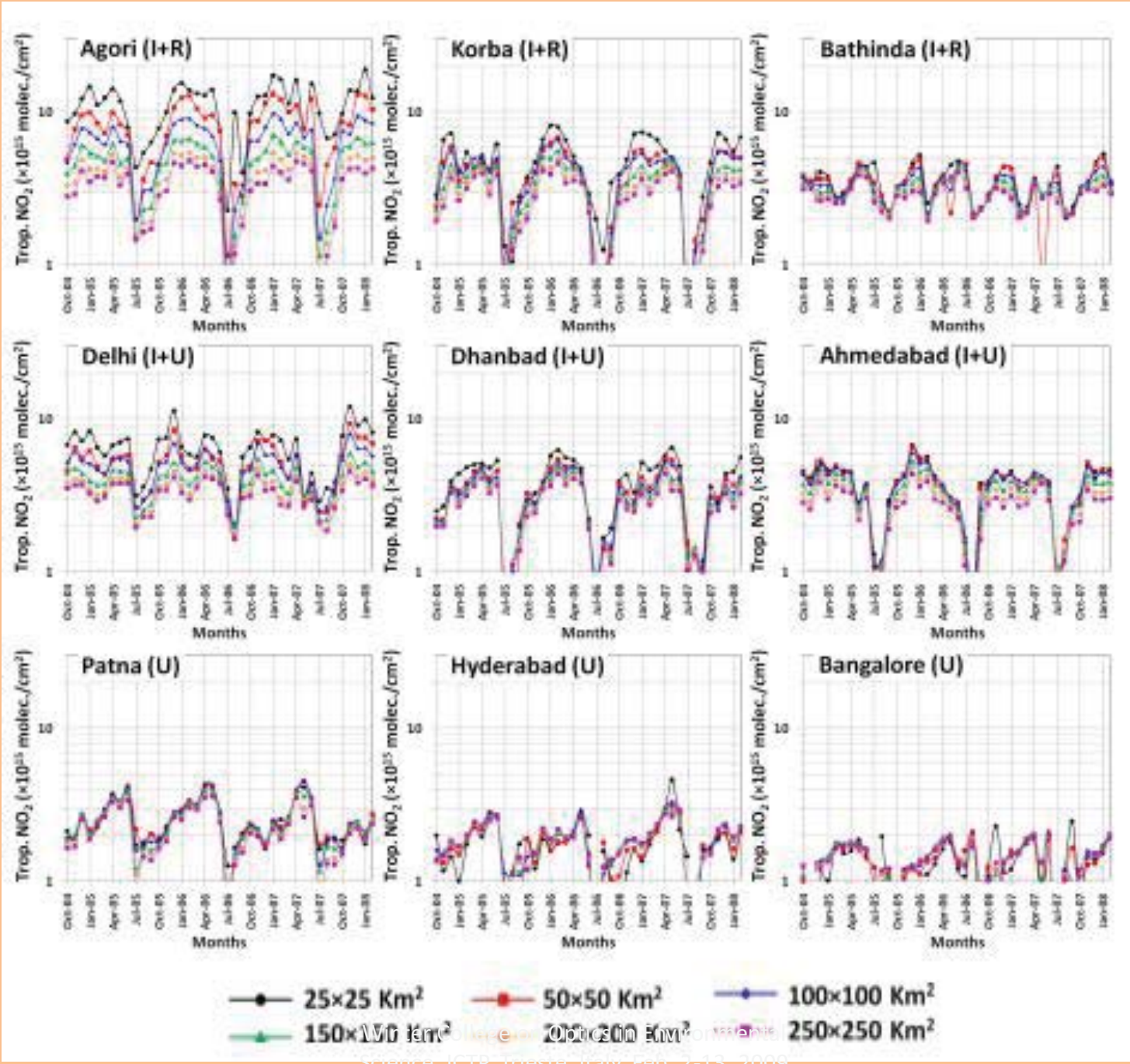

संजीवनी
8 8:59PM

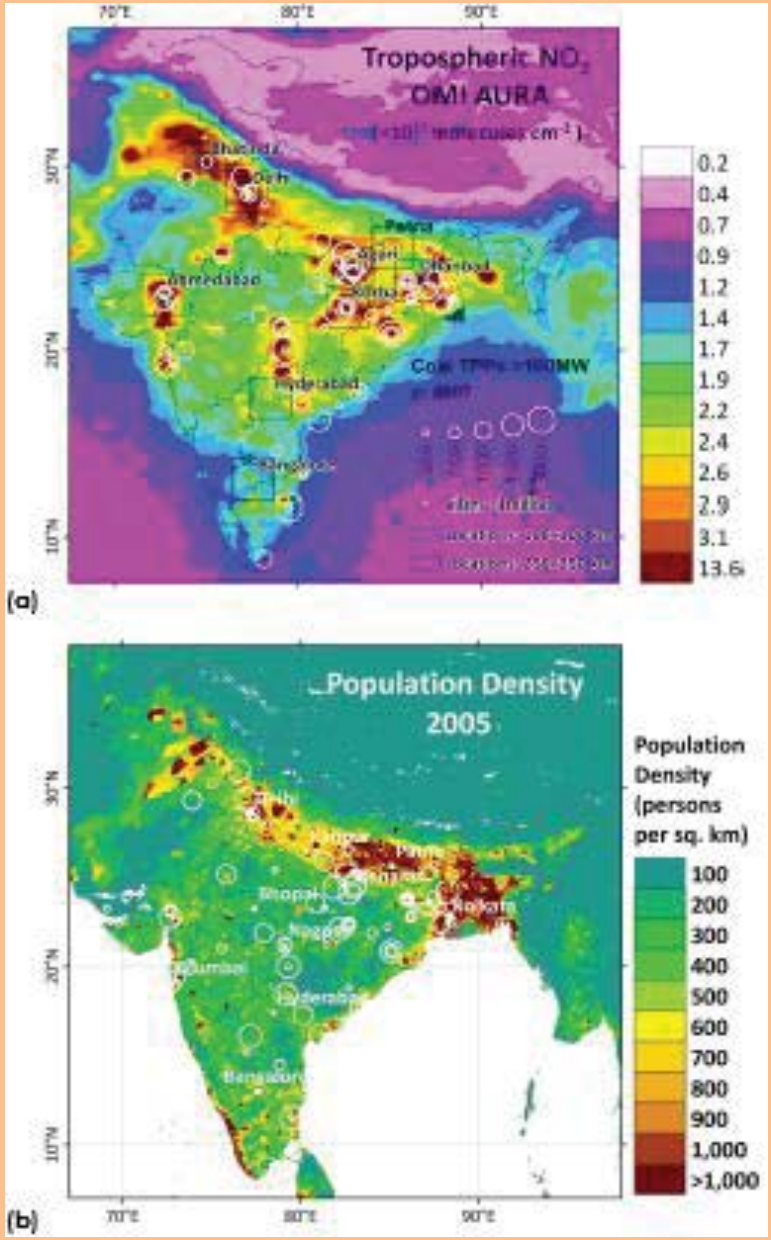

IIT Kanpur
Ganga river
Panki TPP
Kanpur city
ASTER
Nov. 6, 2004
N
0 2.5 5 Km
26°30'N
26°25'N
80°15'E
80°20'E

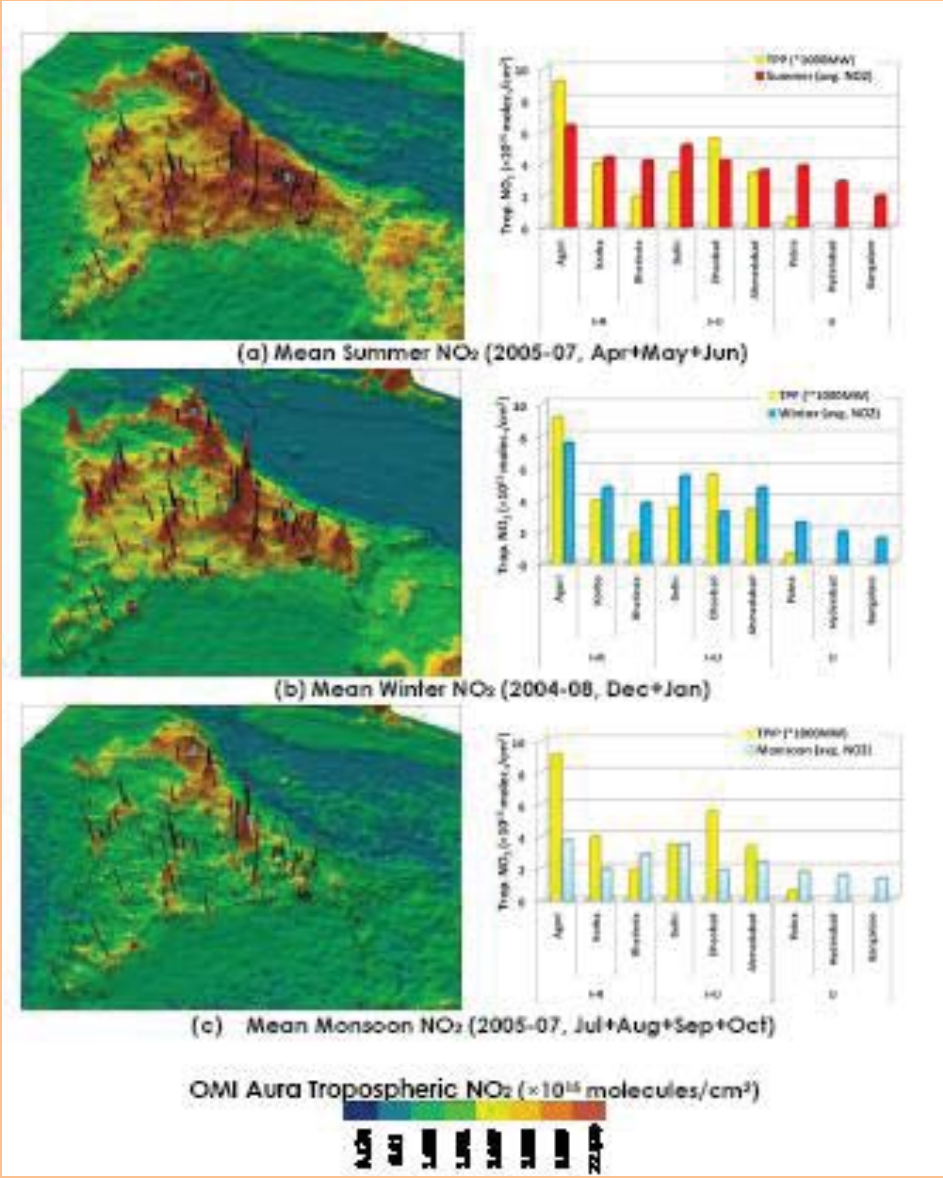

IIT Kanpur
Ganga river
Panki TPP
Kanpur city
ASTER
Oct. 3, 2003
Chakeri
N
0 2.5 5 Km
26°30'N
26°25'N
80°15'E
80°20'E
80°25'E


Son river
Agori
Landsat 7 (ETM+)
Sept. 26, 2000
24°30'N
83°0'E
(a)
MODIS Aqua
Dec. 16, 2004
Son river
Agori
Renusagar
Shaktinagar
Rihand
24°20'N
24°0'N
82°40'E
83°0'E
(b)
Korba
MODIS Aqua
April 12, 2006
22°0'N
83°0'E
84°0'E
(c)

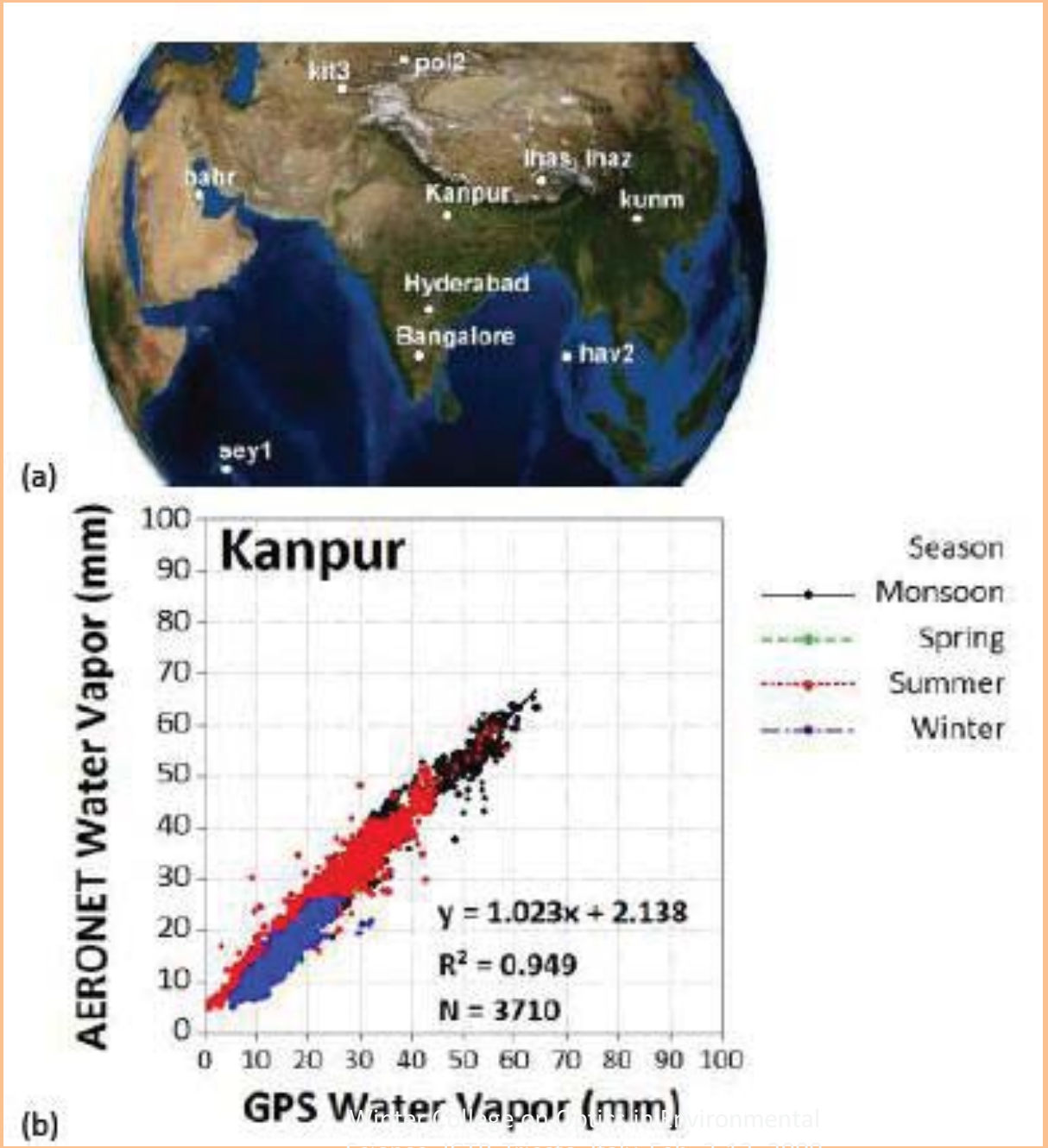

Son river
Agori
MODIS Terra
Jan. 1, 2006
MODIS Terra
Jan. 2, 2006
MODIS Terra
Jan. 3, 2006
MODIS Terra
Jan. 4, 2006
MODIS Terra
Jan. 5, 2006
MODIS Terra
Jan. 8, 2006
MODIS Terra
Jan. 9, 2006
MODIS Terra
Jan. 10, 2006
MODIS Terra
Jan. 11, 2006
MODIS Terra
Jan. 12, 2006
MODIS Terra
Jan. 13, 2006
MODIS Terra
Jan. 14, 2006
82°50'E
83°0'E


Agori (I+R)
Korba (I+R)
Bathinda (I+R)
Delhi (I+U)
Dhanbad (I+U)
Ahmedabad (I+U)
Patna (U)
Hyderabad (U)
Bangalore (U)
Trop. NO2 (×10^15 molec./cm^2)
Months
25×25 Km²
50×50 Km²
100×100 Km²
150×150 Km²
200×200 Km²
250×250 Km²

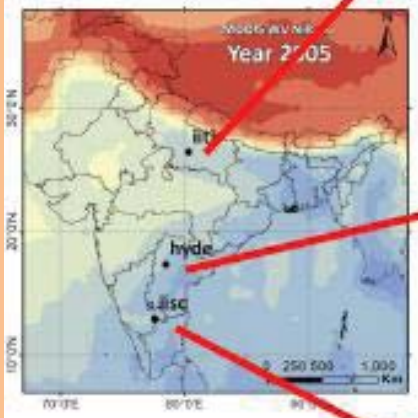

Tropospheric NO2
OMI AURA
0.2
0.4
0.7
0.9
1.2
1.4
1.7
1.9
2.2
2.4
2.6
2.9
3.1
13.6
(a)
Population Density
2005
Population
Density
(persons
per sq. km)
100
200
300
400
500
600
700
800
900
1,000
>1,000
(b)

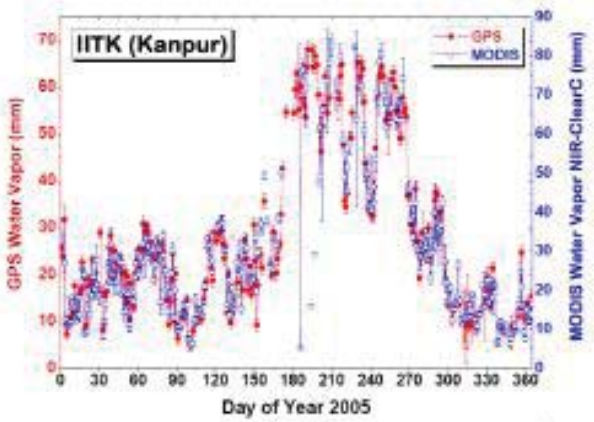

(a) Mean Summer NO2 (2005-07, Apr+May+Jun)
(b) Mean Winter NO2 (2004-08, Dec+Jan)
(c) Mean Monsoon NO2 (2005-07, Jul+Aug+Sep+Oct)
OMI Aura Tropospheric NO2 (×10^15 molecules/cm²)

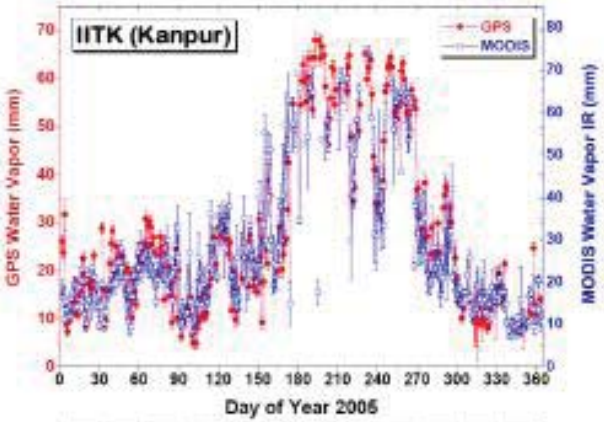
Atmospheric Water Vapor

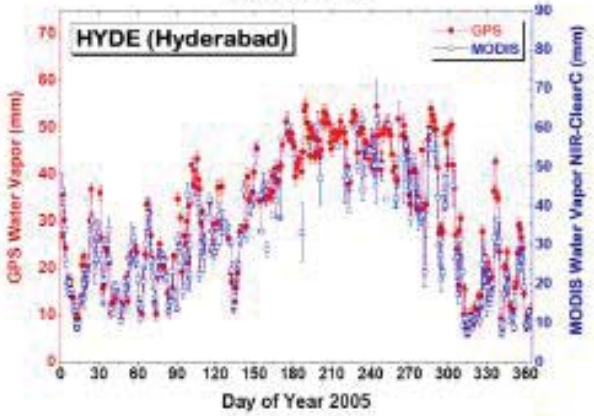

(a)
kit3
pol2
bahr
Kanpur
ihas, ihaz
kunm
Hyderabad
Bangalore
hav2
sey1
(b)
Kanpur
AERONET Water Vapor (mm)
GPS Water Vapor (mm)
y = 1.023x + 2.138
R² = 0.949
N = 3710
Season
Monsoon
Spring
Summer
Winter

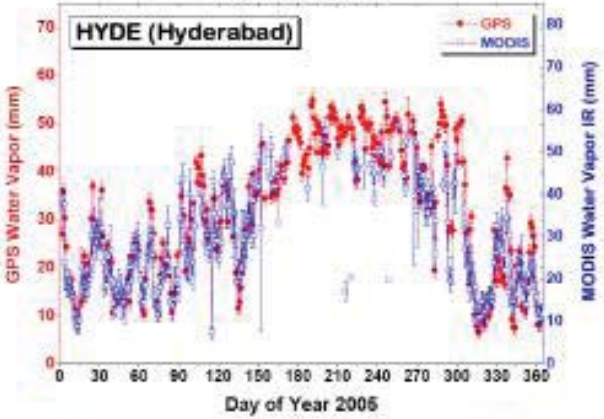
MODIS (NIR-CC) and GPS Water

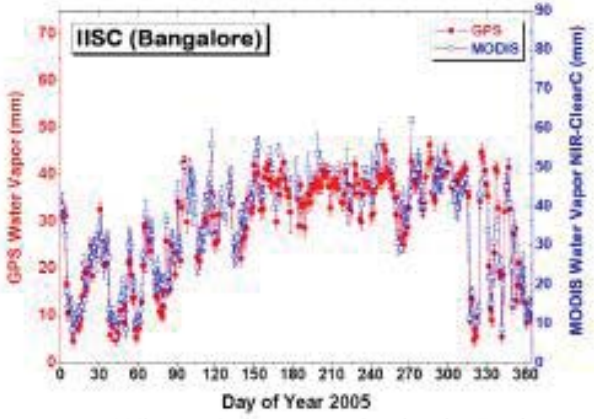


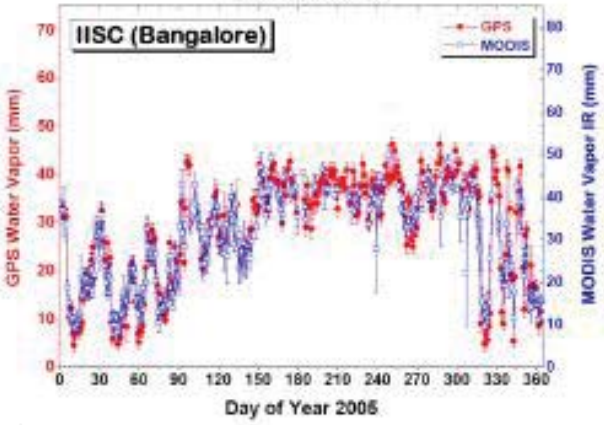


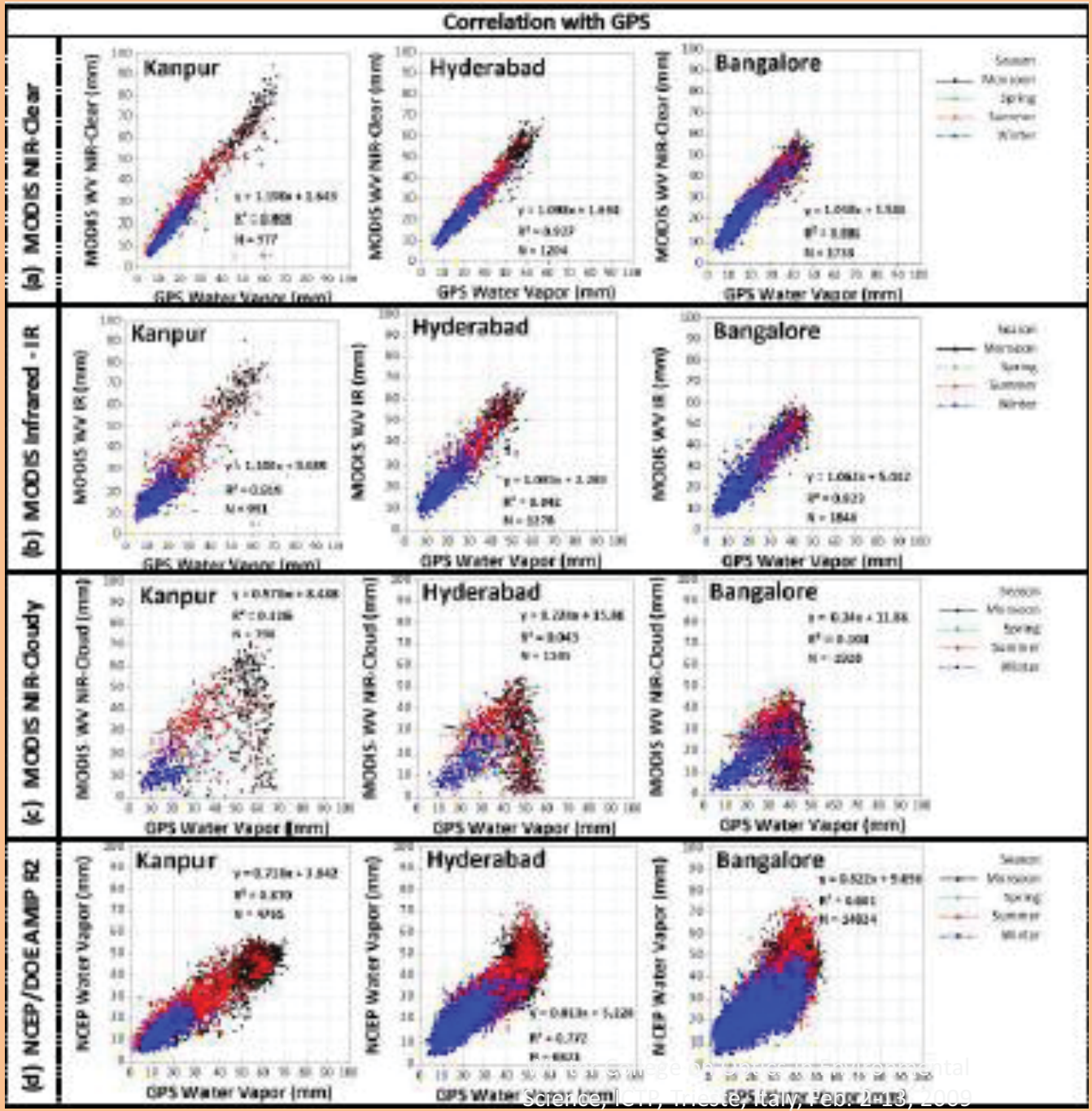




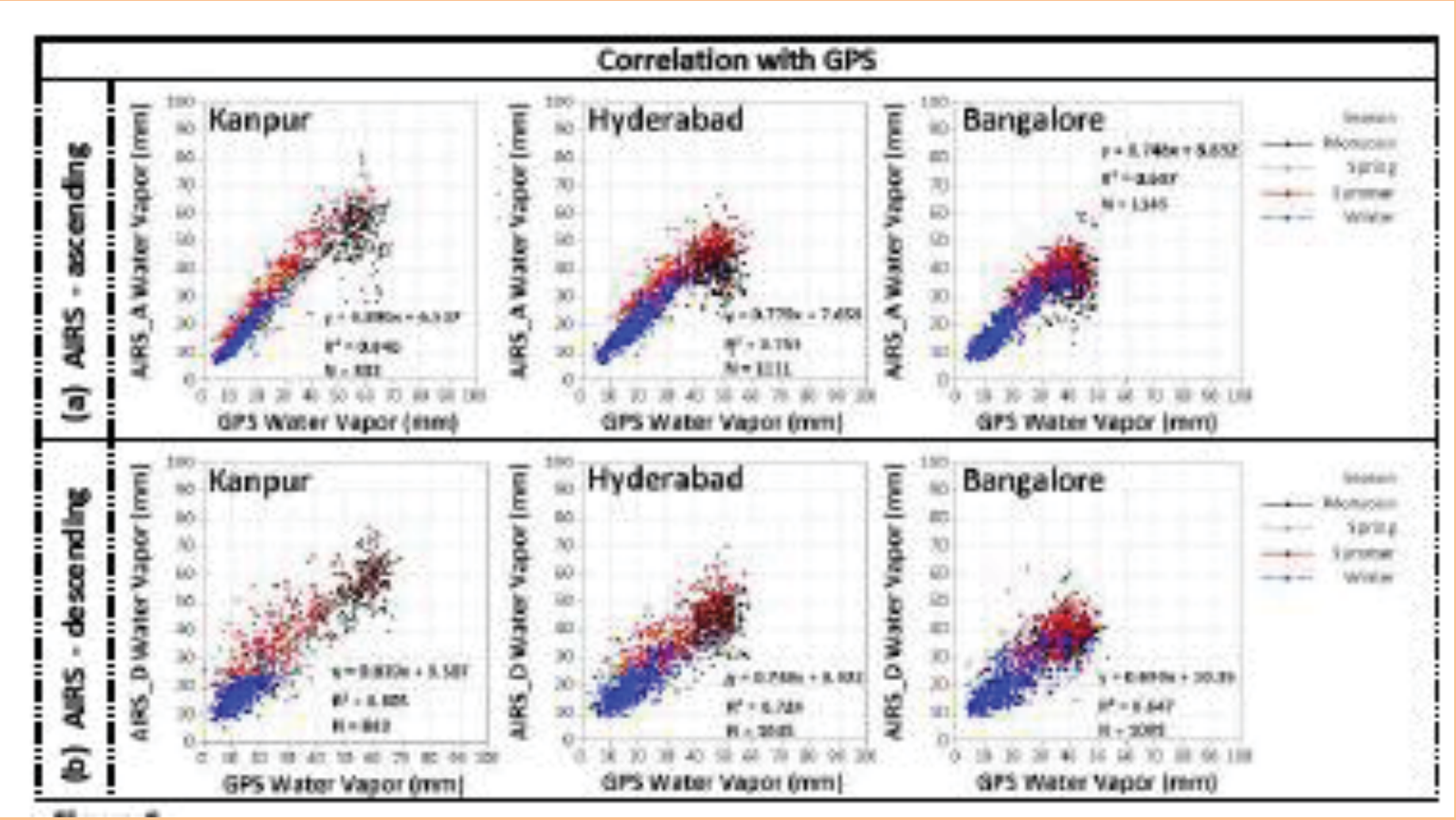




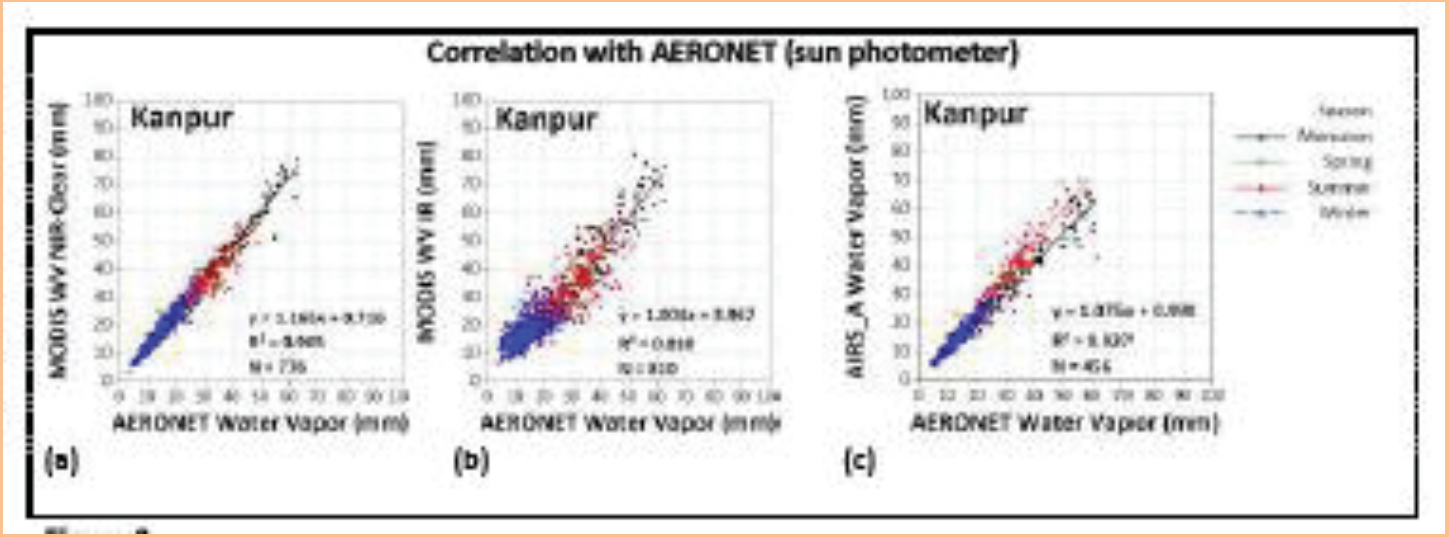




Prasad and Singh, JGR, 2009



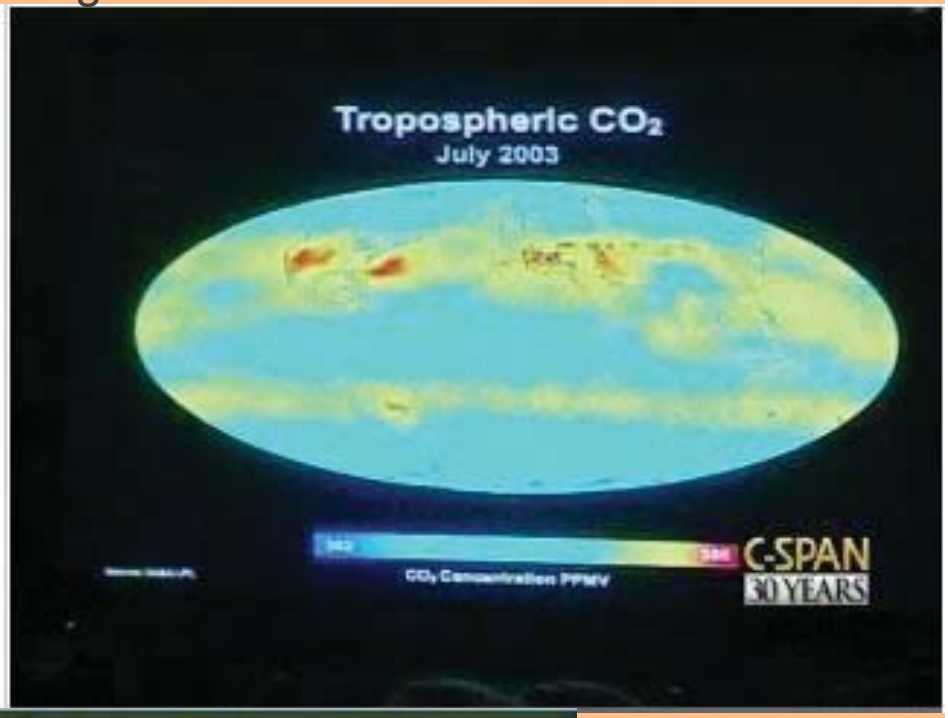
Prasad and Singh, JGR, 2009

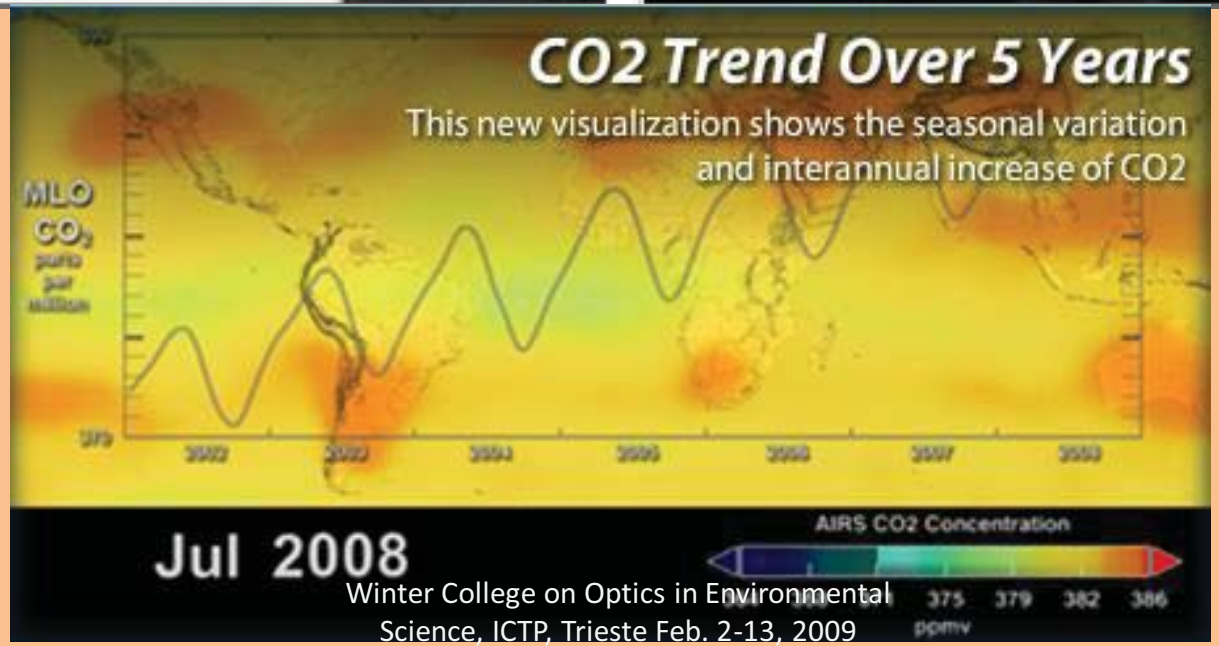


Prasad and Singh (2009)

Carbon Monoxide

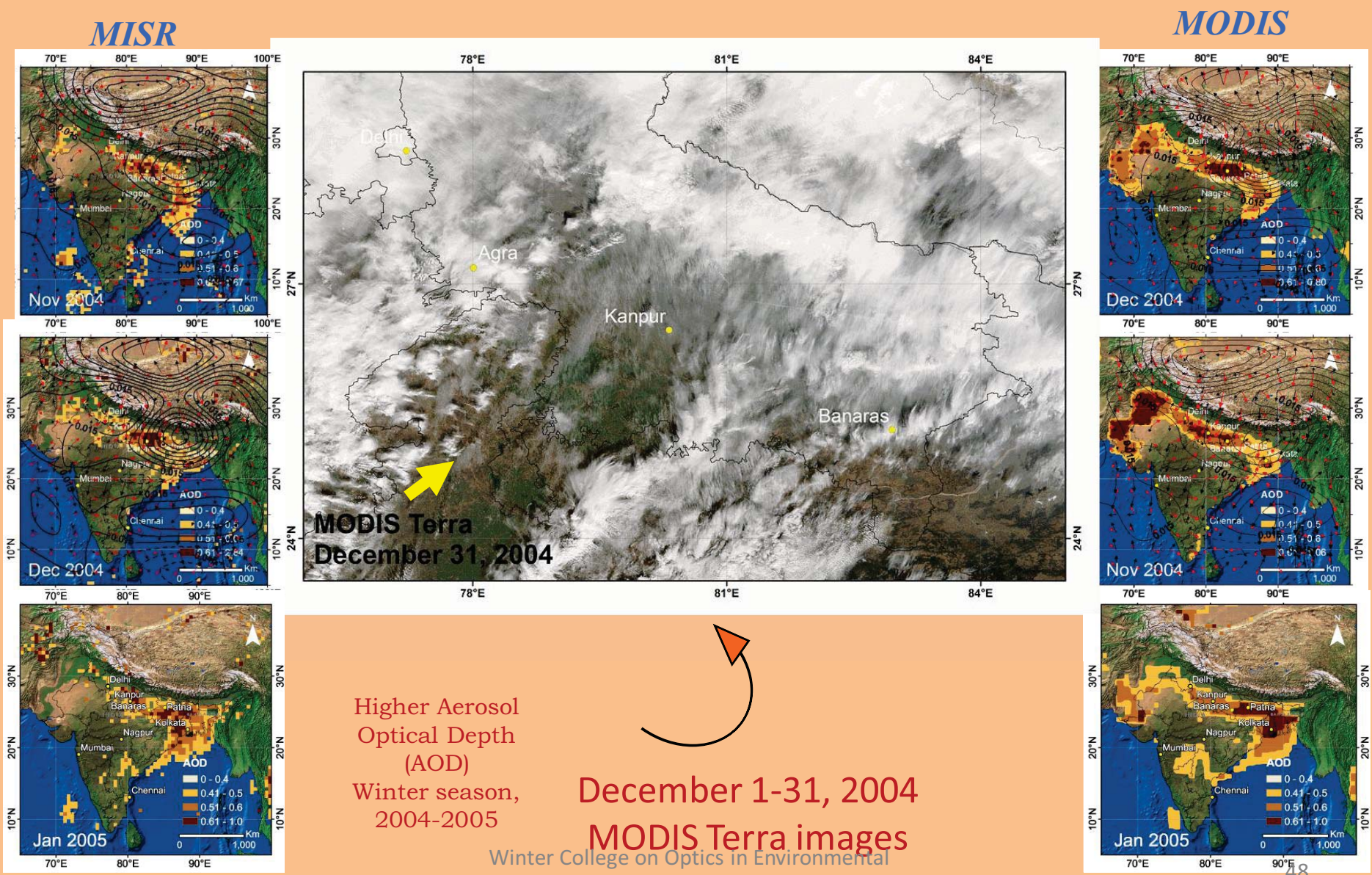
http://airs.jpl.nasa.gov/

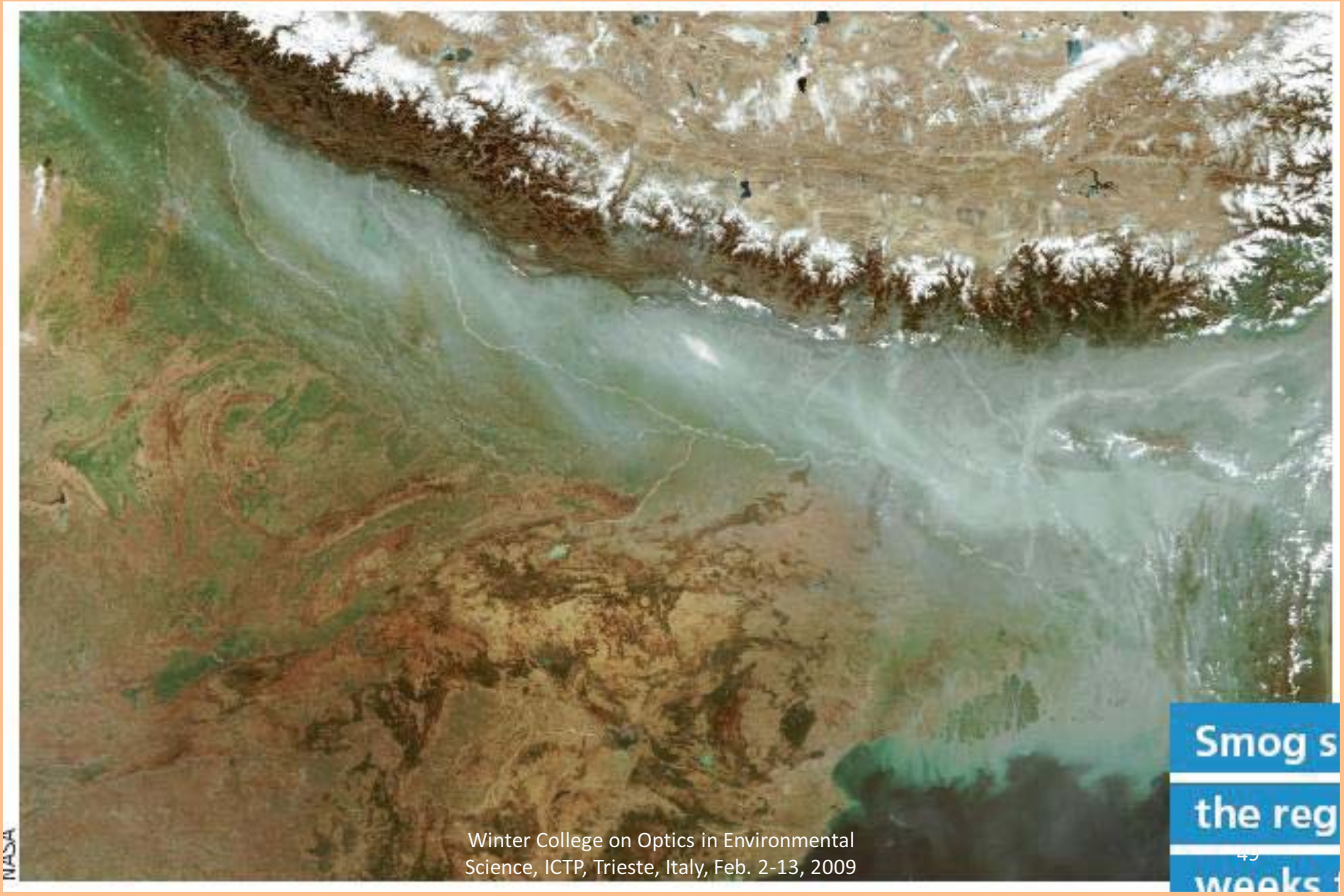


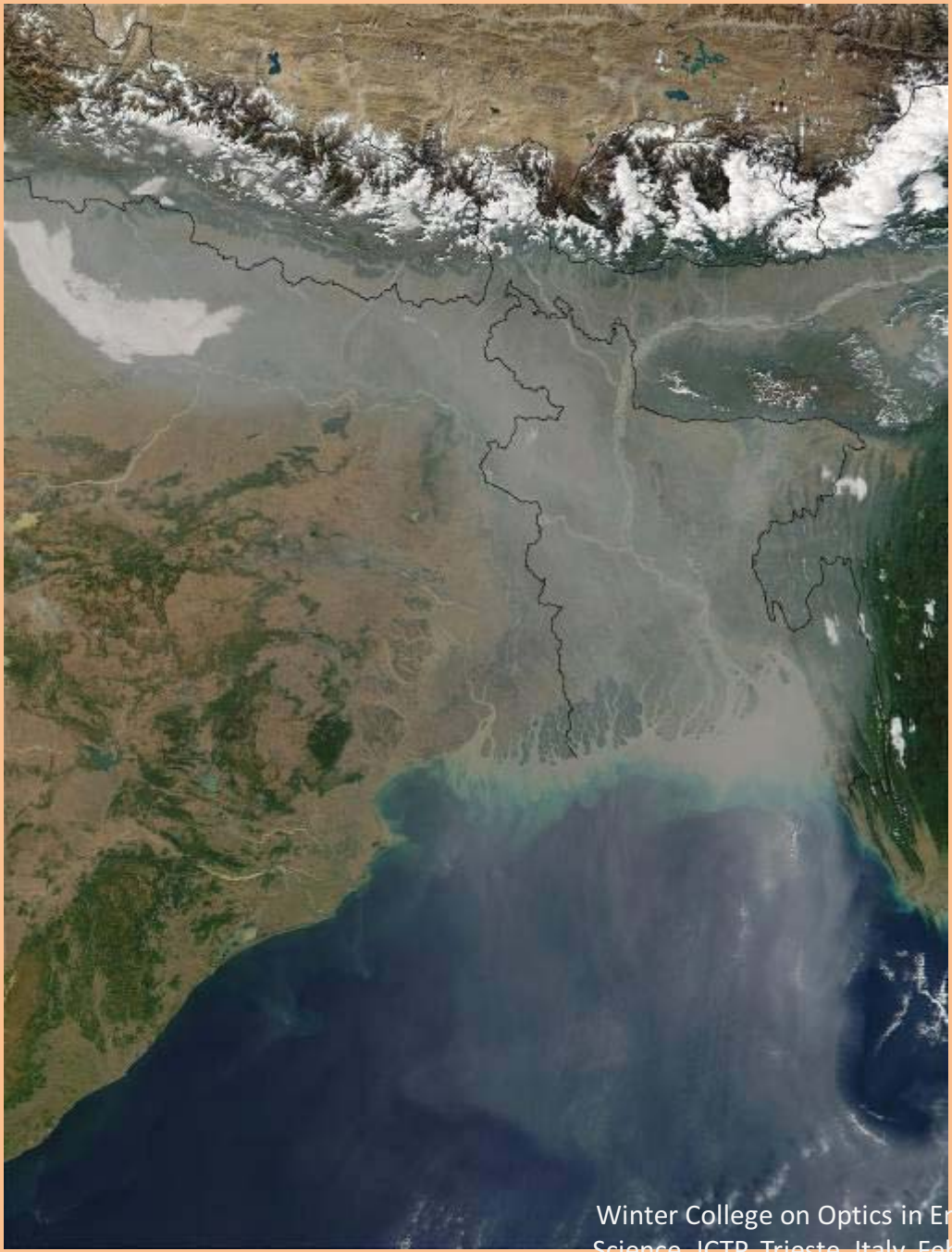


Dense Haze, Fog and Smog

Thick Haze and Smog Across Northern India



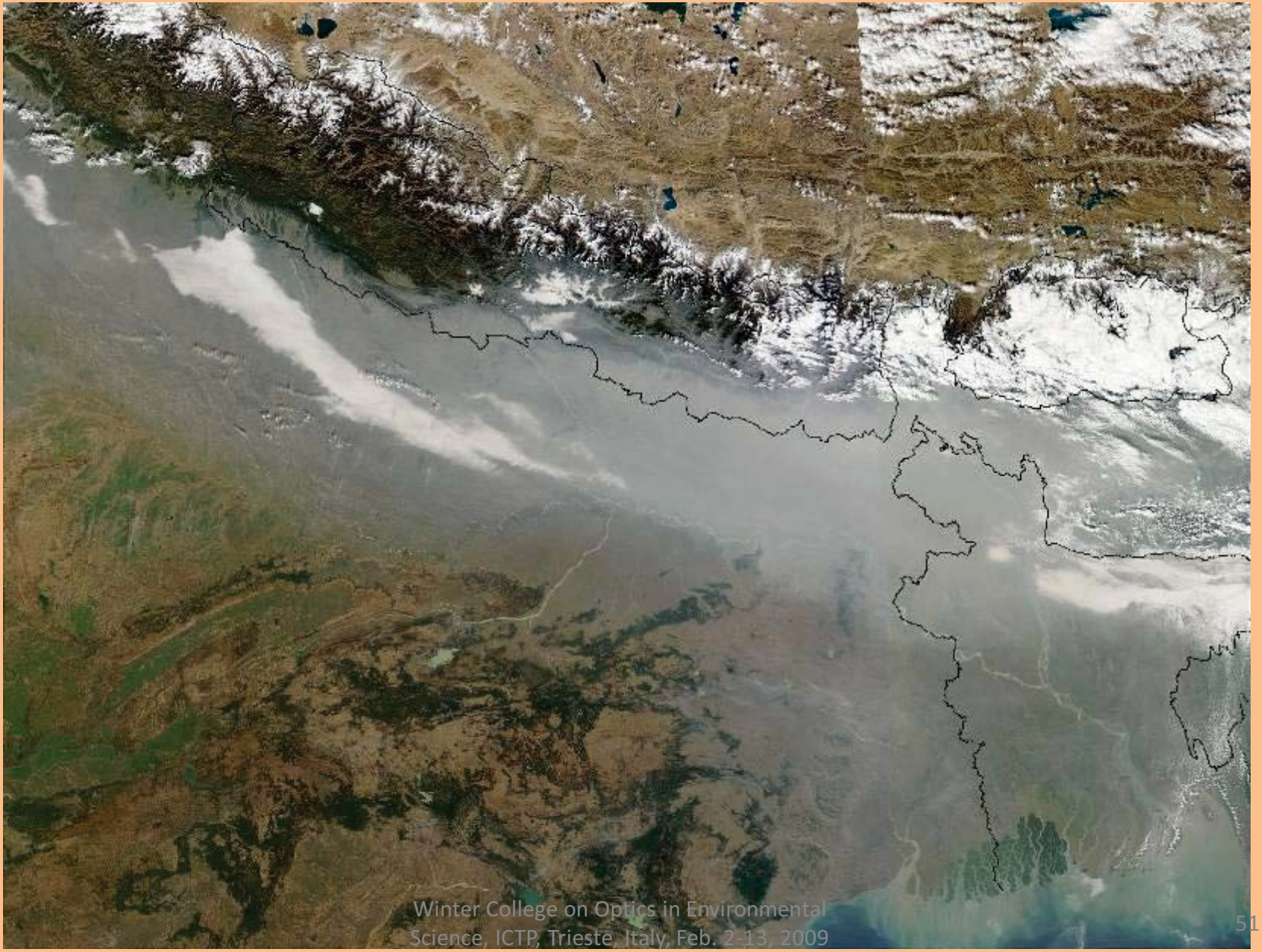

NASA
Smog s
the reg

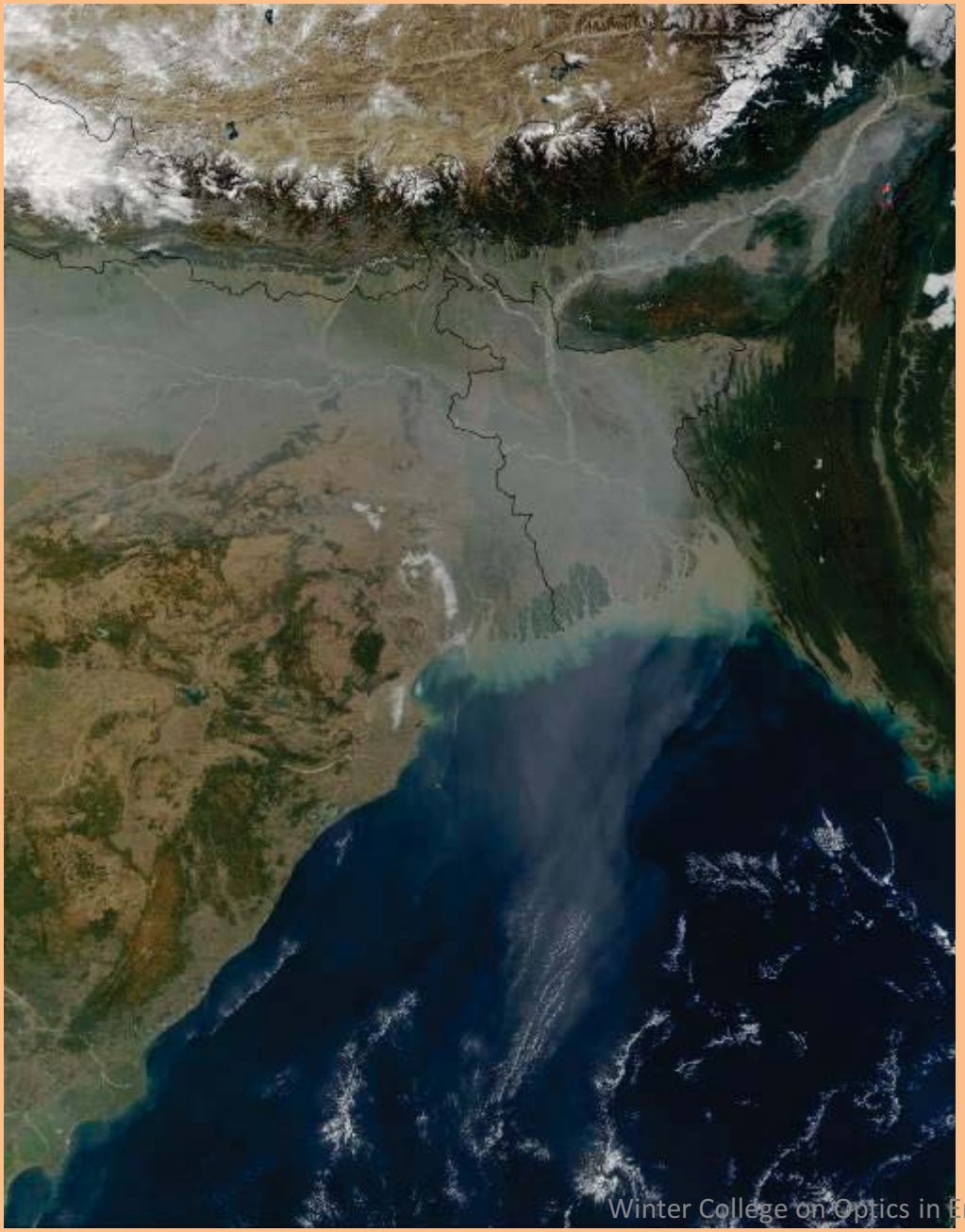


Dec 4, 2001 at 10 :35 local time,

MODIS Terra

Dec 19, 2002, at 10 :55 local time, MODIS Terra and Aqua combination

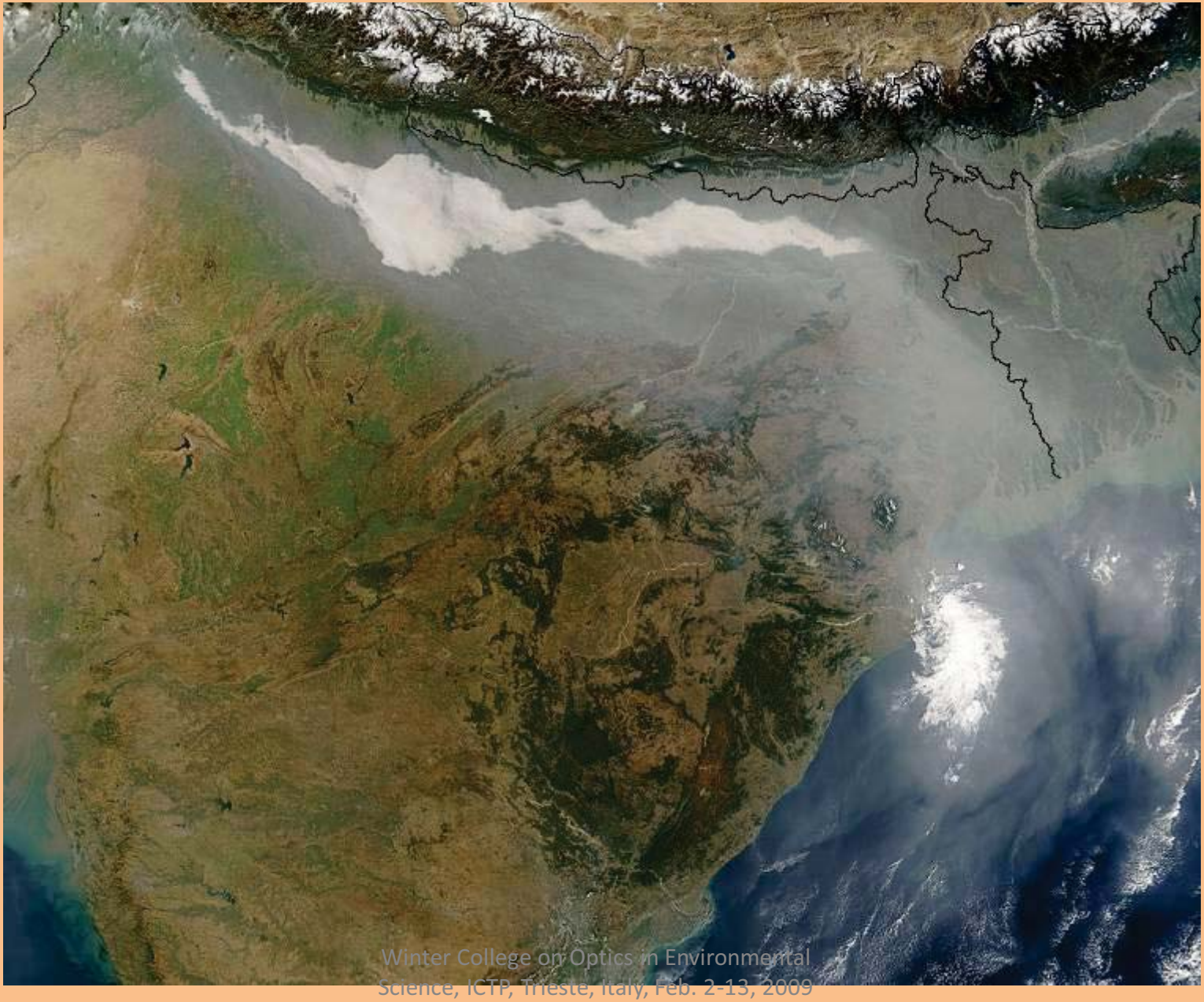




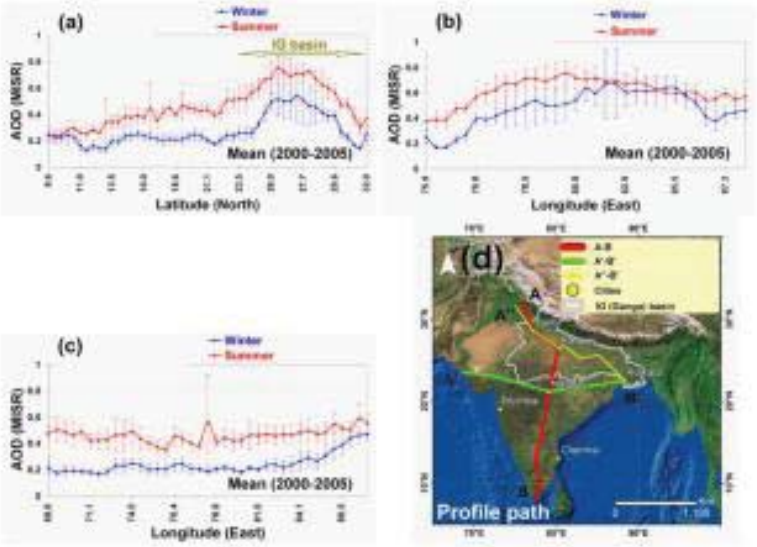
Jan 14, 2002 10 :25 local time,

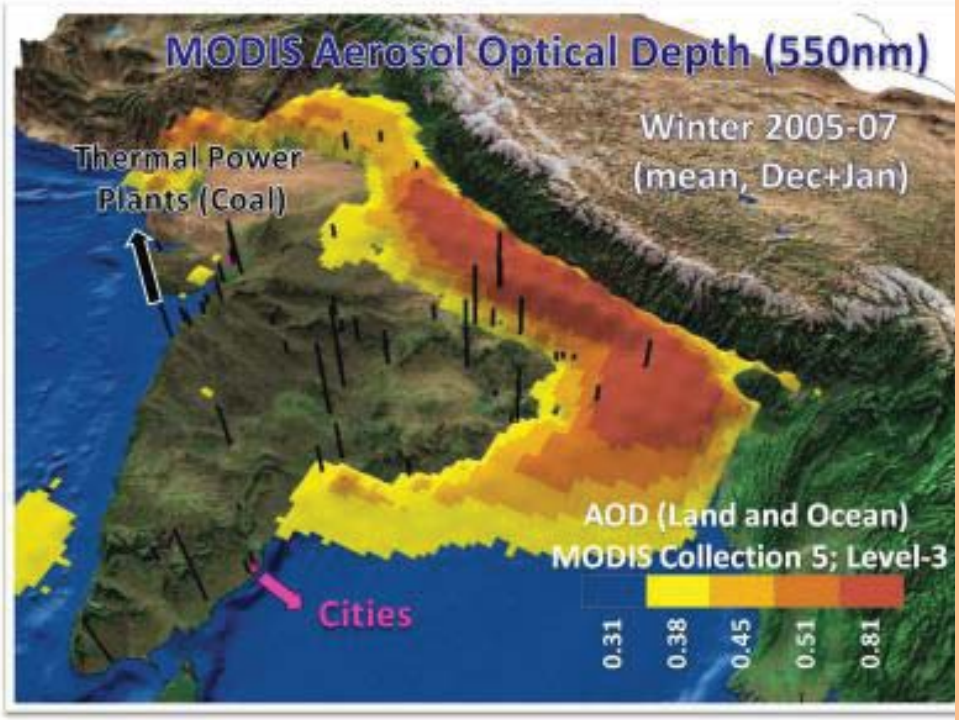
MODIS Terra

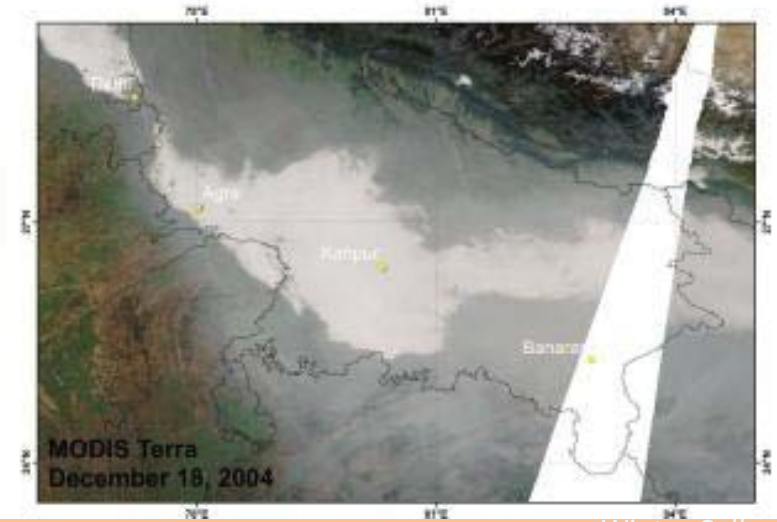
Dec 17, 2004 at 10 :50 IST , MODIS Terra

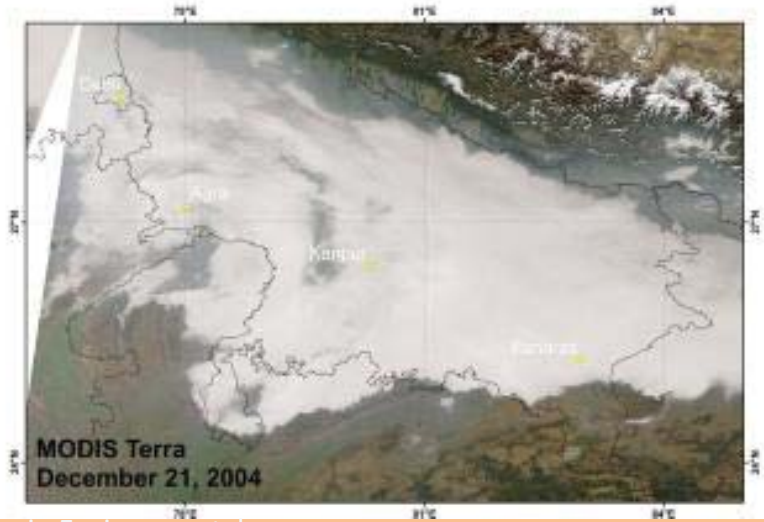


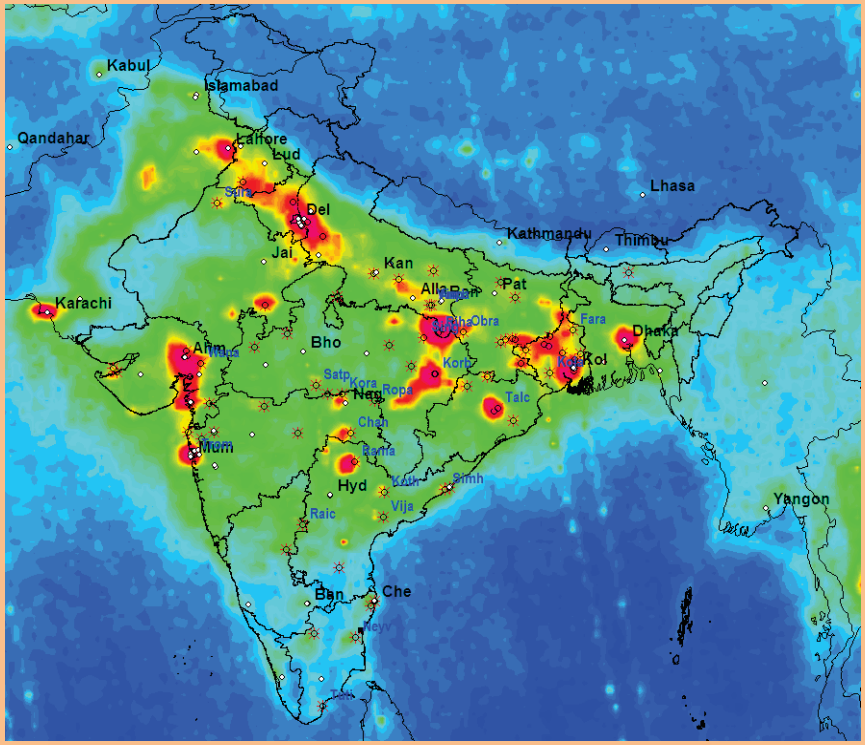
Aerosols and Fog formation



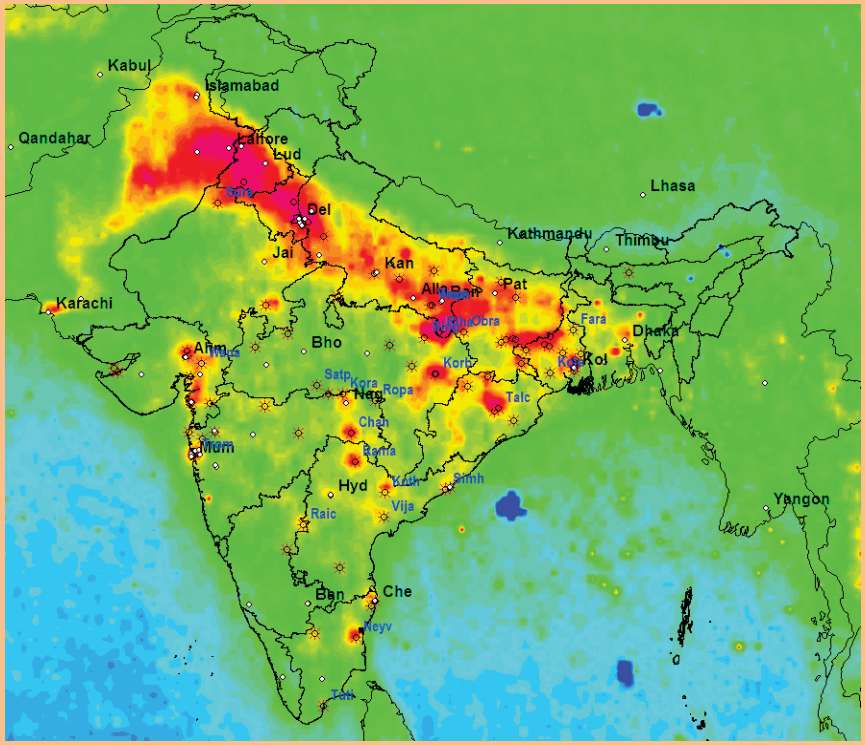








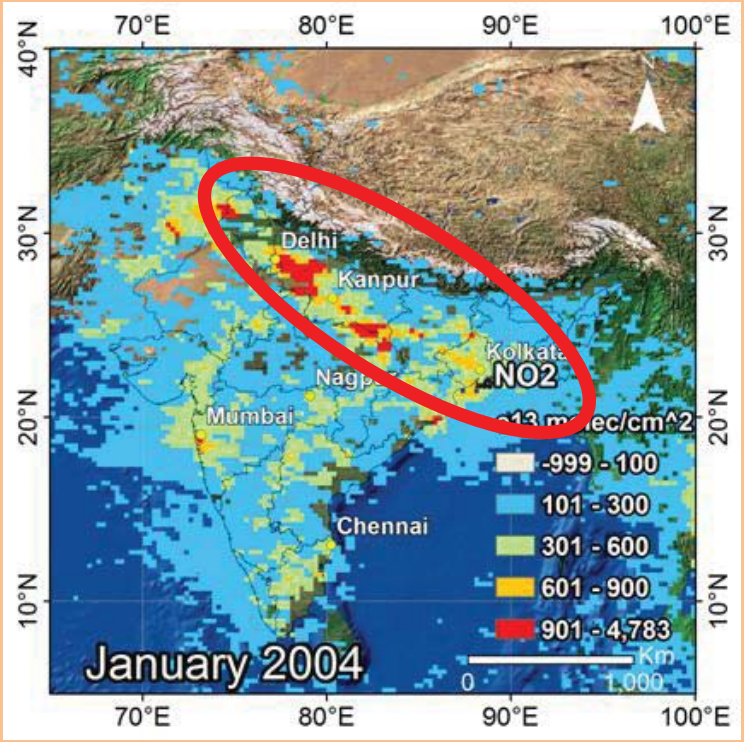
Winter
(2005-06)

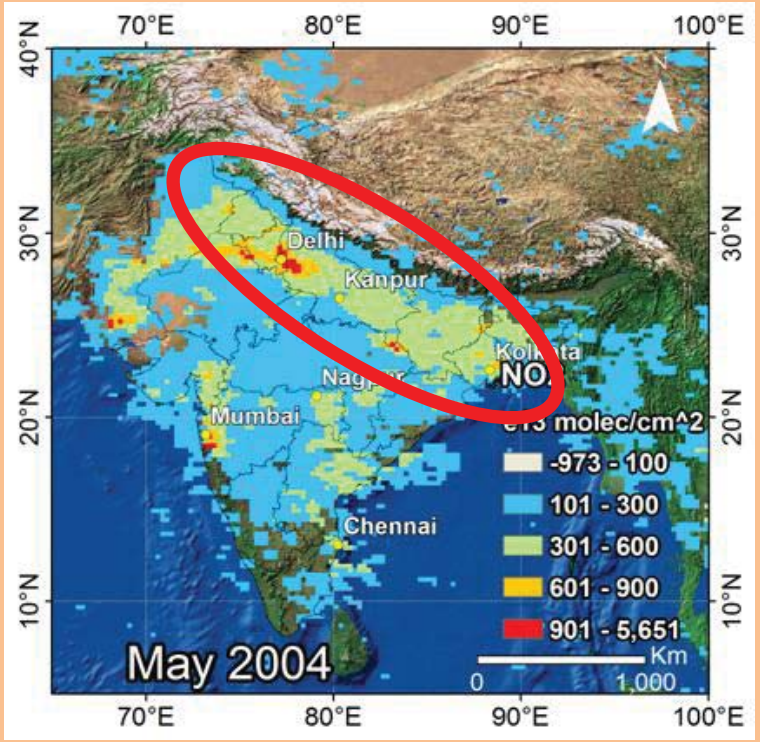


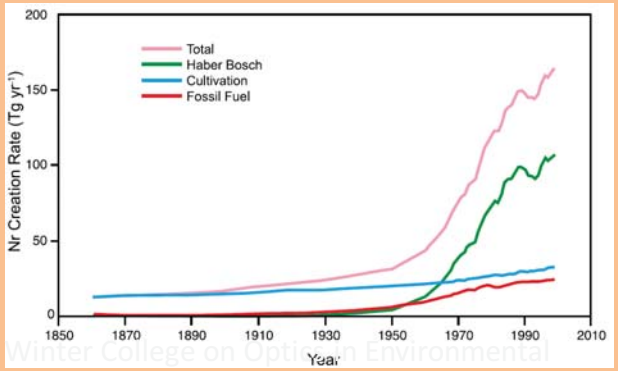
Summer
(2006)

Sciamachy Troposheric NO_2

(relatively higher NO2 level in the IG basin)





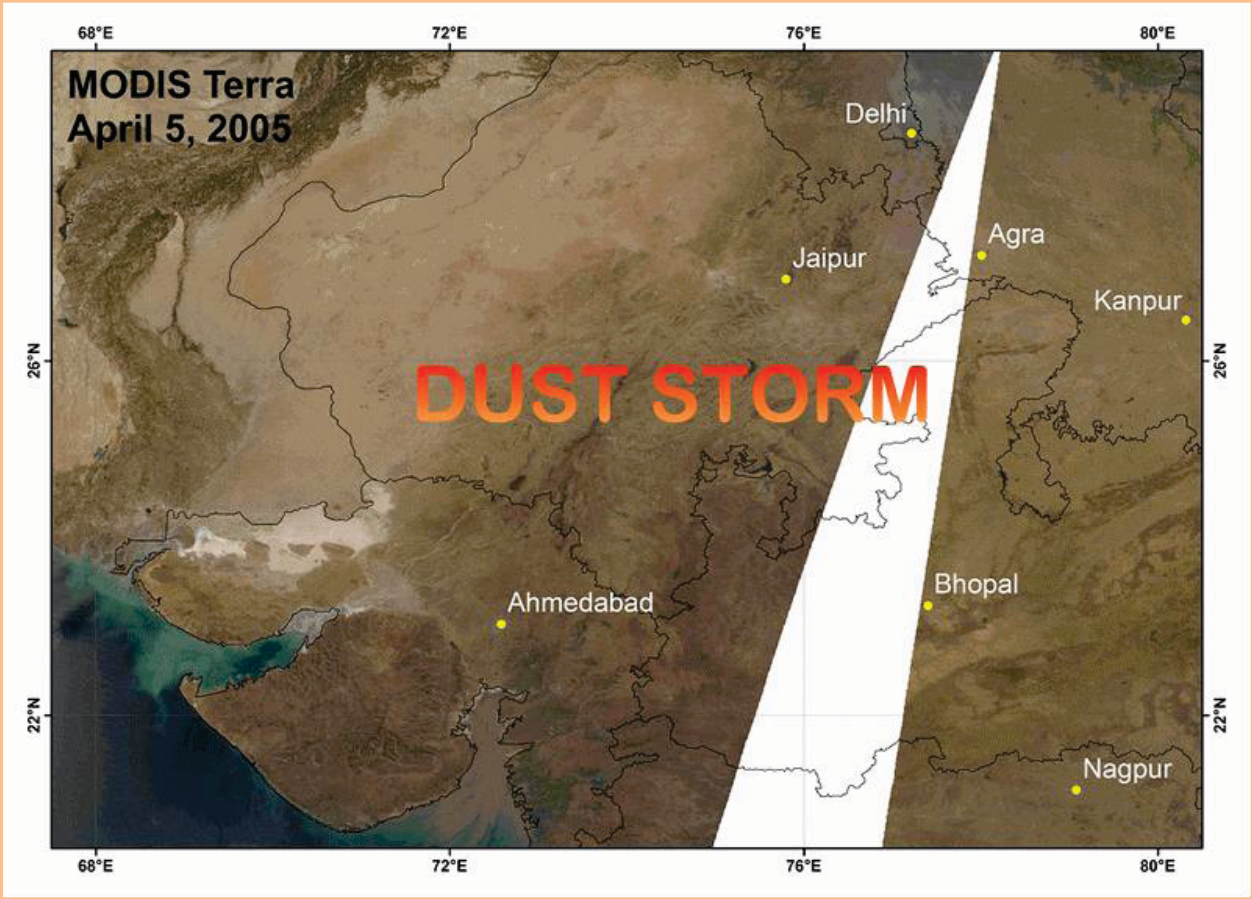


Global anthropogenic creation rates of reactive nitrogen

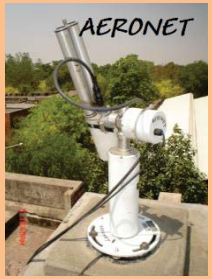
Dust Storms

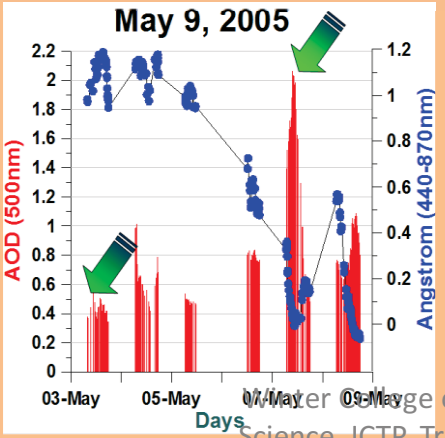
Dust Storms

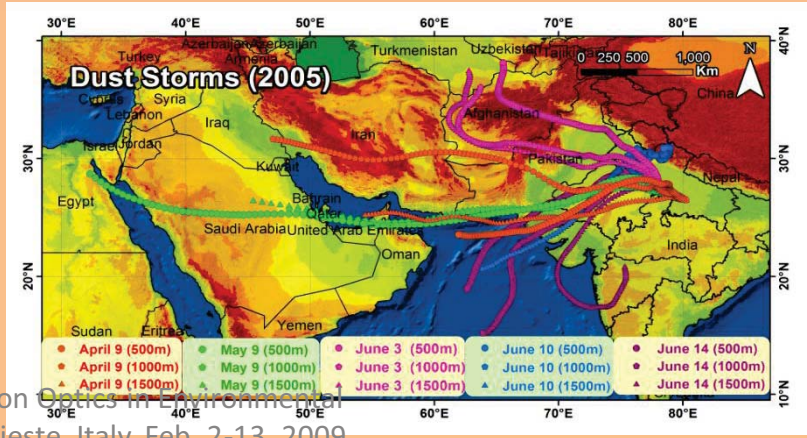
Satellite (daily)
MODIS Terra
and Aqua)



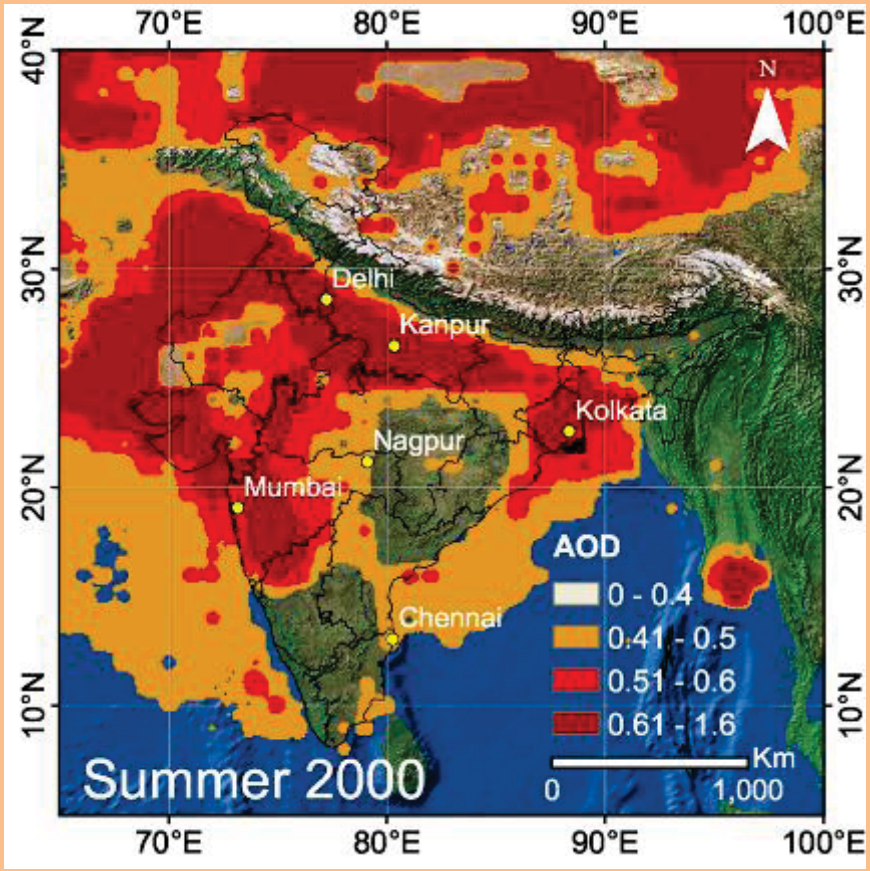
Ground based
CIMEL
Sun-photometer

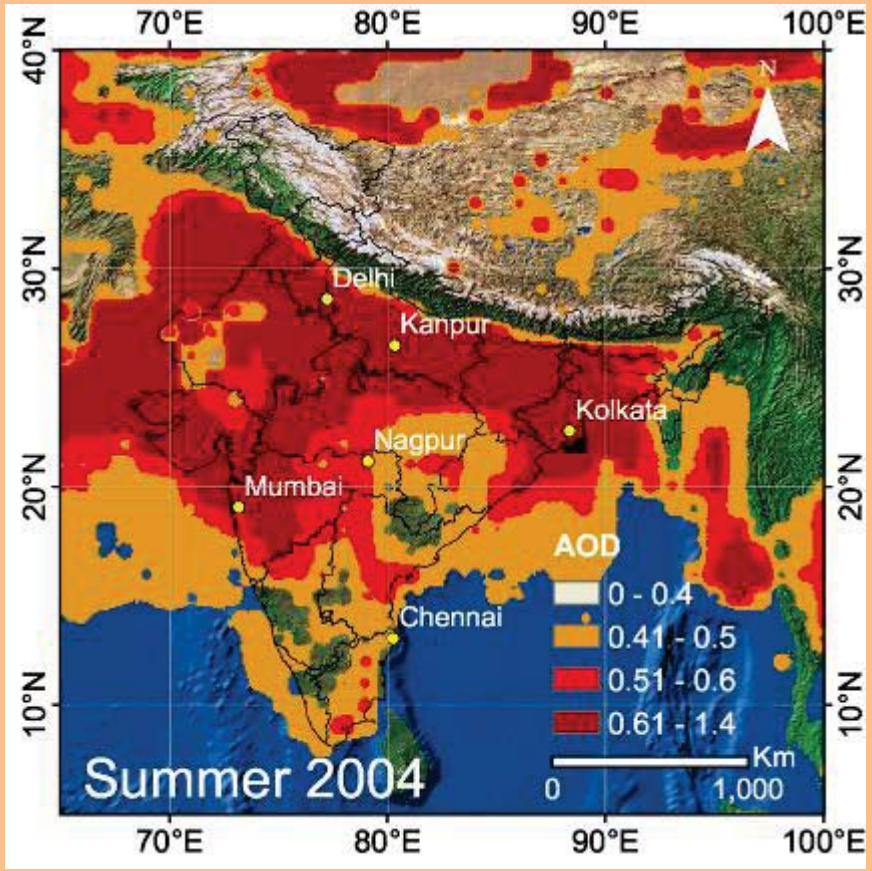






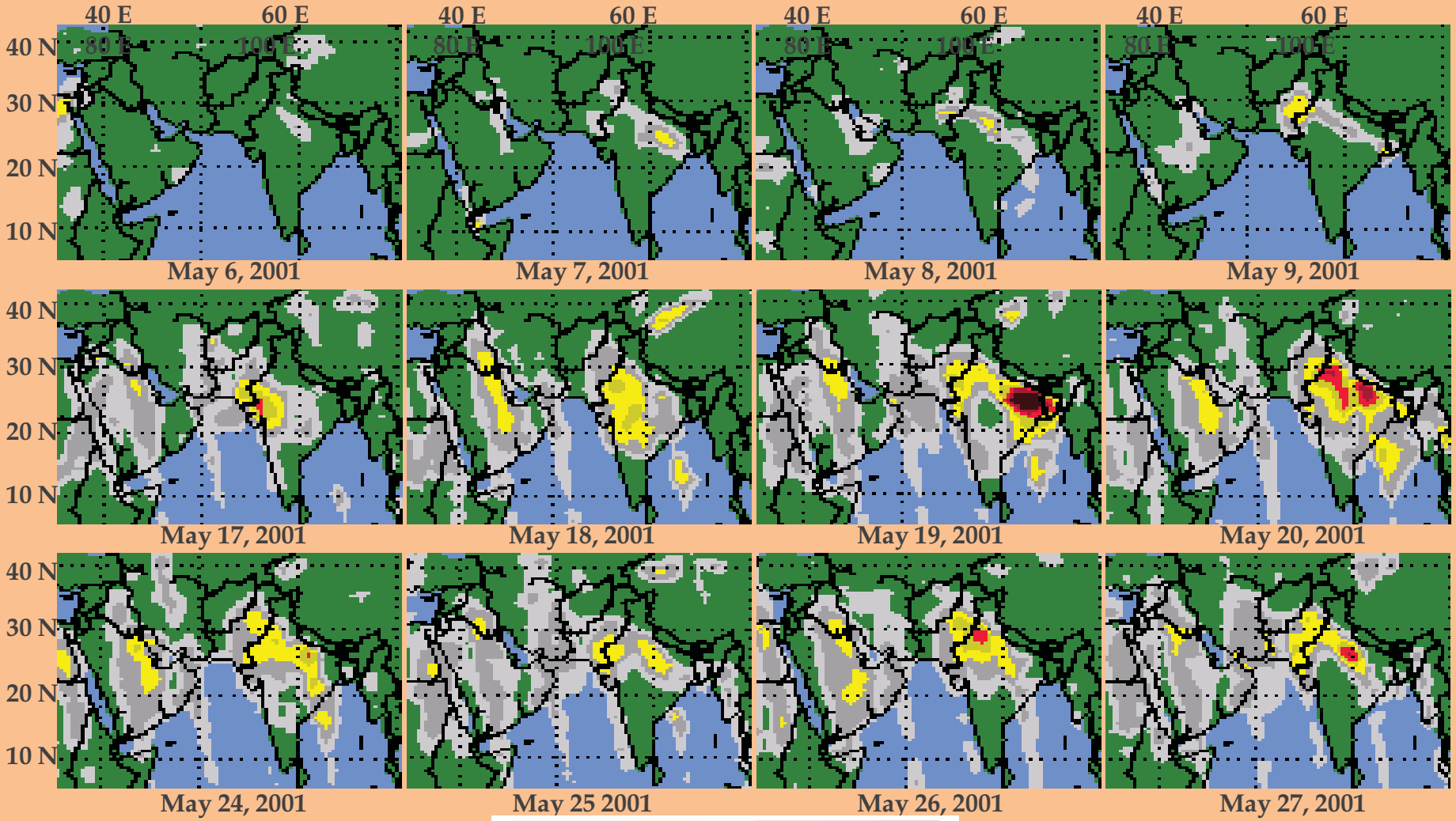
Rise in AOD over the Indian Subcontinent (summer season)



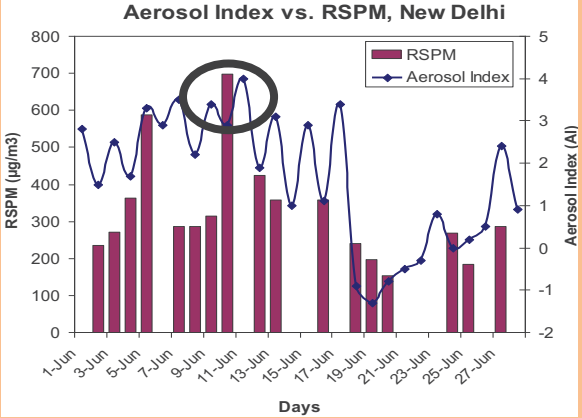


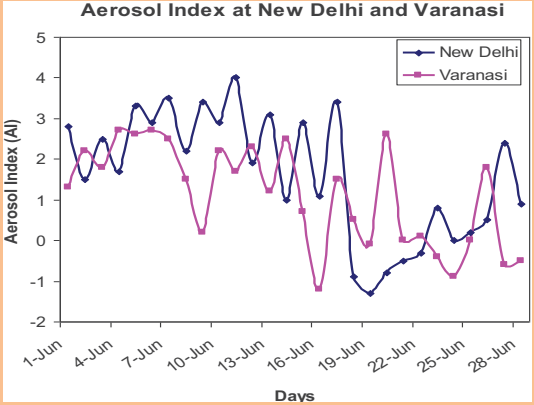
Prasad et al., JISRS, (2005),

Spread of Dusts as seen in TOMS AI Images

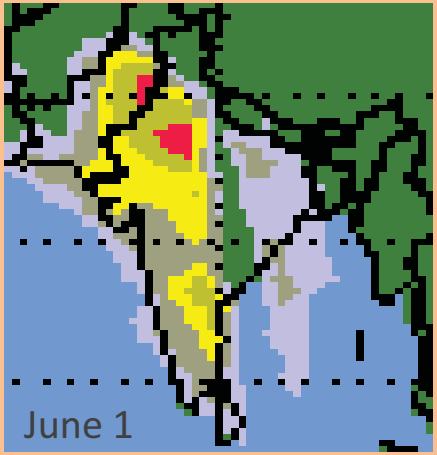


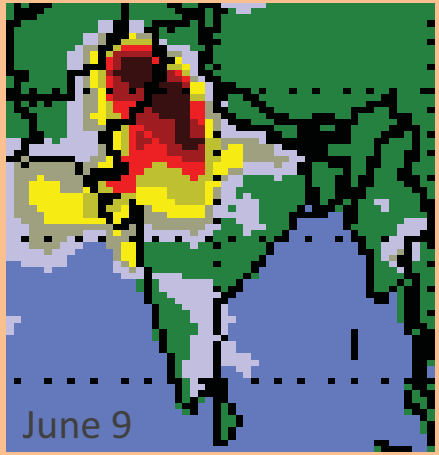
Aerosol Index vs. RSPM

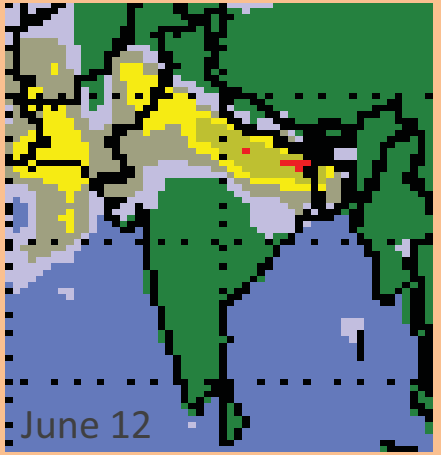


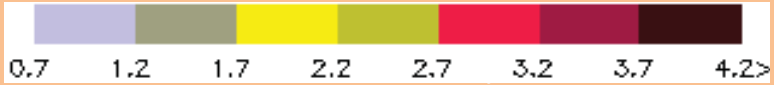


- Aerosol index (AI) data taken from TOMS shows maximum value due to the dust outbreak in the IG basin in June 2003.
- Ground based *Respiratory Suspended Particulate Matter (RSPM)* data shows significant increase of particulate matter concentration in atmosphere, thus confirming the presence of dust particles.

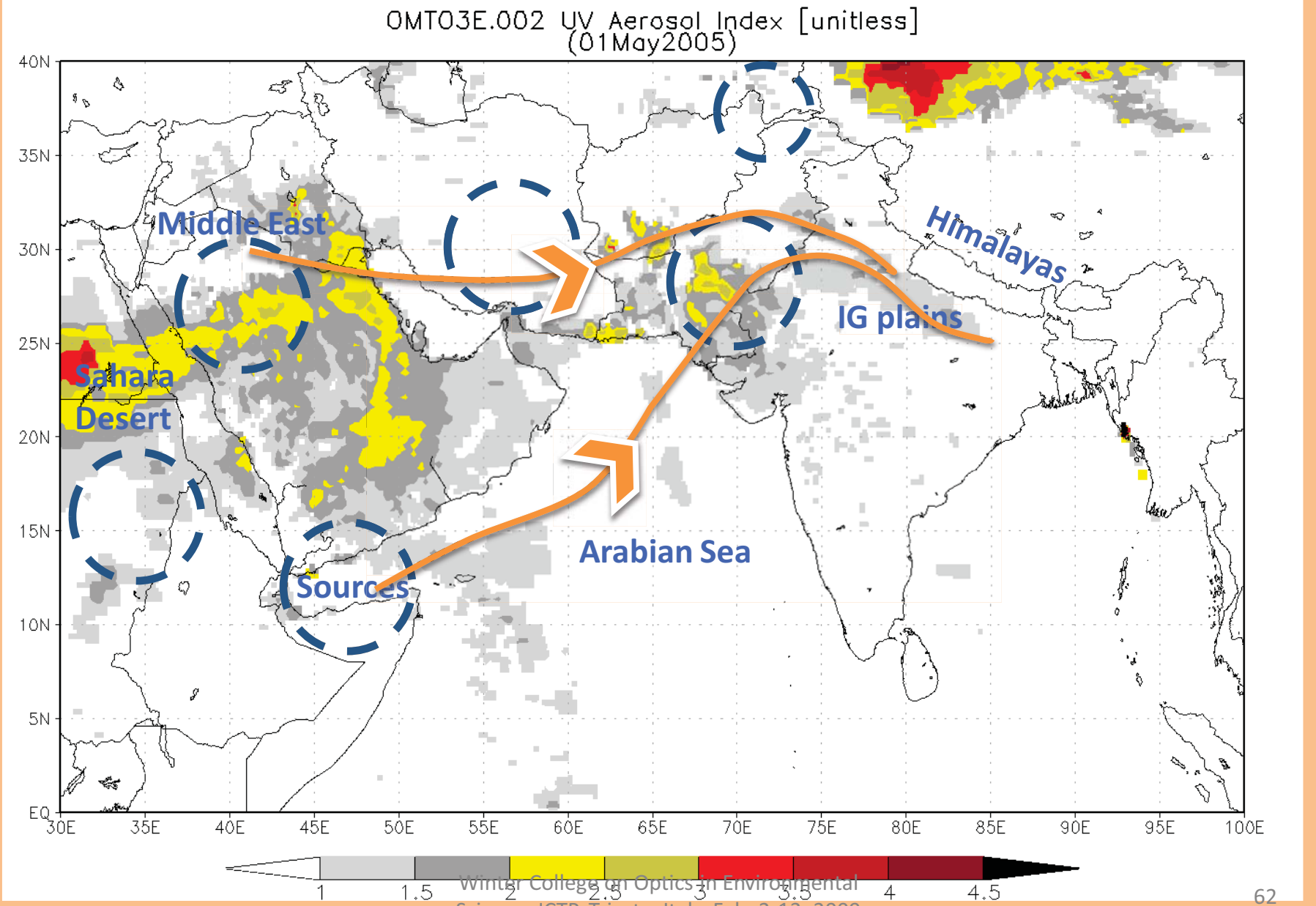




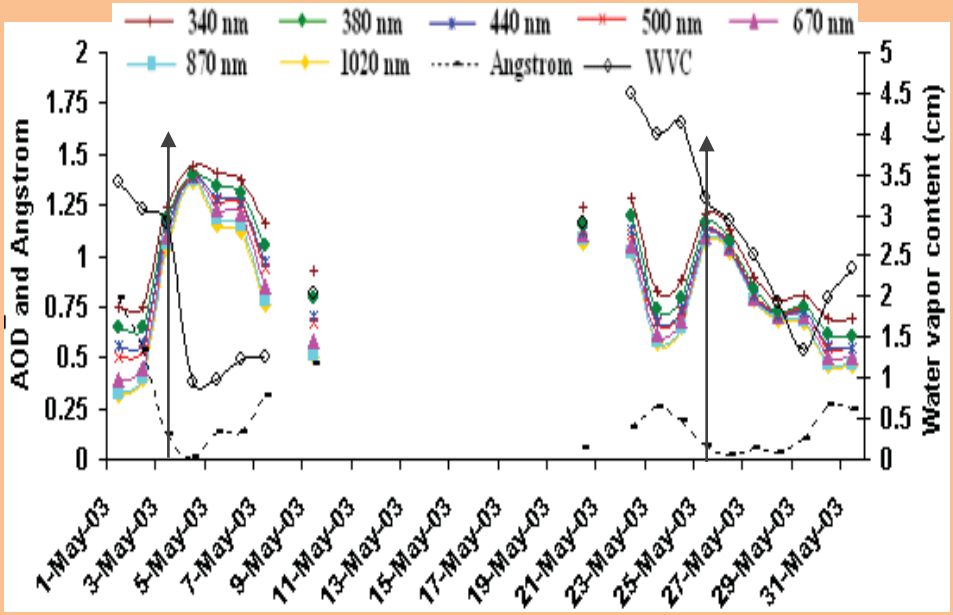


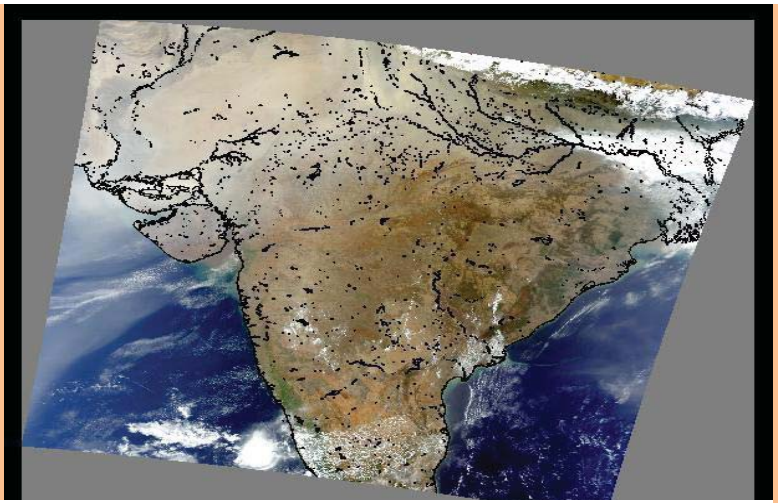


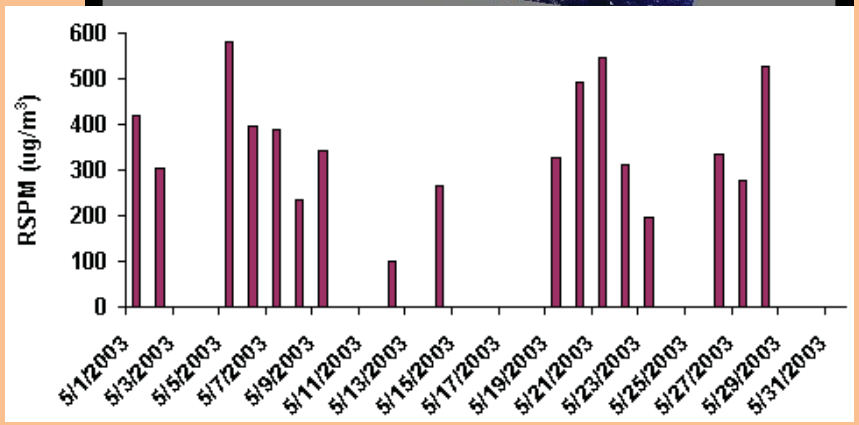
Dust storms (May 7-8-9, 2005)

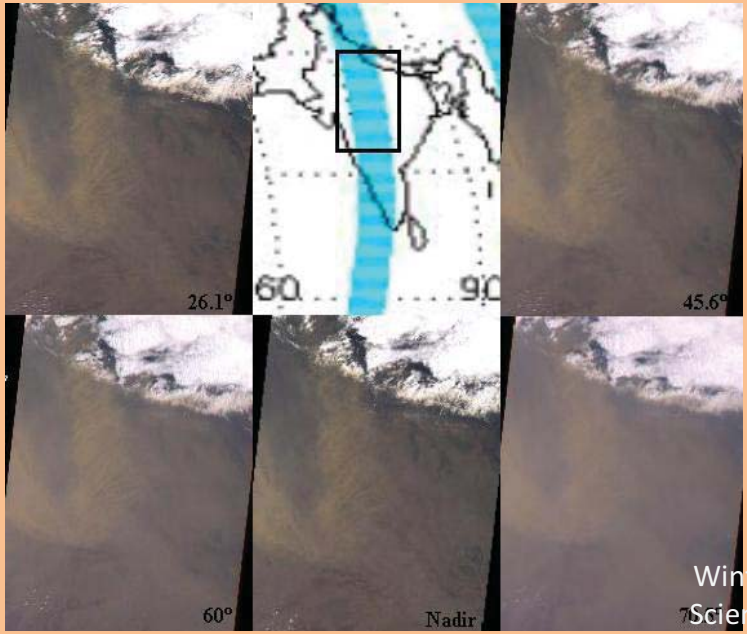


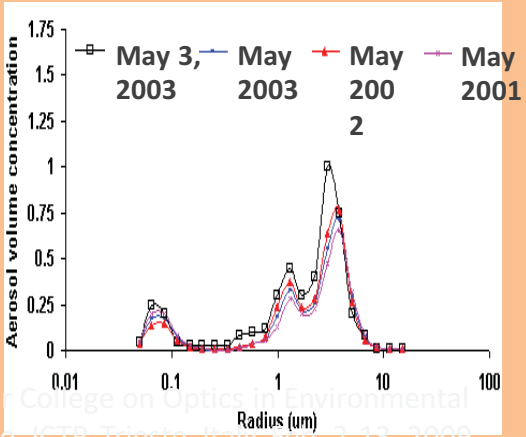
Remote Sensing of Dust Storms

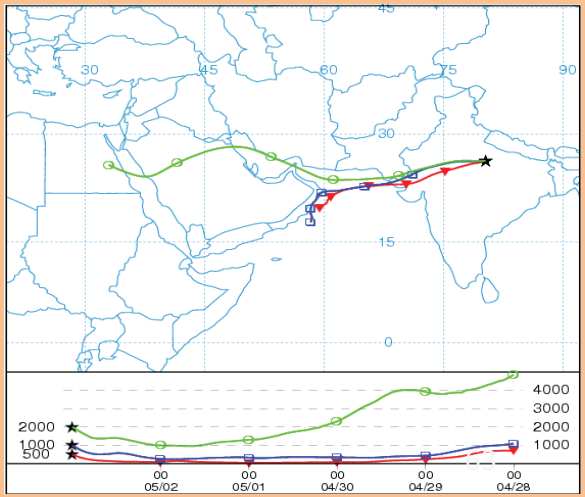












Delhi Dust storm May 14, 2008

Rain after Dust storm of May 14, 2008

Delhi: Rain throws normal life out of gear

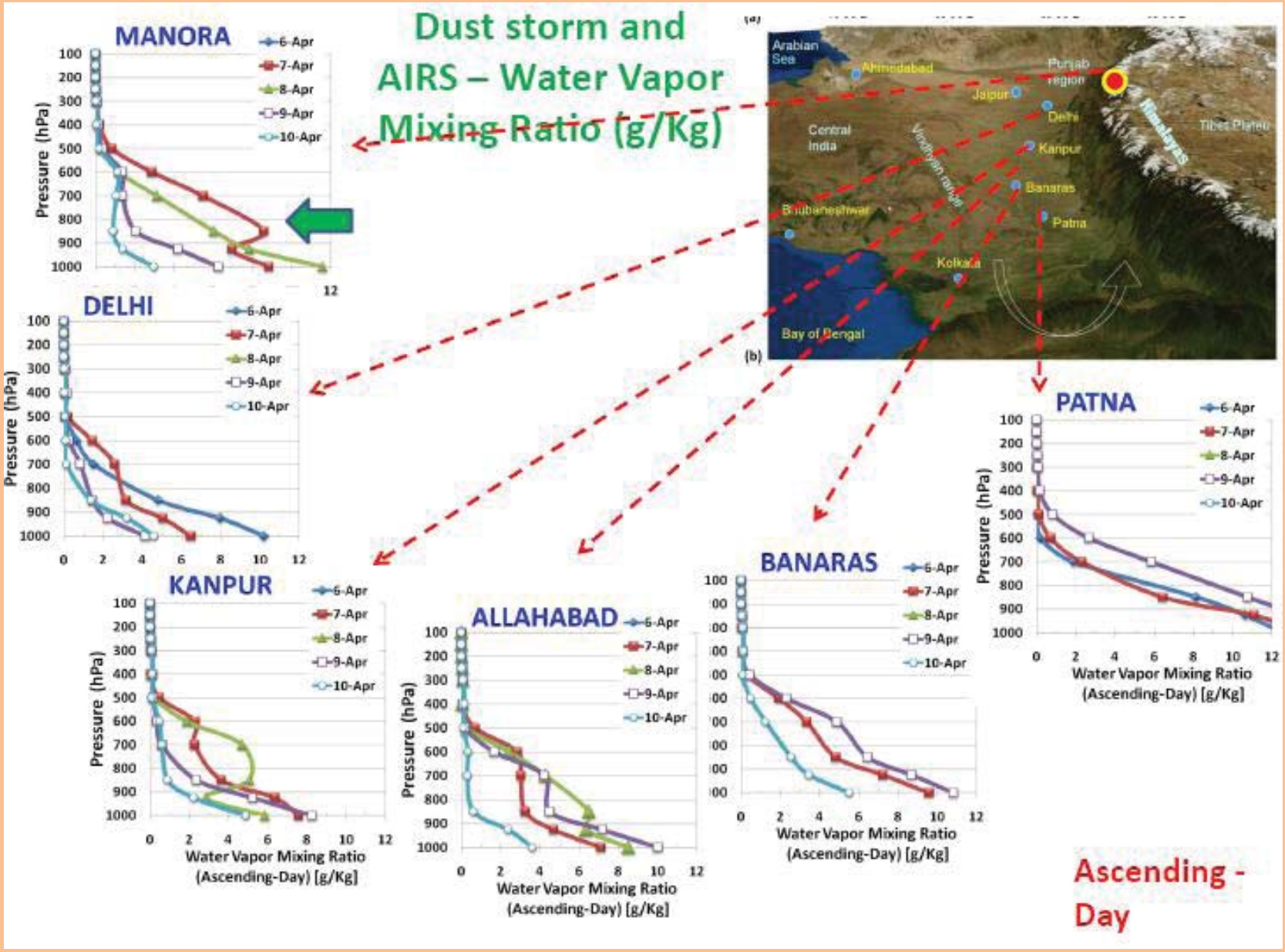
Press Trust of India

Wednesday, May 14, 2008 (New Delhi)

Heavy dust storm followed by torrential rains lashed the Capital on Wednesday, throwing normal life out of gear.

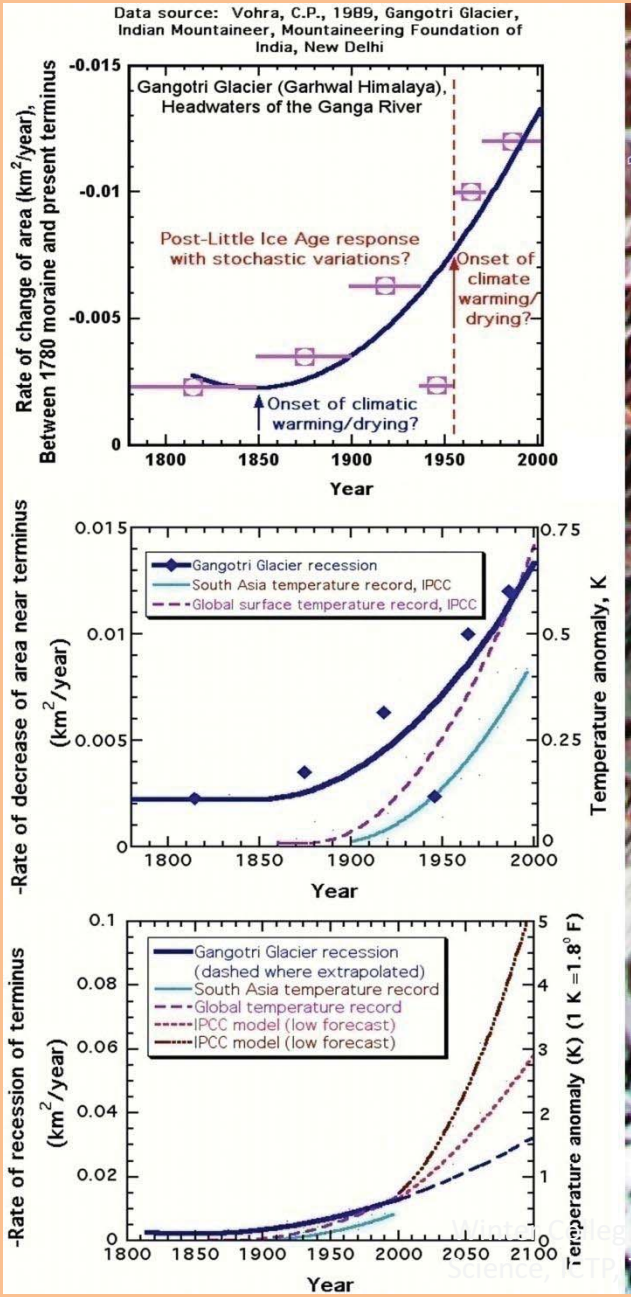
Office-goers had a tough time reaching their destination as heavy rains lashed the city from around 9 am.

There were also reports of trees being uprooted in many parts of the city.


Dust storm and
AIRS – Water Vapor
Mixing Ratio (g/Kg)
MANORA
DELHI
KANPUR
ALLAHABAD
BANARAS
PATNA
6-Apr
7-Apr
8-Apr
9-Apr
10-Apr
Pressure (hPa)
Water Vapor Mixing Ratio
(Ascending-Day) [g/Kg]
Arabian Sea
Ahmedabad
Punjab region
Jaipur
Delhi
Central India
Kanpur
Banaras
Bhubaneshwar
Patna
Kolkata
Bay of Bengal
Himalayas
Tibet Plateau
(a)
(b)
Ascending - Day

Snow Mapping and Monitoring of Snow Environment

Gangotri Glacier, Garwhal Himalaya (India)



Wessels, Kargel, and Hasnain

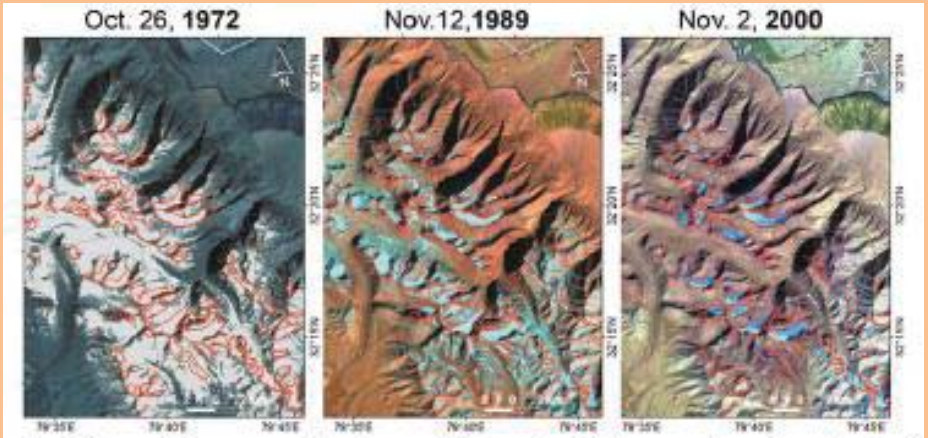


Fig. 1. Change in the snow and glacier cover in the western Himalayan region as shown in Landsat multispectral scanner (1972), thematic mapper (1989), and Enhanced Thematic Mapper Plus (2000) images. Areas outlined in red indicate information from the GLIMS database.

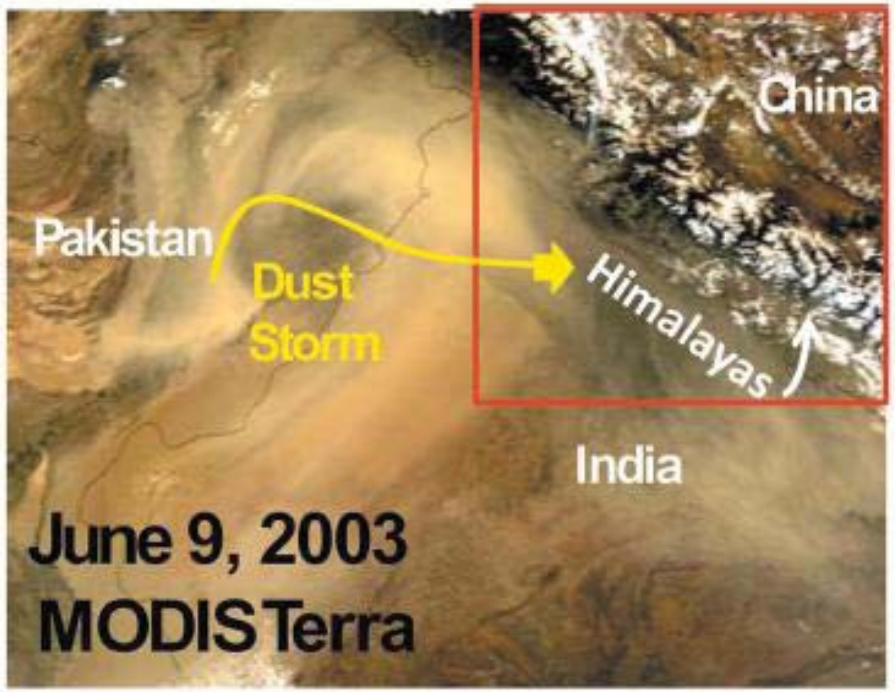
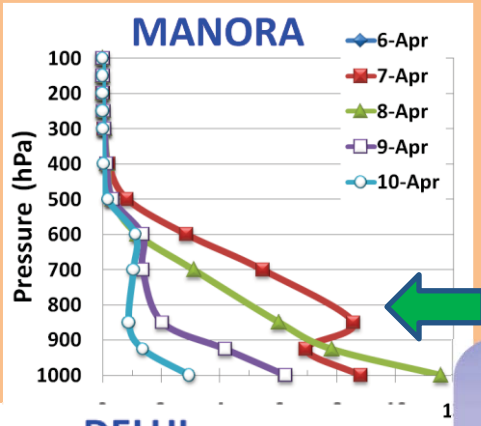
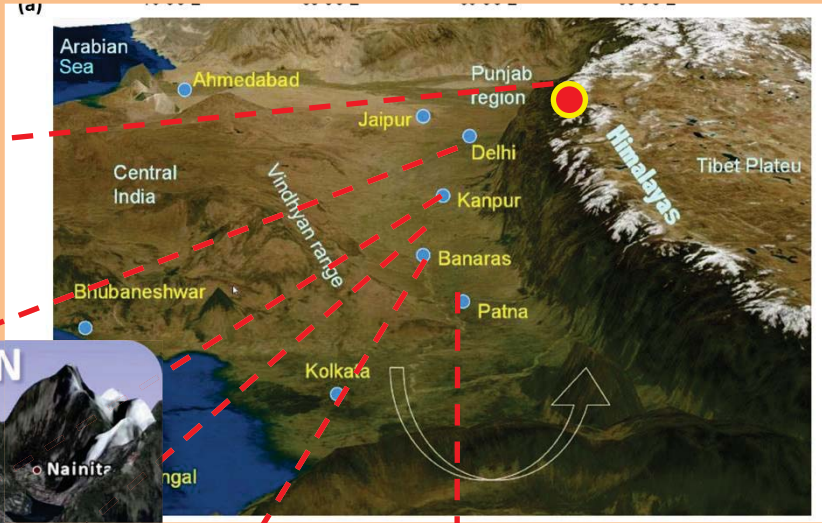
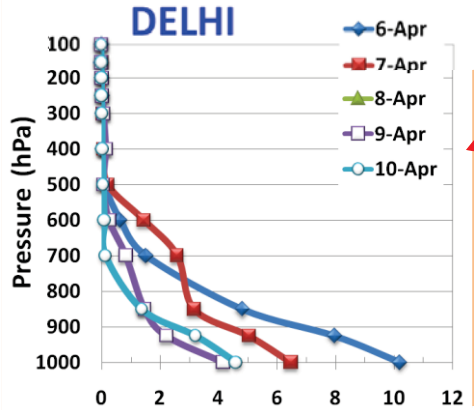


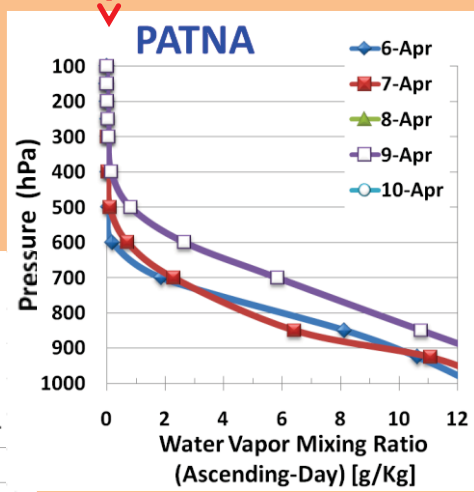
Fig. 2. Dust storms reach up to snow and glacier of Himalayas (box outlined in red) as visible in this 9 June 2003 MODIS Terra image obtained from the MODIS Web site (http://modis.gsfc.nasa.gov/).

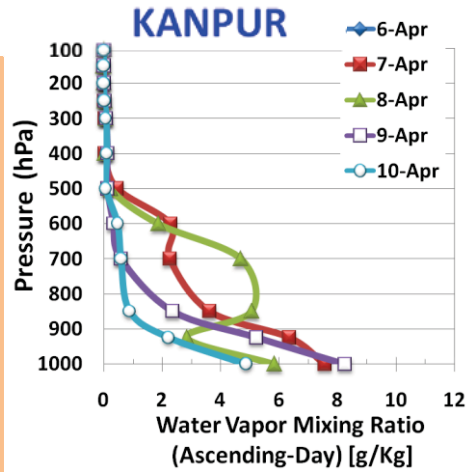
Dust storm and AIRS – Water Vapor Mixing Ratio (g/Kg)

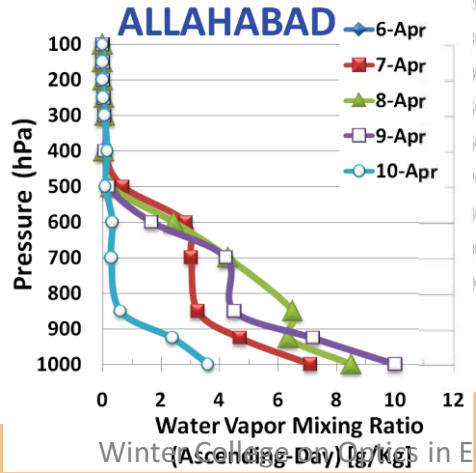


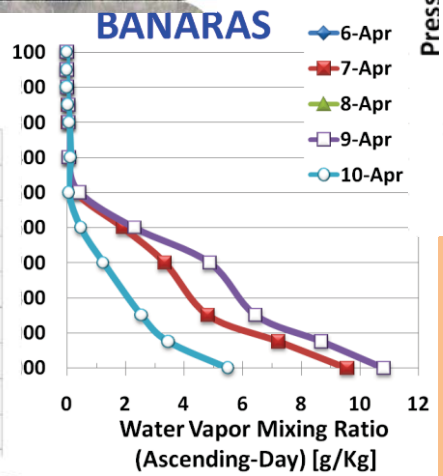








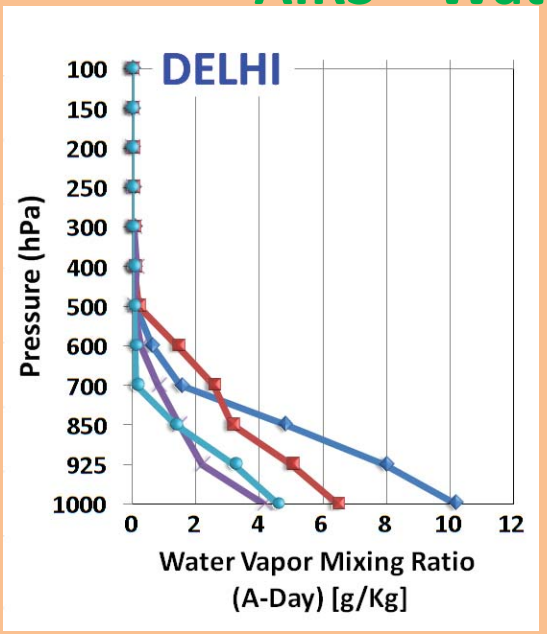


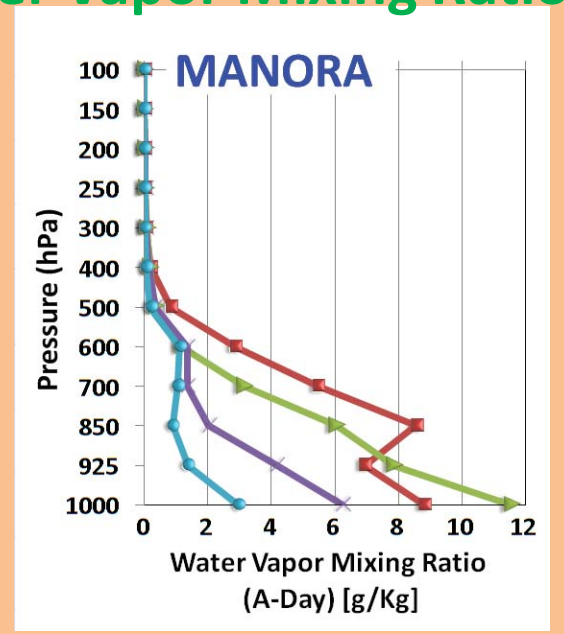


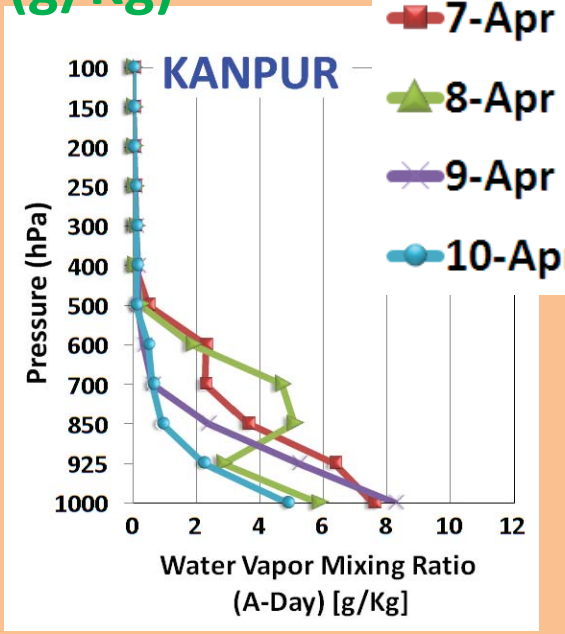
Ascending - Day

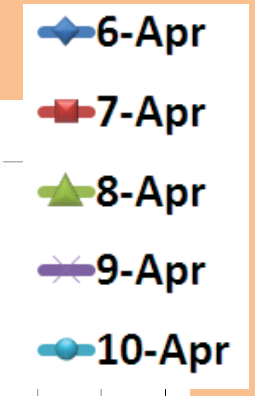
AIRS – Water Vapor Mixing Ratio (g/Kg)

Ascending - Day

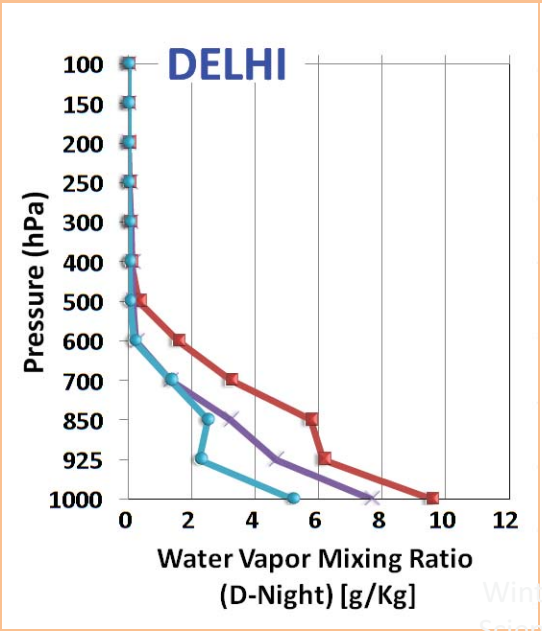


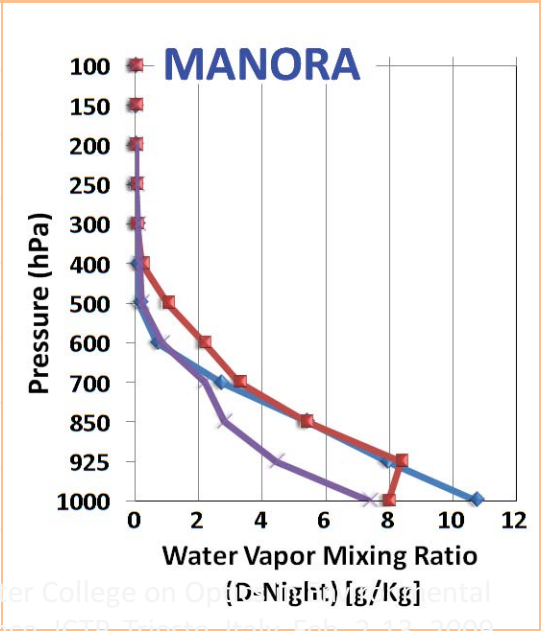


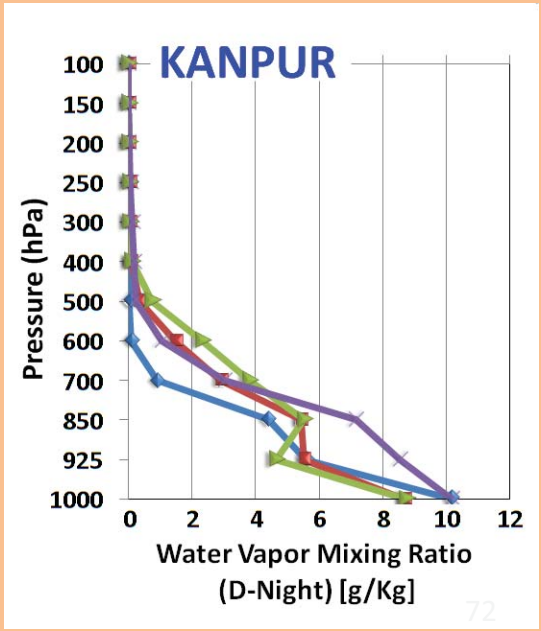




Descending - Night

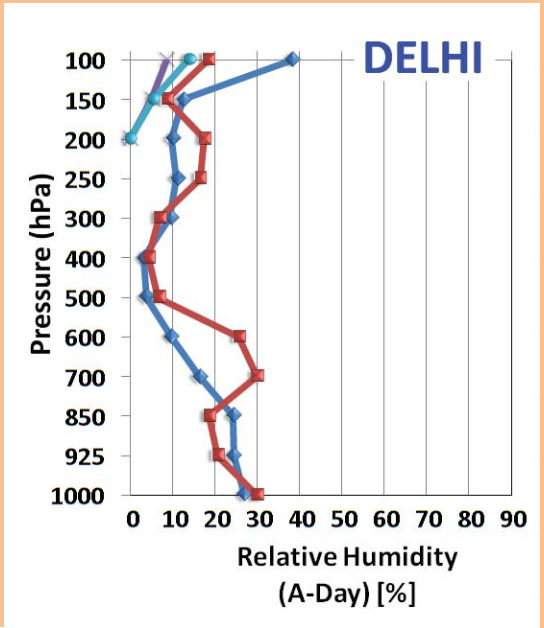


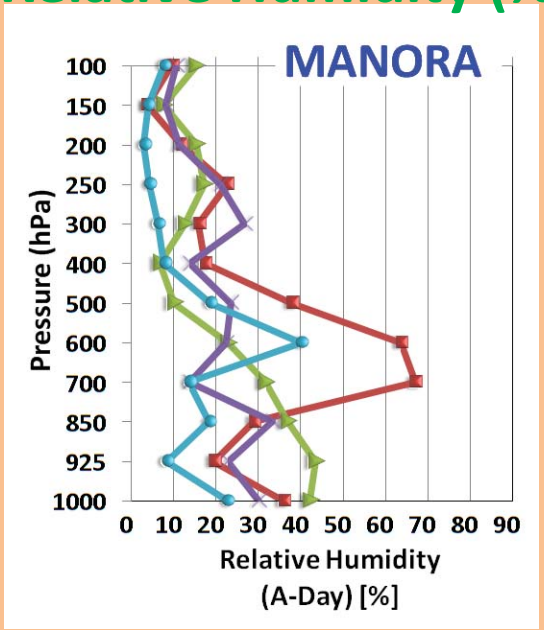


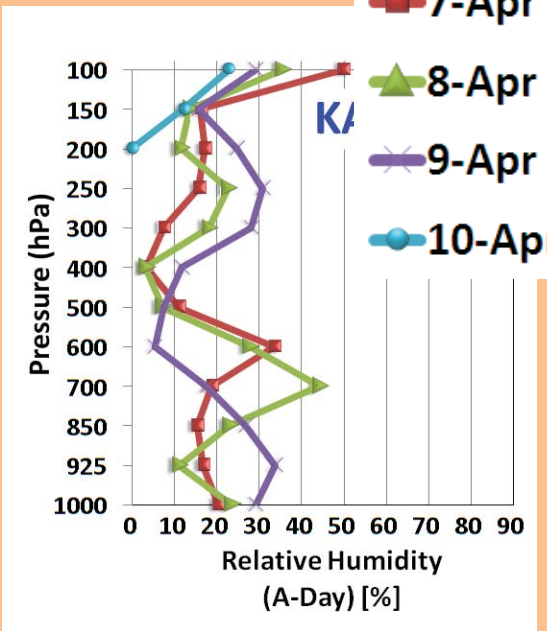


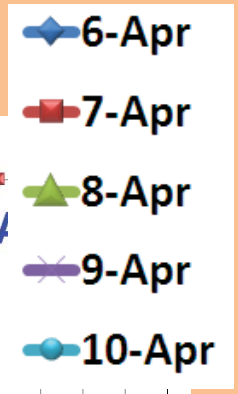
AIRS – Relative Humidity (%)

Ascending - Day

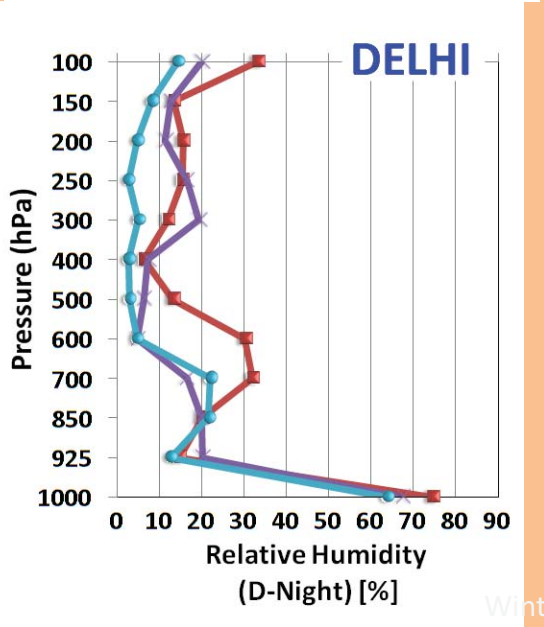


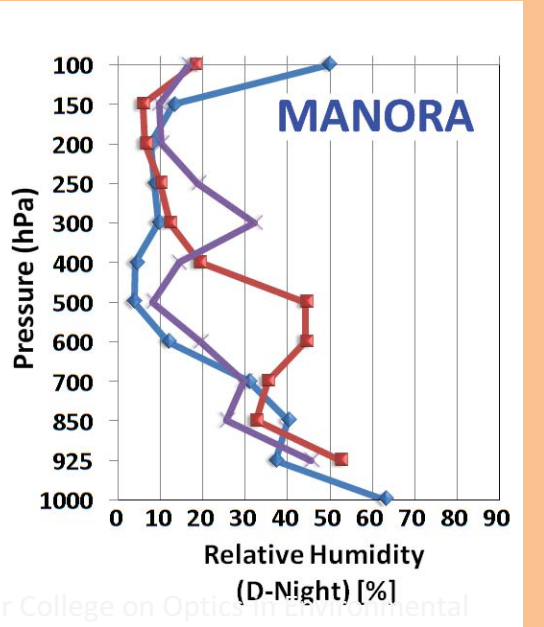


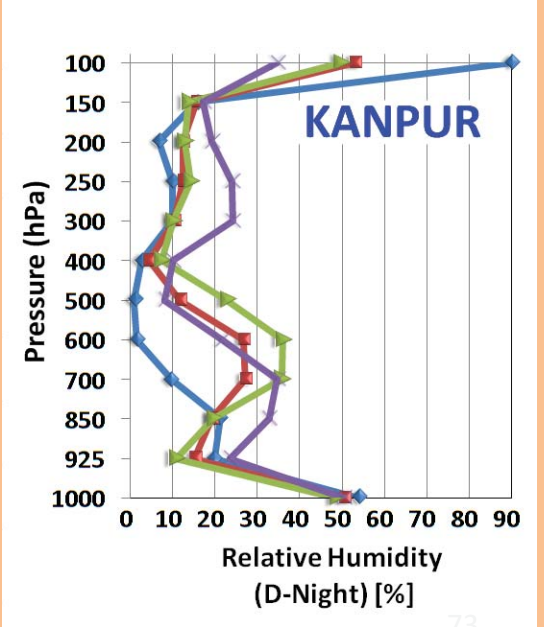




Descending - Night

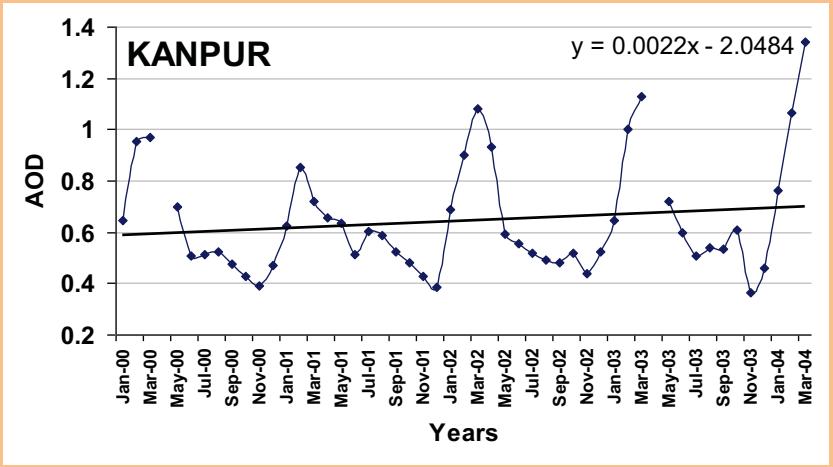


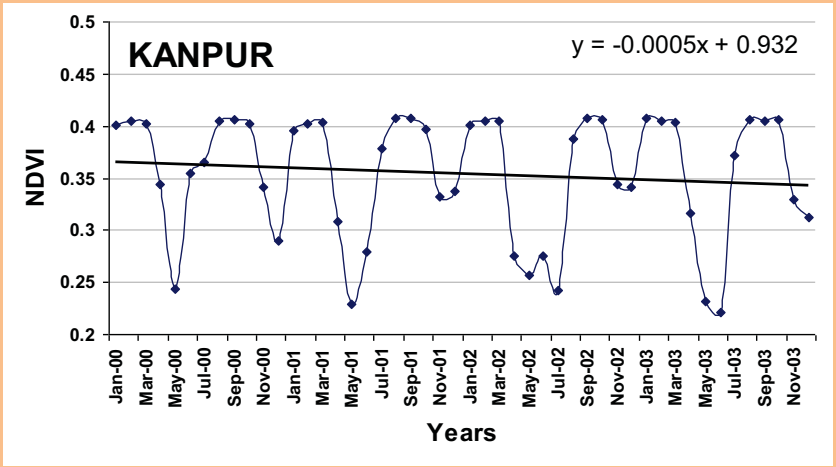


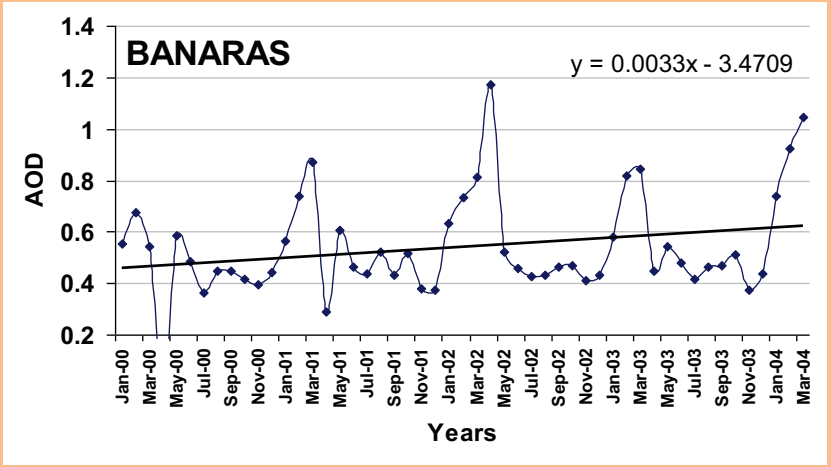


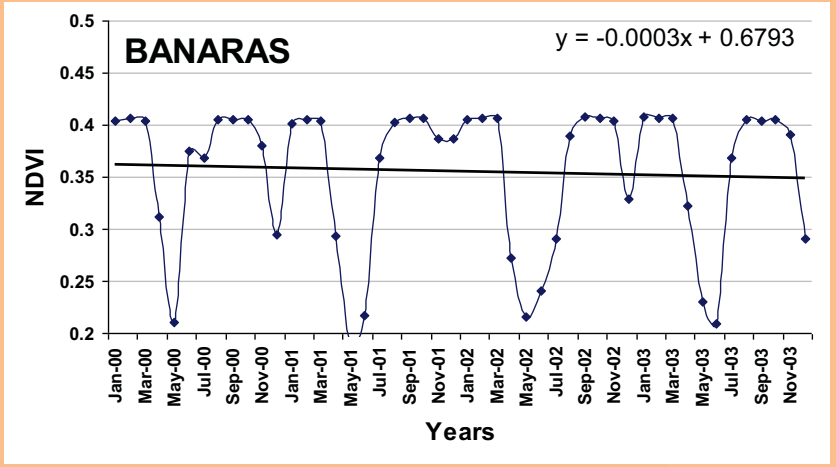
Pollution and Vegetation

Effect of AOD on NDVI







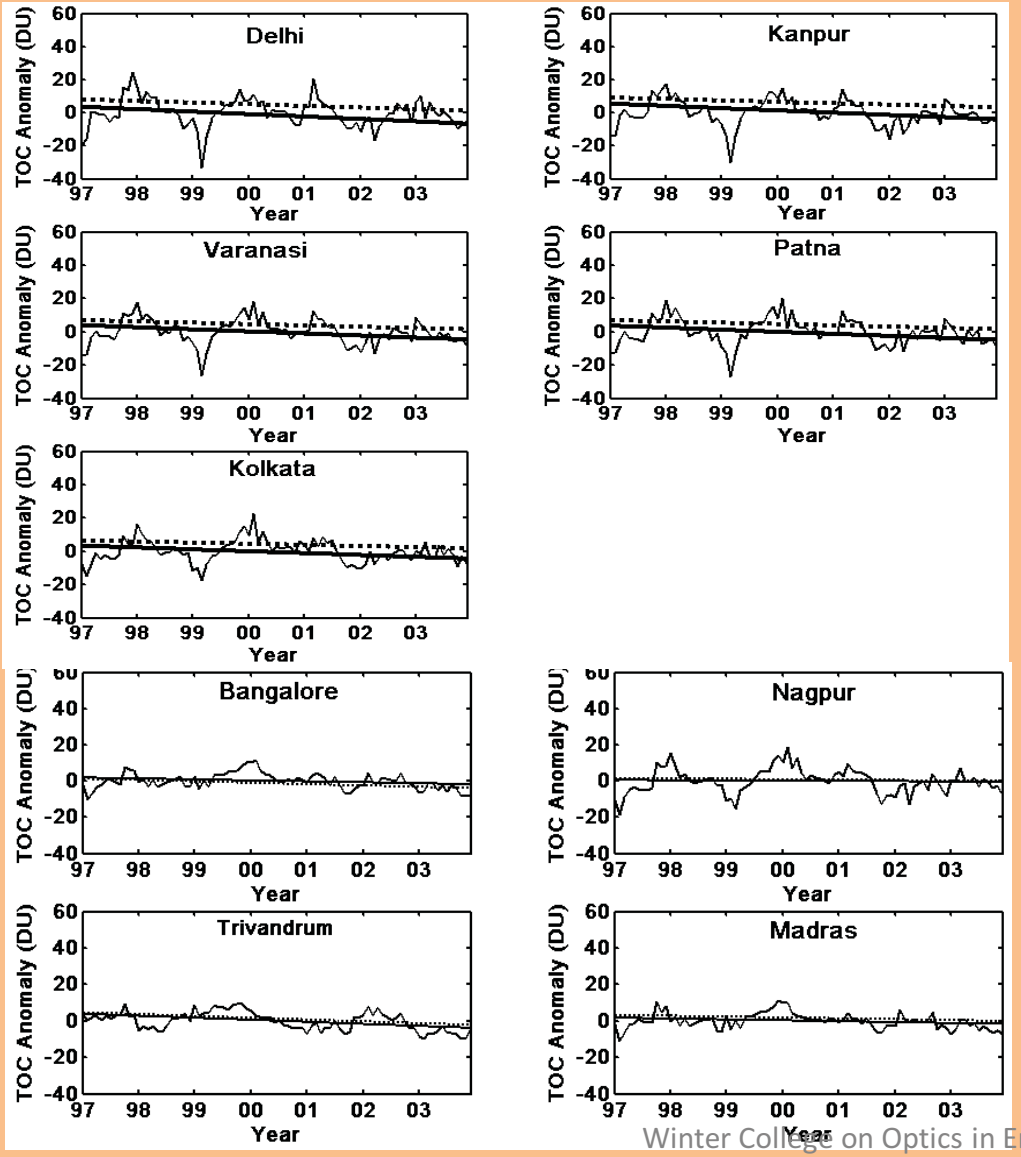


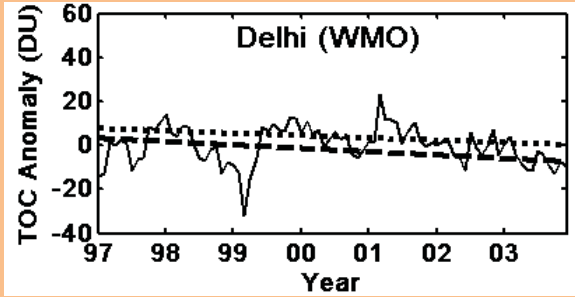
- Percent decrease in NDVI is ~8% in Kanpur and ~5% in Banaras region (average of 100km^2) corresponding to 16% and 32% increase in AOD over the same time period respectively.

Prasad et al. (2005)

Total Ozone Column

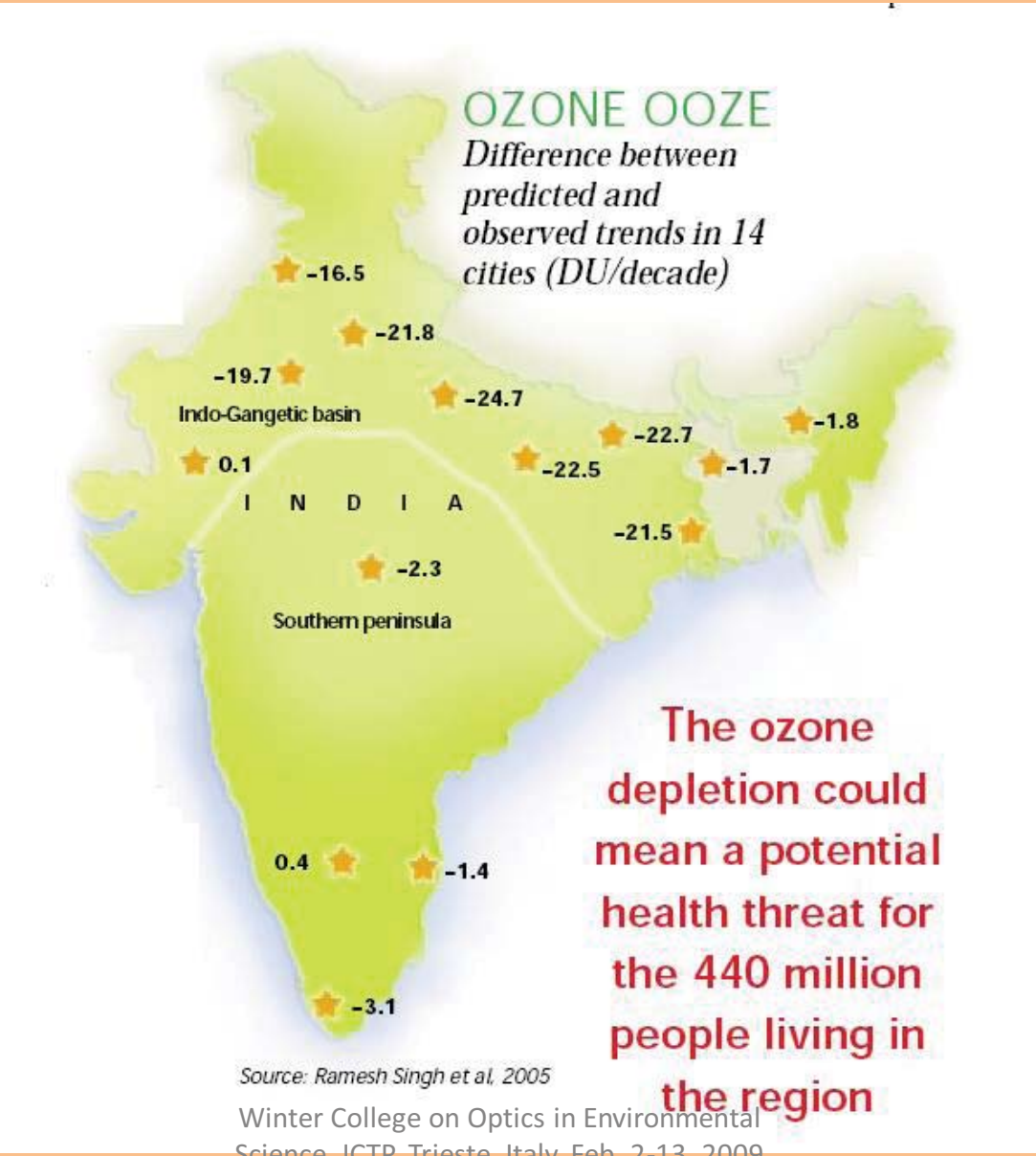
Large Difference between Projected (1979-1993) and Observed Trend (1997-2003)



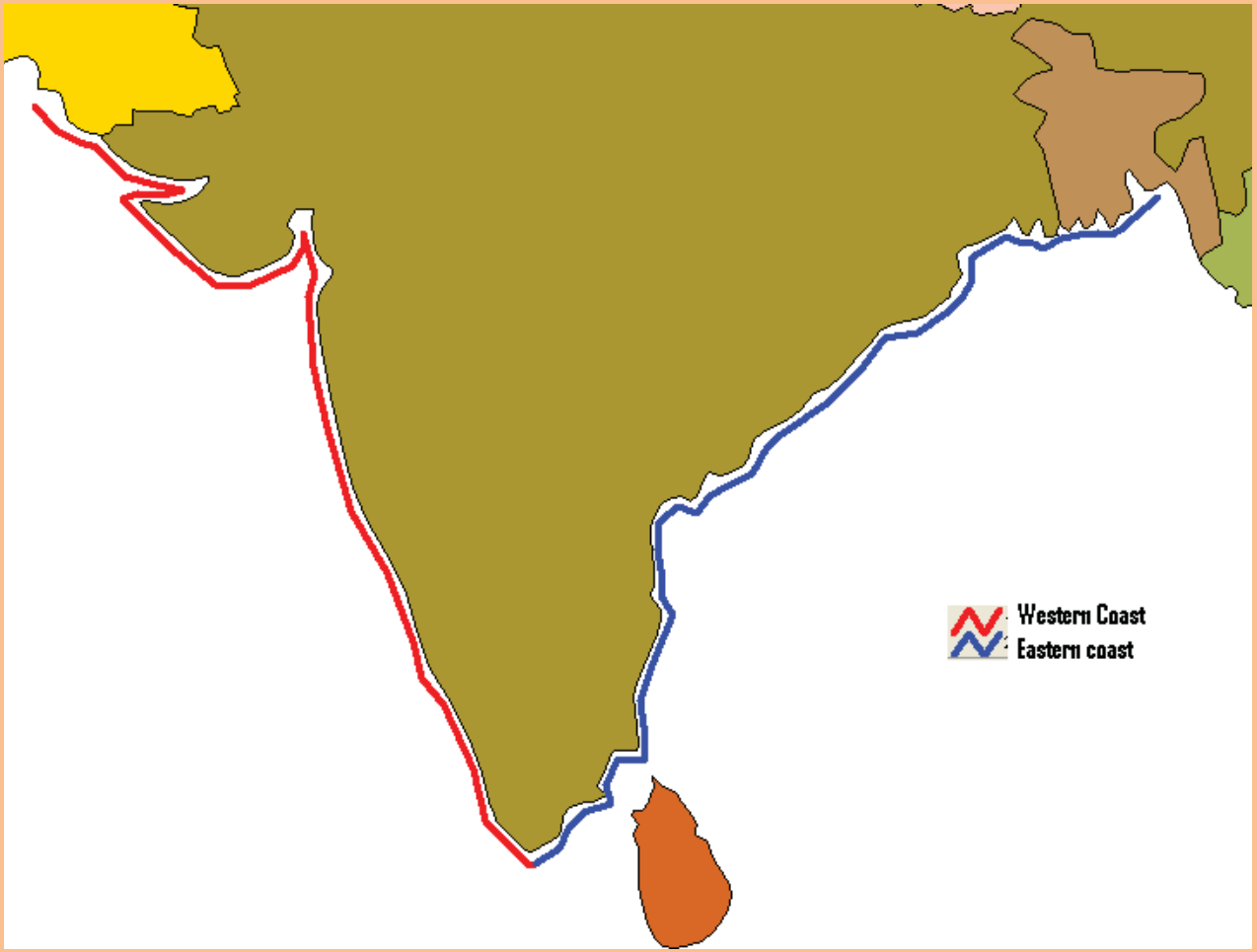


Sahoo et al. (2005) IJRS

Ozone depletion in the Ganga basin

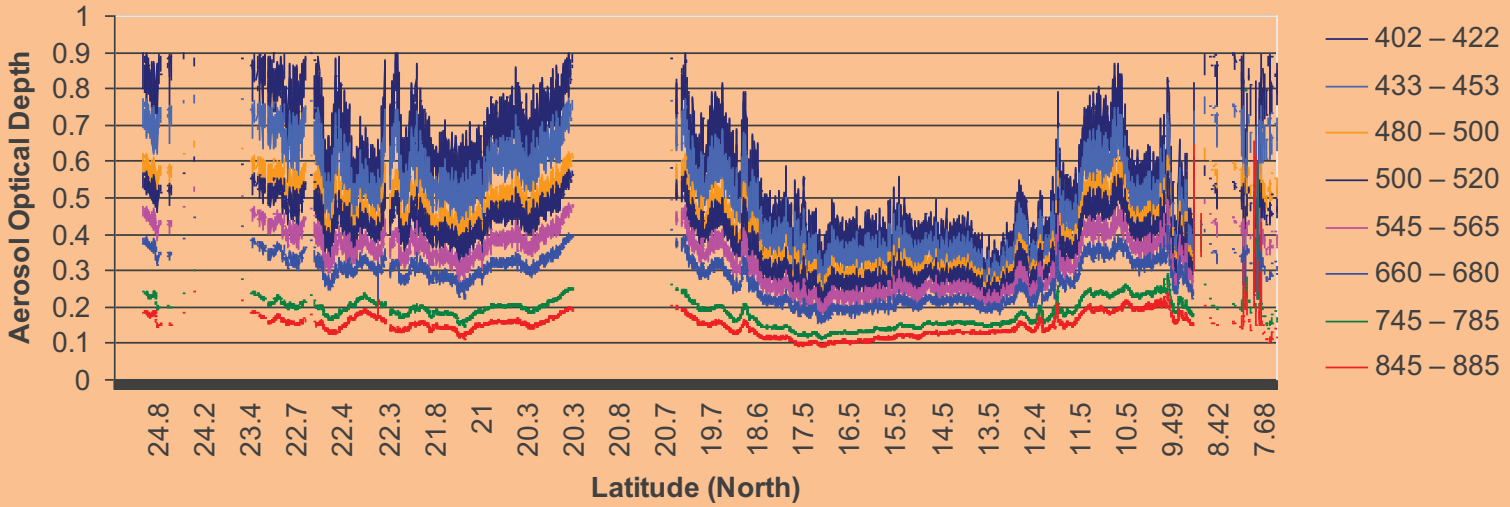


Coastal Pollution


Western Coast
Eastern coast

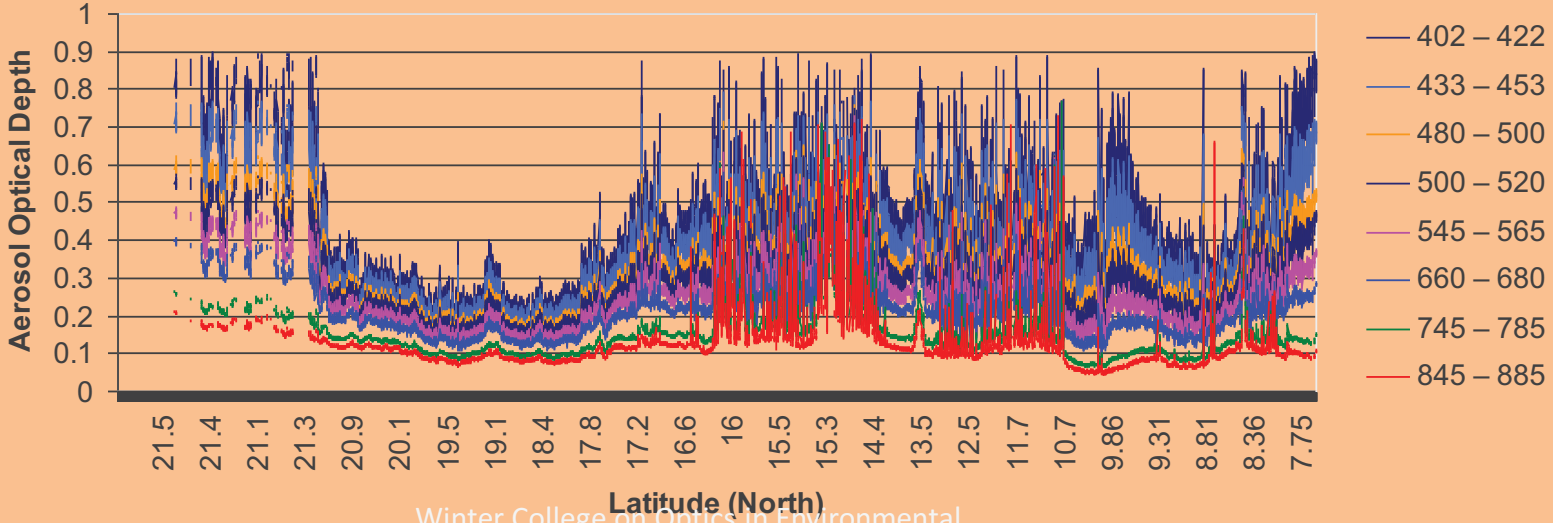
AOD variation for Western Coast of India

January 2000

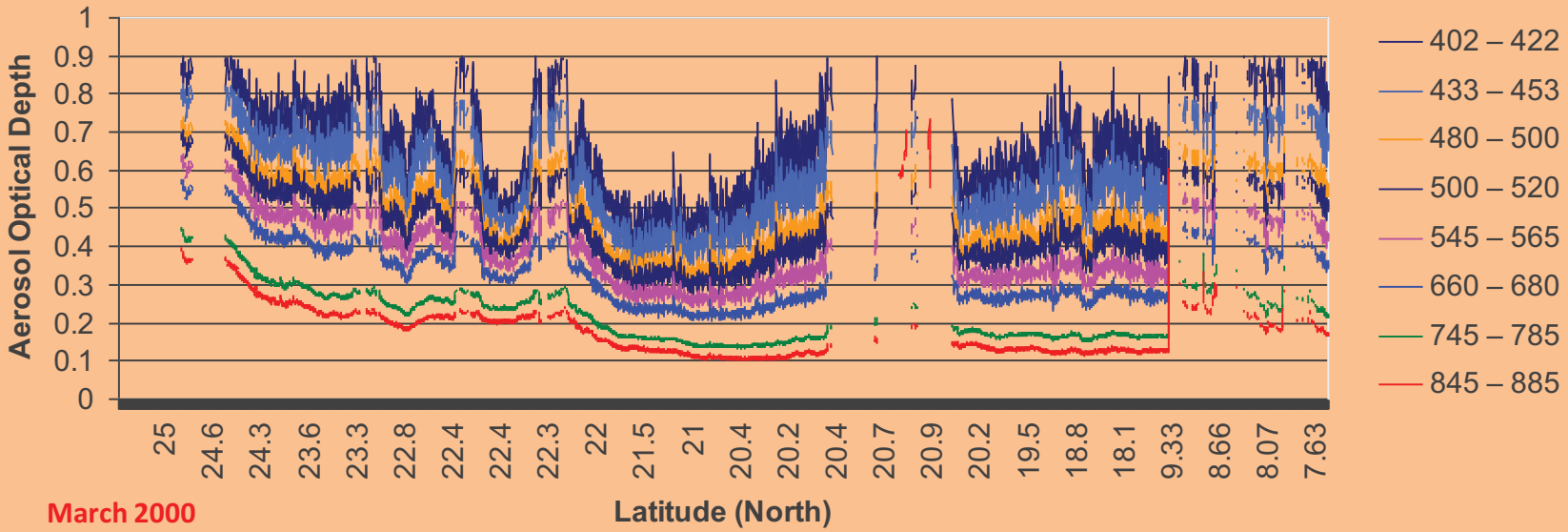


AOD variation for Eastern Coast of India

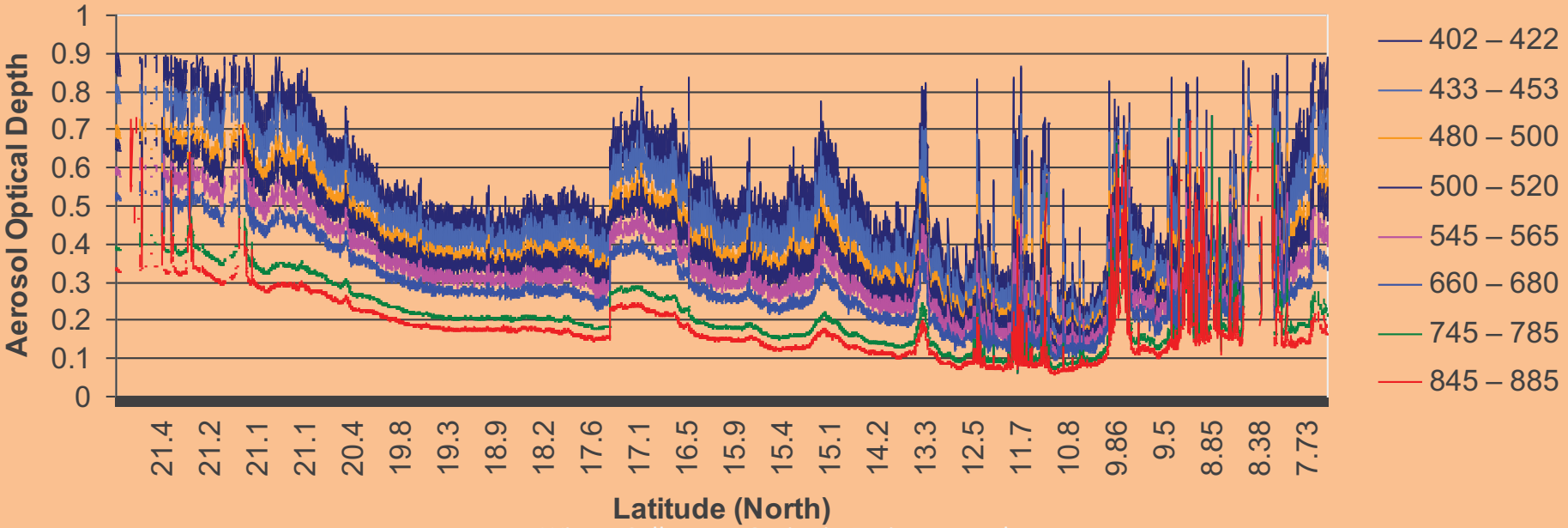
January 2000



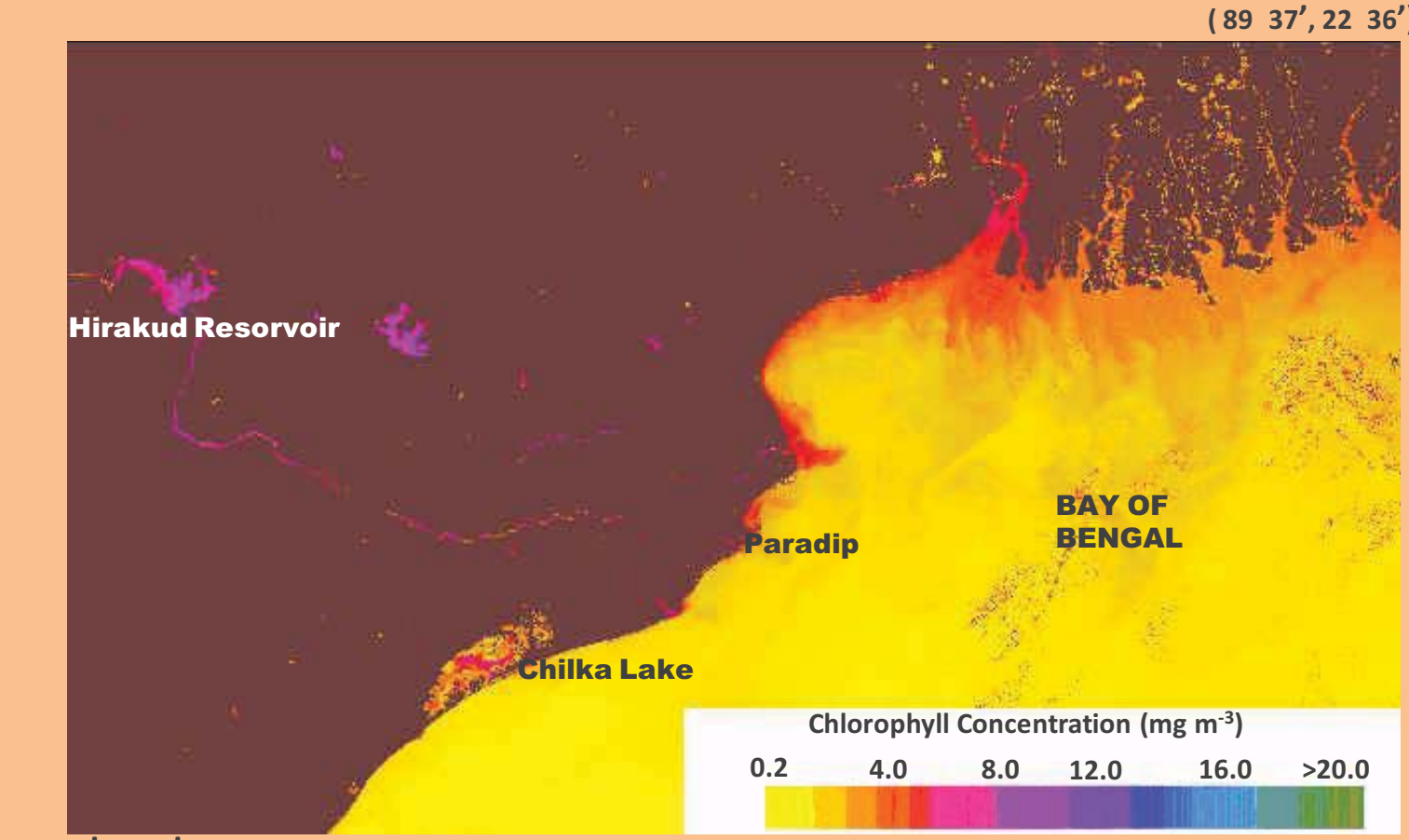
March 2000



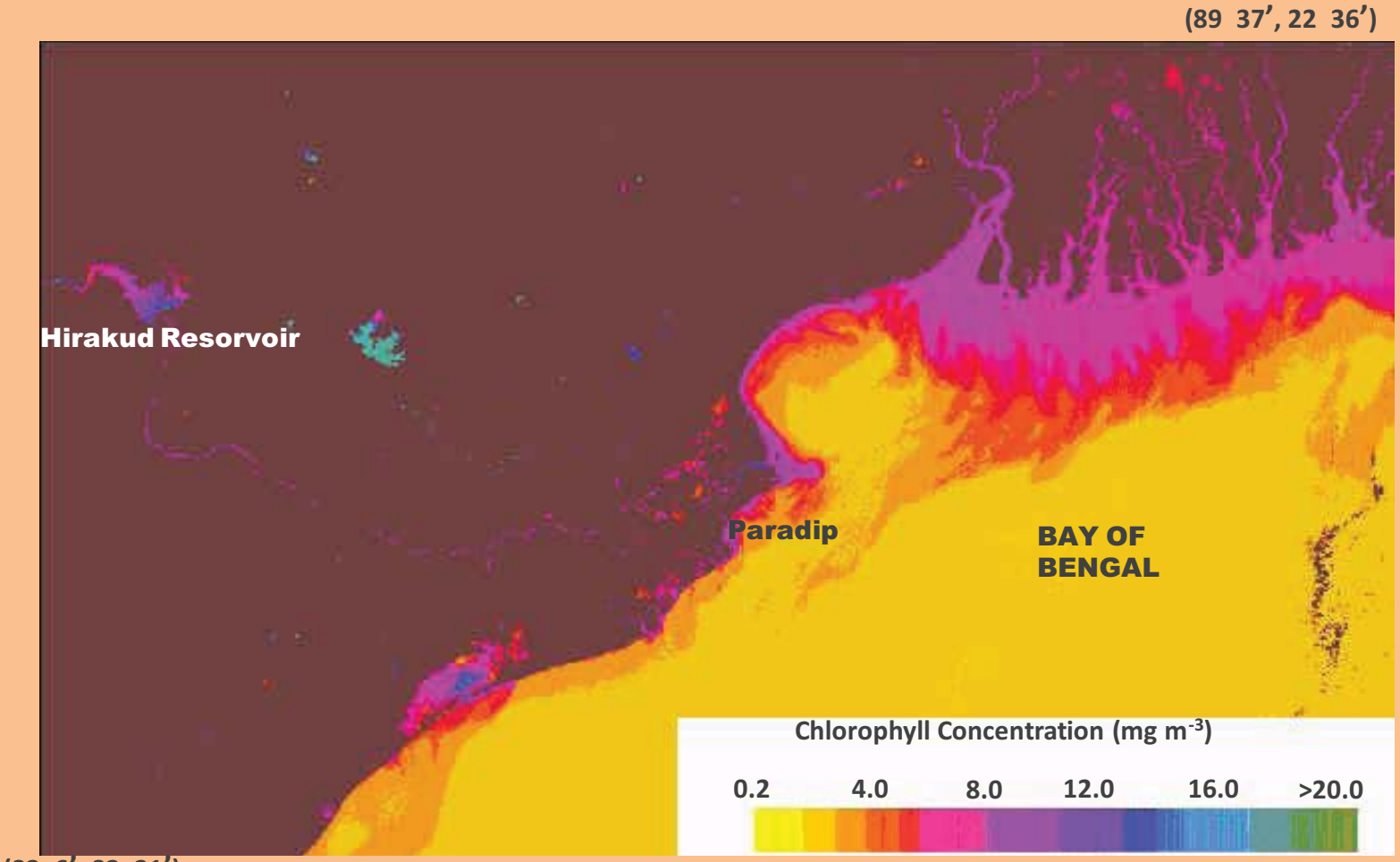
March 2000



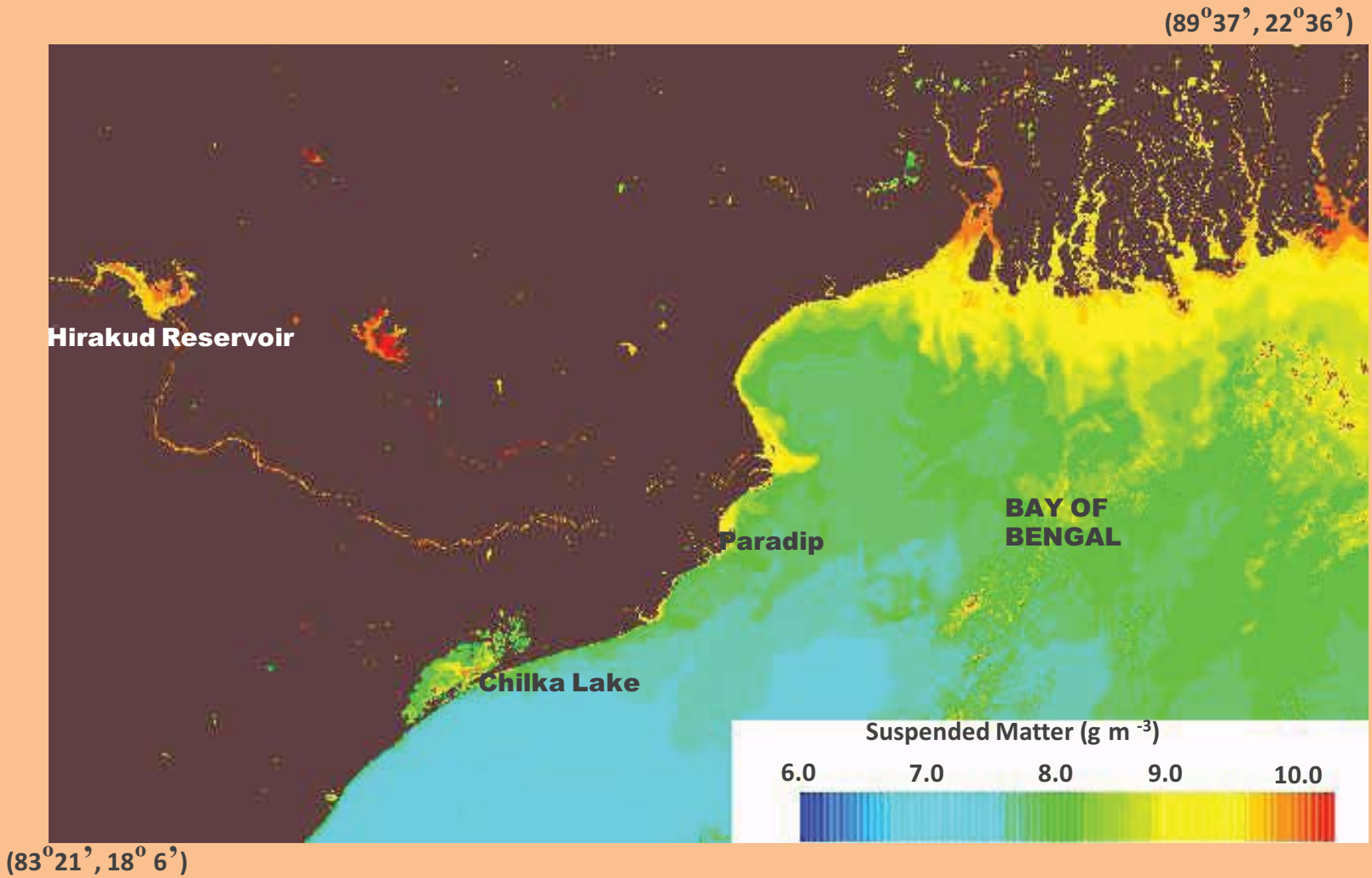
Cyclone and Hurricanes



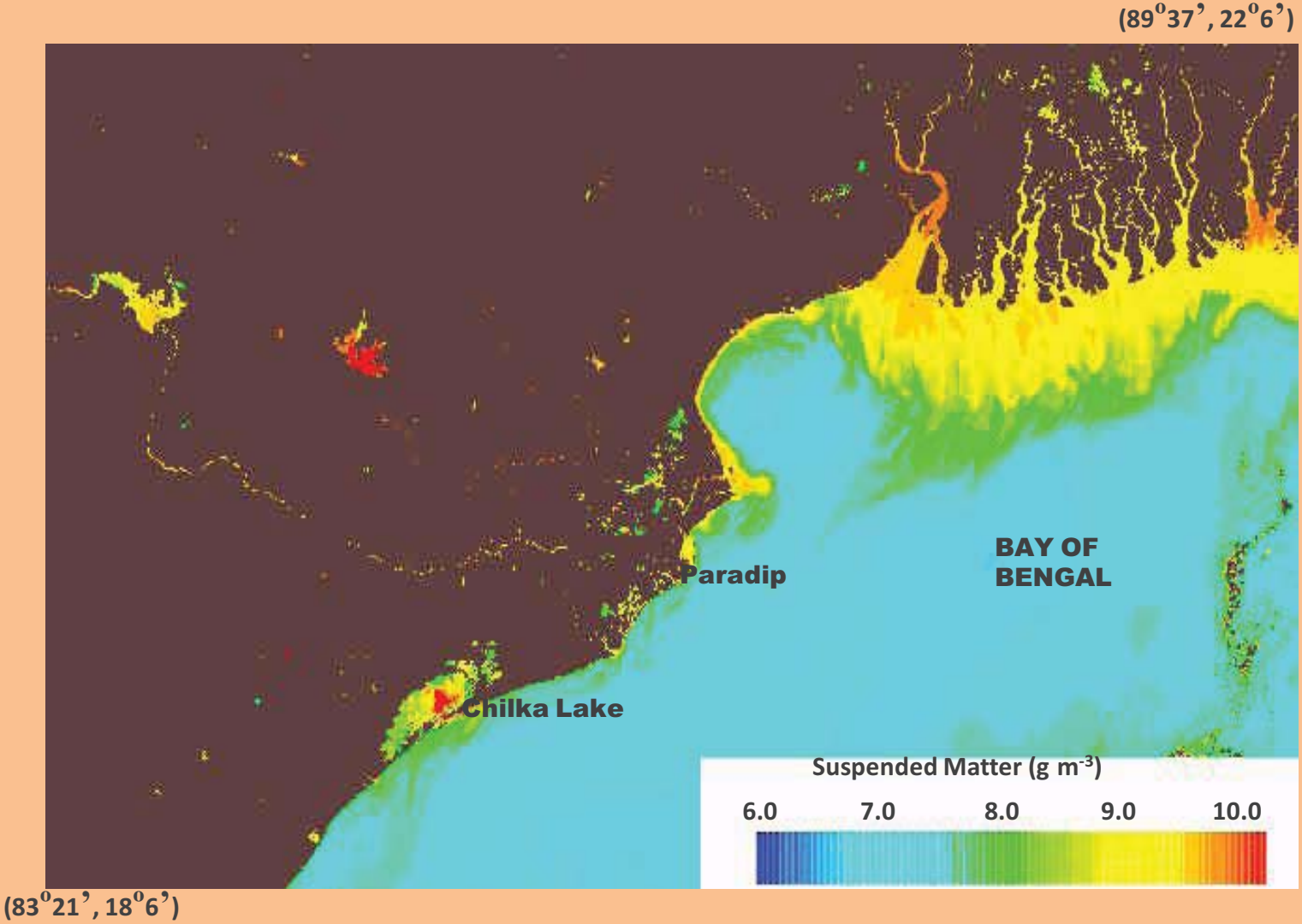
Chlorophyll image generated from October 11, 1999 OCM data



Chlorophyll image generated from November 10, 1999 OCM data



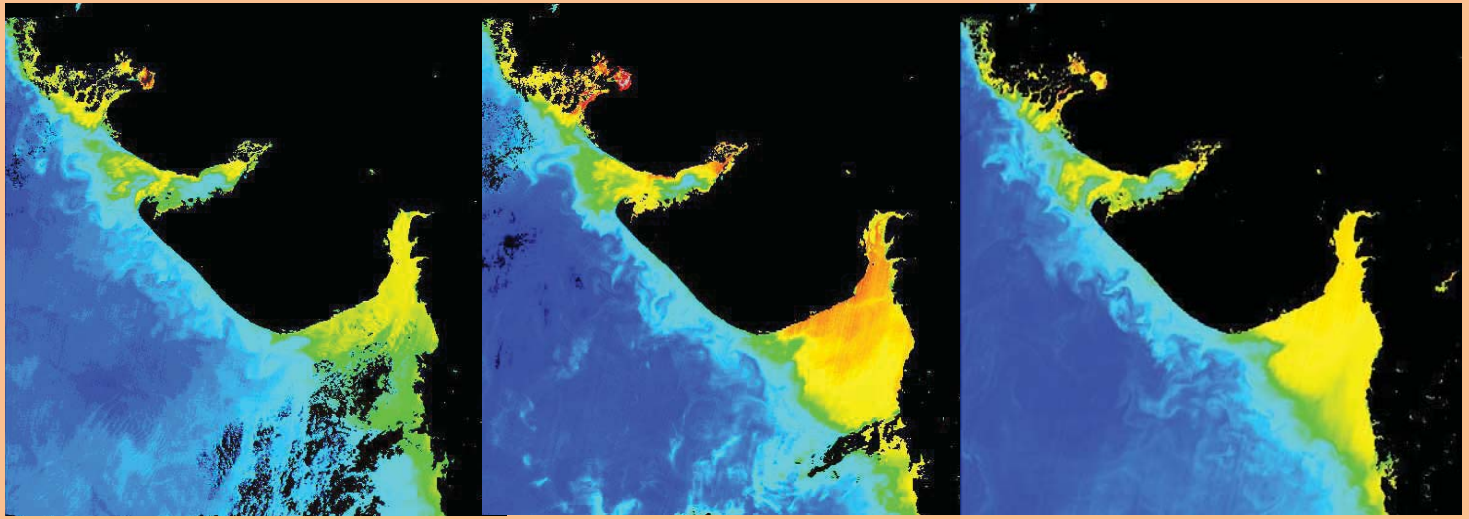
Suspended matter concentration image generated from October 11, 1999 OCM data



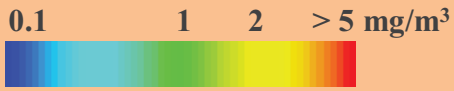
Suspended matter concentration image generated from November 10, 1999 OCM data

Changes in Ocean Associated with Earthquakes

Chlorophyll Concentration

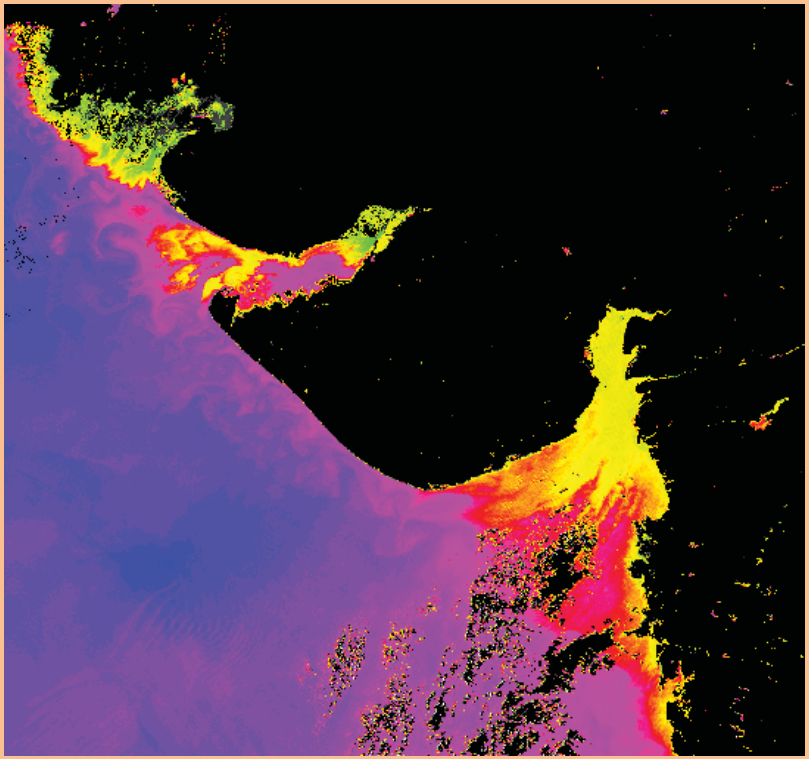


(a) January 18, 2001 (b) January 26, 2001 (c) February 3, 2001

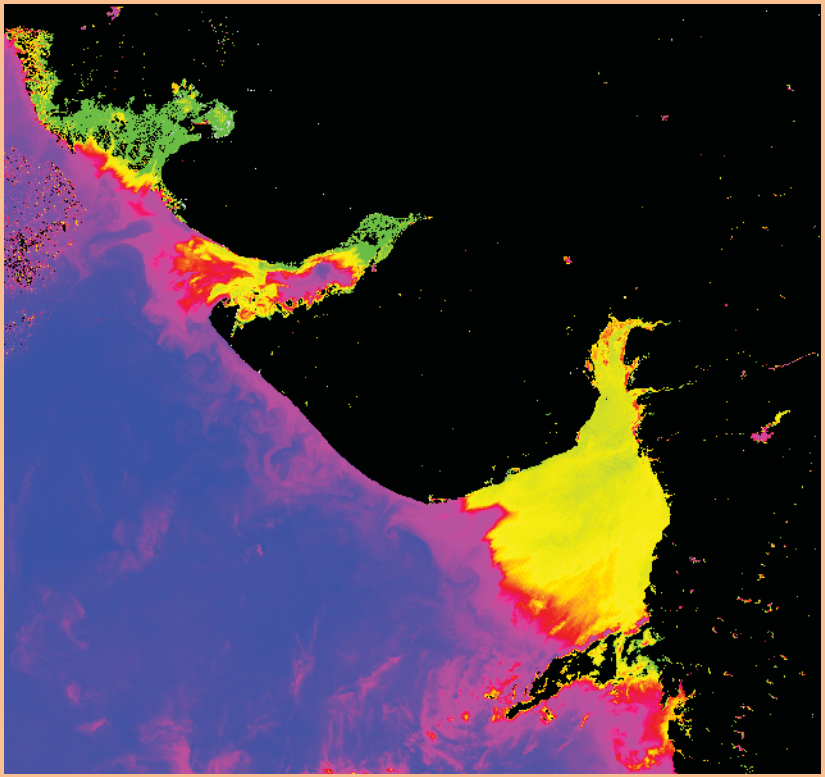


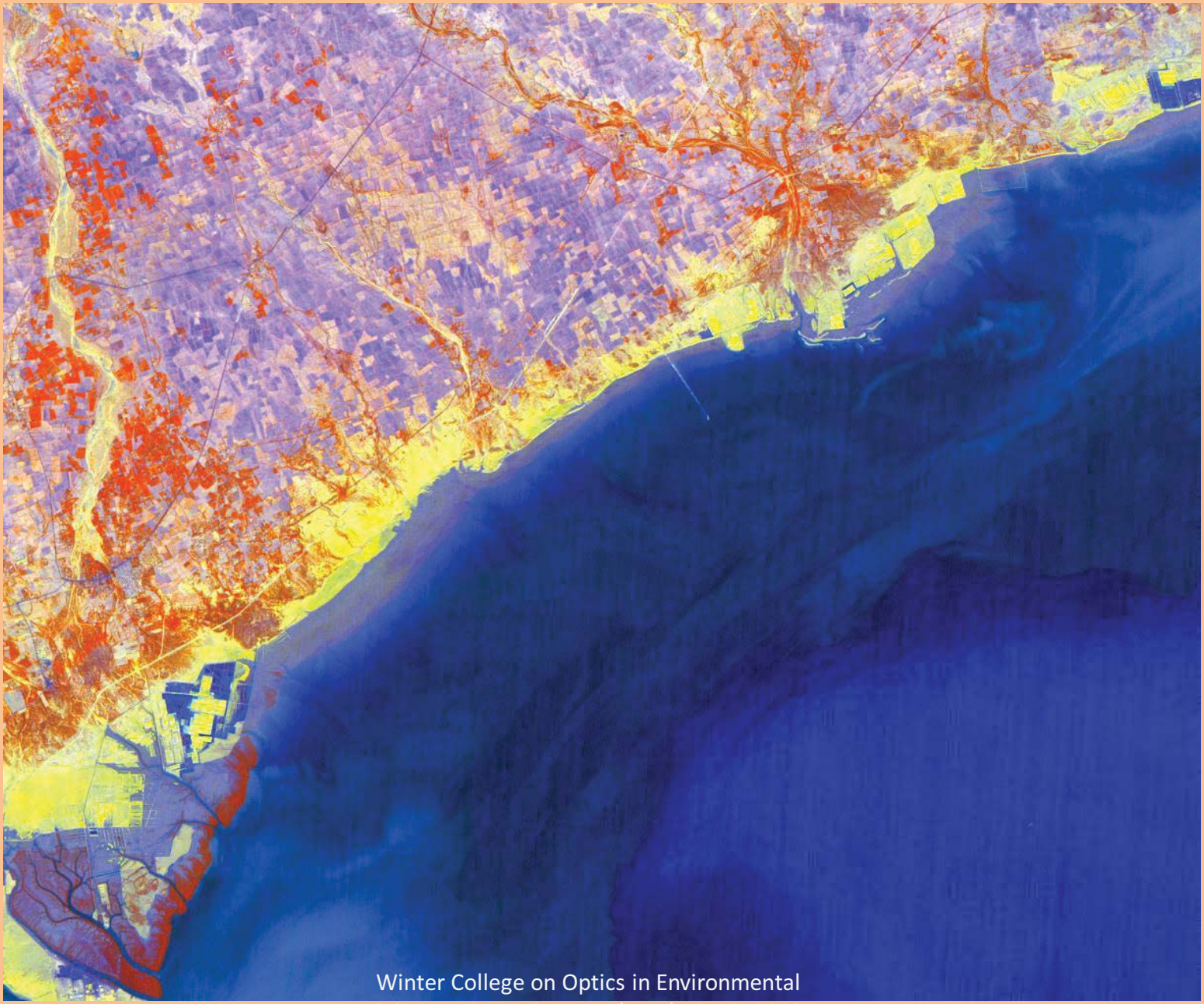
Suspended Solid Concentration

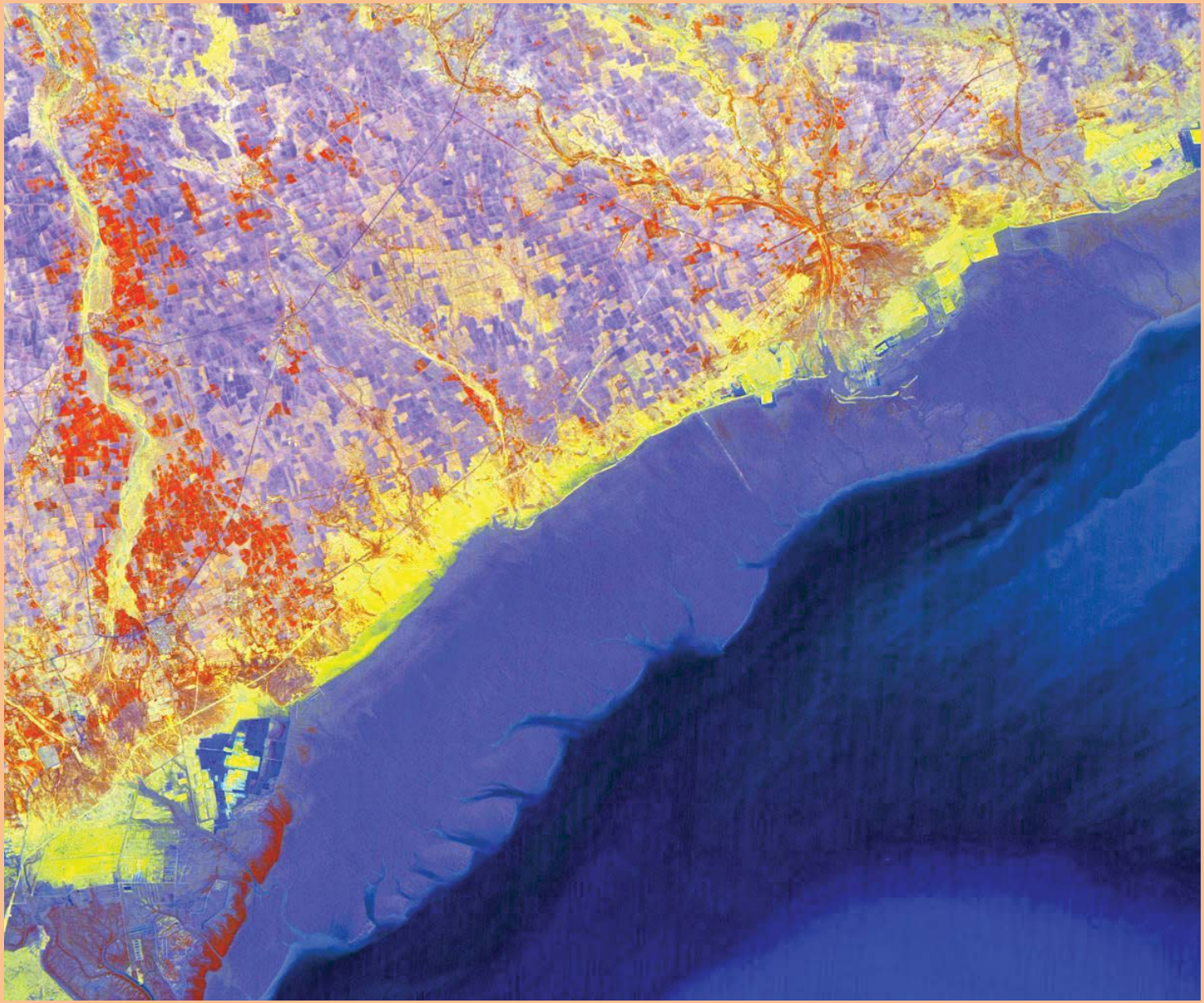
Pre

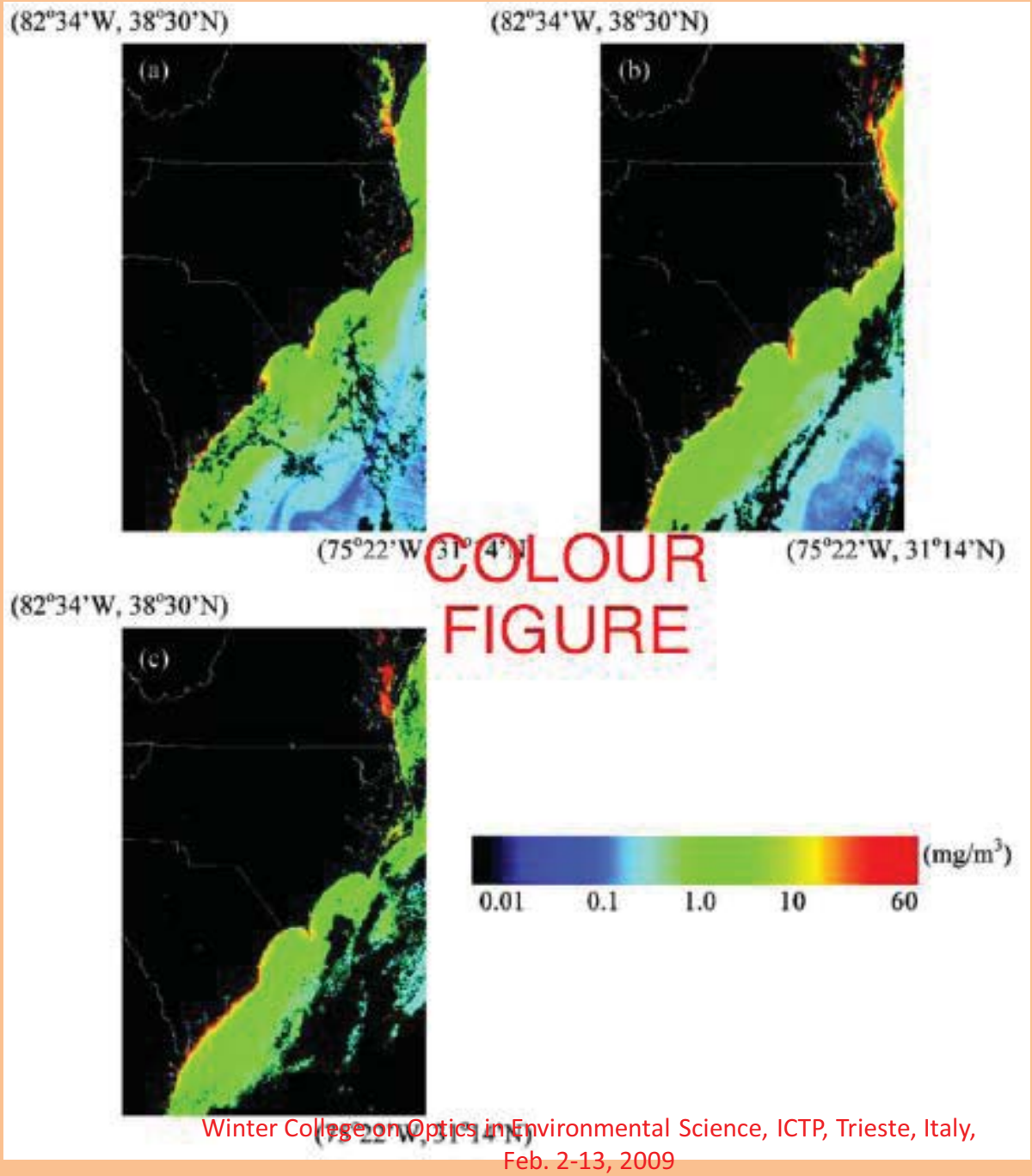


Post








(82°34'W, 38°30'N)
(a)
(82°34'W, 38°30'N)
(b)
(75°22'W, 31°14'N)
COLOUR FIGURE
(82°34'W, 38°30'N)
(c)
(mg/m³)
0.01
0.1
1.0
10
60

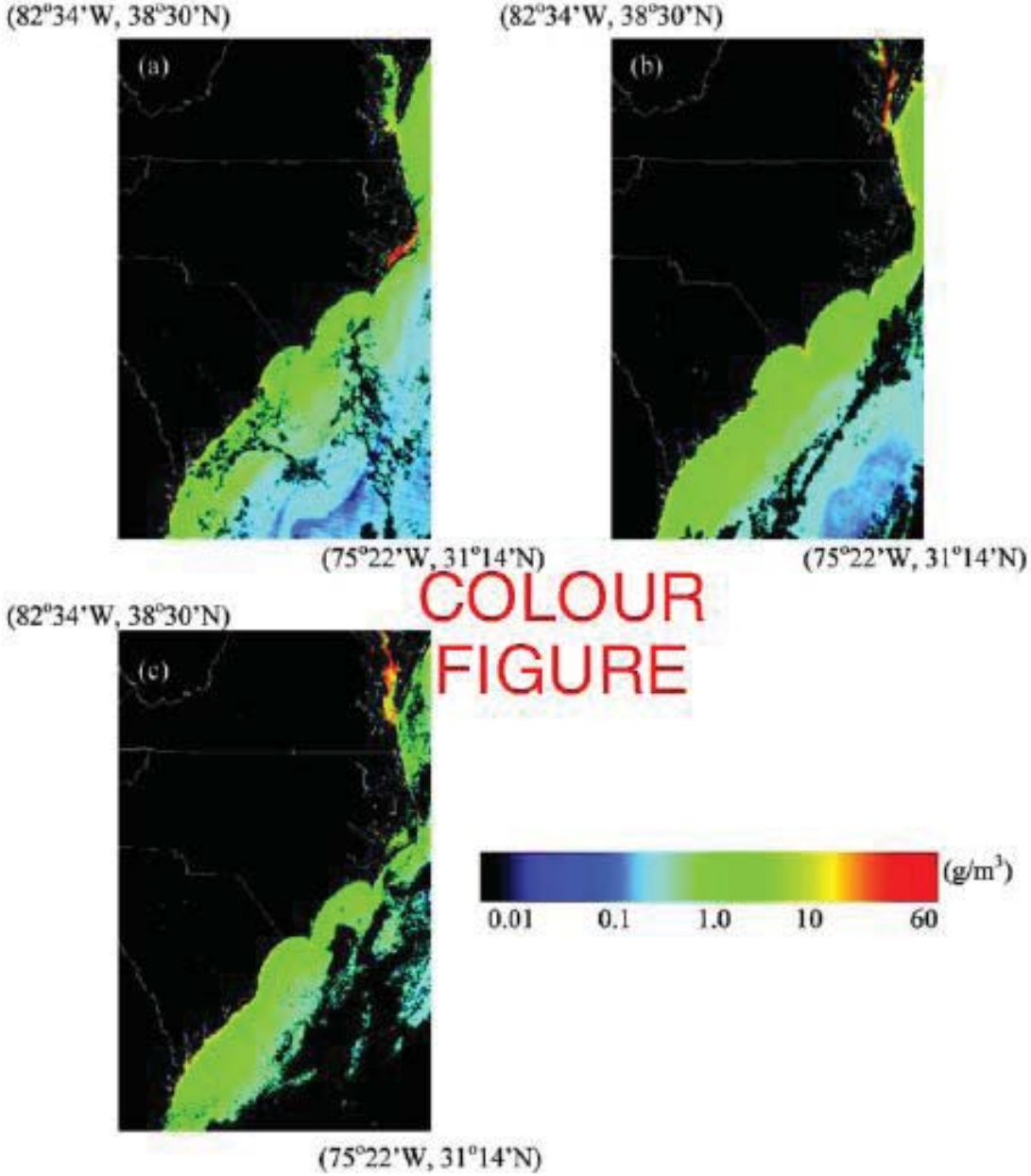
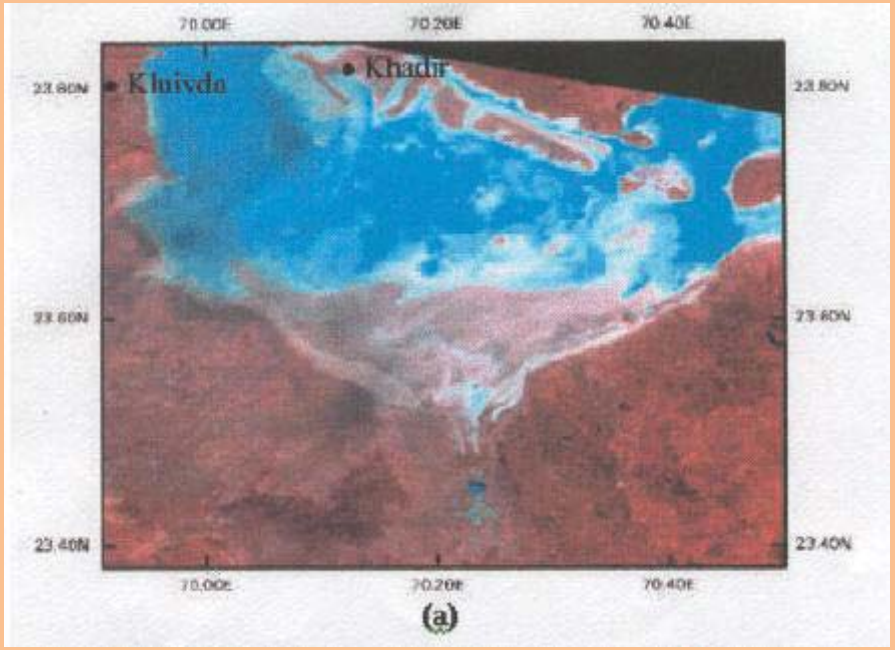
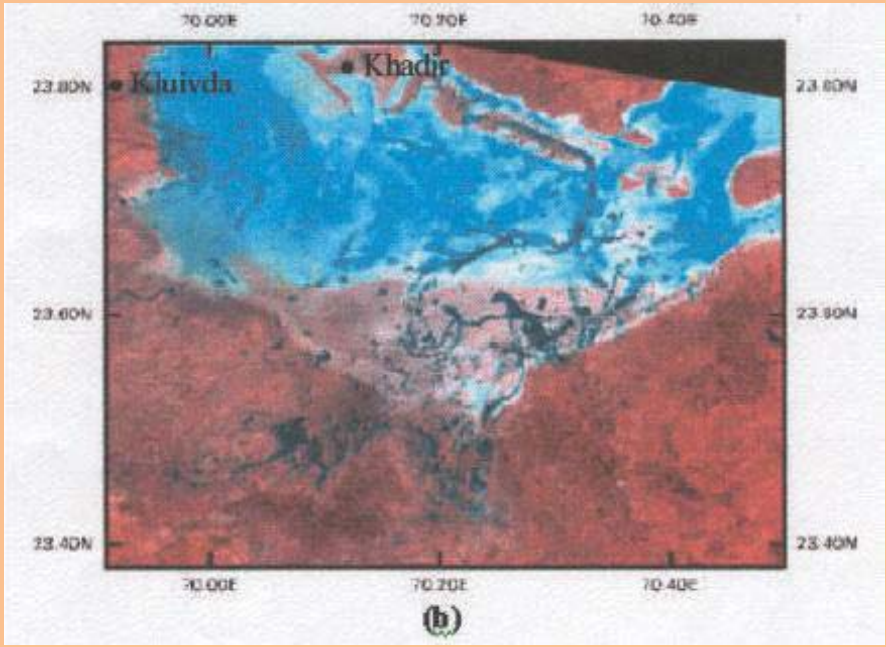
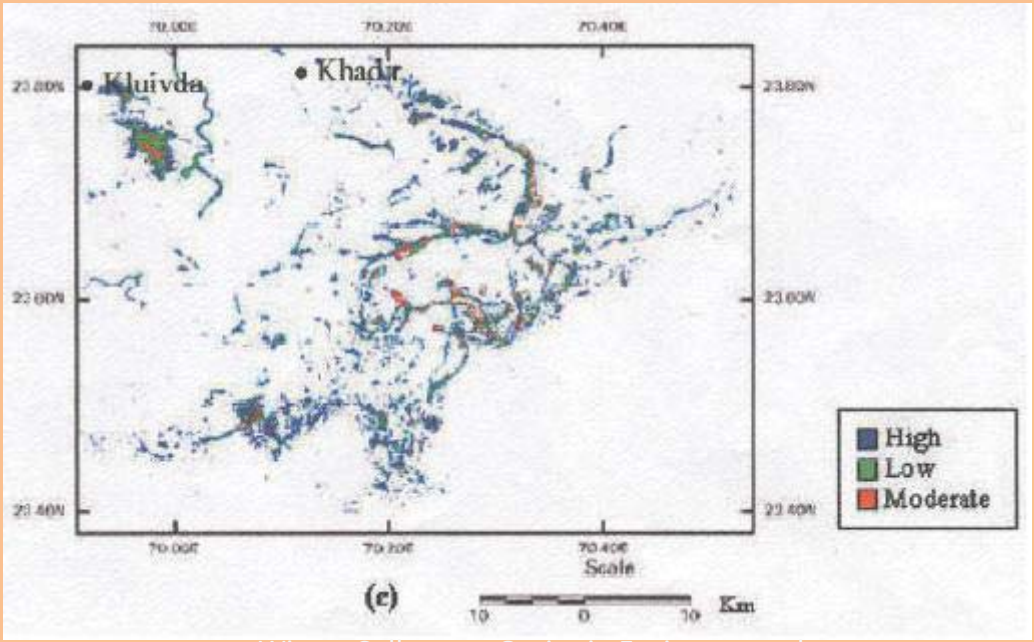


Figure 3. Suspended matter concentration along the east coast on (*a*) 2, (*b*) 19 and (*c*) 30 September 2003.

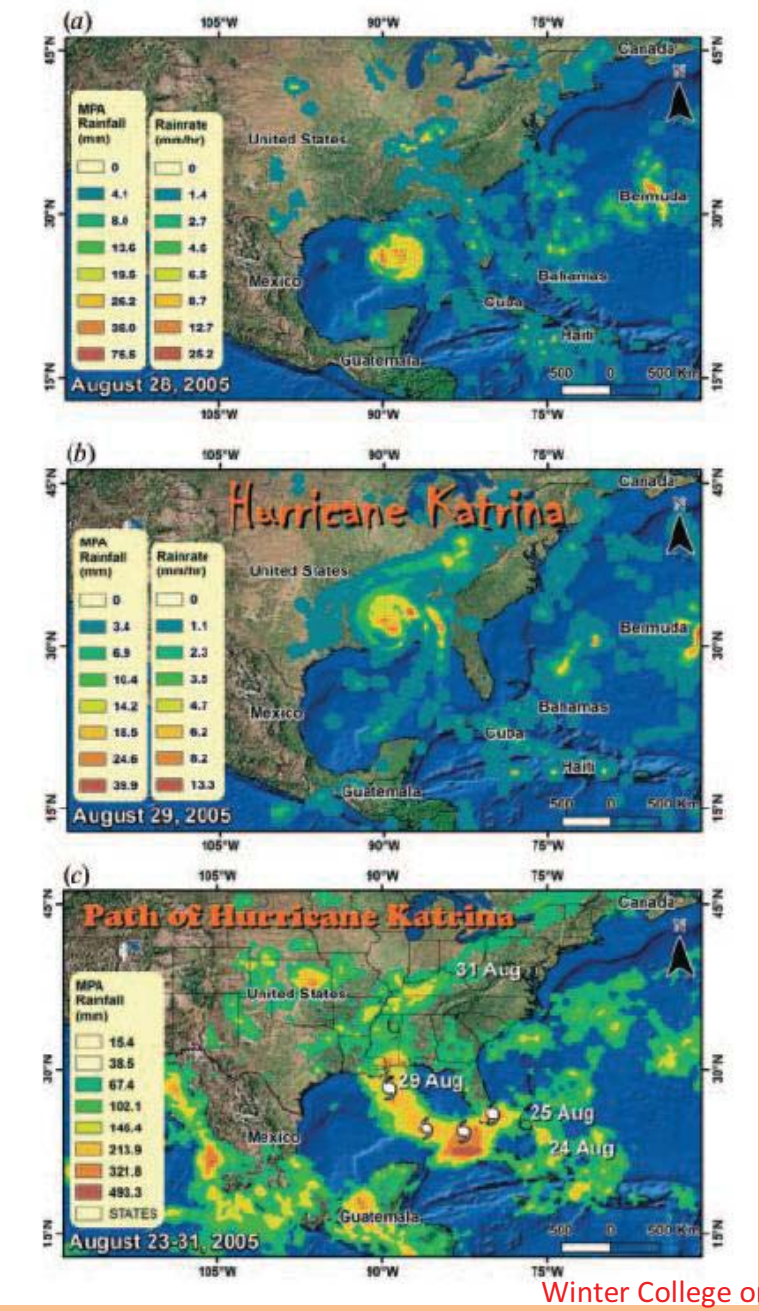


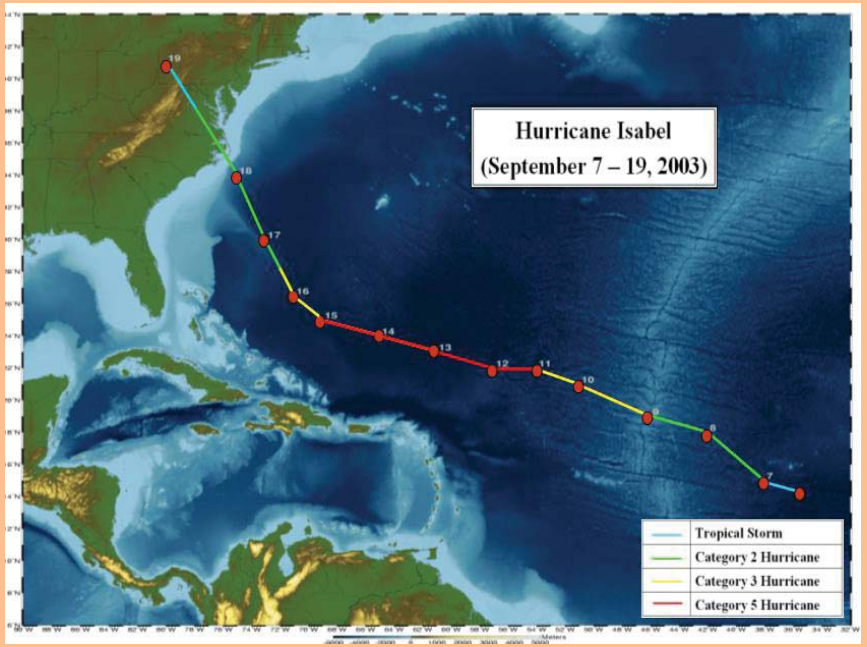




Surface manifestations after the Gujarat earthquake (IRS 1C LISS III data)

Hurricanes/Cyclone Typhoons,



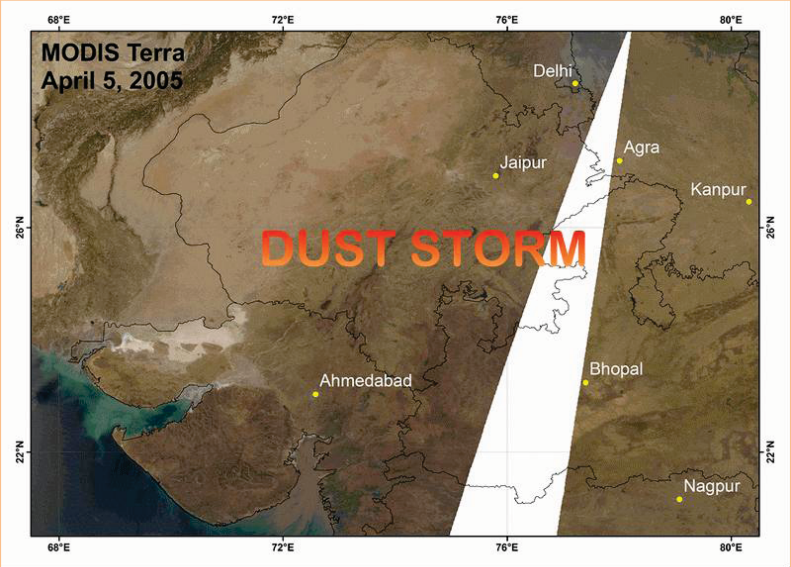


Changes in Ocean Parameters Associated with Dust Storms

Dust Storms

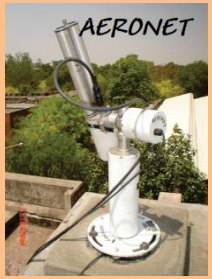
Satellite (daily)
MODIS Terra
and Aqua)

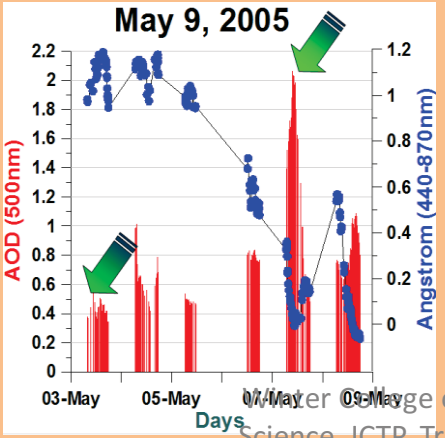
(Prasad and Singh, 2007, RSE)

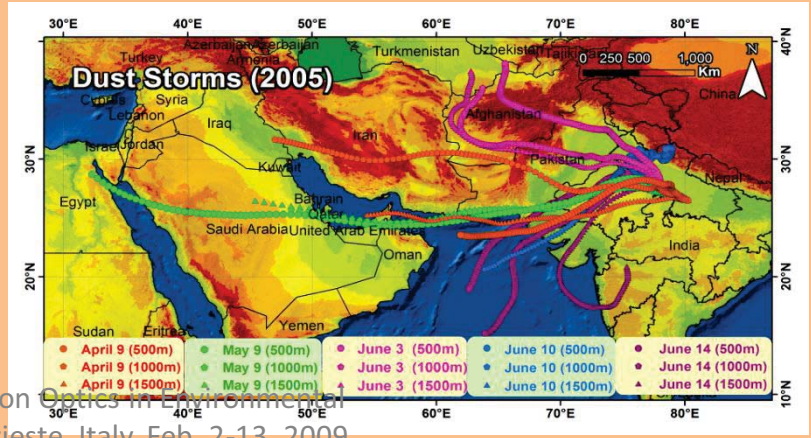


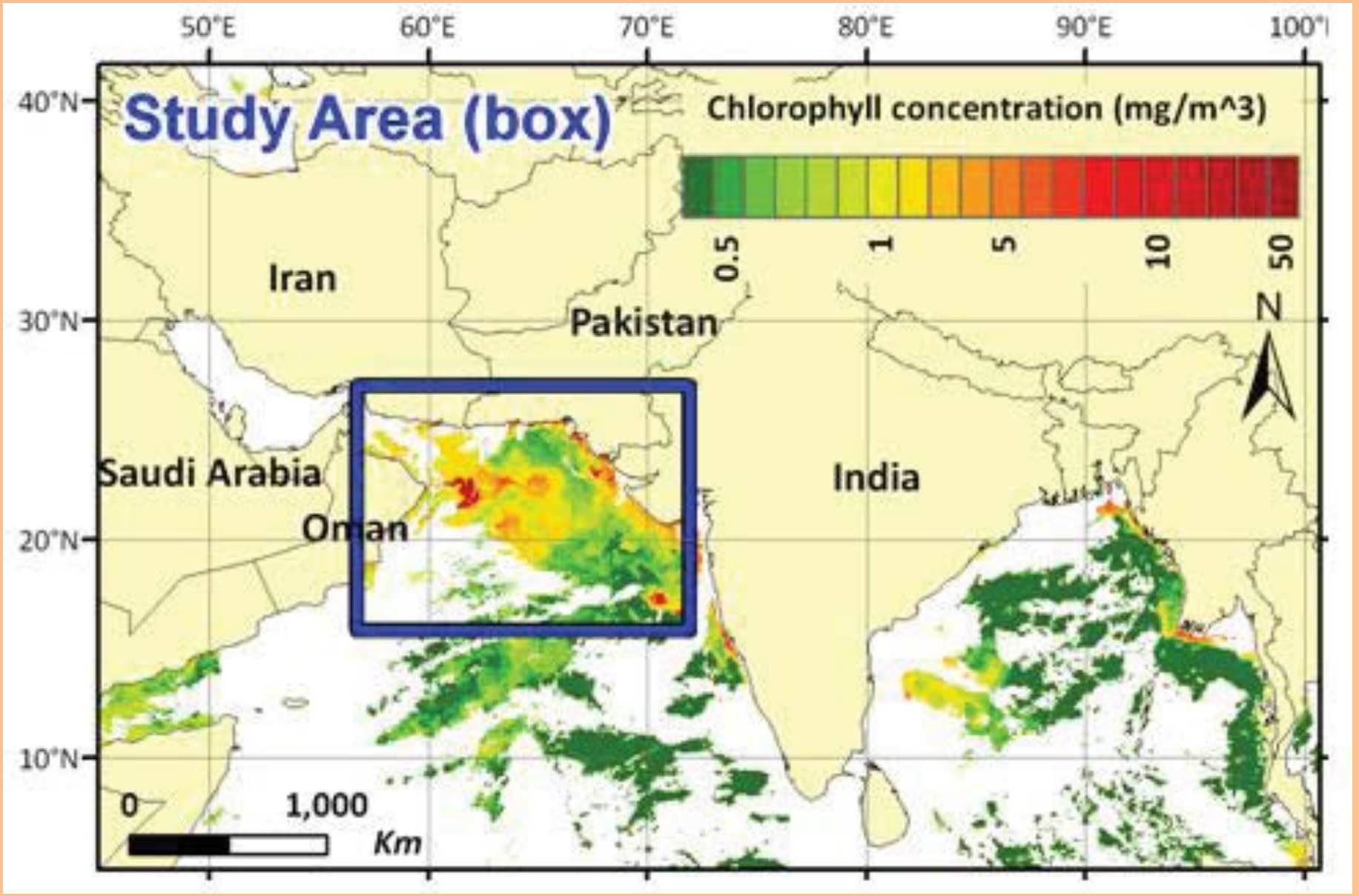
(April 3-12, 2005, MODIS Terra images)

Ground based
CIMEL
Sun-photometer

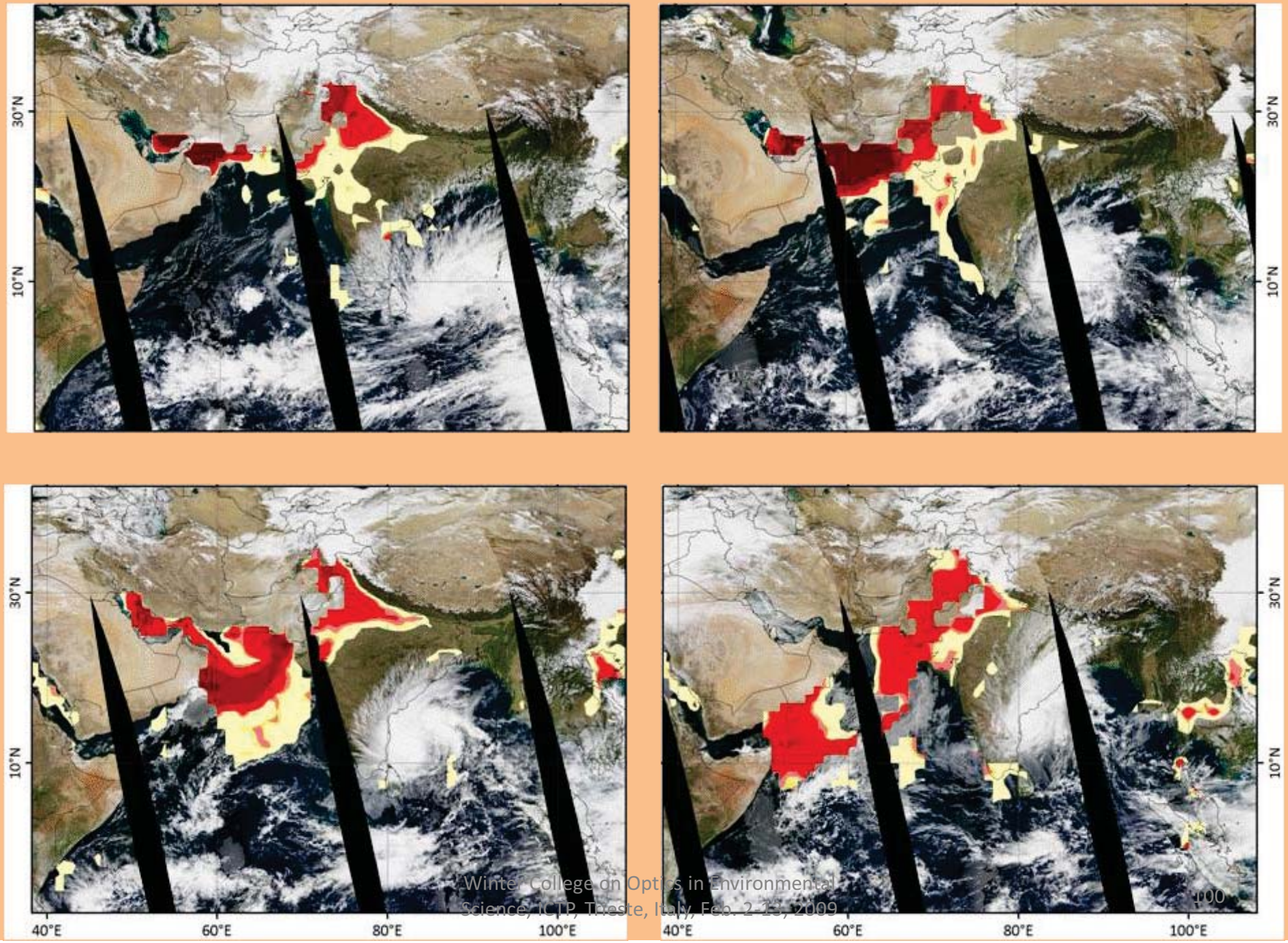


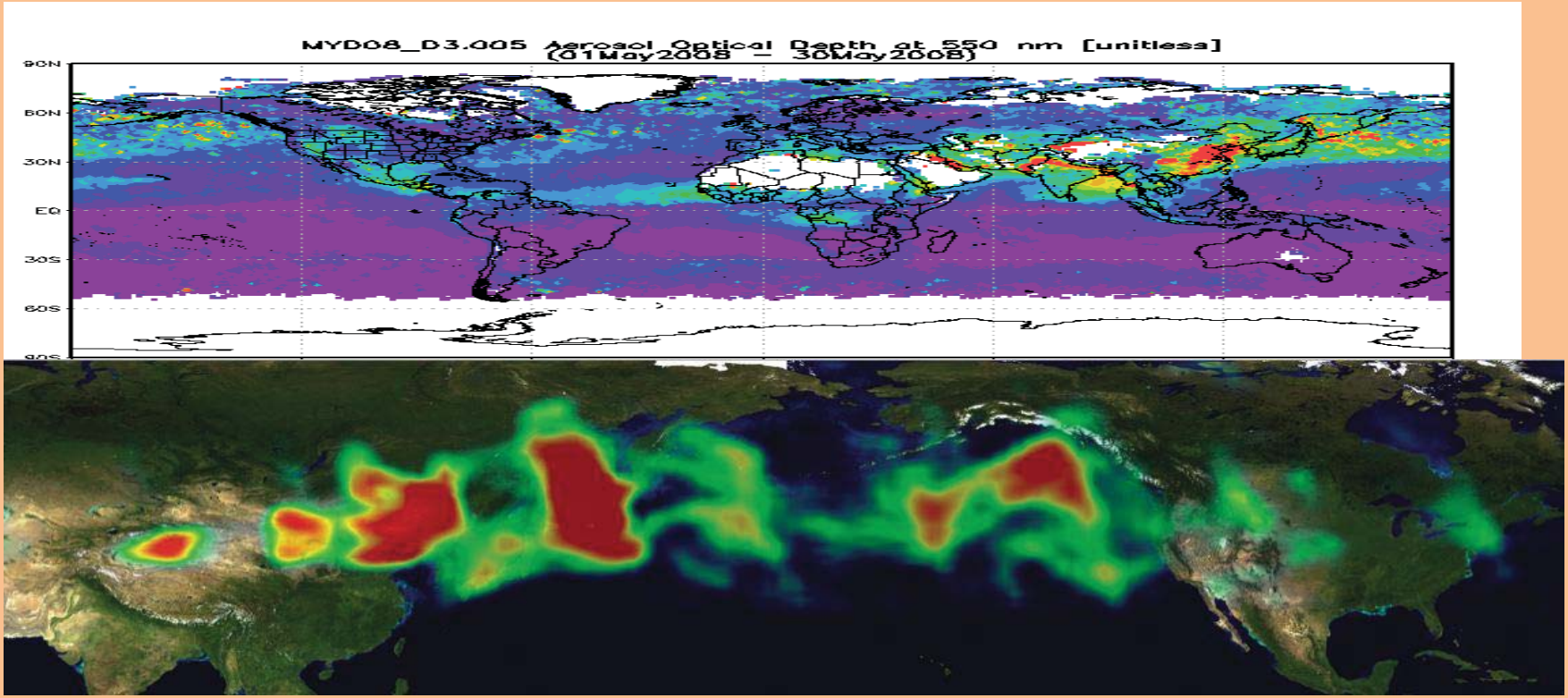


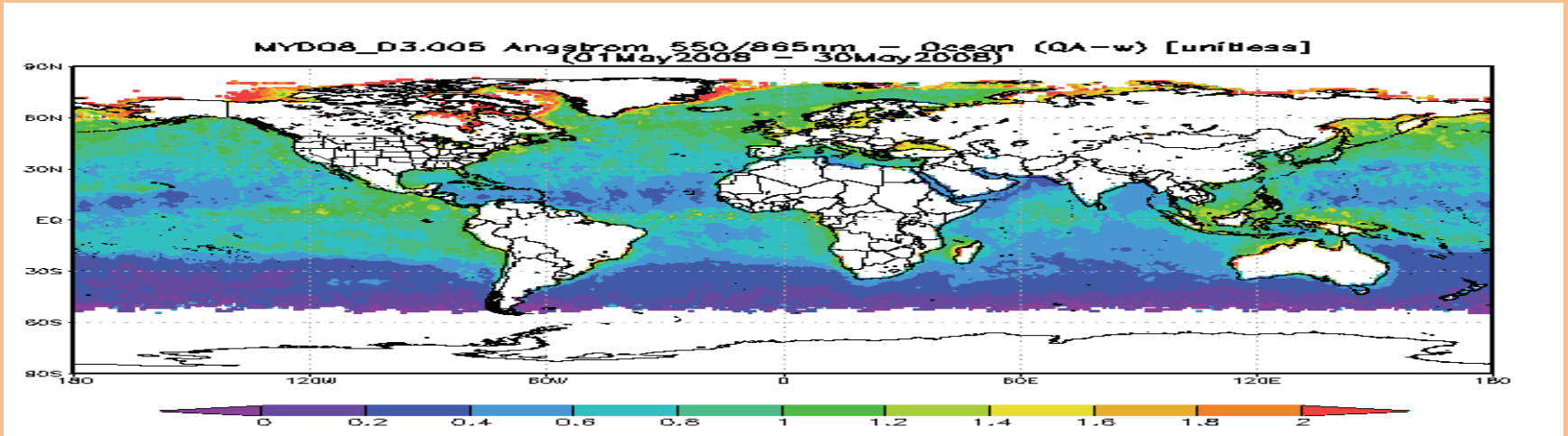


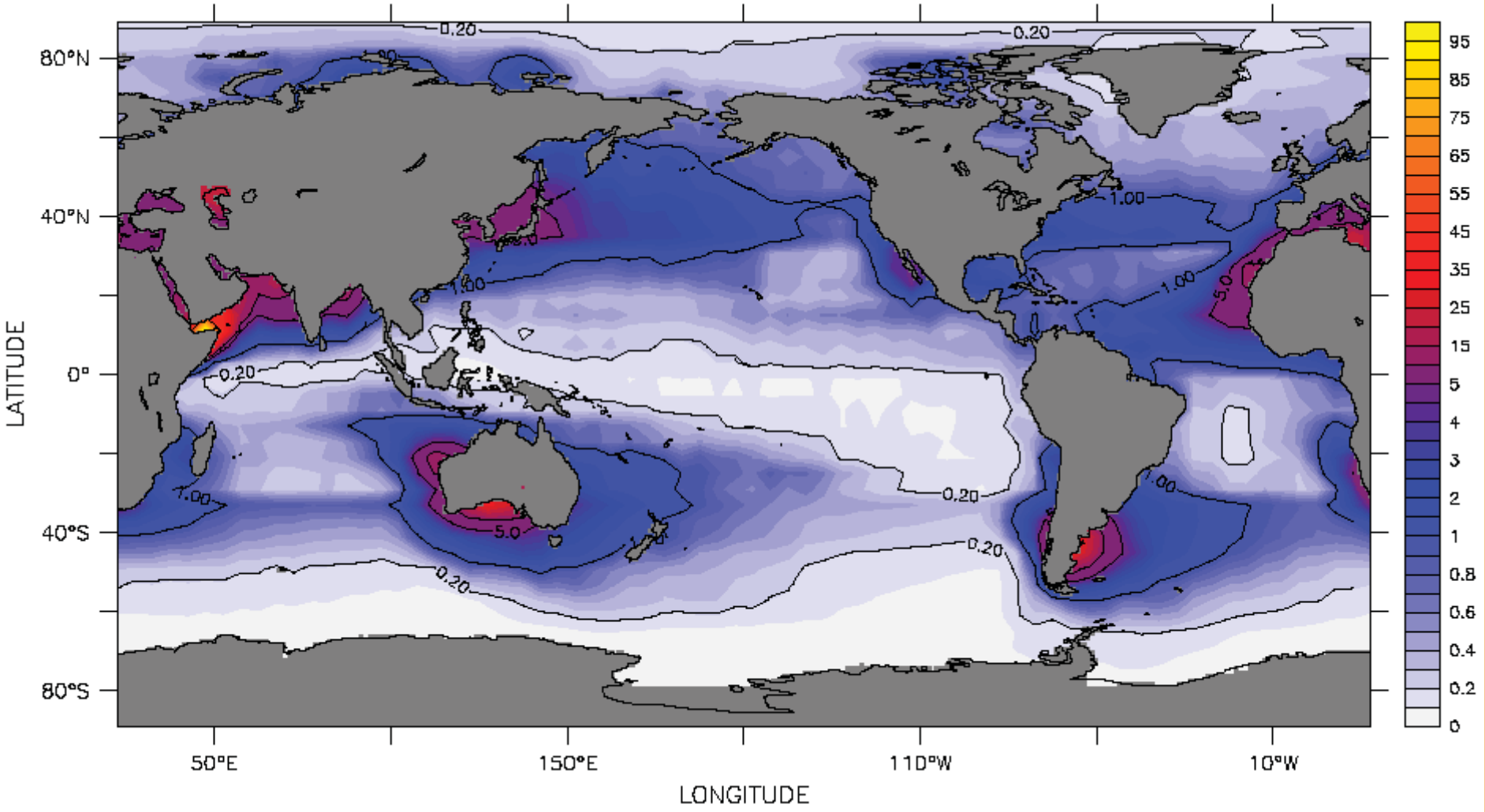


(Singh et al. 2008, JGR)


30°N
10°N
40°E
60°E
80°E
100°E


MYD08_D3.005 Aerosol Optical Depth at 550 nm [unitless]
(01May2008 – 30May2008)
90N
60N
30N
EQ
30S
60S
90S

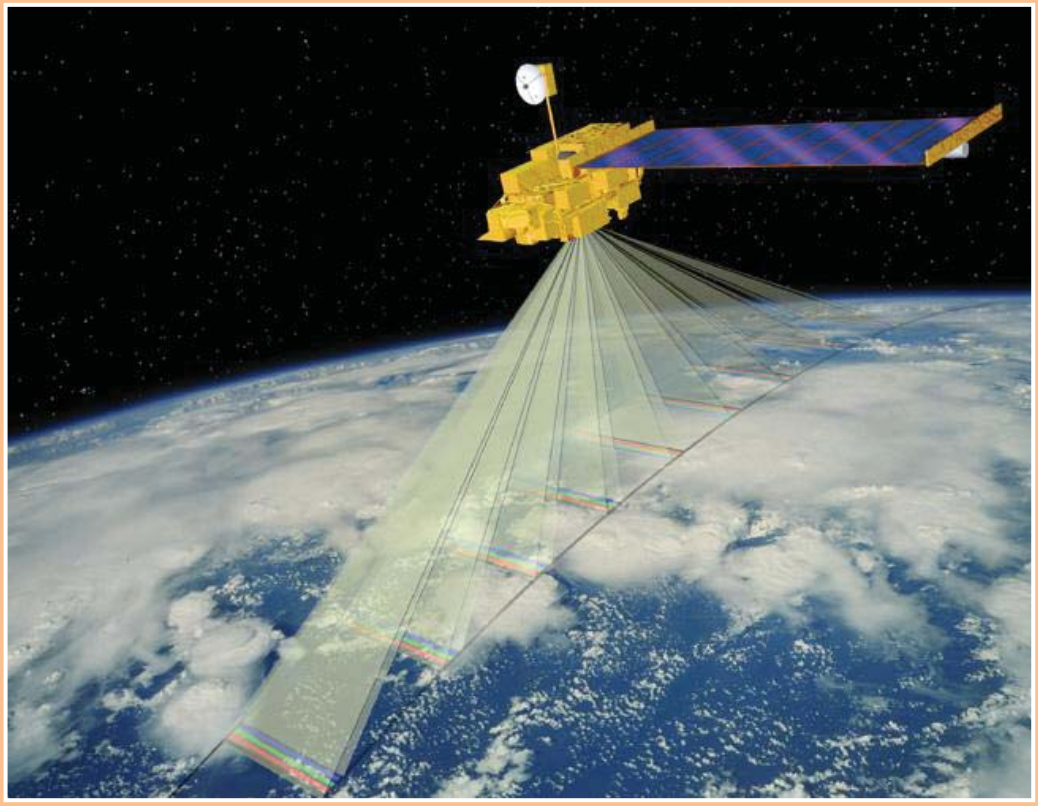

MYD08_D3.005 Angstrom 550/865nm – Ocean (QA=w) [unitless]
(01May2008 – 30May2008)
90N
60N
30N
EQ
30S
60S
90S
180
120W
60W
0
60E
120E
180
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2



Dust deposition over the ocean:

The input of dust has different impacts in different oceanic environments

(Tegen & Fung 1997)



Nine view angles at Earth surface: 70.5º forward to 70.5º aft

Four spectral bands at each angle: 446, 558, 672, 866 nm

Seven minutes to observe each scene at all 9 angles

400-km swath

Global coverage about once per week

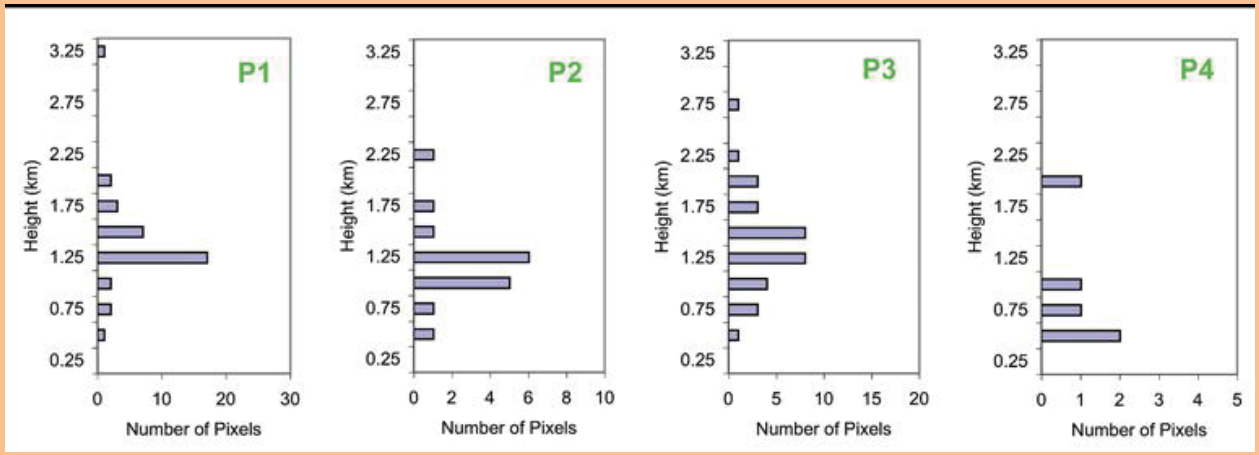
275 m - 1.1 km spatial sampling

Air mass factors from 1 (nadir) to 3

Scattering angles from ~60˚ to ~160˚ in mid-latitudes

Plume dispersal from the World Trade Center, 9/12/2001

MISR 70º image

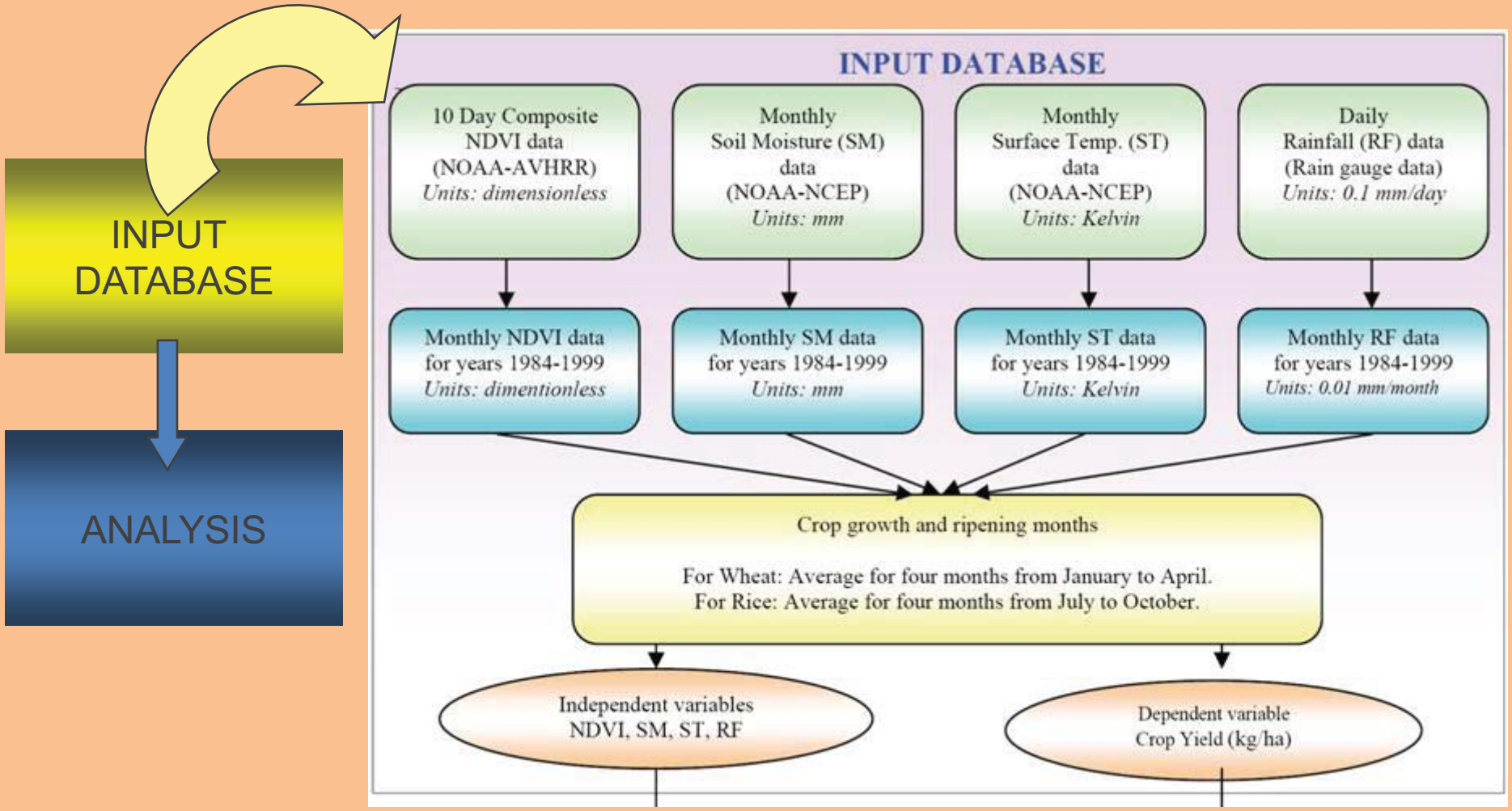


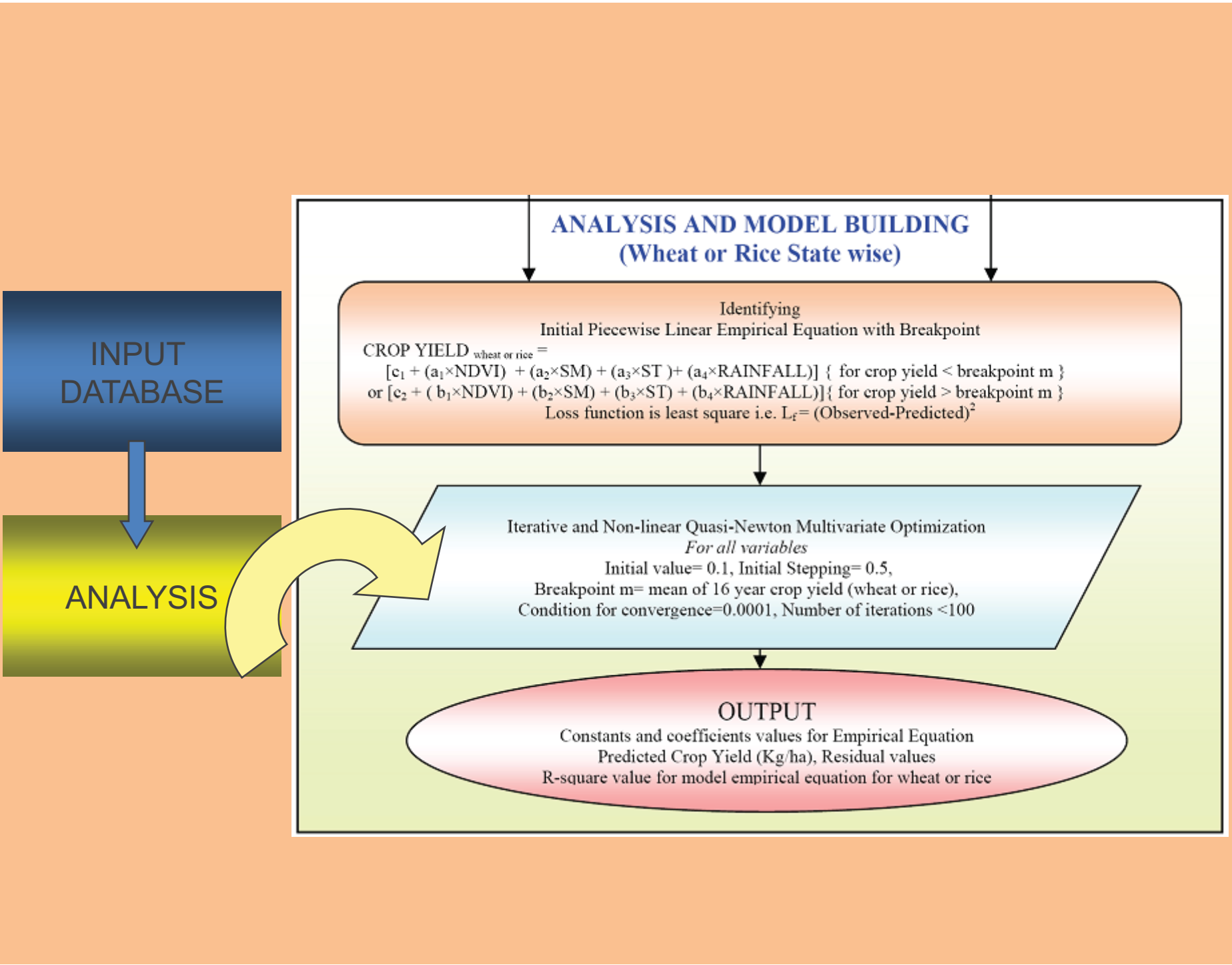
MISR stereo heights of plume patches

MISR provides key stereo-derived aerosol plume height, directionality, and timing data for initializing and checking high-resolution pollution transport models used to estimate hazardous aerosol and gas fluxes emanating from the burning WTC.

Gera Stenchikov (Rutgers Univ.), Ralph Kahn, David Diner (JPL)

Flow Chart


INPUT DATABASE
ANALYSIS
INPUT DATABASE
10 Day Composite NDVI data (NOAA-AVHRR) Units: dimensionless
Monthly Soil Moisture (SM) data (NOAA-NCEP) Units: mm
Monthly Surface Temp. (ST) data (NOAA-NCEP) Units: Kelvin
Daily Rainfall (RF) data (Rain gauge data) Units: 0.1 mm/day
Monthly NDVI data for years 1984-1999 Units: dimentionless
Monthly SM data for years 1984-1999 Units: mm
Monthly ST data for years 1984-1999 Units: Kelvin
Monthly RF data for years 1984-1999 Units: 0.01 mm/month
Crop growth and ripening months
For Wheat: Average for four months from January to April.
For Rice: Average for four months from July to October.
Independent variables NDVI, SM, ST, RF
Dependent variable Crop Yield (kg/ha)


INPUT DATABASE
ANALYSIS
ANALYSIS AND MODEL BUILDING
(Wheat or Rice State wise)
Identifying
Initial Piecewise Linear Empirical Equation with Breakpoint
CROP YIELD wheat or rice =
[c1 + (a1×NDVI) + (a2×SM) + (a3×ST)+ (a4×RAINFALL)] { for crop yield < breakpoint m }
or [c2 + (b1×NDVI) + (b2×SM) + (b3×ST) + (b4×RAINFALL)]{ for crop yield > breakpoint m }
Loss function is least square i.e. Lf= (Observed-Predicted)2
Iterative and Non-linear Quasi-Newton Multivariate Optimization
For all variables
Initial value= 0.1, Initial Stepping= 0.5,
Breakpoint m= mean of 16 year crop yield (wheat or rice),
Condition for convergence=0.0001, Number of iterations <100
OUTPUT
Constants and coefficients values for Empirical Equation
Predicted Crop Yield (Kg/ha), Residual values
R-square value for model empirical equation for wheat or rice

Crop Yield Prediction

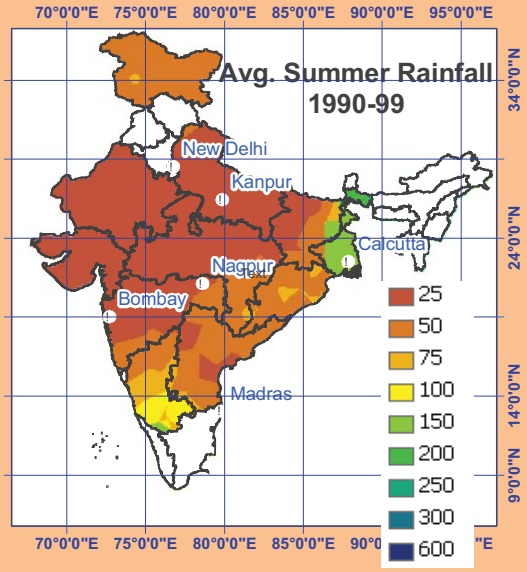
Data Used:

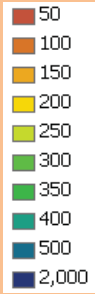
- NDVI: AVHRR NDVI 1981-2000 - Monthly average
- RF: Rainfall (rain gauge) - Monthly average
- SM: Soil Moisture (1984-1999) - Monthly average [NCEP]
- ST: Surface Temperature (1984-1999) - Monthly average [NCEP]
- Crop Yield data for wheat and rice from 1984-1999 [Published Book]

Strong spatial and temporal variation of above input parameters require division of agricultural areas into zones for crop yield modelling

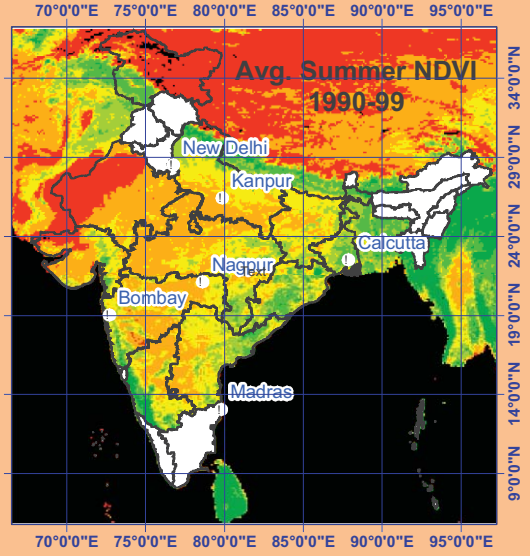
Spatial Variation of Input parameters

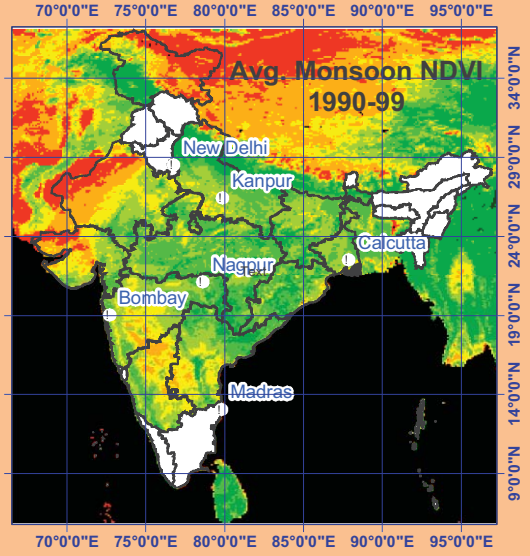
- Rainfall



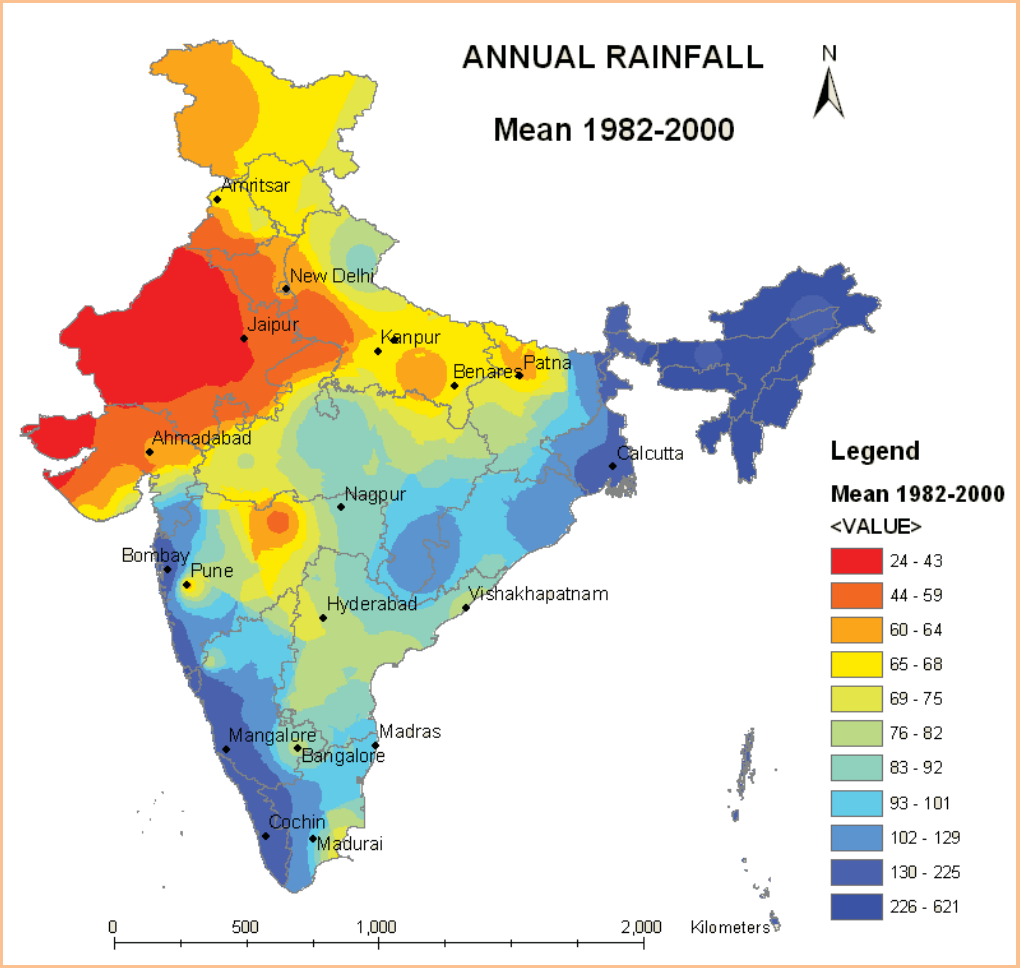


- NDVI

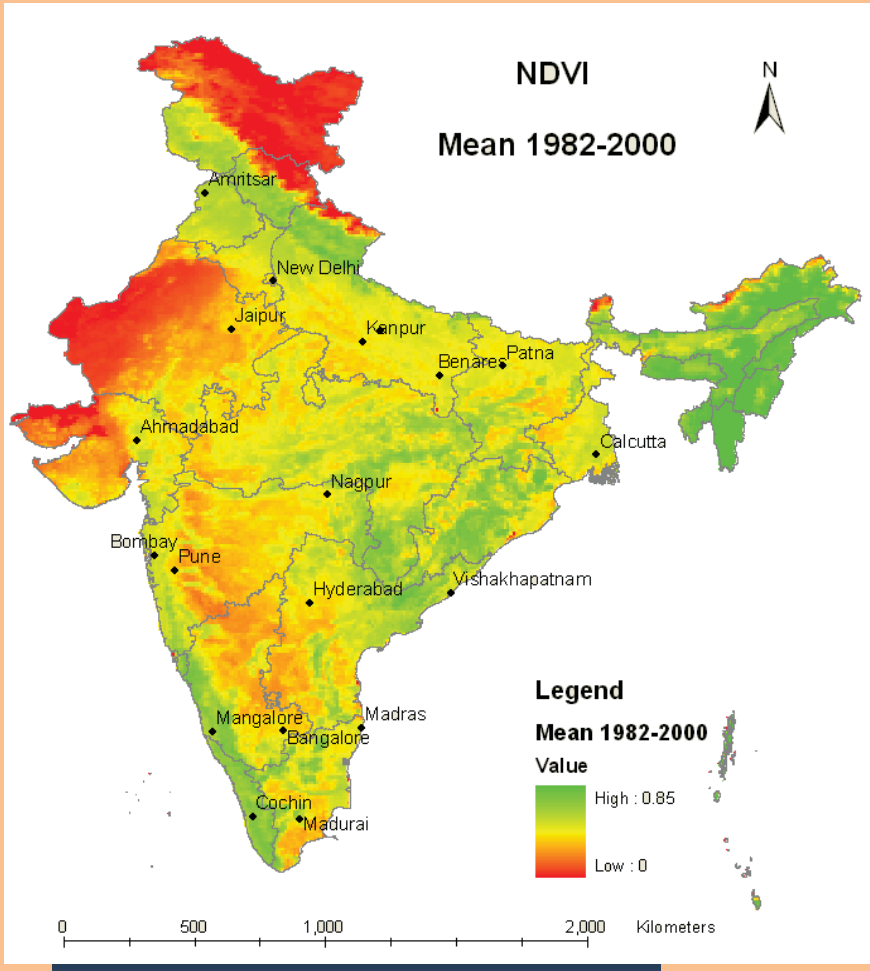




Spatial Variation of Input parameters



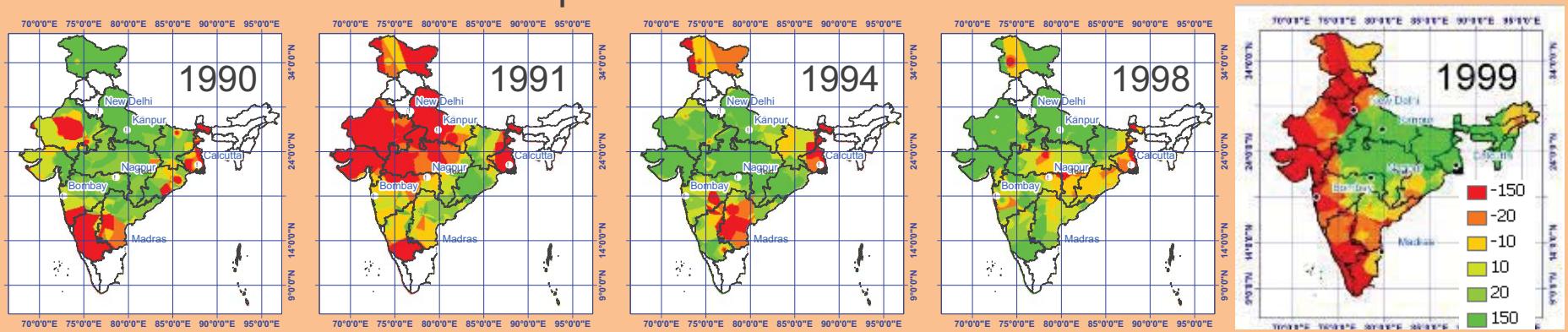
Annual RAINFALL

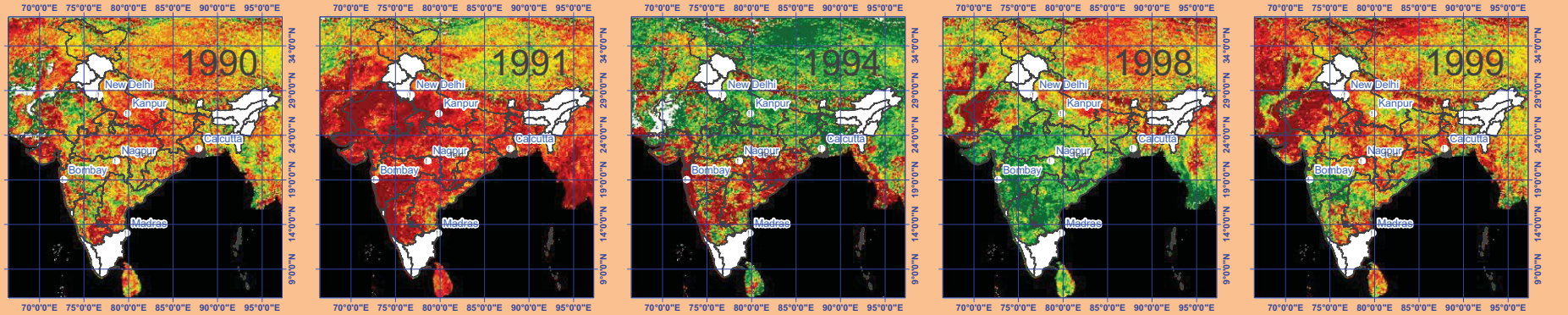


Annual AVHRR NDVI

Temporal variation of input parameters

Percent Deviation Rainfall Map - Monsoon season



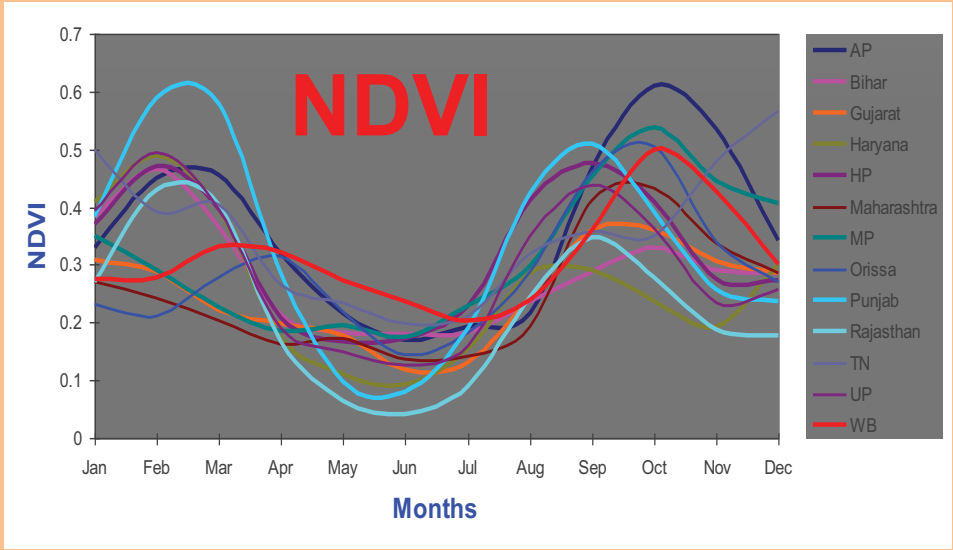


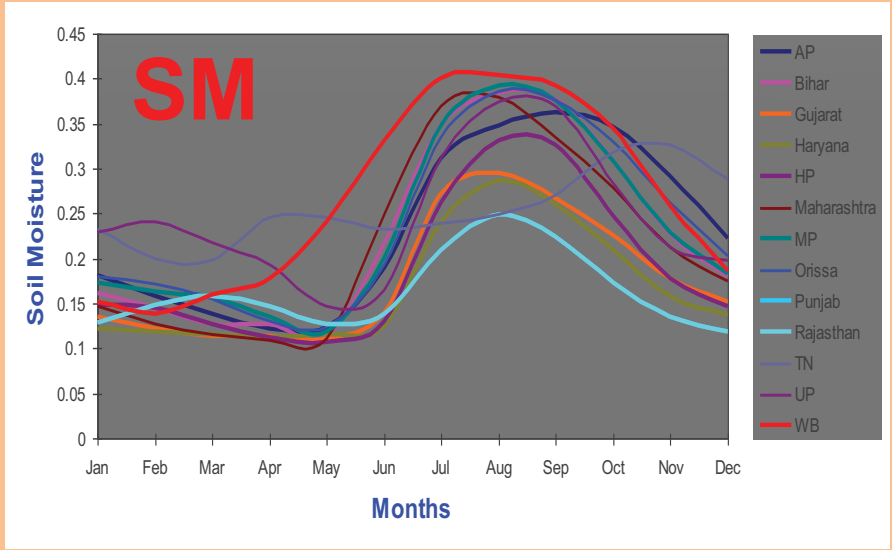
Percent Deviation NDVI Map - Monsoon season

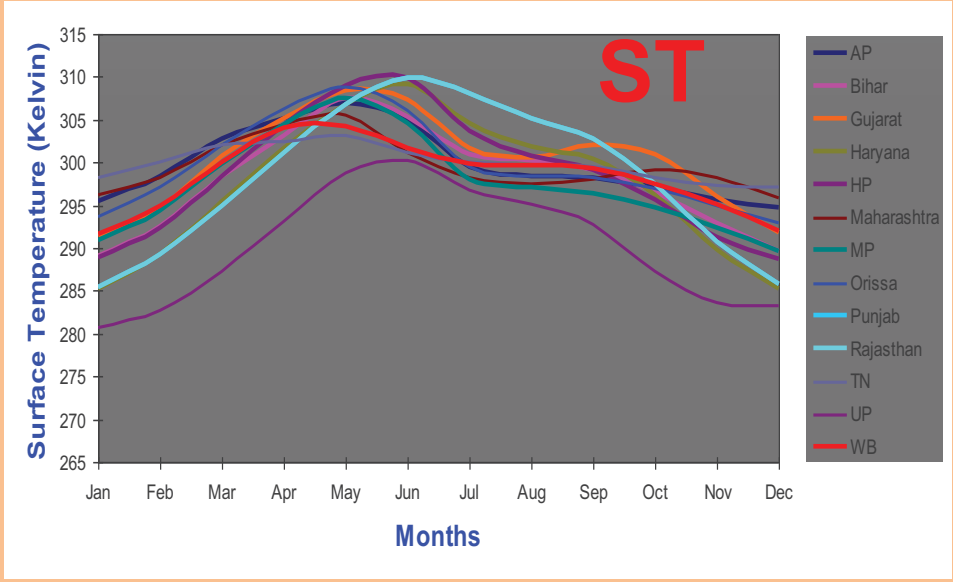
Percent Deviation (NDVI)
for Monsoon Months (July, August, September)

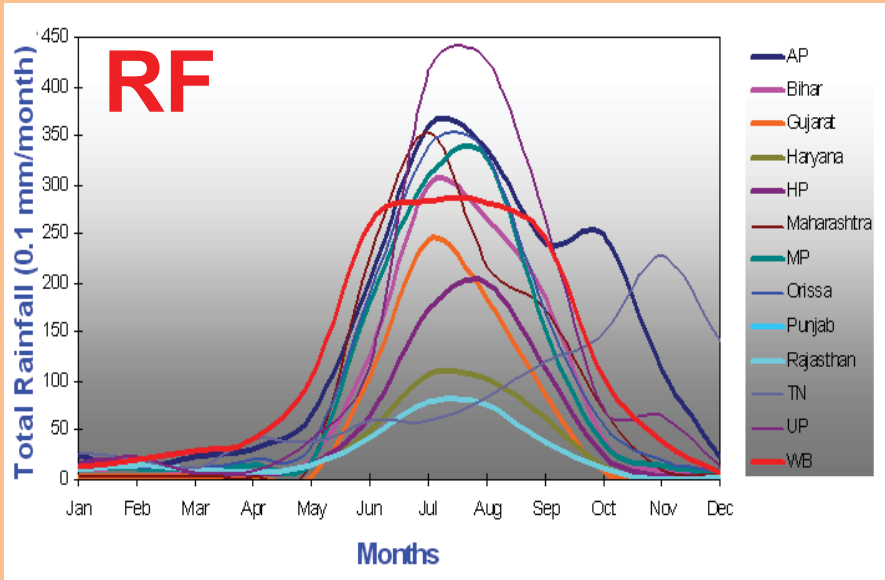
Lower limit	Upper Limit
-100	-20
-20	-10
-10	0
0	10
10	20
20	100

Data used

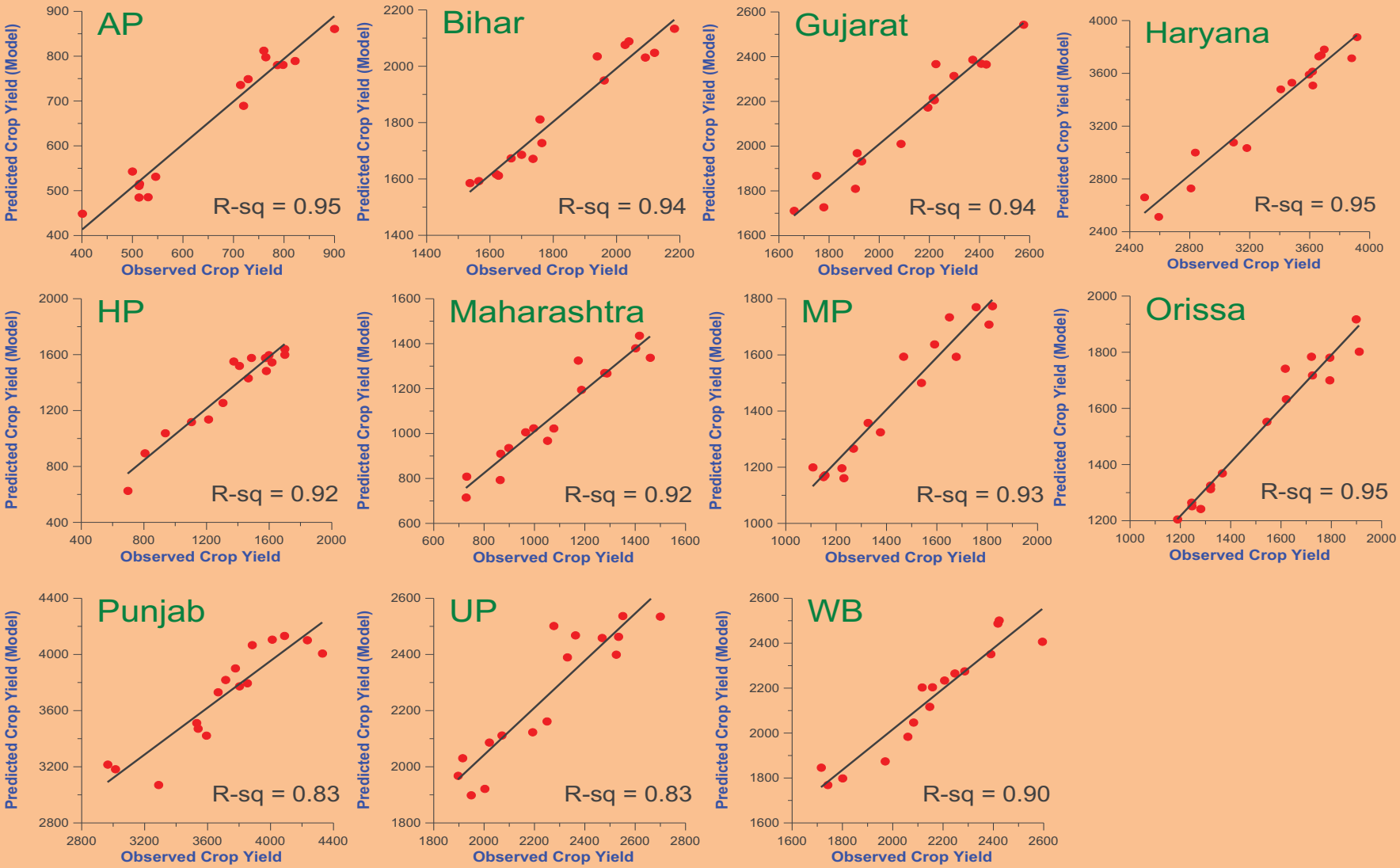

NDVI
NDVI
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Months
AP
Bihar
Gujarat
Haryana
HP
Maharashtra
MP
Orissa
Punjab
Rajasthan
TN
UP
WB


SM
Soil Moisture
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Months
AP
Bihar
Gujarat
Haryana
HP
Maharashtra
MP
Orissa
Punjab
Rajasthan
TN
UP
WB

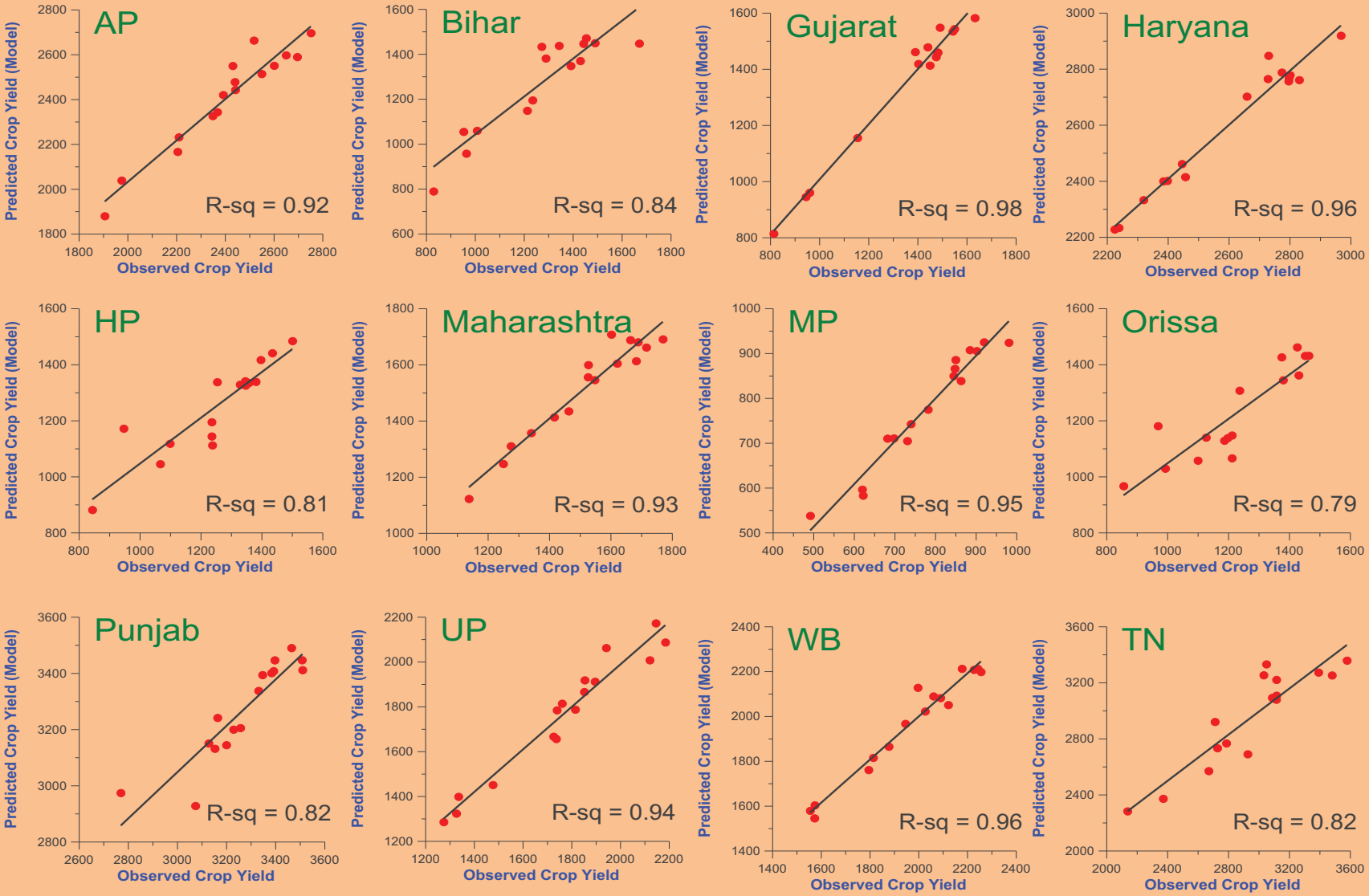

ST
Surface Temperature (Kelvin)
315
310
305
300
295
290
285
280
275
270
265
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Months
AP
Bihar
Gujarat
Haryana
HP
Maharashtra
MP
Orissa
Punjab
Rajasthan
TN
UP
WB

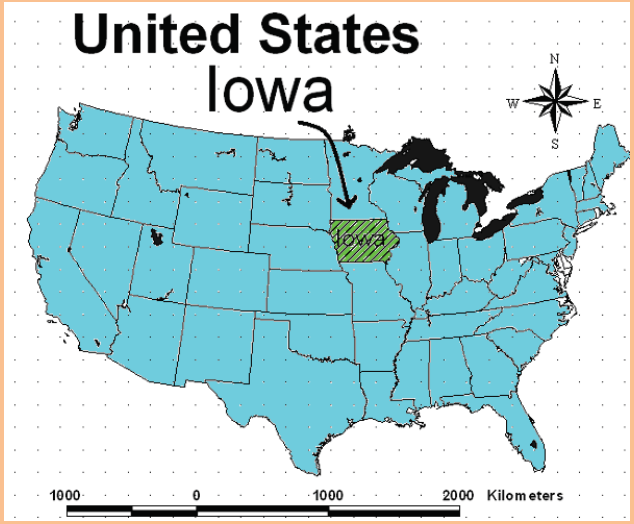

RF
Total Rainfall (0.1 mm/month)
450
400
350
300
250
200
150
100
50
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Months
AP
Bihar
Gujarat
Haryana
HP
Maharashtra
MP
Orissa
Punjab
Rajasthan
TN
UP
WB

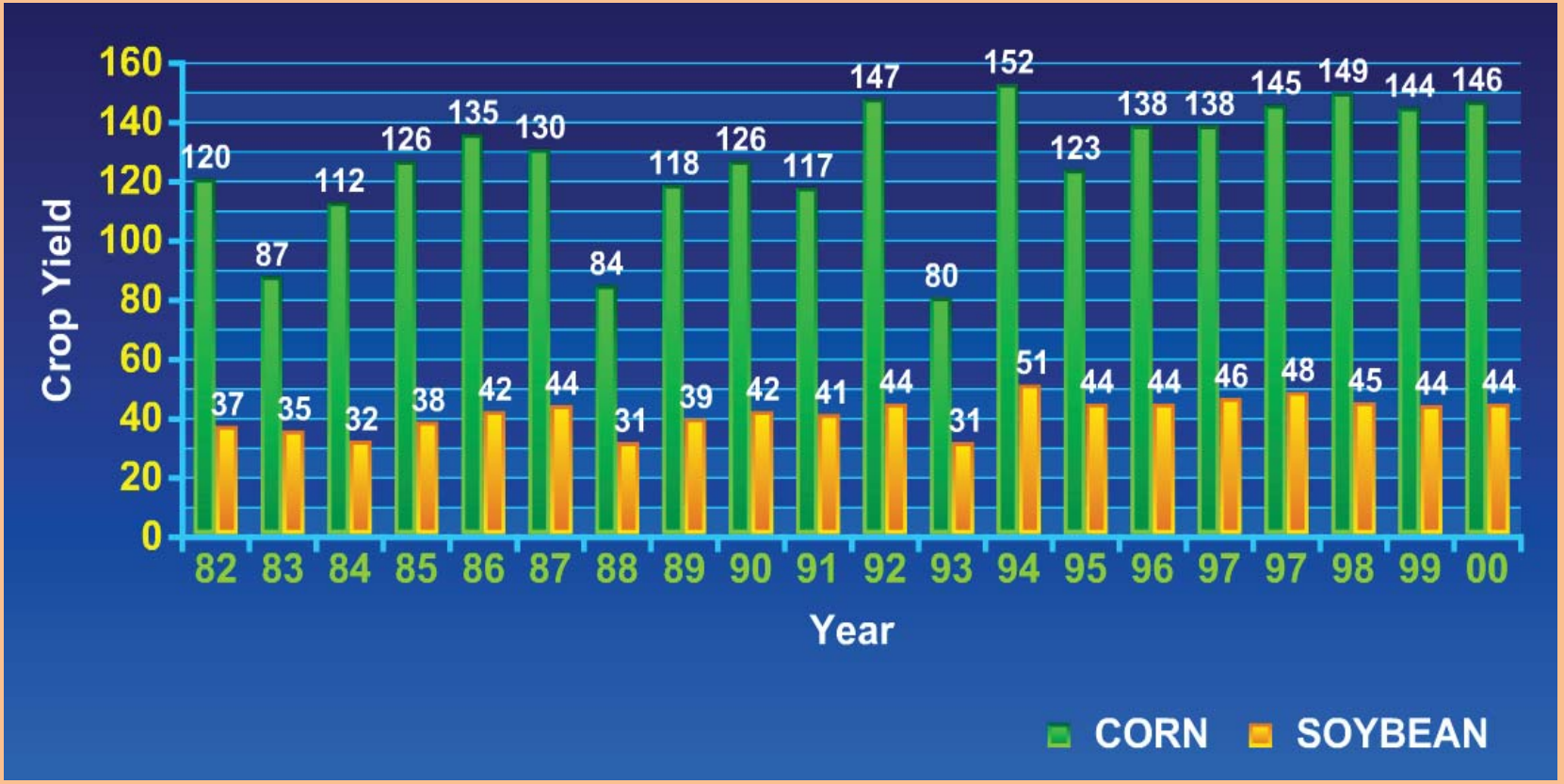
Wheat


AP
R-sq = 0.95
Bihar
R-sq = 0.94
Gujarat
R-sq = 0.94
Haryana
R-sq = 0.95
HP
R-sq = 0.92
Maharashtra
R-sq = 0.92
MP
R-sq = 0.93
Orissa
R-sq = 0.95
Punjab
R-sq = 0.83
UP
R-sq = 0.83
WB
R-sq = 0.90
Predicted Crop Yield (Model)
Observed Crop Yield

Rice

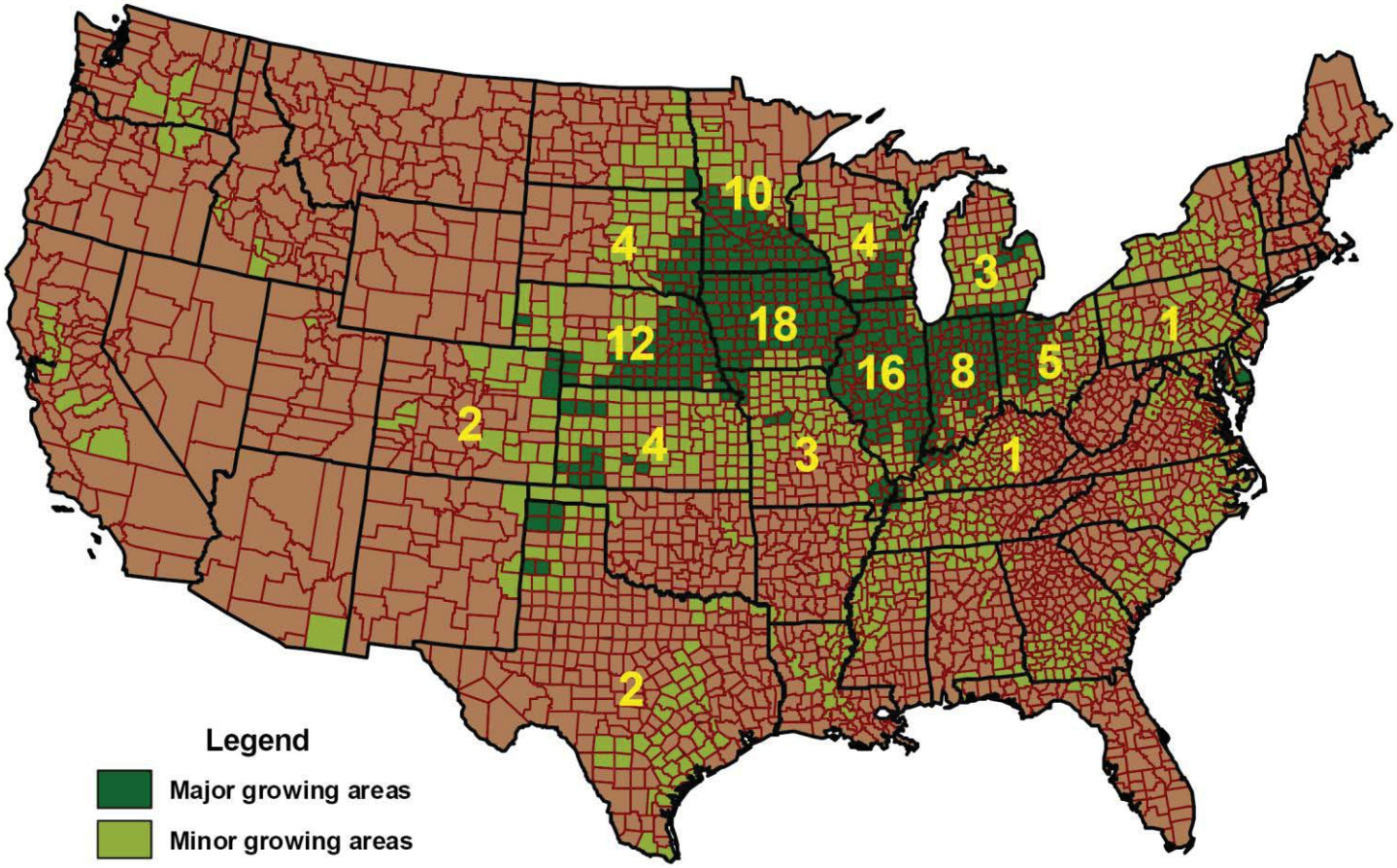

AP
R-sq = 0.92
Bihar
R-sq = 0.84
Gujarat
R-sq = 0.98
Haryana
R-sq = 0.96
HP
R-sq = 0.81
Maharashtra
R-sq = 0.93
MP
R-sq = 0.95
Orissa
R-sq = 0.79
Punjab
R-sq = 0.82
UP
R-sq = 0.94
WB
R-sq = 0.96
TN
R-sq = 0.82
Predicted Crop Yield (Model)
Observed Crop Yield


United States
Iowa
N
W
E
S
Iowa
1000
0
1000
2000 Kilometers


Crop Yield
160
140
120
100
80
60
40
20
0
120
87
112
126
135
130
84
118
126
117
147
80
152
123
138
138
145
149
144
146
37
35
32
38
42
44
31
39
42
41
44
31
51
44
44
46
48
45
44
44
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
97
98
99
00
Year
CORN
SOYBEAN

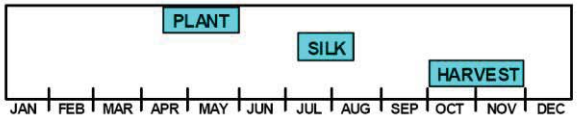
United States: Corn

Yellow numbers indicate percent of national total each state contributes to national production annually. States not numbered contribute less than 1% to the national total.



- Major growing areas combined account for 75% of total national production annually
- Major and minor growing areas combined account for 99% of total national production annually
- Major and minor growing areas and state production percentages based upon averaged NASS county-level and state production data from 1996-2000

Corn crop calendar for most of the Midwest United States



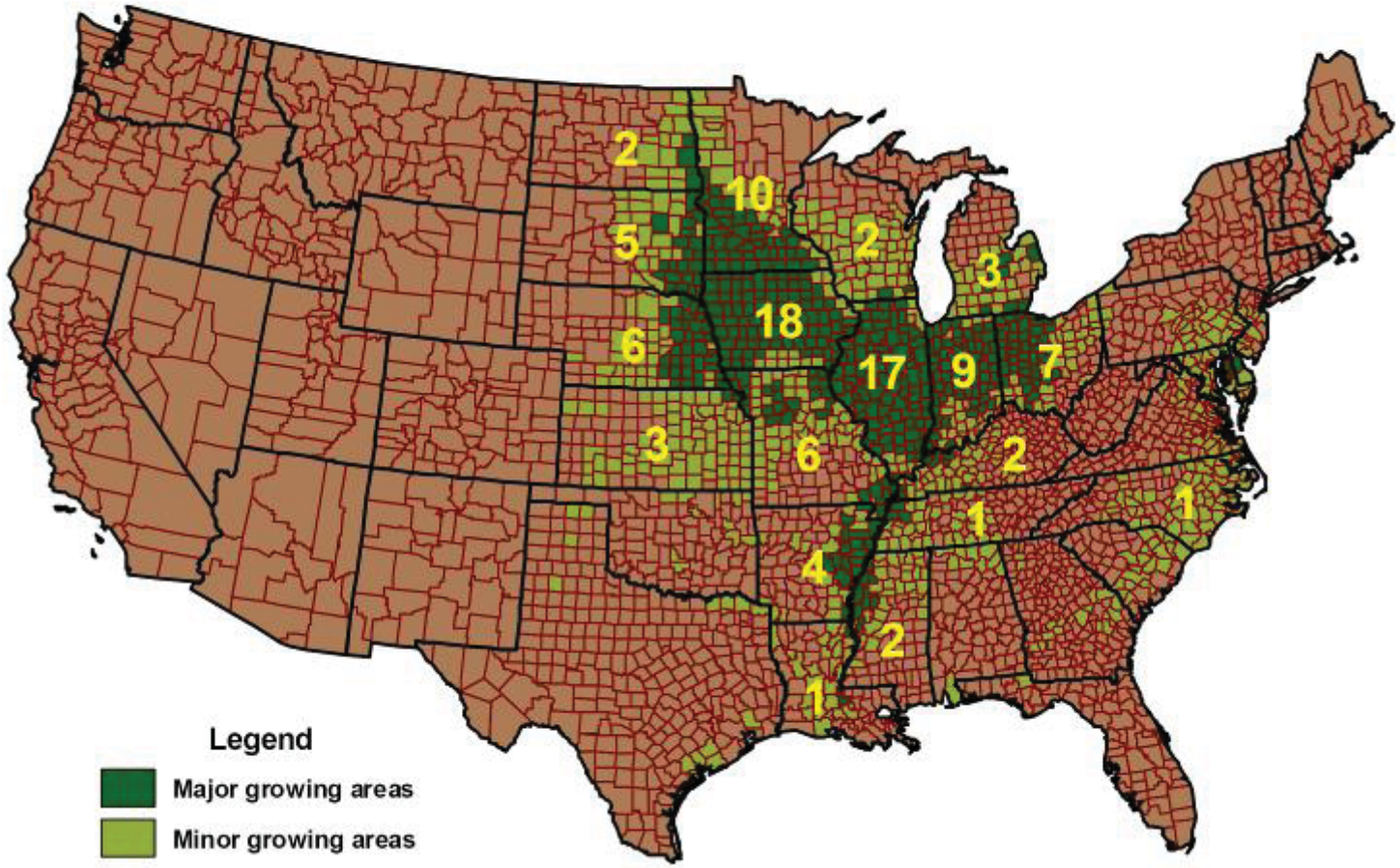
The corn crop calendar is typically 1 month ahead across the southern United States.

USDA

JOINT AGRICULTURAL WEATHER FACILITY (JAWF)

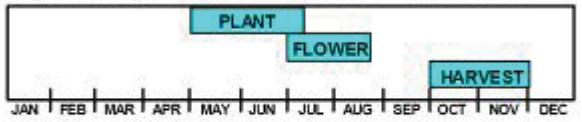
United States: Soybeans

Yellow numbers indicate percent of national total each state contributes to national production annually. States not numbered contribute less than 1% to the national total.



- Major growing areas combined account for 75% of total national production annually
- Major and minor growing areas combined account for 99% of total national production annually
- Major and minor growing areas and state production percentages based upon averaged NASS county-level and state production data from 1996-2000

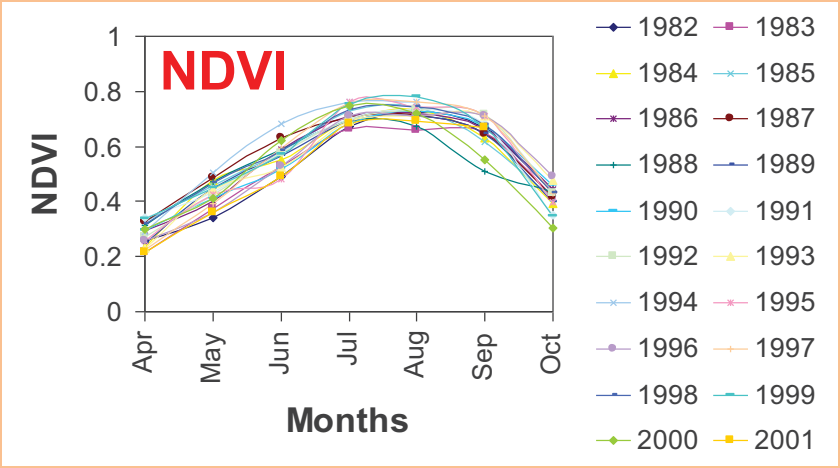
Soybean crop calendar for most of the United States

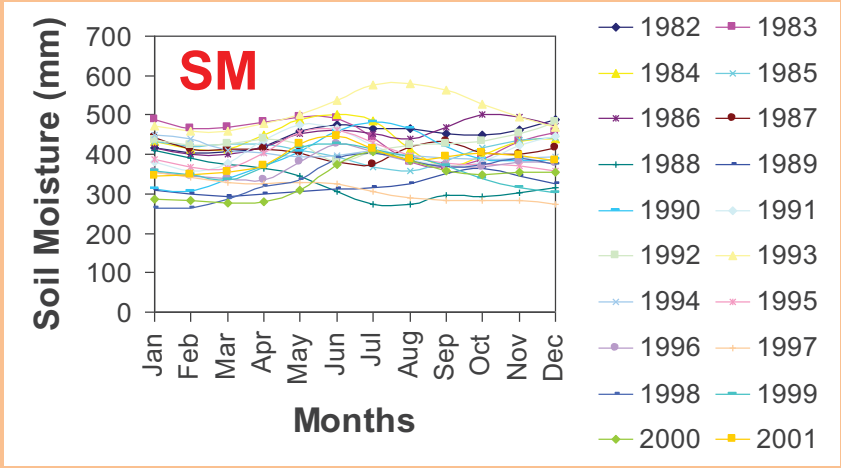


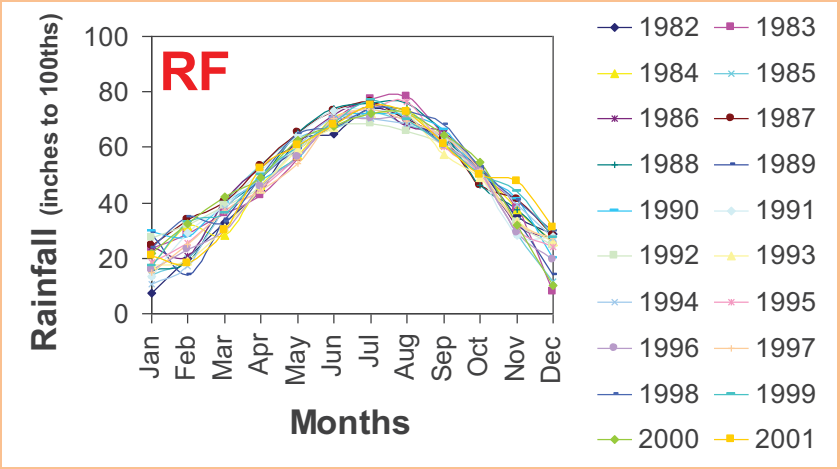
USDA

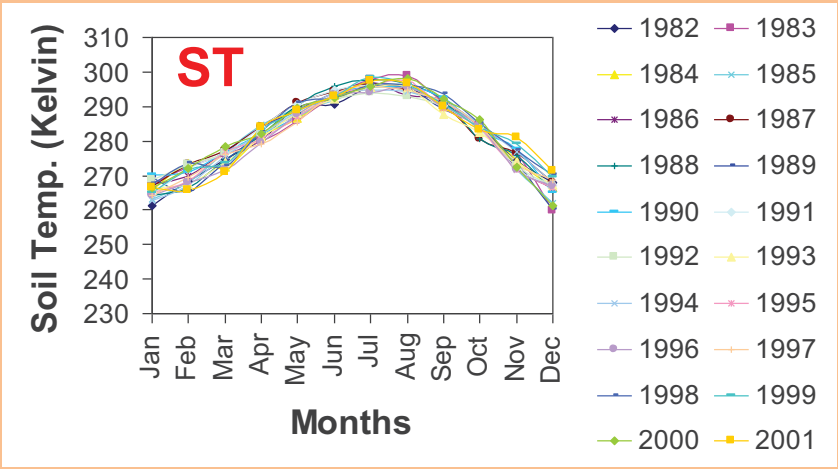
JOINT AGRICULTURAL WEATHER FACILITY (JAWF)

Iowa

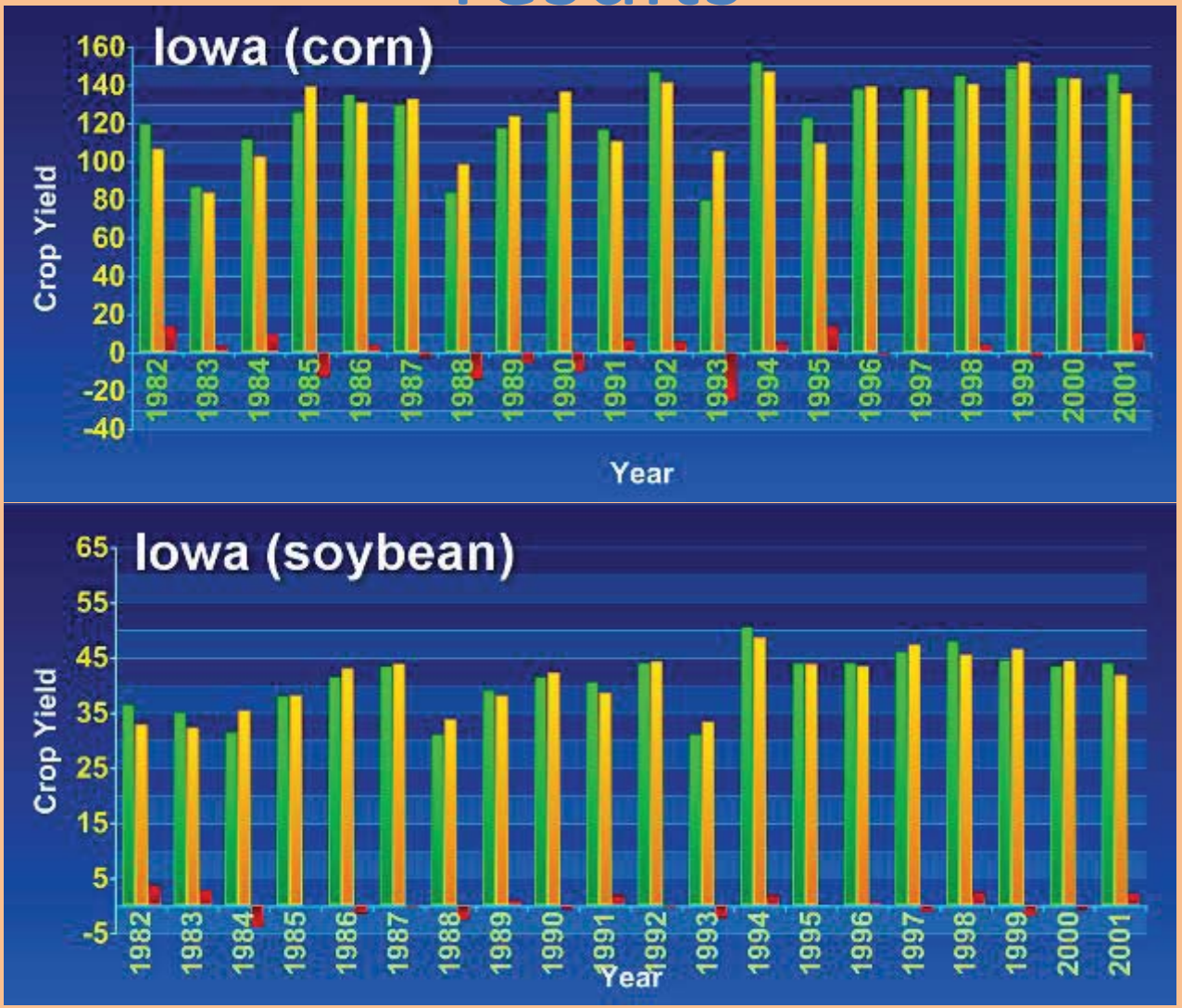

NDVI
NDVI
1
0.8
0.6
0.4
0.2
0
Apr
May
Jun
Jul
Aug
Sep
Oct
Months
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001

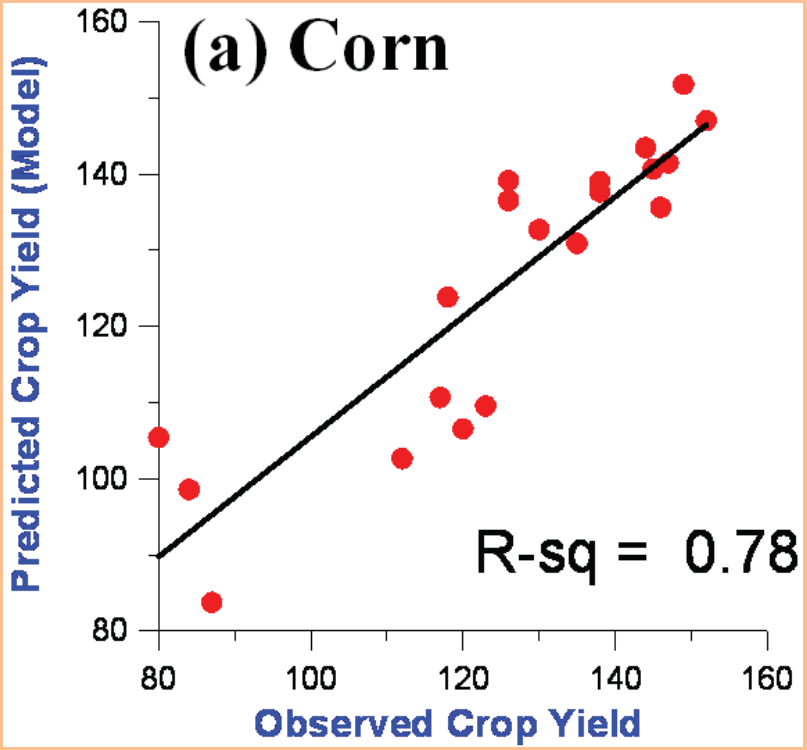

SM
Soil Moisture (mm)
700
600
500
400
300
200
100
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Months
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001

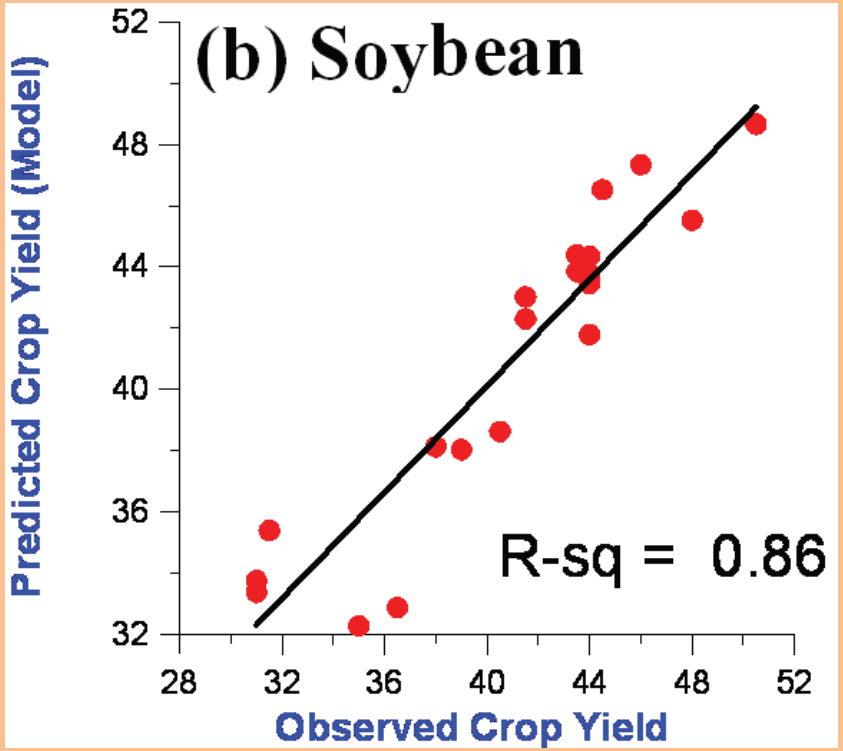

RF
Rainfall (inches to 100ths)
100
80
60
40
20
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Months
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001


ST
Soil Temp. (Kelvin)
310
300
290
280
270
260
250
240
230
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Months
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001

results


Iowa (corn)
Crop Yield
160
140
120
100
80
60
40
20
0
-20
-40
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
Year
Iowa (soybean)
Crop Yield
65
55
45
35
25
15
5
-5
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
Year
Observed
Predicted
Residual


(a) Corn
Predicted Crop Yield (Model)
Observed Crop Yield
R-sq = 0.78
160
140
120
100
80
80
100
120
140
160


(b) Soybean
Predicted Crop Yield (Model)
Observed Crop Yield
R-sq = 0.86
52
48
44
40
36
32
28
32
36
40
44
48
52

Thank you