# Radiative effects of lower stratospheric volcanic and carbon aerosol as simulated by the CCM EMAC for 2002 to 2011

MAX-PLANCK-INSTITUT FÜR CHEMIE

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Contribution to SSIRC (Stratospheric Sulfur and its Role in Climate) of SPARC (Stratosphere-troposphere Processes and their Role in Climate), WCRP/WMO

## Volcanic $SO_2$ injections into stratosphere

| Volcano Region | Time | Latitude | Longitude | Altitude (km) | $SO_2$ Mass (kt) |
|---|---|---|---|---|---|
| Ruang | 26 Sep 2002 | 2 | 125 | 18 | 70[c,d] |
| Reventador | 5 Nov 2002 | 0 | −80 | 19 | 49[c,d] |
| Rabaul+Mayon | 10 Mar 2003 | −5, 13 | 150, 124 | 17,15 | 15[e] |
| Ulawun | 9 Apr 2003 | −5 | 151 | 17 | 18[e] |
| Anatahan | 14 May 2003 | 16 | 143 | 17 | 16[e] |
| Soufriere Hills | 13 Jul 2003 | 16 | −62 | 15–18 | 51[d] |
| Gamalama+Japan | 22 Aug 2003 | 1, 33 | 128, 131 | 16 | 27 |
| Lokon+Masaya | 26 Sep 2003 | 2, 12 | 125, −86 | 16 | 16 |
| Manam? | 21 Oct 2003 | 5 | 145 | 16 | 16 |
| Philippines? | 10 Nov 2003 | 5 | 120 | 16 | 20[e] |
| Colombia? MIPAS | 25 Dec 2003 | 5 | −78 | 17 | 13 |
| Manam? MIPAS | 9 Jan 2004 | −5, 5 | 140? | 17 | 27 |
| Langila | 3 Feb 2004 | −5 | 150 | 17 | 14 |
| Soufriere Hills | 4 Mar 2004 | 10 | −62 | 17 | 22[e] |
| Anatahan | 12 Apr 2004 | 16 | 143 | 15 | 28 |
| Pacaya | 16 Jul 2004 | 15 | −91 | 17 | 31 |
| Manam | 31 Oct 2004 | −4 | 144 | 17 | 25[d] |
| Manam | 24 Nov 2004 | −4 | 144 | 17 | 35 |
| Manam | 28 Jan 2005 | −4 | 144 | 19 | 169[c,d] |
| Anatahan | 3 Apr 2005 | 16 | 143 | 15 | 15 |
| Anatahan + Soufriere Hills | 23 Apr 2005 | 16 | 143, −62 | 16 | 50[d] |
| Anatahan + Fernandina | 17 May 2005 | 16, 0 | 143, −91 | 15 | 27[d] |
| Anatahan | 12 Jun 2005 | 16 | 143 | 15 | 25 |
| Anatahan + Santa Ana | 12 Jul 2005 | 16 | 143, −90 | 15 | 26[d] |
| Anatahan + Conception | 5 Aug 2005 | 16 | 143, −85 | 15 | 42 |
| Anatahan | 16 Aug 2005 | 16 | 143 | 15 | 59[d] |
| Sierra Negra | 23 Oct 2005 | −1 | −91 | 15 | 48[d] |
| Karthala | 24 Nov 2005 | −10 | 43 | 16 | 28 |
| Tinakula + | 23 Jan 2006 | −9 | 152 | 16 | 15 |
| Ulawun | 1 Mar 2006 | −5 | 150 | 17 | 68[e] |
| Tinakula + Lascar | 18 Apr 2006 | −5, −23 | 152, −68 | 17 | 35 |
| Soufriere Hills | 21 May 2006 | 16 | −62 | 19 | 147[c,d] |
| Ulawun + Ecuador | 16 Jul 2006 | −5 | 150, −80 | 17 | 20 |
| Rabaul | 17 Aug 2006 | −4 | 150 | 19 | 88[e] |
| Rabaul | 9 Oct 2006 | −4 | 150 | 17 | 150[d] |
| Peru (?) + Pit.Fourn.R. | 24 Oct 2006 | −20, −10 | −70, 57 | 17 | 48 |
| Ambrym | 8 Nov 2006 | −10 | 160 | 17 | 40 |
| Nyamuragira | 28 Nov 2006 | 5, −15 | 30 | 17, 15 | 66[d] |
| Sulawesi + Japan | 24 Dec 2006 | 5, 30 | 125 | 18, 15 | 34 |
| Nevado del Huila | 19 Feb 2007 | 0 | −70 | 16 | 23 |
| Pit.Fourn.R + Reventador + | 3 Apr 2007 | −20, 0 | 57, −80 | 16 | 52[d] |
| Ulawun + Vanuatu | 3 May 2007 | −5, −25 | 160 | 15 | 21 |
| Vanuatu, Japan + Kam. | 13 May 2007 | −15, 35 | 150 | 16 | 25[e] |
| Llaima + | 23 May 2007 | −25–15 | −70 | 15 | 25 |
| Lengai +? | 2 Jul 2007 | −2, 20 | 29 | 16, 15 | 22 |
| Raung, Monsoon? | 27 Jul 2007 | −5, 35 | 110 | 15 | 23[d] |
| Manda Hararo | 11 Aug 2007 | 15–35 | 40 | 15 | 32 |
| Vanuatu +? | 20 Sep 2007 | −5 | 165? | 16 | 22 |
| Jebel al Tair | 1 Oct 2007 | 15–40 | 42[f] | 16 | 74[d] |
| Nicaragua | 5 Nov 2007 | 15 | −85 | 16 | 27 |
| Soputan or Krakatau | 14 Nov 2007 | −5 | 110 | 15 | 35[e] |
| Talang (?) | 9 Dec 2007 | −5 | 100 | 16 | 24[d] |
| Mexico? Llaima | 29 Dec 2007 | 5, −35 | −75 ? | 17 | 27[d] |
| Nevado del Huila | 8 Jan 2008 | 1 | −71 | 15 | 30 |
| Ecuador, Mexico? | 28 Jan 2008 | −5, 15 | −80? | 16 | 32 |
| Ecuador? | 11 Feb 2008 | −5 | −80 | 16 | 28[d] |
| Vanuatu+ | 8 Mar 2008 | −15, 5 | 167 | 16 | 23 |
| Vanuatu+Africa(?) | 28 Mar 2008 | −15, 5 | 167 | 16 | 28 |
| Bismarck A. + Egon | 12 Apr 2008 | −5, 5 | 152, 122 | 15 | 27 |
| Mexico+ Chaiten | 3 May 2008 | 15,−5,−35 | −90, −70 | 16 | 22[d] |
| Mexico+Barren I.+Chaiten | 12 May 2008 | 10, −35 | −90, 90 | 16 | 29 |
| Nicaragua? Soputan? | 16 Jun 2008 | 5 | −85, 125 | 16 | 38[e] |
| Okmok | 13 Jul 2008 | 53 | −168[f] | 15 | 89[d] |
| Kasatochi | 8 Aug 2008 | 52 | −175[f] | 13–17 | 376[d] |
| Colombia+Dallafilla | 12 Nov 2008 | 5 | −78, 40 | 17 | 89[d] |
| Ecuador+Kamchatka? | 17 Dec 2008 | 5, 40 | −80, 160 | 17, 15 | 35 |
| Karangetang? | 2 Jan 2009 | 2 | 125 | 17 | 29[e] |
| Indonesia? | 27 Jan 2009 | −5 | 100 | 16 | 26[e] |
| Ecuador+Villarrica | 16 Feb 2009 | −5, −35 | −75 | 16 | 28 |
| Redoubt | 23 Mar 2009 | 60 | −155[f] | 13 | 105[d] |
| Fernandina+ | 8 Apr 2009 | 0 | −90 | 16 | 28[d] |
| Rinjani ? | 7 May 2009 | 5 | 120 | 15 | 28 |
| Rinjani+Vanuatu? | 22 May 2009 | 5, −15 | 116, 165 | 16 | 27[d] |
| Sarychev | 14 Jun 2009 | 48 | 153[f] | 16 | 562[d] |
| Vanuatu+Mayon | 4 Oct 2009 | −15, 25 | 165, 120 | 17 | 27[e] |
| Costa Rica? | 24 Oct 2009 | 5 | −83 | 16 | 26[e] |
| Ecuador? Langila? | 3 Dec 2009 | −5 | −78, 148 | 17 | 29[d] |
| Nyamuragira + Tungurahua | 2 Jan 2010 | −5, 15 | 30, −75 | 16 | 30[d] |
| Turrialba? | 17 Jan 2010 | 5 | −82 | 16 | 29 |
| Soufriere Hills | 13 Feb 2010 | 16 | −62 | 16–18 | 42[d] |
| Costa Rica | 2 Apr 2010 | 9 | −84 | 15 | 34 |
| Tungurahua ? | 2 May 2010 | −5 | −78 | 16 | 39[e] |
| Pacaya | 1 Jun 2010 | 15 | −91 | 17 | 49[d] |
| Ulawun +Costa Rica+Kuril | 16 Jul 2010 | −5, 20, 35 | 150, −83 | 16 | 32[d] |
| Karangetang, Nicaragua | 10 Aug 2010 | 9, 35 | 128, −85 | 16 | 38 |
| Galeras + Sinabung (?) | 27 Aug 2010 | 5, 25 | −77, 100 | 16 | 34[d] |
| Karangetang + America? | 4 Oct 2010 | 5 | 128, −80 | 16 | 42[d] |
| Merapi | 6 Nov 2010 | −7 | 110 | 18 | 107[d] |
| Java, Ecuador, Villarrica | 24 Dec 2010 | −5, −35 | 110, −78 | 17 | 51 |
| Villarrica + Java | 7 Jan 2011 | −45, −5 | −75, 110 | 16 | 35[d] |
| Lokon-Empung, Planchon? | 26 Feb 2011 | 5, −40 | 110, −75 | 16 | 36[d] |
| Rabaul + Merapi? | 25 Mar 2011 | −5 | 150, 107 | 15 | 27 |
| Colombia? Karangetang | 12 Apr 2011 | 5 | −77, 128 | 16 | 22[d] |
| Tungurahua, Rabaul | 2 May 2011 | −3 | −78, 150 | 16 | 38[d] |
| Grimsvötn + Rabaul | 27 May 2011 | 65, −5 | −20, 150? | 14, 16 | 48[e] |
| Nabro | 13 Jun 2011 | 10–55 | 41[f] | 16–19 | 386[e] |
| Vanuatu (?) | 19 Oct 2011 | −15 | 165 | 16 | 24[d] |
| Nyamuragira? | 13 Nov 2011 | −2 | 29 | 16 | 31[d] |

[a] $SO_2$ masses above 14 km in low latitudes, above 13 km in midlatitudes, and 12 km in high latitudes. The altitudes and latitudes refer to the maxima in the zonal mean "plume" in the MIPAS $SO_2$ data if available. On several days more than one volcano has to be considered. The $SO_2$ is injected at the listed days, in most cases based on the strongest signal(s) in OMI data, i.e., not necessarily the first day of an eruption. For eruptions lasting over a period of months or years this can be several days. Most volcano names are from the Smithsonian database (http://www.volcano.si.edu).

[c] Above 15 km only.
[d] Approximately as in other simulation.
[e] Strongly underestimated in other simulation.
[f] Longitudinal sawtooth function.

Less volcanoes, blue curves

**EMAC (V1.9/1.10)**

- MECCA1 chemistry module, modified for SOx (with COS and DMS oxidation, enhanced $H_2SO_4$ NIR photolysis [966nm, q=0.2] and SOx sink on meteoritic dust) + GMXE aerosol module (4 soluble and 3 insoluble modes with EQSAM chemistry, $\sigma_{nuc,ait}$=1.59, $\sigma_{acc}$=1.49, $\sigma_{cs}$=1.7; lower mode boundaries aitken 0.006, accum 0.07, coarse 1.6µm) + scavenging by clouds
- AEROCOM aerosol emissions at surface (sulfate, organics; Dentener, ACP 2006)
- Resolution T42/L90 (to 1Pa with internal Quasi-Biennial Oscillation), GCM ECHAM5.
- Optical properties of aerosol from lookup-table (Mie based, types: $H_2O$, water soluble, OC, BC, dust, sea salt)
- Aerosol radiative forcing calculated diagnosticly (multiple calls of radiation routine online, with aerosol and feedback to dynamics, and without aerosol and feedback)

References:

Model: Jöckel et al., 2006, Atmos.Chem.Phys. 6, 5067-5104. Brühl et al., 2012, Atmos.Chem. Phys., 12, 1239-1253; 2015, J. Geophys. Res., 120, 2103-2118; Pringle et al., 2010, Geosci.Model Dev. 3, 391-412; Giorgetta et al., 2006, J. Clim 19, 3882-3901.

MIPAS: Höpfner et al, 2015, Atmos.Chem.Phys., 15, 7017–7037.

Other satellite data: Santer et al, 2014, Nature Geosci. 7, 185-189, Bourassa et al, 2012, Atmos.Chem.Phys. 12, 605-614.

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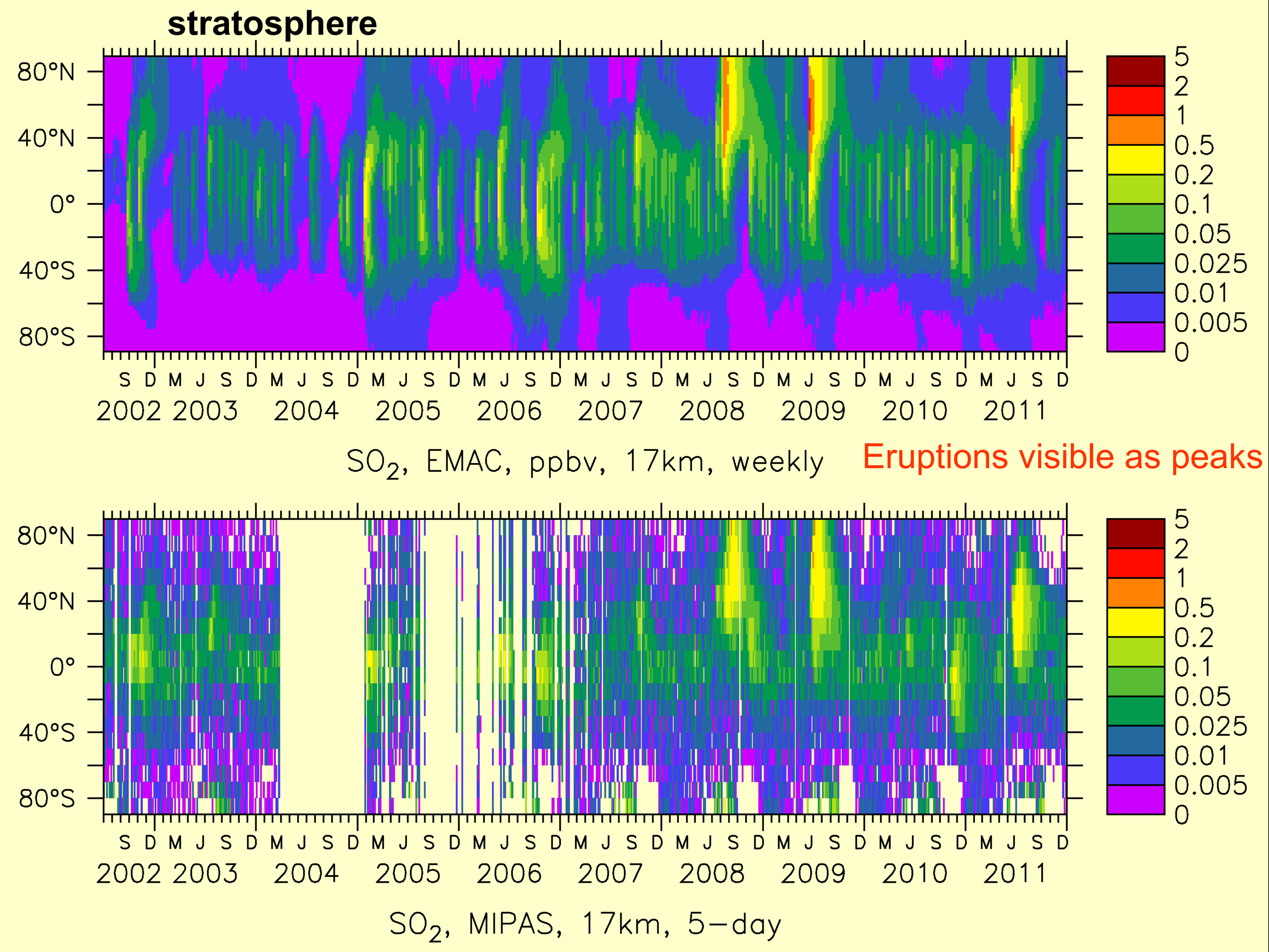
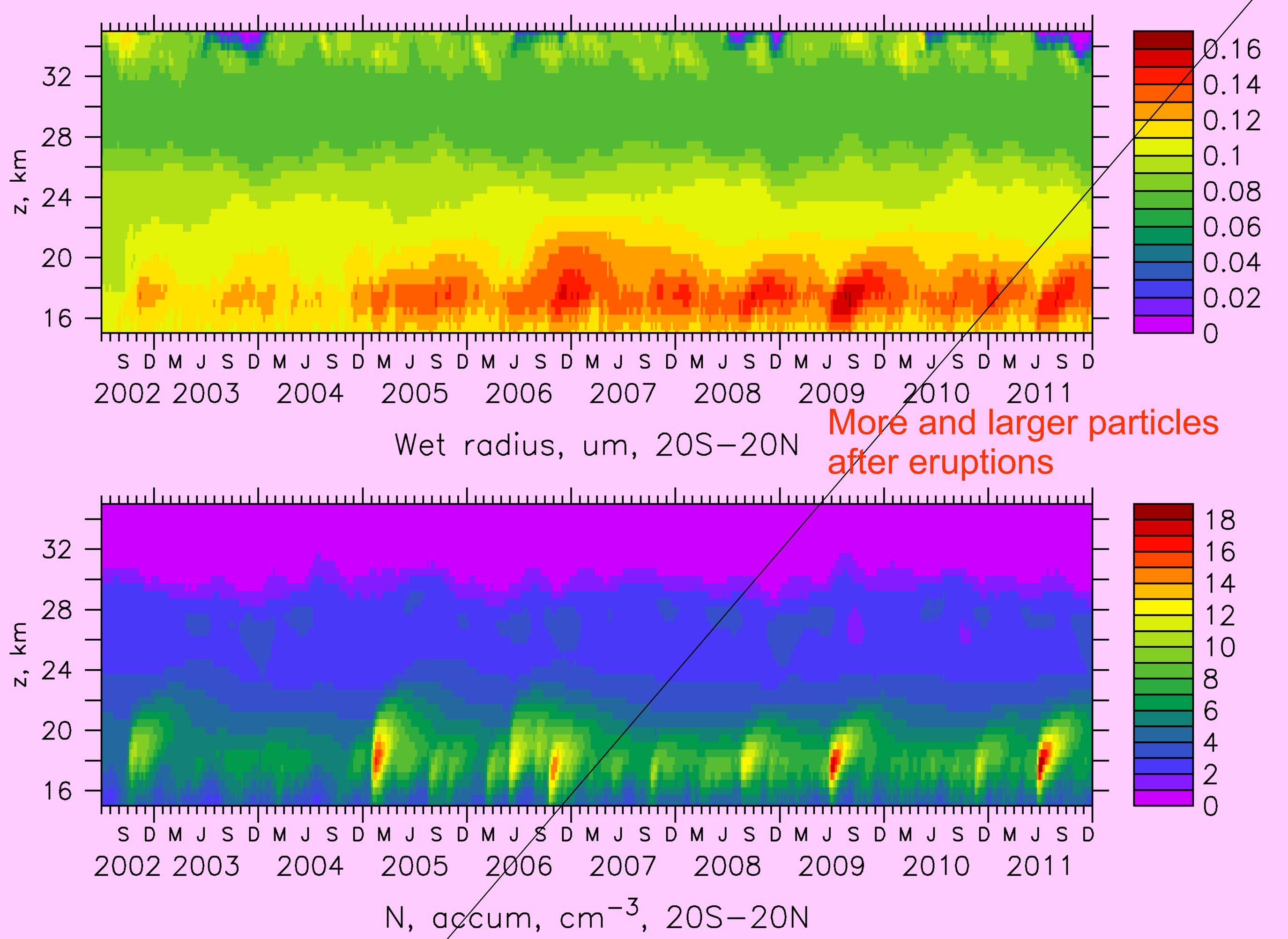
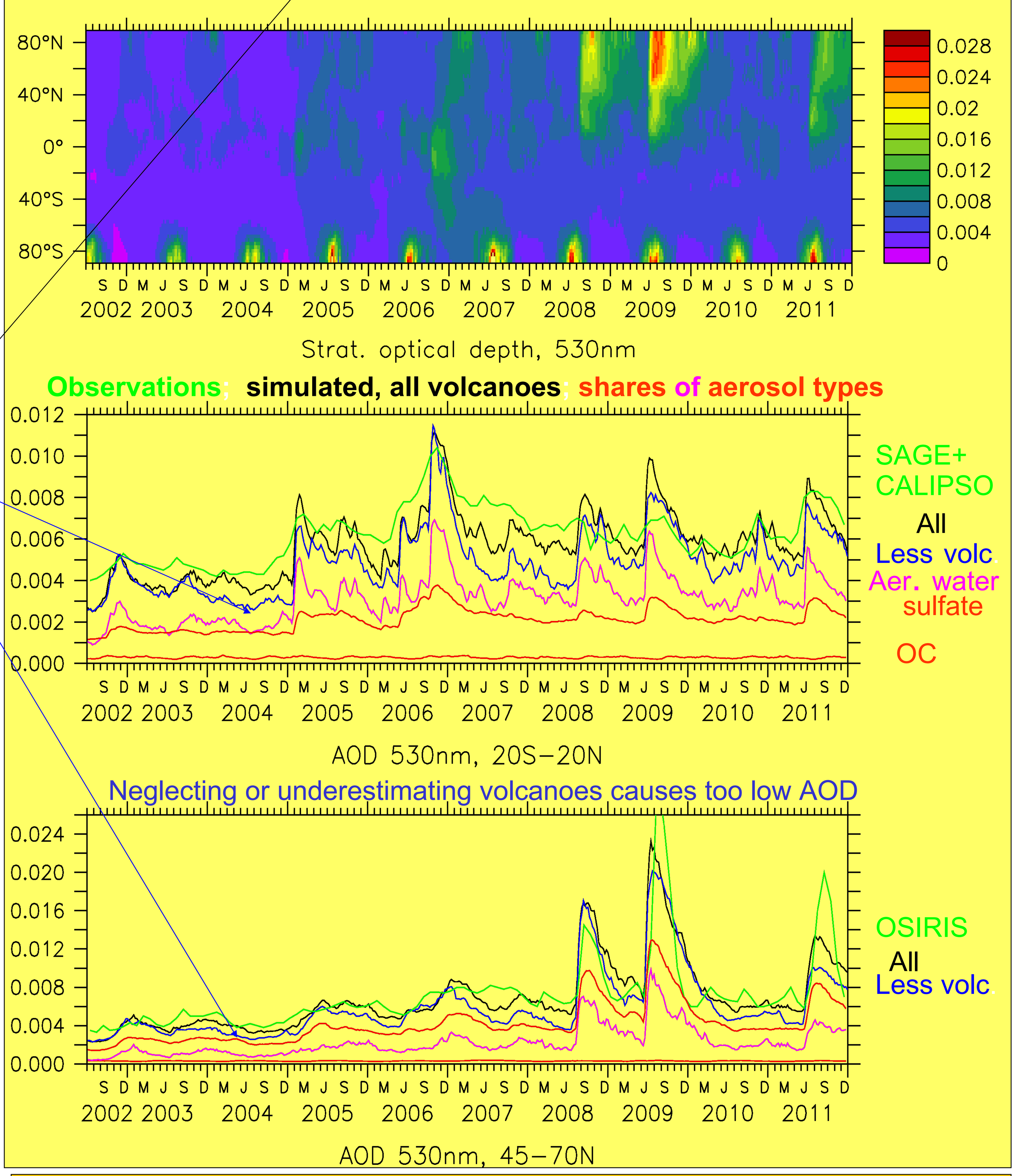
### Simulated and observed $SO_2$ in the lower stratosphere



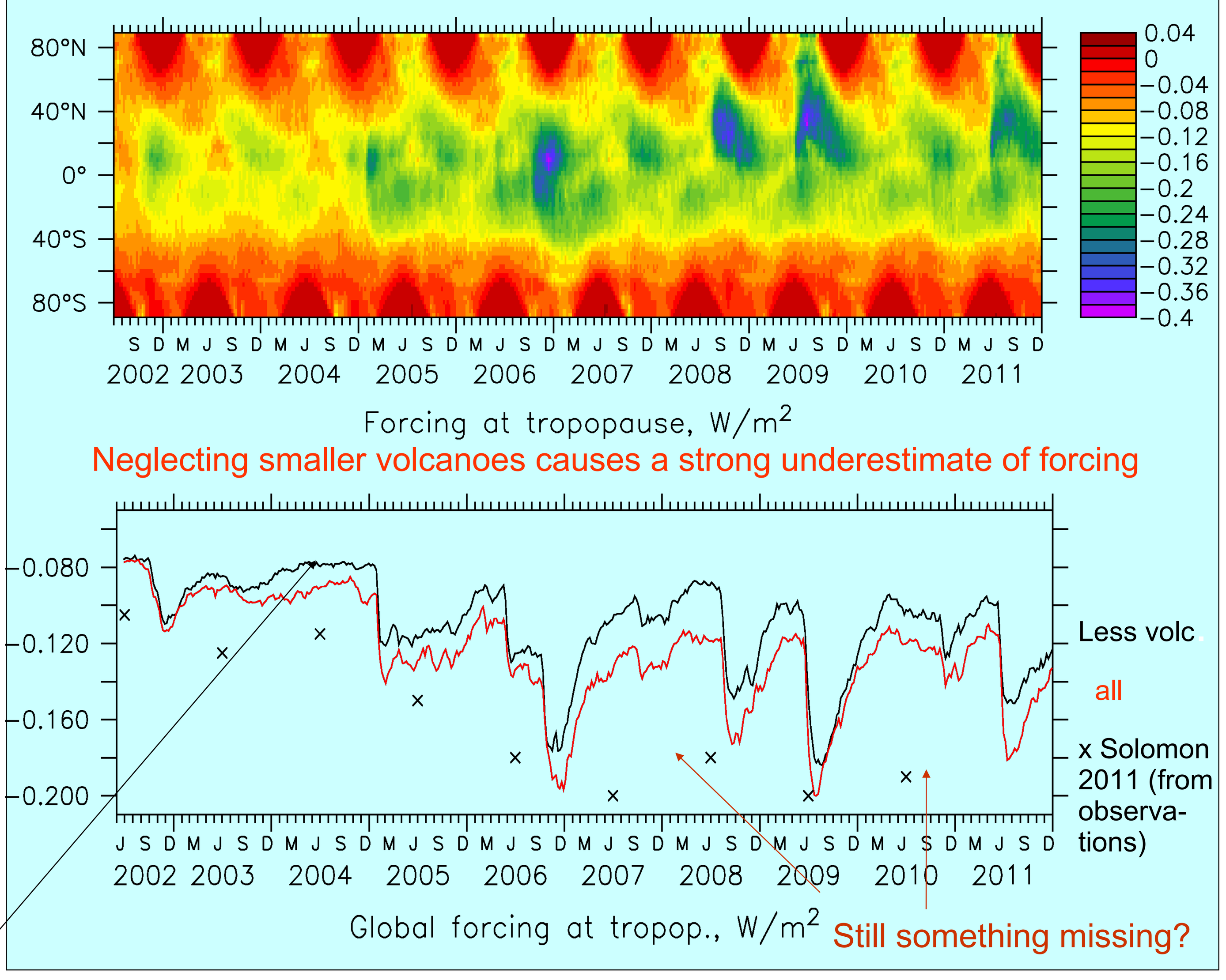

### Size distribution parameters, accumulation mode, tropics



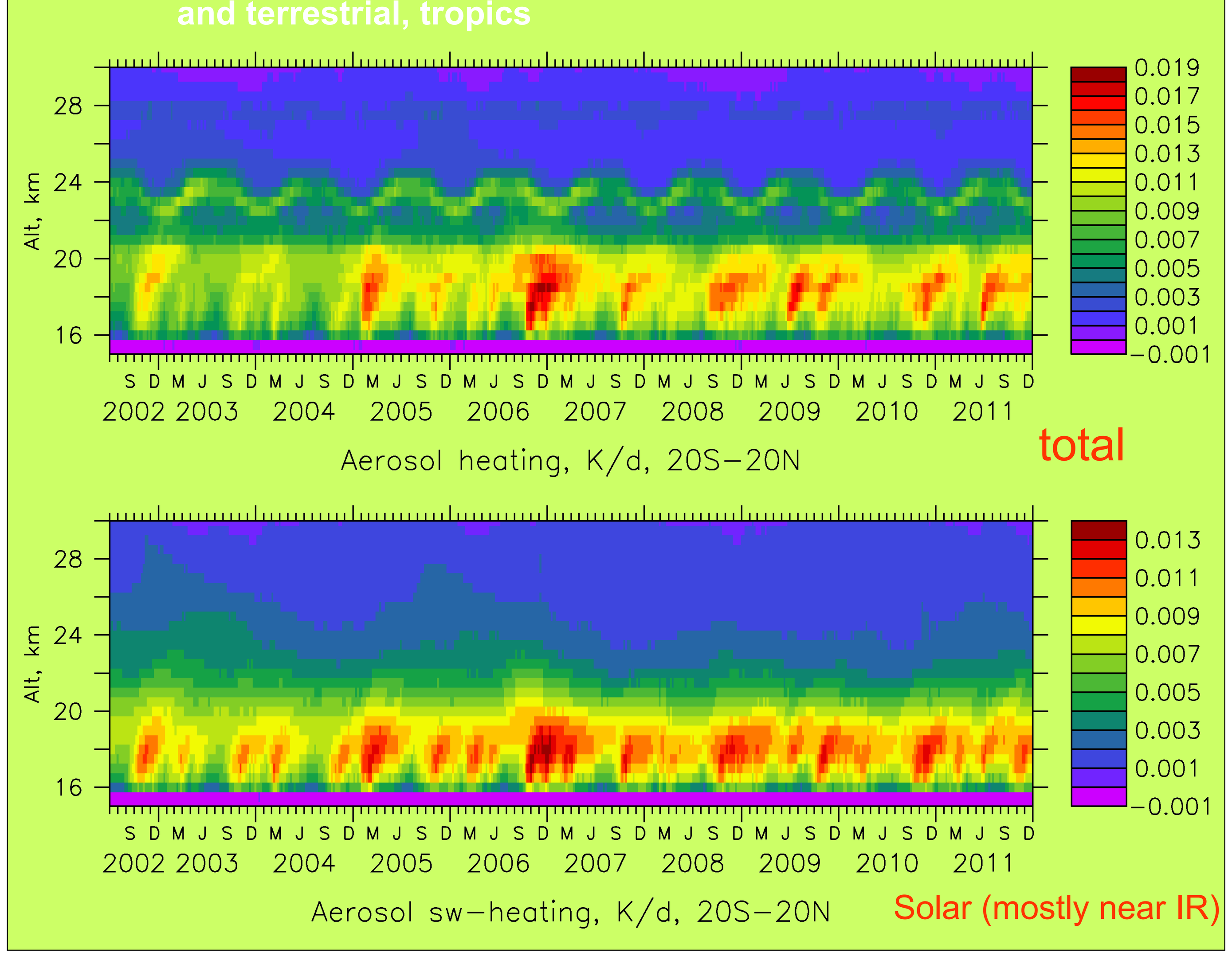

### Optical depth of stratospheric aerosol (above 185hPa), visible



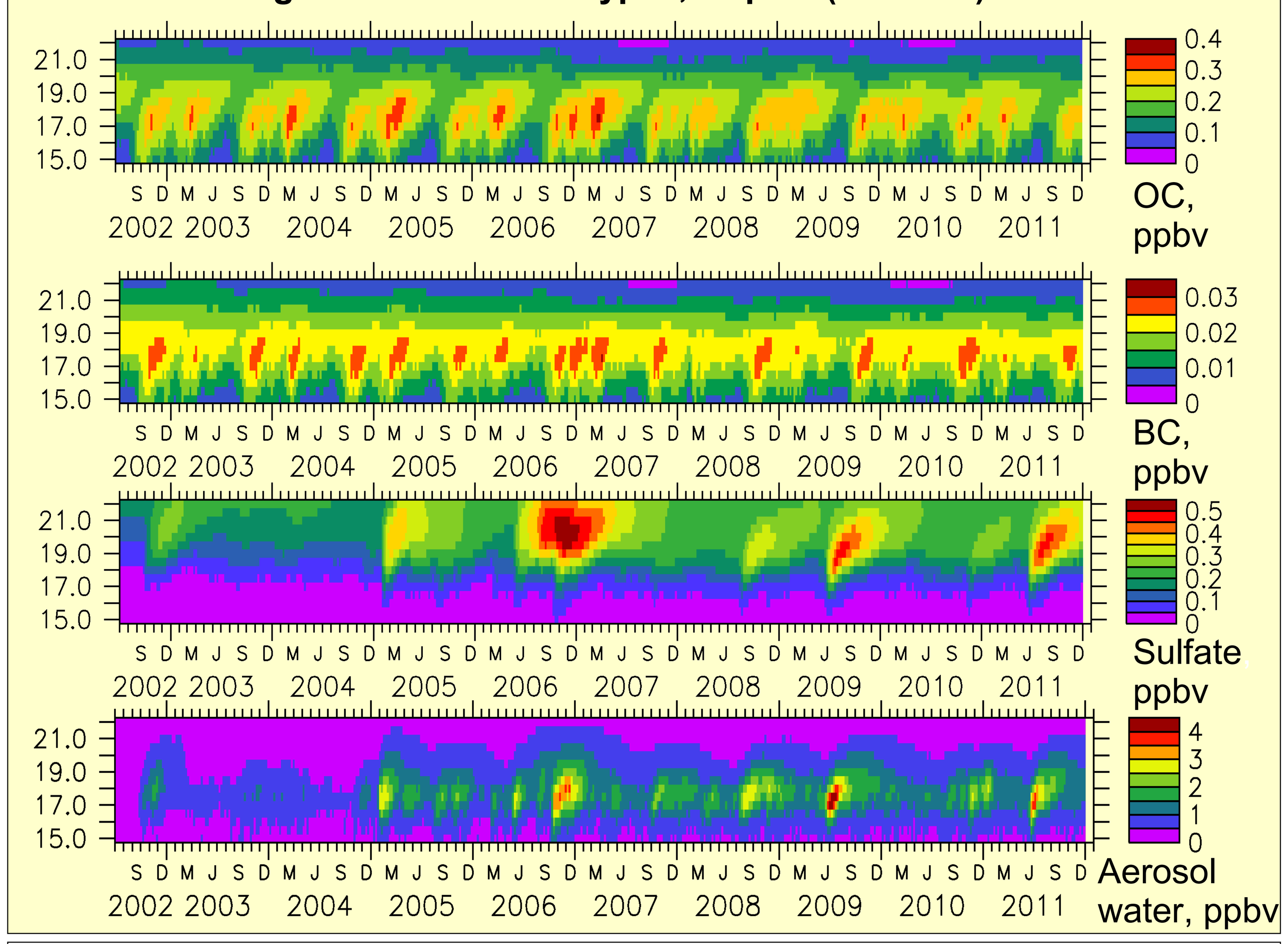

### Stratospheric aerosol radiative forcing, 185hPa



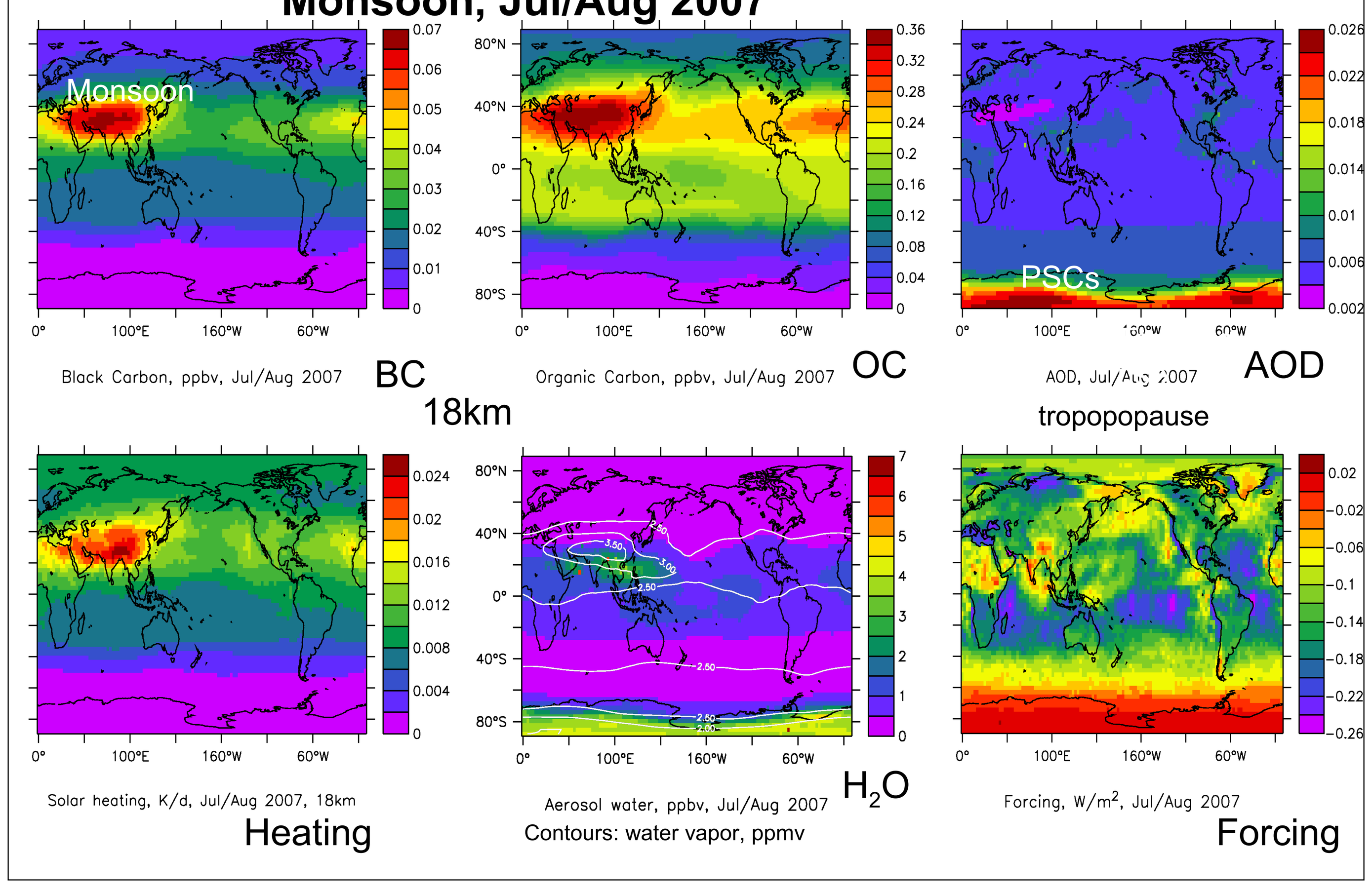

### Aerosol radiative heating, total, solar and terrestrial, tropics




### Volume mixing ratios of aerosol types, tropics (20S-20N)




### Monsoon, Jul/Aug 2007




### Conclusions

- Medium and small explosive volcanic eruptions contribute significantly to stratospheric aerosol forcing and optical depth (AOD)
- Especially in the tropics and Antarctic winter aerosol water contributes a large fraction to AOD
- Organic and black carbon cause local radiative heating of the lower stratosphere which can exceed the contribution of sulfate aerosol and aerosol water in case of low volcanic activity (while the share of Organic Carbon and Black Carbon in AOD is small)
- In the Asian Monsoon aerosol radiative heating is clearly visible while clouds mask a clear signal in radiative forcing.

Also part of EU-StratoClim and ESA Aerosol CCI with partners at MPI-M, Hamburg and BIRA, Brussels