

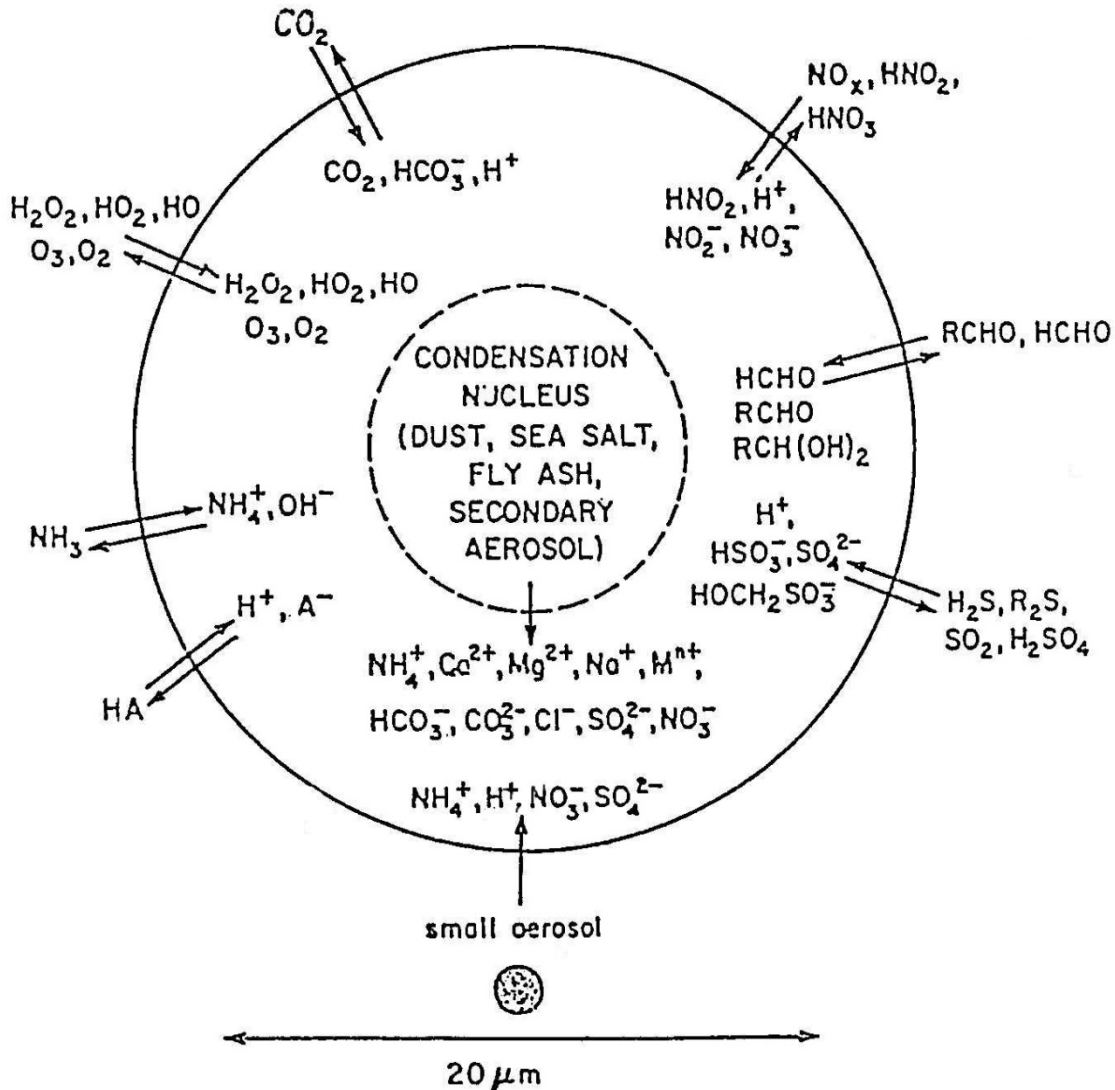
# **Sulfur Dioxide and Oxidations in Atmospheric Droplets and Deposition**

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(Fall Semester 2011)

## *Content:*

1. Oxidations in atmospheric droplets
2. Dry deposition
3. Sulfur dioxide and its time evolution
4. Polluted precipitation („acid rain“)

# 1. Oxidations in atmospheric droplets



Tropospheric droplets  
as chemical reactor:  
*Mass transfer*

**Figure 1**

## Notes to Fig. 1

- Atmospheric droplets (such as cloud, fog and rain drops) are reactors for tropospheric chemistry.
- Atmospheric droplets have limited life times implying that only relatively fast chemical reactions in drops are important for tropospheric chemistry.
- Except species of cloud nuclei the reactants in cloud chemistry need to be transported from the gas phase into the aqueous phase, implying a preference for water soluble species as reactants in tropospheric drop chemistry.

Fig. 2: Henry Constants ( $H_x = [X] / p_x$ ,  $[X]$  aquatic conc. in M and  $p_x$  gas phase conc. in atm., for  $T=25^\circ \text{C}$ ); <sup>1)</sup> ignoring acid base equilibria

Compound	H (Matm <sup>-1</sup> )	Comp.	H (Matm <sup>-1</sup> )
O <sub>2</sub>	1.3 10 <sup>-3</sup>	HONO <sup>1)</sup>	49
NO	1.9 10 <sup>-3</sup>	NH <sub>3</sub> <sup>1)</sup>	62
C <sub>2</sub> H <sub>4</sub>	4.9 10 <sup>-3</sup>	H <sub>2</sub> CO	6.3 10 <sup>3</sup>
NO <sub>2</sub>	1.0 10 <sup>-2</sup>	H <sub>2</sub> O <sub>2</sub>	(0.7-1.5) 10 <sup>5</sup>
O <sub>3</sub>	1.3 10 <sup>-2</sup>	HNO <sub>3</sub> <sup>1)</sup>	2.1 10 <sup>5</sup>
N <sub>2</sub> O	2.5 10 <sup>-2</sup>	HO <sub>2</sub>	(1-3) 10 <sup>3</sup>
CO <sub>2</sub> <sup>1)</sup>	3.4 10 <sup>-2</sup>	PAN	5
SO <sub>2</sub> <sup>1)</sup>	1.24	CH <sub>3</sub> SCH <sub>3</sub>	0.56

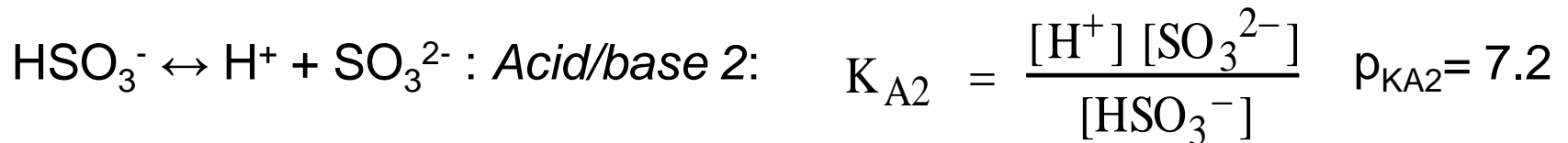
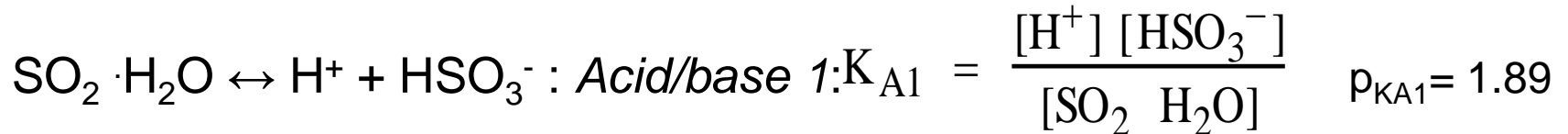
Notes to Fig. 2 (from Seinfeld and Pandis, 1998, p. 341).

- For equilibrium conditions water solubility is described by Henry's law.
- Water solubility strongly depends on the properties of the individual species.
- Water solubility is very small for many molecules unless they dissociate in aqueous solution.
- Water solubility is much larger for the polar molecules such as  $\text{H}_2\text{O}_2$  than for others e.g.  $\text{O}_3$ .
- Acids and bases dissociate in cloud droplets. Note that in Fig. 2 acid base equilibria are ignored (comp. Fig 3).

# Fig. 3: Solubility of SO<sub>2</sub> in tropospheric droplets

([ ]: conc. in cloud or fog drop),

p<sub>SO<sub>2</sub></sub>: partial pressure of SO<sub>2</sub> in gas phase)

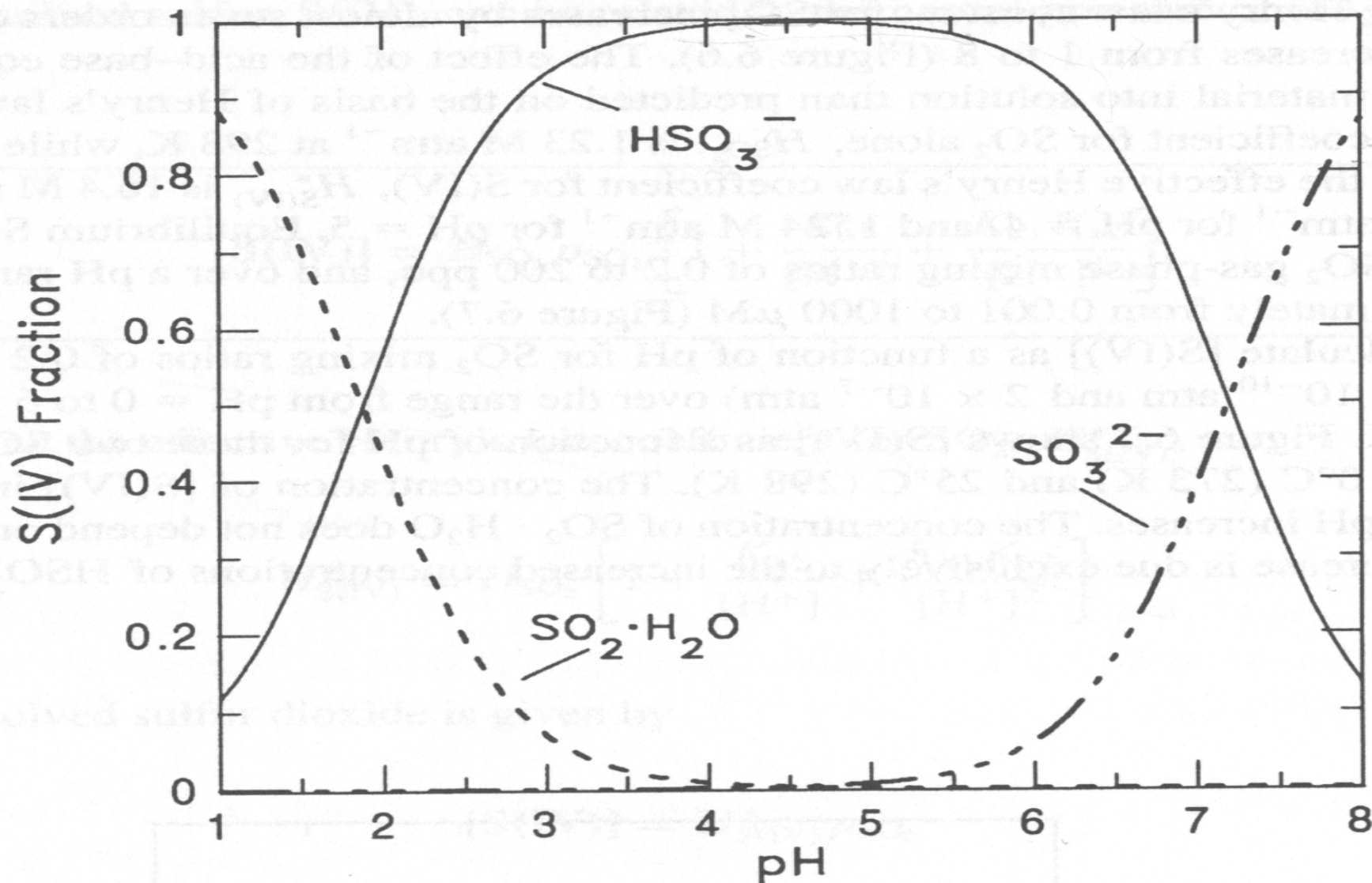


$$[\text{SO}_2 \cdot \text{H}_2\text{O}] = K_{\text{H}} p_{\text{SO}_2}$$

$$[\text{HSO}_3^-] = K_{\text{A1}} \frac{[\text{SO}_2 \cdot \text{H}_2\text{O}]}{[\text{H}^+]} = K_{\text{A1}} \frac{K_{\text{H}} p_{\text{SO}_2}}{[\text{H}^+]}$$

$$[\text{SO}_3^{2-}] = K_{\text{A2}} \frac{[\text{HSO}_3^-]}{[\text{H}^+]} = K_{\text{A1}} K_{\text{A2}} \frac{K_{\text{H}} p_{\text{SO}_2}}{[\text{H}^+]^2}$$

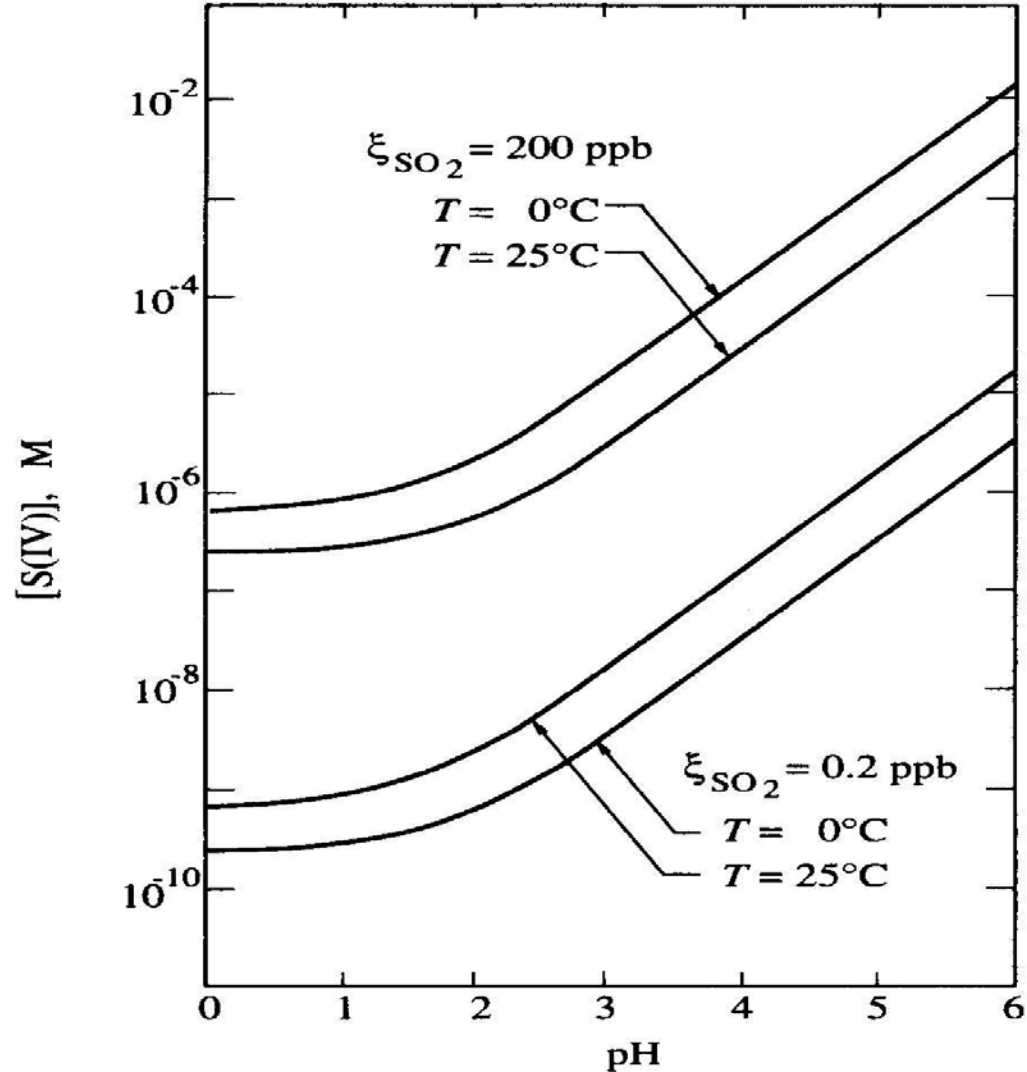
Fig. 4: Speciation of S(IV) species as a function of pH (Seinfeld and Pandis, 1998, p. 352)



$[S(IV)] = [SO_2 \cdot H_2O] + [HSO_3^-] + [SO_3^{2-}]$  (see Fig. 3):

$$[S(IV)] = K_H P_{SO_2} \left\{ 1 + \frac{K_{A1}}{[H^+]} + \frac{K_{A1} K_{A2}}{[H^+]^2} \right\}$$

**Fig. 5**

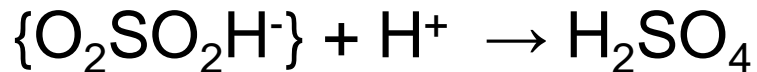
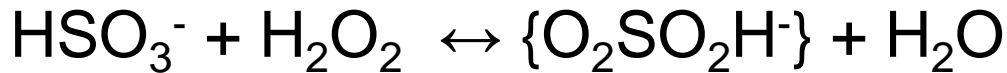


# Notes to Fig. 3 - 5 (from Seinfeld and Pandis, 1998, p. 351)

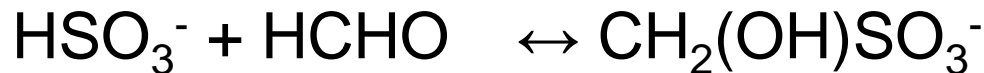
- The solubility of  $\text{SO}_2$  is characterized by the Henry constant and two acid-base equilibria.
- The acid-base equilibria include bisulfite ( $\text{HSO}_3^-$ ) and sulfite ( $\text{SO}_3^{2-}$ ).
- The ratio of the ions depends on pH (see Fig. 3; note that acid-base reactions in aqueous solutions are very fast).
- Fig. 5 shows the solubility of S(IV) ( $=\text{SO}_2 \cdot \text{H}_2\text{O} = \text{H}_2\text{SO}_3$  and ionic S(IV) species) based on phase transfer and acid-base equilibria.
- Aqueous concentrations of S(IV) species depend on gas phase concentrations of  $\text{SO}_2$ , pH and temperature.
- Note that in Fig. 5 gas phase concentrations are predefined. However, if a drop is formed in the troposphere,  $\text{SO}_2$  is expected to be dissolved very efficiently in the aqueous phase which results in a decrease in gas phase concentration of  $\text{SO}_2$ .

# Fig. 6: Oxidation of SO<sub>2</sub> in tropospheric drops

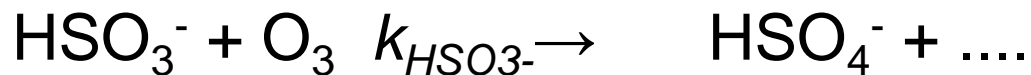
## ***Oxidation by H<sub>2</sub>O<sub>2</sub>:***



Inhibition by equilibr. with HCHO:

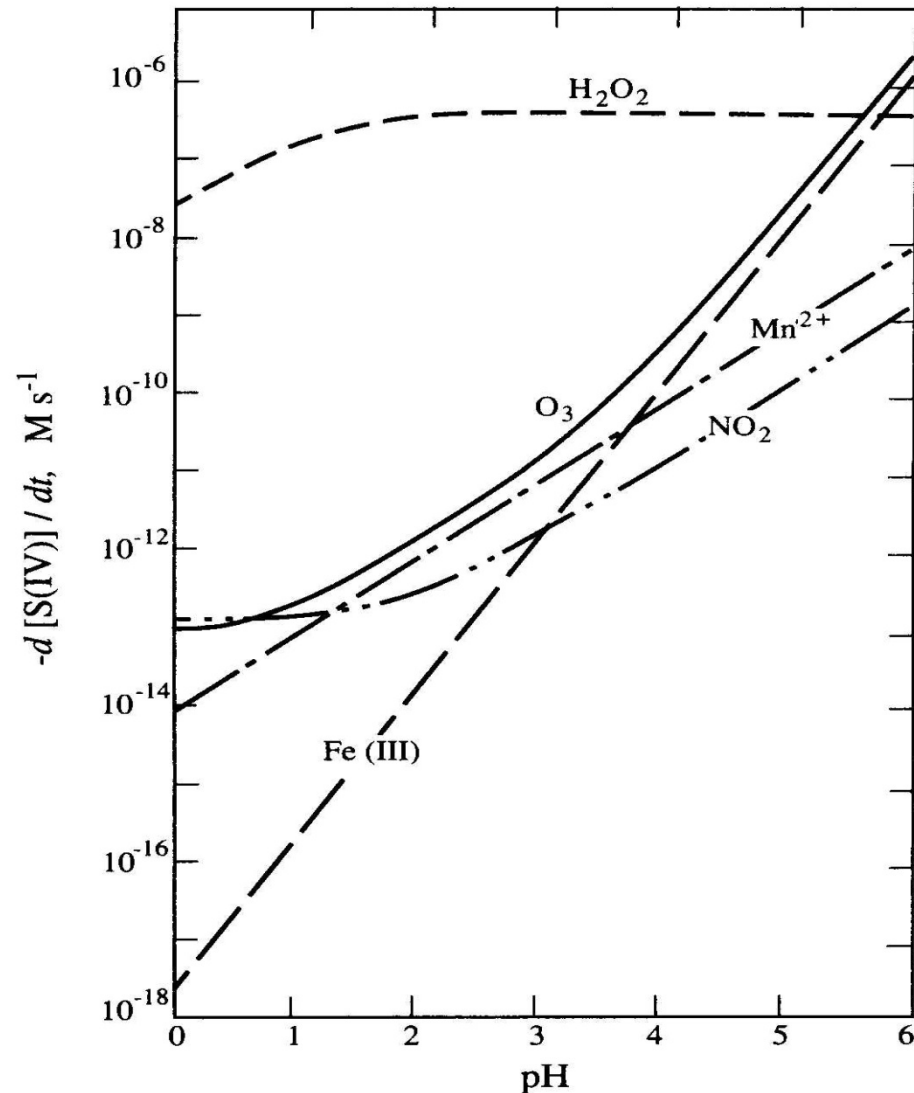


## ***Oxidation by O<sub>3</sub>:***



(Oxidation catalyzed by trace metals (Fe<sup>3+</sup> or Mn<sup>2+</sup>))

Fig. 7: pH dependence of  $\text{SO}_2$  oxidation rate  
(from Seinfeld and Pandis, 1998, p. 379)



# Notes to Fig. 6 and 7

- Sulfuric acid ( $\text{H}_2\text{SO}_4$ ) is one of the most important species for acidification of wet deposition (see Chapter 4).
- The anthropogenic precursor for  $\text{H}_2\text{SO}_4$  is  $\text{SO}_2$  resulting from burning of S-containing fossil fuels (see Chapter 3).
- The oxidation from  $\text{SO}_2$  to  $\text{H}_2\text{SO}_4$  can proceed in the gas or in aquatic phase, the conversion in drops is believed to dominate in the global troposphere.
- $\text{H}_2\text{O}_2$  and  $\text{O}_3$  are the most important oxidants for aqueous S(IV) oxidation.
- The oxidation of S(IV) by  $\text{H}_2\text{O}_2$  includes an intermediate ( $\{\text{O}_2\text{SO}_2\text{H}\}$ ), which is converted to  $\text{H}_2\text{SO}_4$  by acid catalysis (see Fig. 6).
- S(IV) oxidation by  $\text{H}_2\text{O}_2$  proceeds faster at low pH because  $\text{H}_2\text{O}_2$  reacts with  $\text{HSO}_3^-$  and because of the acid catalysis of the intermediate (see Fig. 6. and 7).
- $\text{HSO}_3^-$  forms an equilibrium with aldehydes which can inhibit S(IV) oxidation by  $\text{H}_2\text{O}_2$  (depending on the concentrations of the aldehydes) (see Fig. 6).
- Oxidation of S(IV) species by  $\text{O}_3$  is faster in alkaline solution, because  $\text{O}_3$  reacts much faster with  $\text{SO}_3^{2-}$  than with  $\text{HSO}_3^-$  (see Fig. 6 and 7).
- The dominance of the 2 pathways critically depends on pH in the tropospheric drop.

# Notes to Fig. 7

- Fig. 7 shows the oxidation rates for S(IV) oxidation for  $\text{SO}_2(\text{g}) = 5$  ppb,  $\text{H}_2\text{O}_2(\text{g}) = 1$  ppb,  $\text{O}_3(\text{g}) = 50$  ppb.
- Fig. 7 confirms the strong dependency of S(IV) oxidation on pH in accordance with the equations of Fig. 6.
- (The pathways of S(IV) by  $\text{NO}_2$  (for  $[\text{NO}_2] = 1$  ppb) and Fe (III) [ $\text{Fe(III)(aq)} = 0.3 \mu\text{M}$ ] and  $[\text{Mn(II)}(\text{aq}) = 0.03 \mu\text{M}$ ] are believed to be usually less important and ignored here).
- The concentrations used for Fig. 7 can be viewed as typical for initial conditions of a polluted air parcel. However they are expected to be strongly changing over time, because  $\text{H}_2\text{O}_2$  and  $\text{SO}_2$  have a high water solubility (see Fig. 2) leading to a strong decrease in their gas phase concentrations. After removal and reaction with S(IV) species  $\text{H}_2\text{O}_2$ -oxidation no longer proceeds (unless mixing with surrounding  $\text{H}_2\text{O}_2$  containing air occurs).
- Both oxidants ( $\text{H}_2\text{O}_2$  and  $\text{O}_3$ ) are formed in gas phase tropospheric oxidation (comp. Chapt. 2. Tropospheric Chemistry of Gas Phase, e.g. Fig. 12).
- $\text{O}_3$  is formed in much higher concentrations in ambient air by tropospheric photooxidation than  $\text{H}_2\text{O}_2$  which is only formed as product in one termination reaction.
- Water solubility of  $\text{O}_3$  is very low, but the reservoir in ambient air is usually much larger than for  $\text{H}_2\text{O}_2$ .
- The characteristics of the two oxidation pathways are summarized in Fig. 8.

# Fig. 8: Summary of aqueous $\text{SO}_2$ oxidation

- *At low pH:*  $\text{H}_2\text{O}_2$  oxidation fast
- *At high pH:*  $\text{O}_3$  oxidation fast
- $\text{H}_2\text{O}_2$  dissolves quickly in drops, but  $\text{H}_2\text{O}_2$  concentration (formed in gas phase chemistry) is limited
- Solubility of  $\text{O}_3$  in water very small, but  $\text{O}_3$  concentration in ambient air is usually much larger than of  $\text{H}_2\text{O}_2$

## ***2. Dry Deposition***

### ***Figure 9***

Description of dry deposition:  $F = - v_d [c]$

$F$ : Dry deposition flux

$v_d$ : vertical velocity (neg. sign: Flux to Earth's surface)

$c$ : concentration of trace compound in air.

Dry deposition velocity  $v_d$  depends on many processes. It can be parametrized by the following equation:

$$1/v_d = r_a + r_b + r_c$$

$r_a$ : atmospheric resistance

$r_b$ : transport through laminar layer surrounding objects

$r_c$ : surface resistance

# Notes I to Fig. 9

- Dry and wet deposition (see Chapter 4) balances (in addition to transport from and into the stratosphere) the fluxes of tropospheric compounds.
- Dry deposition means removal of air pollutants by sticking on materials of the Earth's surface.
- Many of the gaseous species (e.g.  $\text{NO}_x$ ) are first oxidized in the troposphere (e.g. to  $\text{HNO}_3$ ) before removal.
- Deposition decreases the concentration of the air pollutants. It leads to a flux from the troposphere to the Earth's surface, i.e. contributing to acidification of soils and lakes.
- Dry deposition always takes place while wet deposition only occurs during precipitation.
- Dry deposition is particularly important for the removal of  $\text{O}_3$  and  $\text{HNO}_3$ .
- A realistic description of dry deposition flux is difficult because it depends on many different variables.
- Realistic dry deposition fluxes needs to be incorporated in numerical simulations (e.g. for  $\text{O}_3$ ).
- Dry deposition fluxes of aerosol particles depend also on particulate radii and are not discussed here.

## Notes II to Fig. 9

- Dry deposition flux velocity includes different types of processes and is usually described in the same form as electrical resistances:
- $r_a$  includes all types of transport of the air pollutants from the atmosphere to the laminar layer surrounding the objects at the Earth's surface. The respective velocity depends on variables such as temperature structure, wind field and turbulence. These processes are described by micro meteorology.
- $r_b$  describes the transport velocity through the laminar layer surrounding the objects, which depends on the type of object. The sublayer transport is different for a house, an open agricultural field, trees or forrests, etc.
- $r_c$  is the surface resistance which describes the „stickiness“ of a compound and a particular surface. These interactions have a strong influence on the large differences of dry deposition fluxes of the individual compounds (see Fig.10).

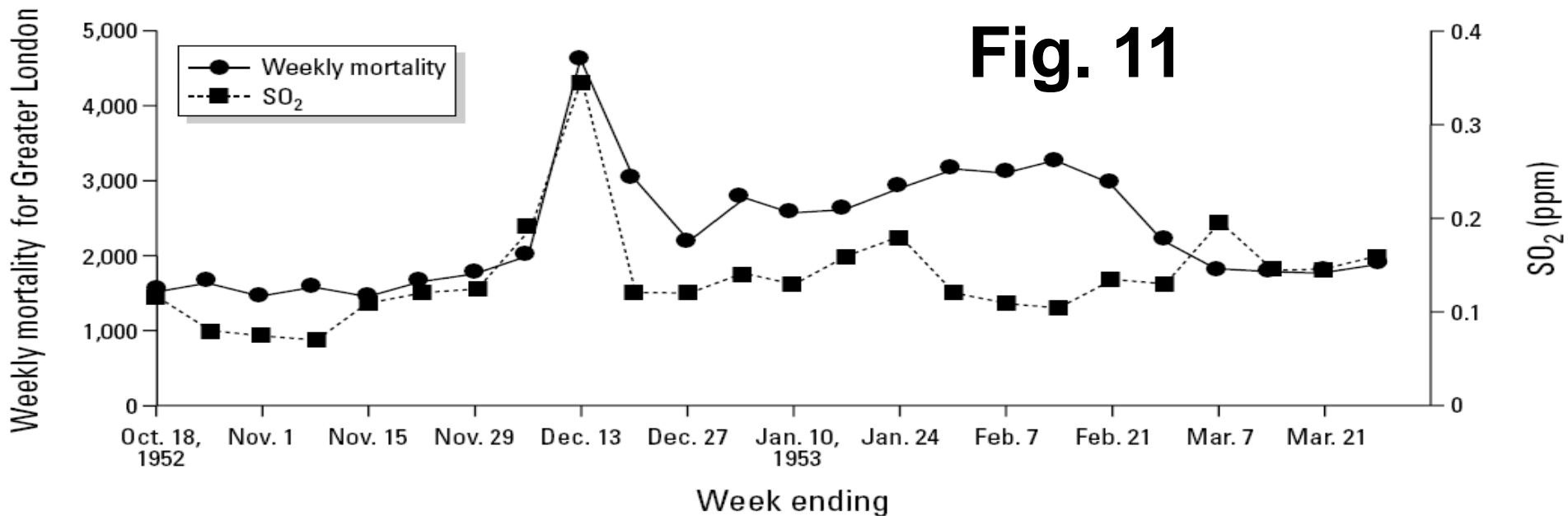
Fig.10: Dry deposition rates for selected gases (in  $\text{cm s}^{-1}$ ) (from Seinfeld and Pandis, p. 969)

compound	Continent	Ocean	Ice/Snow
CO	0.03	0	0
N <sub>2</sub> O	0	0	0
NO	0.016	0.003	0.002
NO <sub>2</sub>	0.1	0.02	0.01
HNO <sub>3</sub>	4	1	0.5
O <sub>3</sub>	0.4	0.07	0.07
H <sub>2</sub> O <sub>2</sub>	0.5	1	0.32

## Notes to Fig.10

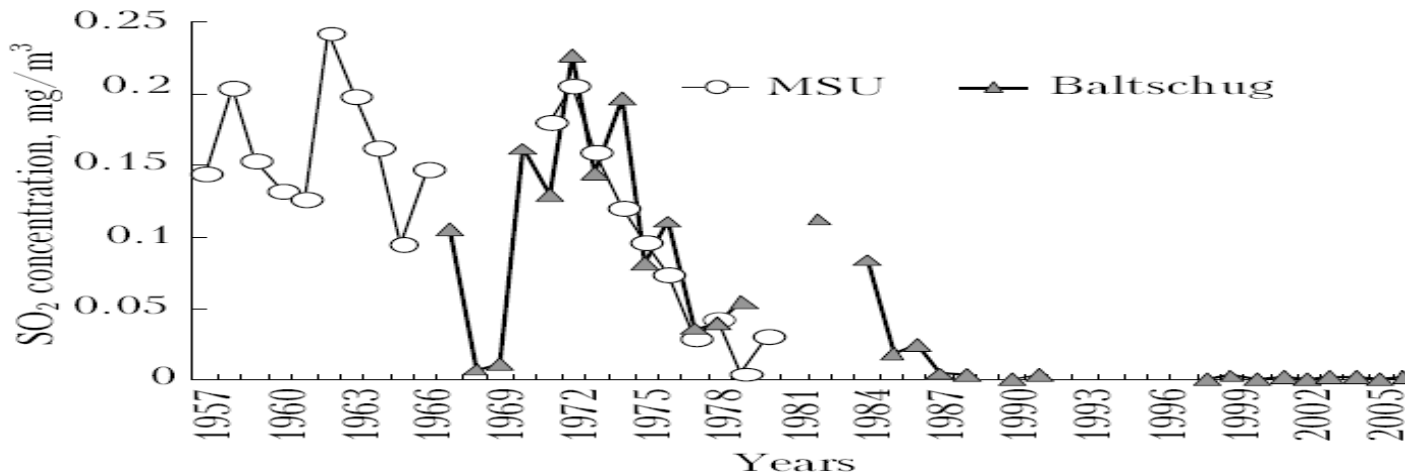
- The table shows dry deposition rates as used in numerical simulations which describe the overall flux.
- Dry deposition rates are largest for  $\text{HNO}_3$  and  $\text{H}_2\text{O}_2$ , because they stick very efficiently on most surfaces.
- Dry deposition is an important sink in the budget of  $\text{O}_3$  in the planetary boundary layer, while its influence on its precursors (e.g.  $\text{NO}_x$ ) is much smaller.
- Dry deposition rates of several compounds strongly depend on the type of surface, reflecting type of (molecular) interaction between the compound and the surface, which also influences water solubility.
- Dry deposition rates are smallest for non polar and hydrophobic compounds.

# 3. Sulfur Dioxide and its time evolution



Sulfur dioxide measurements of London during the 1953 winter smog episode (Bell and Davis, 2001); the conversion factor for SO<sub>2</sub> from ppb in  $\mu\text{g}/\text{m}^3$  is 2.66 yielding a maximal daily concentration on Dec. 13 of approx.  $1000 \mu\text{g}/\text{m}^3$  !

# Fig.12: Sulfur dioxide measurements from Moscow (1970s), Lokoshchenko et al., 2008



Seasonal variation of SO<sub>2</sub> concentration in early 1970s at MSU

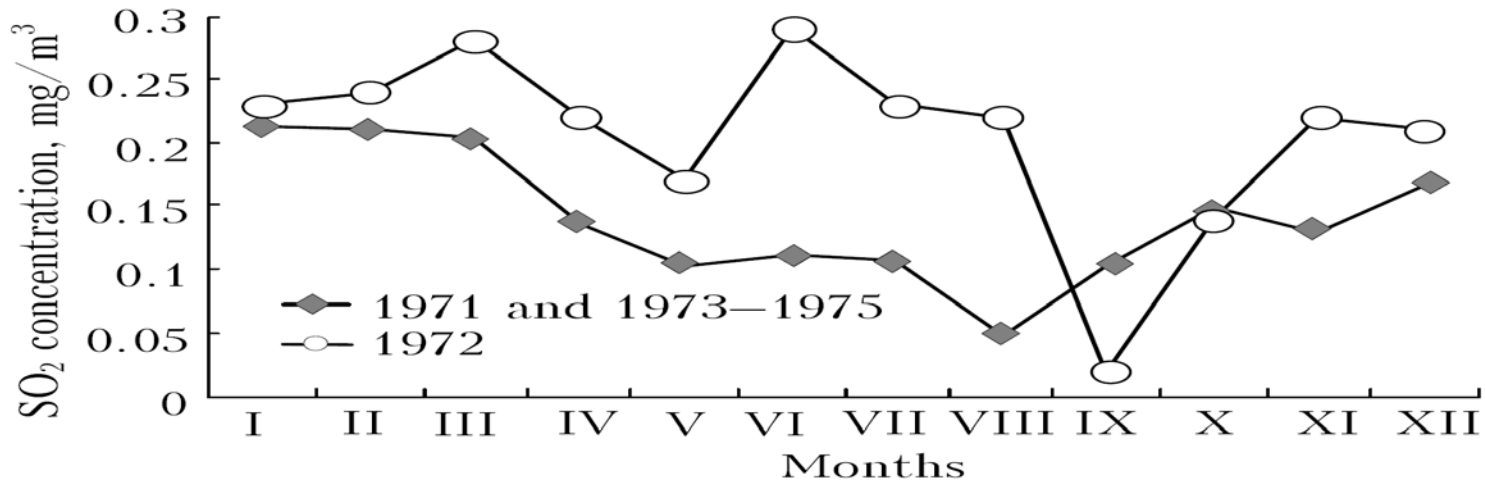
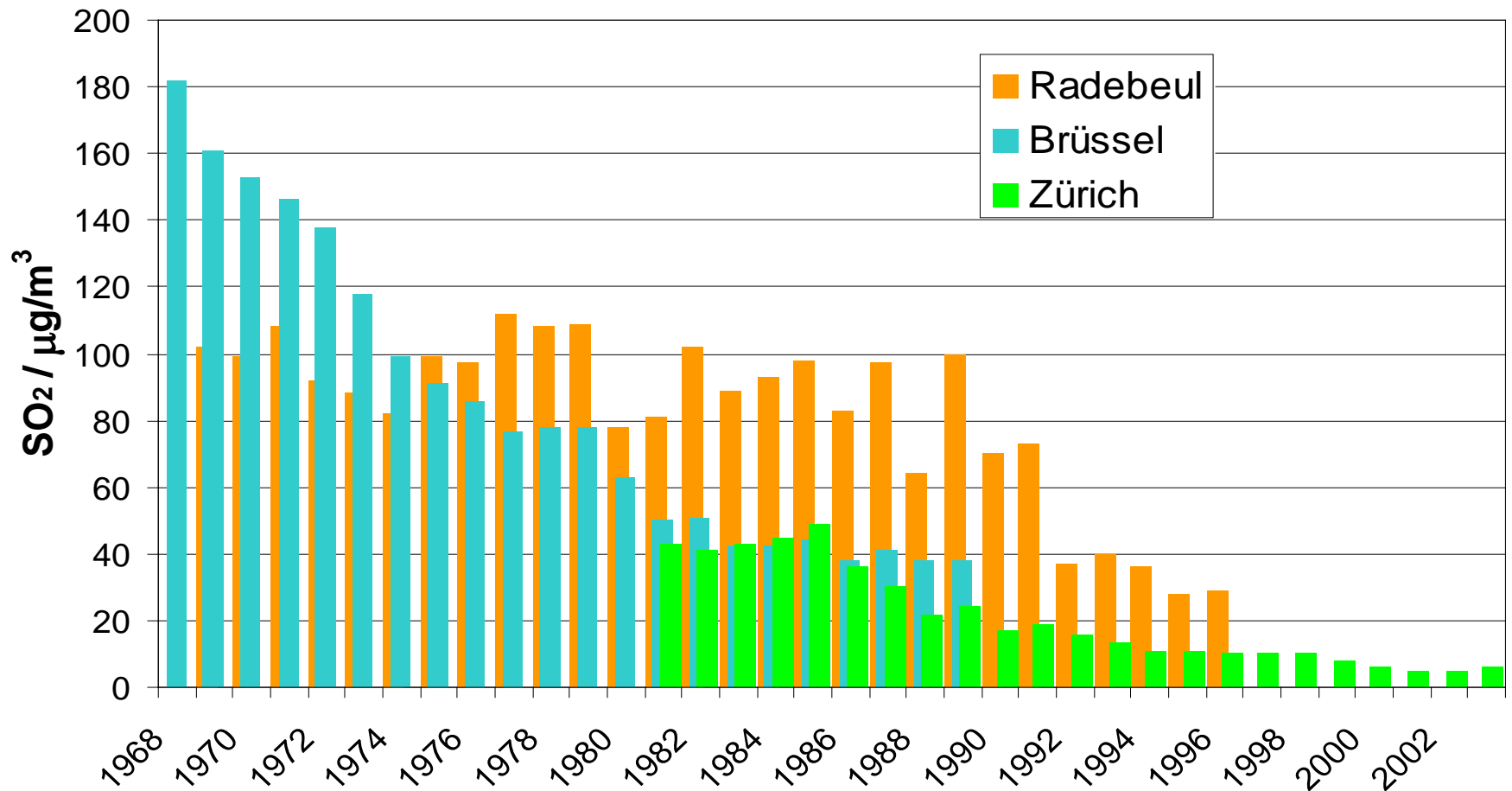


Fig. 13: Sulfur dioxide changes at selected European sites (Staehelin et al., 2000)



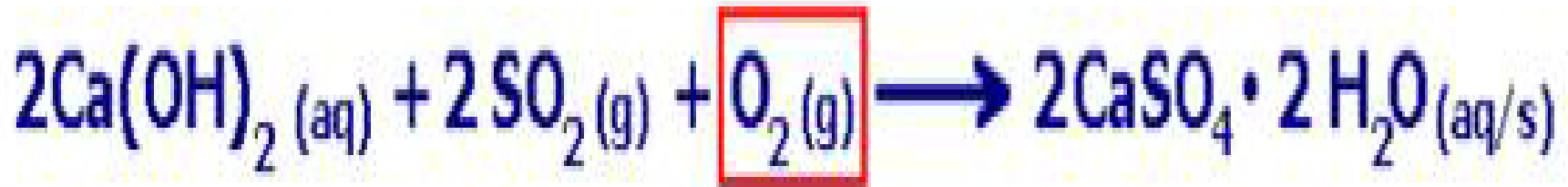
# Notes to Fig.11 – 13

- Largest sulfur dioxide were reported from the winter smog episode of London, which took place in 1952 (Fig. 11). These concentrations were very large compared to the thresholds of the Swiss legislation and the World Health Organization (WHO) (see (see Fig. 21 and 22 in Tropospheric Chemistry of Gas Phase)
- During this episode mortality was strongly enhanced in the capital of London (see Fig. 11) .
- Very high SO<sub>2</sub> concentrations were also measured in Moscow during the 1970s (Fig. 12). They gradually decreased during the 1970s and the 1980s.
- During the late 1960s very high (annual mean) concentrations of SO<sub>2</sub> occurred at many urban sites in Europe such as at a polluted site in Brussels (Fig. 13).
- SO<sub>2</sub> concentrations strongly decreased in Brussels during the 1970s and the 1980s because of the decreasing SO<sub>2</sub> emission (Fig.13).
- The site Radebeul (Fig.13) is located in Eastern Germany. SO<sub>2</sub> concentrations stayed very high until the early 1990s. In these regions SO<sub>2</sub> was emitted in large quantities because of the use of coal in large electricity production plants and in heavy industry which were shut down in the early 1990.
- The monitoring measurements of Switzerland, Zürich (Fig. 13) started in the early 1980s showing a strong decrease starting in the second half of the 1980s.

## Fig. 14. Flue gas desulfurization (Rauchgasentschwefelung)

Kalk ( $\text{CaCO}_3$ )  $\rightarrow$  gebrannter Kalk ( $\text{CaO}$ )  $\rightarrow$  gelöschter Kalk ( $\text{Ca(OH)}_2$ )

Grosser Energieaufwand, den Kalk zu brennen



[Zur Bildung von Gips muss das Schwefeldioxid weiter oxidiert werden. Der dazu benötigte Sauerstoff wird mit dem Schwefeldioxid als Bestandteil der Luft im Versuch mit durch das Kalkwasser gesaugt.]

# Notes to Fig. 14: Sulfur dioxide emission sources

- $\text{SO}_2$  is emitted by the combustion of fossil fuels. The emissions depend on the S-content in the fossil fuel, generally decreasing from coal to oil to gas.
- $\text{SO}_2$  emissions were particularly large in the surrounding of electrical power plants using coal and heavy industry (Ruhr area)
- $\text{SO}_2$  emissions produced in industrial processes can be removed by flue gas desulfurization (see Fig. 14). However, this process needs substantial amount of energy.
- The substitution of coal by oil in many applications (e.g. for room heating) significantly contributed to the decrease in  $\text{SO}_2$  emissions in industrial countries
- The maximally allowed sulfur content in the fuel can be fixed by legislation leading to a reduction in ambient air concentrations.

# Fig. 15: Changes in Swiss anthropogenic emissions ([http://www.umweltschweiz.ch/buwal/de/fachgebiete/fg\\_luft/quellen/uebersicht/index.html](http://www.umweltschweiz.ch/buwal/de/fachgebiete/fg_luft/quellen/uebersicht/index.html))

and ambient air concentrations of SO<sub>2</sub> (NABEL, Luftbelastung 2010)

- Stadt, Verkehr
- Stadt, Nord
- Stadt, Süd
- ▲ Land, Nord
- △ Land, Süd
- ◆ Voralpen

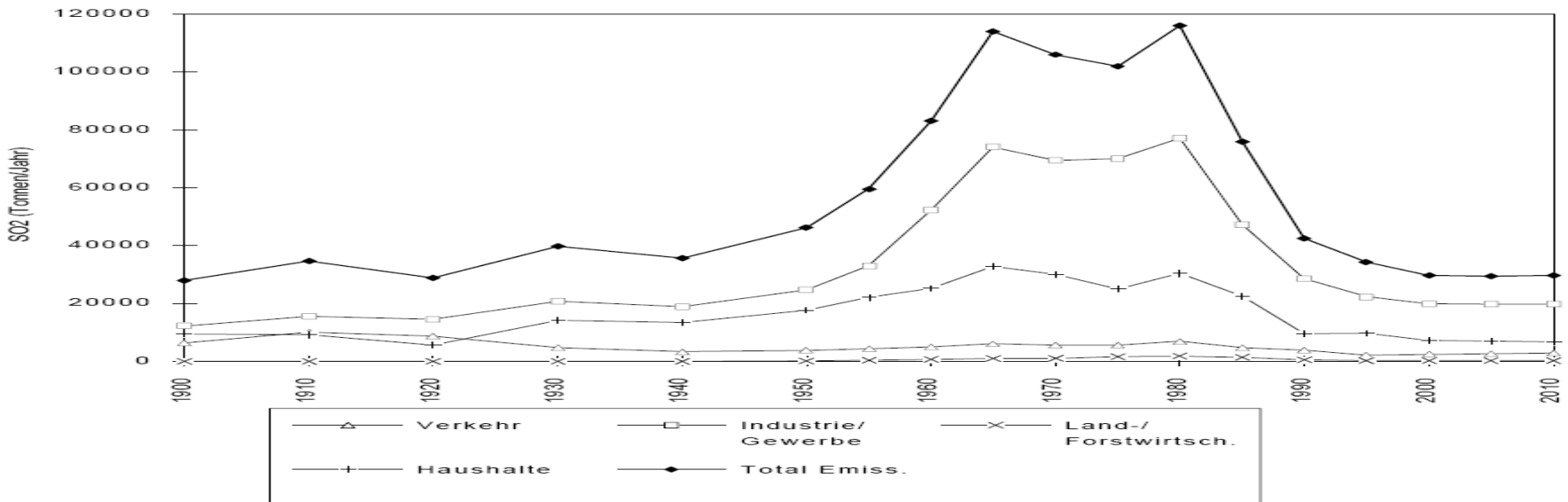
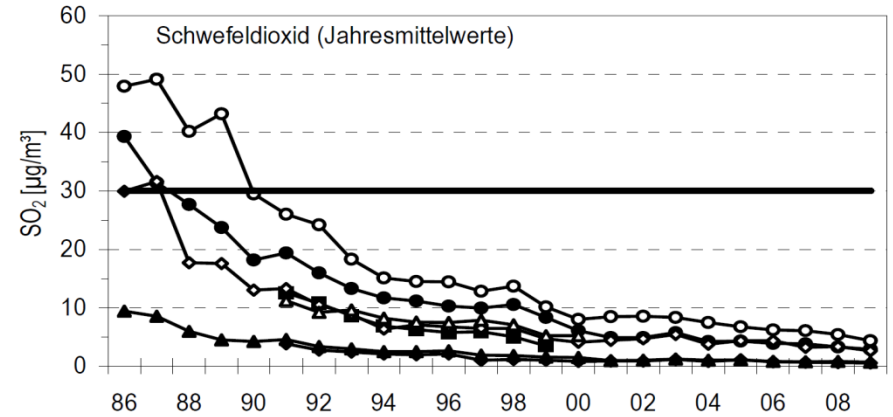
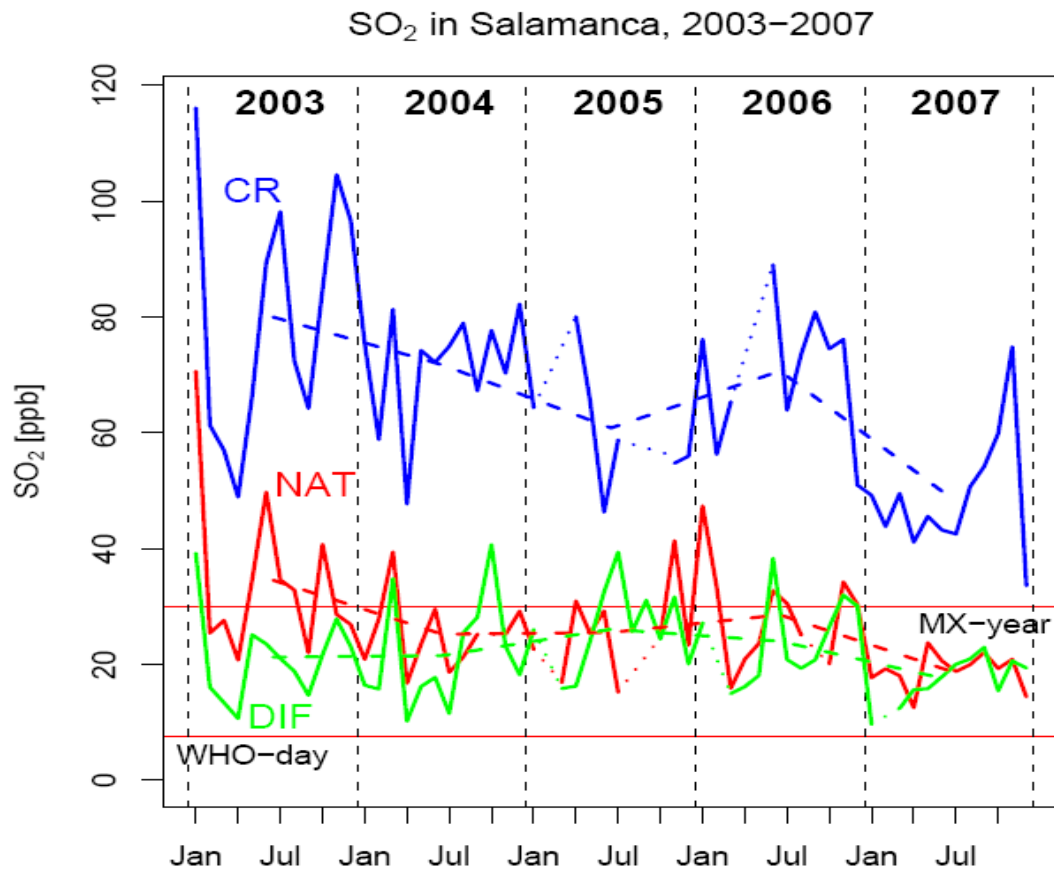


Fig. 4.1 Schwefeldioxid-Emissionen 1900 - 2010

# Notes to Fig. 15: SO<sub>2</sub> concentrations in Switzerland

- The emission inventory of SO<sub>2</sub> shows largest emissions in 1965 and 1980.
- Swiss SO<sub>2</sub> emissions were probably never extremely high because fossil fuels were (almost) never used for electricity production.
- The largest SO<sub>2</sub> emissions originated from industry.
- The large decrease in Swiss SO<sub>2</sub> emissions are reflected in the monitoring measurements.
- Today SO<sub>2</sub> concentrations don't exceed the air quality standards any more in Switzerland.

Fig. 16: Sulfur dioxide concentrations (in ppb) in Salamanca, Mexico (Keller et al., 2009)



Statistical analysis of SO<sub>2</sub> data

		CR	NAT	DIF	LS
April/May	Mean	43.2	18.1	11.3	11.1
	Sd	58.5	30.9	21.2	19.8
	Min	3.2	1.8	1.3	3.0
	Max	400.1	498.4	308.6	179.0
August	Mean	43.2	16.5	15.6	10.2
	Sd	58.9	22.1	15.8	20.9
	Min	0.9	4.2	3.4	2.0
	Max	806.3	281.4	270.6	432.0
November	Mean	71.0	21.0	20.2	15.1
	Sd	80.6	29.1	32.6	18.4
	Min	1.6	1.7	1.4	1.0
	Max	730.1	635.1	519.3	278.0
<b>Average</b>		52.5	18.5	15.7	12.1

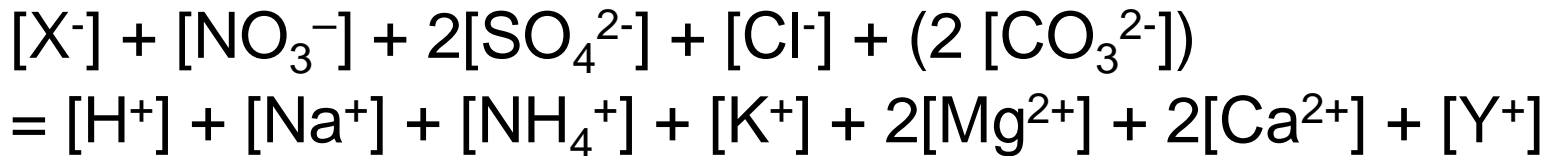
CR, NAT, DIF, LS: Abbreviations for monitoring sites see Keller et al., 2009

# Notes to Fig.16

- SO<sub>2</sub> is still an important air pollutant in many regions, such as in China, where high sulfur containing coal is widely used for electricity generation.
- SO<sub>2</sub> concentrations are very high in Salamanca, a strongly industrialized city in central Mexico (Fig. 16): Monitoring measurements of different sites show a decreasing tendency in ambient air concentrations (see left Figure), but annual mean concentrations are still very high and hourly mean maxima up to 800 ppb were found in 2008 (right pannel).
- The two largest emissions sources close to the central part of the city include an (old) oil refinery and a power plant. Data analysis assisted by application of a dispersion model indicated that the old oil refinery is the emissions source that most strongly affects SO<sub>2</sub> concentrations at the surface.
- Though the two emission sources (power plant and oil refienery) are believed to emit approximately the same amount of SO<sub>2</sub> the emissions of the power plants reach higher altitudes above ground leading to lower concentrations near surface (see Keller et al., 2009).

## ***4. Polluted precipitation („acid rain“)*** ***(Figure 17)***

Composition precipitation: Ion balance



*Strong acids* ( $NO_3^-$ ,  $SO_4^{2-}$ : (dominantly) anthropogenic  
(from  $NO_x$  and  $SO_2$  oxidation)

$X^-$ : organic acids

$Cl^-$ ,  $Na^+$ : marine origin

$Cl^-$ : originating from  $HCl$ : anthropogenic

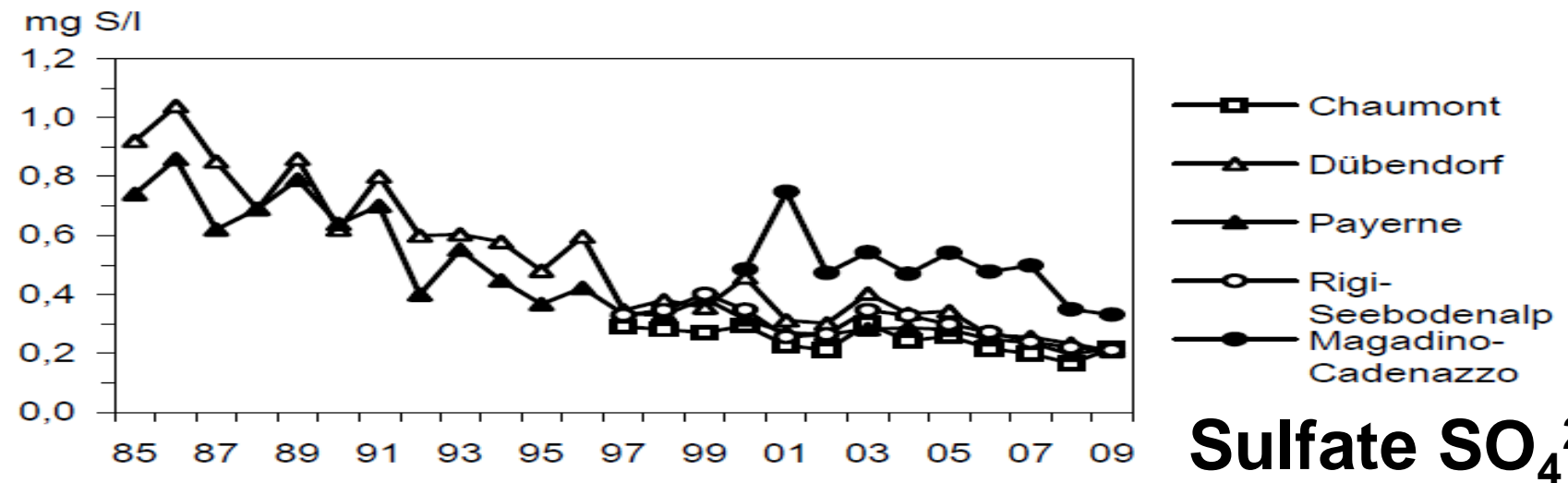
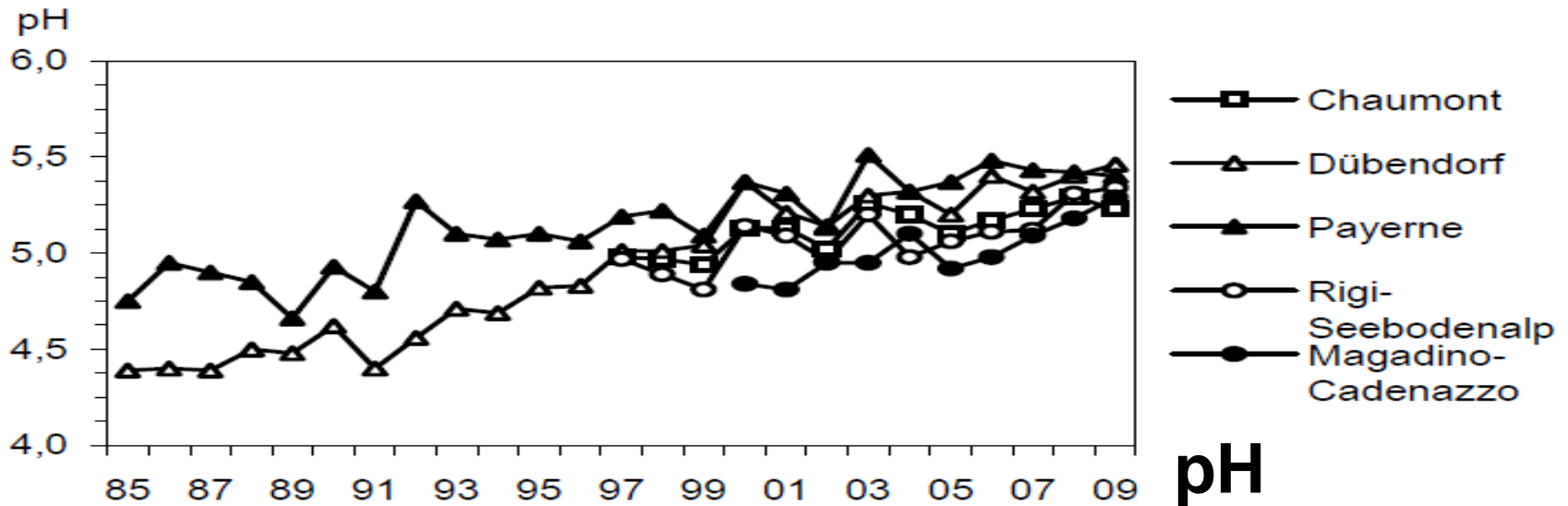
Bases:  $NH_3$  (often anthropogenic origin)

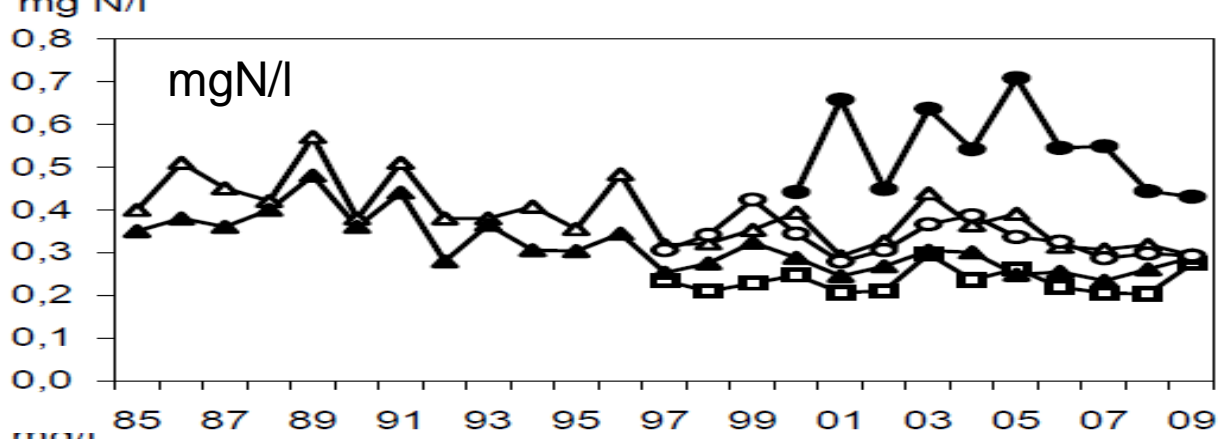
$Mg^{2+}$ ,  $Ca^{2+}$ : mostly from soil

# Notes to Fig. 17

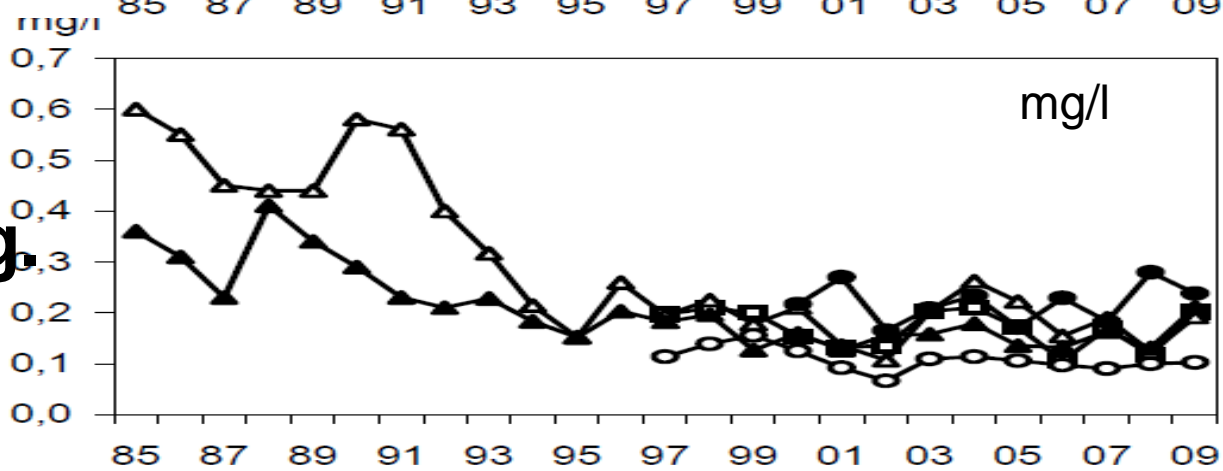
- Wet deposition is an important „cleansing process“ of tropospheric air.
- The chemical composition of wet deposition results from different types of scavenging processes of particles and gases and chemical conversions in the drops (see Chapter 1.).
- The ion balance relates the chemical composition of wet deposition with acidity.
- The dissolution of  $\text{CO}_2$  makes the precipitation slightly acidic by its equilibrium with  $\text{H}_2\text{CO}_3$ .
- The input of strong mineral acids ( $\text{HNO}_3$  and  $\text{H}_2\text{SO}_4$ ) acidifies precipitation leading to „acid rain“.
- The mineral acids are strongly related to anthropogenic emissions of nitrogen and sulfur species, mostly related to the use of fossil fuel.
- $\text{HNO}_3$  is formed in the gas phase while  $\text{H}_2\text{SO}_4$  is mostly produced by oxidation in the drops (comp. Section 1).
- The balance between the input of acidic and alkaline compounds determines the pH of the precipitation.
- Alkaline compounds originate from scavenging of soil dust particles or from scavenging of  $\text{NH}_3$  which is emitted from agriculture and other anthropogenic sources.

# Fig. 18: Precipitation concentration in Switzerland (NABEL, 2010)

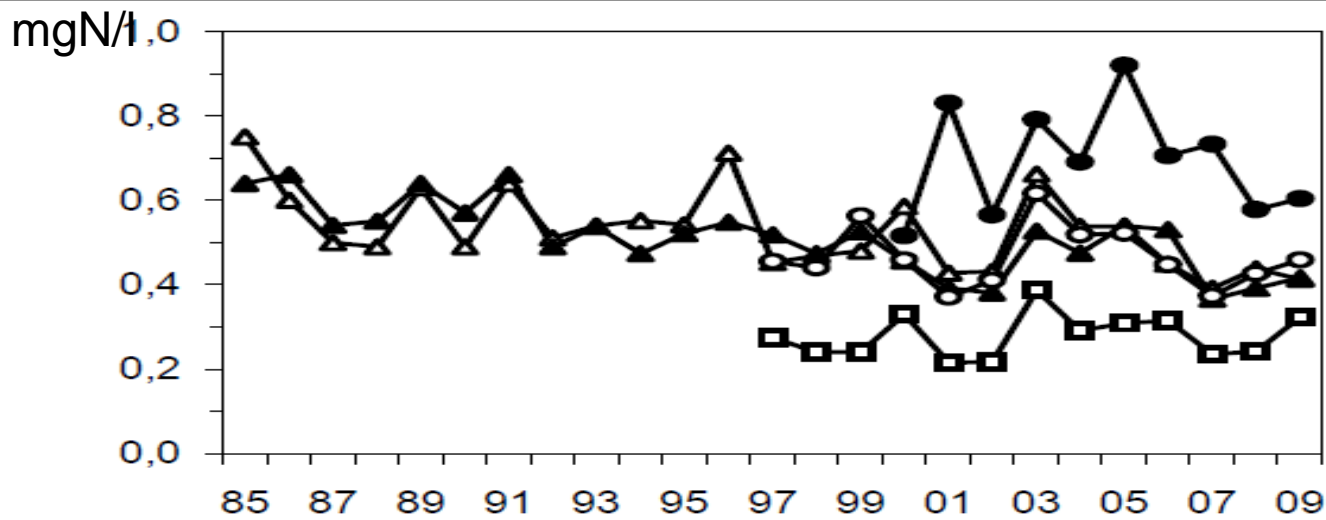




**Nitrate ( $\text{NO}_3^-$ )**



**Chloride ( $\text{Cl}^-$ )**



**Ammonia ( $\text{NH}_4^+$ )**

**Fig. 19**

# Notes to Fig. 18 and Fig. 19

- At the two NABEL sites Dübendorf and Payerne the chemical deposition is measured since 1985, at other selected sites measurements started later.
- pH values strongly increased during this period (remember that pH is defined as a logarithmic scale).
- The increase in pH is strongly linked to the decrease in  $\text{SO}_4^{2-}$  in precipitation which reflects the strong decrease in  $\text{SO}_2$  concentration in Switzerland (see Fig. 18) which is consistent with the expectation of the emission inventory of Switzerland (and the surrounding countries).
- The decrease in  $\text{Cl}^-$  concentrations in the first decade might be caused by decreasing emissions of HCl by waste incinerators.
- $\text{NO}_3^-$  concentration decrease in precipitation is rather small (Fig. 19). Though NABEL data show that  $\text{NO}_x$  concentration decrease much less than for  $\text{SO}_2$  emissions (comp. Fig. 15 and Fig. 37 in Tropospheric Chemistry of Gas Phase)  $\text{NO}_x$  concentrations also decreased by up to a factor 2 since the early 1990s. The small decrease in  $\text{NO}_3^-$  concentrations is possibly influenced by the fact that  $\text{HNO}_3$  is produced in the gas phase and strongly removed by dry deposition while  $\text{SO}_2$  is dominantly removed by wet deposition after oxidation in the drops.
- Decrease in the  $\text{NH}_4^+$  concentrations is small.

# References

- Bell, M.L., and D.L. Davis (2001) Reassessment of the Lethal London Fog of 1952: Novel Indicators of Acute and Chronic Consequences of Acute Exposure to Air Pollution, *Environm. Health Persp.*, **109**, Suppl., 389-394.
- Keller, C.A., H. Wöhrnschimmel, E. Reyes, C. Marquez, C. Barcenas, B. Cardenas, and J. Staehelin (2009), Ambient sulfur dioxide concentrations and its sources in a heavily industrialized city in central Mexico, *unpublished manuscript*.
- Lokoshchenko, M.A., N.F. Elansky, V.P. Malyashova, and A.V. Trifanova (2008), Dynamics of sulfur dioxide surface concentration in Moscow, *Atmos. Oceanic Opt.*, **21**, 384-391.
- Seinfeld, J. H., and Pandis, S. N., *Atmospheric Chemistry and Physics*, John Wiley and Sons, New York, 1998.
- Staehelin, J., Prévôt A.S.H., and Barnes, J. (2000) Photochemie der Troposphäre, in: R. Guderian (Ed.), *Handbuch der Umweltveränderungen und Ökotoxikologie*, Band IA: Atmosphäre, Springer Verlag, pp. 207-341.
- NABEL, 2010: Luftbelastung 2009, Messresultate des Nationalen Beobachtungssnetzes für Luftfremdstoffe (NABEL), herausgegeben vom Bundesamt für Umwelt und der Eidg. Materialprüfungs- und Forschungsanstalt EMPA, Umweltzustand 1016, Bundesamt für Umwelt (BAFU), Bern, 2010