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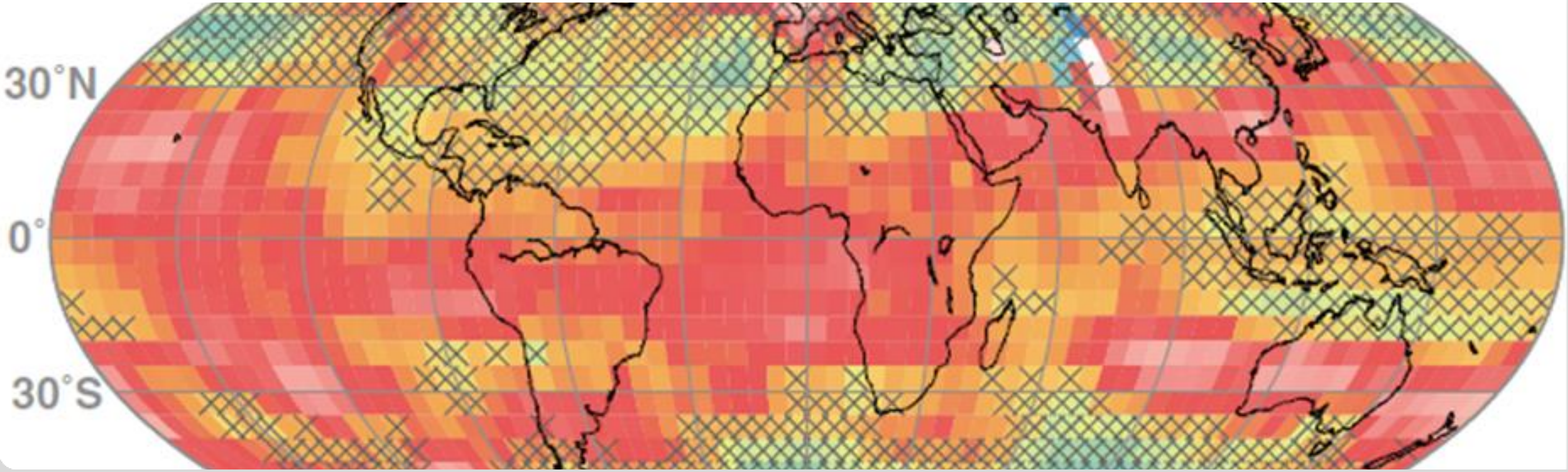
REKLIM
Helmholtz-Verbund Regionale Klimaänderungen

Scientific Computing in Climate Science

Peter Braesicke

LSDMA

IMK-ASF



Structure

- Motivation: Understanding and projecting climate change
- Observations and Models
  - Observing the climate system with state-of-the-art observatories
  - Modelling the climate system with state-of-the-art models
- Why?
  - Can we learn from the past? Yes!
  - Can we inform planning für the future? Certainly!

Classic Climate Change

ipcc
INTERGOVERNMENTAL PANEL ON climate change
WMO UNEP

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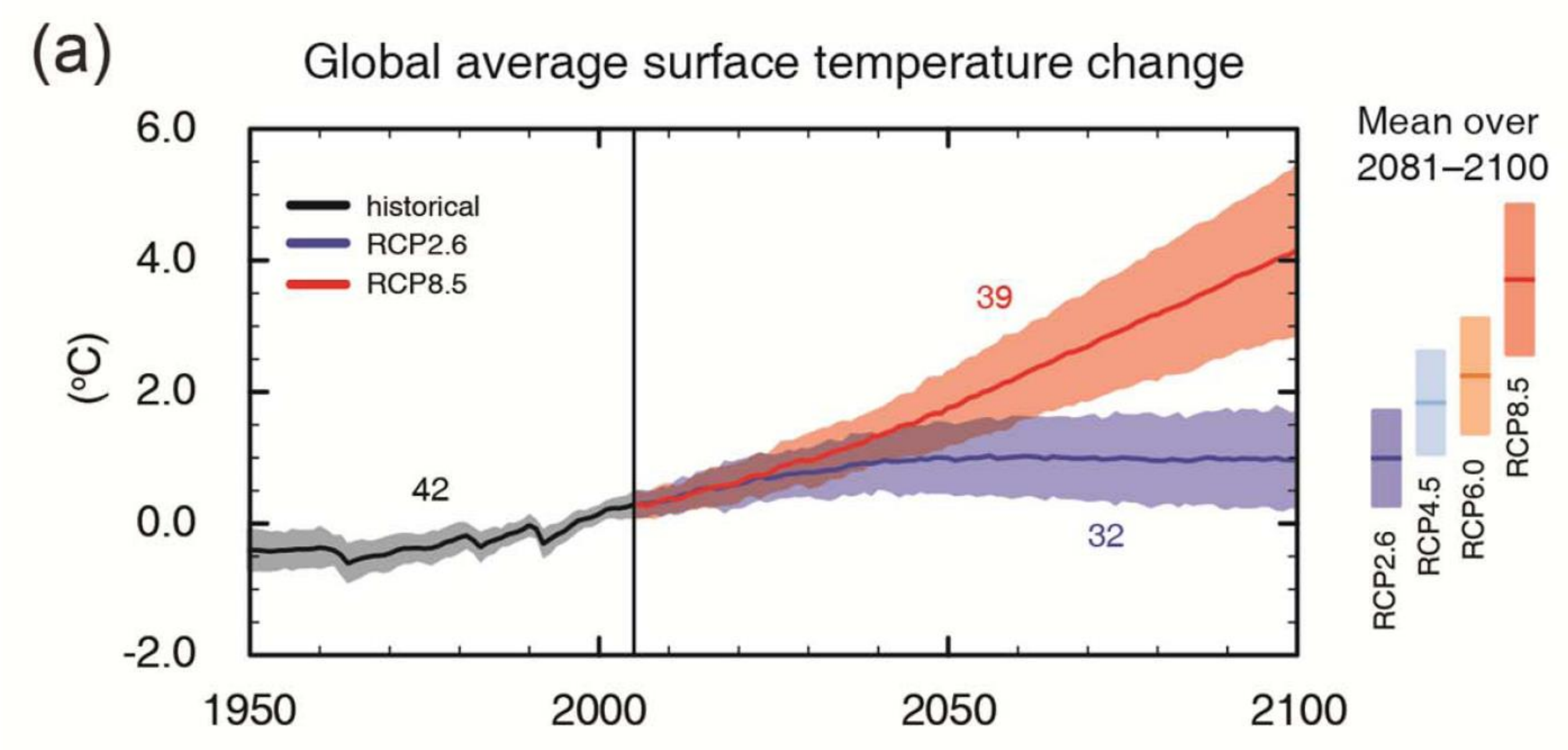
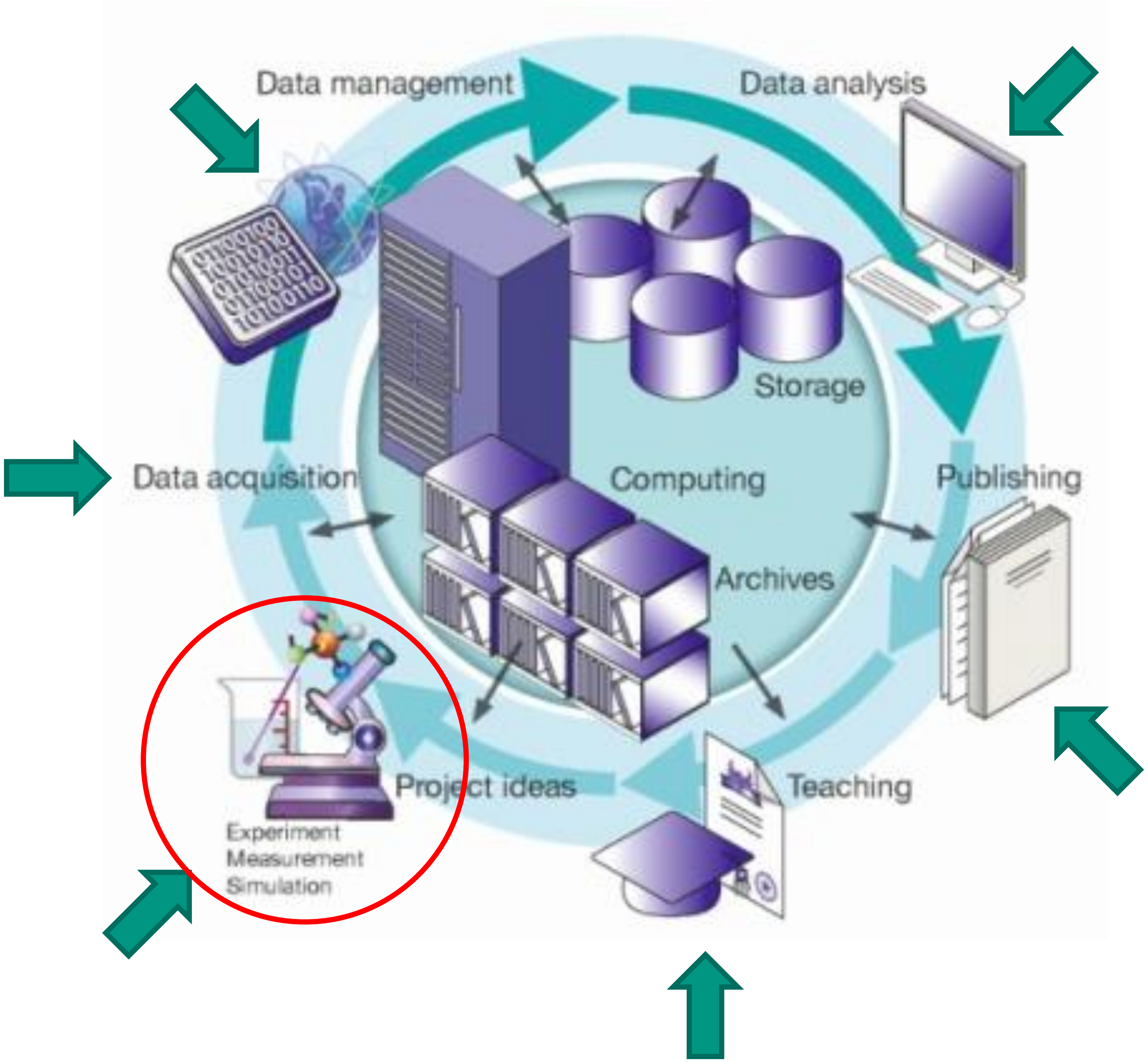


Large-Scale Data Management and Analysis



Run a model
Fly an instrument

Archive/store data
(NetCDF, CF convention)

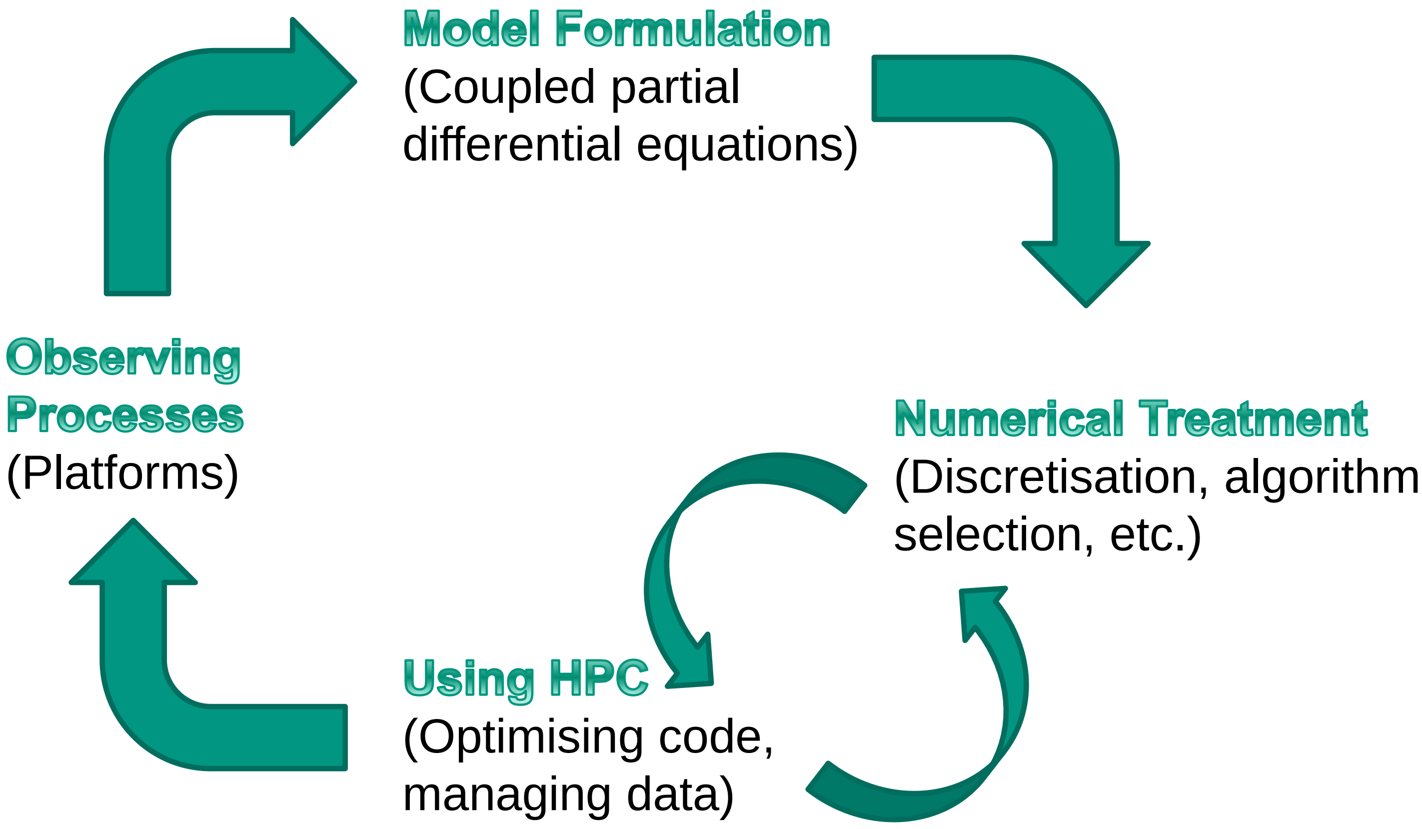
Make sure meta-data is
sufficient and consistent

Analyse data (e.g. trends)
Create added-value data

Publications with firm
conclusions (e.g. trends)

Teaching (based on the
whole experience)

Philosophy


Model Formulation
(Coupled partial differential equations)
Numerical Treatment
(Discretisation, algorithm selection, etc.)
Using HPC
(Optimising code, managing data)
Observing Processes
(Platforms)

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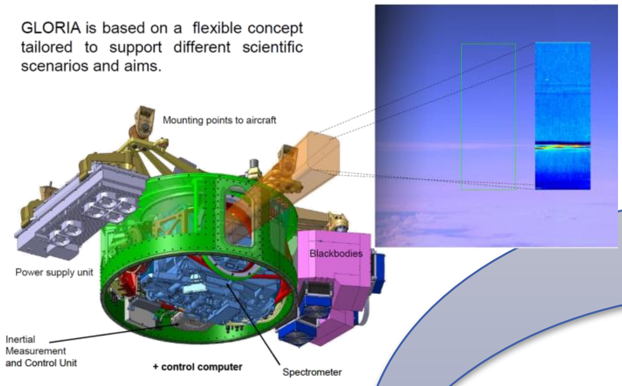
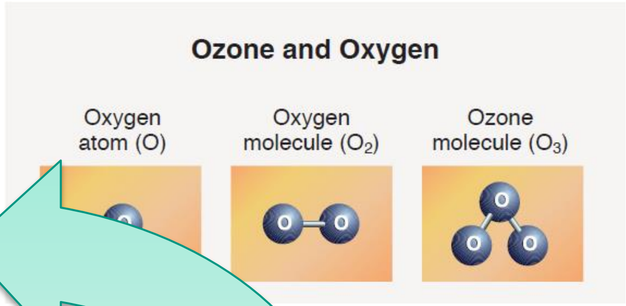
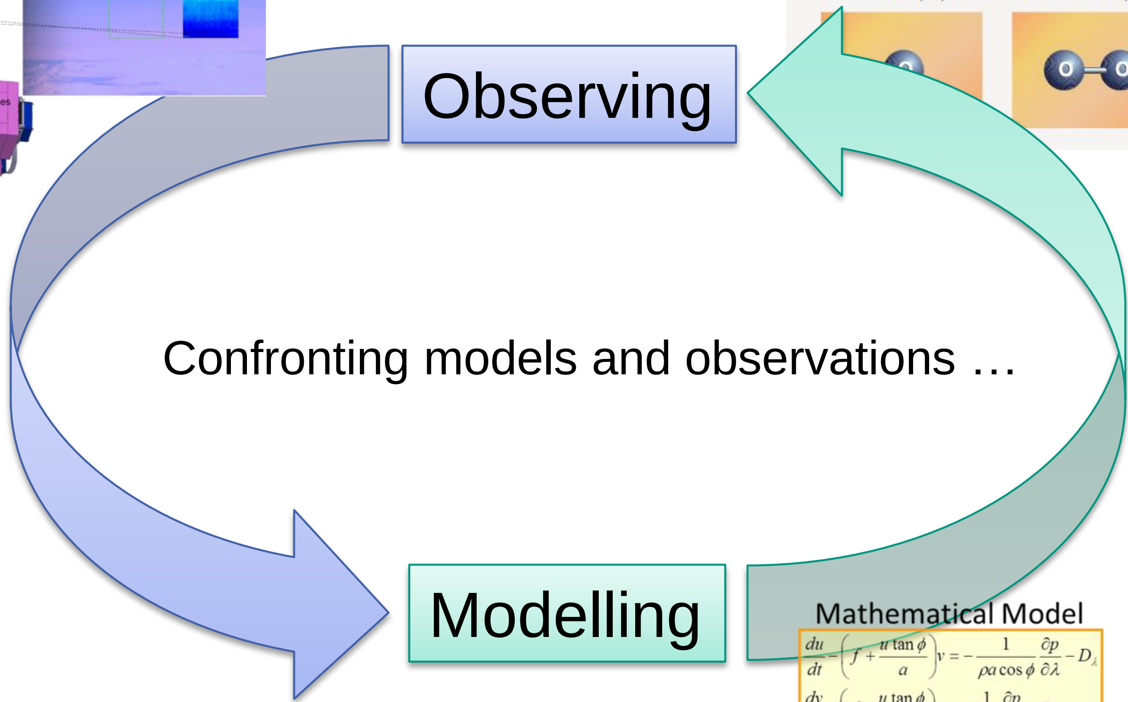
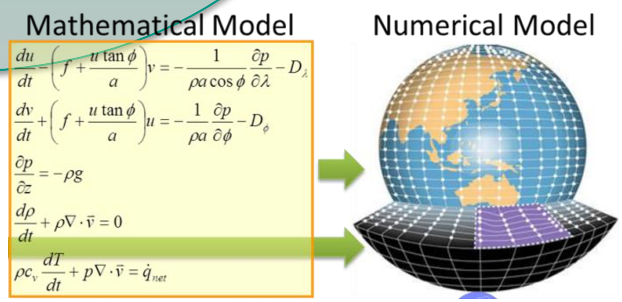
Modelling and Observing



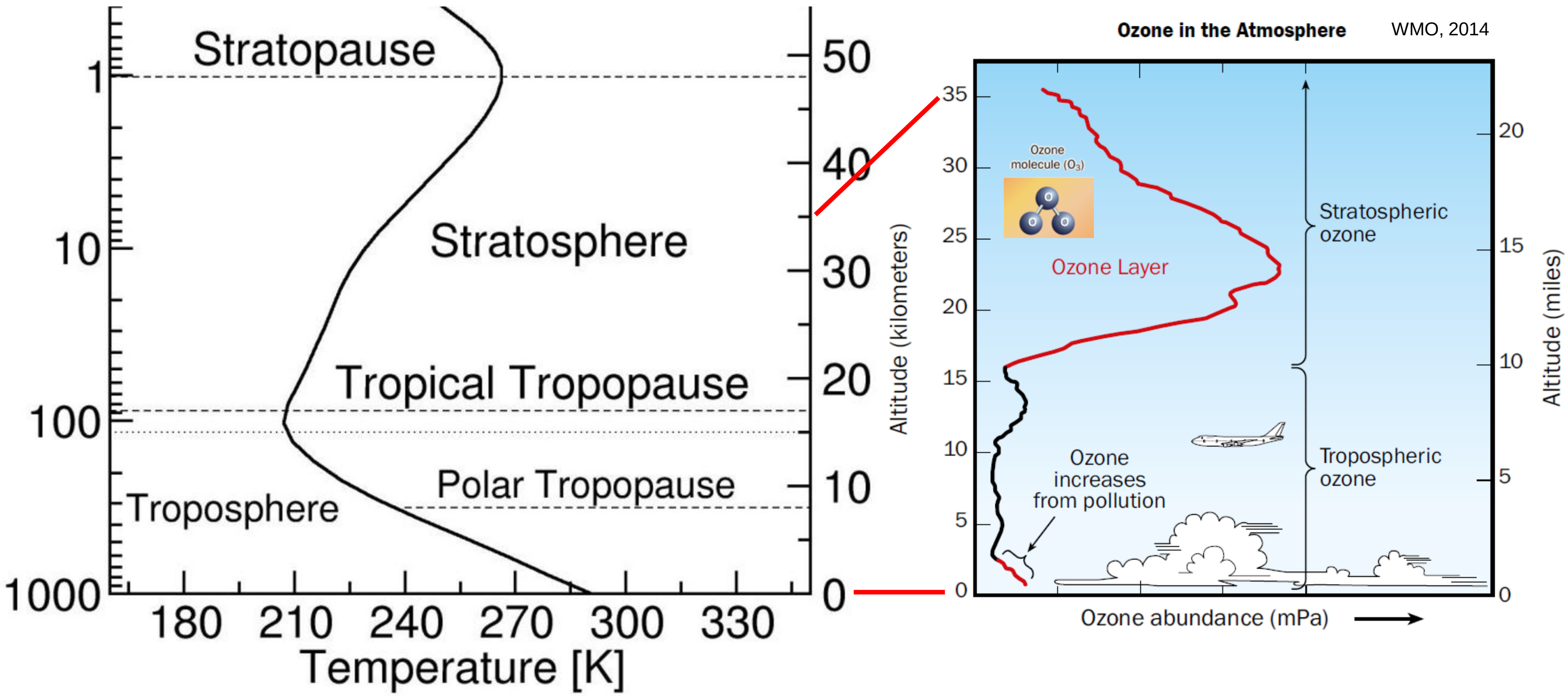






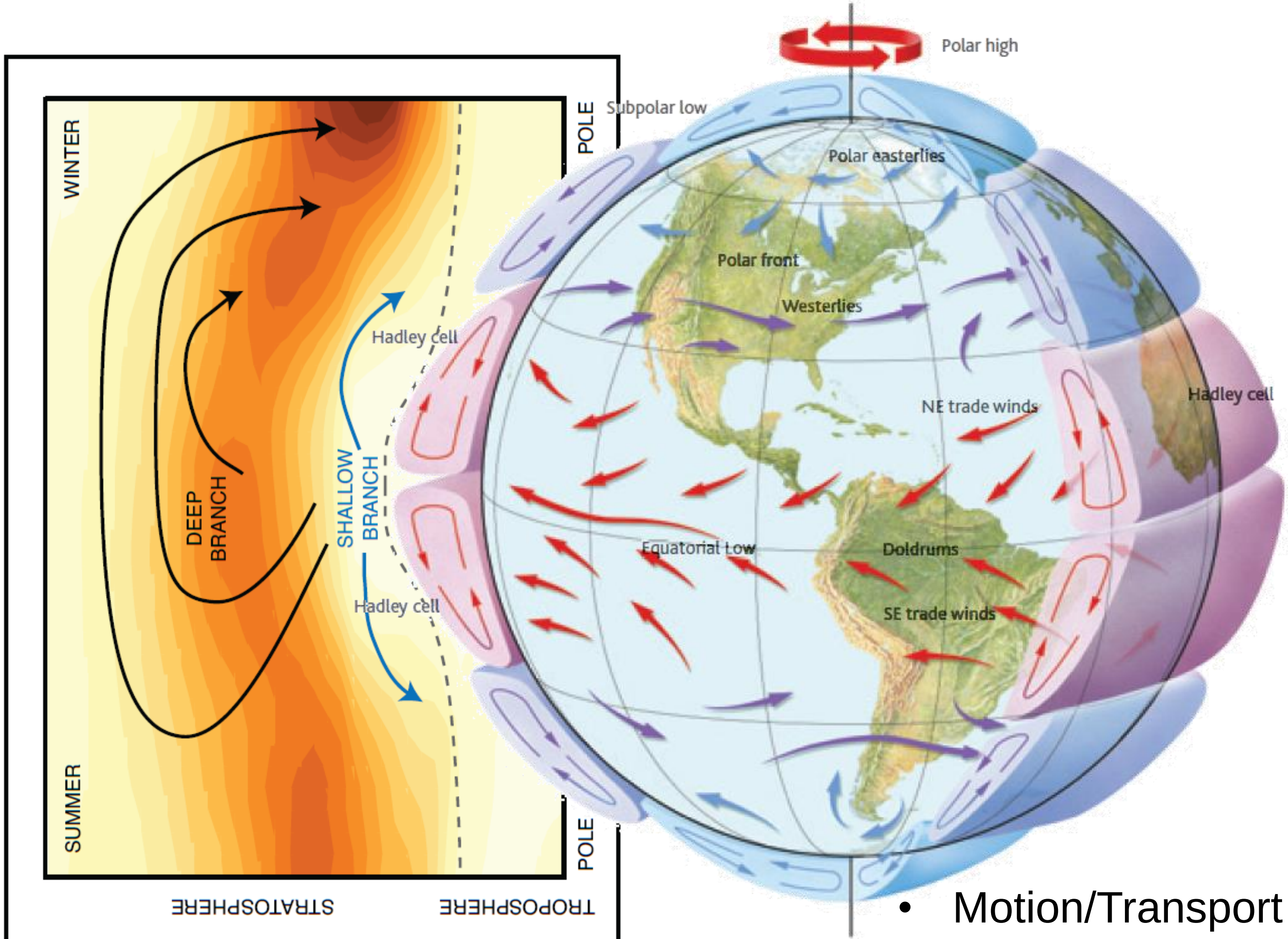
Generating a model (evidence for processes)
Initialising a model (initial value problem - **weather**)
Providing boundary conditions for model (**climate**)
Testing a model (modelling the past)
Homogenising observations (data assimilation)

Vertical Structure (Strat. - Trop.)



Braesicke, doi:10.1016/B978-0-12-382225-3.00227-9

Global Circulation



Source: Gary Hicks, Science Photo Library

- Motion/Transport (dynamics)
- Composition/Chemistry (e.g. ozone)
- Other spheres and interactions

Modelling the Atmosphere

Observations

Mathematical Model

$$\frac{du}{dt} - \left(f + \frac{u\tan\phi}{a}\right)v = -\frac{1}{\rho a\cos\phi}\frac{\partial p}{\partial\lambda} - D_\lambda$$

$$\frac{dv}{dt} + \left(f + \frac{u\tan\phi}{a}\right)u = -\frac{1}{\rho a}\frac{\partial p}{\partial\phi} - D_\phi$$

$$\frac{\partial p}{\partial z} = -\rho g$$

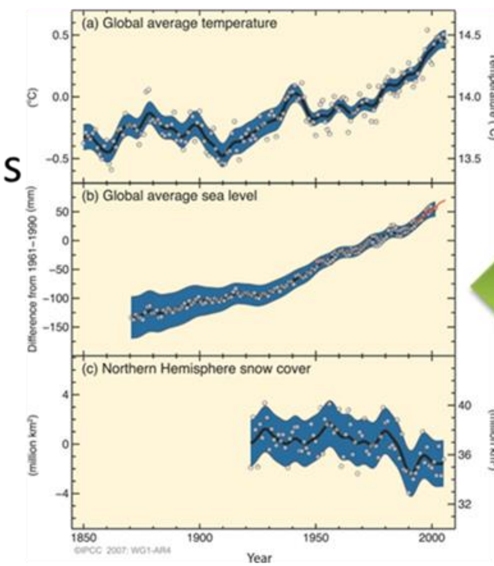
$$\frac{d\rho}{dt} + \rho\nabla\cdot\vec{v} = 0$$

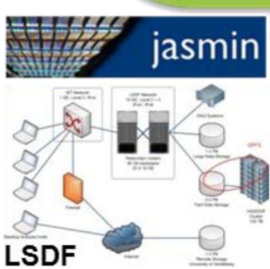
$$\rho c_v\frac{dT}{dt} + p\nabla\cdot\vec{v} = \dot{q}_{net}$$

BVs

Numerical Model

Processed observations





Confronting model and observations

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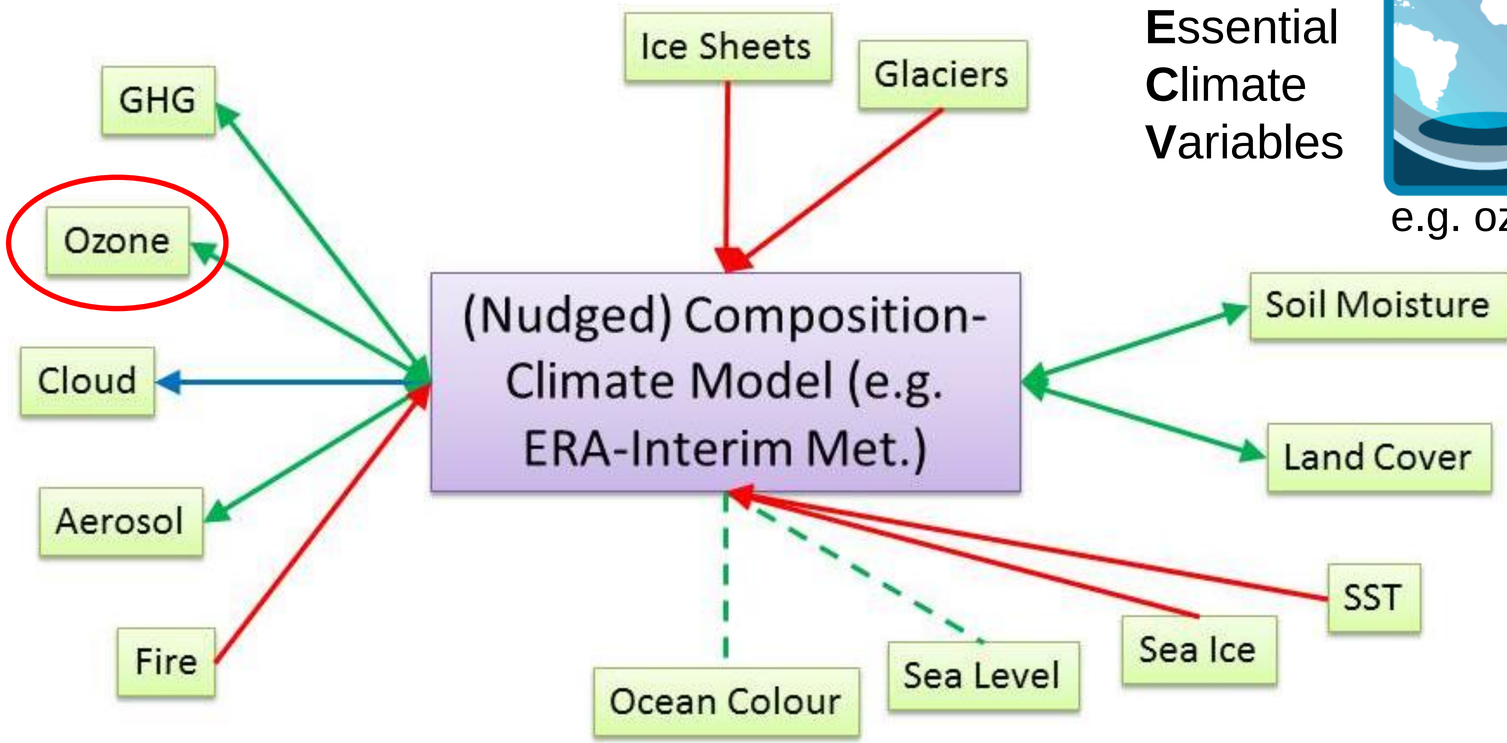
Essential **C**limate **V**ariables

e.g. ozone



Boundary condition

Boundary condition/Confrontation

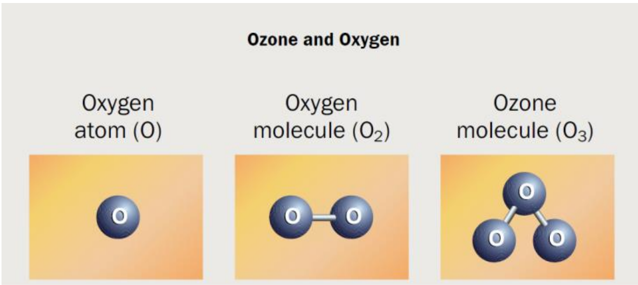
Confrontation only

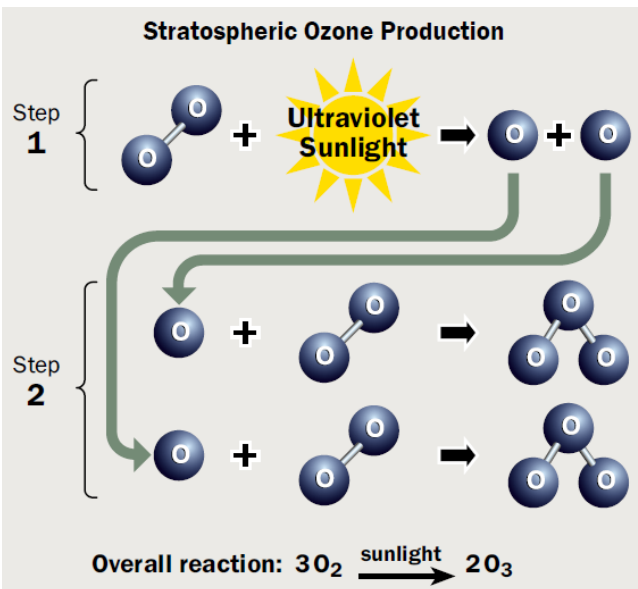
Information

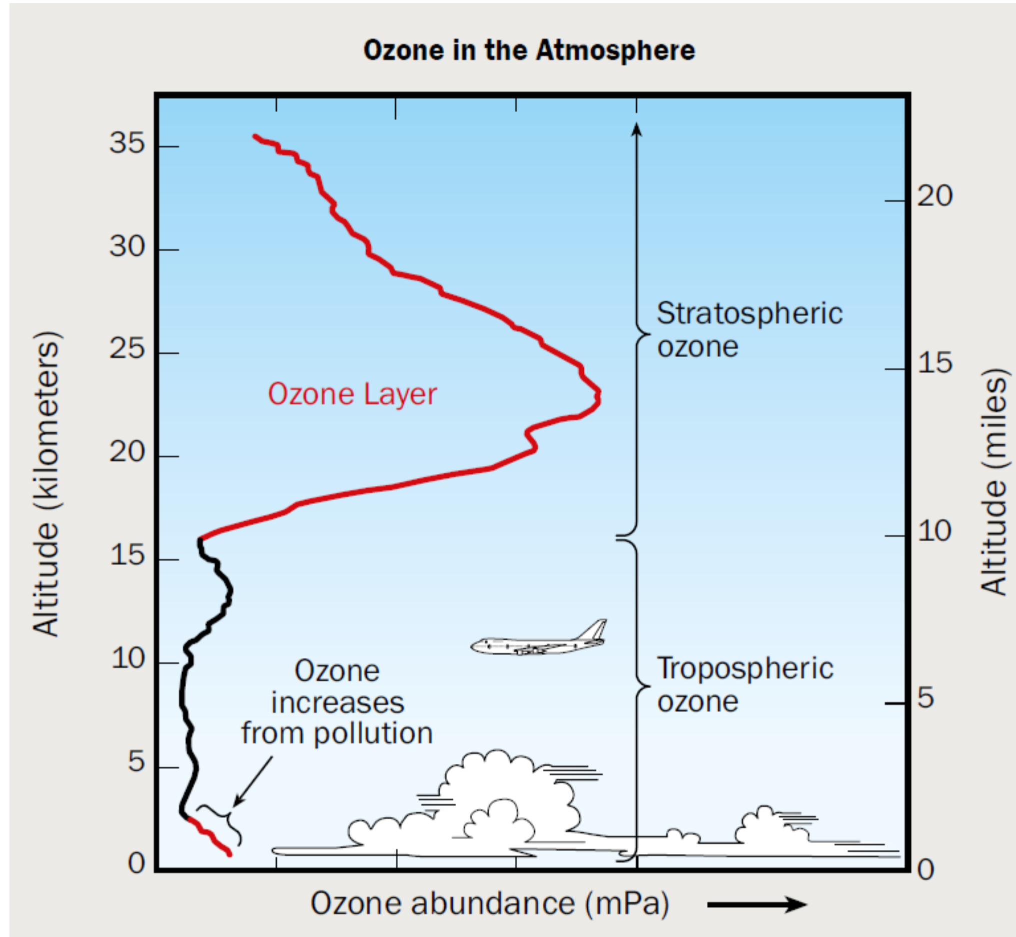
The two-way link means a CCM can model a particular ECV and the result can be confronted with the measurements, or the CCM can use the ECV measurement as a boundary condition and the impact of this particular ECV on other ECVs can be assessed within the CCM framework.

Note: The above is a typical example, other configurations are possible.

Ozone in the Atmosphere

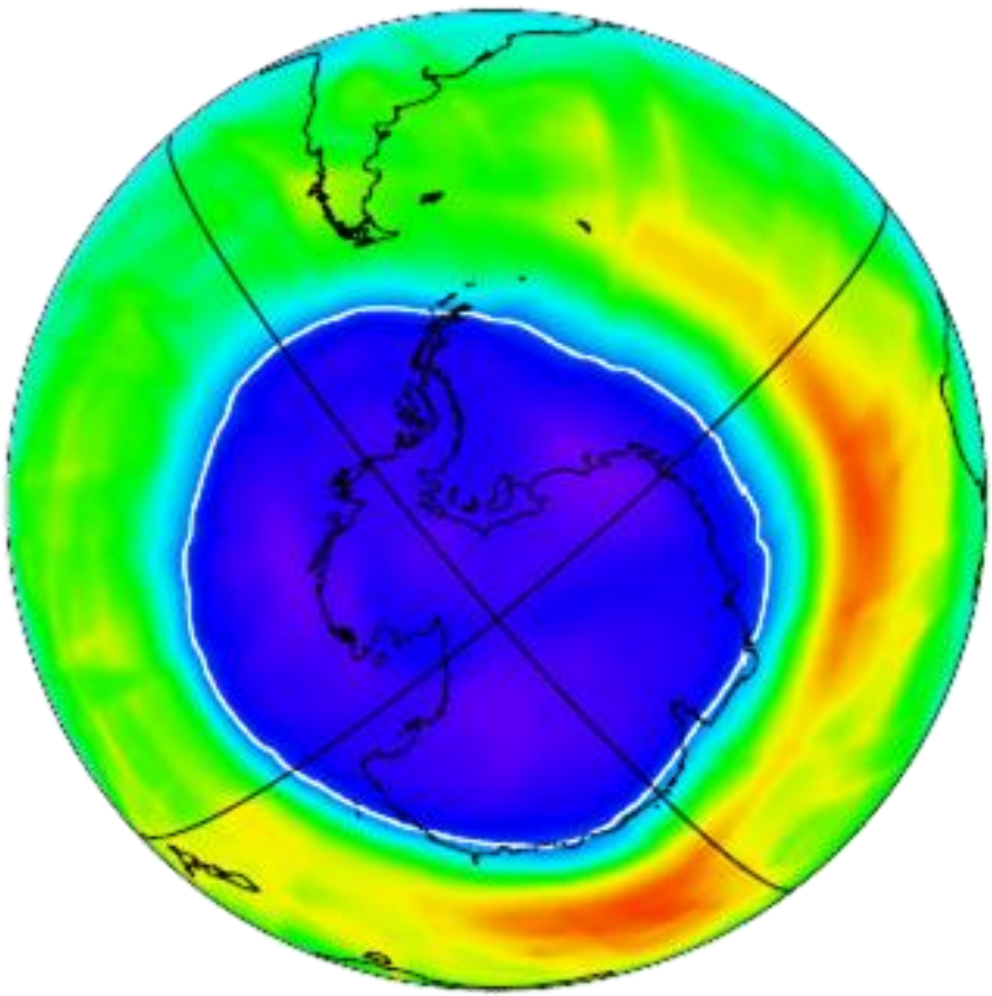






WMO, 2014

The Ozone Hole



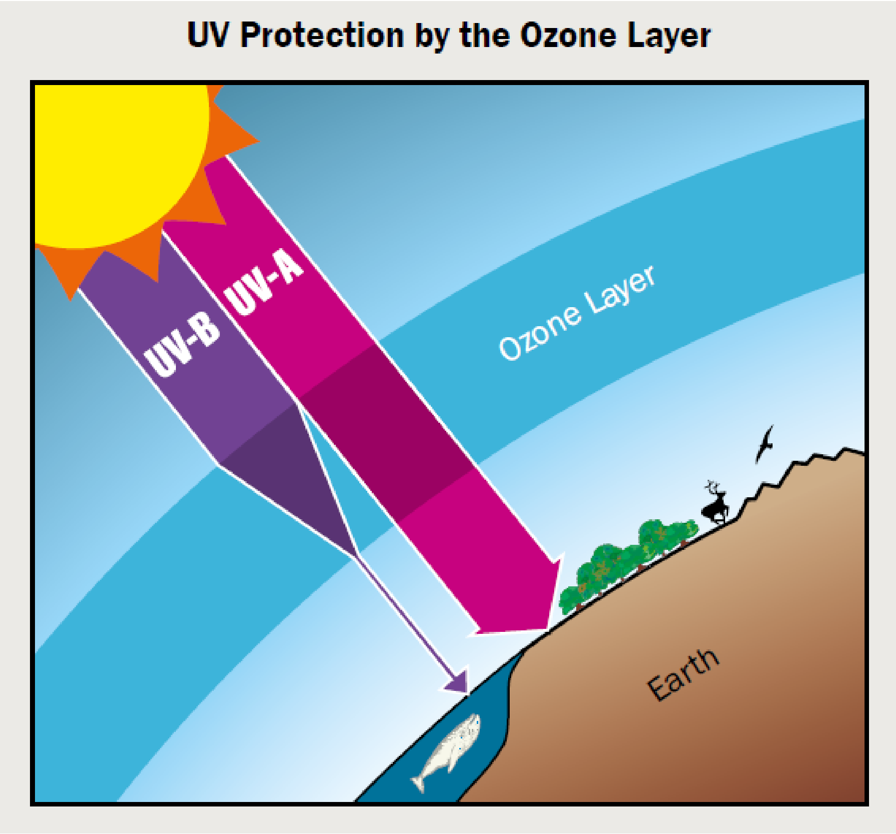
17 September 2009

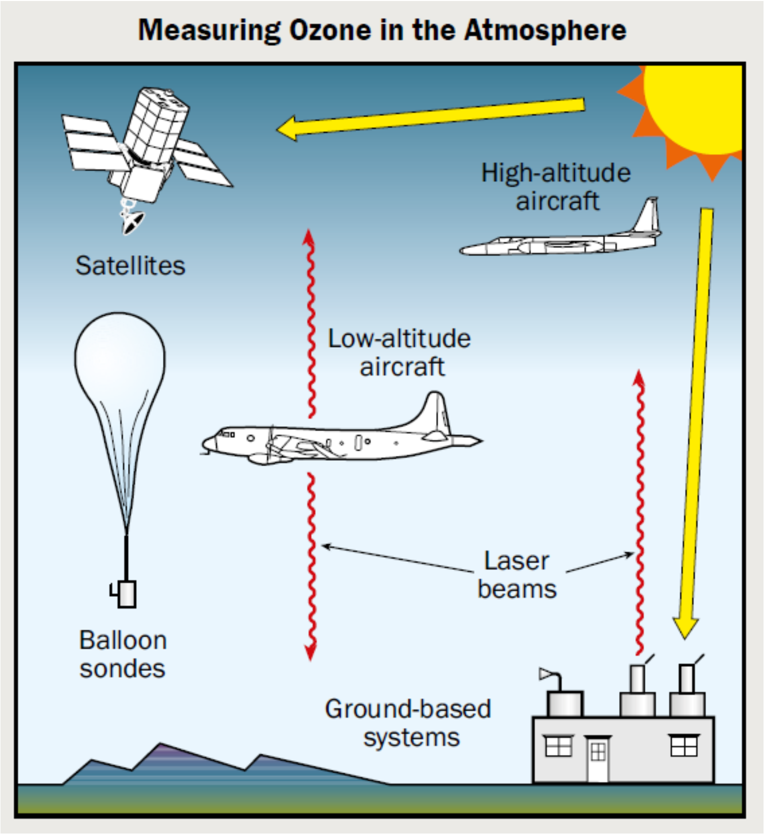
Where does it occur:
Over Antarctica
(in the stratosphere)

When doe it happen:
In southern hemisphere spring

Why does it occur:
Men made pollutants (so-called CFCs) provide halogens that destroy ozone

Measuring our Sun Glasses

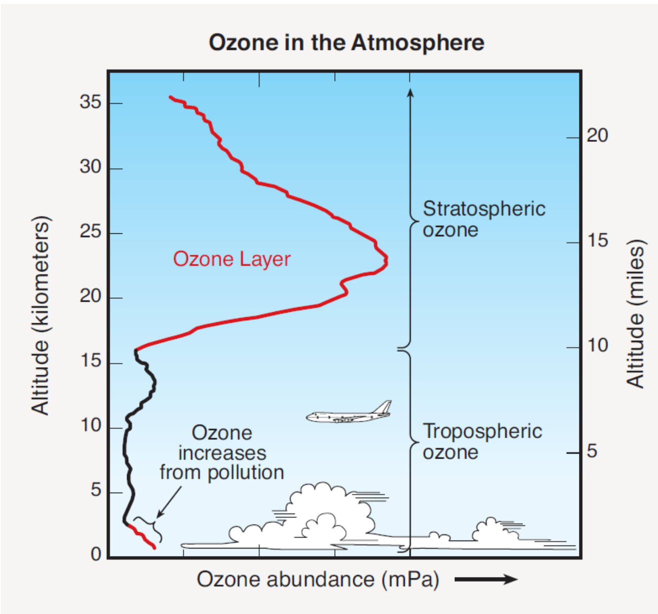




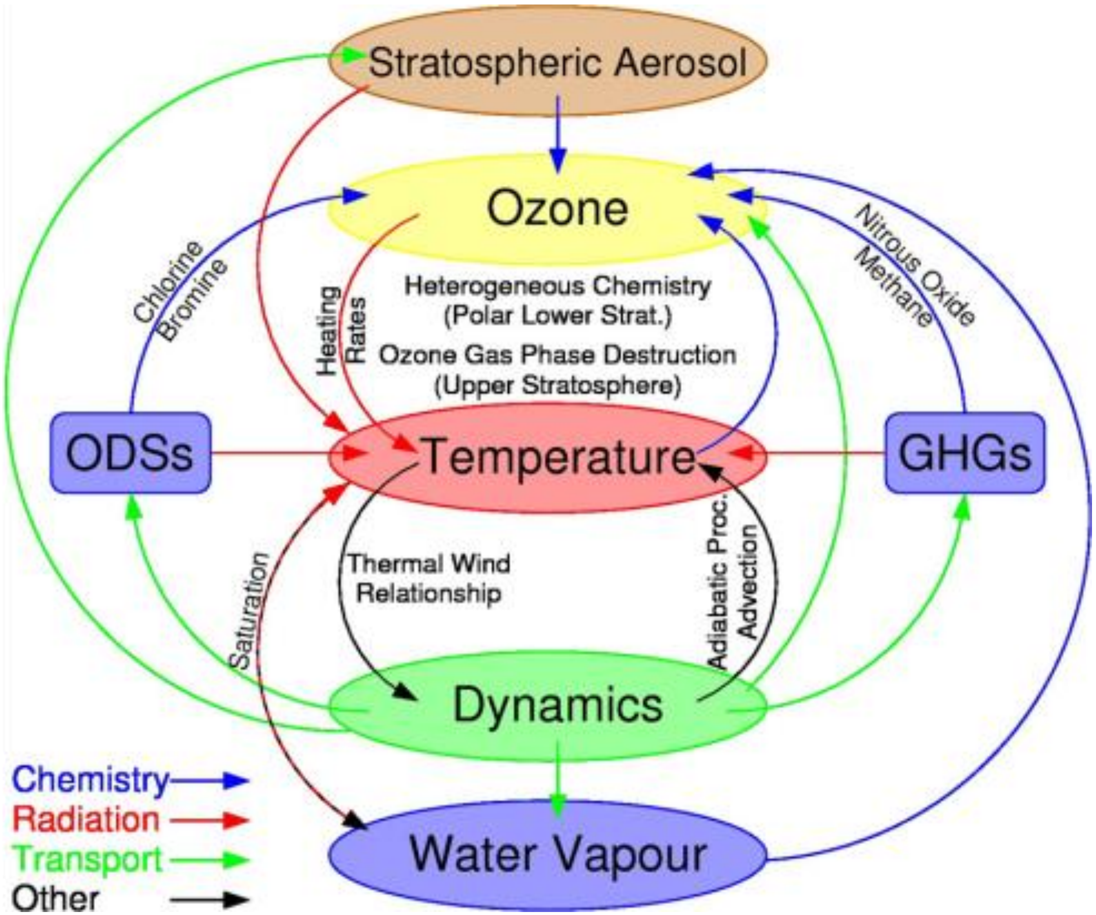
UV-B radiation: 280 to 315-nanometer (nm) wavelength
UV-A radiation: 315 to 400-nm wavelength

WMO, 2014

Feedbacks

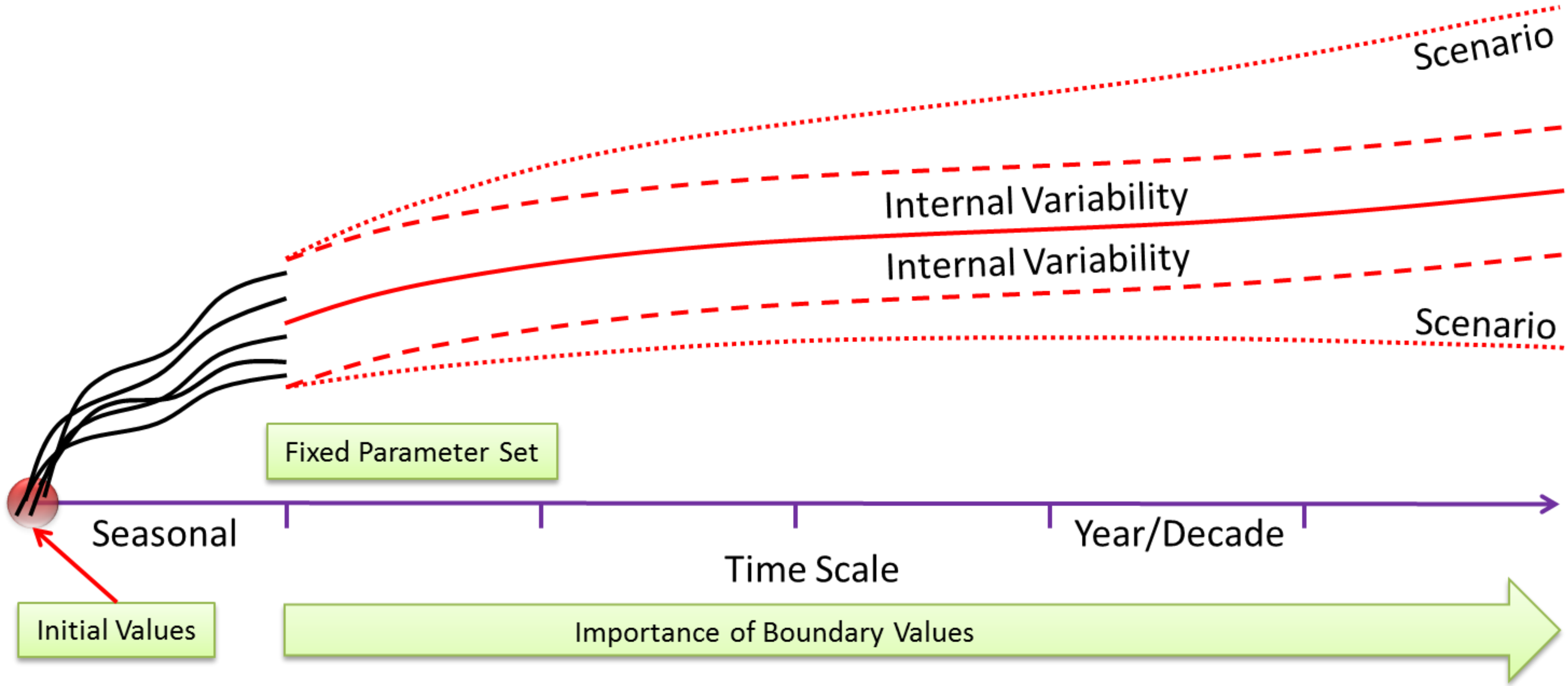


Ozone in the Atmosphere
Altitude (kilometers)
35
30
25
20
15
10
5
0
Altitude (miles)
20
15
10
5
Ozone Layer
Stratospheric ozone
Tropospheric ozone
Ozone increases from pollution
Ozone abundance (mPa)



Stratospheric Aerosol
Ozone
Chlorine
Bromine
Heating Rates
Heterogeneous Chemistry (Polar Lower Strat.)
Ozone Gas Phase Destruction (Upper Stratosphere)
Nitrous Oxide
Methane
ODSs
Temperature
GHGs
Saturation
Thermal Wind Relationship
Adiabatic Proc.
Advection
Dynamics
Water Vapour
Chemistry
Radiation
Transport
Other

Why ensembles? (Weather versus Climate)



Quantifying uncertainty!

Joint PhD with SCC/LSDMA to explore the **efficient** processing of climate data.

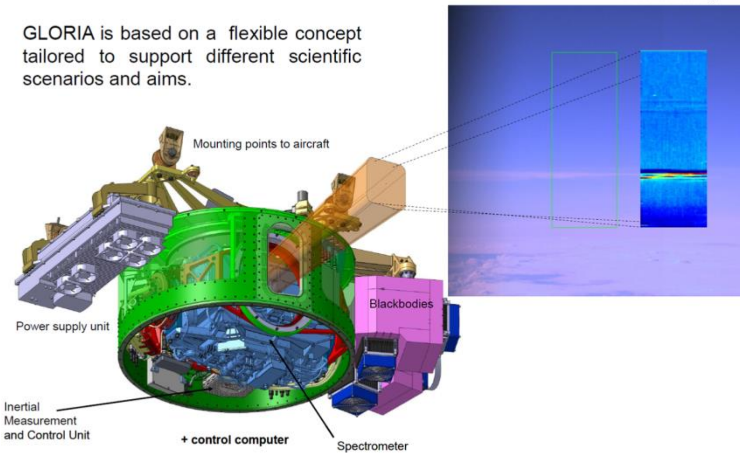
HALO Research Aircraft

Gimballed **L**imb **O**bserver for **R**adiance **I**maging of the **A**tmosphere (GLORIA)

A hierarchy of data …

A (satellite) remote sensing example:

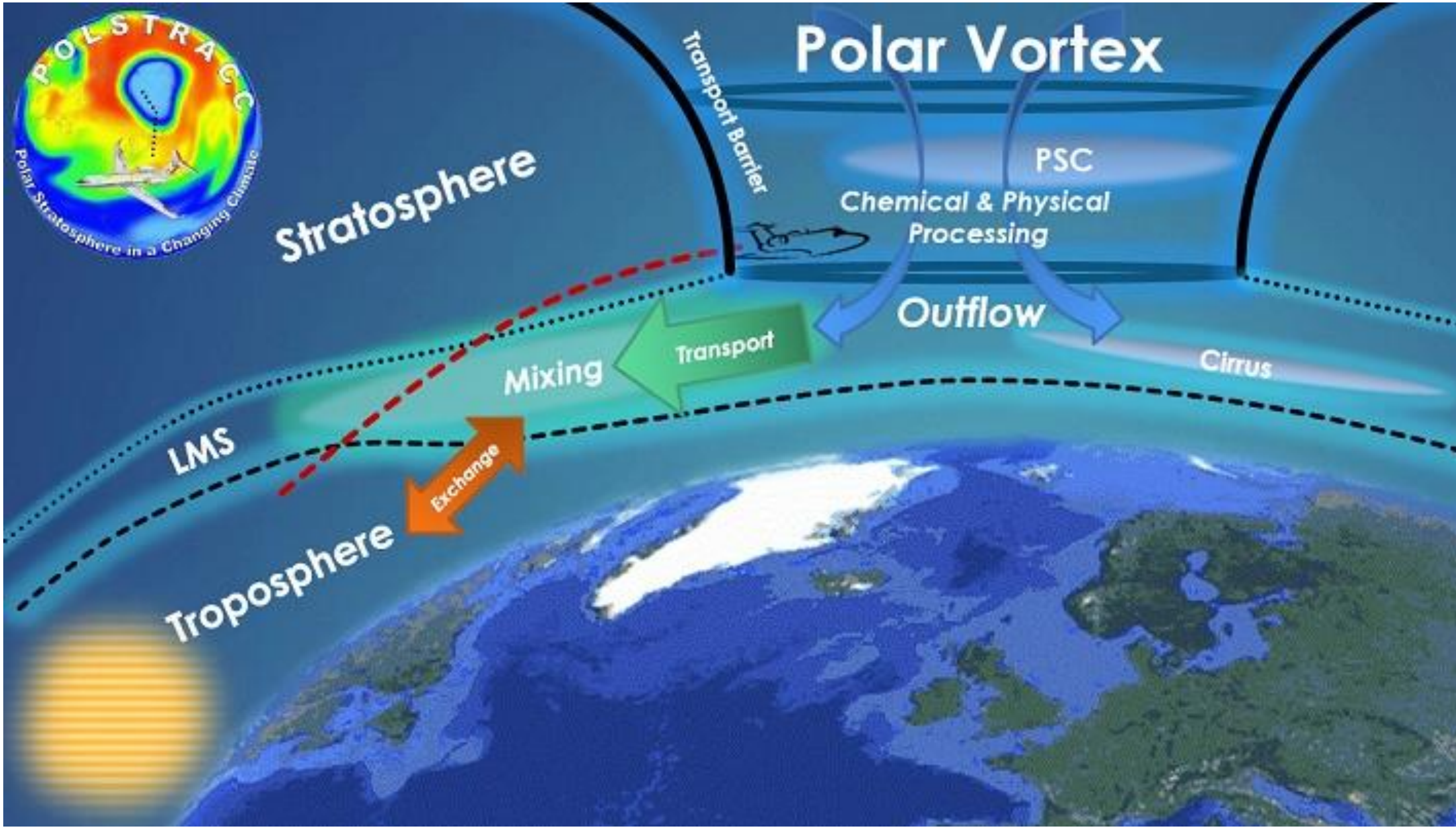
Level	Description
0	Raw radiances
1	Calibrated radiances
2	Retrieved variables
3	Value added products (e.g. gridded fields) – observations only
4	Value added products (e.g. assimilated fields) – observations and models



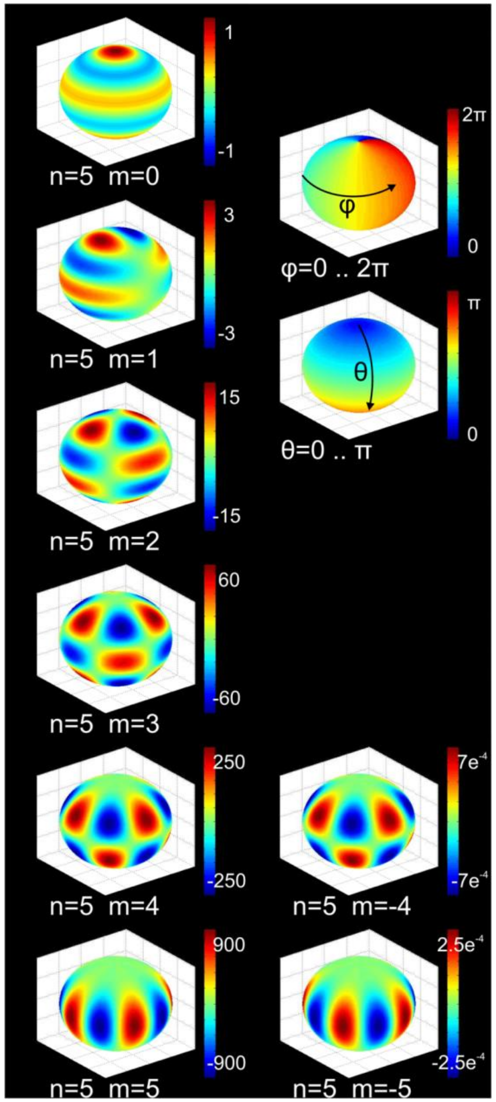
Traceability of products!
(35+28) TB/year=63 TB/year Level-0/1
More than one Level-1 version!

Lifetime of instrument: 5-10 years
~1 TB/year Level-2
Different Level-3 and 4 products!

POLSTRACC Winter 2015/16



The importance of model resolution

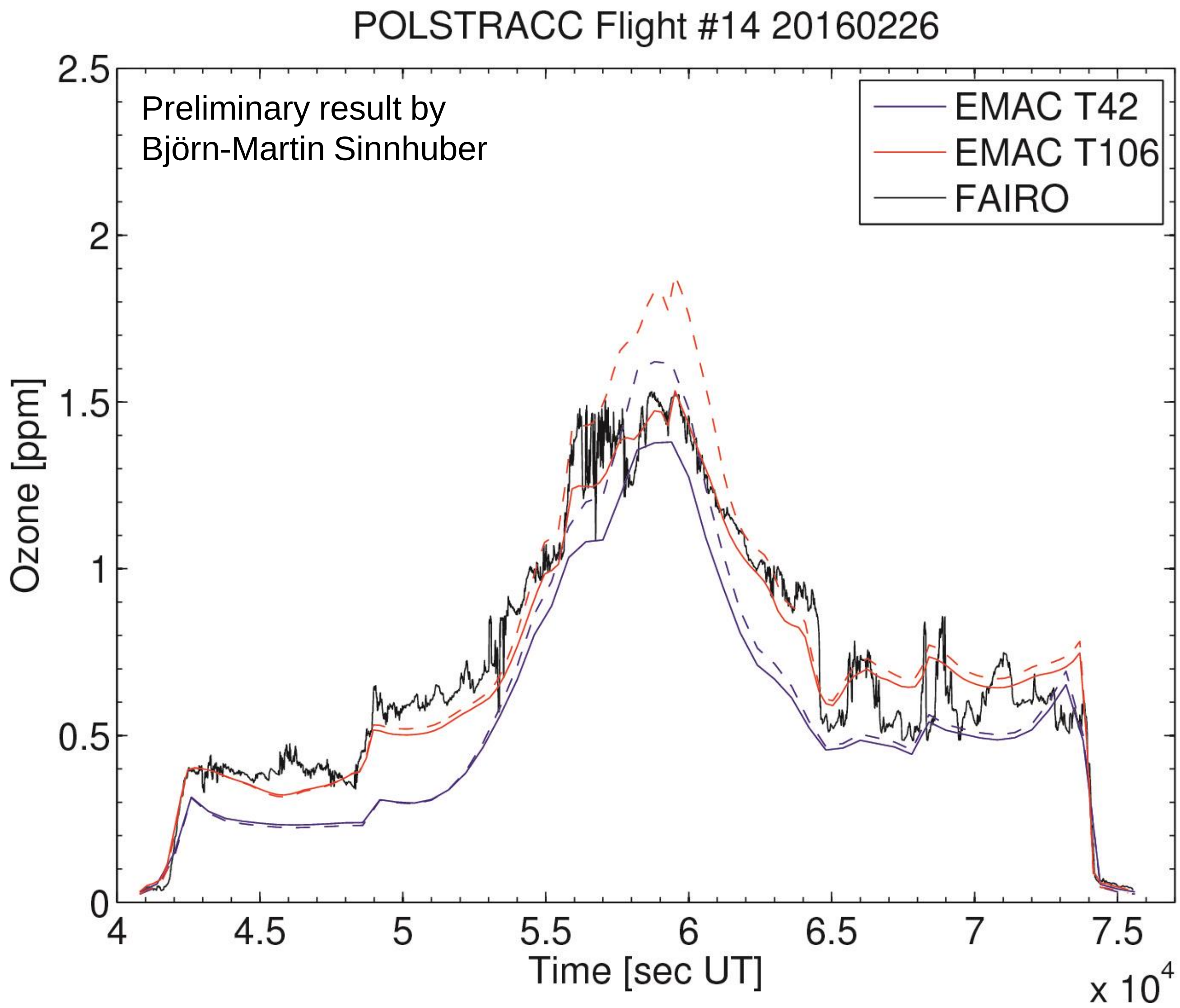


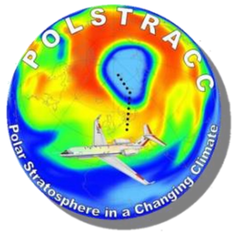
ECHAM5/MESSy for Atmospheric Chemistry (**EMAC**) [Jöckel et al., 2006]

SCC: Simulation Lab Klima und Umwelt: https://www.scc.kit.edu/forschung/7659.php
IMK-ASF: MOD/MSK/IAS Groups: http://www.imk-asf.kit.edu/198.php

Truncation	lat x lon	km at Eq.	deg. at Eq.
T21	32x64	625	5.625
T42	64x128	310	2.8125
T62	94x192	210	1.875
T63	96x192	210	1.875
T85	128x256	155	1.4
T106	160x320	125	1.125
T255	256x512	60	0.703125

The importance of model resolution





The product rule

For one model	
nlon	Number of longitudes
nlat	Number of latitudes
nlev	Number of vertical levels
ntime	Number of time steps
nensm	Number of ensemble member
nvar	Number of variables (e.g. T, u, v, etc.)

Typical values for an ESM:
96x72x60x(4x360x50)x5x50=7464960000000 (~55 TB)

Typical values for a „high resolution“ climate model:
640x480x90x(4x360x50)x5x50=497664000000000 (67xESM)

International assessments: many models and many settings (parameter space)!

Unified Model

Met Office

$$\frac{D_r u}{Dt} - \frac{uv\tan\phi}{r} - 2\Omega\sin\phi v + \frac{c_{pd}\theta_v}{r\cos\phi}\frac{\partial\Pi}{\partial\lambda} = -\left(\frac{uw}{r} + 2\Omega\cos\phi w\right) + S^u$$

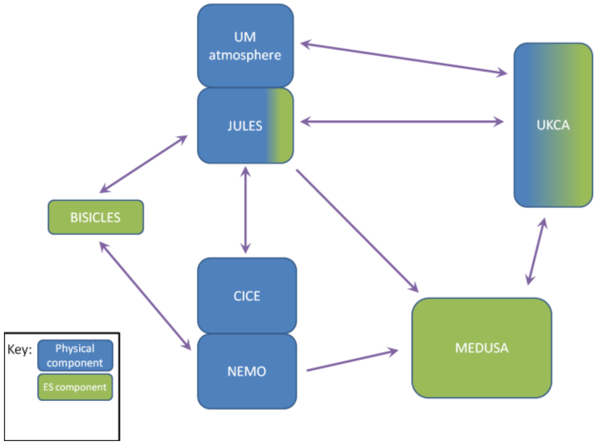
$$\frac{D_r v}{Dt} + \frac{u^2\tan\phi}{r} + 2\Omega\sin\phi u + \frac{c_{pd}\theta_v}{r}\frac{\partial\Pi}{\partial\phi} = -\left(\frac{vw}{r}\right) + S^v$$

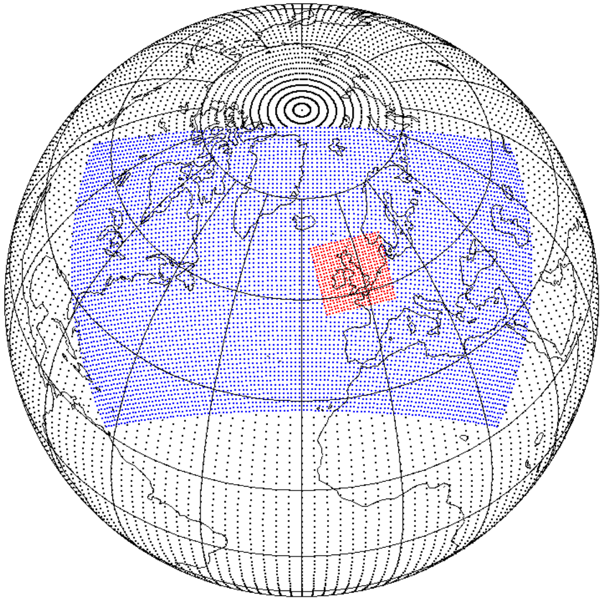
$$\frac{D_r w}{Dt} + c_{pd}\theta_v\frac{\partial\Pi}{\partial r} + \frac{\partial\Phi}{\partial r} = \left(\frac{u^2+v^2}{r}\right) + 2\Omega\cos\phi u + S^w$$

$$\frac{D_r}{Dt}(\rho_y r^2\cos\phi) + \rho_y r^2\cos\phi\left(\frac{\partial}{\partial\lambda}\left[\frac{u}{r\cos\phi}\right] + \frac{\partial}{\partial\phi}\left[\frac{v}{r}\right] + \frac{\partial w}{\partial r}\right) = 0$$

$$\frac{D_r\theta}{Dt} = S^\theta$$

The fully compressible, nonhydrostatic, deep-atmosphere equations in spherical geometry. In the shallow-atmosphere approximation the terms in yellow boxes are dropped and in the hydrostatic approximation the term coloured red is dropped.





Avoid shallow atmosphere approximation

Avoid hydrostatic approximation

Ozone Feedback

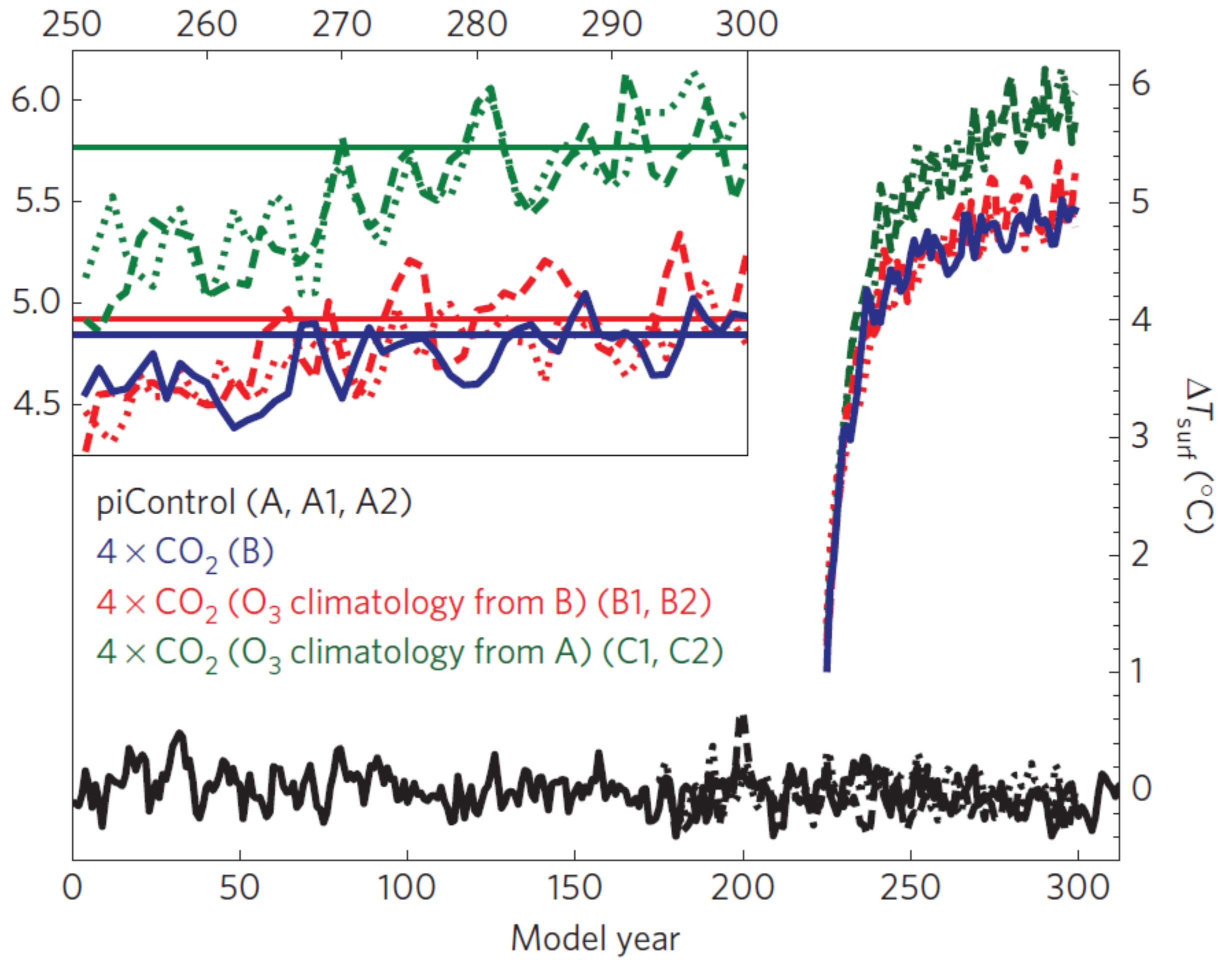


Figure 1 | Temporal evolution of the annual and global mean surface temperature anomalies. All anomalies (°C) are shown relative to the

Nowack et al., Nature Climate, 2014

Next Generation Model

The new modelling framework - ICON

$$\frac{\partial v_n}{\partial t} + \frac{\partial K_h}{\partial n} + (\zeta + f)v_t + w\frac{\partial v_n}{\partial z} = -c_{pd}\theta_v \frac{\partial \pi}{\partial n} + F(v_n), \quad (3)$$

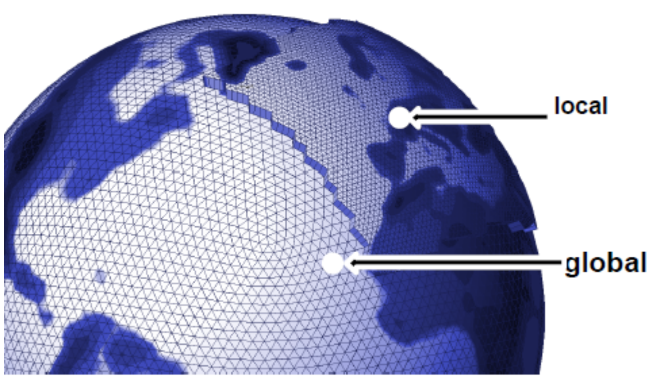
$$\frac{\partial w}{\partial t} + \mathbf{v_h} \cdot \nabla w + w\frac{\partial w}{\partial z} = -c_{pd}\theta_v \frac{\partial \pi}{\partial z} - g, \quad (4)$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\mathbf{v}\rho) = 0, \quad (5)$$

$$\frac{\partial \rho\theta_v}{\partial t} + \nabla \cdot (\mathbf{v}\rho\theta_v) = \tilde{Q}. \quad (6)$$

Grid	Number of cells	Number of edges	Effective grid resolution (km)	Max/min cell area ratio
R2B04	20 480	30 720	157.8	1.38
R2B05	81 920	122 880	78.9	1.44
R2B06	327 680	491 520	39.5	1.49
R2B07	1 310 720	1 966 080	19.7	1.53

Zängl et al., QJRMS, 2014



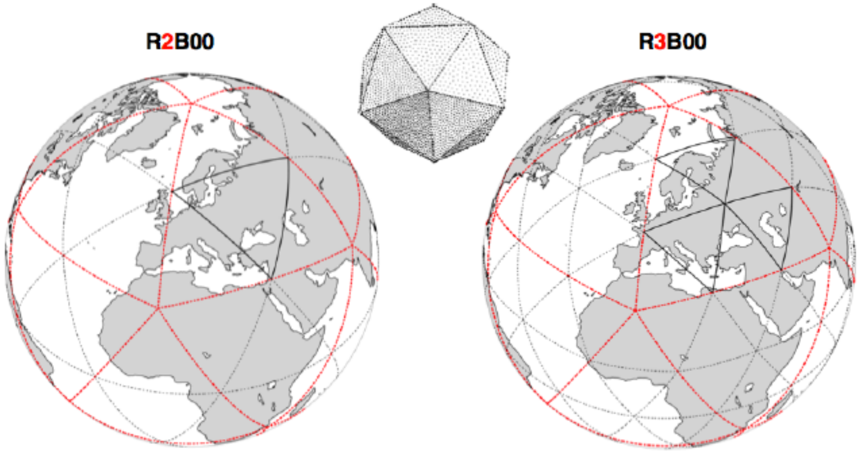


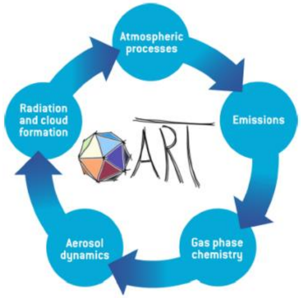
image courtesy: D.Reinert (DWD) and F. Prill (DWD)

Max-Planck-Institut für Meteorologie

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Next Generation Model

The new modelling framework - ICON

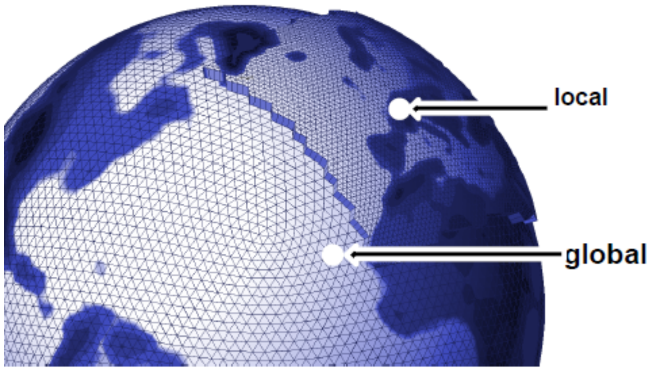


ICON = ICOsahedral Nonhydrostatic modelling framework

Joint development project of DWD and Max-Planck-Institute for Meteorology for building a next-generation global NWP and climate modelling system.

KIT joined for incorporating the module **ART**

ART = Aerosols and Reactive Trace gases



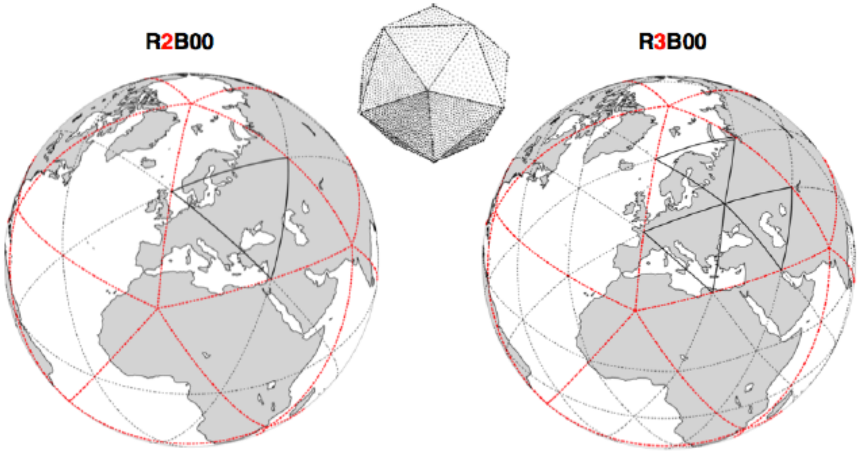


image courtesy: D.Reinert (DWD) and F. Prill (DWD)

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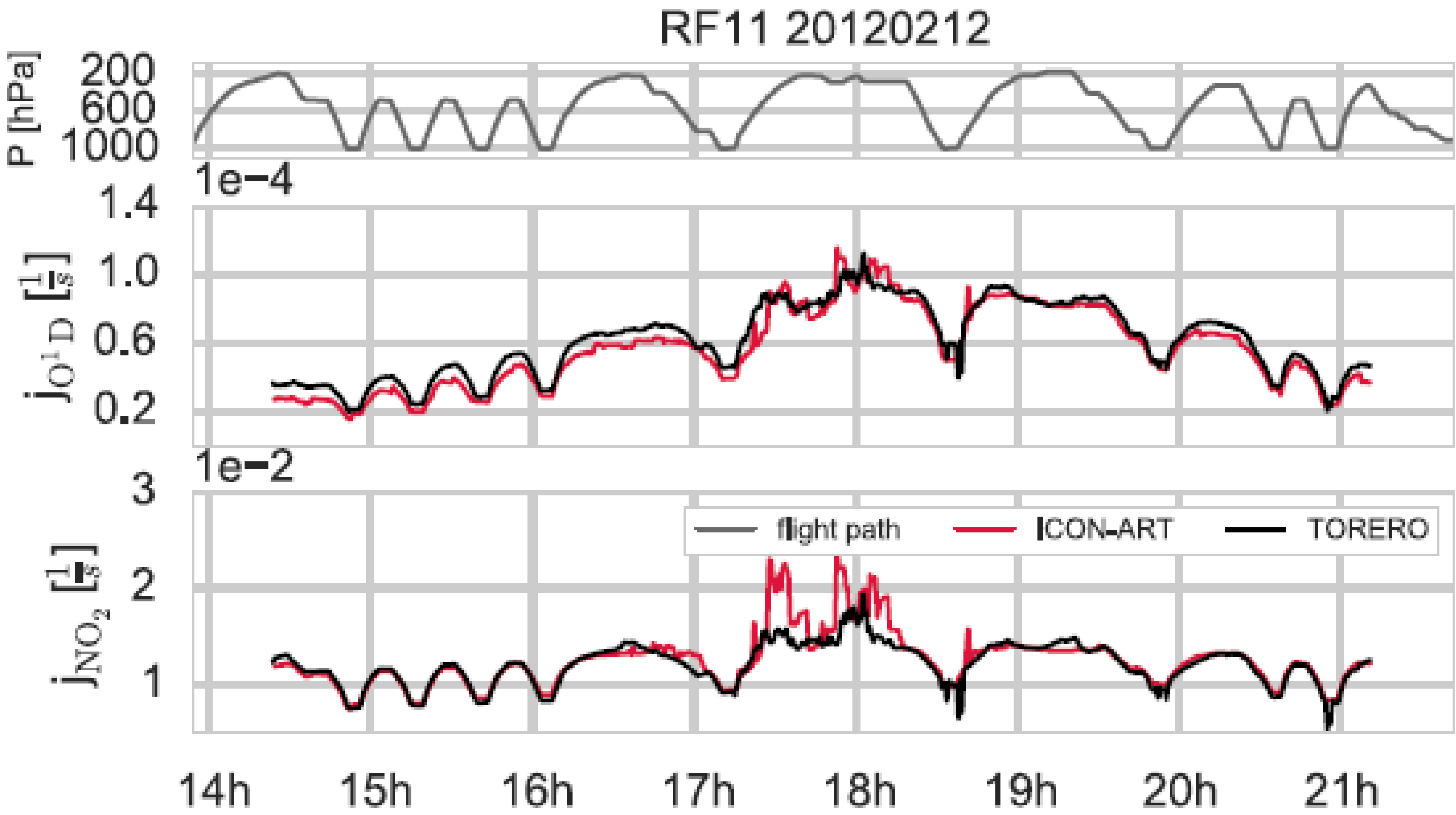
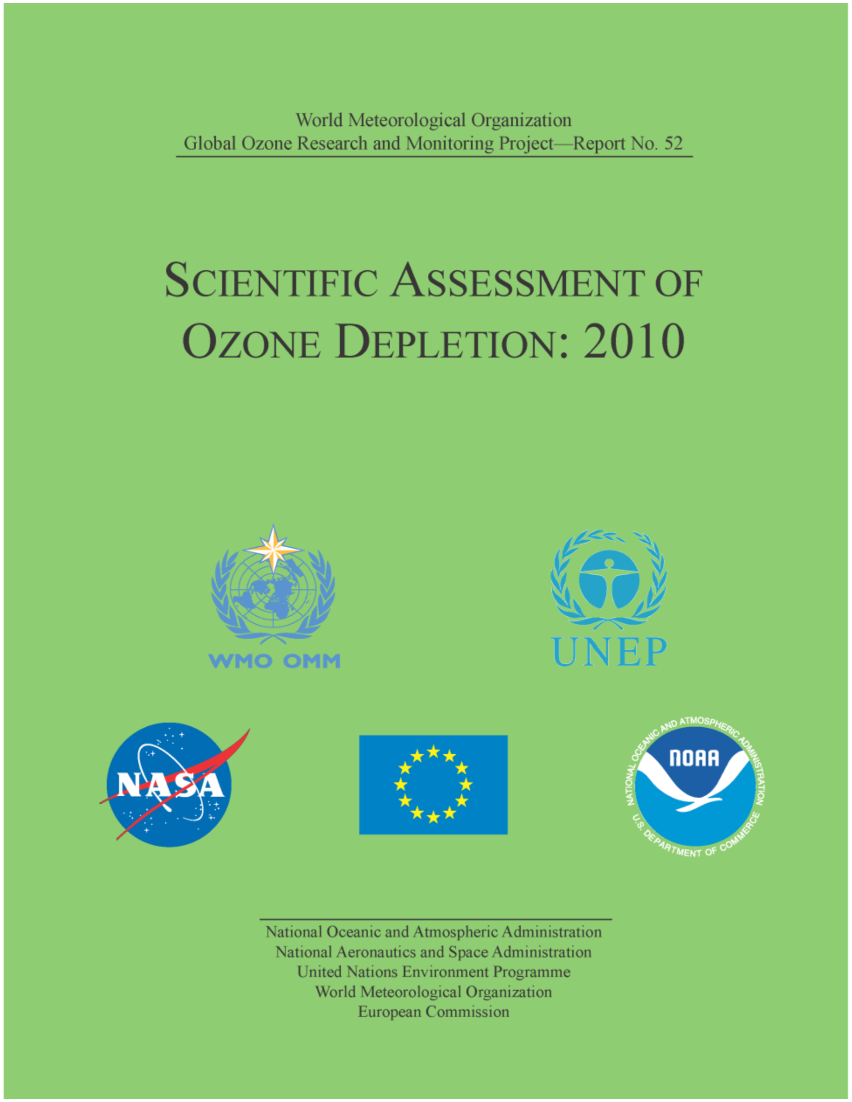
Wetter und Klima aus einer Hand

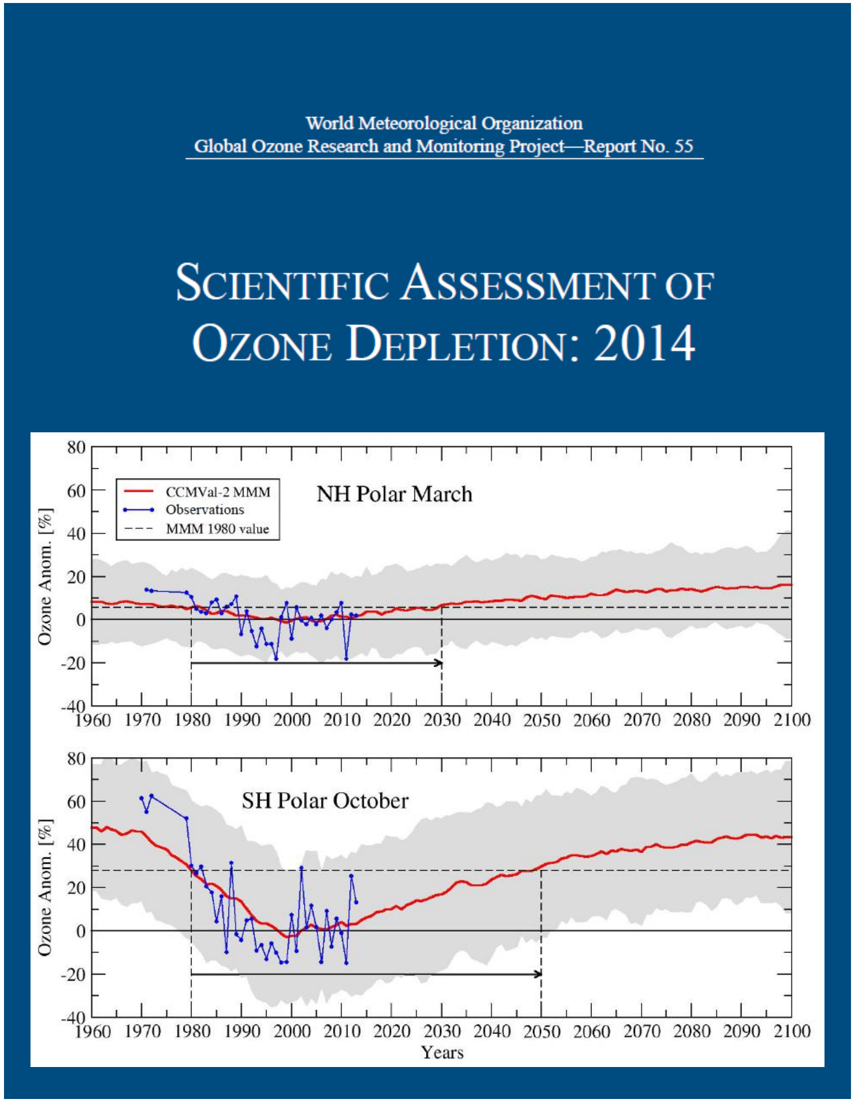
Photolysis rates: Modelled and observed



Courtesy: Jennifer Schröter, PhD candidate, IMK-ASF

WMO Ozone Assessments





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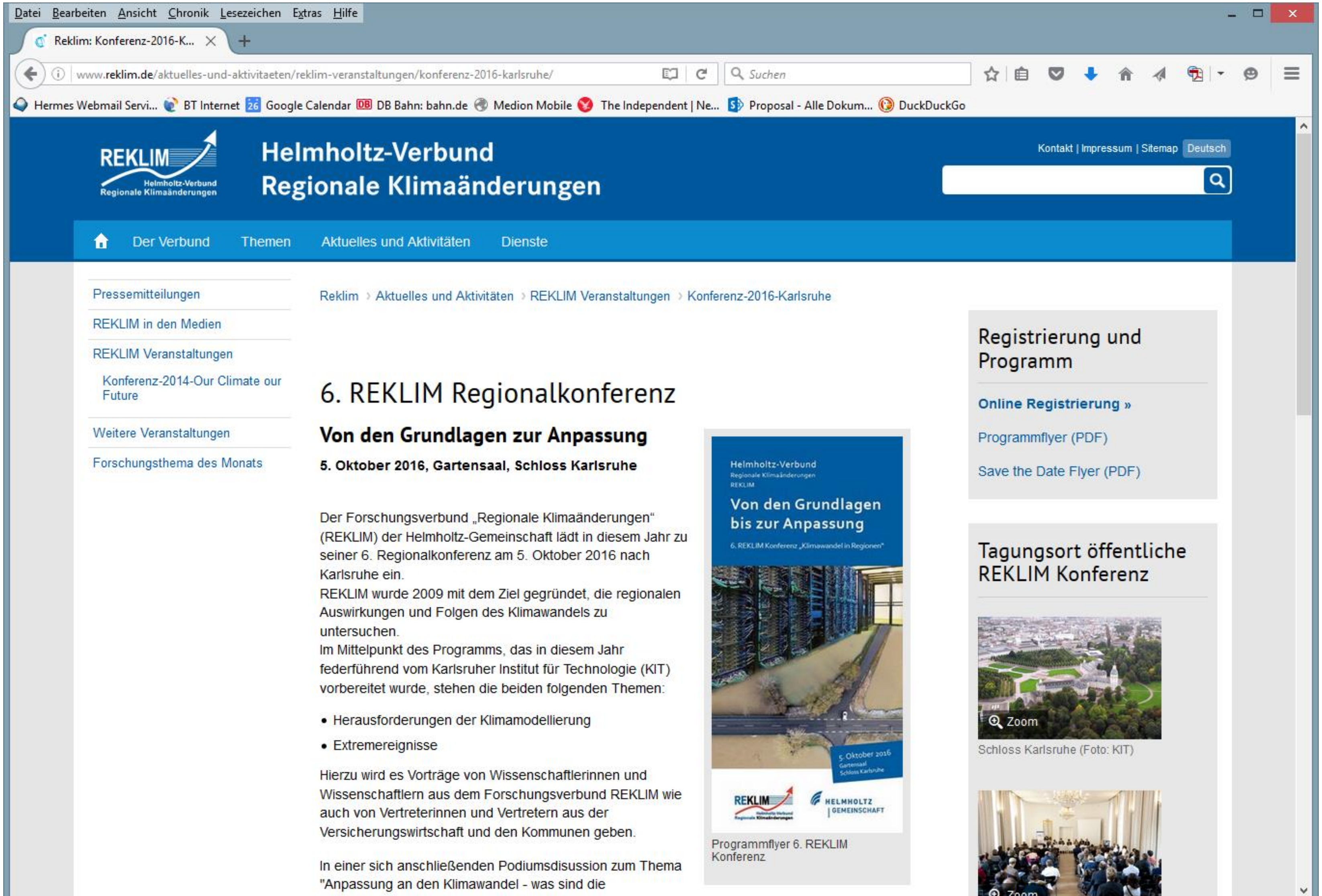

The End

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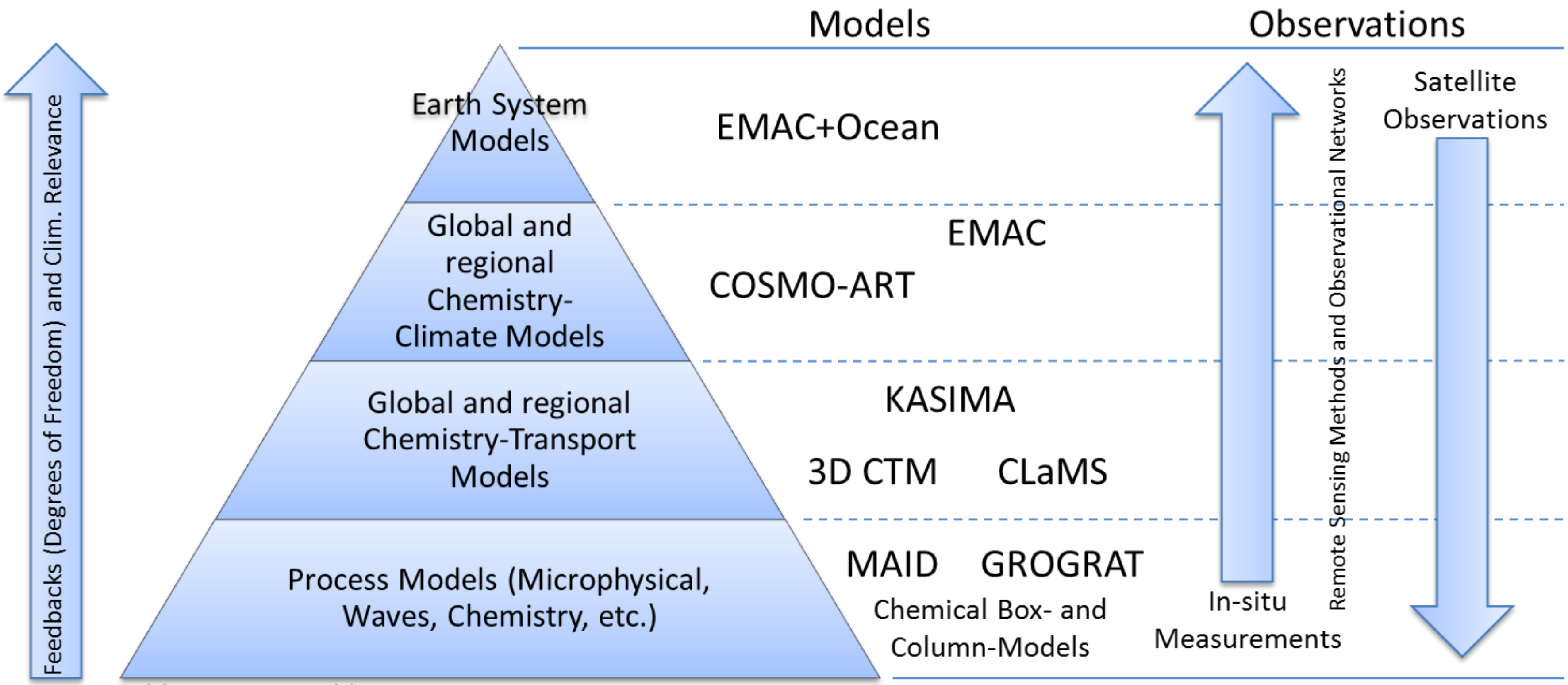
Thank you!

… and models



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