A new approach to linear ozone modelling

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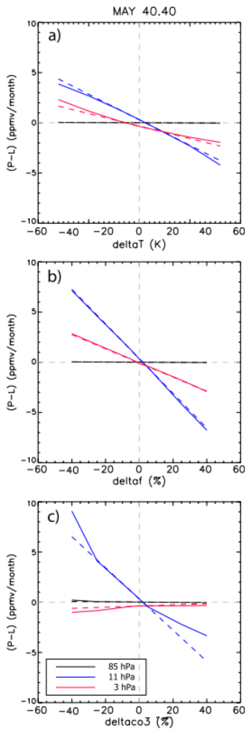
Existing approach

- Linearized ozone models are a parameterization of ozone
  - Low cost, approximate representation of ozone
  - Typically created by linearization around a basic state from a full chemistry model
  - Examples: Cariolle scheme (operational in IFS) and BMS scheme (also tested in IFS)

Cariolle, D. and Teyssèdre, H.: A revised linear ozone photochemistry parameterization for use in transport and general circulation models: multi-annual simulations, Atmos. Chem. Phys., 7, 2183–2196, doi:10.5194/acp-7-2183-2007, 2007.

Monge-Sanz, B. M., Chipperfield, M. P., Cariolle, D., and Feng, W.: Results from a new linear O3 scheme with embedded heterogeneous chemistry compared with the parent full-chemistry 3-D CTM, Atmos. Chem. Phys., 11, 1227-1242, https://doi.org/10.5194/acp-11-1227-2011, 2011.

- Conceptual strengths
  - Some variations in chemistry are quite linear (in relevant regime)
  - Consistent framework
- Conceptual weaknesses:
  - Some chemistry is very non-linear (especially “ozone hole”)
  - Linearization aims to reproduce another model, not reality



From Monge-Sanz et al, 2011

Can we do better?

- Problem 1: linearizing about wrong mean state
  - Mean state errors/differences can be large, in T as well as O3
  - Could try using an observed O3 estimate instead – can help in upper stratosphere

Geer, A. J., Lahoz, W. A., Jackson, D. R., Cariolle, D., and McCormack, J. P.: Evaluation of linear ozone photochemistry parametrizations in a stratosphere-troposphere data assimilation system, Atmos. Chem. Phys., 7, 939-959, https://doi.org/10.5194/acp-7-939-2007, 2007.

- Problem 2: lower stratosphere ozone has slow relaxation timescales
  - Amount depends on net production and on transport, not climatology we relax to
  - If full chemistry model does not give accurate ozone, no way of knowing how to fix it

A new approach

- Keep formulation of a linear representation of net ozone production

- Specify the **mean terms** from ozone and temperature analyses
  - Use our best knowledge
  - Ensures good behaviour in upper stratosphere

- Diagnose the **net production term** from inverse modelling

- Take the three **sensitivity terms** (*b*,*c*,*d*) from a full chemistry model
  - Make adjustments where necessary to ensure physical consistency

Hybrid linear ozone model: basic equation

$$\left.\frac{\partial O_3}{\partial t}\right|_{chem} = a + b(O_3 - \overline{O_3}) + c(T - \overline{T}) + d(TCO - \overline{TCO})$$

a: climatological mean production rate, diagnosed from model nudged to analyses

"bar" terms calculated directly from ozone and T analyses

b, c and *d* specified based on linearization of a full chemistry model (for now, Cariolle)

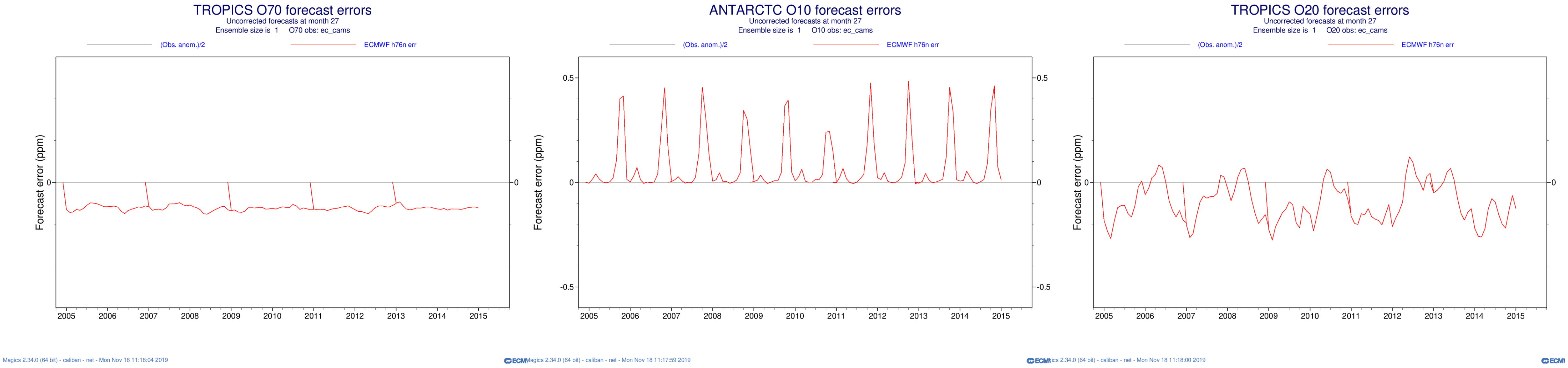
In a linear world, this should give a climatology of ozone that matches that of the specified ozone analysis, if the model temperature climatology matches the analysed temperature climatology.

Estimating mean production rate: Nudged run

- VO, T and O3 are nudged towards analysed values (6h data, model levels).
  - Vorticity (VO) with a 12 h timescale, constrains the synoptic evolution well
  - T with a 10 day timescale, keeps lower strat temperatures realistic without messing up troposphere
  - O3 with 12 h timescale, fast enough to keep close to analysis, but loose enough to measure difference
  - O3 analyses taken from CAMS L60 re-analysis eac4, 2005-2012 (8 years)
  - T taken from ERA5, same set of years

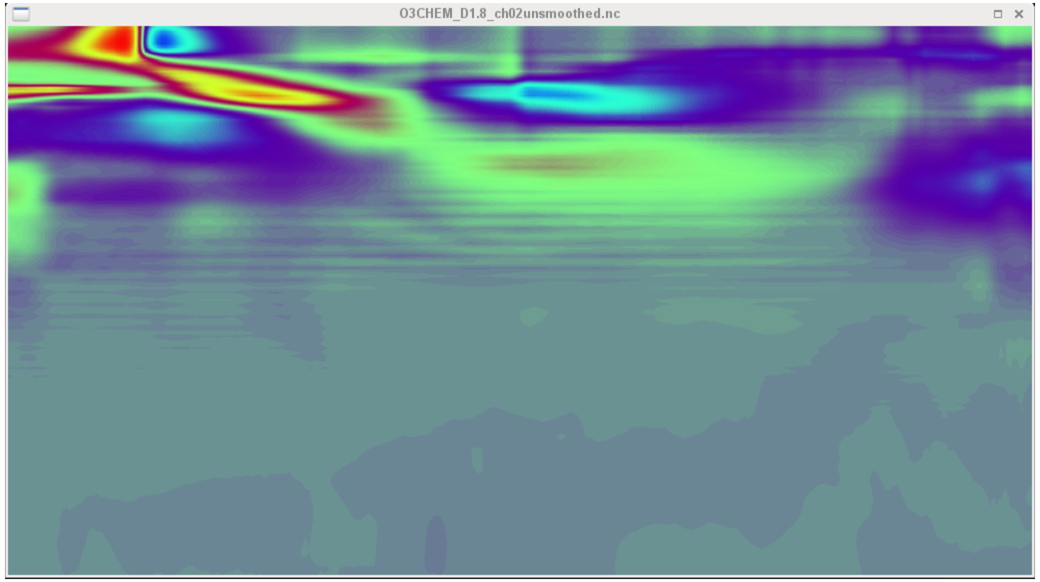
- Model is run with prognostic ozone, but ozone chemistry switched off
  - The nudging is going to do the net work of the chemistry, and we are going to diagnose this
  - Can be shown that the time-averaged increments (i.e. the chemistry) needed to keep model ozone close to analysis is just the time-averaged relaxation term $k(O3\text{-}O3_{an})$.

Diagnosed ozone production rates

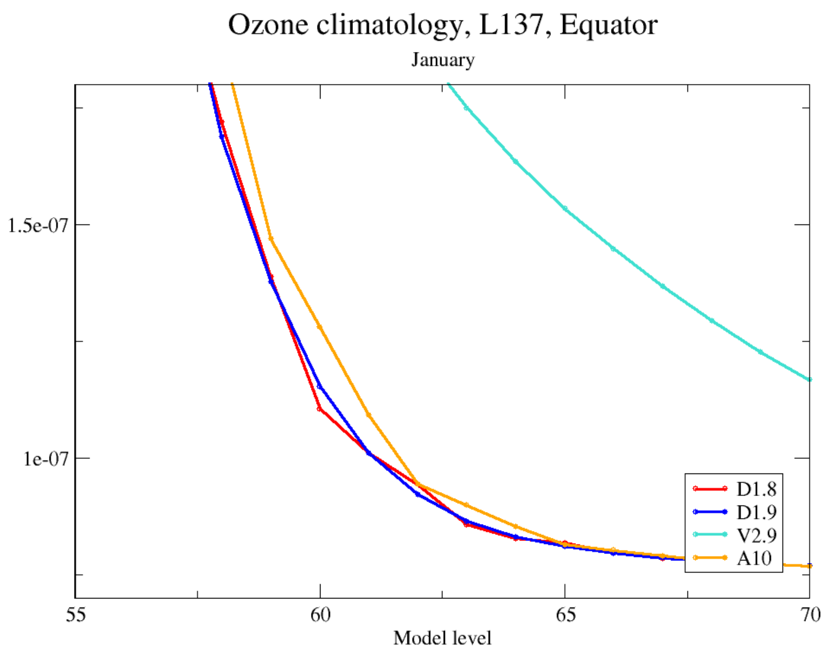


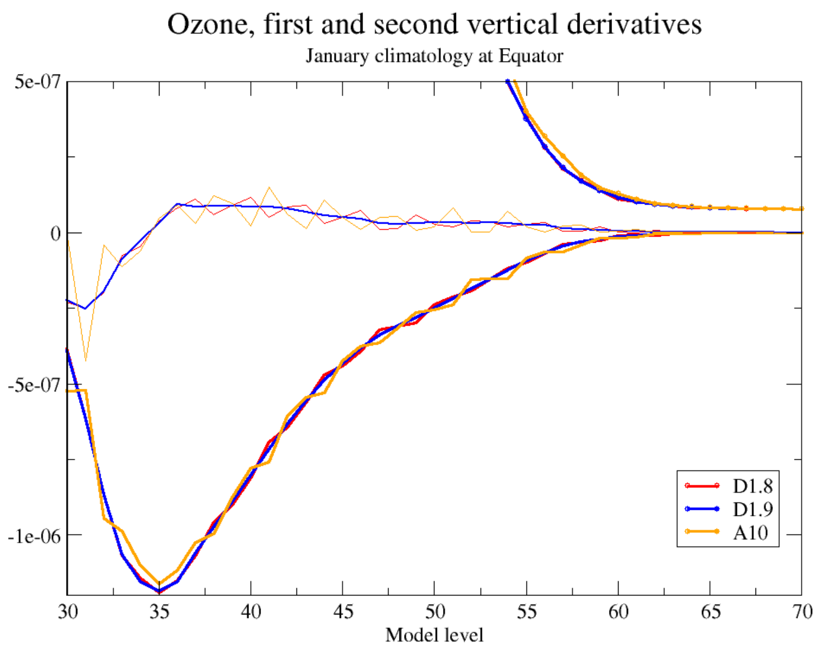
(Time-series shows error in nudged run: diagnosed real-world ozone production is proportional to the negative of this

L60 to L137 interpolation issues

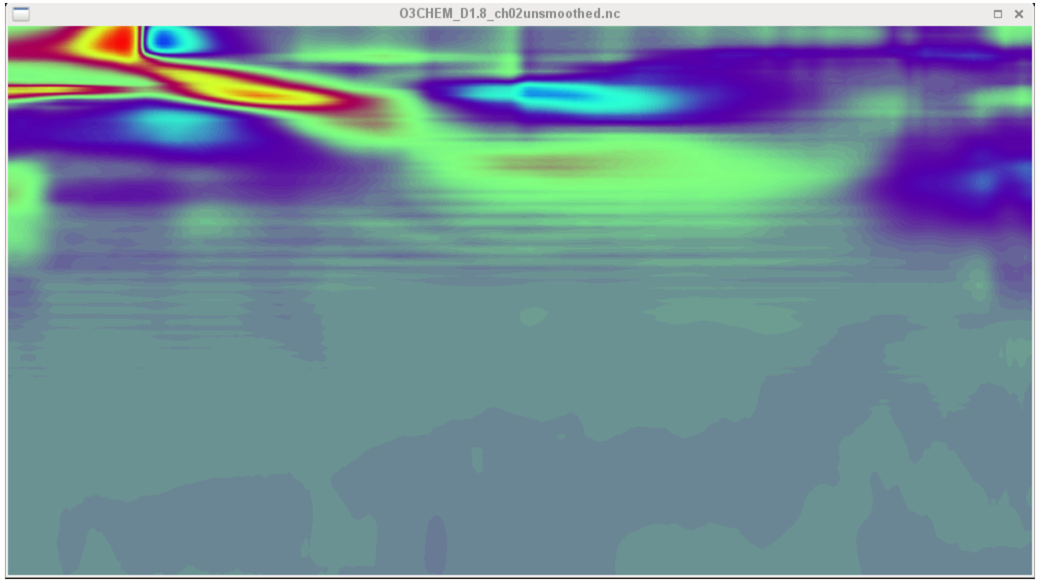


With original vertical interpolation of ozone input analyses

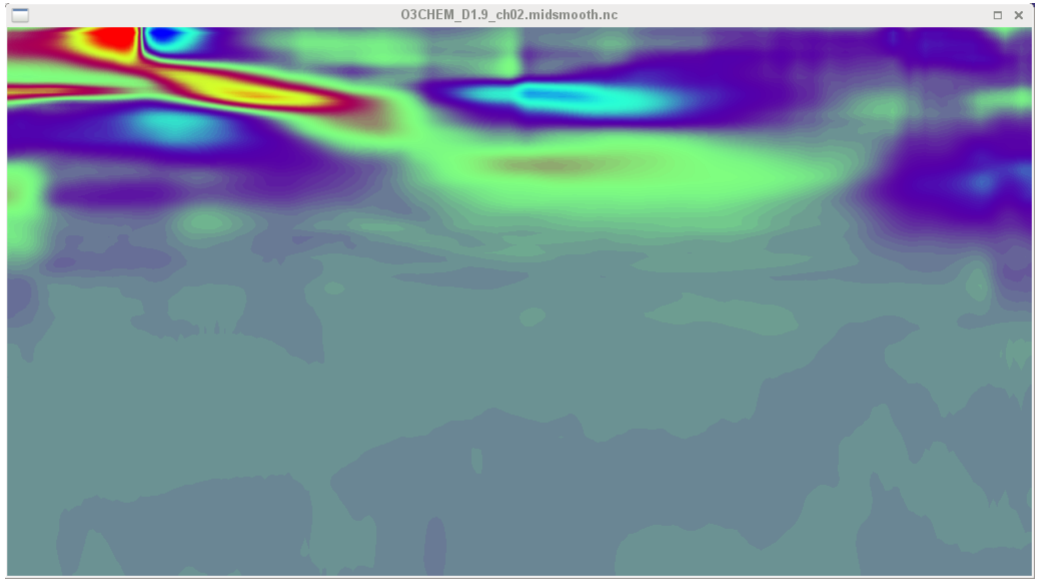




Diagnosed mean production



With original vertical interpolation of ozone input analyses



With conservative positive-definite quartic-spline-based interpolation of input ozone analyses

Method is a slight enhancement of Yao and Nelson, 2018: An Unconditionally Monotone C2 Quartic Spline Method with Nonoscillation Derivatives. Advances in Pure Mathematics, **8**, 25-40.

Other technicalities

Mesospheric ozone data is from a specially prepared climatology, based on external data, courtesy of Johannes Flemming (CAMS).

Temperature sensitivity term scaled with ratio of new to old ozone climatologies, to better represent temperature sensitivity.

Mean ozone, mean temperature and mean ozone production all adjusted to give “mid-month” values which lead to correct monthly means when interpolated in time.

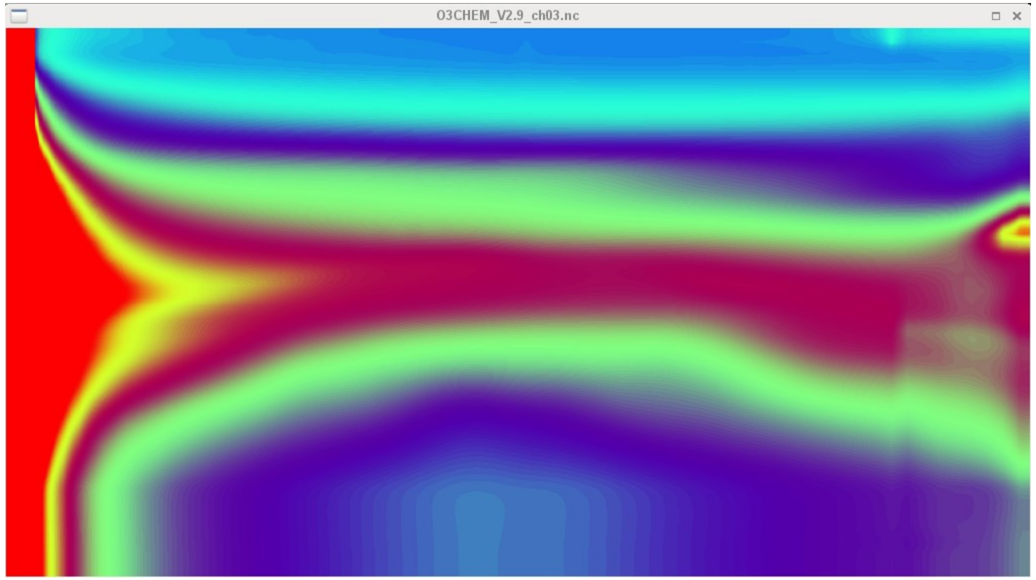
Minimum 10-day relaxation timescale below 900 hPa, blending to 160 days at 700 hPa

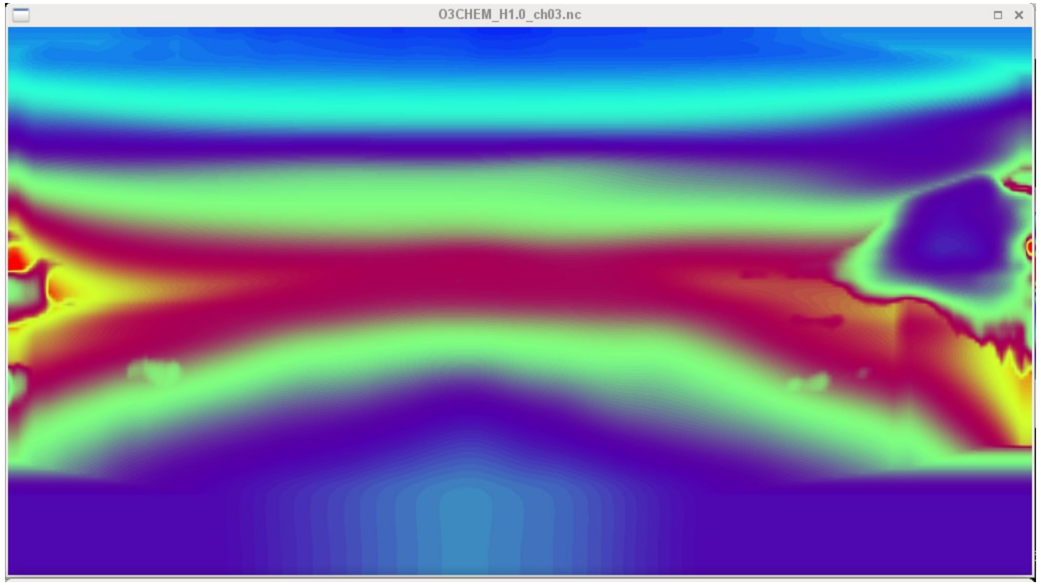
Relaxation rate increased if needed in regions of diagnosed ozone destruction, so that equilibrium ozone field does not become negative.

Mesosphere has very fast minimum relaxation timescale imposed, also in polar night; blended logarithmically across the stratopause (1 day at 0.5 hPa, 100 days at 1.5 hPa).

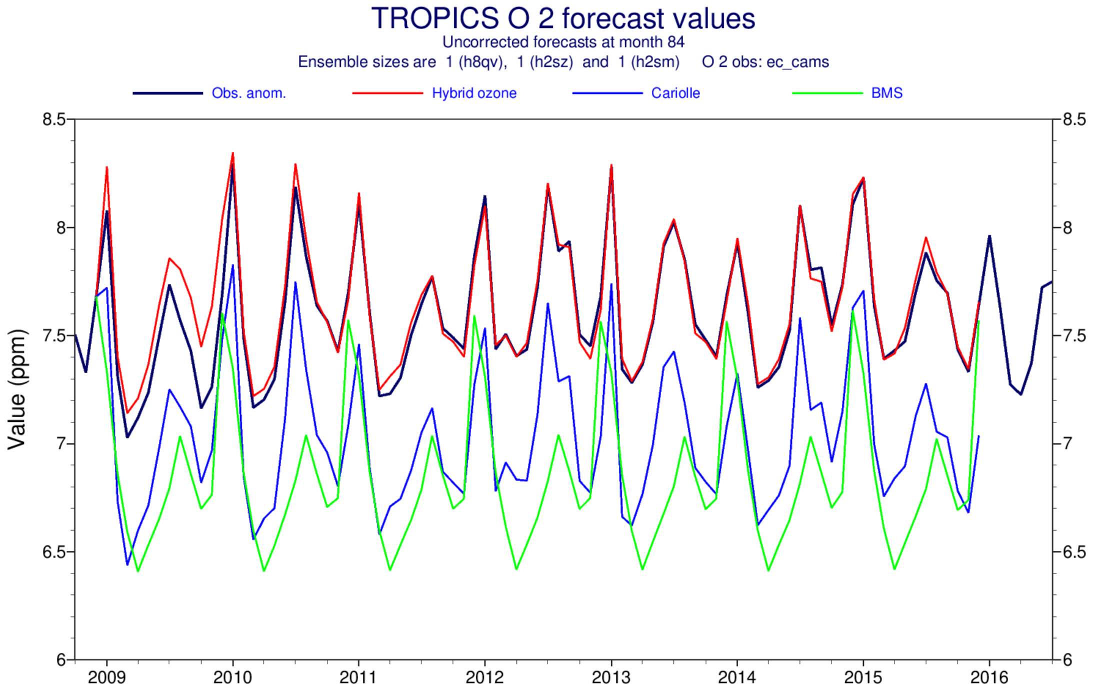
If relaxation rate small, increased to control equilibrium response to temperature perturbations > 20K

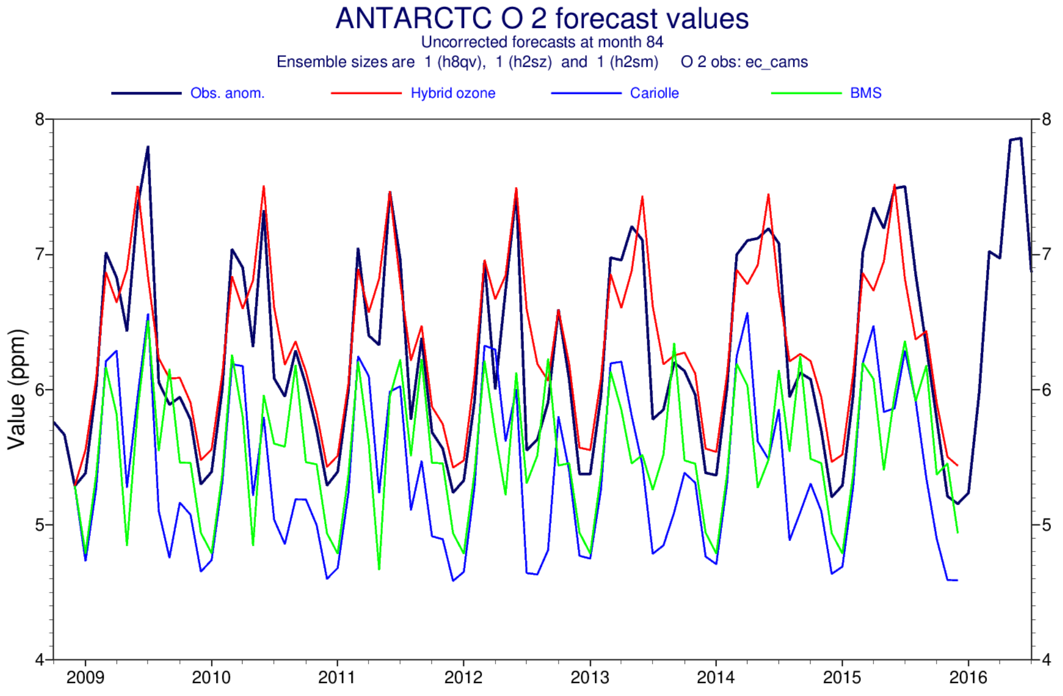
Relaxation rate, October: Cariolle vs Hybrid ozone scheme



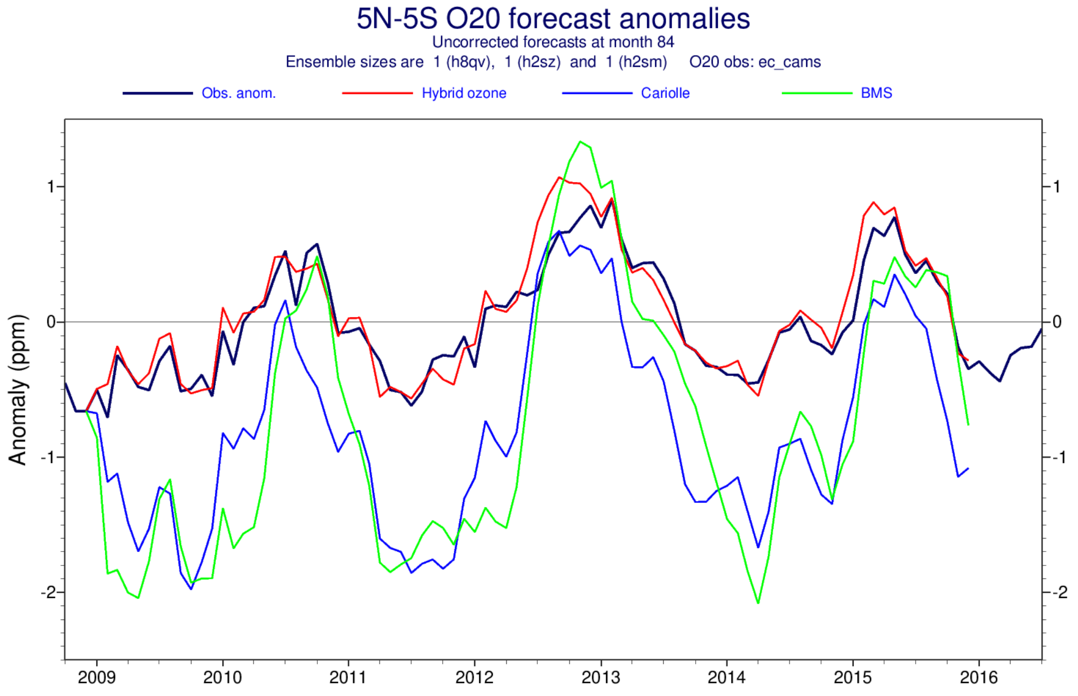


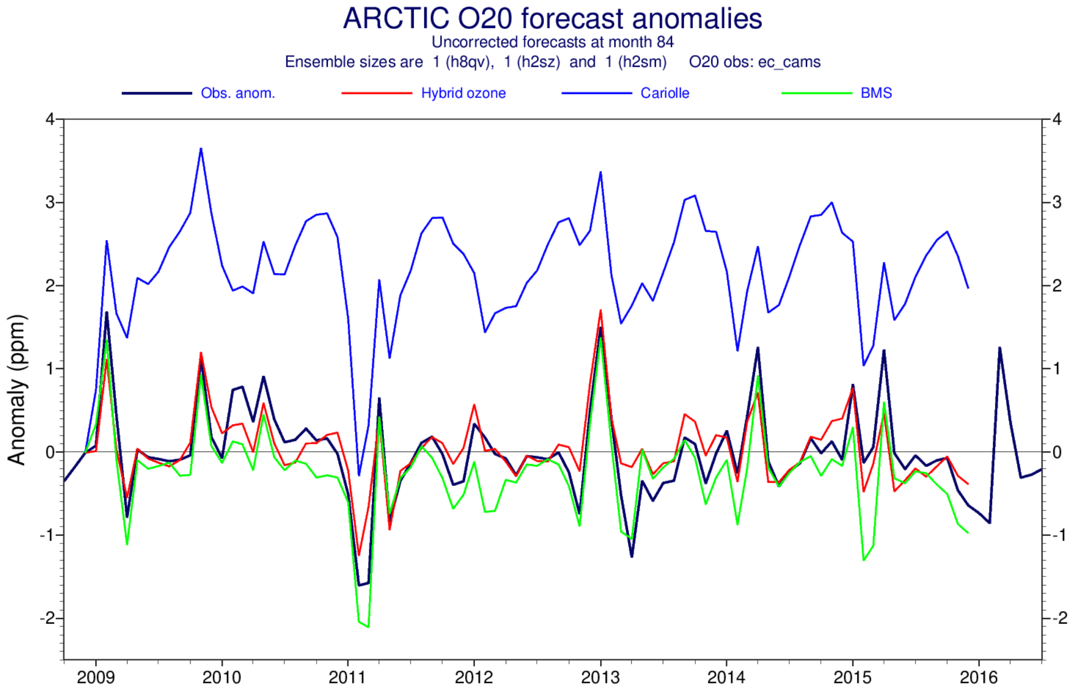
Prescribed winds, 2 hPa



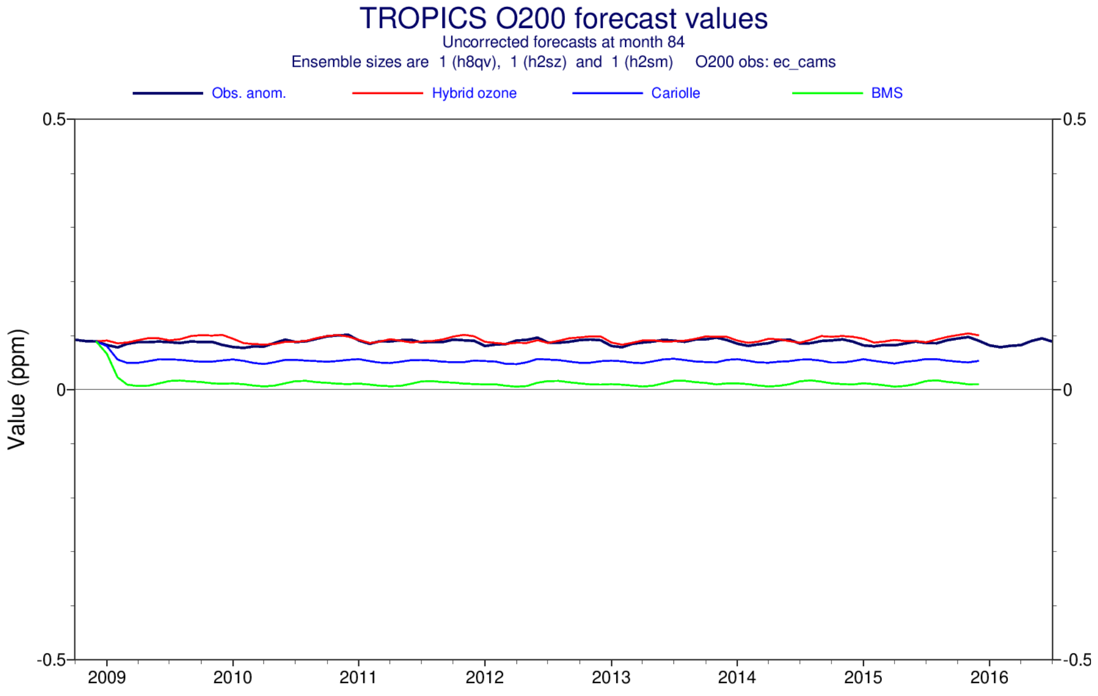


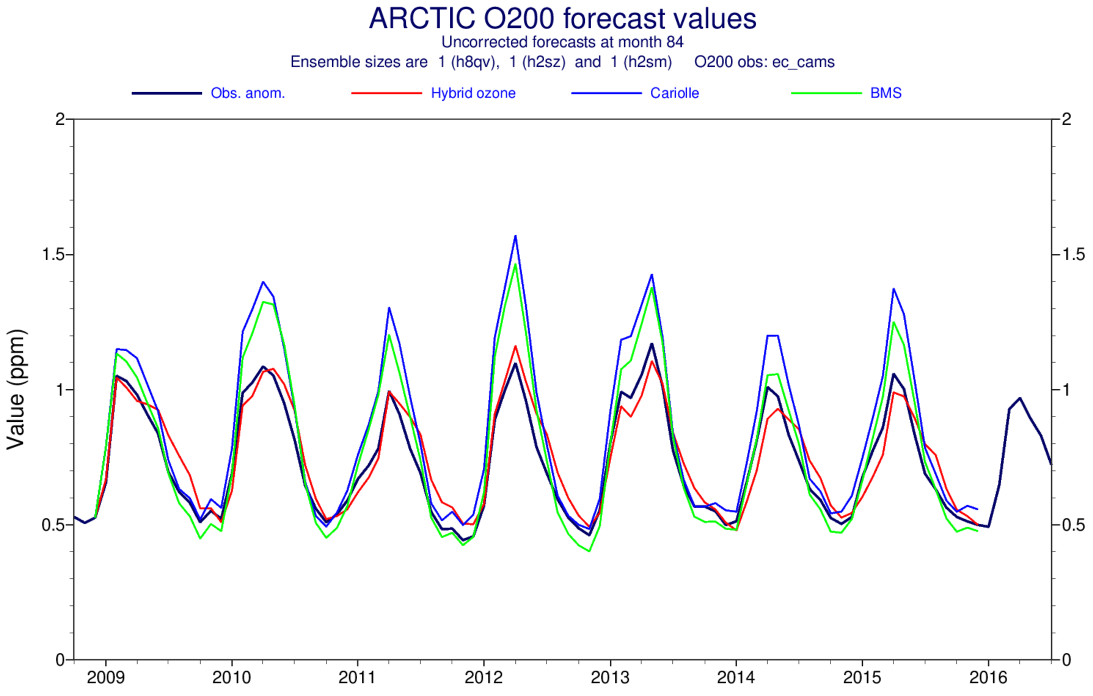
Prescribed winds, 20 hPa



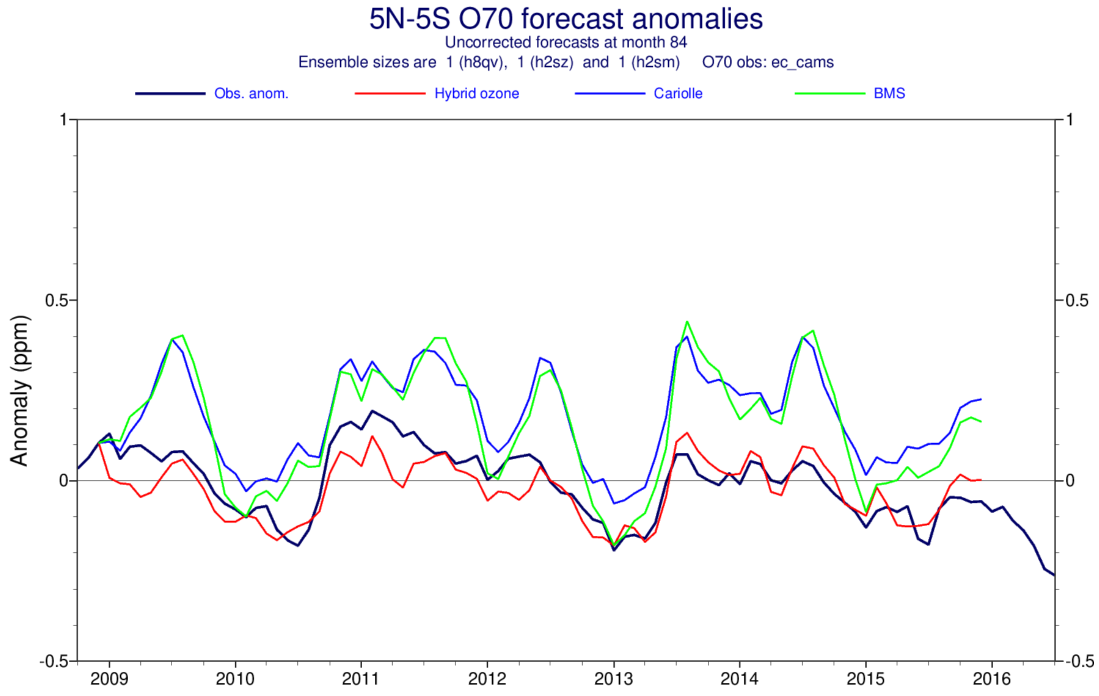


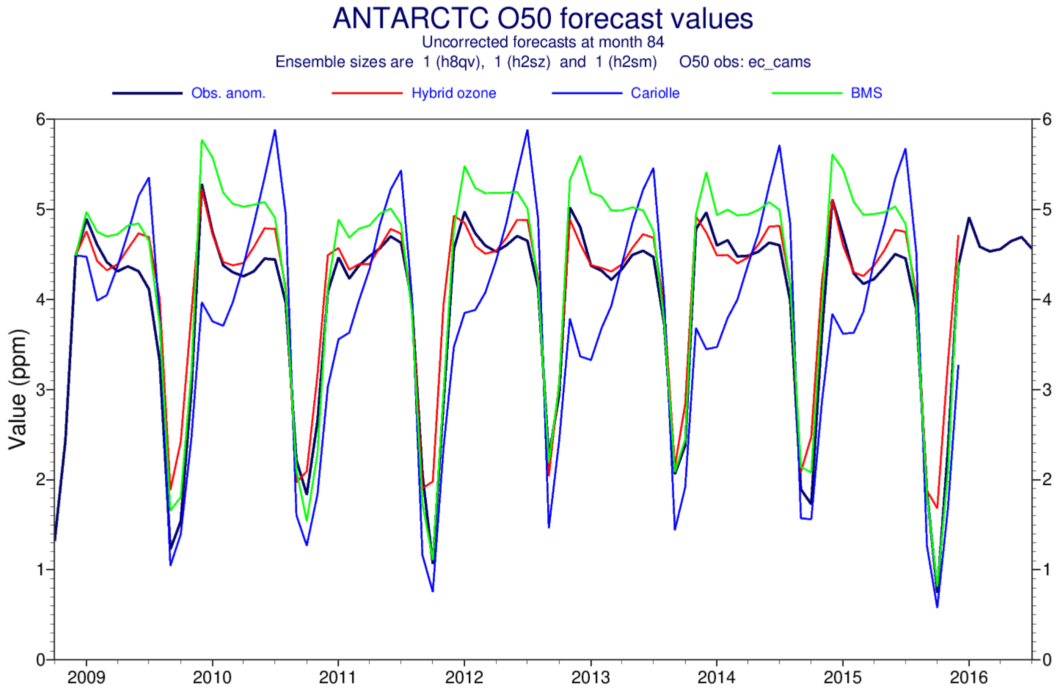
Prescribed winds, 200 hPa



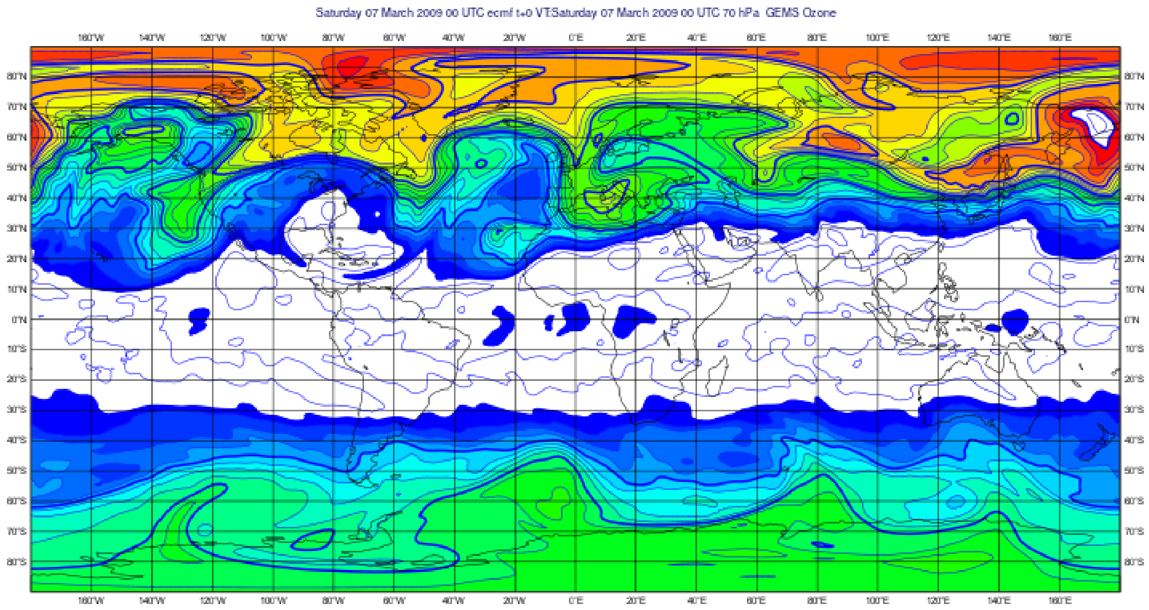


Prescribed winds, other regions of interest

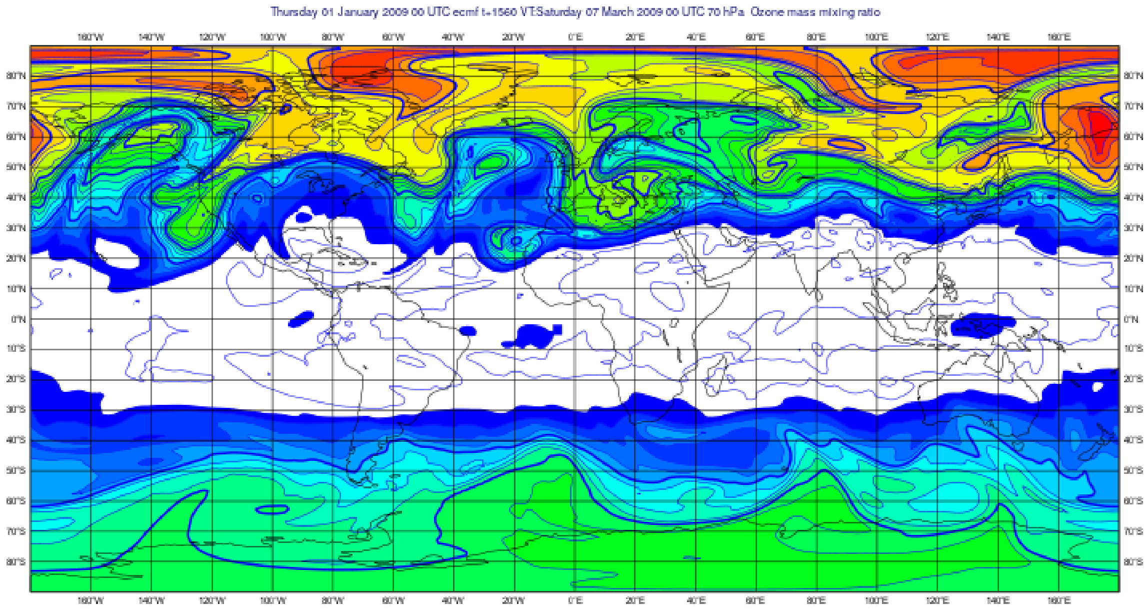




Snapshot, 7 March 2009: 70 hPa ozone



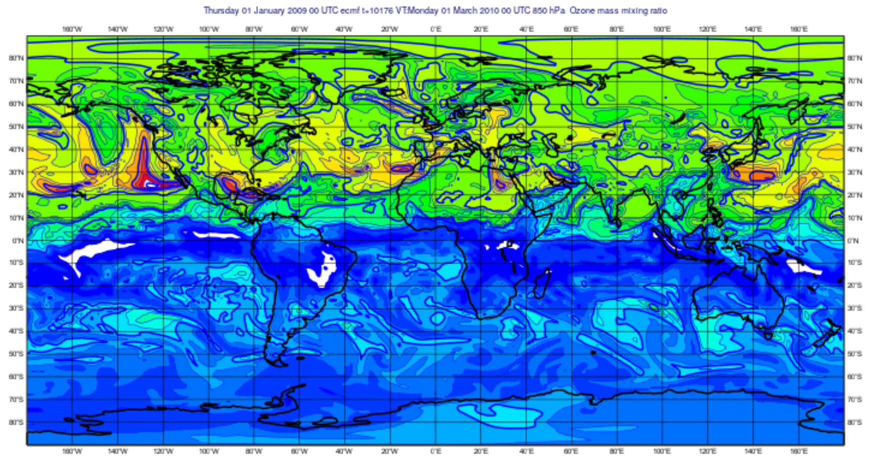
CAMS reanalysis



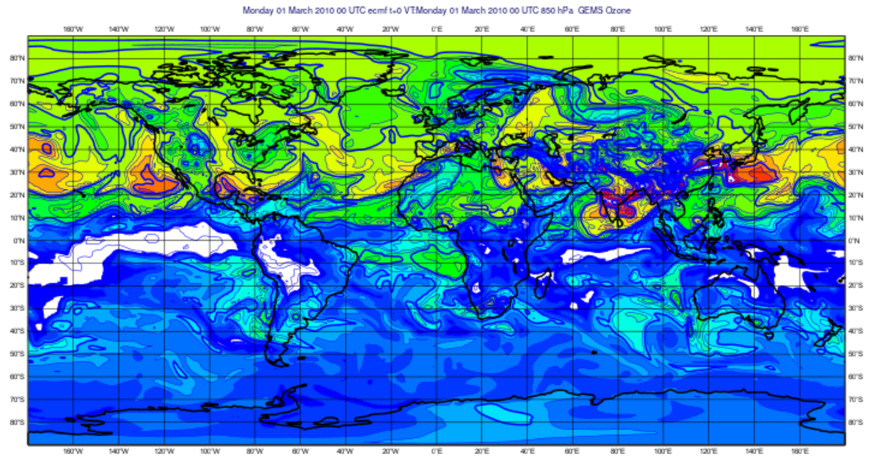
HLO model, initialized 1 Jan 2009

Snapshot, 1 March 2010: 850 hPa ozone

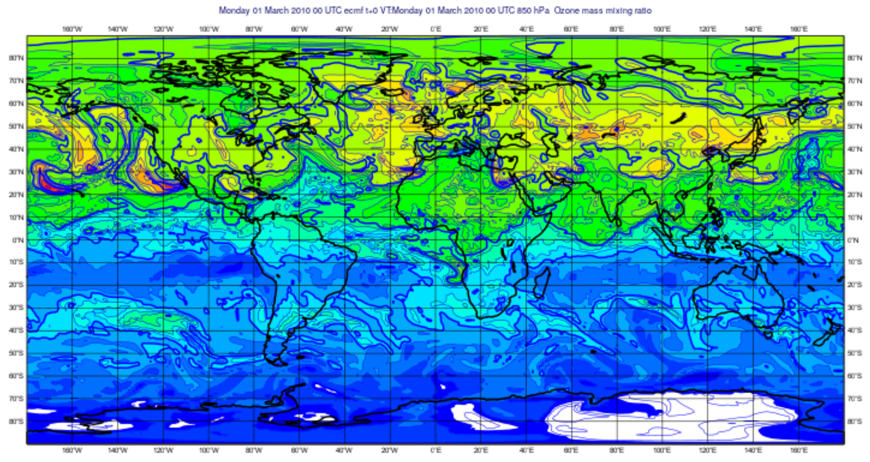
HLO



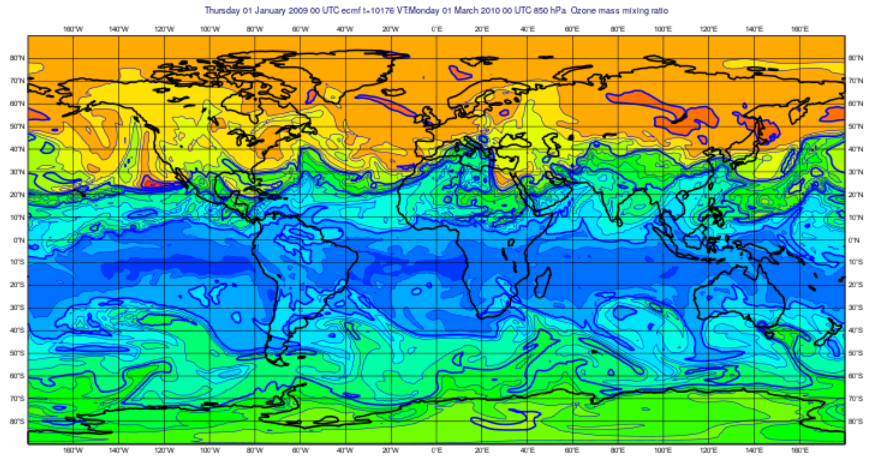
CAMS RA



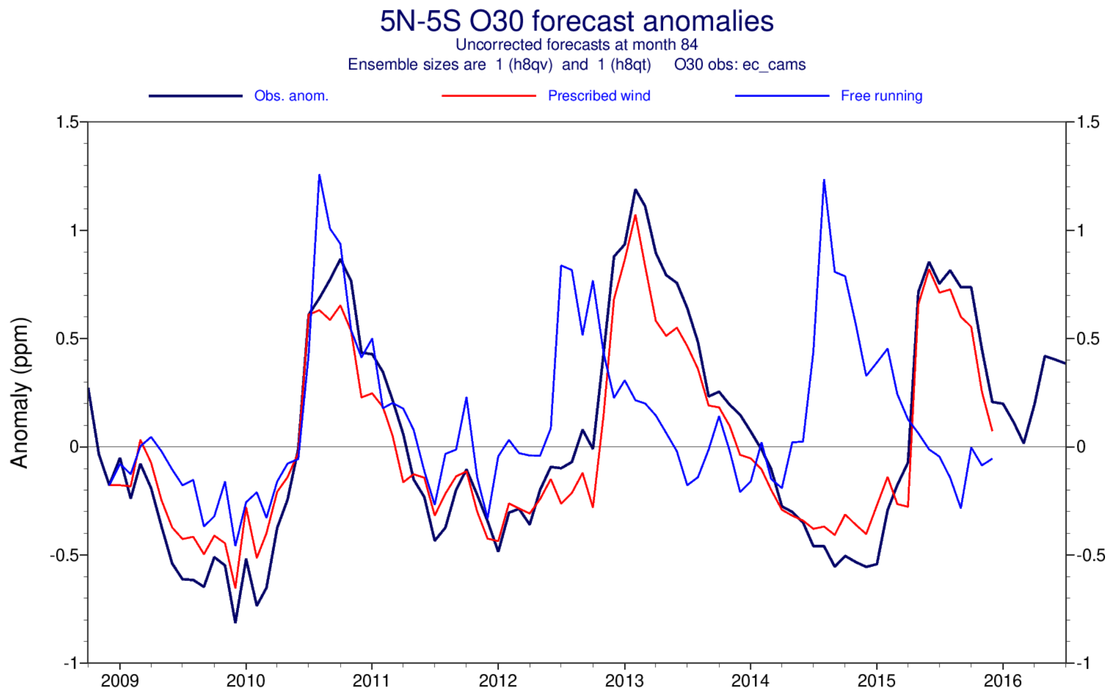
ERA5

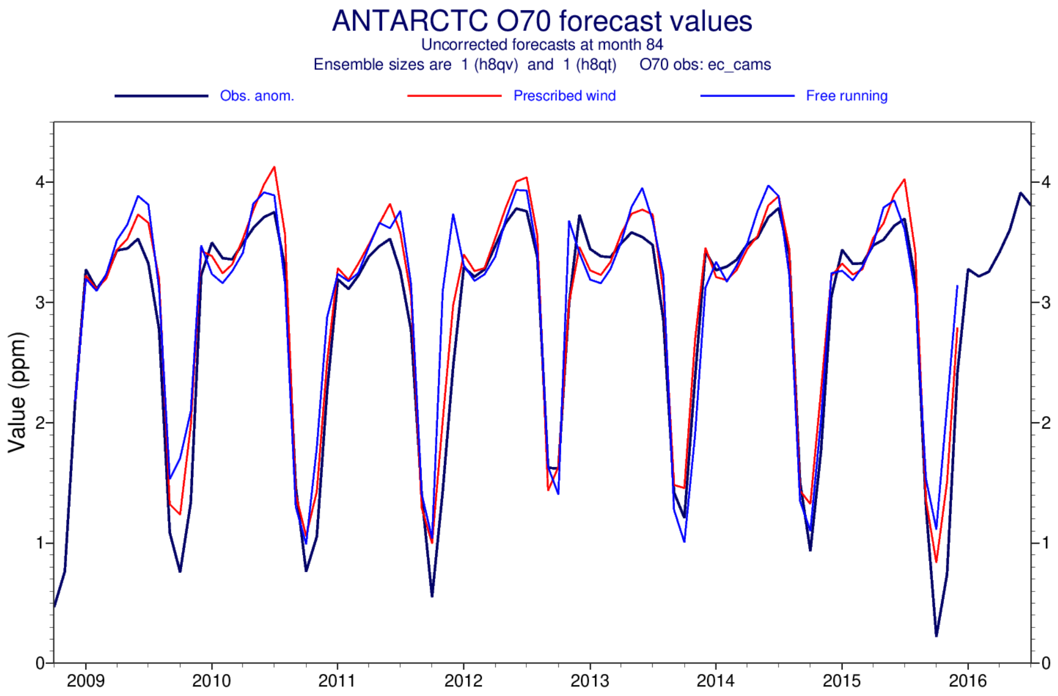


Cariolle

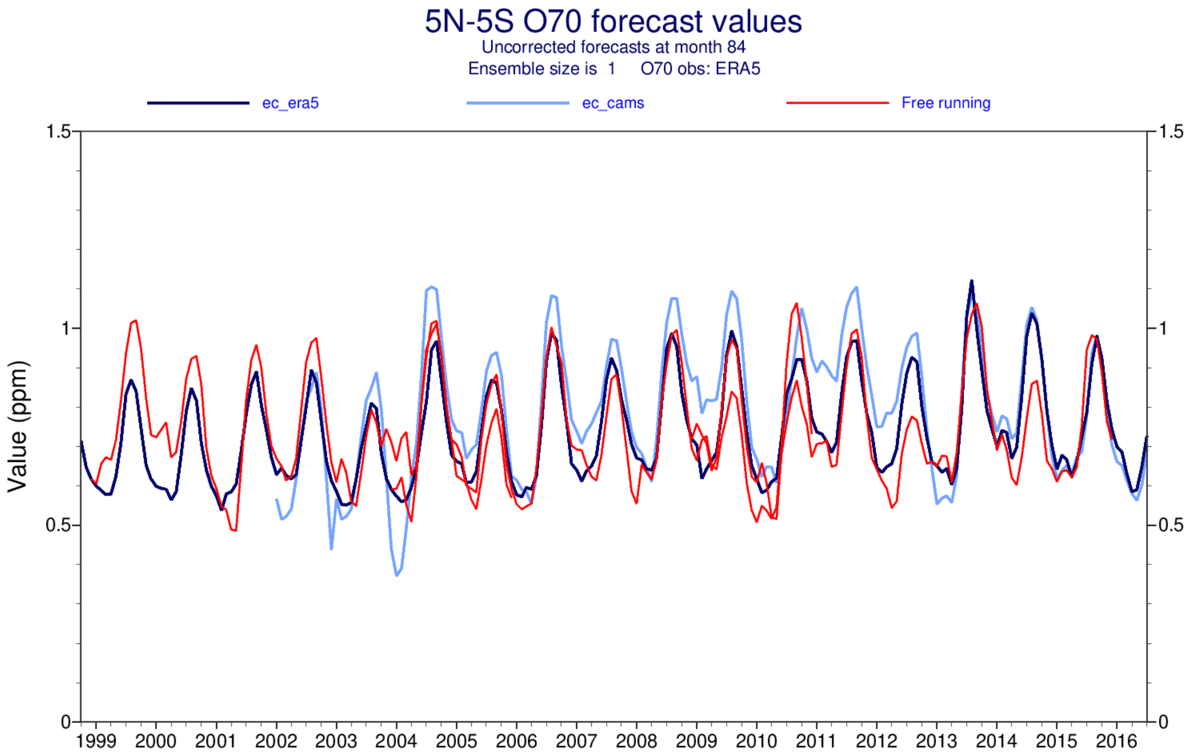


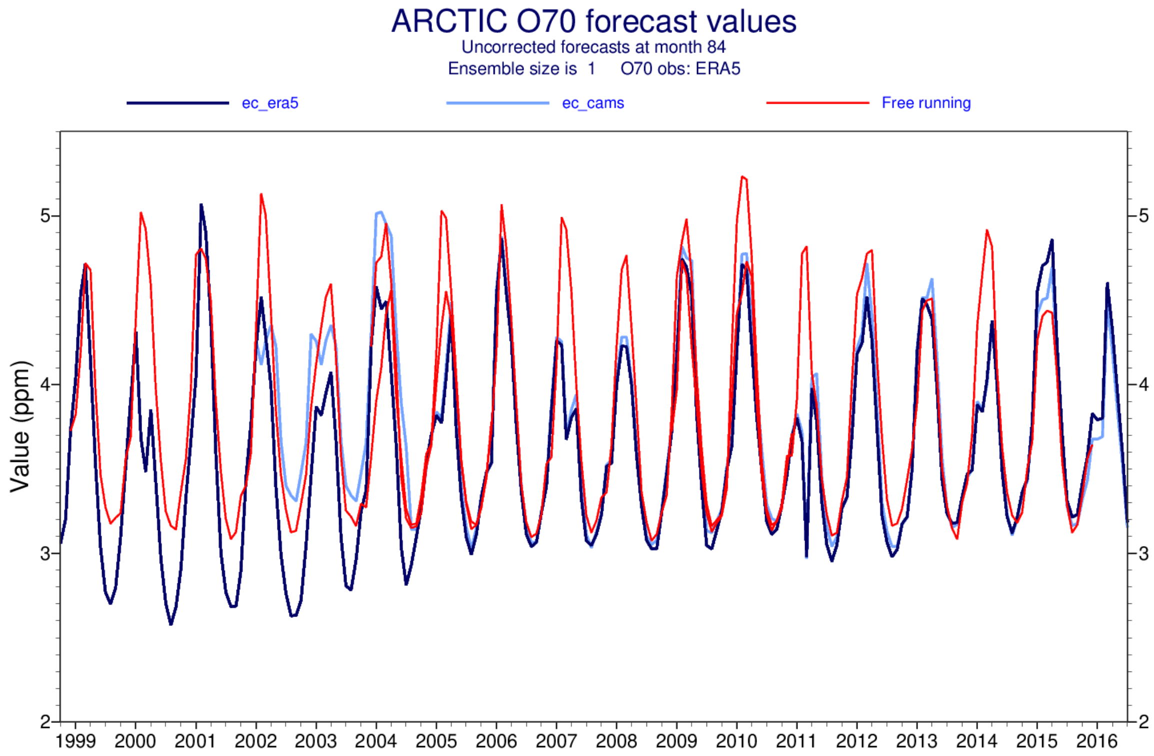
Free-running model test



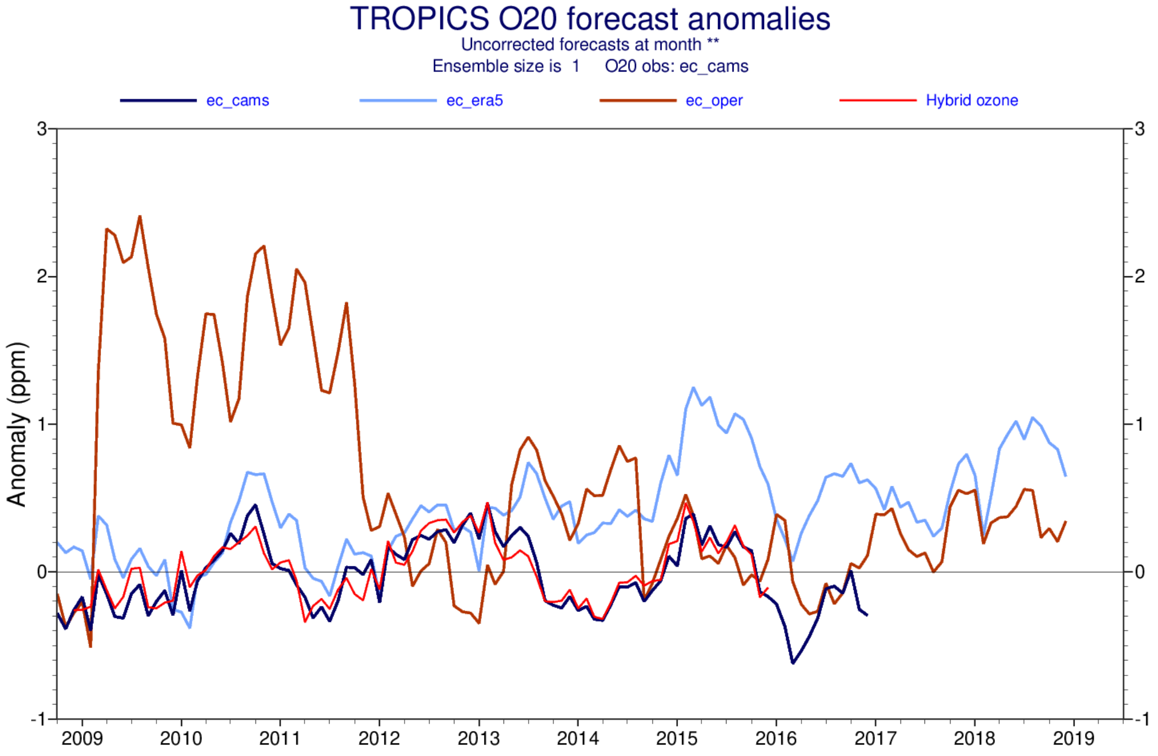


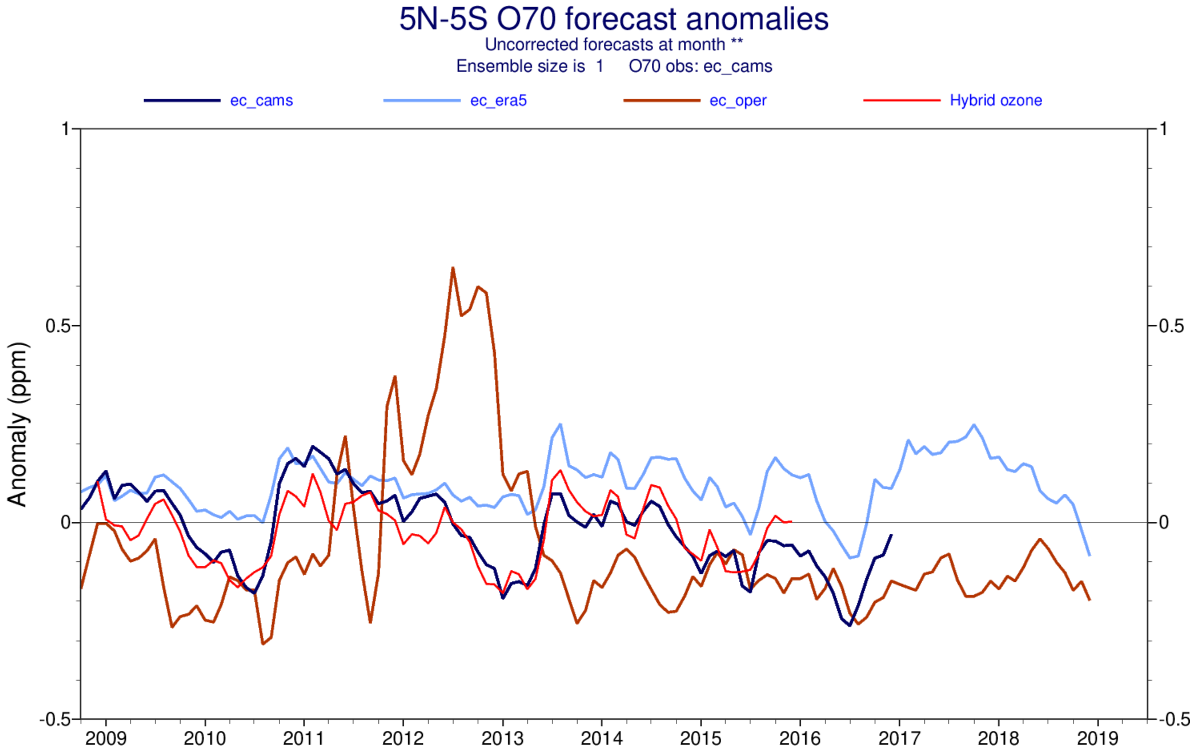
Free-running model test





Are our analyses good enough?





Hybrid linear ozone model:

- Does the model reproduce the specified ozone climatology? YES
  - Ozone will respond to temperature errors, though (–ve feedback)
- Does the model reproduce synoptic variability? YES
- Does the model reproduce interannual / large scale variability YES
- Does the model reproduce decadal variability associated with changing chemistry? NO
  - It is trained on a specific period, and doesn't know any chemistry!
  - Should work for changes in transport, though
- Other weaknesses
  - Only as good as the input analysis – we needed to specify mesospheric climate
  - Cannot reproduce accurately all variability in Antarctic ozone hole – chemistry too complex

- Big unknown: is the diagnosed production term model-specific?