The Basis and Development of the CMIP6 Stratospheric Aerosol Record

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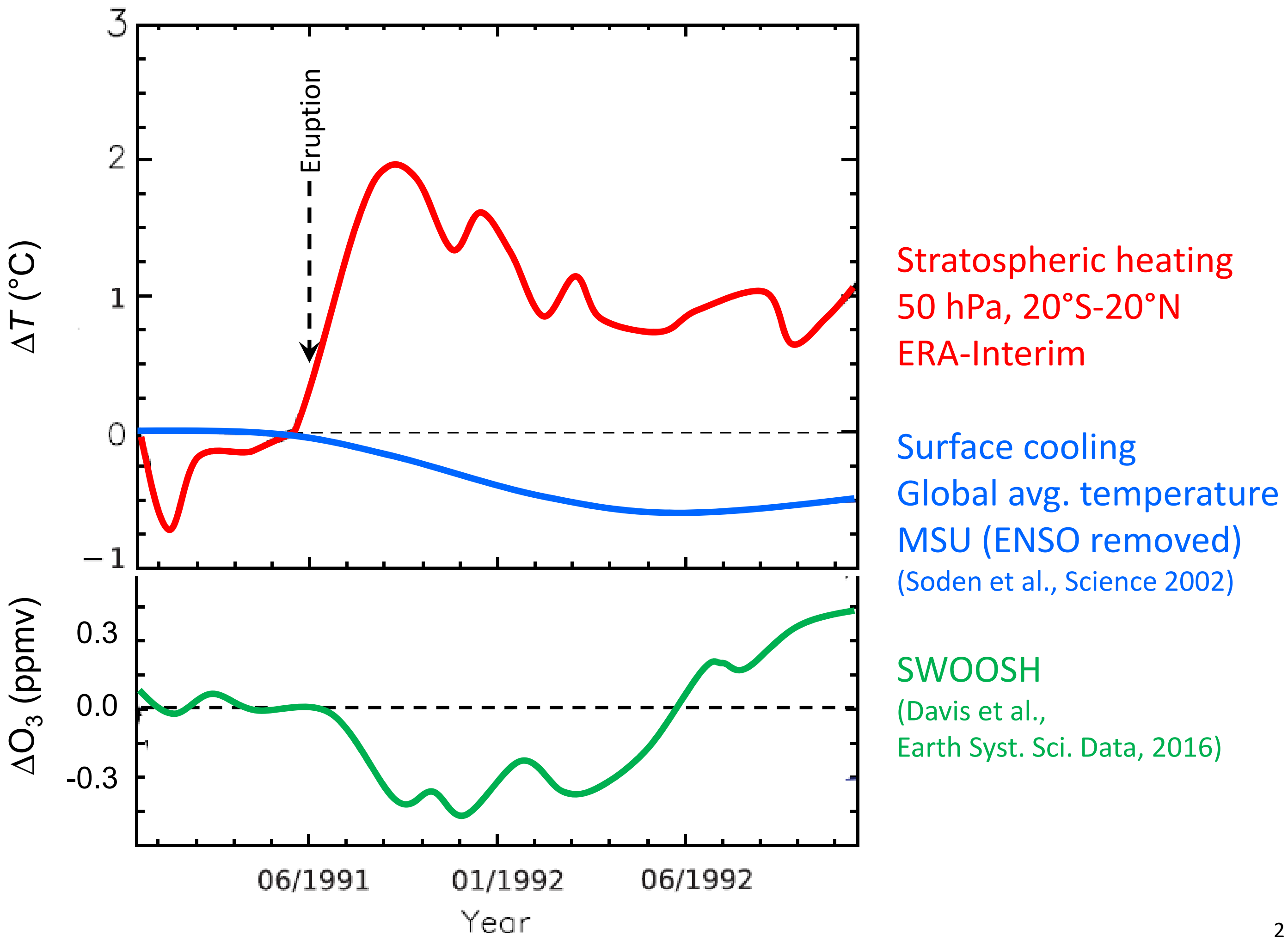
Stratospheric Aerosols…

- are an important climate influencers
- play an important role in stratospheric chemistry ($N_2O_5 + H_2O \rightarrow 2\ HNO_3$)

Attribution remains difficult.

Preaching to the choir…



Paul Crutzen's back-of-the-envelope estimate

Geoengineering consideration:

1 Tg S stratospheric burden

- **1 ppbV** sulfur (6×background)
- **0.007** average optical depth
- **-0.75 W / m²**

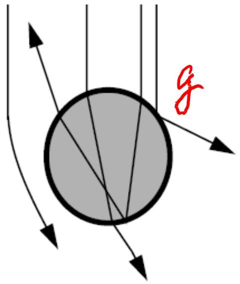
  downscaling Pinatubo:

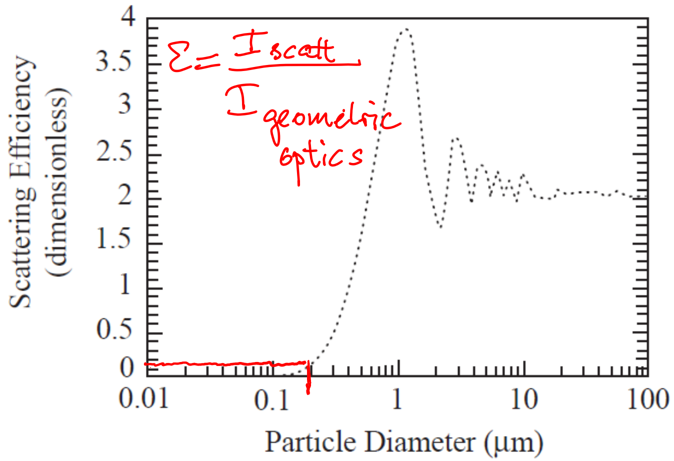
  10 Tg S injected into stratosphere

  6 month after eruption 6 Tg S still caused -4.5 W/m² radiative cooling

- **2 % of S** from fossil fuel burning
- **US$ 25×10⁹ / yr**

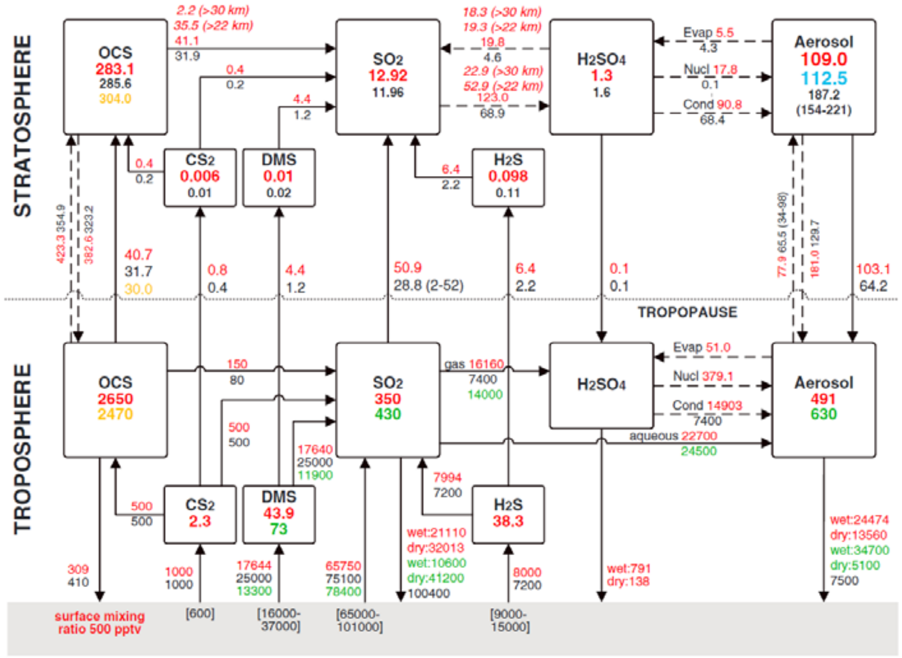
  ≈ 2.5% global military expenditures





When your model has detailed stratospheric microphysics:

You are all set!



But what, when your model has no detailed microphysics?

The Coupled Model Intercomparison Project Phase 6 (CMIP6) requires input data for GCMs and CCMs for 1850-2014:

The CMIP6 Stratospheric Aerosol Record offers:

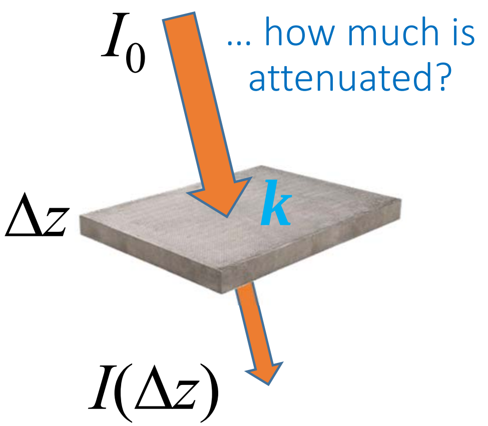
Monthly, spatially resolved (alt/lat) values of

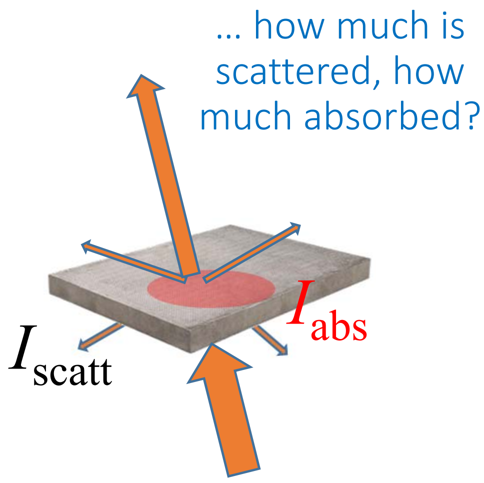
(1) Aerosol radiative properties UV-IR
→ Extinction coefficients, single scattering albedos, asymmetry factors
→ Each spectrally resolved and adapted to each model

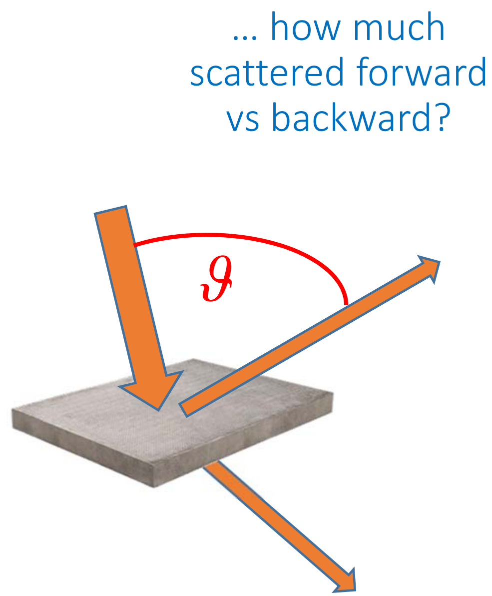
(2) Surface area densities/Mean radii for chemical heterogeneous reactions

Time:	1850-2014 monthly means
Latitude:	pole to pole, 5° latitudinal resolution (cloud-cleared)
Altitude:	5-39.5 km, 0.5 km resolution

GCMs need to know:







$$\frac{dI}{dt}(z,\lambda) = -k(z,\lambda) \times I(z,\lambda)$$

wavelength

extinction coeff. $k(z,\lambda)$

$$\omega(z,\lambda) = \frac{I_{scatt}}{I_{scatt} + I_{abs}}$$

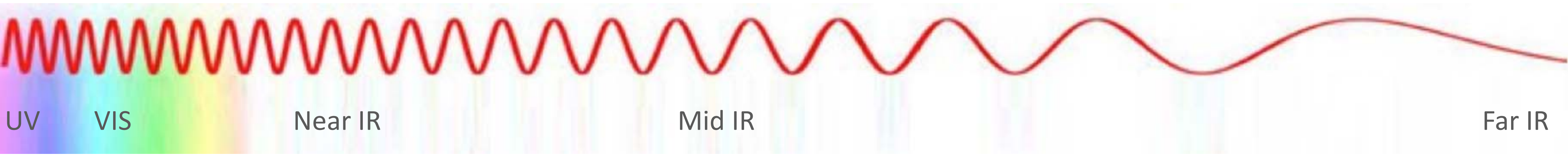
single scattering albedo $\omega(z,\lambda)$

$$g(z,\lambda) = \langle \cos(\vartheta) \rangle$$

asymmetry factor $g(z,\lambda)$

$g > 1$ predominantly forward

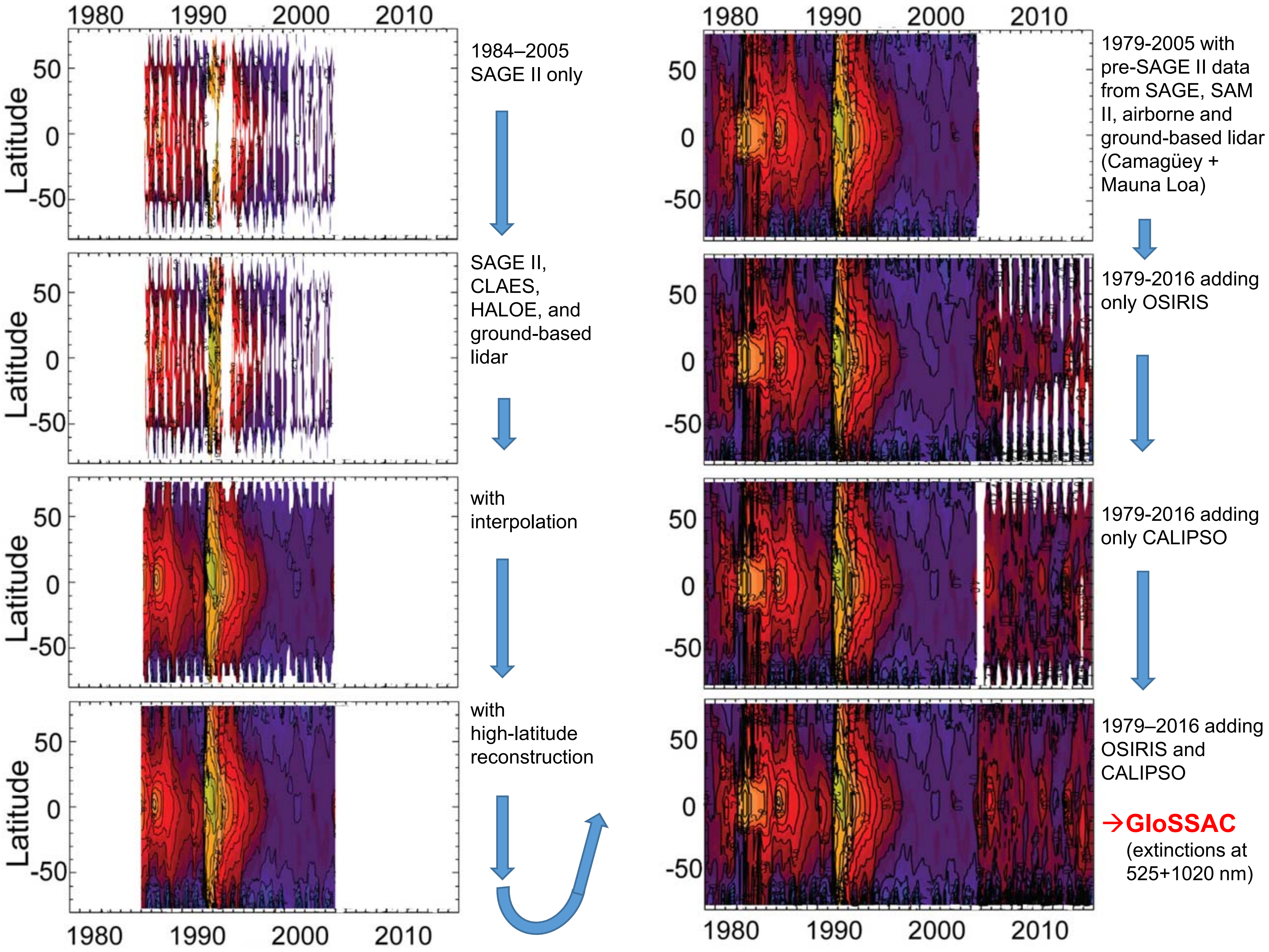
$g < 1$ predominantly backward



What is on offer…

GloSSAC:

Global Space-based Stratospheric Aerosol Climatology, 1979-2016



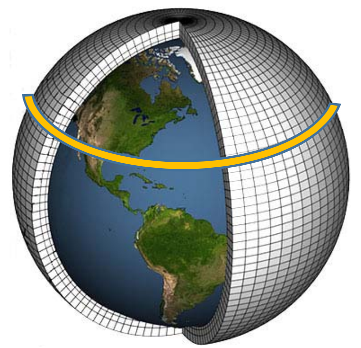
Left:
1020-nm extinction at 21 km altitude

Thomason et al., Earth Syst. Sci. Data, 2018

Utilized atmospheric data

GloSSAC

1850-1880



2-D AER Aerosol Model

AER aerosol microphysical model driven by **ice core sulfate** mass estimates

and historical data on the latitude and date of eruptions.

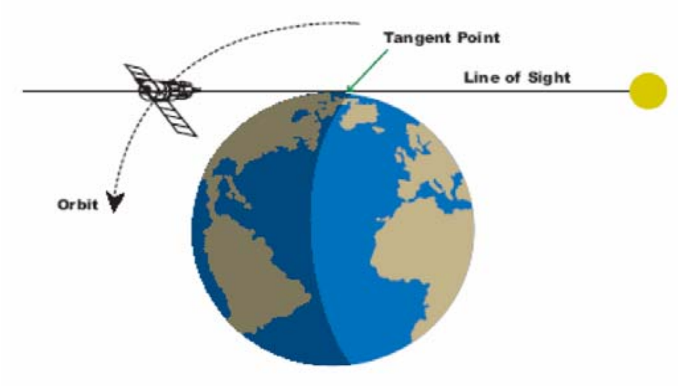
1881-1978

Pyrheliometer/Photometer

Ground solar pyrheliometers (starting 1881) and stellar photometers (starting 1960): **Optical depths @ 550 nm.**

Thereafter, **AER-2D model** is used for the temporal and spatial evolution of volcanic perturbed stratospheric aerosol

1979-2005



SAGE I, SAM II, SAGE II, HALOE, CLAES

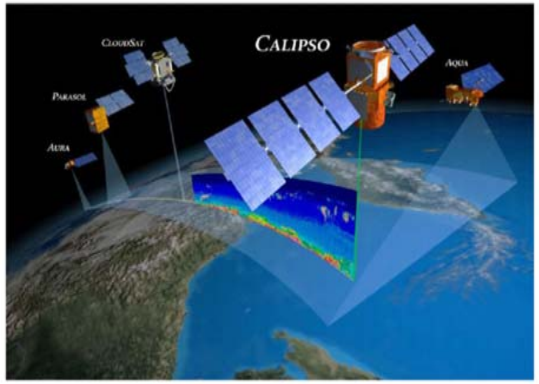
SAGE: 1979-1980
Extinction coefficients at 1020 nm

SAM II: 1981-1984
Extinction coefficients at 1020 nm

SAGE II: 1984-2005
Extinction coefficients at 1020, 525 and 452 nm (and 386 nm)

CLAES+HALOE: 1991-93 **for gap filling**

2006-2014



CALIOP/OSIRIS

CALIOP: Backscatter and extinction coefficients at 532 nm.

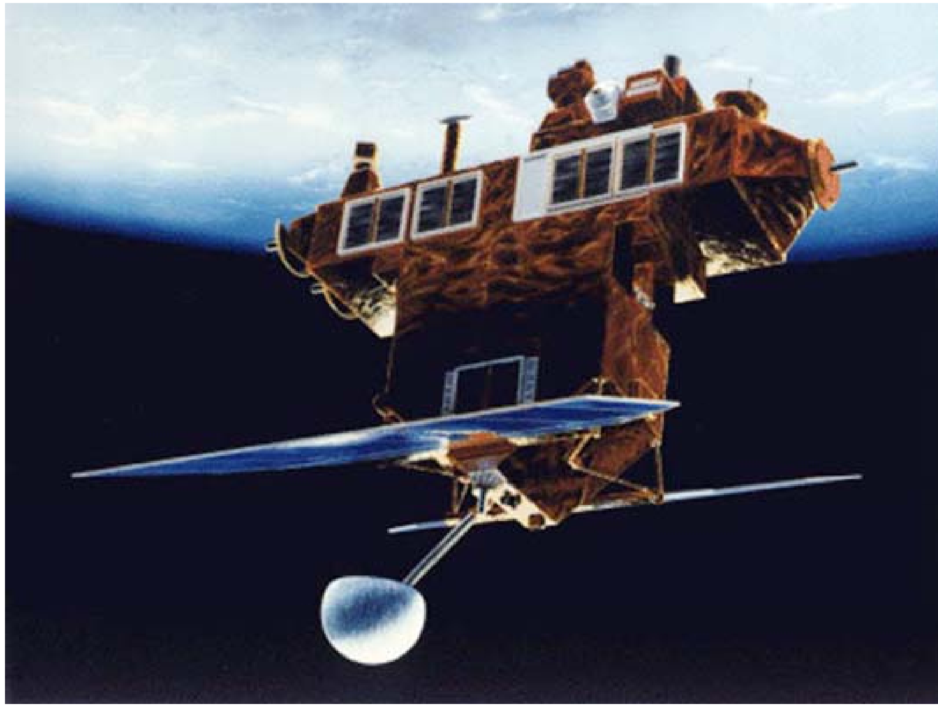
OSIRIS: extinction coefficients

Composite product (GloSSAC)

Extinction coefficients at 525 nm


OWEL

SAGE II DATA



Advantages:

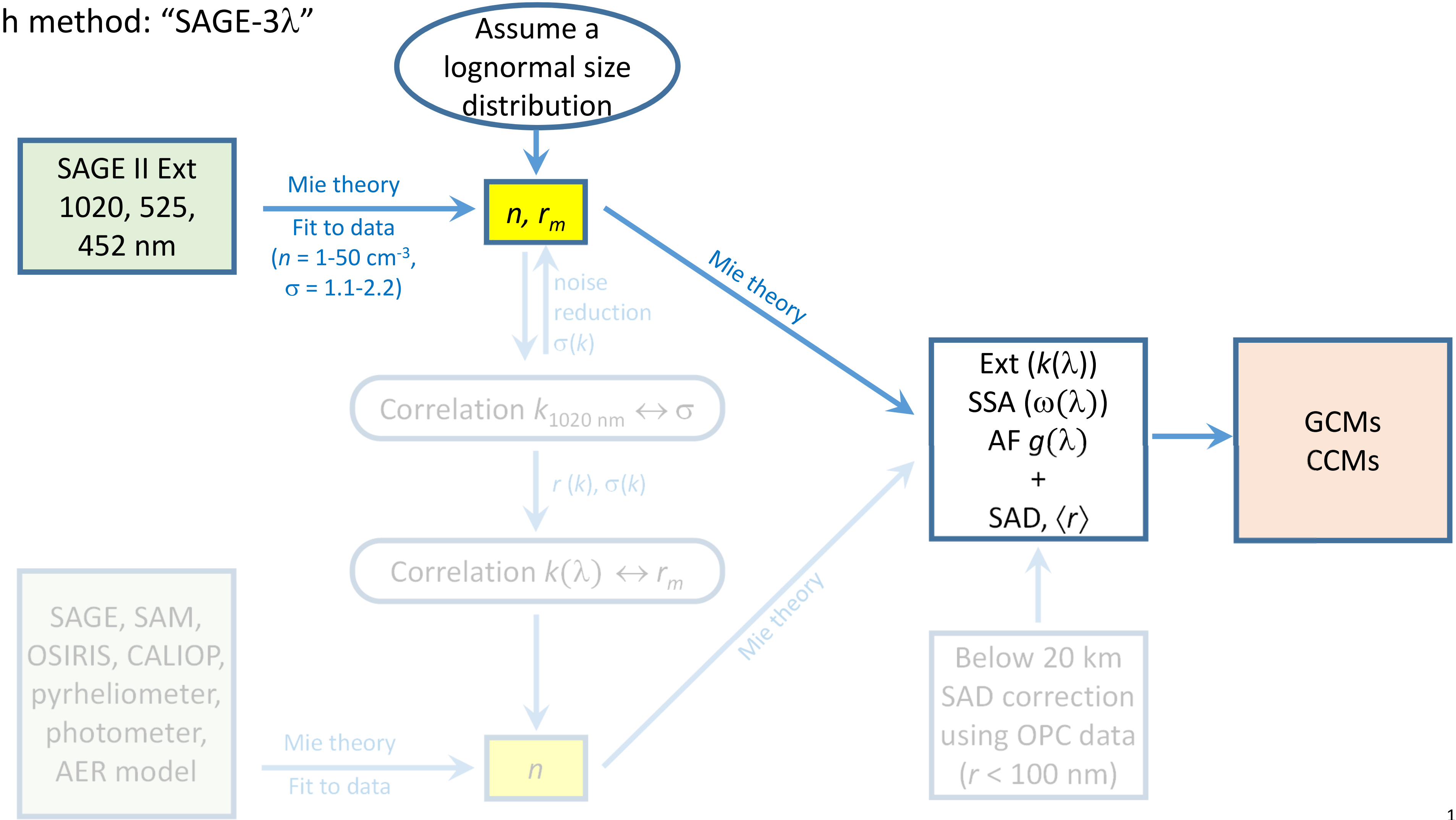
- Long Duration, global coverage
- Multi-wavelengths data enable retrieval of size distributions
- Backbone for the microphysical retrieval.

What had to be done:

- Missing data had to be filled (using mainly CLAES+HALOE data and a few records from ground lidar stations)
  - See Global Space-based Stratospheric Aerosol Climatology, 1979-2016 (GloSSAC), by Thomason et al., Earth Syst. Sci. Data, 2018
- Procedure of retrieval of size distributions has been developed and validated

Microphysical retrieval algorithm of data

3 wavelength method: “SAGE-3λ”



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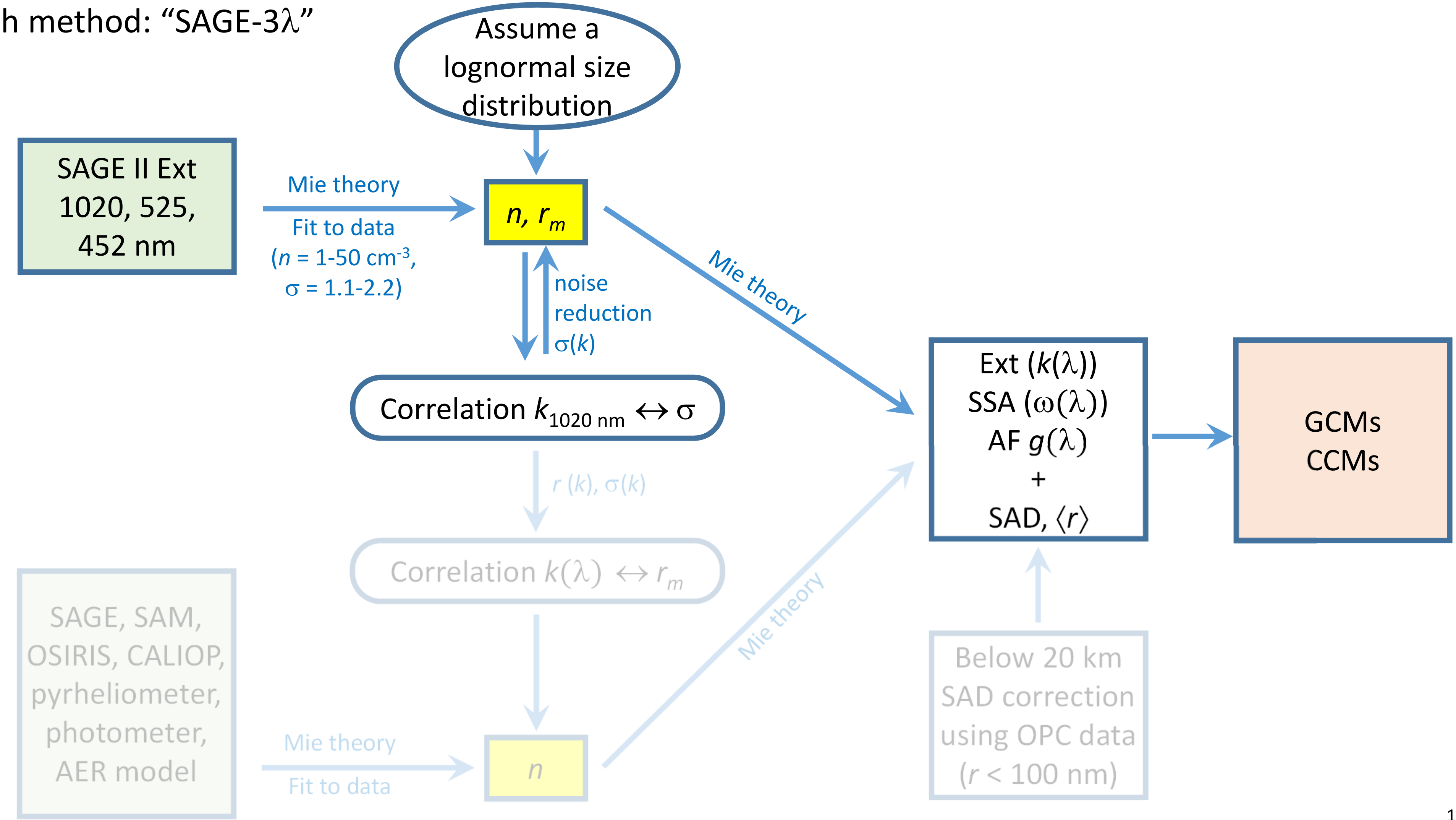

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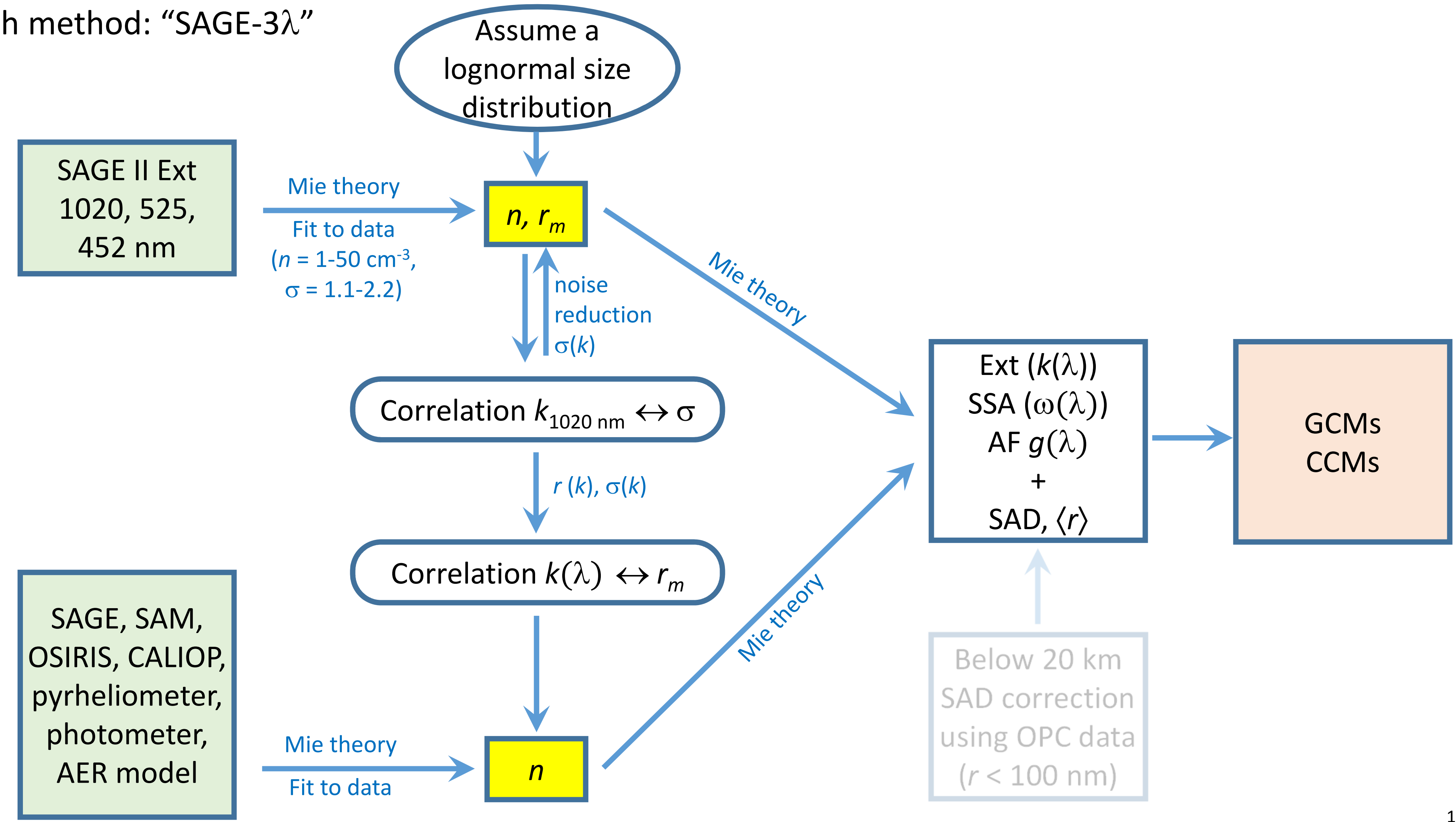

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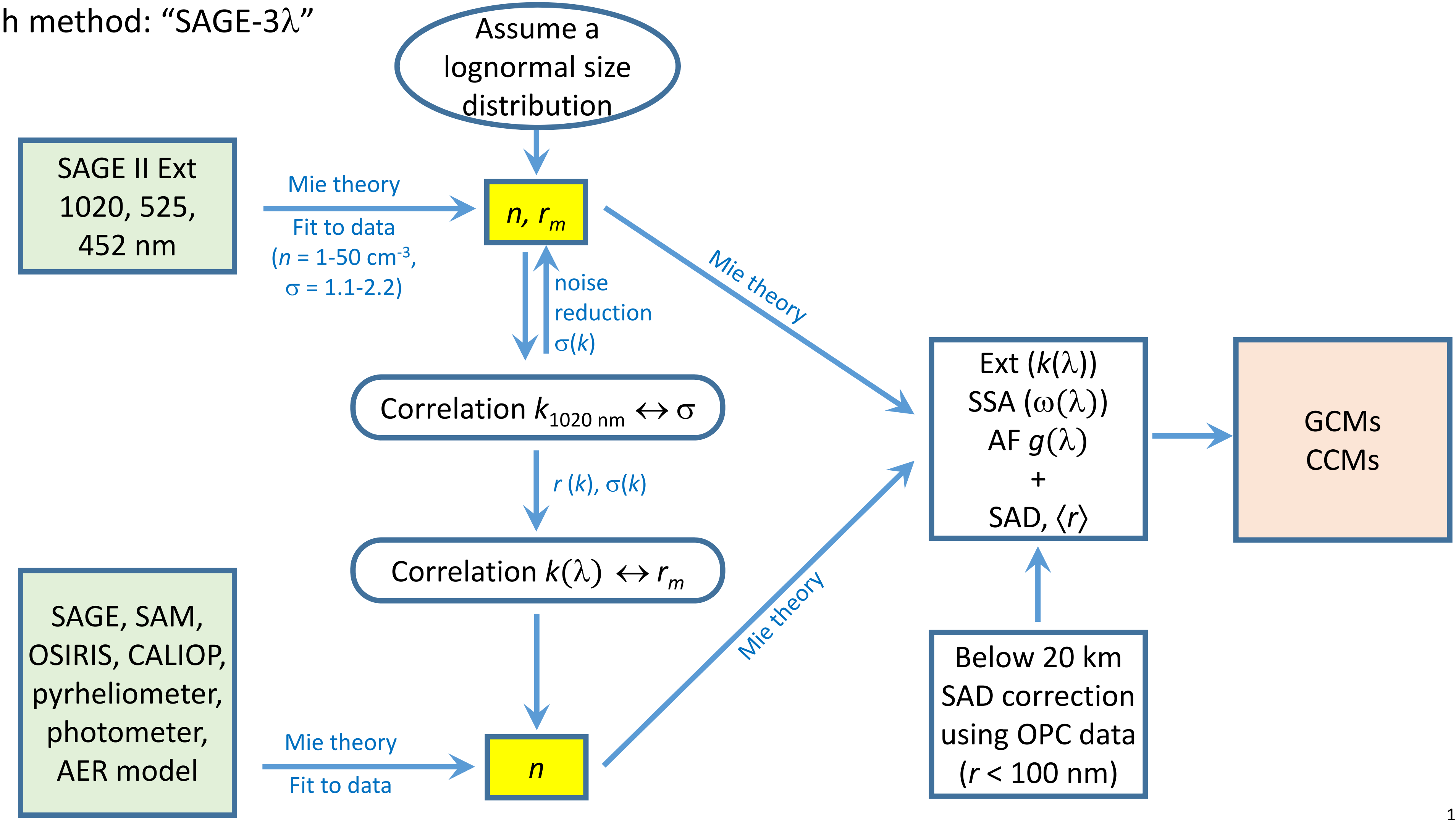
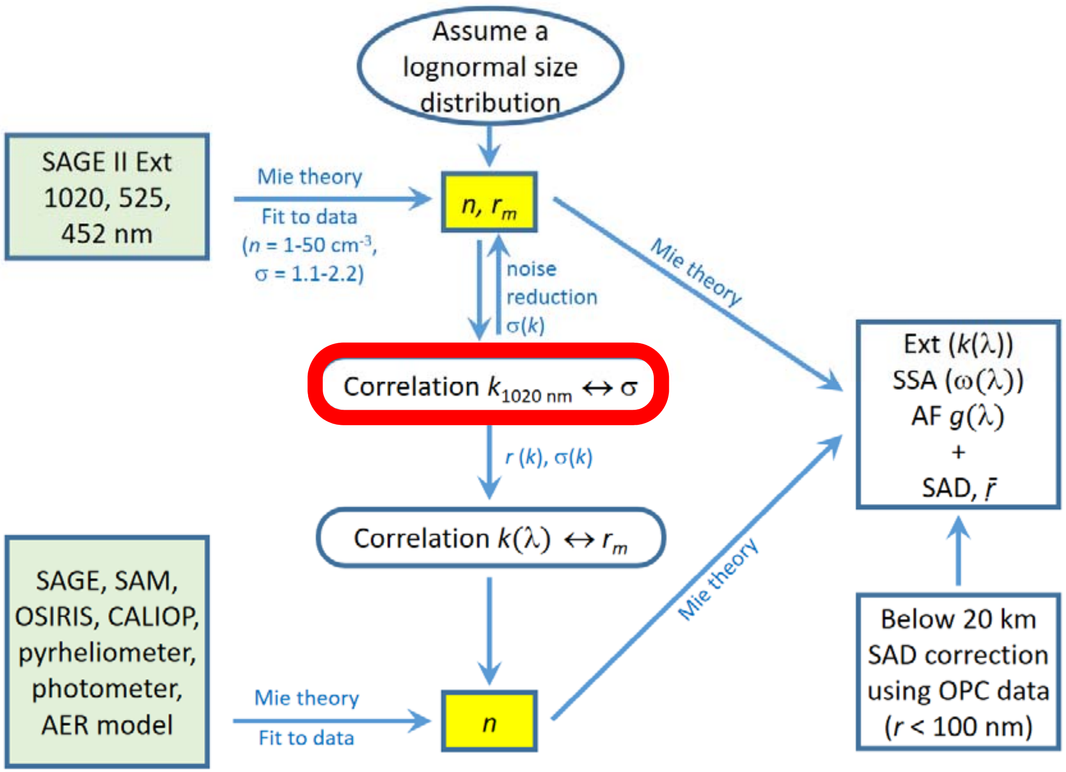
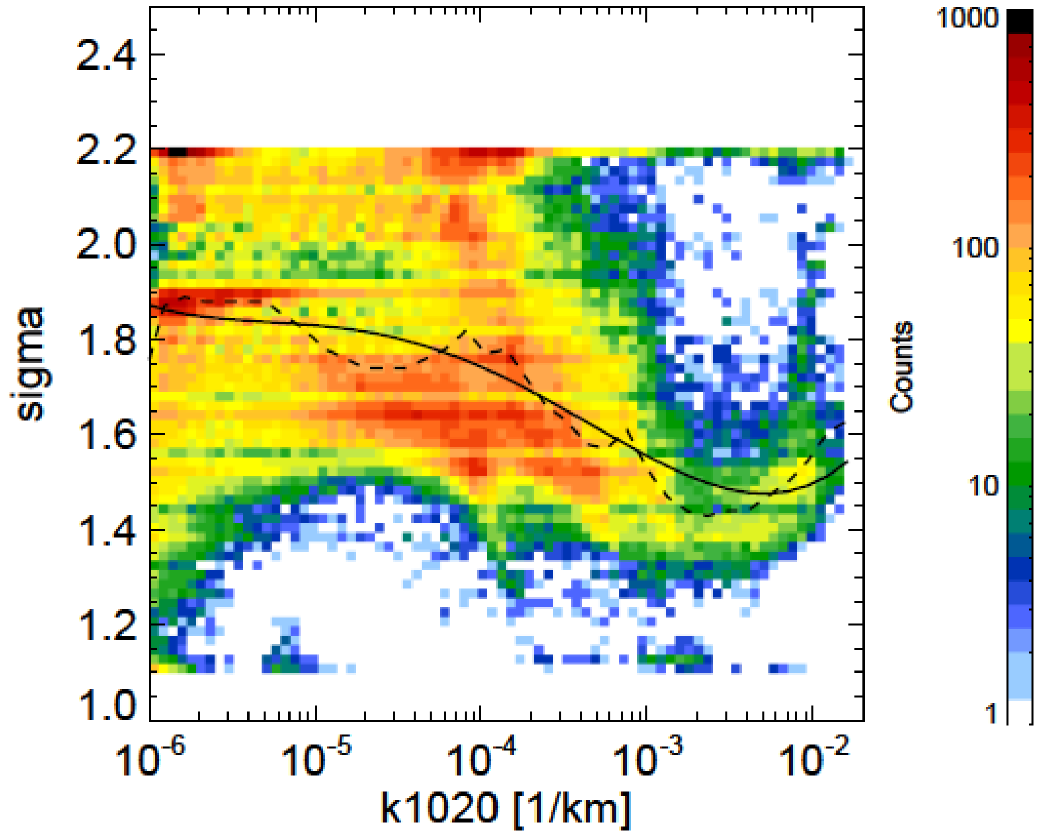


Width of size distribution obtained from SAGE II data



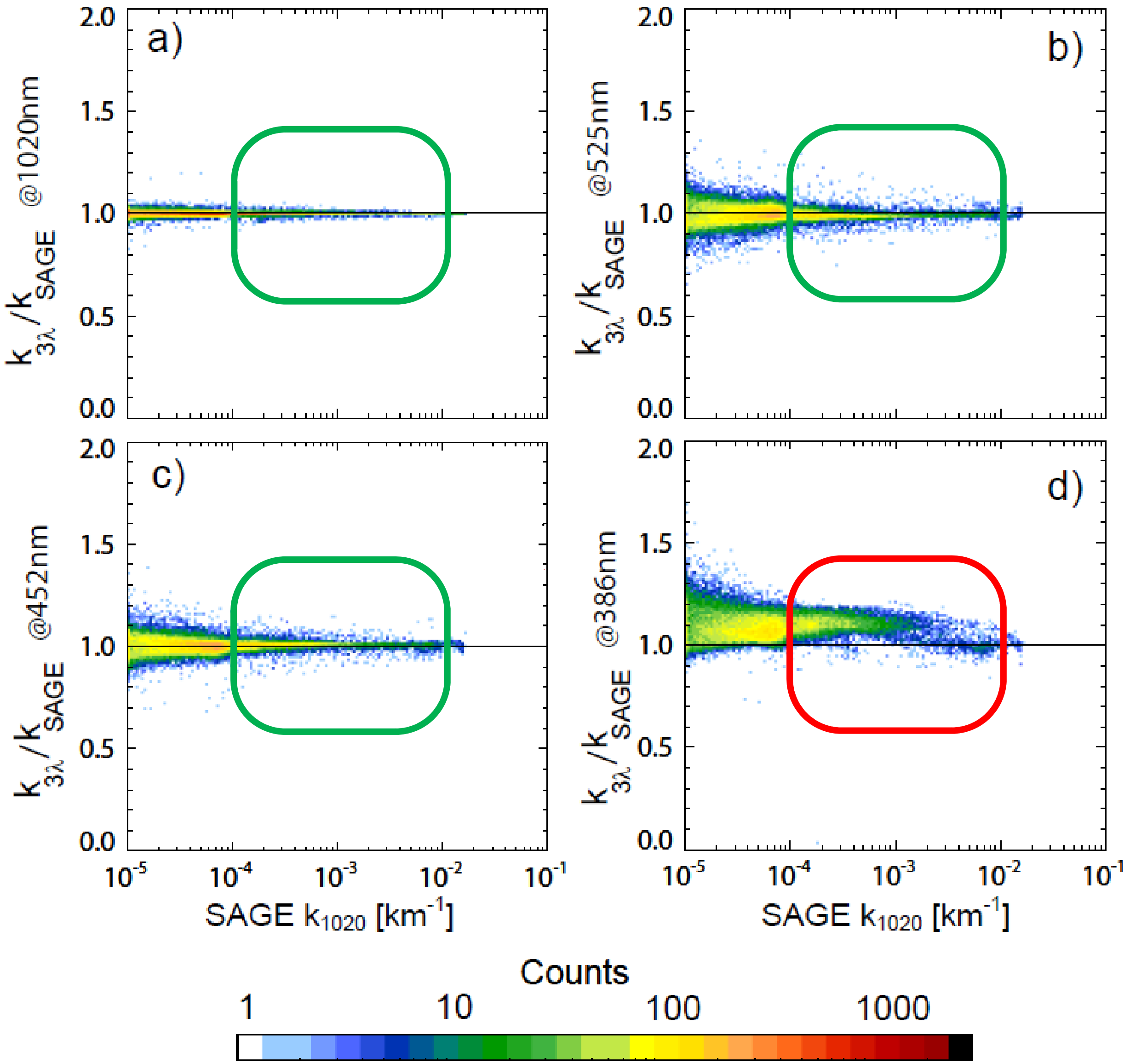


Noise reduction.
Dashed: median. Solid: fit used.
Similar procedure for other λ.

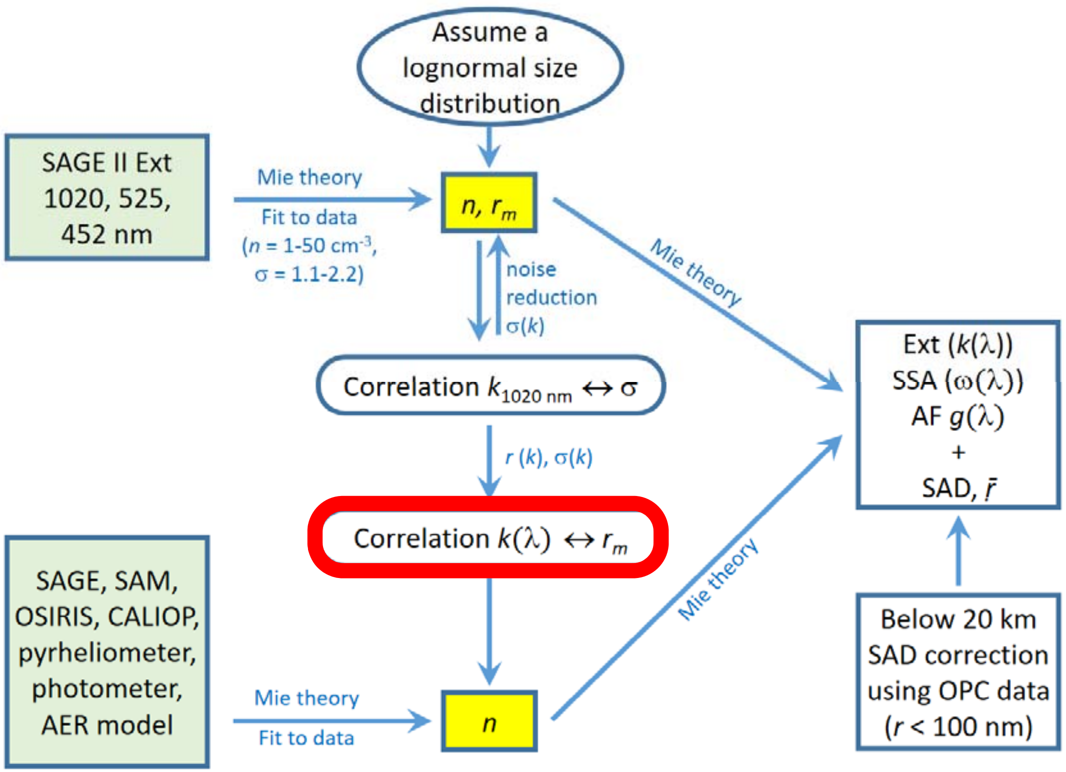
Comparison with the original SAGE II data

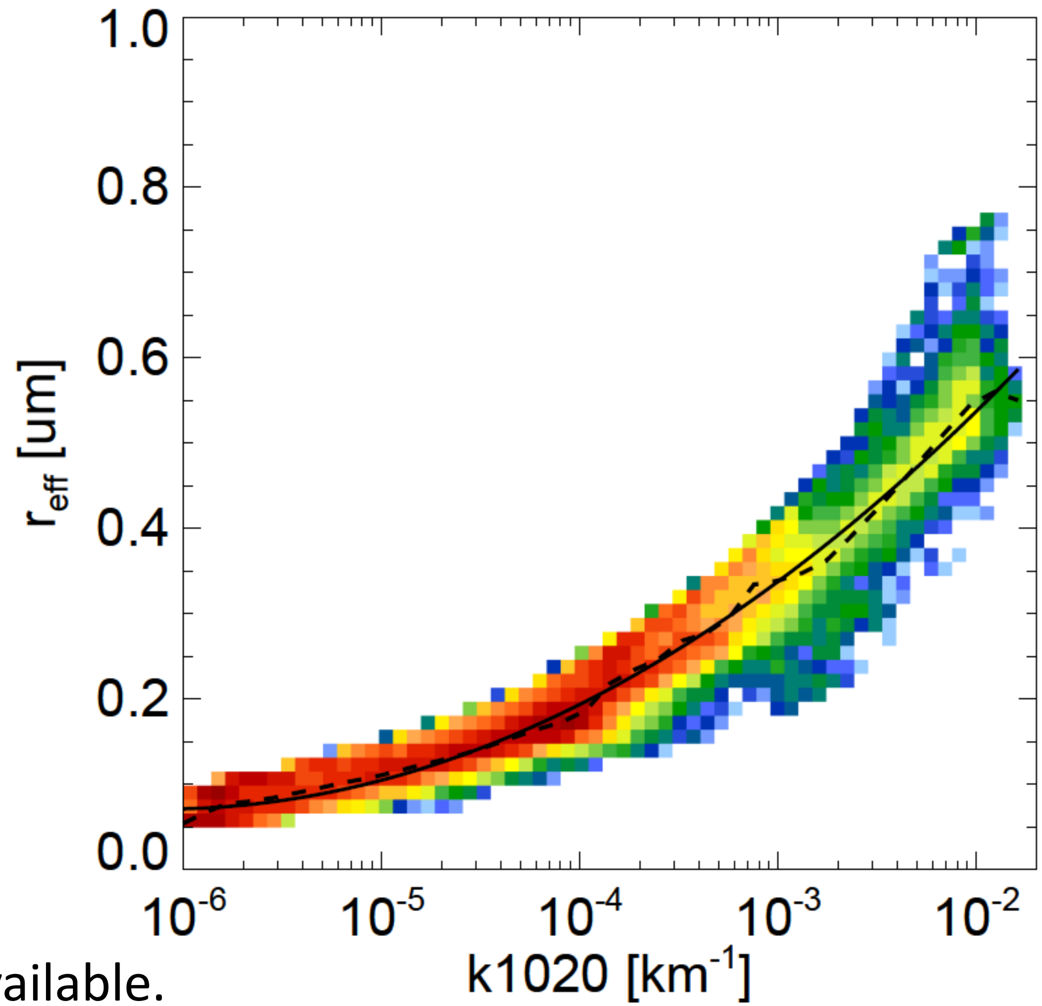
Extinction in the visible

- responsible for surface cooling by stratospheric aerosol;
- the SAGE-3λ dataset reproduces the measured extinctions at 1020, 525 and 452 nm to within 5-10 %;
- at 386 nm the uncertainty of extinction is large (high molecular Rayleigh scattering and absorption); thus, these data were not used in the retrieval.



Correlation of r_{eff} and k

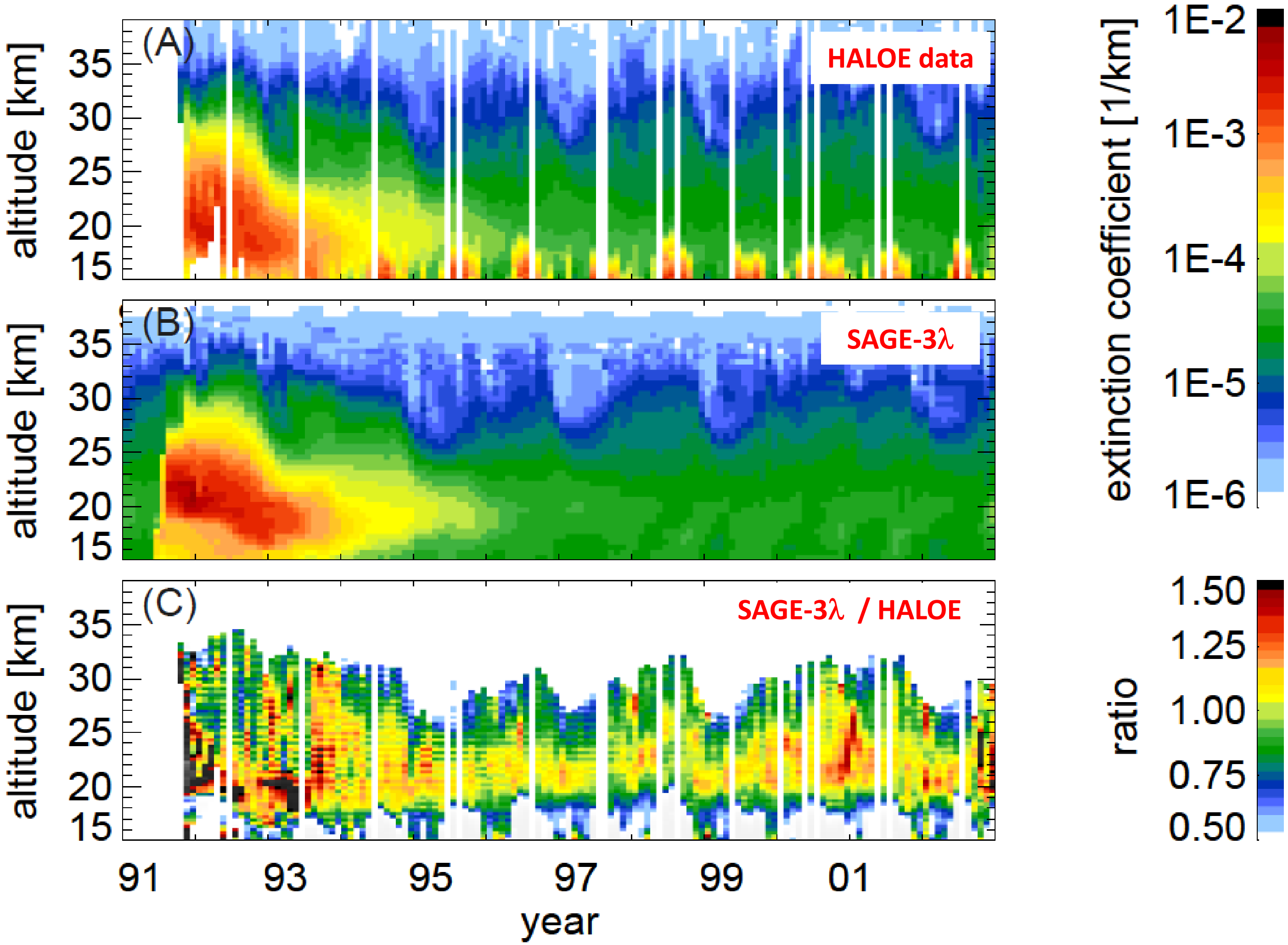




Required when k at only one wavelength are available.
SAGE-3λ provides reasonable effective radii.
Correlations calculated at 1020, 525, 550 nm.

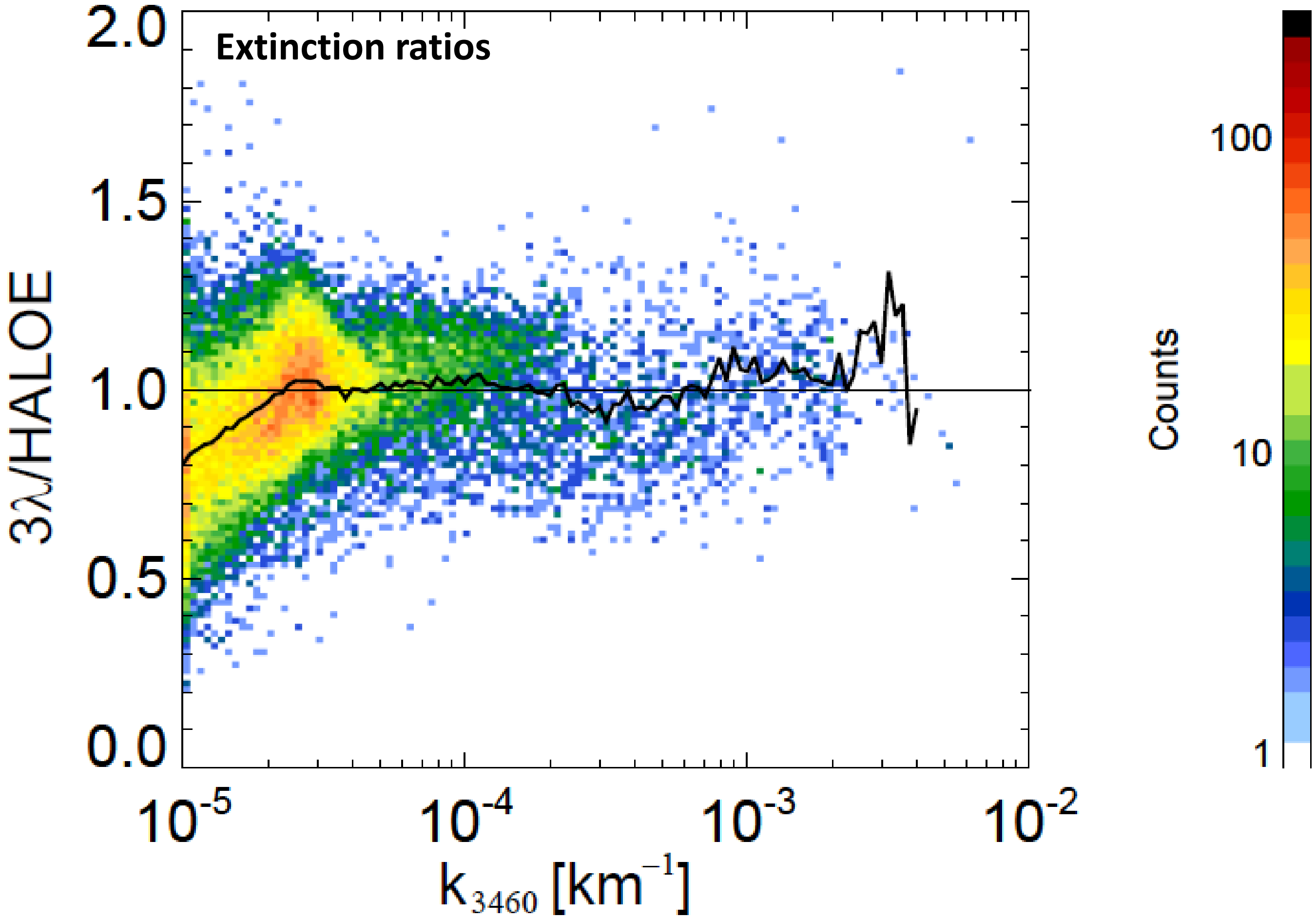
Comparison with HALOE measurements (at 25°N)

- HALOE extinction at 3460 nm
- Sensitive to the aerosol volume
- Proxy for in-situ heating due to absorption of terrestrial (and solar) IR
- Very good agreement in the Junge layer (± 10 %)
- Below 18 km, the HALOE data are contaminated by clouds
- Above Junge layer, lack of agreement less relevant

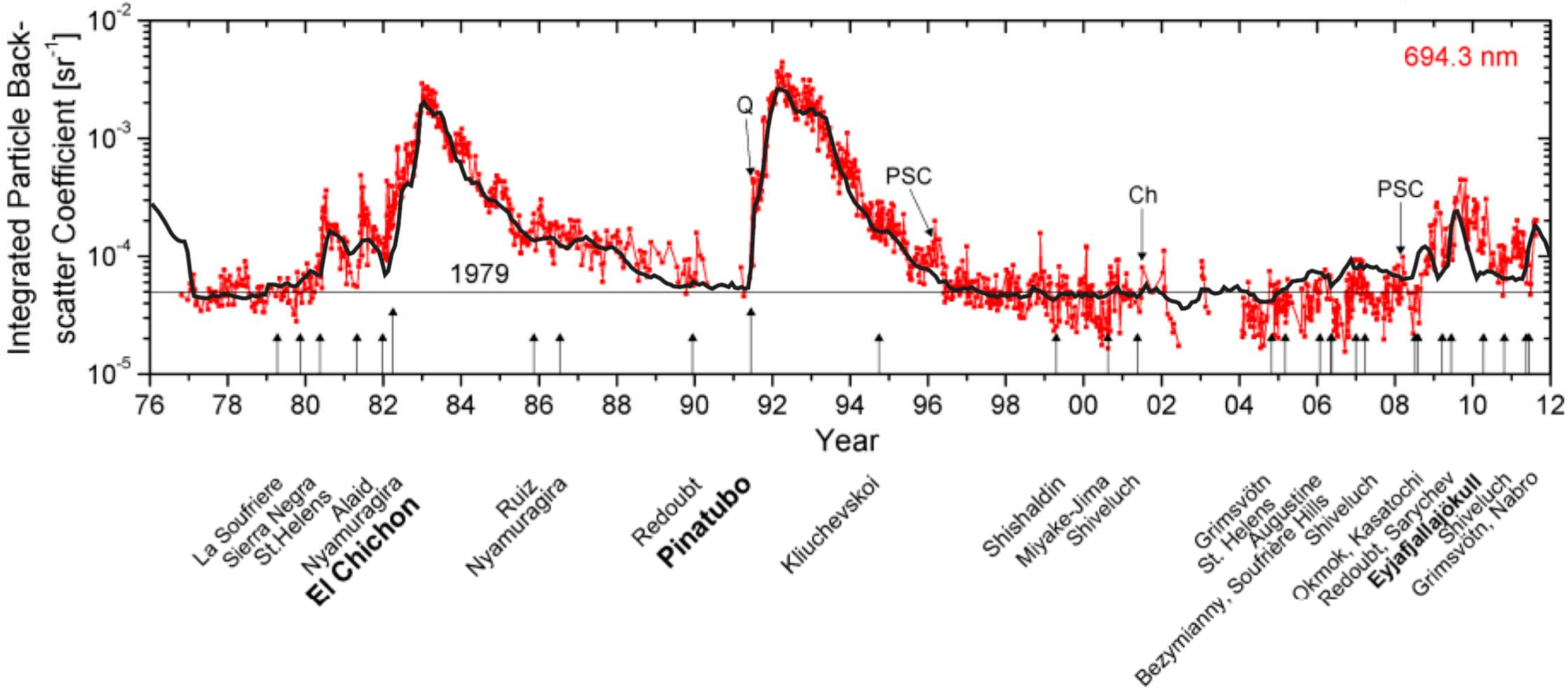


Comparison with HALOE measurements (20-25 km, global)

- **HALOE extinction at 3460 nm**
- **Generally very good agreement in the center part of the Junge layer**
- **Biases there less than ± 10 %**
- **For relevant extinctions (*k* > 10^{-4} km^{-1}), individual errors are less than ± 30 %**



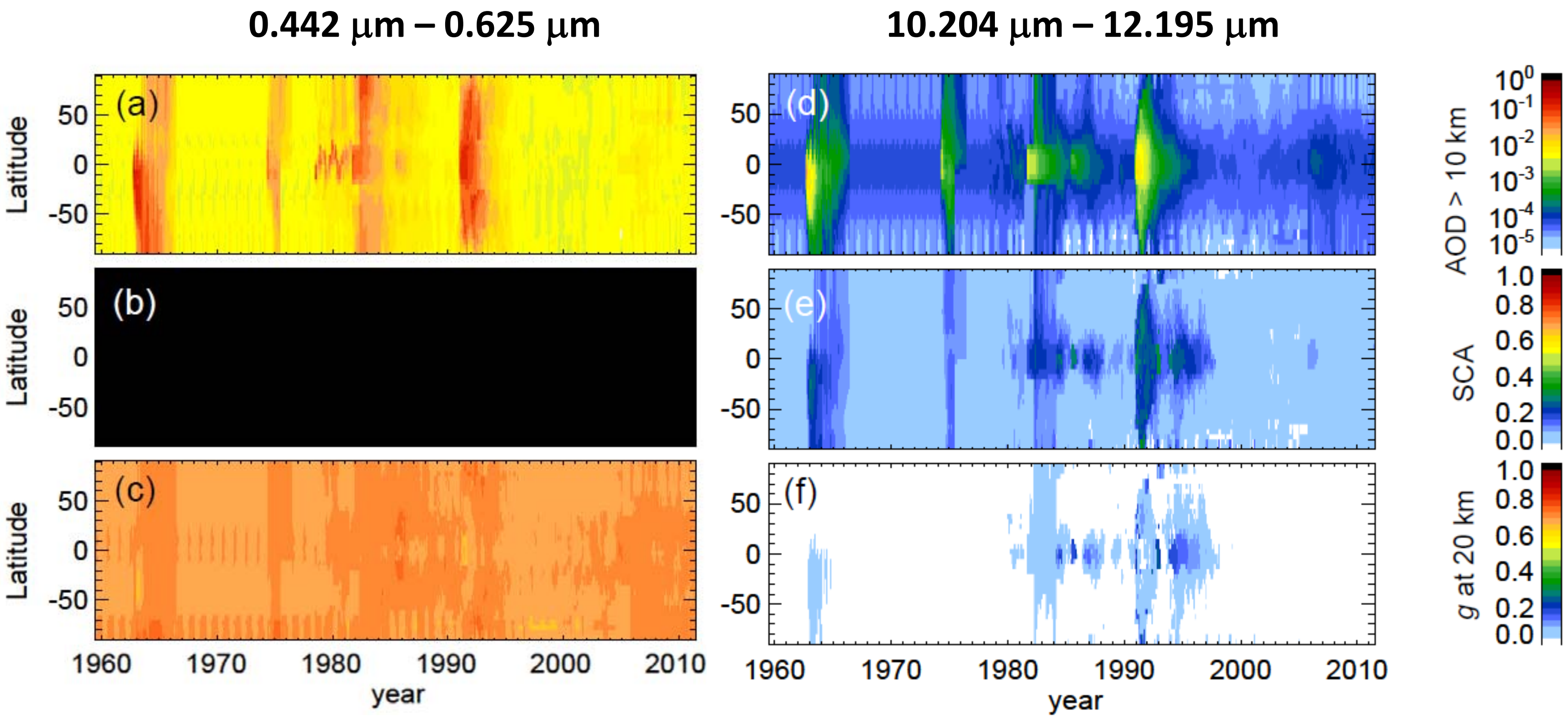
Comparison with Garmisch-Patenkirchen Lidar

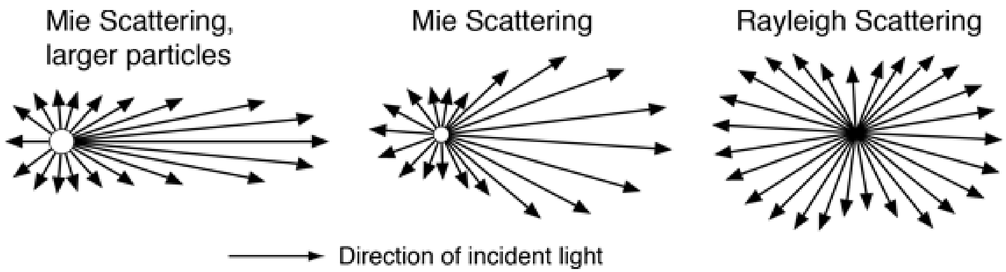


Data: Trickl et al., ACP 2013

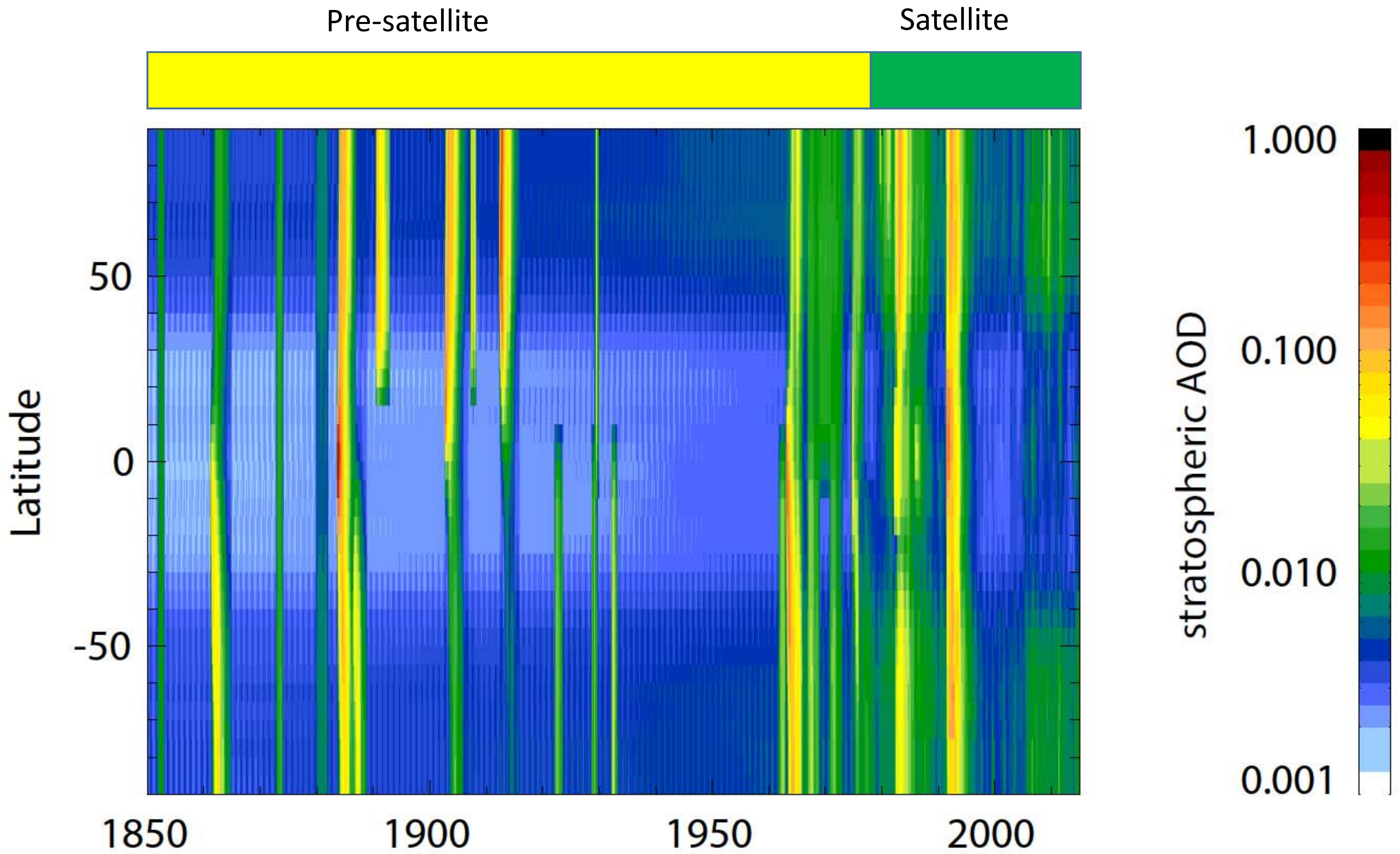
- **Generally very good agreement (± 50 % in integrated backscatter)**
- **High bias (factor of 2) of CMIP6 dataset during 2004-2008 – reason unclear**

Final products: radiative properties



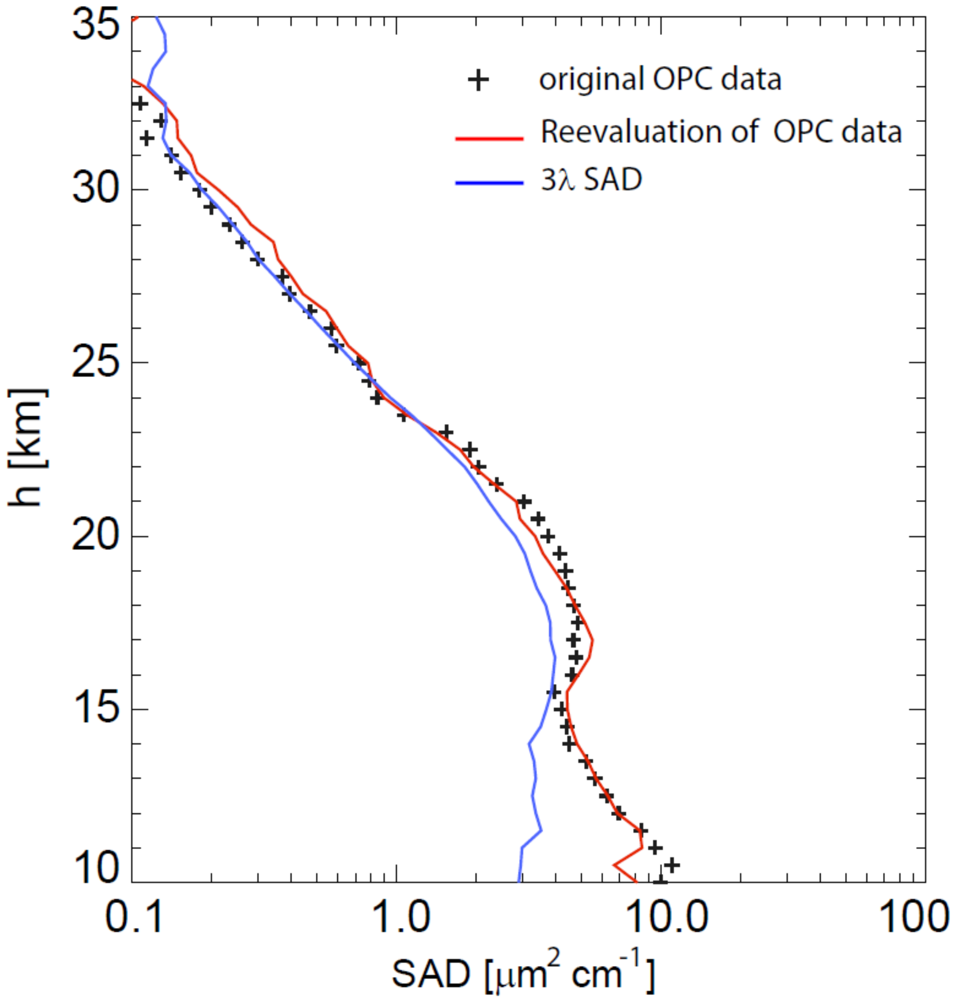


Final products: 1850-2014 CMIP6 vs3

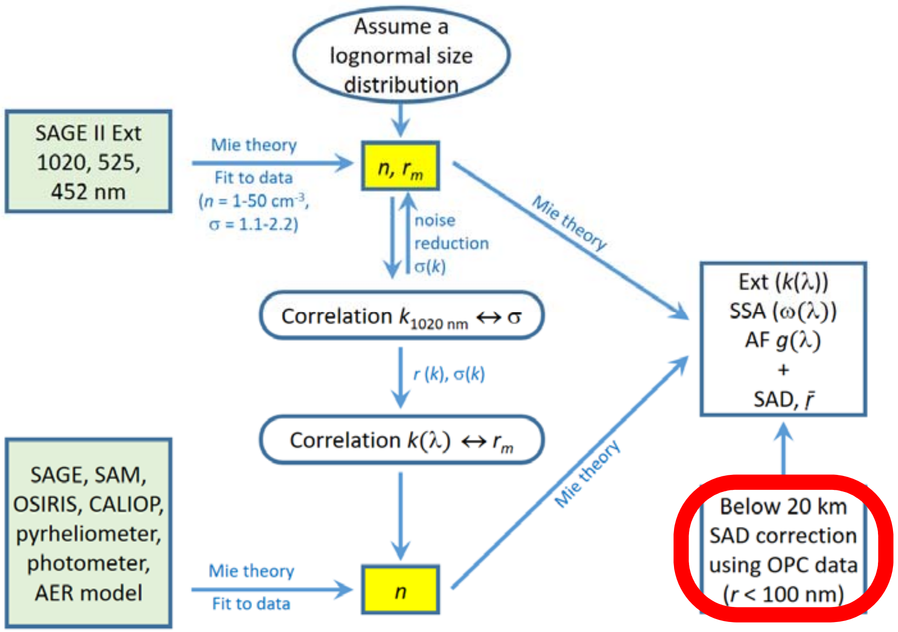


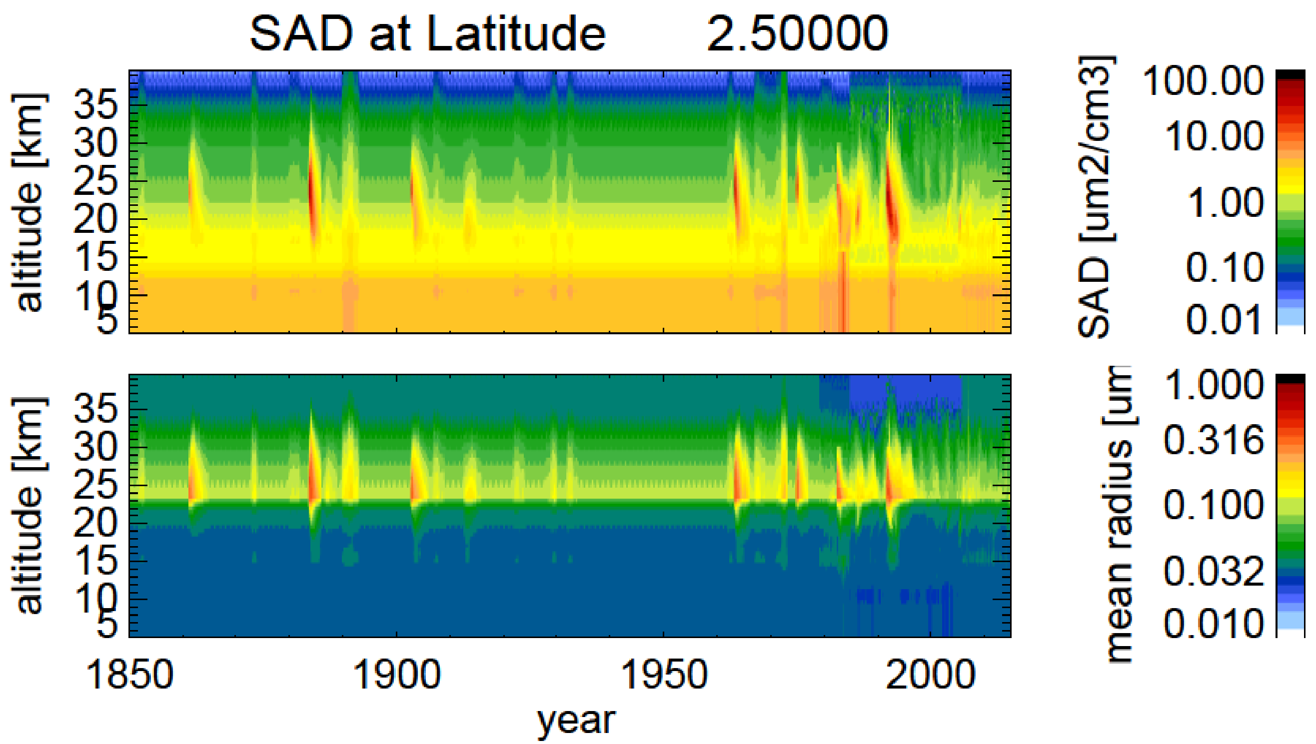
Comparison of surface area density, SAD, with OPC

- **All Laramie measurements 1971-2013 (~ 150 flights)**
- **SAD from SAGE-3λ agrees well with OPC data in the Junge layer**
- **However, large deviations in the lowermost stratosphere**
  - **reason are very small particles (*r* < 100 nm);**
  - **the satellites cannot see these particles;**
  - **these particles are radiatively irrelevant (*k* ∞ r^6);**
  - **however, they increase SAD!**



Final products: SAD and ⟨*r*⟩





Uncertainties…

- 10-20 % in the shortwave
- 20-30 % in the longwave

Quantity	Error source	Uncertainty
k_{1020}	SAM, SAGE I	~ 10% [a]
k_{1020}	SAGE II	5-10% [a]
k_{525}	CALIOP+OSIRIS	tbd [b]
k_{525}	SAGE II	10% [a]
k_{452}	SAGE II	10% [a]
k_{550}	before 1978	tbd
3λ-$k_{shortwave}$	Retrieval algorithm	<5%
3λ-$k_{longwave}$	Retrieval algorithm	20%
1λ-$k_{shortwave}$	Retrieval algorithm	10%
1λ-$k_{longwave}$	Retrieval algorithm	20%
3λ-SAD	Retrieval algorithm	10% [c]
1λ-SAD	Retrieval algorithm	20% [c]
Total uncertainty	**Instrument+Retrieval**	Σ

[a] Instrument-related uncertainties according to Thomason et al., Earth Syst. Sci. Data, 2018

[b] This uncertainty consists of the measurement uncertainty and the conversion uncertainty to k_{525}

[c] Below 20 km, the single-mode size distribution underestimates SAD by up to a factor 2.

First corrections: CMIP6 vs2 → vs3

Comparison of the pyreheliometer and SO_4^{2-} data (by Mike Mills):

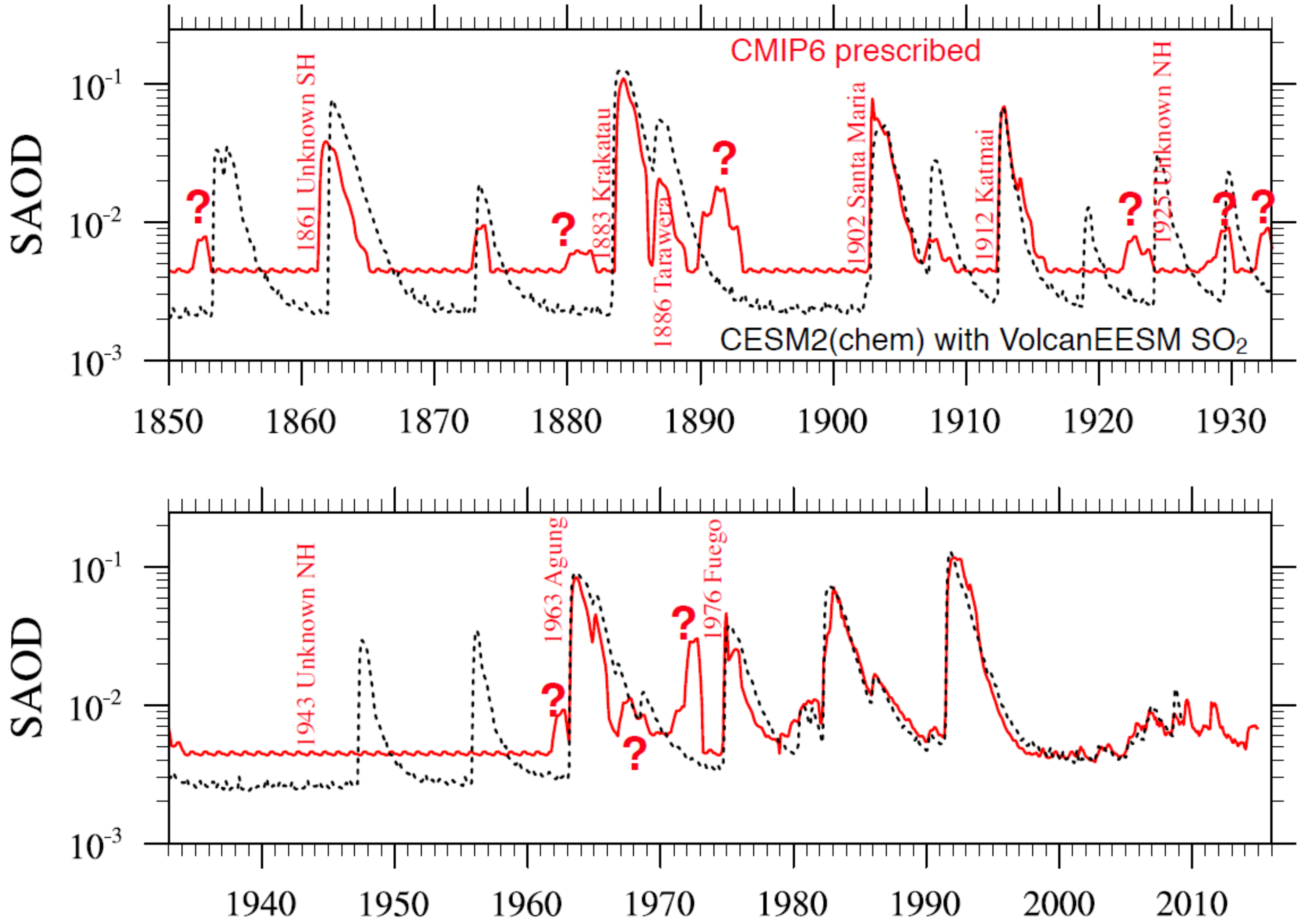
(1) 1972 AOD corrected: a typo had caused a factor of 10 higher AOD.

(2) Revised background values: vs3 takes OCS trend into account.

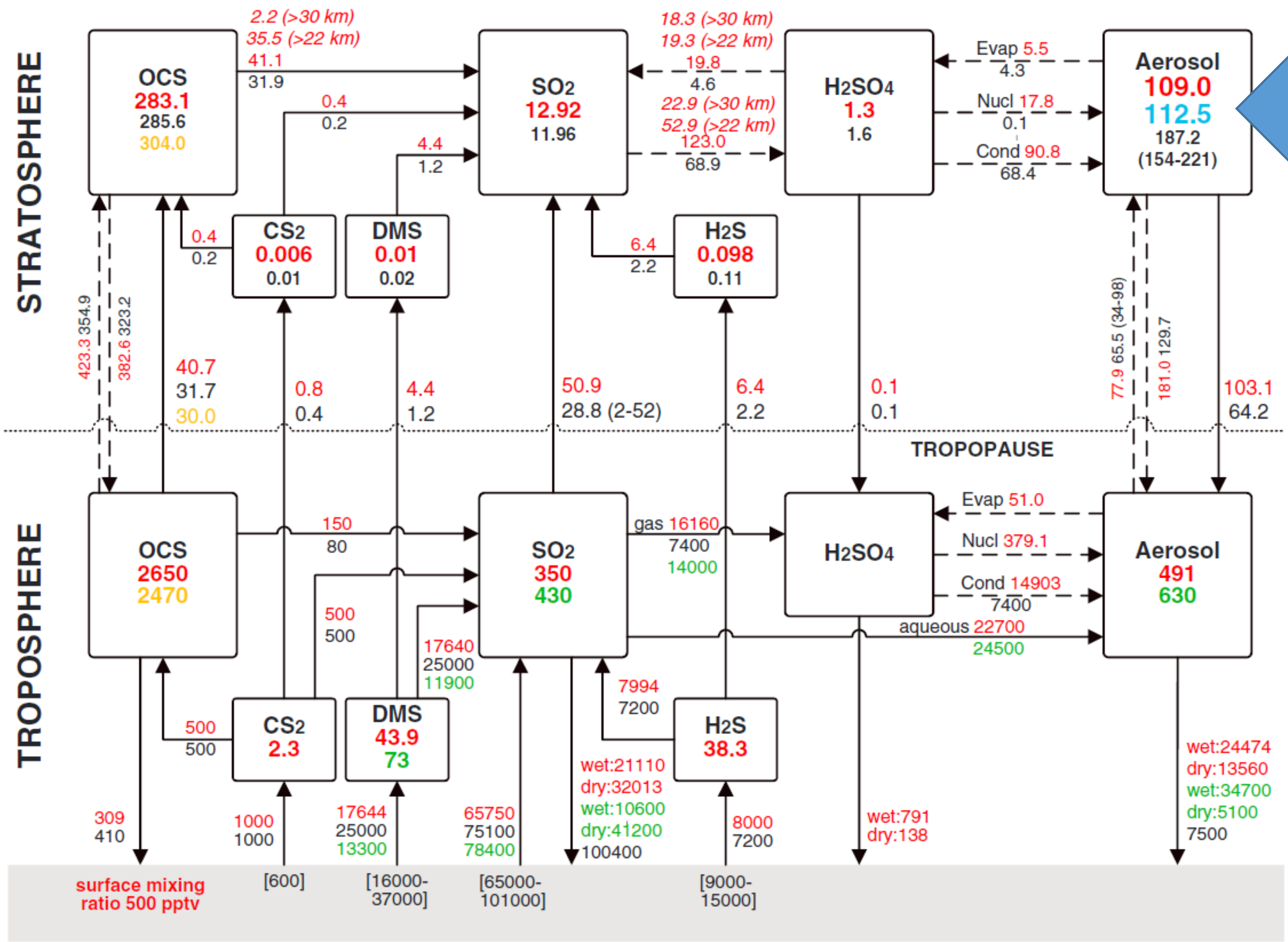
(3) 1883 Krakatoa emissions adapted to account for uncertainties in Mont-pellier pyrheliometer data.

(4) However, many of the SO_4^{2-} peaks not adopted. E.g., Bezy-mianny 1956: “Pyrheliometric observations made at Davos, Albuquerque, Blue Hill, Madison, and at Tucson show no significant stratospheric disturbance in 1956” (Stothers, 1996).

Thanks to Mike Mills, Anja Schmidt and Ryan Neely!



CMIP6 stratospheric burden under quiescent conditions



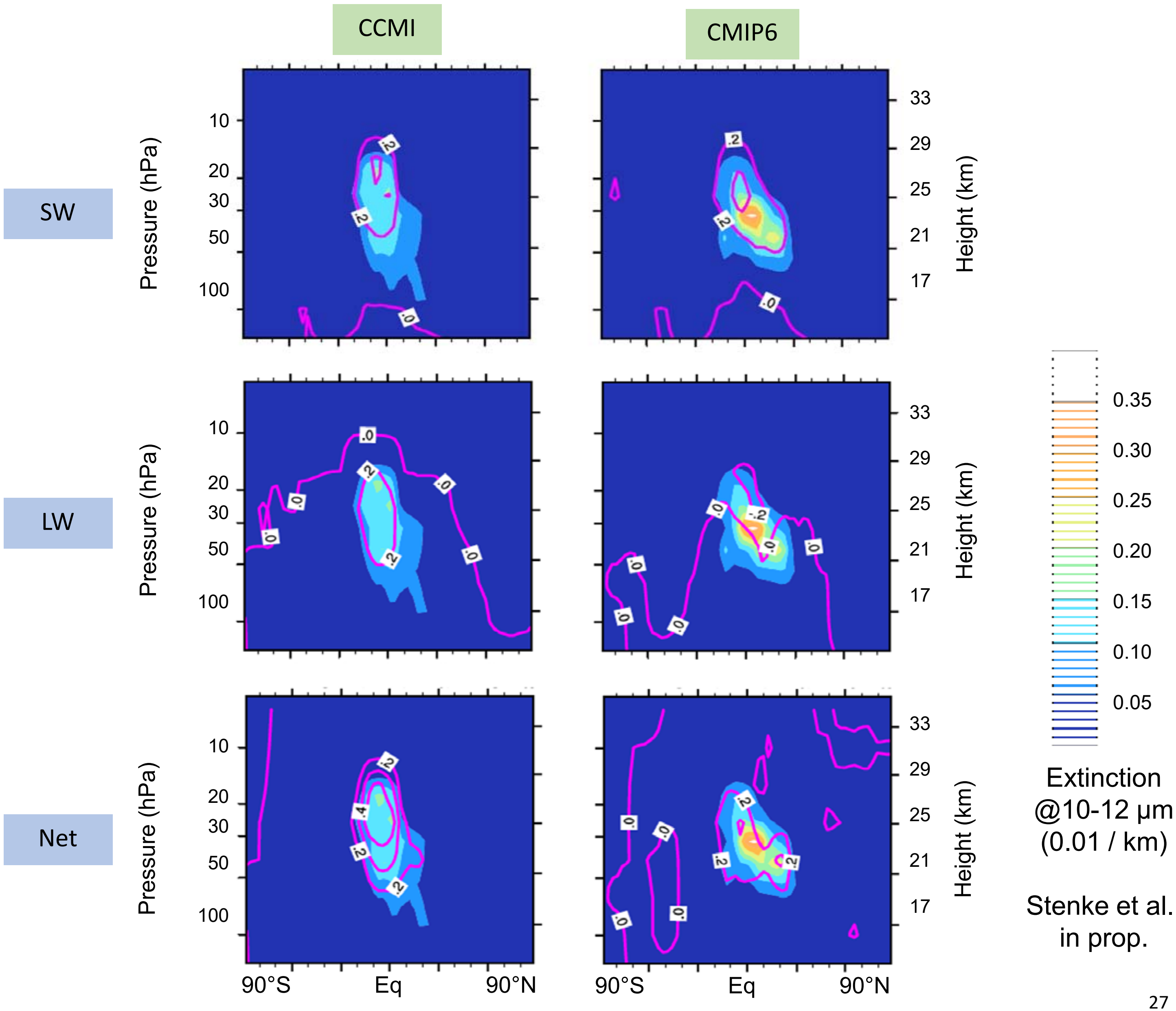
112.5 Gg S from the CCMI dataset

Quiescent burden in CMIP6:
164 Gg S ,
i.e. 40 % more

Figure from Sheng et al., JGR, 2015

Aerosol heating rates in K/day ☺
(all sky, Aug 1991)

- CMIP6 data set yields better LS temperatures after Pinatubo despite higher mass loading
- Reasons: higher loading
  - at high altitudes and temperatures leads to more IR emission,
  - more blocking of upwelling radiation.
- See SOCOL results (right) and Laura Revell's and Timofei Sukhodolov's presentations



Stenke et al., in prop.

The Basis and Development of the CMIP6 Stratospheric Aerosol Record – summary

- Use only SAGE at 1020 nm, 525 nm, 452 nm (abandon 386 nm, i.e. 3λ instead 4λ)
- Improve gap-filling by using CLAES and HALOE instead only ground-based lidar
- Include OSIRIS data together with CALIPSO
- Extend from 1960-2011 (CCMI) to 1850-2015 (CMIP6)
- Forcing parameters calculated for the wavelength bands of all models
- The input data in the visible and IR are well represented
- Good agreement with long term lidar data
- Estimated uncertainties: 10-20 % for SW, 20-30 % for LW
- The SAD in Junge layer agrees well with OPC data
- In the lowermost stratosphere, SAD needs to be corrected for smallest particles