Biomass burning emissions from fire remote sensing

Charles Ichoku
NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

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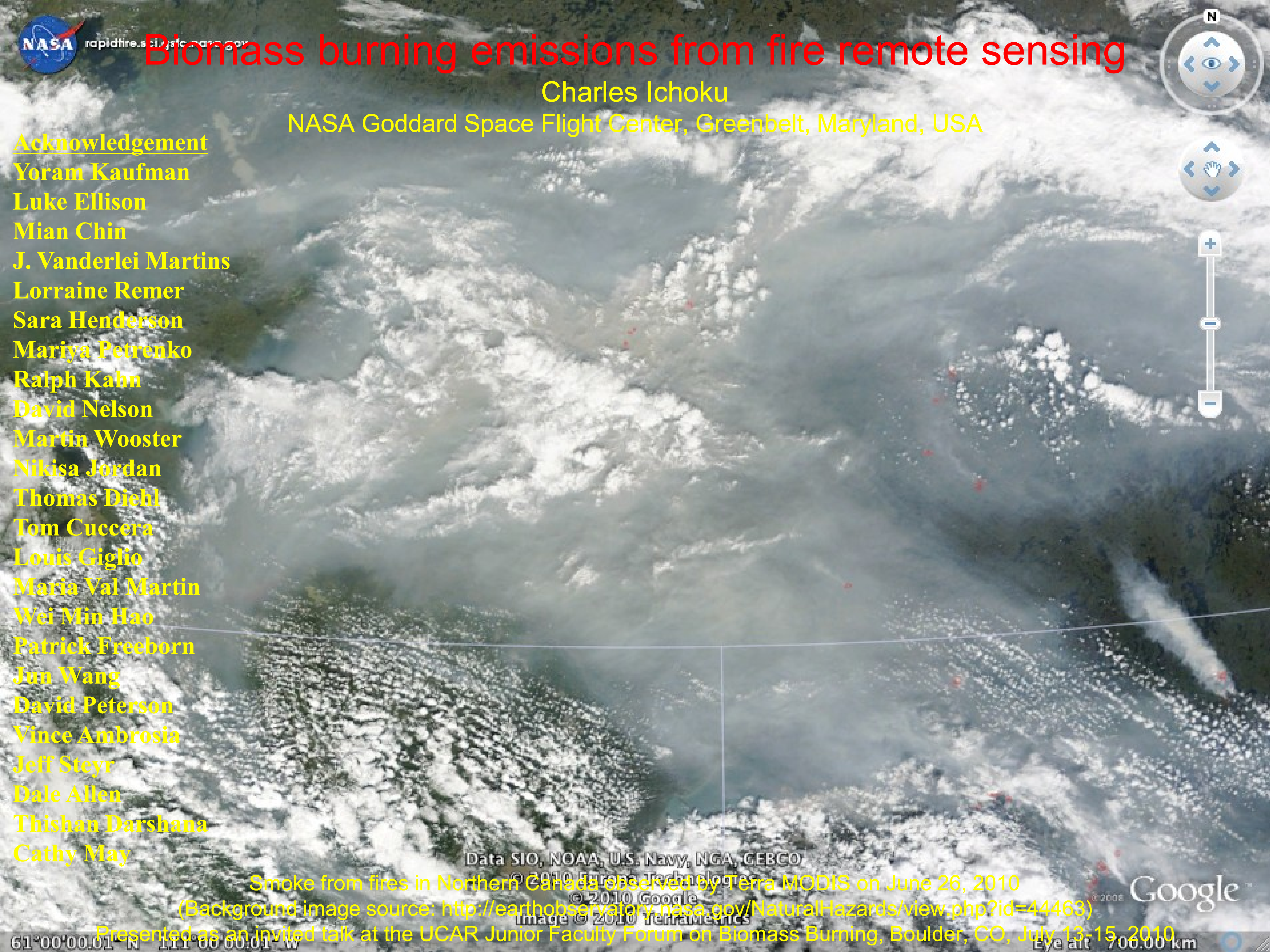


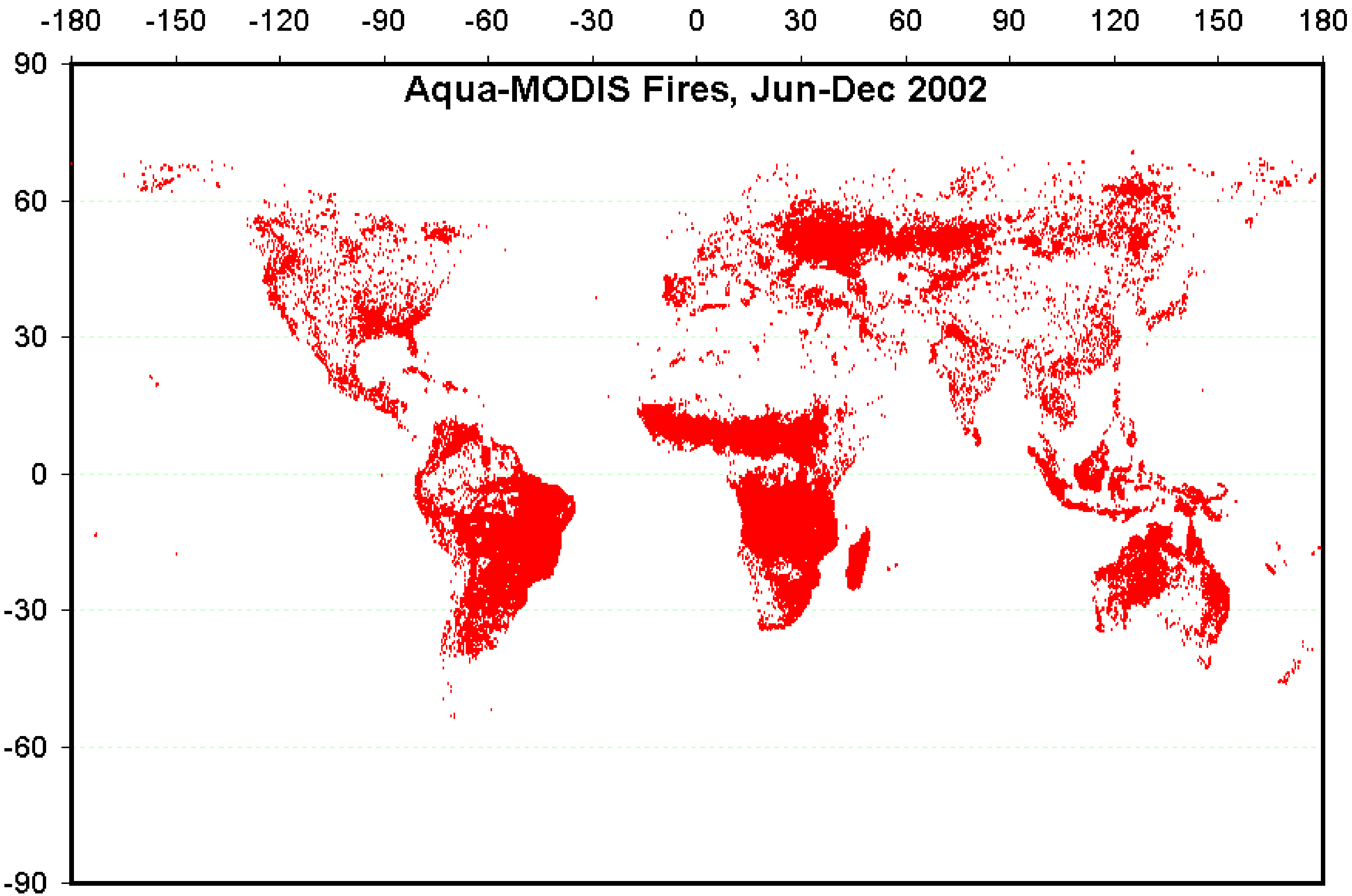
Smoke from fires in Northern Canada observed by Terra MODIS on June 26, 2010
(Background image source: http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=44463)

Presented as an invited talk at the UCAR Junior Faculty Forum on Biomass Burning, Boulder, CO, July 13-15, 2010

Outline

- Global Fire Occurrence and Effects.
- Fire Radiative Power (FRP) from Space.
- Developing Emissions from MODIS FRP.
- Detailed Evaluation of FRP and Challenges.
- Future Outlook and Conclusions.

Global Fire Occurrence

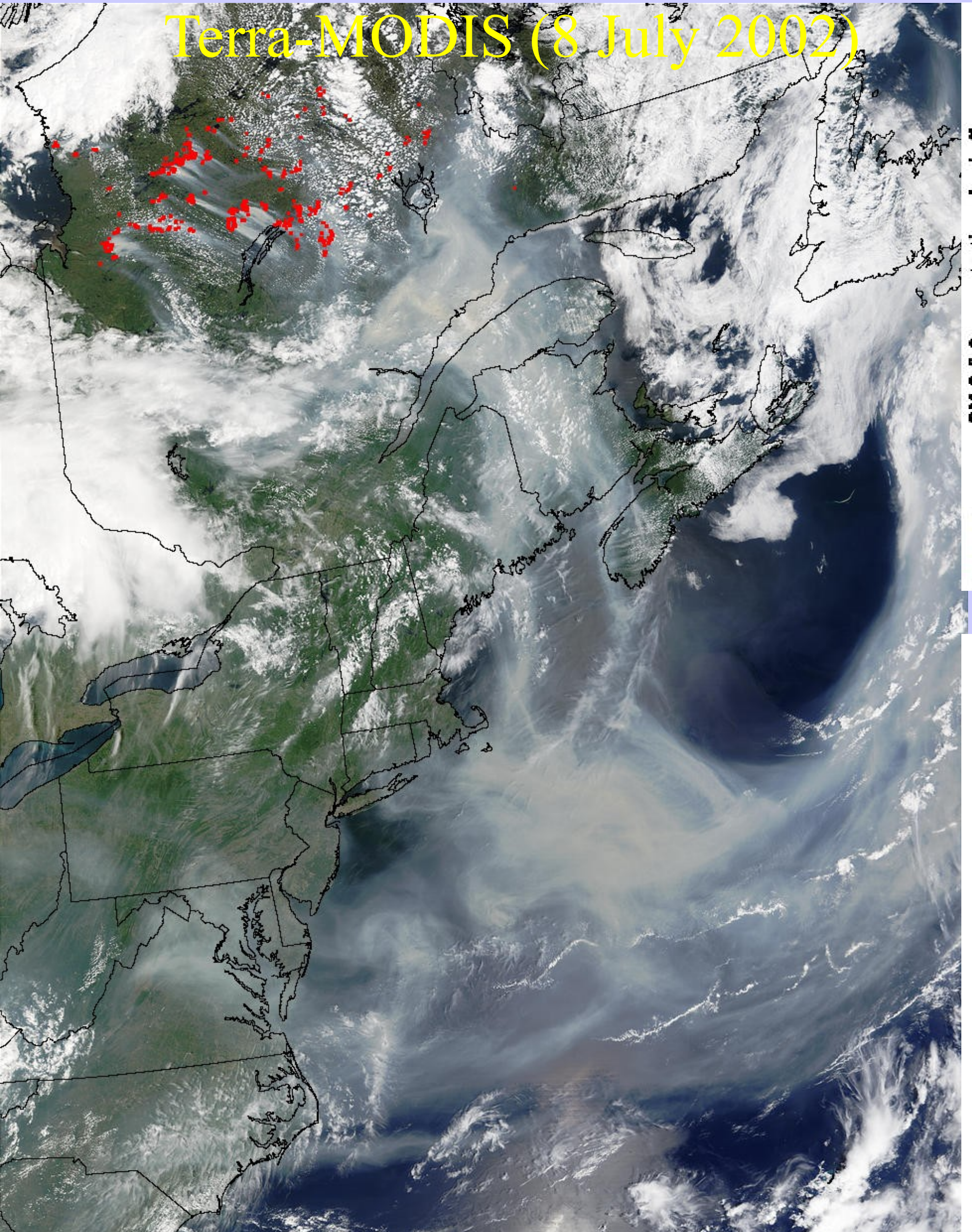


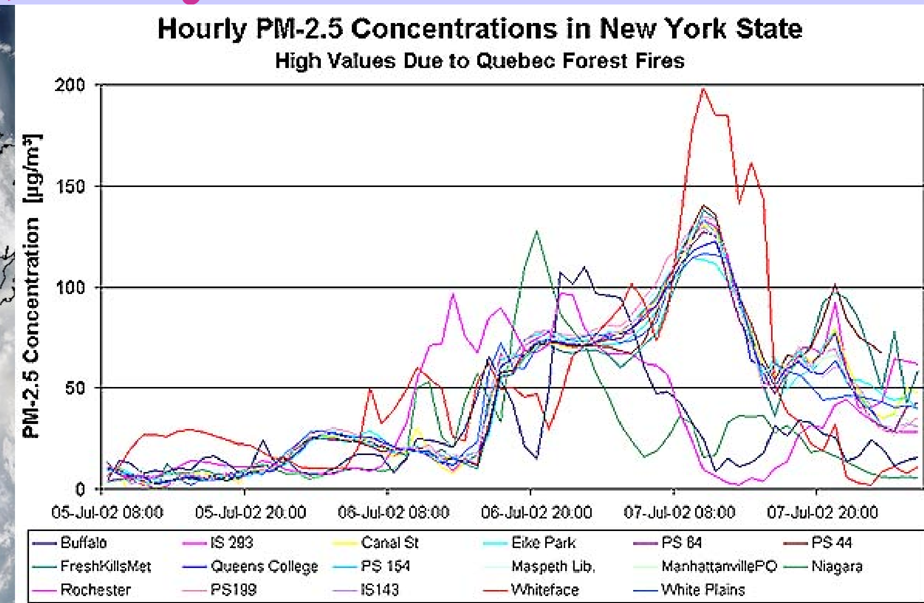
Georgia wildfires of April/May 2007: Facts

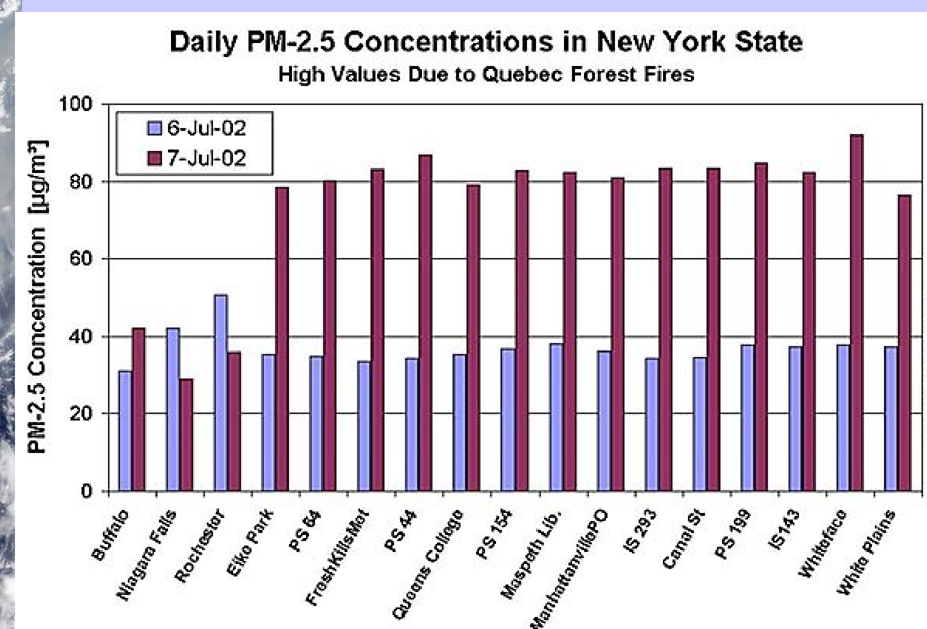
- Remained largely out of control after 6 weeks.
- Burned about 500,000 Acres.
- Destroyed 18 homes.
- More than 3,300 people from 44 states worked to control the fires.
- $8 million needed to reforest the burned area.
- $62 million spent in FY 2007 for fire control by Georgia Forestry Commission.

http://www.gfc.state.ga.us/GFCNews/documents/GAWildfires2007SummaryFactsCostsRecovery.pdf

Quebec fires, July 2002



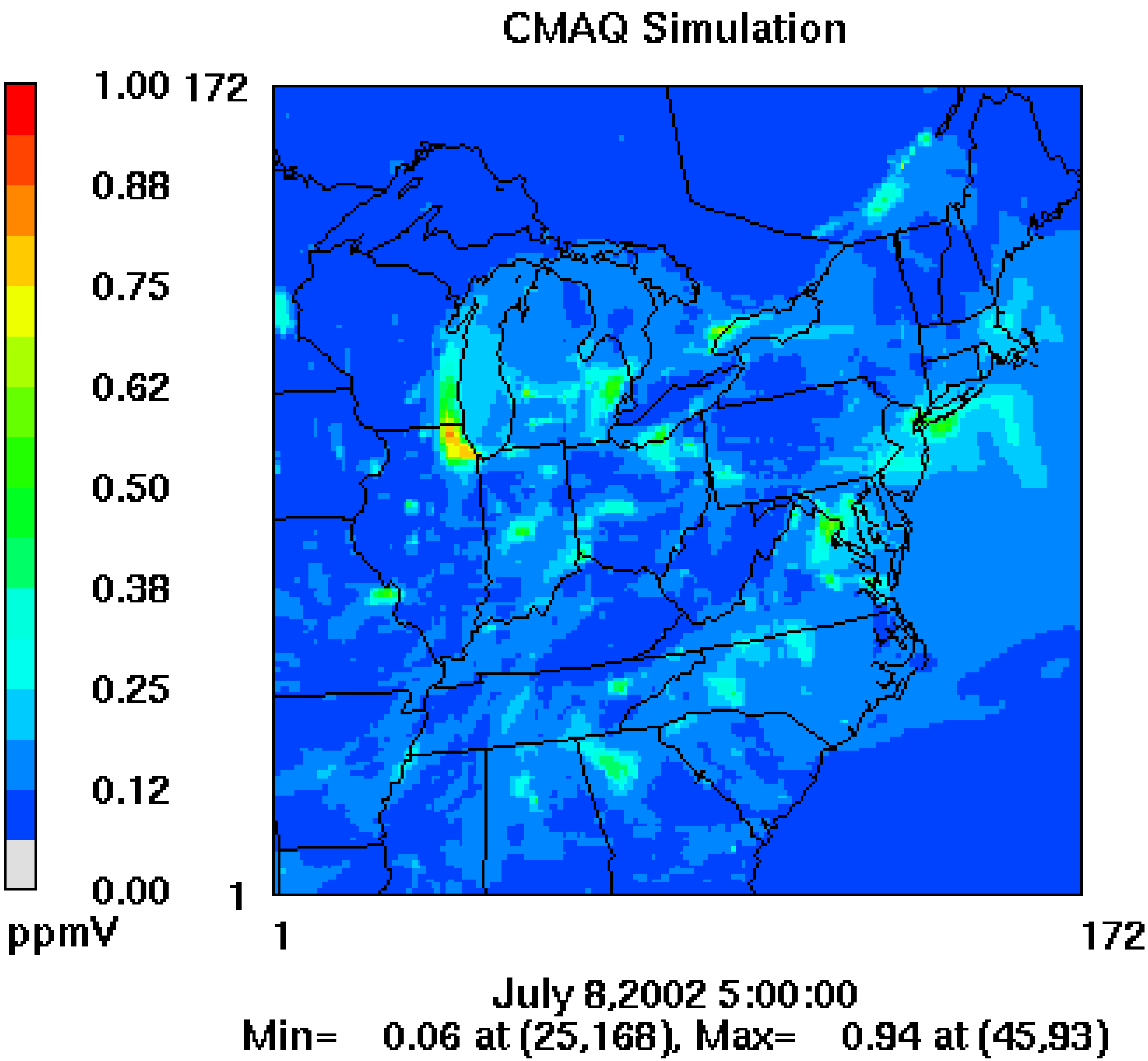




http://earthobservatory.nasa.gov/

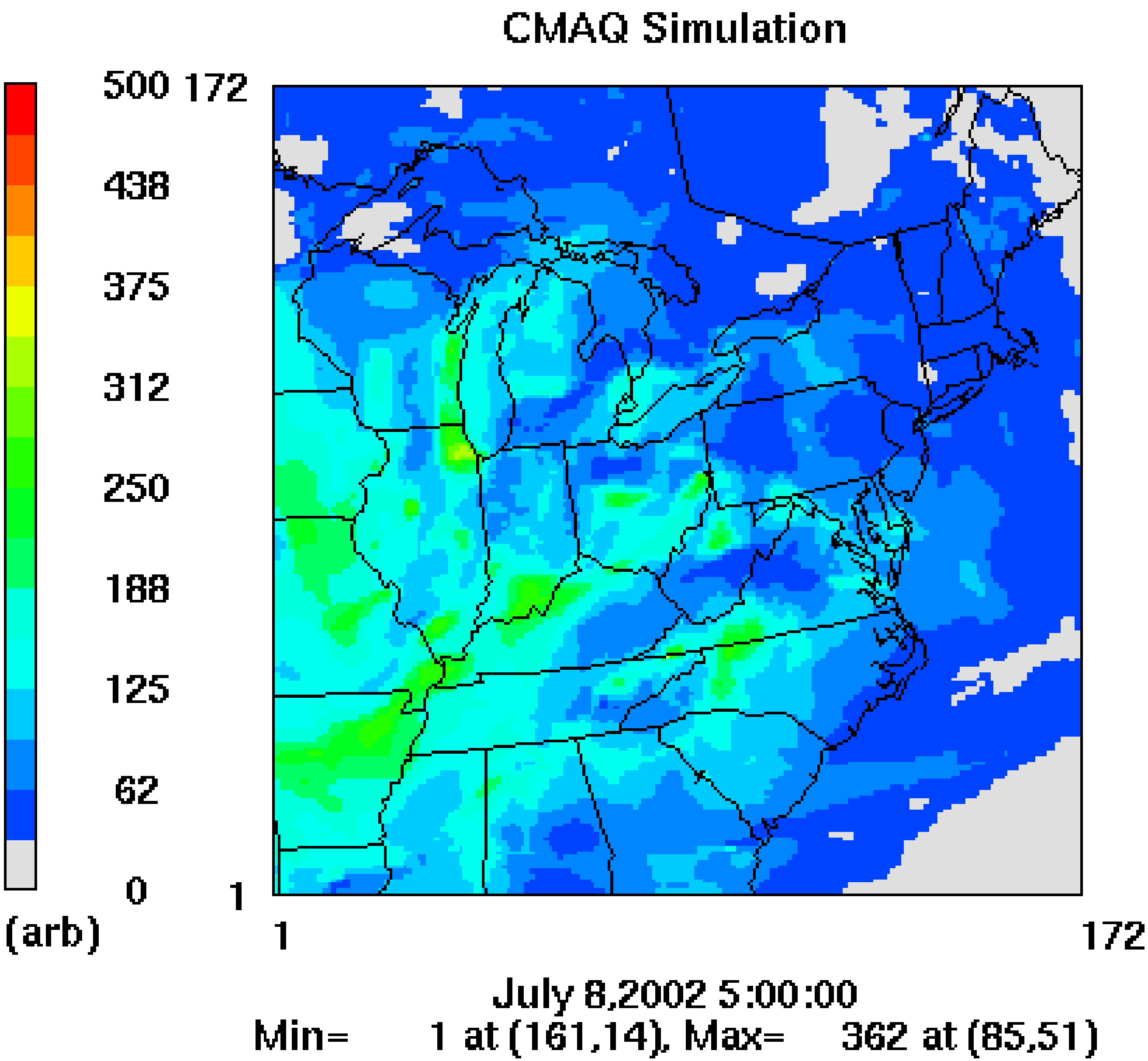
http://www.rpco.com/news2001-2004/quebecfires.htm

Hourly Average Surface CO

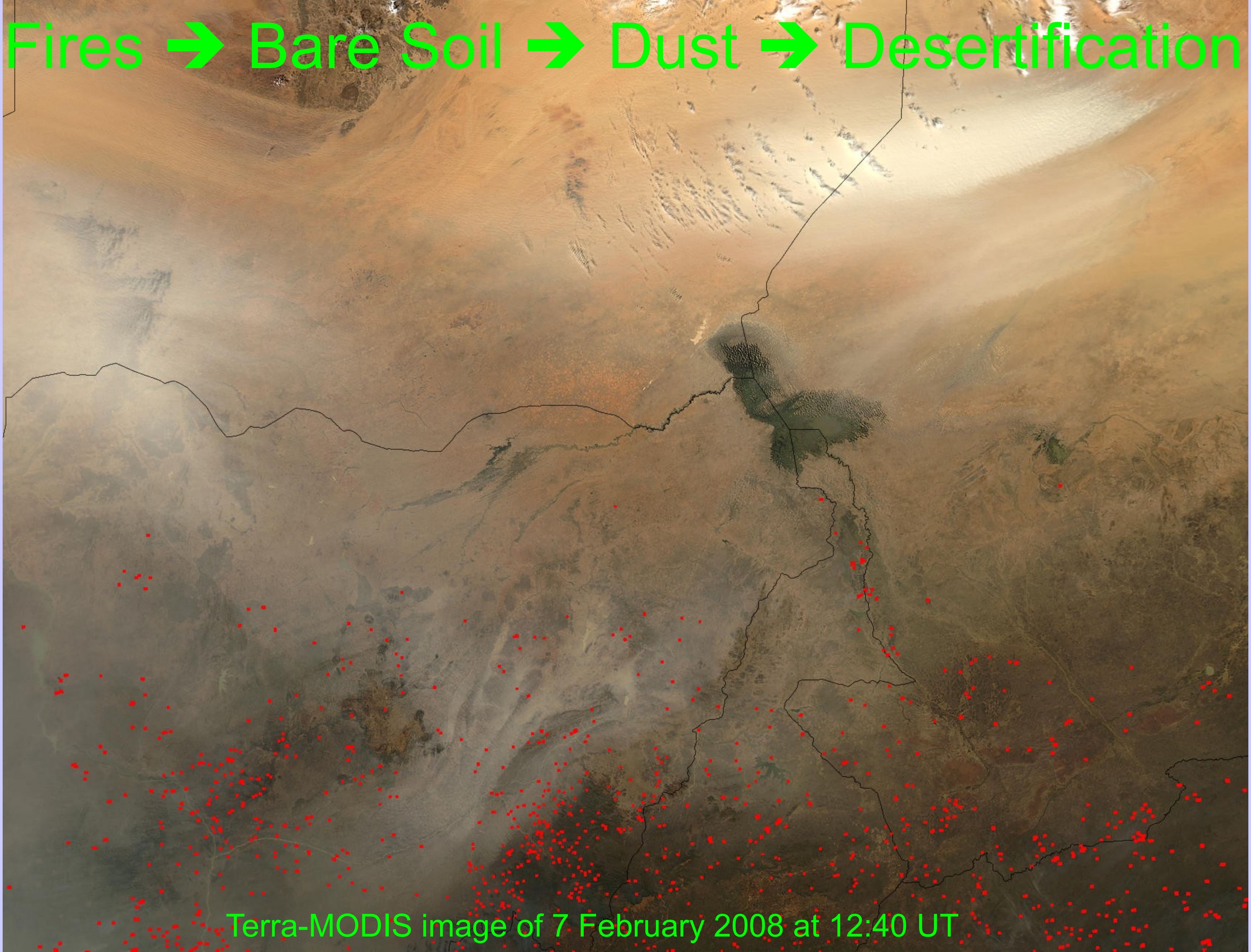


Jeff Steyr (UMCP)

Integrated Column PM2.5



Jeff Steyr
(UMCP)


Fires ➔ Bare Soil ➔ Dust ➔ Desertification
Terra-MODIS image of 7 February 2008 at 12:40 UT

Forest Reserves Under Pressure in Ghana

In the 1973 image the vegetation inside and outside the protected areas appears green and robust

In the 2002/2003 dramatic change is apparent; some of the northern reserves have been decimated and the northern edge of the forest zone has moved south

Theory of fire remote sensing

Peak wavelength of radiation

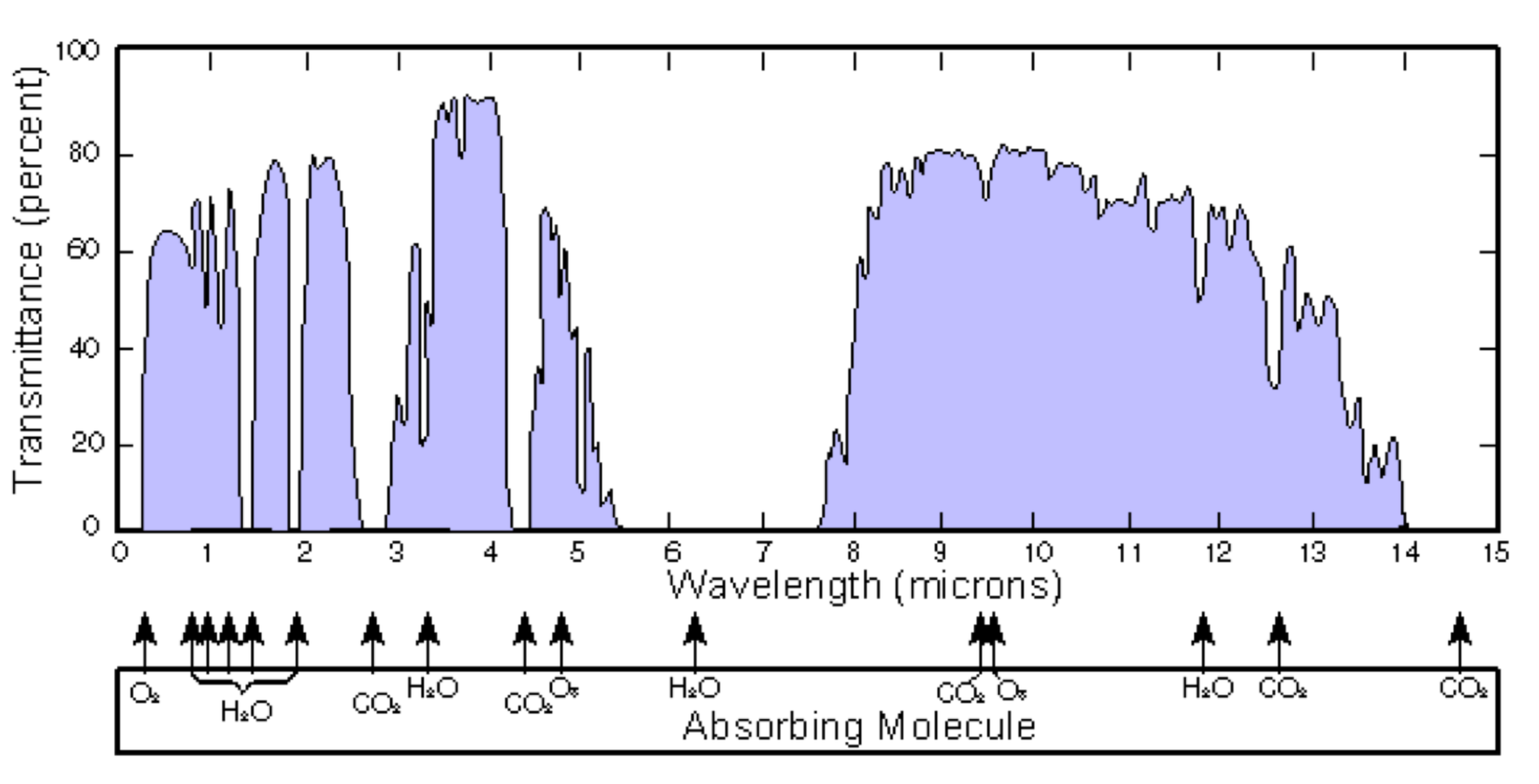
Wien's displacement law =>

$$\lambda_{max} = \frac{b}{T}$$

Wien's disp. constant ~ 2.9×10^6 nm K

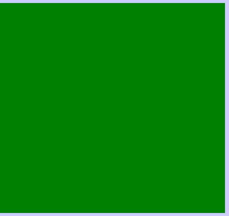
Temperature of blackbody in K

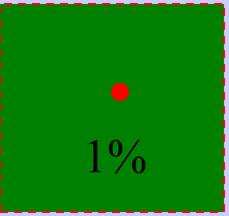
For biomass fires: T ~ 600 – 1,200 K => ~ 4.8 – 2.4 μm



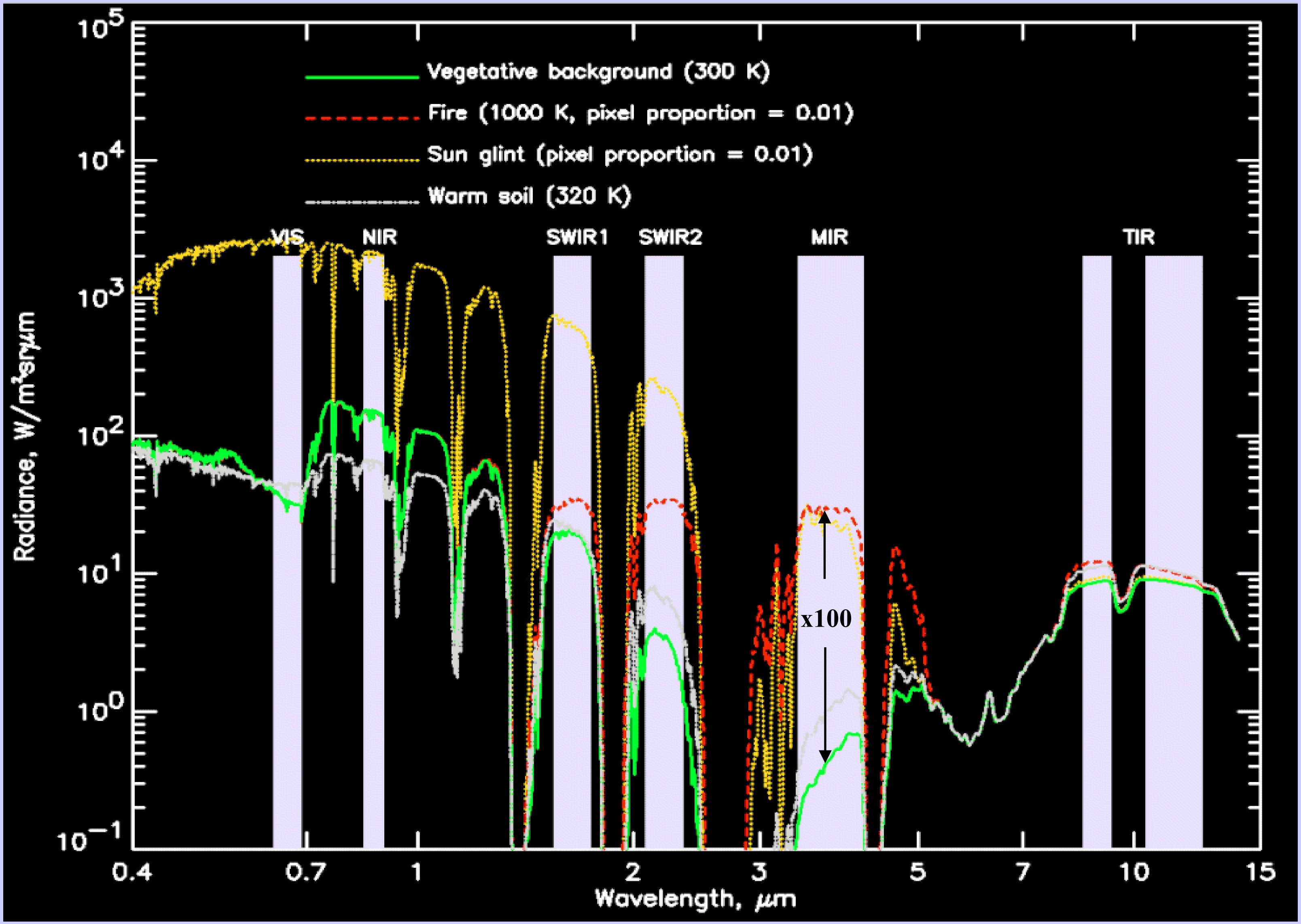
Sub-Pixel Fire Detection and Measurement

Veg Only
(300 K)





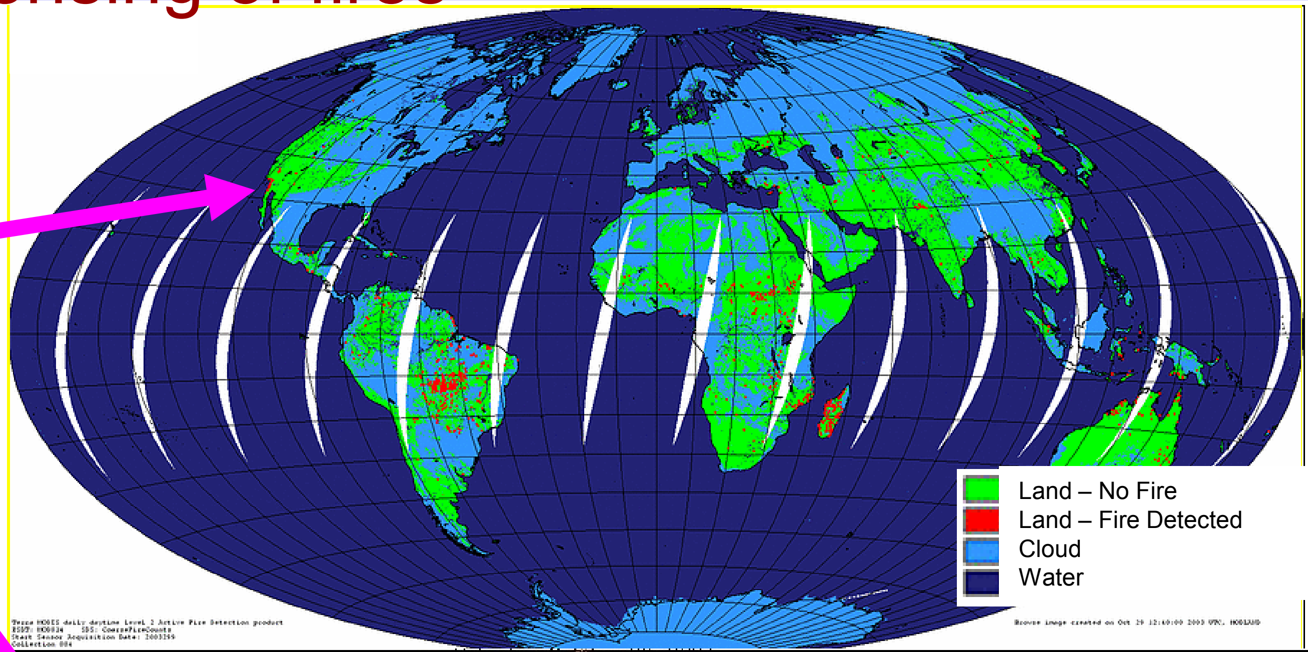
Veg +
1% Fire



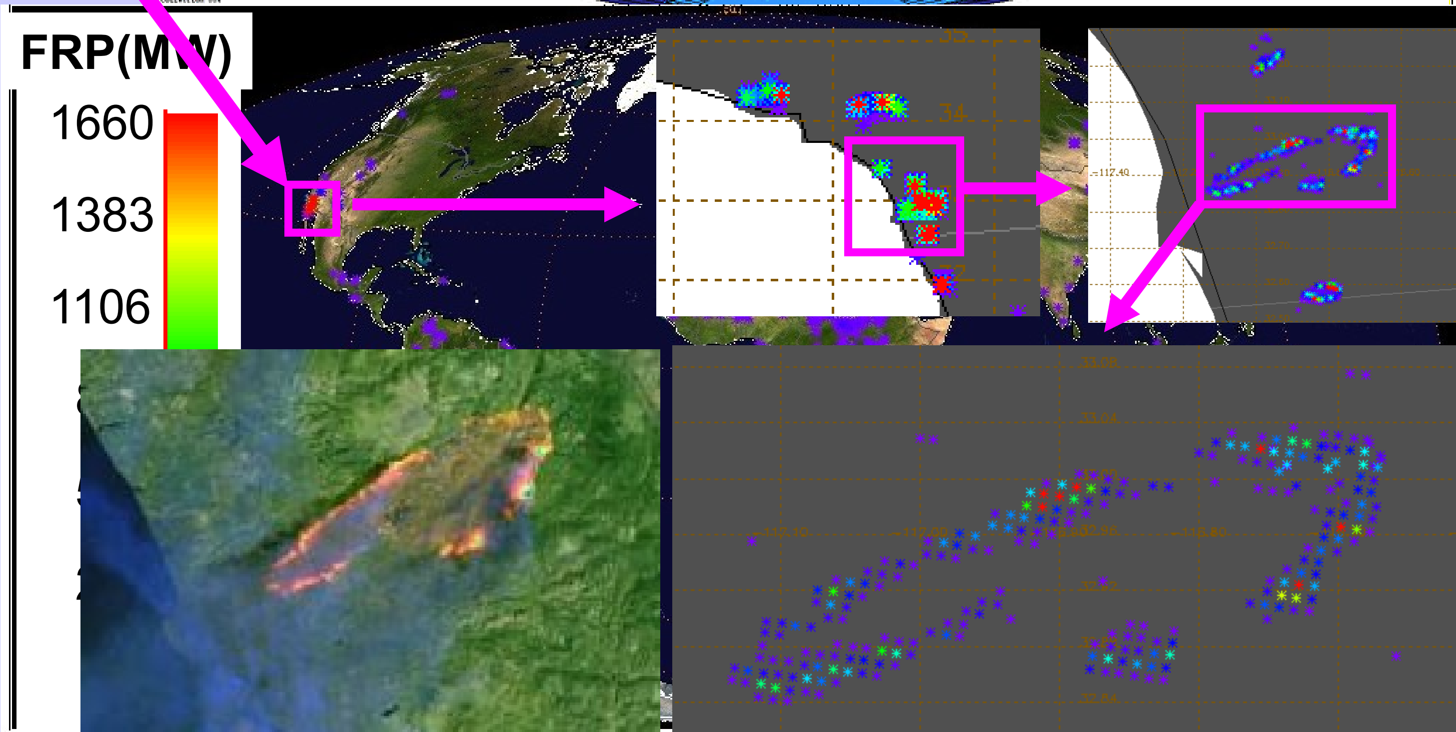
The MIR (~4 μm) channel is ideal for detection and measurement of radiative energy of active fires covering < 1000th of pixel!

Zhukov et al., 2006 (Provided by Martin Wooster)

Satellite remote sensing of fires



- ➢Where?
- ➢How Big?
- ➢Where to deploy crew?
- ➢How much smoke emitted?
- ➢How far & What Effects?



What is Fire Radiative Power?

Rate of release of the radiant component of its heat energy

Kaufman et al., 1998, JGR

$$R_{fre} = 4.34 \times 10^{-19}(T_4^8 - T_{4b}^8)$$

where

R_{fre} (in MW or MJ/s) is the pixel fire radiative power,

T_4 (in K) is the fire pixel brightness temperature at the 4-μm channel

T_{4b} is the 4-μm brightness temperature of the background surrounding the fire pixel

Wooster et al., 2003, RSE

$$R_{fre} = \frac{A_p \sigma \varepsilon}{a \varepsilon_{MIR}}(L_{MIR} - L_{MIR,bkg})$$

where,

Subscript MIR represents any MIR waveband of interest, e.g. 4-μm.

A_p = Area of fire pixel

σ= Stefan-Boltzmann constant = 5.67x10^{-8} Js^{-1}m^{-2}K^{-4}

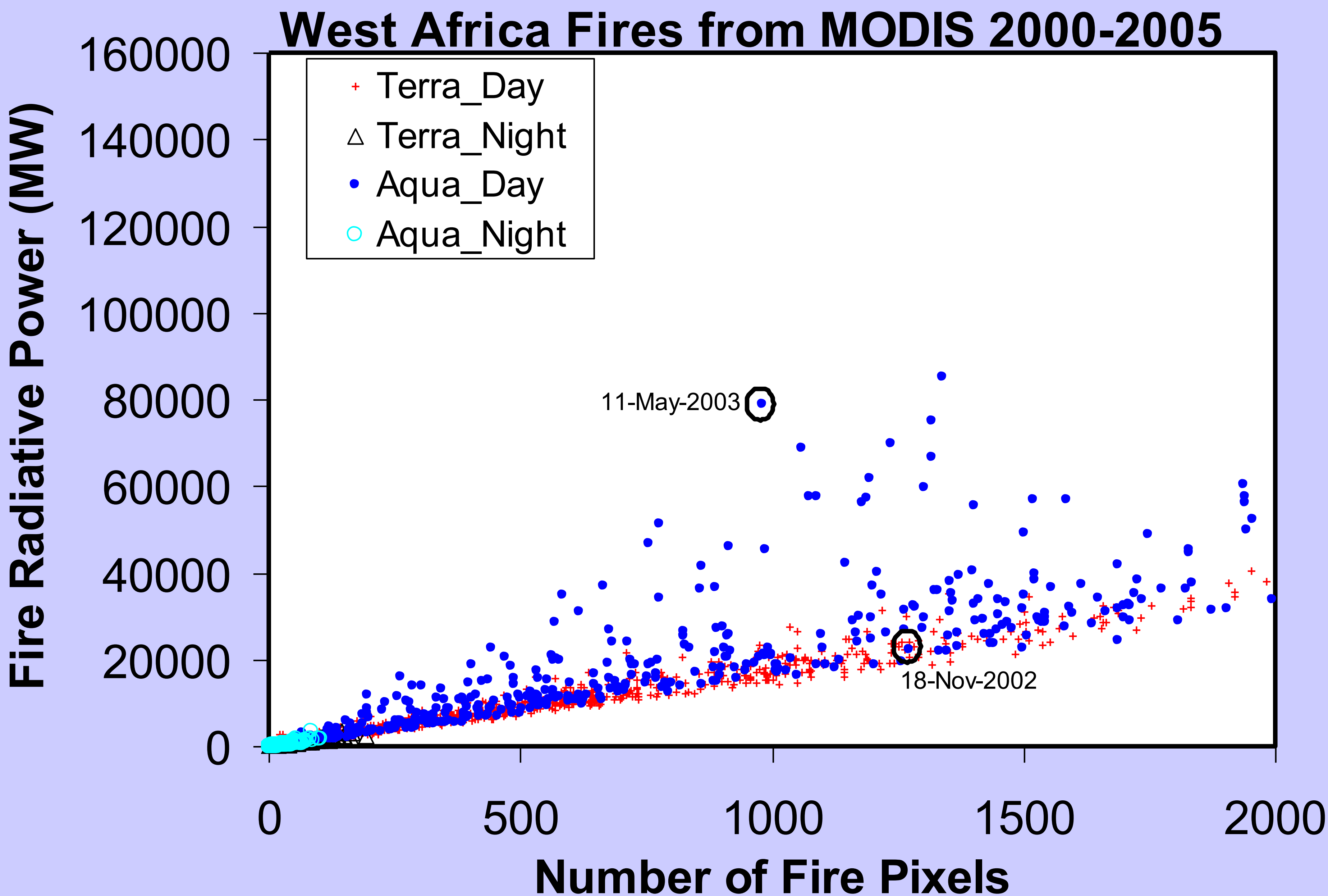
ε=emissivity

a=empirically determined constant

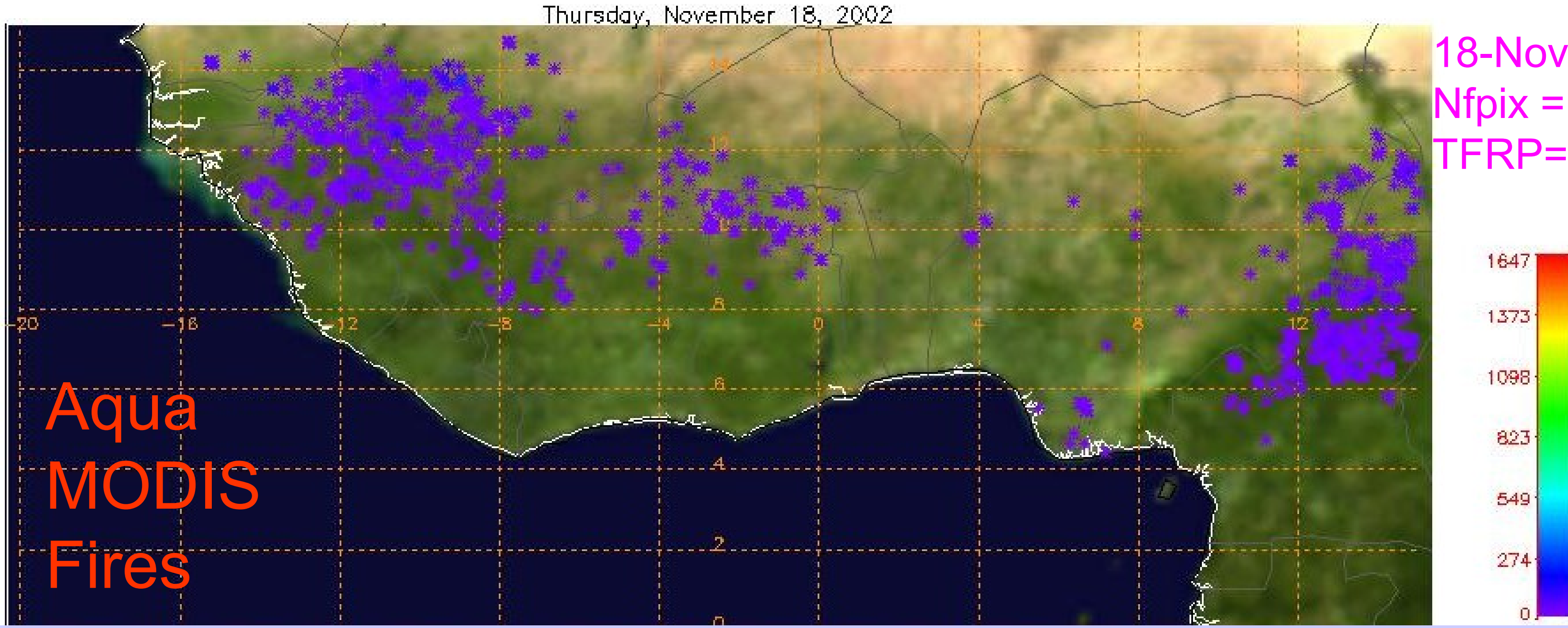
ε_{MIR}=spectral emissivity at MIR wavelength

L_{MIR} and $L_{MIR,bkg}$ = pixel and background spectral radiance at MIR

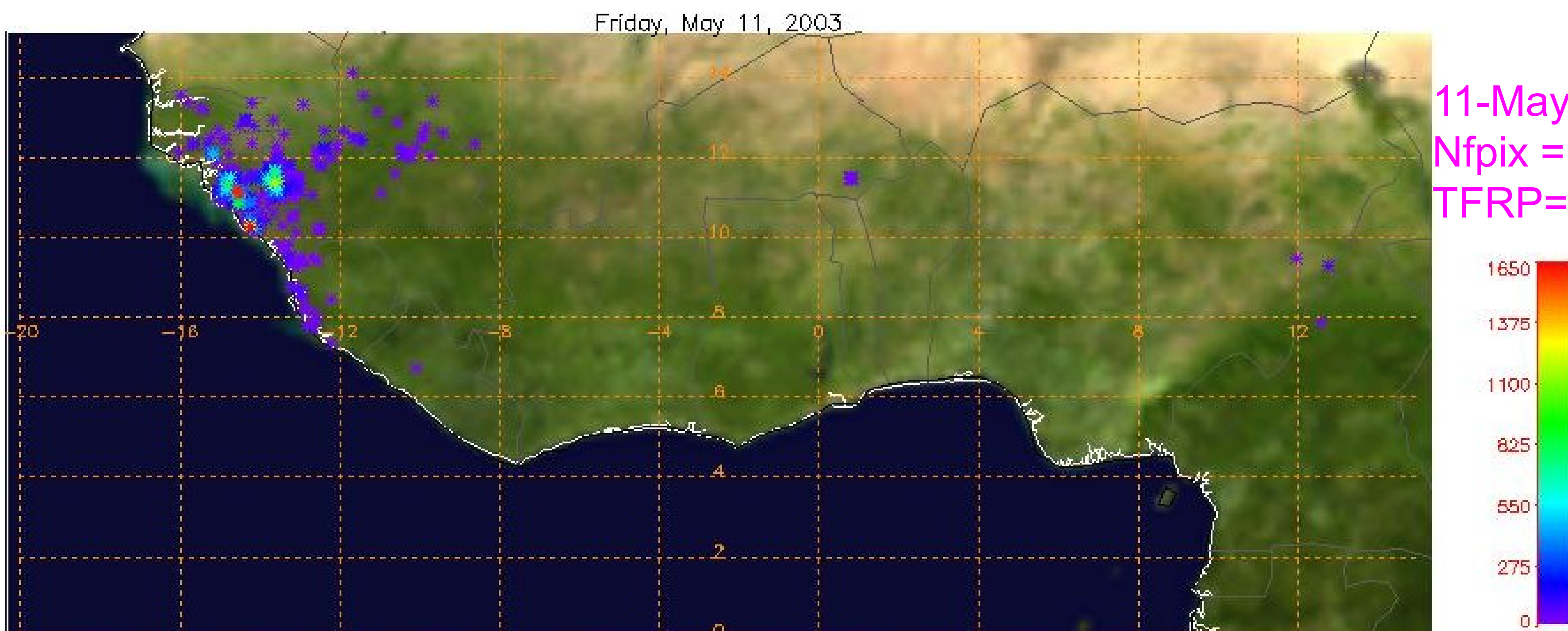
How does FRP compare with fire pixel count



Aqua MODIS Fires

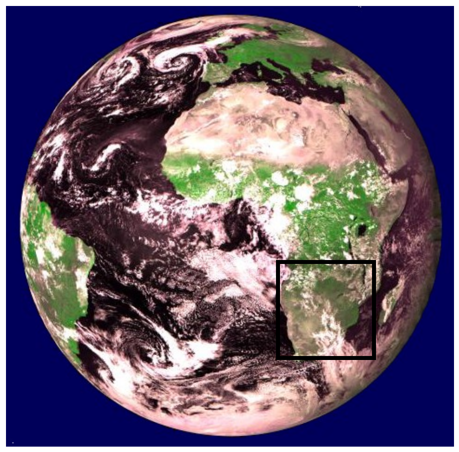


18-Nov-2002
Nfpix = 1272
TFRP= 22 GW

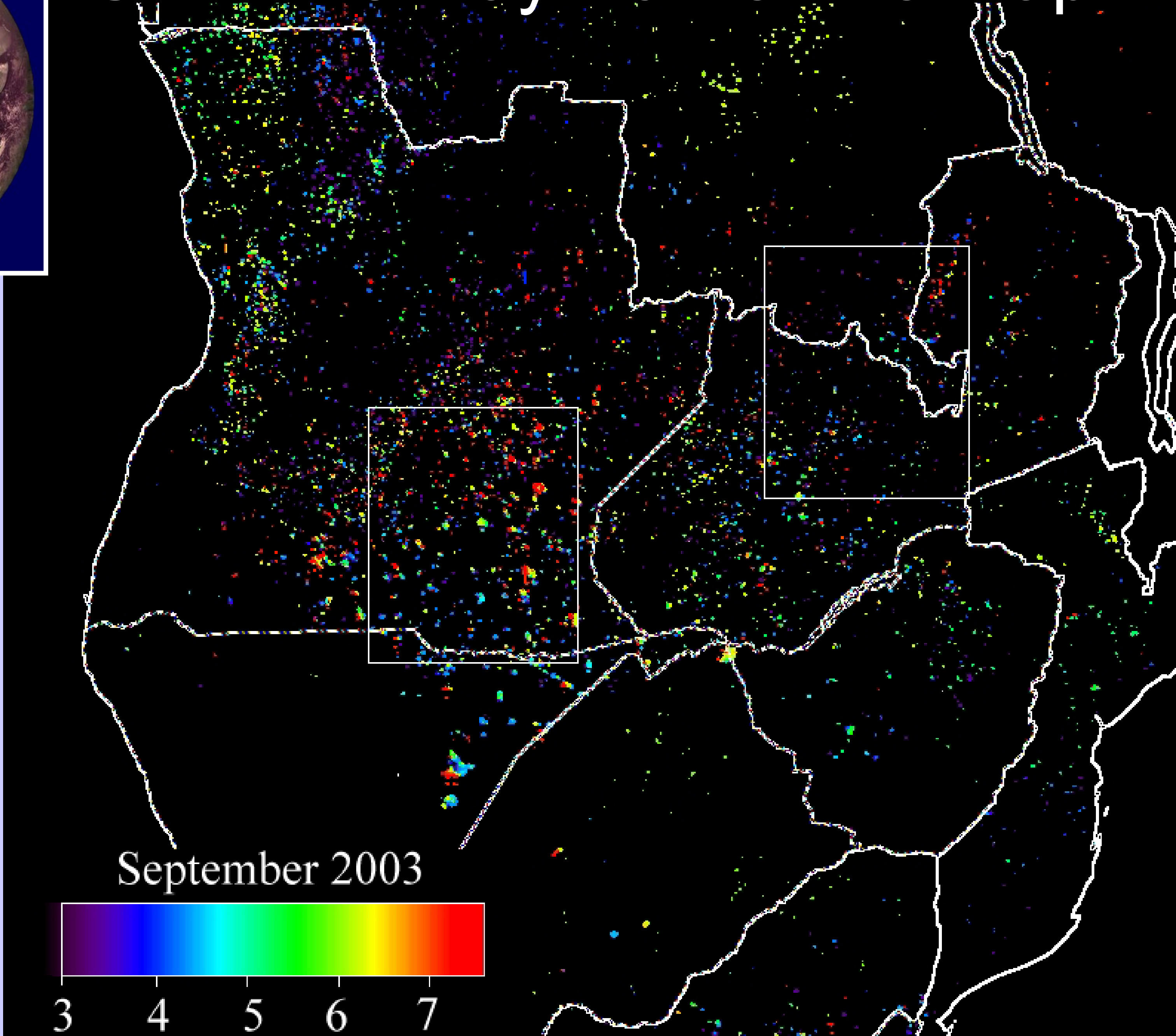


11-May-2003
Nfpix = 981
TFRP= 79 GW

SEVIRI 5-Day Active Fire Map

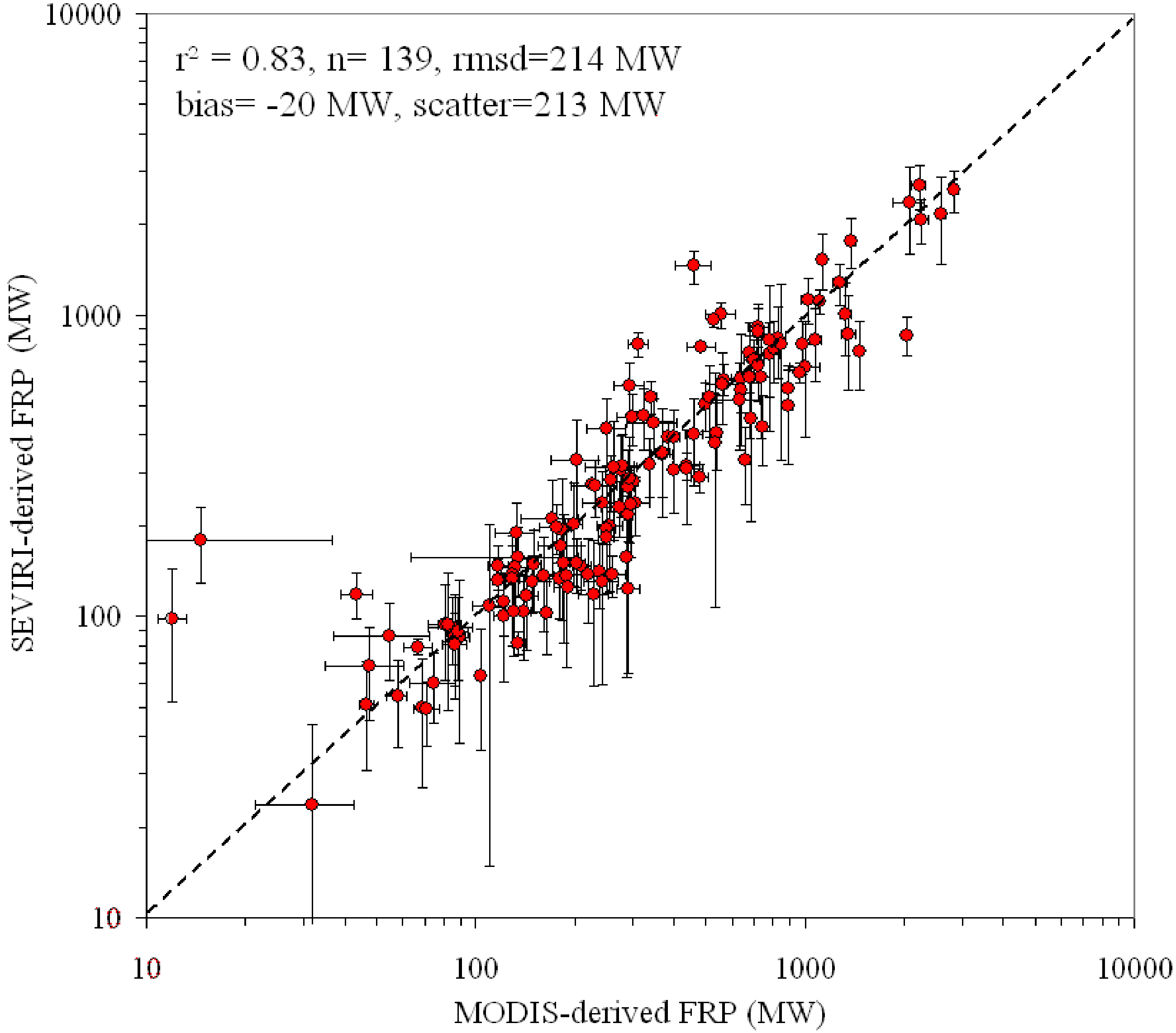


15 mins frequency



Wooster and Roberts, 2005

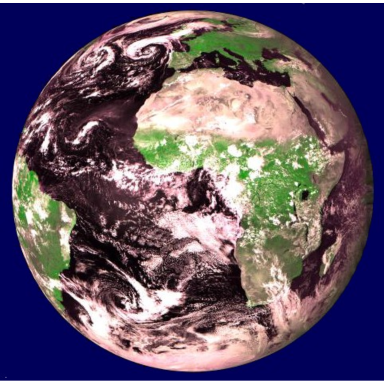
SEVIRI vs. MODIS FRP Comparison



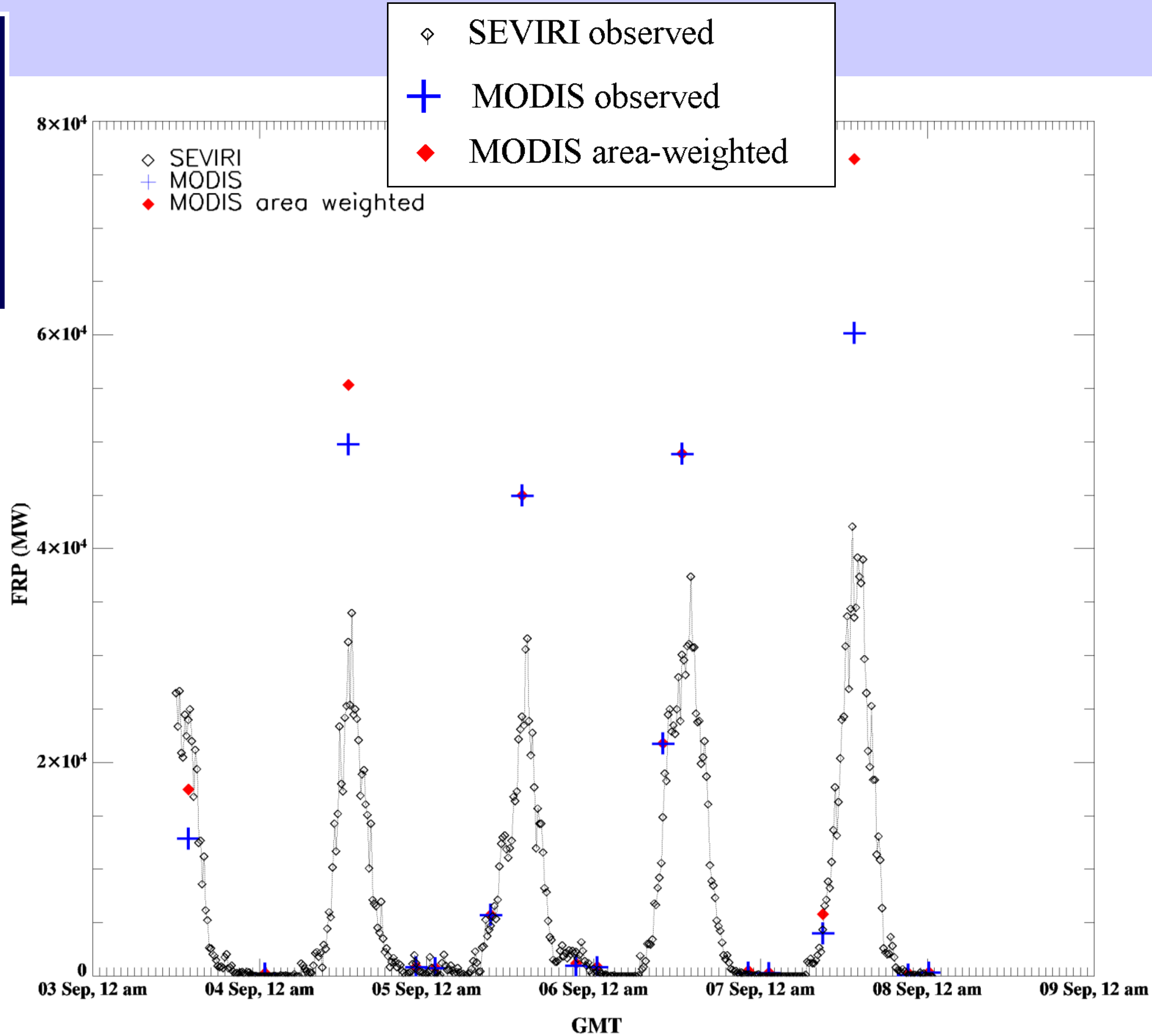
Wooster and Roberts, 2005

Per fire <u>NOT</u> per pixel (due to differences in SEVIRI/MODIS pixel size)

SEVIRI vs. MODIS FRP Time-series

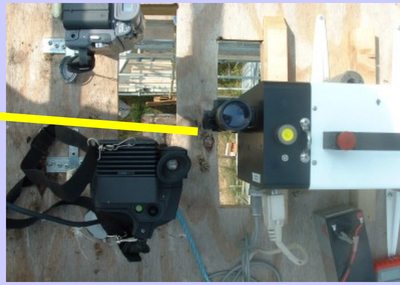


15 mins frequency

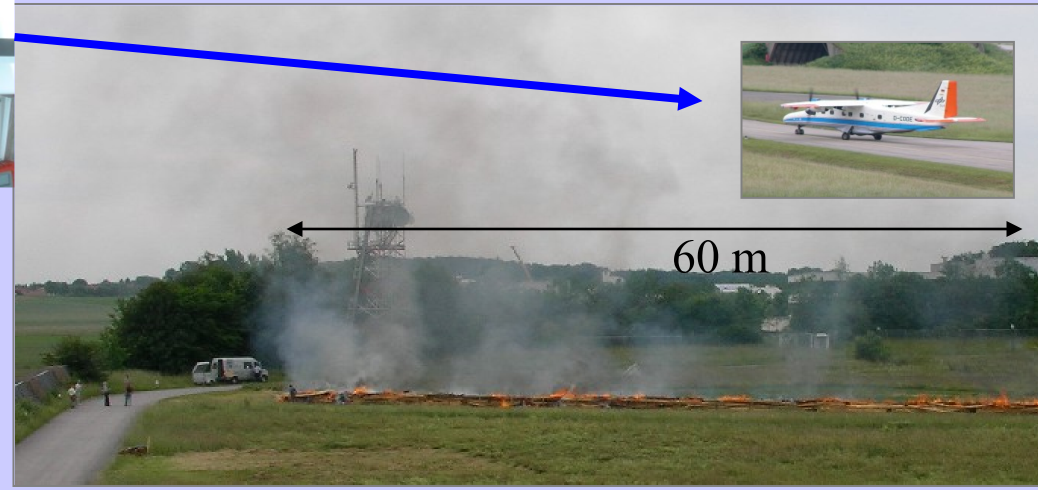


Wooster and Roberts, 2005

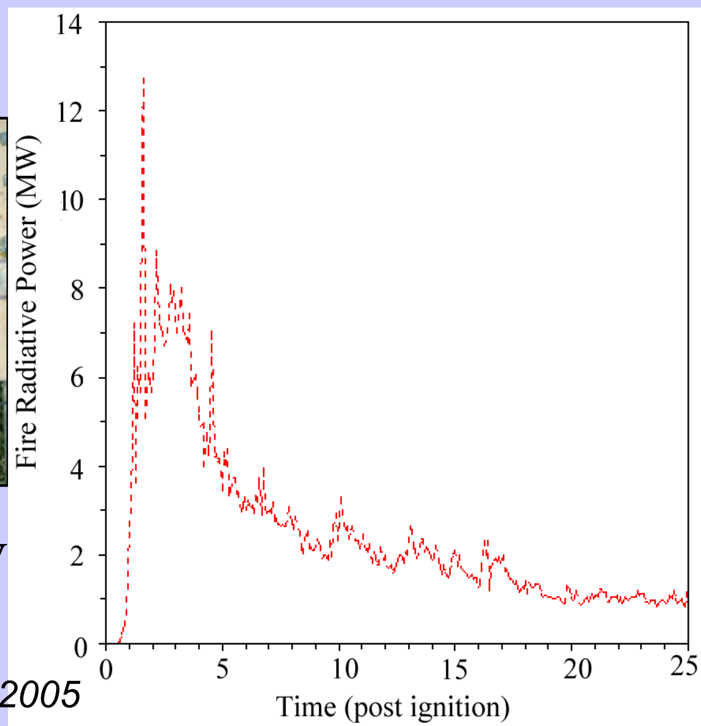
Fire Radiative Energy and Burned Biomass

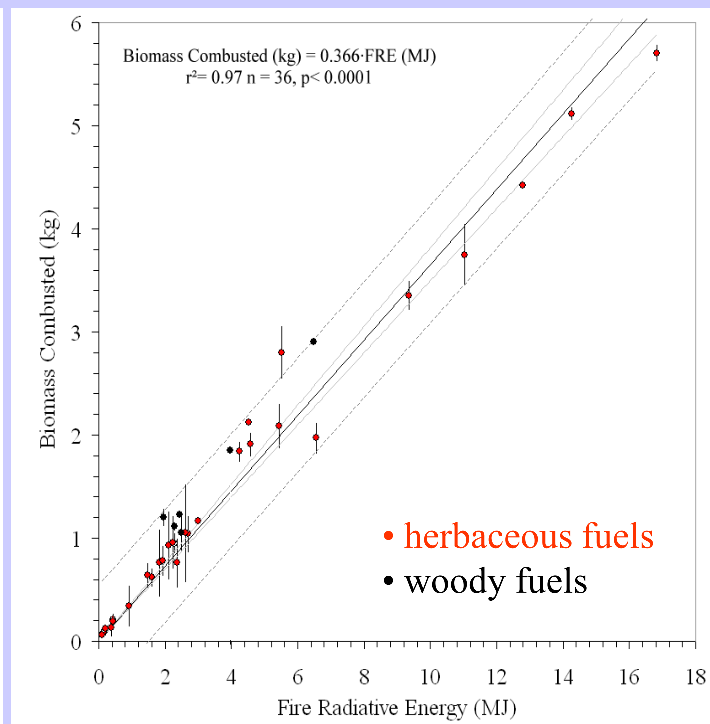


Spectro-
Radiometer
or IR Camera



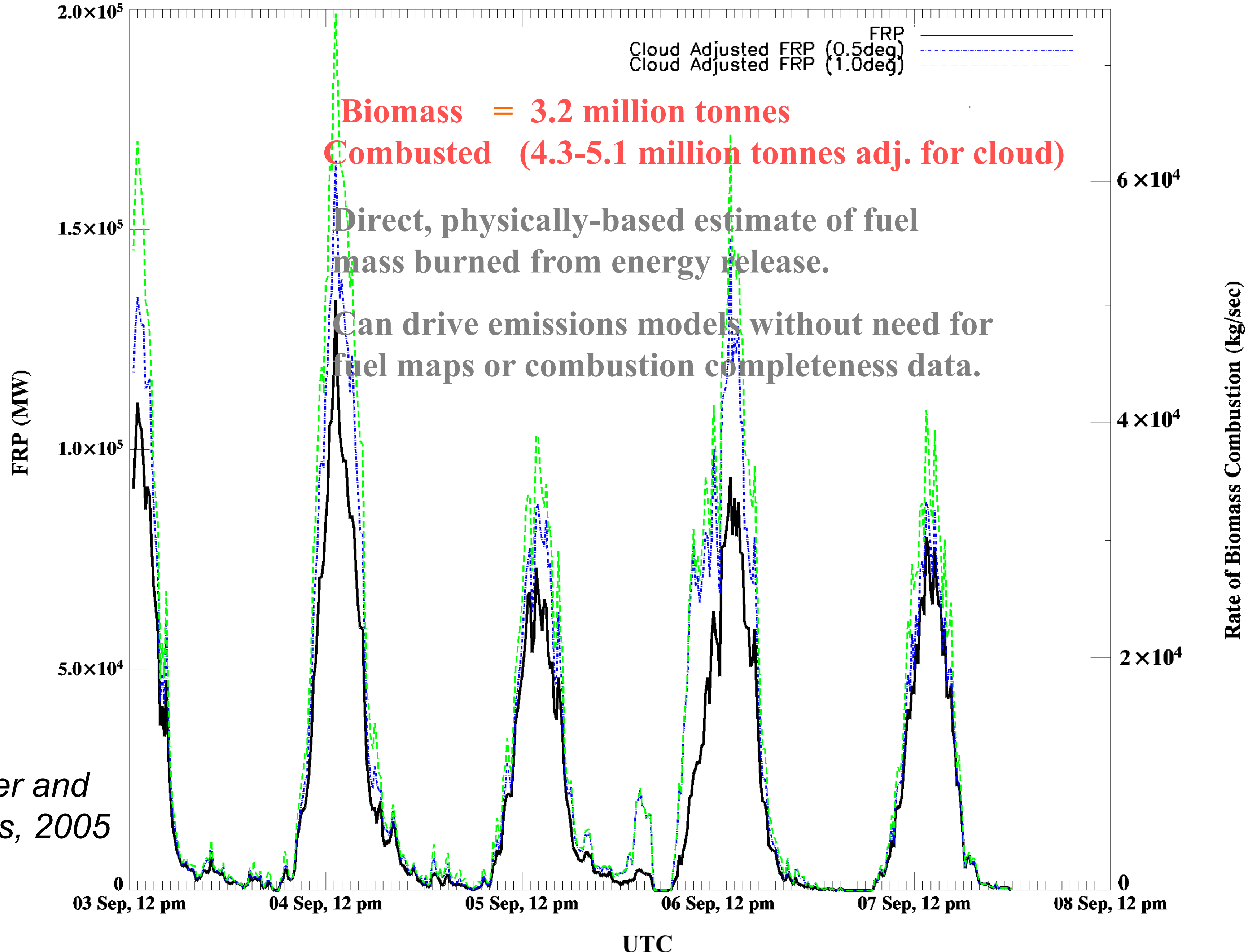
Spectro-radiometer FOV





Wooster, 2002, 2003, 2004, 2005

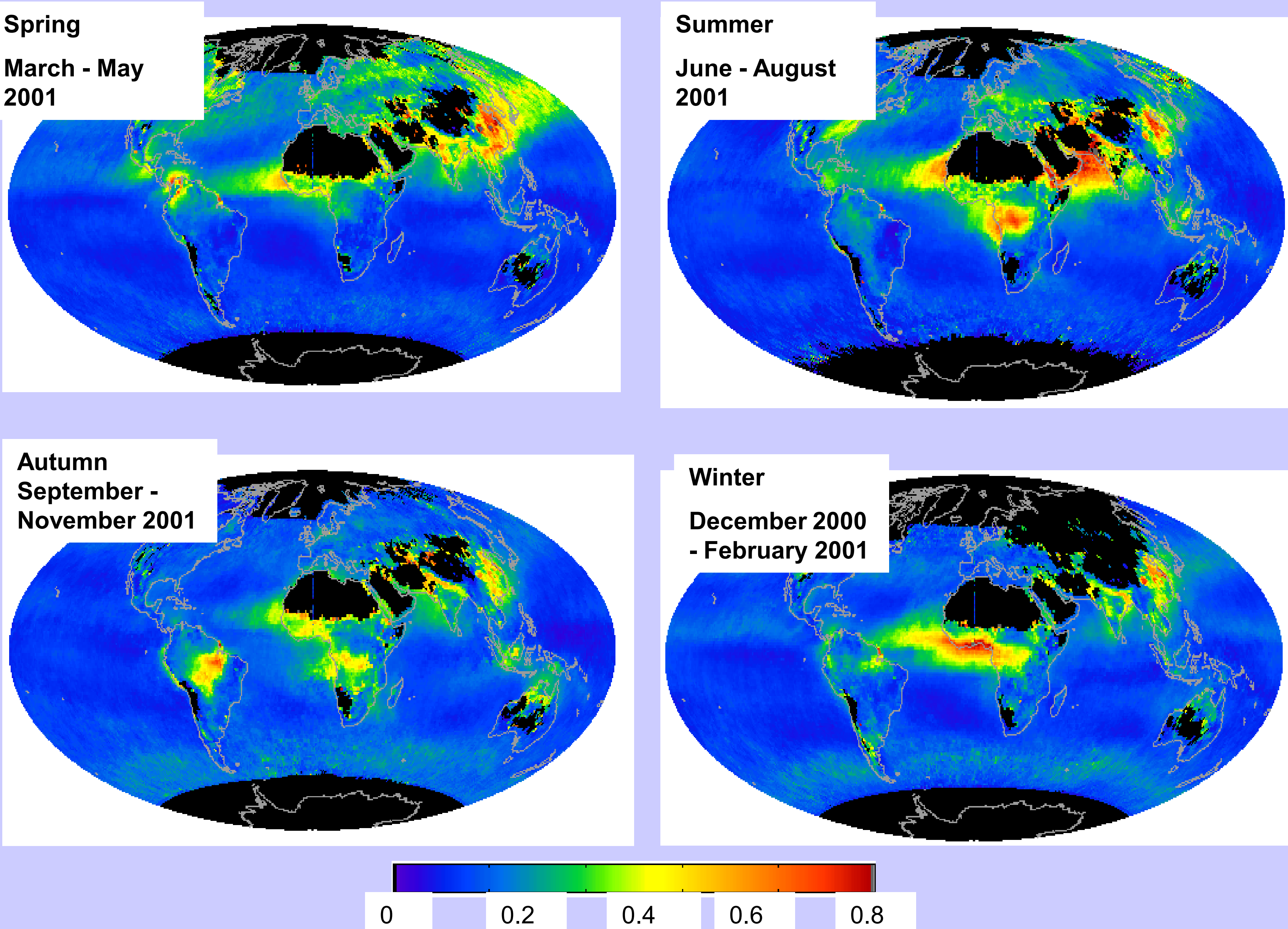
SEVIRI FRP Southern Africa, 3-8 September 2003



Wooster and Roberts, 2005

Now about Smoke

MODIS Level 3 Global Monthly Product : AOT at 550 nm wavelength



Average optical thickness

Kaufman, 2003

How can we separate Dust and Smoke ?

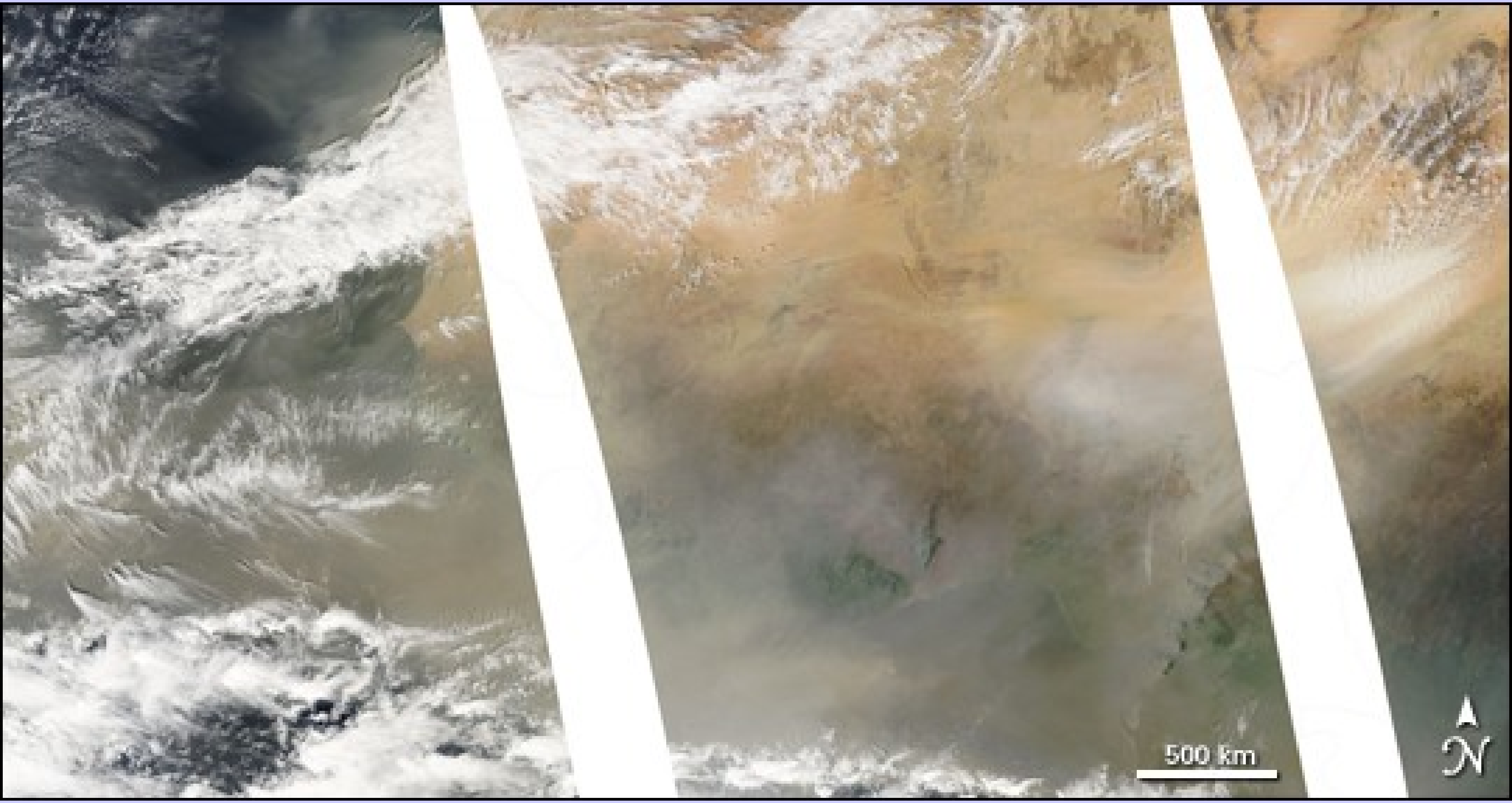
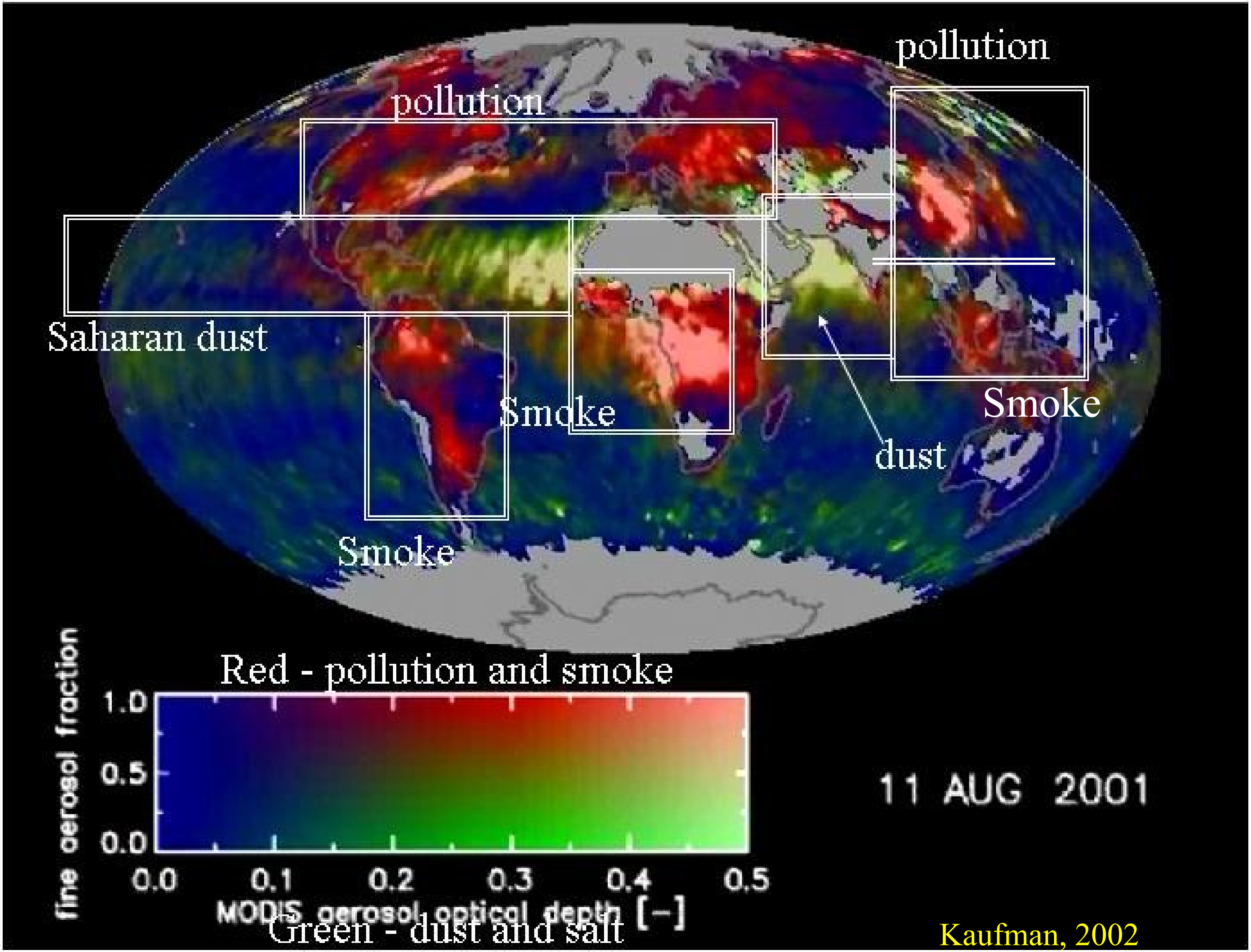


Image: Aqua-MODIS true color RGB of 09-Jan-2005 (courtesy: NASA EarthObservatory and MODIS Rapid Response Teams)


pollution
pollution
Saharan dust
Smoke
Smoke
dust
Smoke
Red - pollution and smoke
fine aerosol fraction
1.0
0.5
0.0
0.0
0.1
0.2
0.3
0.4
0.5
MODIS aerosol optical depth [-]
Green - dust and salt
11 AUG 2001
Kaufman, 2002

Deriving Smoke Emissions Quantitatively

Traditional Emissions Estimation Approach

Emissions = Emission Factor (EF) × Burned Biomass (BM)

$BM = A \times B \times \alpha \times \beta$

Where: **A=Area burned,** **B=Biomass density,** **α=Above ground biomass proportion,** **β=Combustion Efficiency**

Picture taken from Baldocchi presentation on “Oak Savanna and Grazed Grassland

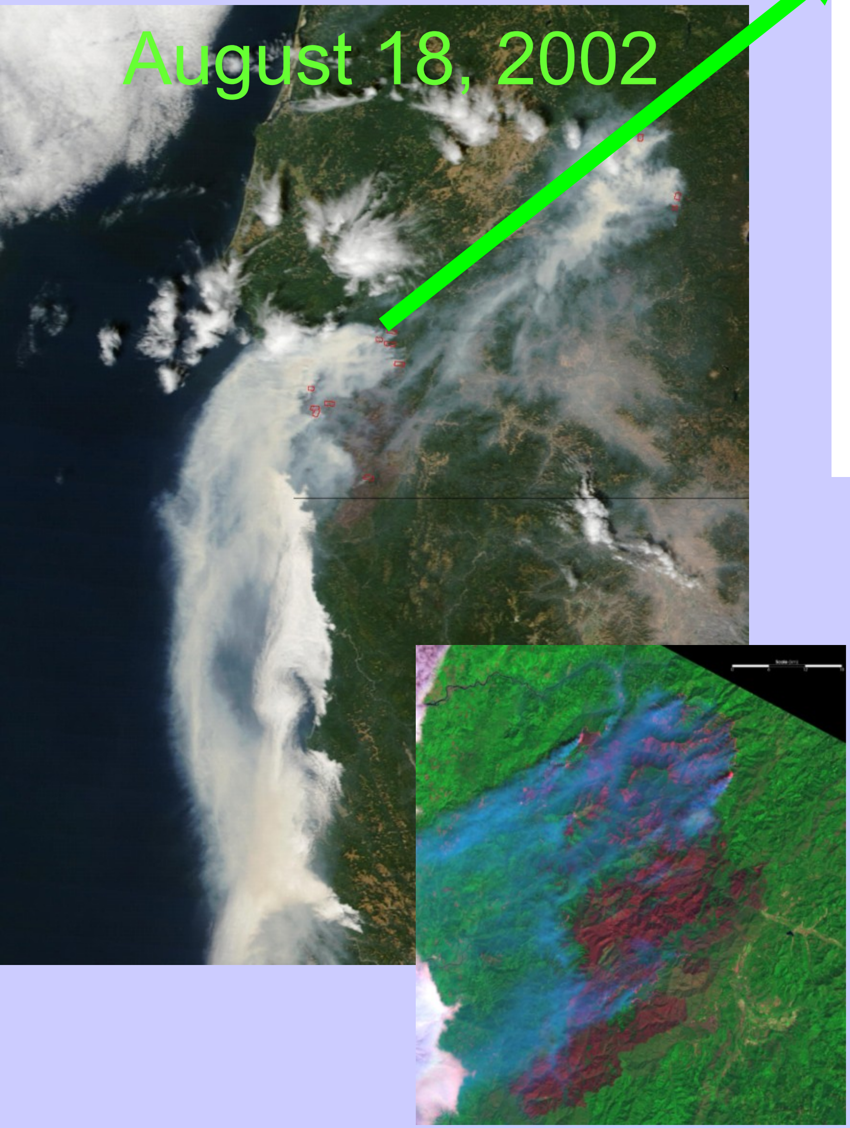
FRE-based smoke emissions estimation approach

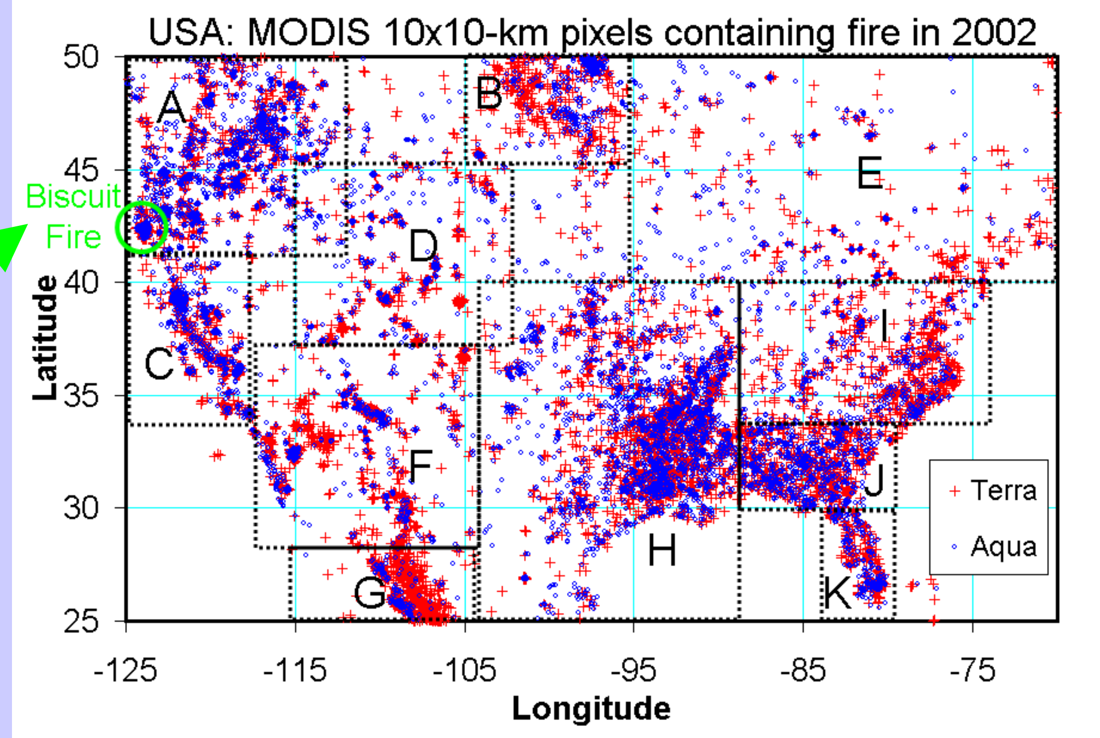
(1)Emissions = EF × BM (from FRE) *[Wooster]*

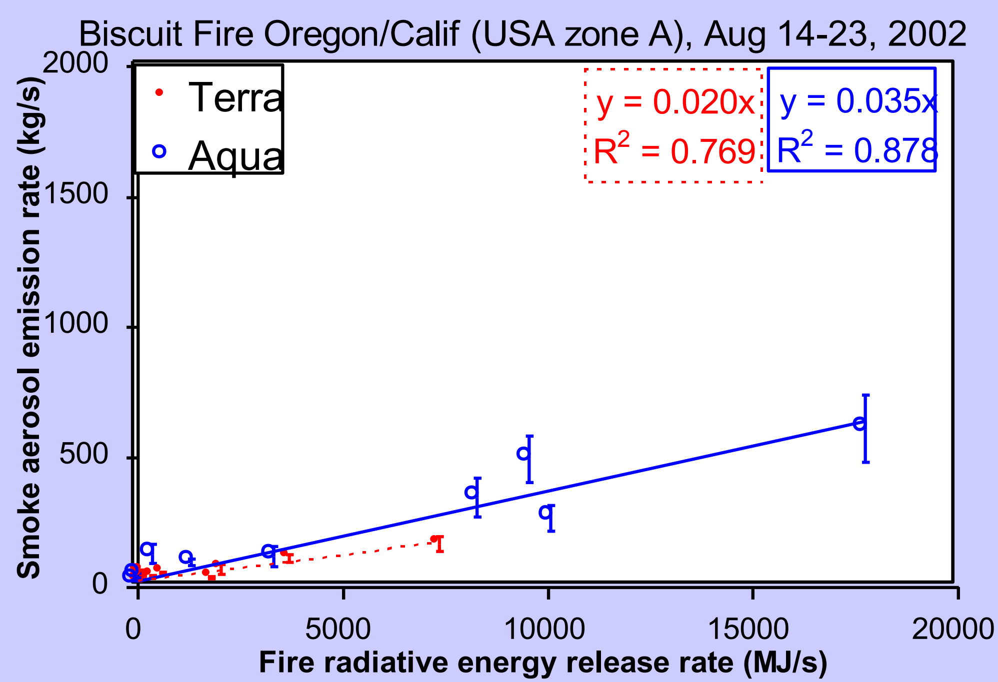
(2)Emissions = Emission Coeff. (Ce) × (FRP or FRE) *[Ichoku]*

MODIS Fire Emissions

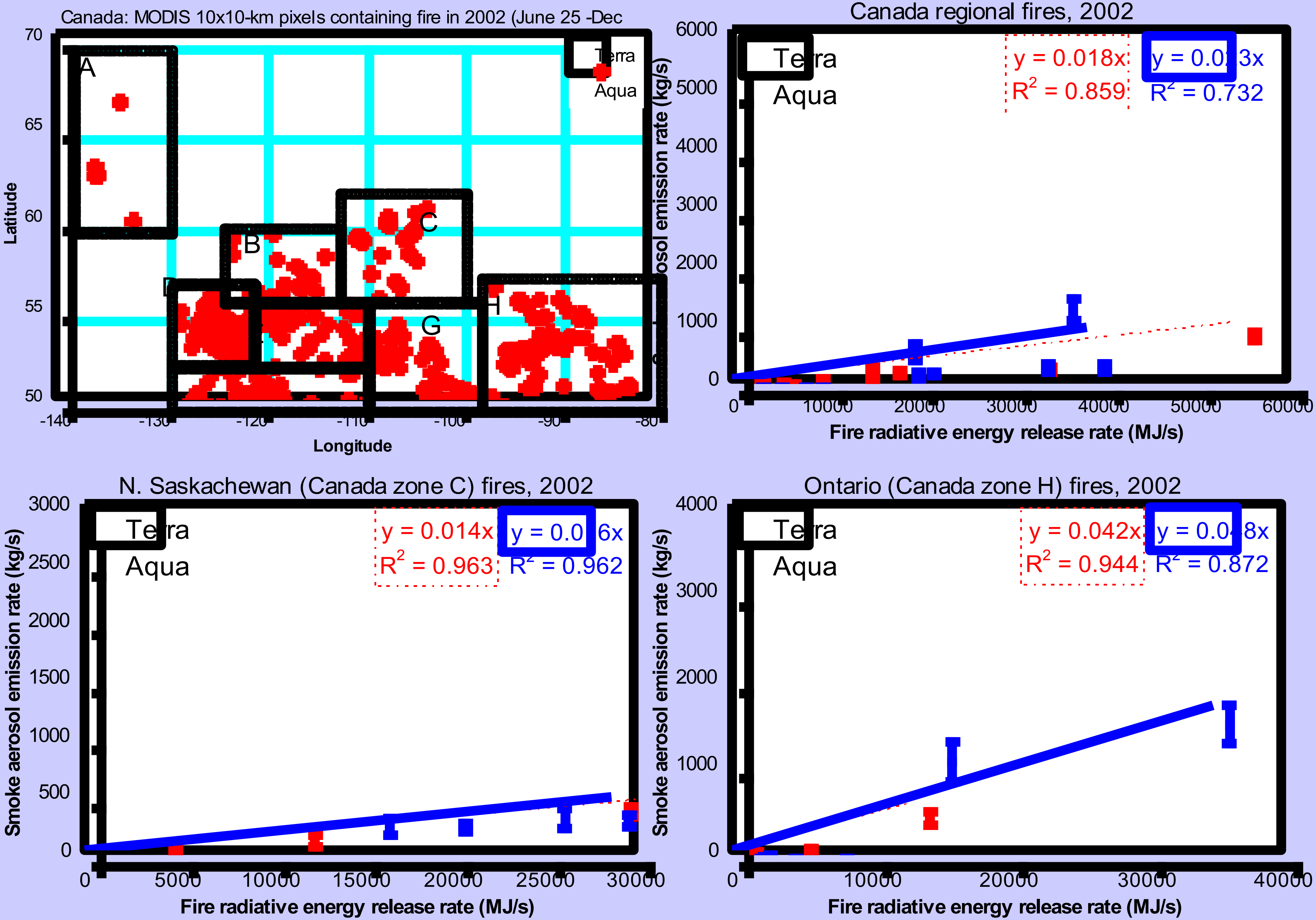
Biscuit Fire, Oregon, USA



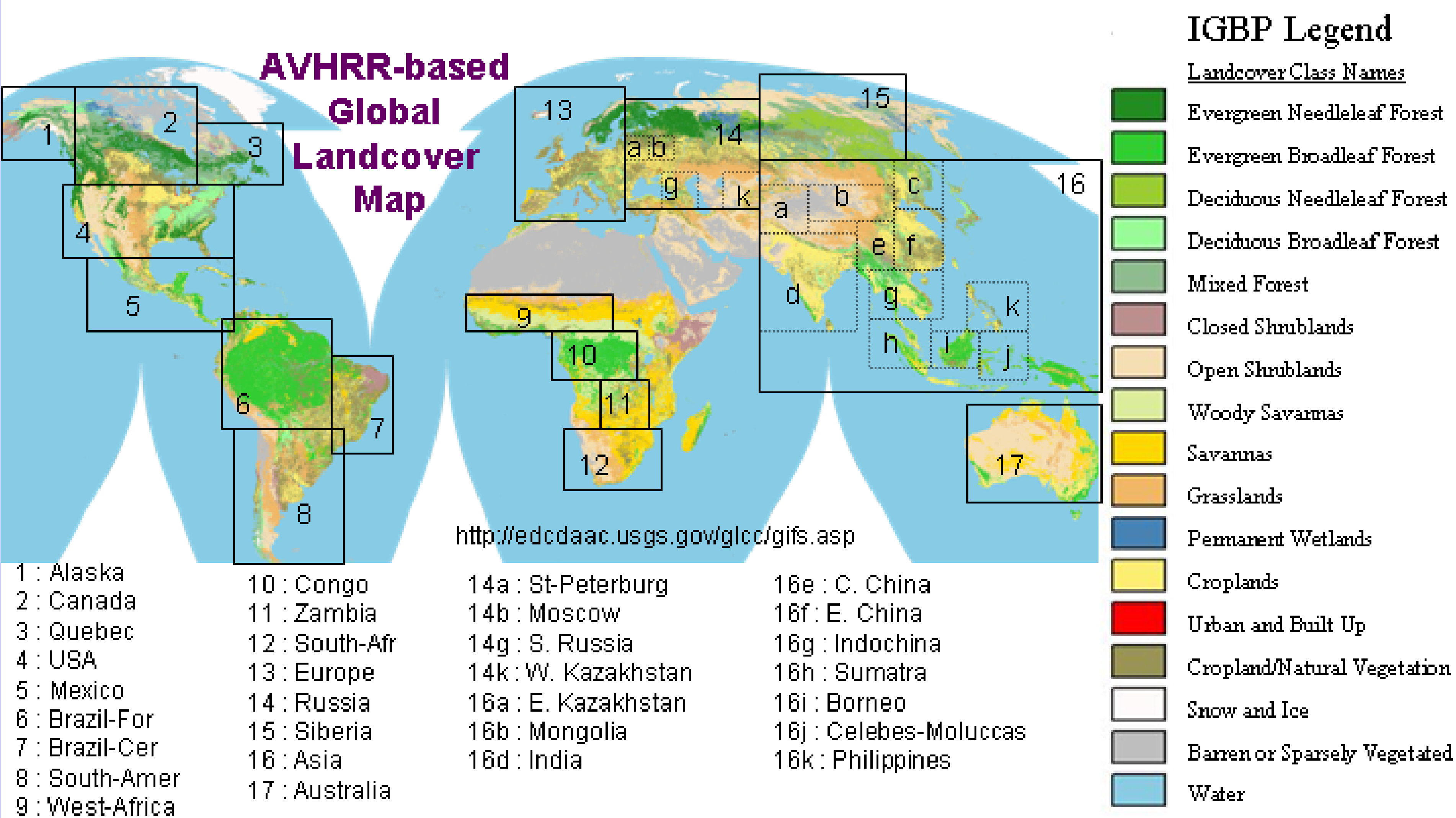




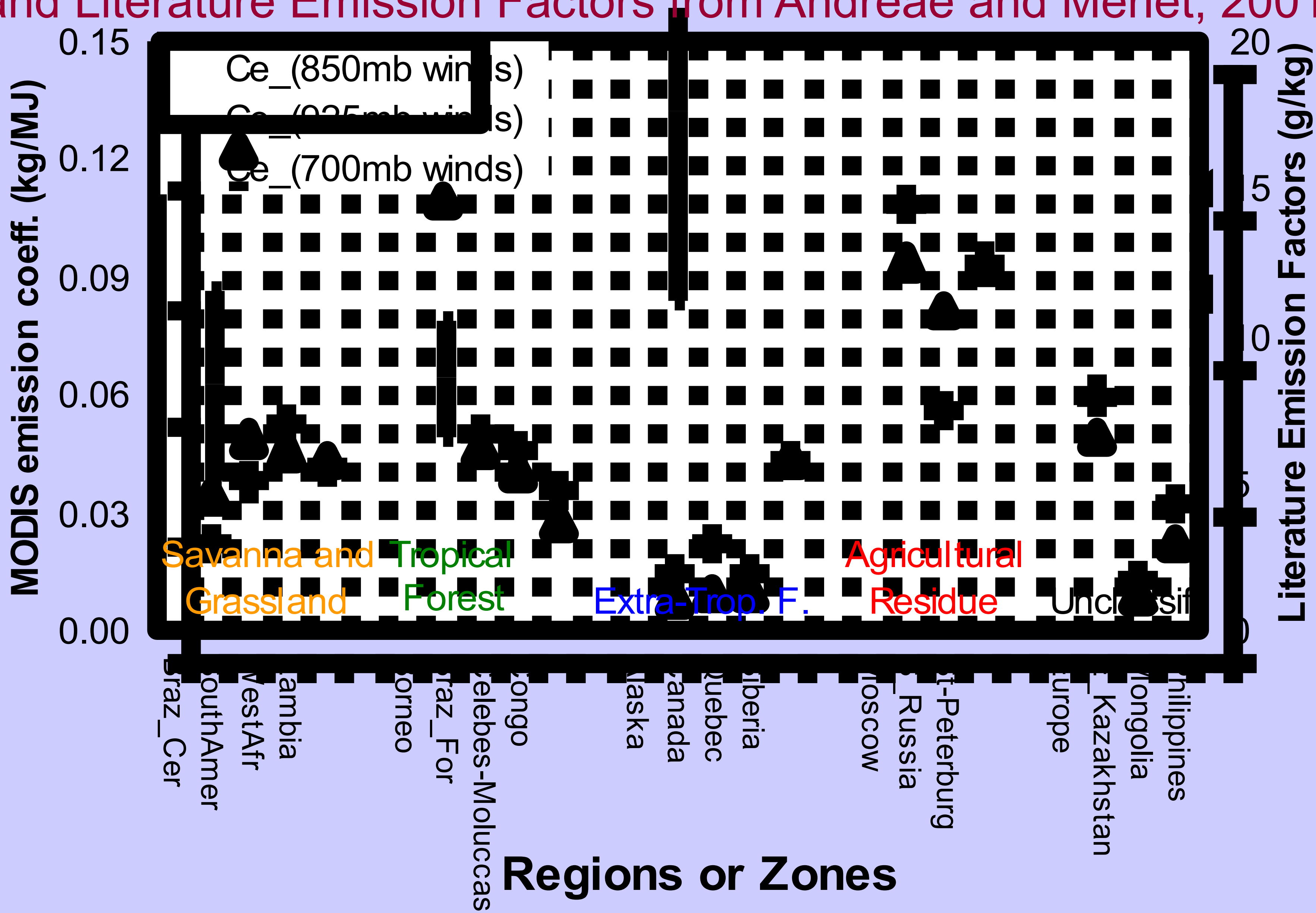
MODIS Fire Emissions: Canada



Regional study of smoke emission coefficients

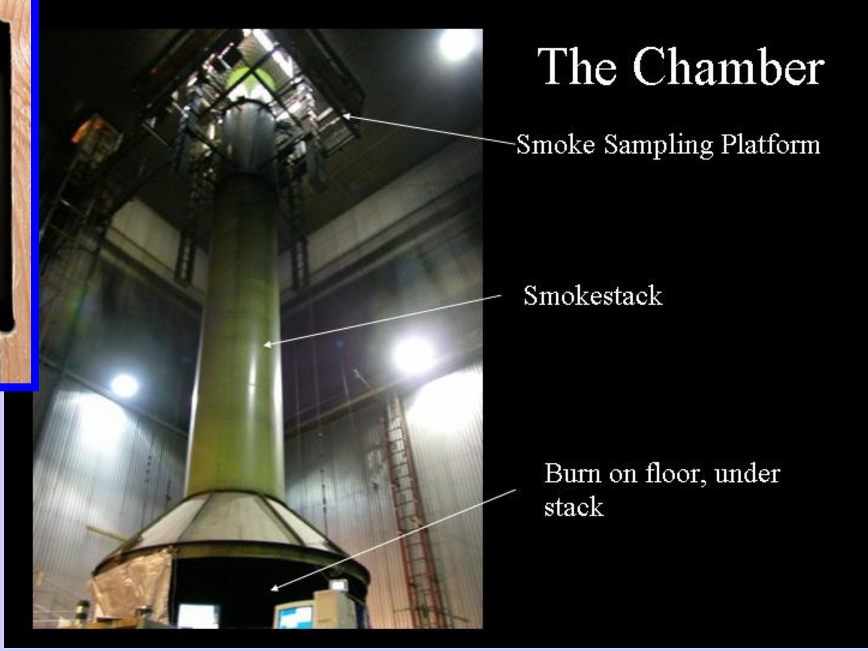


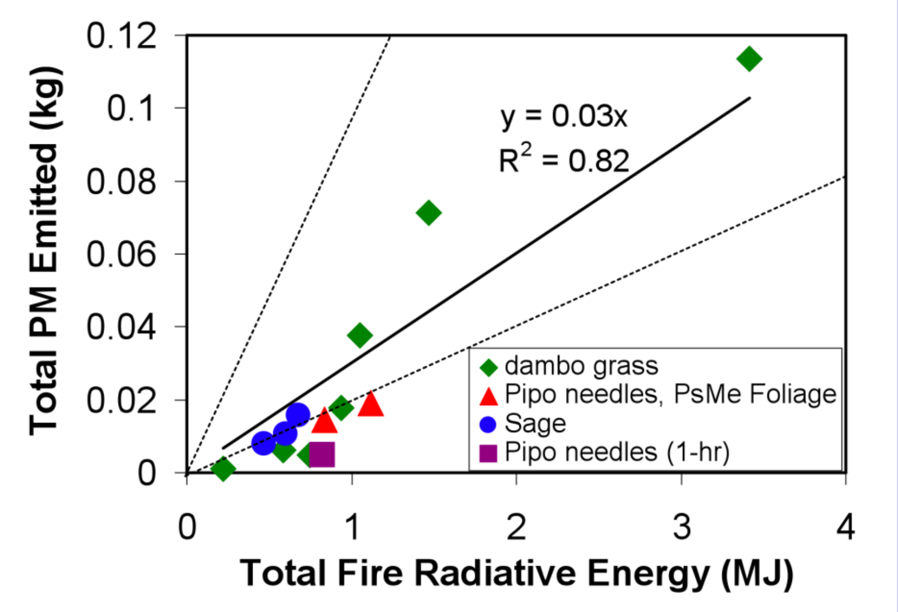
Qualitative Comparison of MODIS-derived Emission Coefficients and Literature Emission Factors from Andreae and Merlet, 2001

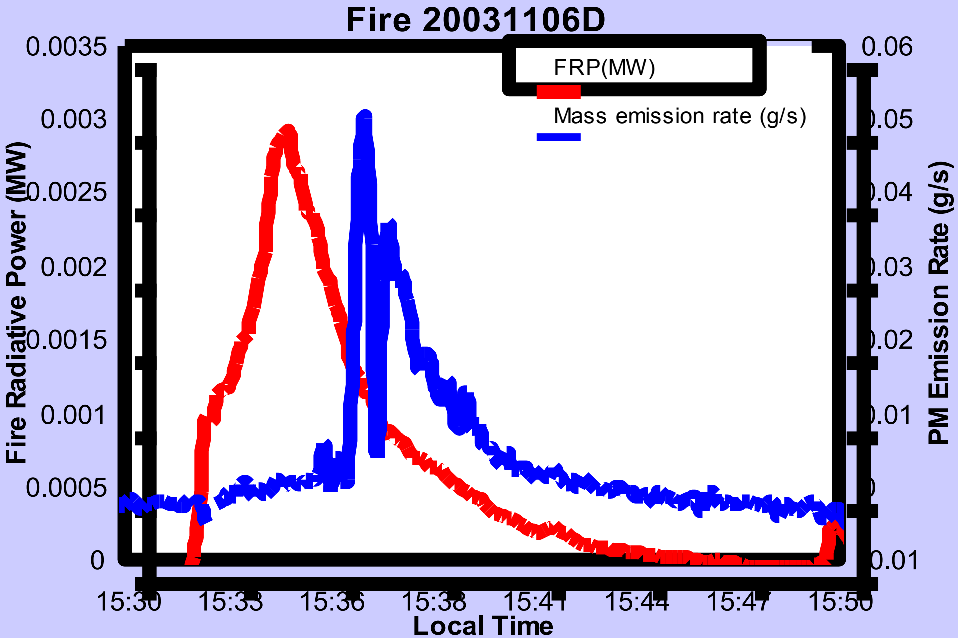


Ichoku and Kaufman, 2005, IEEE-TGARS; Jordan et al., 2008, AE

Laboratory measurement of Fire Radiative Energy and emissions during November 2003 controlled burns conducted inside the Burn Chamber of the Fire Sciences Laboratory, USFS, Missoula, Montana







Ichoku et al., 2008, JGR; Freeborn, et al., 2008, JGR

Toward Global Gridded FRE-Based Smoke Emission Coefficients

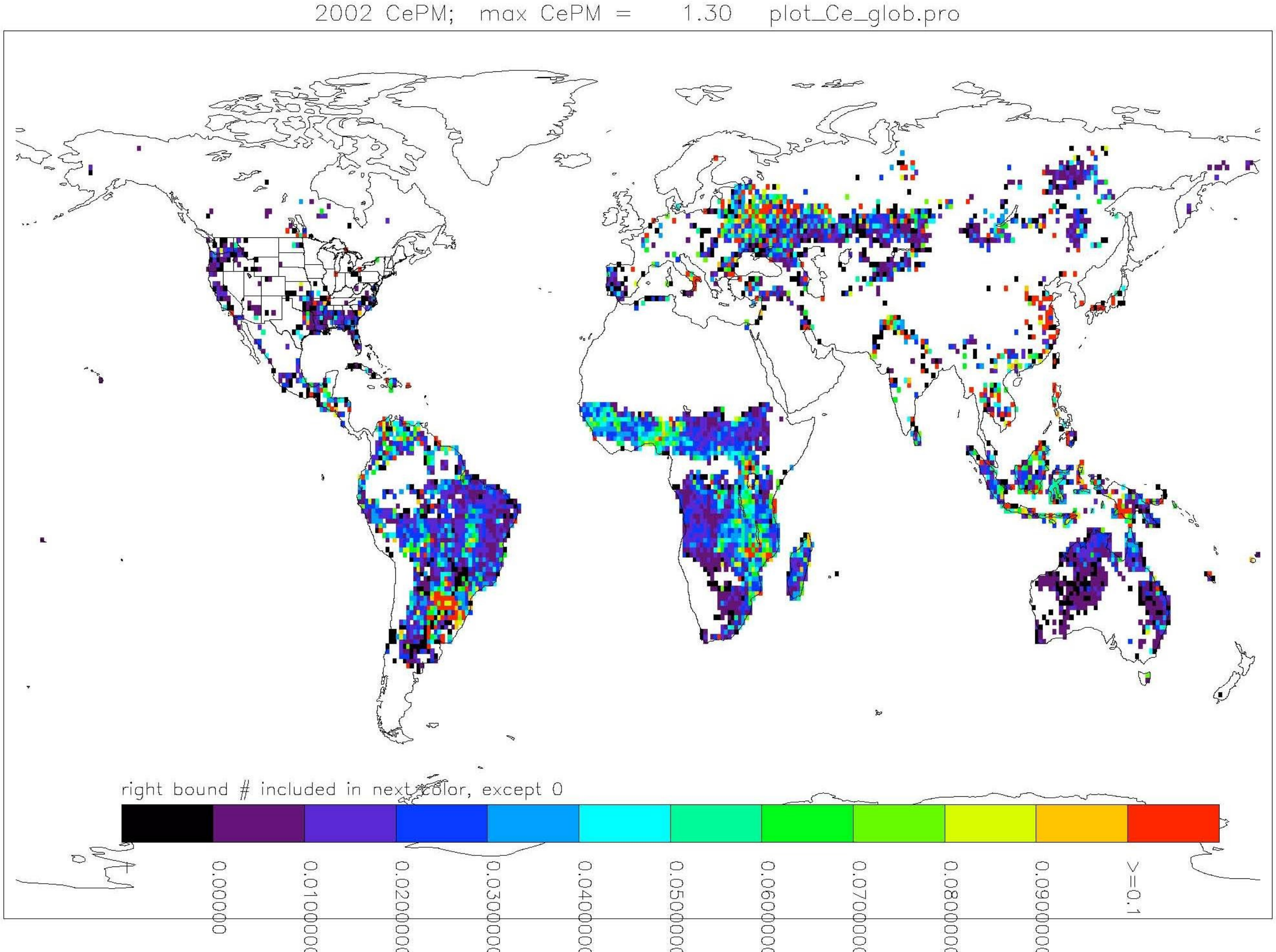
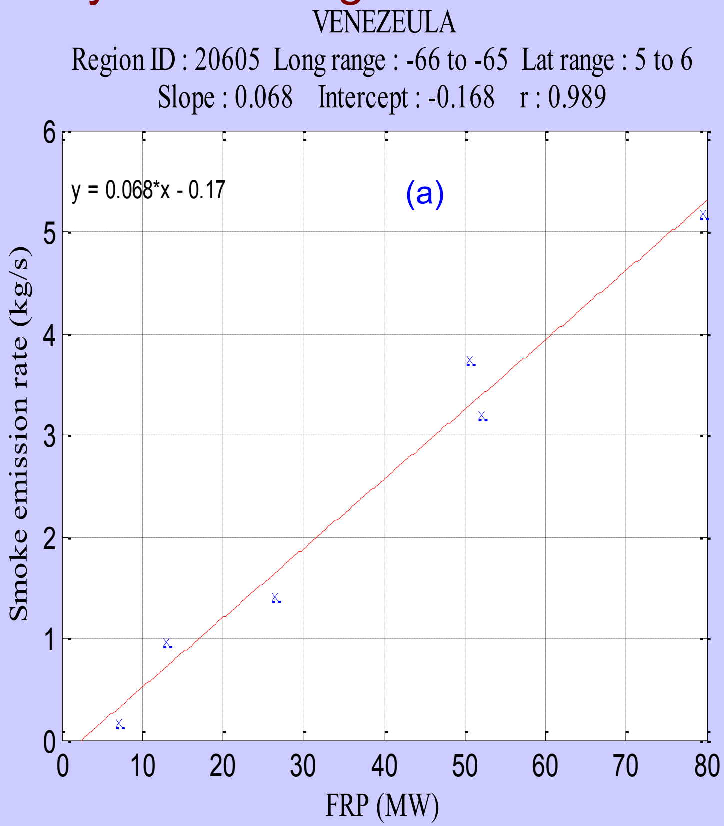


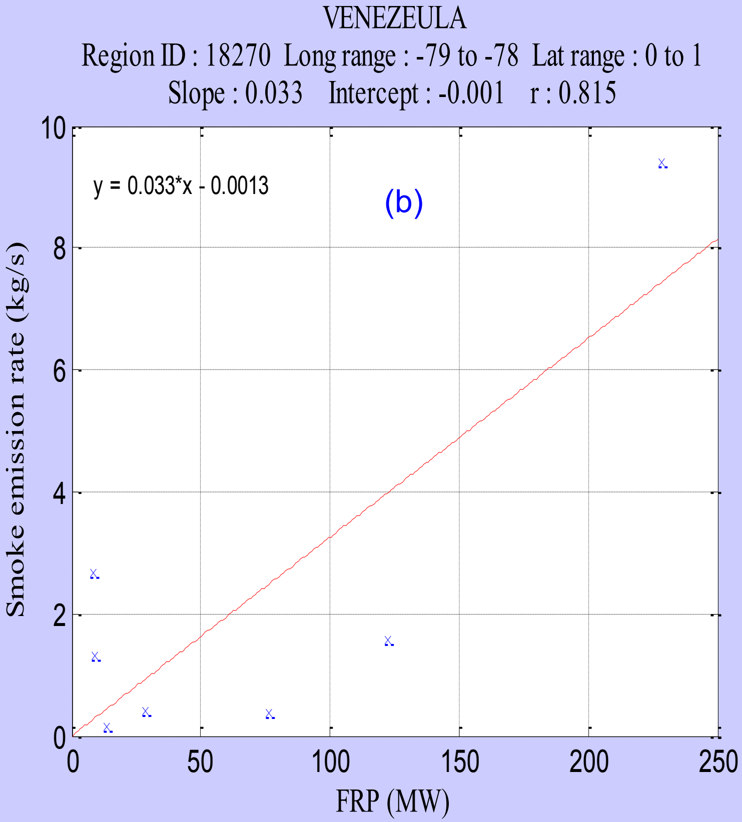
Image prepared by Mariya Petrenko, NASA GSSP, Purdue Univ. (Advisor: Mian Chin)

Challenges and Present Activities

- Detailed Error Analysis of FRP/PM Correlation.
- FRP Diurnal Cycle Analysis.
- Detailed Evaluation of satellite FRP measurement.

Error analysis on fitting smoke emission rates against FRP at 1-deg grid resolution





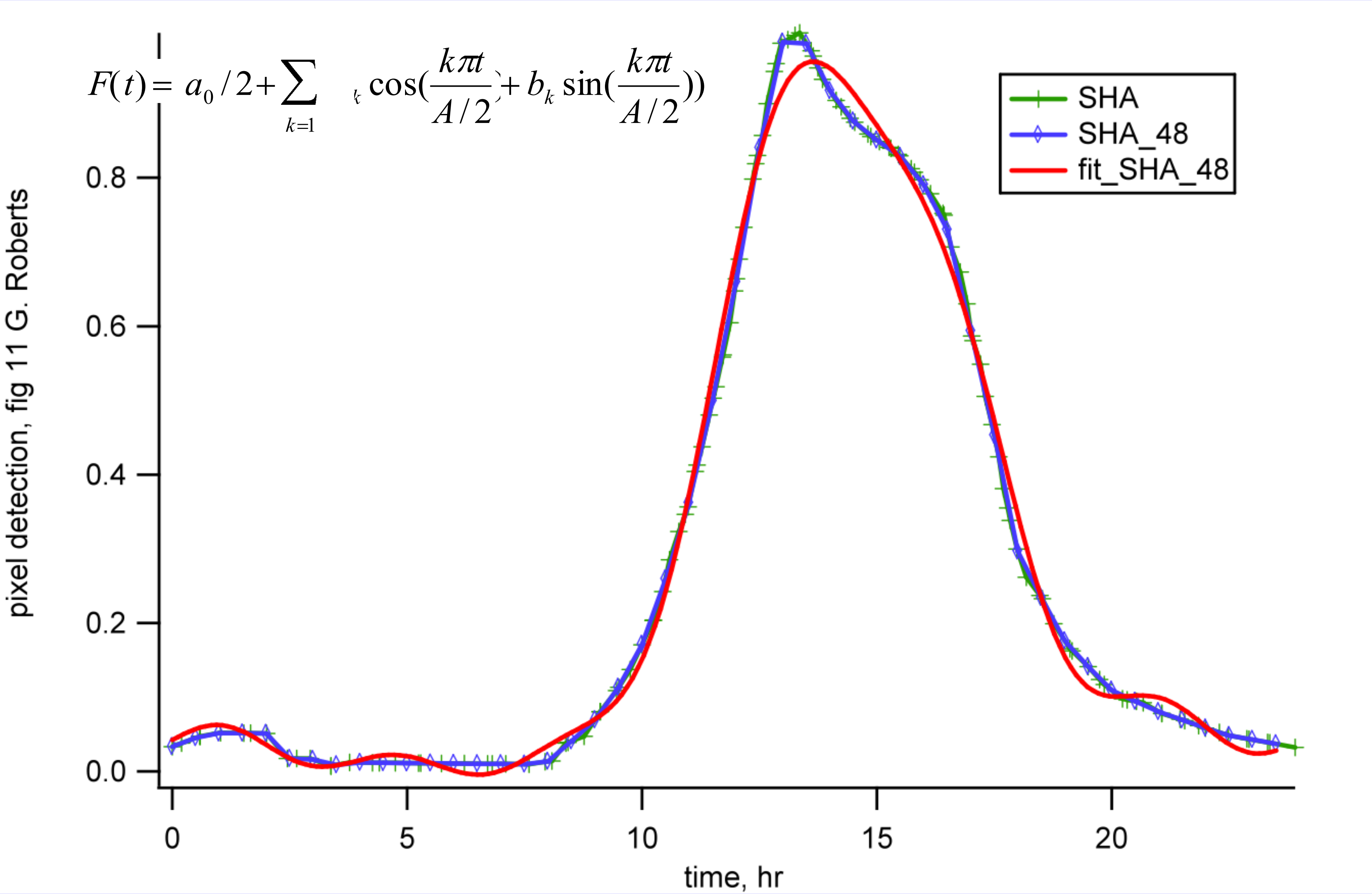
Examples of point scatter patterns: a) desired and b) misleading

- Parameters considered for the analysis

Static parameters	**Non-static parameters**
ecosystem type	Angstrom exponent
elevation	***cloud fraction over land***
land/water	horizontal and vertical wind speeds
slope	temperature
aspect	relative humidity
	aerosol optical thickness
	scan angle

Thishan Darshana, 2009 summer

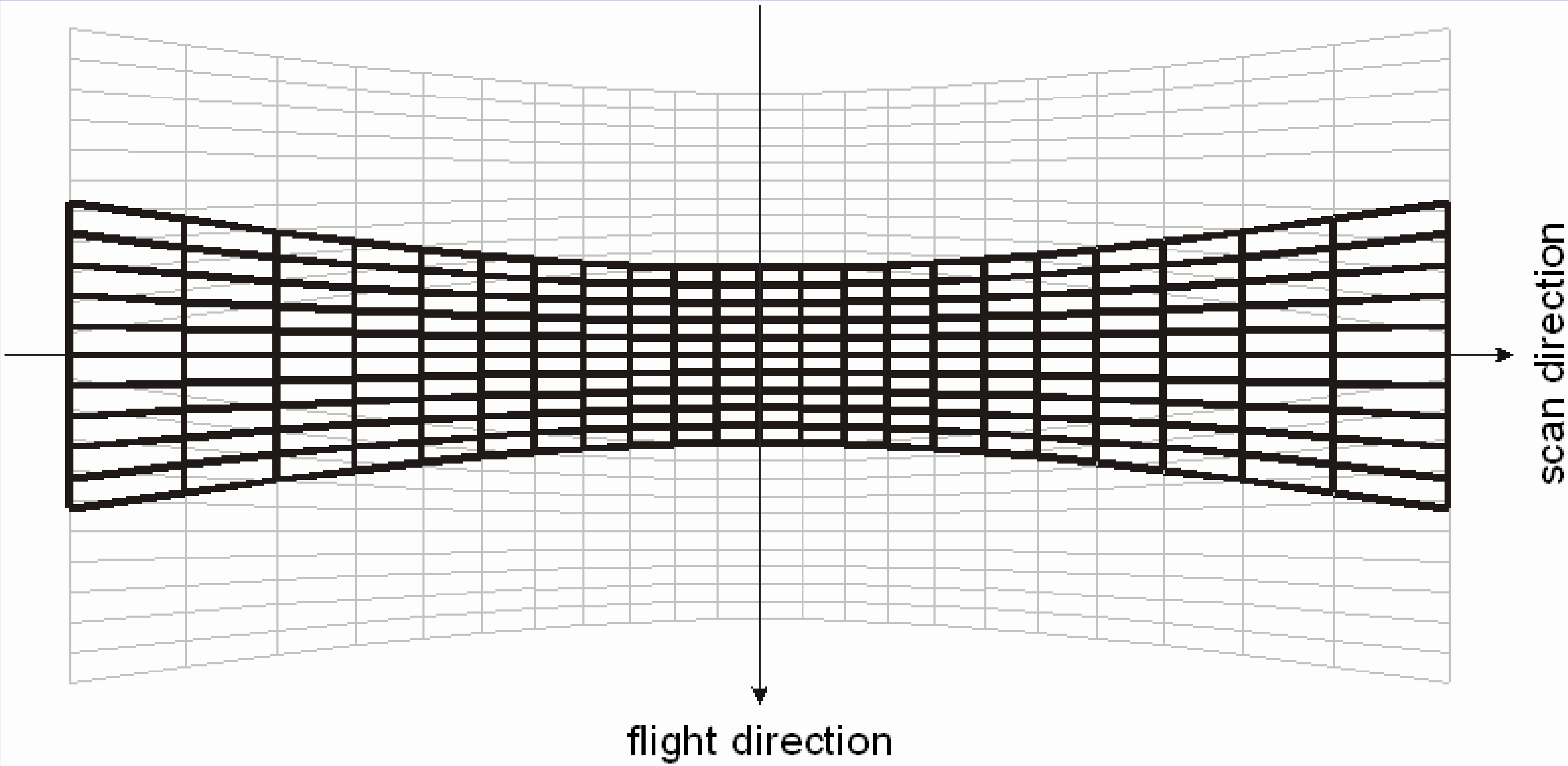
FRP Diurnal Cycle Curve Fitting for Modeling



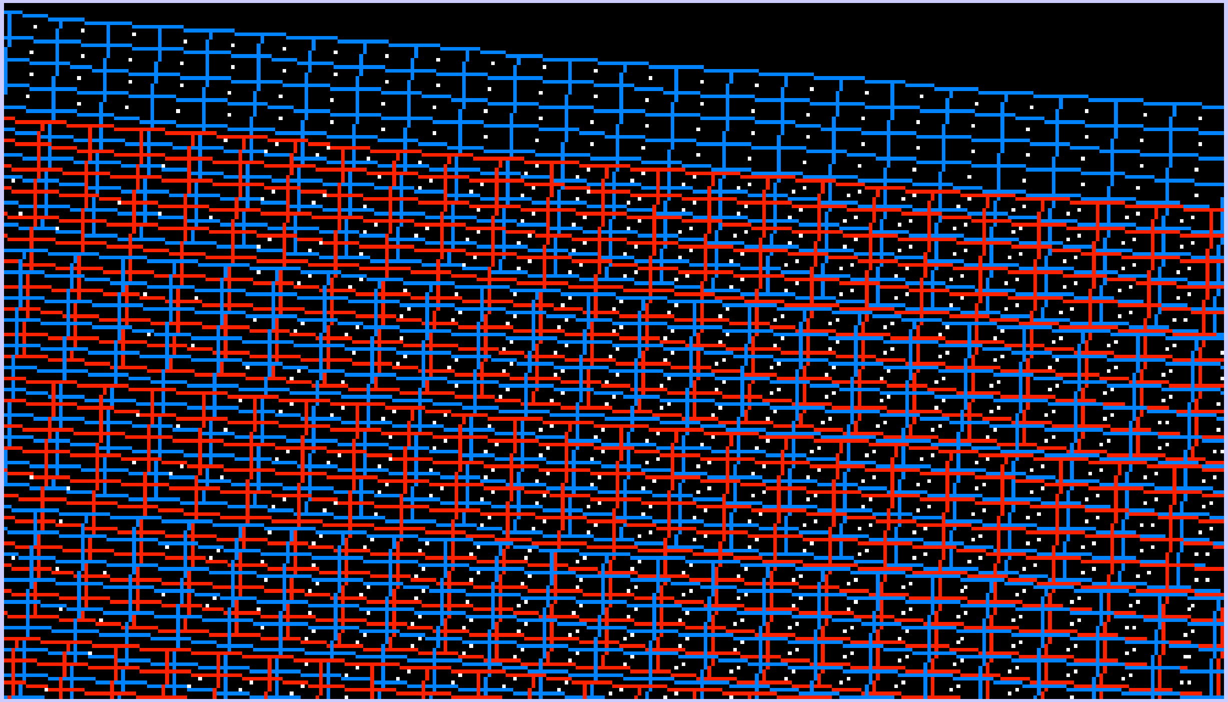
Curve digitizing and fitting by Mariya Petrenko, based on Roberts et al., 2008, ACPD

Detailed Evaluation of MODIS FRP

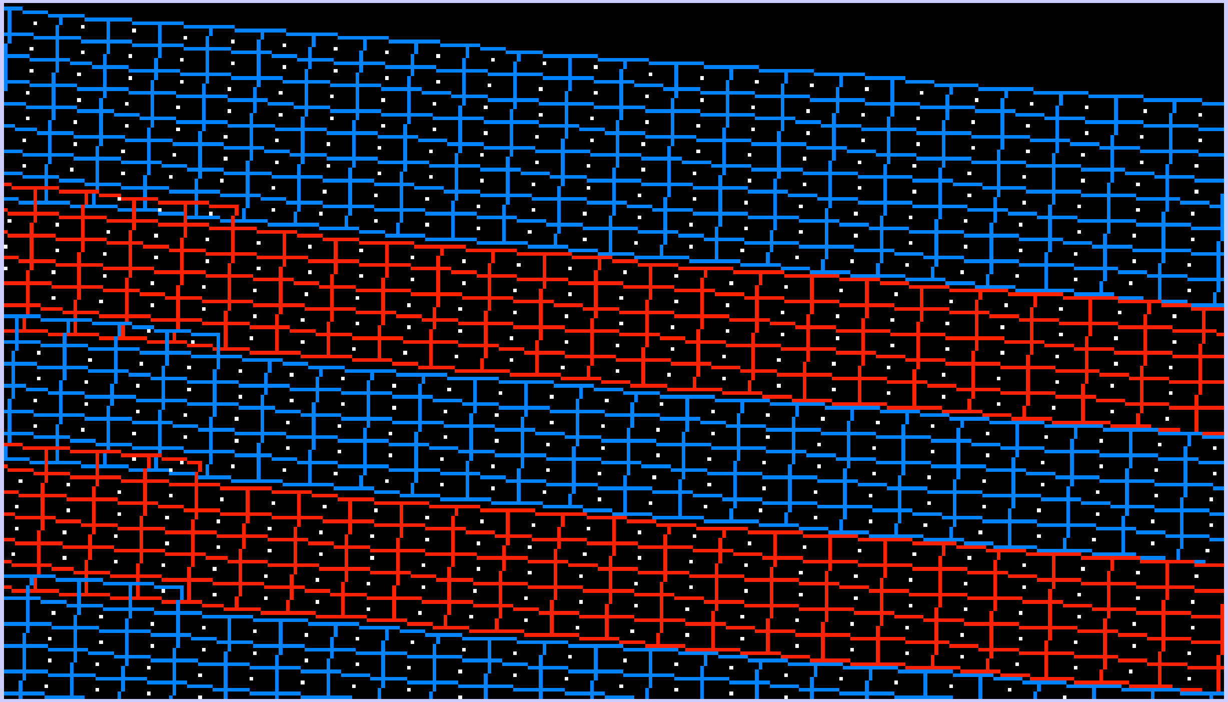
MODIS Bow-tie Effect and Fire Measurement

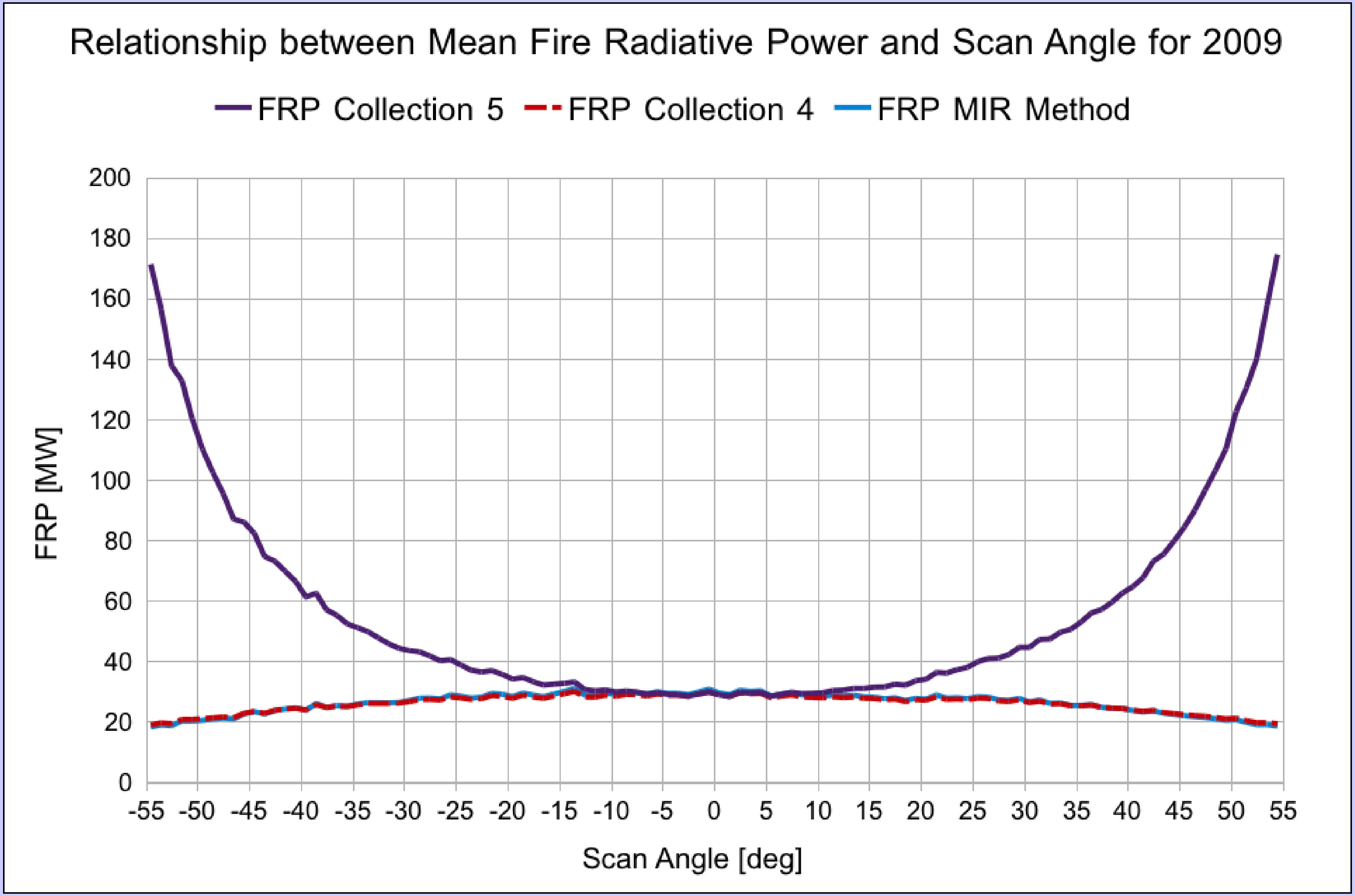


Part of a MODIS granule showing pixel overlap from scan-to-scan (scans are colored in alternating blue and red) at larger scan angles.

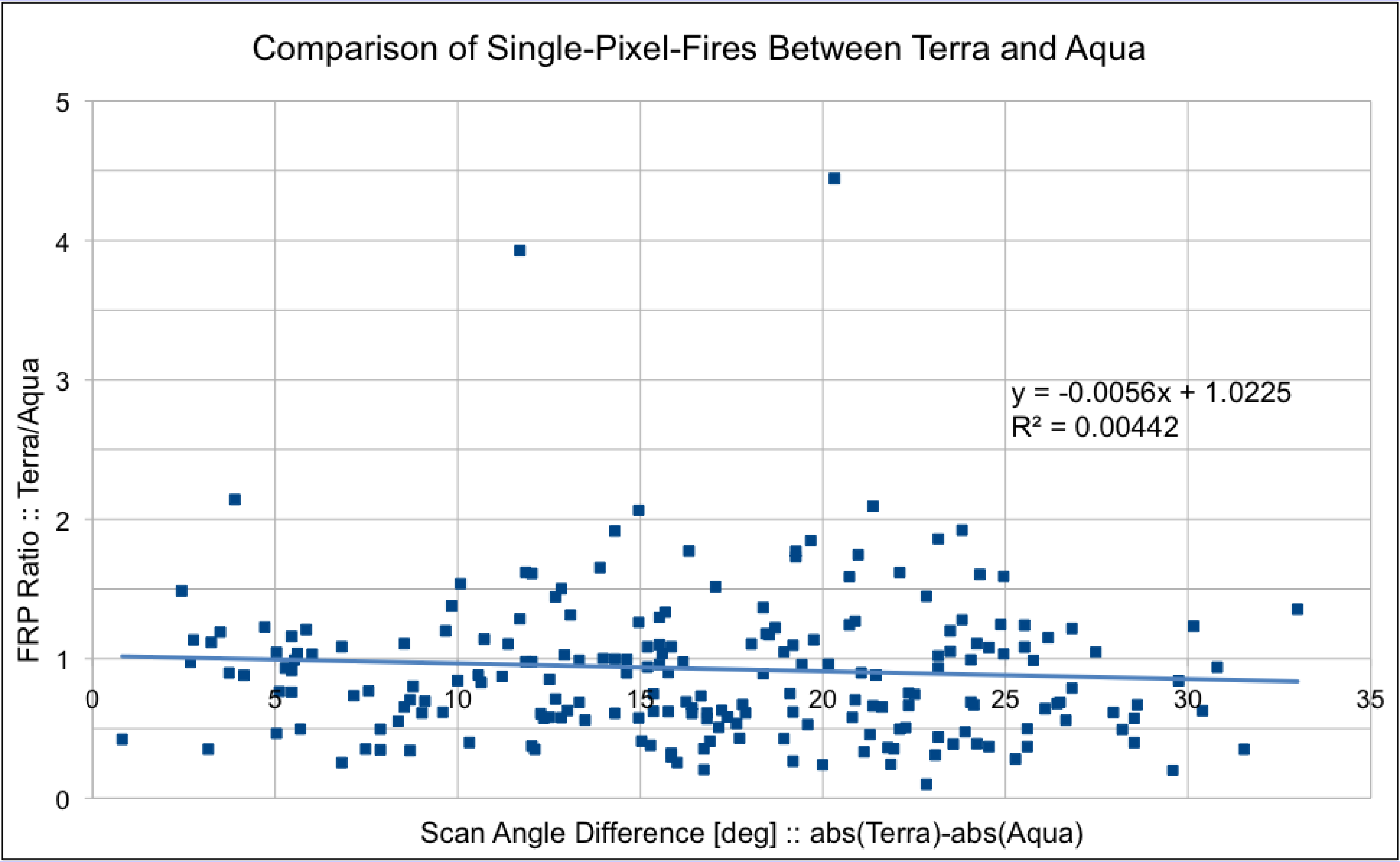


The same section of the same MODIS granule after the algorithm is applied eliminating those pixels in subsequent scans that overlap any pixels in the previous scan by more than 50%.

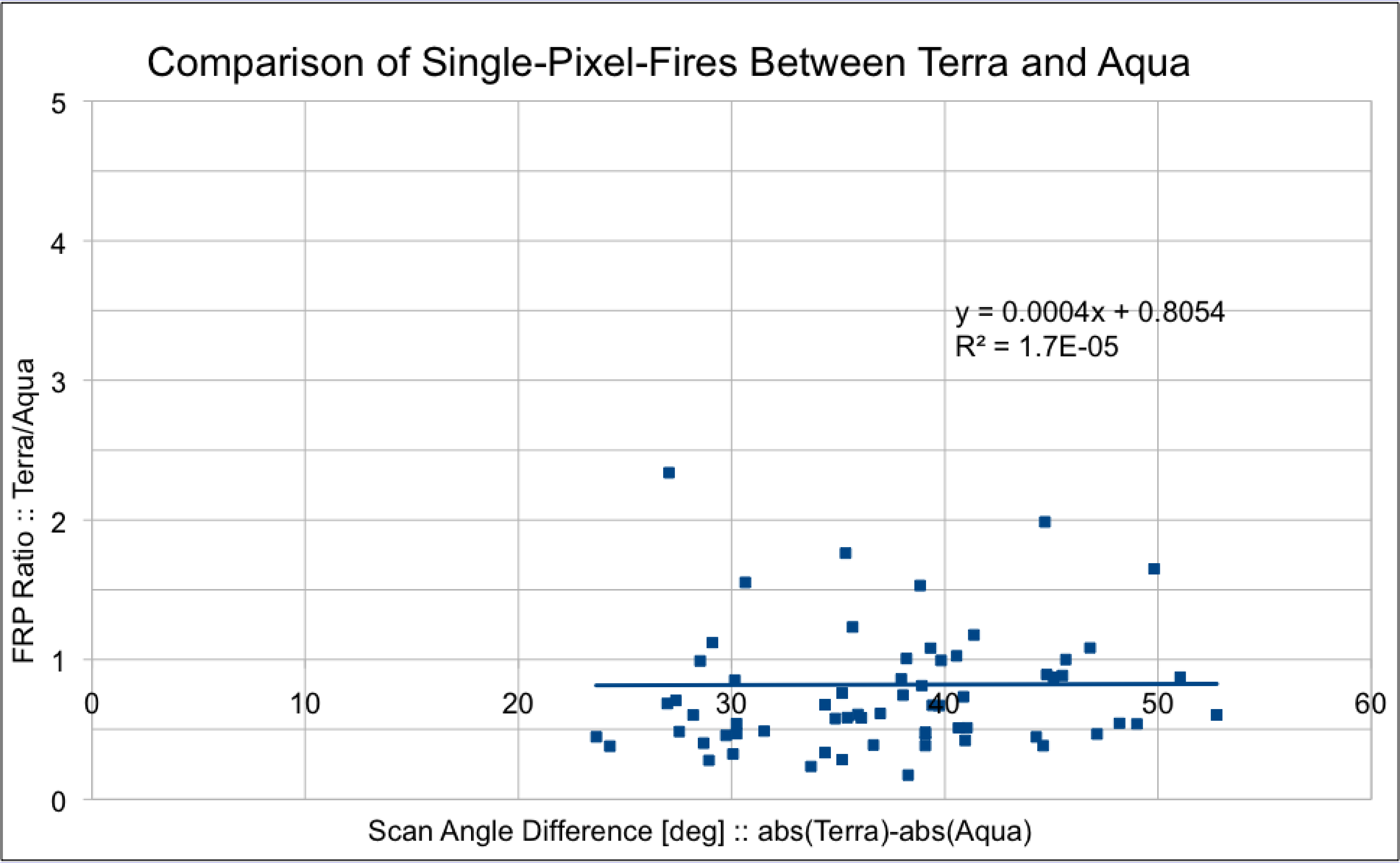




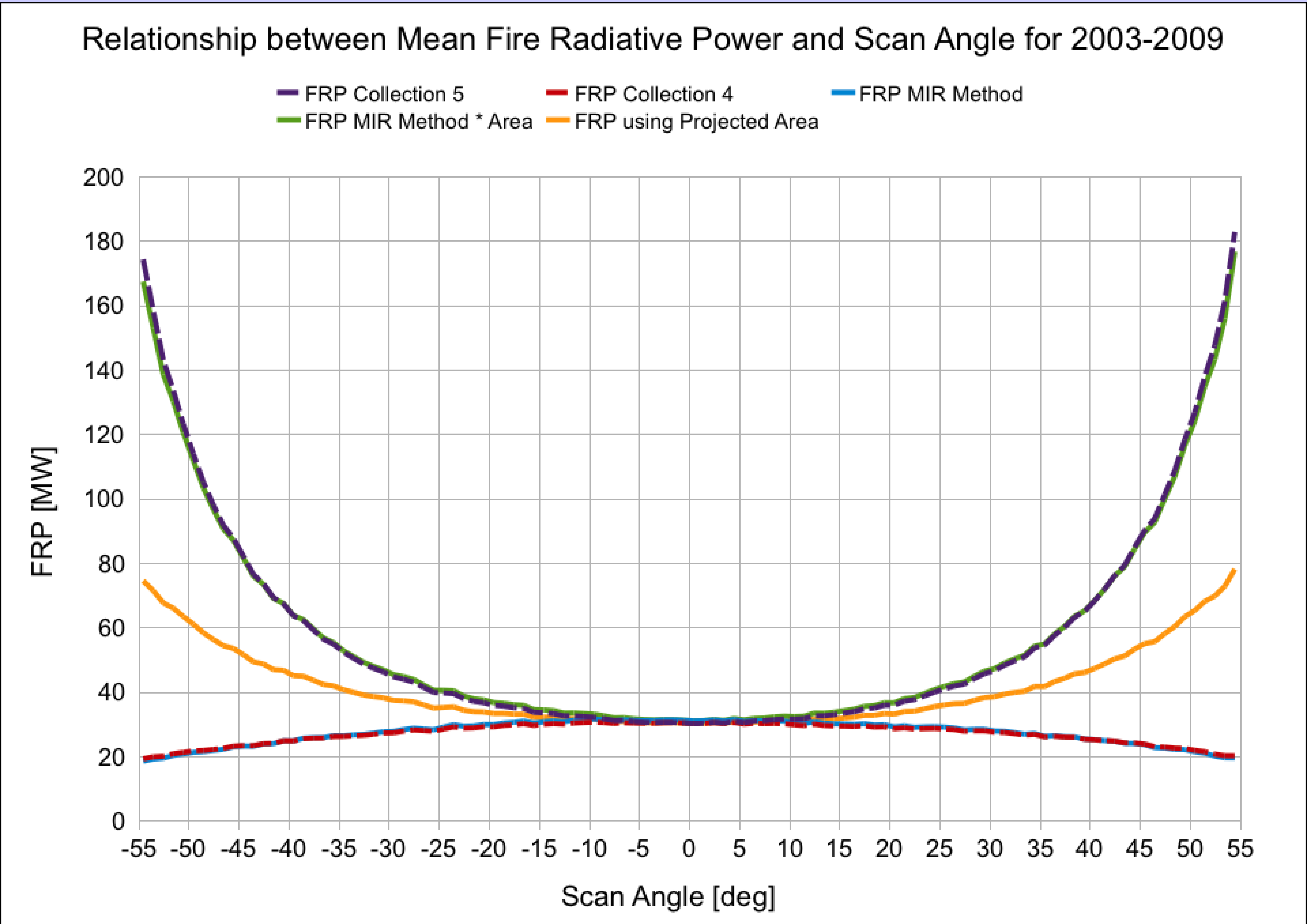
Relationship between Mean Fire Radiative Power and Scan Angle for 2009
FRP Collection 5
FRP Collection 4
FRP MIR Method
FRP [MW]
0
20
40
60
80
100
120
140
160
180
200
-55
-50
-45
-40
-35
-30
-25
-20
-15
-10
-5
0
5
10
15
20
25
30
35
40
45
50
55
Scan Angle [deg]

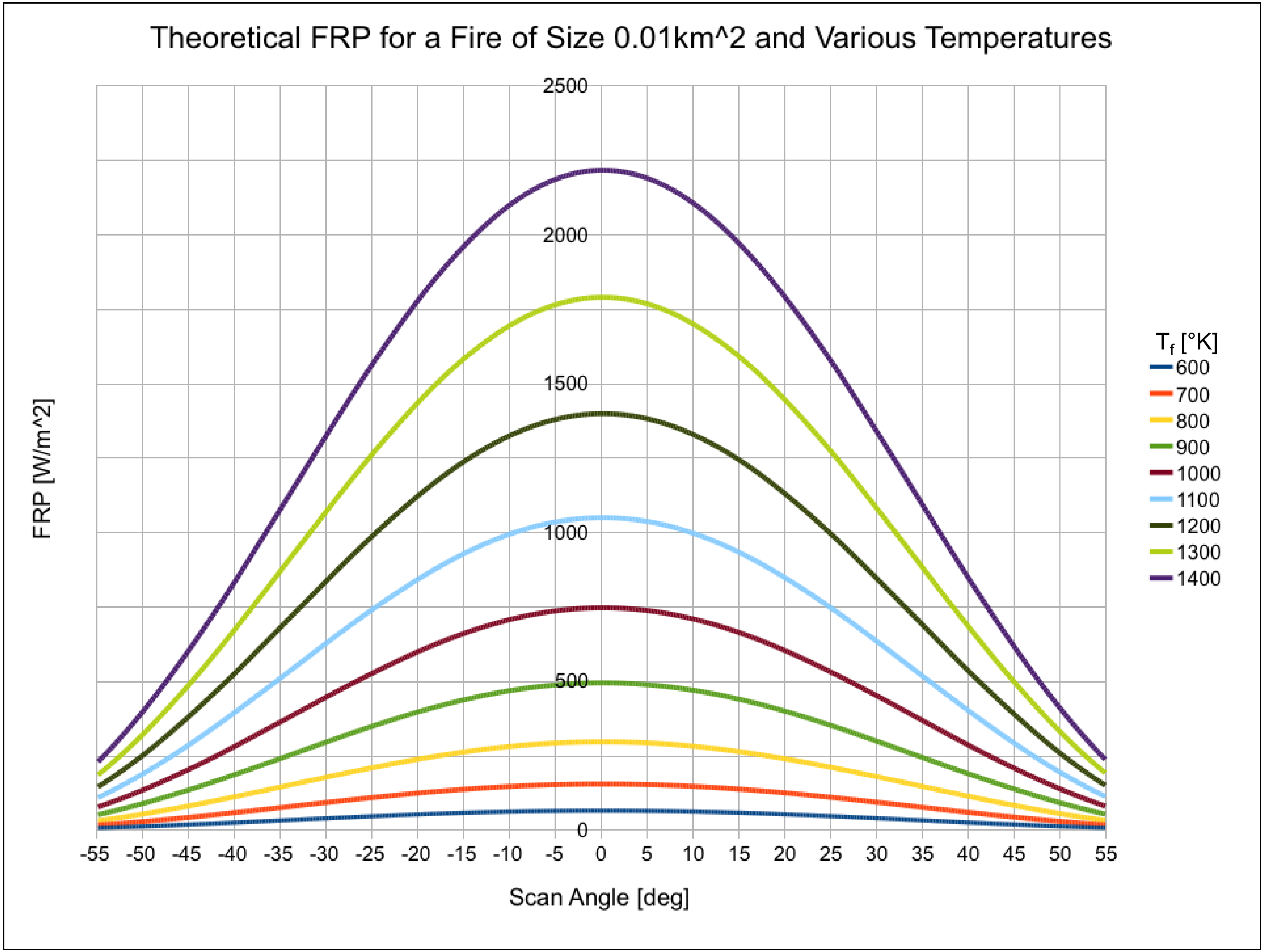


Terra Large (40 -55 deg), Aqua medium (20 – 40 deg)



Terra Large (40 -55 deg), Aqua small (0 – 20 deg)

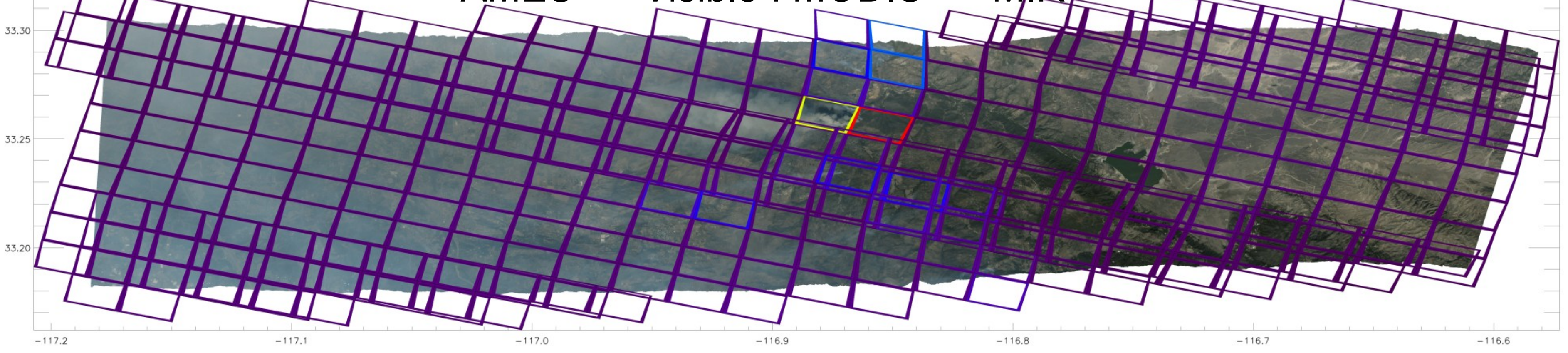

Relationship between Mean Fire Radiative Power and Scan Angle for 2003-2009
FRP Collection 5
FRP Collection 4
FRP MIR Method
FRP MIR Method * Area
FRP using Projected Area
FRP [MW]
0
20
40
60
80
100
120
140
160
180
200
-55
-50
-45
-40
-35
-30
-25
-20
-15
-10
-5
0
5
10
15
20
25
30
35
40
45
50
55
Scan Angle [deg]


Theoretical FRP for a Fire of Size 0.01km^2 and Various Temperatures
FRP [W/m^2]
2500
2000
1500
1000
500
0
-55 -50 -45 -40 -35 -30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30 35 40 45 50 55
Scan Angle [deg]
T_f [°K]
600
700
800
900
1000
1100
1200
1300
1400

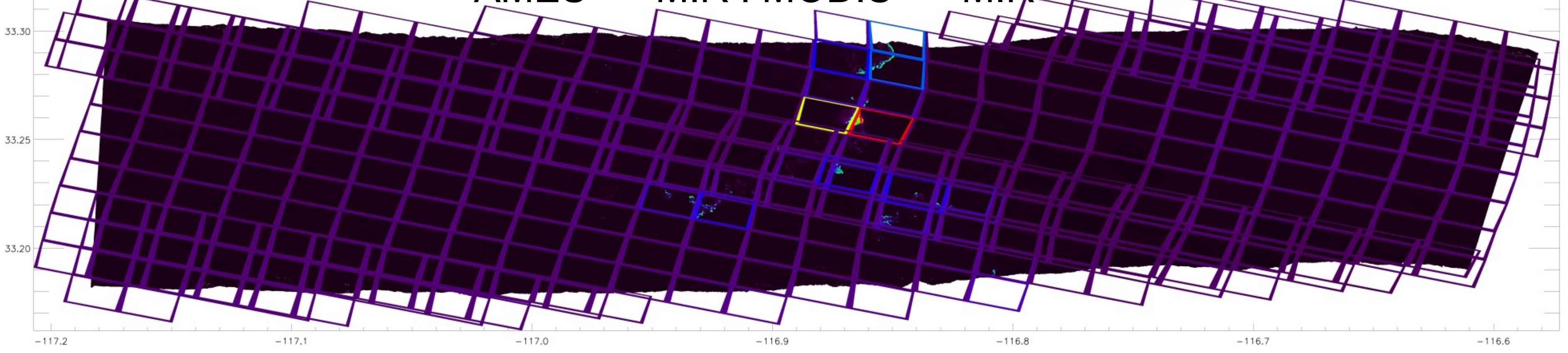
Evaluation of MODIS using Autonomous Modular Sensor (AMS) Data from NASA Ikhana Unmanned Aircraft

MODIS Footprints over AMS

AMES => Visible : MODIS => MIR

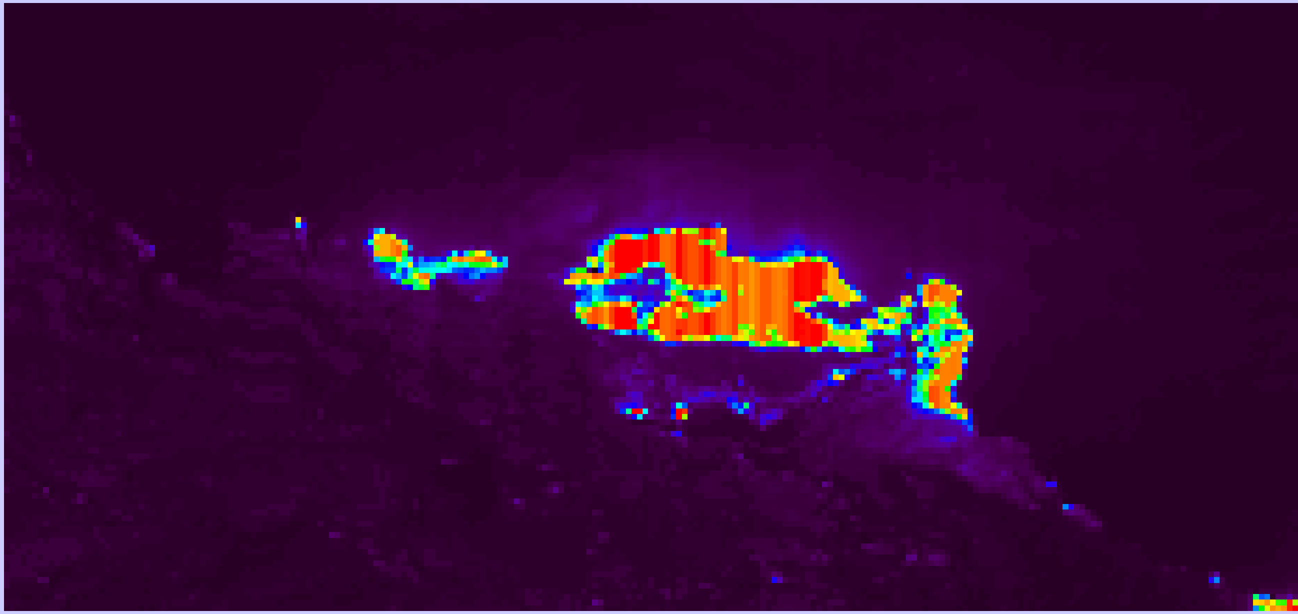


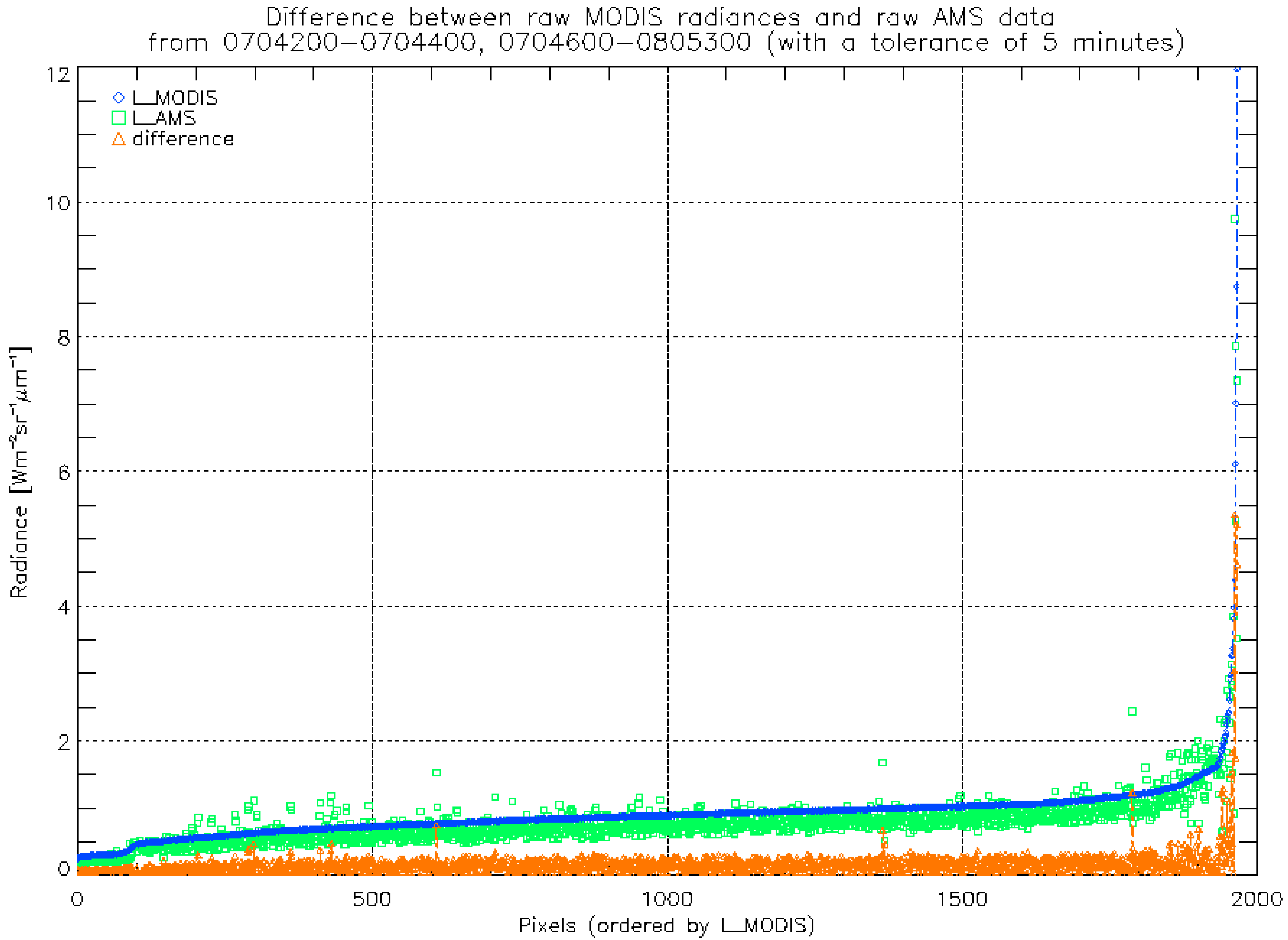
AMES => MIR : MODIS => MIR



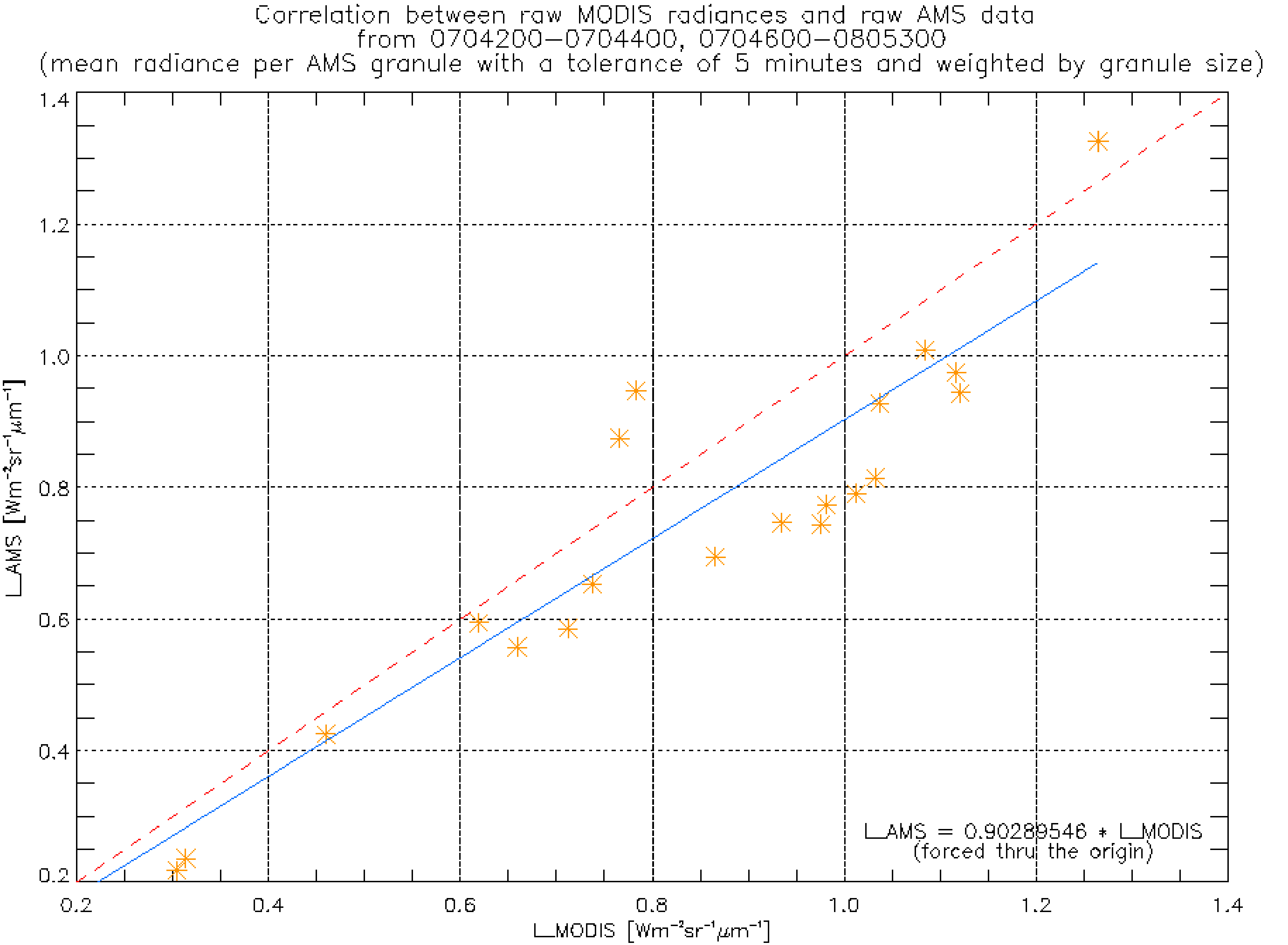
Autonomous Modular Sensor (AMS) Data from NASA Ikhana Unmanned Aircraft

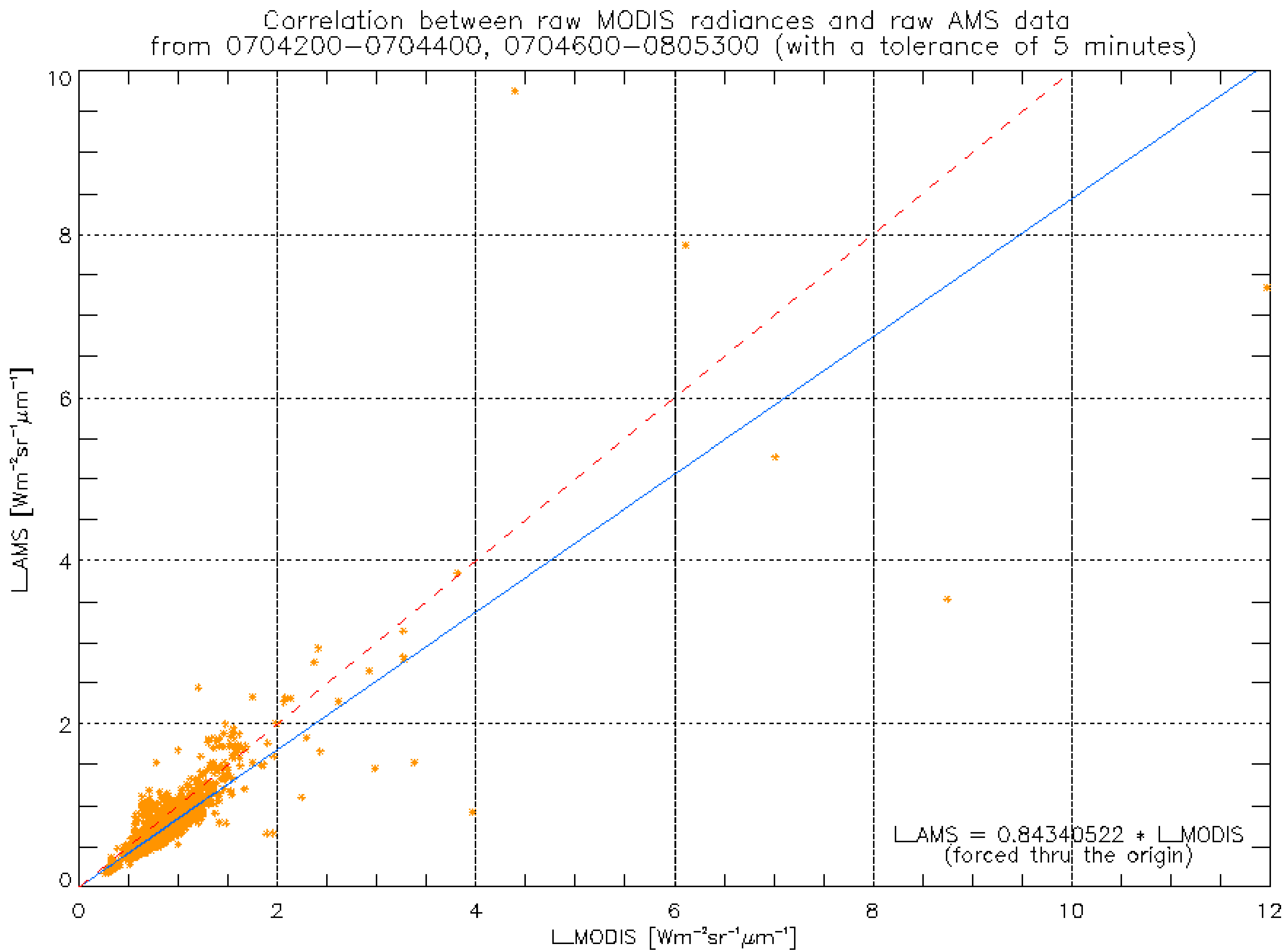
A section of the AMS granule (track 8) on 8/16/2007 showing AMS' unusual saturation characteristics. There is blooming that produce streaks of like charge along the scan direction. Furthermore, as can be seen in the picture with the orange streaks, saturation occurs at levels lower than AMS' maximum saturation level.



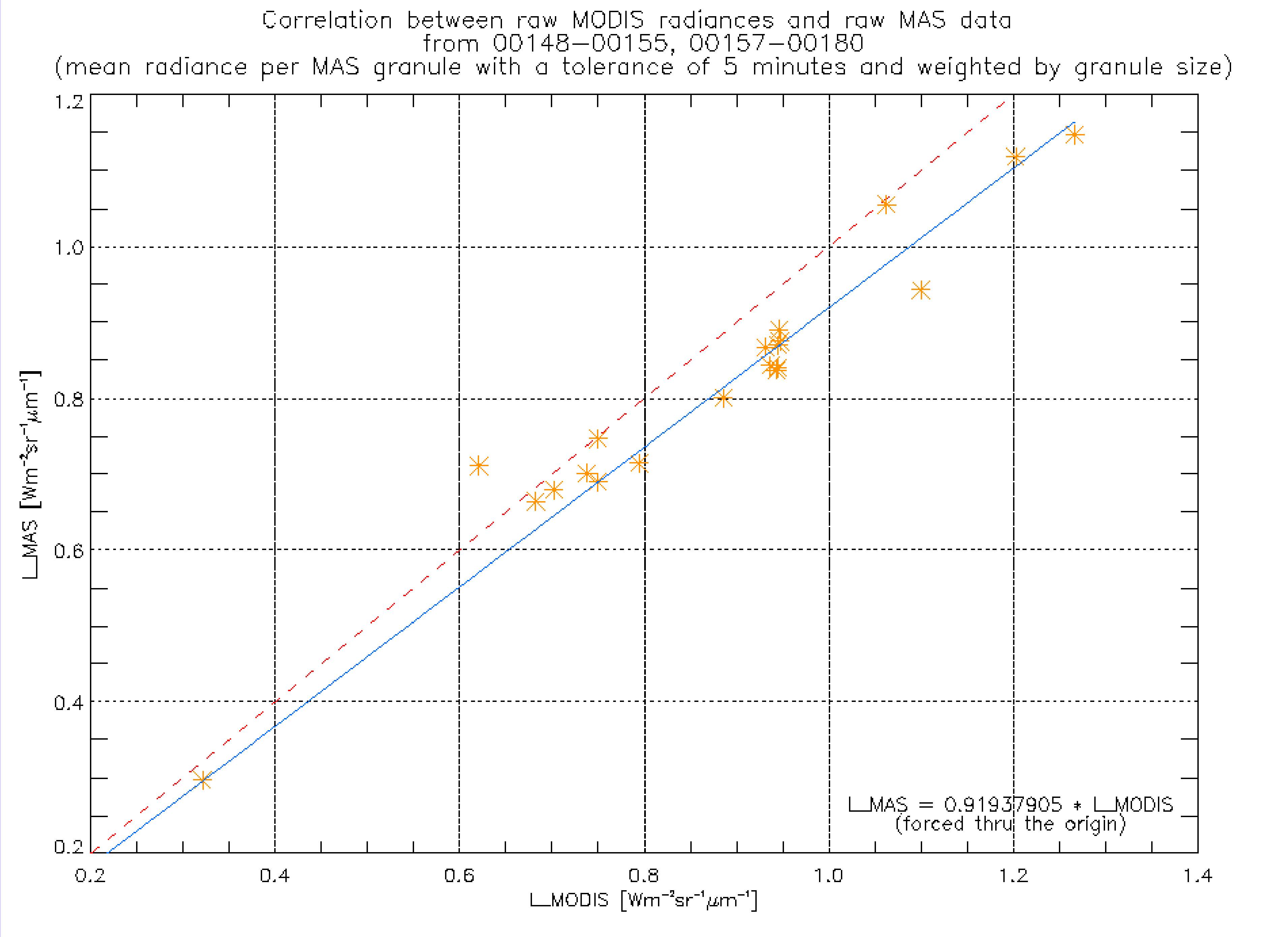


Difference between raw MODIS radiances and raw AMS data
from 0704200–0704400, 0704600–0805300 (with a tolerance of 5 minutes)
L_MODIS
L_AMS
difference
Radiance [Wm^{-2}sr$^{-1}\mu$m^{-1}]
Pixels (ordered by L_MODIS)
0
2
4
6
8
10
12
0
500
1000
1500
2000

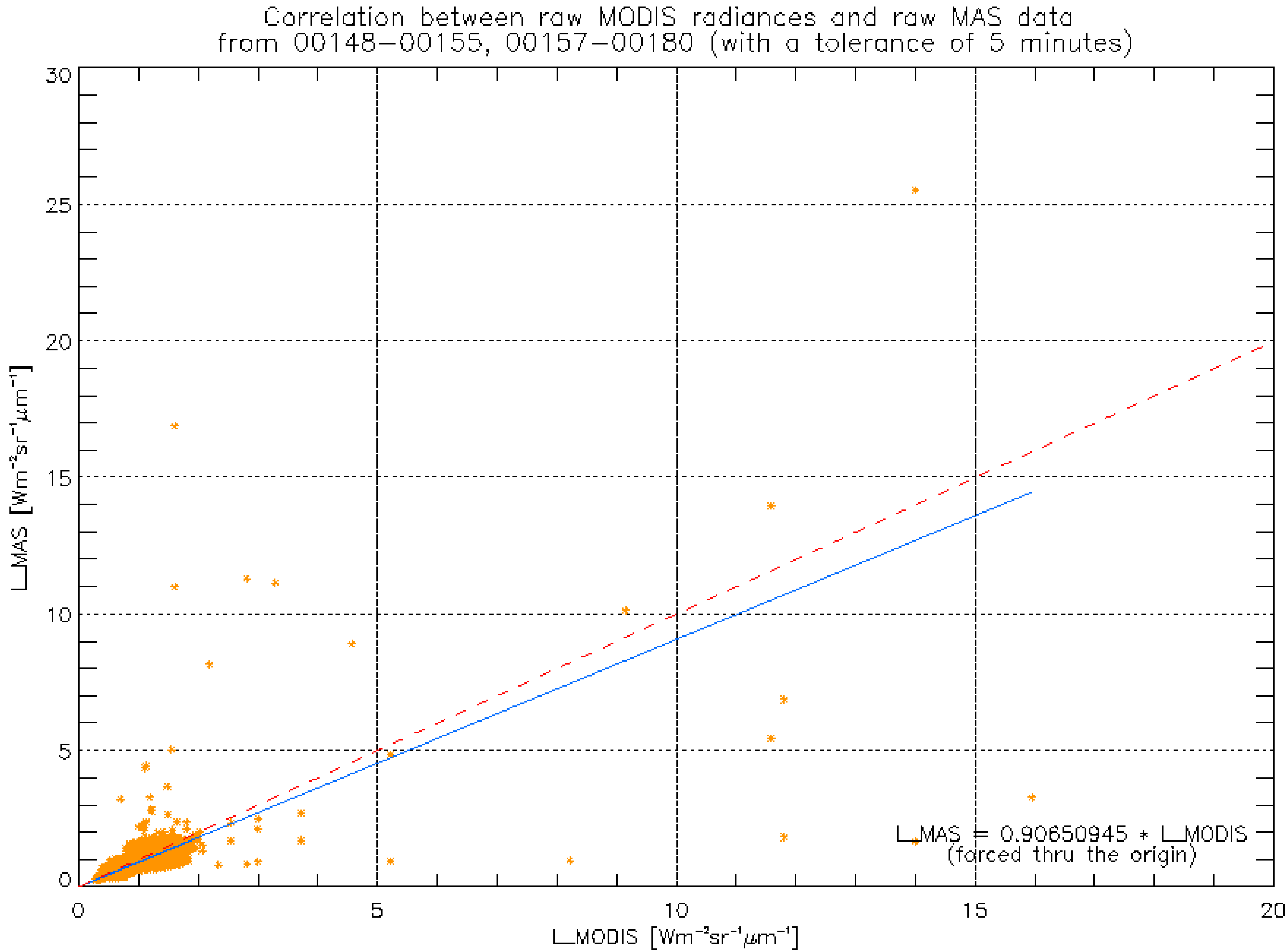

Correlation between raw MODIS radiances and raw AMS data
from 0704200–0704400, 0704600–0805300
(mean radiance per AMS granule with a tolerance of 5 minutes and weighted by granule size)
L_AMS [Wm⁻²sr⁻¹μm⁻¹]
L_MODIS [Wm⁻²sr⁻¹μm⁻¹]
L_AMS = 0.90289546 * L_MODIS
(forced thru the origin)
0.2
0.4
0.6
0.8
1.0
1.2
1.4



Correlation between raw MODIS radiances and raw AMS data
from 0704200-0704400, 0704600-0805300 (with a tolerance of 5 minutes)
L_AMS = 0.84340522 * L_MODIS
(forced thru the origin)
L_AMS [Wm^-2sr^-1μm^-1]
L_MODIS [Wm^-2sr^-1μm^-1]
0
2
4
6
8
10
12



Correlation between raw MODIS radiances and raw MAS data
from 00148–00155, 00157–00180
(mean radiance per MAS granule with a tolerance of 5 minutes and weighted by granule size)
1.2
1.0
0.8
0.6
0.4
0.2
L_MAS [Wm⁻²sr⁻¹μm⁻¹]
0.2
0.4
0.6
0.8
1.0
1.2
1.4
L_MODIS [Wm⁻²sr⁻¹μm⁻¹]
L_MAS = 0.91937905 * L_MODIS
(forced thru the origin)

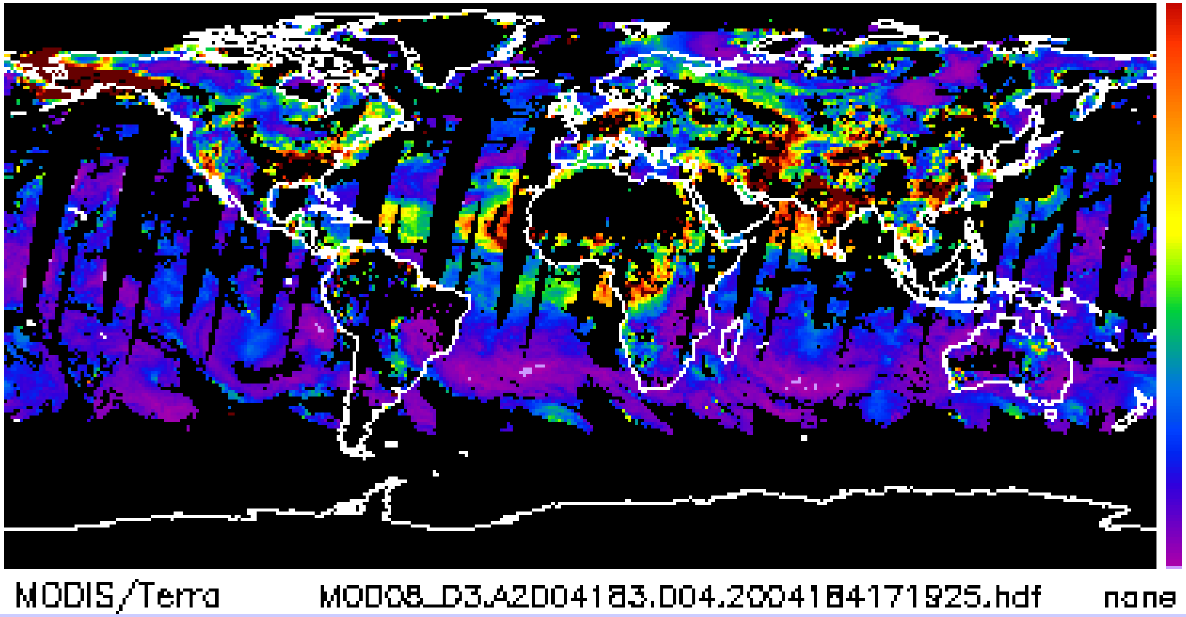

Correlation between raw MODIS radiances and raw MAS data
from 00148-00155, 00157-00180 (with a tolerance of 5 minutes)
L_MAS [Wm⁻²sr⁻¹µm⁻¹]
L_MODIS [Wm⁻²sr⁻¹µm⁻¹]
L_MAS = 0.90650945 * L_MODIS
(forced thru the origin)
0
5
10
15
20
25
30
0
5
10
15
20

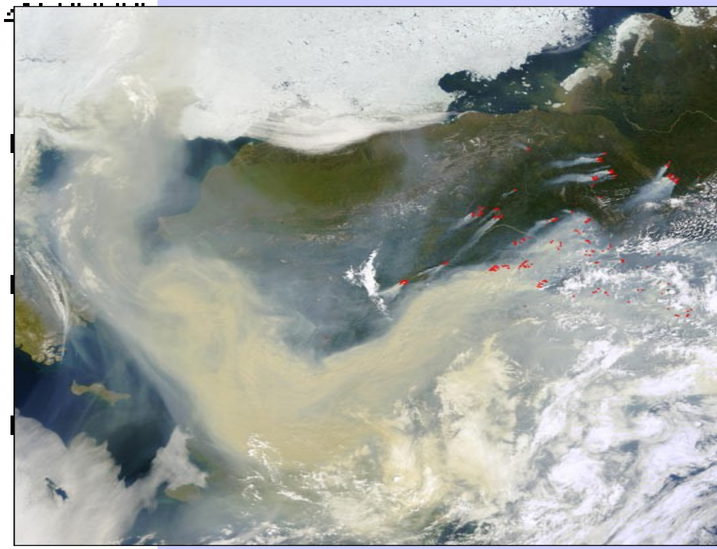
Potential Applications and Future Outlook

- Smoke source characterization for models.
- Real-time smoke monitoring and forecasting.
- Delivery of results through Google Earth.

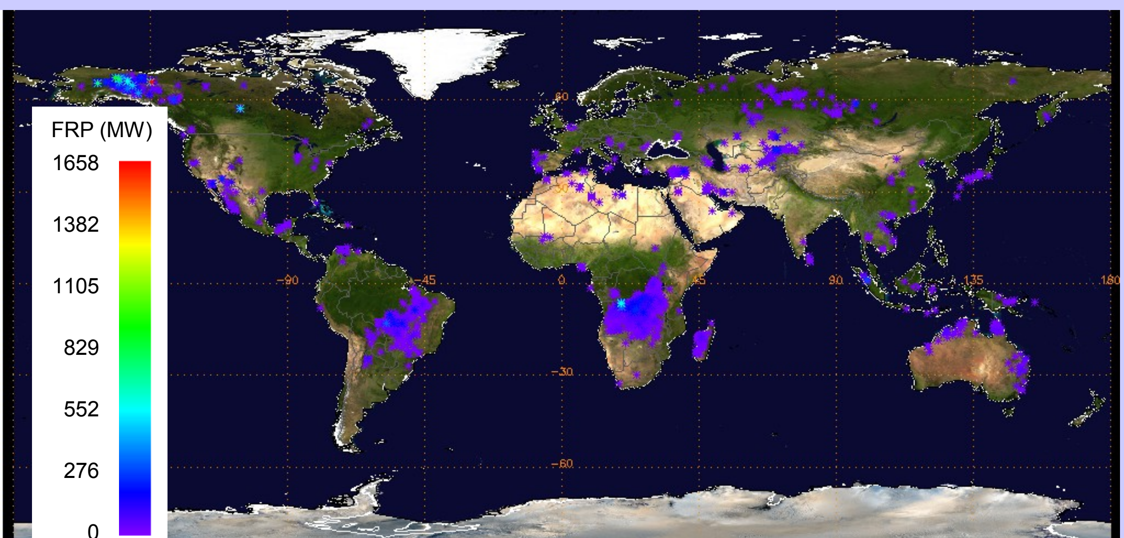
Global Snapshot on 01-July-2004

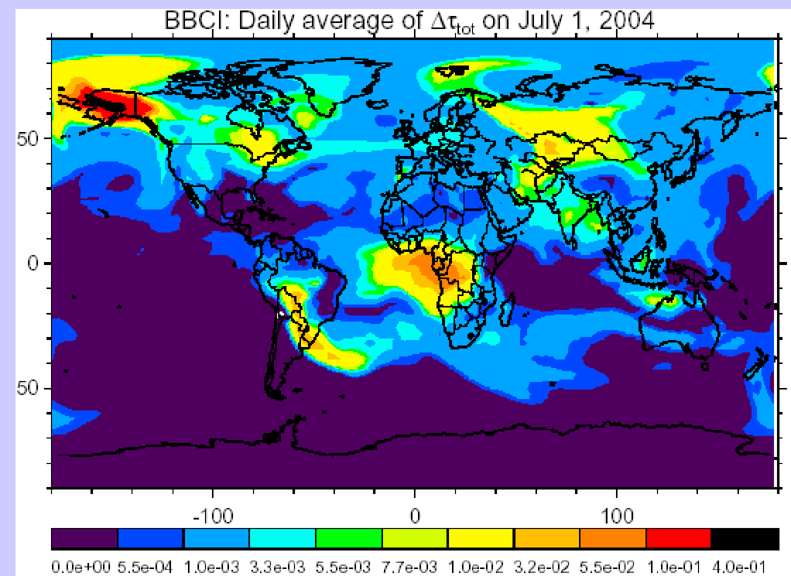
MODIS Measurements of Aerosol Optical Depth (AOD)





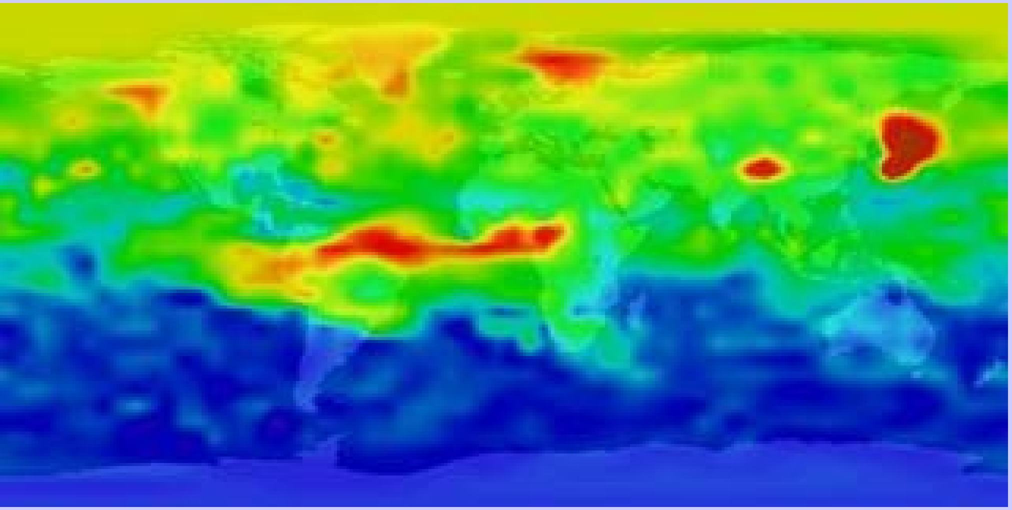
MODIS Fire Radiative Power use in simulation of smoke emissions with GOCART



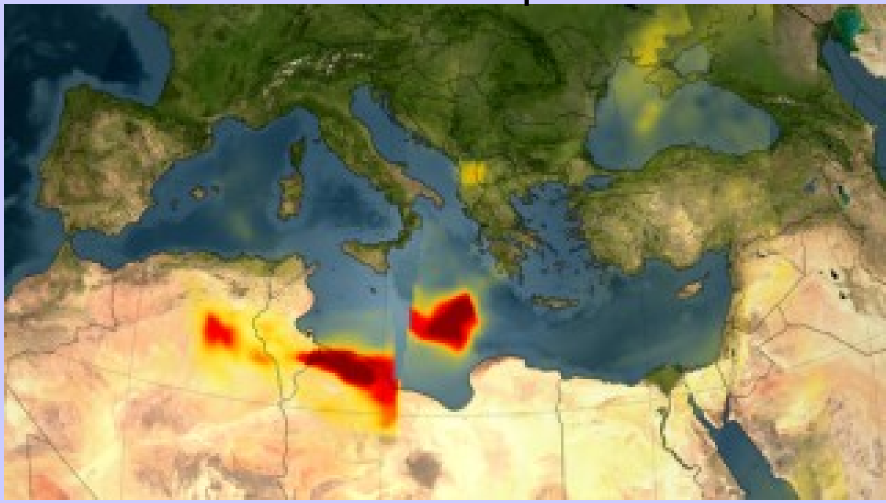


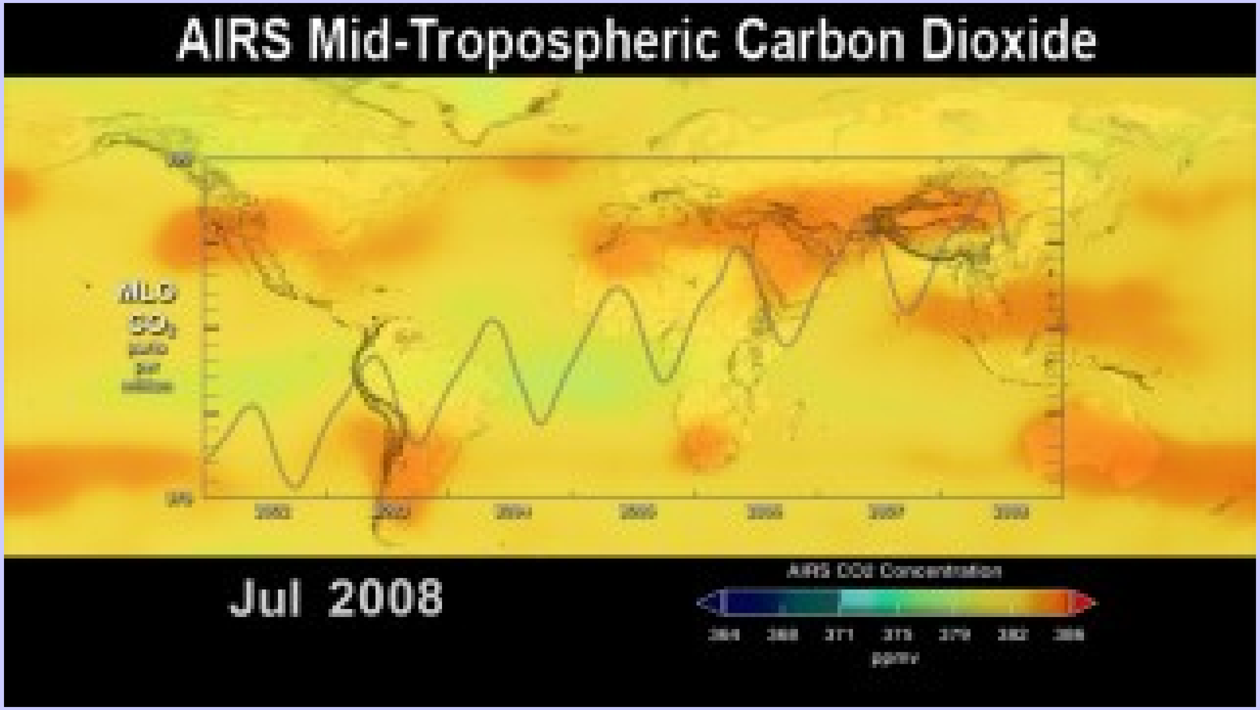
Toward Estimation of CO and CO_2 Emissions from FRP

Terra-MOPITT CO



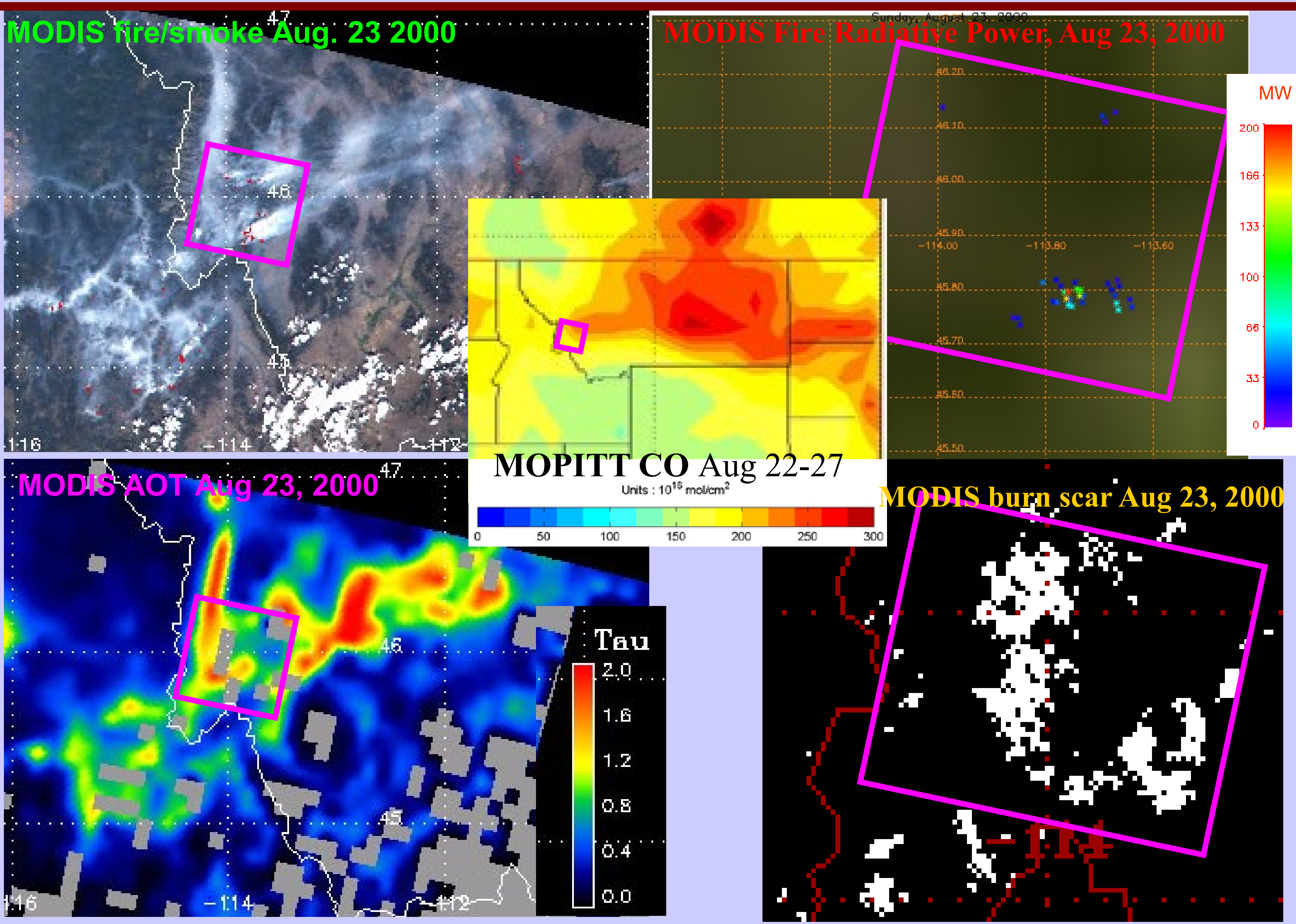
Aqua-AIRS CO





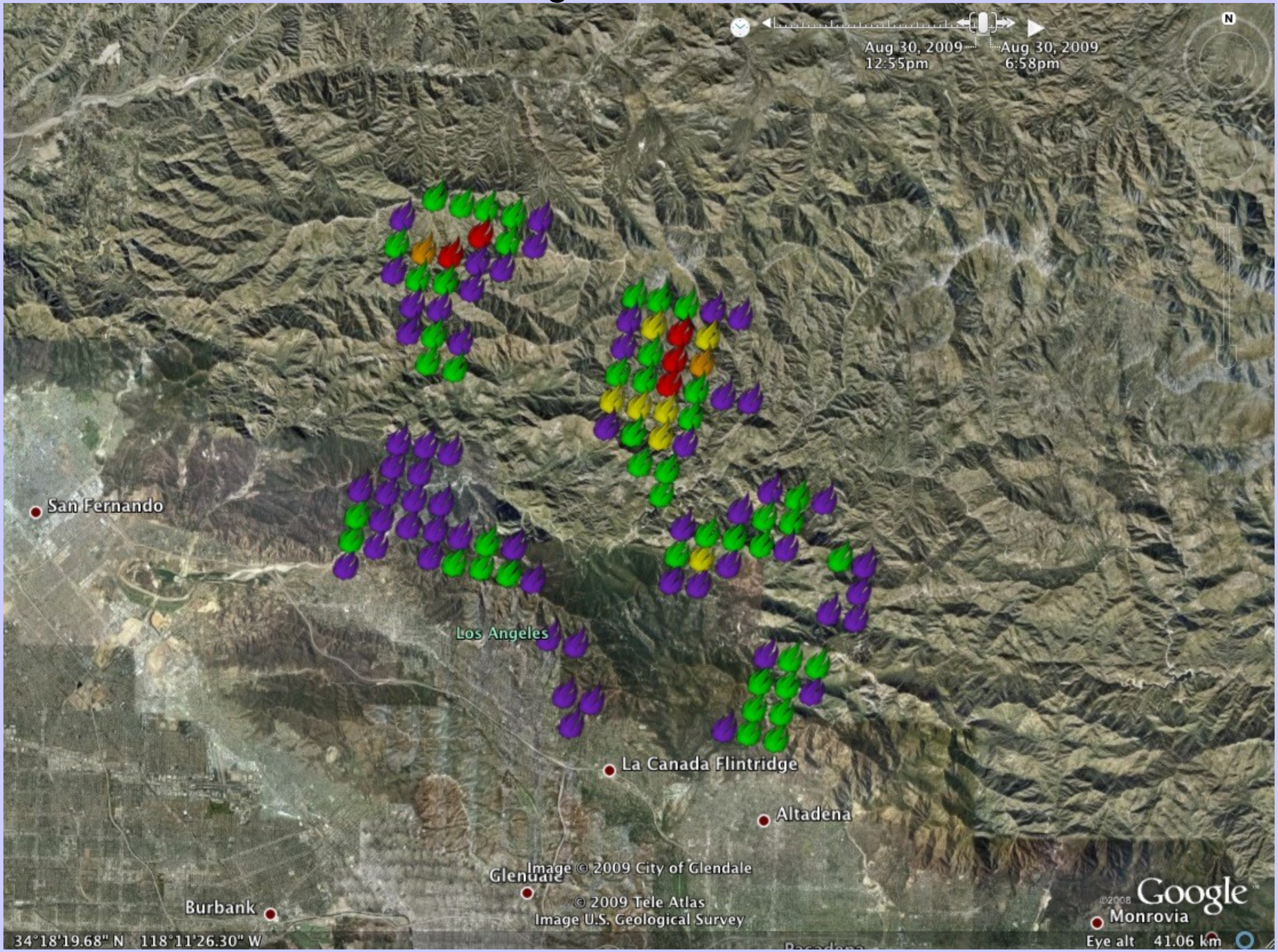
http://svs.gsfc.nasa.gov/vis/a000000/a003500/a003562/index.html

Fires in MT/ID, Aug 2000 : Image, FRP, burn scar, aerosol, CO



MODIS Station Fire Categories on Google Earth

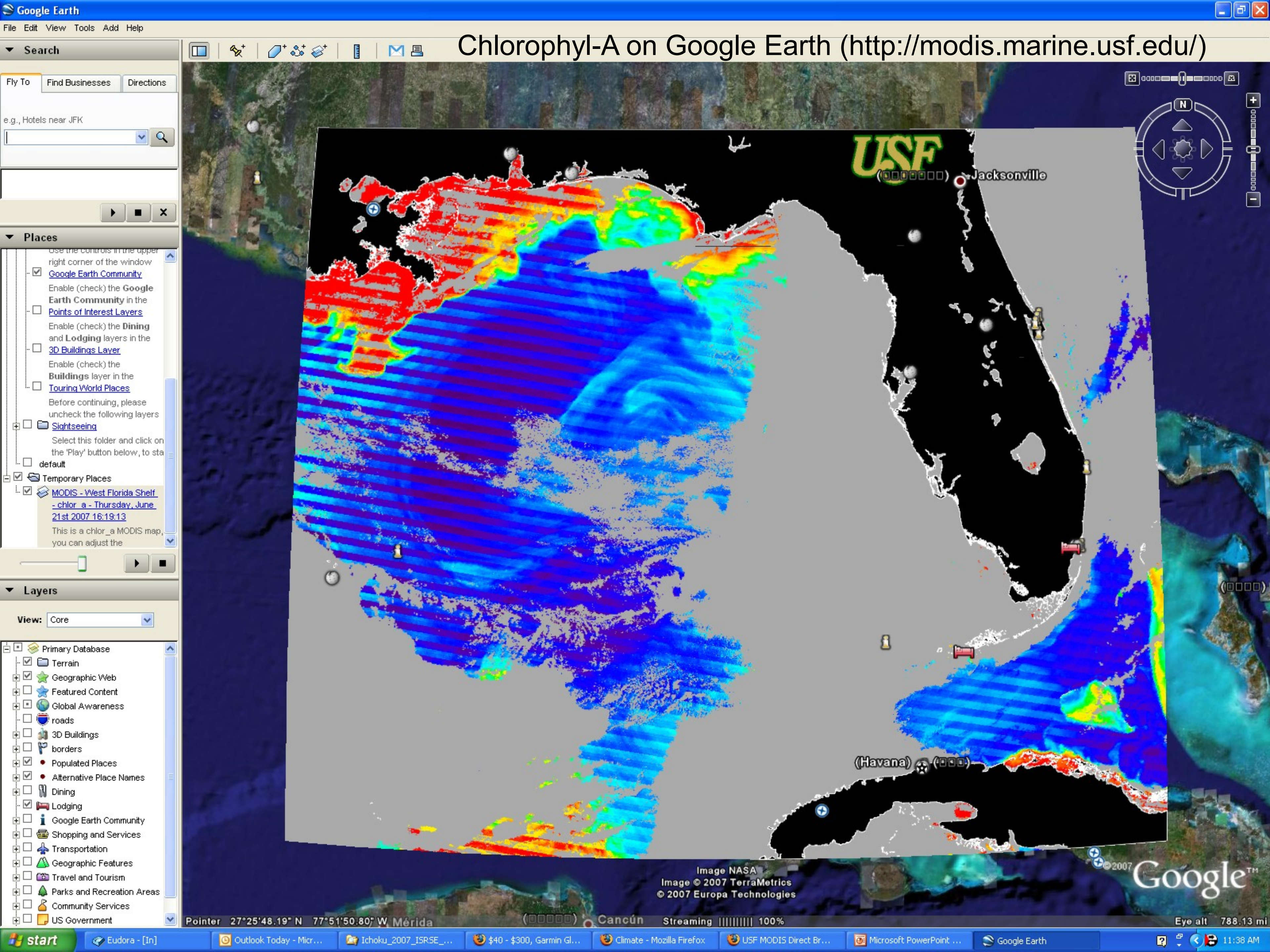
August 30, 2009



Fire categories (1-5) based on Terra MODIS FRP: 1=purple, 2=green, 3=yellow, 4=orange, 5=red

Developed by Luke Ellison

Chlorophyl-A on Google Earth (http://modis.marine.usf.edu/)



Conclusions

- It is extremely important to characterize fires quantitatively and include robust smoke parameterization in air-quality and climate models, to enhance accurate surveillance of smoke impacts.

- Satellite measurements of fire radiative power (FRP) provides a unique opportunity to accomplish that, because FRP is directly related to fire strength, biomass consumption, and smoke emission.

- Advantages of FRP: quantitative, more direct, fewer assumptions, less uncertainty, etc.

- Application potential is varied and far-reaching: real-time, air quality, climate, etc.).

- Future Field Campaigns should include Detailed Quantitative Fire Characterization (e.g. FRP, emissivity, smoke/cloud obscuration/attenuation, etc.).