IGAC · APARC Atmospheric Processes And their Role in Climate · ccmi chemistry-climate model initiative

The challenges and need for multi-model intercomparisons of chemistry climate models in the troposphere

CCMi Co-chairs: Tatsuya Nagashima, David Plummer

<u>CCMi Scientific Steering Committee</u>

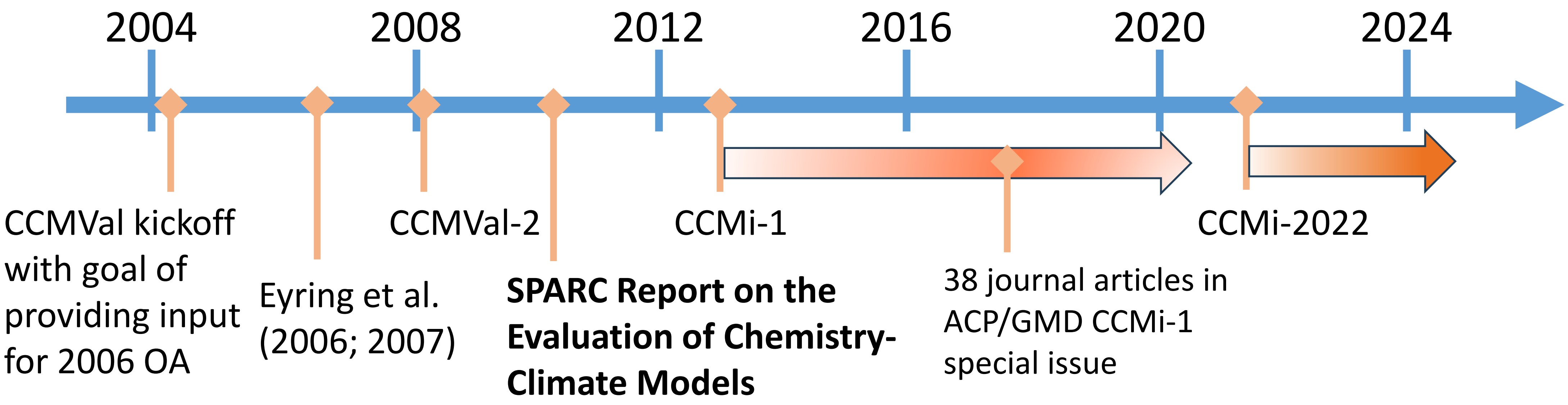
Alex Archibald, Gabriel Chiodo, Suvarna Fadnavis,

Hella Garny, Beatrice Josse, Joowan Kim, Olaf Morgenstern,

Lee Murray, Clara Orbe, Amos Tai

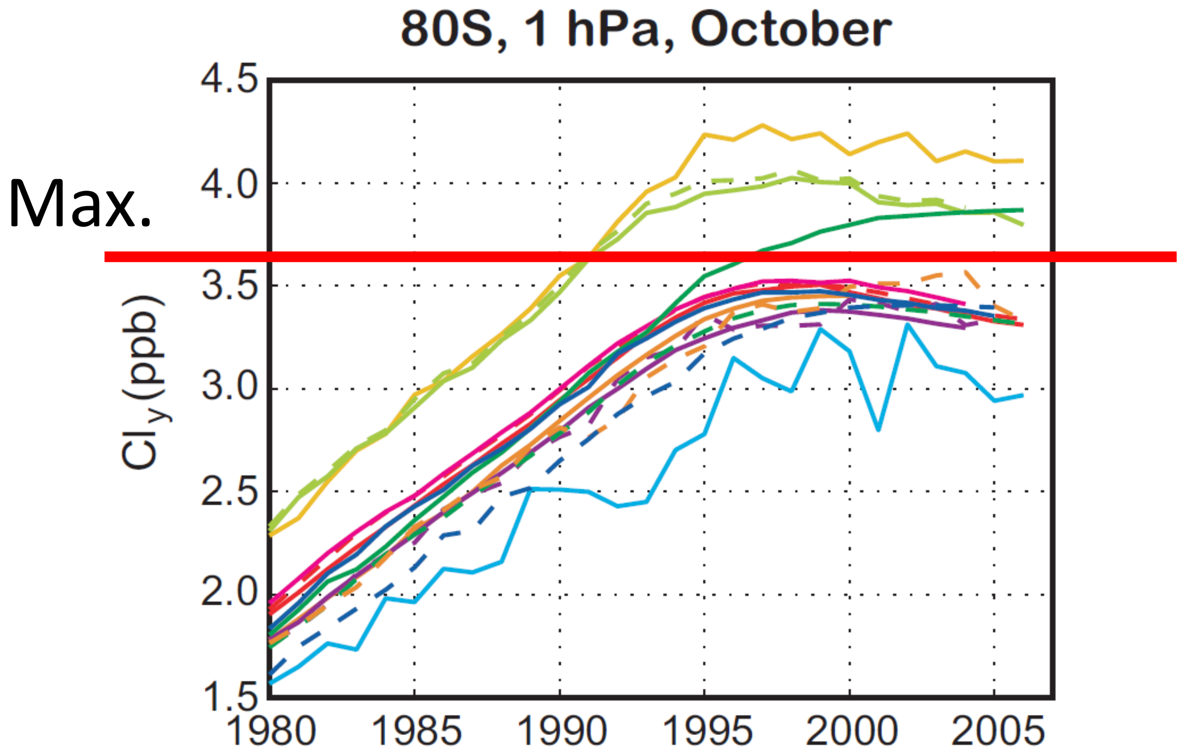
CCM Intercomparisons

- Chemistry Climate Model initiative (CCMi) grew out of the Chemistry Climate Model Validation (CCMVal) activity
  - stretches back to early 2000s when CCMs first began performing long transient simulations
  - these activities have always had as a focus the provision of CCM projections for the WMO/UNEP Ozone Assessment
  - considerable focus on model assessment and ‘process-based’ diagnostics

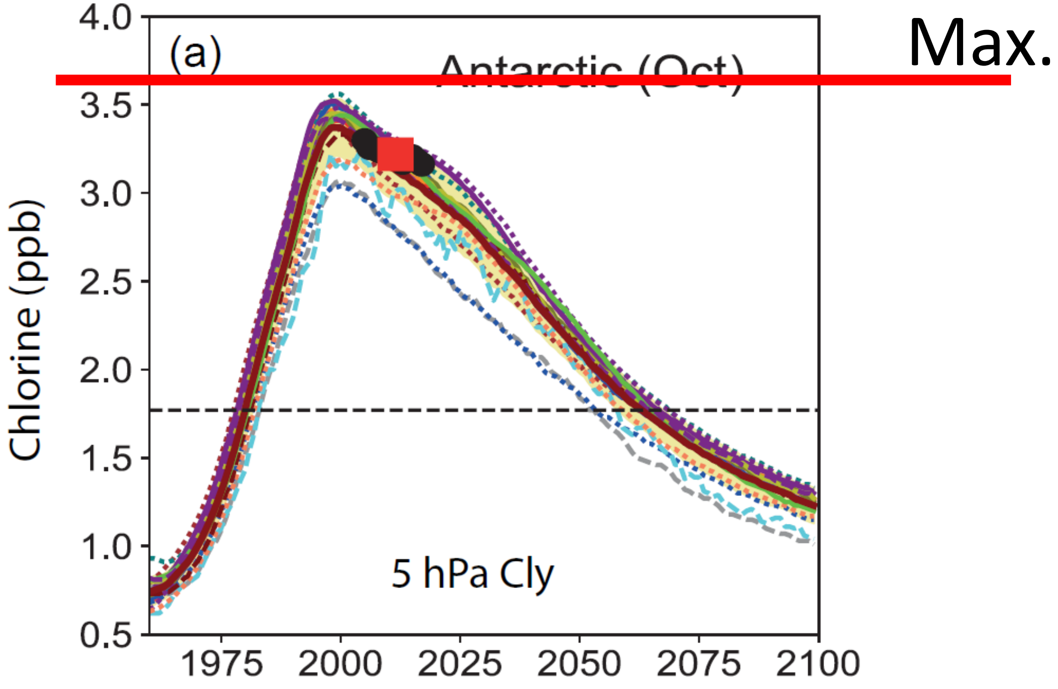


Stratospheric issues in CCMs

- some early-generation CCMs showed unphysically large mixing ratios of Cly
  - very evident problems of mass conservation now much reduced



Total inorganic chloring at 80°S in October at 1 hPa from the CCMVal-2 set of models. SPARC CCMVal (2010) Figure 5.11



Total inorganic chloring at 80°S in October at 5 hPa from the CCMI-1 set of models. Dhomse et al. (2018) Figure 7.

Stratospheric issues in CCMs

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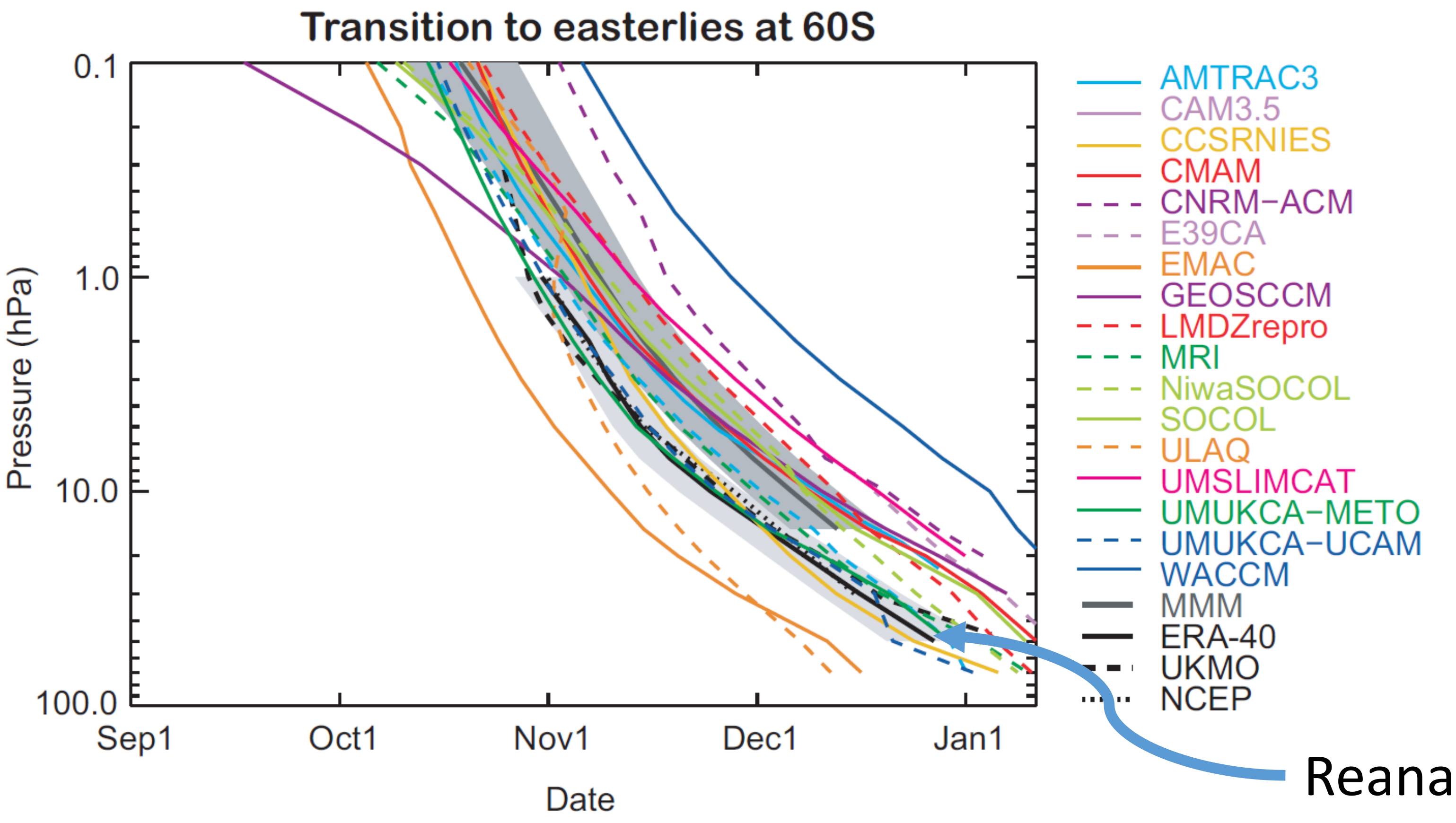
- many models show a too late breakdown of the Antarctic vortex
  - delayed transition to easterlies
  - maintains Antarctic ozone hole too late into spring

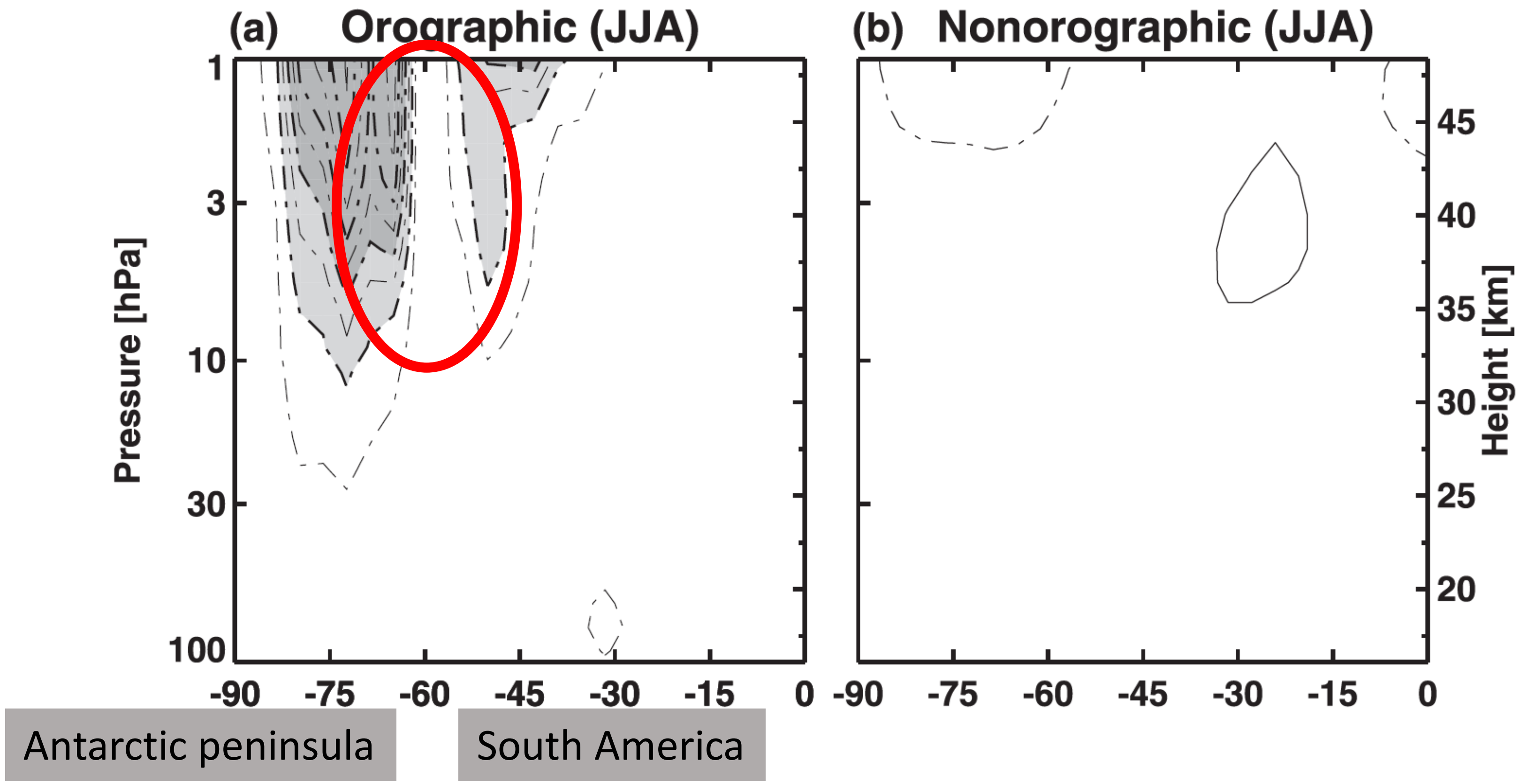


Reanalysis

Average date of zonal average wind at 60°S passing through zero, transitioning from westerly to easterly, in the CCMVal-2 models. Figure 4.2 from SPARC CCMVal (2010).

Stratospheric issues in CCMs

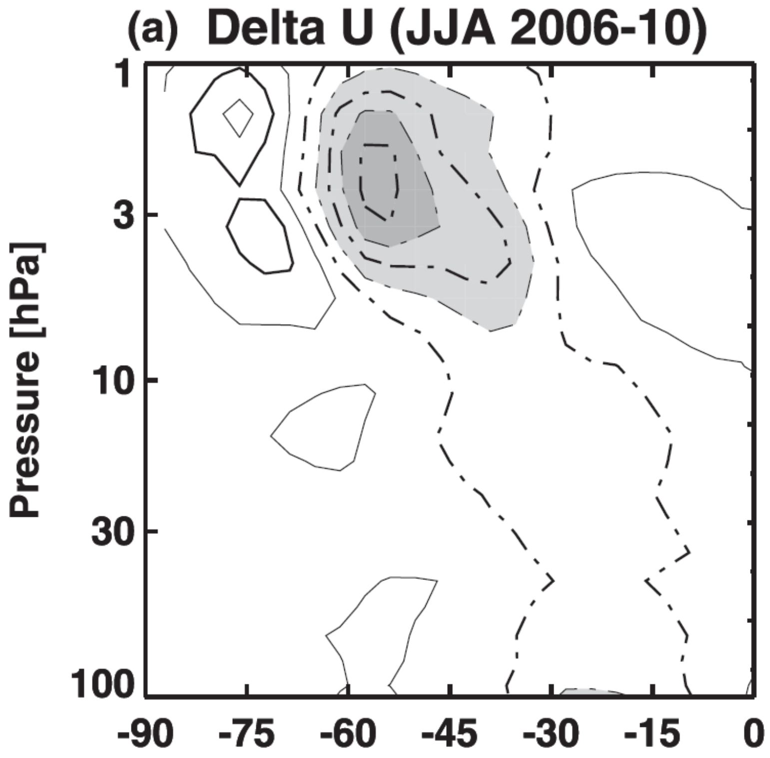
- McLandress et al. (2012) investigated drag in a version of a middle atmosphere model with data assimilation
  - model drag dominated by orographic
  - gap in drag around 60°S tied to gap in land between South America and Antarctic peninsula



Zonal average wind tendency (m s^{-1} day^{-1}) due to orographic and non-orographic gravity wave drag parameterizations. Figure 5 from McLandress et al., (2012).

Stratospheric issues in CCMs

- McLandress et al. (2012) investigated drag in a version of a middle atmosphere model with data assimilation
  - analysis increment for zonal wind add significant extra drag into the area around 60°S
  - free running model with addition of extra orographic GWD around 60°S compared better with observations for temperature, winds vortex breakdown



Zonal average wind tendency (m s^{-1} day^{-1}) due to analysis increments. Figure 1 from McLandress et al., (2012).

Stratospheric issues in CCMs

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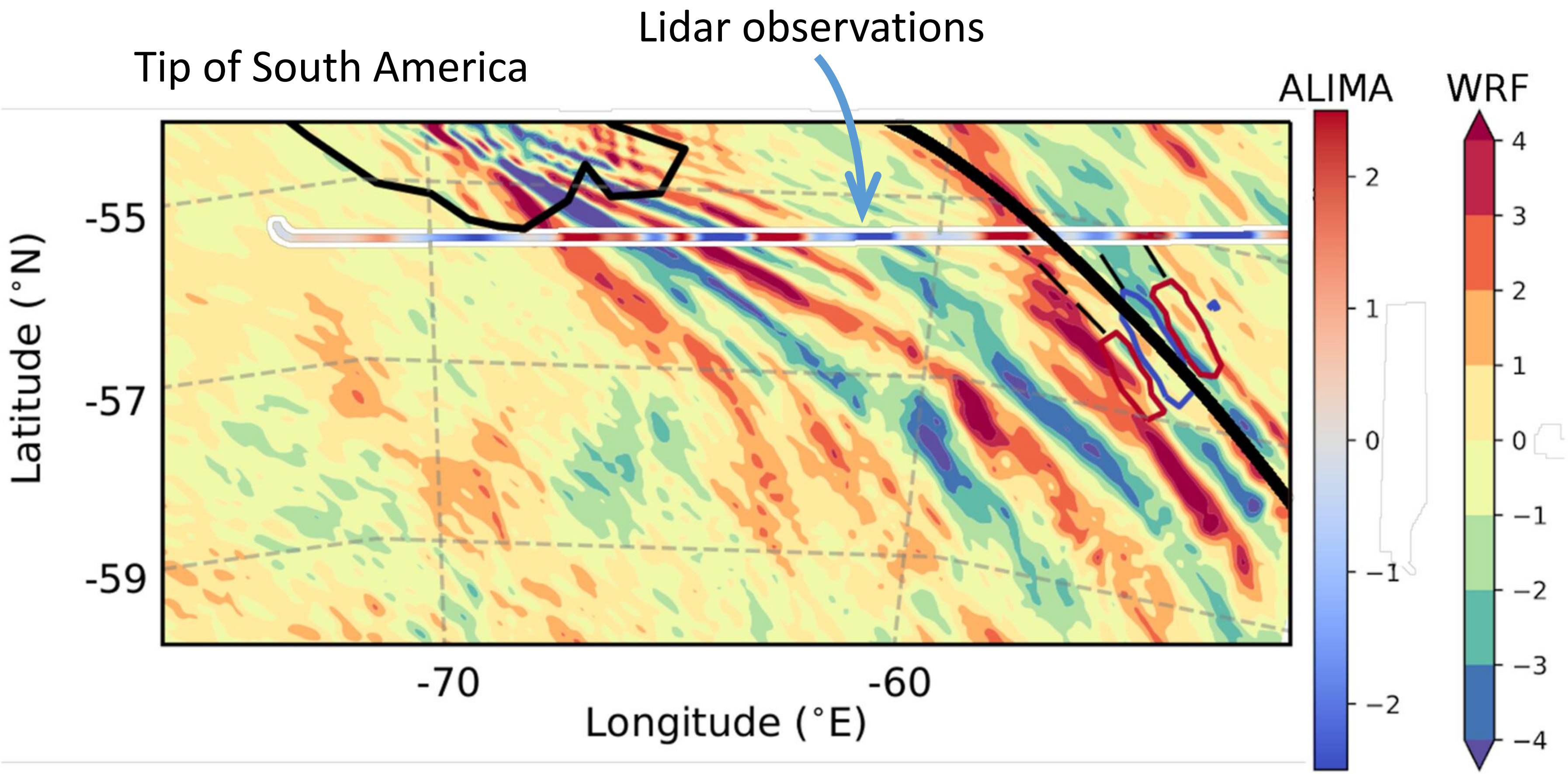
- source of extra drag around 60°S is still unclear
  - orographic waves from small islands (e.g. Hoffmann et al., 2016)
  - secondary gravity waves generated by breaking orographic waves (e.g. Satomura & Sato, 1999)
  - waves generated by winter storms over southern oceans (e.g. Hendricks et al., 2014)
  - horizontal advection and meridional refraction of GWs (e.g. Sato et al., 2012)
    - GWD schemes in models typically assume GWs move vertically
- part of the motivation for the Southern Hemisphere Transport, Dynamics, and Chemistry–Gravity Waves (SOUTHTRAC-GW) mission in 2019
  - aircraft observations of tip of South America with lidar and limb imager

Stratospheric issues in CCMs

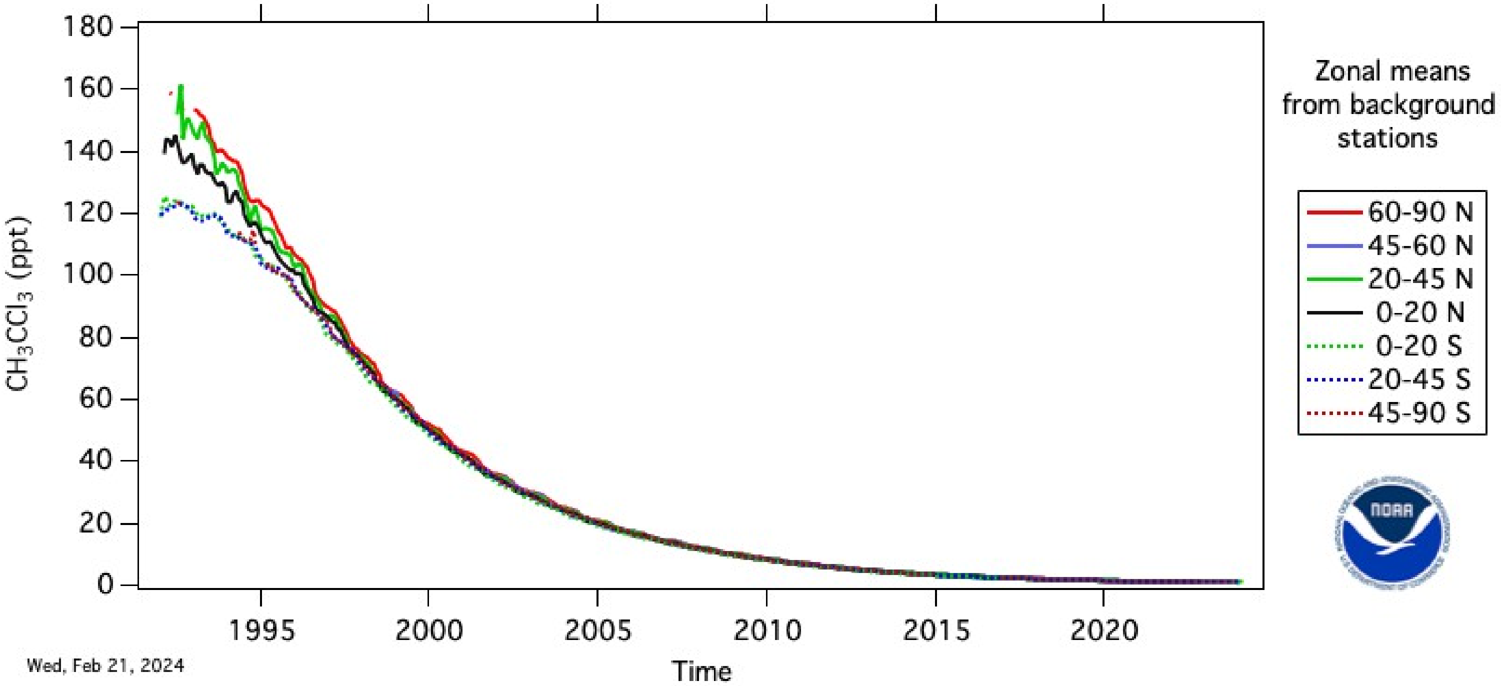
- SOUTHTRAC-GW aircraft observations and modelling show evidence for refraction
  - importance of other processes has not been ruled out



Temperature anomalies at 27 km on September 12 2019, 06Z, from a 3 km WRF simulation and reconstructed from the airborne lidar observations. Figure 6 from Geldenhuys et al. (2023).

Tropospheric issues in CCMs

- methane lifetime to loss by reaction with OH in the troposphere is nicely constrained by observations of other species
  - methyl chloroform was controlled under the Montreal Protocol with emissions dropping to near zero in the late 1990s
  - accounting for the relative rates of reaction with OH, methane lifetime estimated at 11.2 +/- 1.3 years for reaction with OH (Prather et al., 2012)

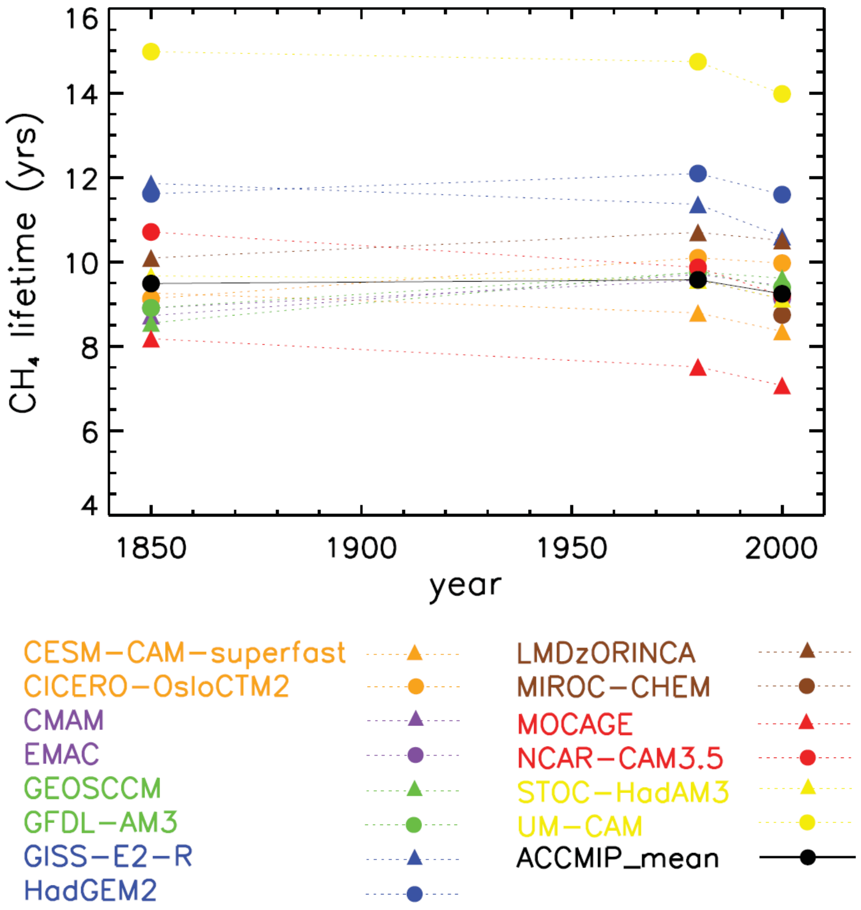


Monthly average near-surface concentrations of methyl chloroform in different latitude bands derived from NOAA Global Monitoring Laboratory observations. See Montzka et al. (2011).

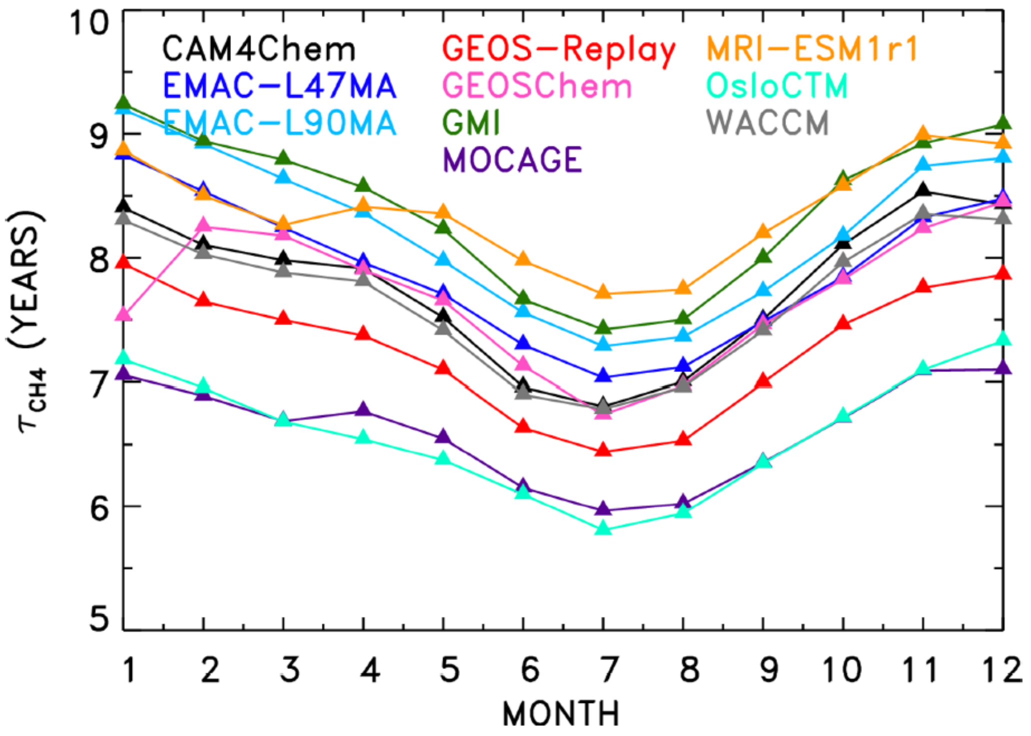
https://gml.noaa.gov/hats/gases/CH3CCl3.html

Tropospheric issues in CCMs

- CCMs show a wide range of lifetimes (obs. 11.2 +/- 1.3 years)



The methane lifetime to reaction with OH for the Atmospheric Chemistry and Climate Model Intercomparison (ACCMIP) models. Figure 1 from Voulgarakis et al. (2013).



The annual cycle in methane lifetime to reaction with OH for the CCMi-1 models and additional chemical transport models for year 2000 conditions. Figure 2 from Nicely et al. (2020).

Tropospheric issues in CCMs

- Nicely et al. (2020) created neural networks to reproduce the 3-D distribution of OH in each model from a selection of input variables
  - swapping inputs from the native model to another one to investigate the sensitivity of OH to different factors

Original CH_4 lifetime in GMI and OsloCTM for January 2000

Change in CH_4 lifetime using the OsloCTM HCHO as input to the GMI emulator and vice versa.

Residual

Table 1. Accounting of CH_4 lifetime differences between GMI and OsloCTM simulations for January 2000.

		GMI	OsloCTM
$\tau^{a}_{CH_4,ORIG}$ (year)		9.24	7.18
$\Delta\tau_{CH_4}$ due to[b]:	O_3	−0.91	+0.79
	JO^1D	−0.59	+0.60
	HCHO	−0.64	+0.51
	NO_x	−0.45	+0.33
	JNO_2	−0.34	+0.15
	Isoprene	−0.03	+0.28
	CO	+0.19	−0.07
	H_2O	+0.10	−0.13
	CH_4^{NORM}	+0.11	−0.06
	NO/NO_x	+0.07	−0.05
	O_3 COL	−0.02	−0.06
	T	−0.02	+0.00
$\Delta\tau^{c}_{CH_4,TOT}$		−2.52	+2.30
$\tau_{CH_4,ORIG} + \Delta\tau_{CH_4,TOT}$		6.71	9.48
Mech.[d]		+0.47	−0.24

Table 1 from Nicely et al. (2020).

Tropospheric issues in CCMs

- summary of changes across all possible permutations of input fields from different models into the emulator of each model

Residual

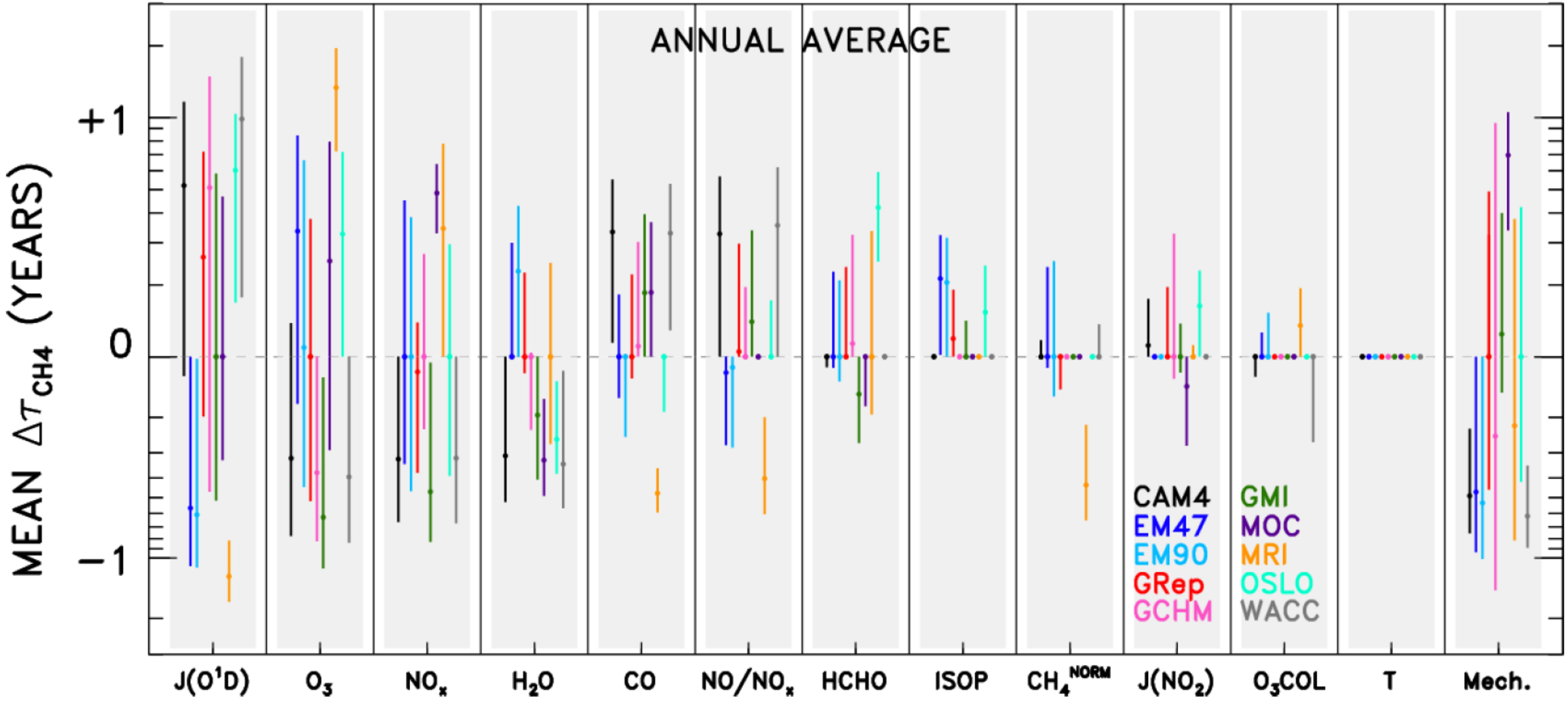


Figure 5 from Nicely et al. (2020).

Tropospheric issues in CCMs

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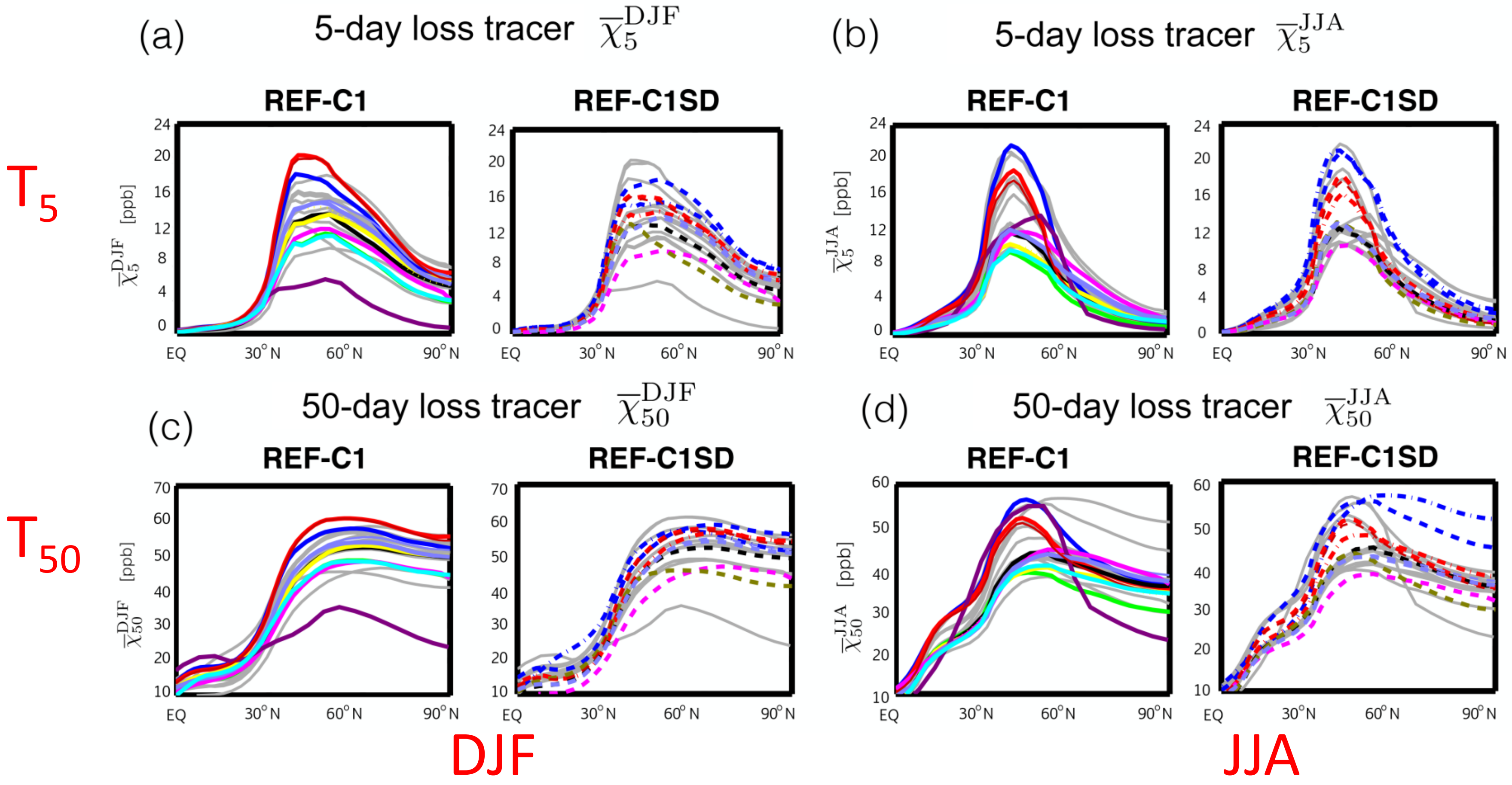
- CCMi-1 specified two types of historical hindcast
  - REF-C1 – free running model with specified historical SSTs / sea-ice
  - REF-C1SD – historical SSTs / sea-ice plus nudging of dynamics to reanalysis
- a number of synthetic tracers in the troposphere to estimate transport timescales in the models
  - specified tracer concentration (100 ppb) at the surface for all points between 30°N to 50°N
  - concentration decays with a specified lifetime of 5 days (T_5) or 50 days (T_{50})

Tropospheric issues in CCMs

- Orbe et al. (2018) showed that the climatological distribution in mid-troposphere shows a large range across models
  - tied to a large range in the parameterized convective updraft mass flux



The 2000 – 2009 seasonal average zonal average concentrations over 700 – 400 hPa for the 5- and 50-day idealized tracers. Figure 2 from Orbe et al. (2018).

Conclusions

- by highlighting aspects with considerable model diversity or common biases, MIPs have the ability to highlight model shortcomings or uncertainties
- longer history of model intercomparison / assessment in the stratosphere
  - some progress on understanding processes and improving models
    - the role of mixing in age of air is better understood, even though issues remain
- Nicely et al. ML analysis of CCMi-1 models showed a number of factors are important in explaining the model variability for OH / CH4 lifetime
  - J[O3-> O(1^D)], O_3, NO_x, H_2O, CO, NO/NO_x ratio, HCHO, residual (unidentified) factors
- Orbe et al. analysis showed a range (2X – 3X) of transport timescales from boundary layer to free troposphere and to the Arctic
- likely a lot of linkages between these two findings

Conclusions

- the state of the atmosphere is underconstrained by observations and the troposphere is such a 'messy' place, we need new and thoughtful ways to analyse processes in models
  - can we still make progress asking for monthly average fields from models
- for a process like vertical transport by deep convection, what is 'correct'
  - is there a role for convection resolving global models as a benchmark?
- we are (just) beginning to think of a new phase of CCMI with a focus on the troposphere and we welcome participation by people with ideas for new types of analyses, diagnostic fields, process studies, observations to compare against, ….