H. Horvath July 27, 2019

Black Carbon aerosols as a climate change driver

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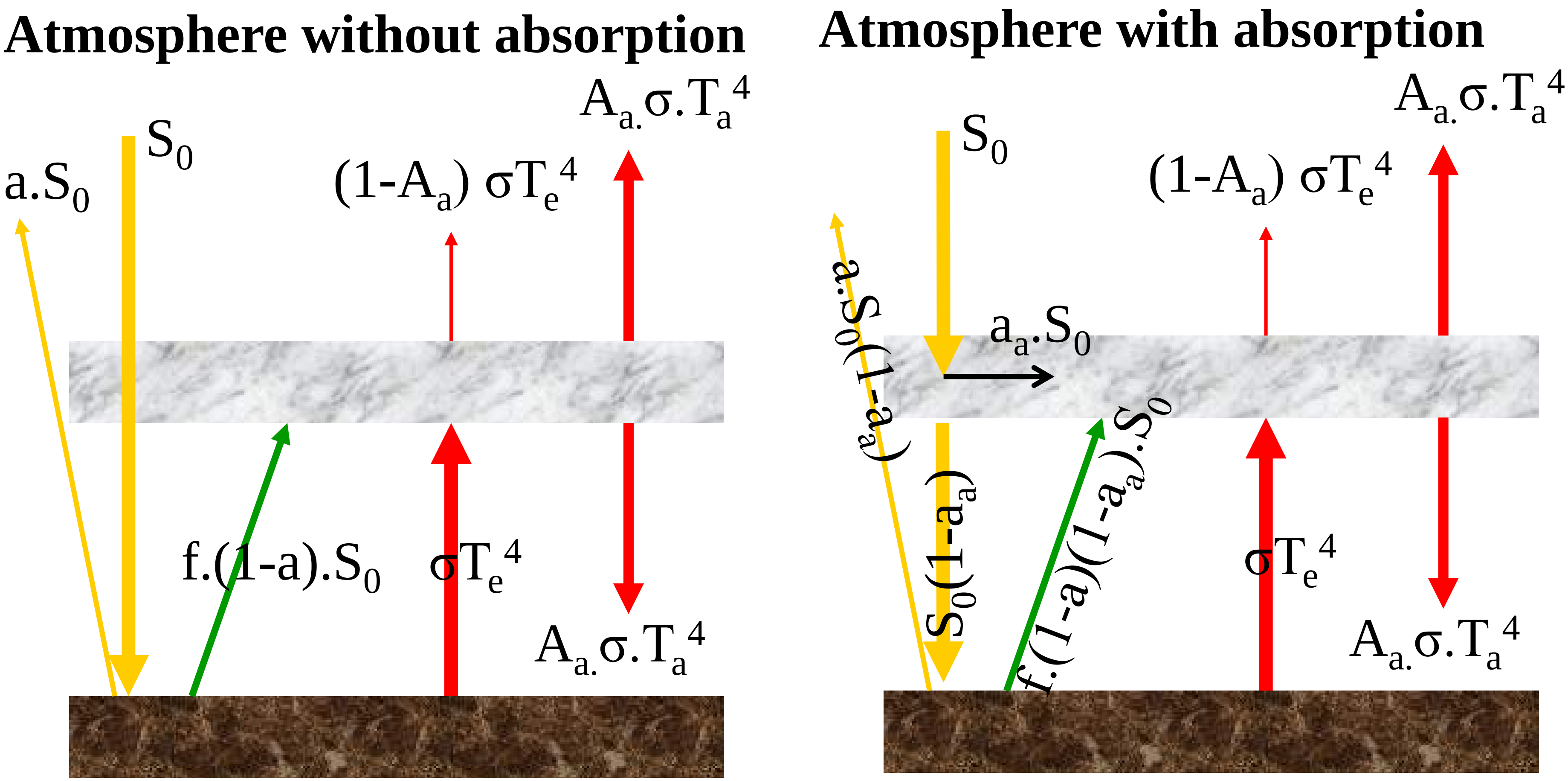
Black Carbon and global warming.

Black carbon is light absorbing → model with light absorption in the atmosphere needed



Dfference to case without absorption:

Fraction $S_0.a_a$ of the incident Solar flux density is transferred to the atmospher due to absorption.

Temperature without

$$T = \sqrt[4]{\frac{(2-f)(1-a).S_0}{\sigma.(2-A_a)}}$$

with absorption

$$T = \sqrt[4]{\frac{[(2-f)(1-a)(1-a_a)+a_a].S_0}{\sigma(2-A_a)}}$$

With albedo a=0.3, a_a=0.02 (2% absorption), f=0.3, and A_a=0.92 …. 0.97 one obtains

T= 11.95 …. 15.35 °C

T= 11.72……. 15.12°C

0.2°C colder ¿?¿?¿?¿?¿ !i!i!i!i! i

YES, since less solar radiation to ground

Temperature of the atmosphere:
-21.86 ……. -19.91 °C

-21.21 …….. -19.32 °C

Atmosphere slightly warmer 0.6°C
Not much difference ?????

Not much difference ?????   Black carbon not important???

BUT: Picture not complete: black carbon can be deposited on snow→alters albedo
Multiple scattering → enhances absorptive effects
Multiple reflections → enhances absorptive effects
Feedbacks: more melted snow/ice
change in salt concentrations of sea water,
large scale ocean fluxes (thermohaline circulation) may change

Preamble: Black carbon in most parts of the world is ***the* important** light absorbing substance in the atmosphere .(at least in the visible)

Definition: Black carbon is a perfeclty light absorbing substance consisting (almost exclusively) of carbon atoms. Black means absorption at all wavelengths (at least in the visible).

Black carbon can be generated by

- Combustion under lack of oxygen (incomplete conbustion), e.g. in Diesel engine, uncontrolled fire (e.g. burning oil well),
- Pyrolysis of organic matter: in fire, charcoal production (dry destill

Other names for black carbon:

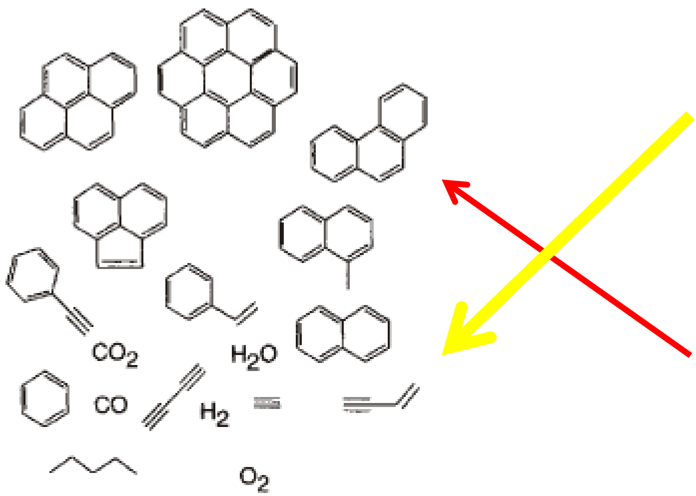
- Elemental carbon i.e. substance containing only carbon: graphite (b (transparent), Fullerenes (strong absortion 200 to 400 nm, some a nm, brown appearance), carbon nanotubes (maybe black depend almost perfectly black for forest of nanotubes) – not suitable name
- Graphitic cabon: implies graphite structure, mostly true but black carbon (as a product of combustion) but Black Carbon contains some organic carbon .

By EPA - U.S. Environmental Protection Agency, Public Domain, https://commons.wikimedia.org/w/index.php?curid=3867874

Black carbon usually insoluble, refractory, consist of chain aggregates.

Formation of black carbon:

Bockhorn, Henning, (ed.) Soot formation in combustion : mechanisms and models Berlin Springer ; 1994 pp 2-7



Fuel and oxygen

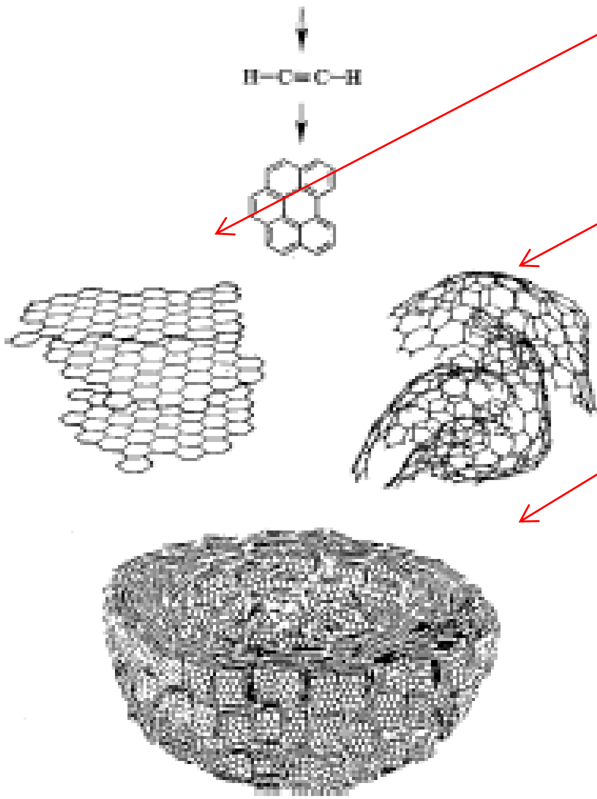
During the combustion process in some parts of the flame lack of oxygen and high temperatures radicals are formed

→ favor the formation of intermediate molecules,

later of poly-aromatic hydrocarbons (PAHs), which are a consolidation of benzene rings. The structure is similar to graphite

Further consolidation reduces H/C ratio, graphitisation increases, H/C <0.2 black carbon
H/C>1 …. Amorphous carbon.
Transition from amorphous organic carbon to graphitic cabon requires energy → only possible in hot flames
Low tempearture combustion produces mainly amorphous organic carbon (brown carbon).

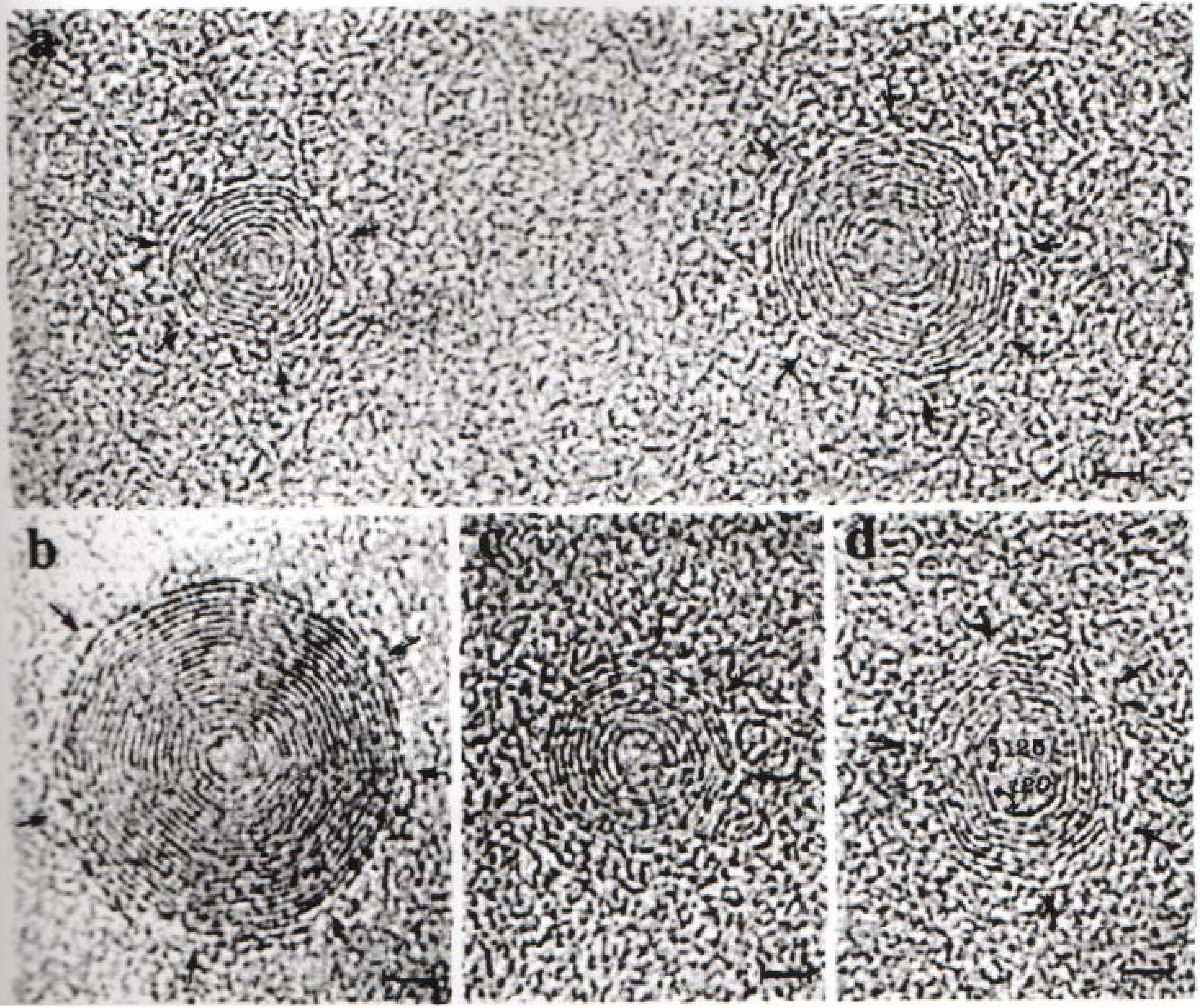
in hot flame: small plates of graphite (~2nm) are formed. (not exactly graphite.
(distance of planes is 0.35 to o.37 nm instead of 0.3354 nm for graphite)



Entstehung von Russpartikeln (Stegmann)

Honeycomb net not perfect, in between instead of rings with six C-Atoms also rings with five C-atoms,
→ honeycomb net is not plane but arches.
Sometimes Fullerenes form, if reactive ends meet (more the exception)
Usually a shell structure is formed.

agglomerate to small spheres
(20 .. 30 nm)
of very high concentration



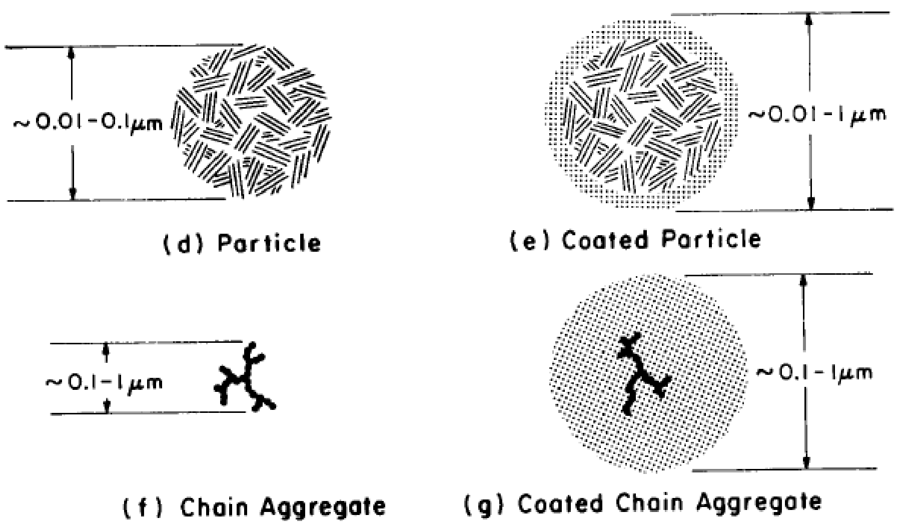
Electron micrograph of soot particle, shell structure easily visible

S. Iijima (1989) Direct observation of tetrahedal bonding of graohitized carbon black by high resolution electron microsopy. *Journal of crystal groth* **50** 674-683

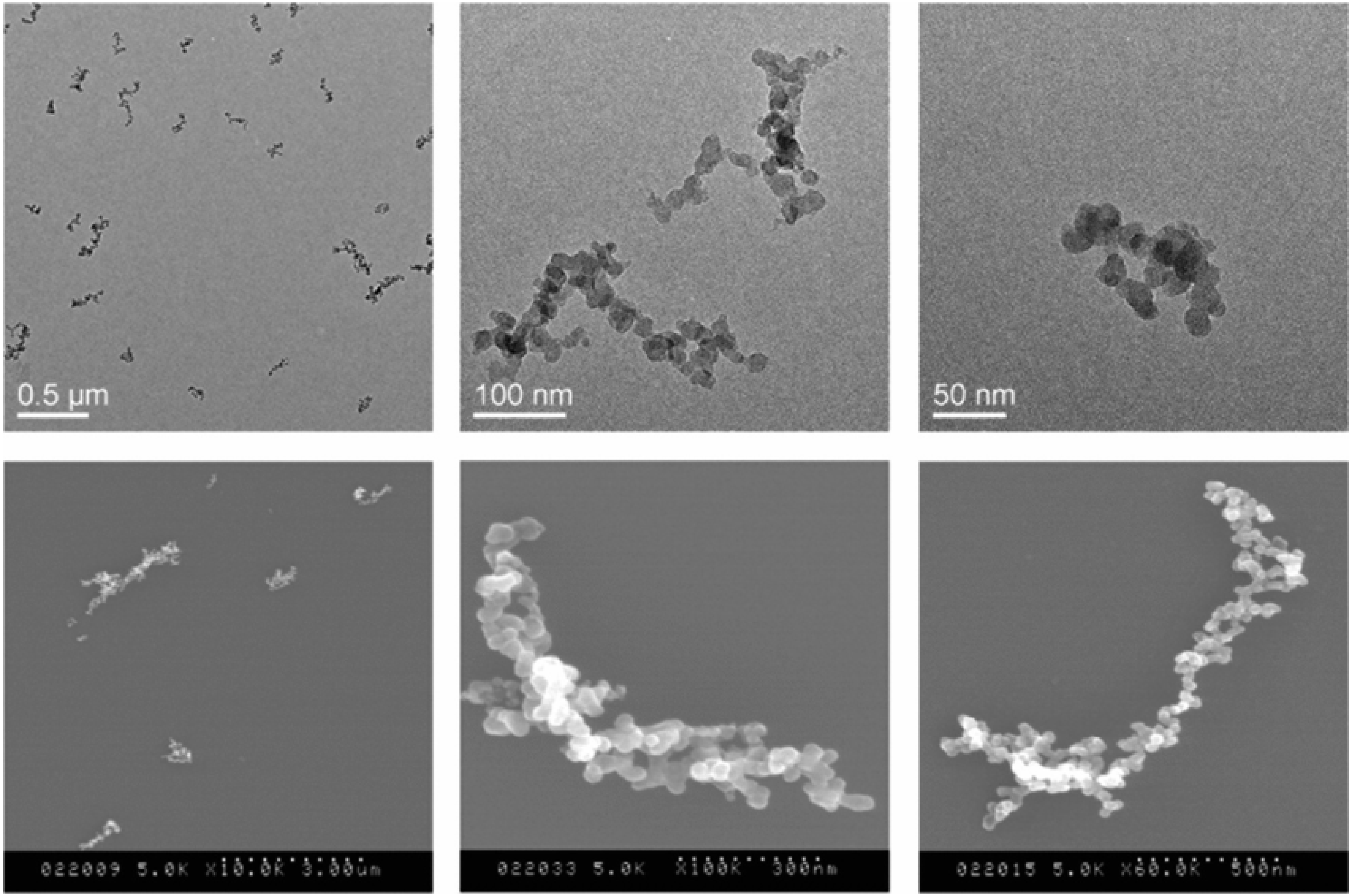
Pure graphite consists of many layers of C (honeycomb) layers.
In the hexagonal structure each Carbon atom is connetcted to three equally distant carbon atoms by electron pairs.
The fourth electron is free and can move freely (like in metals) thus absorb a large range of energy of photons, thus black and glossy.
The different layers of graphite have much bigger distance as C atoms in honeycomb
→ attractive forces between atoms in layers are smaller
→ layers can move with respect to each other and graphite is soft.

So far only primary particles are considered; spheres of 20 to 30 nm of high concentration.

Rapid coagulation to agglomerates, and covered with condensed organic matter



J.A. Ogren and R.J. Charlsom (1983) Elemental Carbon in the Atmosphere: Cycle and Lifrtime. Tellus 35B 241-254



Kim, Seong & Wang, Jing & Gyu Shin, Weon & Scheckman, Jacob & Y. H. Pui, David. (2009). Structural Properties and Filter Loading Characteristics of Soot Agglomerates. Aerosol Science and Technology. 43. 10.1080/02786820903131081.

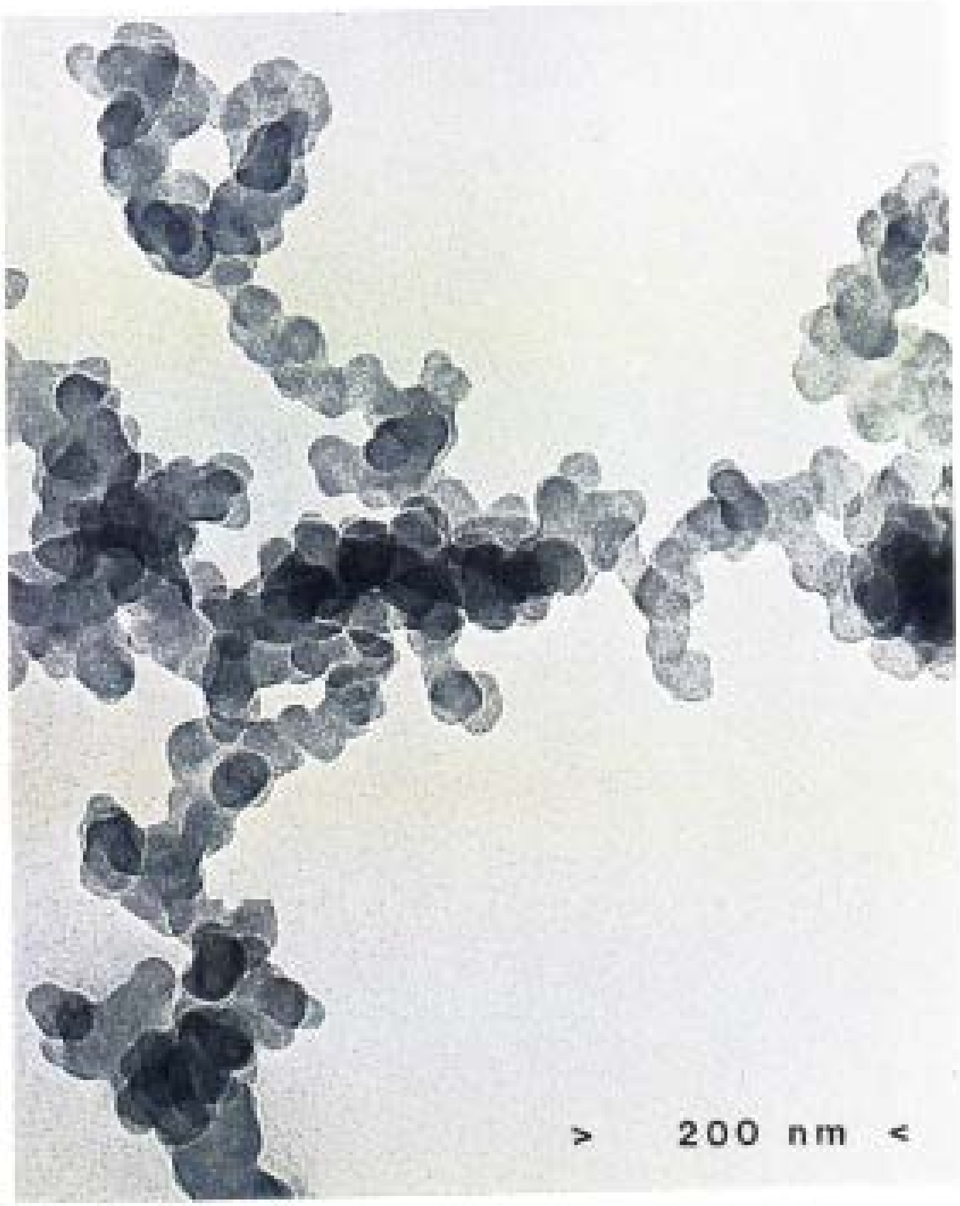


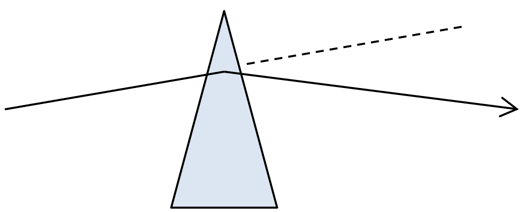
Fig. 17.3. Micrograph of a soot particle sampled from the upper buoyancy dominated diffusion flame, $h = 330$ mm

R.A.Dobbins, H.Subramaniasivn
Soot precursor partiicles in flames
Pp 291-301 in Bockhorn, Henning, (ed.) Soot formation in combustion : mechanisms and models Berlin Springer ; 1994

Black carbon is similar to mixed particles. Not a perfect graphite, sometimes H in lattice, condensed hydrocarbons on it (always present in flames)

Optical properties of an aerosol is described by the absorption coefficient.

For modelling of the absorption coefficient the complex refractive index of black carbon is needed. No direct method possible, since Black Carbon is **BLACK**



Classical method:
Measure change in direction and angle of prism
→ Yields refractive index n (straight forward)

For black carbon: Snell method not possible
Other possibilities:

- **Ultrathin slab,** make transmssion and reflection measurement
- **Polished sample,** measure polarisation, phase shift and intensity of refected light, apply Fresnel (formulae)
- **Measure angular scattering;** Produce spherical particles, measure angular scattering and calculate scattered light by Mie theory and find best fitting refractive index.
- **Photon Correlation:** Measure scattering and attenuation of soot aerosol and size by photon correlation and use Mie theory
- .....

A few values for black carbon complex refractive index

Values for the refractive index of black carbon (at λ=550 nm)				
Re(m)	Im(m)	substance	Method	Reference
1.97	-0.67	Carbon arc electrode, 0.7% impurity	Reflection measurement of polished surface	Senftleben and Benedict (1918)
1.56 **1.57**	-0.46 -0.50	Acetylene soot Propane soot	Polarization ratio of reflection on compressed pellets	Dalzell & Sarofin (1969)
2.15	-0.66	Graphite	Reflection	McCartney J.T. & Ergun (1967)
1.86	-0.33	low volatile bituminous coal	Reflection	McCartney J.T. & Ergun (1967)
2	-1	Carbon black	Transmission of liquid suspension of nanospheres and Mie theory	Janzen (1979)

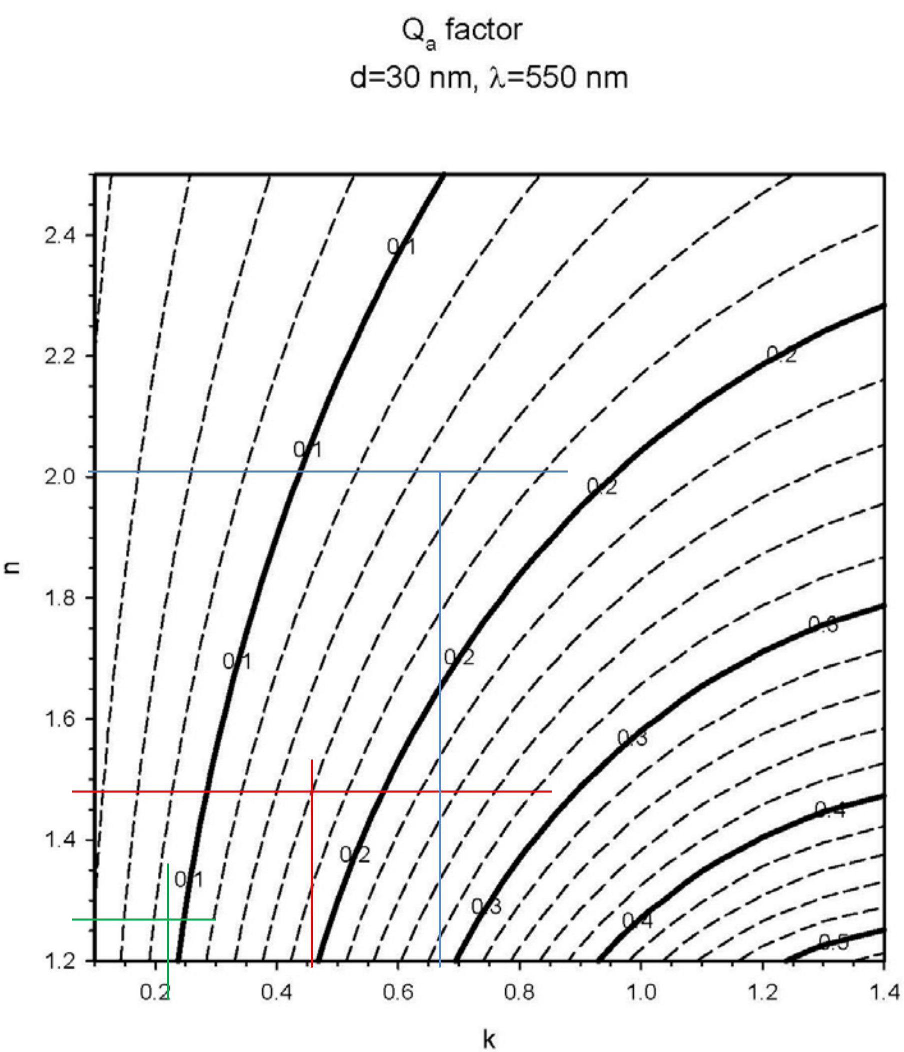
1.7	**-0.7**	**Carbon black**	**Angular scattering of levitated mircometer sized particles**	**Pluchino et al. (1980)**
1.28 **1.35** **1.36**	-0.22 -0.19 -.113	Kerosene soot Acetylene soot Propane soot	Polarization ratio, angular reflectance method of compressed samples	Batten 1985
2.649	-1.395	Graphite, crystalline	Ellipsometry	Stagg and Charalampopulous (1993)
2.337	-0.997	Graphite, amorphous	Ellipsometry	Stagg and Charalampopulous (1993)
1.701	-0.508	Propane soot	Ellipsometry of compressed pellets	Stagg and Charalampopulous (1993)
--	-0.72	Black carbon from vehicle emissions	Transmission of filter deposit	Kirchstetter et al (2004)
1.4…1.9	-0.77 … -1.25	Methane, ethylene and kerosene soot	Transmission and scattering of suspended soot particles	Shaddix and Williams (2009)
1.66	-0.59	Soot in burning propane flame	Photon correlation and extinction/scattering measurement	Chang and Charalampopoulos (1990)
1.46	-0.45		Value used in model	Shettle & Fenn (1972)
2.0	-0.66		Value used in model	Bergstrom (1973)
1.95	-0.66		Value used for modelling	Kattawar & Hood (1976)
1.57	-0.56	Soot	Suggestion for a representative value	Smyth and Shaddix (1996)

Values vary considerably. No unique value for soot (black carbon), Depends on type of soot (method of production, C/H ratio).

Carbon black: m=2 - i (Janzen), m=1.7 - 0.7.i (Pluchino)

Kerosene soot m = 1.28 – 0.22.i

Value in model: m = 1.46 – 0-45.i (Shettle & Fenn), m = 2.0 – 0.66.i (Bergstrom)



Absorption coefficient depends on refractive index:

Example for particles 30 nm.

Kerosene soot m = 1.28 – 0.22.i
Q_a=0.095

For Shettle & Fenn,m = 1.46 – 0.45.i
Q_a=0.16

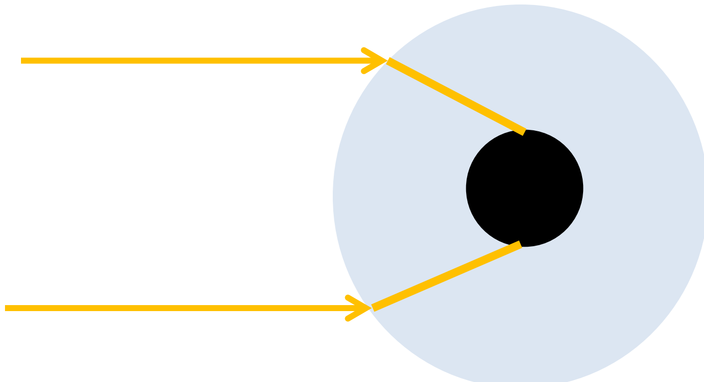
For m = 2.0 – 0.66.i (Bergstrom)
Qa=0.155

$$Q_a \propto \sigma_a$$

Mostly black carbon particles have some kind of coating

(Hydrocarbons, water after some time of interaction with O_3)

Increases absorption coefficient: „lensing effect“ already known 1920 (Rubinowitz A., 1920: Radiometerkräfte und Ehrenhaftsche Photophorese (I and II), *Annalen der Physik,* **62**, 691-715 and 716-737)



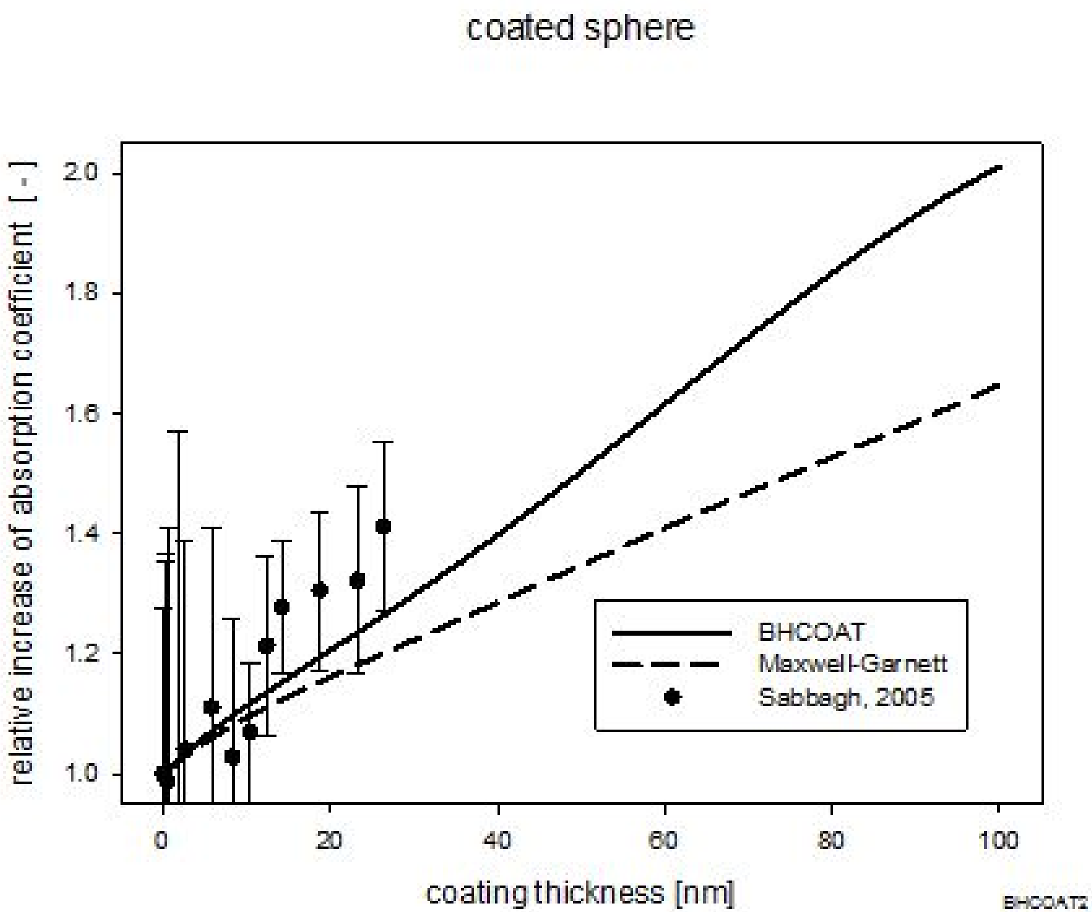
Idea: transparent coating acts like a lens, concentrates light to absorbing core

→ more light is absorbed compared to black carbon particles without coating

But: This explanation would require particles much largen than wavelength of light. Not the case for carbon nano-particles.

Mie thery can be expanded to coated spheres. (Program BHCOAT, in C.F. Bohren and D.R. Huffman Absorption and Scattering of Light by Small Particles Wiley, pp181-3, the computer program is on pp. 483-9.)

Also experimentally proven: By coating spark generator carbon particles with canauba wax, absorption can be increased considerably



Spherical black carbon particle of 78 nm diameter is covered with Canauba Wax of thickness given on x-axis

78 nm particles with 28 nm coating → absorption increased by factor 1.4

(Sabbagh N., 2005: *Optische Eigenschaften von Aerosolpartikel: Absorptionserhöhung durch Beschichtung (Optical properties of aerosol particles: Absorptioin increase by coating)*. Vienna: MS. Thesis, University of Vienna, 2005

Black Carbon mixed particles. Refractive index of mixture??

Optical characterization of medium by complex refractive index *m=n – i.k* (see above) or by relative permittivity ε = ε' – i.ε'', with $m = \sqrt{\varepsilon}$
Mixing on atomic scale mostly not possible. If mixture with structure << λ: mixing rules have theoretical base

- Maxwell Garnett theory (1904): small spherical particles with permittivity ε embedded in matrix with ε_m. The volume fraction of particles be *f*. Then the effective macroscopic permittivity is:

$$\varepsilon_{MG} = \varepsilon_m \frac{\varepsilon(1+2f)+2\ \varepsilon_m(1-f)}{\varepsilon(1-f)+\varepsilon_m(2+f)}$$

- Bruggeman-Wassenaar (1935) ε_{Br} obtained by solving the equation:

$$f\frac{\varepsilon-\varepsilon_{Br}}{\varepsilon+2\ \varepsilon_{Br}}+(1-f)\frac{\varepsilon_m-\varepsilon_{Br}}{\varepsilon_m+2\ \varepsilon_{Br}}=0$$

- Volume mixing rule : $m = f_1 m_1 + f_2 m_2$

Table 4: Effective refractive index of mixed media using various rules						
volume fraction	Maxwell Garnett		Bruggeman		Volume mixing	
f	n	K	N	k	N	k
0.00	1.528	0.000	1.528	0.000	1.528	0.000
0.02	1.533	-0.014	1.533	-0.014	1.531	-0.014
0.04	1.538	-0.028	1.538	-0.027	1.535	-0.028
0.06	1.543	-0.041	1.543	-0.041	1.538	-0.042
0.08	1.548	-0.055	1.547	-0.055	1.542	-0.056
0.10	1.553	-0.069	1.552	-0.068	1.545	-0.070
0.12	1.558	-0.083	1.556	-0.082	1.549	-0.084
0.14	1.562	-0.097	1.560	-0.096	1.552	-0.098
0.16	1.567	-0.111	1.564	-0.109	1.556	-0.112
0.18	1.572	-0.125	1.569	-0.123	1.559	-0.126
1.00	1.700	-0.700	1.700	-0.700	1.700	-0.700

Not much difference, but structures assumed to be << λ

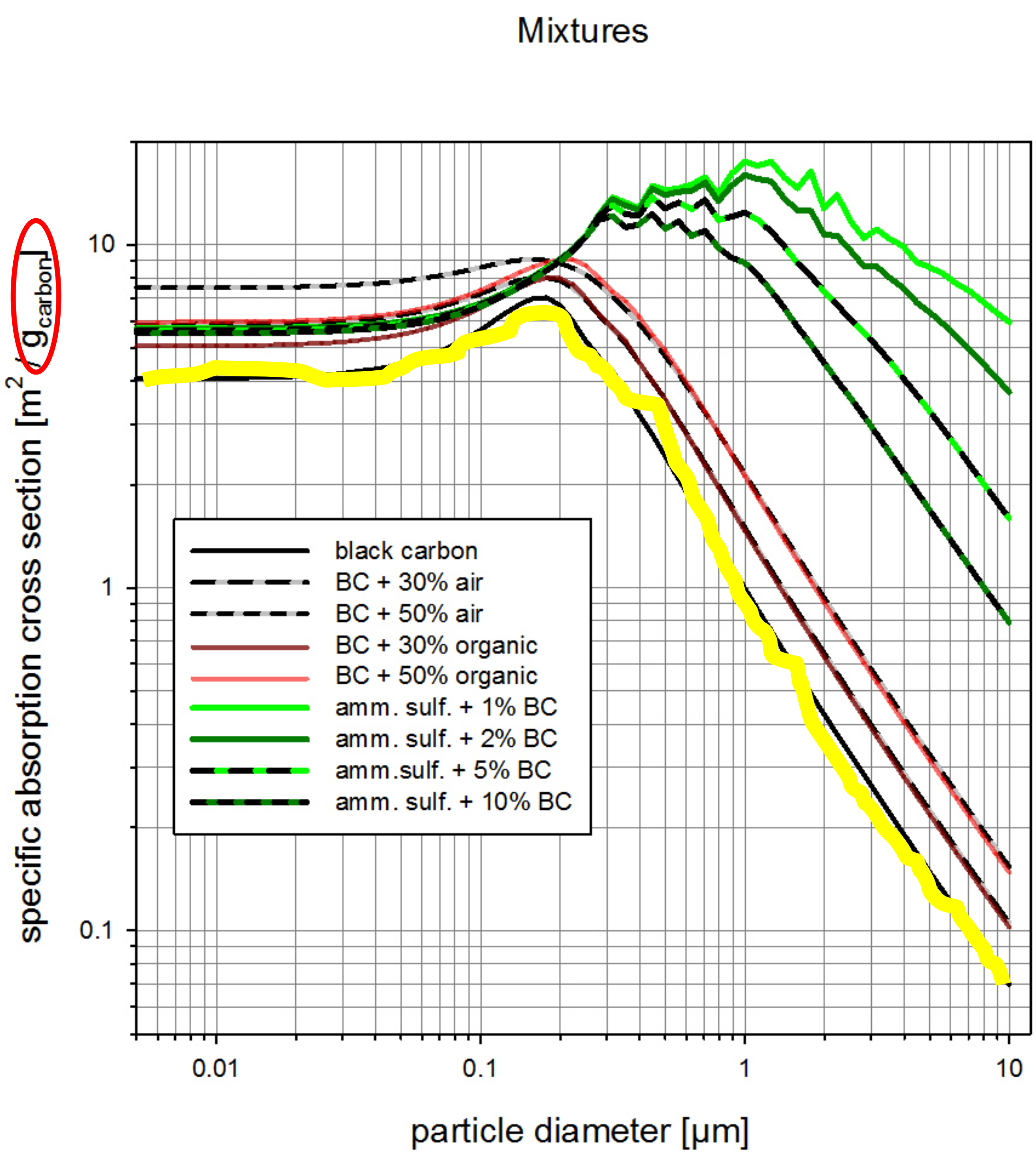
One more (not completely exact, since mixing rule!) verry instructive example

Specific absoption coefficient of black carbon particles.

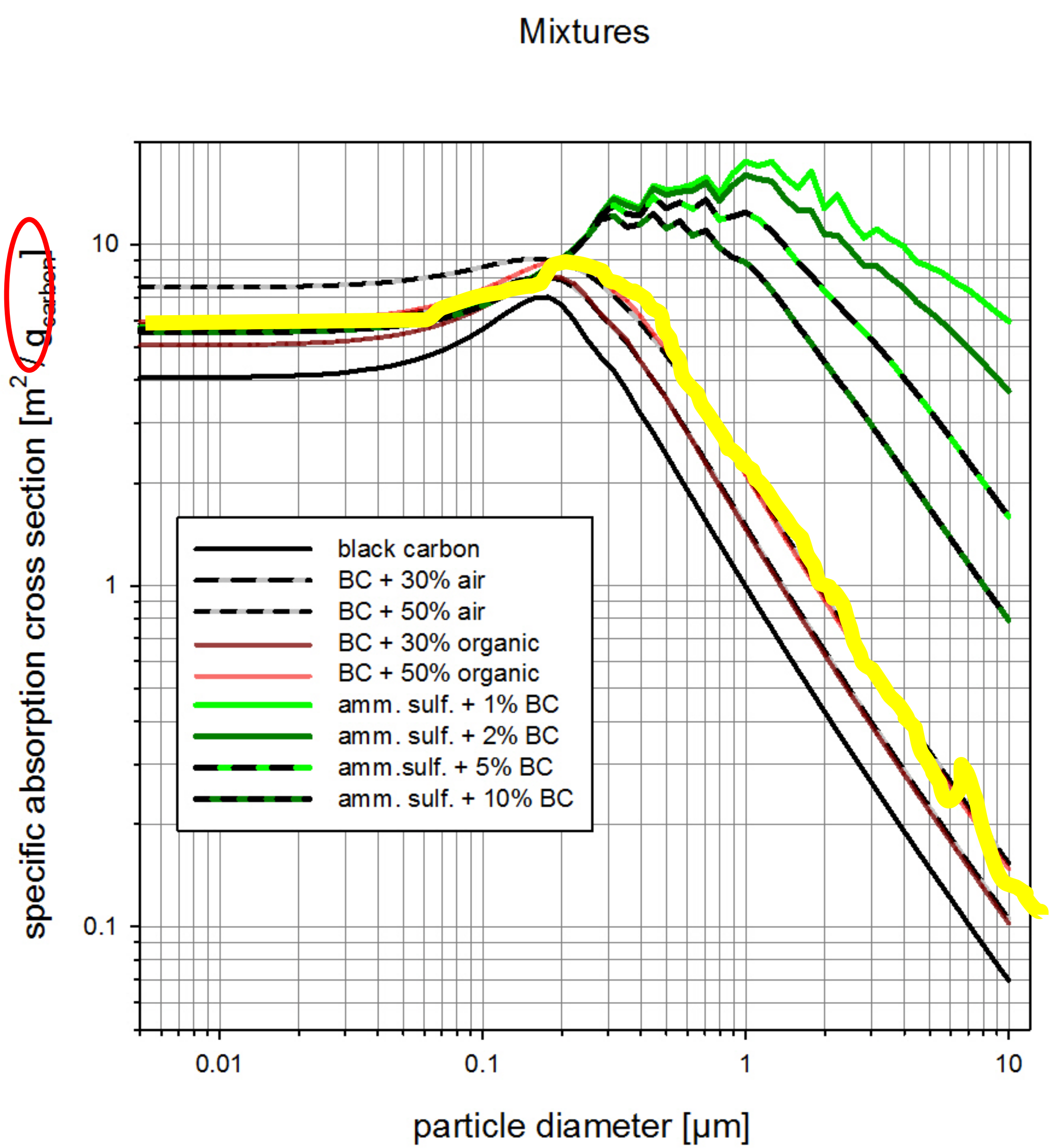
Specific absorption coefficient = $\frac{absorption\ coefficient\ of\ aerosol\ particles}{mass\ of\ particles\ per\ m^3\ of\ air}$

Is a measure how efficient the particles absorb light

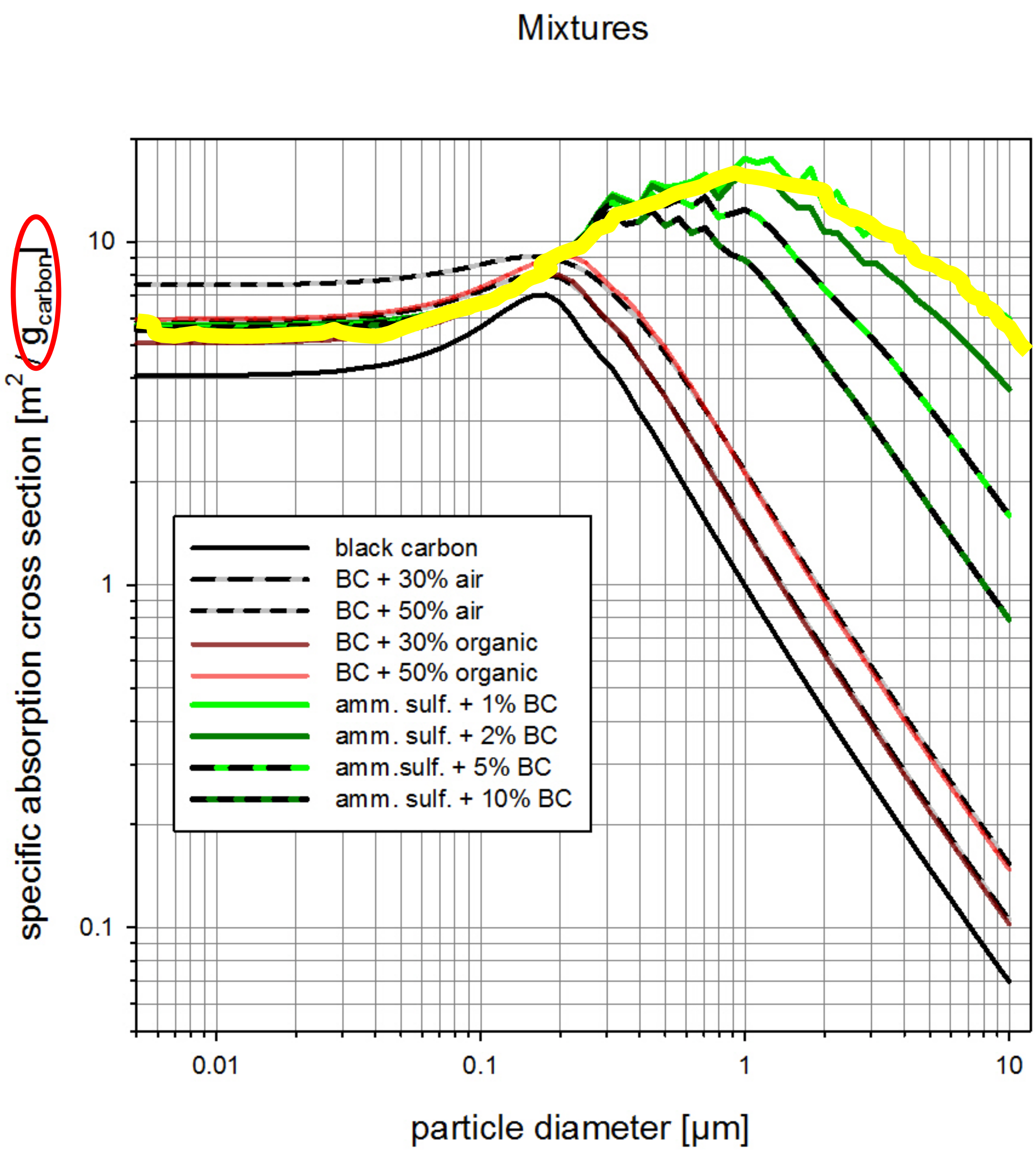
Values between 0.1 and 20 m^2/g are possible



Case 1: Pure black carbon:
Up to 70 nm constant value of $4m^2g^{-1}$. At 0.2µm maximum of absorption (some resonance), then decrease (light is completely absorbed in the first few 100 nm's, no light left to be absorbed in the rest of the particles).



Case 2 - black carbon with 50% organic material:
Higher specific absortion than pure carbon: 50 to 100% more absorption with the same amount of carbon



Case 3 - Amonium sulfate with 1% black carbon:
Larger specific absorption for all sizes compared to pure black carbon, especially > 0.5 µm

Also the case for cloud droplets containing black carbon. Have light absorption even with a small amount of black carbon

Primary Black Carbon particles are nanometer sized: For these $Q_e \propto x$ (slide 35 of aerosol optics) since $x = \frac{2r\pi}{\lambda}$ the absorption coefficient is proportional to $\frac{1}{\lambda}$ can be used for distinction from other absorbing substances.

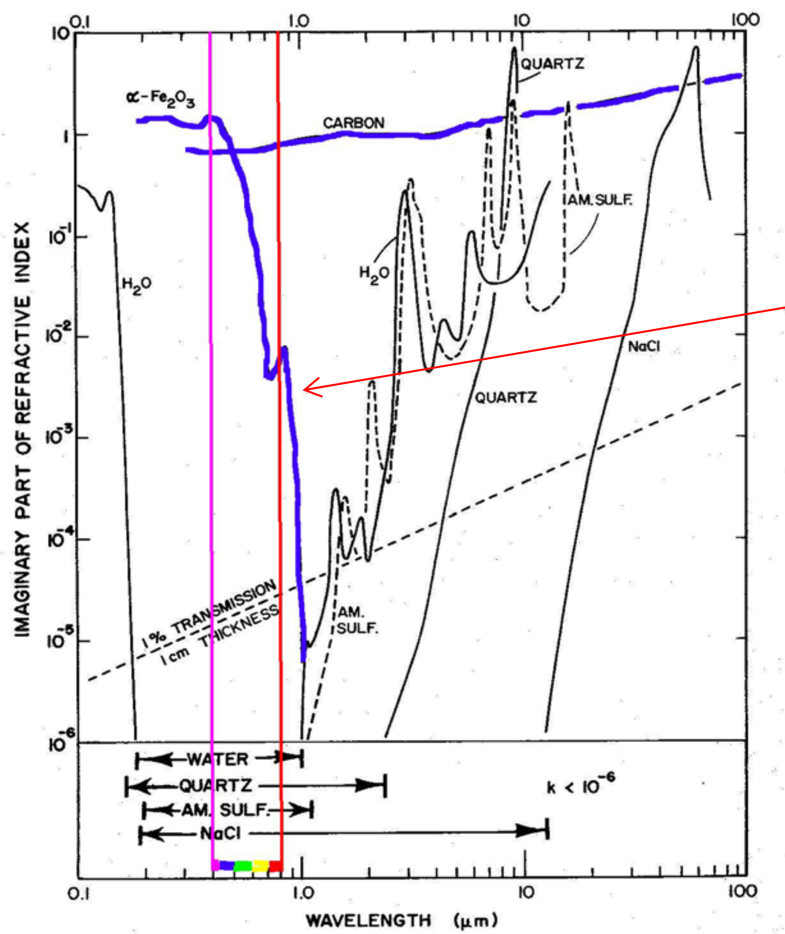


Figure 14.1 Imaginary part of the refractive index of several solids and liquids that are fou atmospheric particles.

from C.F. Bohren and D.R. Huffman Absorption and Scattering of Light by Small Particles Wiley,

Other light absorbing substances in particles in the atmosphere:

$\alpha - Fe_2O_3$ hematite. Strong absorption in blue, some absortion in red. Pure hematite i s black (sufficient absorption in bulk with k=0.01).
When low concentrations of hematite → red (Falu red, originally from tailings of Falu iron mine)

https://commons.wikimedia.org/wiki/File:Keittomaalilla_maalattu_hirsitalo_%C3%84%C3%A4nekoskella.jpg

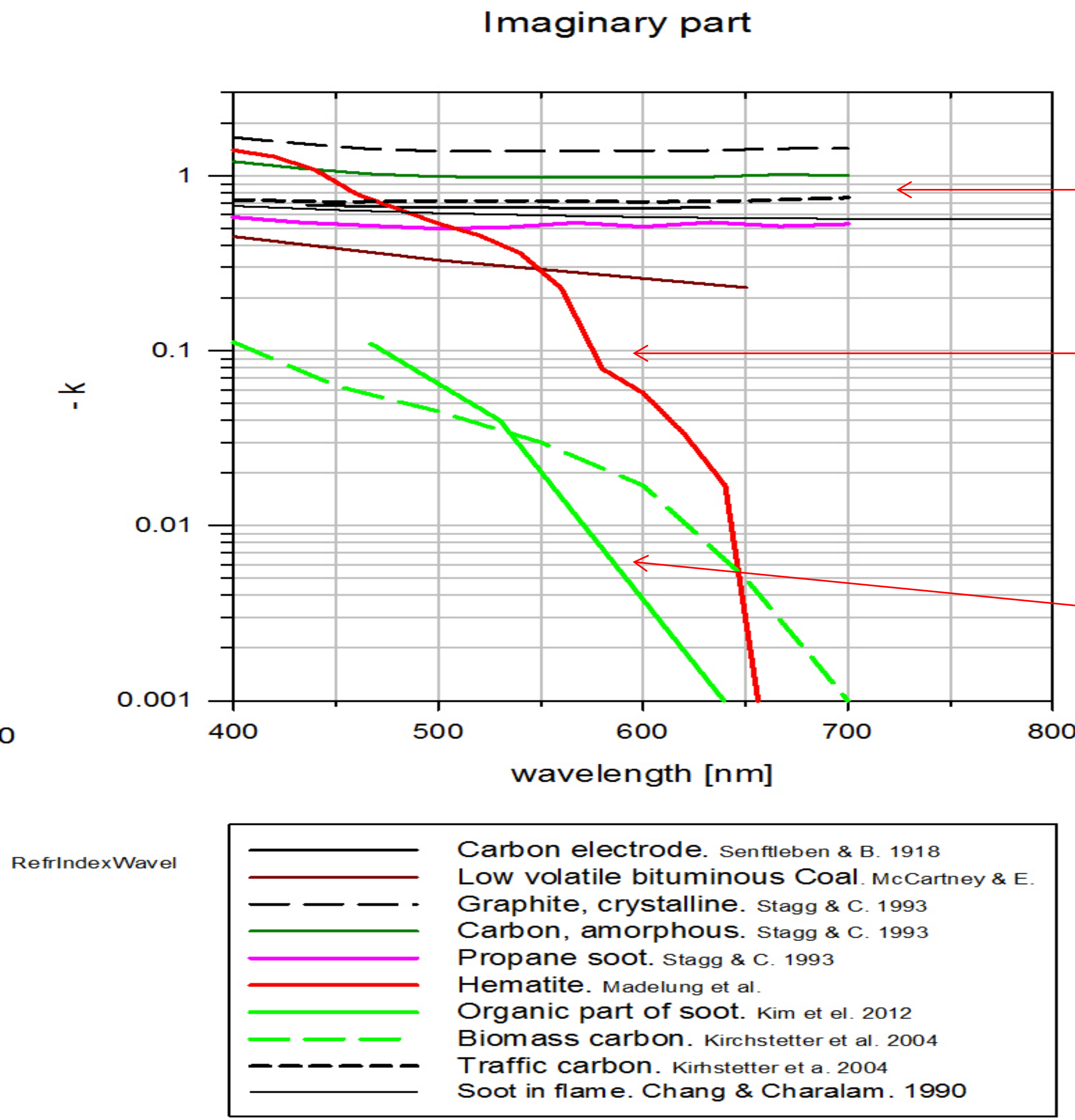
Brown Carbon (BrC)

Usually released by biomass combustion (lower temperature)but simultaneously with black carbon.

H/C Ratio > 0.2. Contains tar materials from smoldering fires, breakdown products from biomass burning, a mixture of organic compounds emitted from soil, and volatile organic compounds given off by vegetation.

Strong absorption in ultraviolett/blue, lesser in red. Stronger wavelength dependence can be used to distinguish Brown Carbon from Black Carbon.

Global estimate: 19% of absorption by aerosol is by brown carbon, 81% due to black carbon.



Imaginary part of refractive index of black carbon

Hematite

And

Brown Carbon

Summing up:

black carbon (light absorbing aerosol) *vs.* transparent particles

Nano-particles:

black carbon (light absorbing aerosol)	transparent particles
light absorption proportional to mass	-o-
Light scattering very small s ince $\sigma_s \propto r^6$	Light scattering very small since $\sigma_s \propto r^6$

Life time is weeks: particles can be transported thousands of kilometers, omnipresent

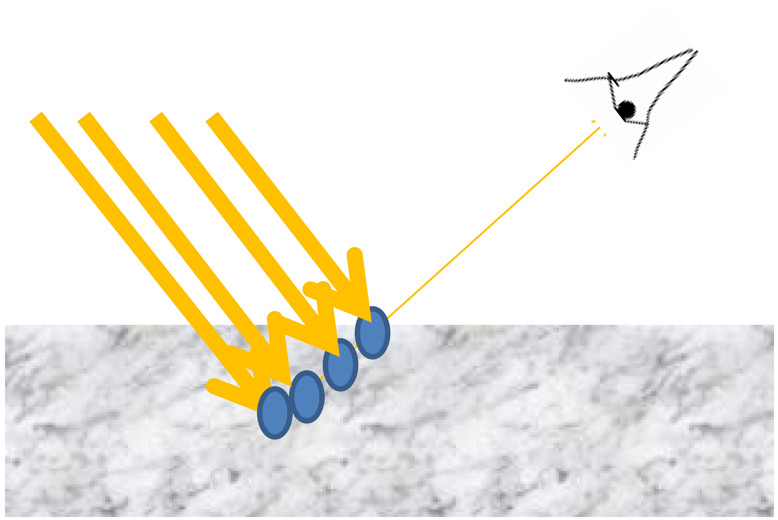
Absorption is increased considerably when black carbon particles are mixed with transparent particles

Micrometer sized particles:

black carbon (light absorbing aerosol)	transparent particles
Specific absorption coefficient decreases with size, since light is absorbed in the first layers.	Scattering coefficient approximately twice compared to strongly absorbing particle
But: Micrometer sized pure black carbon particles in atmosphere unlikely. Micrometer sized transparent particles with some black carbon inclusions: can be strongly absorbing.	Scattering coefficient approximately twice compared to transparent particles with black carbon inclusion

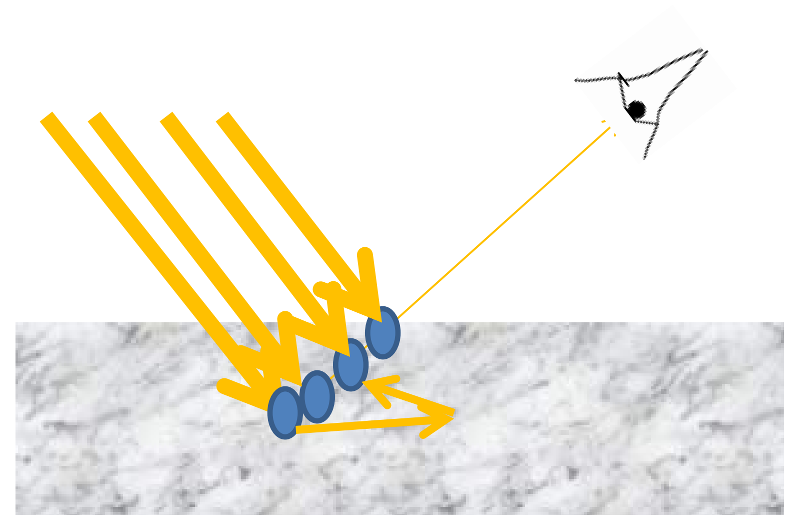
Other effects specific to light absorbing particles:

Single scattering



Light seen by observer is the sunlight scattered in volume elements along the sight path

Multiple scattering:



Light seen by observer is the sunlight scattered in volume elements along the sight path
Plus light scattered at an intermediate volume element and then at one of the considered volume elements.

Since scattering from all directions is possible: average light path is longer than for single scattering.→ more absorption.

Calculation of multiple scattering not easy.
The classic book: Chandrasekhar, Subrahmanyan, Radiative transfer. New York, NY : Dover Publ. ; 1960 ; Dover ed., 1. publ. in 1960

Solution of radiaitve transfer equation only possible -- if at all -- for very special cases. Usually model phase function are used: Henyey Greenstein Phase function

(Henyey, L. C. ; Greenstein, J. L. Diffuse radiation in the Galaxy The Astrophysical Journal, 05/1941, Vol.93, pp.70-83

$$P(\theta) = \frac{1-g^2}{(1+g^2-2g\cos\theta)^{1.5}}$$

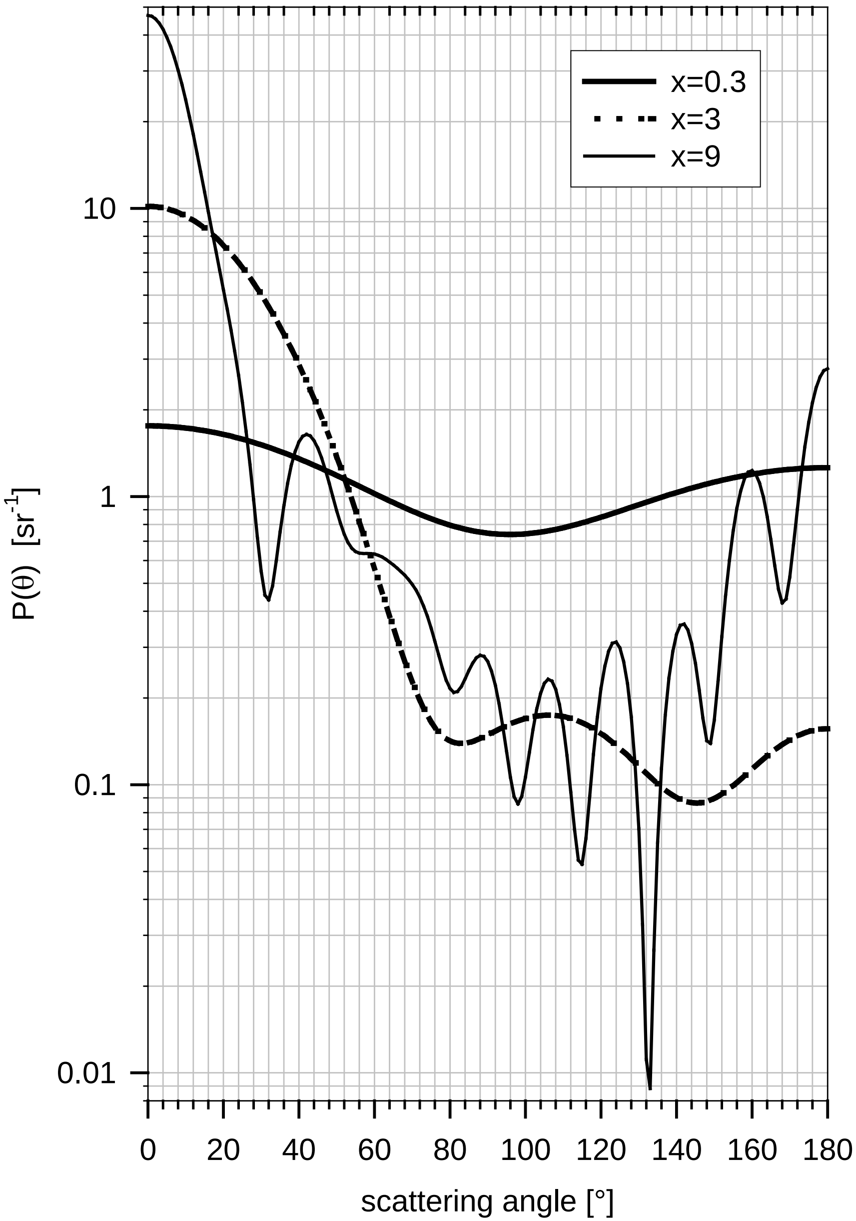
Advantage: only one parameter g (asymmetry parameter)

Disadvantege: Not very similar to real phase function.

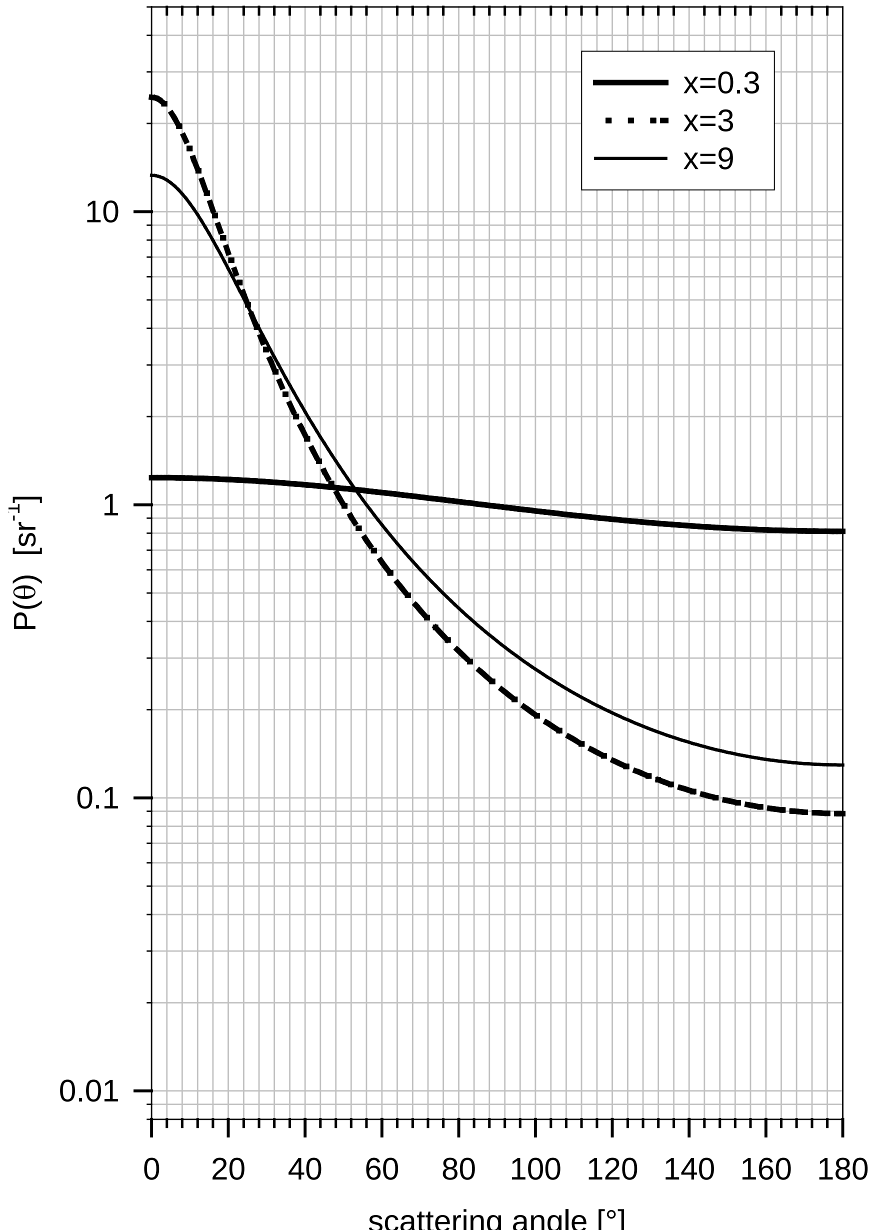
Advantage: Many model caculations with H-G- Functions

Phase function for spherical particles with
refractive index 1.5 - 0.0 i and size parameters 0.3, 3, and 9

D=0.06, 0.52, 1.6 µm



Henyey Greenstein phase function for spherical particles with
refractive index 1.5 - 0.0 i and size parameters 0.3, 3, and 9
having the same assymetry parameter



Example

Solar radiation incident at zenith angle 0°
on atmosphere with vertical optical
depth between 0.5 and 18

Slightly dirty
atmosphere

Thin cloud

Single scattering albedo of aerosol $\omega = 0.95$

Using tables published in Van de Hulst H.C. Multiple scattering. Academic press. Academic Press, New York, 1980

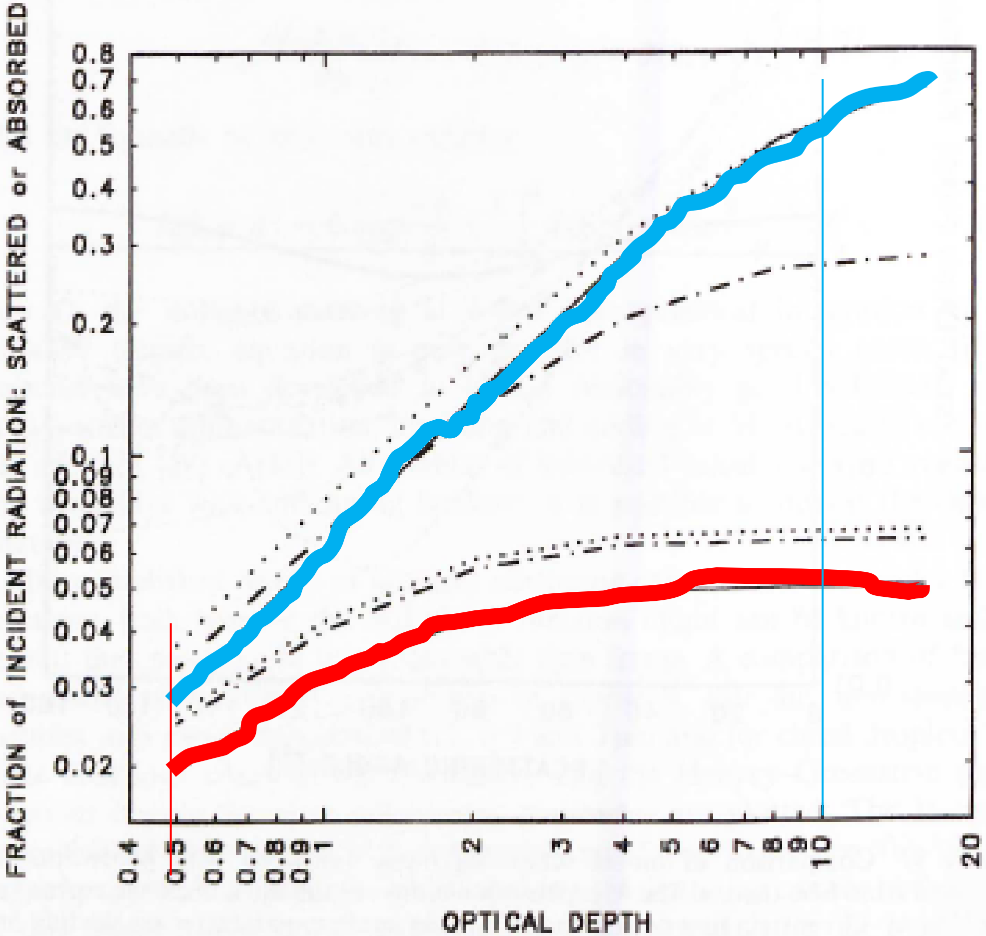


Figure 10. Comparison of the light scattered upwards and the light absorbed by a horizontal slab of scattering medium with vertical incidence and variable optical depth. The Henyey–Greenstein scattering phase function with $g = 0.75$ has been used. The fraction of the incident light scattered or absorbed has been obtained by radiative transfer (upper set of curves) and for comparison the results neglecting multiple scattering (lower set of curves) are shown. The dotted line gives the upwards scattered light by a purely scattering aerosol. The dash-dot line gives the scattered fraction of the incident solar radiation for an aerosol with $\bar{\omega} = 0.95$ and the solid line gives the absorbed fraction

Amount of light absorbed in atmosphere

Single scattering only

Including multiple scattering

At optical depth of 0.5 (slightly polluted atmotshere) : absorption due to multiple scattering amounts to 50%

When optical depth of 10 (thin cloud): Absorption due to multiple scattering is 17 times the amount due to single scattering

H. Horvath (1998) Influence of atmospheric aerosols upon the global radiation balance. Chapter 13 of “Environmental particles” R.M. Harrison and R.E. van Grieken, eds. pp 543-596, John Wiley & Sons, London, revised second edition 1999 Page 580

Deposition of black carbon on snow. Ice

Remember:
Albedo of old snow   a = 0.4 … 0.9
clean
dirty

using
$$T = \sqrt[4]{\frac{(2-f)(1-a).S_0}{\sigma.(2-A_a)}}$$

We obtain: T = 1.17 and 4.44°C for a = 0.4 **(dirty snow)** and A_a= 0.92 and 0.97

and T = -62.22 and -64.71°C for a = 0.8 **(clean snow)** and A_a= 0.92 and 0.97

Attention: temperatures would be averages for whole earth covered with snow

A short extempore:

Whole earth covered with snow would give temperatures much below 0°C,
→ very stable situation, since positive feedback: lower temperature, →more snow,
→ still lower temparature .

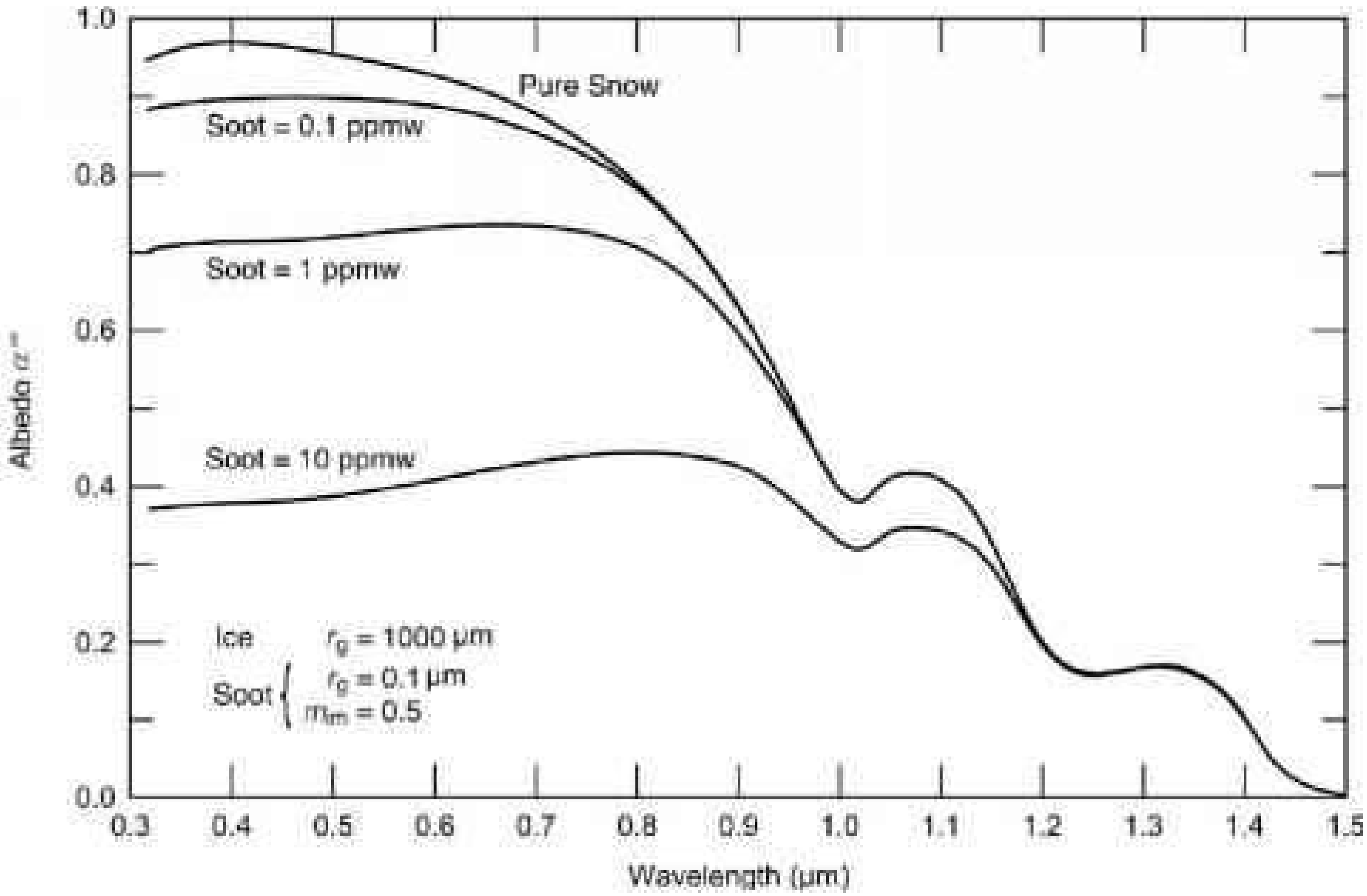
„Snowball earth hypothesis“ between 760 and 490 Million years before present, there is geological evidence, that Earth's surface became entirely or nearly entirely frozen at least once. Cannot be completely neglected:
Kerr, Richard An appealing snowball earth that's still hard to swallow. Science, Mar 10, 2000, Vol.287(5459), pp.1734-1736

End of extempore

Snow albedo is important, depends on material deposited on the snow surface.

Possible deposits: Mineal dust, black carbon, biofilms.

Black carbon is omnipresent.



Spectral albedo of snow dependence on BC concentrations

Figure 7 of (A Model for the Spectral Albedo of Snow. II: Snow Containing Atmospheric Aerosols Stephen G. Warren and Warren J. Wiscombe Journal of the atmospheric sciences (1980) 37, 2734-2745 https://doi.org/10.1175/1520- 469(1980)037%3C2734:AMFTSA%3E2.0.CO;2)

Dirty snow melts faster: Soot contributes to glacier decline. Wiener Zeitung 26 March 2019 p1 and 17

Schmutziger Schnee schmilzt schneller

Ruß trägt zum Verschwinden der Gletscher bei.
Seite 17

Black carbon is very efficient: 1000 ppmw of „red desert dust“ have the same effect as 10 ppmw black carbon (figure 3, Warren & Wiscombe (1980))

Spectral dependence of albedo of black snow is flat: Iron oxide (desert dust) cannot be the cause
-→ black carbon

Even in Antarctica Black Carbon from fossil fuel emissions can be found. Even if no visible change in reflectivity can be observed, the albedo can have decreased by 25% . In Antarctica radiative forcing by black carbon on snow can amount up to 70W/m2
C.A. Casey et al. J. Geoph Res. Atm. Doi: 10.1002/2016JD024618

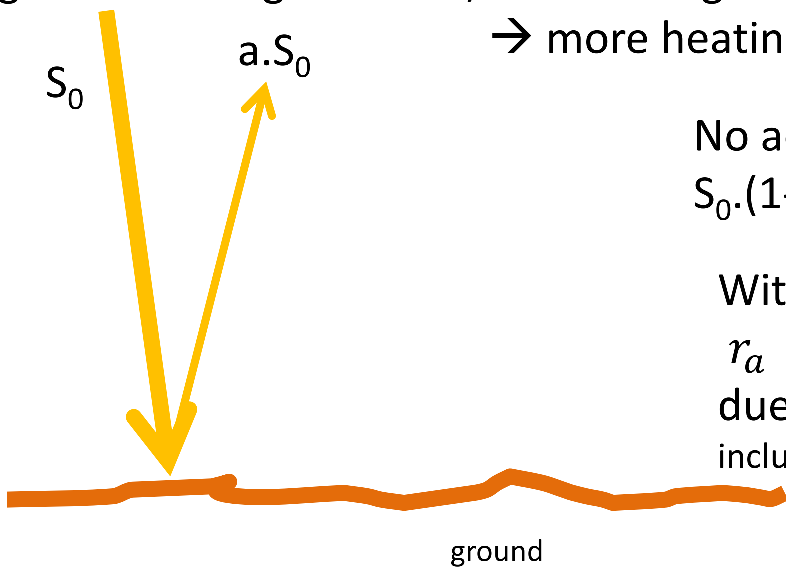
Remember: Black carbon is insoluble, refractory, consist of chain aggregates, thus remains with the snow (life time in snow much larger than weeks (lifetime in the air).

Atmosphere Earth System

Interaction of ground (albedo) with atmosphere and aerosol has to be considered.
Scattering by aerosol causes less sunlight reaching the ground → cooling of the ground
No change for the atmosphere, since nothing is absorbed

Absorption of the aerosol causes warming of the atmosphere
Less radiation to the ground → cooling of the ground, heating of the atmosphere

If ground has high albedo , much sunlight reflected →again absorbed in the atmosphere
→ more heating of the atmosphere



No aerosol: S_0 incident , $a.S_0$ reflected, $S_0.(1-a)$ absorbed in ground

With aerosol:
r_a is the reflected fraction of incident sunlight due to aerosol (integrated light scattered up wards including multiple scattering)

a_a is the fraction absorbed by the aerosol in the atmosphere.

Reflected flux density with aerosol: $\underbrace{S_0.r_a}_{\text{Reflected by aerosol}} + \underbrace{S_0.a(1-r_a-a_a)}_{\text{Reflected by ground}} =$ $S_0.a(1 - r_a - a_a + \frac{r_a}{a})$

Summary:

Reflected without aerosol: $S_o . a$

Reflected with aerosol $S_0 . a . (1 - r_a - a_a + \frac{r_a}{a})$

Expression $(1 - r_a - a_a + \frac{r_a}{a})$ tells us whether aerosol atmosphere earth system reflects more or less sunlight than without aerosol

If $(1 - r_a - a_a + \frac{r_a}{a})$ <1 …. Less solar flux reflected, positive radative forcing → heating

>1 …. More solar flux reflected, negative radative forcing → cooling

Examples:

Case 1: non absorbing aerosol, $a_a = 0$: $(1 - r_a - \cancel{a_a} + \frac{r_a}{a}) \quad > 1 \quad since \quad 0 < a < 1$

More solar flux reflected, negative radiative forcing → cooling

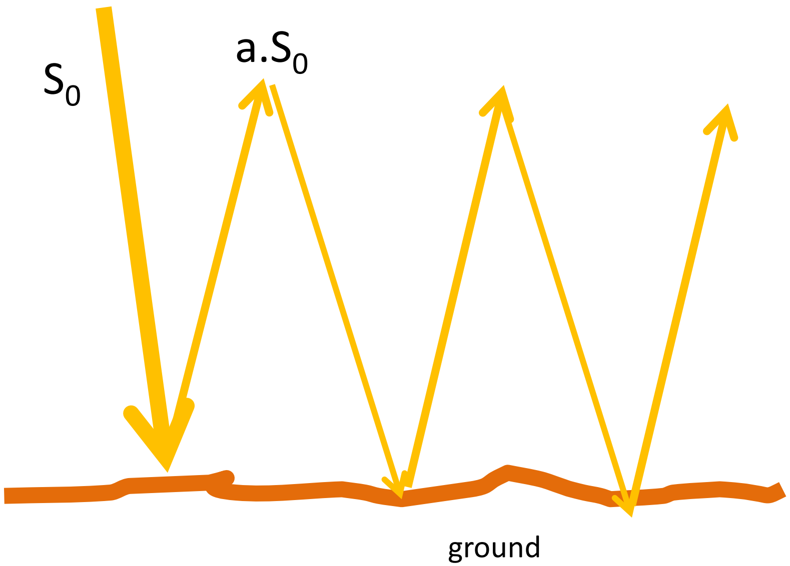
Case 2: strongly absorbing aerosol ($\sigma_s = \sigma_a$) or $r_a = a_a$ $\text{e.g.} = 0.3$

2a) over the sea: $a = 0.15$ $\left(1 - r_a - a_a + \frac{r_a}{a}\right) = (1 - 0.3 - 0.3 + \frac{0.3}{0.15})$ =2.4>1 → cooling

2b) over snow: $a = 0.7$ $\left(1 - r_a - a_a + \frac{r_a}{a}\right) = (1 - 0.3 - 0.3 + \frac{0.3}{0.7})$ =0.83<1 → heating

The same absorbing aerosol can have positive or negatve forcing depending albedo of surface

Multiple reflections between ground and atmosphere must be considered also



Formulae exist, effect is enhanced

…………

Effect of light absorbing black carbon on radiative forcing:

Direct radiative effect due to absorption and scattering of sunlight: absorbed sunlight transferred to the atmosphere.

Positive forcing, 2013 estimate +0.71 W/m^2.

(fossil fuel, biofuel and open burning contribute
+0.29, +0.22, and +0.20 W/m^2)

Black carbon cloud effect:

- Temperature changes by absorbing particles above, within and below the clouds,
- albedo change due to incorporation of particles in cloud droplets,
- change in number of cloud condensation nuclei and thus droplet number and size
- alteration of precipitation in mixed clouds,
- change in ice nuclei
- extent of clouds.

→ estimate: 0.23 W/m2, with large uncertainties.

The black carbon snow and ice effect: Reflection changes of snow cover and ice cover → reflect less light with black carbon deposits. Estimate: +0.13W/m^2.

In total +1.07W/m^2**.**

BUT Black carbon is a product of combustion. Combustion also emits transparent particles (sulfate, organics, …) which have negative forcing, so the system must be seen as a whole:

Excluding open burning an estimate is possible →net forcing 0.22 W/m^2. Including open burning the net forcing could be -0.02 W/m^2.
(very unsecure).

Local effects, e.g. pattern change of monsoon,

Melting of snow and ice partly due to black carbon → change in salinity of sea water

Stop here:

Black carbon is a minority component of the atmospheric aerosol, but important

- Nanometer sized primary particles
- Strongly absorbing, absorption augmented by transparent cover/mixing
- Effect of absorption increased by multiple scattering / Atmosphere earth system
- Insoluble, refractory,
- Life time in air approx. One week, on snow ?????
- Reduces reflectivity of snow/ice
- Involved in many ways in radiative forcing
- ……….

Thank you !!