Emissions of CO and NOx from Biomass Burning in Siberia: Current Uncertainties & Environmental Implications

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Religion, Art, or Biomass Burning?

Daimonji-Yaki in Kyoto, on 16th August （大文字の送り火）

Photo: Siberian forest
(courtesy of T. Machida)

Q: Does Biomass Burning make Ozone?
A: It depends. Contradicting picture.

Q: Why? How? and …

In collaboration with:
CO: Keiichi Sato, Tim Butler, Mark G. Lawrence, Jenny A. Fisher, Monika Kopacz, Robert M. Yantosca, Yugo Kanaya, Shungo Kato, Tomoaki Okuda, Shigeru Tanaka, Jiye Zeng, Hideki Nara
NO2: K. Folkert Boersma, Ronald van der A, Andreas Richter, et al.

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KNMI

MAX-PLANCK-GESELLSCHAFT

AIRS Can Capture Long-range Transport of CO

AIRS: Atmospheric Infrared Sounder

Greater advantage of AIRS is its increased horizontal spatial coverage (70% of the globe each day, versus 3 days by MOPITT)

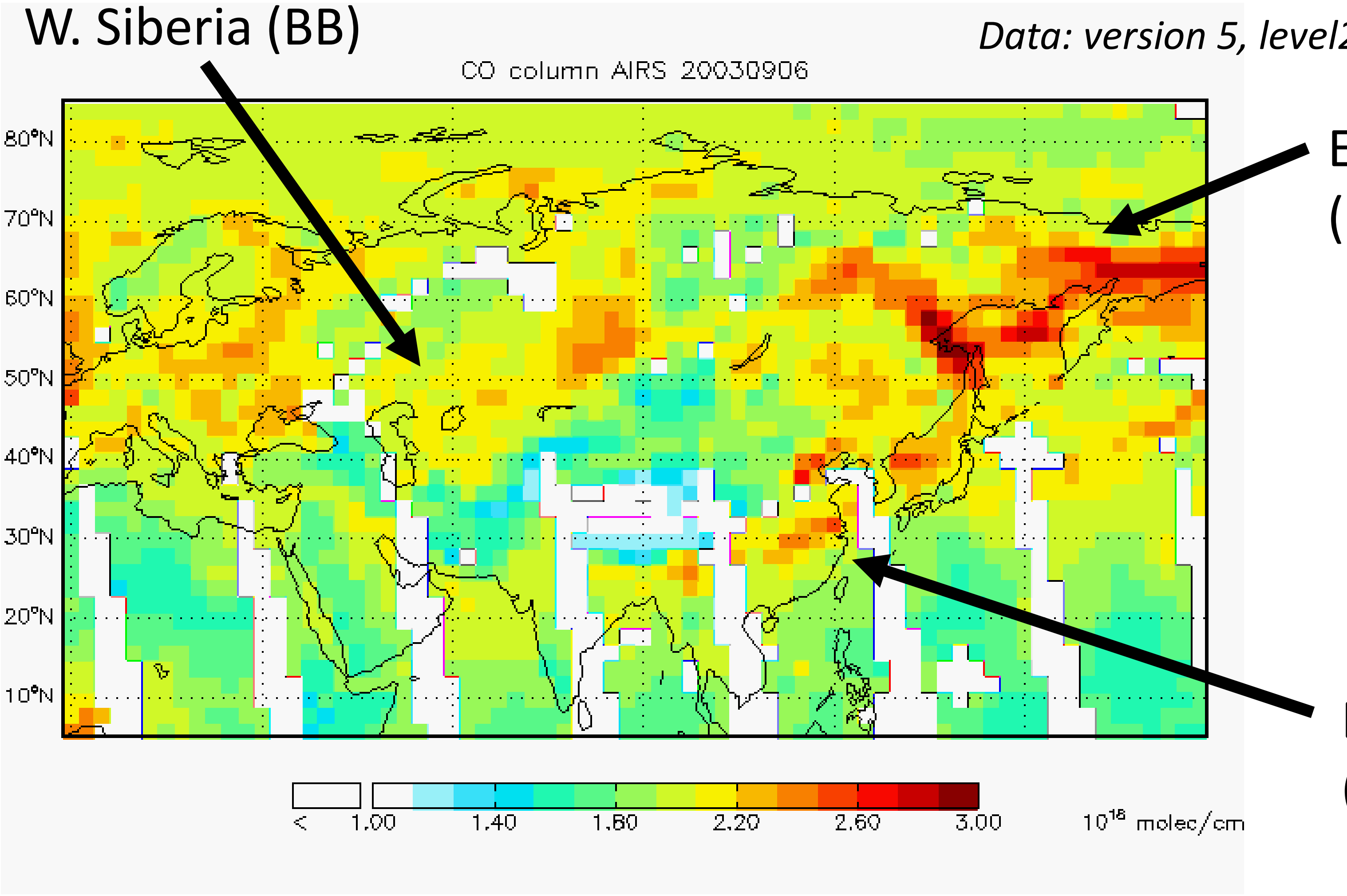
- Onboard NASA's Aqua satellite
- Launched in May 2002
- Retrieval at 4.7 mm
- Spatial resolution of 45 x 1650 km
- Sensitive to CO in the mid-trop.

- Bias of +15-20 ppbv over oceans relative to MOPITT on EOS/Terra satellite (Warner et al. 2007)
- Events can be seen (Yurganov et al. 2008; Zhang et al. 2008)

Greater spatial coverage allows us to track CO plumes transported from the emission sources to distances of several thousands km on each day

How can AIRS see CO over Siberia?

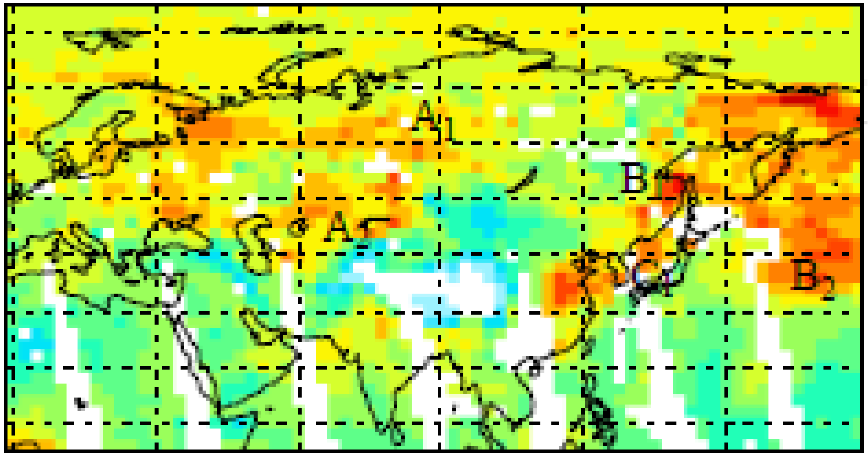
Tanimoto et al., Tellus-B, 2009



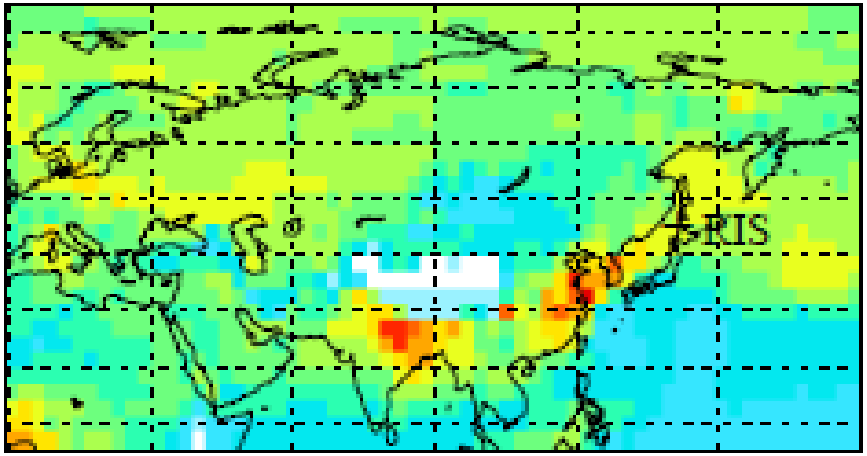
- AIRS detected CO enhancement over source regions
- AIRS tracked biomass burning CO plumes over Eurasia on a daily basis

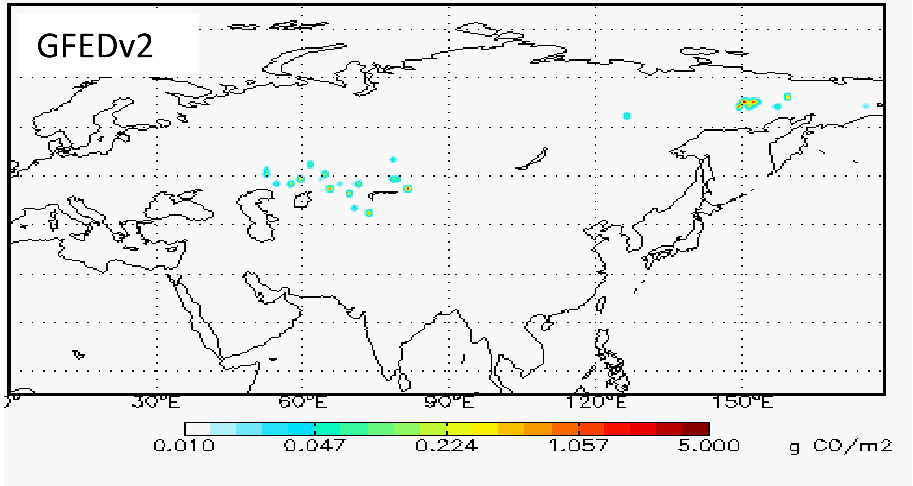
AIRS vs. CTM : Sep 10-13, 2003 (BB > FF)

AIRS



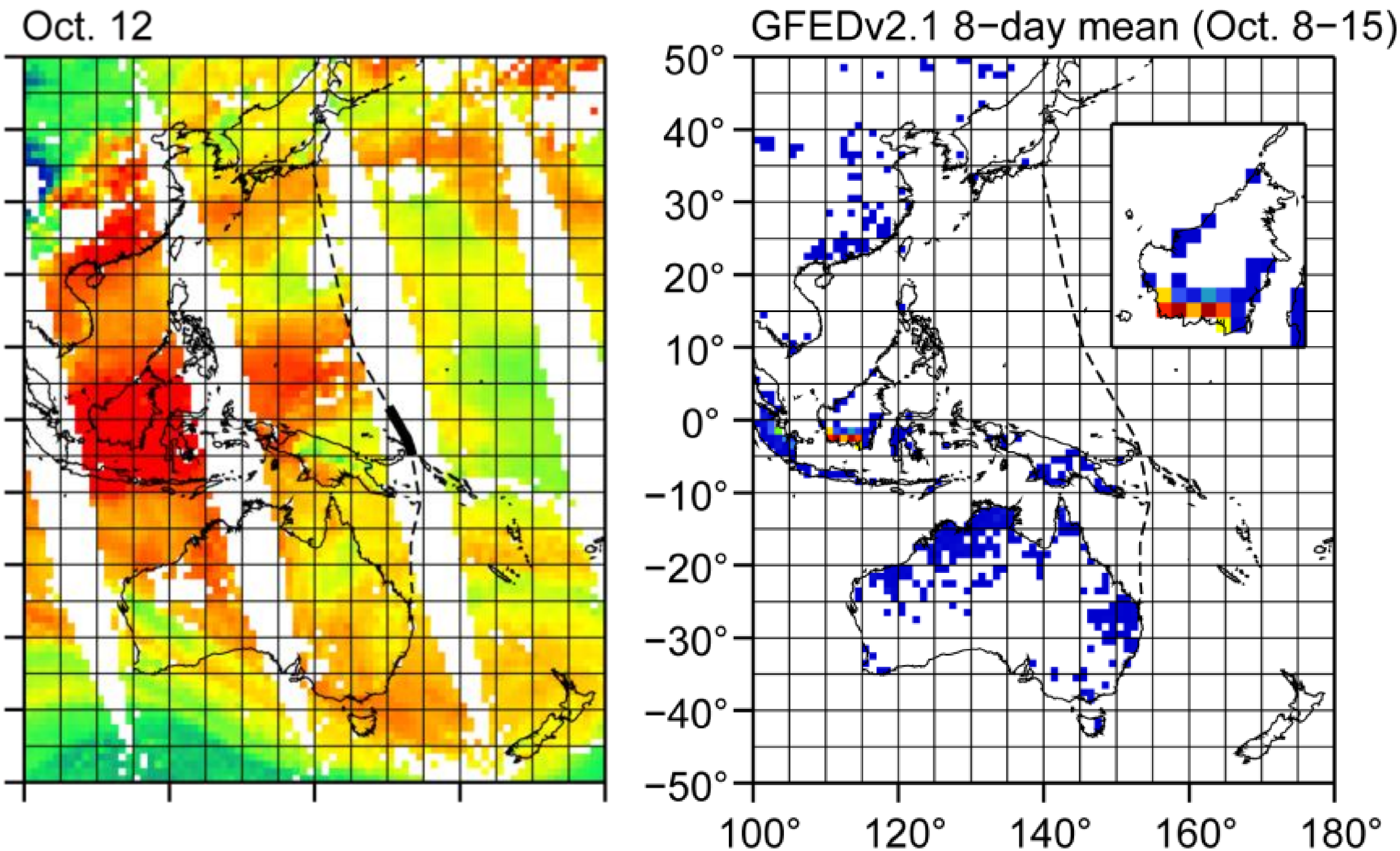
CTM (hybrid-GFEDv2)





- Model is lower and less widespread than AIRS
- GFEDv2 may underestimate CO emissions per area by failing to implement small fires from MODIS
- Peat burning (smoldering)
  - Emissions estimates are very difficult, due to large uncertainties such as the amount of organic matter, depth of organic layers, soil moisture under ground
  - Emission factors may be greatly different from standard numbers

AIRS CO over Southeast Asia



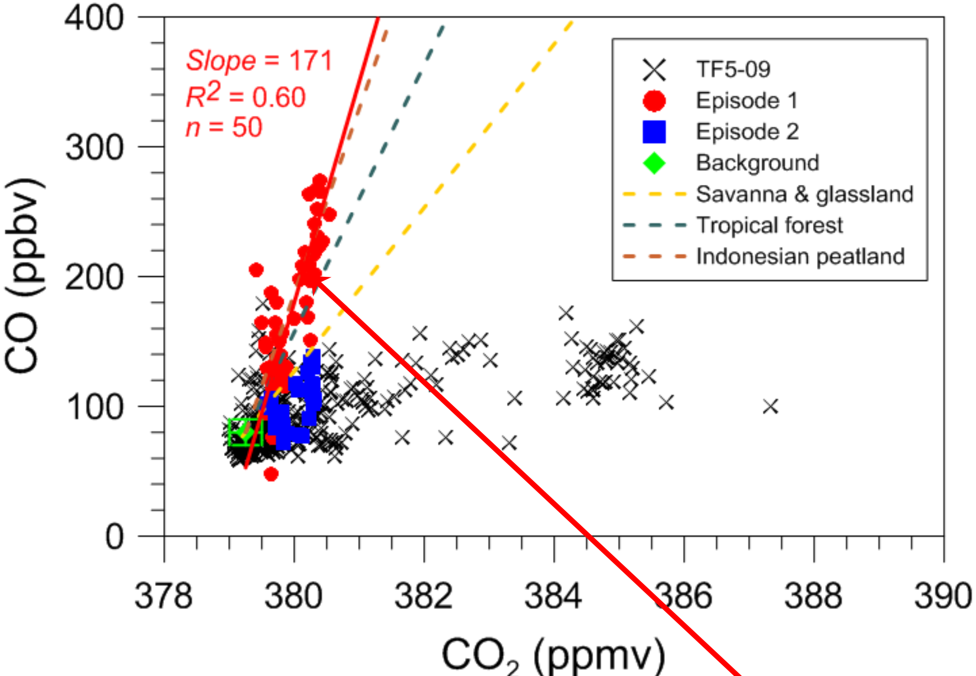
- AIRS captures eastward CO plumes from SE Asia
- GFEDv2 suggests strong CO emissions from Borneo and Sumatra Islands
- High-CO observed is due to BB emissions in SE Asia

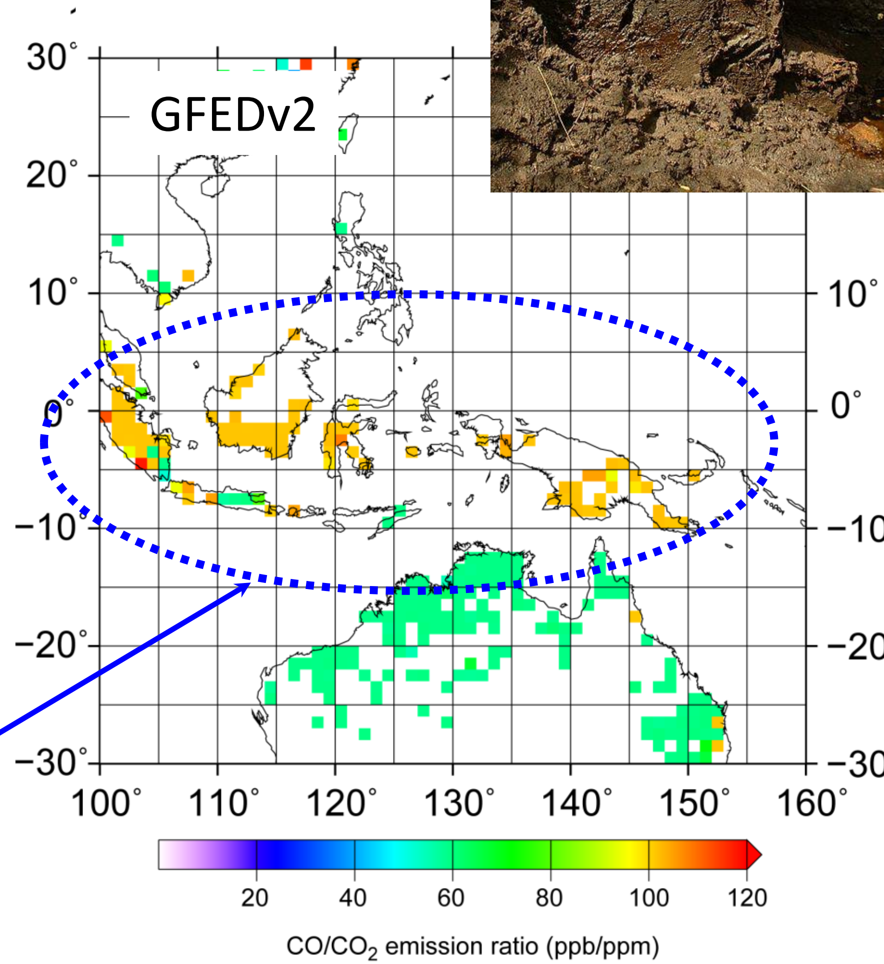
CO-vs-CO_2 Correlation in BB Plumes

Indonesian peatland: 143, 194-279

Tropical forest: 103 (+/-21)

Savanna & glassland: 63 (+/-20)





- Observed CO/CO_2 ratio (171 ppb/ppm) is higher than in GFEDv2 (~110 ppb/ppm)
- Uncertainty in CO emissions by GFEDv2 in Southeast Asia associated with emission factors of peatland fires

Nara et al., Environ. Chem., 2011

Background & Motivation

- Emissions, transport, impacts of CO are well-studied
- CO is simple: atmospheric mixing ratios ≈ emissions

- Those of O_3 is less known, it is much more complicated
- Important roles of boreal forest fires in day-to-day variability, interannual variability, and long-term trend of trop. O_3
- O_3 production depends on …
  - fire emissions
  - photochemical reactions
  - meteorology
  - aerosol effects
- Still lots of discussions on magnitude of O_3 prod/loss
- O_3 enhancements are subtle, “several (0-5) ppbv”
- NOx is a key species, but not extensively examined, because of limited measurements nearby fires

Does Biomass Burning make tropospheric ozone?

Review

Ozone production from wildfires: A critical review

Daniel A. Jaffe[a,b,*], Nicole L. Wigder[a]

Atmos. Environ., 2012

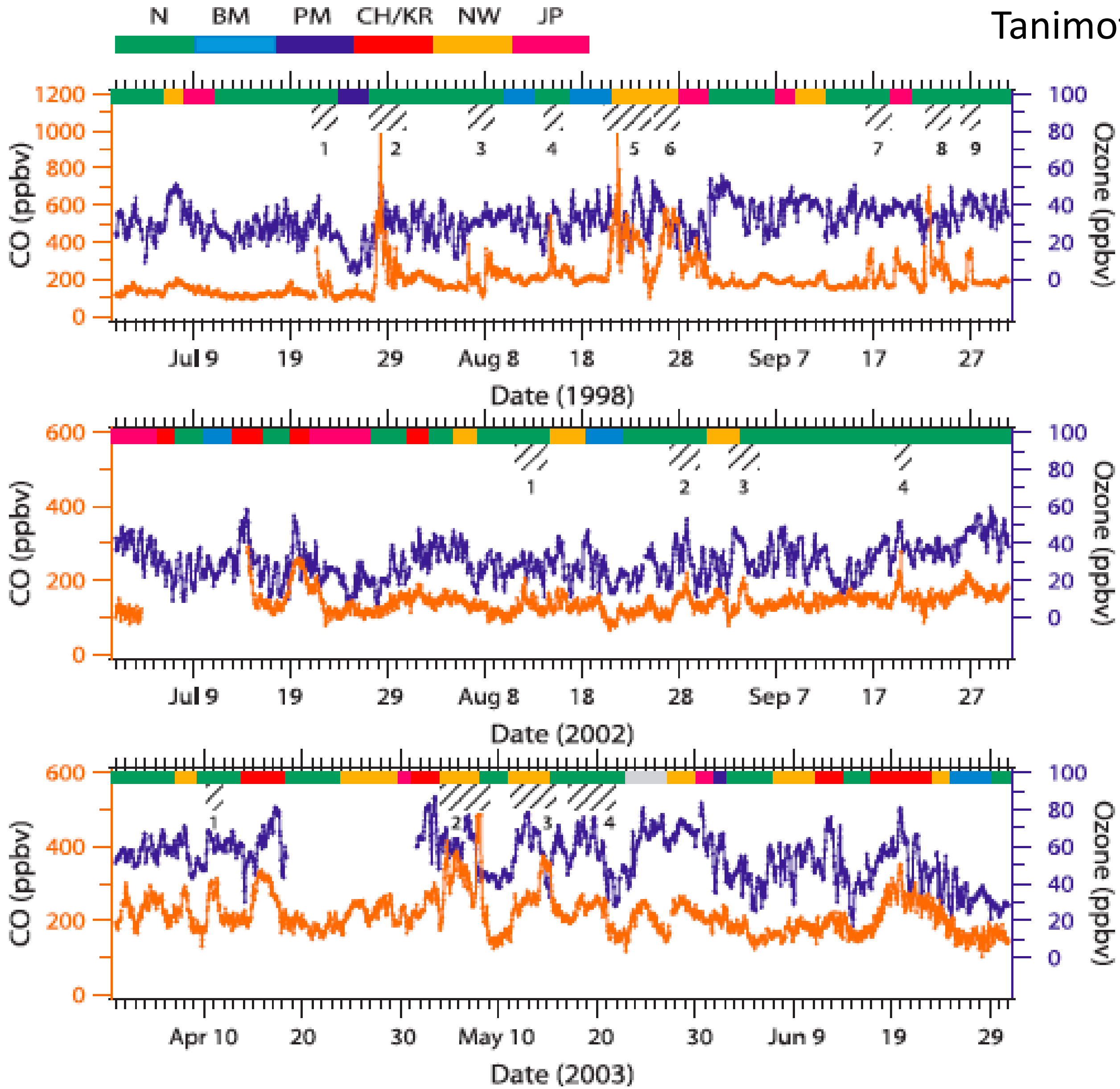
$\Delta O_3/\Delta CO$

Plume age category	Study	Boreal and temperate regions	Approximate plume age	Range of $\Delta O_3/\Delta CO$ (ppbv/ppbv) (number of measurements)	Mean $\Delta O_3/\Delta CO$ (ppbv/ppbv)
≤1–2 days	Alvarado et al., 2010	Canada	4–10 h	−0.032–0.052 ($n = 16$)	0.005 ± 0.019
	Alvarado et al., 2010	Canada	14 h–2 days	−0.94–0.34 ($n = 15$)	−0.06 ± 0.28
	Goode et al., 2000	Alaska	2 h	0.064–0.089 ($n = 3$)	0.079 ± 0.024
	Singh et al., 2010	Siberia/North America	<1 day	range not specified ($n = 18$)	0.03 ± 0.04
	DeBell et al., 2004	Canada	1–3 days	0.014–0.062 ($n = 3$)	0.035
average					0.018
2–5 days	Mauzerall et al., 1996	Canada	not specified[a]	0.00–0.66 ($n = 9$)	0.13
	Paris et al., 2009	Siberia	2 days	0.14 ($n = 1$)	0.14 ± 0.50
	Singh et al., 2010	Siberia/North America	1–5 days	range not specified ($n = 20$)	0.11 ± 0.09[b]
	Tanimoto et al., 2008	Siberia	≤5 days	−0.07–0.42 ($n = 8$)	0.17
	Wofsy et al., 1992	Alaska/Canada	not specified[a]	0.18 ($n = 1$)	0.18
average					0.15
≥5 days	Alvarado et al., 2010	Canada	2–11 days	−0.20–0.00 ($n = 3$)	−0.07 ± 0.12
	Bertschi et al., 2004	Siberia	6–10 days	0.22–0.36 ($n = 5$)	0.27
	Bertschi & Jaffe, 2005	Siberia	7–10 days	0.15–0.84 ($n = 5$)	0.44
	Honrath et al., 2004	Siberia	13–15 days	0.45–0.93 ($n = 4$)	0.59
	Paris et al., 2009	Siberia	13 days	−0.04 ($n = 1$)	−0.04
	Pfister et al., 2006	Alaska/Canada	not specified[a]	range/number not specified	0.25
	Real et al., 2007	Alaska	6–9 days	−0.0088–0.078 ($n = 2$)	0.035
	Val Martin et al., 2006	northern North America	6–15 days	−0.42–0.89 ($n = 9$)	0.27
average					0.22

- Some people say “YES” or “A LOT”, some say “NO” or “NOT MUCH”

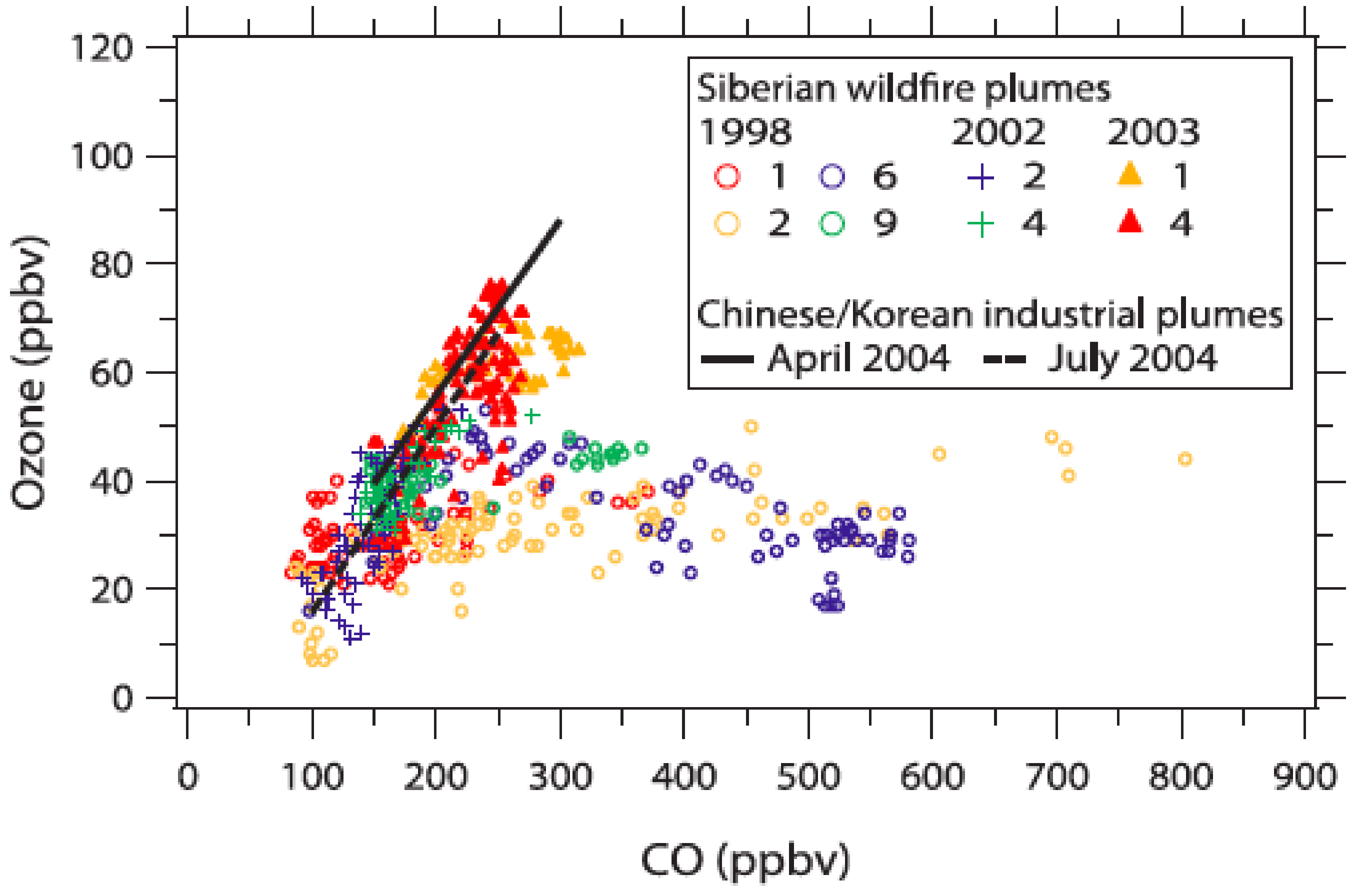
Ozone production in Siberian BB plumes

Tanimoto et al., SOLA, 2008



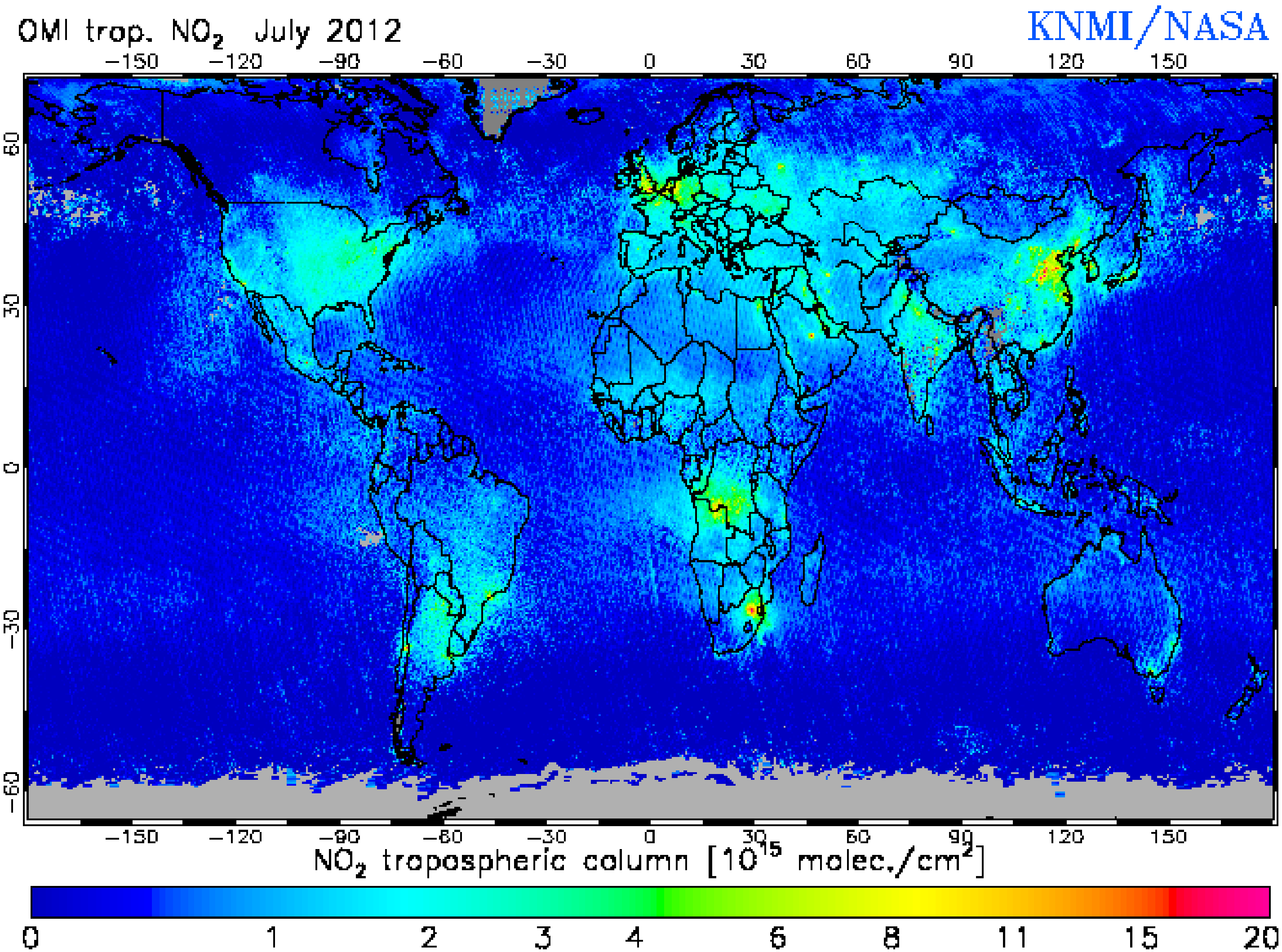
Ozone production in Siberian BB plumes

Tanimoto et al., SOLA, 2008



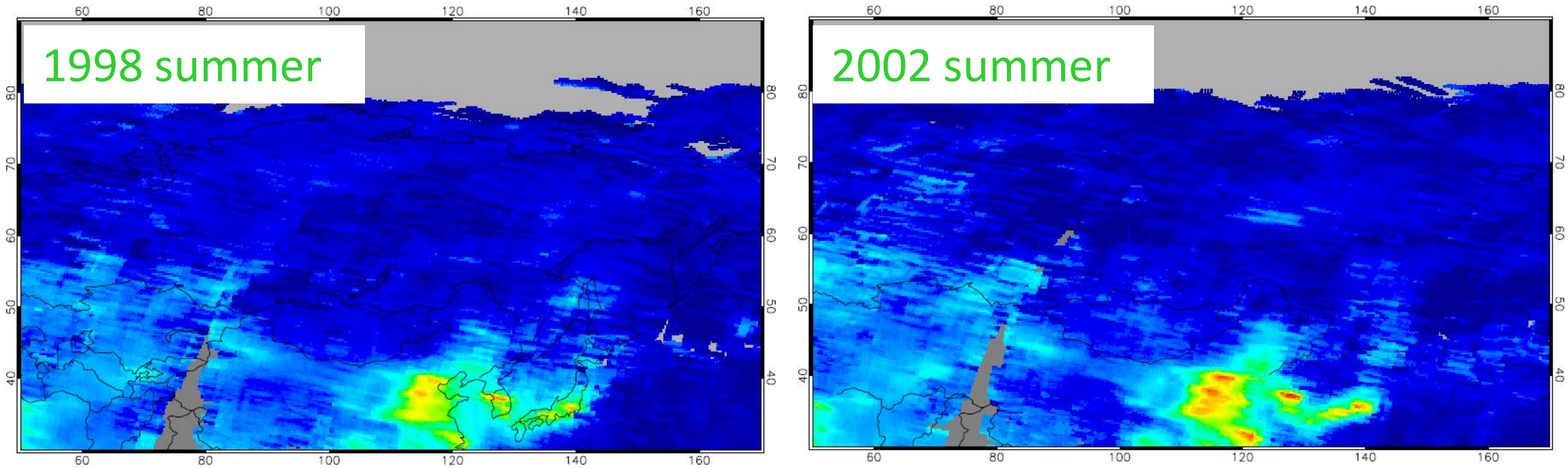
- Observations of ΔO3/ΔCO in fire plumes range from -0.1 to 0.9
- Ozone production takes place in SOME wildfire plumes
- Wildfires can contribute to exceedances of the ozone air quality standard

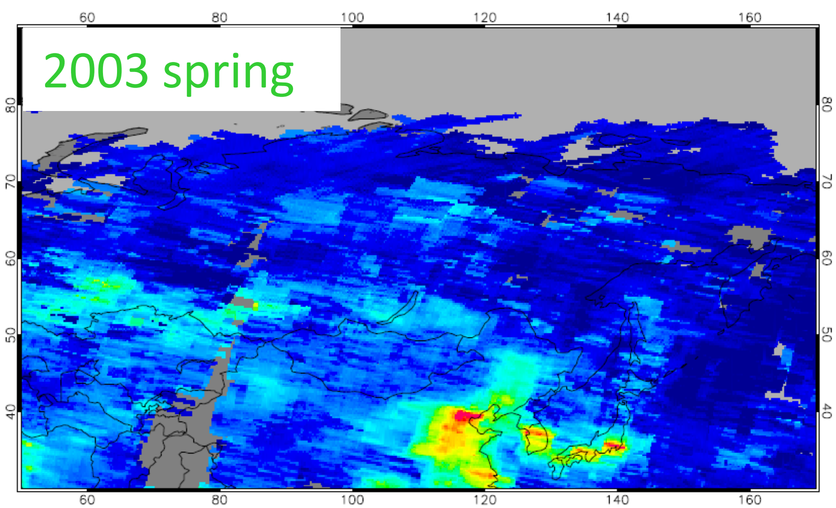
Trop. NO_2 column over Siberia viewed from space



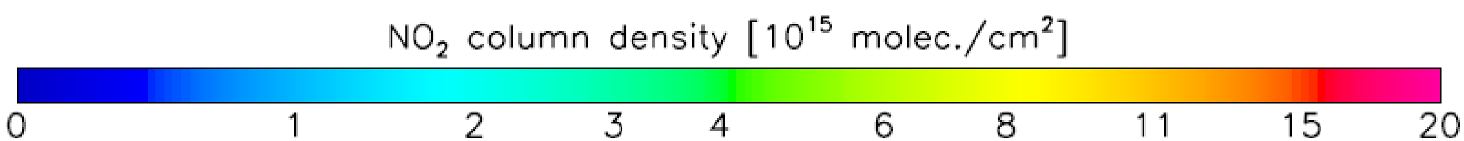
- In general, NO_2 is very low over Siberia, due to small anth. activities
- Enhancement of NO_2 is negligible in "low-fire-year"

Trop. NO_2 columns in BB-years (1998, 2002, 2003)



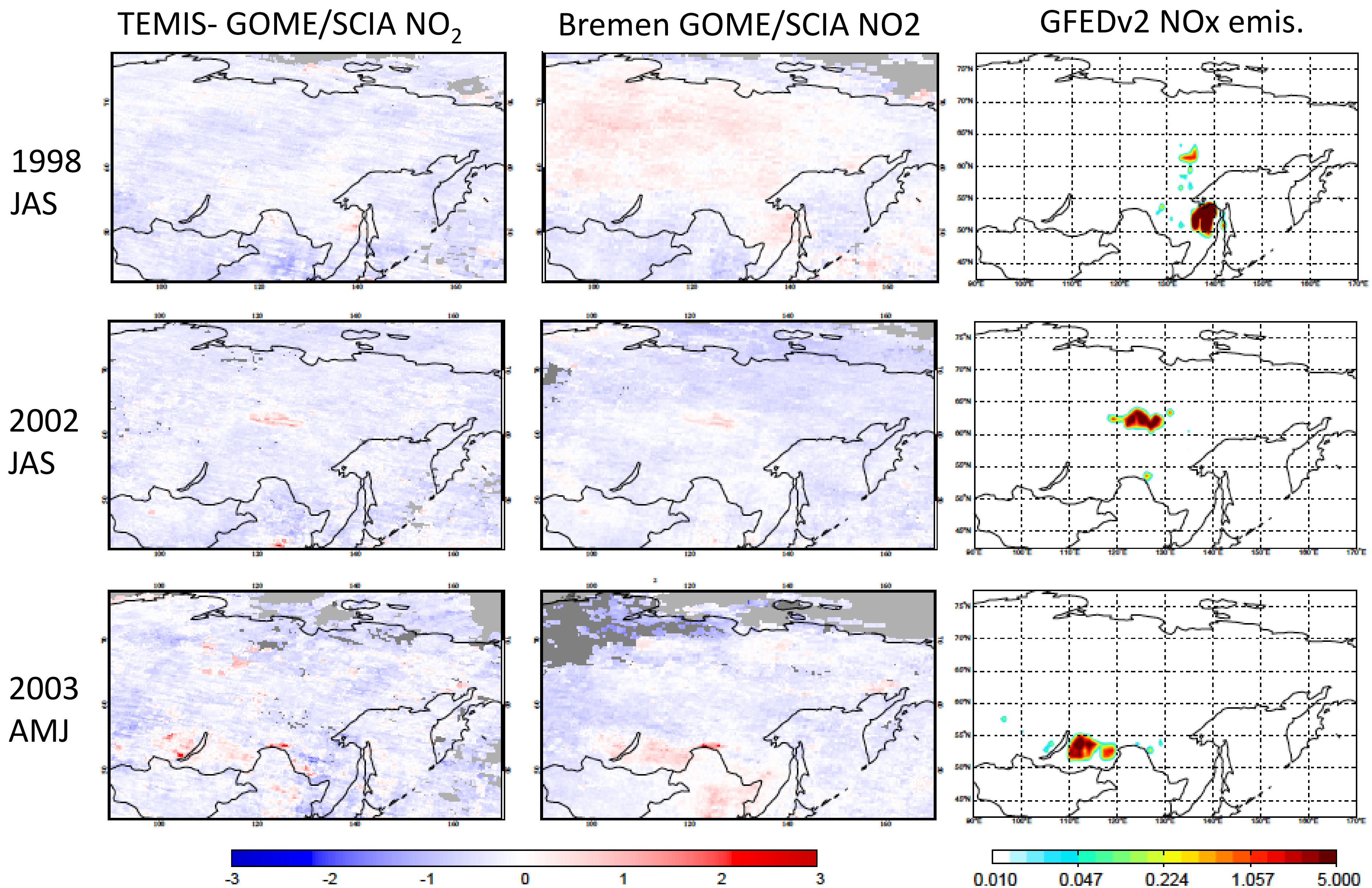


- Weak but significant enhancement of NO_2 in 1998, 2002, 2003
- Locations of NO_2 enhancements differ depending on year



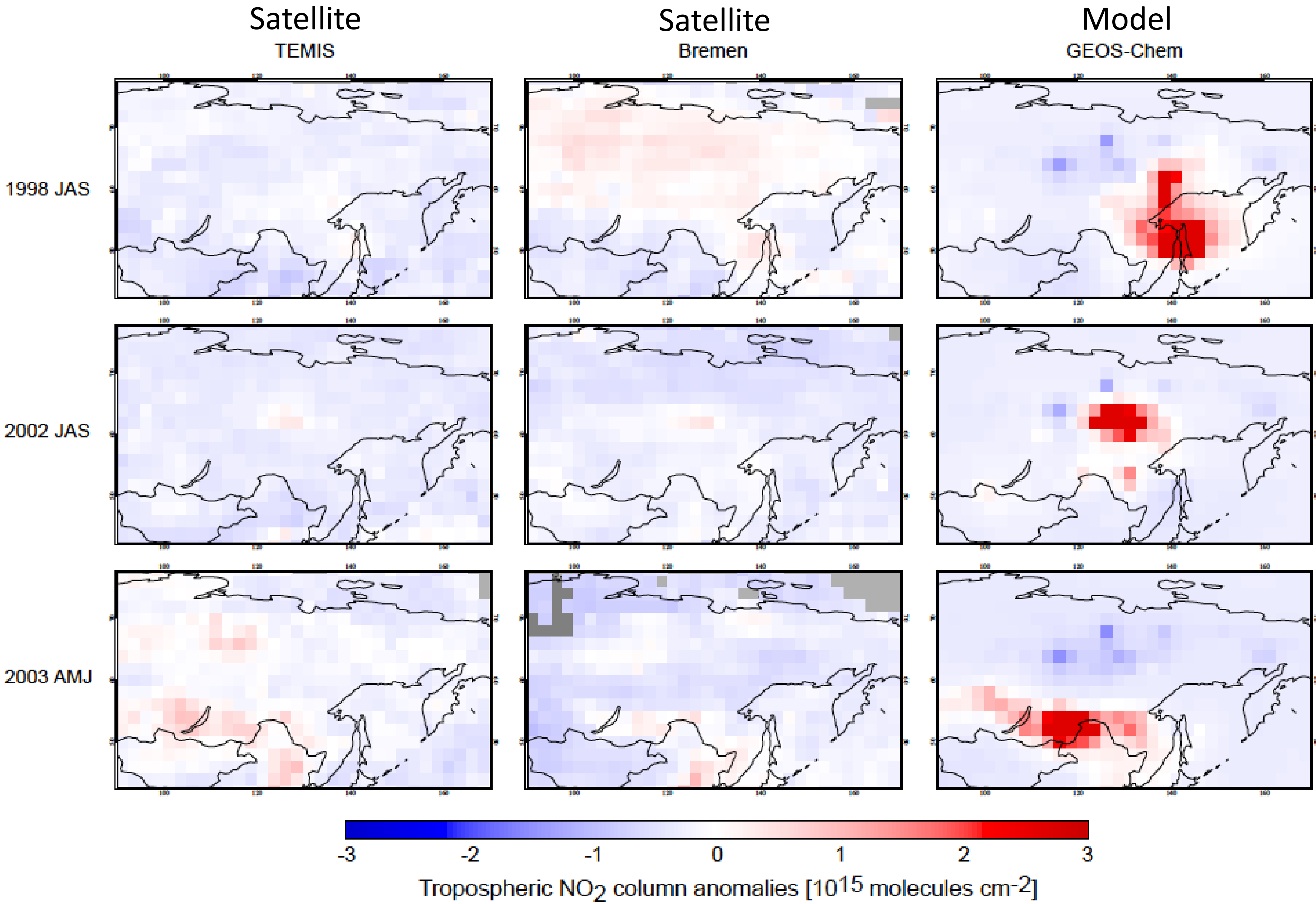
Anomalies of NO_2 in 1998, 2002, 2003

Tanimoto et al., submitted

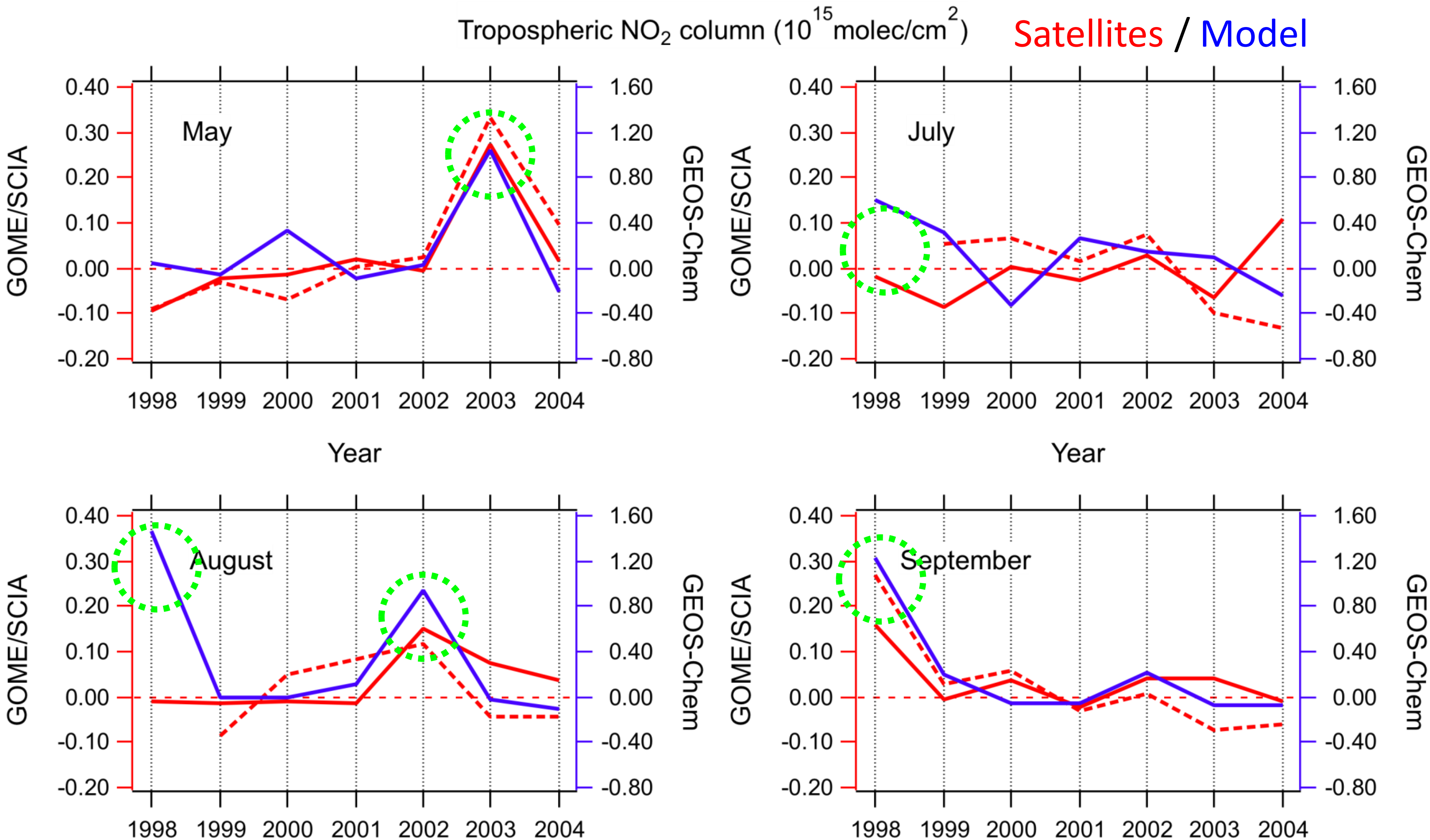


- Locations of NOx enhancement are consistent between satellites and inventory

Satellites vs. Model – Anomalies in 1998, 2002, 2003

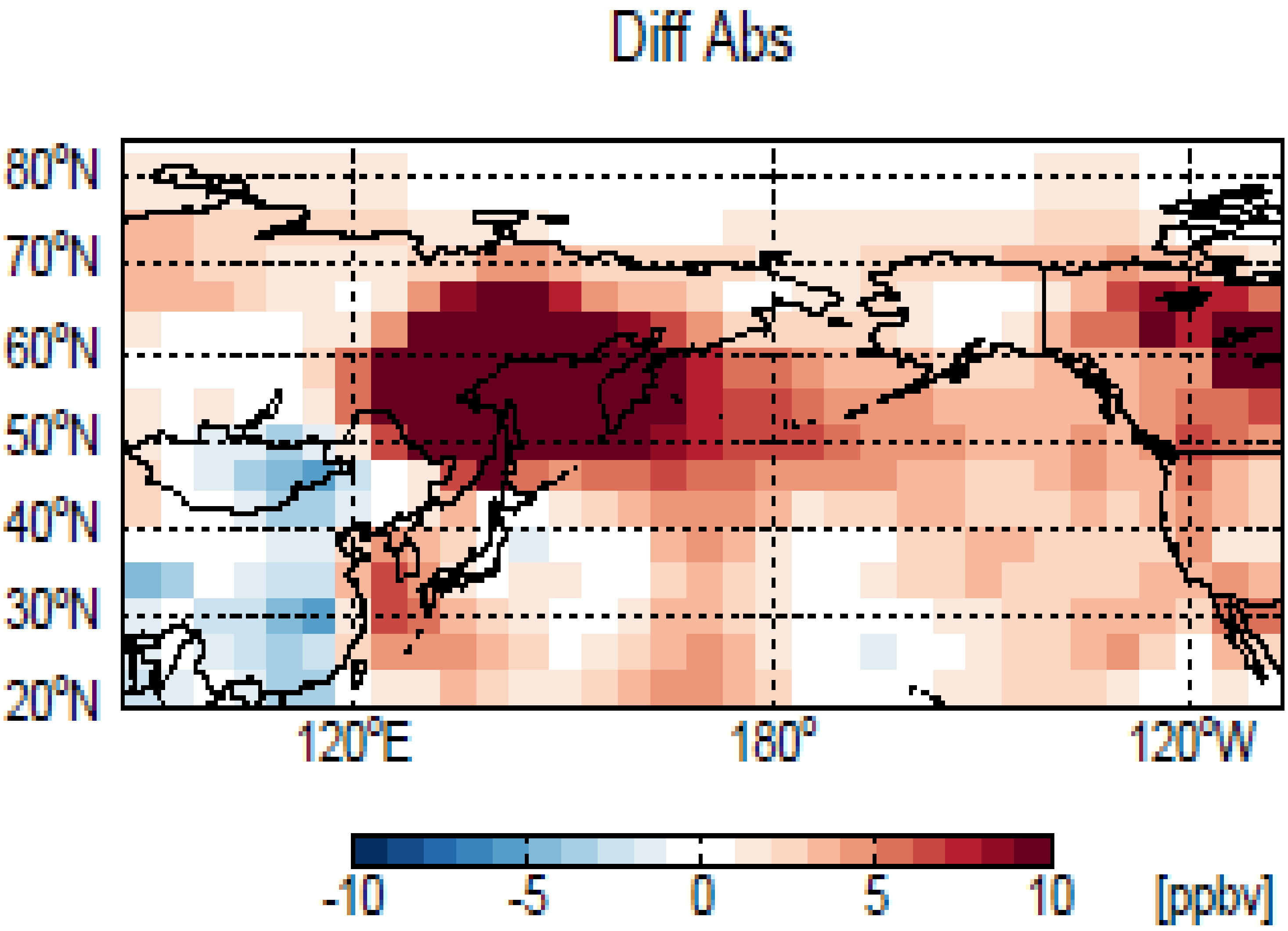


Satellites vs. Model – Comparison of regional means



- Satellites can detect NOx emissions from “large” & “medium”-scale fires
- Model agrees well with satellites in a qualitative manner (x4) = overestimates

Anomalies in ozone by Model, surface level (L=1)

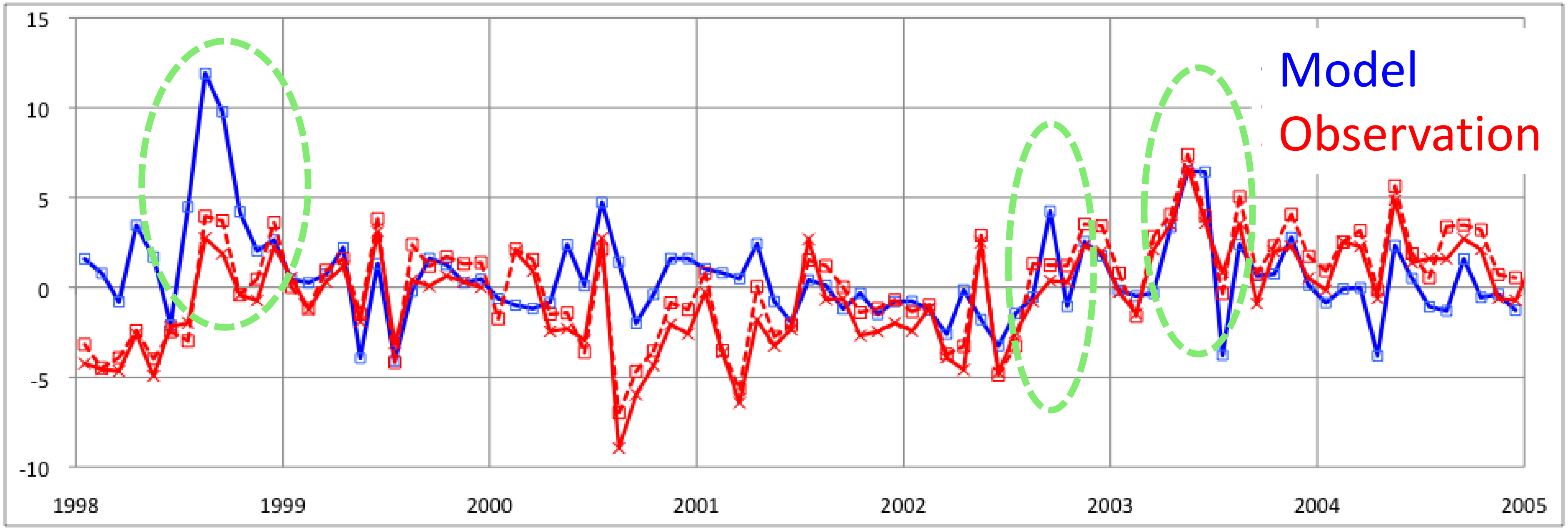


Summary

- Biomass burning is a substantial source for many species of atmospheric importance
  - BB-CO is easy to detect but BB-NO_2 is not. “Large-scale” BB-NO_2 emissions are now detectable from space!
  - In principle, NO_2 is easier to identify than CO over sources due to short lifetime
- GFED is one of the state-of-science inventories for BB, but it may still need improvements for boreal fires in Siberia
  - CO tends to be underestimated but NOx overestimated
  - Peat burning and small fires are challenging
- Current chemistry transport model(s) produce too much O3
  - Non-linearity chemistry in sub-grid scale
  - Better representation of chemical processes in fire plumes are important, in addition to reducing uncertainty for emissions
- Multi-species approach is useful to constrain emissions from BB, and to test/improve model transport schemes
  - Anthropogenic/BB, Region, location, amount, etc
  - Synergetic use of satellites – whatever satellites, we use!

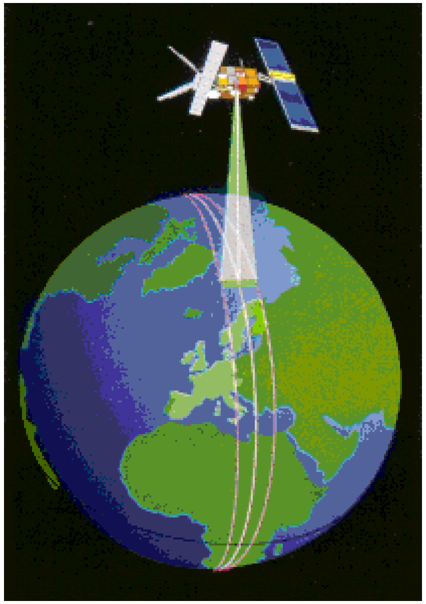
Interannual variability of surface ozone – Obs vs. Model

Rishiri Island, Japan (45N, 141E)



- Interannual variability = meteorology + emissions + stratospheric
- Model (w/ interannual BB) reproduces O_3 anomalies at Rishiri
- Good: Summer 2002 / Spring 2003
- Bad: Summer 1998 (obs. < model)

Questions & Tools



Tanimoto, Boersma, et al., in preparation, 2012

- Can satellites see NOx (NO_2) enhancement due to boreal fires?
- Does the GFED-driven model reproduce the NOx enhancement, and predict O_3 enhancement?
- Are satellites, model, and surface data consistent with each other? (top-down vs. bottom-up)

- GOME
  - *1998-2002, 10:30LT, 40x320 km*
- SCIAMACHY
  - *2002-2004, 10:00LT, 30x60 km*
- KNMI (TEMIS) & Bremen (A. Richter)
  - *monthly grid data*
  - *cloud-free & nearly cloud-free (cloud radiance <50%)*

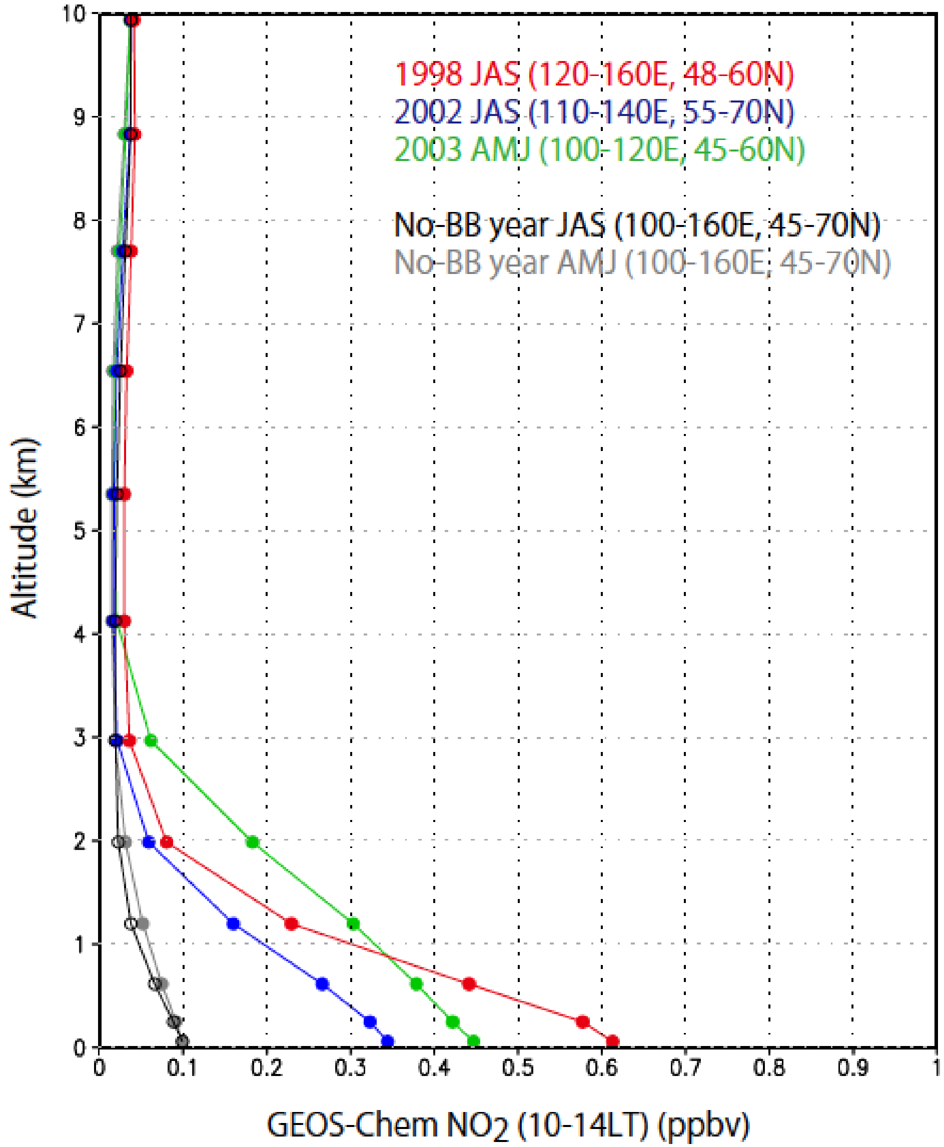
- GEOS-Chem (Harvard Univ.)
  - *Version: v8-01-01*
  - *Met. Field: GEOS4*
  - *Horizontal Grid: 4x5 deg*
  - *Vertical Layers: 30 layers*
  - *Tracers: 43 species*
  - *Emissions: GFEDv2, monthly*
  - *Period: Apr – Sep, 1998, 1999, 2000, 2001, 2002, 2003, 2004*

Summary & Future work

To be more precise…

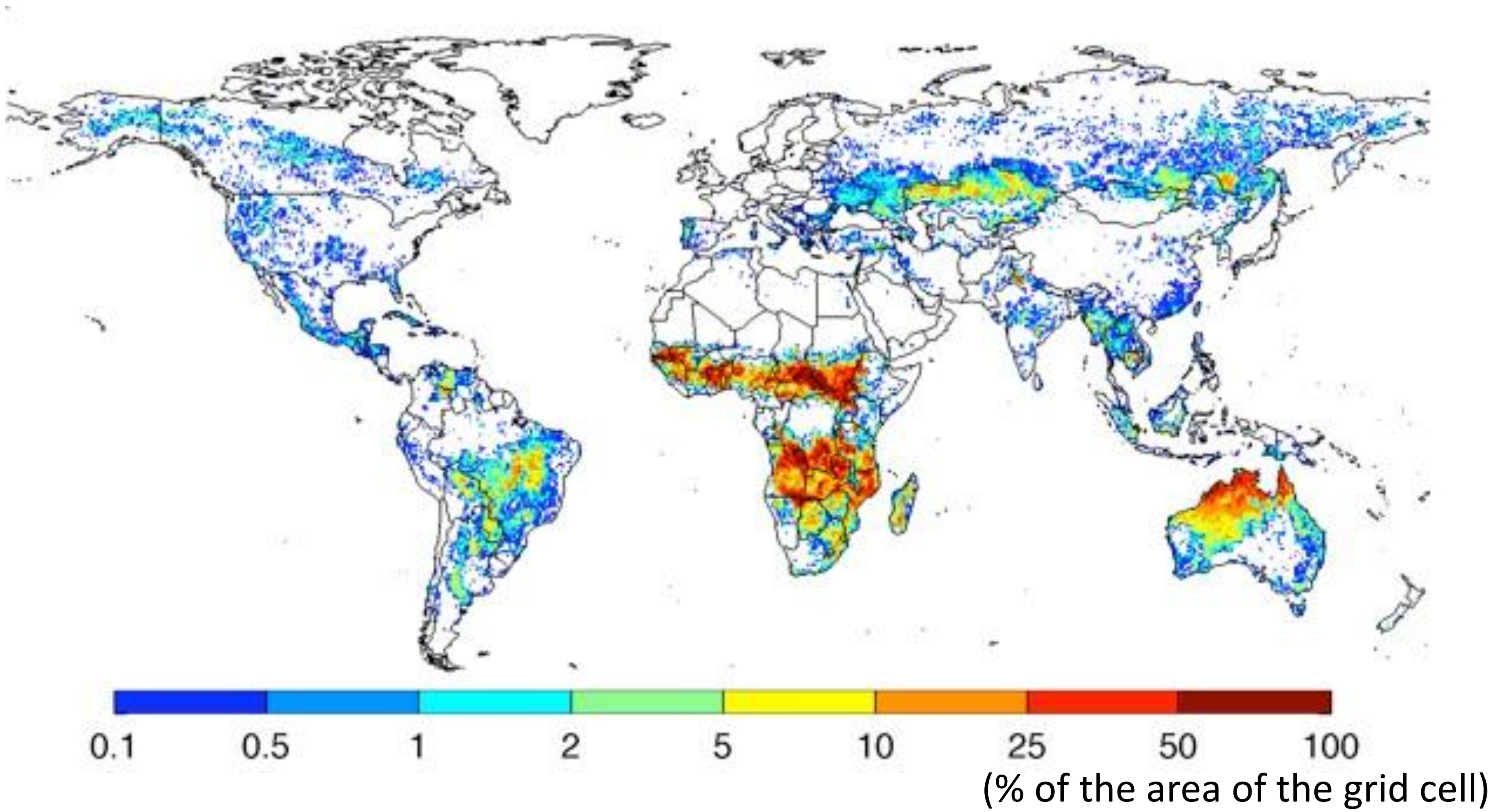
- Satellites' overpass time
  - GOME: 0930LT, SCIA: 1000LT, OMI: 1330LT
- Spatial resolution
  - Satellites < Model
- Clouds
  - Model < satellites, sampling issue
- Retrieval w/r/t a priori
  - Stratospheric NO_2 from model
- Vertical sensitivity (Averaging Kernel)
  - AK to model to have the same sensitivity to boundary layer NO_2
- Diurnal cycles
  - NOx emissions from BB, NO/NO_2 partitioning
  - Treatment of these factors in models

Vertical NO_2 profiles in Model



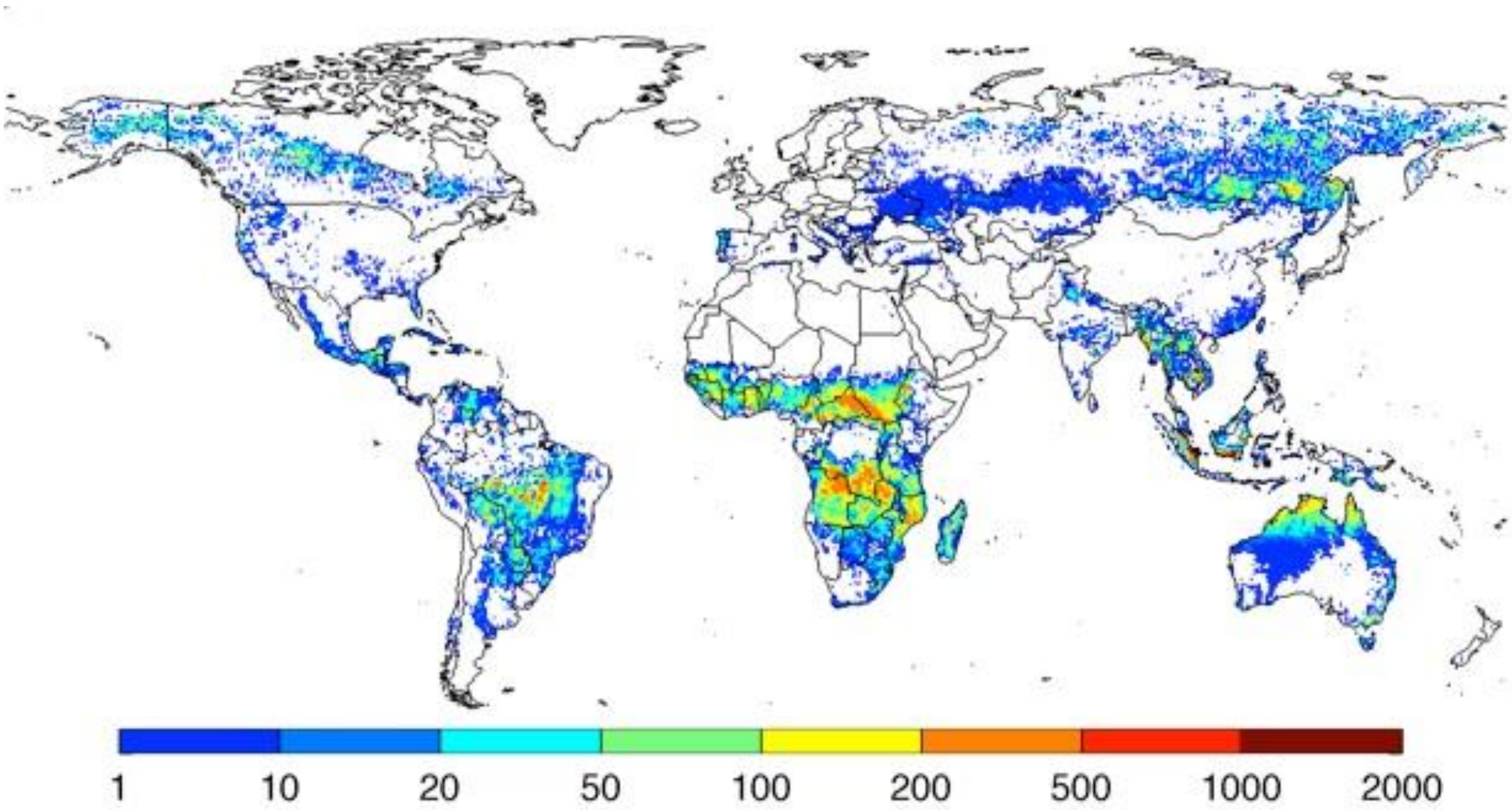
- Model predicts large enhancement in boundary layer (0-2 km) in BB years
- Enhancement is x 5-6

Annual burned area, 1997-2009



- Global Fire Emission Database: GFEDv1, v2, v3, v4, ...
- Burned area is basically derived from MODIS

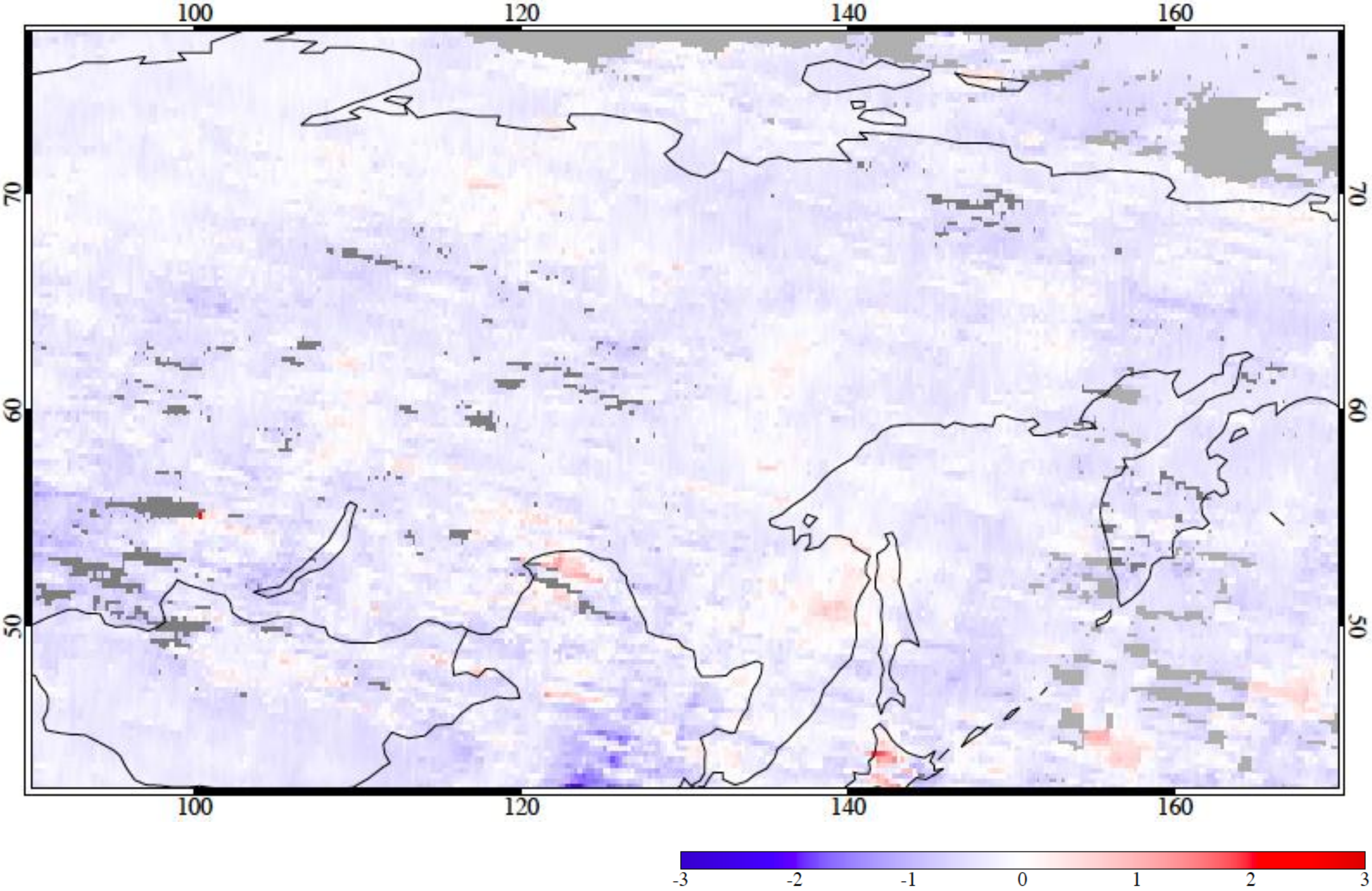
Annual carbon emissions, 1997-2009



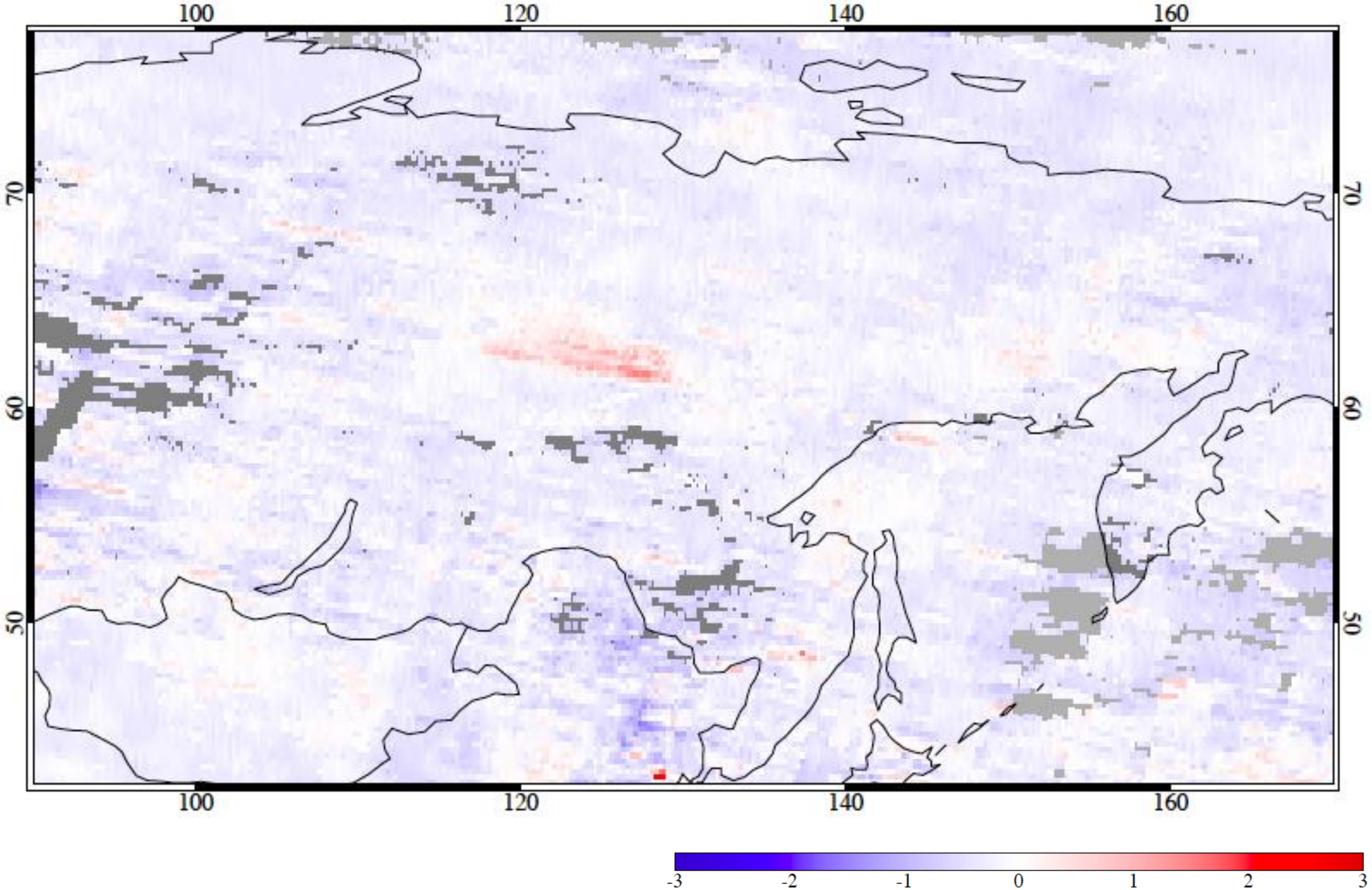
(g C m-2 year-1)

- Emission is not simply proportional to burned area
- Emission = burned area * biomass * combustion completeness * emission factor, …

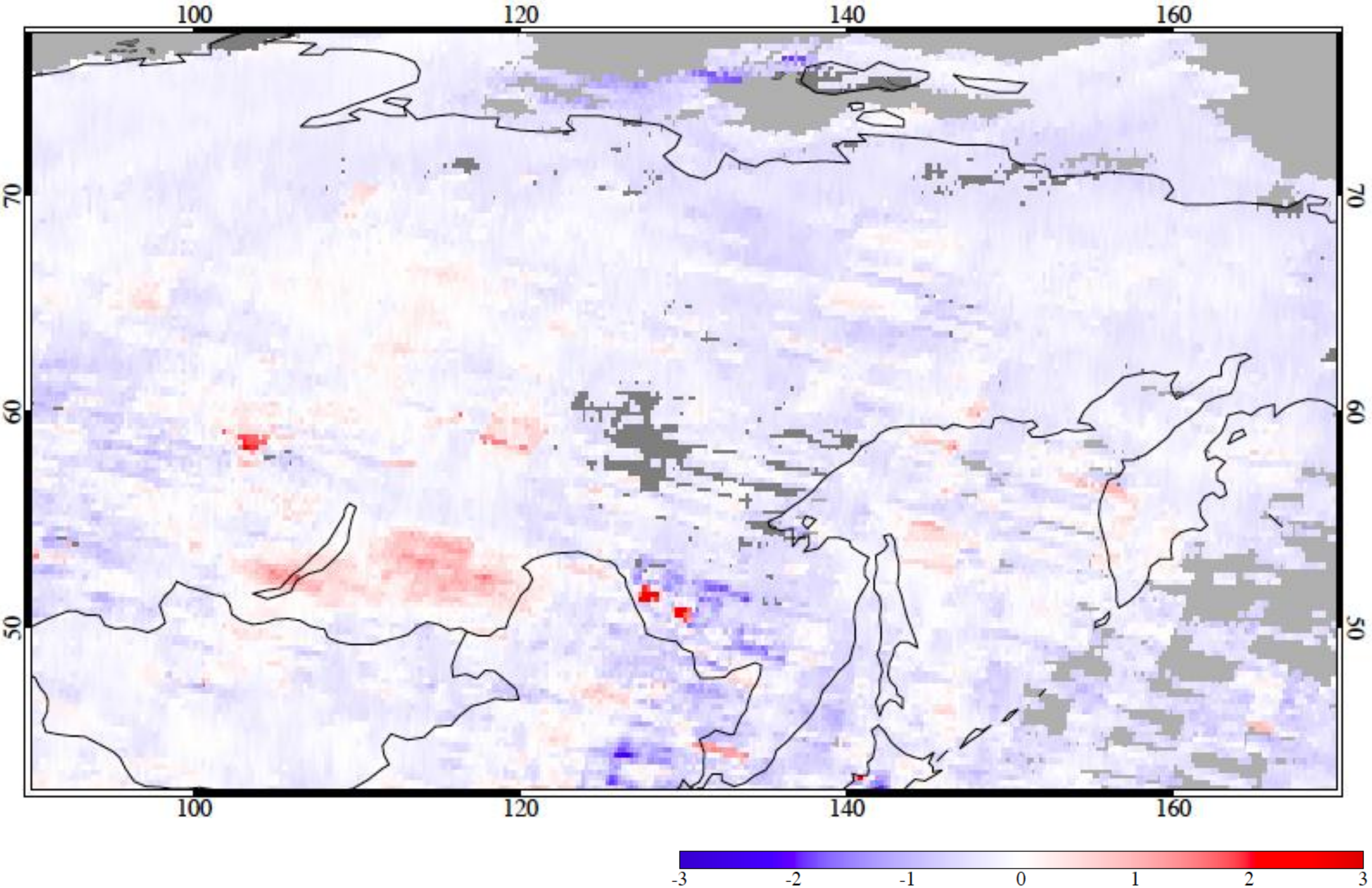
Summer 1998 – climatology



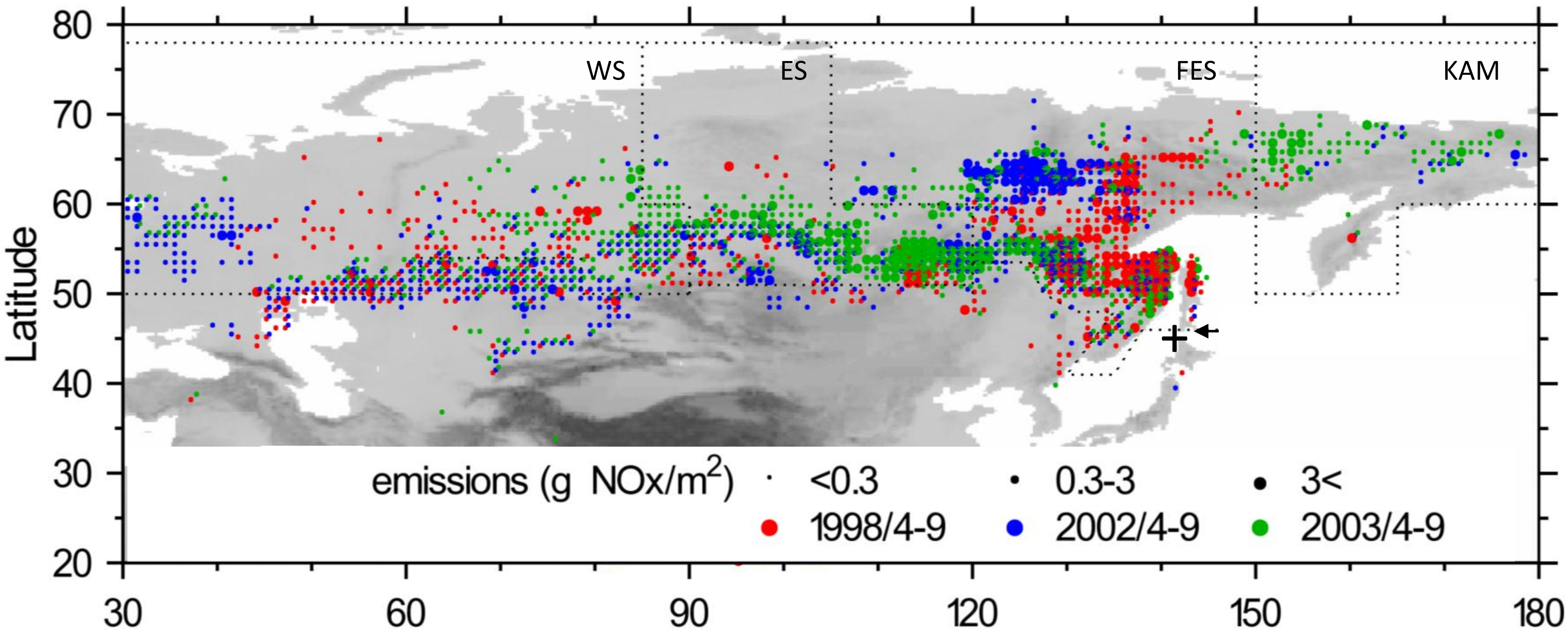
Summer 2002 – climatology

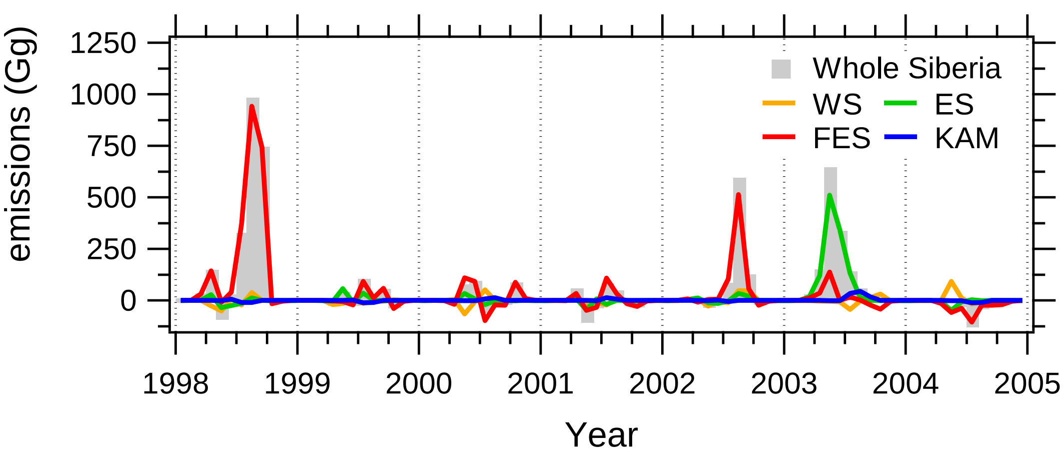


Spring 2003 – climatology



Biomass Burning Emissions in Siberia





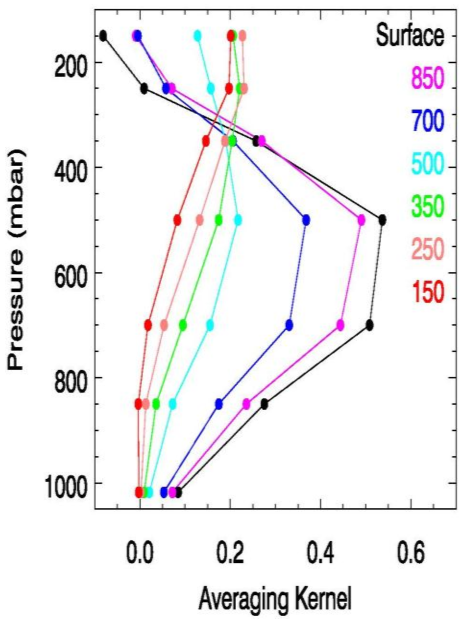
- FES (Far-Eastern Siberia) & ES (Eastern Siberia)
- "low-fire-year": 1999, 2000, 2001, 2004 = reference
- "high-fire-year": 1998, 2002, 2003

Satellite instruments providing CO column

Monika Kopacz (Harvard)

MOPITT

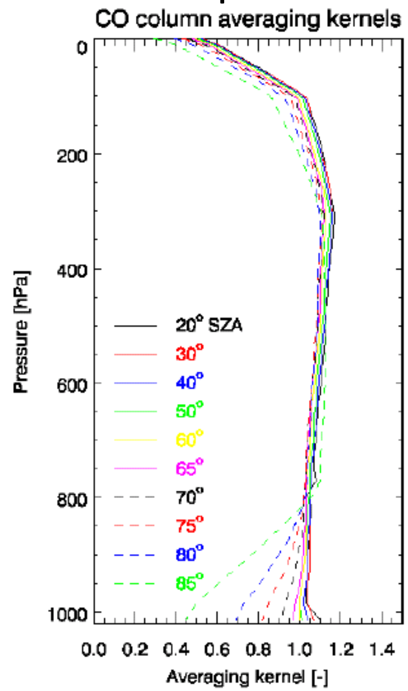
4.7 µm



validated data product, global coverage every 3 days, used in inversions and comparisons previously

SCIAMACHY

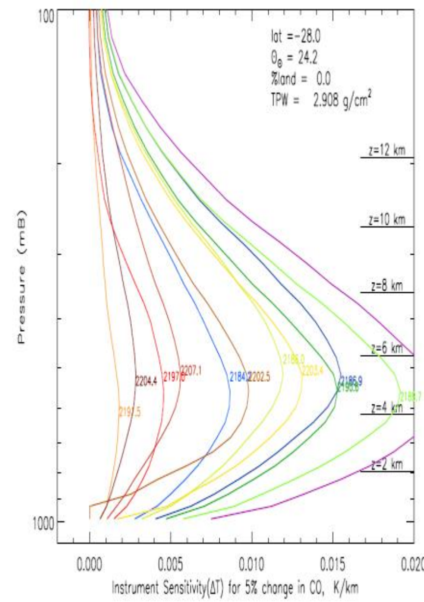
2.3 µm



sensitive throughout the column, large errors, relatively unexplored

AIRS

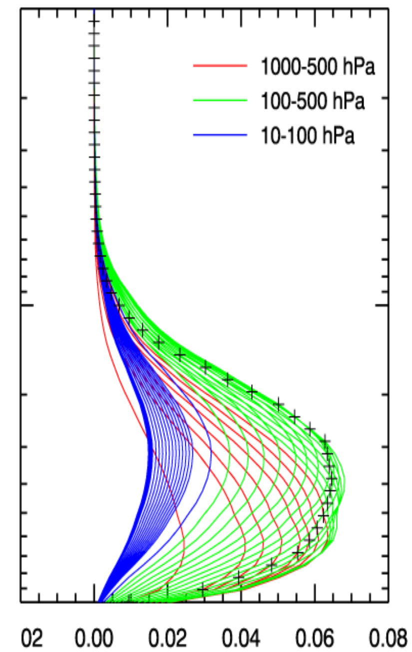
4.7 µm



extremely dense coverage (daily global), v5 retrieval not used so far

tes

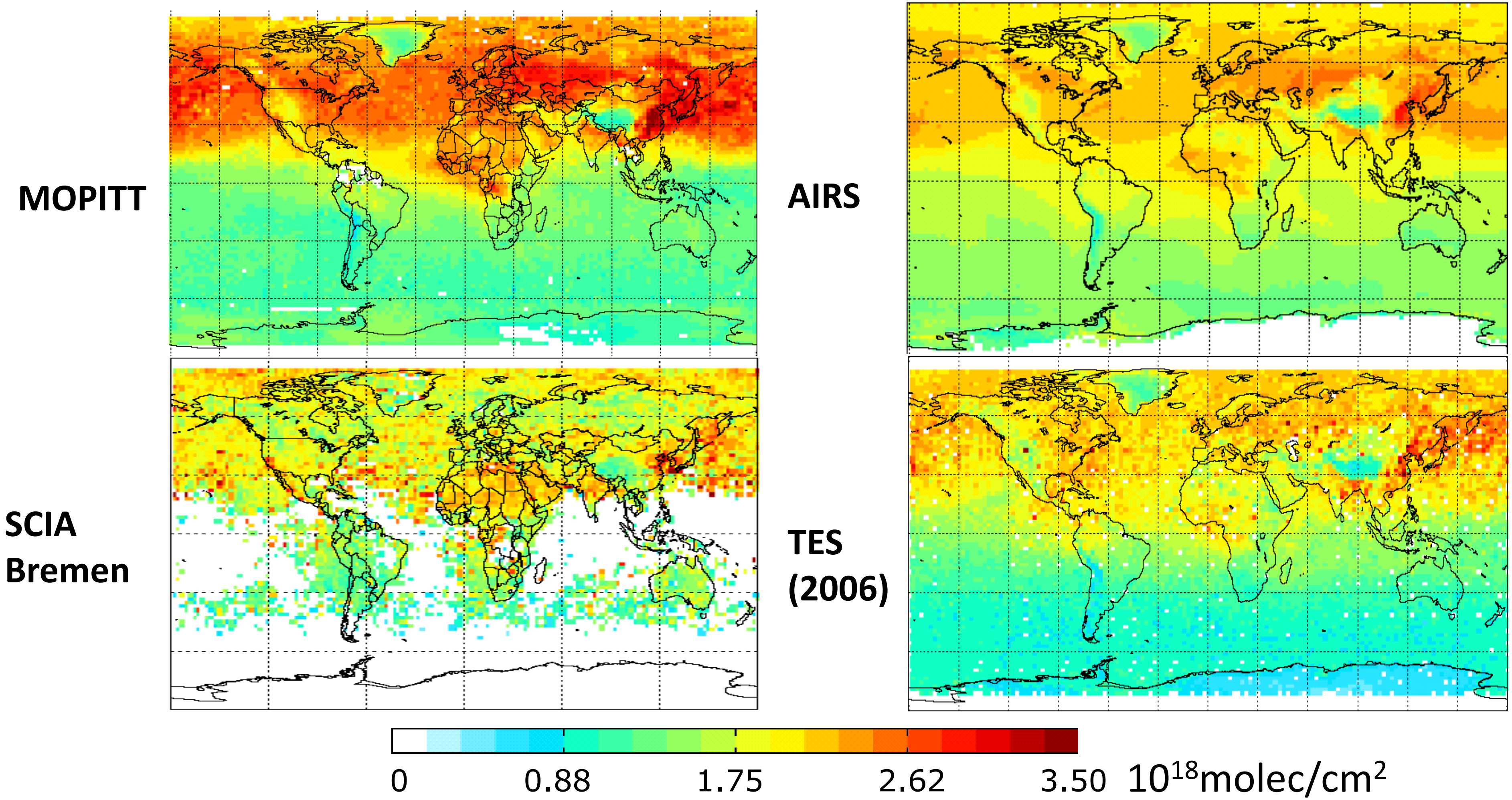
4.7 µm



relatively unexplored, provides collocated information on

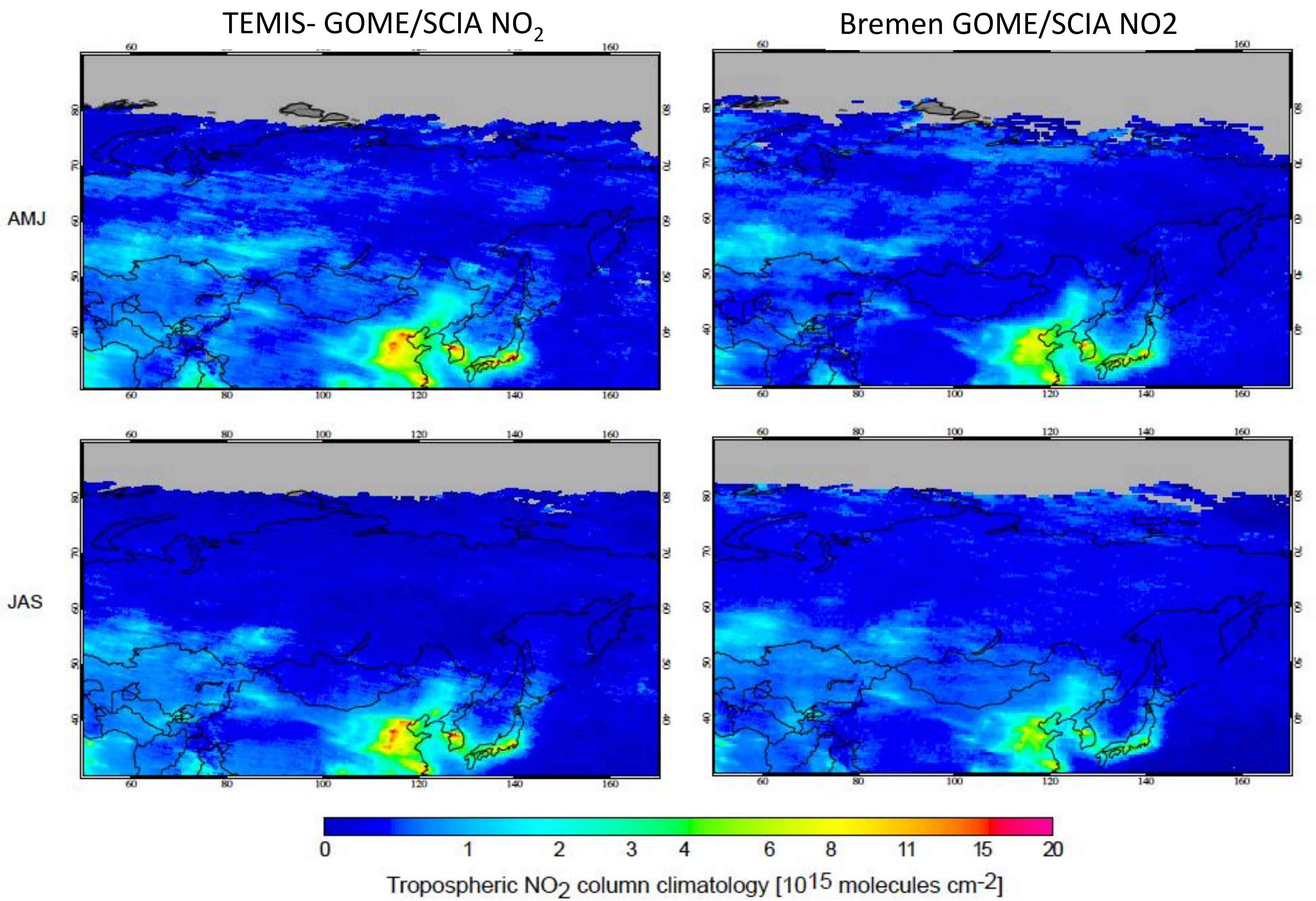
Available satellite CO (column) data

May 2004



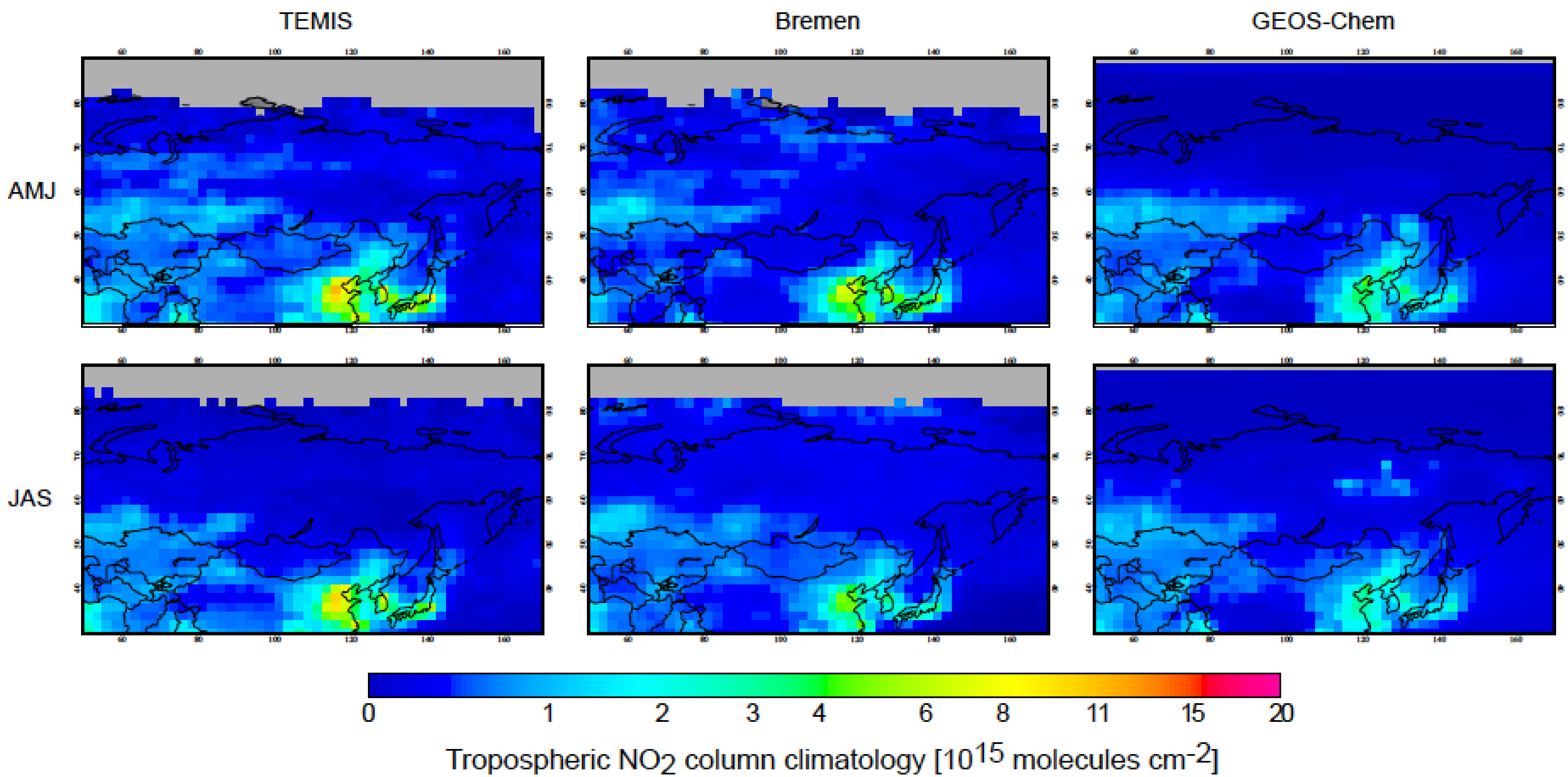
CO columns expected to be different due to different vertical sensitivity

Testing Two Retrievals – KNMI (TEMIS) & Bremen



Satellites vs. Model – gridded, climatology

Satellite | Satellite | Model



- In general, satellites > model over source regions
- Both the satellites and models look reasonable in non-BB years