A semi-empirical model of the stratosphere in the Antarctic climate system

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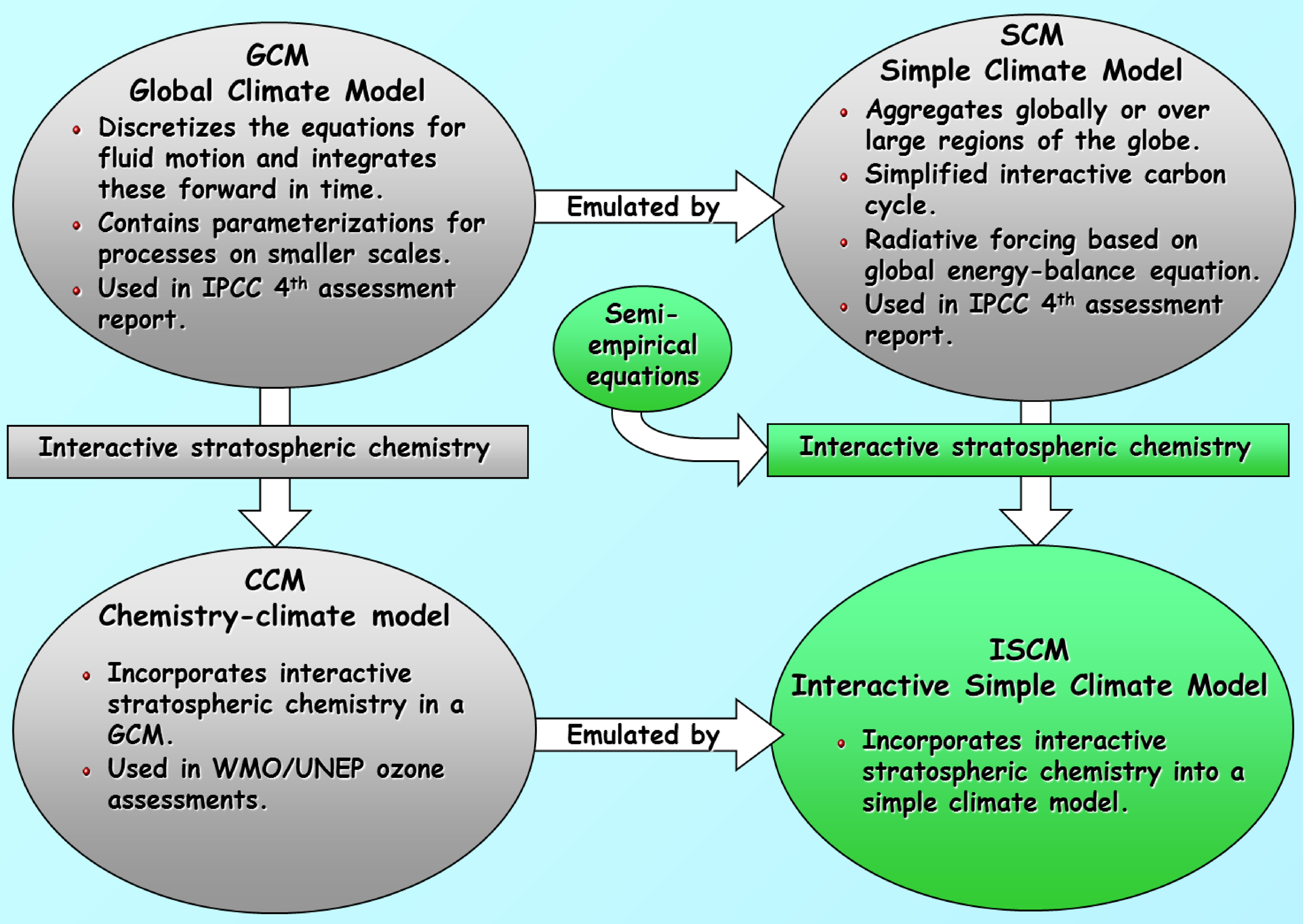


The goal

Develop a new and fast method to simulate the evolution of the Antarctic ozone layer and its coupling to the climate system.

We are building a fast emulator of complex atmospheric-ocean global climate models (see green regions in figure on left) using:

The MAGICC simple climate model

+

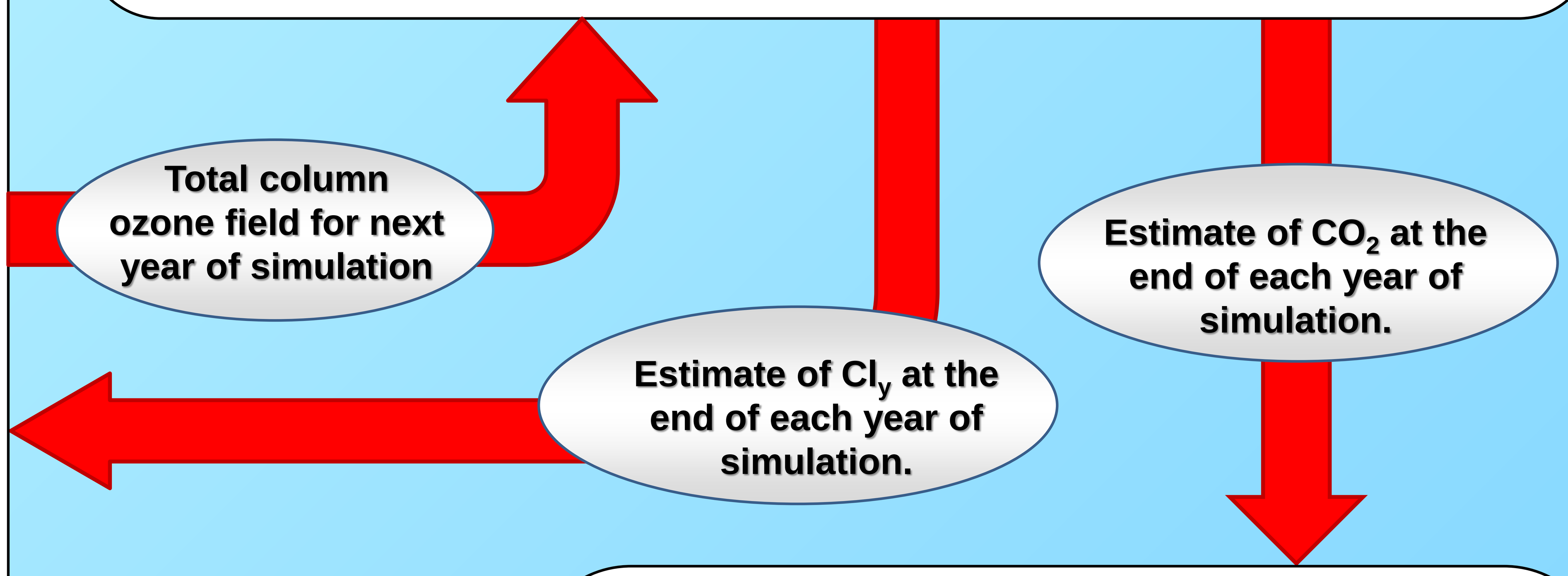
A novel semi-empirical module that describes the key processes governing stratospheric ozone

We can then simulate the evolution of the Antarctic ozone layer for a wide range of greenhouse gas (GHG) and ozone depleting substance (ODS) emissions scenarios.

The MAGICC simple climate model

MAGICC = Model for the Assessment of Greenhouse-Gas Induced Climate Change[1,2]

- Inputs: emissions of GHGs, sulfur, black carbon and organic carbon and ODSs.
- Simulates changes in concentrations of radiatively active gases and equivalent effective stratospheric chlorine (EESC).
- Simulated changes in radiative forcing drive changes in surface temperature and in sea-level.
- MAGICC uses a simple correlation between EESC and ozone to model changes in stratospheric ozone and its radiative forcing.
- Changes in stratospheric temperatures, and other links between GHGs and ozone.
- Focus of this project is to extend MAGICC to include such functionality.



SWIFT: Simulating Antarctic stratospheric ozone

SWIFT = Semi-empirical Weighted Iterative Fit Technique[4,5].

- Set of coupled first order differential equations describing time rate of change of key species in the polar stratosphere.
- Driven by time series of FAP (fractional area of vortex with T<195K) and FAS (fractional area of vortex exposed to sunlight) → derived from temperature fields provided by STePS.

Governing equations:

$$d[O_3]/dt = -d \cdot [ClO_x] \cdot FAS \quad (1)$$

Represents overall effect of ClO+ClO, ClO+BrO, and ClO+O reaction cycles on ozone loss. O_3 loss scales nearly linearly with ClO_x (Cl + ClO + 2×ClOOCl) and with vortex average sunlit time per day. Requires good estimates of ClO_x through the winter.

To estimate ClO_x, SWIFT needs to represent conversion of reservoir species $ClONO_2$ and HCl into ClO_x. With $ClONO_2$ and HCl, ClO_x is calculated using

$$[ClO_x] = [Cl_y] - [HCl] - [ClONO_2] \quad (2)$$

where Cl_y comes from MAGICC.

$$d[ClONO_2]/dt = -a \cdot [ClONO_2] \cdot [HNO_3] \cdot FAP + b \cdot [HNO_3]_g \cdot FAS \quad (3)$$

describes time evolution of vortex averaged $ClONO_2$. First term represents net effects of HCl + $ClONO_2$ → HNO_3 + Cl_2 followed by Cl_2 + hv → Cl + Cl. Second term represents net effect of HNO_3 + hv → OH + NO_2 followed by ClO + NO_2 → $ClONO_2$.

$$d[HCl]/dt = -a \cdot [ClONO_2] \cdot [HNO_3] \cdot FAP + c \cdot [ClO_x] \cdot FAS \cdot 1/[O_3] \quad (4)$$

describes evolution of vortex averaged HCl. Second term represents effects of Cl + CH_4 → HCl + CH_3. The term $[ClO_x]/[O_3]$ gives concentration of Cl since fraction of ClO_x that is Cl is controlled by $1/[O_3]$.

$$d[HNO_3]/dt = -e \cdot \max((FAP-yy), 0) \quad (5)$$

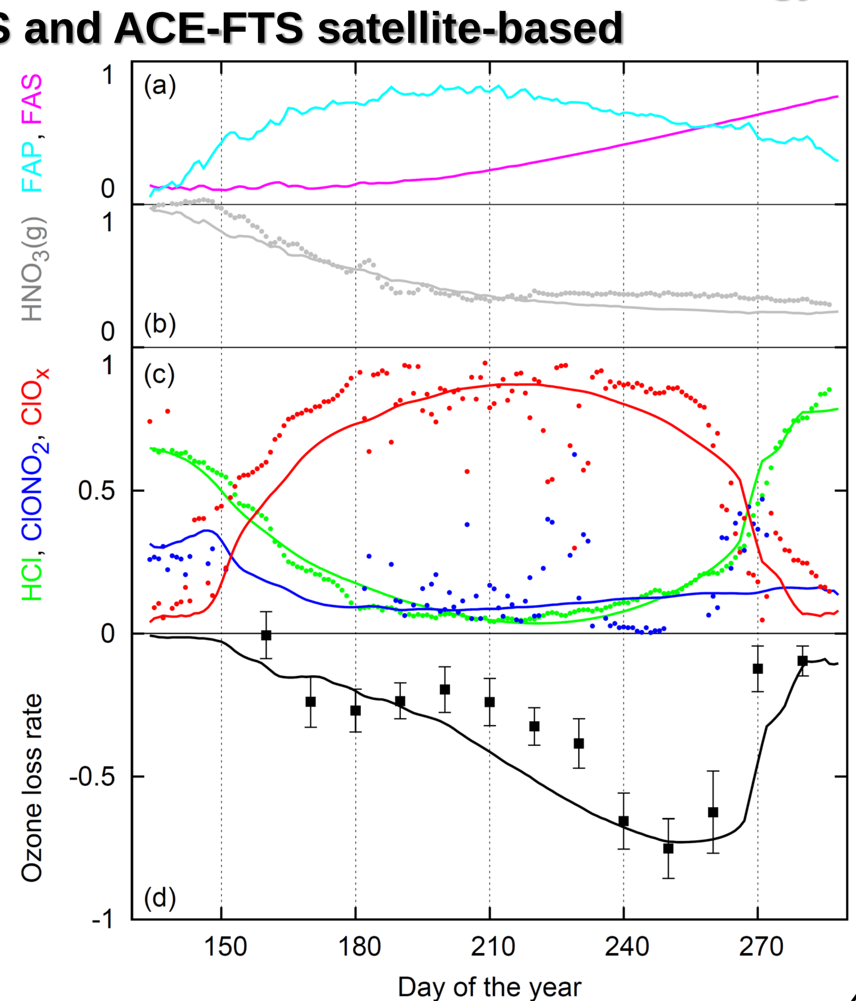
represents denitrification. Assumes that denitrification becomes efficient only if FAP exceeds a certain threshold value yy and then scales with FAP above that threshold.

$$[HNO_3]_g = [HNO_3] \cdot (1-FAP) + zz \cdot [HNO_3]_g \cdot FAP \quad (6)$$

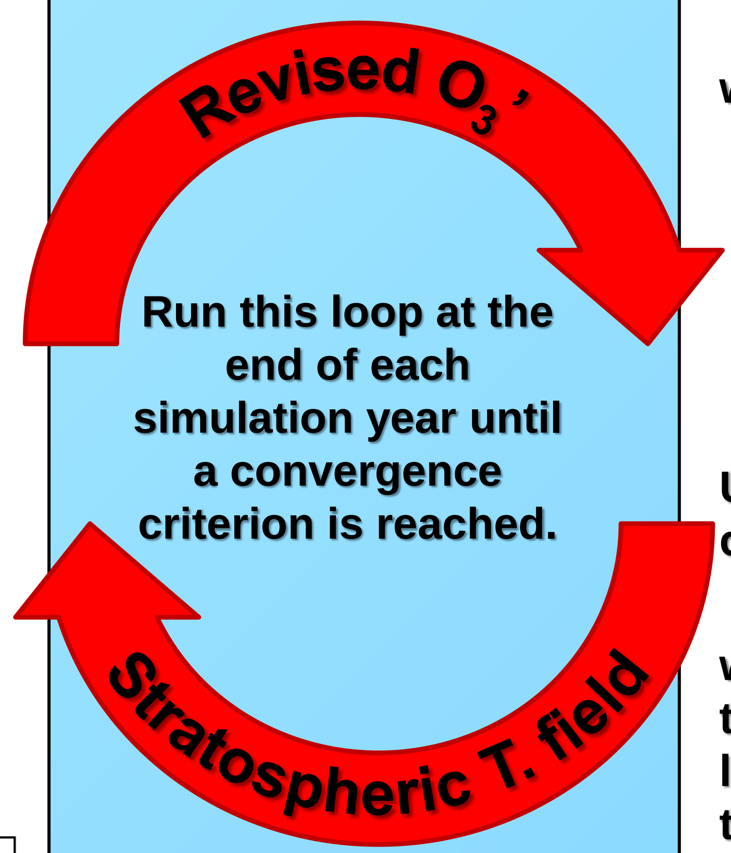
instantaneously calculates gas phase HNO_3 from total HNO_3. Second term represents HNO_3 that is in the gas phase due to nucleation barrier even in areas colder than PSC cloud formation threshold.

Fit coefficients, shown in red, are derived by fitting these 6 equations to measurements from AURA MLS (HCl and HNO_3), from ACE-FTS ($ClONO_2$), and ClOx loss rates determined for the Antarctic stratosphere.

Prognostic variables are initialized at the beginning of the winter season (1 May). Initial ozone values obtained from a global vertically resolved ozone climatology[6]. HNO_3 values obtained from SPARC Data Initiative climatology. Based on measurements by the MLS and ACE-FTS satellite-based instruments, [HCl] is set to 70% of $[Cl_y]$ and $[ClONO_2]$ to 30% of $[Cl_y]$.



Overview of SWIFT results and observations for the Antarctic winter pf 2006. All data are shown in normalized units. (a) FAP (cyan) and FAS (magenta). Lines in (b)–(d) represent SWIFT results, dots represent vortex-averaged observations. (b) HNO_3 (gas phase, gray, observations from Aura MLS). (c) HCl (green, observations from Aura MLS), $ClONO_2$ (blue, observations from ACE-FTS), and ClO_x (red, 'observed' ClOx is derived by using a constant Cl_y minus the HCl and $ClONO_2$ observations). (c) Ozone loss rates (observations from Match). The loss rates of normalized ozone have been multiplied by 50 to facilitate plotting on the same scale. Error bars represent 1σ statistical uncertainties[5].



The STePS module for simulating stratospheric temperatures

STePS = Stratospheric Temperature Pattern Scaling

$$T' = f(CO_2', O_3') + g$$

where:

T' is perturbation in temperature at some location in the Antarctic stratosphere w.r.t. a 1961-1990 climatology.

CO_2' and O_3' are perturbations in vortex averaged CO_2 and O_3 w.r.t. a 1961-1990 climatology.

g represents stochastic variability in the temperature anomaly fields.

Use climate pattern scaling[3] to determine the functional dependence of T' on CO_2' and O_3'. Set this up as:

$$T'_{i,j} = \alpha_{i,j} \times O_3' + \beta_{i,j} \times O_3'^2 + \gamma_{i,j} \times CO_2' + \delta_{i,j} \times CO_2'^2$$

where α, β, γ, and δ are fit coefficients derived by fitting the equation to CCM output at each pressure level and latitude (denoted by i,j subscripts) based on zonal mean temperature fields, vortex average ozone and vortex average CO_2.

First guess of CO_2' comes from MAGICC output and first guess of O_3' is set to zero.

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