Fire Locating and Monitoring of Burning Emissions (FLAMBE): A Near-Real-Time Smoke Estimation Model based on Satellite Active Fires

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In This Talk

- FLAMBE overview: A little context
- Emissions estimation with active fires:
  - The worst
  - Except for every other method
- The Major Challenges for emissions estimates from active fire data
- Big Unknowns: potential for new discovery
- How can field missions help?

Context and Philosophy of FLAMBE

- Navy objective: accurate forecasts of visibility-reducing events
  - Near Real Time
  - Fully Automated
  - Maintainable (Minimum Moving Parts)
- Navy Aerosol Analysis and Prediction System (NAAPS)
  - First operational global aerosol forecast model
  - 144-hour forecasts 4x/day of dust, *smoke*, sea salt, anthropogenic and biogenic fine mode aerosols
- FLAMBE provides smoke for NAAPS
  - Simple+transparent > complex+opaque
  - Traceability to field measurements
  - NRT data only
  - Consistent estimates for atmospheric modeling at scales 10-200km

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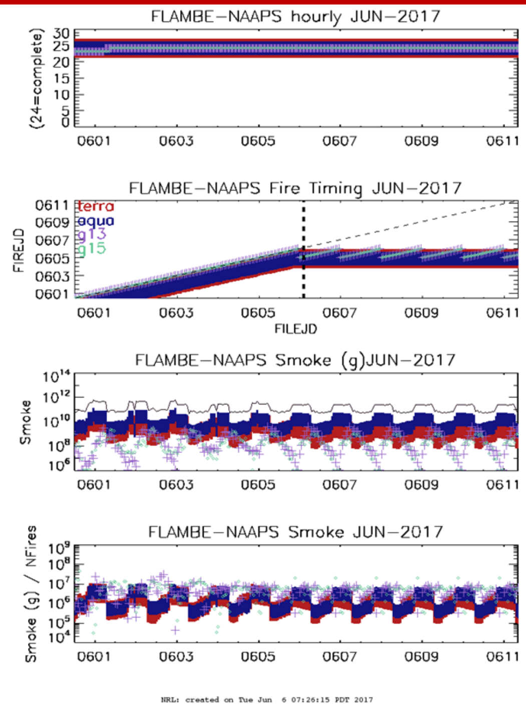
FLAMBE's First Decade+

FLAMBE in Navy Operations: 24/7/365 since 2007



Personnel

- The originators (1999):
  - Jeffrey Reid at SPAWAR/NRL
  - Elaine Prins at UW-CIMSS
  - Douglas Westphal at NRL (developer of NAAPS)
- The satellite product teams
  - Chris Schmidt and Jay Hoffman, UW-CIMSS
  - Louis Giglio, Ivan Csiszar, Wilfrid Schroeder at UMD/NASA/NOAA
- Fire science and observability: Edward Hyer (NRL), Jun Wang (U.Iowa), Jukka Miettinen(NUS), David Peterson(NRL), many more
- The maintainers (NRL): Edward Hyer, Peng Xian, Cindy Curtis (retired)

FLAMBE Current Operational

Requirement: Provide rapid smoke source function for aerosol forecasting at broad scales

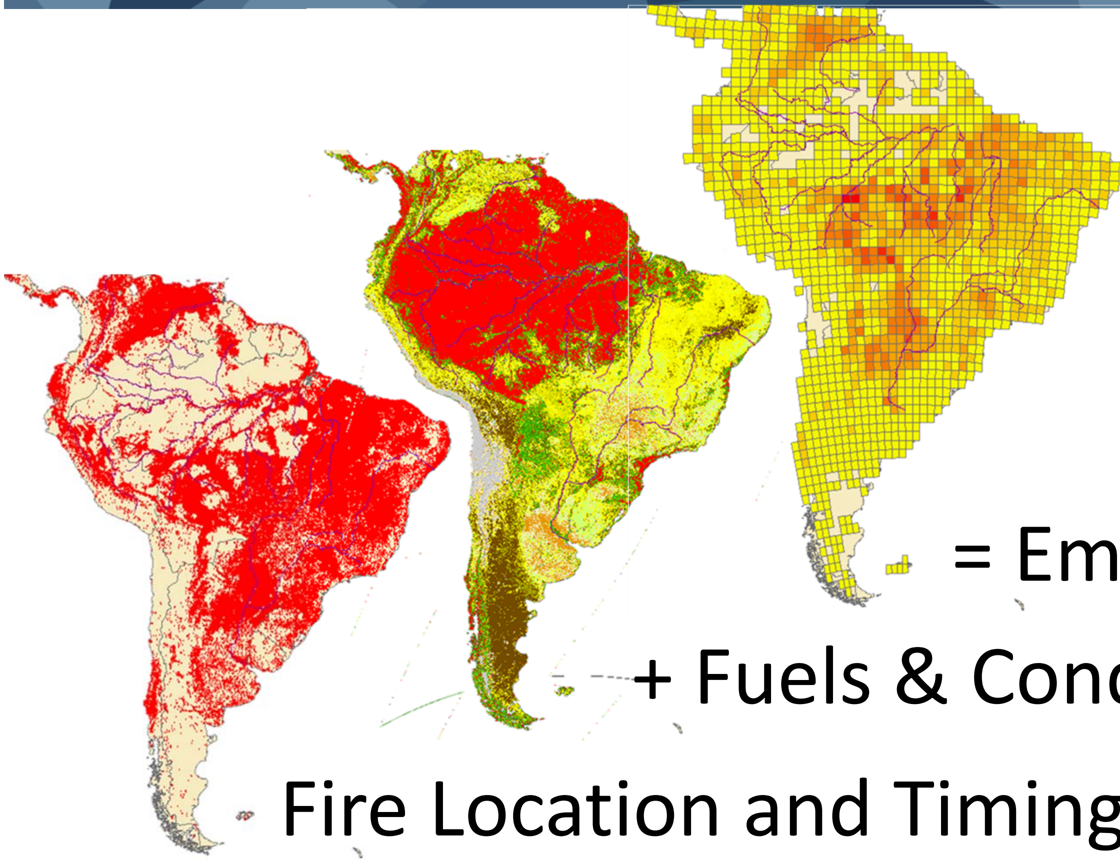
Input

- GOES-E/GOES-W
  - Location: 4km+
  - Fire size: Dozier
  - Emissions applied over 60min
- MODIS
  - Terra + Aqua
  - Location: 1km+
  - Fire size: fixed 0.85ha
  - Emissions scaled over 24 hours using empirical diurnal cycle by ecosystem
- Land Cover/Ecosystem
  - GLCC(AVHRR)

Output

- Scope: Global
- Temporal: Hourly
  - Hourly FLAMBE (T to T+1) based on:
    - 1h GOES (T to T+1)
    - 24h MODIS (T-23 to T+1)
  - Persistence forecast for NRT use
- Spatial: resolution of satellite inputs (1-4km)
  - Identical emissions for global and mesoscale
- PM2.5
  - Based on Reid et al. (ACP, 2005)
- Total carbon release
  - For speciation (e.g. Akagi et al. *ACP* 2011)

Emissions Estimation



- One simple concept
- Endless permutations in implementation!

= Emissions

+ Fuels & Conditions Data

Fire Location and Timing Data (+Energy)

Fire Location/ Timing for Emissions Estimation

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Option 1: Active Fire

- Pro:
  - ***Suitable for NRT***
  - Exact timing
  - Principle limitations easy to quantify
    - Pixel size drives detection efficiency
    - Obscuration by opaque clouds
  - FRP is closer to physical model of combustion
- Con:
  - Miss lots of fires, lots of places, lots of time
    - Extrapolation mandatory
  - Stochastic factor: fire location within pixel (PSF)
  - Systematic factor: pixel size variation
    - Between sensors
    - For a single sensor

Both satellite methods have drawbacks. For NRT, active fires are the only suitable option.

Option 2: Burned area

- Pro:
  - Globally consistent methods/algorithms
  - Potential to catch fire under cloud
  - Simple GIS integration
- Con:
  - Miss lots of fires
    - Efficiency varies by fire regime / ecosystem properties
  - ***Not suitable for NRT***
    - (*) maybe with GOES-R?
  - End of season = end of detection
    - Algorithm requires post-fire image
    - Tropics: rain
    - Temperate/boreal: snow

Option 3: "Good Data" (ground-based, aerial)

- Pro: detailed, accurate
- Con: Inconsistent, Incomplete, Unavailable
  - Especially timing!

Active Fires Degrade Sharply at AQ-relevant scales

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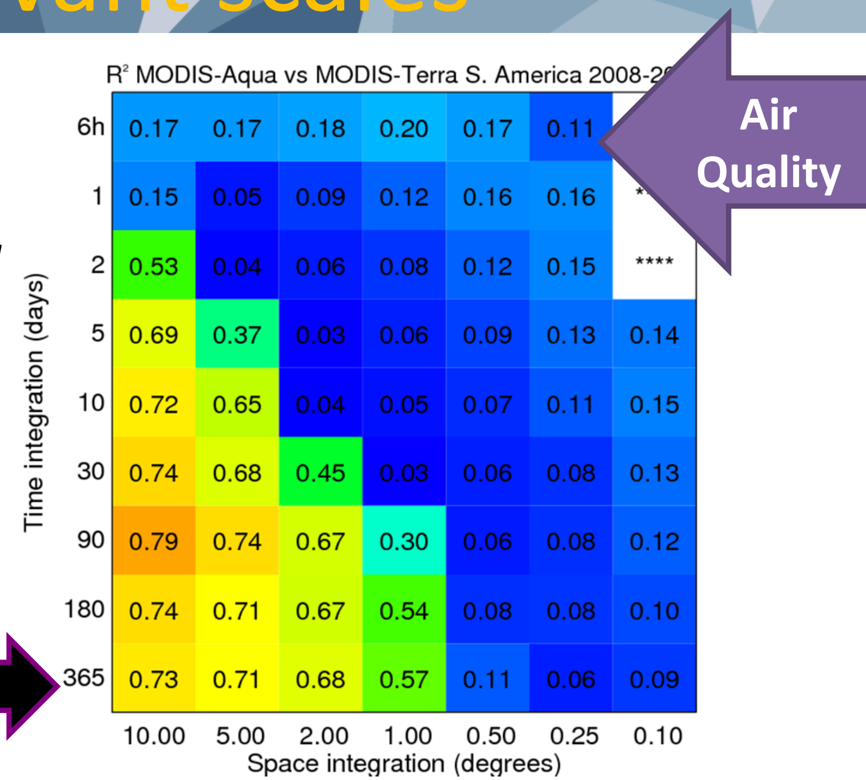
- ***Q: Do Terra and Aqua seem the same <u>patterns</u> of fire activity?***
- ***A: Yes, at sufficiently coarse scales***
- ***At right: correlation between MODIS-Terra and Aqua FRP (MOD14) as a function of spatial (X-axis) and temporal(Y-axis) scale***
  - **At the scales of climate (upper right), these sensors show the same patterns**
  - **At scales relevant for AQ forecasting, sampling differences manifest themselves: Terra and Aqua look at different fires**
- **What about two sensors looking at the same fires?**



CLIMATE

Active Fires Degrade Sharply at AQ-relevant scales

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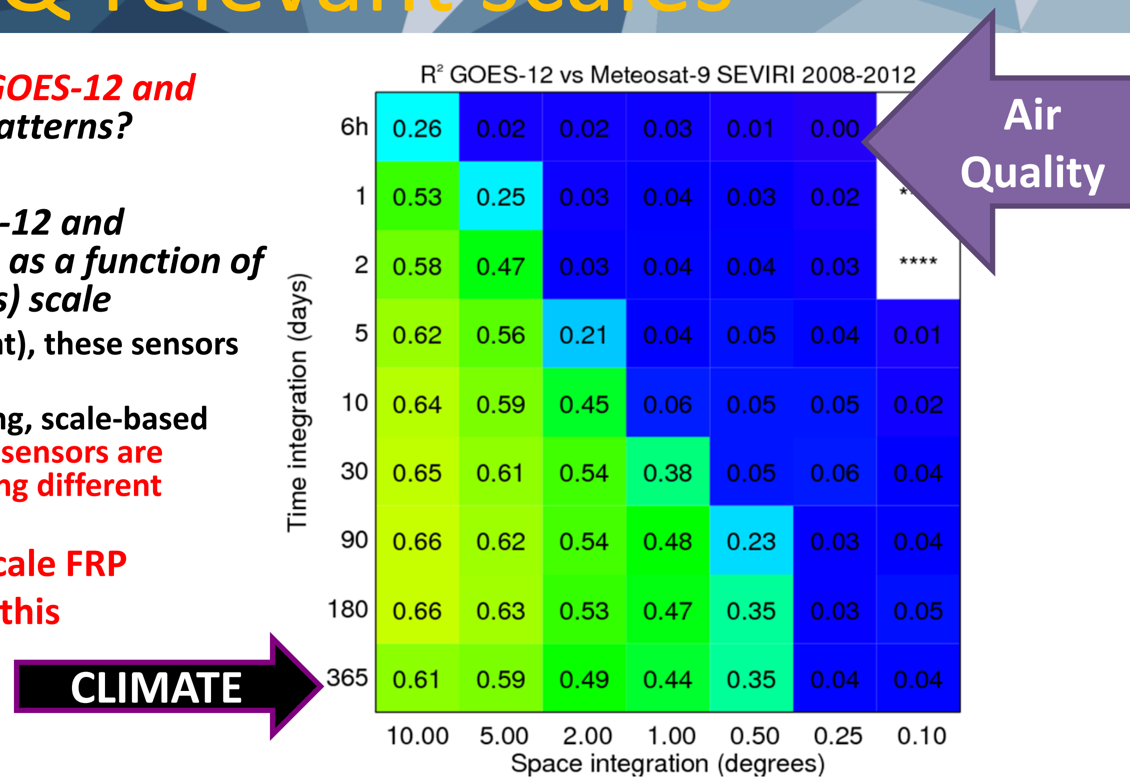
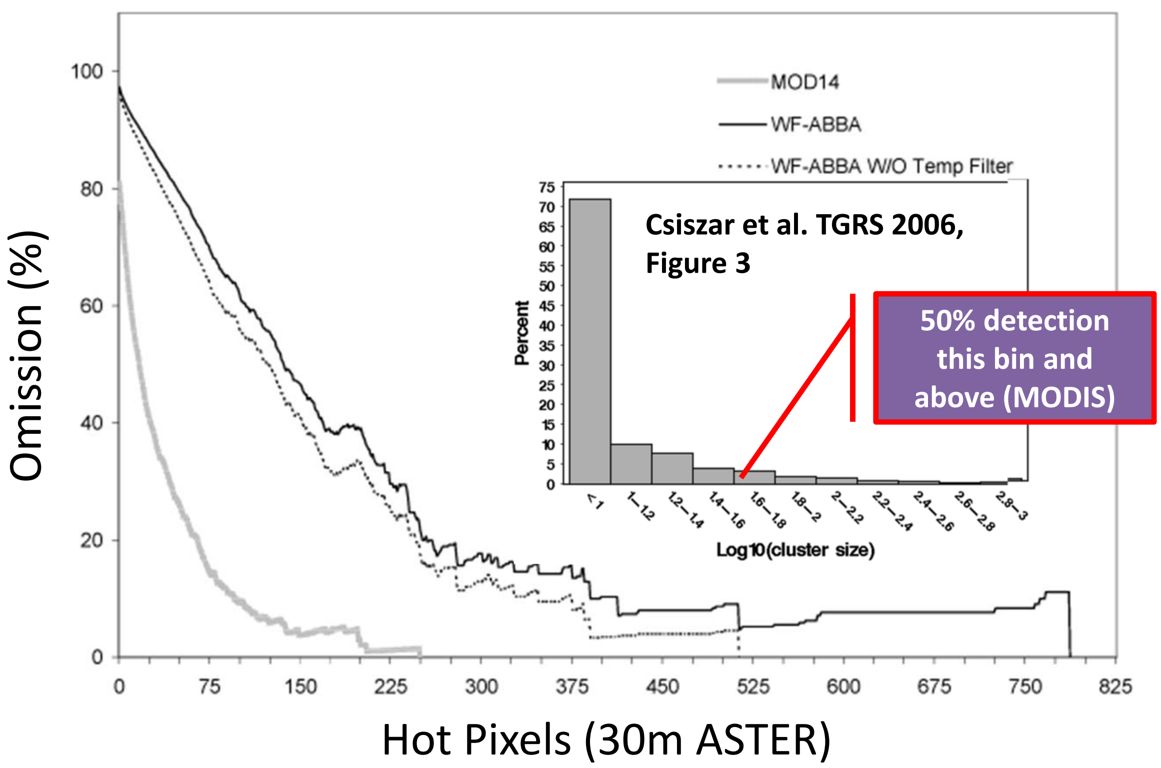
- *Q: Do two geostationary sensors (GOES-12 and Meteosat-9 SEVIRI) see the same patterns?*
- *A: Yes, at sufficiently coarse scales*
- *At right: correlation between GOES-12 and Meteosat-9 SEVIRI FRP (WF_ABBA) as a function of spatial (X-axis) and temporal(Y-axis) scale*
  - At the scales of climate (upper right), these sensors show very similar patterns
  - At scales relevant for AQ forecasting, scale-based uncertainty manifests itself: these sensors are looking at the same fires and getting different answers
- No correlation means no basis to scale FRP
- Three related factors contribute to this degradation:
  - Zero-value grids;
  - Truncation of FRP distribution
  - Noisy single-pixel FRP retrievals



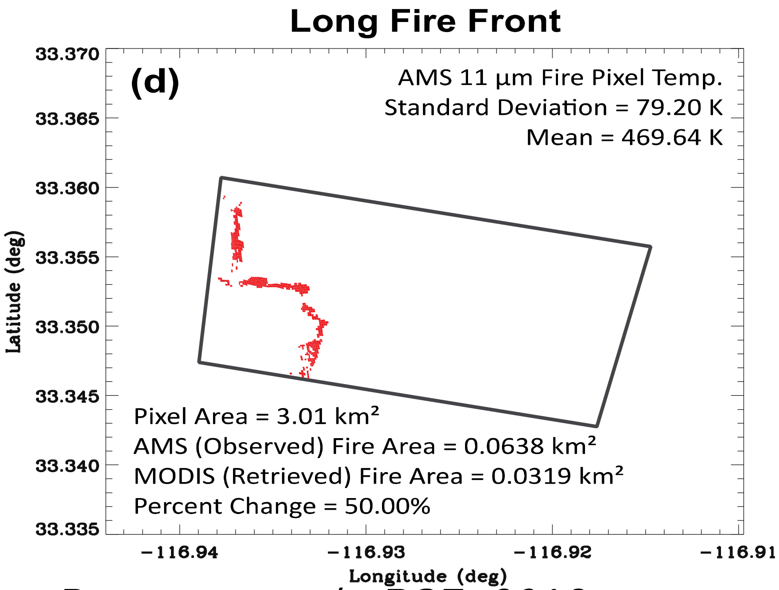
Active Fire Detection Challenges: Most Fires Are Missed

Schroeder et al. RSE 2008, Figure 6



- "Most fires" does not necessarily mean "most fire activity"
- In some ecosystems, over some periods, total emissions are dominated by the largest fires
  - This is scale-dependent

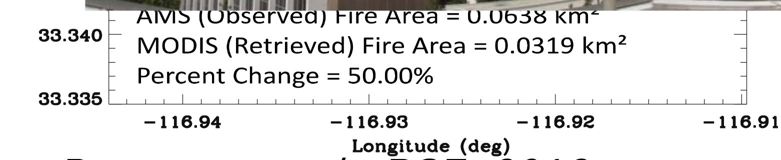
Active Fire Detection Challenges: Spatial Resolution



Peterson et al., RSE 2013

- The big box is the MODIS pixel
  - mid-swath, ~3km^2
- The red area is the fire front from aircraft
  - AMS-Wildfire on NASA Ikhana, ~20m resolution
- The fire front is 2% of the MODIS pixel
- This is a HUGE fire
  - SoCal Santa Ana-driven fires 2007

Active Fire Detection Challenges: Spatial Resolution



Peterson et al., RSE 2013

ircraft

solution

xel

This is a HUGE fire

- SoCal Santa Ana-driven fires 2007

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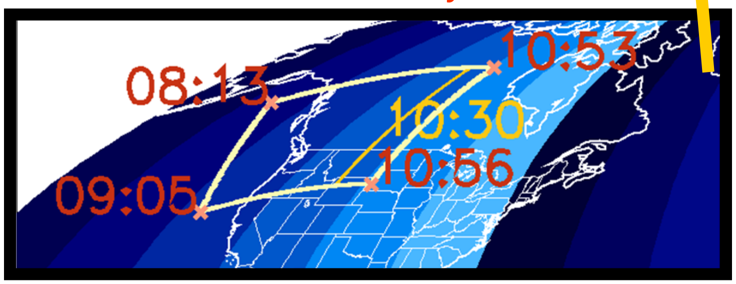
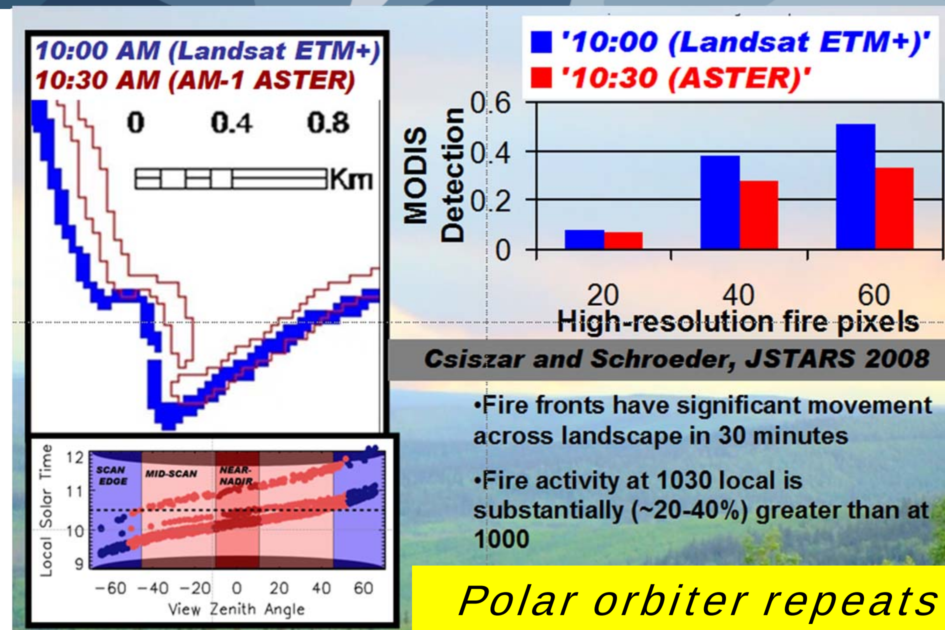
Active Fire Detection Challenges: Temporal Resolution of Polar Orbiters

Nominal overpass time ≠ center of scan

Scan Angle and Overpass Time Interact to Determine Detection Efficiency

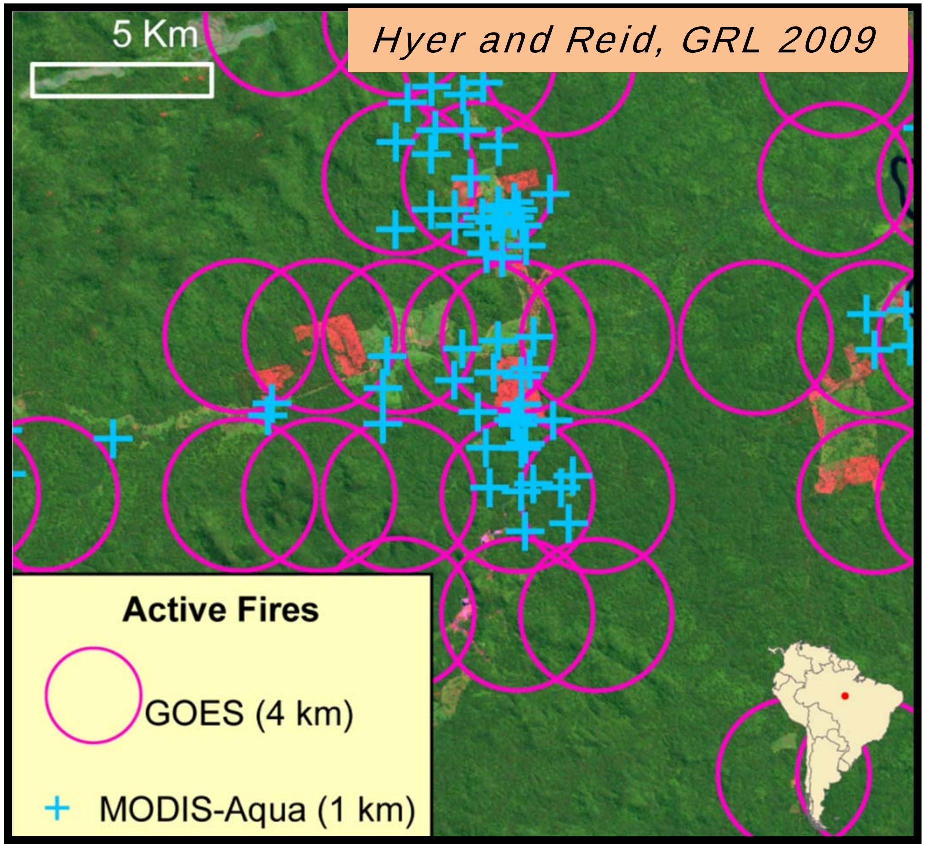




- **Fire is a highly dynamic process**
- **30 minutes is a long time!**
- **3-9-3-9 hours (MODIS-Terra+Aqua) is basically forever**

Polar orbiter repeats are not frequent enough to constrain mechanistic spread models

Active Fire Detection Challenges: Spatial Resolution



- Landsat image shows recent and older clearings
- Is the fire in the previously cleared area? Or is the fire being used to expand the clearing?
- Both random and systematic errors are large

In many landscapes where fires are important, satellite data are not precise enough to isolate fuel properties

If we have FRP, do we need to know what's burning?

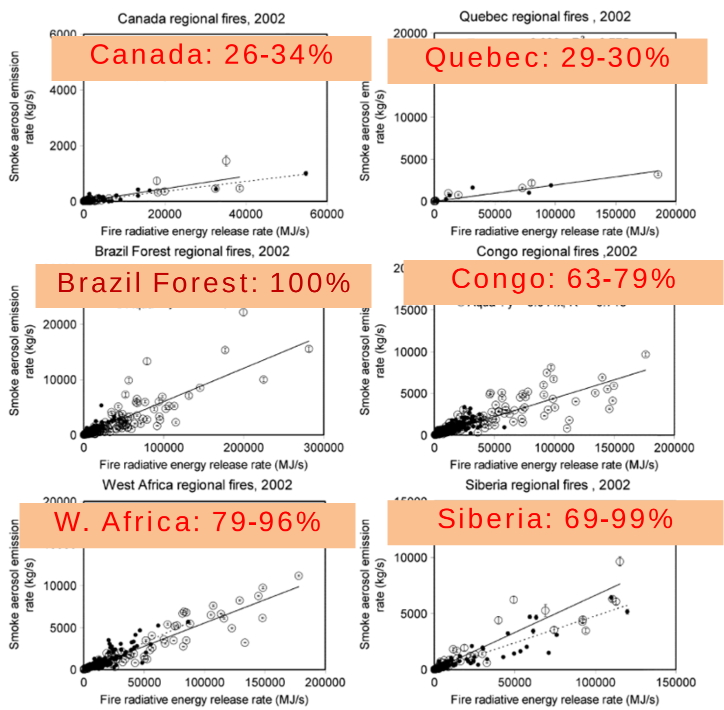


Fig. 2. Regional correlations between rates of emission of smoke aerosols R_{sa} (kilograms per second) and the rates of release of fire radiative energy R_{fre} (megajoules per second or megawatts) from fires detected by MODIS on (dots and dotted lines) Terra and (circles and solid lines) Aqua throughout the designated regions in 2002. Each data point represents one MODIS daytime overpass over the region. Vertical error bars represent the standard errors of R_{sa}.

- Ichoku and Kaufman (*TGRS,* 2005) show large regional variation in smoke(Y-axis) per FRE(X-axis)
- This can be explained by sampling bias of FRE:
  - Fire duration vs. sampling
  - Fire size distribution
- If these sampling factors could be directly accounted for, FRE could be used without geographic data

Some proxy for fire regime properties is needed to extrapolate satellite FRP data

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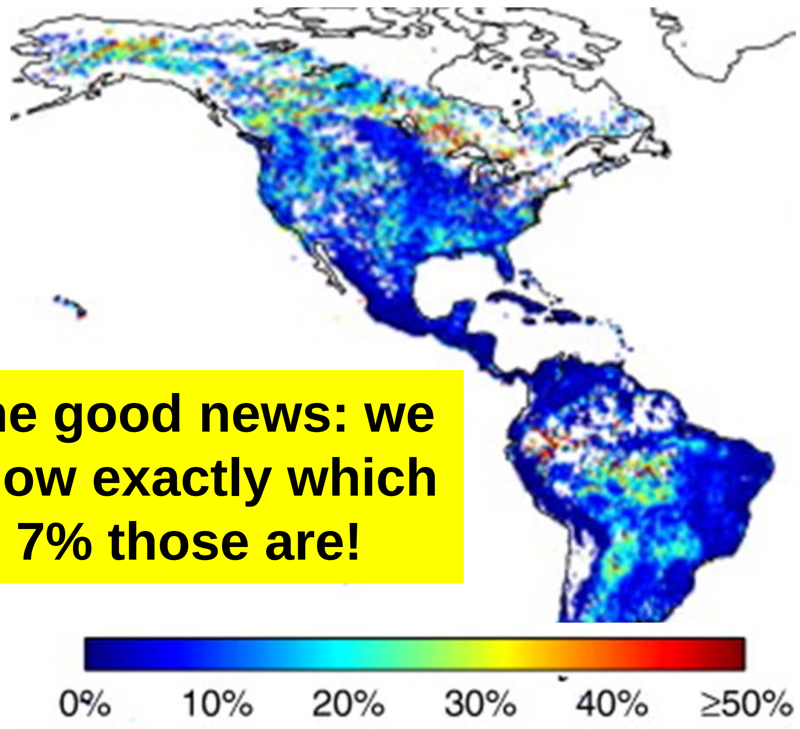
What About Bispectral Fire Retrievals?

- Bispectral retrievals (e.g. Dozier(1981) method) use two IR channels to retrieve two subpixel fire properties: size and Temp.
- Giglio and Schroeder (RSE, 2015) did a rigorous theoretical analysis of uncertainty in bispectral retrieval
- The bad news:
  - Retrieving fire fraction within a factor of 2 requires +4Z above background in 11um channel
  - This occurs in 7% of MODIS fire globally
  - Assumptions of this study are optimistic: many other sources of uncertainty ignored



The good news: we know exactly which 7% those are!

Implications of These Limitations for Emissions Estimation

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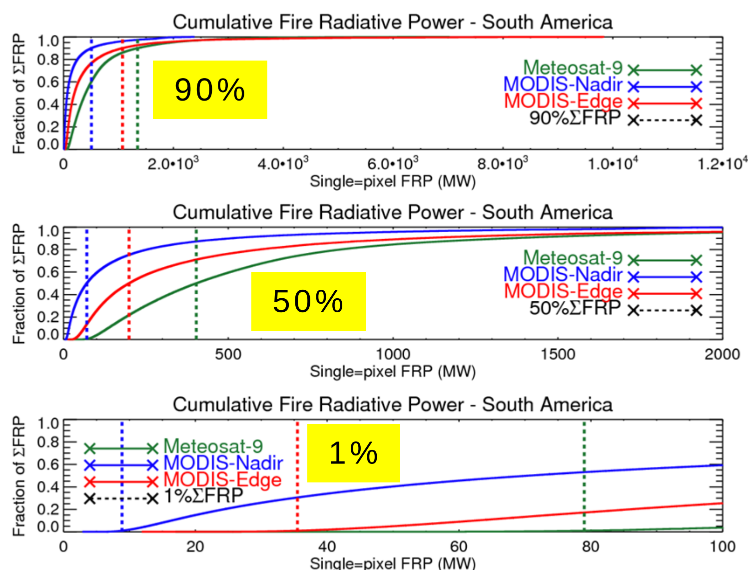
1. Omission errors dominate, so don't discard data
   - Use all available sensors all the time
   - Find a way to use both MODIS and GEO data: MODIS is more sensitive, but GEO provides diurnal information very valuable for modeling plume transport
   - Grid boxes with zero fire detections are the limiting factor in scale
2. Scaling will be necessary: observations cannot 'close the loop' of fire energy
   - FRP gives a physically meaningful number, but scaling/extrapolation in multiple dimensions is required to get to emissions
3. Satellite overpasses are best treated as independent snapshots
   - Stochastic nature of fire detection dictates that observations are never "duplicates"
4. Extrapolating from detected fires to total fire activity is dependent on fire regime
   - Can't escape from the need to characterize fuel type/condition
   - What are the best proxies (e.g. region, season, land cover)?

Big Unknown: Bottom of FRP distribution

From South American area data:

- 53% of MODIS NADIR (pixel dim < 1.25km along-scan) FRE is below the 1% detection limit of Meteosat-9 SEVIRI
  - 37% of total MODIS FRE
- 31% of MODIS NADIR FRE is below the 1% detection limit of MODIS EDGE (pixel dim >2.5km along-scan)

- Shape of FRP distribution at low values determined by detection efficiency
- There is no “reference standard” for this distribution
  - Thus, our extrapolations can only be as good as MODIS at nadir



What would this curve look like at 20m resolution?

Big Unknown: Flaming / Smoldering retrieval

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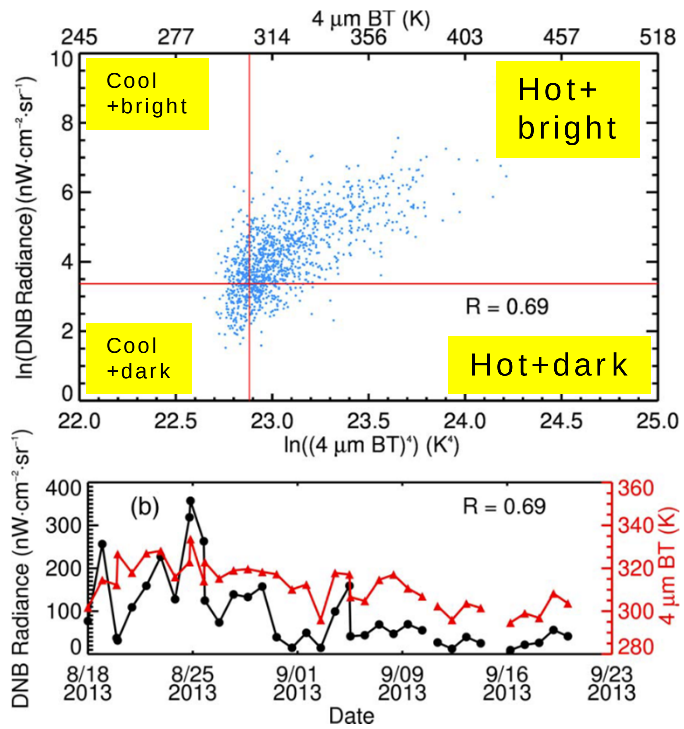
- Combustion phase is supposed to drive smoke composition
- Combustion phase evolves over fire lifetime
- Field results have not had good success at capturing this
- Polivka et al. (TGRS, 2016) evaluated using visible signal to identify nighttime burning (modify IR detection thresholds)
- ***Can a satellite retrieval yield information related to combustion phase?***



Polivka et al., TGRS 2016

Conclusions: How Can Field Campaigns Improve FLAMBE?

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1. High-resolution observations of fire energetics
   - Large and small fires
2. Combustion phase / efficiency observations of very large fires / smoke plumes
3. Expectation rules for fires in mixed landscapes
   - How much in forest vs chaparral?
   - Fuel properties thresholds to determine where fire is not?
4. Additional information on nighttime burning
   - Can deviation from climatology be well-predicted?
   - What are the chemical/microphysical implications of smoke release at night?

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Ackowledgements

- **NRL FLAMBE Group**
- **UNL and UI Wang Groups**
- **Fire product teams: MODIS, WF_ABBA (CIMSS)**

THANK YOU!

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Extra Slides

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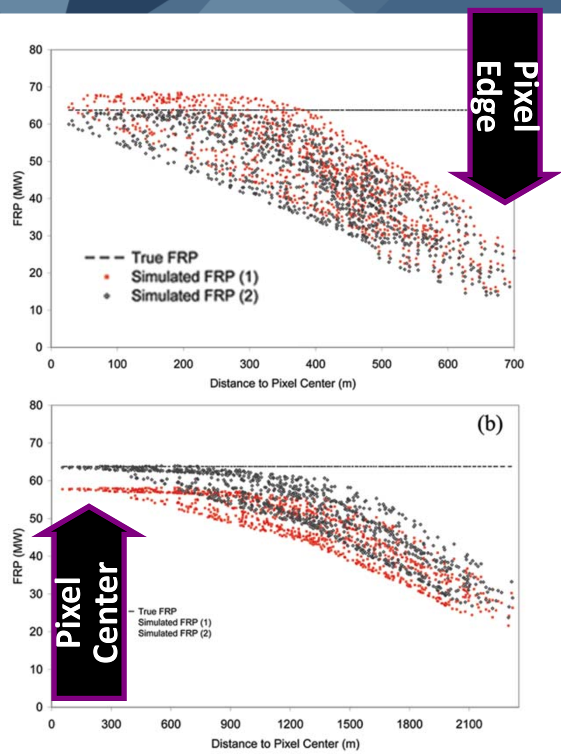
Stochastic Uncertainty in FRP: Fire Location within Satellite Pixel



- Giglio & Csiszar, *JGR* 2010
  - Nominal FRP = 63.7MW
  - Black = calc. using nominal pixel area
  - Red = calc. using realistic *best-case* pixel area
  - Fire at pixel edge has ~40% FRP of nominal
- Implication: “limit of detection” is a range from FRP_{min} to $2.5*FRP_{min}$
- VIIRS pixel aggregation scheme complicates things further
  - See Polivka et al., *IEEE GRSL* 2015