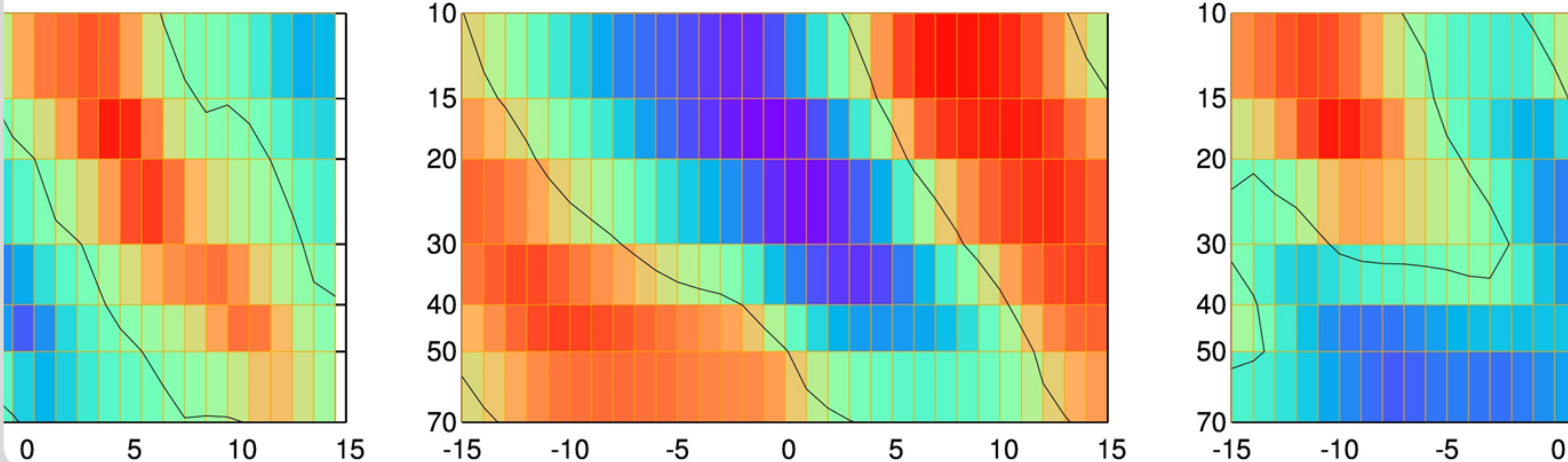
Chemistry-Climate Modelling

Peter Braesicke

IMK-ASF



KIT – Universität des Landes Baden-Württemberg und
nationales Forschungszentrum in der Helmholtz-Gemeinschaft

Structure

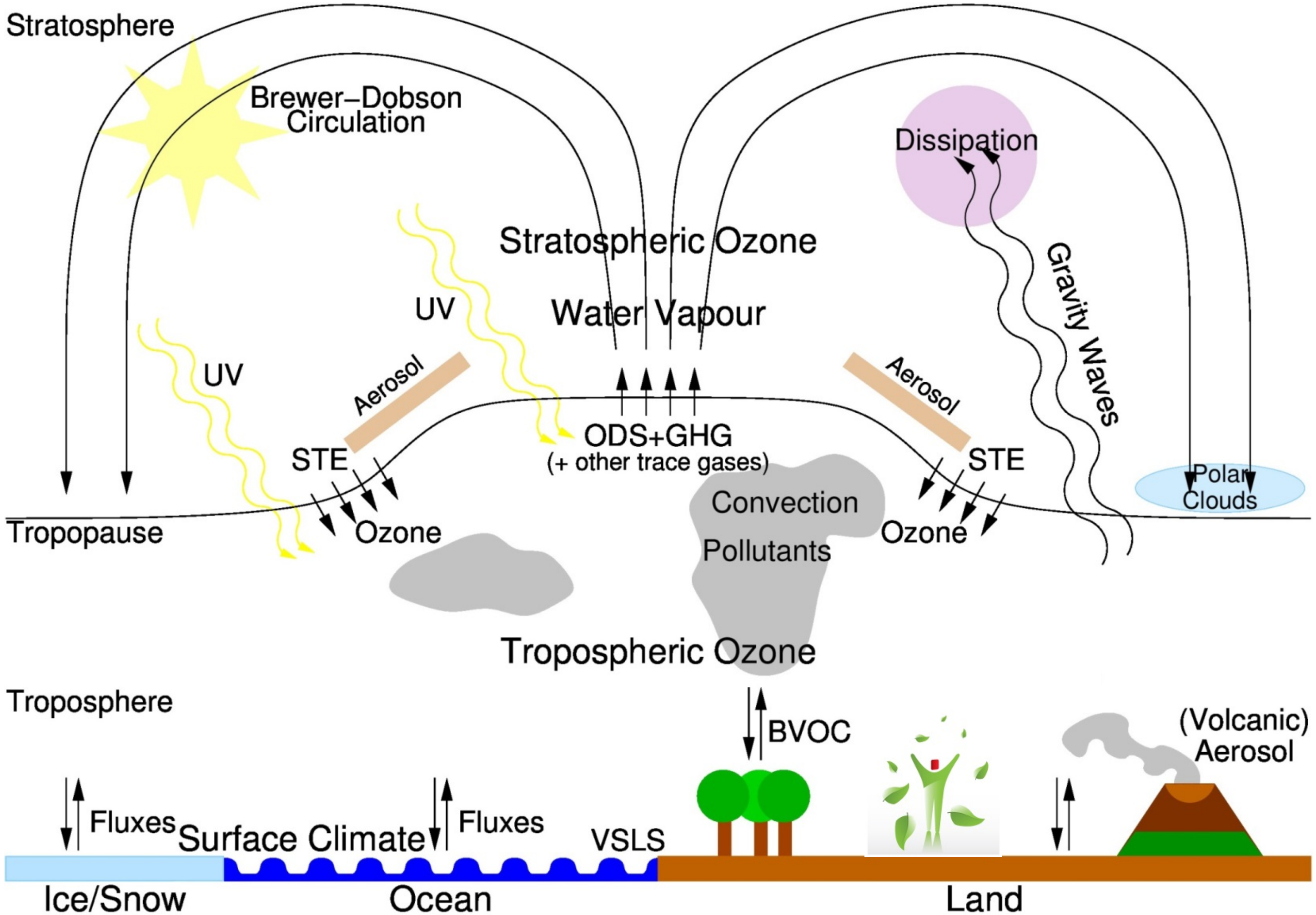
- What is a Chemistry-Climate Model?
  - Model components (sub-models)
  - Model validation (confrontation with observations)
  - CCMs in the context of a model hierarchy

- Examples of processes (Practical, [BDC]):
  - High latitudes: Polar Ozone Depletion
  - [Low latitudes: Quasi-Biennial Oscillation]

What is a Chemistry-Climate Model?

MODEL COMPONENTS

A complex system …



… and we are right in the middle!

Chemistry-Climate Model (CCM) Schematic

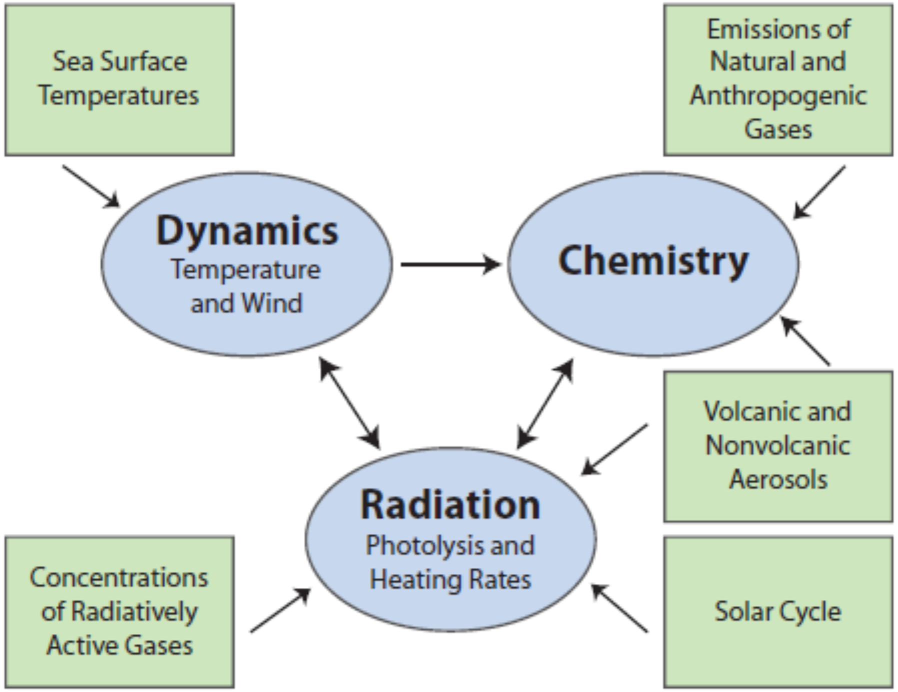
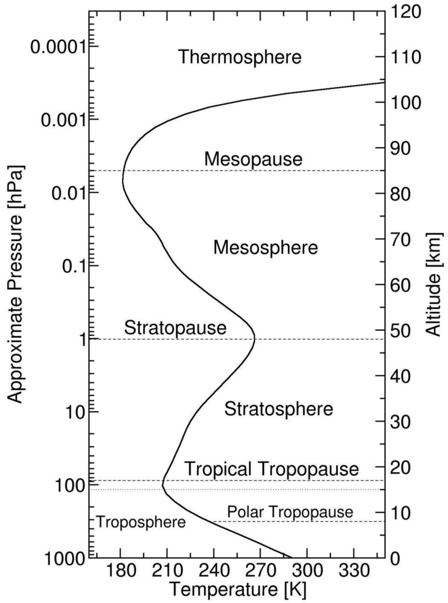


Figure 5-1. Schematic of a Chemistry-Climate Model (CCM). The core of a CCM (oval symbols) consists of an atmospheric general circulation model (AGCM) that includes calculation of the heating and cooling rates and a detailed chemistry module. They are interactively coupled. Photolysis rates are calculated online or are determined from a lookup table. Arrows indicate the direction of effect. Rectangular boxes denote external impacts. In current CCMs, sea surface temperatures (SSTs) are prescribed based on observations or are adopted from calculations with a climate model. Natural and anthropogenic emissions of gases are considered. Tropospheric and stratospheric aerosol loading (especially after volcanic eruptions) can be taken into account. CCMs often consider the changes of solar radiation caused by the 11-year activity cycle of the Sun.

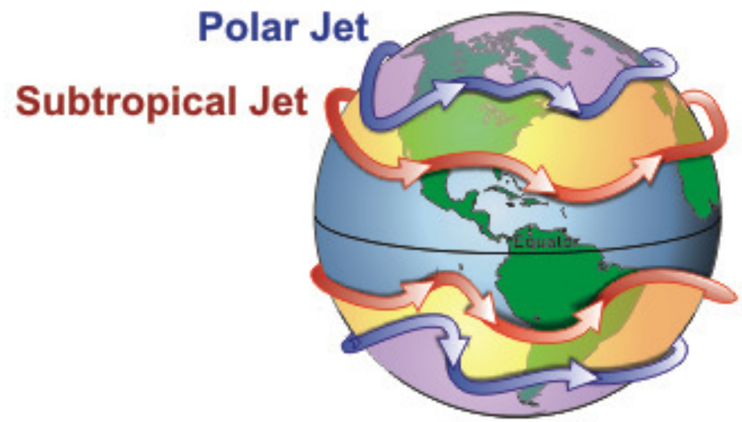
Scientific Assessment of Ozone Depletion: 2006

Dynamics (Thermodynamics)

- Example: Primitive Equations
  - Equations of Motion
    - $\partial u/\partial t = -v \cdot \nabla u - \omega \partial u/\partial p + fv - \partial \Phi/\partial x$
    - $\partial v/\partial t = -v \cdot \nabla v - \omega \partial v/\partial p - fu - \partial \Phi/\partial y$



Vertical Coordinates:
↓ Pressure (p)
Height (z) ↑



Dynamics (Thermodynamics)

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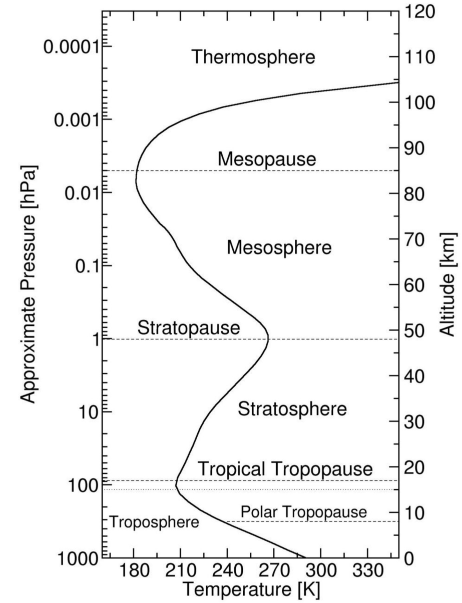
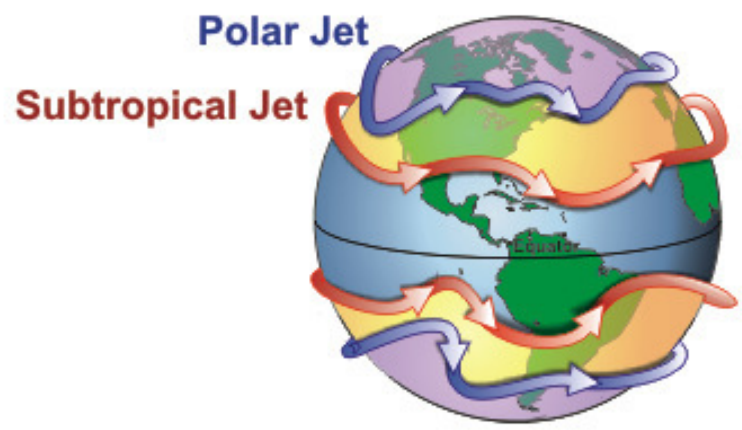
    - $\partial v/\partial t = -v \cdot \nabla v - \omega \partial v/\partial p - fu - \partial \Phi/\partial y$
  - Hydrostatic Assumption (Equation)
    - $\partial \Phi/\partial p = -1/\rho$
  - Temperature Tendency Equation
    - $\partial T/\partial t = -v \cdot \nabla T - \omega \partial T/\partial p + \omega \kappa T/p + T/c_p \; ds/dt$
  - Continuity Equation
    - $\partial \omega/\partial p = -\partial u/\partial x - \partial v/\partial y$





Dynamics (Thermodynamics)

- Example: Primitive Equations
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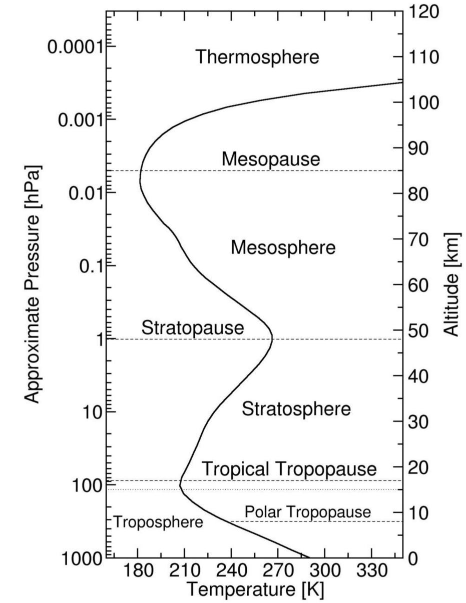
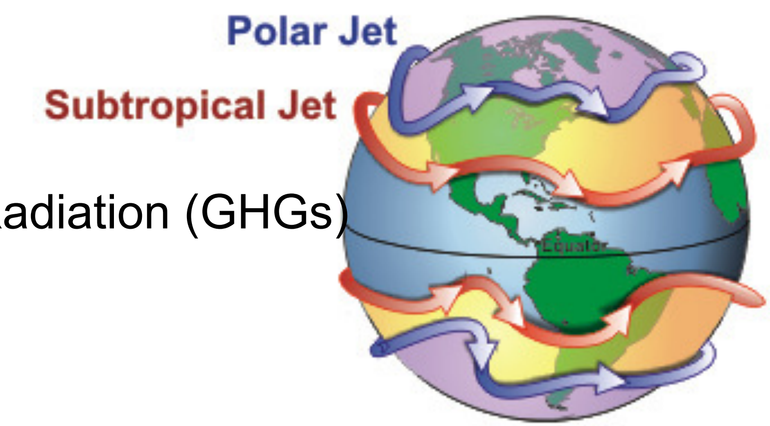


Prognostic Equations
Diagnostic Equations



- 5 Variables: (u, v, w, T, Φ) with $\rho = \rho(T, p)$
- Missing: Specific Humidity (H_2O) and Radiation (GHGs)

Dynamics (Background)

- Geopotential:
  - $g = d\Phi/dz$; $d\Phi = g dz$
  - $[\Phi] = m^2/s^2$
- Geopotential Height:
  - $z = \Phi/g_0$
- Hydrostatic Equilibrium:
  - $dp/dz = -\rho g$
  - $g dz/dp = d\Phi/dp = -1/\rho$
- Ideal Gas Law:
  - $p = \rho R T$
  - $(p = p_A + p_W)$
- Vertical Velocity:
  - $dp = -\rho g dz$
  - $\omega = -\rho g w$
- Enthalpy (specific):
  - $dh = 1/\rho\, dp + T ds$
  - $dh = c_p\, dT$
  - $\Rightarrow p = const. \rightarrow dT = T/c_p\, ds$
- Heating Rate:
  - $dT/dt = T/c_p\, ds/dt$
  - $[dT/dt] = K/s$

$R_A = 287.04\ J/k$

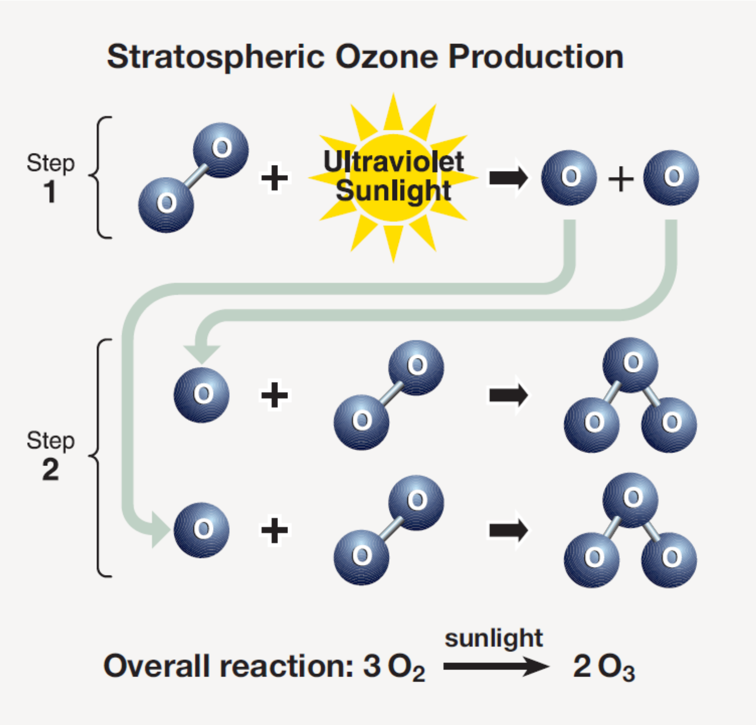
$R_W = 461.50\ J/$

$\kappa = R/c_p = 2/7$

$c_p = 1010\ J/kg$

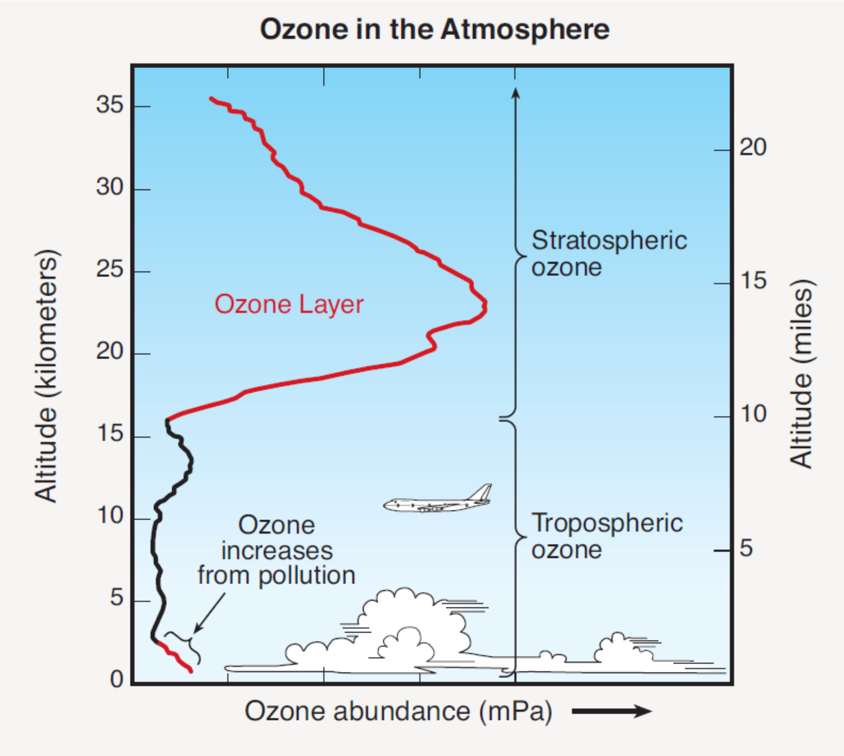
Chemistry (Radiation)

- Gas Phase Ozone Chemistry



(Example)

- Vertical O_3 Distribution



UNEP/WMO Ozone Assessment: 20 Questions

Chemistry (Radiation)

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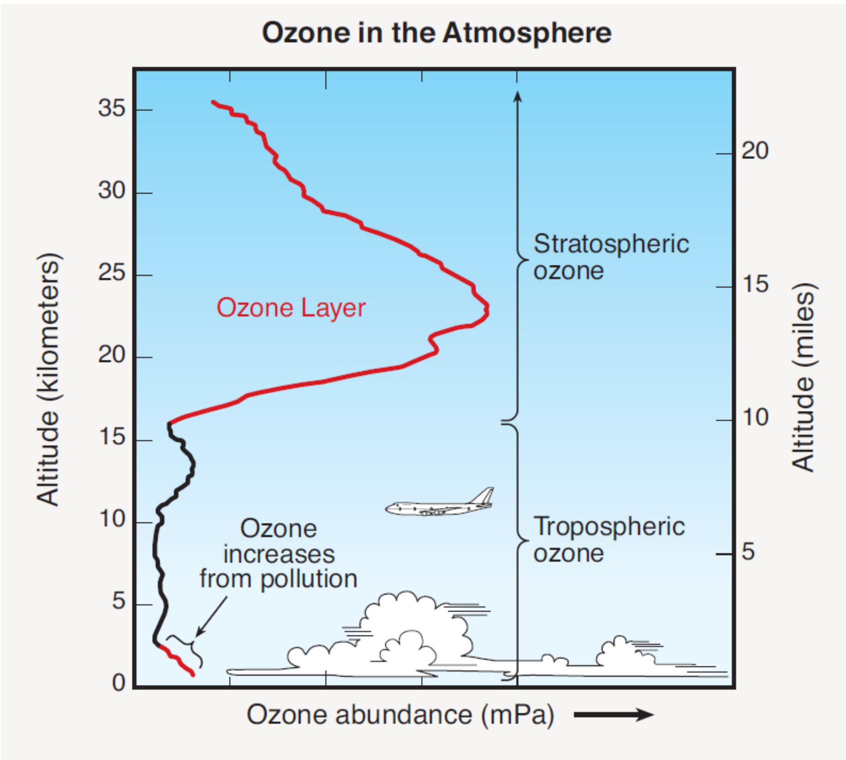
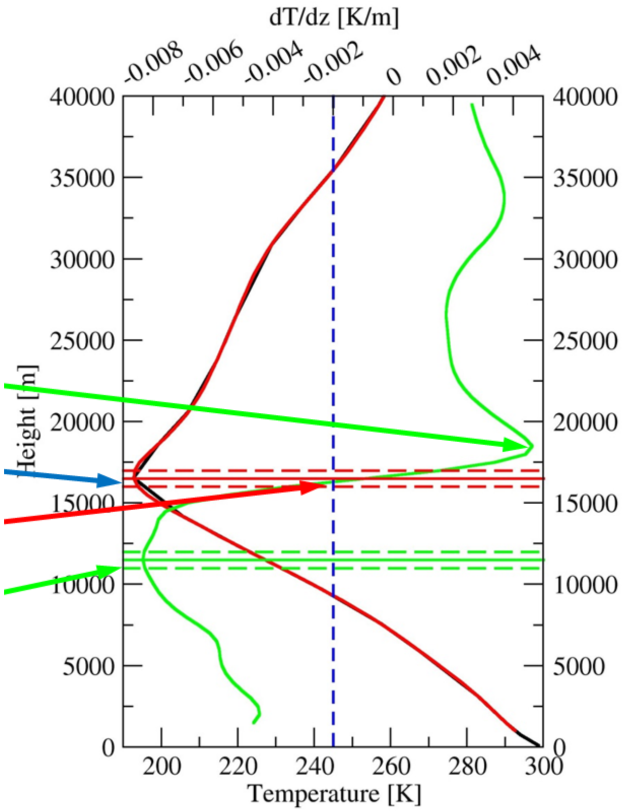
- Vertical O_3 Distribution
- Vertical Temperature Distribution



UNEP/WMO Ozone Assessment: 20 Questions



Chemistry (Radiation)

- Vertical Temperature Distribution

Temperature (tropical latitudes)

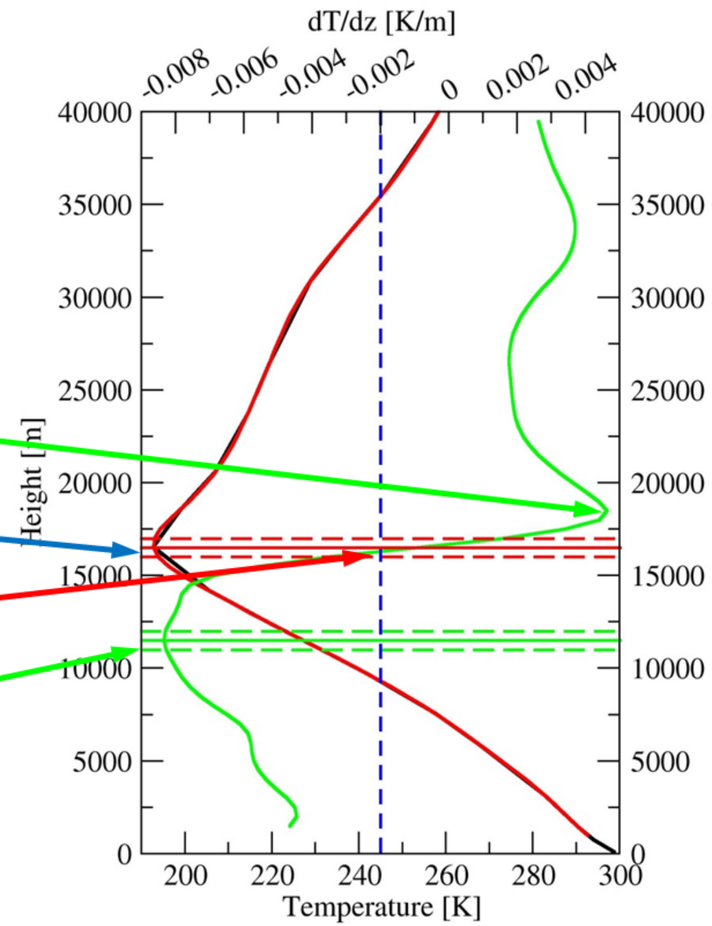
$$-\Gamma = \frac{dT}{dz} > -2\frac{K}{km}$$

Lapse Rate Maximum

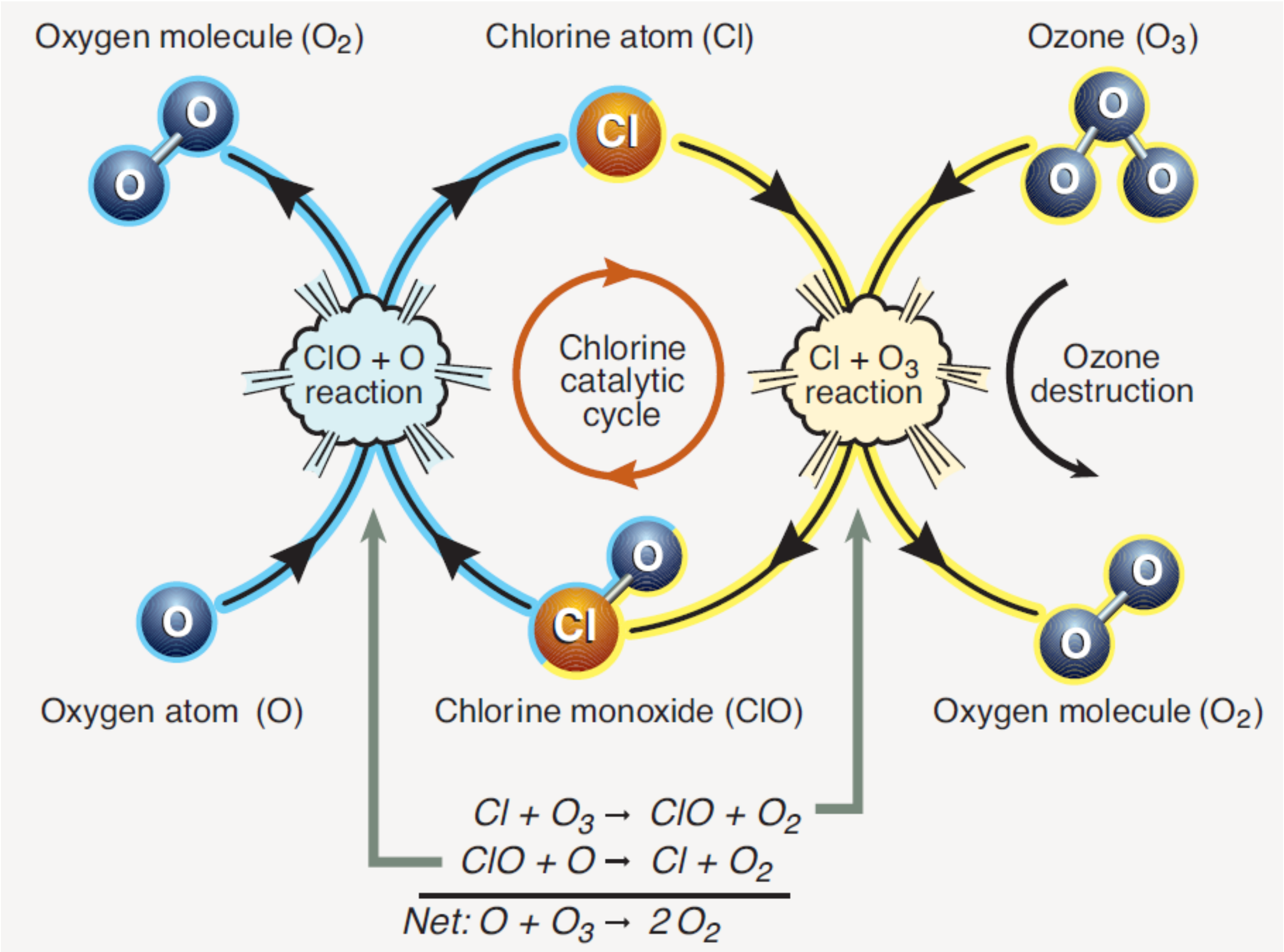
Cold Point

WMO Tropopause

Lapse Rate Minimum



More Chemistry: Ozone Destruction



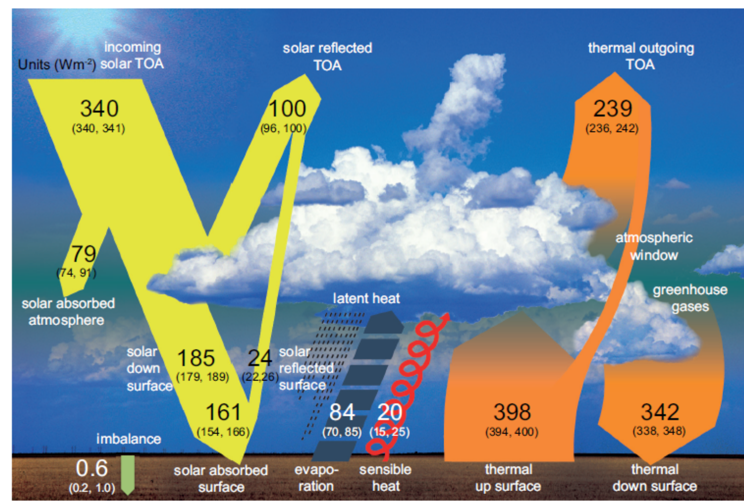
UNEP/WMO Ozone Assessment: 20 Questions

Radiation (Thermodynamics)

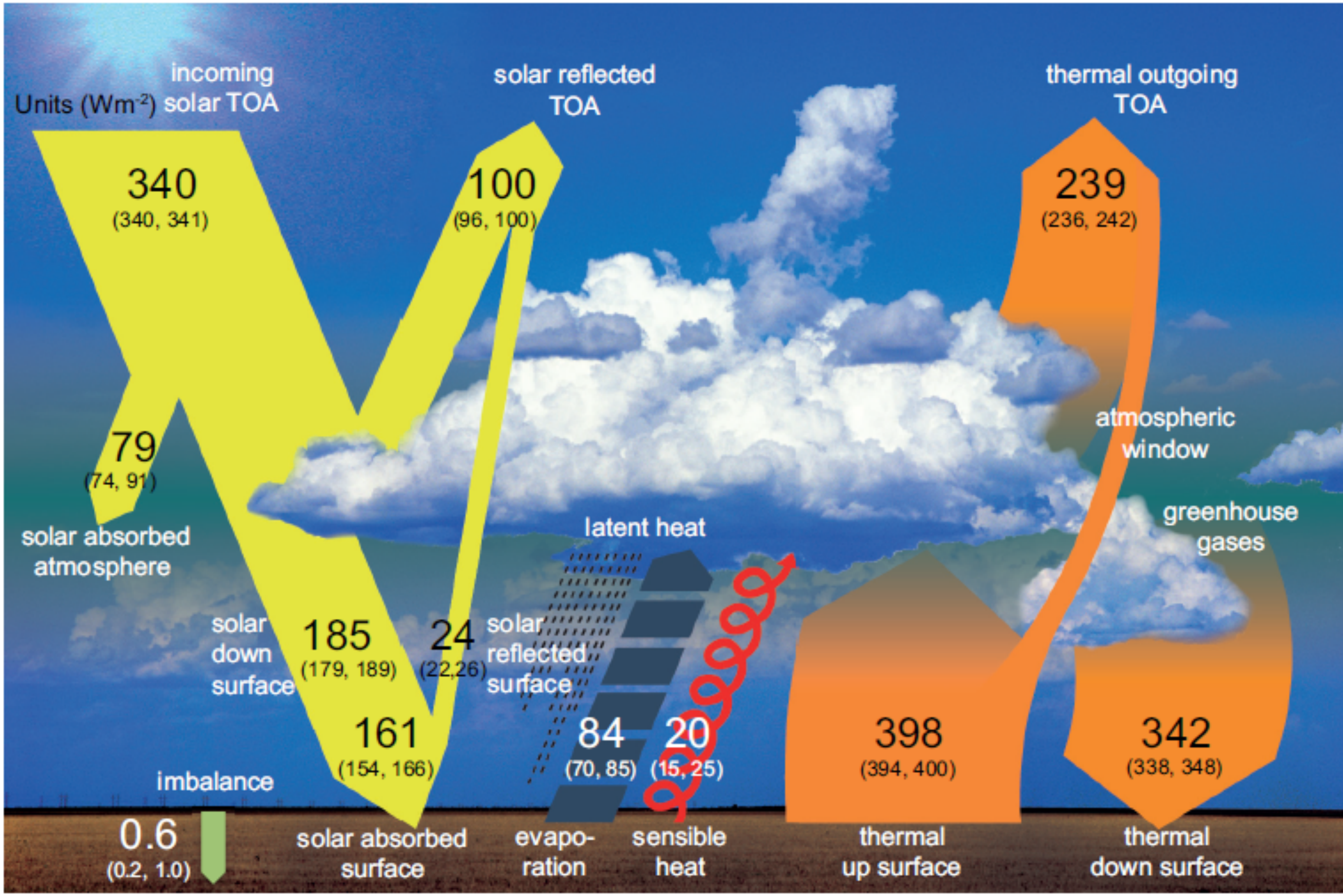
- Black Body / Full Insolation:
  - $E_{out}=\sigma T^4$
  - $E_{in}=1/4\ S_0=342\ W/m^2$
  - $E_{in}=E_{out}\ \Rightarrow T \top T_{Earth}=5°C$
- Black Body / Albedo Effect ($\alpha=0.3$)
  - $E_{out}=\sigma T^4$
  - $E_{in}=1/4\ (1-\alpha) S_0=239\ W/m^2$
  - $E_{in}=E_{out}\ \Rightarrow T \top T_{Earth}=-18°C$
- GHG Effect ($\varepsilon=0.74$) / Albedo Effect
  - $E_{out}=\varepsilon\sigma T^4$
  - $E_{in}=1/4\ (1-\alpha) S_0=239\ W/m^2$
  - $E_{in}=E_{out}\ \Rightarrow T \top T_{Earth}=15°C$

Fact:
$T_{Earth}\sim 15°C$

α: $Albedo$ (~ 0.3)
ε: $Emissivity$ (~ 0.74)

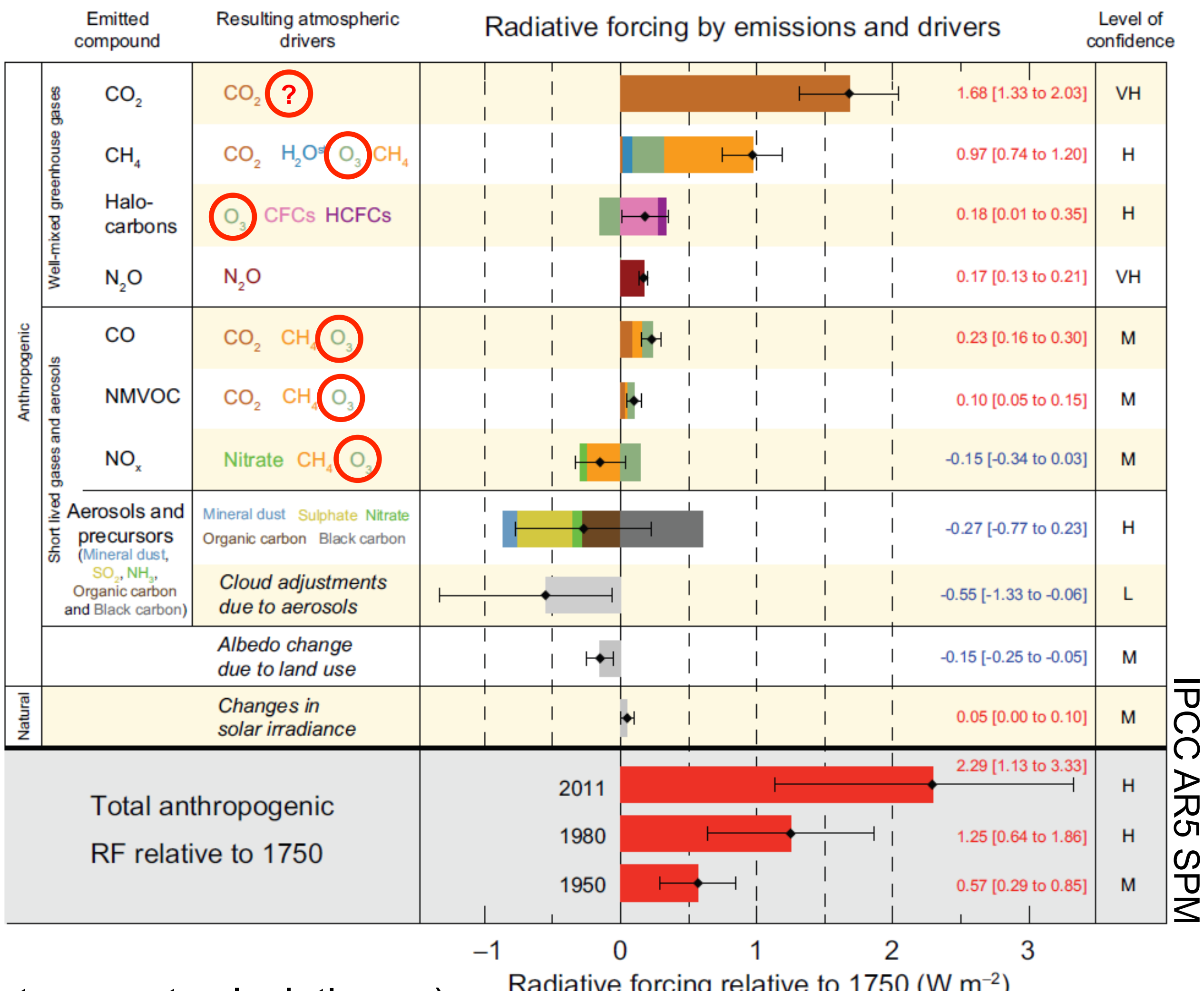


Radiation Budget



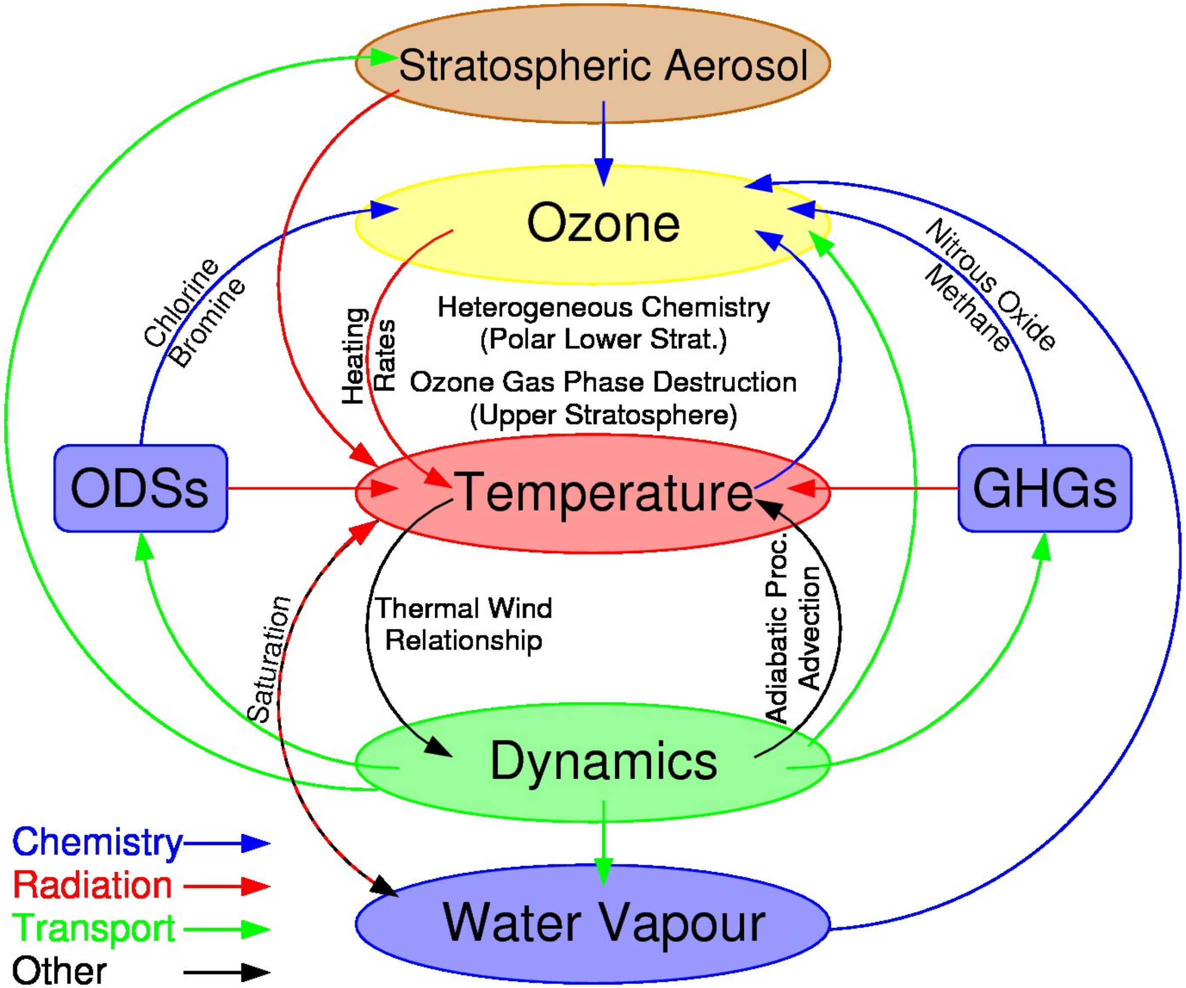
IPCC AR5

Radiative Forcing



(Full radiative transport calculation …)

Interactions



Chemistry-Climate Model (CCM) Schematic

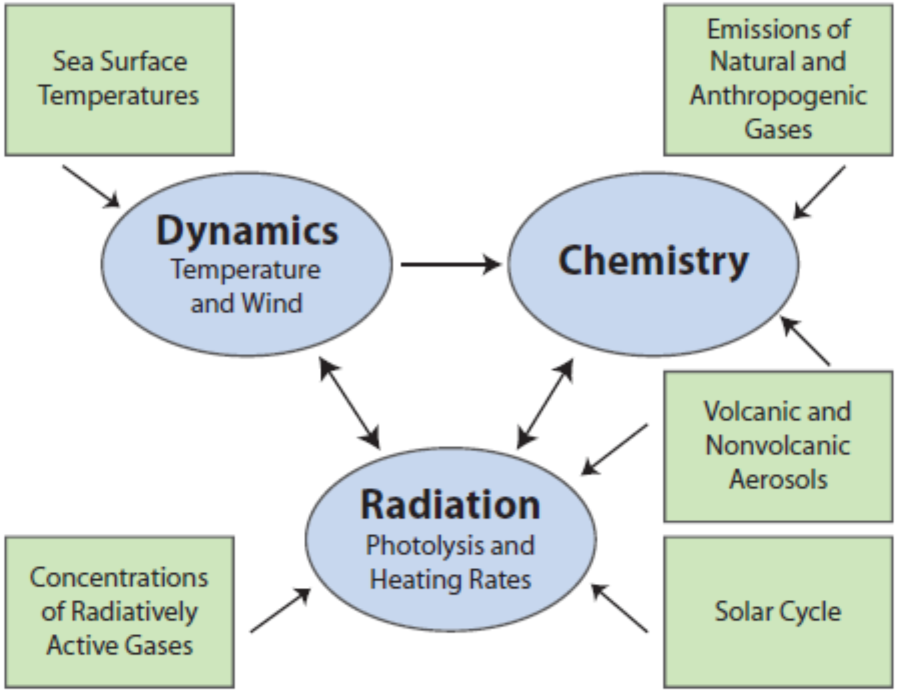


Figure 5-1. Schematic of a Chemistry-Climate Model (CCM). The core of a CCM (oval symbols) consists of an atmospheric general circulation model (AGCM) that includes calculation of the heating and cooling rates and a detailed chemistry module. They are interactively coupled. Photolysis rates are calculated online or are determined from a lookup table. Arrows indicate the direction of effect. Rectangular boxes denote external impacts. In current CCMs, sea surface temperatures (SSTs) are prescribed based on observations or are adopted from calculations with a climate model. Natural and anthropogenic emissions of gases are considered. Tropospheric and stratospheric aerosol loading (especially after volcanic eruptions) can be taken into account. CCMs often consider the changes of solar radiation caused by the 11-year activity cycle of the Sun.

Missing: Boundary conditions, numerical treatment

Scientific Assessment of Ozone Depletion: 2006

What is a Chemistry-Climate Model?

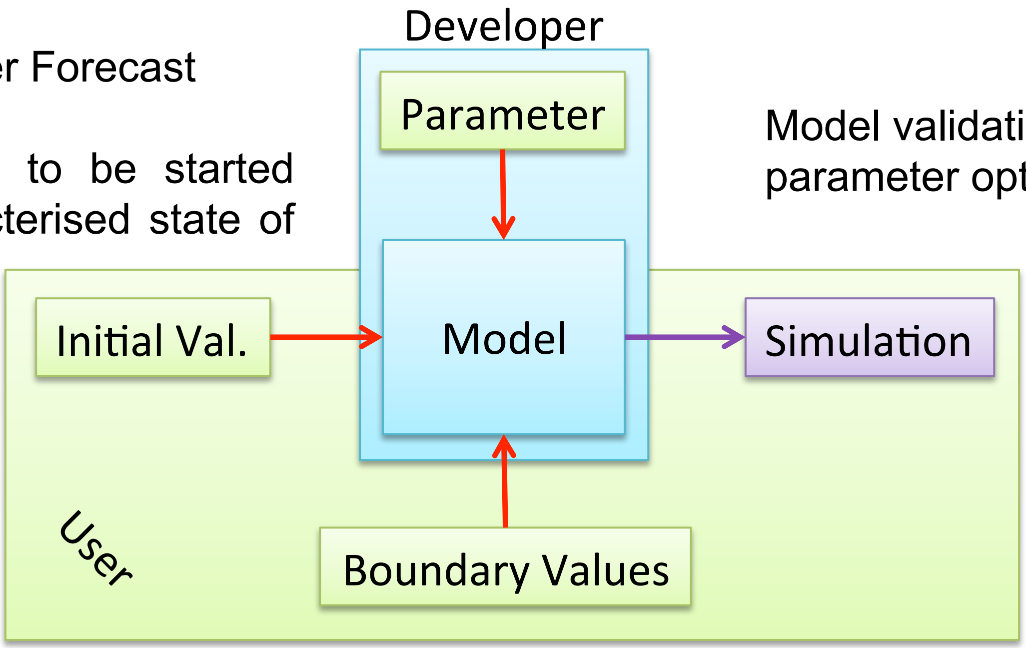
MODEL VALIDATION

Model and Auxiliary Data

Initial Values:
(Chemical) Weather Forecast

The model needs to be started from a well characterised state of the atmosphere.

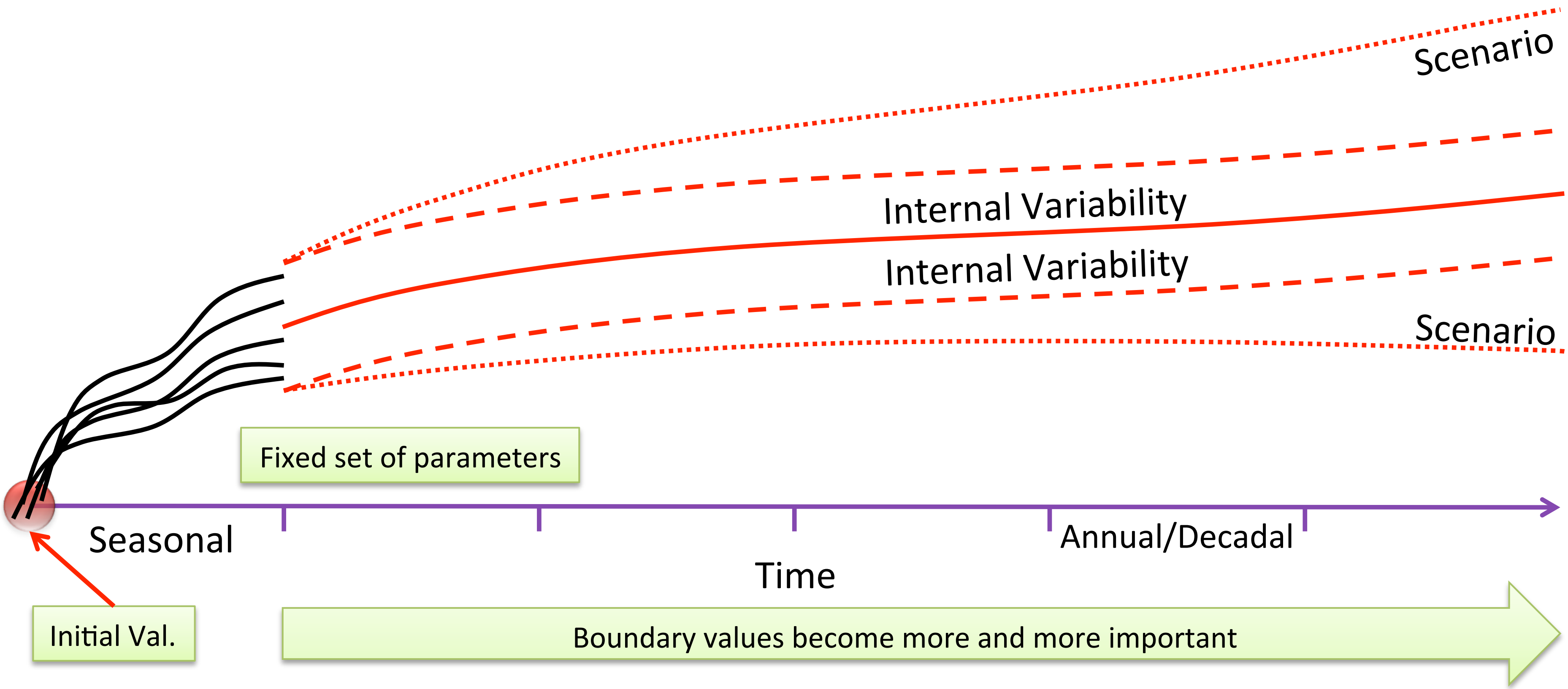
Model validation allows parameter optimisation.



Boundary Values:
(Chemical) Climate Prediction

The model needs to know about expected changes (scenarios). How much CO2 is emitted due to the use of fossil fuels?

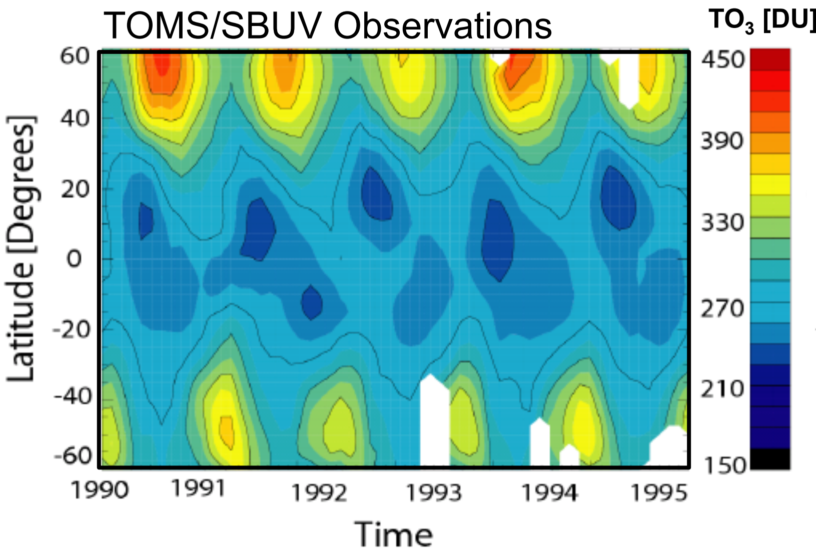
Predicting Weather and Climate

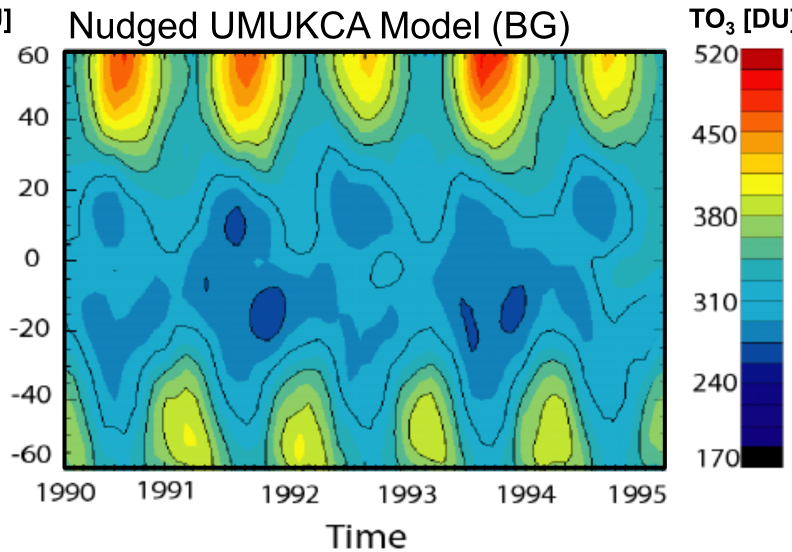


Model Validation

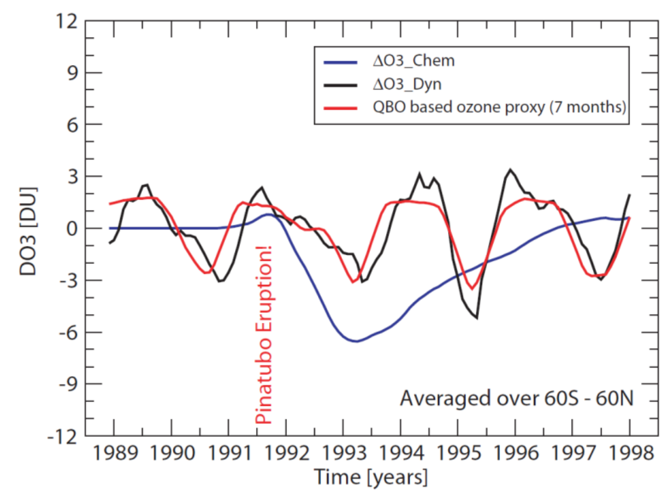
- Two Approaches:
  - Define a constraint in the model, so that some results of the model become directly comparable with observations, e.g. nudge meteorology to compare trace gases.
  - Simulate a particular case (year) over and over again and compare the statistics of the time-slice results to the measurements and their error bars.

Nudged Model Validation / Attribution





There are biases, but we look at differences!

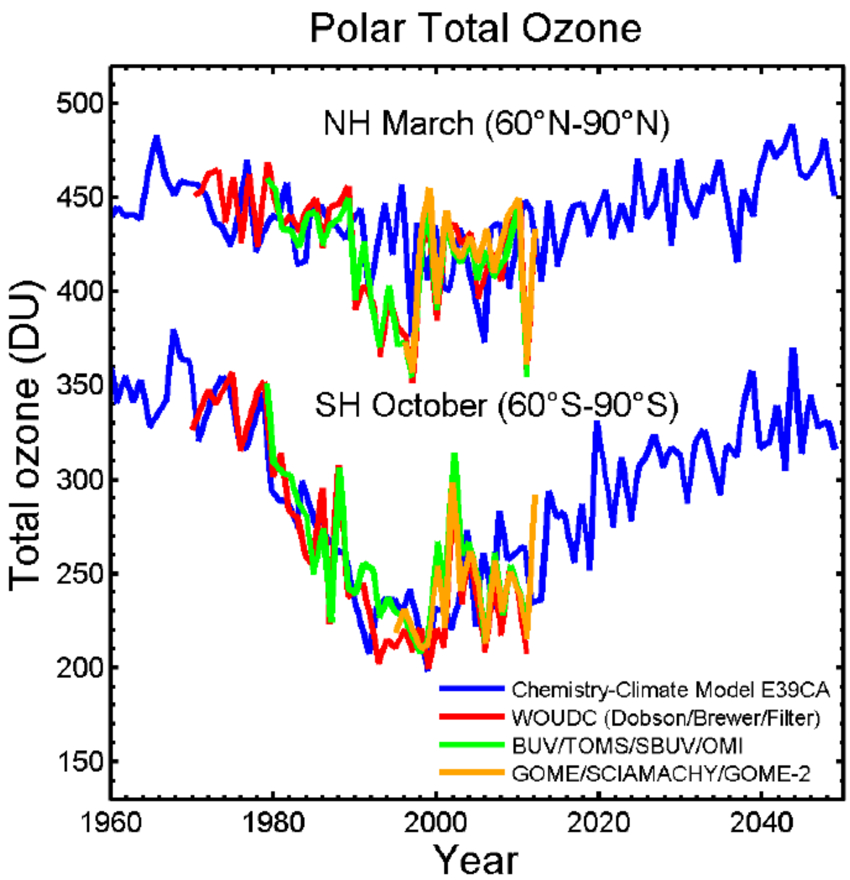


<u>Attribution:</u>

Chemical effect of volcanic aerosol on ozone:
The model can run with and without the Pinatubo eruption.
Dynamical changes in ozone (check):
Observations-(chemical effect);
the residuum can be explained by dynamics

Telford, P., Braesicke, P., Morgenstern, O., and Pyle, J.: Reassessment of causes of ozone column variability following the eruption of Mount Pinatubo using a nudged CCM, Atmos. Chem. Phys., 9, 4251-4260, doi:10.5194/acp-9-4251-2009, 2009.

Transient Changes



Total polar ozone in the northern and southern hemispheres as measured by various instruments, including GOME, SCIAMACHY and GOME-2 flown on ERS-2, Envisat and MetOp, respectively (in orange). The blue line depicts projections based on simulations from the Chemistry Climate Model E39CA. The total ozone reached its lowest levels in both hemispheres in the late 1990s, and it is expected to increase in the coming years.

Credits: ESA/DLR/Eumetsat/NASA/WMO /GAW

Dameris, M. and D. Loyola, Recent and future evolution of the stratospheric ozone layer, Chapter 45 in Atmospheric Physics, Background-Methods-Trends, Ed. U. Schumann, Springer Heidelberg New York Dordrecht London, doi: 10.1007/978-3-642-30183-4, ISBN 978-3-642-30182-7, pp. 747-761, 2012.

Statistical Model Validation

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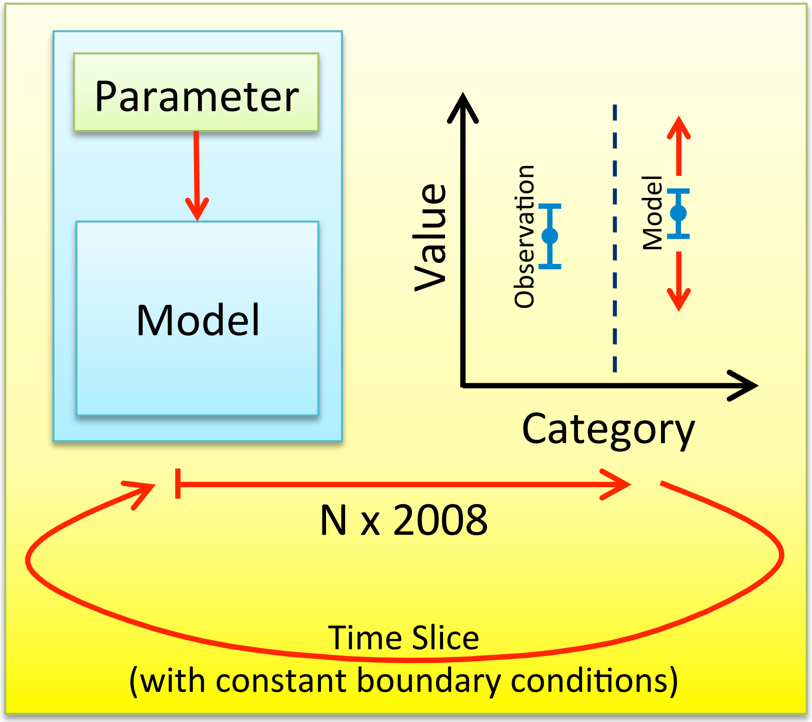
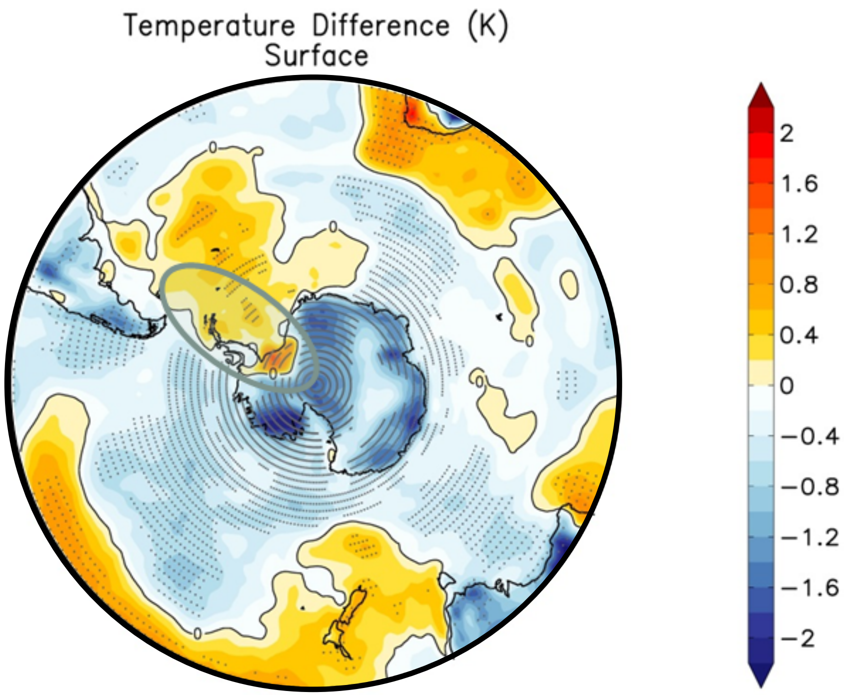


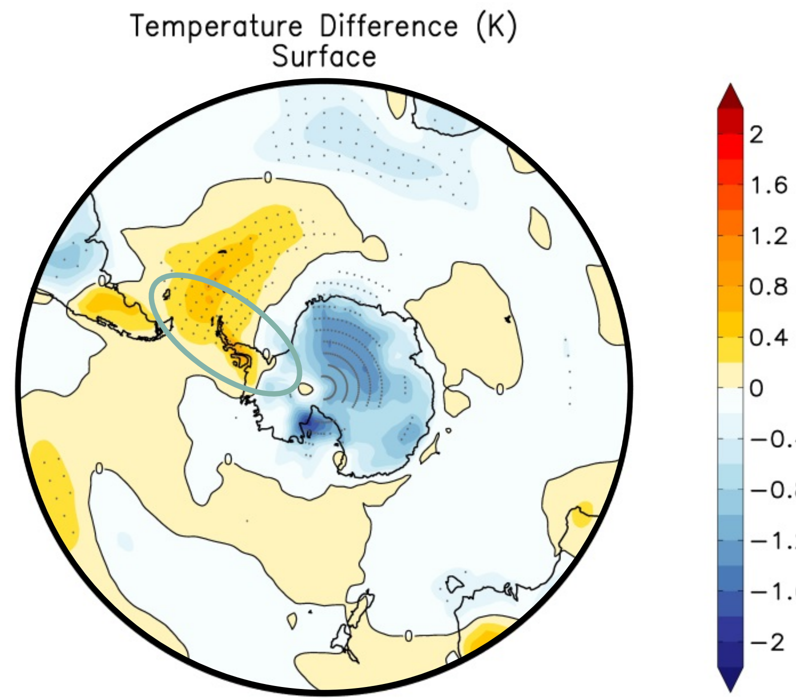
Antarctic Climate Change

„Observations“



ERA-Interim Reality:
Mean(1998 to 2002) - Mean(1979 to 1983)

Chemistry-Climate Model



UM-UKCA:
Ozone Hole (~2000) – No OH (~2000)

Keeble, J., Braesicke, P., Abraham, N. L., Roscoe, H. K., and Pyle, J. A.: The impact of polar stratospheric ozone loss on Southern Hemisphere stratospheric circulation and climate, Atmos. Chem. Phys. Discuss., 14, 18049-18082, doi:10.5194/acpd-14-18049-2014, 2014.

Ozone Hole and Climate Change Attribution

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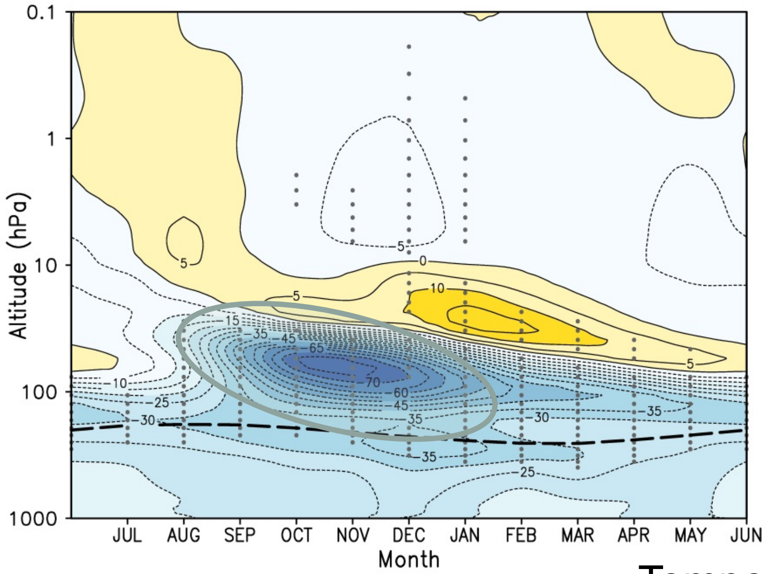
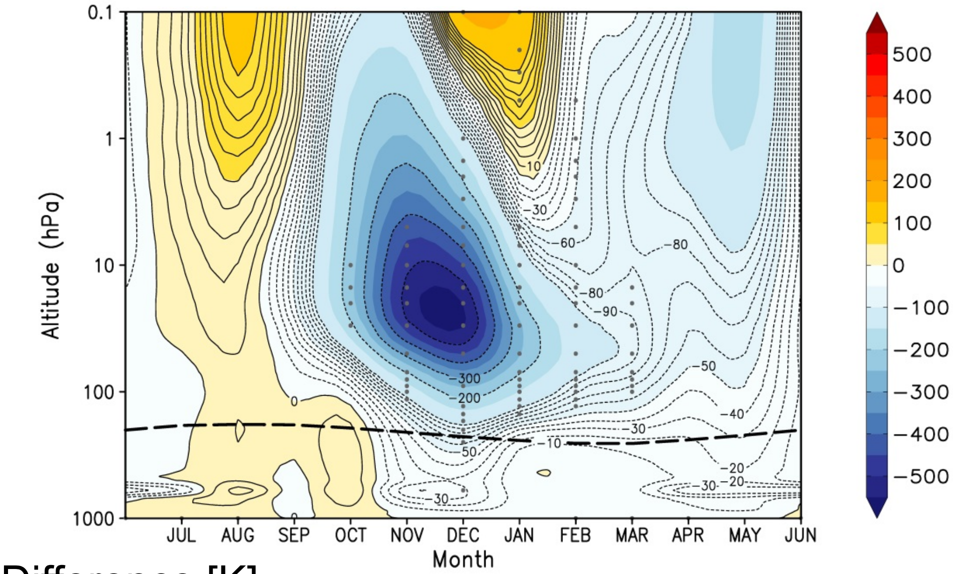
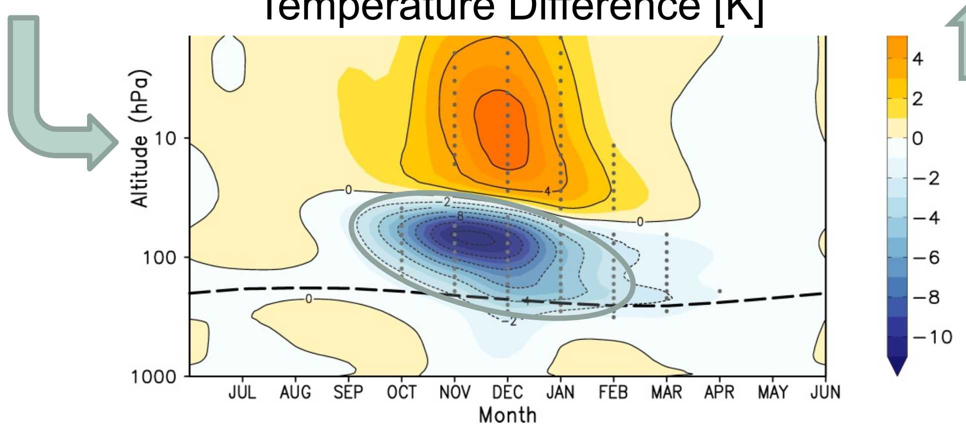
Ozone Difference [%] – 90º-75ºS



Height Difference [m] – 90º-75ºS



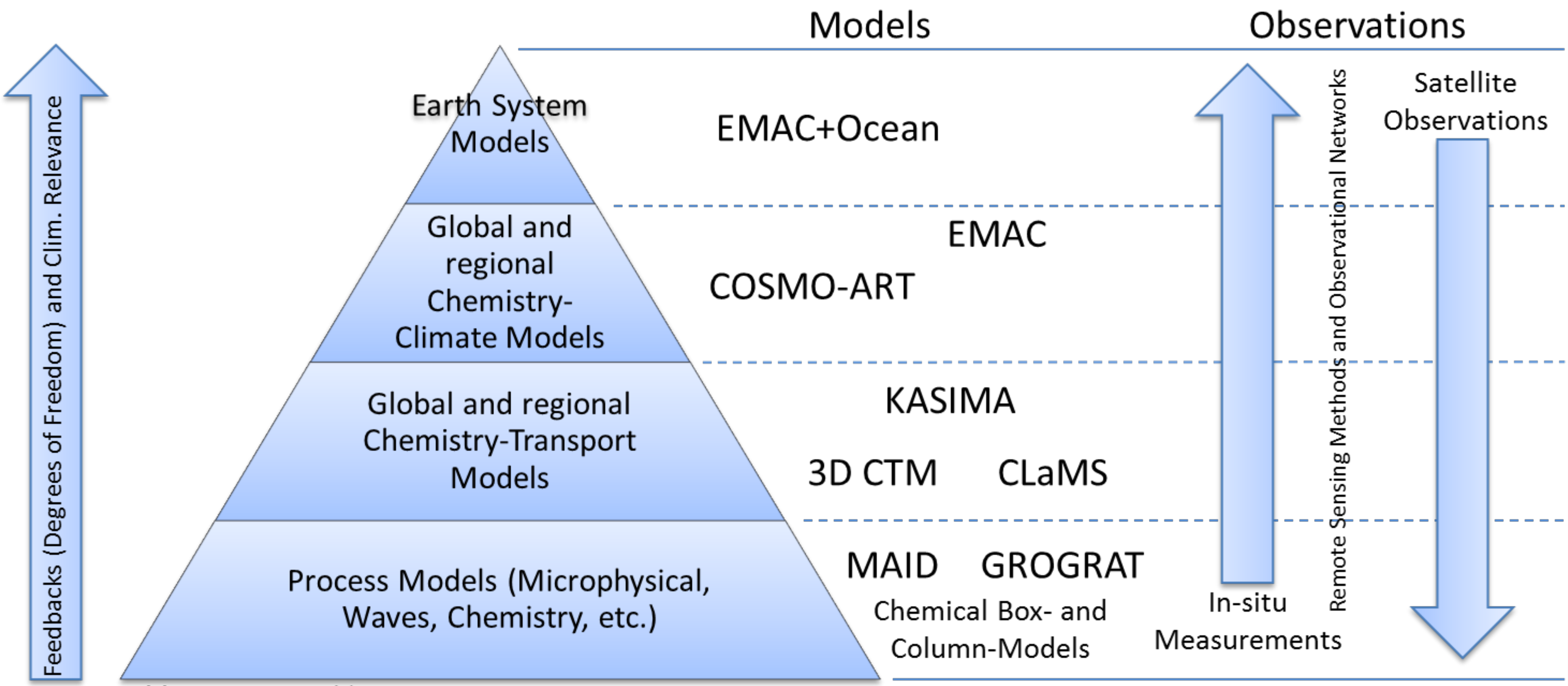
Temperature Difference [K]



What is a Chemistry-Climate Model?

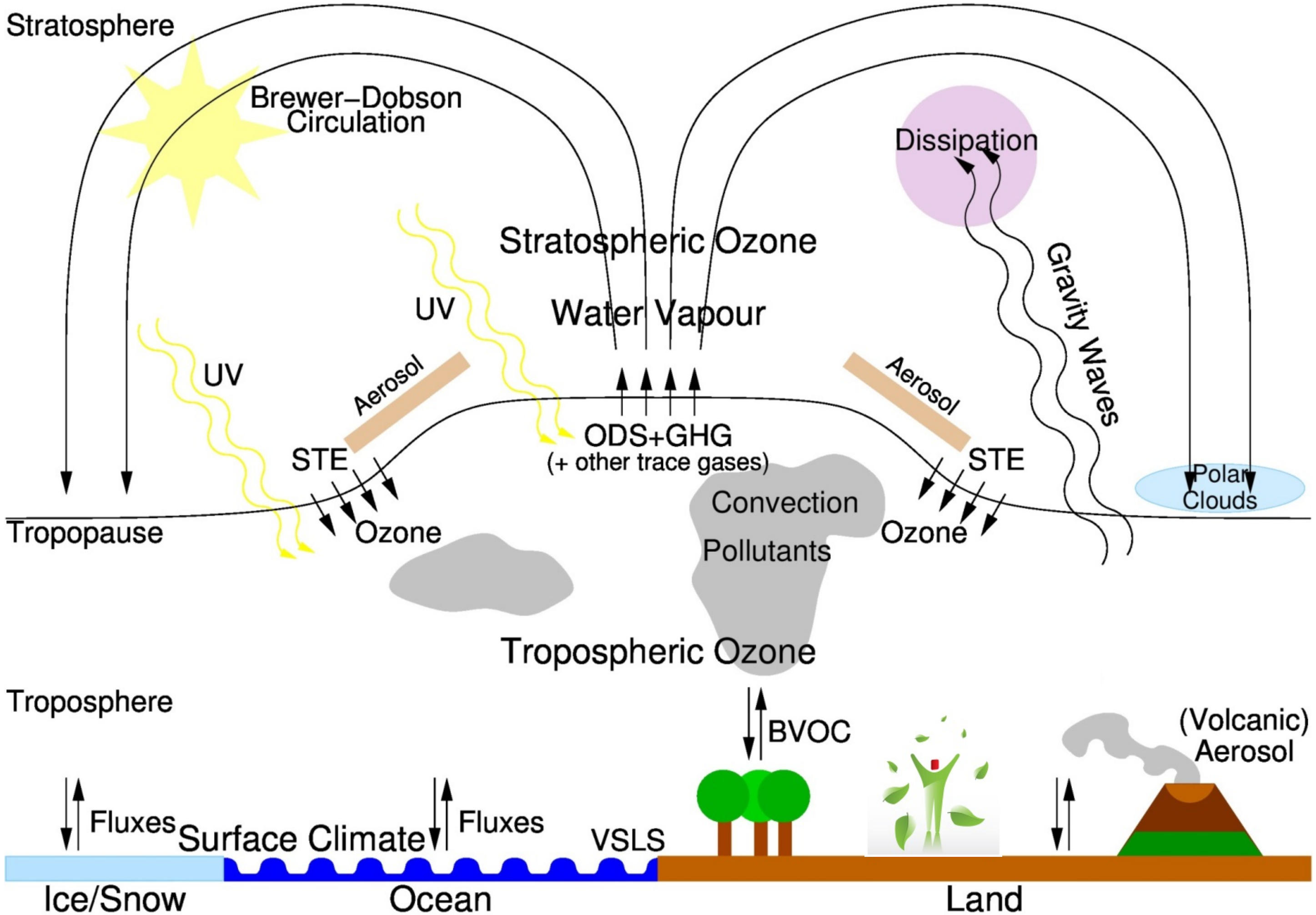
MODEL HIERARCHY

Model Hierarchy (PT4 Example)



Originator: Peter Braesicke, IMK-ASF, v2, 6.6.2014

A complex system …



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Questions?

THANK YOU!

Temperature Profile

Temperature (tropical latitudes)

$$-\Gamma = \frac{dT}{dz} > -2\frac{K}{km}$$

Lapse Rate Maximum

Cold Point

WMO Tropopause

Lapse Rate Minimum