Processes controlling tropical tropopause temperature and stratospheric water vapour

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Stratospheric water vapour

Why do we care?

Stratospheric water vapour can:

- cool stratosphere and warm surface climate
- directly impact stratospheric circulation and tropospheric jet streams
- impact stratospheric chemistry

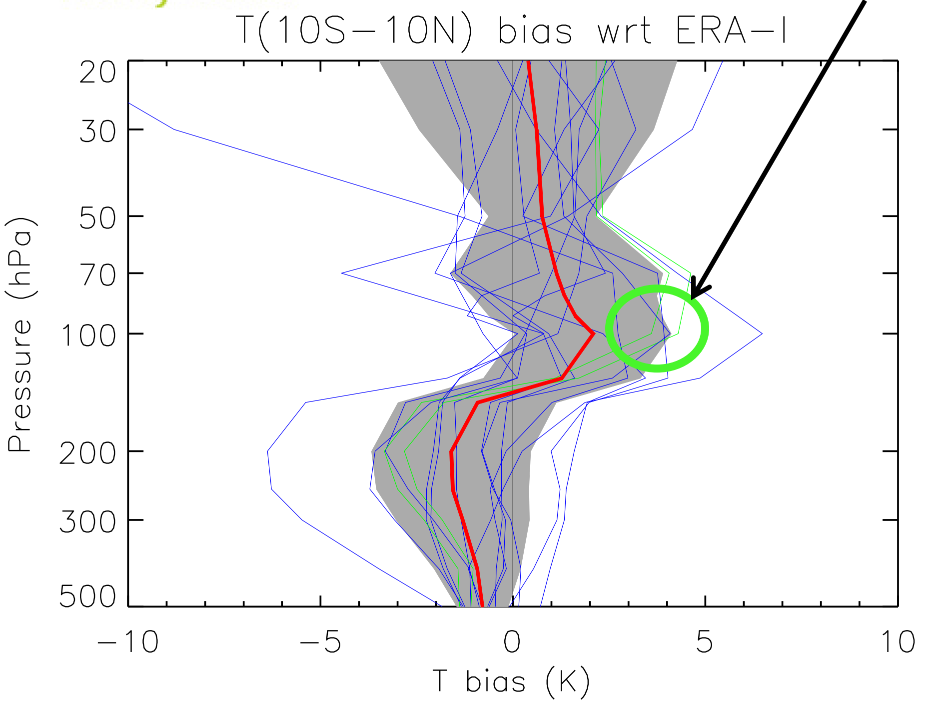
How can we fix model biases?

In climate models, processes can influence stratospheric water vapour by:

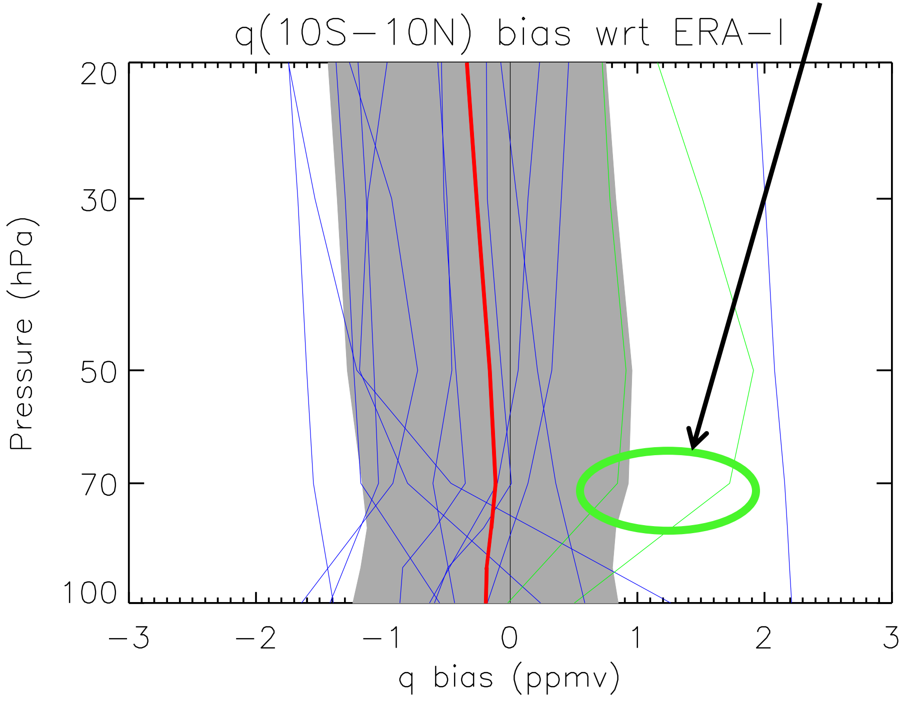
- changing the tropical tropopause temperature (“cold point”)
- changing the UTLS water vapour concentrations directly

How do physical processes influence these two quantities in the model?

T and q biases in CMIP5 models



Use T(10S-10N, 100hPa)
as measure of cold point T

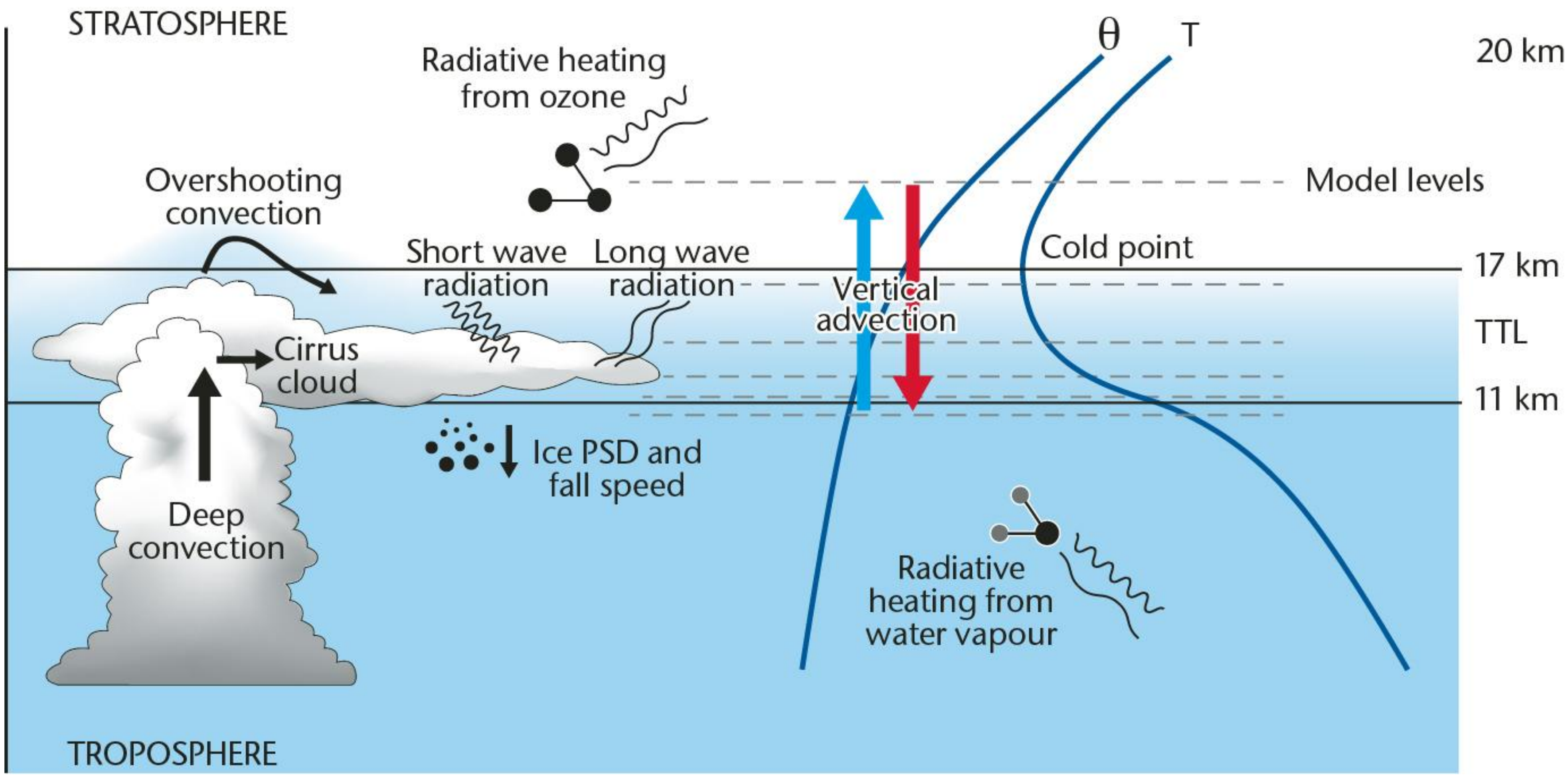


Use q(10S-10N, 70hPa)
as measure of strat wv

- T bias in troposphere and lower stratosphere qualitatively *the same in most CMIP5 models*!
- HadGEM amongst the worst for cold point T bias and stratospheric q bias.
- Bias not seen in q for most models.

How do physical processes influence these two quantities in the model?

Schematic of physical processes



Sensitivity experiments

Run a series of sensitivity experiments with the Met Office Unified model, to understand the impacts of individual processes on cold point temperature and lower stratospheric water vapour.

Some represent improvements to the model physics, and some are simply a modification (or tuning) of model parameters.

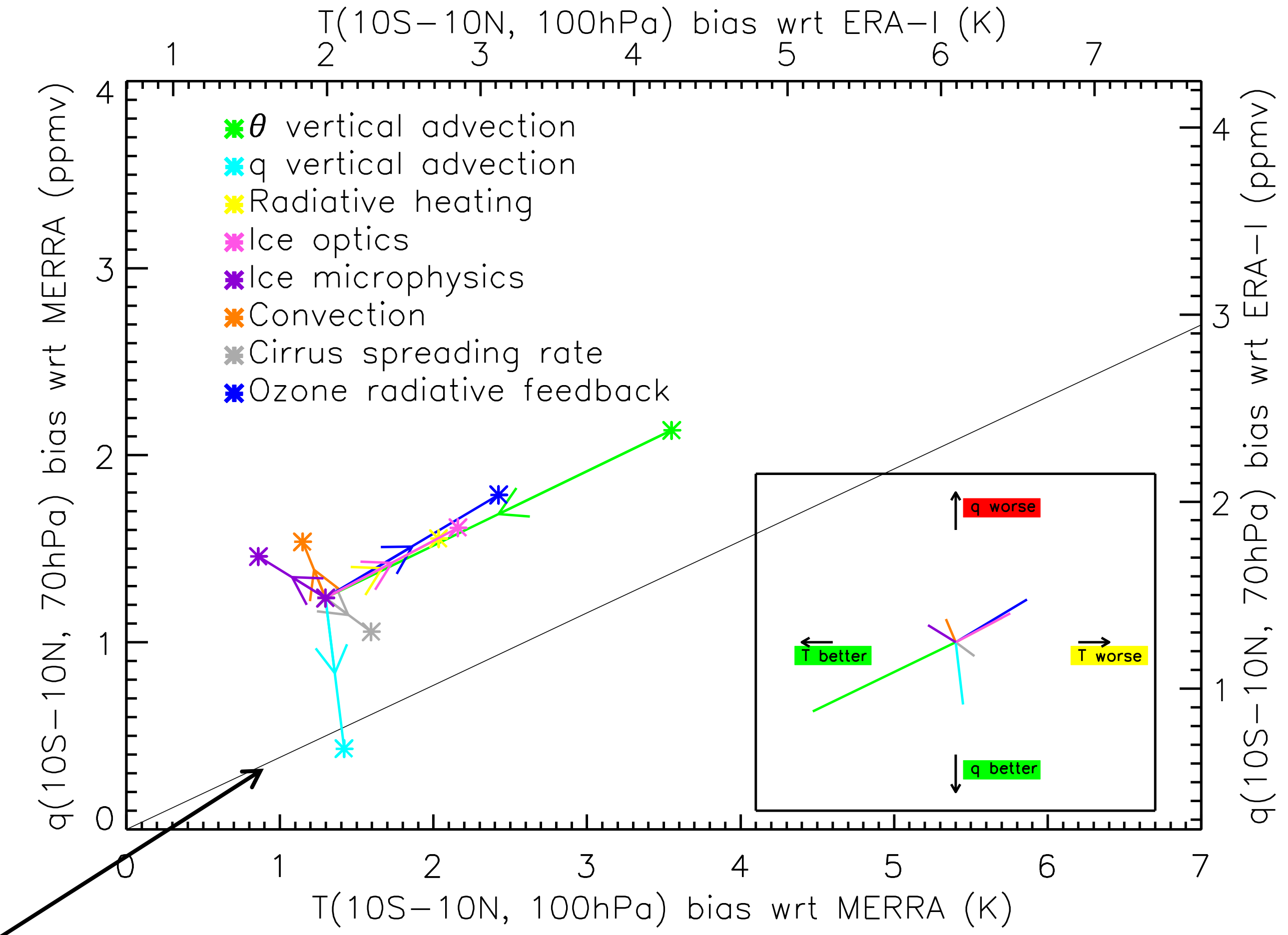
However, all represent a change in the model representation of a physical process which has an impact on tropical tropopause temperature and stratospheric water vapour.

Use T(10S-10N, 100hPa) as measure of cold point T
Use q(10S-10N, 70hPa) as measure of lower stratospheric water vapour

Effect of physical processes on q and T biases

Influence q through T
ө vertical advection
Radiative heating
Ice optics
Ozone radiative feedback

Influence q directly
q vertical advection
Ice microphysics
Convection
Cirrus spreading rate

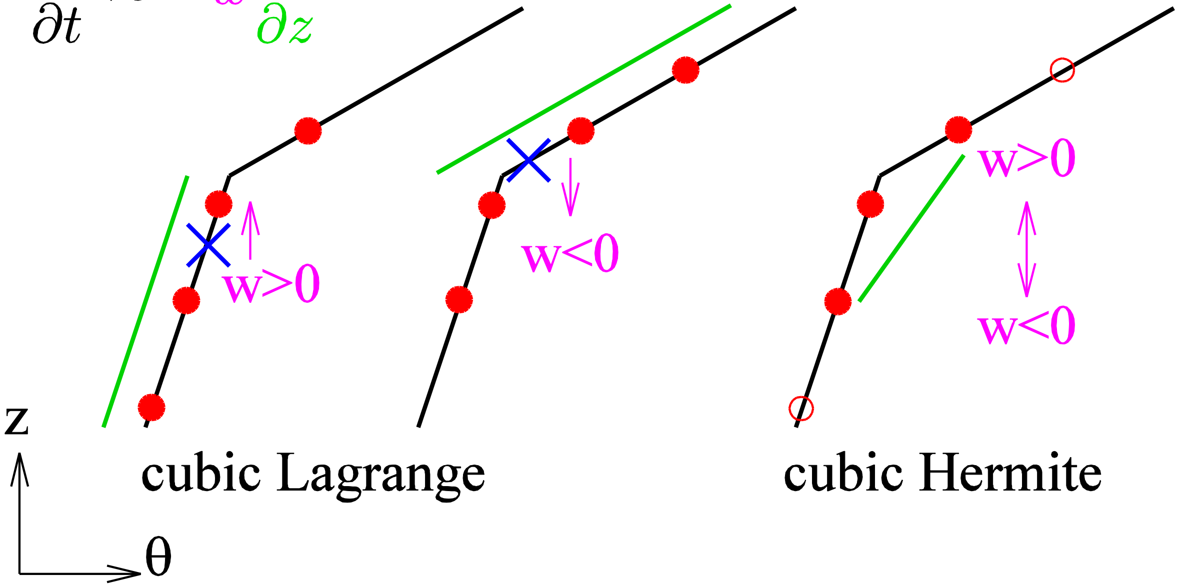


Empirically derived
“Clausius-Clapeyron”
relation

The value of T(100hPa, 10S–10N) in ERA-I is 192.4K and in MERRA is 193.1K.
The value of q(70hPa, 10S–10N) in ERA-I is 3.49ppmv and in MERRA is 3.74ppmv.
These are in good agreement with observations

Vertical advection of potential temperature

$$\frac{\partial \theta}{\partial t} \approx -w\frac{\partial \theta}{\partial z}$$

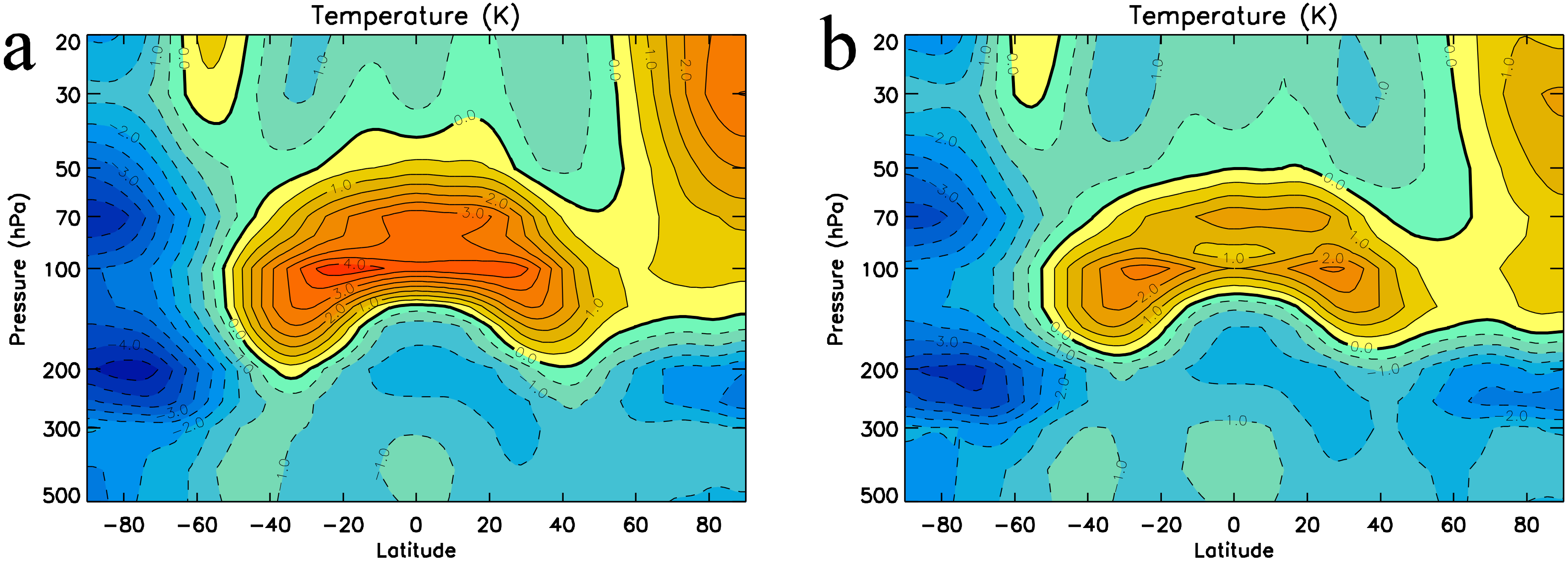


cubic Lagrange

cubic Hermite

Vertical advection algorithm should be reversible for small oscillations. Cubic Lagrange adds systematic heating at first-order, cubic Hermite is second-order accurate.

Vertical advection of potential temperature

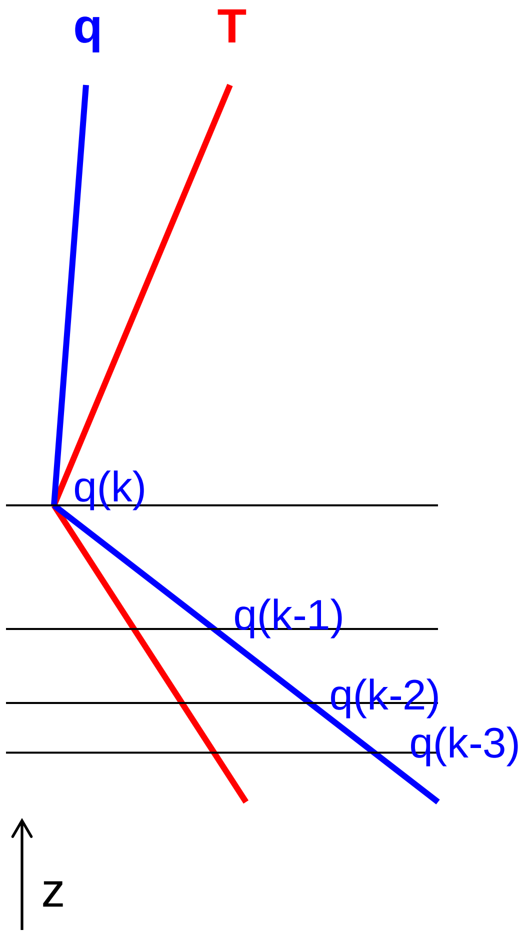


Cubic Lagrange

Cubic Hermite

Removing spurious heating term dramatically reduces T bias

Vertical advection of moisture



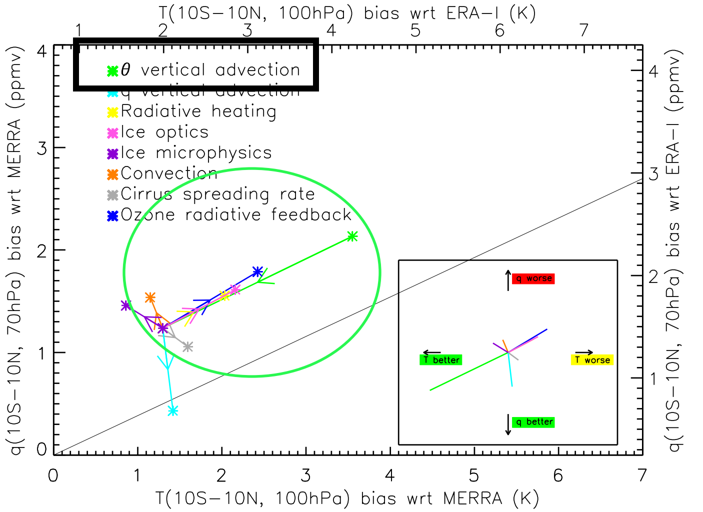
Interpolation by fitting a polynomial over several vertical model levels inevitably incorporates information about the water vapour concentrations over several model levels (spatial smoothing).

Thus stratospheric water vapour in models depends not only on the cold point T but also water vapour concentrations in the upper troposphere.

The choice of polynomial for q vertical advection, plus any processes acting to directly influence upper tropospheric water vapour concentrations (Ice microphysics, Convection, Cirrus Spreading) will influence stratospheric water vapour concentrations directly, NOT following the Clausius-Clapeyron relation based on cold point T.

Cubic Hermite interpolation …

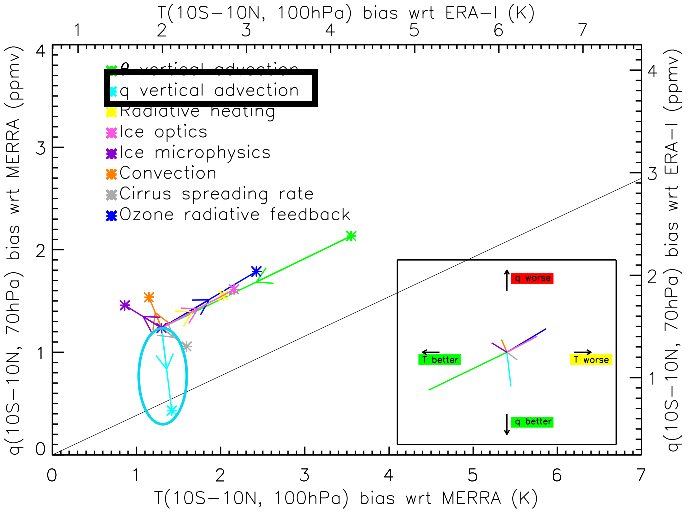
…applied to theta



Improves the temperature bias, and therefore also the water vapour bias.

Conservation of mass integrated potential temperature also important

… applied to water vapour



Cubic Hermite scheme has lower vertical spatial smoothing than cubic Lagrange, leading to more realistic stratospheric water vapour concentrations.

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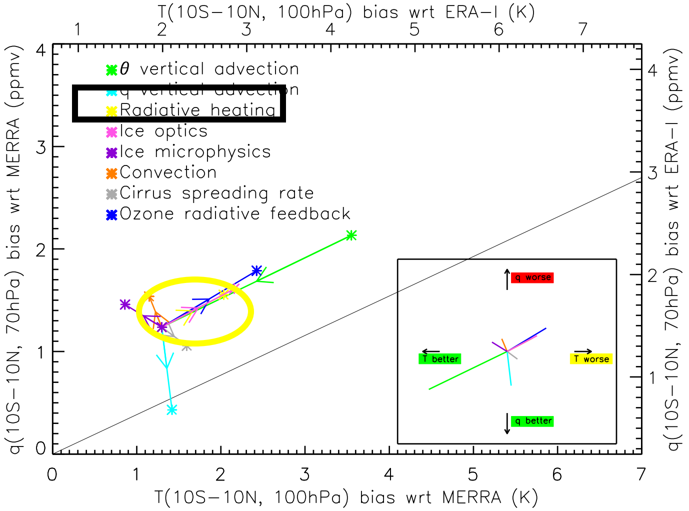
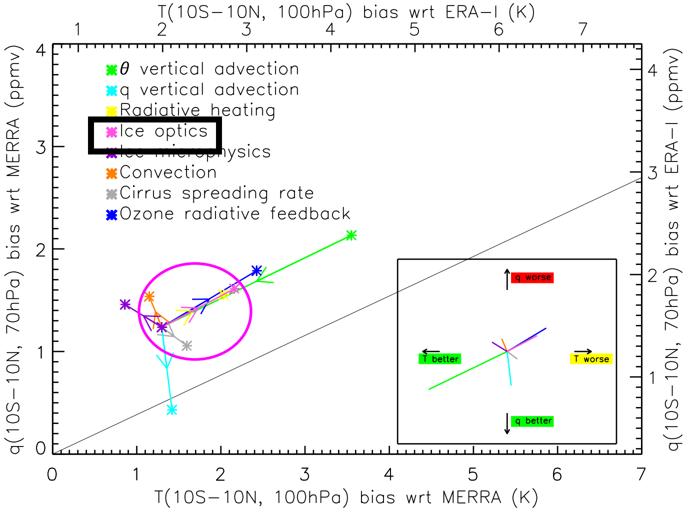
Radiative heating



Ice optics



Radiative heating:

Improvements to scaling of absorption w.r.t. pressure and temperature

→ more radiation (both LW and SW) is absorbed by stratospheric gases

→ direct heating of the tropical tropopause

Ice Optics:

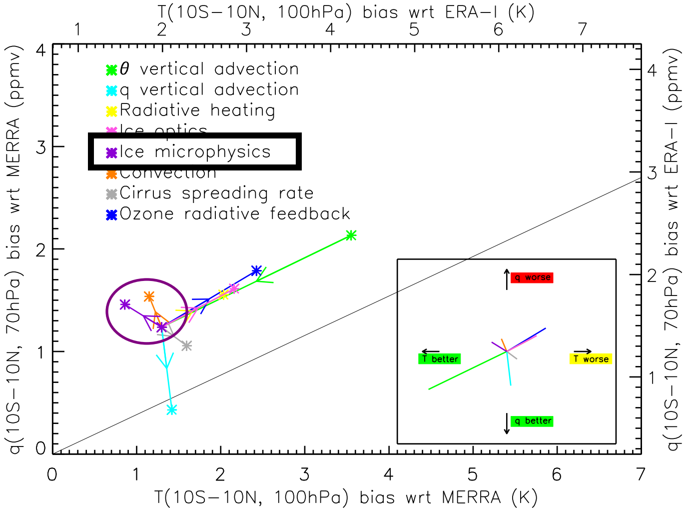
Improve cirrus bulk optical properties

→ reduction in LW absorption within cold tropical cirrus

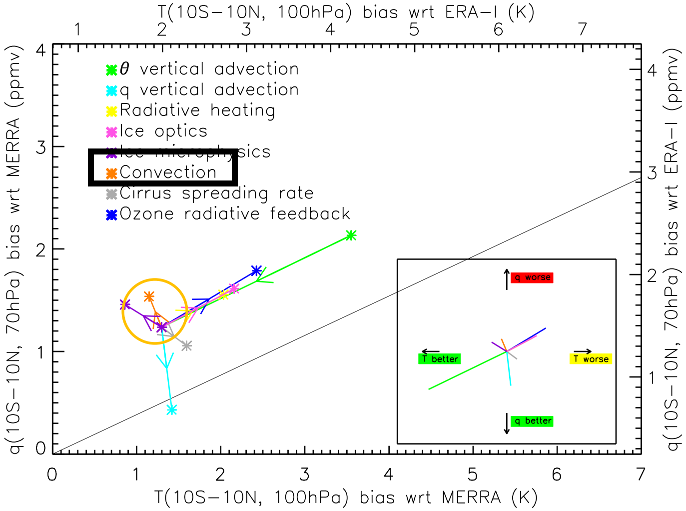
→ increase in upwelling longwave (originating from warm layers below cloud)

→ warming of tropical tropopause region

Ice microphysics



Convection



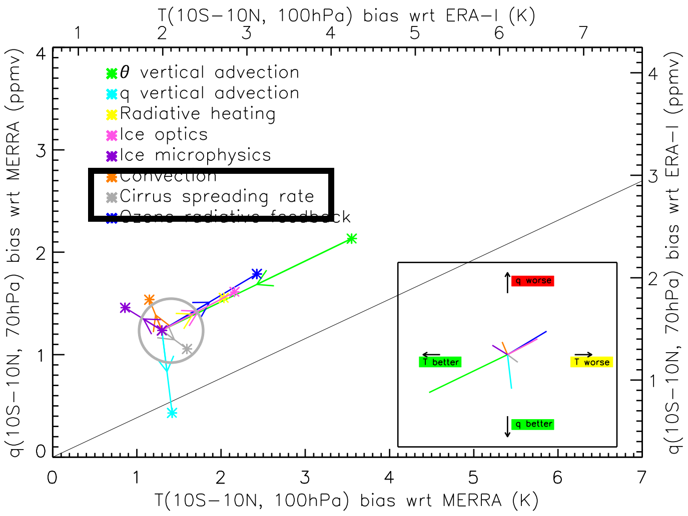
Ice PSD changes:

slow down the sedimentation of ice crystals → increased amounts of ice cloud
→ reflected SW goes up and emitted LW goes down
→ net cooling near cloud tops and a net warming of the troposphere below

make the ice crystals less efficient sinks of water vapour
→ the water vapour can build up to higher values in the high cloud region
→ this may then be advected across the tropopause

Improvements to Convection scheme raise cloud top height, again leading to more water vapour in the upper troposphere and making things 'brighter and colder'

Cirrus spreading rate



Reduction of the cirrus spreading rate counteracts effects of 6A convection scheme and Ice PSD a little by decreasing the cirrus cloud fractions.

Importance of cirrus spreading rate for stratospheric water vapour can be *much greater* when applied to different model configuration

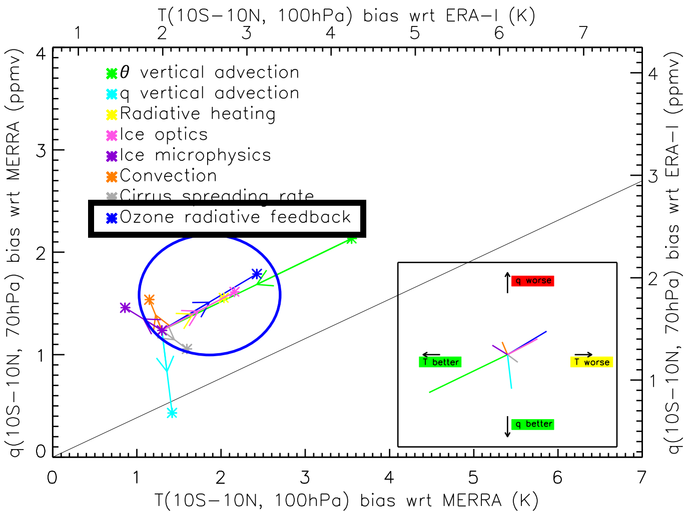
Processes:

- are not linear
- do not always add linearly (*although they almost do!*)

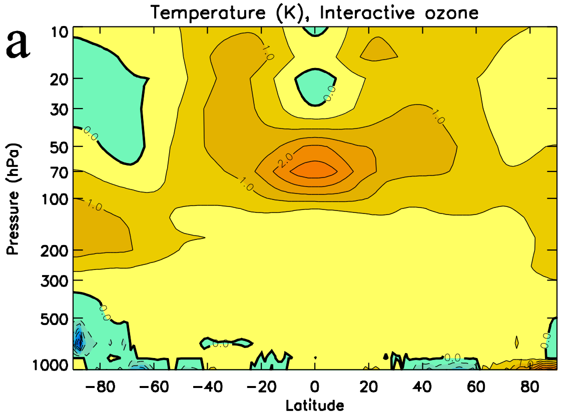
Qualitative physical impact should be robust

Ozone radiative feedback

Too much ozone in tropical tropopause layer leads to too much radiative heating

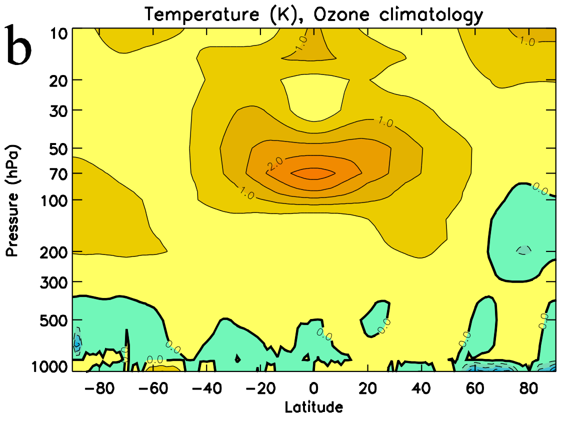


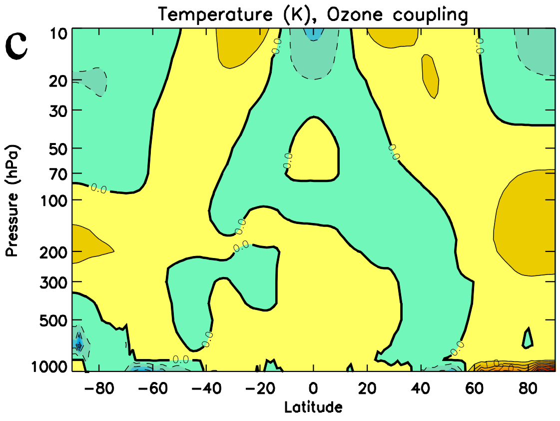
Total



Climatology

Coupling



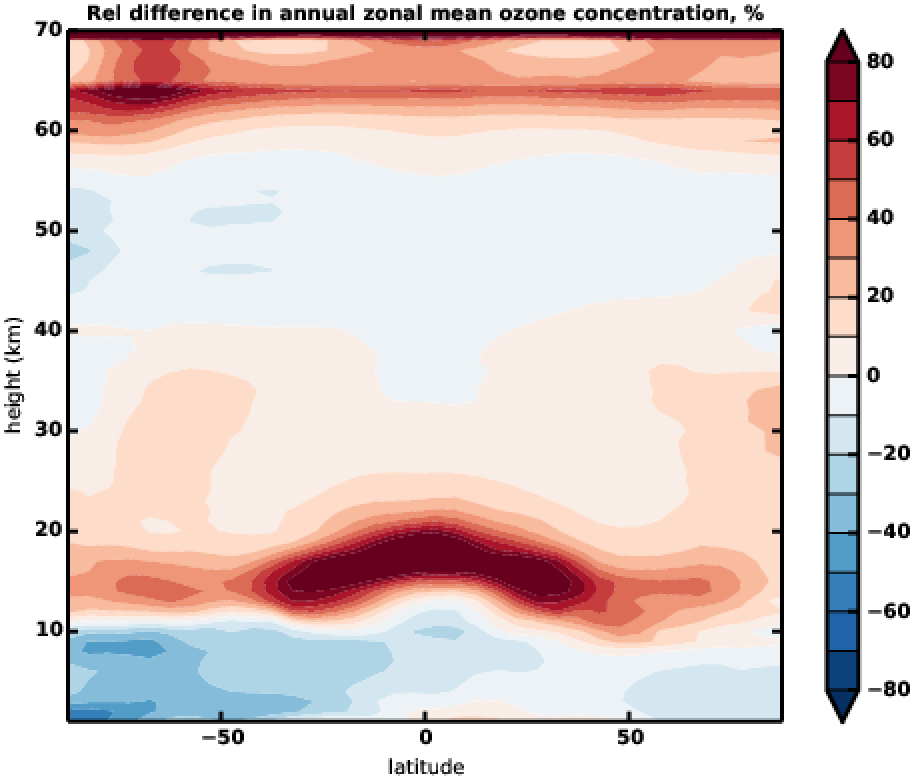


Effect of interactive ozone is due to differences in ozone climatology, not two-way coupling.

Ozone radiative feedback

Modelled ozone found to be ~16% too high on average in tropics, and up to ~80% too high in tropical tropopause layer.

Transport scheme and composition model will both influence this.



% difference between interactively modelled ozone and “observed” Bodeker ozone climatology

Caveats

- Not mentioned processes that don't significantly influence T and q biases in our model. In particular
    - magnitude of gravity wave flux into the stratosphere, influencing the magnitude of the Brewer-Dobson circulation
    - latent heat of vaporization of ice in the tropical tropopause layer

- Focus here is on annual mean biases. In our model annual mean T and q biases are positive, but the seasonal cycle in T and q is too weak. Most of the processes discussed tend to increase or decrease both. So improving both annual mean and seasonal cycle is a subject for further work.

Summary

The tropical tropopause is a region sensitive to many dynamical, microphysical and radiative processes, and changes to any one of these processes can produce biases in stratospheric water vapour large enough to impact the simulated surface temperature, atmospheric circulation and stratospheric chemistry.

Stratospheric water vapour can be influenced by the cold point temperature and the upper tropospheric water vapour concentrations in climate models.

Sensitivity experiments demonstrate the impacts of individual processes on tropical tropopause temperature and lower stratospheric water vapour in the Met Office climate model, and can be used to determine how to reduce model biases in a physical way.