World-avoided simulations using a fully-coupled chemistry-climate model

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WACCM
Whole Atmosphere Community Climate Model

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Outline

- Motivation
- Model and simulations
- Results
- Conclusions

CFC are both ozone depleting substances (ODS) and greenhouse gases (GHG)

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The importance of the Montreal Protocol in protecting climate

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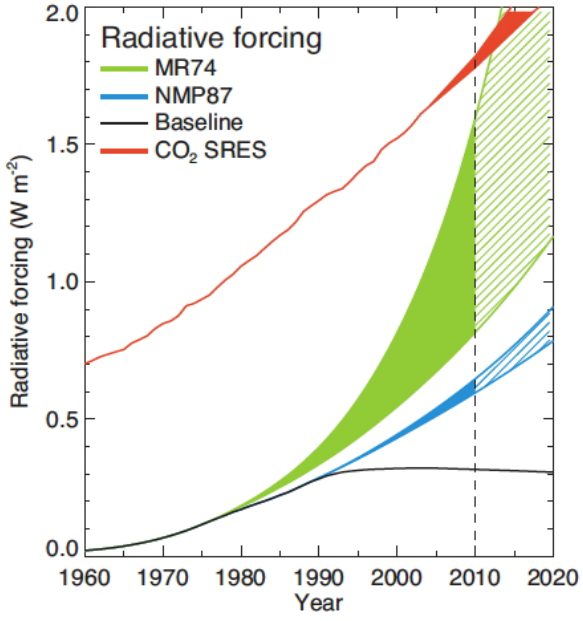
The 1987 Montreal Protocol on Substances that Deplete the Ozone Layer is a landmark agreement that has successfully reduced the global production, consumption, and emissions of ozone-depleting substances (ODSs). ODSs are also greenhouse gases that contribute to the radiative forcing of climate change. Using historical ODSs emissions and scenarios of potential emissions, we show that the ODS contribution to radiative forcing most likely would have been much larger if the ODS link to stratospheric ozone depletion had not been recognized in 1974 and followed by a series of regulations. The climate protection already achieved by the Montreal Protocol alone is far larger than the reduction target of the first commitment period of the Kyoto Protocol.



- Velders et al. (*PNAS*, 2007) pointed out that control of ODS by the Montreal Protocol produced a significant reduction in radiative forcing (the “World avoided”)

Consequences of continued growth of ODS into the 21st century

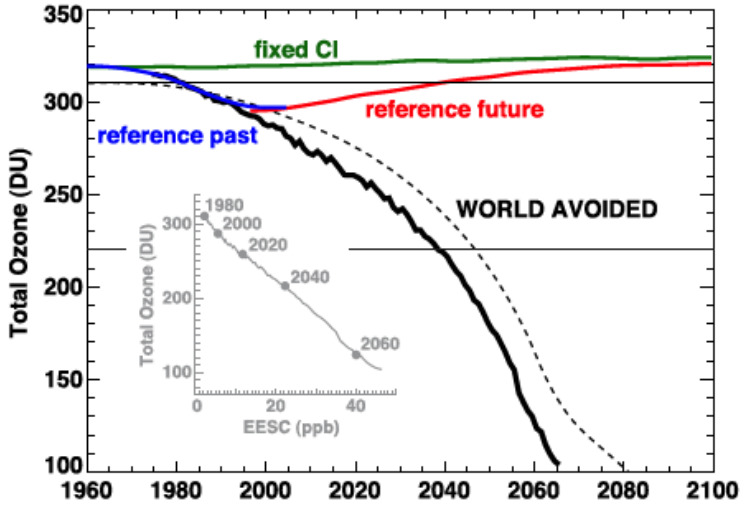


Fig. 2. Annually-averaged global ozone for the *WORLD AVOIDED* (solid black), *reference future* (red), *fixed chlorine* (green), and *reference past* (blue) simulations. The curves are smoothed with a Gaussian filter with a half-amplitude response of 20 years, except for the *WORLD AVOIDED*, which is unsmoothed. The dashed line shows the 2-D coupled model simulation of the "world avoided". The grey-shaded inset shows the *WORLD AVOIDED* total ozone plotted against global annually-averaged EESC at 4.5 hPa from Fig. 1.

- Newman et al. (*ACPD*, 2009) demonstrated a rapid collapse of the Ozone layer after midcentury, with corresponding very large increases in UV index

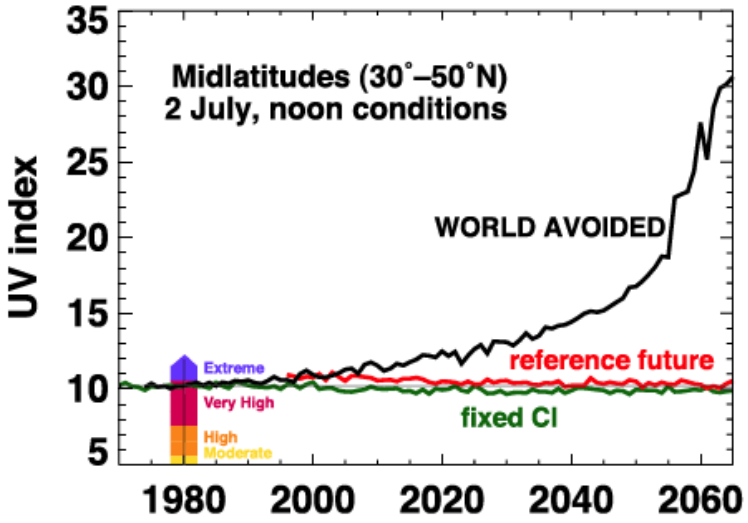


Fig. 14. UV index versus year for the *WORLD AVOIDED* (black), *reference future* (red), and *fixed chlorine* (green) simulations. As with Fig. 13, the UV index is calculated using the July 30°–50° N zonal-mean ozone, and assuming a time of local noon on 2 July. The standard UV index "risk" scale is also superimposed on the bottom left. The horizontal grey line shows the 1975–1985 average of the UV index from the *fixed chlorine* simulation.

- but Newman et al. used a model with specified SST, so they could not assess climate change due to greenhouse effects of ODP

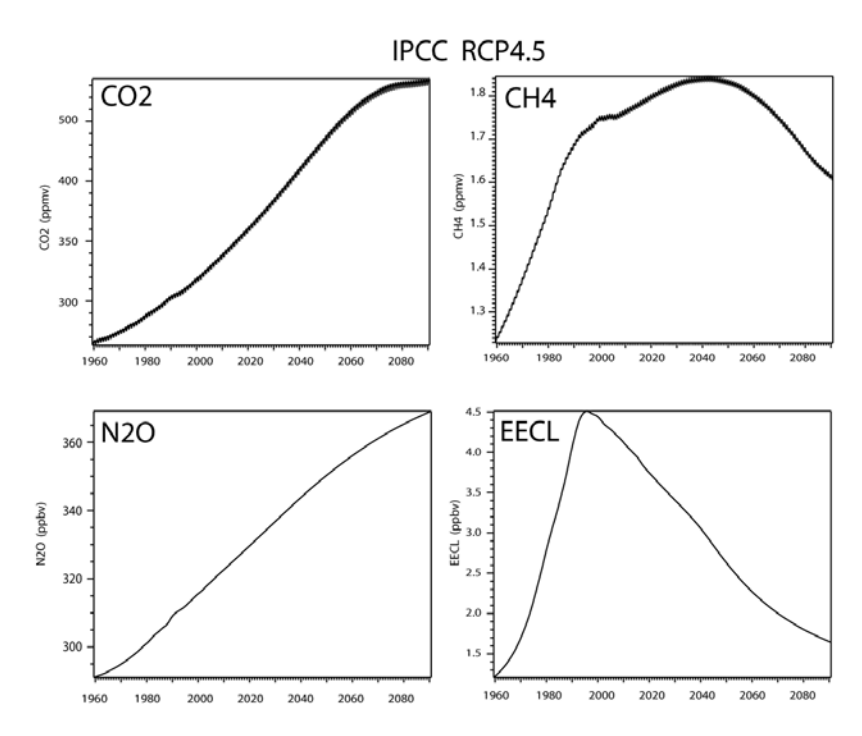
A *fully coupled* model is the right tool for looking at *tropospheric climate change*

Whole Atmosphere Community Climate Model

Model Framework	Dynamics	Tracer Advection	Resolution	Chemistry	Other Processes
Based upon NCAR Community Atmosphere Model, CAM4 Part of the NCAR Community Earth System Model, v.1	Finite Volume Dynamical Core (Lin, 2004) Fully-interactive, i.e., consistent with model-derived, radiatively active gases: O_3, CO_2, CH_4, N_2O, H_2O, CFC11, CFC12, O_2, NO QBO may be specified from observations Coupled to full ocean model (NCAR POP)	Flux-form Finite Volume (Lin, 2004)	Horizontal: 1.9° x 2.5° or 4.0° x 5.0° (lat x lon) Vertical: 66 levels 0-140km < 1.0km in UTLS 1-2 km in stratosphere 3 km in MLT	Middle Atmosphere Mechanism 57 Species including Ox, HOx, NOx, BrOx, and ClOx No NMHCs Includes het. chemistry on LBS, STS, NAT, ICE E-region Ion Chemistry	Gravity-wave parametrization (for unresolved, mesoscale gravity waves) Molecular diffusion (Banks and Kockarts, 1973) Auroral processes, including ion drag, and Joule heating Longwave, shortwave, and chemical potential heating

Simulations

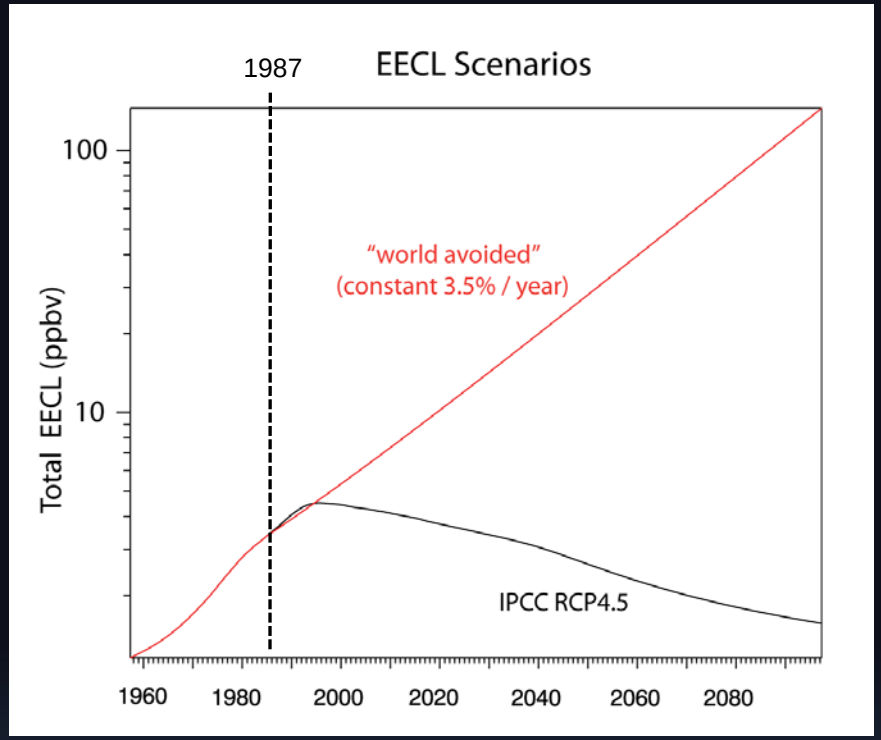
Control: 1985-2070; IPCC CMIP-5 scenario RCP4.5 beyond 2005



RCP4.5 is a "moderate" scenario, with GHG stabilization towards the end of the 21st century

EECL: Equivalent effective chlorine. Follows Montreal protocol in the *Control* run

World-Avoided: same as *Control*, but Cl and Br from anthropogenic sources increase at 3.5% from 1987

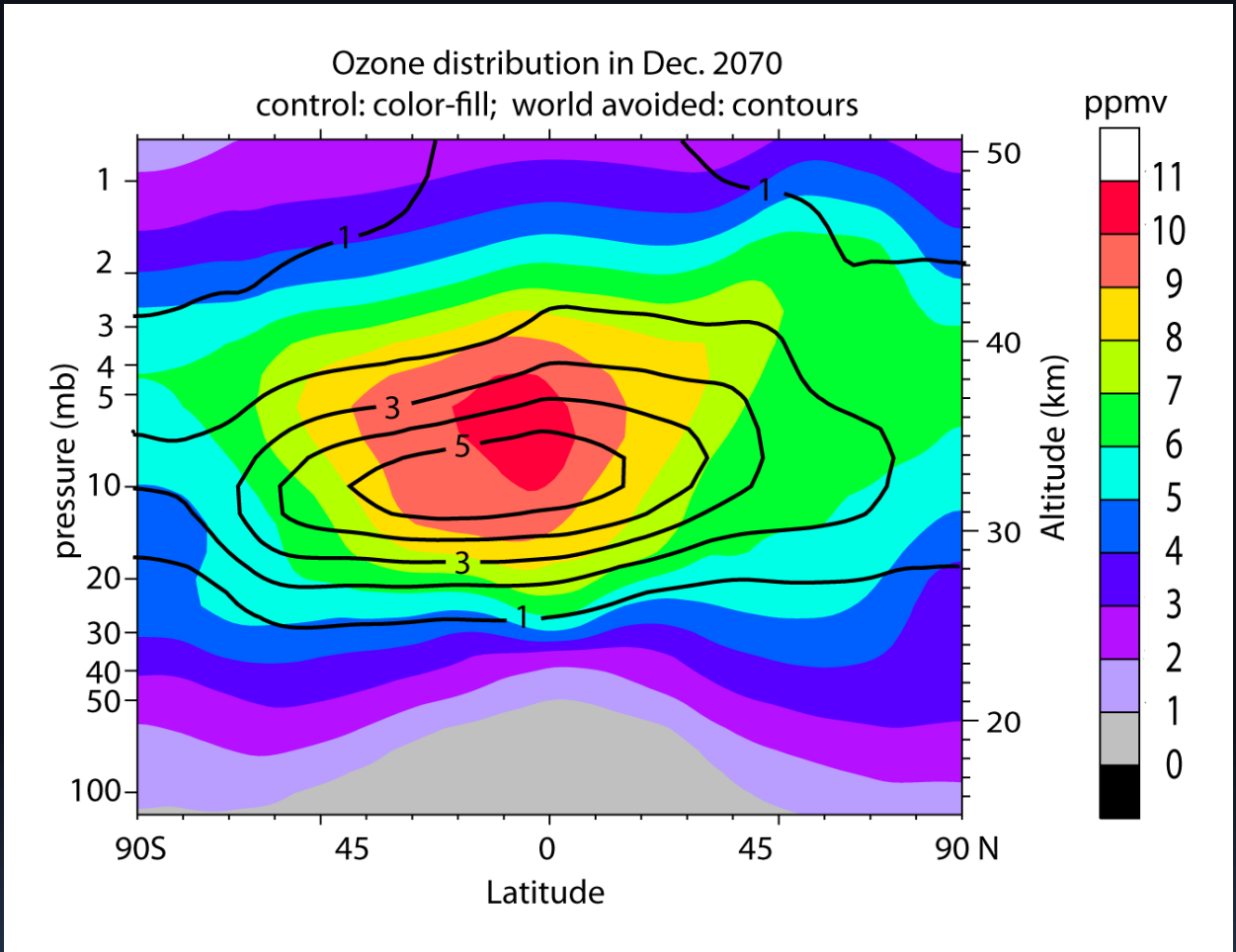


In the *World avoided* simulation, EECL continues to grow at 3.5% per year throughout 21st century

Results

- stratospheric composition and dynamics
- global climate change
- look at behavior in 21st century (through 2070)

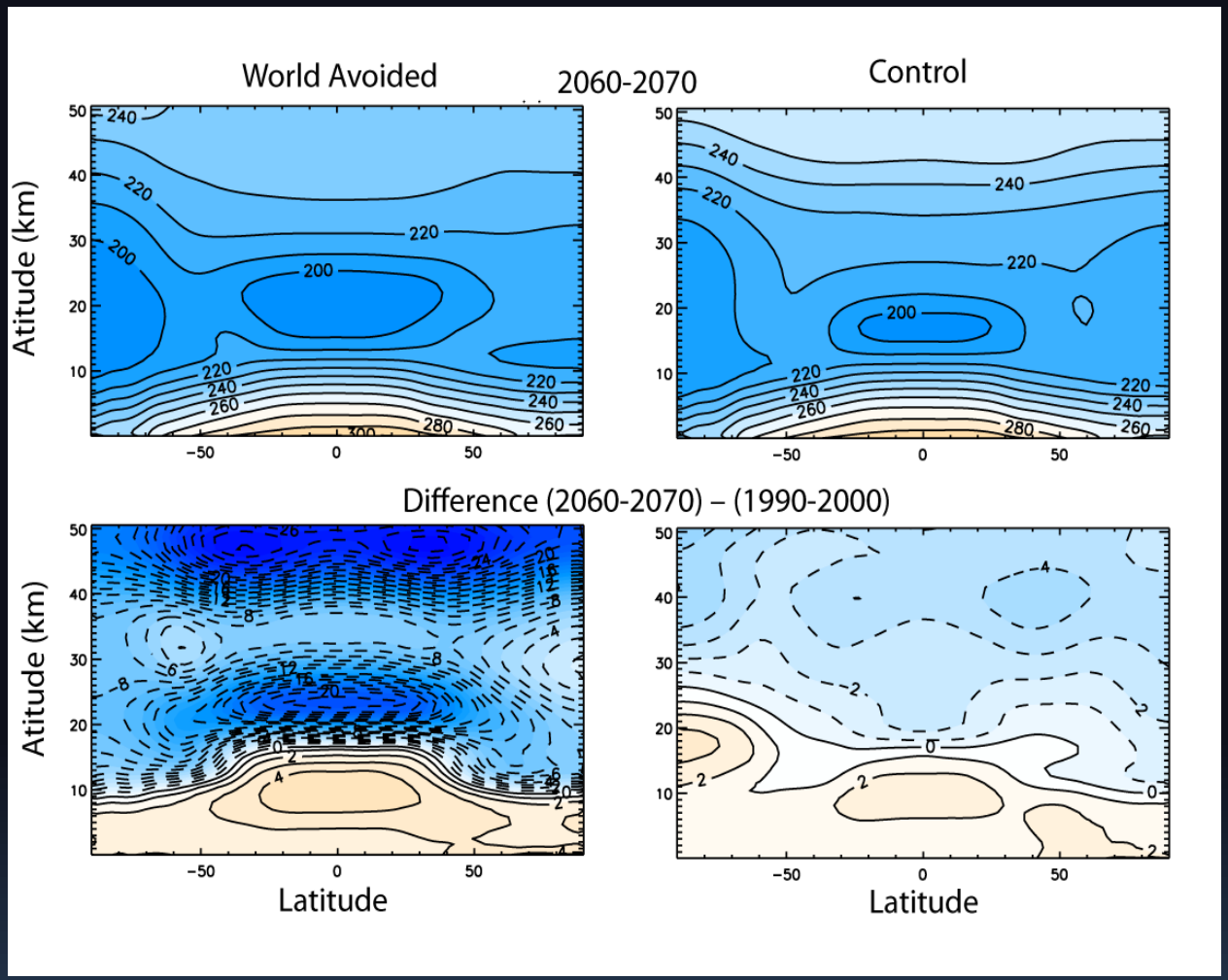
Stratospheric Ozone in 2070



World avoided compared to *Control*, in 2070:

- ozone maximum is reduced by more than half in the middle stratosphere
- the ozone maximum moves to lower altitude (self-healing)
- ozone loss in the lower and upper stratosphere is even greater than in the middle stratosphere

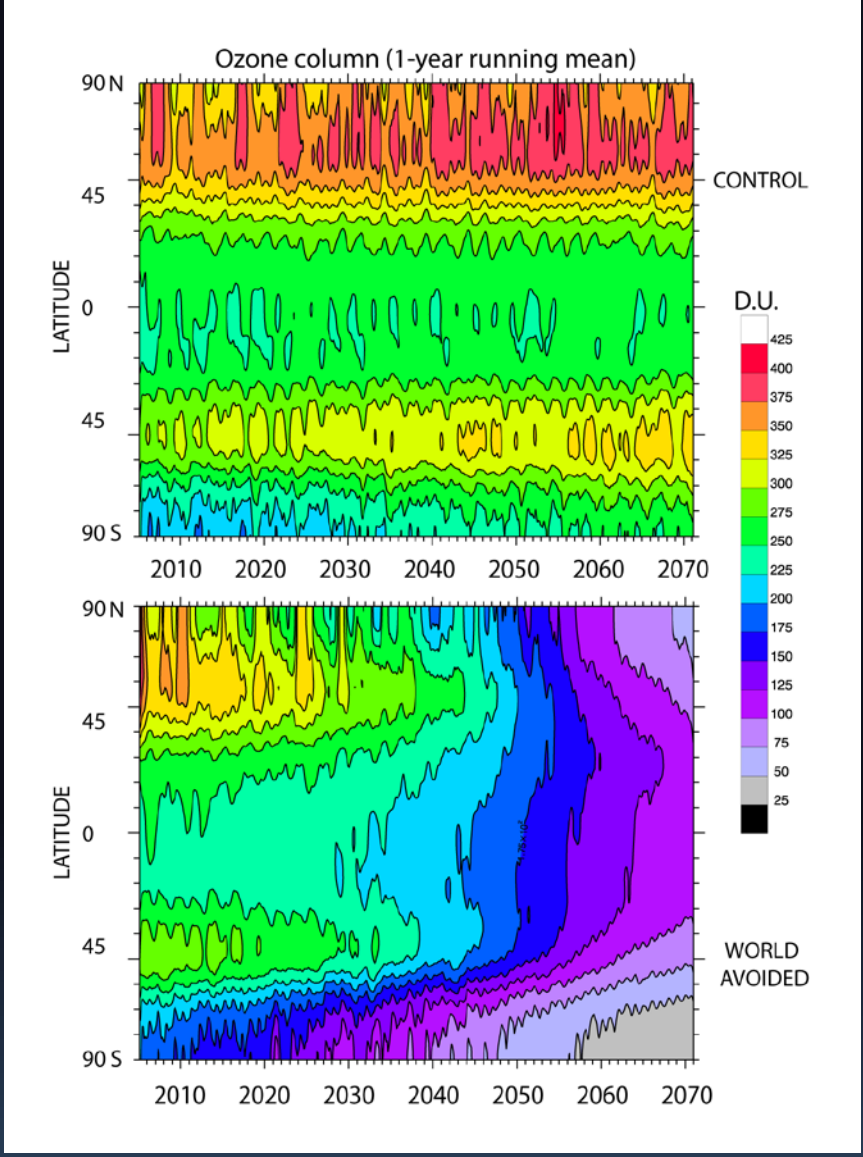
Zonal-mean temperature changes



- much larger changes in *World avoided* than in the *Control* case: 2X in the troposphere, and up to 10X in the stratosphere (which cools due to both enhanced IR emission *and* reduced ozone heating)

- tropical tropopause altitude increases to ~20-22 km in *World avoided* case

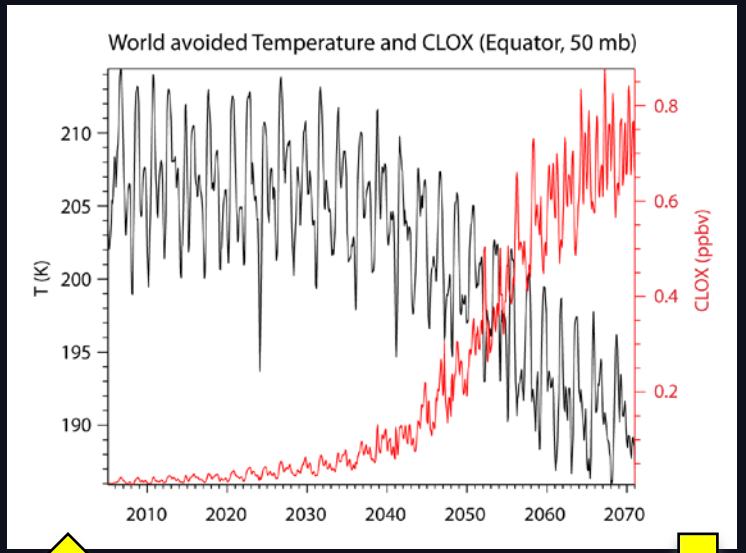
Ozone column evolution: 2005-2070



- plot shows ozone columns smoothed with 12-month running mean to emphasize the long-term trend
- the ozone column decreases through the 21st century in the *World avoided* run (*cf.* ozone recovery in the *Control* run)
- decrease is gradual at high latitudes; at lower latitudes, the ozone column collapses rapidly after ~2045. This is driven by the evolution of ozone in the lower stratosphere

O_3 in the tropical lower stratosphere

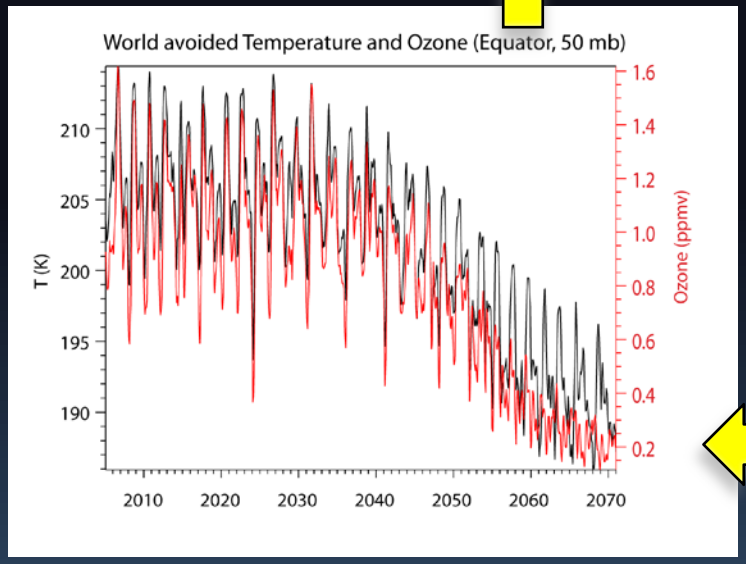
CLO_X-O_3-T *positive feedback* leads to collapse of tropical ozone (*cf.* Newman et al., 2009)



T ↓

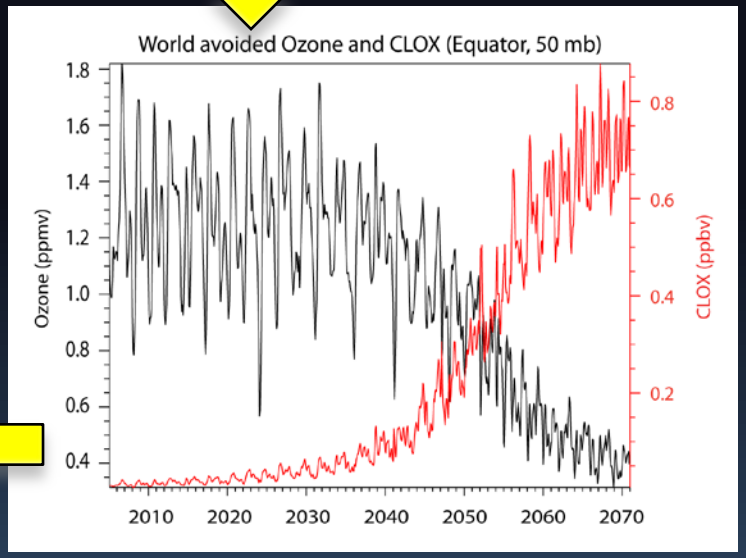
CLO_X ↑

CLO_X: "active chlorine" (Cl +2 Cl_2 + ClO + OClO + 2 Cl_2O_2 + HOCl + BrCl)



O_3 ↓

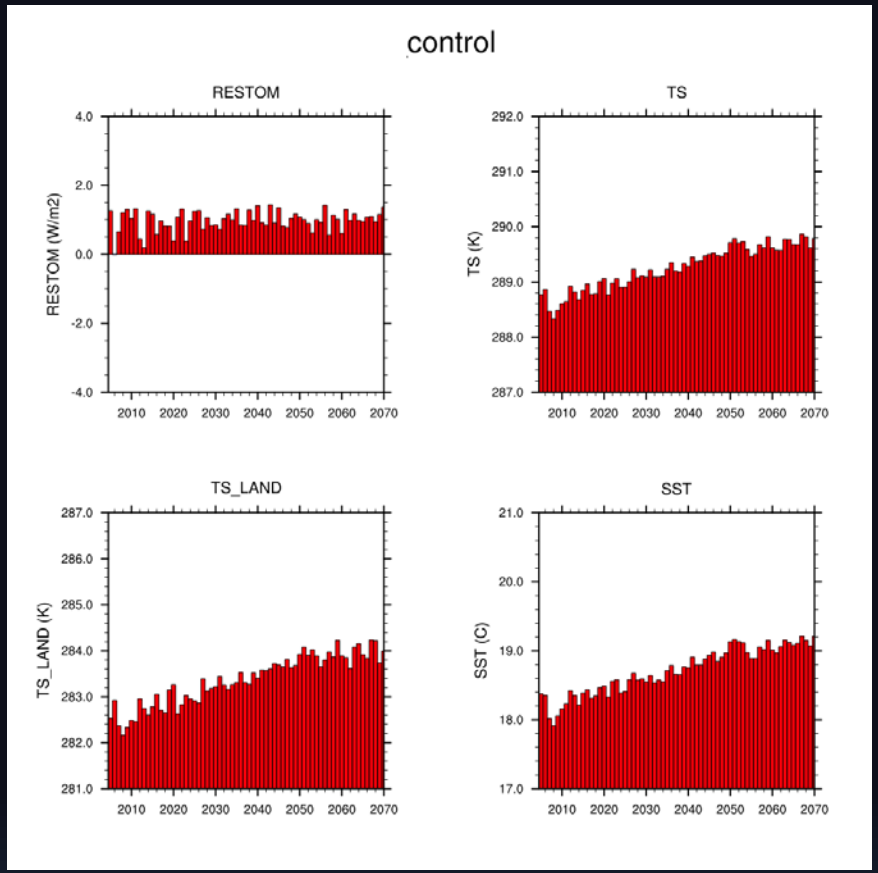
T ↓

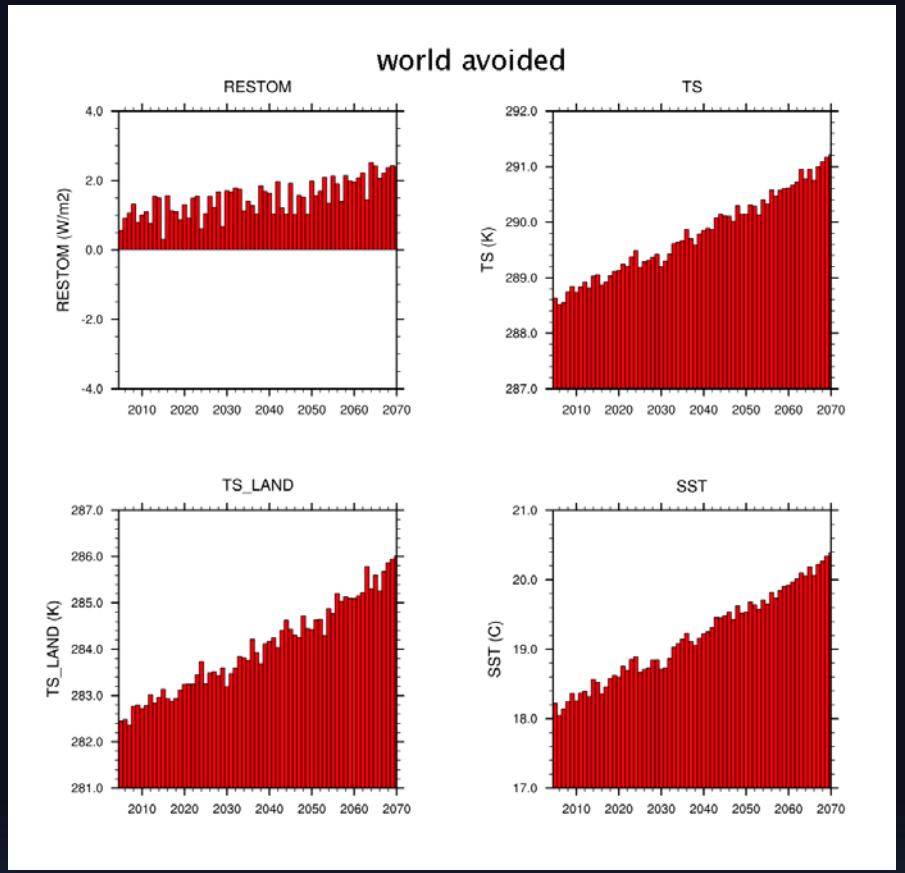


CLO_X ↑

O_3 ↓

Global Climate Indicators

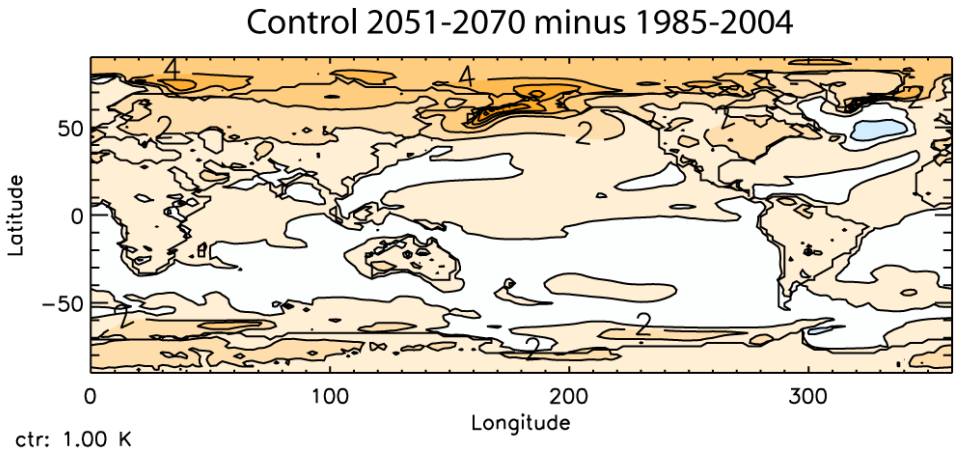


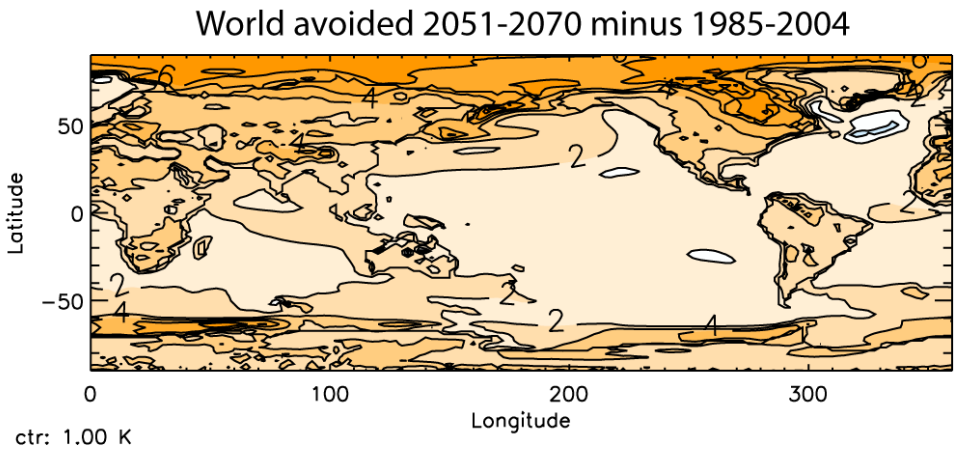


RESTOM: global residual flux at "top of model"
TS: global surface temperature
TS LAND: global land temperature
SST: global sea-surface temperature

- the *World avoided* global radiation budget is increasingly out of balance as CFC concentrations increase over the period studied
- over 2005-2070, TS increases ~2.5 K in the *World avoided* simulation (*vs*. ~ 1 K in the *Control* case)

Surface temperature changes



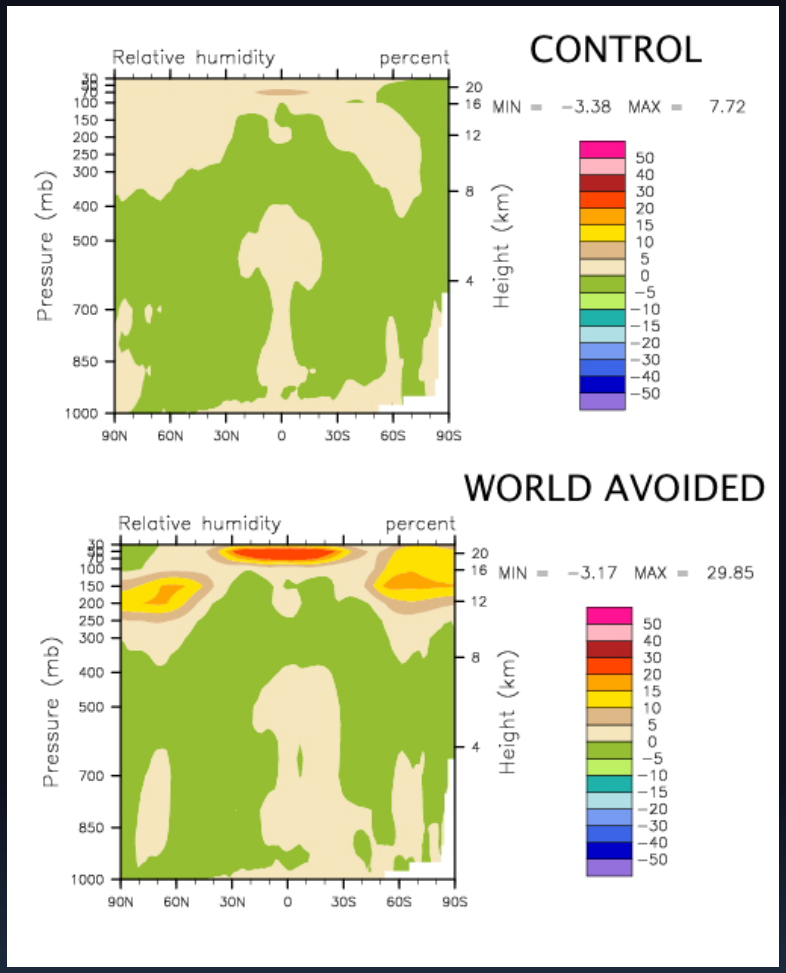


- surface T changes in the *Control* case are in line with expectations for a "moderate" scenario of GHG (CO_2, N_2O, CH_4) growth

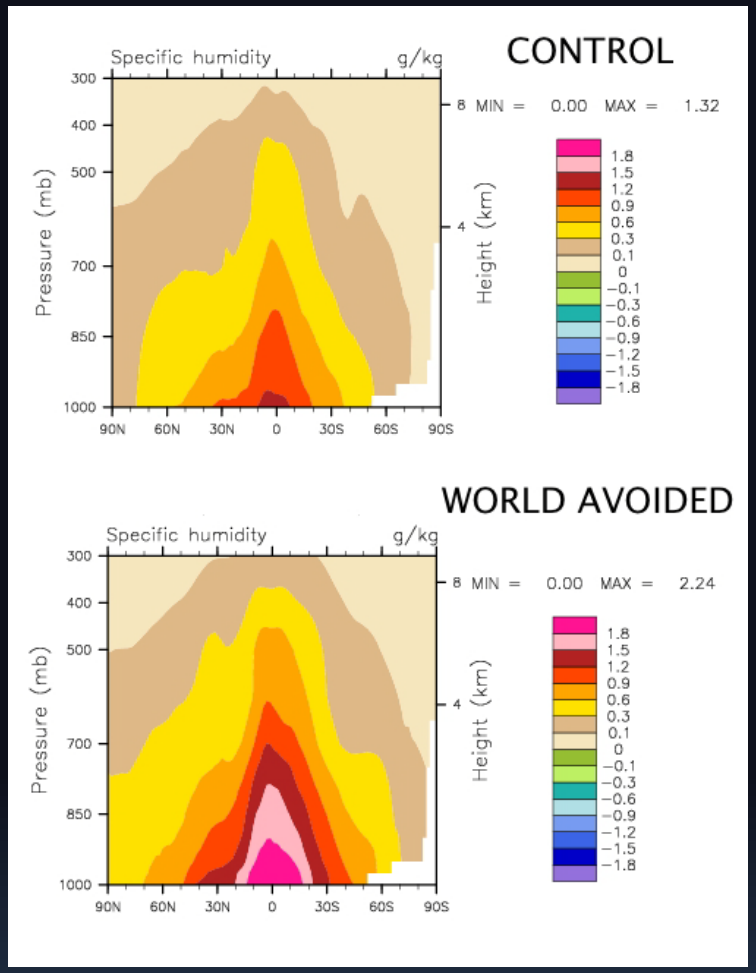
- the *World avoided* case produces substantially larger surface T changes, approaching 8 K in the Arctic, and 2-4 K over all land areas

Annual-mean Humidity Changes

relative humidity

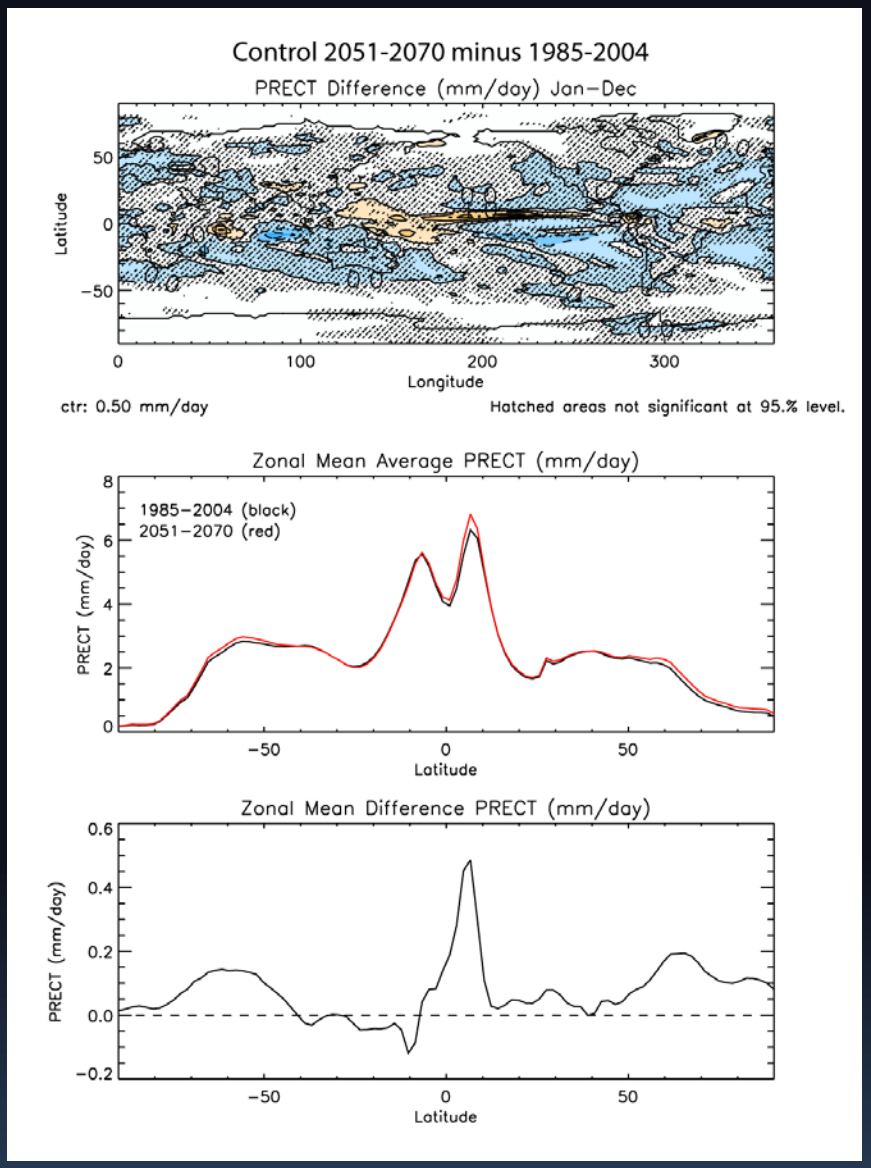


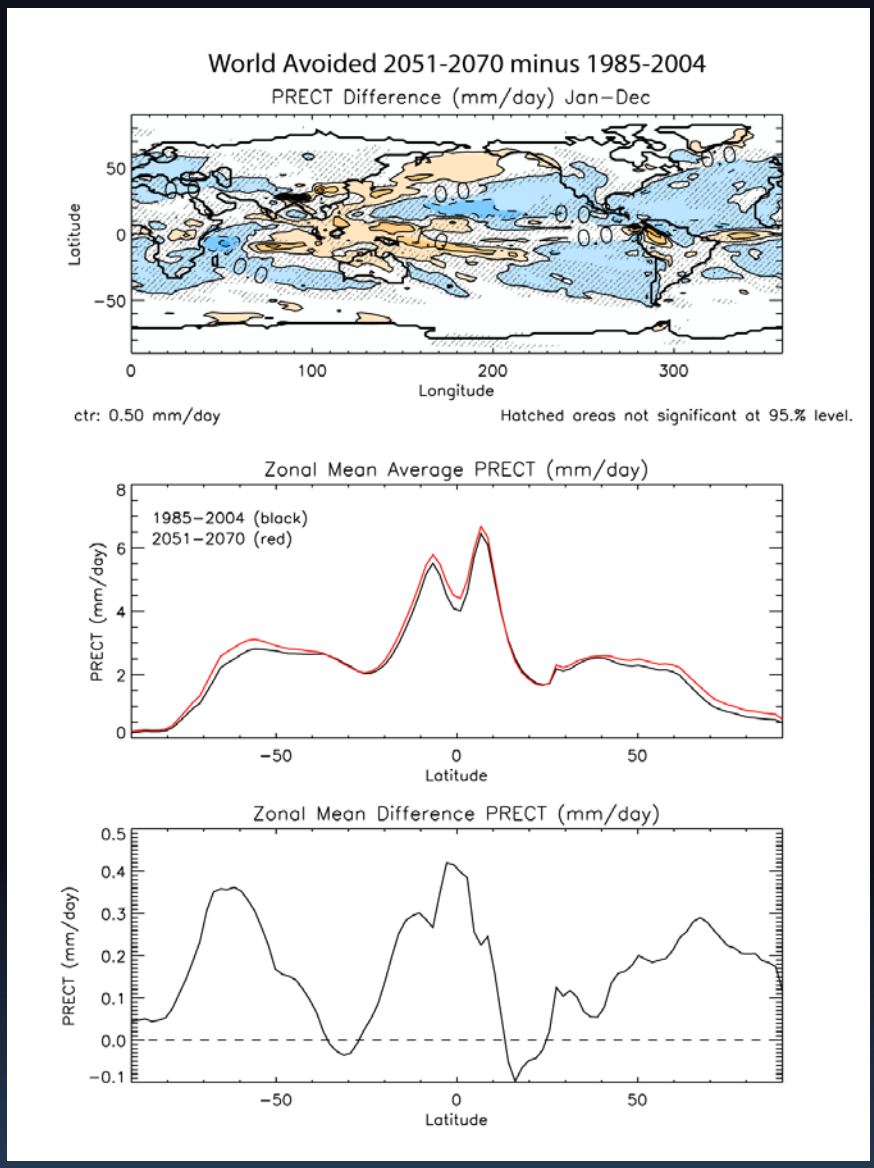
specific humidity



- changes in relative humidity are small (except where the tropopause moves up)
- changes in specific humidity are large, especially in *World avoided* case

Annual Precipitation rate changes

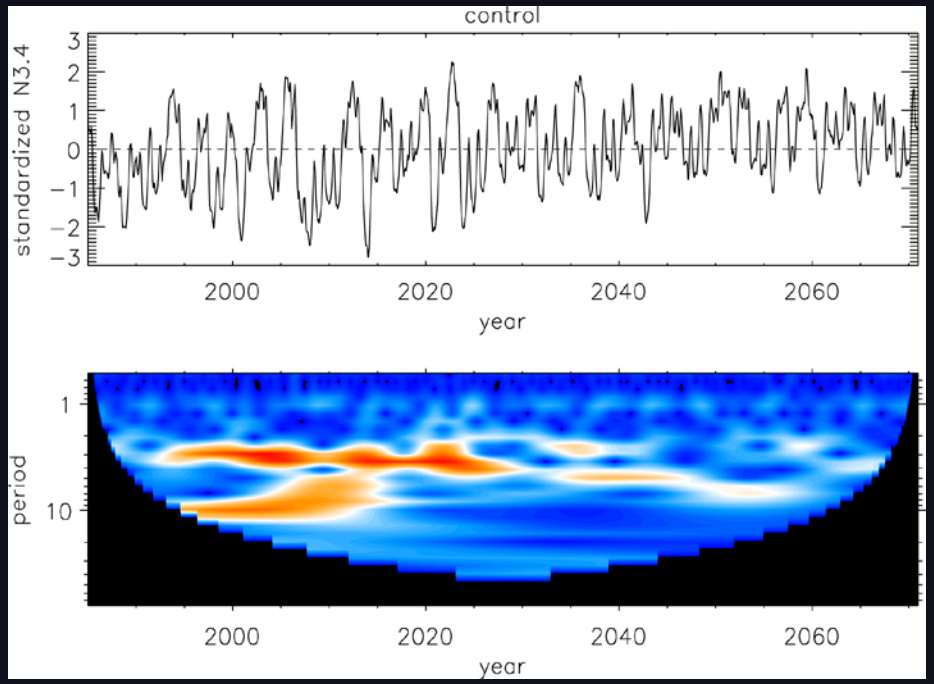




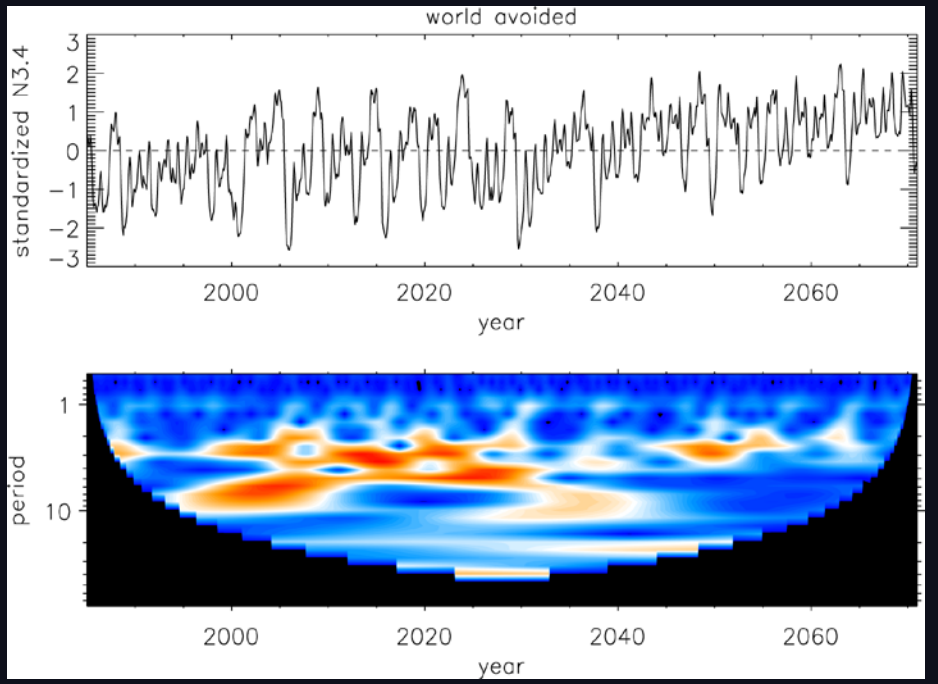
- Drying in the subtropics intensifies in the *World avoided* simulation compared to *Control*
- The climate is overall much wetter in *World avoided* and the changes are highly significant

Changes in the Ocean: ENSO

Control



World avoided



- Increase in tropical ocean T is seen in both simulations; stronger in *World avoided*
- There is a significant decrease in ENSO power after about 2030; more marked in *World Avoided*

Conclusions

- Fully coupled simulations allow study of both composition and climate changes due to continued CFC growth into the 21st century
- Composition and temperature change radically by 2070: In the *World avoided* run, temperature decreases by up to 20 K in the lower stratosphere and increases by over 4 K in the tropical troposphere. The stratospheric ozone column collapses worldwide after ~2045
- The Brewer-Dobson circulation in the lower stratosphere accelerates strongly in the *World avoided* simulation as a result of changes in the propagation and dissipation of Rossby waves in the subtropical lower stratosphere
- Surface temperature increases (and precipitation decreases) by 2070 are substantially larger in the *World avoided* simulation than in the *Control* case
- There is substantial ocean warming in *World avoided* and significant changes in ENSO