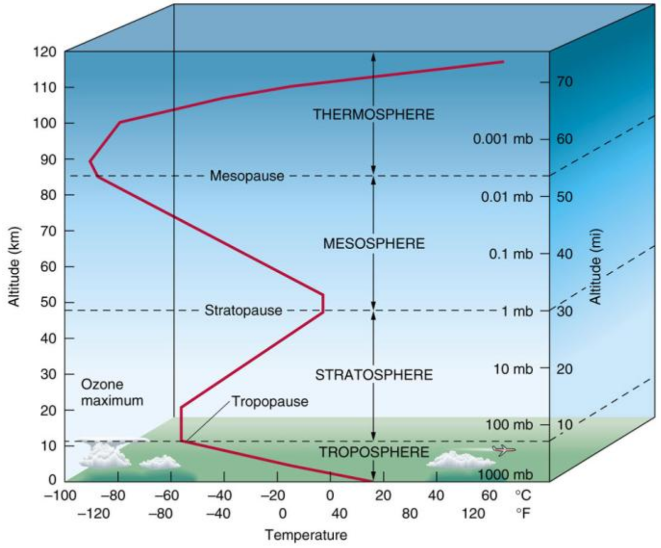
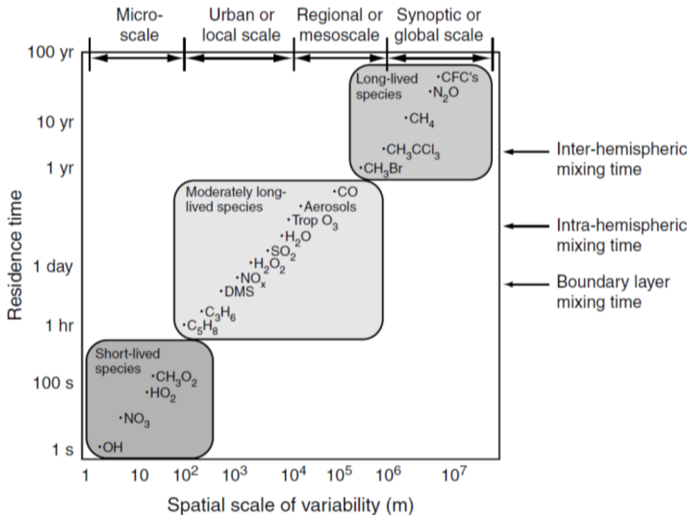
Recap from last lecture

- Know the temperature profile of the atmosphere and the reasons for it.
- Be able to convert units.
- Know the concept of lifetime and what it depends on.
- Know the carbon, sulfur and nitrogen compounds present in the atmosphere.





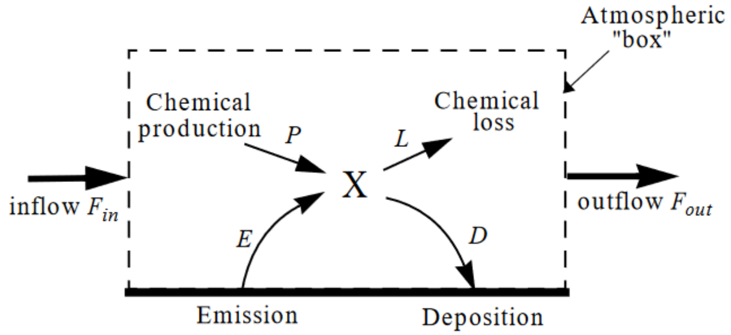


Figure 3-1 One-box model for an atmospheric species X

Stratospheric Chemistry

https://cloudatlas.wmo.int/en/nacreous-clouds.html

Outline

- Stratospheric circulation
- Ozone chemistry
  - Chapman reactions
  - Catalytic cycles
  - Ozone hole
  - Polar stratospheric clouds
- Junge Layer

«Discovery» of the Stratosphere

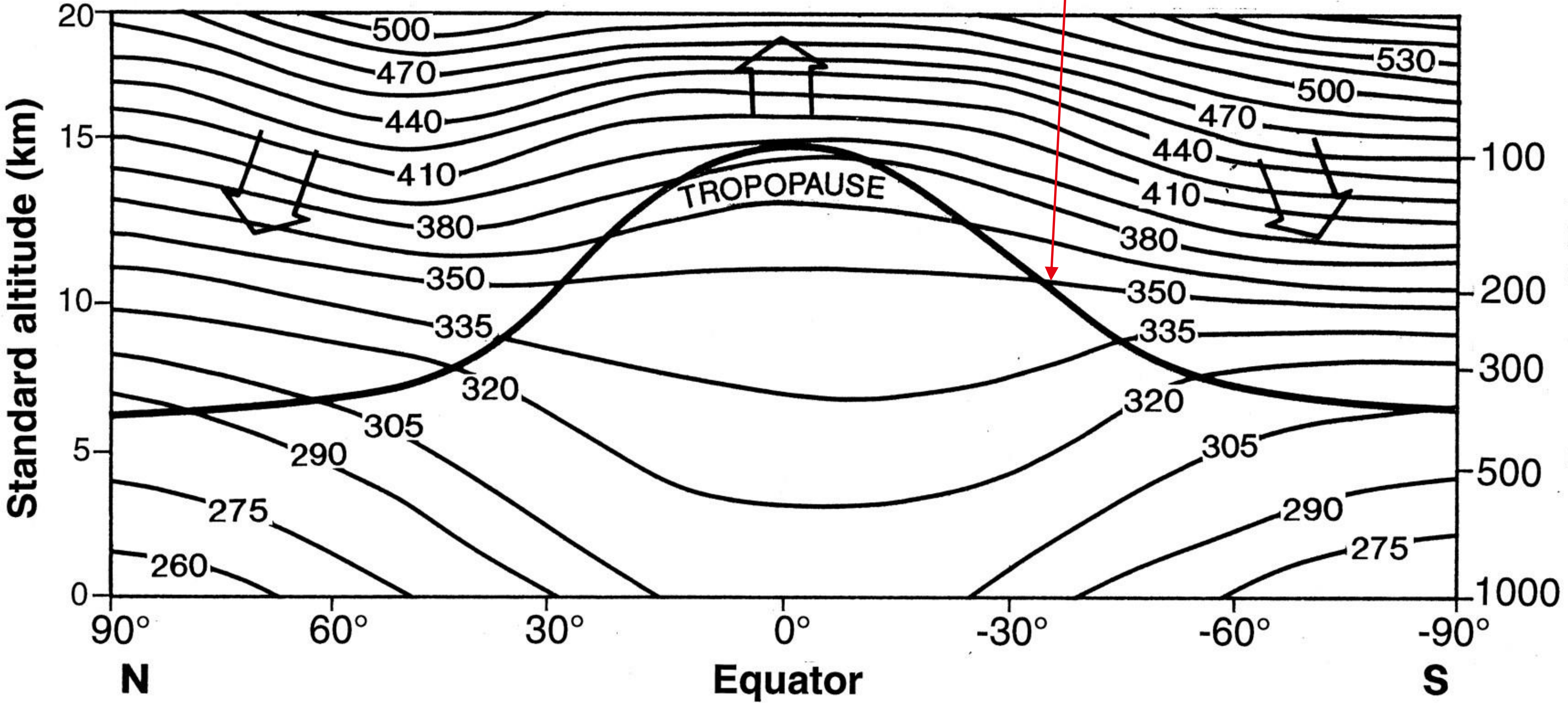
- In 1901, balloon flight to 10.5 km altitude by Reinhard Süring and Arthur Berson of the Prussian Royal Meteorological Institute
- 5400 m^3 hydrogen balloon.
- Objective: temperatue measurements. No trust in measurements with balloon soundings.
- tropos (gr.) → «turbulent»
  strato (gr.) → «layered»

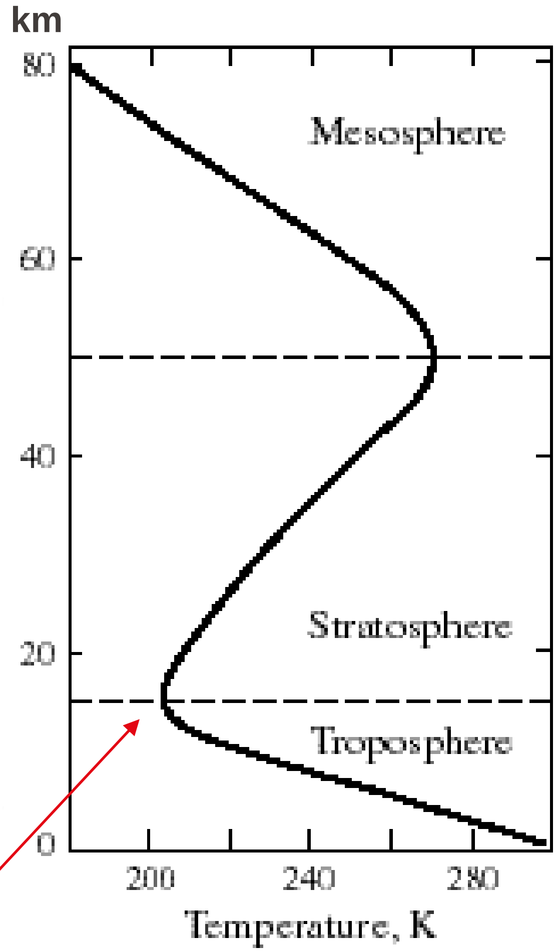
- https://www.pik-potsdam.de/de/produkte/infothek/telegraphenberg-d/suering-haus/reinhard-suring/hochfahrt

Tropopause

Air mass transport occurs along istentropes, meaning that low-latitude air enters the stratosphere at high latitudes.

isentropes

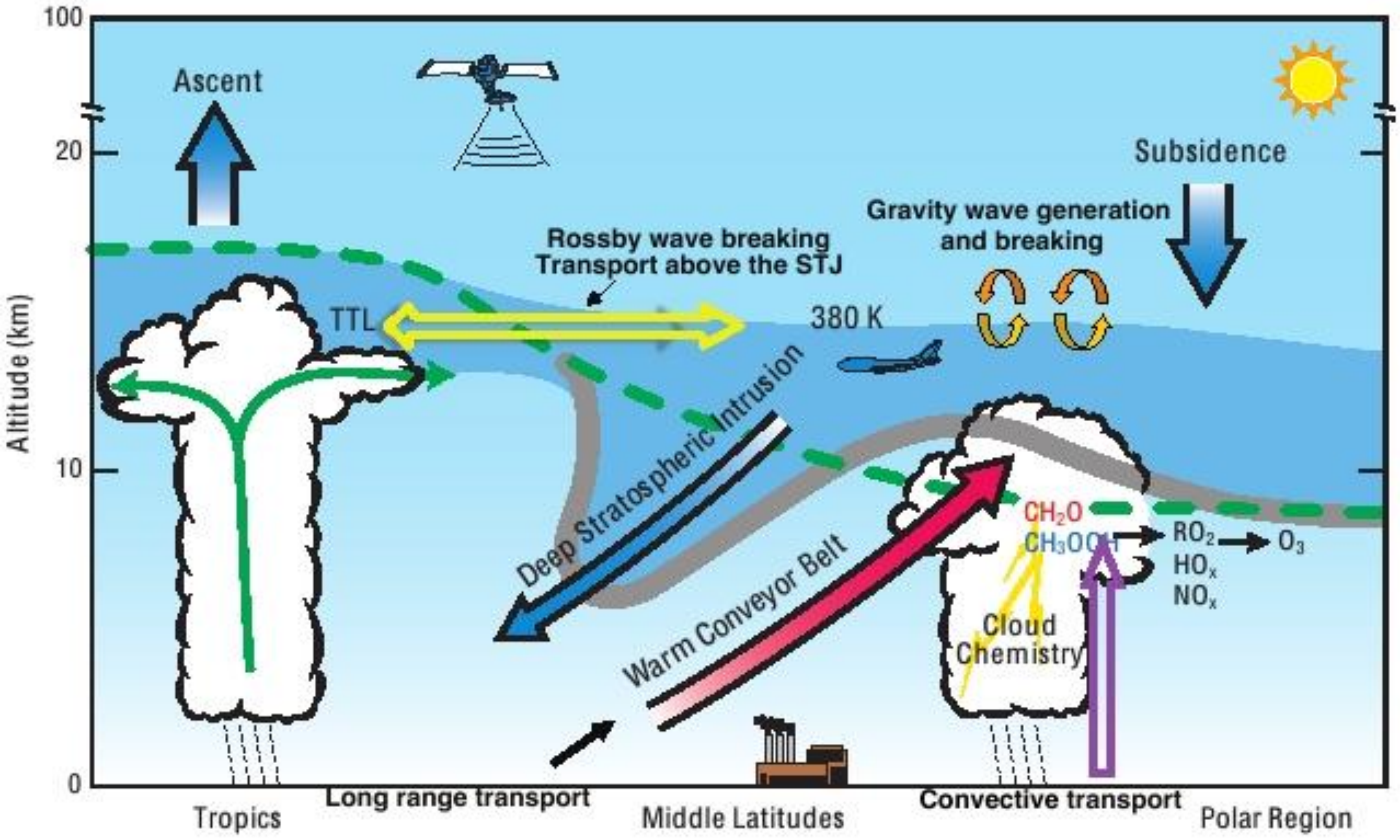




- Mahlman et al., Science, 1997, DOI: 10.1126/science.276.5315.1079

Strong inversion.

Exchange processes across the tropopause



TTL : tropical transition layer
STJ: subtropical jet

Water vapor, ozone, aerosols and cirrus cloud in the upper troposphere and lower stratosphere (UTLS) region, controlled by these coupled processes, have important impacts on the Earth's radiation budget.

- https://www.acom.ucar.edu/utls/

Brewer Dobson Circulation

Fig. 1.Schematic of the Brewer Dobson Circulation as the combined effect of residual circulation and mixing in the stratosphere and mesosphere.

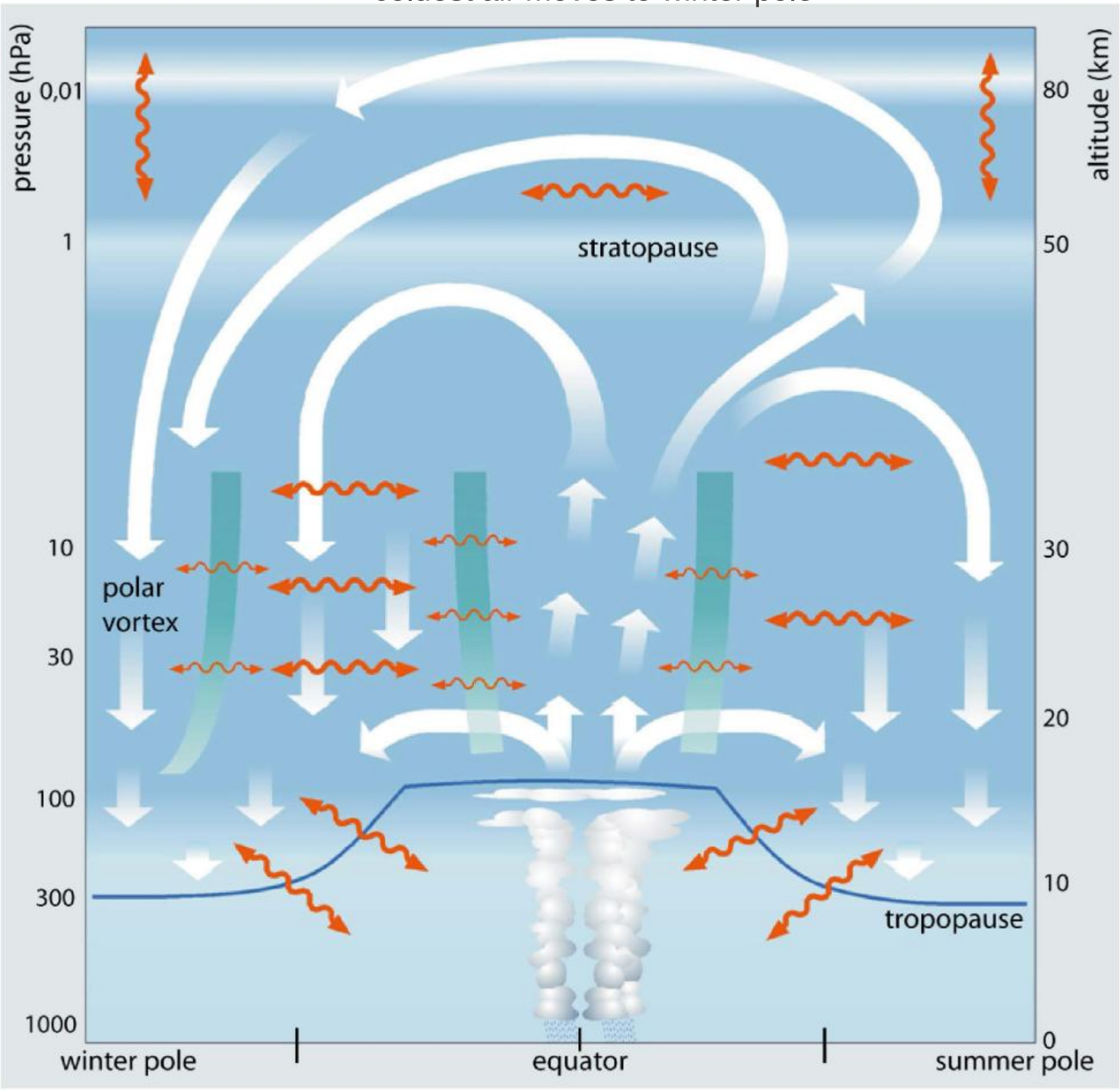
- The thick white arrows depict the general air mass movement as representation of the residual circulation,
- the wavy orange arrows indicate two-way mixing processes.

Both, circulation and mixing are mainly induced by wave activity on different scales (planetary to gravity waves).

- The thick green lines represent stratospheric transport and mixing barriers.

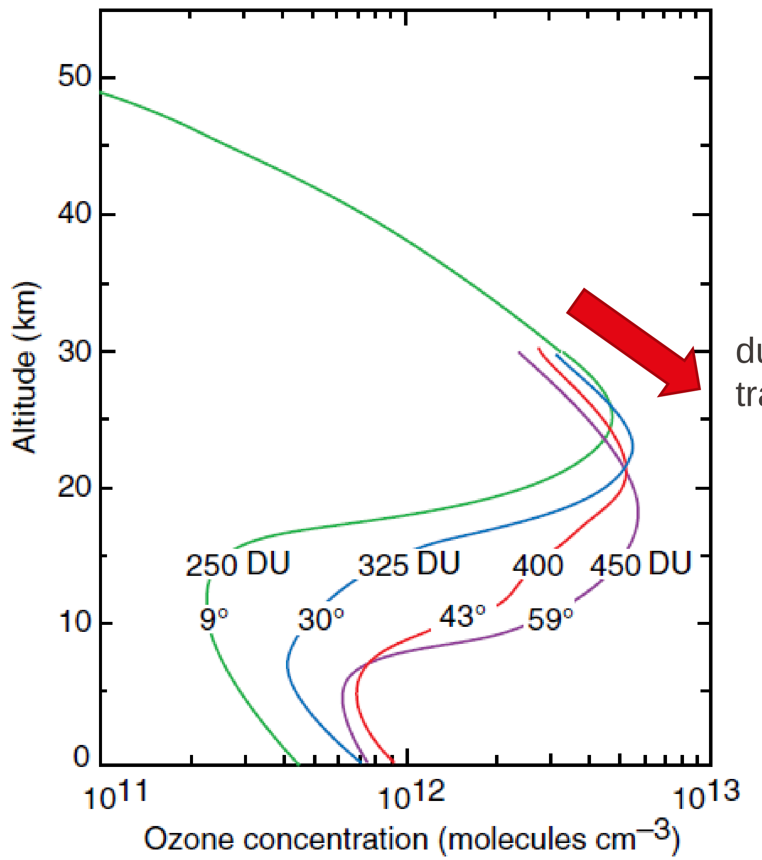
The Figure is by courtesy of Dr. U. Schmidt and it is adapted from a non peer-reviewed research report of our institute.

coldest air moves to winter pole



Bönisch et al., ACP, 2011

Ozone vertical profiles



due to stratospheric transport

- It forms a protective shield that reduces the intensity of UV radiation (with wavelengths between 0.23 and 0.32 µm) from the sun that reaches the Earth's surface.
- Because of the absorption of UV radiation by O_3, it determines the vertical profile of temperature in the stratosphere.
- It is involved in many stratospheric chemical reactions.
- 90 % of atmospheric O_3 is in stratosphere

- Wallace and Hobbs, 2006, Fig. 5.16

Chapman reactions

Assumption: oxygen only atmosphere
Note: reaction coefficients depend on temperature

A. Dissociation of O_2 by UV ($0.180 \leq \lambda \leq 0.240\ \mu m$)

slow

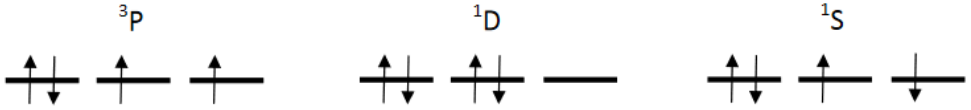
$$O_2 + h\nu \xrightarrow{j_a} 2O$$

$O(^3P) + O(^1D)$ (excited state)

4 electrons of the 2p - orbital

triplet (still highly reactive)

singlet (highly reactive)



B. Atomic O and O_2 react to form O_3 (M is N_2 or O_2)
Occurs more rarely than often.

fast

$$O + O_2 + M \xrightarrow{k_b} O_3 + M$$

Needs M to absorb excess energy to form a stable O_3 molecule. Hence time constant increases with altitude, i.e becomes slower.

C. O_3 undergoes photodissociation ($0.200 \leq \lambda \leq 0.300\ \mu m$)

fast

$$O_3 + h\nu \xrightarrow{j_c} O_2 + O$$

$$O_3 + h\nu \rightarrow O(^1D)$$

$$O(^1D) + M \rightarrow O + M$$

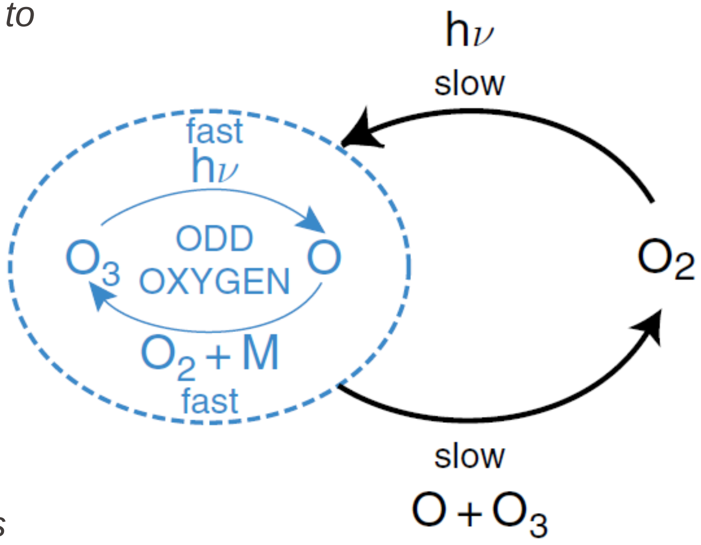
D. Atomic O and O_3 combine to form O_2

slow

$$O + O_3 \xrightarrow{k_d} 2O_2$$

Can be catalytically accelerated by hetero atmos (e.g. Cl, Br).

Reaction becomes faster with higher altitude, because more O is availble there.



Definition of odd oxygen: O + O_3

Is there a diurnal cycle of O3 in the stratosphere?

A. No.

B. Yes.

C. A small one.

A. Dissociation of O_2 by UV (0.180 $\leq \lambda \leq 0.240\ \mu m$)

slow $$O_2 + h\nu \xrightarrow{j_a} 2O$$

B. Atomic O and O_2 react to form O_3 (M is N_2 or O_2)
Occurs more rarely than often.

fast $$O + O_2 + M \xrightarrow{k_b} O_3 + M$$

C. O_3 undergoes photodissociation (0.200 $\leq \lambda \leq 0.300\ \mu m$)

fast $$O_3 + h\nu \xrightarrow{j_c} O_2 + O$$

D. Atomic O and O_3 combine to form O_2

slow $$O + O_3 \xrightarrow{k_d} 2O_2$$

Is there a diurnal cycle of O_3 in the stratosphere?

A. Dissociation of O_2 by UV ($0.180 \leq \lambda \leq 0.240\ \mu m$)

slow

$$O_2 + h\nu \xrightarrow{j_a} 2O$$

B. Atomic O and O_2 react to form O_3 (M is N_2 or O_2)
Occurs more rarely than often.

fast

$$O + O_2 + M \xrightarrow{k_b} O_3 + M$$

C. O_3 undergoes photodissociation ($0.200 \leq \lambda \leq 0.300\ \mu m$)

fast

$$O_3 + h\nu \xrightarrow{j_c} O_2 + O$$

D. Atomic O and O_3 combine to form O_2

slow

$$O + O_3 \xrightarrow{k_d} 2O_2$$

- Stratospheric O_3 concentrations exhibit minor diurnal variations with time of day.
- After sunset, both the source (A) and the sink of O_3 (C) are switched off, and the remaining O atoms are then converted to O_3 within a minute or so by (B).
- When the sun rises, some of the O_3 molecules are destroyed by (C) but they are reformed by (A) followed by (B).

A missing sink

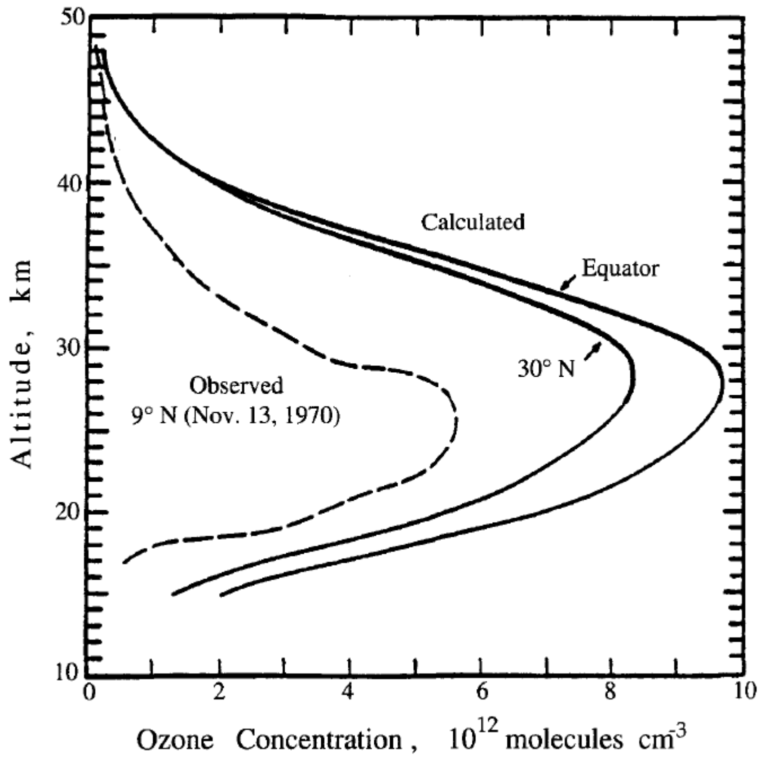


FIGURE 5.5 Comparison of stratospheric ozone concentrations as a function of altitude as predicted by the Chapman mechanism and as observed over Panama (9°N) on November 13, 1970.

Seinfeld and Pandis, 2006, p. 150

- Chapman reactions predict the shape of the vertical profile correctly.
- They overestimate O_3 concentration by a factor of two in the tropics and underestimate O_3 in the higher latitudes.
- The rate of production is too high compared to the actual measured concentration.
- O_3 concentrations are not increasing, hence there must a sink for odd oxygen.

→ Catalytic cycles of O_3 depletion involving H, OH, Cl, Br.

Catalytic cycles

$$X + O_3 \rightarrow XO + O_2$$
$$XO + O \rightarrow X + O_2$$

$$\text{Net:} \quad O + O_3 \rightarrow 2O_2$$

- X catalyst
- XO intermediate product
- Reactions are fast
- Since X is recycled, only a small concentration is sufficient to remove odd oxygen.

X =	altitude
*	lower stratosphere
**	below 30 km
OH	below ~40 km
NO	middle stratosphere
Cl	middle and upper stratosphere

*, ** atomic oxygen is scarce

Hydrogen species as candidate for O destruction: OH, HO_2 (HO_x)

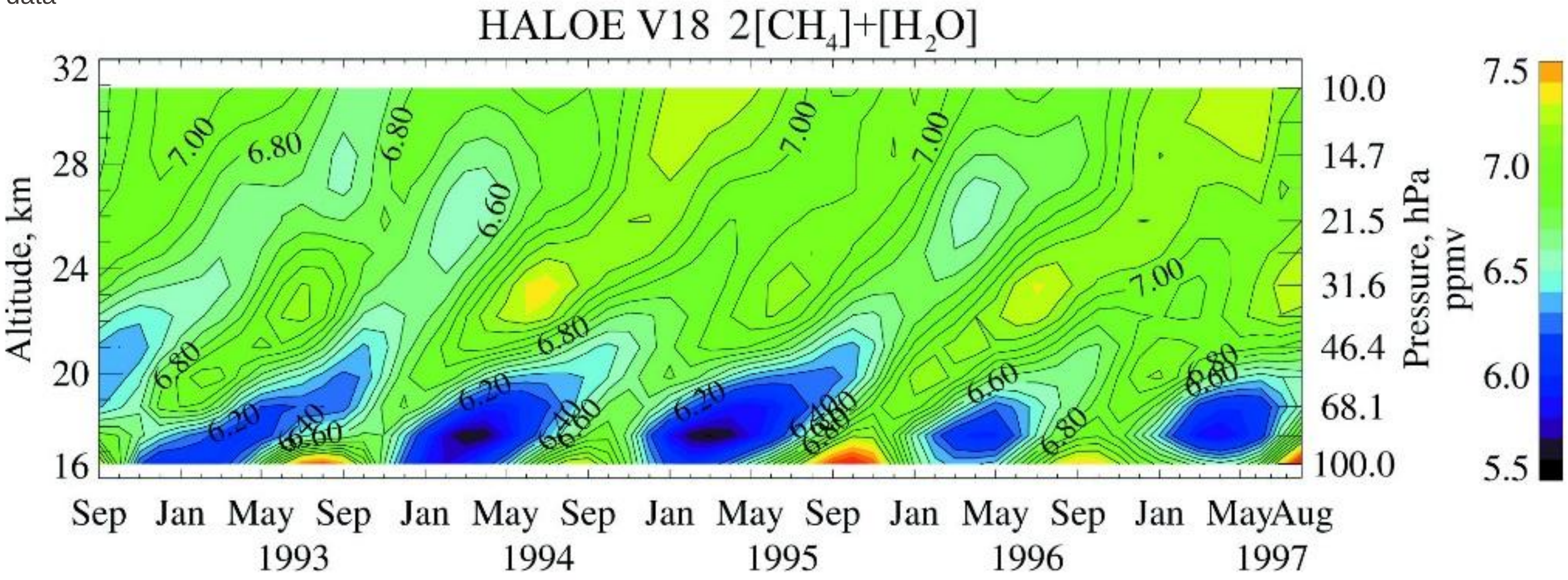
Three sources of OH in the stratosphere:

$$H_2O + O(^1D) \rightarrow 2\,OH$$
$$CH_4 + O(^1D) \rightarrow CH_3 + OH$$
$$H_2 + O(^1D) \rightarrow H + OH$$

Stratospheric tape recorder: source of water vapor and methane

Satellite data

Way of describing total hydrogen (H_2) in stratosphere



MO, Global Ozone Research and Monitoring Project-Report No. 44
Scientific Assessment of Ozone Depletion: 1998, Chapter 7, page 7.21, Fig 7-07.

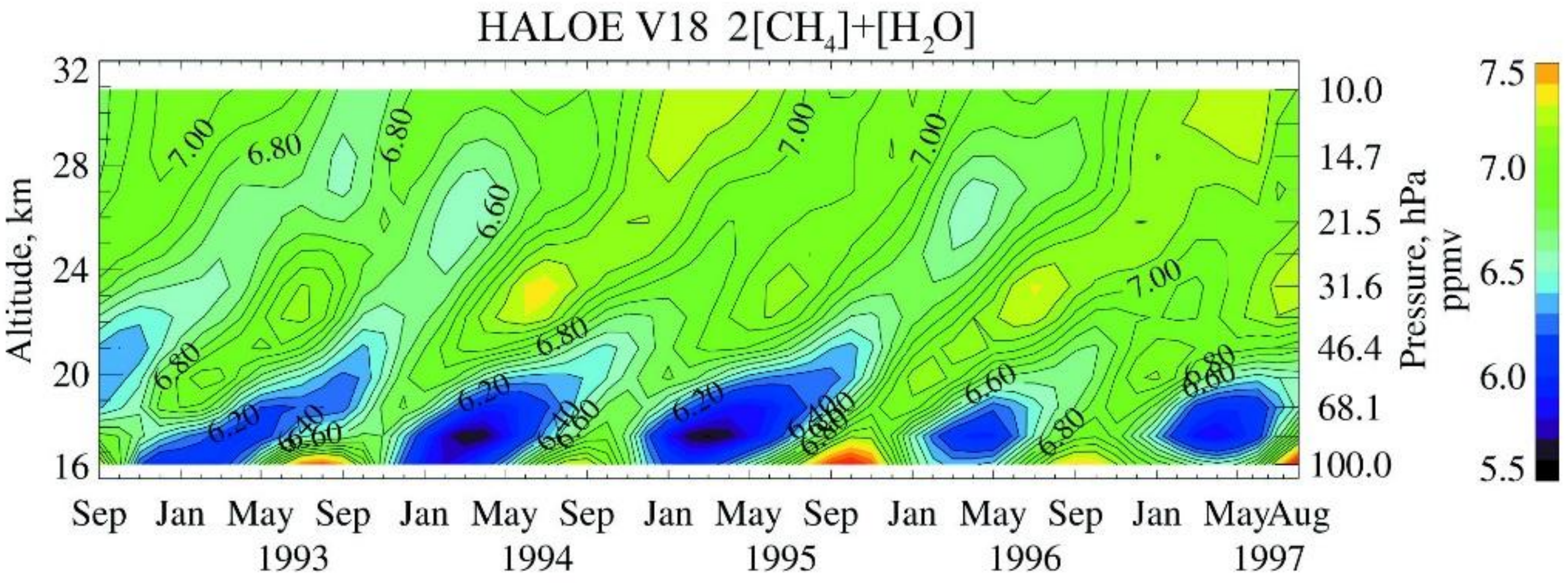
What happens in the annual cycle?

A. There is less methane in winter because of lower emissions.

B. There is less water vapor in summer because of more frequent rain.

C. There is less water vapor in winter because of colder temperatures.

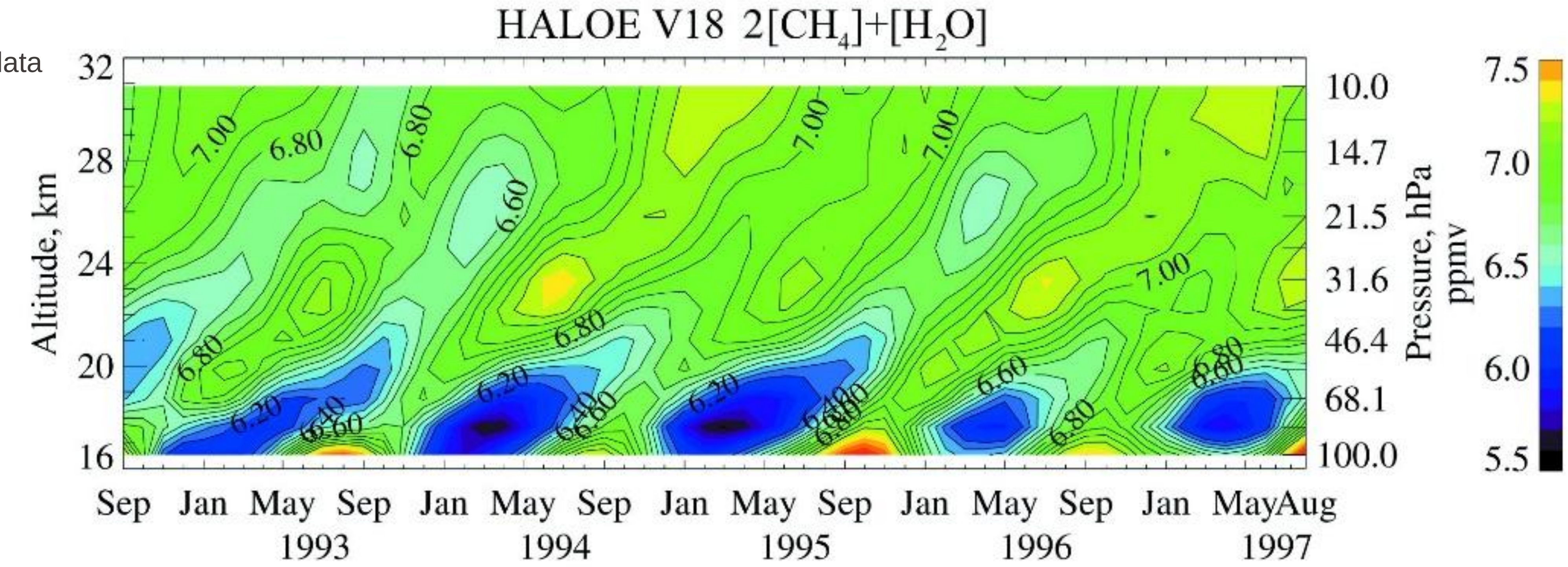
D. A and C.



Stratospheric tape recorder: source of water vapor and methane

Way of describing total hydrogen in stratosphere

Satellite data



Temperatures at tropical tropopause have a yearly cycle. When they are colder, the water vapor mixing ratio is lower (condensation, ice crystal formation, precipitation). Hence less water vapor is introduced into the stratosphere. Methane is not affected by the temperature.

Each air mass which passes the tropopause carries that specific water vapor signature (color code, tape recorder).

MO, Global Ozone Research and Monitoring Project-Report No. 44
Scientific Assessment of Ozone Depletion: 1998, Chapter 7, page 7.21, Fig 7-07.

HO_x Catalytic cycles

Below ~40 km where atomic oxygen is available:

$$OH + O_3 \rightarrow HO_2 + O_2$$
$$HO_2 + O \rightarrow OH + O_2$$

$$\text{Net:} \quad O + O_3 \rightarrow 2O_2$$

Below ~30 km, where less atomic oxygen is available:

$$OH + O_3 \rightarrow HO_2 + O_2$$
$$HO_2 + O_3 \rightarrow OH + 2O_2$$

$$\text{Net:} \quad 2O_3 \rightarrow 3O_2$$

Cycle disruption by removal of HO_x:

$$OH + HO_2 \rightarrow \underline{H_2O} + O_2$$
$$OH + \boxed{NO_2} + M \rightarrow \underline{HNO_3} + M$$
$$HO_2 + NO_2 + M \rightarrow \underline{HNO_4} + M$$

Reservoir species

Reservoir species remove HO_x from fast reaction cycles.

NO_x catalytic cycles

In analogy to HO_x.
Most important in the middle stratosphere.

$$N_2O + O(^1D) \rightarrow 2\,NO$$

$$NO + O_3 \rightarrow NO_2 + O_2$$

$$NO_2 + O \rightarrow NO + O_2$$

Net: $O + O_3 \rightarrow 2O_2$

Cycling between NO and NO_2 (interferrence cycle):

$NO_2 + h\nu \rightarrow NO + O$
$NO + O_3 \rightarrow NO_2 + O_2$
$O + O_2 + M \rightarrow O_3 + M$

NET: No change

Removal of NO_x into **reservoir species**

$NO_2 + OH + M \rightarrow$ **HNO_3** $+ M$
$NO_2 + HO_2 + M \rightarrow$ **HNO_4** $+ M$
$NO_3 + NO_2 + M \rightarrow$ **N_2O_5** $+ M$

Cl_x and Br_x catalytic cycles

$BrO + ClO \rightarrow Br + ClOO$

$ClOO + M \rightarrow Cl + O_2 + M$

$Cl + O_3 \rightarrow ClO + O_2$

$Br + O_3 \rightarrow BrO + O_2$

NET: $2\ O_3 \rightarrow 3\ O_2$

Natural sources of Br and Cl are
- CH_3Br
- CH_3Cl

from oceanic, terrestrial (plants, soils) emissions.
The methyl compounds are photolyzed by UV radiation.

Overall, the many chemical reactions and catalytic cycles constitute a delicate equilibrium that maintains the stratospheric ozone layer.

Anthropogenic changes to catalytic cycles

Source of Cl_x are CFCs, through photolytic generation of Cl (photodissociation)

$(0.190 \leq \lambda \leq 0.220\ \mu m)$.

$$CFCl_3 + h\nu \rightarrow CFCl_2 + Cl$$

$$CF_2Cl_2 + h\nu \rightarrow CF_2Cl + Cl$$

$Cl + O_3 \rightarrow ClO + O_2$

$ClO + O \rightarrow Cl + O_2$

NET: $O_3 + O \rightarrow 2\ O_2$

Transformation into **reservoir species**:

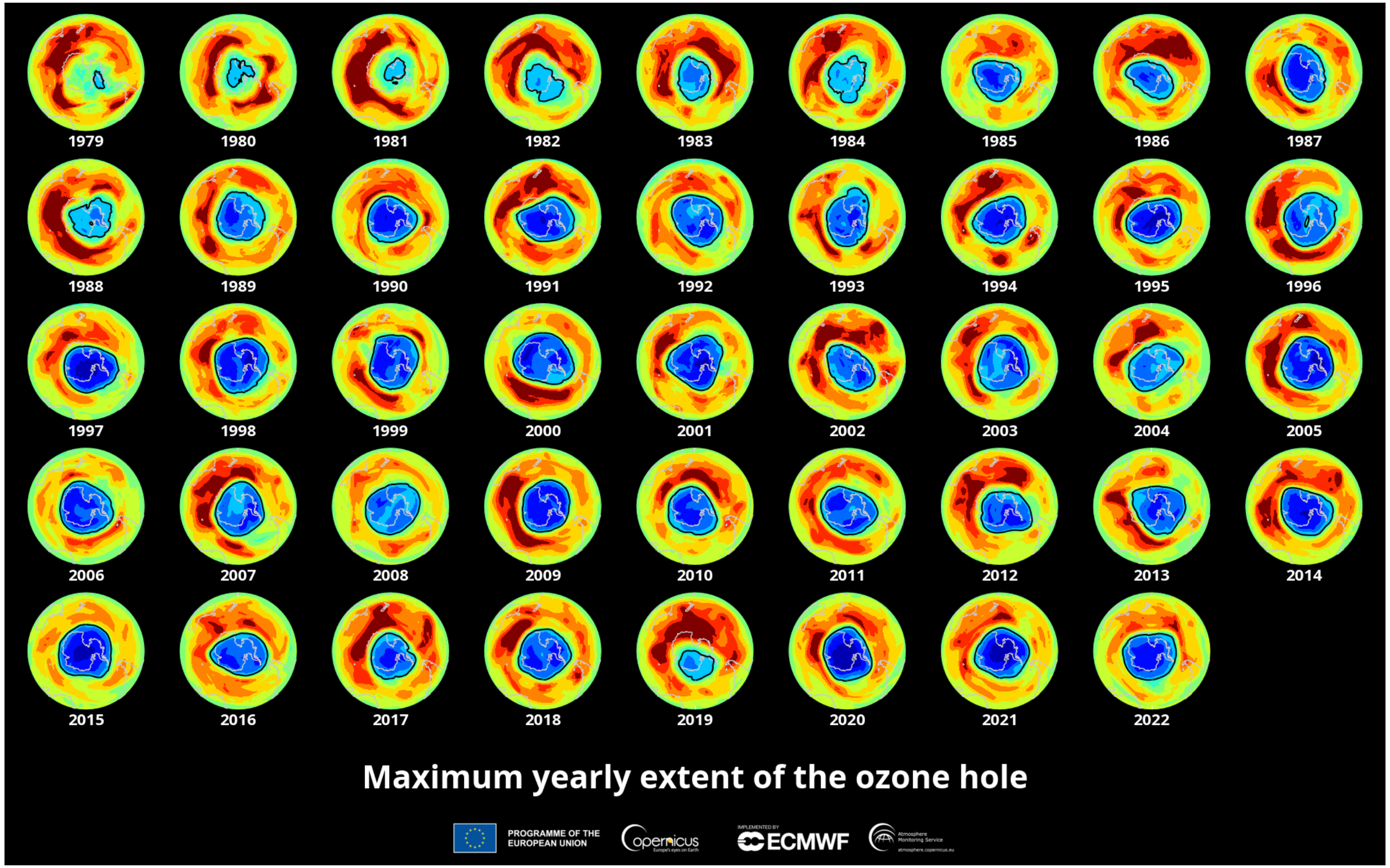
$Cl + CH_4 \rightarrow$ **HCl** $+ CH_3$

$ClO + HO_2 \rightarrow$ **HOCl** $+ O_2$

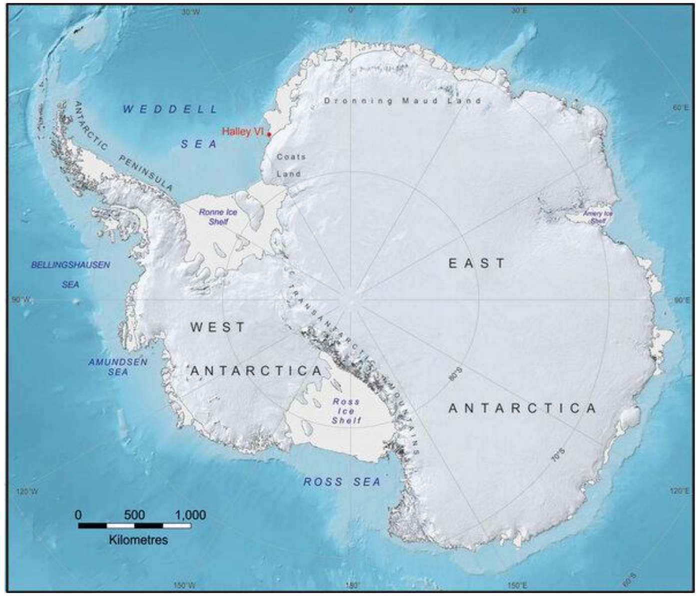
$ClO + NO_2 + M \rightarrow$ **$ClONO_2$** $+ M$

- CFCs originate from cooling agents and other applications. They have first been synthesized in 1928. $CFCl_3$ and CF_2Cl_2 are the most common (Freon).
- They have a long lifetime (several hundred years) because they are basically inert, only solar radiation in the stratosphere can photolyze them.
- In 1990 85 % of stratospheric chlorine originated from anthropogenic sources.
- CFCs absorb strongly in the infrared and are hence potent greenhouse gases.

Antarctic Ozone hole



Discovered by remote sensing of O_3 from Halley base in 1985.



https://atmosphere.copernicus.eu/three-peculiar-antarctic-ozone-hole-seasons-row-what-we-know

https://twitter.com/BAS_News/status/298753260574097408/photo/1

Antarctic Ozone hole

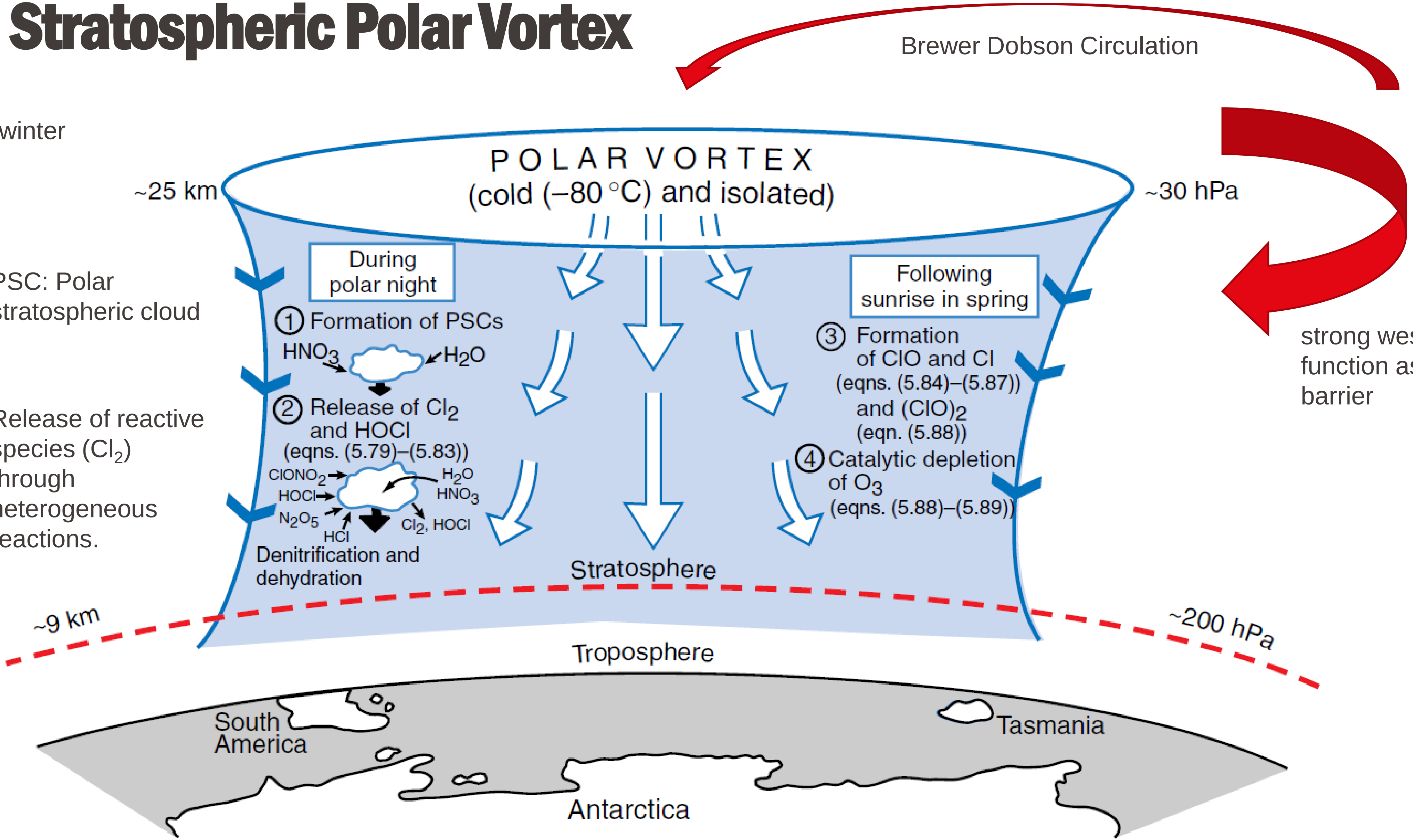
- Why over Antarctica?
- Why during spring?
- Why could models not predict it?

Stratospheric Polar Vortex

Builds up in winter

PSC: Polar stratospheric cloud

Release of reactive species (Cl_2) through heterogeneous reactions.

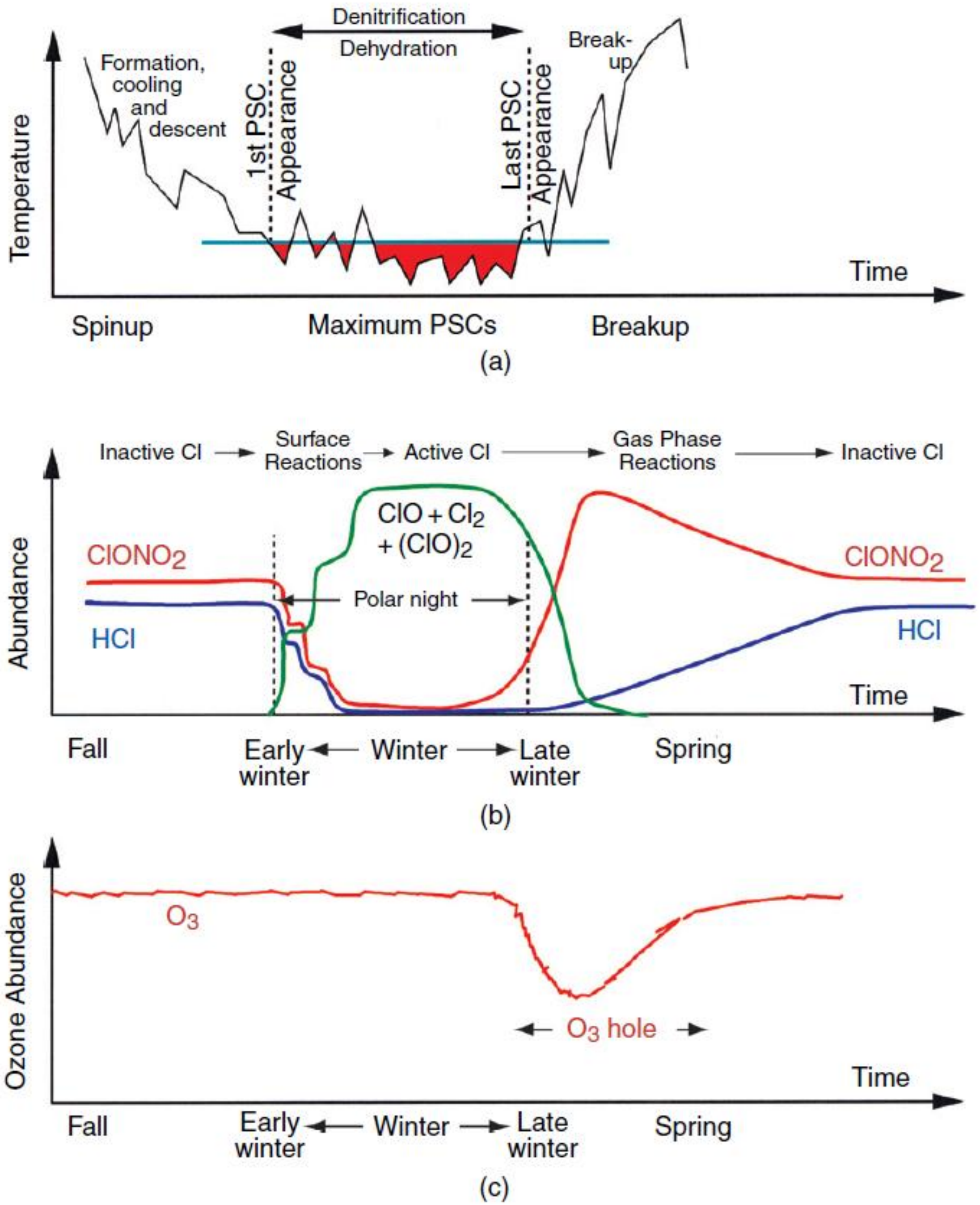


strong westerly winds function as transport barrier

Wallace and Hobbs, 2006, Fig. 5.21

Dynamics and chemistry work together.

Antarctic ozone destruction



Wallace and Hobbs, 2006, Fig. 5.22

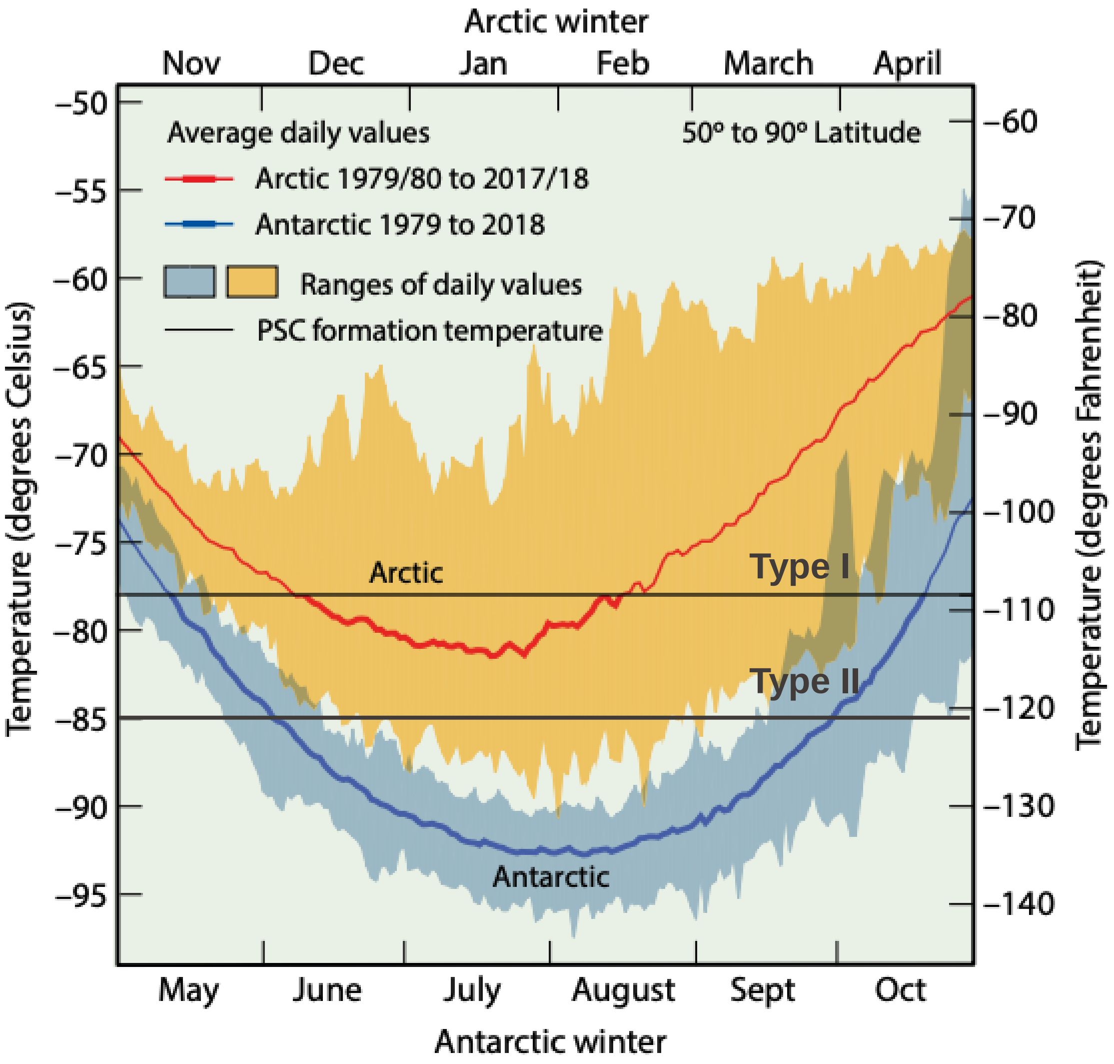
Polar Stratospheric Clouds (PSC)

- Three types of PSCs
  - Type I: forms near -78 °C, mixture of nitric acid trihydrate $HNO_3(H_2O)_3$ (NAT), and HNO_3-H_2O-H_2SO_4, particle size ~1 µm, very slow sedimentation
  - Type II: forms near – 85 °C, HNO_3, H_2O, sulfuric acid tetrahydrate $H_2SO_4(H_2O)_4$ (SAT) particles > 10 µm, settle quickly
  - Type III: rapid freezing of H_2O due to orgagraphic flow, (mother of pearl clouds, short-lived)

https://de.wikipedia.org/wiki/Polare_Stratosph%C3%A4renwolken#/media/Datei:Arctic_stratospheric_cloud.jpg

→ PSCs dehydrate and denitrify the stratosphere.

Polar Stratospheric Clouds (PSC)



Type I:
$HNO_3(H_2O)_3$ (NAT), HNO_3-H_2O-H_2SO_4
Type II:
HNO_3, H_2O, $H_2SO_4(H_2O)_4$ (SAT)

PSCs are responsible for the formation of reactive halogens (e.g., Cl_2) in the stratosphere that deplete ozone.

https://ozone.unep.org/20-questions-and-answers

Heterogeneous chemistry: Adsorption mechanisms

Means at least two phases are involved, e.g., gas and solid or liquid

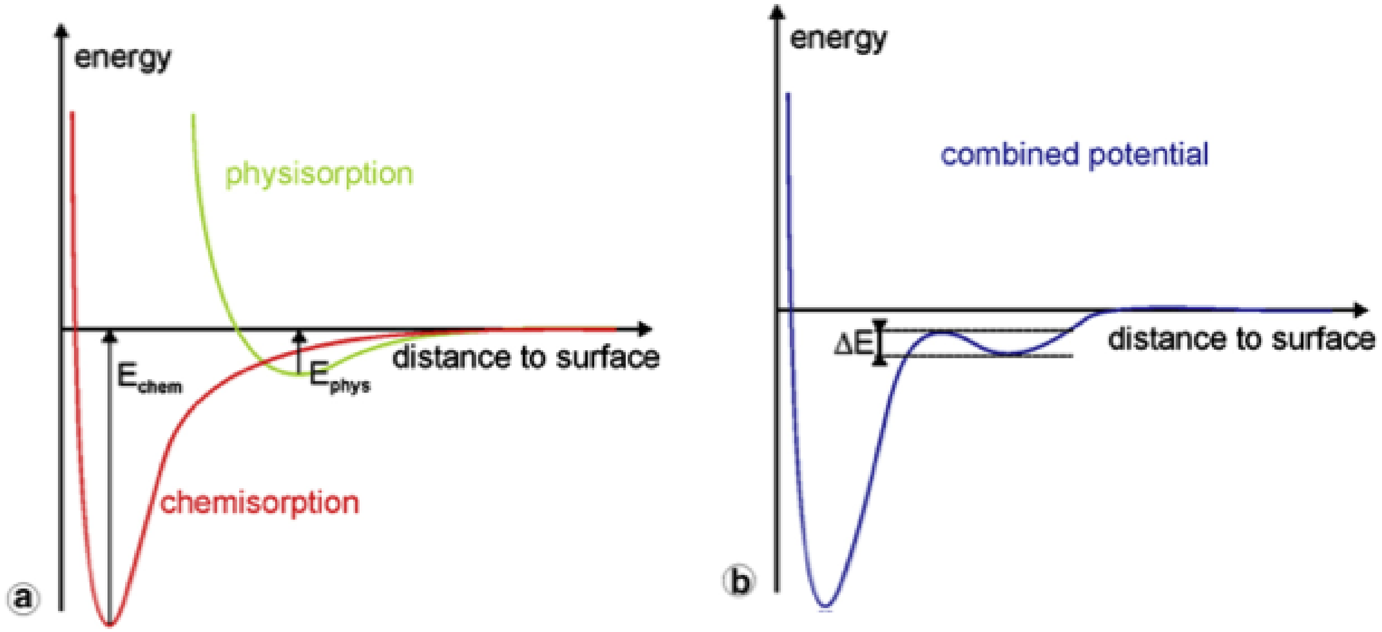
- Physisorption (van der Waals forces)
- Chemisorption (bonds forming)

Key reaction to create reactive Cl_2 is:

a) $ClONO_2$(g) + HCl (g) → Cl_2 (g) + HNO_3(g) slow
b) **$ClONO_2$(g) + HCl (s) → Cl_2 (g) + HNO_3(s) fast**

Why is b faster?
HCl is ionized at the ice surface. That means Cl- ions are available for the reaction with $ClONO_2$. This reaction involving ions is faster.
HCl (s) exists because at the cold temperatures HCl is efficiently absorbed by PSC particles that contain water.

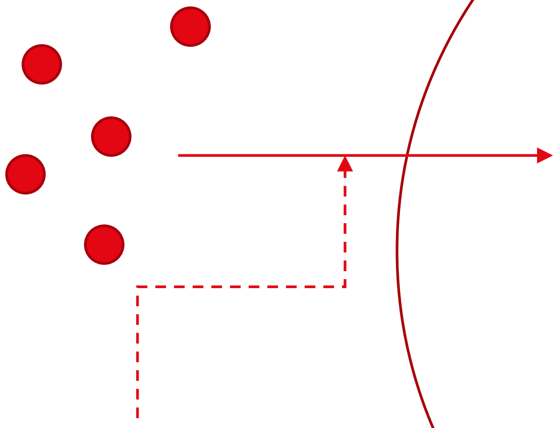
(g) Gas phase
(s) Solid phase, i.e. on ice



Physisorption takes place at larger distances from the surface (d>0.3 nm). Chemisorption originates from strong covalent or ionic bonds at shorter distances. Combining the two effects, a barrier ΔE might exist which needs to be overcome for chemisorption to occur.

Uptake of a gas molecule into a particle

Gas molecules



Aerosol or PSC particle

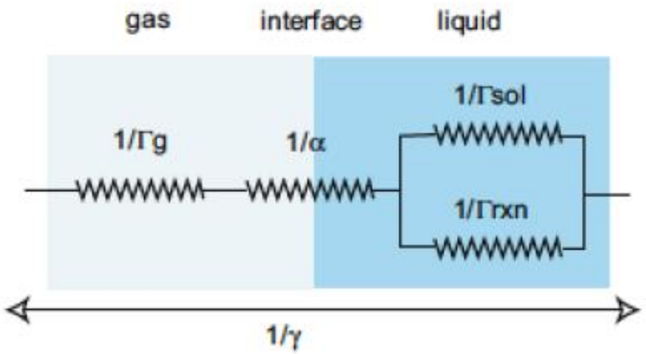


Fig. 1. Schematic of the resistance model for the uptake process.

Morita and Garrett, 2008

The uptake of a molecule *i* into the particle phase needs to overcome a series of resistances to mass transport.

The reciprocal of the overall uptake of molecule *i* is given as the sum of resistances:

$$\frac{1}{\gamma} = \frac{1}{\Gamma_g} + \frac{1}{\alpha} + \frac{1}{\Gamma_{sol} + \Gamma_{rxn}}$$

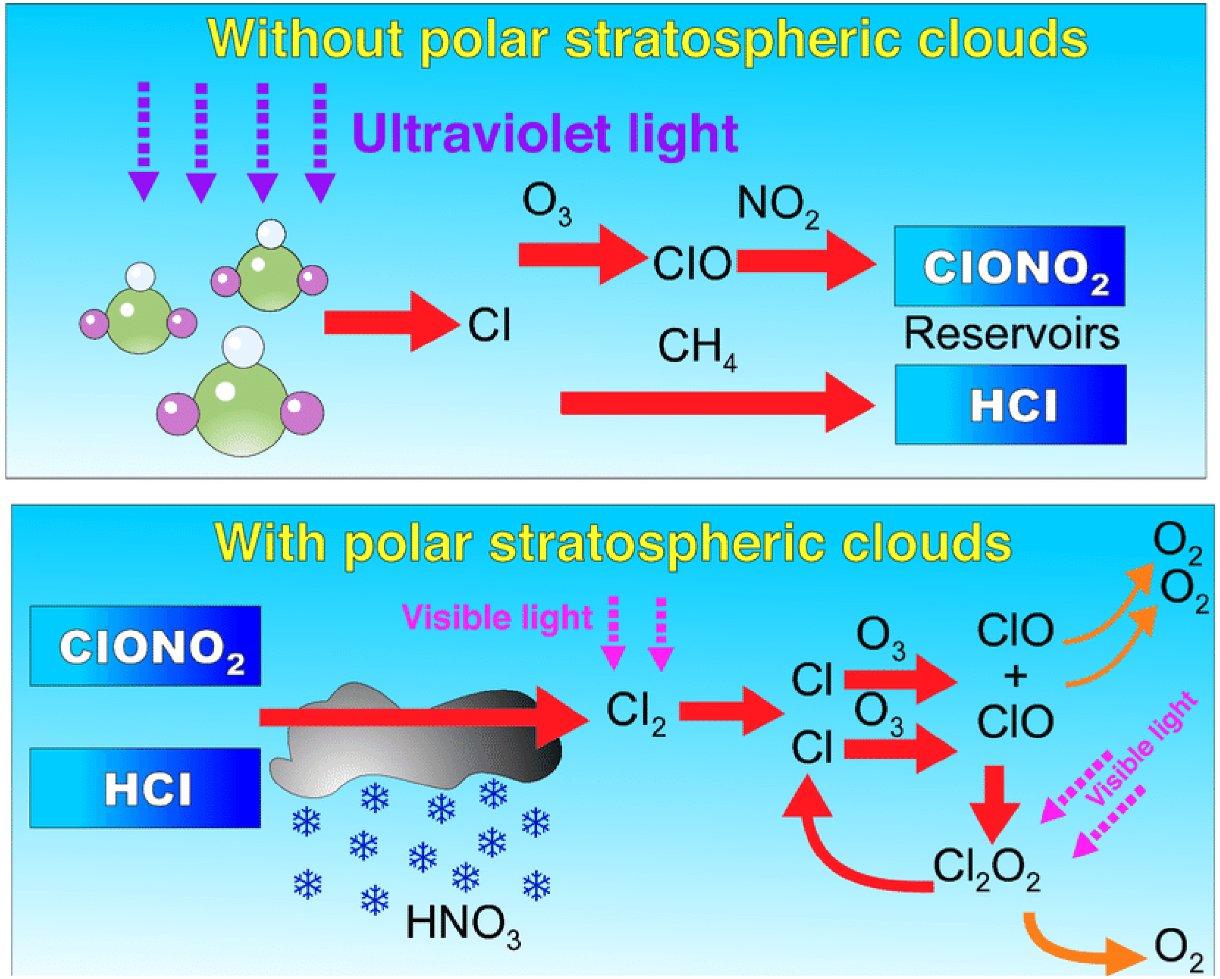
g	gasphase diffusion
α	mass accommodation coefficient (i.e. «sticking probability» of a molecule at the interface)
sol	dissolution
rxn	reaction

Heterogeneous chemistry on PSC

Important because they convert the benign Cl-reservoir species into reactive species, and they remove HNO_3 (denitrification) leaving more reactive ClO (because NO_x is produced from HNO_3, and NO_x produces the reservoir substance $ClONO_2$).

homogeneous chemistry (gas-phase only)

heterogeneous chemisty (gas and particle phases)



$$Cl + CH_4 \rightarrow HCl + CH_3$$
$$ClO + NO_2 + M \rightarrow ClONO_2 + M$$

(g) Gas phase
(s) Solid phase, i.e. on ice

Reservoir → reactive species

$$ClONO_2(g) + HCl(s) \rightarrow Cl_2(g) + HNO_3(s)$$
$$ClONO_2(g) + H_2O(s) \rightarrow HOCl(g) + HNO_3(s)$$
$$HOCl(g) + HCl(s) \rightarrow Cl_2(g) + H_2O(s)$$
$$N_2O_5(g) + H_2O(s) \rightarrow 2HNO_3(s)$$
$$N_2O_5(g) + HCl(s) \rightarrow ClNO_2(g) + HNO_3(s)$$

$$NO_3 + NO_2 + M \rightarrow N_2O_5 + M$$

DOI:10.13140/RG.2.1.4423.6008, **WMO Antarctic Ozone Bulletin no. 4 - 2012.**

Photolysis during spring and ozone destruction

Photolysis

$$Cl_2 + h\nu \rightarrow 2Cl$$

$$HOCl + h\nu \rightarrow OH + Cl$$

$$ClNO_2 + h\nu \rightarrow Cl + NO_2$$

$$Cl + O_3 \rightarrow ClO + O_2$$

Ozone destruction

$$ClO + ClO + M \rightarrow (ClO)_2 + M$$

$$(ClO)_2 + h\nu \rightarrow Cl + ClOO$$

$$ClOO + M \rightarrow Cl + O_2 + M$$

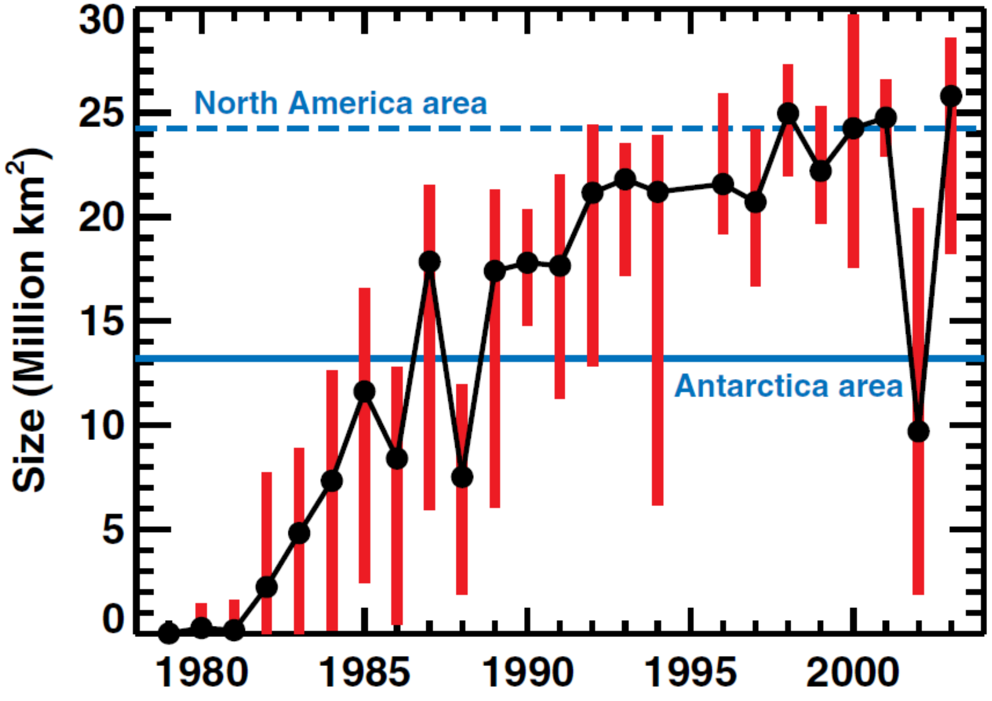
$$2Cl + 2O_3 \rightarrow 2ClO + 2O_2$$

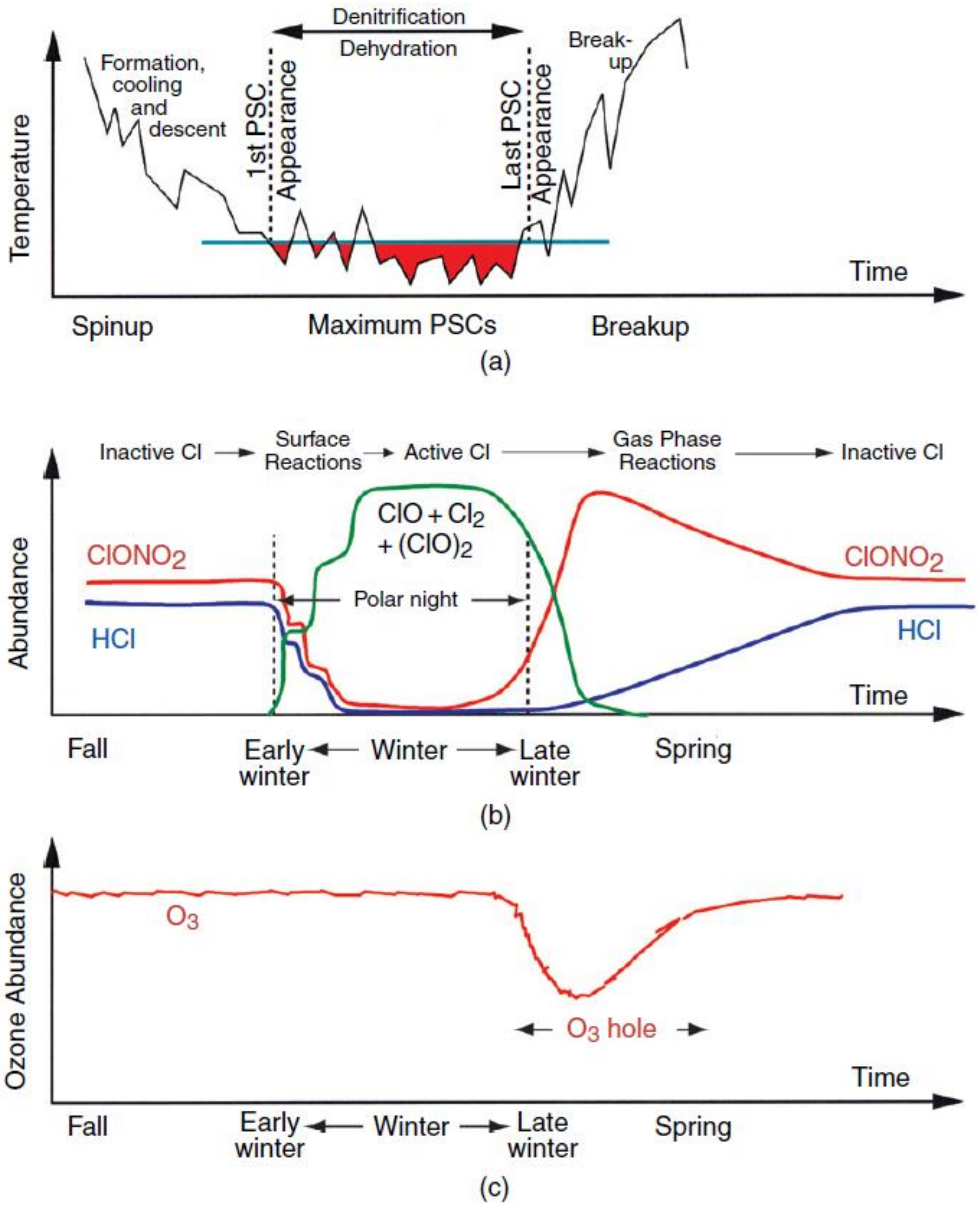
Net: $$2O_3 + h\nu \rightarrow 3O_2$$

- ClO is the catalyst.
- No dependence on atomic oxygen (low abundance at that altitude)
- Cl comes from CFCs, but is normally tied up in reservoir species (HCl, $ClONO_2$)
- In the presence of PSCs, Cl_2, HOCl, and $ClNO_2$ are released and, as soon as the solar radiation reaches sufficient intensity in early spring, Cl and ClO are released, which lead to the rapid depletion of O_3
- The dimer $(ClO)_2$ is formed only at low temperatures. Low enough temperatures are present in the Antarctic stratosphere, where there are also large concentrations of ClO.
- Therefore, the Antarctic stratosphere in spring is a region in which the reaction cycle can destroy large quantities of O_3.

EPFL

Antarctic ozone destruction





Cold temperatures and sunlight are key features that need to be met to produce the ozone hole.

Wallace and Hobbs, 2006, Fig. 5.22

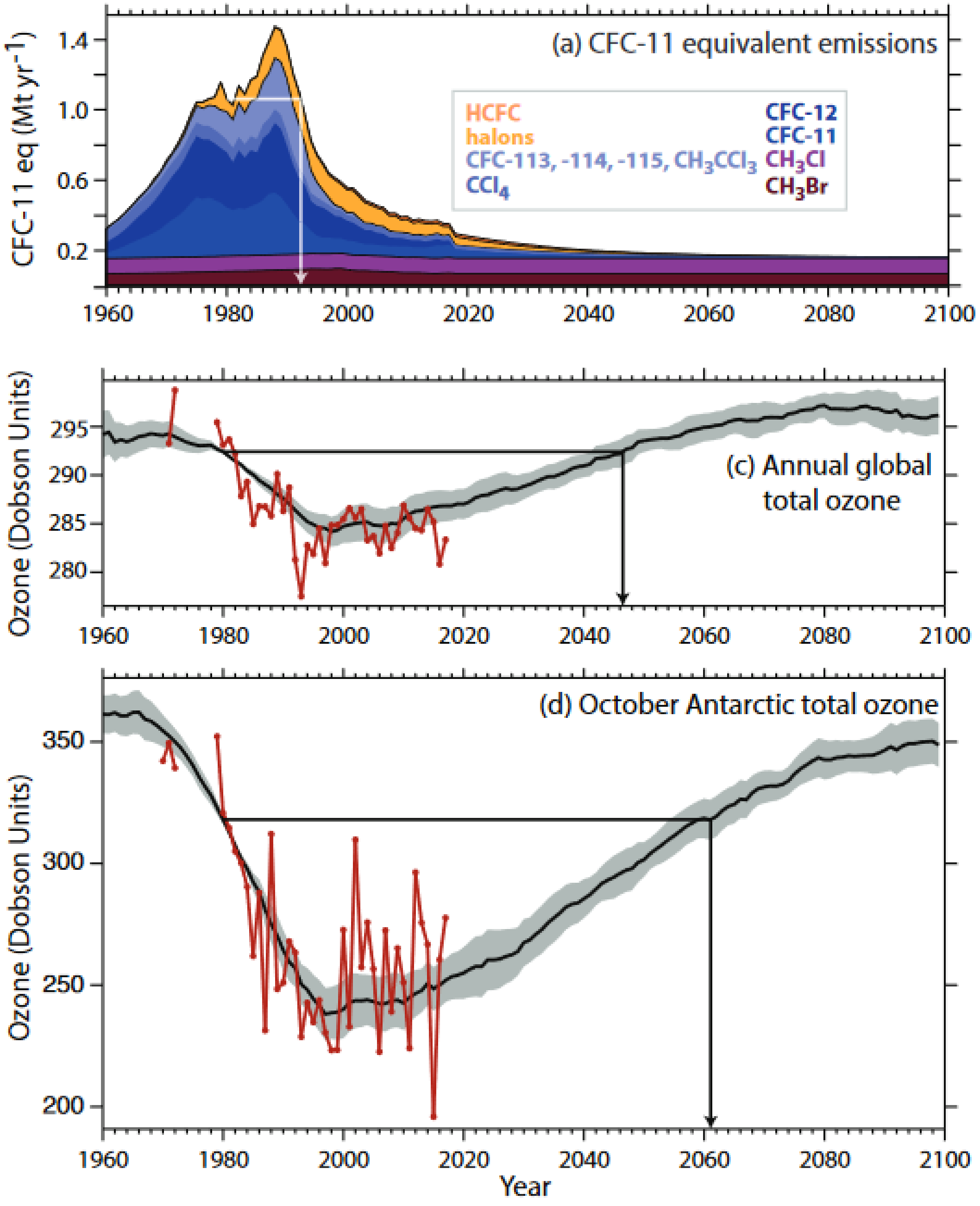
Why was there only a small ozone whole in 2002?

A. The Brewer Dobson Circulation was disturbed by a volcanic eruption.
B. No reservoir species were formed that year, because of a volcanic eruption.
C. There was probably less HCl in the stratosphere.
D. The winter was warm.
E. B and D.

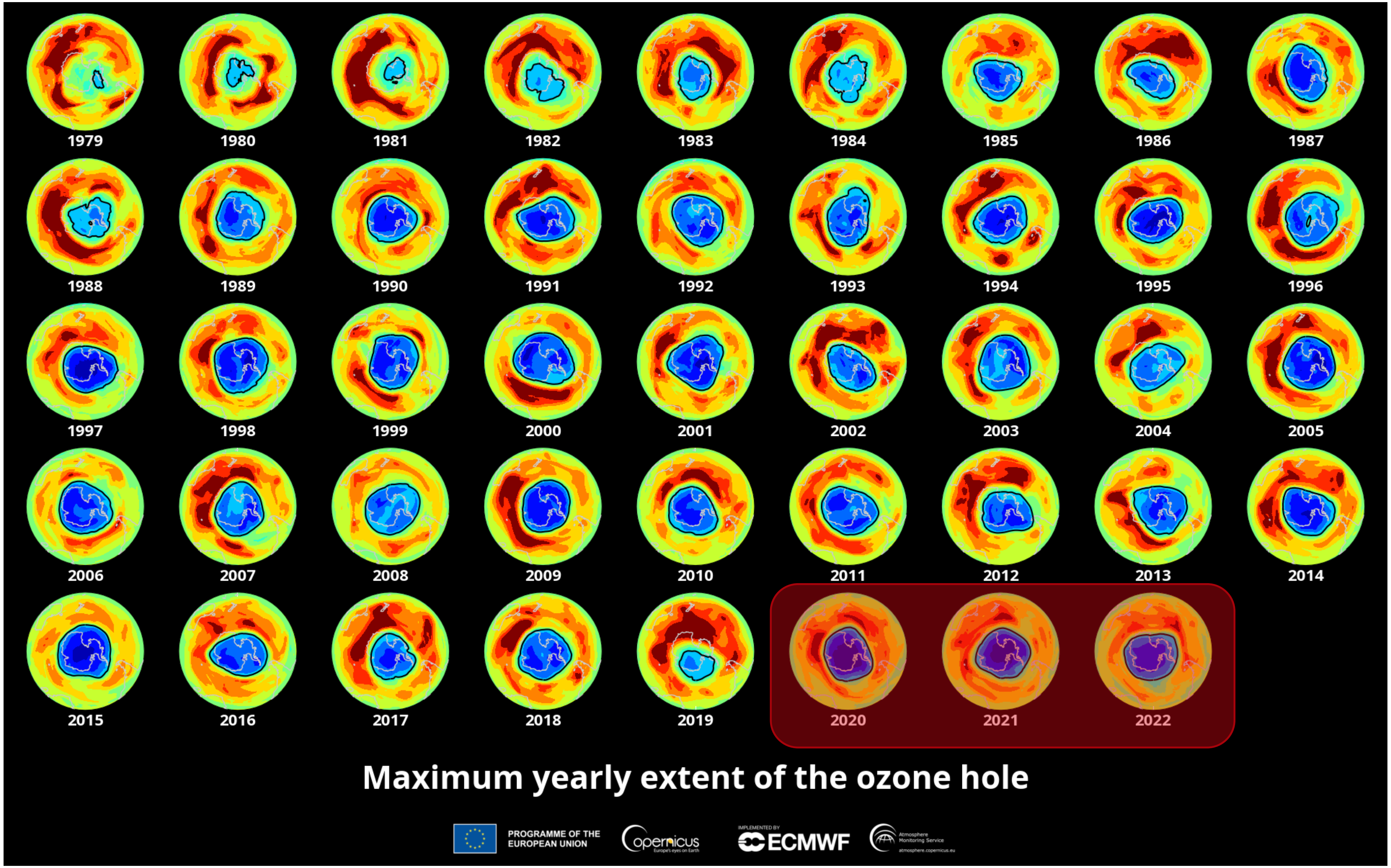
Montreal protocol

WMO (2018) Scientific Assessment of Ozone Depletion: 2018, Figure ES-1

- The Montreal Protocol is the first and only treaty ever to have been ratified by every nation on Earth.
- In 1974 first paper on ozone destruction by CFCs.
- 1985 first paper showing the ozone hole.
- 1985 Vienna convention for the protection of the ozone layer.
- 1987 Montreal protocol to reduce CFCs.
  - Reduction by > 98 % between 1986 and 2016
  - CFCs replaced by HFCs (potent greenhouse gases)
- 1995 Nobel prize (Paul Crutzen, Mario Molina, Sherwood Rowland)
- 2016 Kigali Amendment: reduce HFCs by 85 % in the medium term



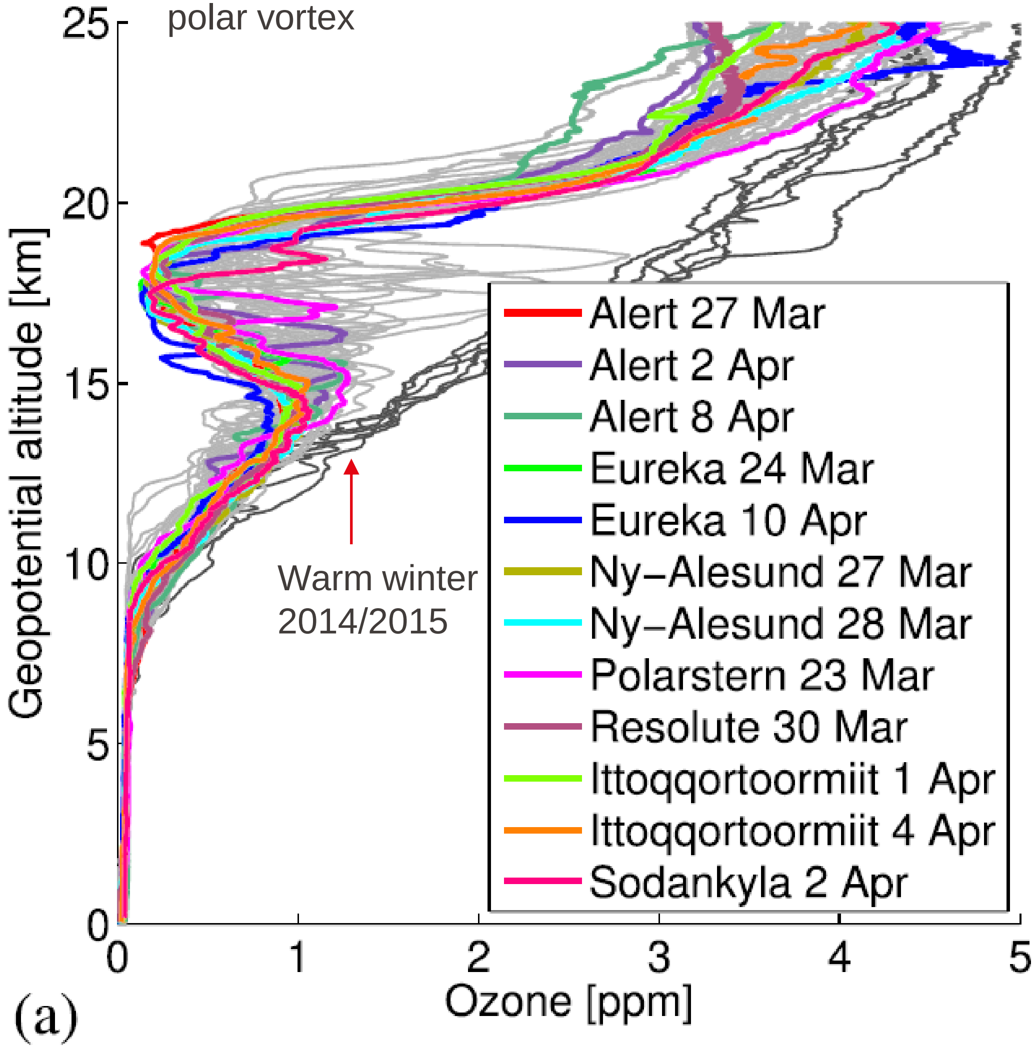
Antarctic Ozone hole



Large ozone holes in 2020-2022

Arctic ozone hole?

Spring 2020, ozone sonde data,
Very cold winter because of very strong polar vortex



- Wohltmann et al., 2020, GRL, DOI: 10.1029/2020GL089547

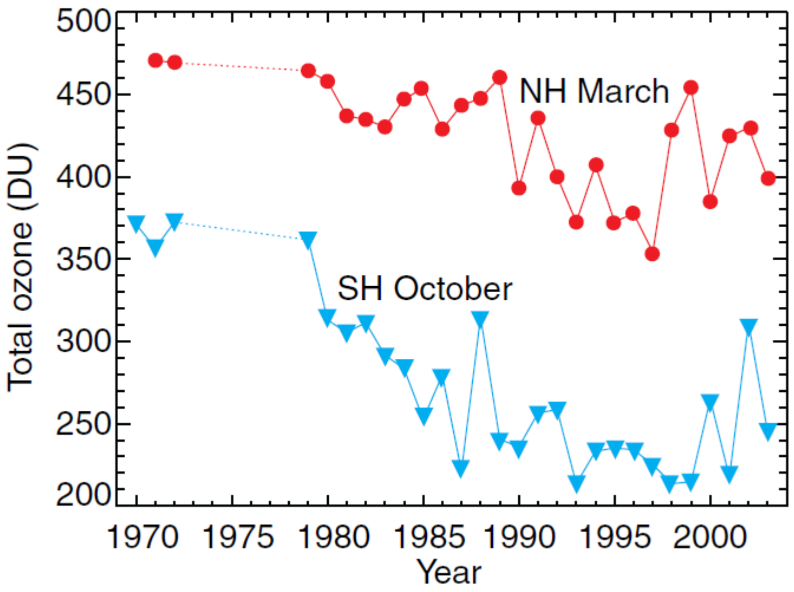


Fig. 5.23 Average ozone columns between latitudes 63°–90° for the northern hemisphere in March (red line and symbols) and the southern hemisphere in October (blue line and symbols). [Adapted with courtesy of P. Newman, NASA Goddard Space Flight Center.]

Wallace and Hobbs, 2006

Can fires contribute to the ozone whole formation?

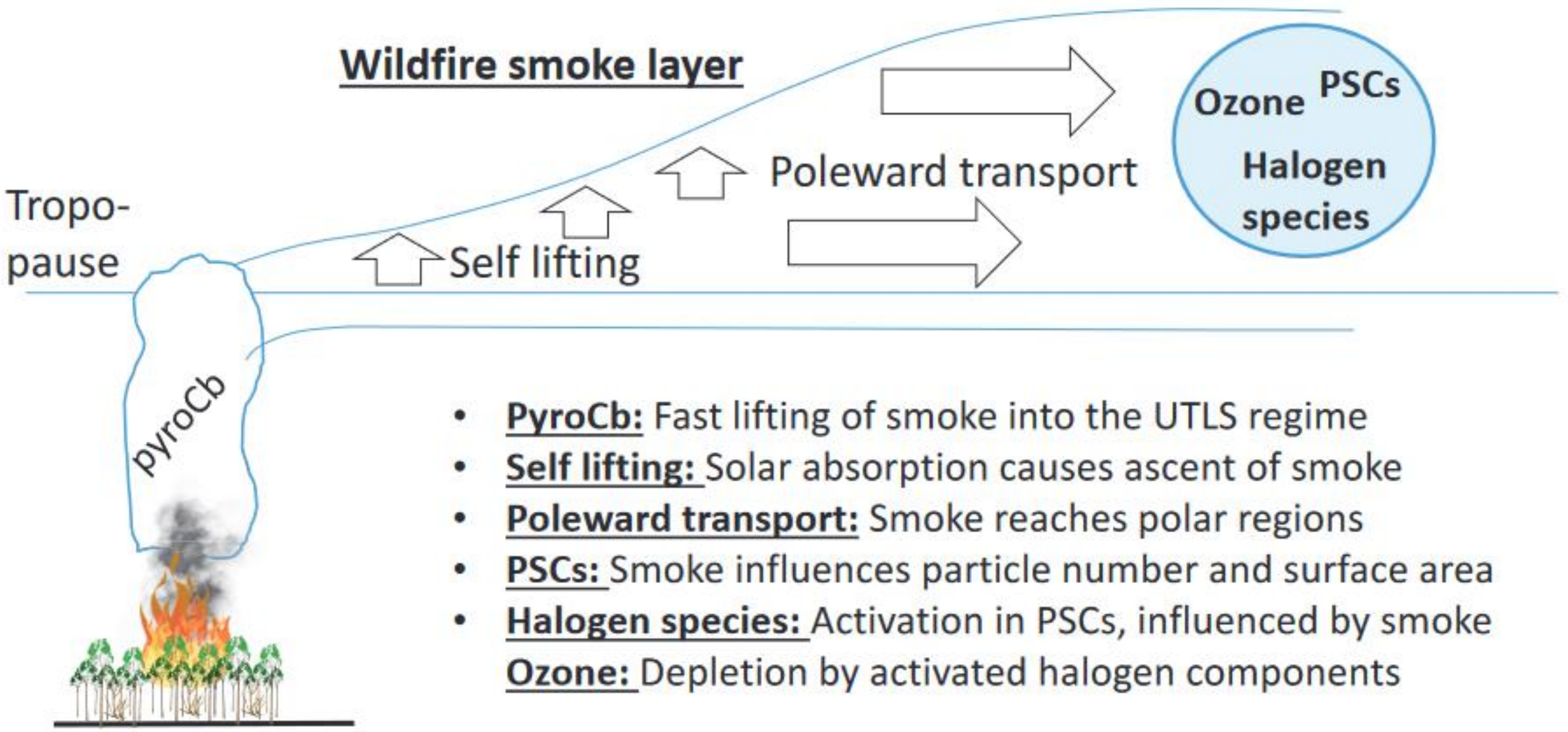
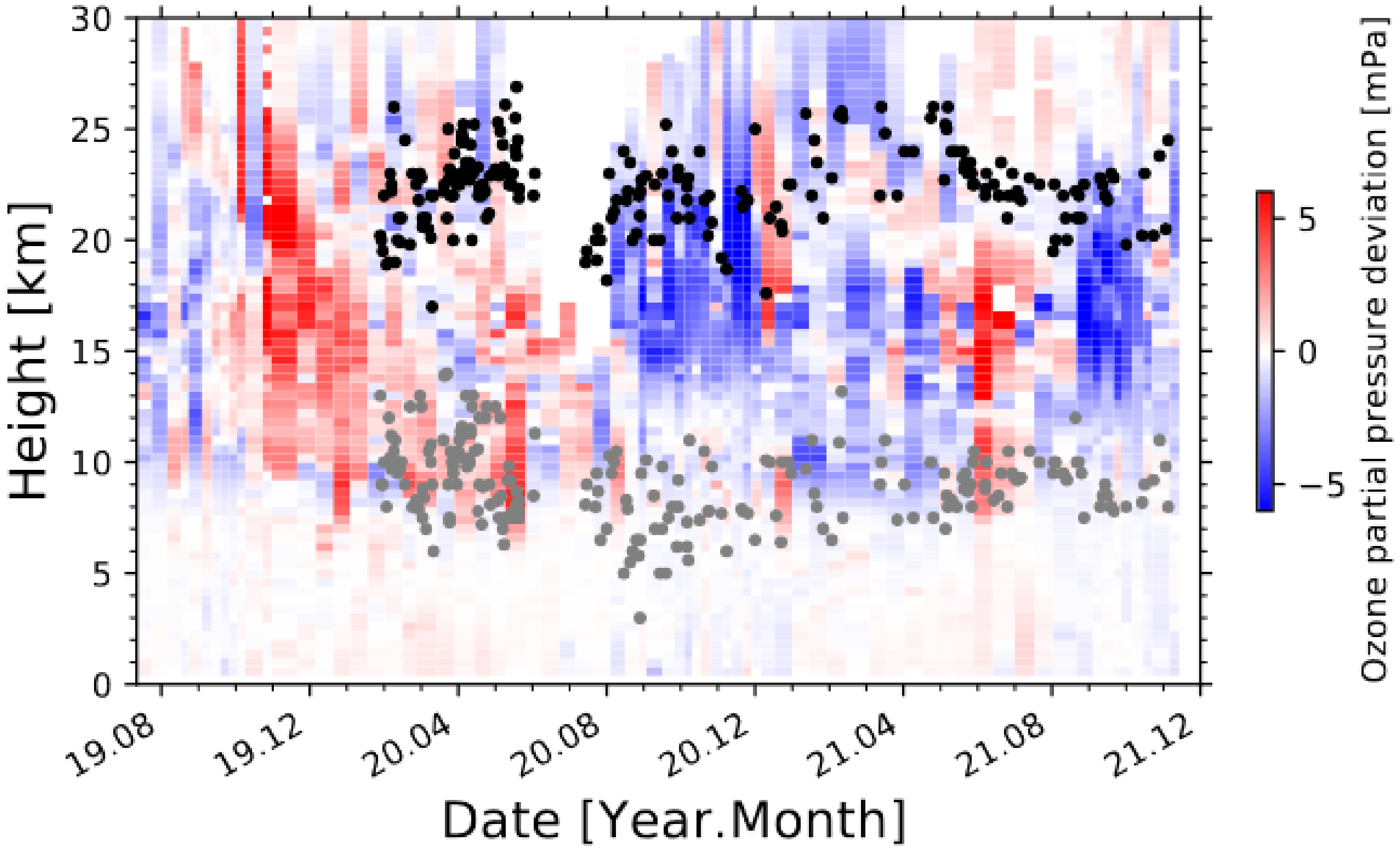


Figure 3. Key processes of the vertical and meridional transport of wildfire smoke from the emission sources to the polar regions.

- Ansmann et al. (2022), https://acp.copernicus.org/preprints/acp-2022-247/acp-2022-247.pdf

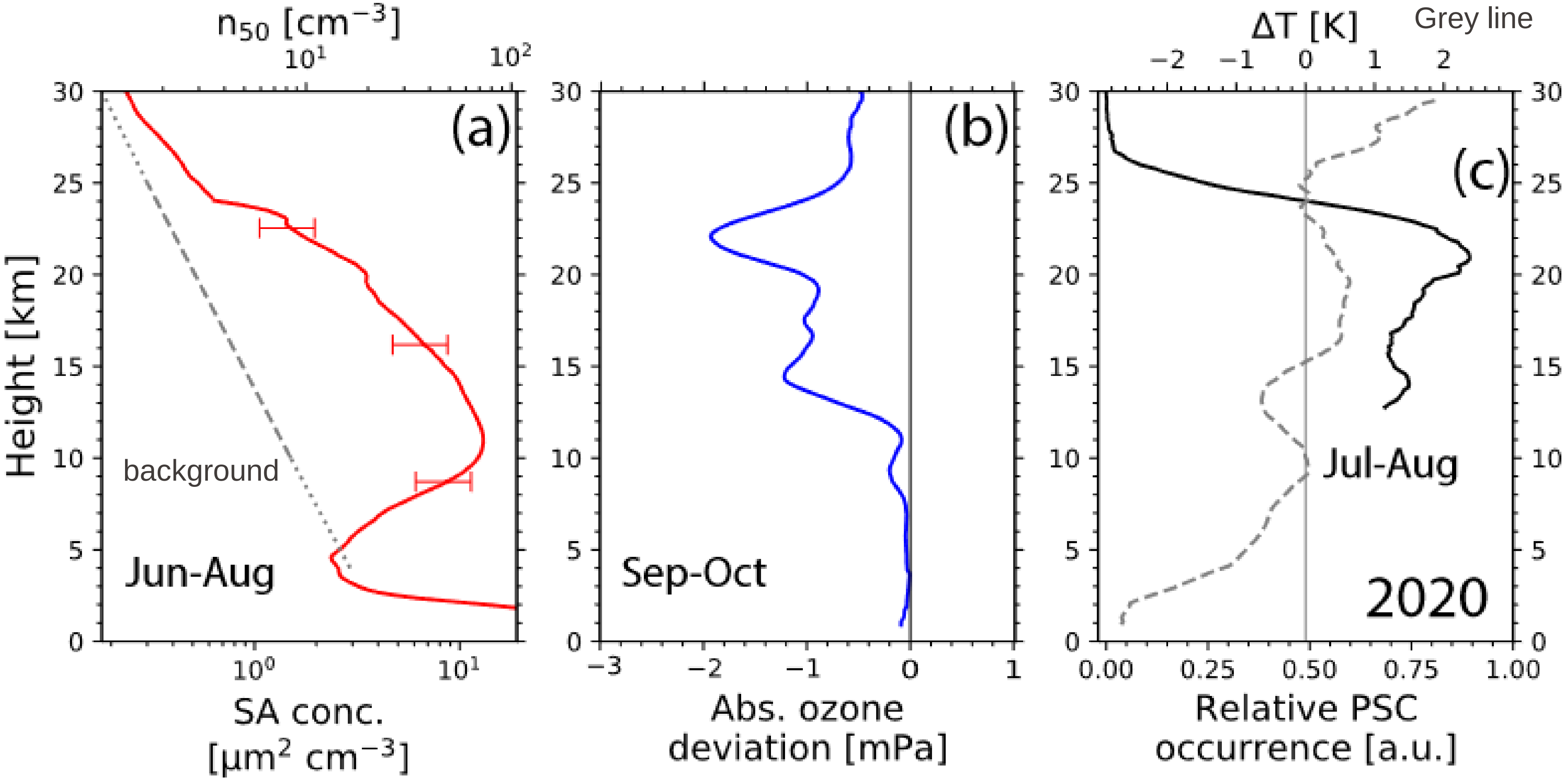
Fires and Antarctic ozone whole



Deviation of individual ozone profiles from the long-term monthly mean (2010-2019) at Neumayer station (70.6°S). Grey and black dots show the aerosol smoke layer from the Australian fires in 2019.

- Ansmann et al. (2022), https://acp.copernicus.org/preprints/acp-2022-247/acp-2022-247.pdf

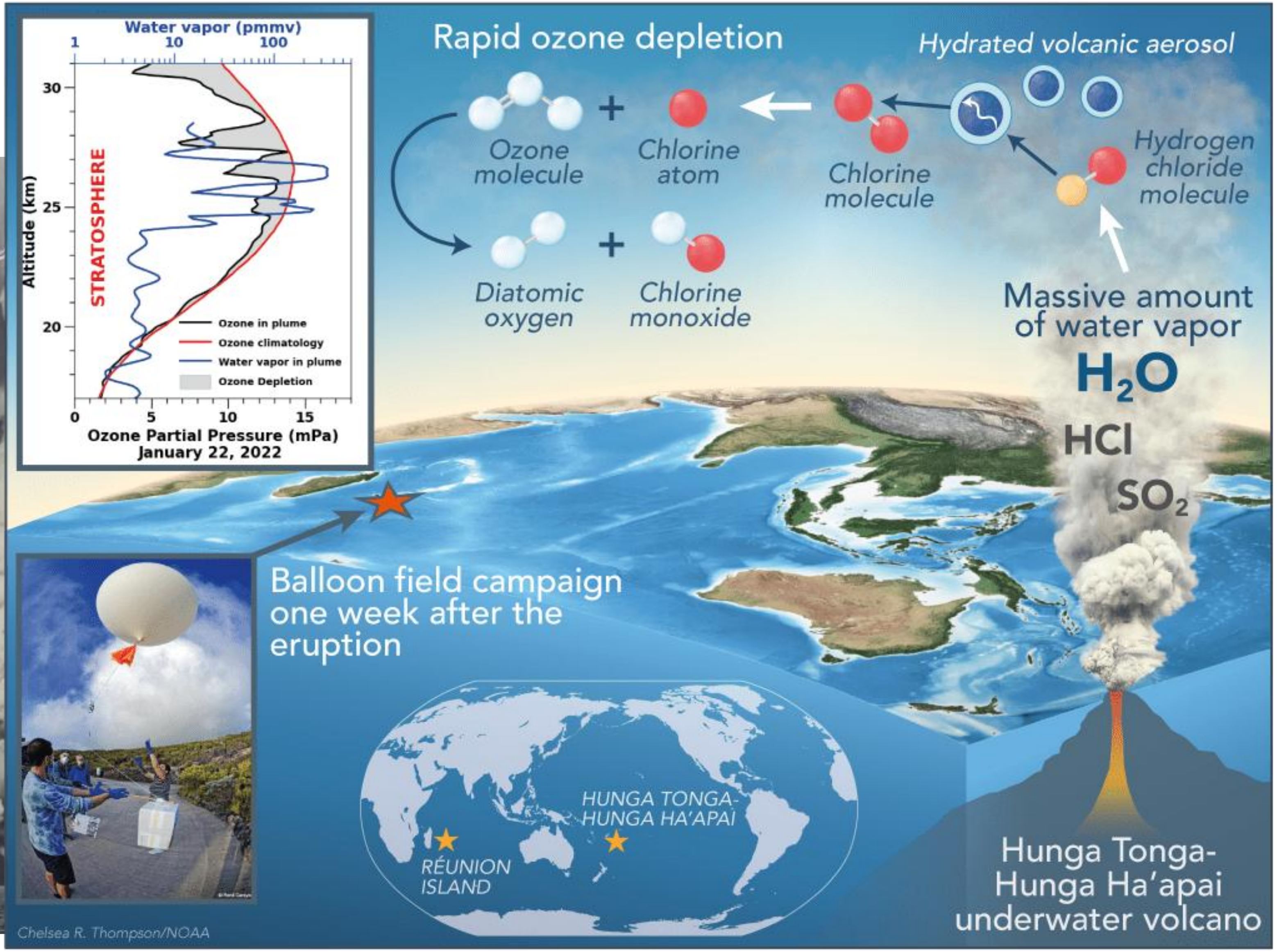
Fires and Antarctic ozone whole



n50 (particles with radius >50 nm)
SA (surface area)
a.u. (arbitrary units)

- Ansmann et al. (2022), https://acp.copernicus.org/preprints/acp-2022-247/acp-2022-247.pdf

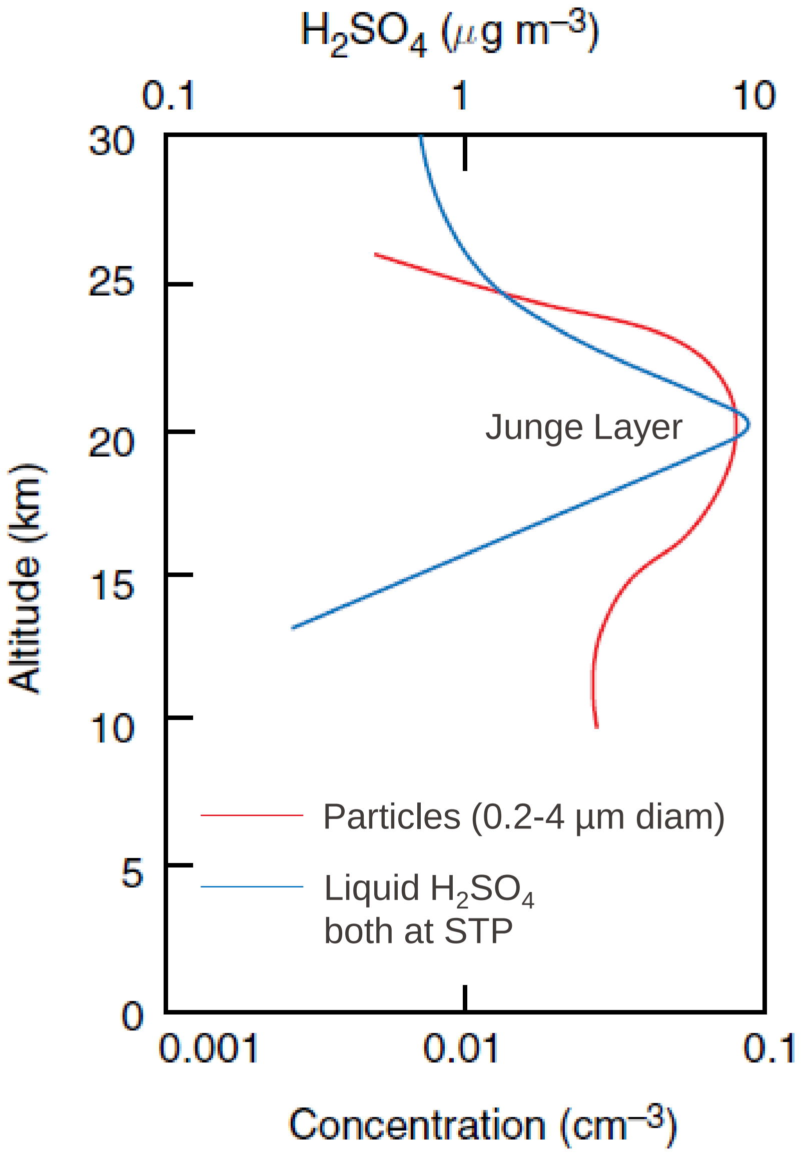
Hunga-Tonga eruption 15 Jan 2022



- https://news.ucsb.edu/2022/020589/tonga-eruption

https://research.noaa.gov/hunga-tonga-2022-eruption/

Stratospheric sulfur (aerosols)



Formation of gaseous H2SO4

$$SO_2 + OH + M \rightarrow HOSO_2 + M$$

$$HOSO_2 + O_2 \rightarrow HO_2 + SO_3$$

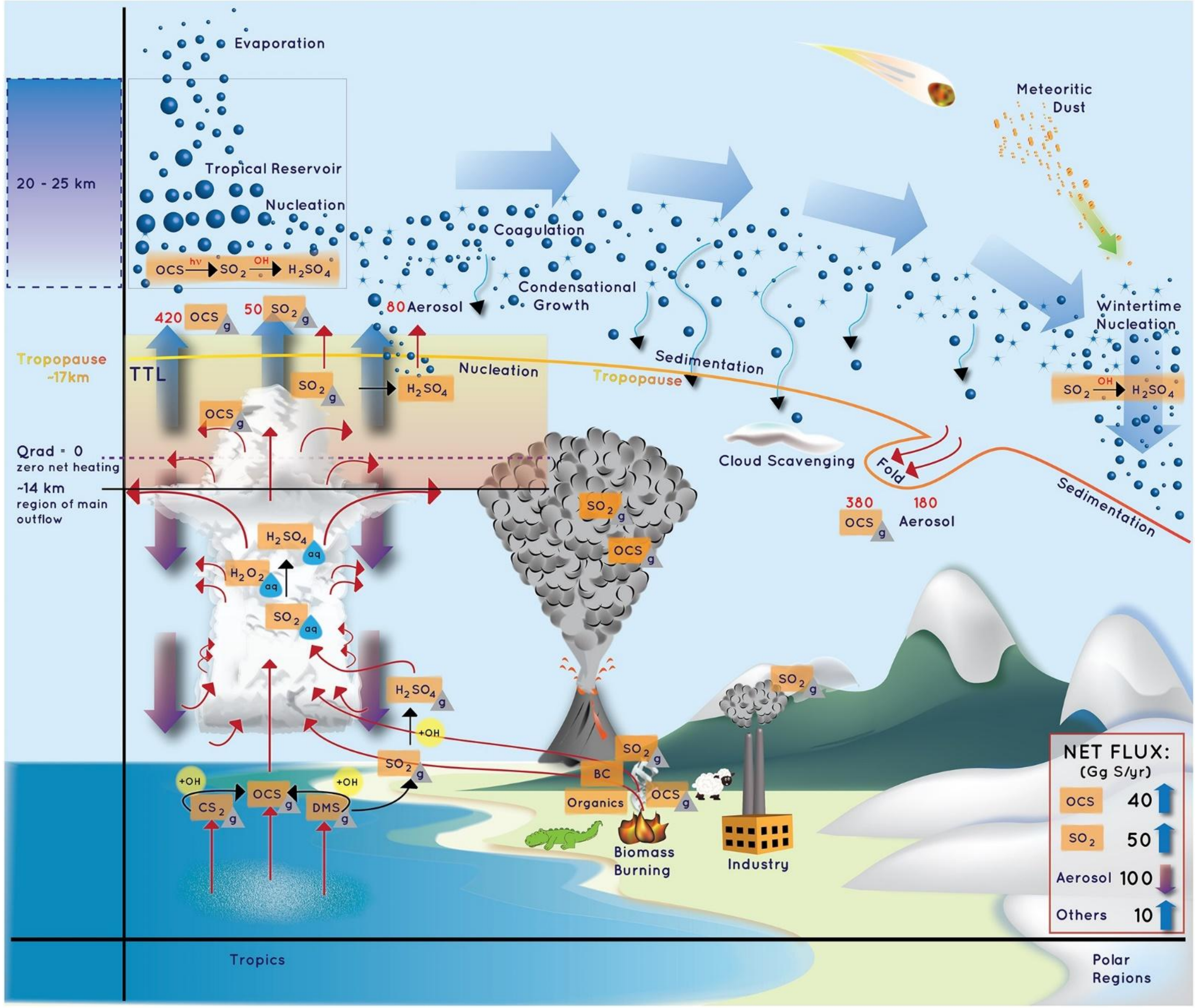
$$SO_2 + O + M \rightarrow SO_3 + M$$

$$SO_3 + H_2O \rightarrow H_2SO_4$$

Particle formation:

- The combination of molecules of H_2SO_4 and H_2O (i.e., ***homogeneous, bimolecular nucleation***) and or the combination of H_2SO_4, H_2O, and HNO_3 to form new (primarily sulfuric acid) droplets (i.e., ***homogeneous, heteromolecular nucleation***).
- Vapor condensation of H_2SO_4, H_2O, and HNO_3 onto the surfaces of preexisting particles with radius 0.15 µm (i.e., ***heterogeneous, heteromolecular nucleation***).

Sources of stratospheric aerosols



In absence of volcanic eruptions COS is the most important supply of S in the stratosphere:

$$COS + h\nu \rightarrow CO + S$$

$$S + O_2 \rightarrow SO + O$$

$$O + COS \rightarrow SO + CO$$

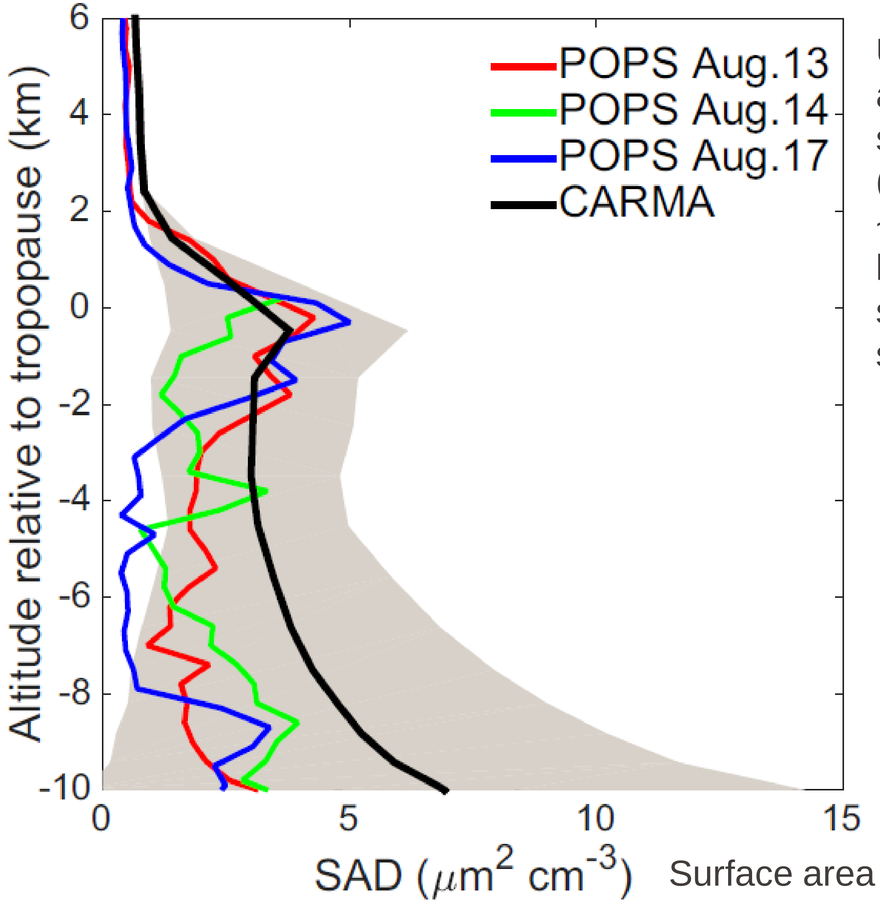
$$SO + O_2 \rightarrow SO_2 + O$$

$$SO + O_3 \rightarrow SO_2 + O_2$$

$$\text{Net: } 2COS + O_2 + O_3 + h\nu \rightarrow 2CO + 2SO_2 + O$$

Kremser et al., 2016, 10.1002/2015RG000511

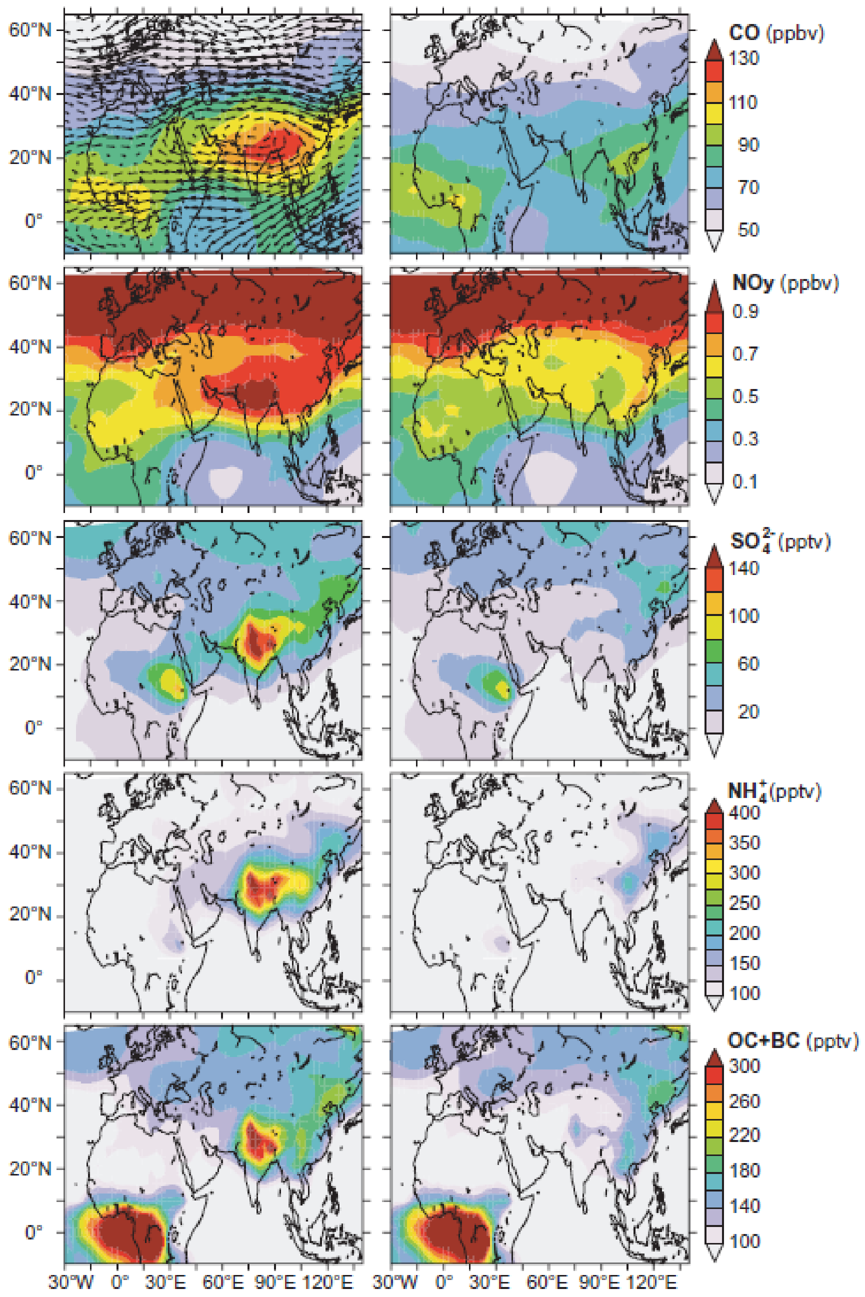
Contribution of Asian Emissions



Surface area density (SAD)

Upward transport of air pollution by Asian summer monsoon (pump).
~15 % of northern hemisphere stratospheric aerosol surface area.

Fig. 2. Influence of South Asian emissions. Model-calculated mean CO, plus wind field, NO_y (NO_x and all other oxidized nitrogen species except N_2O), sulfate, ammonium, and carbonaceous (OC and BC) aerosol at 200 hPa (~12 km altitude) during summer. Results with all emissions (left) and without South Asian anthropogenic emissions (right) are shown. For additional results, also at 100 hPa (~16 km altitude), see figs. S6 to S12.



All emissions | **Without south Asian anthropogenic**

Yu et al., PNAS, 2017, 10.1073/pnas.1701170114

Lelieveld et al., Science, 2018, DOI: 10.1126/science.aar2501

Take home messages

- Know stratosphere-troposphere exchange mechanisms.
- The stratospheric ozone layer protects us from UV radiation.
- Chapman reactions and the missing sink.
- CFCs contribute to ozone destruction at the poles.
  - Cold temperatures and polar stratospheric clouds are needed.
- Also forest fires can contribute to PSC formation.
- There is a natural sulfate aerosol layer in the stratosphere.
- Anthropogenic emissions contribute to aerosol in the stratosphere.