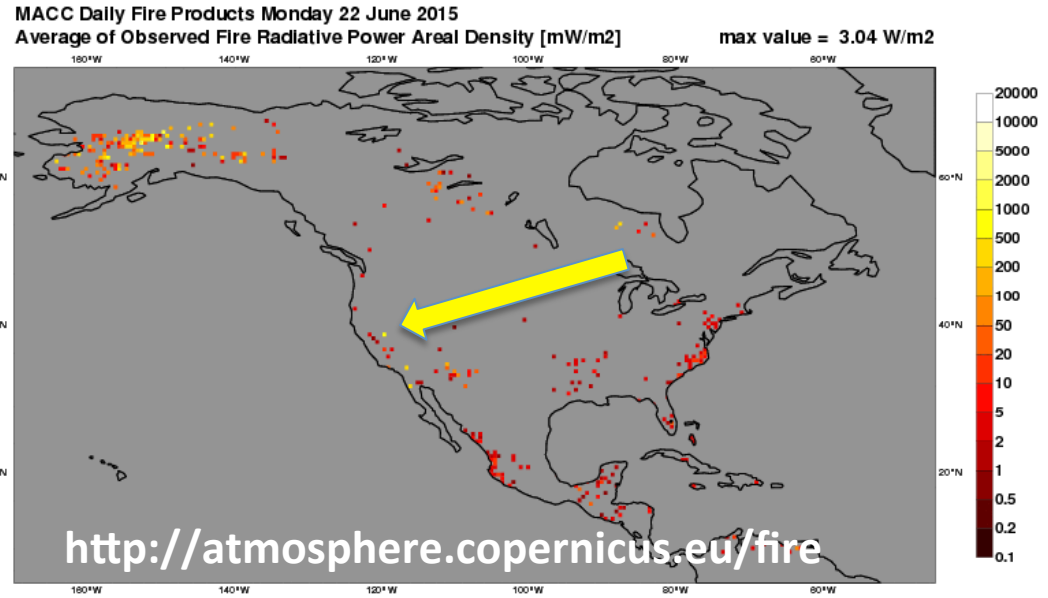
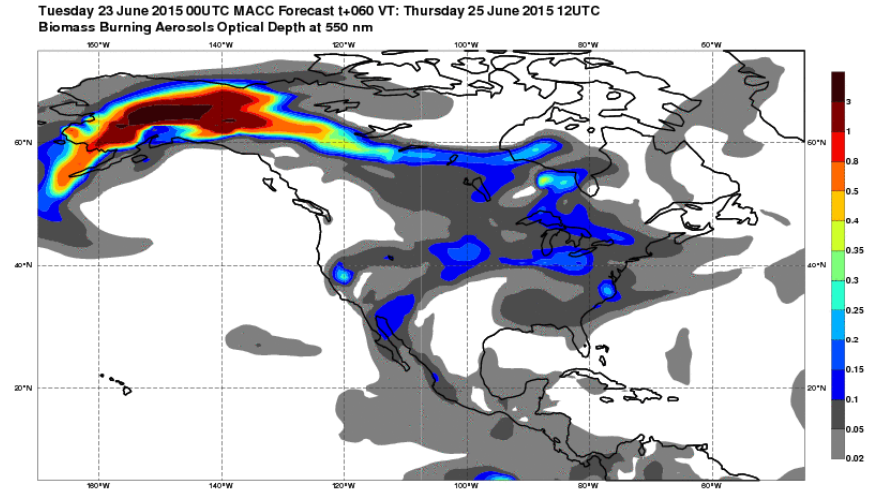
Satellite remote sensing of fires, global emission estimation, Copernicus Atmosphere Monitoring Service

MAX-PLANCK-INSTITUT FÜR CHEMIE

Johannes W. Kaiser

with contributions by N. Andela, A. Benedetti, J. Flemming, A. Heil, A. Inness, R. Paugam, S. Remy, I. Trigo, G. R. van der Werf, M. J. Wooster





HORIZON 2020

opernicus The European Earth Observation Programme

macc Monitoring atmospheric composition & climate - III

MAX-PLANCK-GESELLSCHAFT

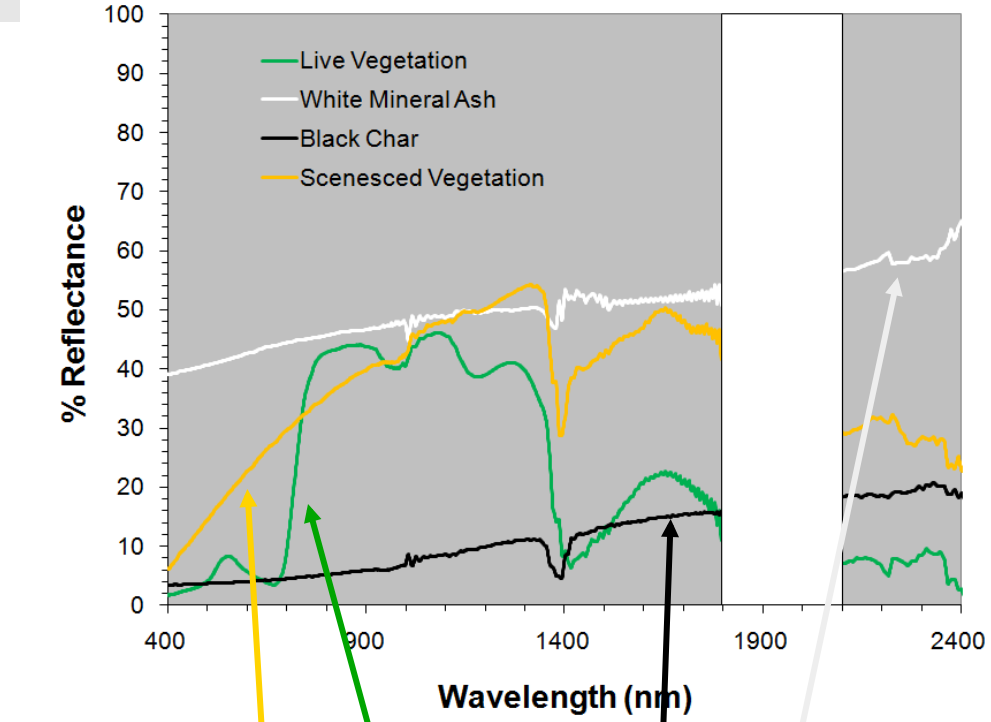
Outline

- Fire emission estimation from satellite
  - GFAS
- Monitoring of ECV Fire disturbance
- Copernicus Atmosphere Monitoring Service (CAMS)
- Fire and smoke plume cases
- Injection heights
- IBBI

Fire emission estimation from satellite

GFAS

Spectral signature of burnt areas

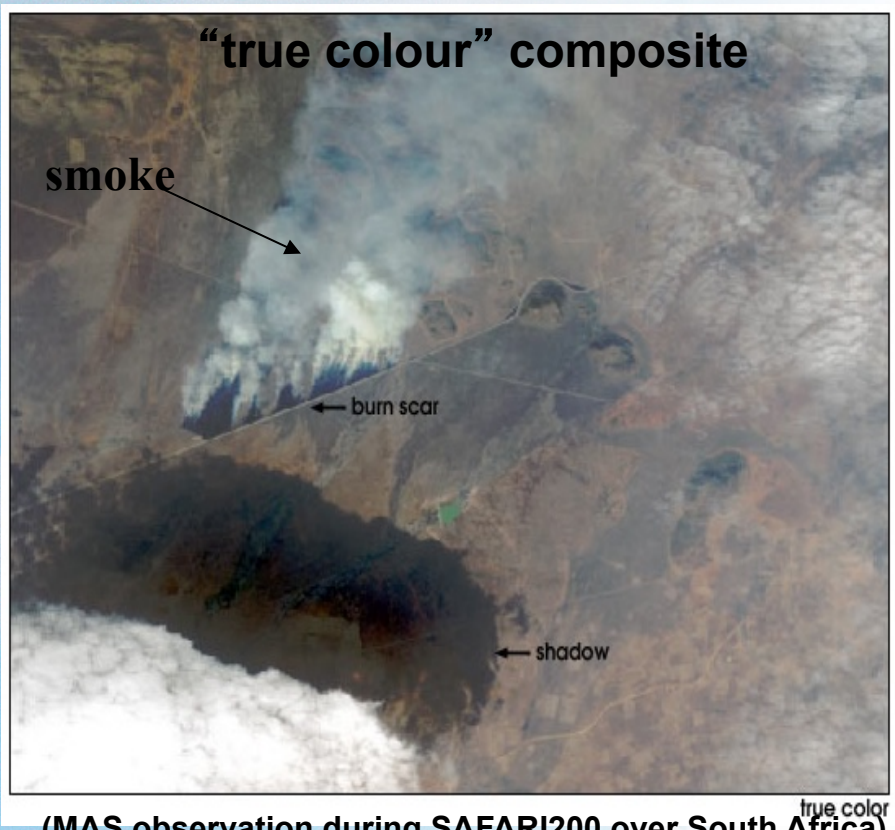


slide courtesy Martin Schultz

Smith, A.M.S., Wooster, M.J., Drake, et al (2005) Testing the potential of multi-spectral remote sensing for retrospectively estimating fire severity in African savanna environments, Remote Sensing of Environment 97: 92-115.

weisse Asche: vollständige Verbrennung
schwarzer Ruß: unvollständige Verbrennung

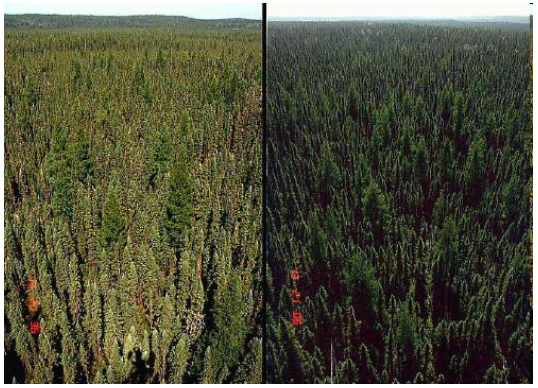
Active Fire Detections – Theory



(MAS observation during SAFARI200 over South Africa)

BRDF

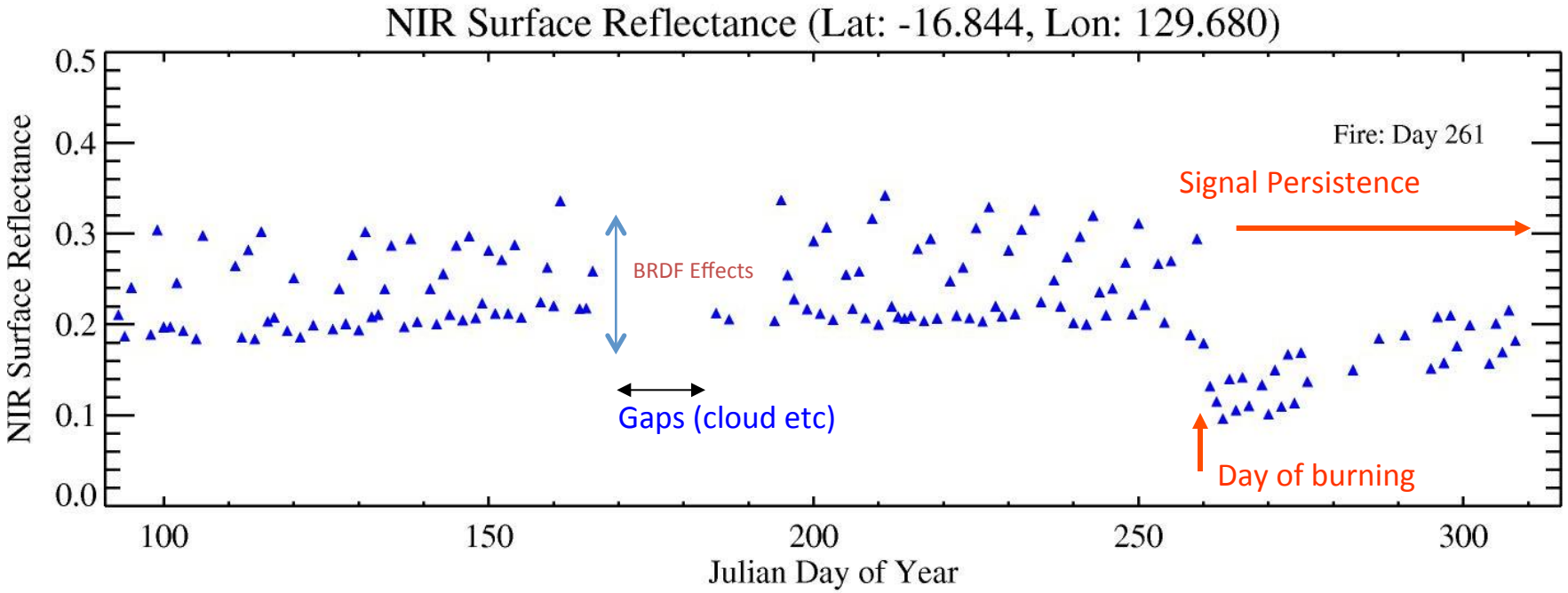
Bidirectional Reflectance Distribution Function



Die wellenlängenabhängige BRDF hängt ab vom Schattenwurf, multipler Streuung, Transmission, Reflektion, usw.

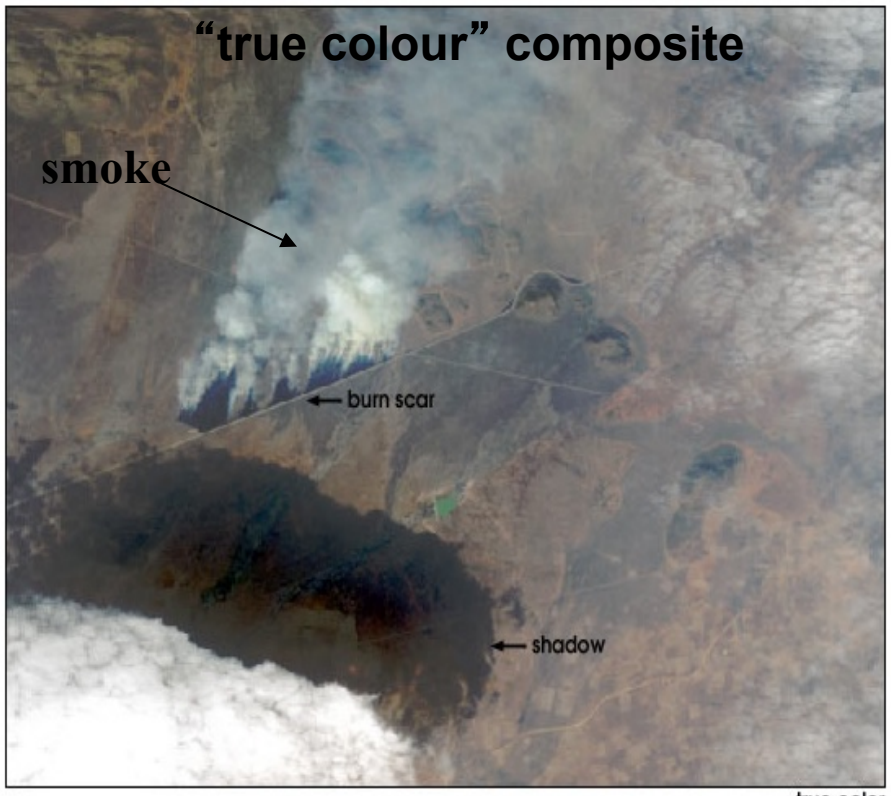
Photos: Don Deering

slide courtesy Martin Schultz



Roy et al. (2002) Burned area mapping using multi-temporal moderate spatial resolution data, Remote Sensing Environ, 83, 263-286.

Active Fire Detections – Theory



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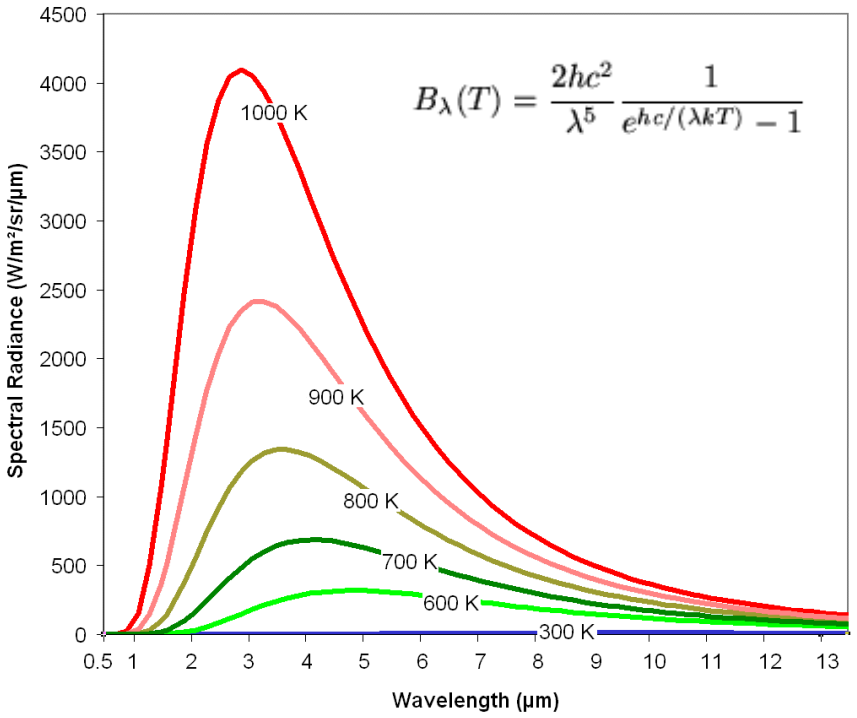
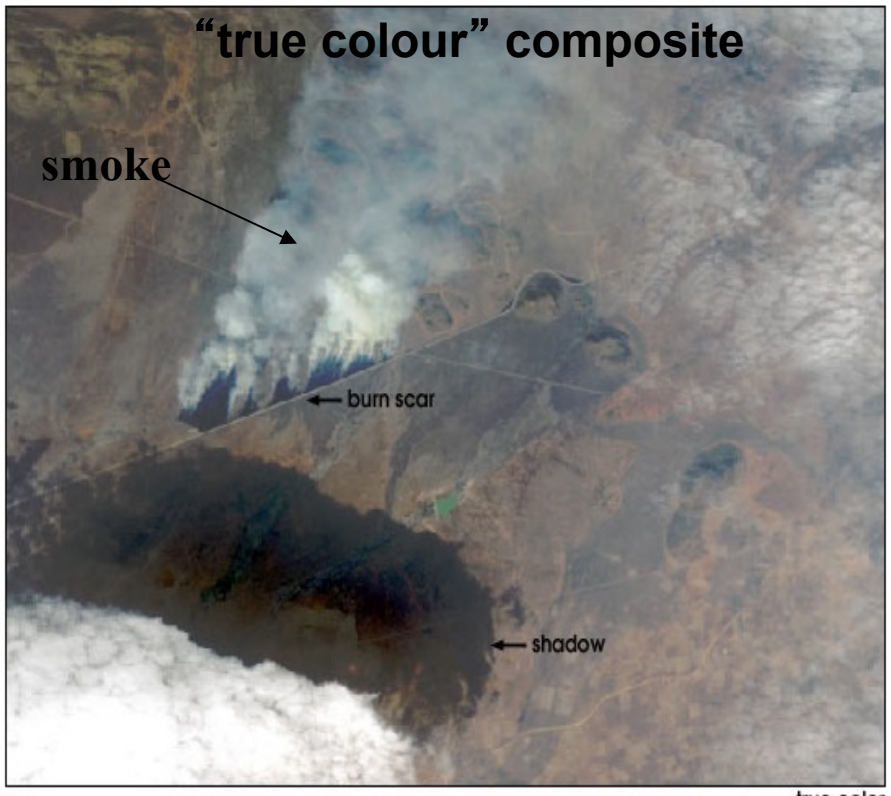


- **Fires have very high temperatures (> 600 K) compared to their ambient surroundings**

Active Fire Detections – Theory



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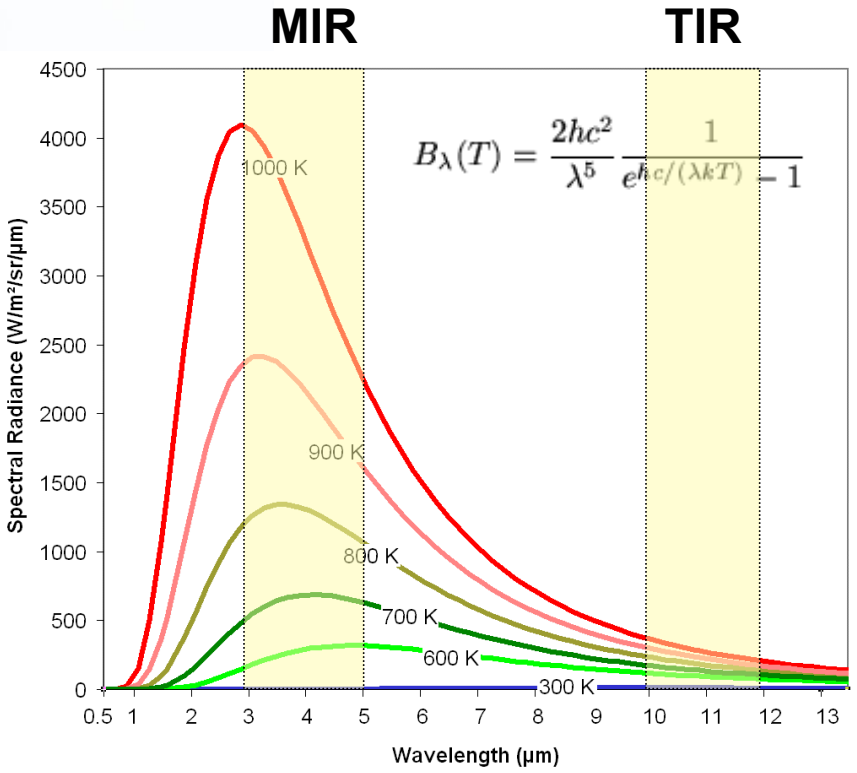
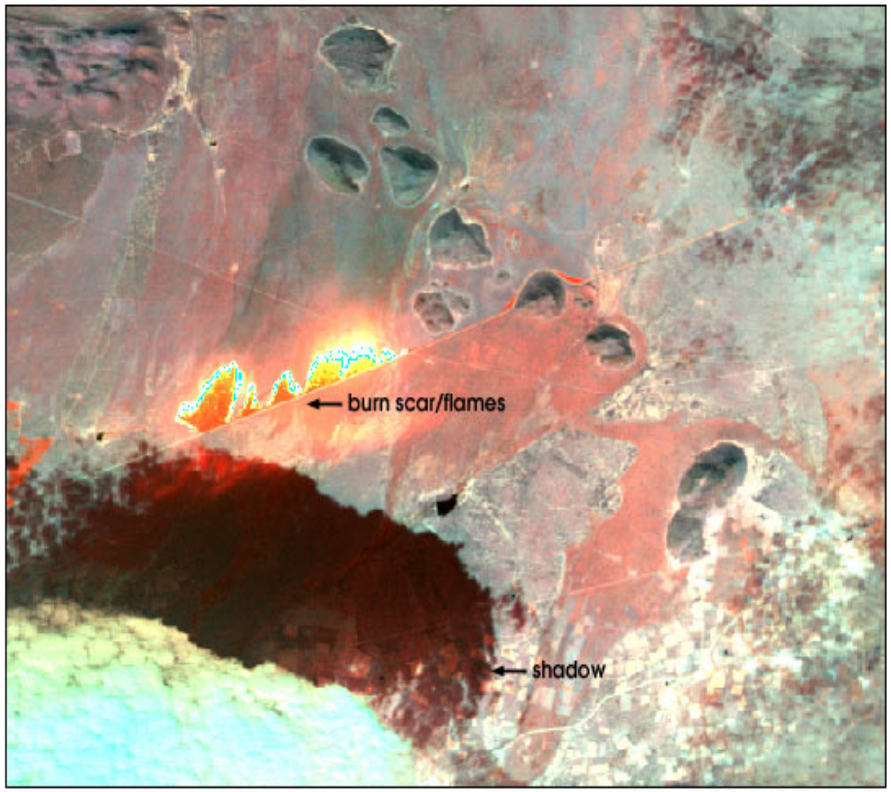


- **Fires have very high temperatures (> 600 K) compared to their ambient surroundings**
- **The high temperatures result in intense IR radiant energy emissions, more so in MIR (3-5 μm) than TIR region.**

Active Fire Detections – Theory



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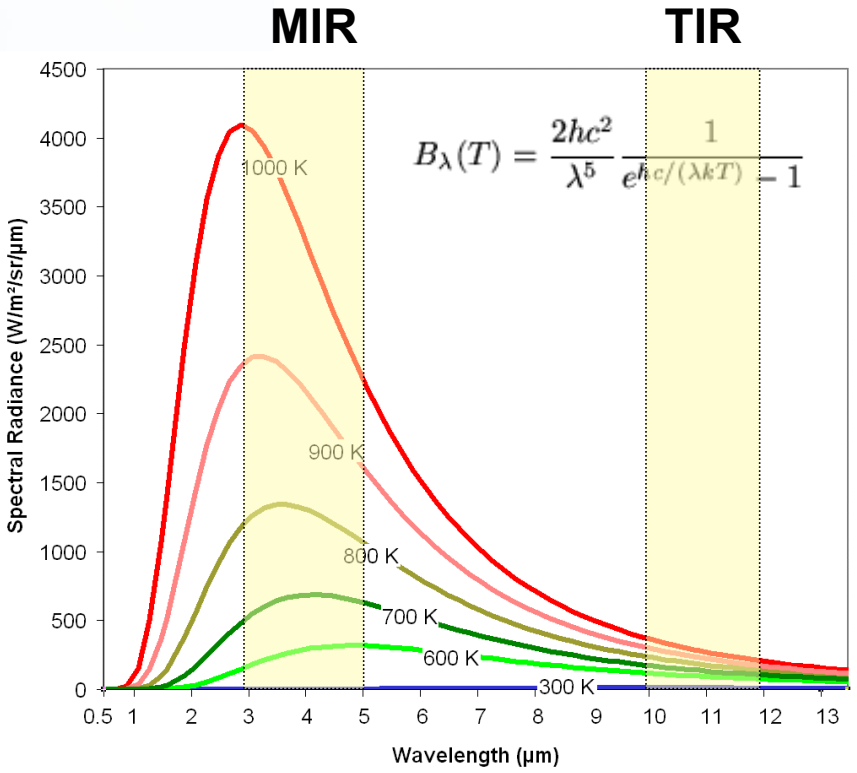
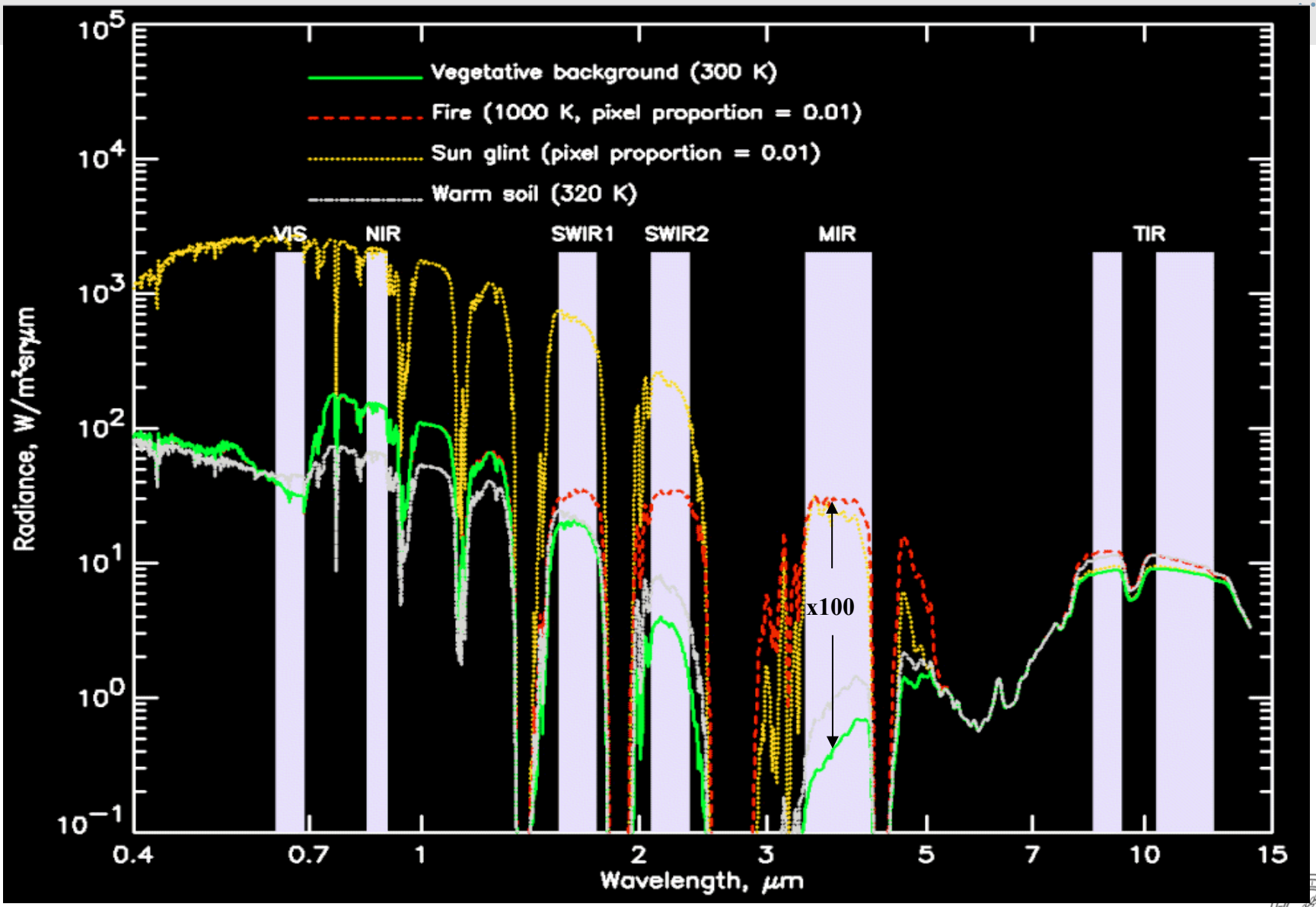


- **Fires have very high temperatures (> 600 K) compared to their ambient surroundings**
- **The high temperatures result in intense IR radiant energy emissions, more so in MIR (3-5 μm) than TIR region.**

Separation von Feuern ggü. anderen Faktoren



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

Bottom-Up Estimation of Fire Emissions

GFAS daily real time production

sat. obs. ~ const. land cover map

$E_i = BA \times AFL \times CC \times EF_i$ (Seiler & Crutzen 1980)

burnt biomass

"key uncertainty" (e.g. Reid et al. 2009)

(dynamic) vegetation model

GFED *(van der Werf et al. 2010),* **also ESA Fire CCI, APIFLAME**

Ei = emission of species i [kg(species i)]

BA = burnt area [m2]

AFL = available fuel load [kg(biomass) / m2]

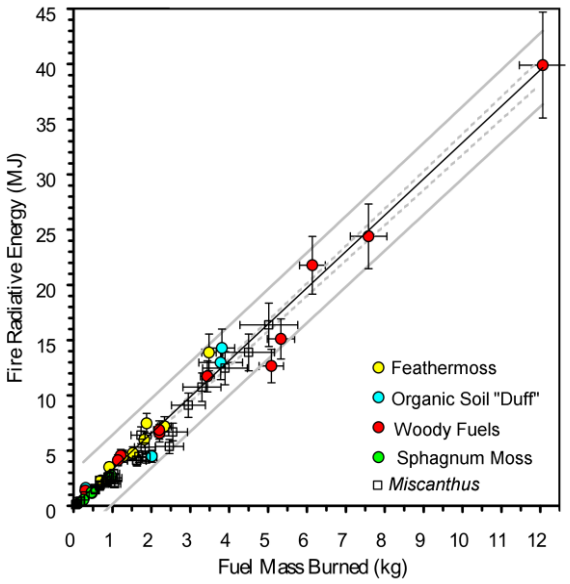
CC = combustion completeness [kg(burnt fuel) / kg (available fuel)]

EFi = emission factor for species i [kg(species i) / kg(biomass)]

FRP = fire radiative power [W]

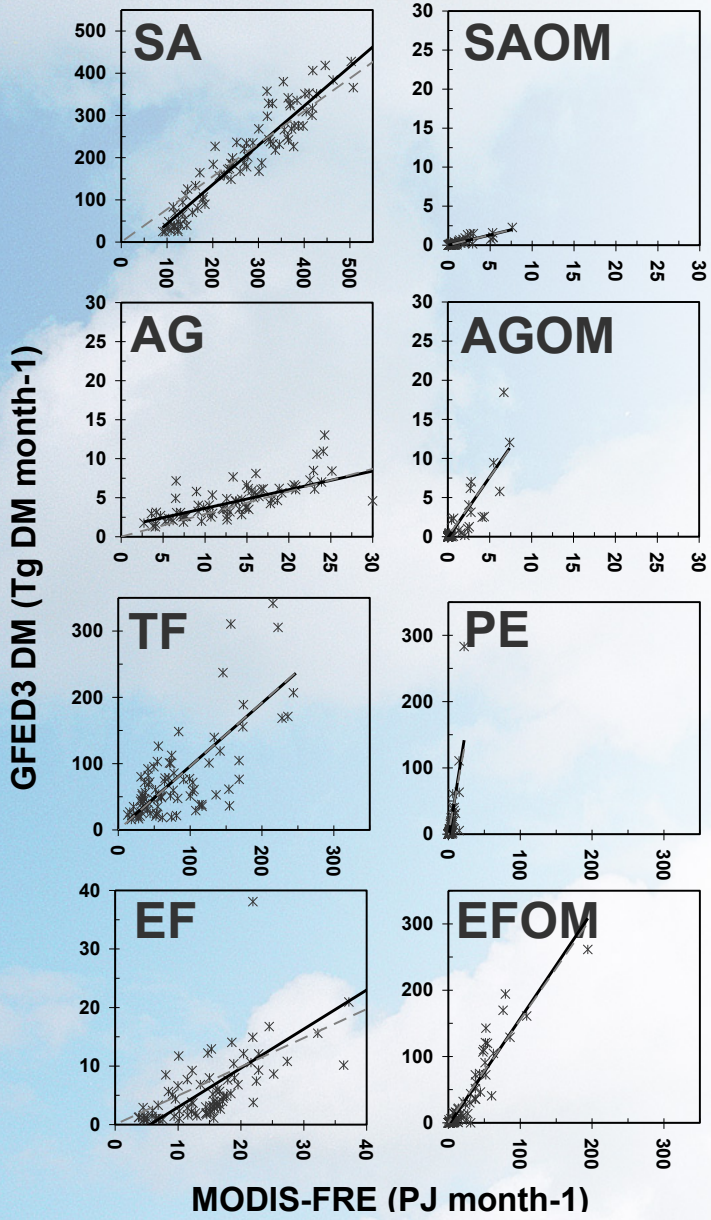
FRE = fire radiative energy [J] = ∫ FRP(t) dt

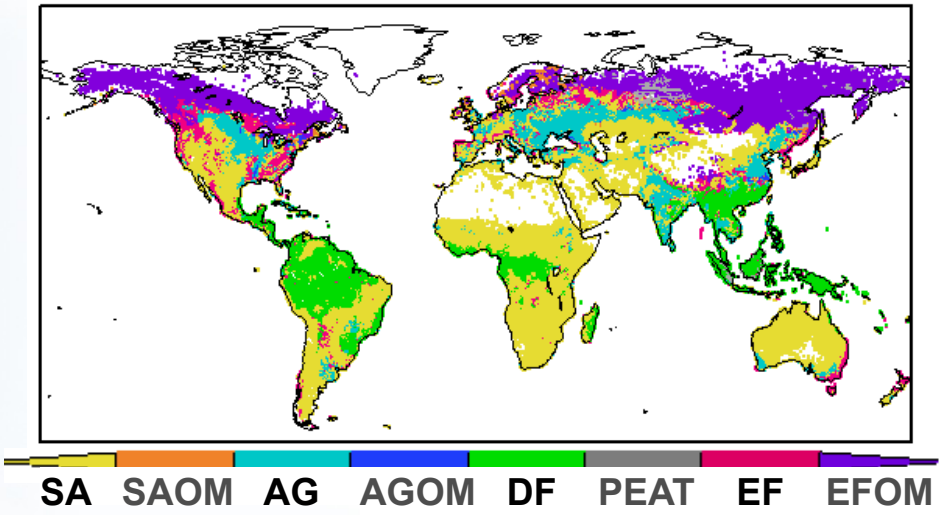
CF = conversion factor [kg(biomass) / W(FRE)]



graphics by M. Wooster

FRP conversion factor analysis against GFEDv3





SA: savannah fires
SAOM: SA with potential OM burning
AG: agricultural fires
AGOM: AG with potential OM burning
DF: tropical fires
PEAT: peat burning
EF: extra-tropical fires
EFOM: EF with potential OM burning

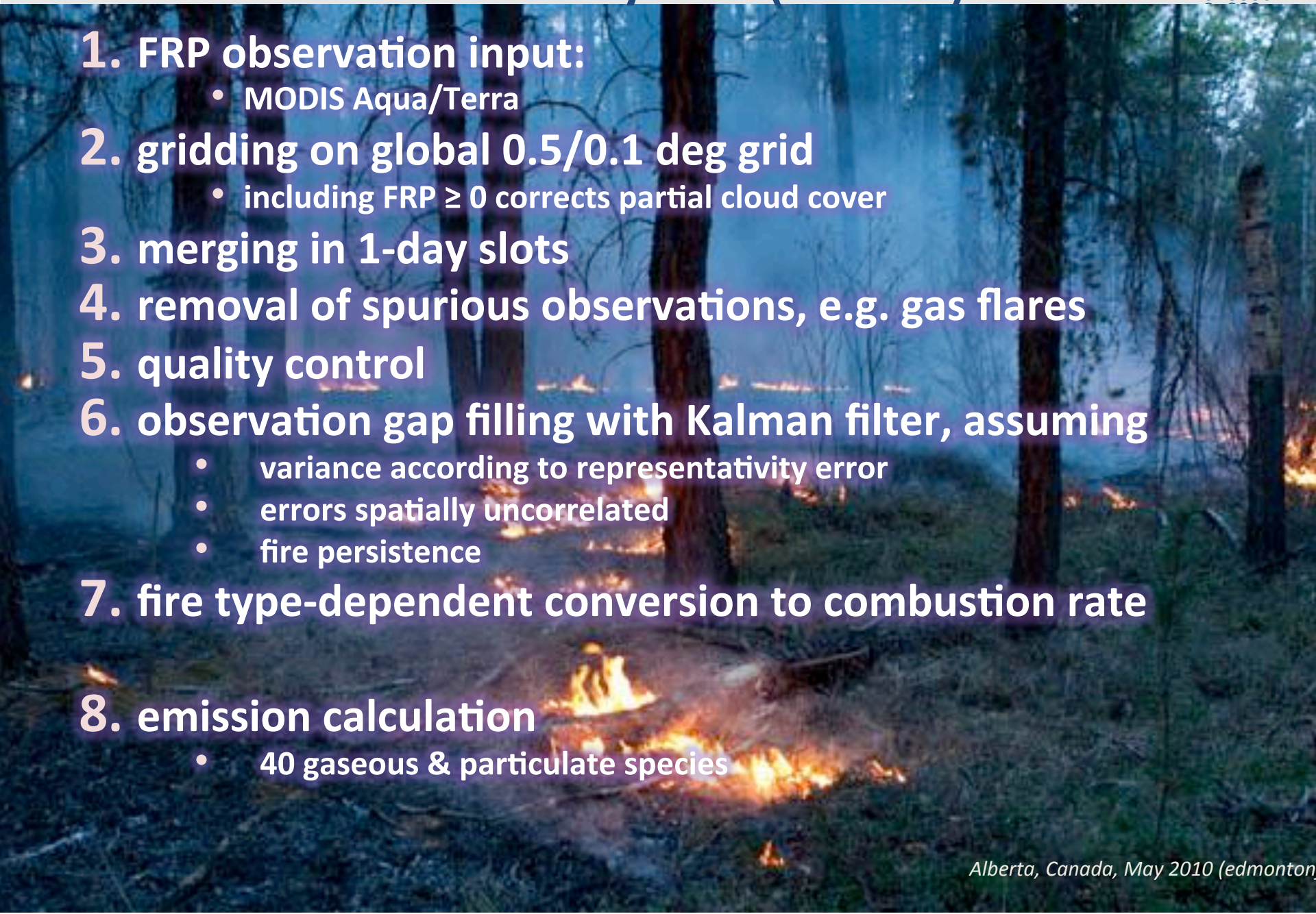
Conversion factor depends on dominant fire type!

[Heil et al., ECMWF TM628, 2010; Kaiser et al. BG 2012]

Paul Crutzen sampling biomass smoke

Brazil Campaign 1978,
Picture by P. Zimmerman

Global Fire Assimilation System (GFASv1)



1. FRP observation input:
   - MODIS Aqua/Terra
2. gridding on global 0.5/0.1 deg grid
   - including FRP ≥ 0 corrects partial cloud cover
3. merging in 1-day slots
4. removal of spurious observations, e.g. gas flares
5. quality control
6. observation gap filling with Kalman filter, assuming
   - variance according to representativity error
   - errors spatially uncorrelated
   - fire persistence
7. fire type-dependent conversion to combustion rate
8. emission calculation
   - 40 gaseous & particulate species

Alberta, Canada, May 2010 (edmonton

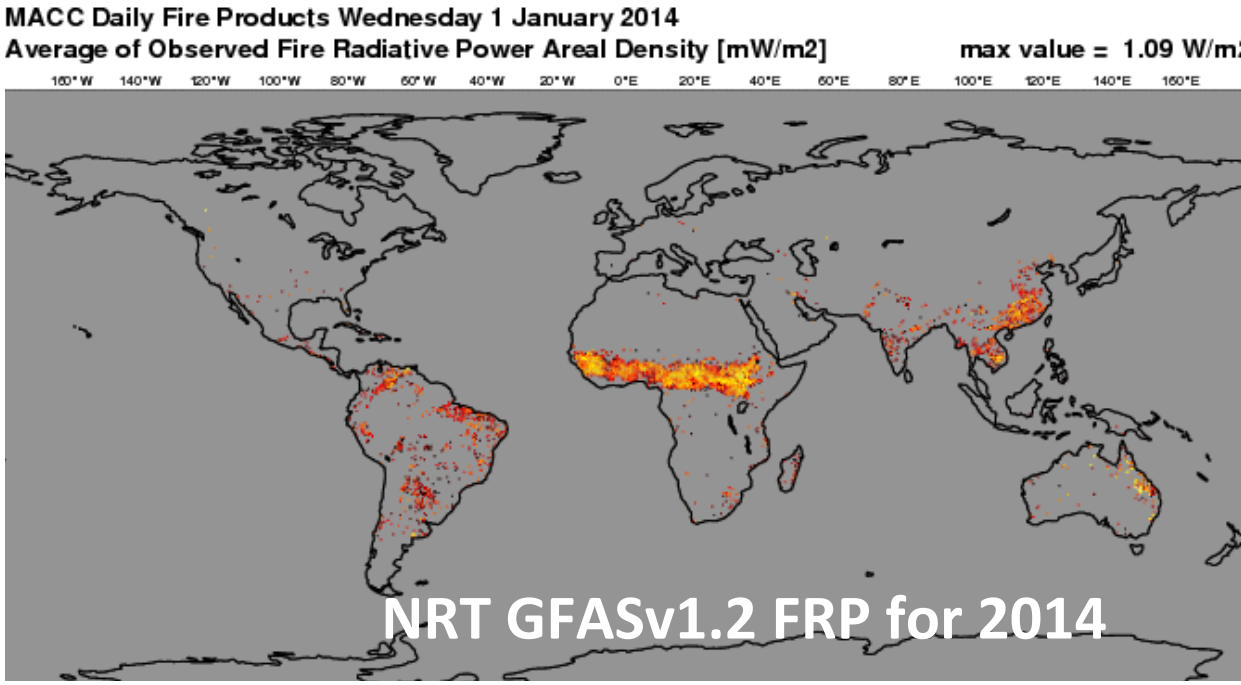
NRT production of daily GFAS FRP and emissions

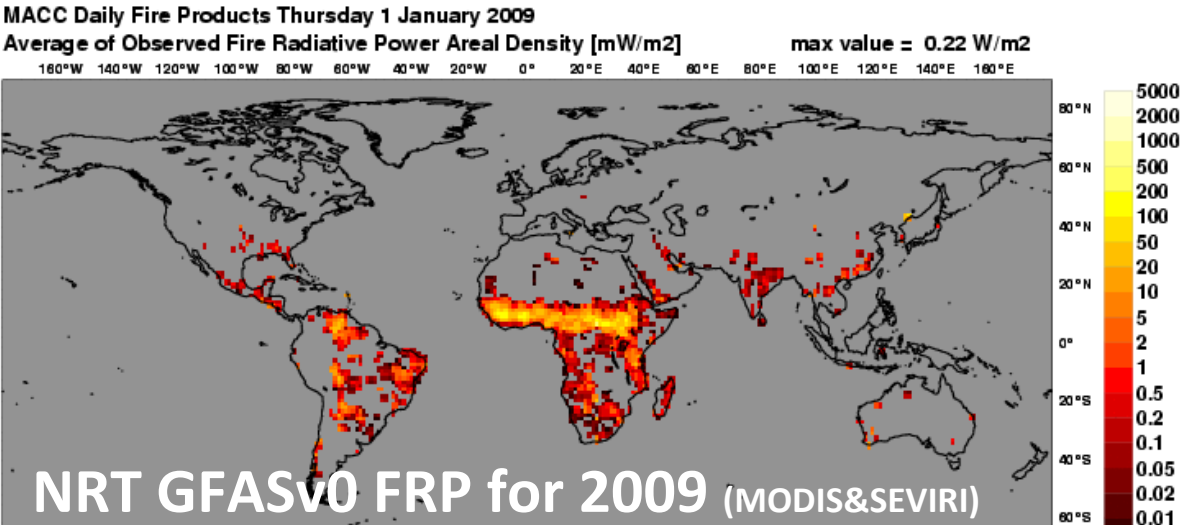
MODIS FRP-based
- quality controlled

FRP corrections
- partial cloud cover
- observations gaps
- **use FRP=0 observations**

spurious signal mask
- volcanoes
- gas flares / industry

FRP-to-combustion rate
- **land cover-dependent**
- regression against GFED3





GFASv1:
- 0.1° (~10 km) resolution
- 1 day resolution
- 2000—yesterday
- 40 species

[Kaiser et al. BG 2012]

Land-cover specific conversion is a combined approach.

- consistent with GFED3 inventory
  - within its accuracy
- advantages
  - quantitative information
  - low detection threshold (c.f. Randerson et al. 2012)
  - real-time availability
- disadvantage
  - cloud cover
  - spares sampling

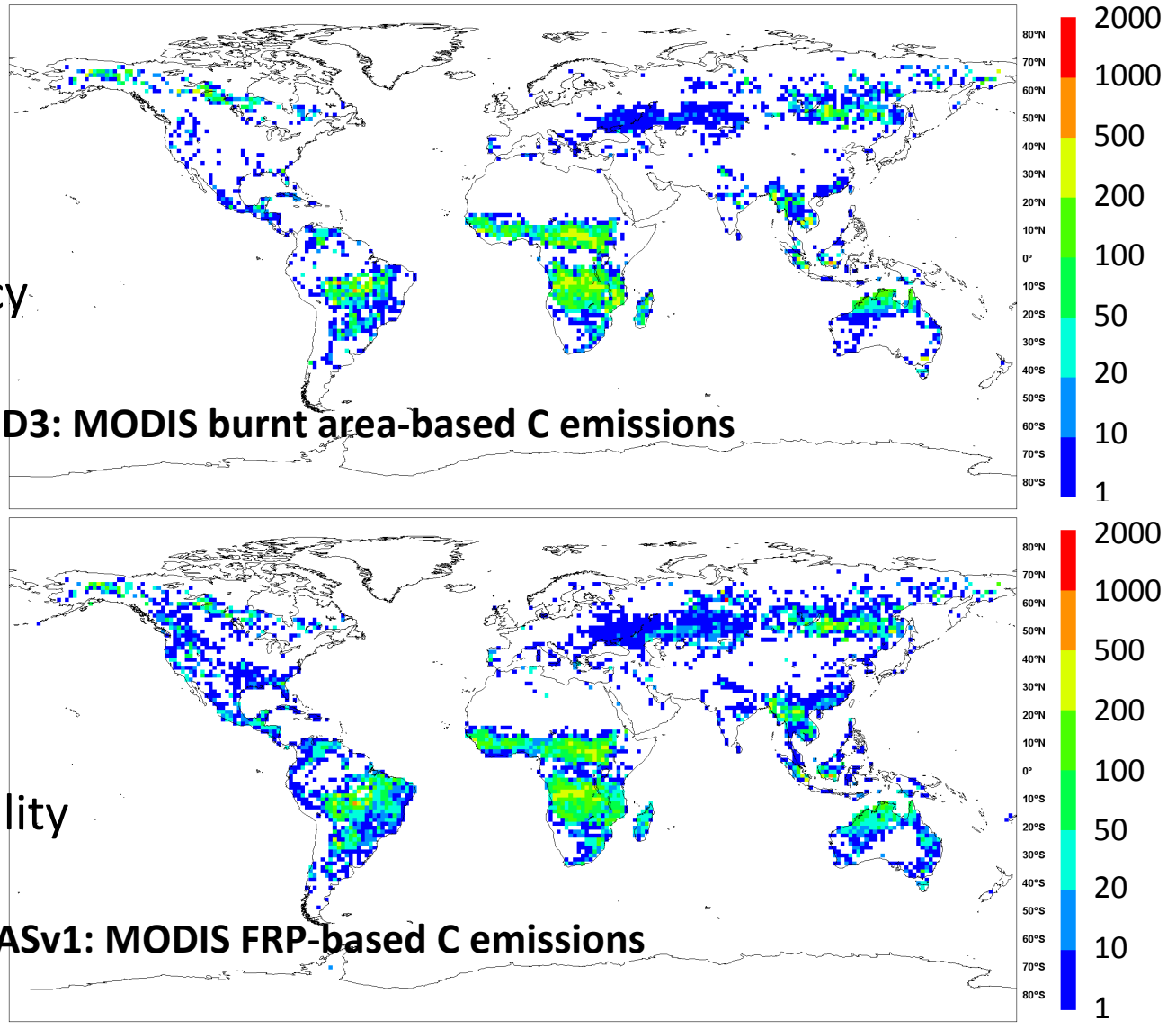
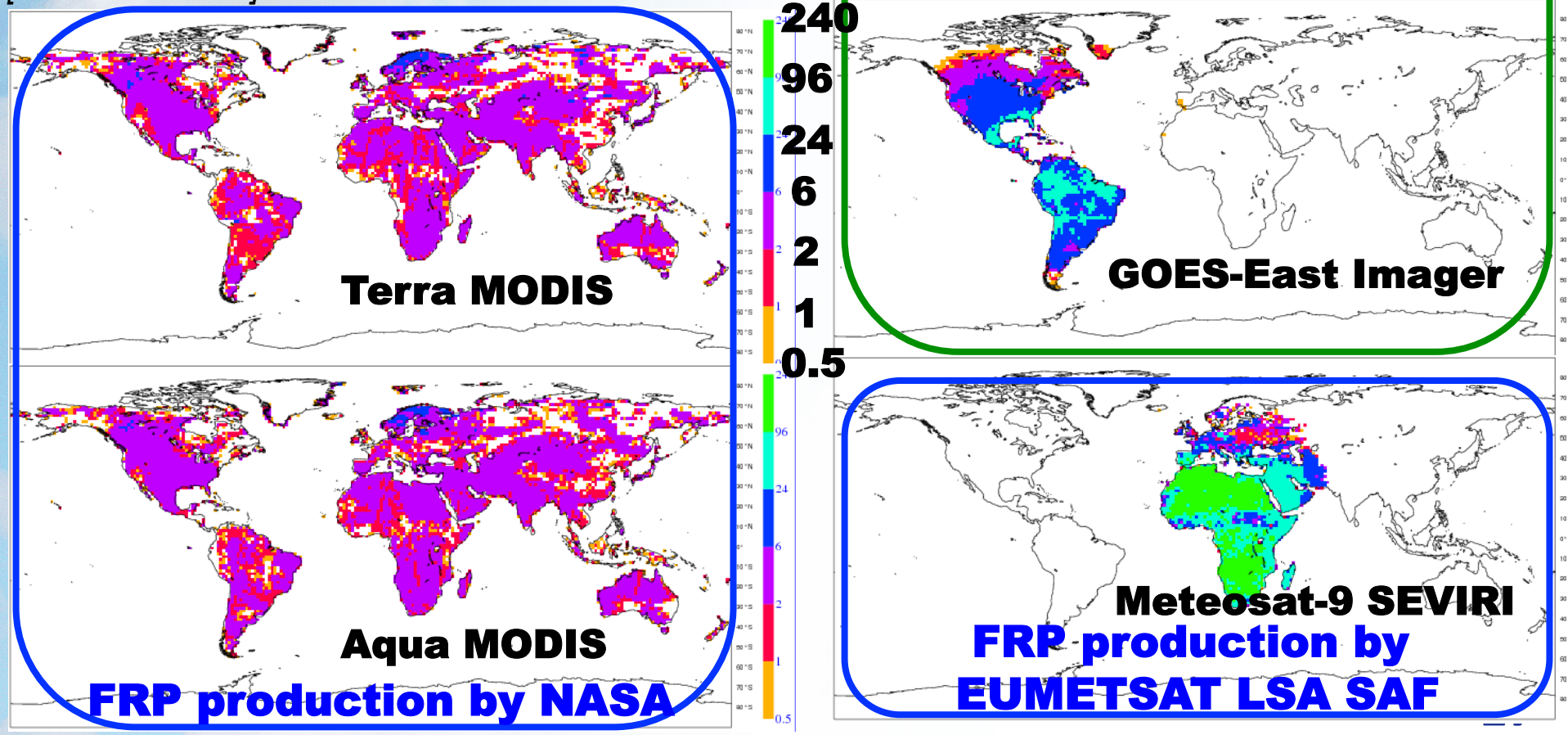


Fig. 5. Average distribution of carbon combustion [g(C) a^{-1} m^{-2}] during 2003–2008 in GFED3.1 (top) and GFASv1.0 (bottom). *(Kaiser et al. 2012)*

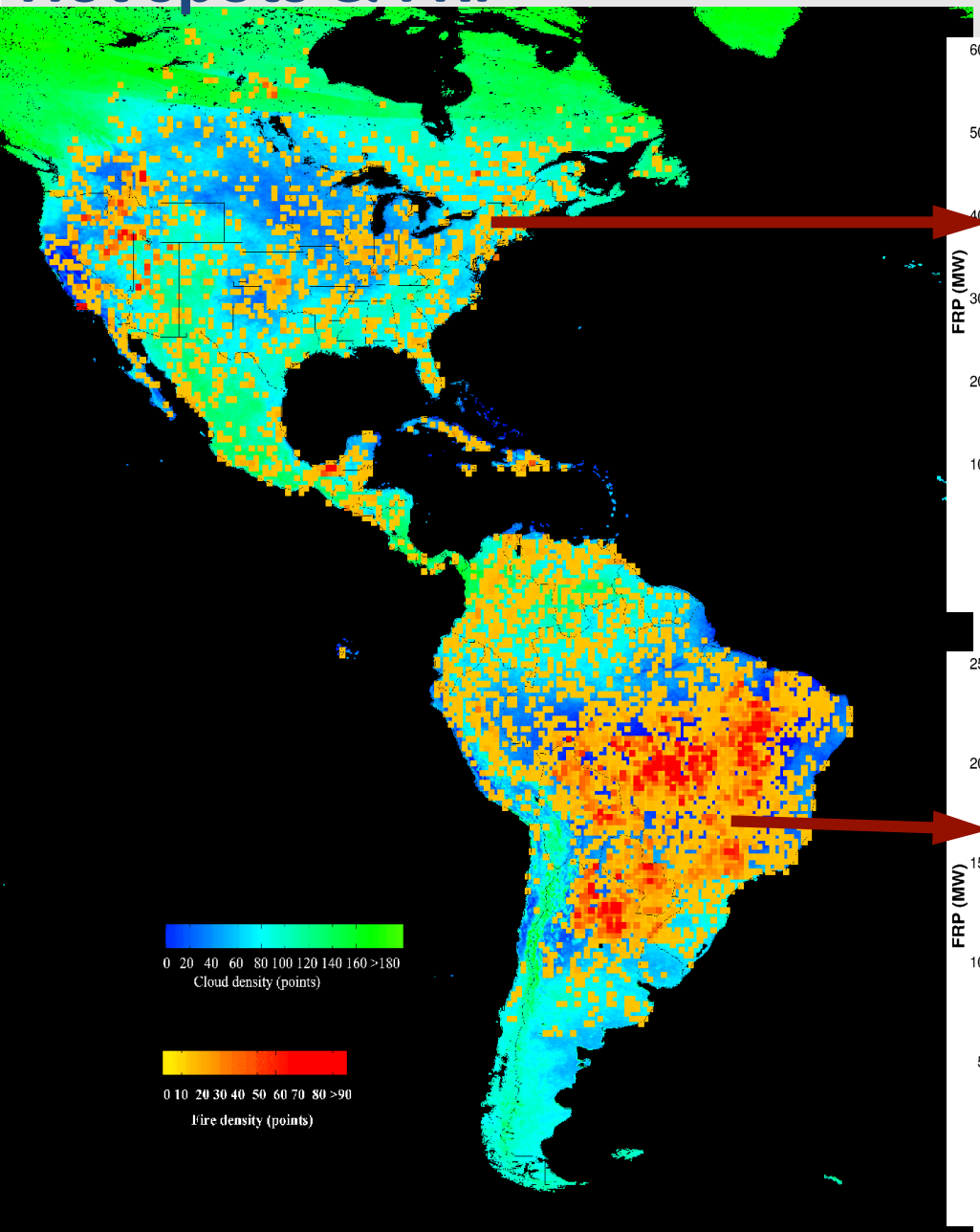
Observational FRP Coverage

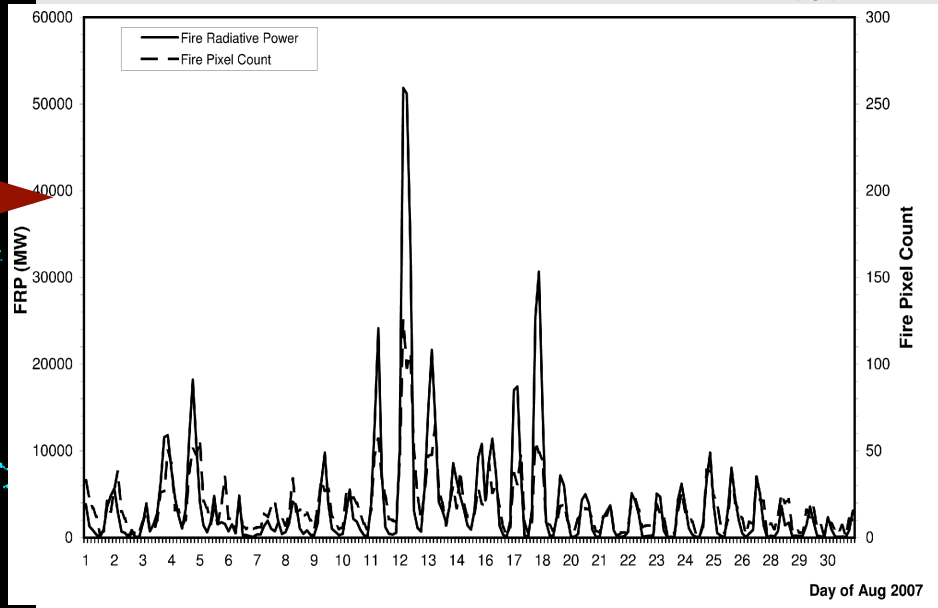
- average number of observations
  - damped for large VA
- of any area in 0.5 deg grid cell
- during 1 day

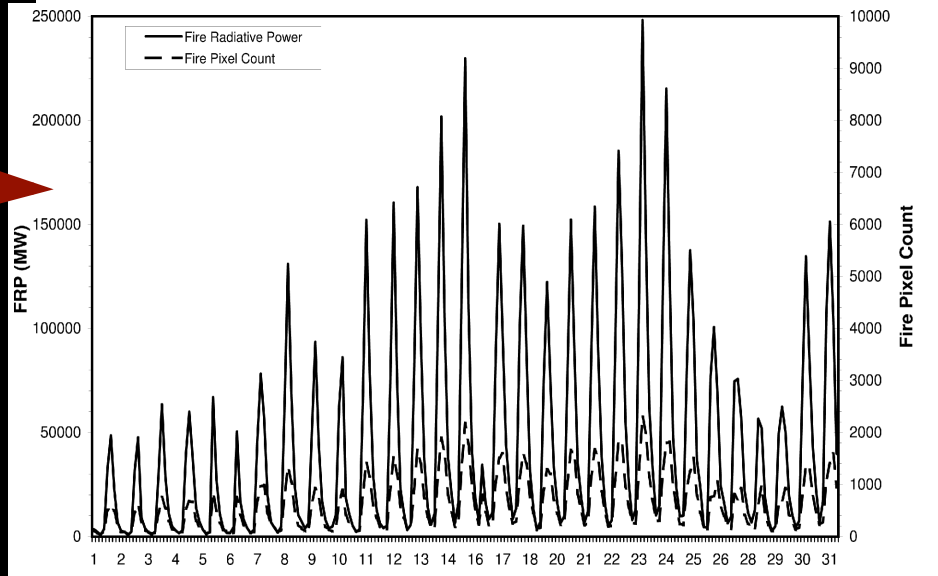
[Kaiser et al. 2011]



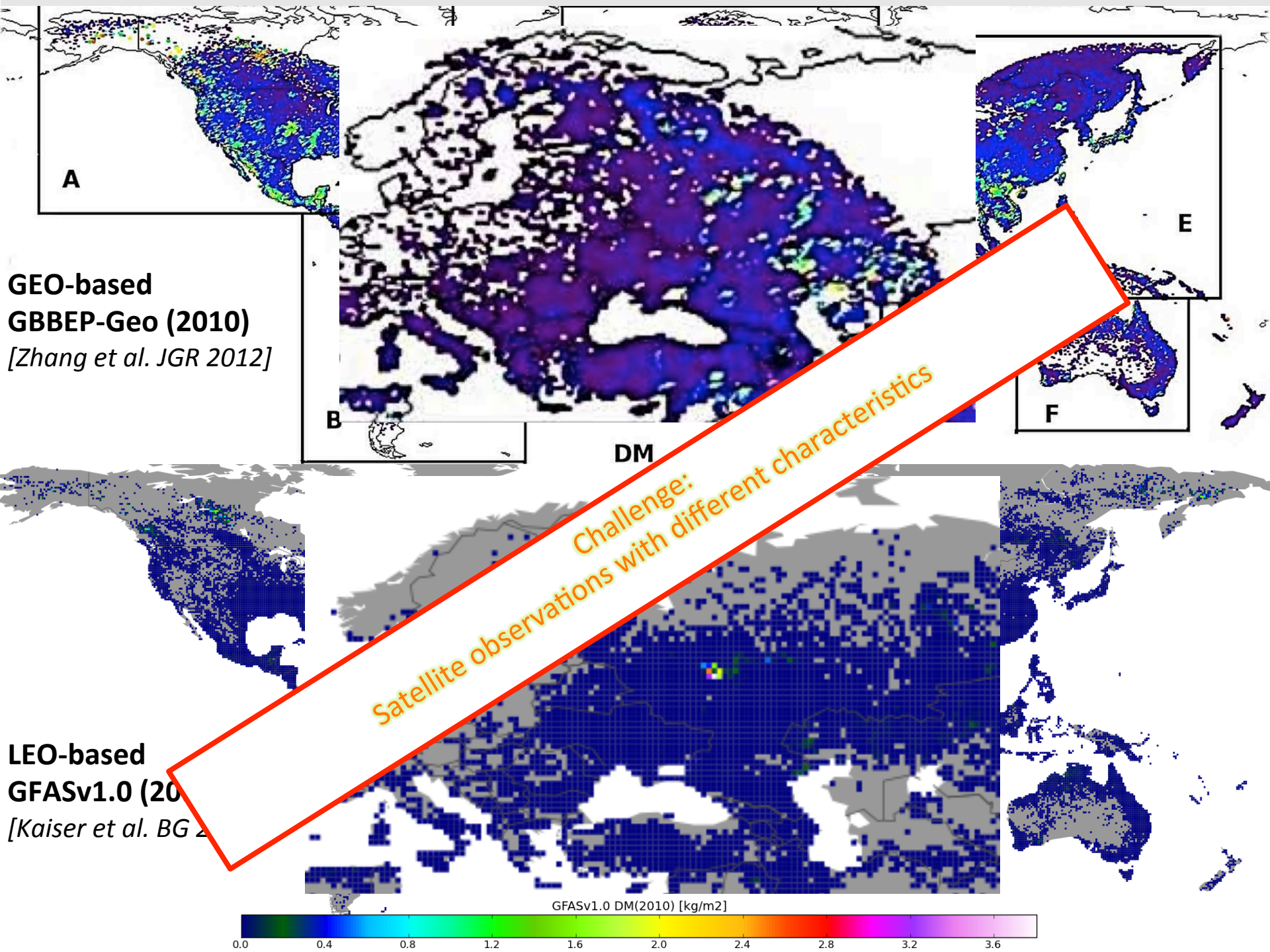
Fires Diurnal Cycle in Americas from GOES-W: Hot spots & FRP







[Xu et al. 2010]


A
B
E
F
DM
GEO-based
GBBEP-Geo (2010)
[Zhang et al. JGR 2012]
Challenge:
Satellite observations with different characteristics
LEO-based
GFASv1.0 (20
[Kaiser et al. BG 2
GFASv1.0 DM(2010) [kg/m2]
0.0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6

Emissions in regional weather model

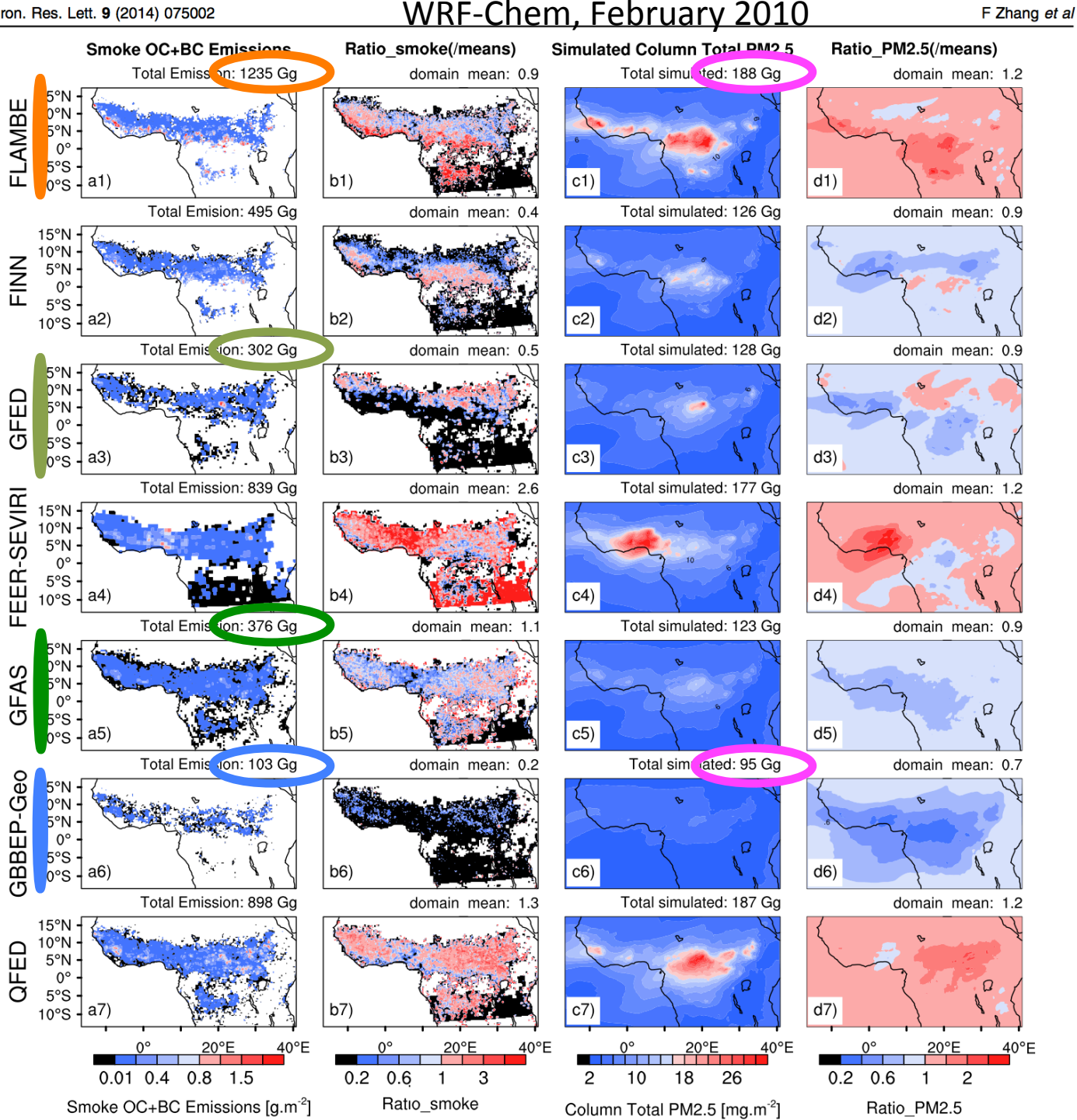
consistent with

- GFED
- other data

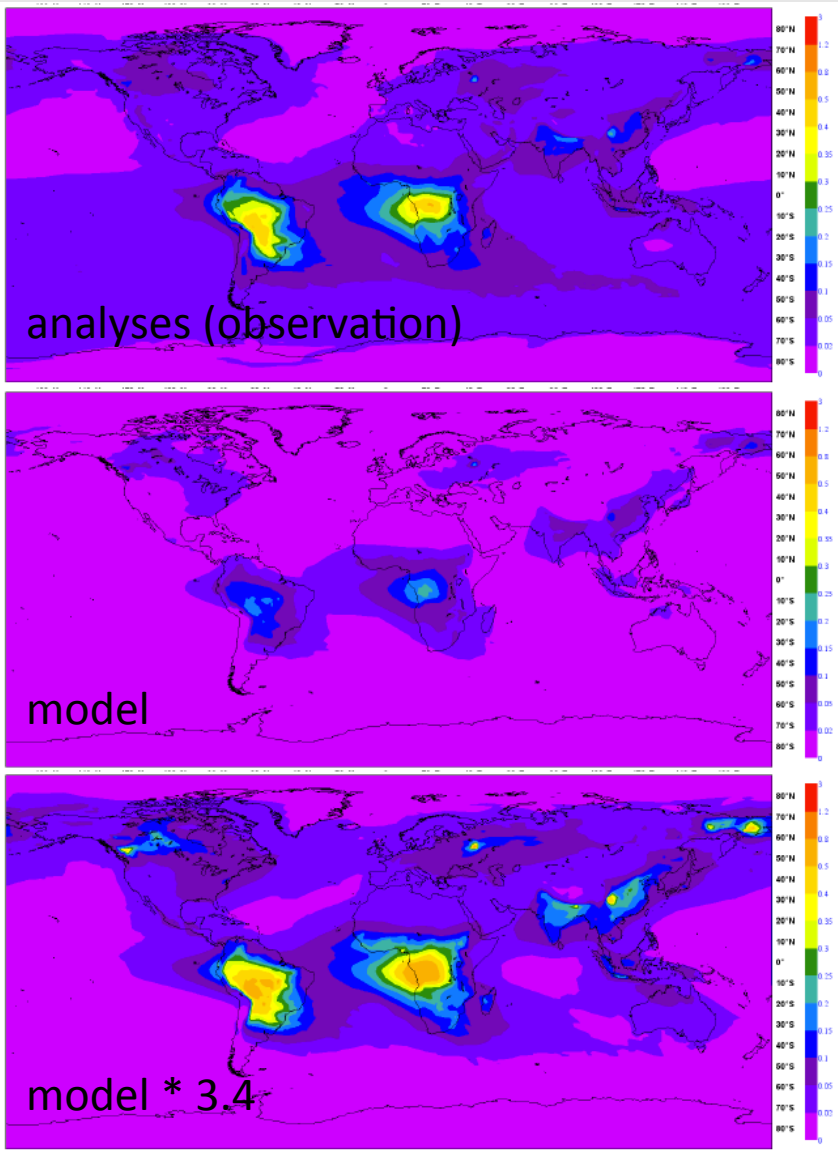
<u>WRF-Chem:</u>

regional atmospheric load and radiative forcing less then linear with emissions

.



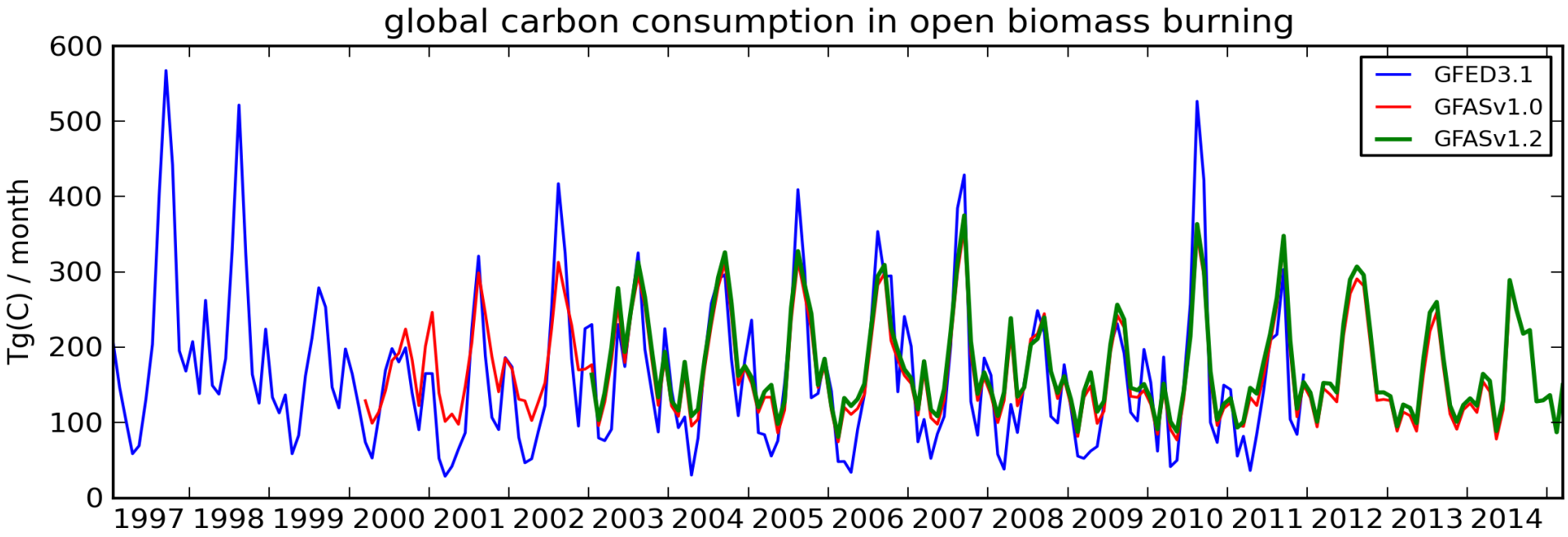
Validation of Aerosol Emissions: AOD(OM) + AOD(BC)



[Kaiser et al. BG 2012]

- assimilation of MODIS AOD
  - active: "analyses"
  - passive: "model"
- average of 15 Jul – 31 Dec 2010
- AOD (OM+BC) low by mean factor 3.4
  - similar to other top-down estimates:
    - NASA (GFED2.2)
    - NRL (Reid et al. 2009)
    - IS4FIRES (Sofiev et al. 2009)
    - aerosol inversions (Huneeus et al. 2012)
  - inconsistent with bottom-up estimates:
    - GFED2/3 (van der Werf et al. 2006/10)
    - published emission factors (e.g. Andreae & Merlet 2001)
    - INPE/CPTEC (Freitas et al. 2005)
- Petrenko et al. 2012: regional variability
- recommendations:
  - correct emissions by factor 3.4
  - do multi-parameter analysis

Bias correction for individual satellites gives long time series



During 2000-2002 only MODIS on Terra satellite is available.

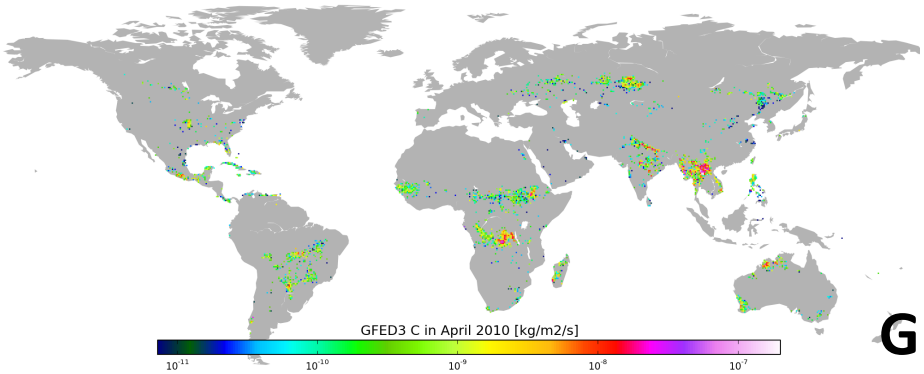
- Terra is sampling the morning with low fire activity.
- correction coefficients derived for operating GFASv1.0 with one MODIS

[Remy & Kaiser ACP 2014]

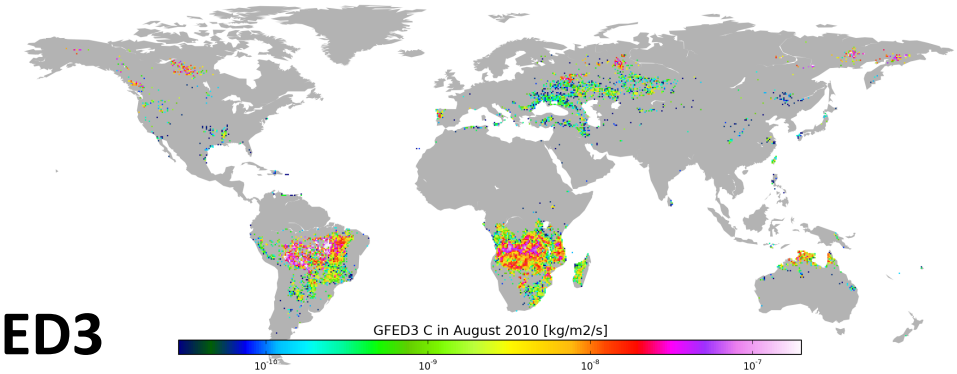
Annual cycle amplitude differences, here 2010

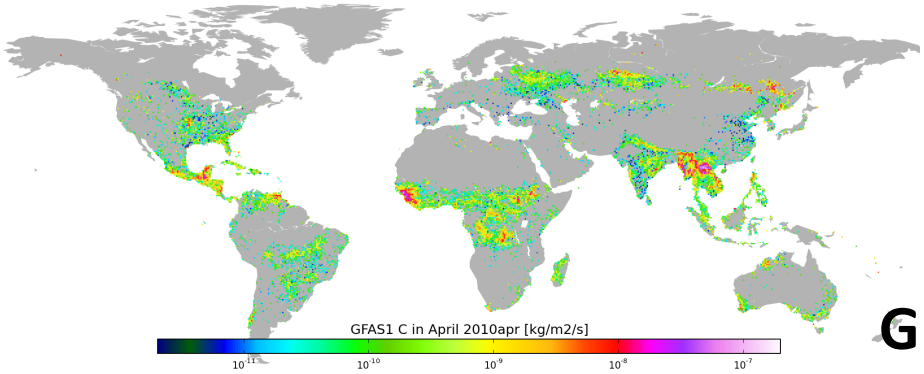
Minimum: April

Maximum: August

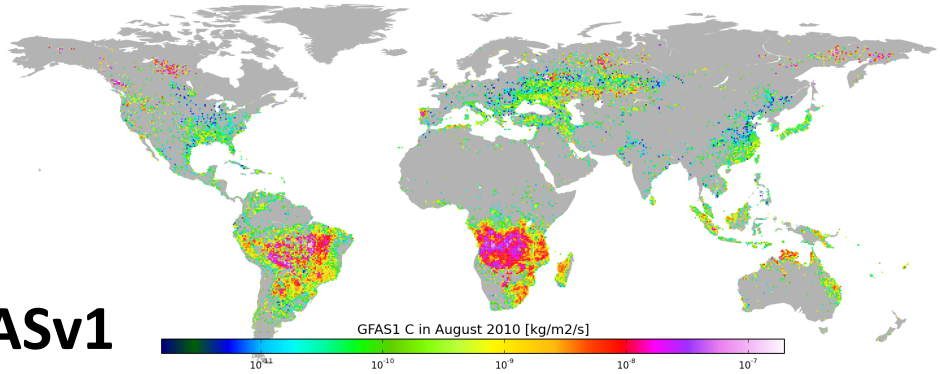


GFED3





GFASv1



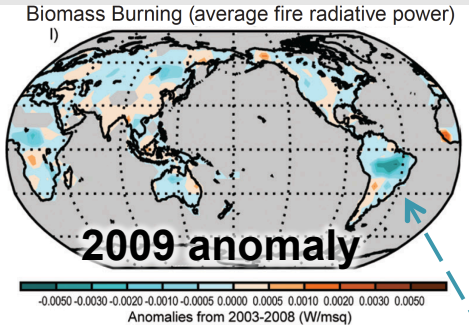
Monitoring of GCOS
Essential Climate Variable Fire disturbance

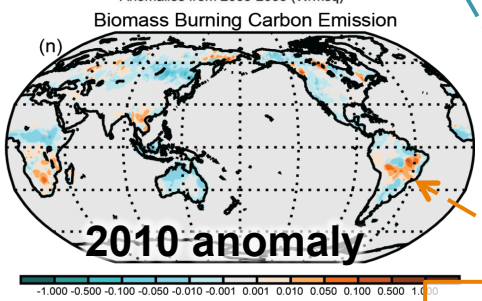
burnt area

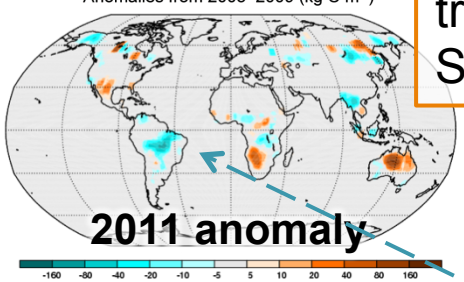
fire radiative power

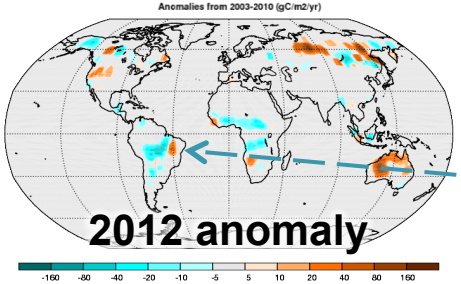
active fire maps

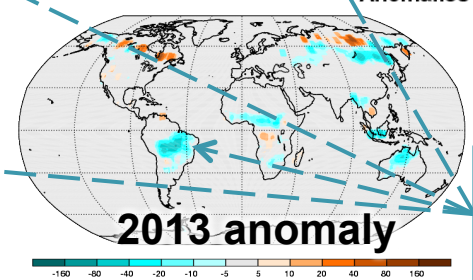
Fire climate monitoring

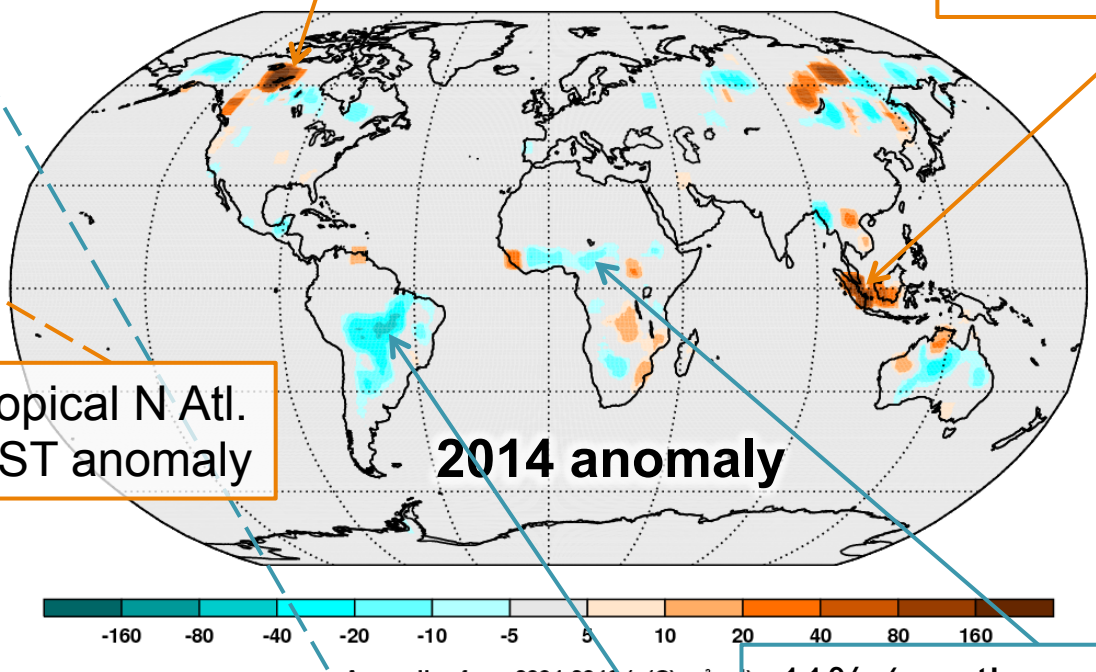












0% global anomaly

+70% (high temp., low precip.)

+129% (decoupled from ENSO)

tropical N Atl. SST anomaly

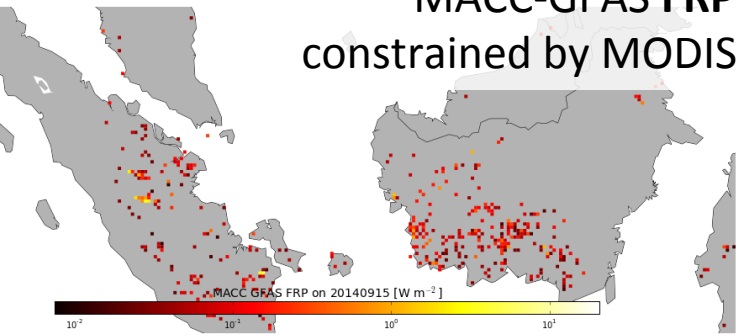
-11% (continued trend, conversion to agriculture) *[Andela & van der Werf 2014]*

-41% (continued trend, reduced deforestation)

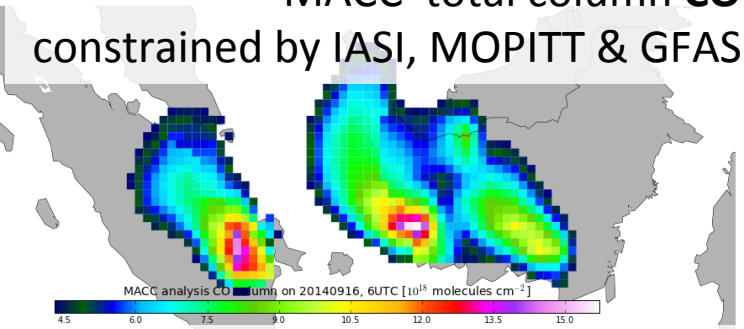
From BAMS *State of the Climate* reports: *[Kaiser & Goldammer BAMS 2010] [Kaiser et al. BAMS 2011] [Kaiser & van der Werf BAMS 2012-2015] graphics courtesy Kate Willett*

Atmospheric analysis consistent with fires

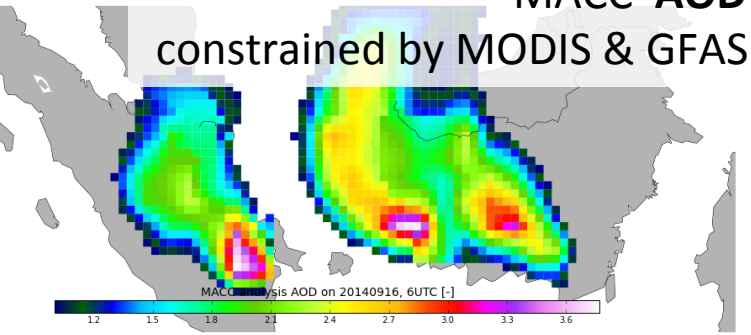
MACC-GFAS **FRP** constrained by MODIS



MACC total column **CO** constrained by IASI, MOPITT & GFAS



MACC **AOD** constrained by MODIS & GFAS

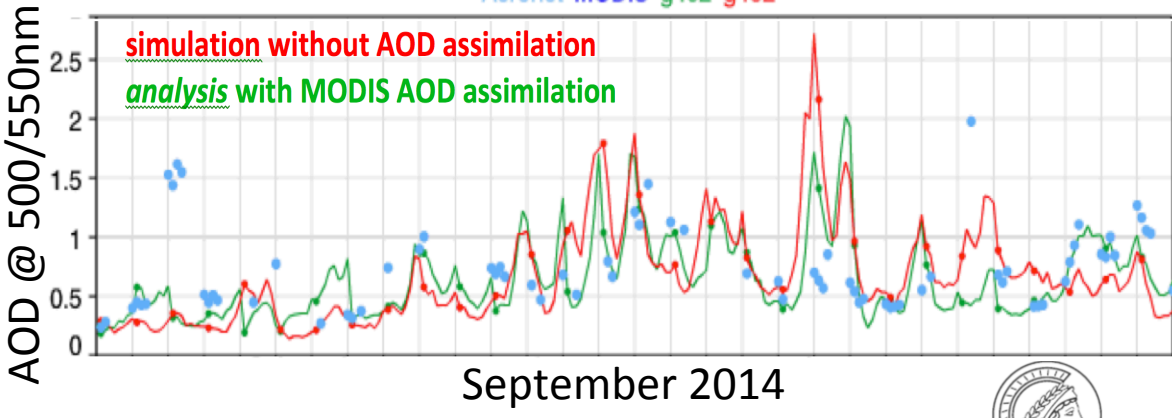


aerosol and CO analysis

- constrained by satellite observations and fire emissions
- validated by independent observations
- confirm fire anomalies

Comparison of g4e2 & g4o2 and MODIS AOT at 550nm and L1.5 Aeronet AOT at 500nm over Singapore (1.30°N, 103.78°E). Model: 00UT, 1-30 Sep 2014, T+3 to T+24.

Aeronet MODIS g4e2 g4o2



Copernicus Atmosphere Monitoring Service

(CAMS)

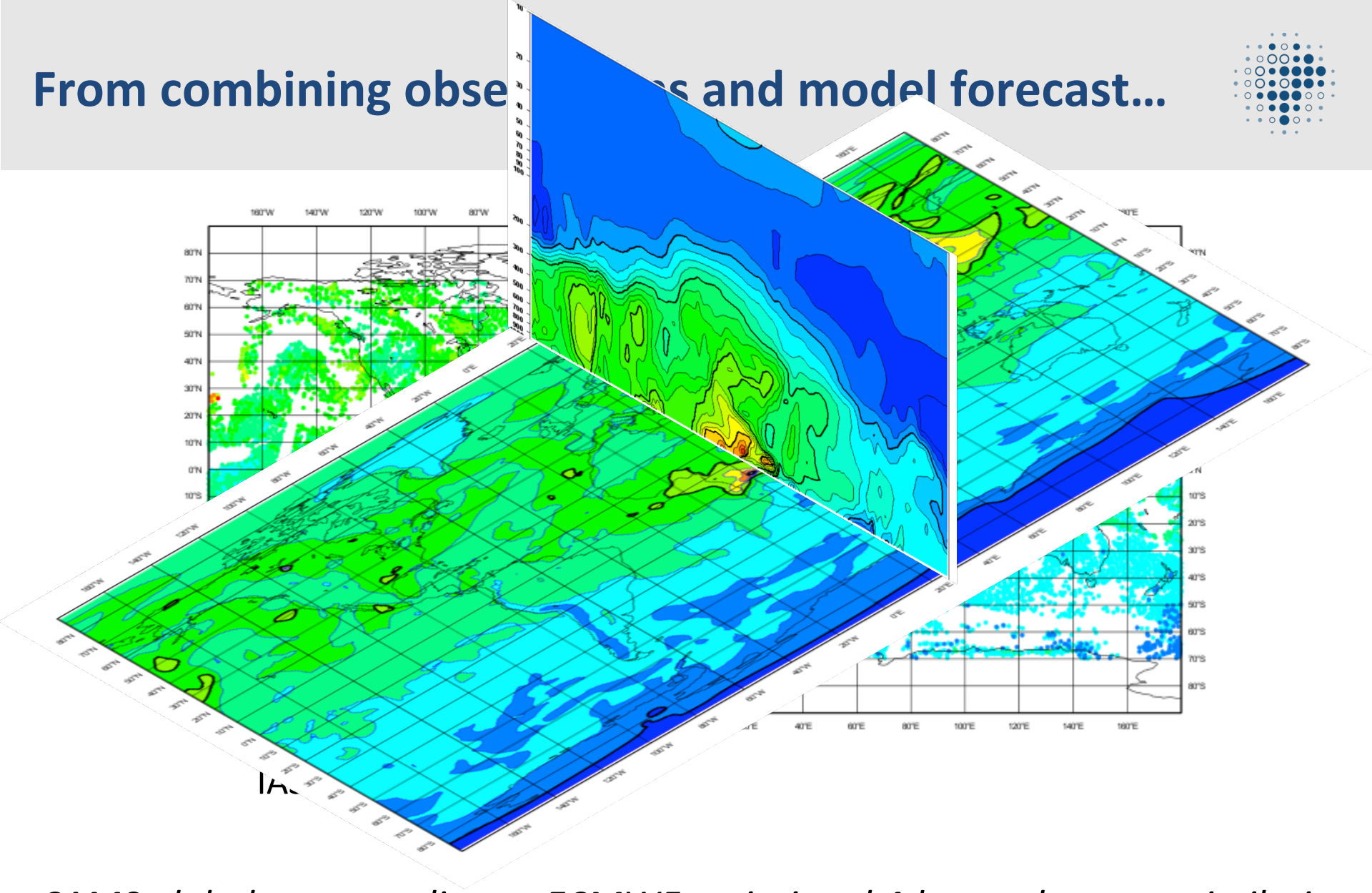
CAMS – MACC - GFAS

- Copernicus Atmosphere Monitoring Service (CAMS)
  - **operational monitoring and forecasting**
  - addressing atmospheric aerosols &reactive/greenhouse gases
  - long-term funded by EU (until at least 2020)

- Monitoring of Atmospheric Composition and Climate projects (MACC-I/-II/-III, GEMS, PROMOTE)
  - developed and implemented **services for CAMS**
  - funded in EU FP-6/-7, H2020

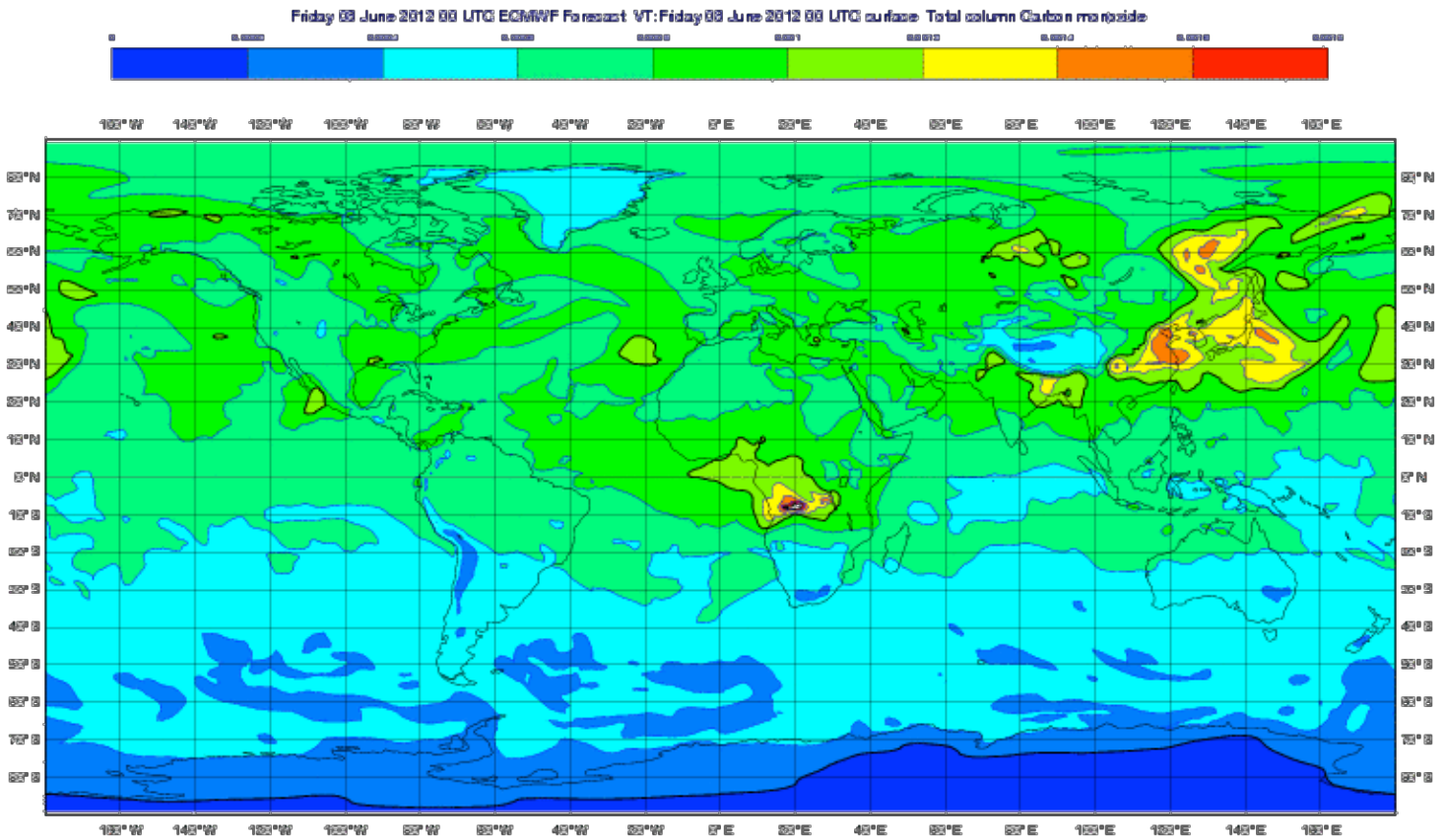
- Global Fire Assimilation System (GFAS)
  - estimate **global FRP and smoke constituent fluxes**
  - uses satellite observations of fire radiative power (FRP)
  - developed in series of MACC projects

From combining obse s and model forecast…



CAMS global system relies on ECMWF variational 4d-var scheme, assimilating a range of remote-sensing data to deliver analyses (illustrated here with the case of Carbon Monoxide, a tracer of combustion sources).

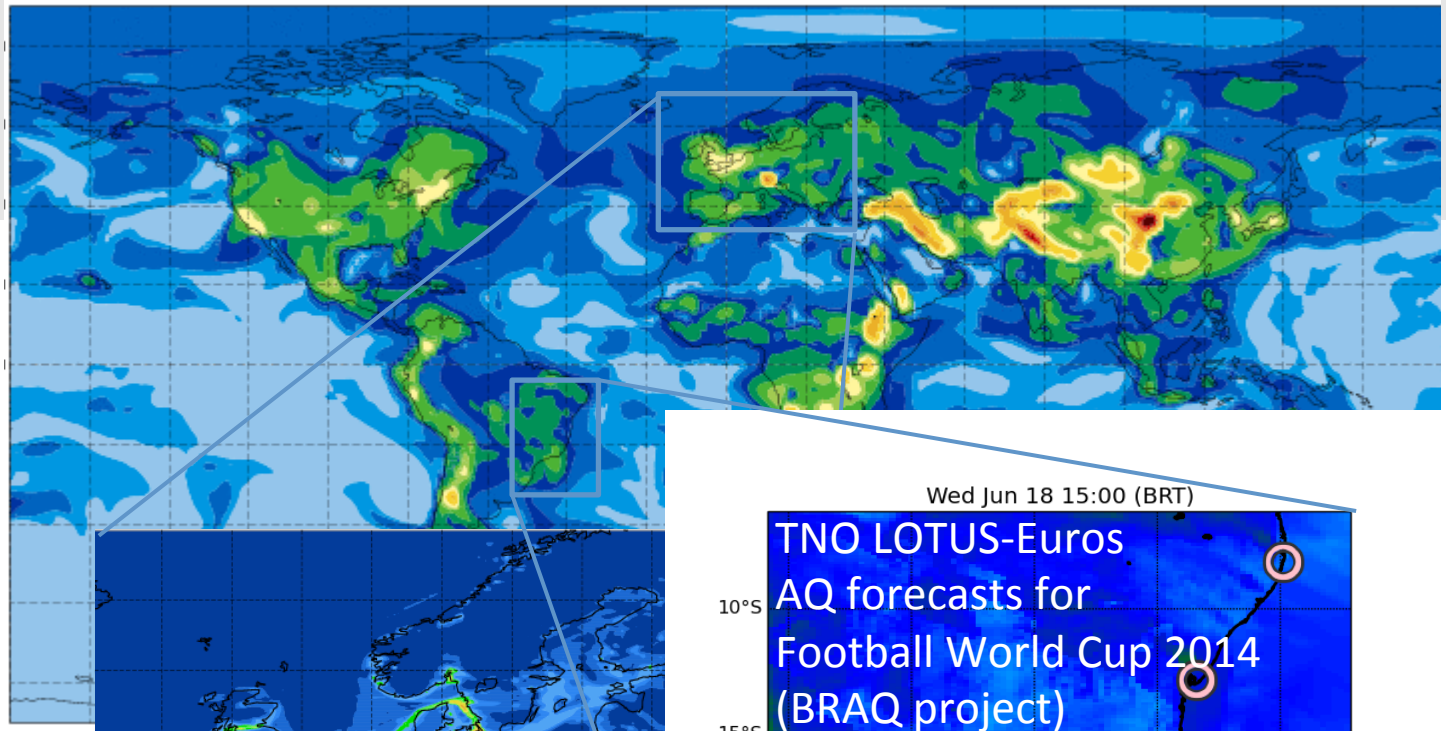
… to global forecasting…

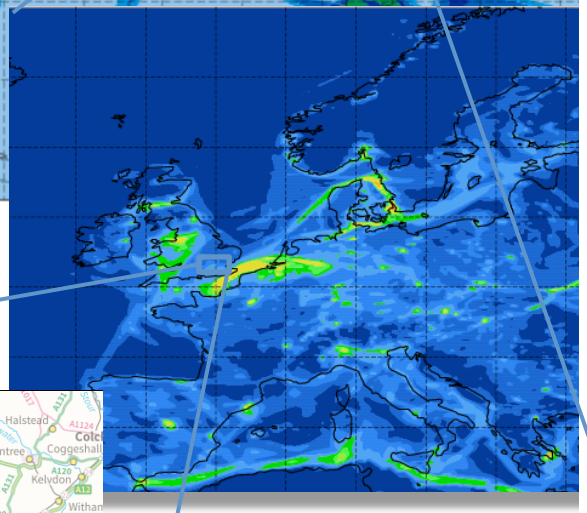


CAMS provides daily 5-day global forecasts with a horizontal resolution of 80km and a time resolution of 3 hours, using a "chemistry-enabled" version of ECMWF/IFS.

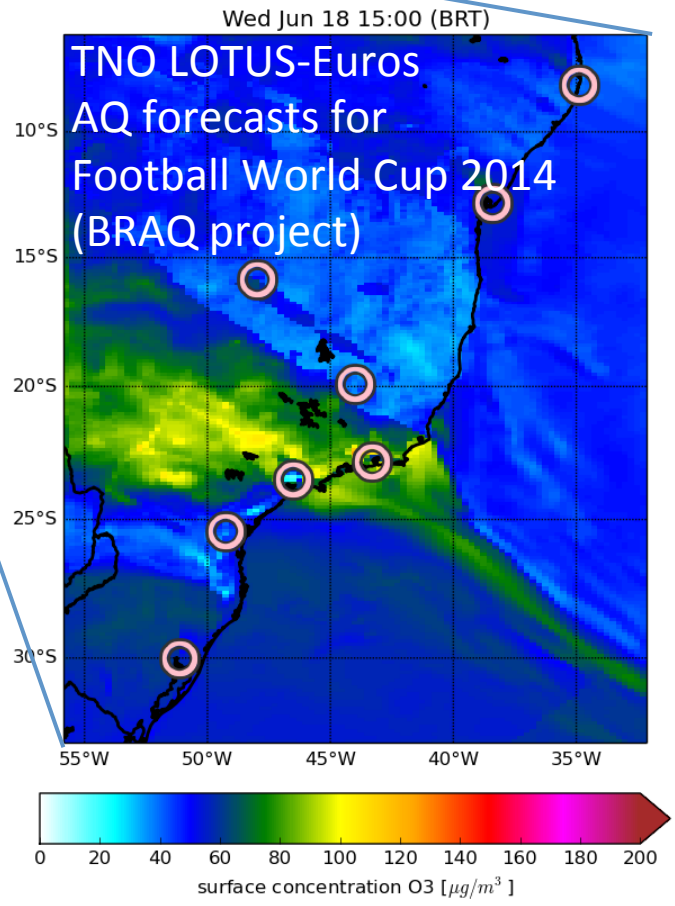
… to local air quality

obsAIRve
a GMES air quality service



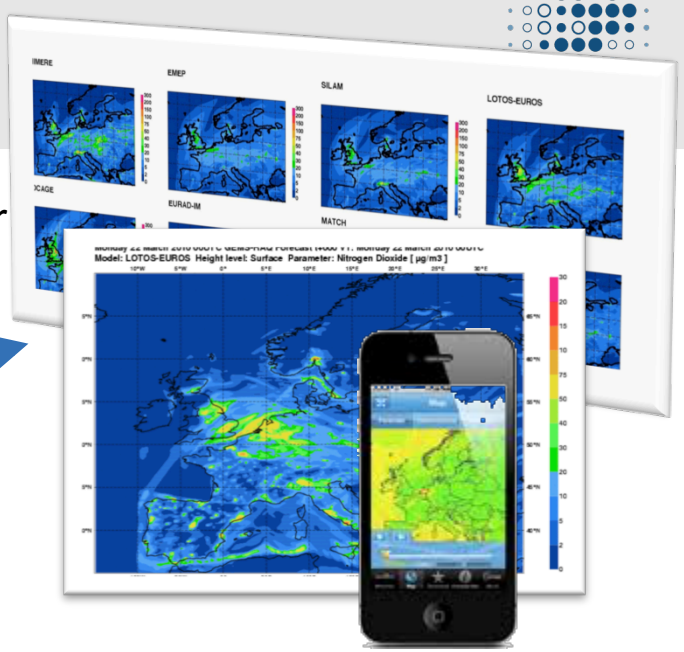


KURIER

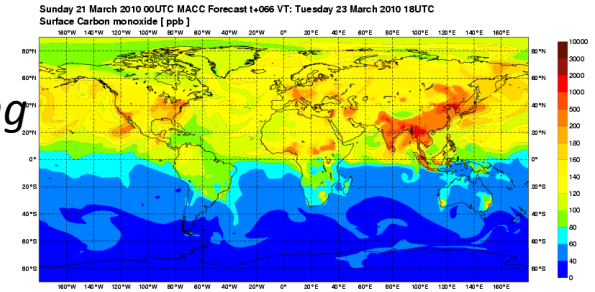


http://atmosphere.copernicus.eu
Near-Real-Time Service Provision

European Air Quality

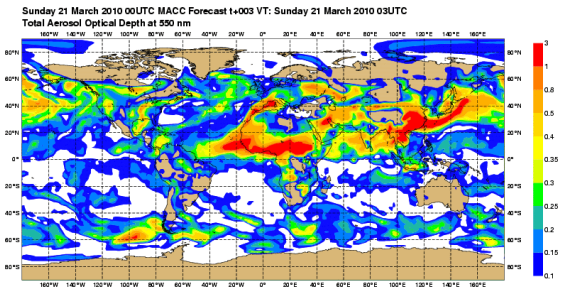


Global Pollution

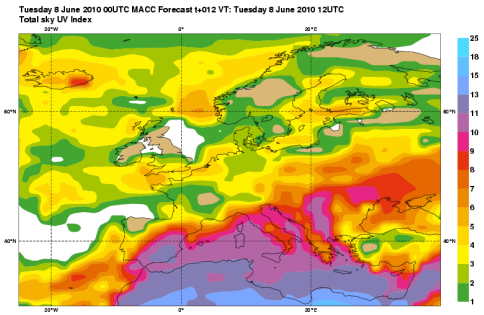


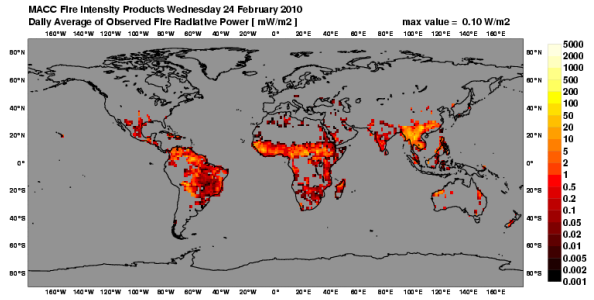
Biomass burning emissions

Aerosol



UV index





CAMS NRT System (AER&RG)

Satellite observations that are assimilated in the global NRT system

Instrument	Satellite	Space Agency	Data Provider	Species
MODIS	EOS-Aqua, EOS-Terra	NASA	NASA	AOD, FRP
MLS	EOS-Aura	NASA		O3 profile
OMI	EOS-Aura	NASA	KNMI	O3, NO2, SO2
SBUV-2	NOAA-16, -17, -18, and -19	NOAA	NOAA	O3 profile
IASI	METOP-A, METOP-B	EUMETSAT/CNES	ULB/LATMOS	CO
MOPITT	EOS-Terra	NASA	NCAR	CO
GOME-2	METOP-A, METOP-B	EUMETSAT/ESA	DLR	O3

Satellite observations that are monitored in the global NRT system

Instrument	Satellite	Space Agency	Data Provider	Species
GOME-2	METOP-A, METOP-B	EUMETSAT/ESA	DLR	NO2, SO2, HCHO
SEVIRI	METEOSAT	EUMETSAT	LandSAF	O3, FRP
Imager	GOES-11, -12	NOAA	UCAR	FRP radiances

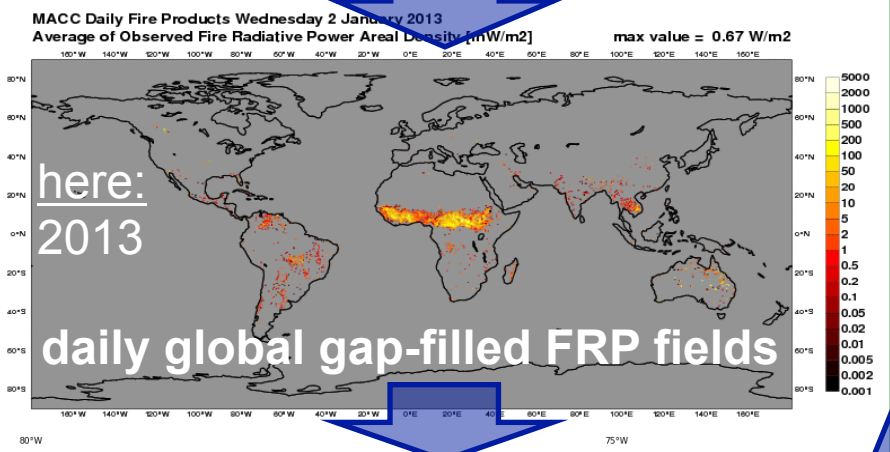
Satellite observations that are planned for the global NRT system

Instrument	Satellite	Space Agency	Data Provider	Species
CALIOP	CALIPSO	NASA		aerosol lidar backscatter
OMPS	Suomi NPP	NASA		O3
IASI	METOP-A, -B	EUMETSAT/CNES	EUMETSAT	O3 radiances
Imager	MTSAT-2	JMA	JMA	FRP radiances
VIIRS	Suomi NPP	NASA/NOAA	EUMETSAT	AOD, FRP
SEVIRI	MSG	EUMETSAT	ICAR	AOD

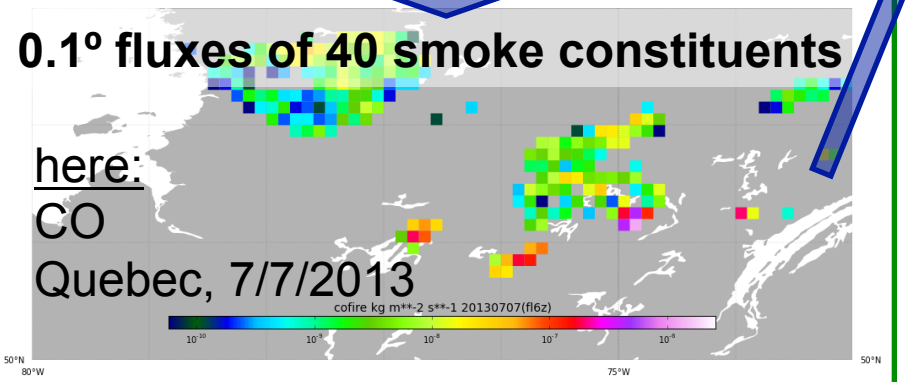
GFAS in MACC & Canadian smoke over Europe (July 2013)

satellite products of CO, AOD, etc.

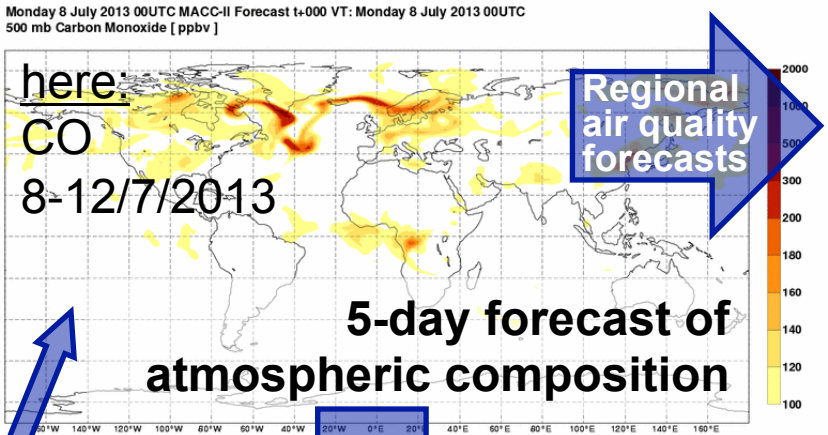
MODIS Fire Radiative Power (FRP)
SEVIRI, GOES, VIIRS, SLSTR in preparation

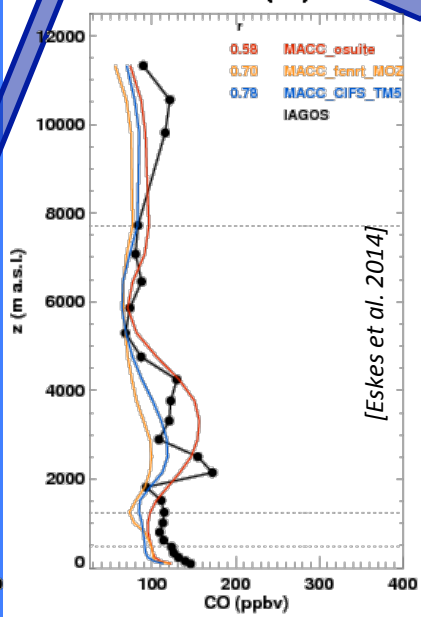


0.1º fluxes of 40 smoke constituents



Global Fire Assimilation System (GFAS) in CAMS *[Kaiser et al. 2012]*





Validation of 1-day forecast over Paris:
observations
model with GFAS
model with GFAS & satellite CO assim.

=> good location and timing, source strength to be improved further

[Inness et al. 2009, Flemming et al. 2014, Morcrette et al. 2009, Benedetti et al. 2009]

Global Atmosphere Modelling in CAMS (up to now "MACC-I/-II/-III")

High resolution atmospheric CO_2 forecast

CO_2 INITIAL CONDITIONS

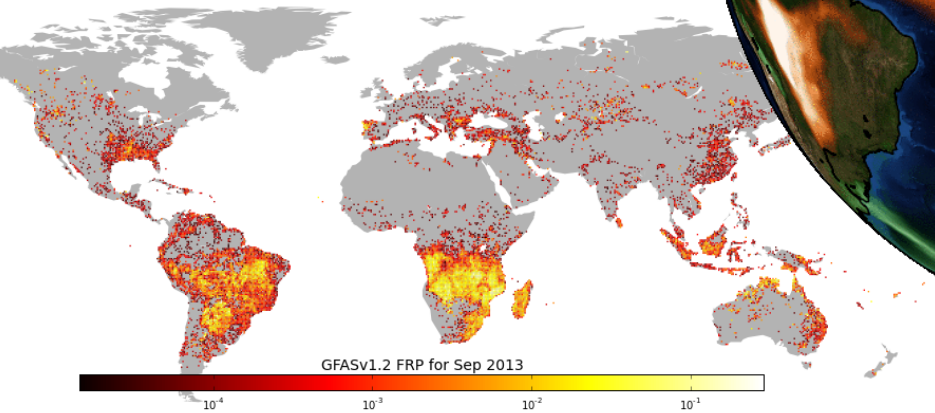
NRT atm. CO_2 analysis, i.e. constrained by GOSAT observation

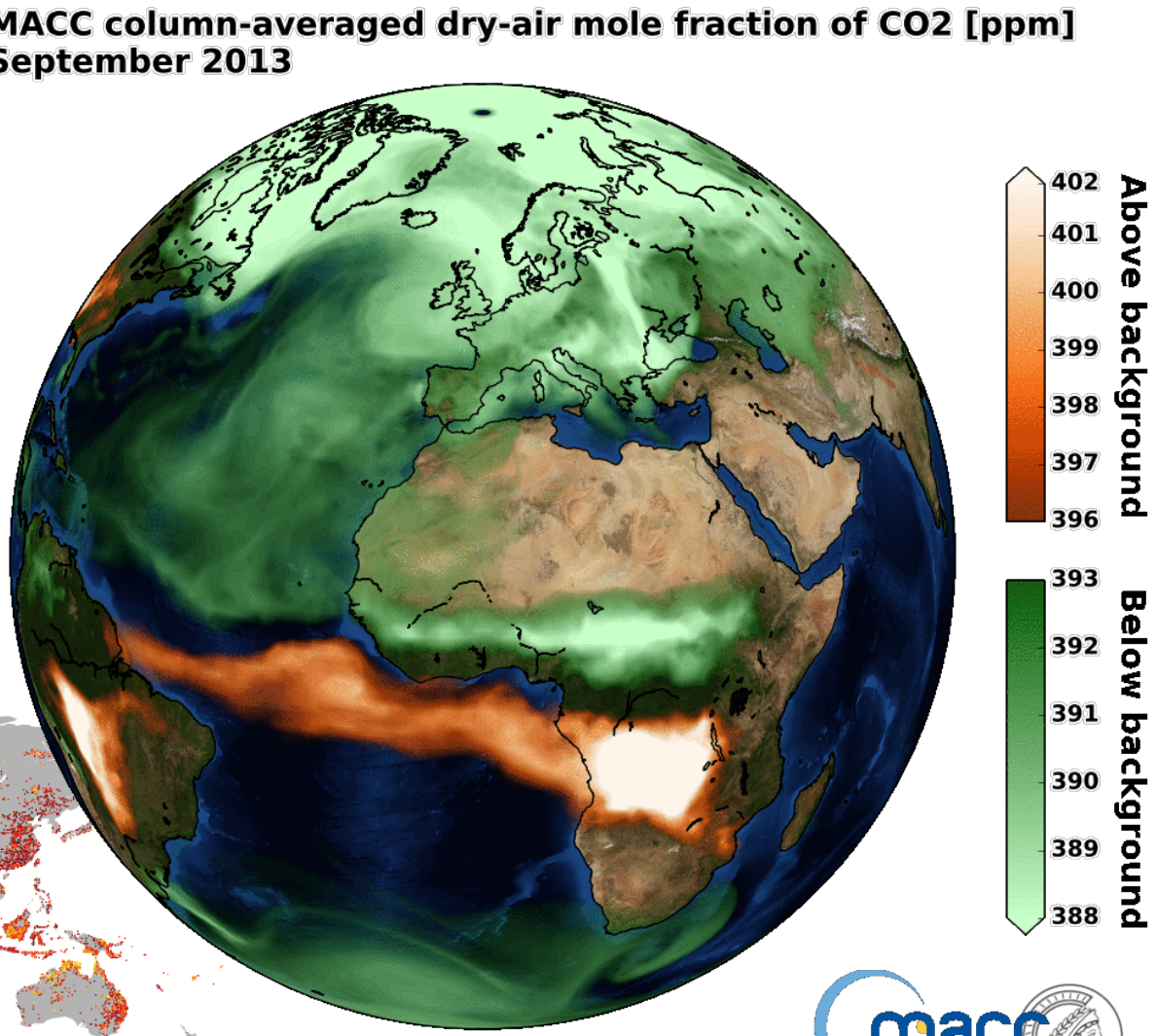
IFS TRANSPORT

At weather forecast resolution (16km,L137)

CO_2 SURFACE FLUXES

Vegetation fluxes + flux adjustment (CTESSEL)
Ocean (inventory)
Anthropogenic (inventory)
Fires (GFAS)





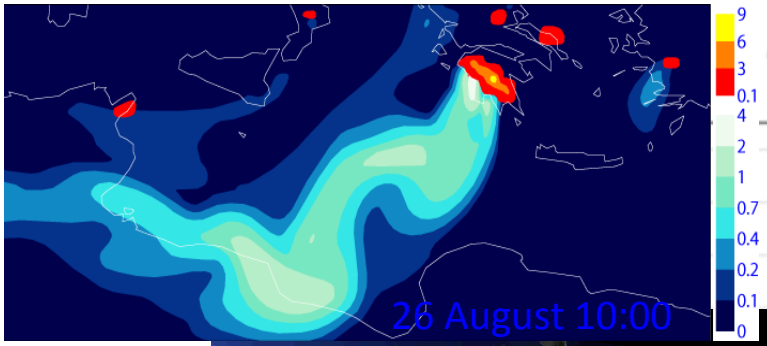
Fire and smoke plume cases

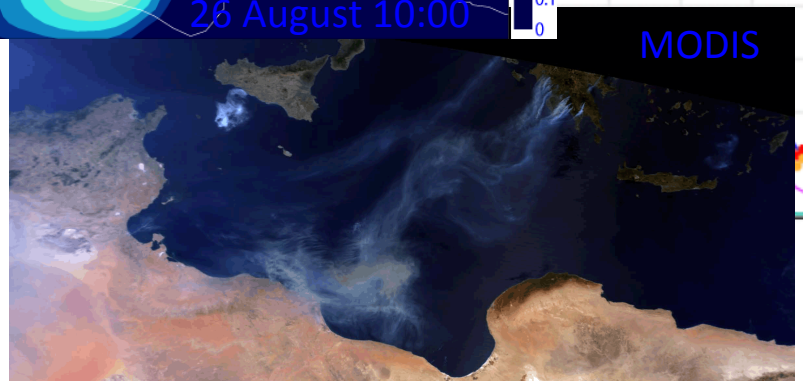
Modelled AOD of Mediterranean Fire Plumes, August 2007

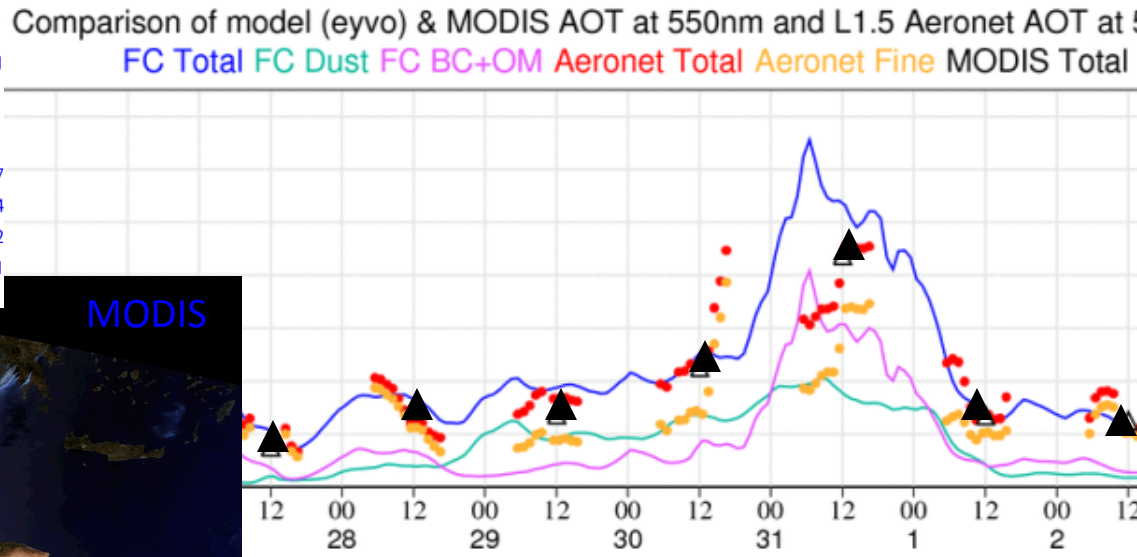
Emissions calculated from Fire Radiative Power observed by SEVIRI on Meteosat.

Emission factors from *Andreae & Merlet 2001* scaled to *Ichoku & Kaufman 2005*.

Run at 25km global resolution, which is typical for regional models.

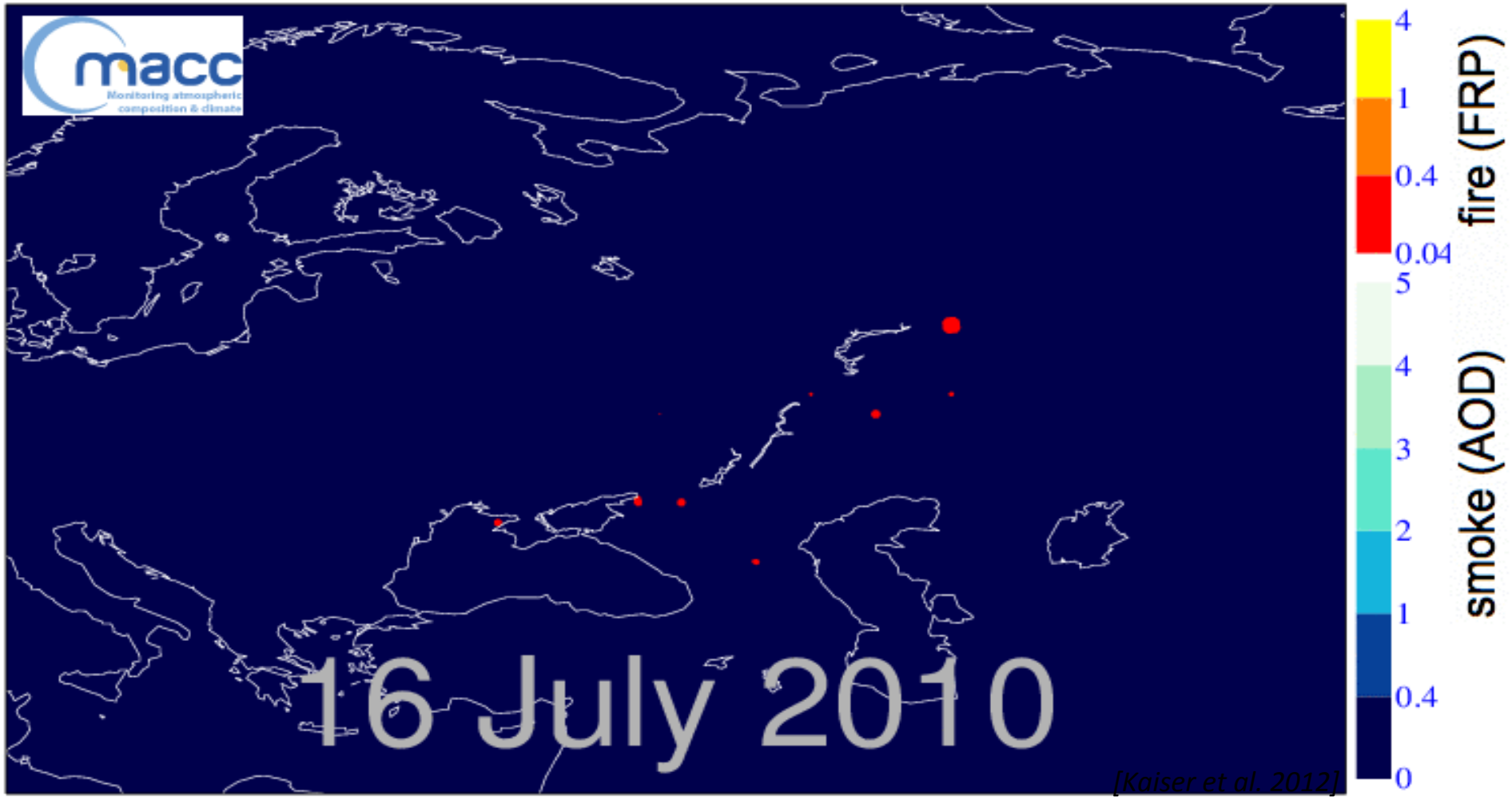






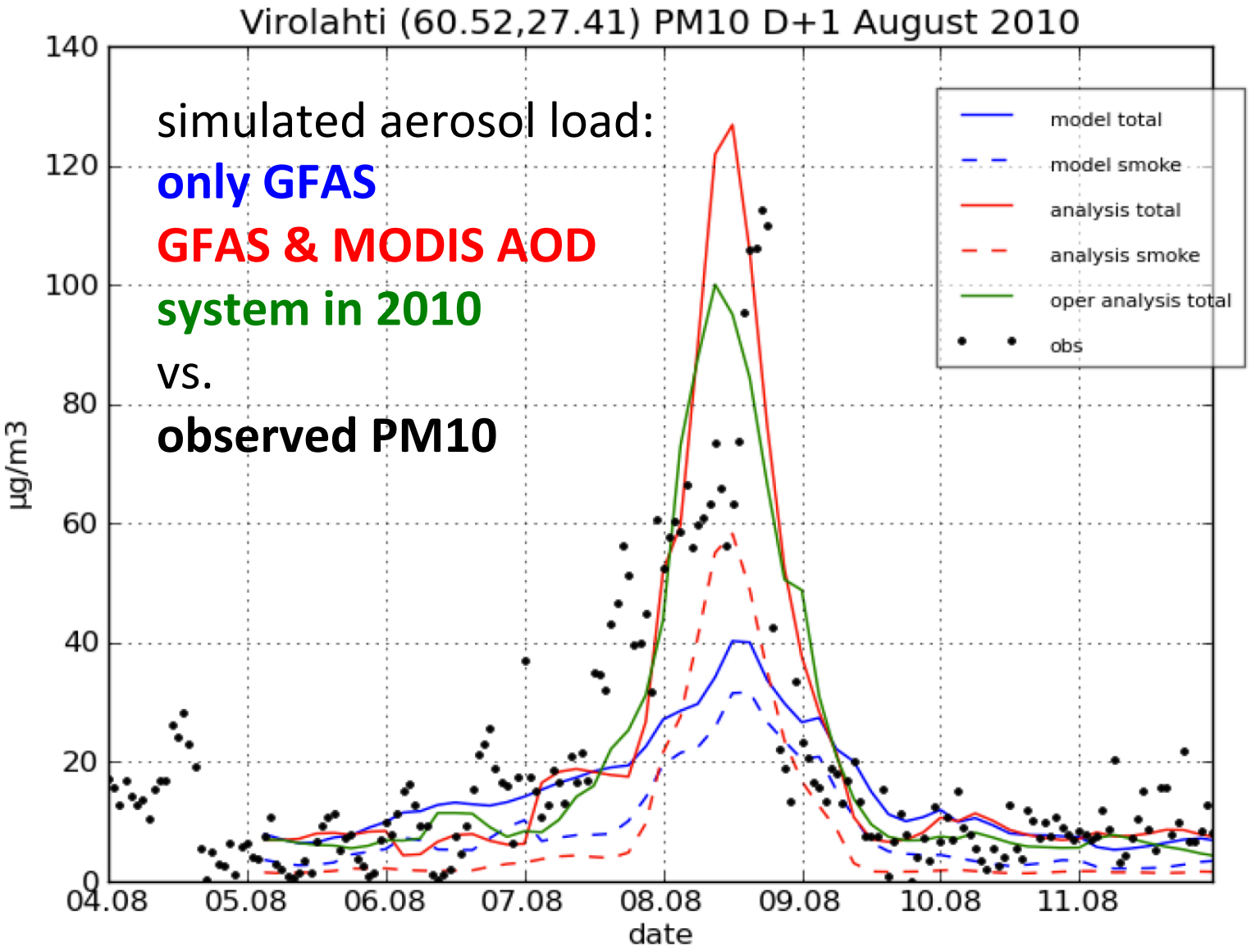
Russian Fires of Summer 2010

- **Assimilation of MODS FRP**
  - **in GFASv1.0**
- **Assimilation of MODIS AOD**
  - **using enhanced GFASv1.0**

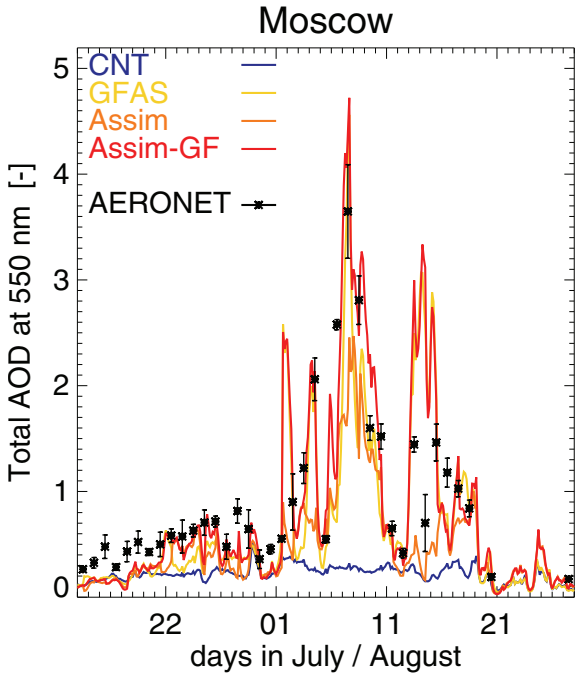


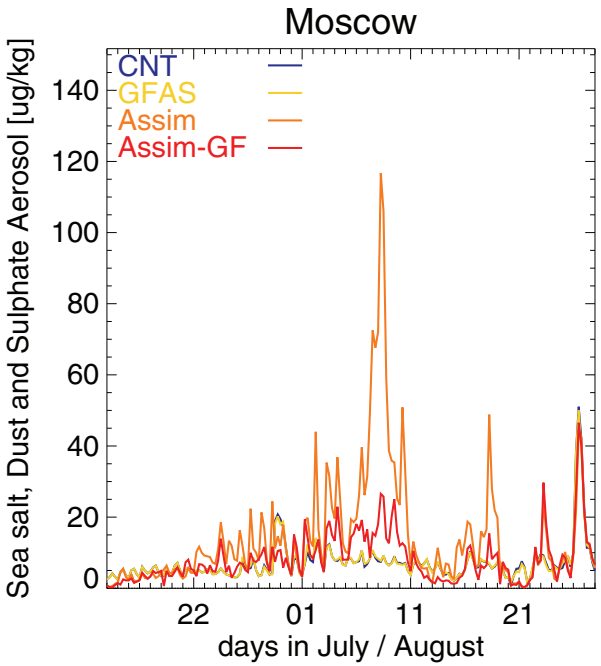
[Kaiser et al. 2012]

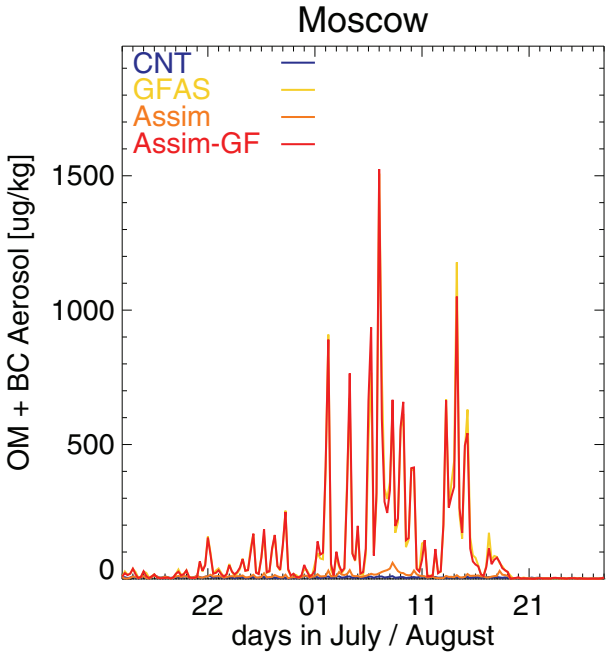
Russian fires in 2010 affect one air quality station in the EU



AOD Simulations with IFS







- Assimilation adapts total AOD.
- Speciation is determined by emissions.
- Forecasts near sources strongly depend on emissions.

Model, with climatological emissions

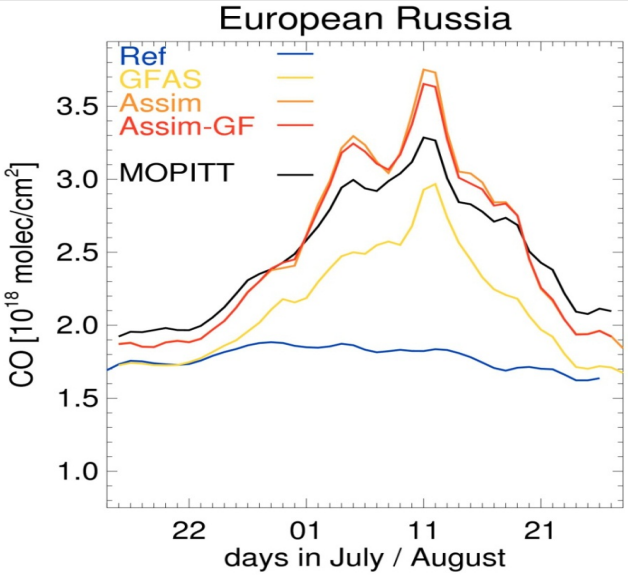
Model, with analysed emissions

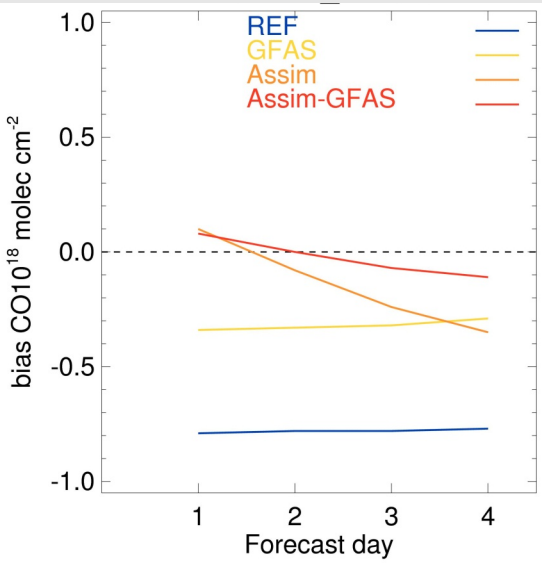
Assimilation of AOD, with climatological emissions

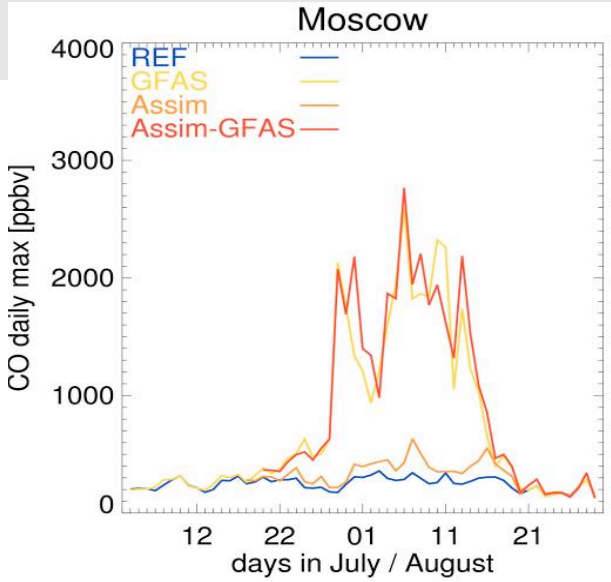
Assimilation of AOD, with analysed emissions

[Huijnen et al. 2012]

CO Simulations with IFS-TM5







- Much of the signal in CO column is captured by **either** emissions or assimilation.
- Accurate column forecasts require **both**.
- Surface concentrations are dominated by emissions.
- Forecasts suffer from poor fire predictions.

Model, with climatological emissions

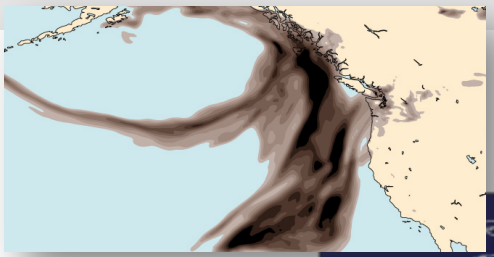
Model, with analysed emissions

Assimilation of IASI CO, with climatological emissions

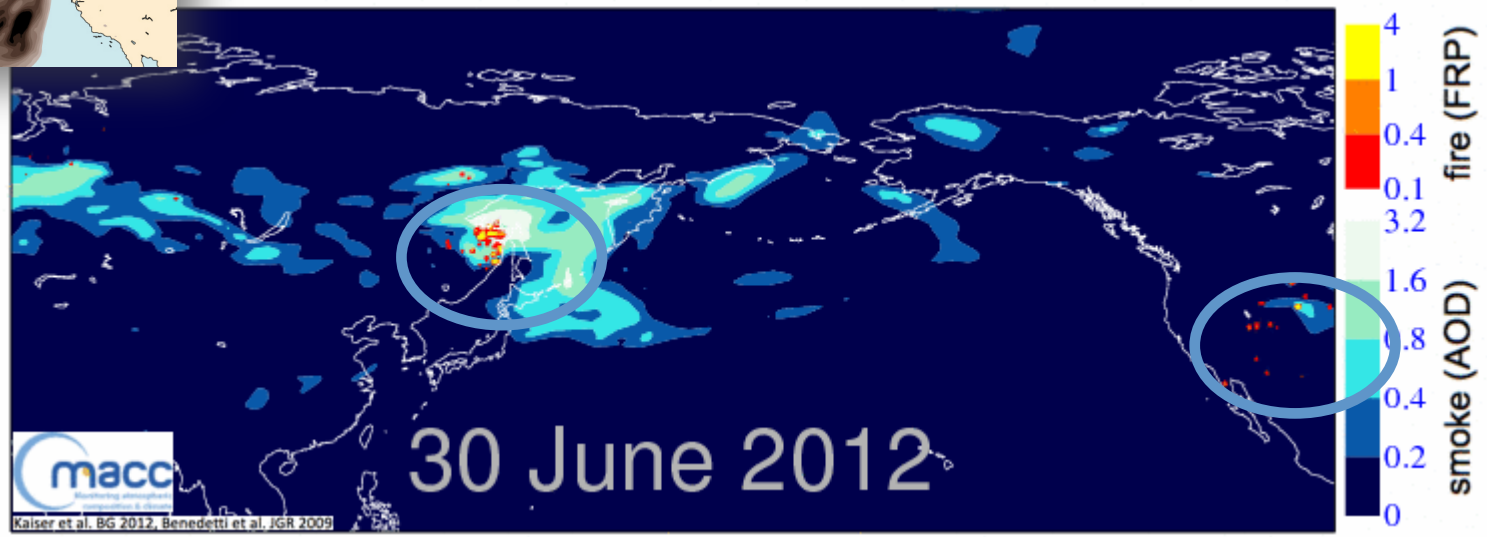
Assimilation of IASI CO, with analysed emissions

[Huijnen et al. 2012]

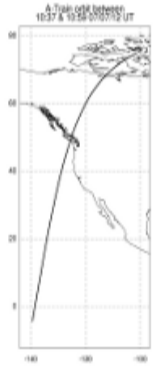
Where did the July 2012 Seattle haze come from?

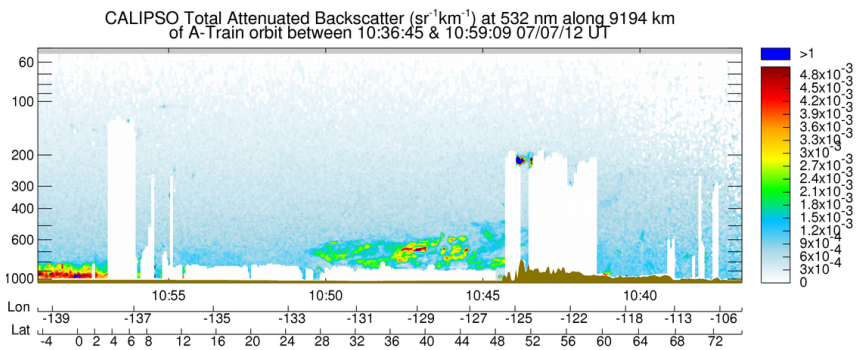


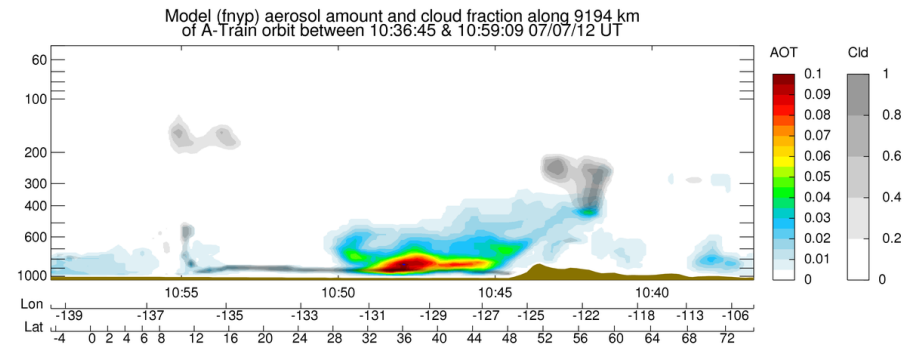
Ubiquitous sources!



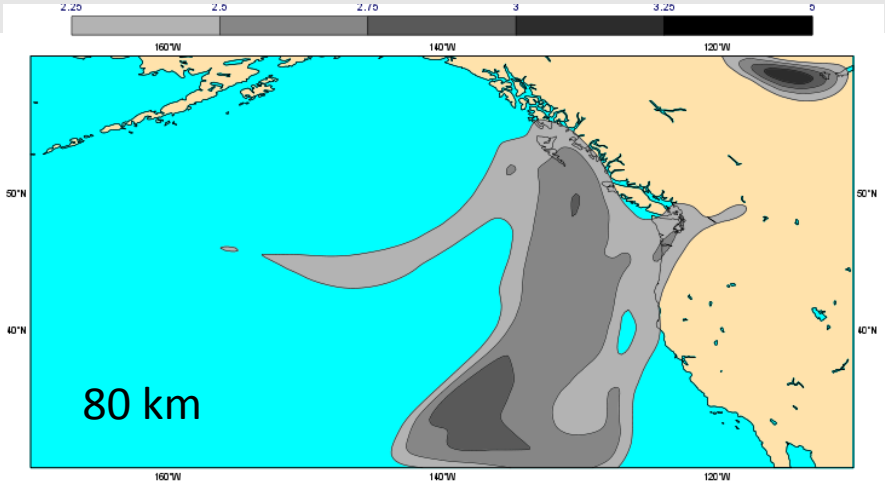
Independent validation against CALIPSO

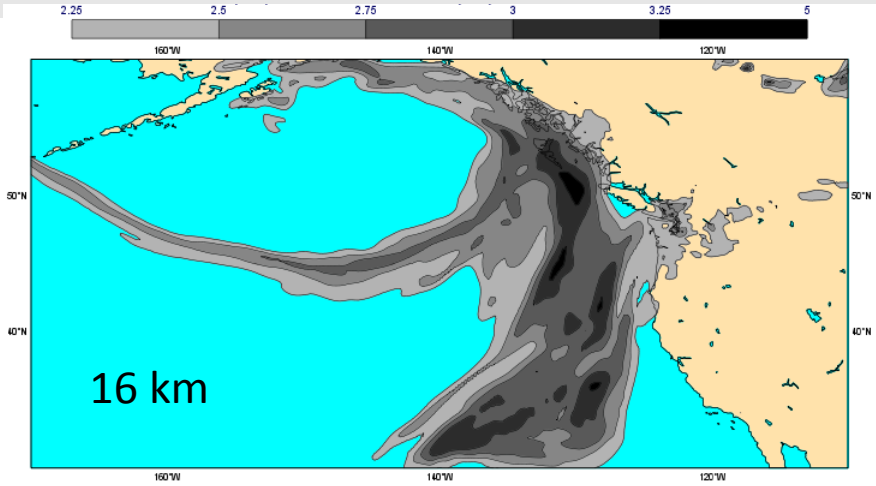


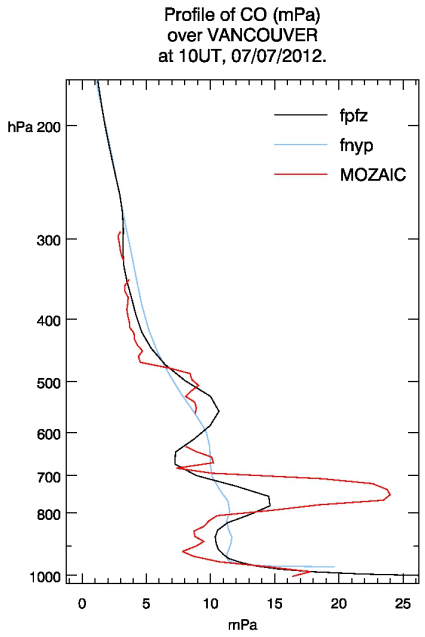


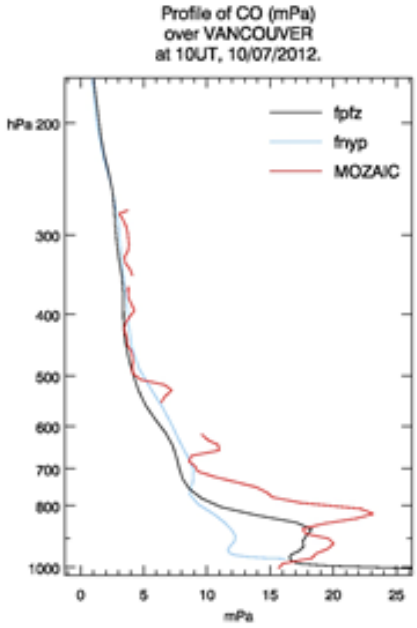


Benefit of high resolution





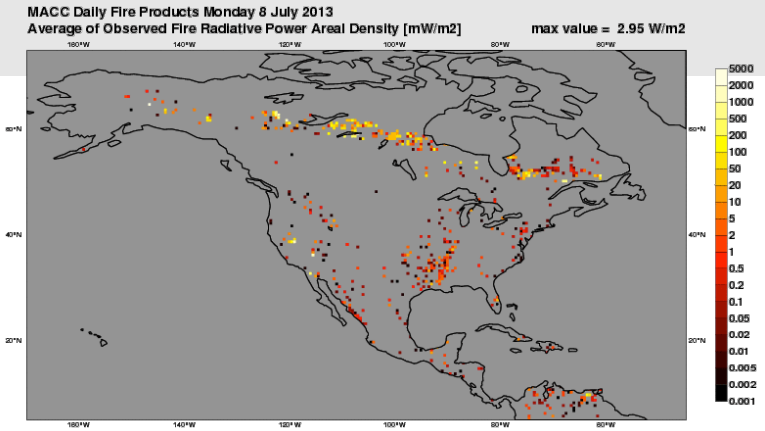


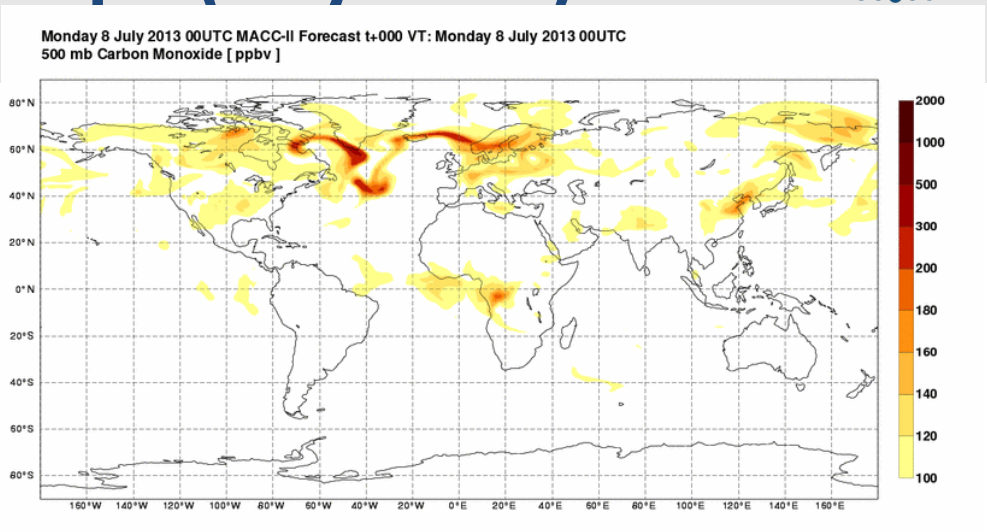


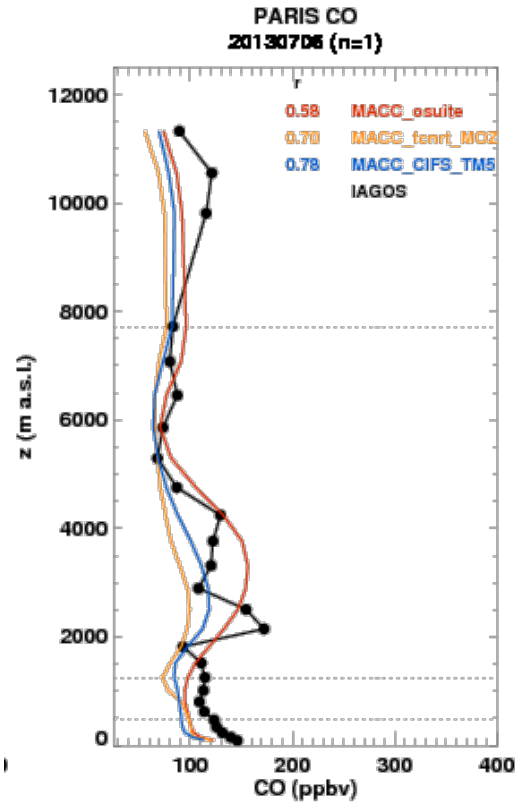
MACC already runs forecasts at high resolution with simplified chemistry for CO.
This provides better forecasts in areas with complicated orography.

- IAGOS observations
- Low resolution model
- High resolution model

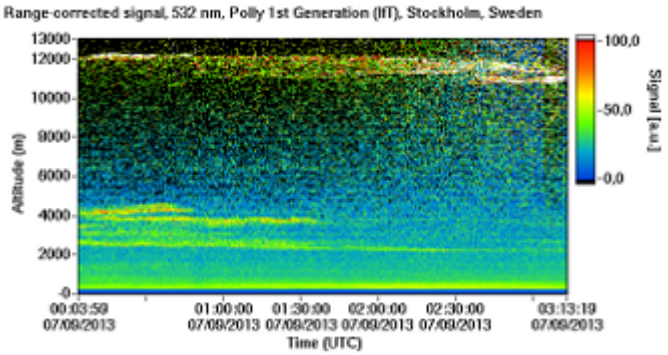
Canadian smoke over Europe (July 2013)







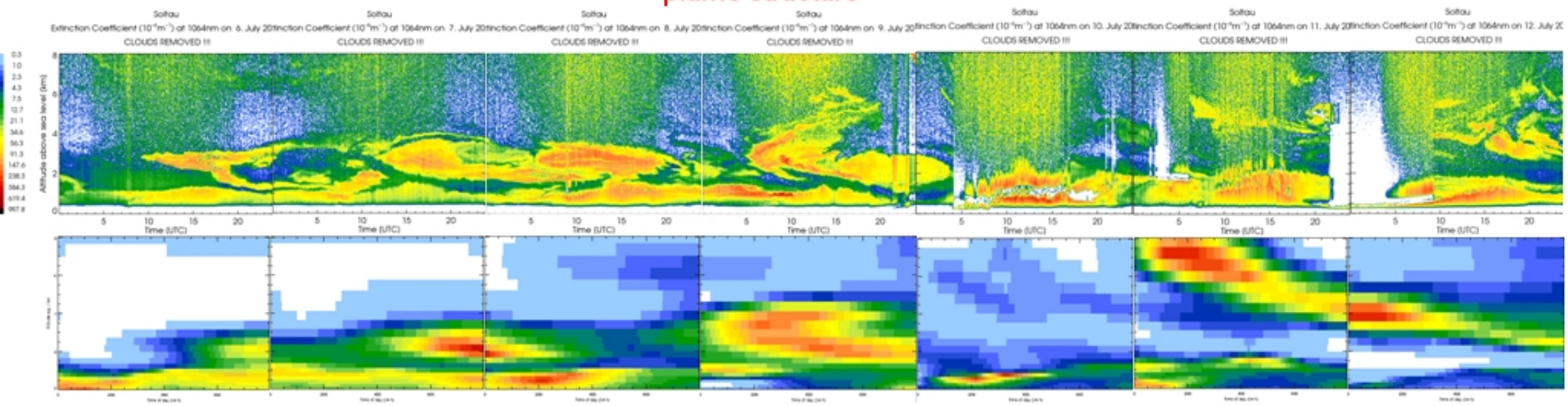
The assimilation run (red, MACC o-suite) pick ups increased levels of pollutants, here Carbon Monoxide, between 2 and 4 km. Independent aircraft observations (black) confirm the presence of the plume, which is seen also by European lidars and ceilometers.

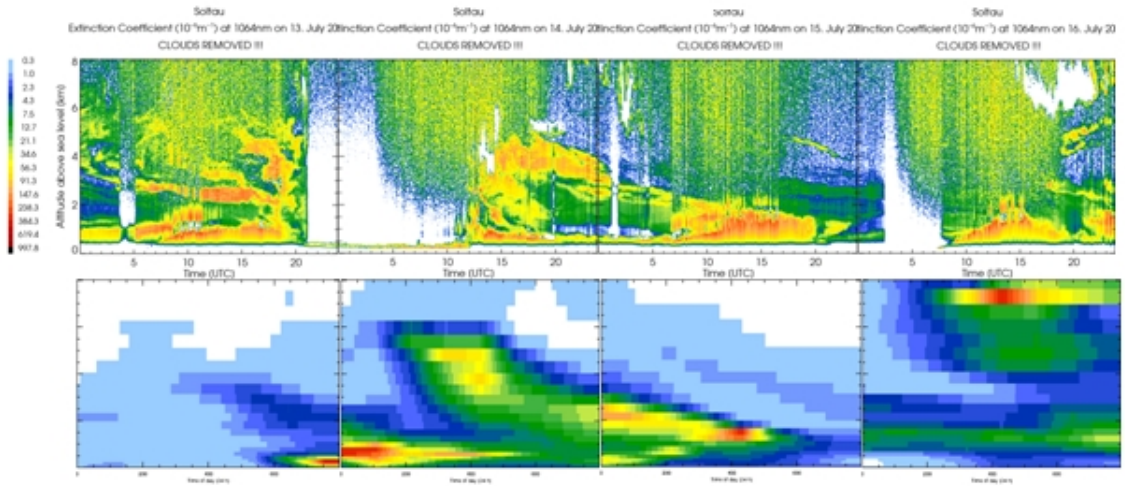


MACC-II analysis vs. DWD Ceilometer

Comparison of Canadian forest fire plume seen by Ceilometers over Soltau, North Germany, 6 – 12 July 2013

MACC-2D plot is QUALITATIVE and linear scale in contrast to ceiloplot!!! Shall just show the reproduction of the plume structure

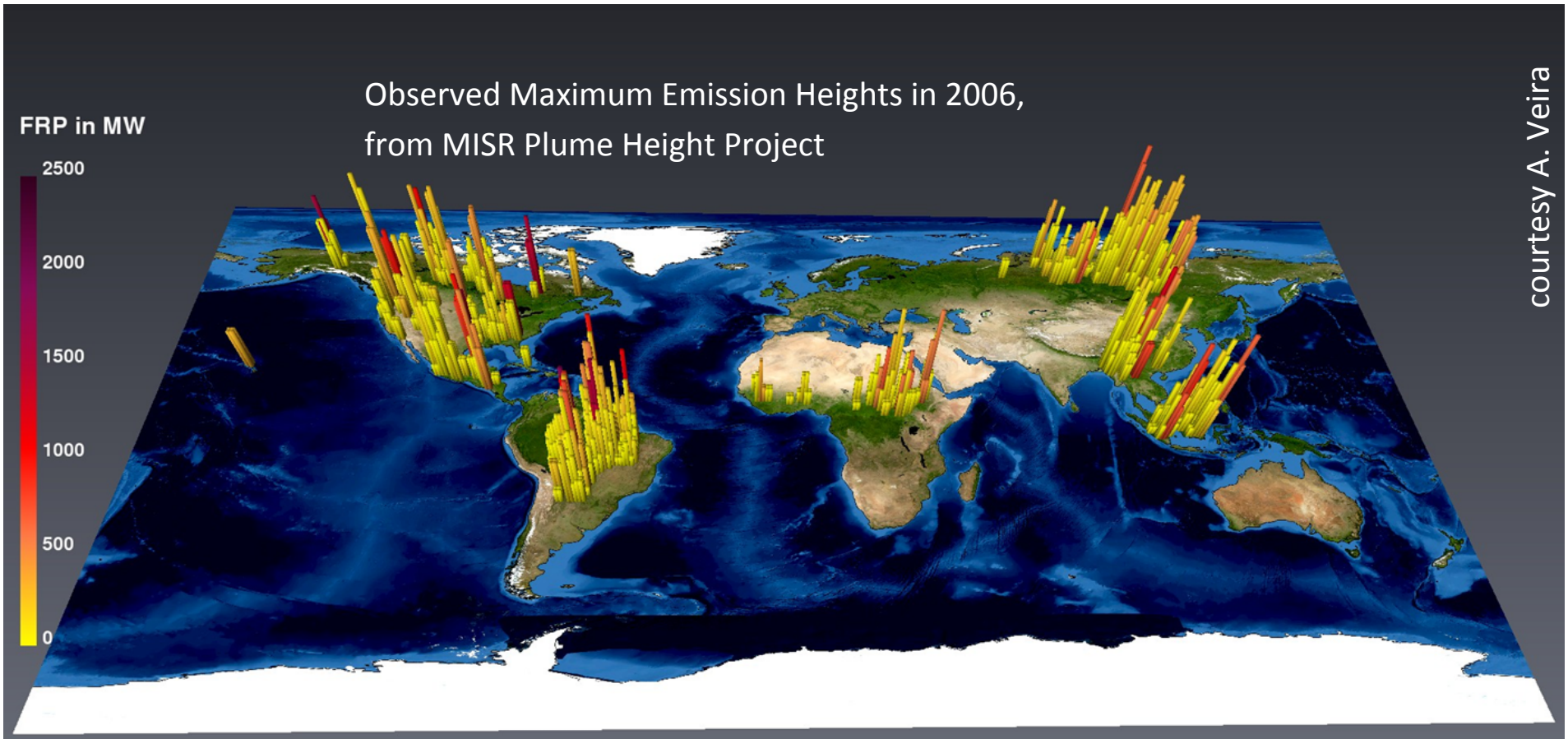




- Plume shape compare well.
- Remaining discrepancies due to missing injection height?

Injection Heights

MAX-PLANCK-INSTITUT
FÜR CHEMIE



- Approximately 7000 individual plumes for 2001-2009
- Composite of regional studies, no global coverage

Injection heights from 1-d plume rise model

[Paugam et al. ACPD 2015]

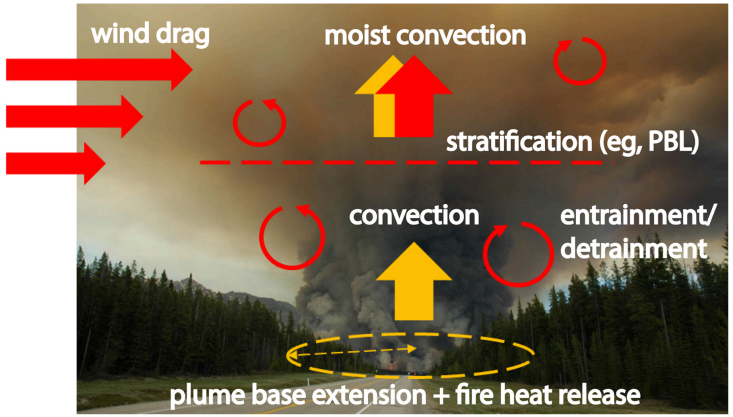


Figure 2. Schematic view of the physical processes involved in fire plume dynamics. Red and yellow colours stand for atmospheric or fire induced mechanisms respectively.

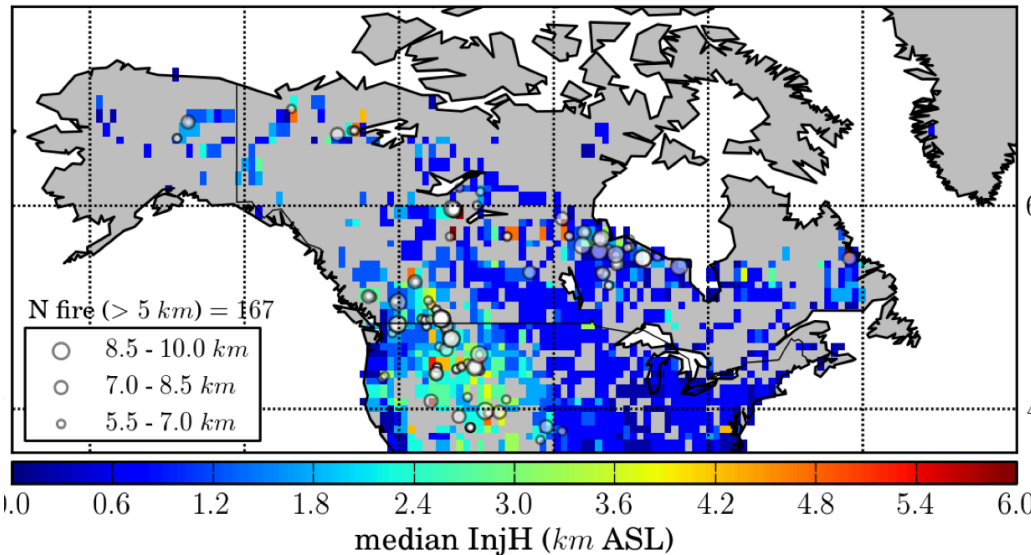
- extension of Freitas et al. 2007
- fitted to MISR observation

<u>input:</u> ECMWF meteorology & MODIS fire observations

<u>output:</u> detrainment profile

- incorporated in GFASv1.2
- availability: 2003–present
  - mean height of maximal injection
  - minimal height of injection
  - maximal height of injection
  - height injection following Sofiev et al. 2012

Summer 2003 *[Paugam et al. ACPD 2015]*



Mostly injection into boundary layer

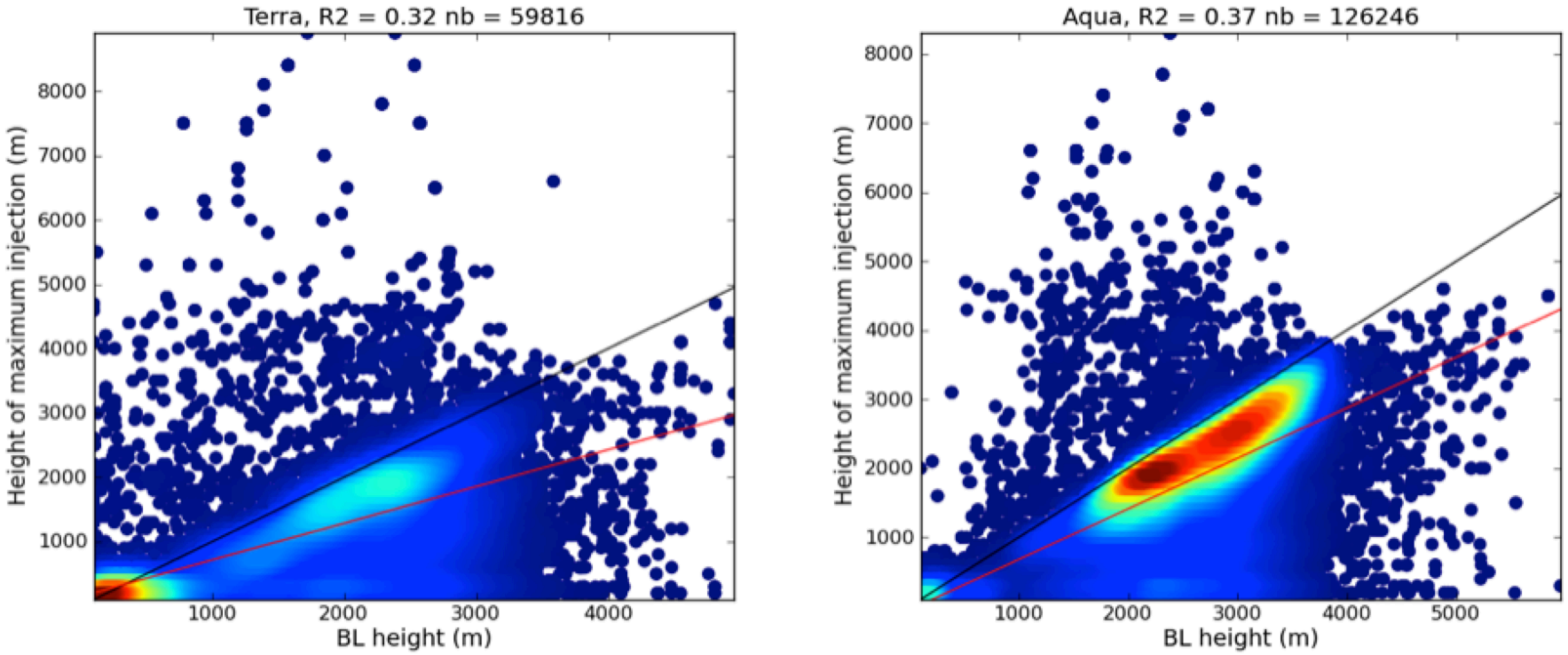
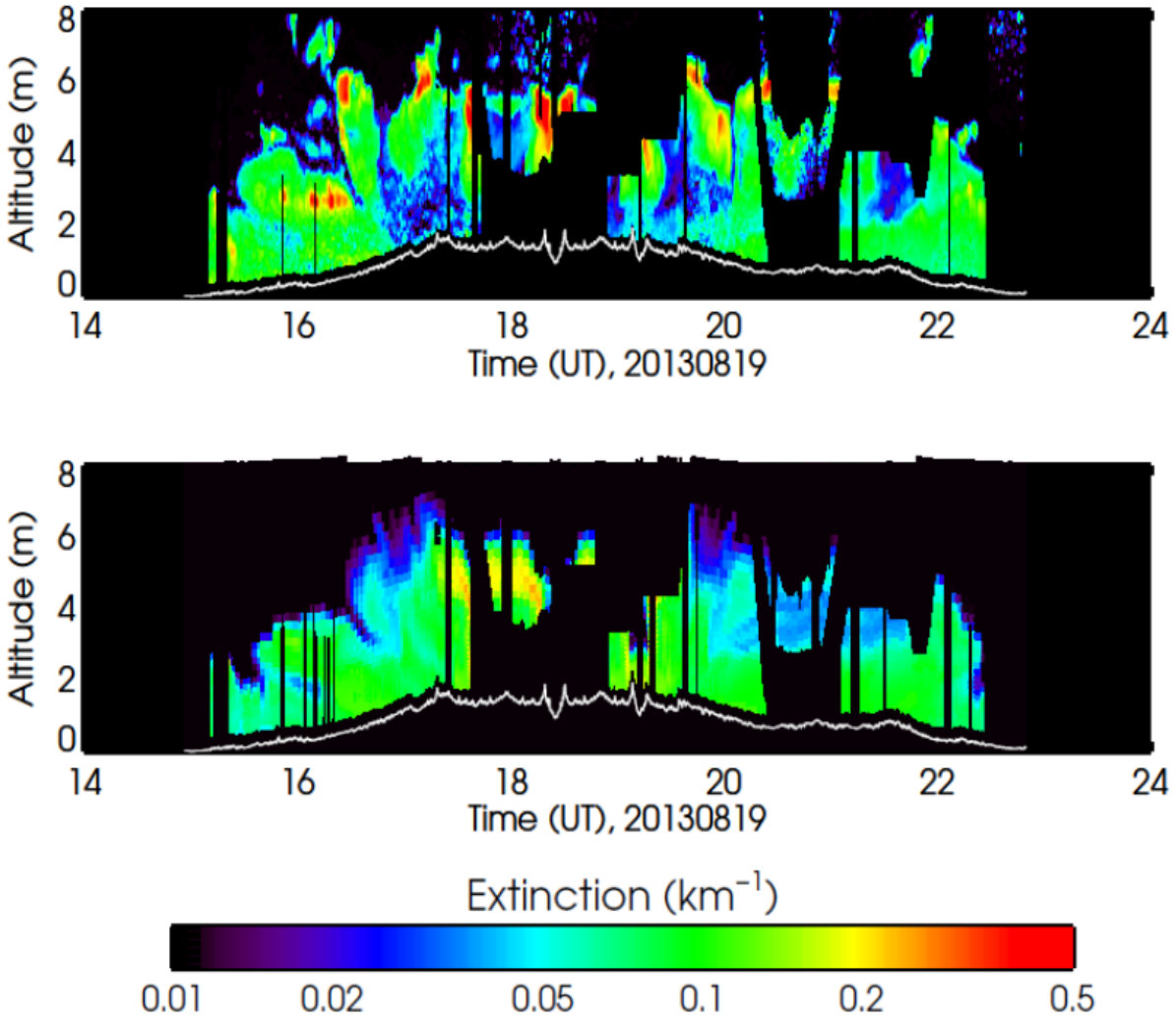


Figure 4 Height of maximum injection versus boundary layer height for FRP observations from MODIS on Terra (left) and Aqua (right).

To be tested against field campaign data

Comparison of SAEC^{4}RS lidar observations of aerosol extinction with a model simulation that does not use the fire emission injection height



Interdisciplinary Biomass Burning Initiative

What is IBBI?

"Interdisciplinary Biomass Burning Initiative"

IBBI is a networking initiative under the auspices of

- IGAC, iLEAPS and WMO.

Primary goal: *To* improve atmospheric composition and air quality monitoring and forecasting through **better scientific understanding** of the various processes around biomass burning.

Approach: To instigate new interdisciplinary research

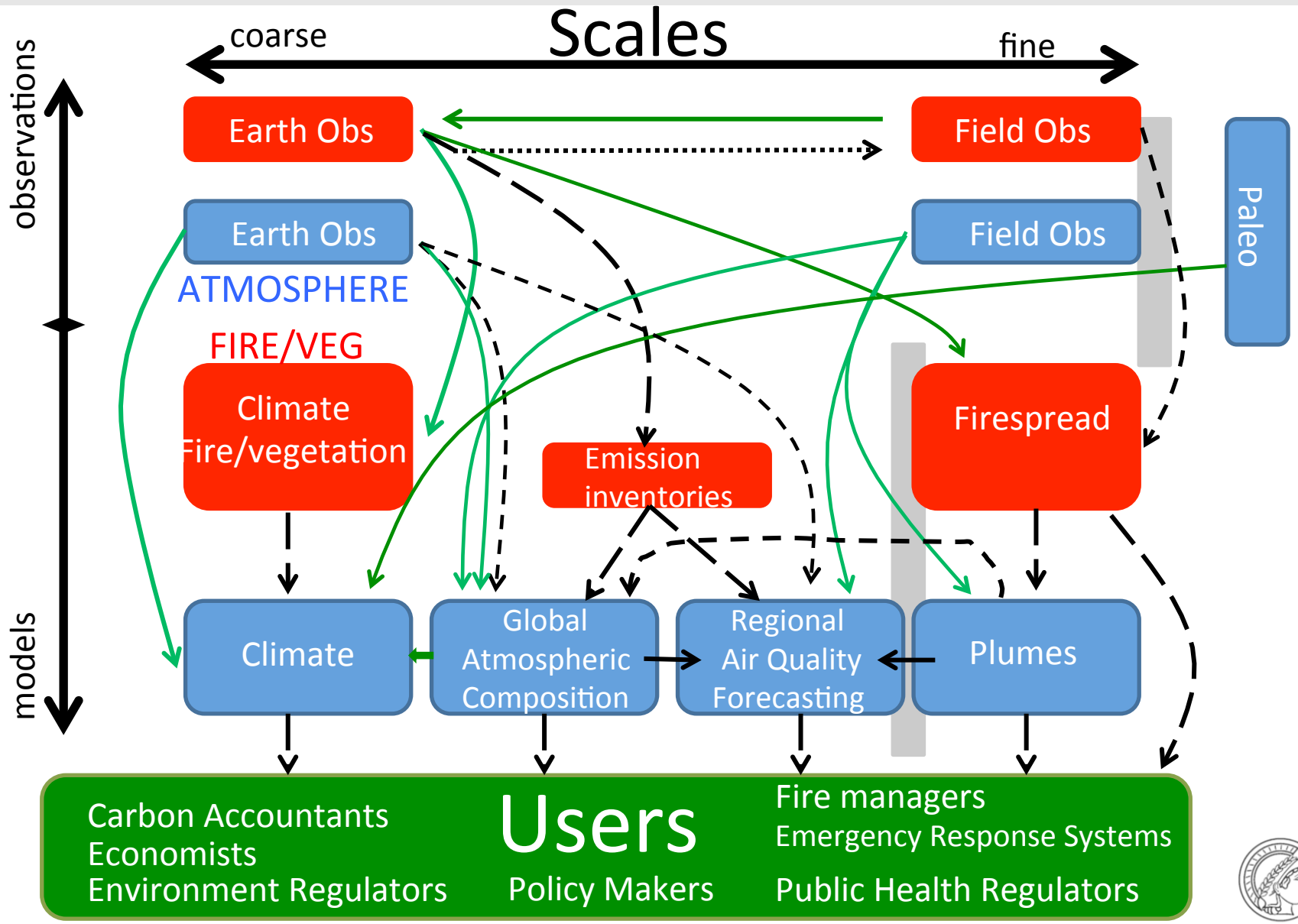
IBBI is thus science-driven & application-oriented.

IBBI is evolving through a series of workshops.

IBBI special issue of *Atmospheric Environment* about to be published

IBBI is co-chaired by Melita Keywood and Johannes Kaiser.

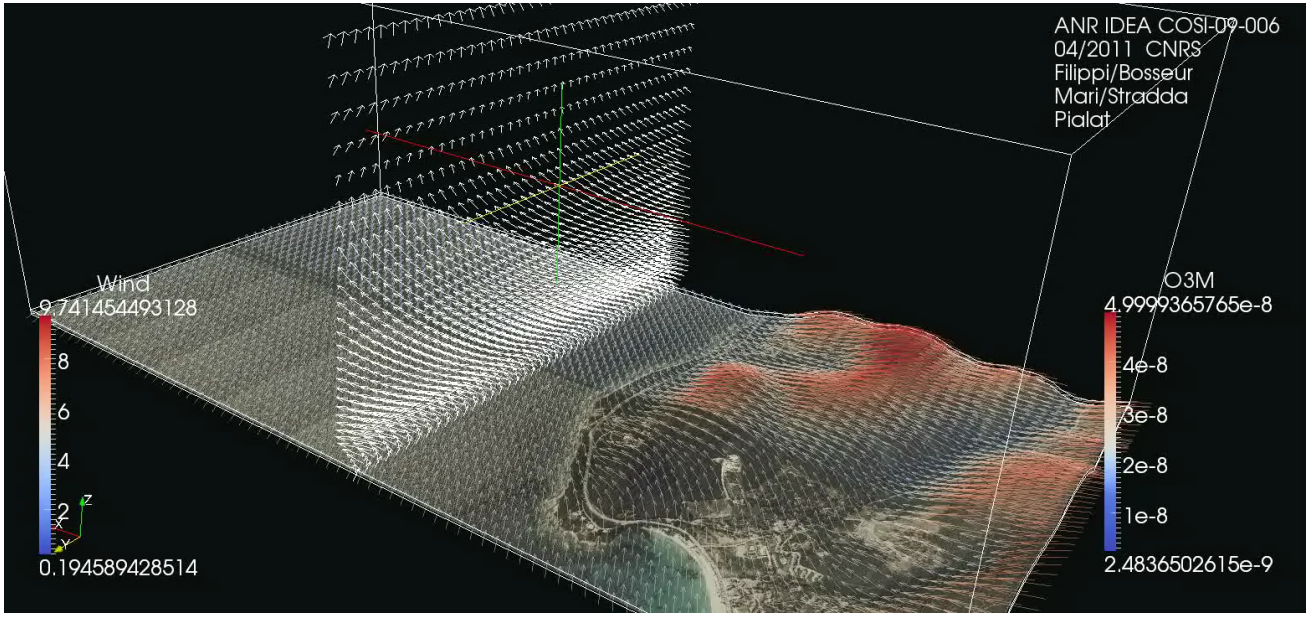
Why IBBI? Bridge disciplines!



Specific Results: Address major blocks

two ad-hoc IBBI working groups:

- **fire emission since 1750 for use in climate modelling** for IPCC as contribution to initiative coordinated by Claire Granier et al.
  - combine emission inventories, fire models and charcoal records
- **integrated case study of individual fire/plume event**
  - combine fire and plume modelling across scales and with earth observation
  - address address effect of rapid in-plume chemistry



URLs

- http://atmosphere.copernicus.eu (/fire)
  - CAMS real time plots, reanalysis of atmospheric composition since 2003, full data catalogue, helpdesk
- http://join.iek.fz-juelich.de/access
  - interactive & scriptable WCS boundary condition server for CAMS
- http://eccad.sedoo.fr
  - GFAS archive on GEIA emission database server
- (ftp://ftp.ecmwf.int)
  - operational dissemination ftp server of ECMWF (need login)
- http://www.mpic.de/forschung/kooperationen/ibbi.html
  - IBBI, with mailing list