Challenges and recent progress in representing radiative processes in NWP models

…especially radiatively interactive ozone, pathways to predictability & moving beyond two streams

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ECMWF Annual Seminar 2022

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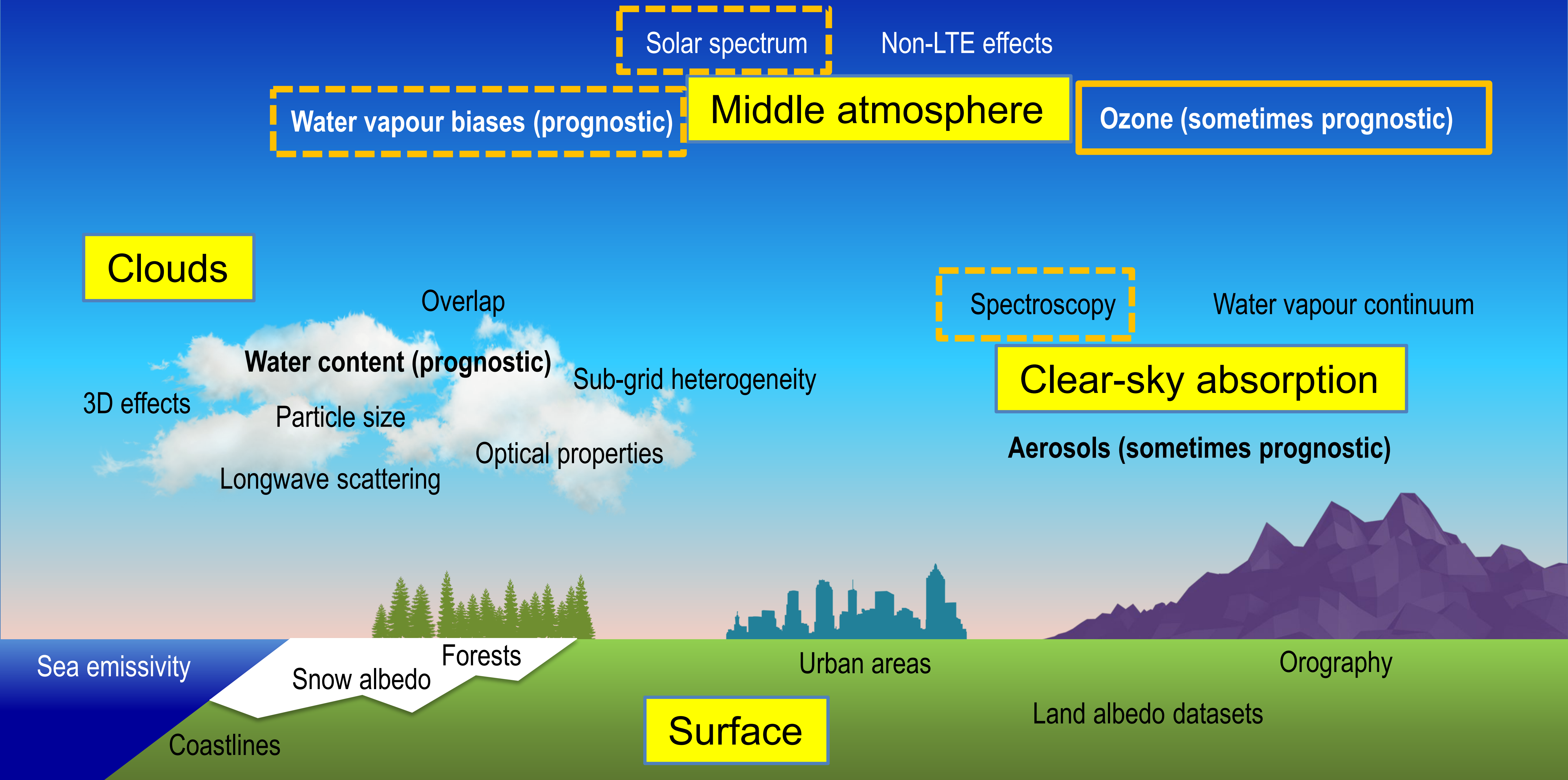
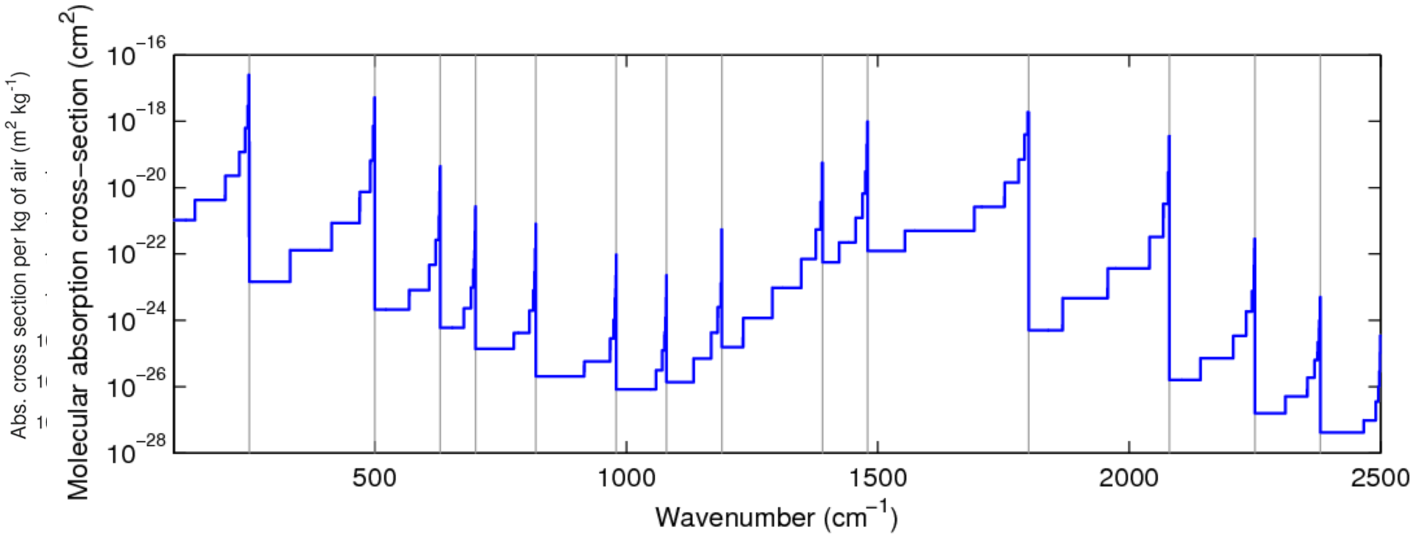
Challenges for radiation in NWP: inputs and boundary conditions



Accuracy & efficiency

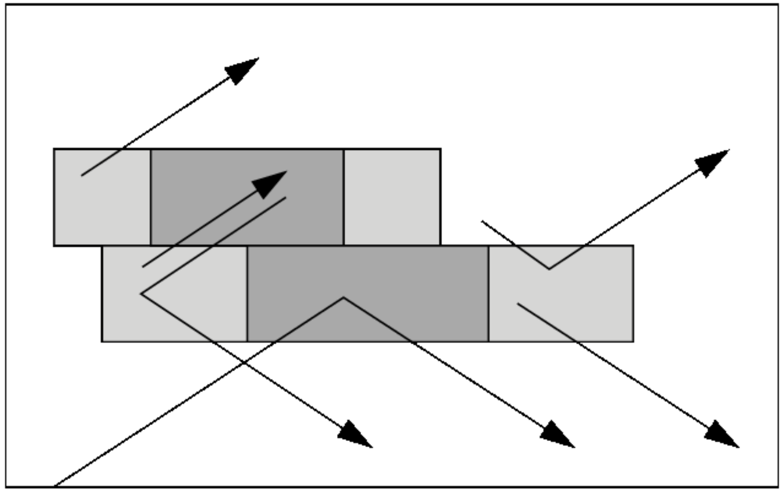
$$F = \int\int\int\int\int I(\lambda, x, X, t, \theta)\, d\lambda\, dx\, dX\, dt\, d\theta$$

- Scheme numerically integrates instantaneous monochromatic radiances I to get broadband fluxes F
- Accuracy and efficiency depend on number of quadrature points used in each dimension



Wavelength λ

- At ECMWF we use "RRTMG" to approximate gas spectrum: **252** spectral points (solar+infrared)
- Testing new "ecCKD" gas optics at ECMWF: similar accuracy with **64** points
- *Jan will describe ACRANEB2, and Helen will discuss spectral evaluation*



Sub-grid horizontal distance *x*

- "Tripleclouds" solver uses **3** quadrature points (only in cloudy layers)
- "McICA" solver presents each spectral interval with a different stochastic cloud profile: no additional quadrature points, but some noise if too few spectral intervals
- Large uncertainty in sub-grid cloud structure, so more quadrature points probably not justified

Accuracy & efficiency

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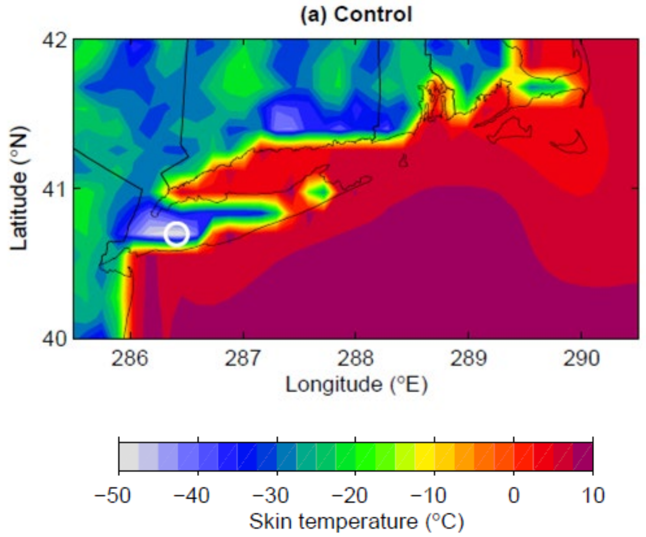
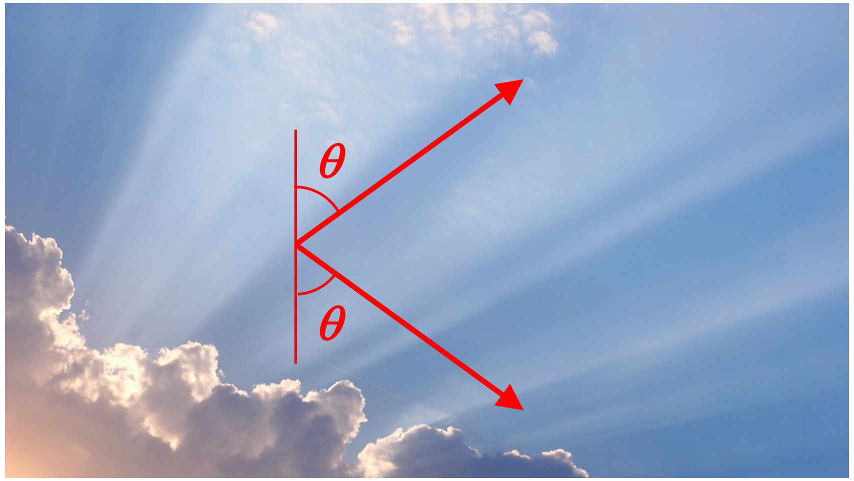


Sub-sampling model points in space *X* and time *t*

- Radiation called every hour (better than 3-hourly) with 10x fewer spatial gridpoints
- Little detectable improvement when more frequent in time or space!
- Partly due to "approximate updates" (Hogan & Bozzo 2015) every gridbox/timestep



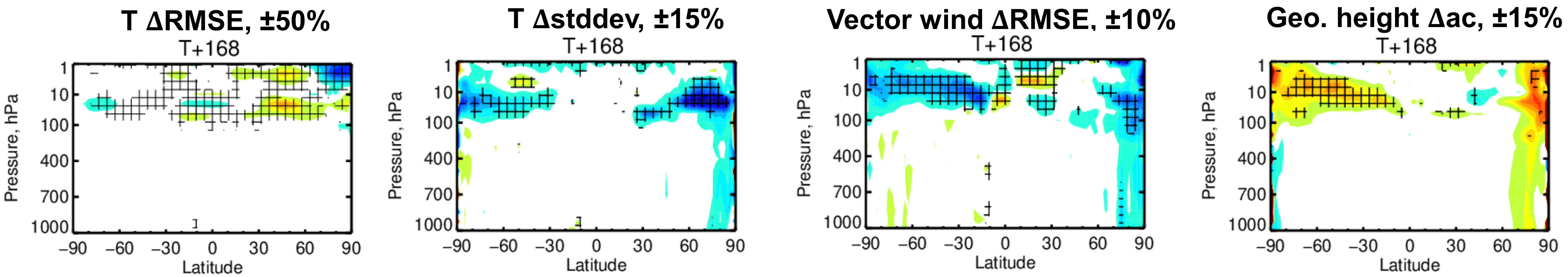
Zenith angle θ

- Virtually all atmospheric models assume diffuse radiation propagates with **2** zenith angles: the two-stream approximation (Schuster 1905), although solar radiation adds the direct beam so effectively **3** zenith angles
- Cost of *N*-stream scheme: no scattering O(*N*), with scattering O(N^3)!
- *What is the accuracy gain of more streams, and how can we do it cheaply?*
- *Bernhard will discuss how we can represent 3D effects of these horizontally-propagating light rays*

Prognostic ozone interactive with radiation (for 48r1, 2023)

- Tim Stockdale has developed a new Hybrid Linear Ozone (HLO) scheme, trained on the CAMS ozone reanalysis and an improvement in predictive mode over previous Cariolle and BMS linear ozone schemes
- Radiatively interactive HLO already operational in CAMS forecasts, planned for HRES in 48r1

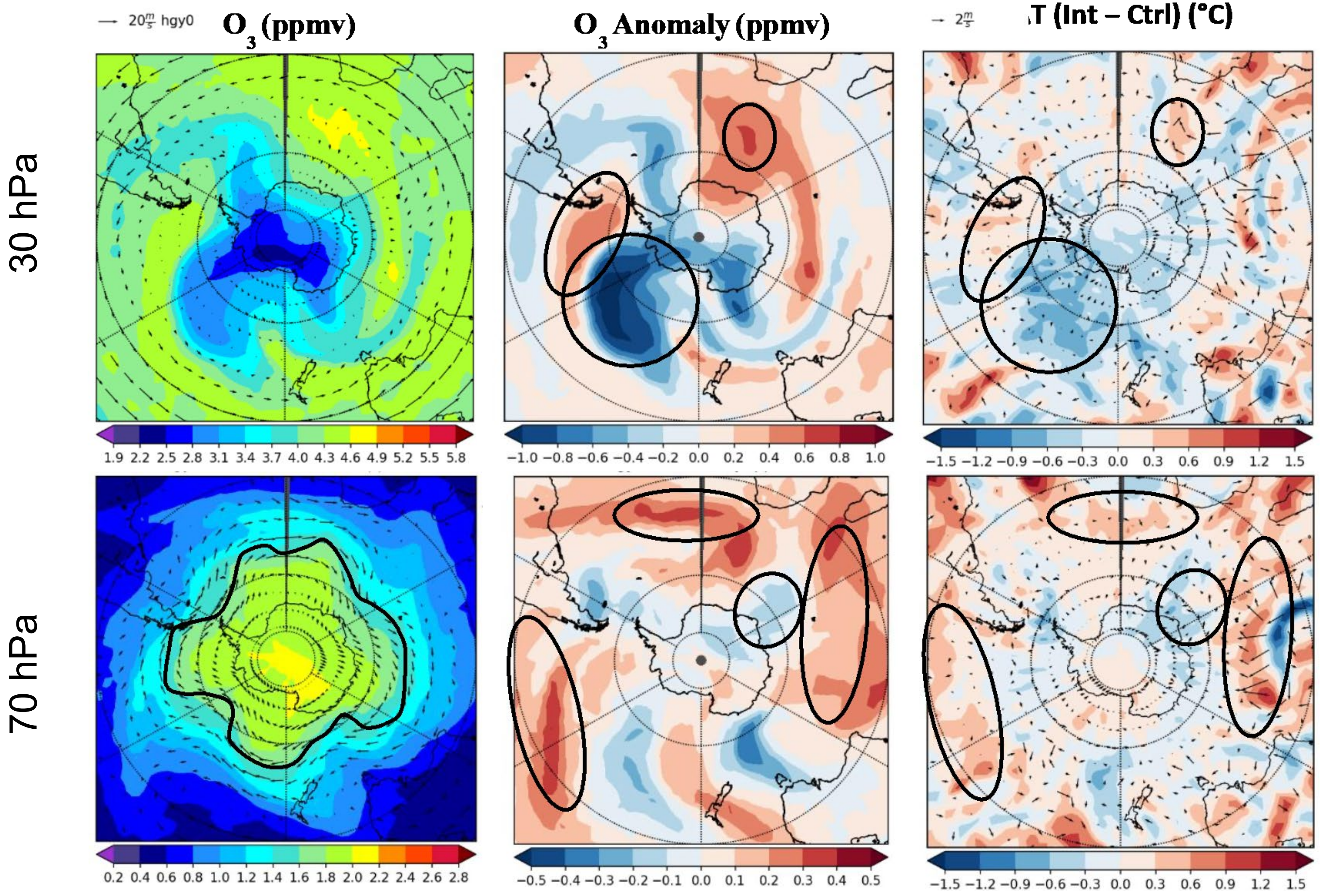
<u>Percentage change to 7-day forecast skill, Tco1279 (9-km), June-September 2019</u>



← Blue is an improvement | Red is an improvement

- Scores insensitive to temperature bias are improved substantially in the mid stratosphere (5-70 hPa)
- Training on the latest CAMS ozone changes the mean slightly, leading to a mean cooling at 50 hPa by a fraction of a degree; this means that RMSE is not improved, but the temperature bias will be improved by other changes, e.g. better vertical filtering and new gas optics scheme (in 49r1)

5-day impact of prognostic ozone, 2 Feb 2018, southern hemisphere



- Ozone anomalies of up to 20% (1 ppmv) occur in a wave pattern around the polar vortex
- These are correlated with temperature anomalies of up to 1 K, but stronger away from pole with increased solar heating
- Winds impacted via thermal wind balance
- Infrared effect tends to oppose solar heating: higher ozone and warmer air (from solar heating) both lead to more infrared cooling

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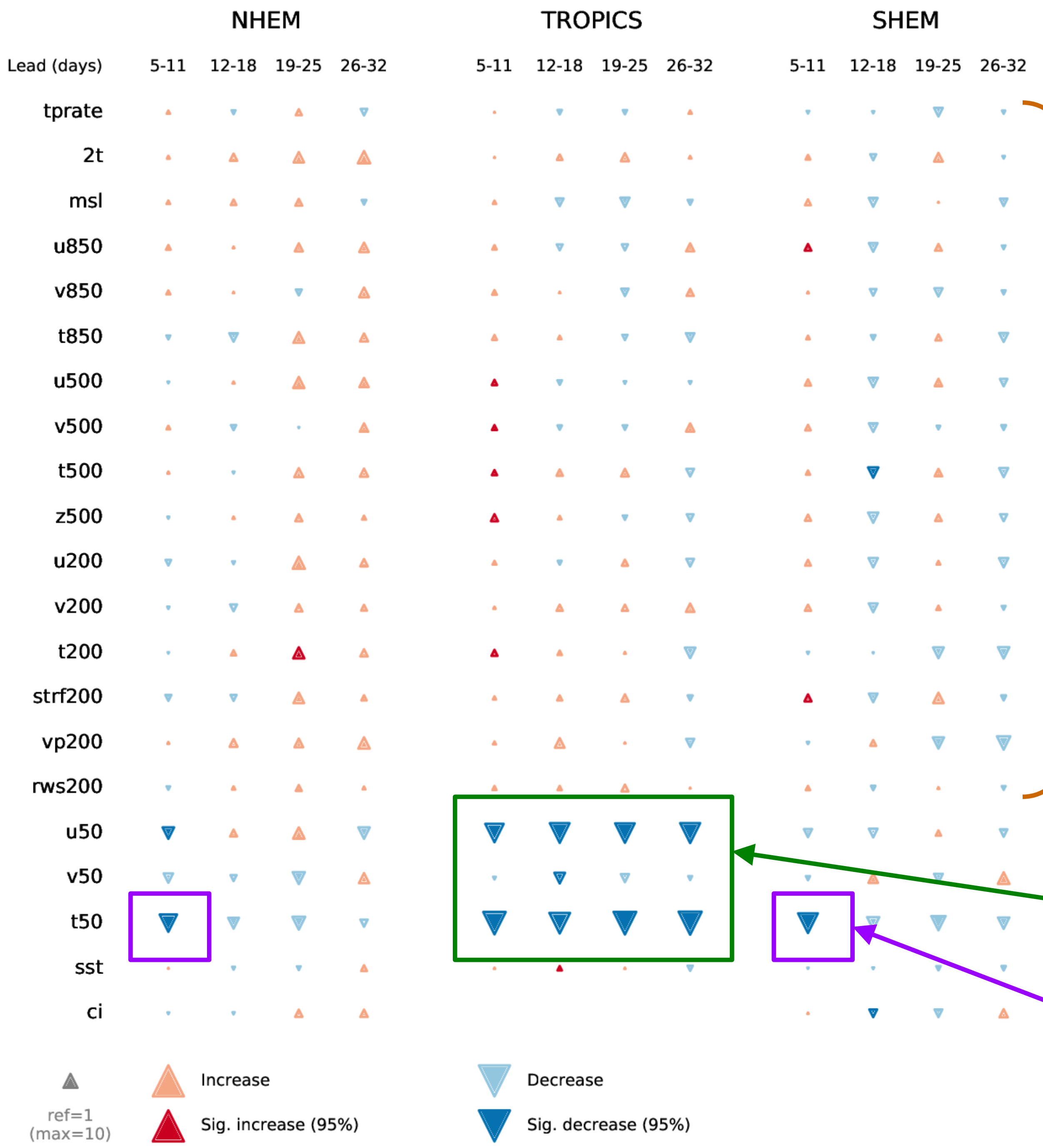
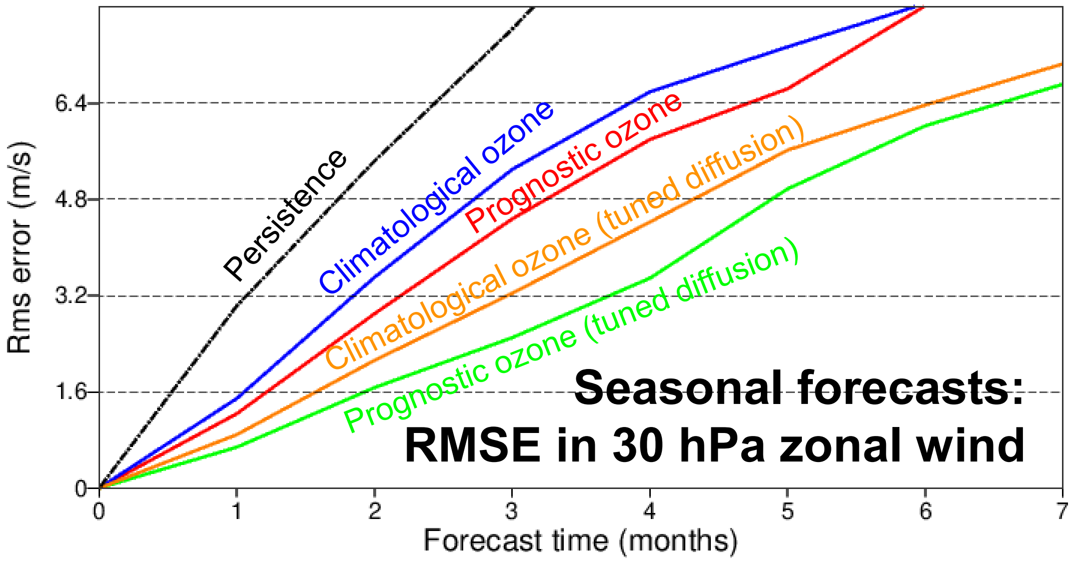


Impact on monthly forecasts

Chris Roberts

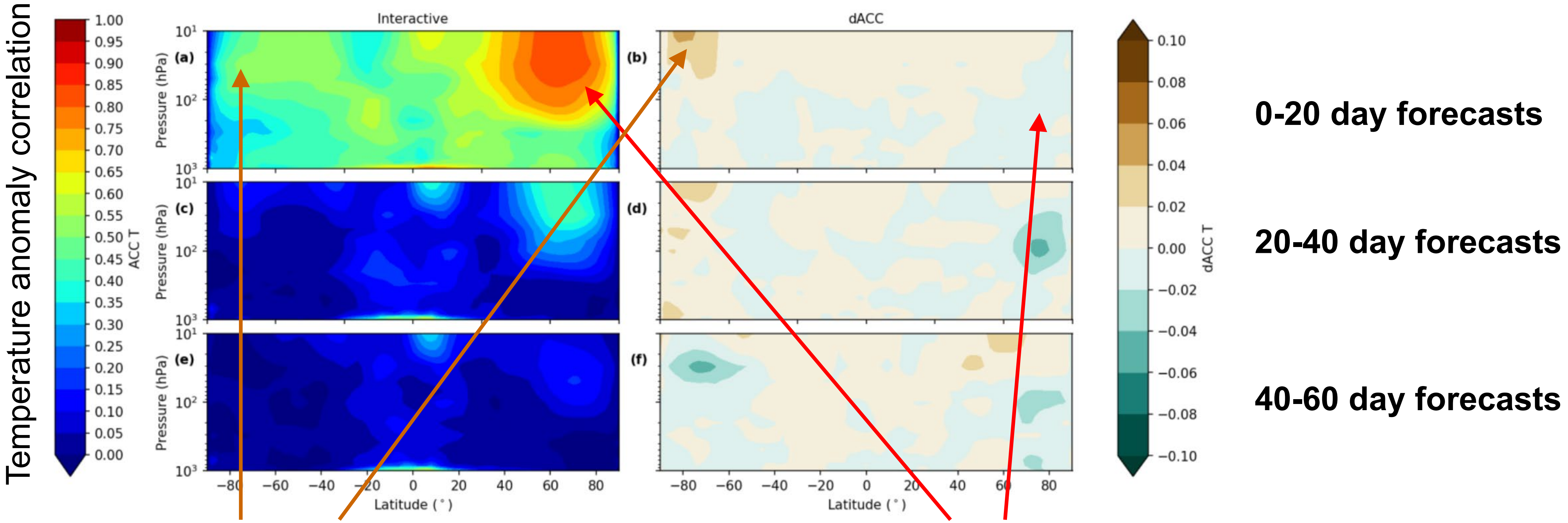
- Tco319 hindcasts 1989-2016
- Score the change in bias-corrected RMS error
- No significant impact on tropospheric scores



- Statistically significant impact on tropical 50 hPa winds & temperatures to 1 month: *QBO*
- Significant impact on extra-tropical 50 hPa temperatures up to 11 days ahead

In what situations does ozone improve mid-latitude temperature and winds?

- Ryan Williams (visiting scientist Nov 2020 to May 2021) studied sub-seasonal forecast skill following six strong Jan/Feb Sudden Stratospheric Warmings (SSWs), when ozone is strongly perturbed (51-member ensembles)



- **Southern hemisphere:** modest measurable improvement (up to 0.05); note stronger shortwave heating in this season
- **Northern hemisphere:** SSWs already lead to a massive increase in stratospheric forecast skill, so limited scope for prognostic ozone to improve forecasts further

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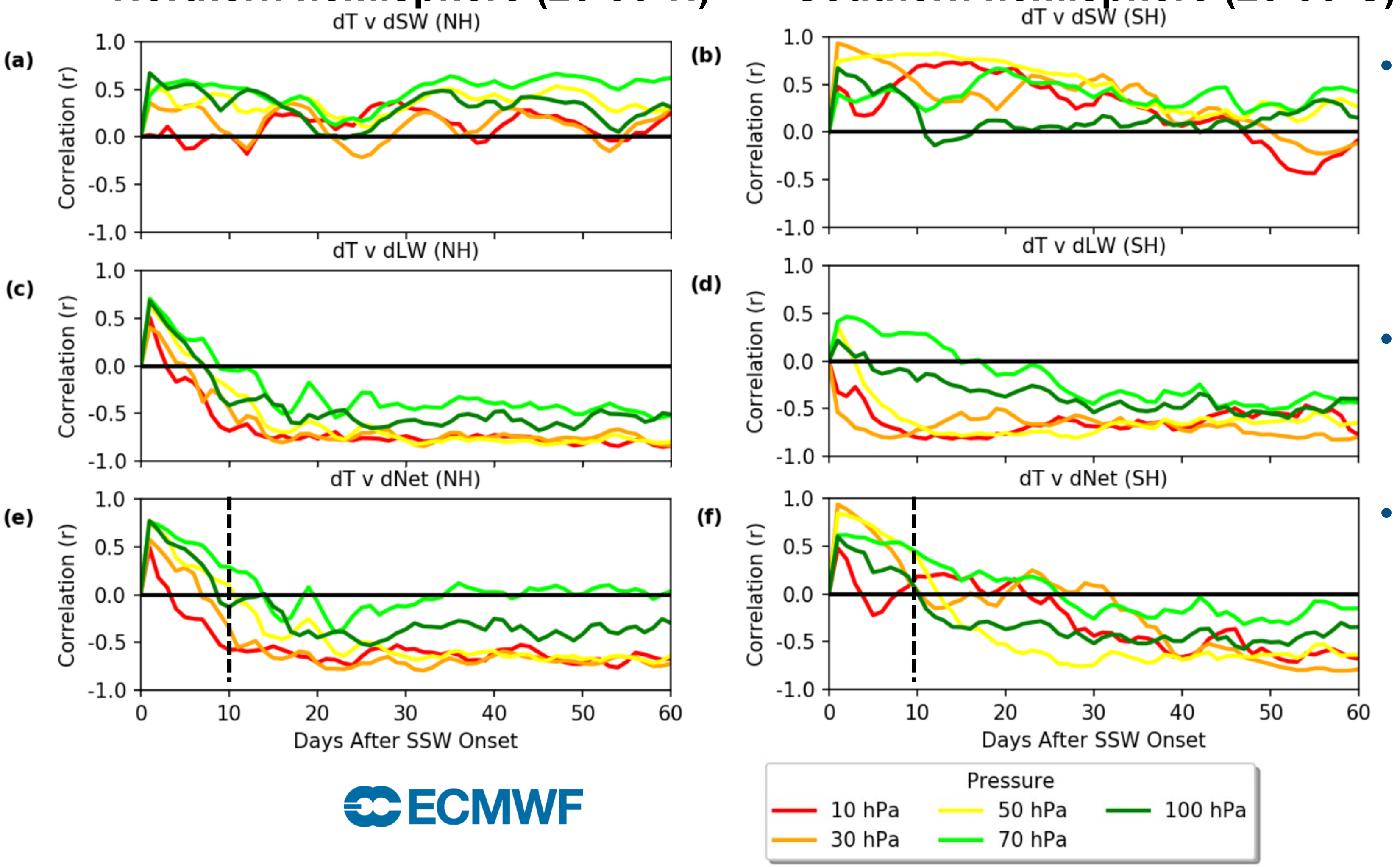
Timescales of radiative heating impact

Williams et al. (2021, ECMWF Tech Memo 887)

- Predictive timescale of mid-latitude stratospheric ozone and temperature is ~2 weeks to ~2 months
- Why is the impact timescale of prognostic ozone ~10 days in mid-latitudes (but > 1 month in tropics)?

Northern hemisphere (20-90°N) **Southern hemisphere (20-90°S)**



- Temperature difference between interactive-ozone and control is correlated with difference in **shortwave heating** rate (primarily due to ozone heating)
- **Longwave heating** is (generally) anti-correlated with temperature difference: warm anomalies cool faster
- *Net heating is shortwave-dominated until ~10 days when ozone forces temperature difference, then longwave-dominated as temperature differences are damped and non-linear effects become important*

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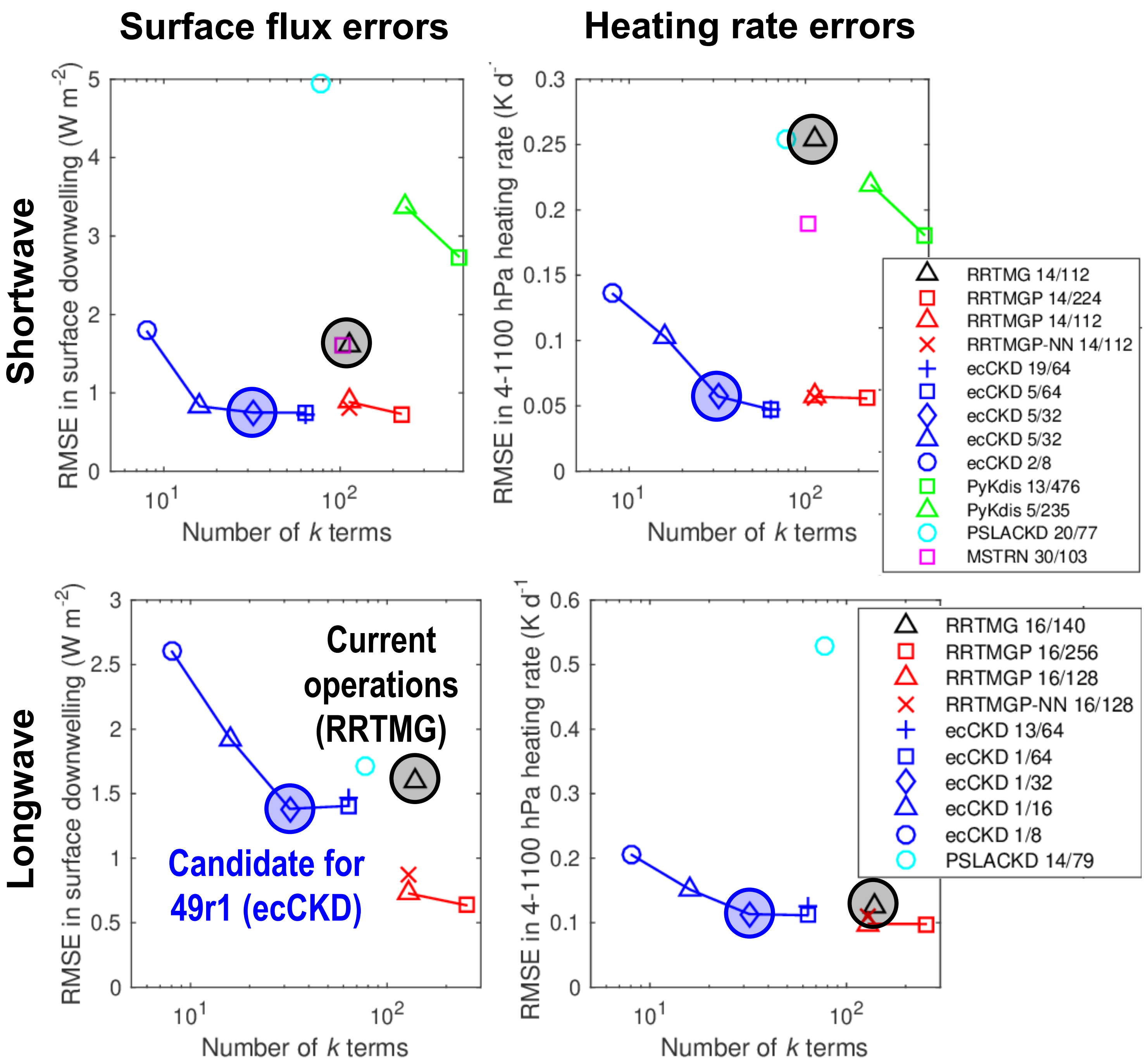
ecCKD gas optics scheme (for 49r1, 2024)

- Can generate a gas-optics scheme trained against the latest spectroscopy from a user-specified error tolerance: lower error means more accuracy but more spectral intervals (Hogan & Matricardi, JAMES 2022)
- My "CKDMIP" intercomparison project is evaluating numerous gas optics scheme worldwide against "line-by-line" calculations, including operational **252-term RRTMG**
- **ecCKD models with total of 64 points** (32 in each of shortwave and longwave) is good compromise between accuracy & speed
- Overall radiation cost is halved, while some middle-atmosphere temperature biases are reduced



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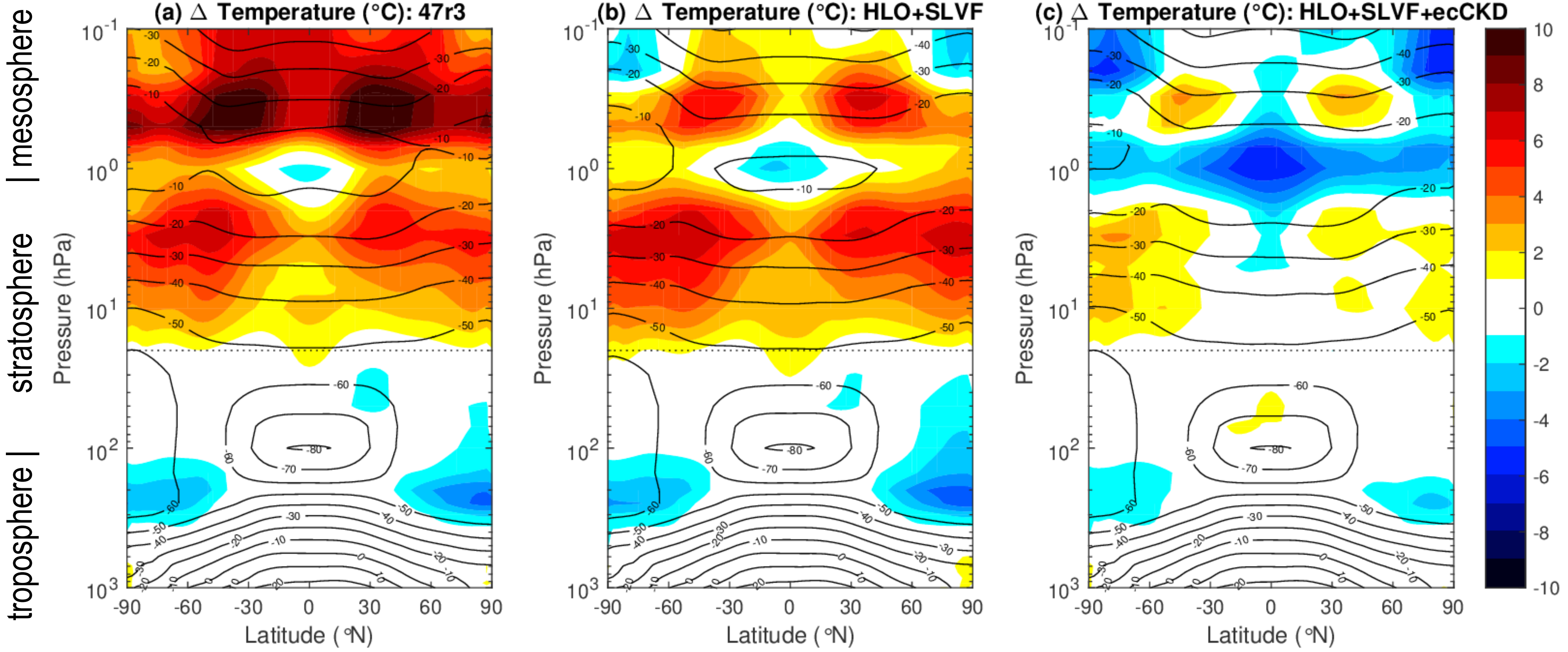
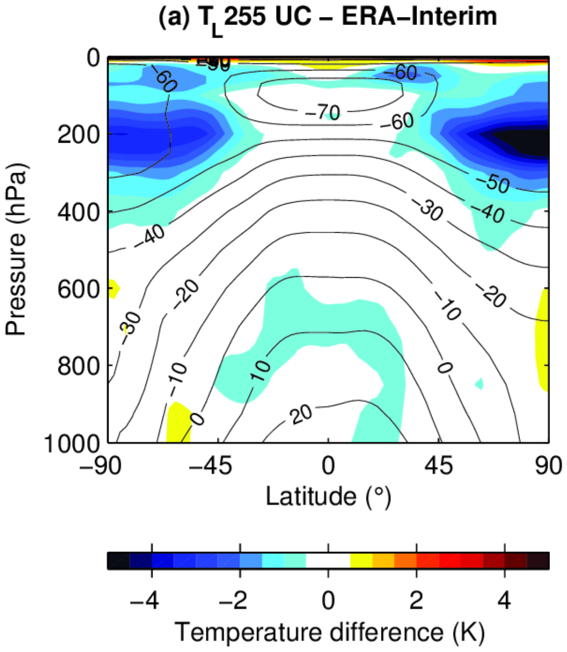
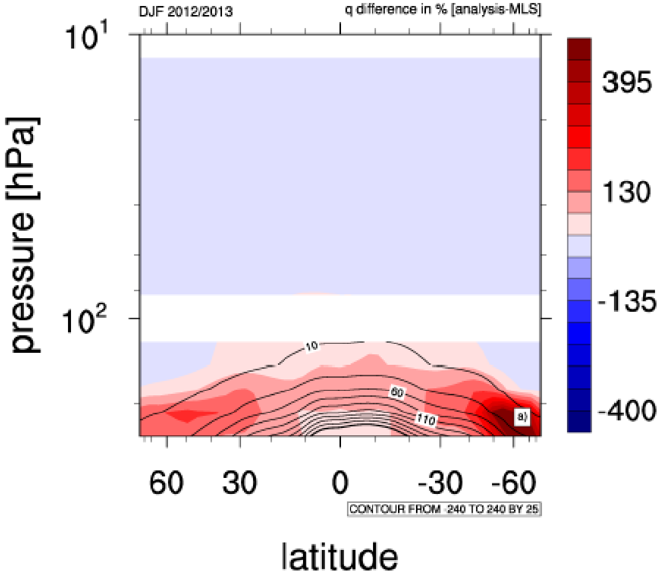
Temperature biases in free-running IFS in recent and future cycles

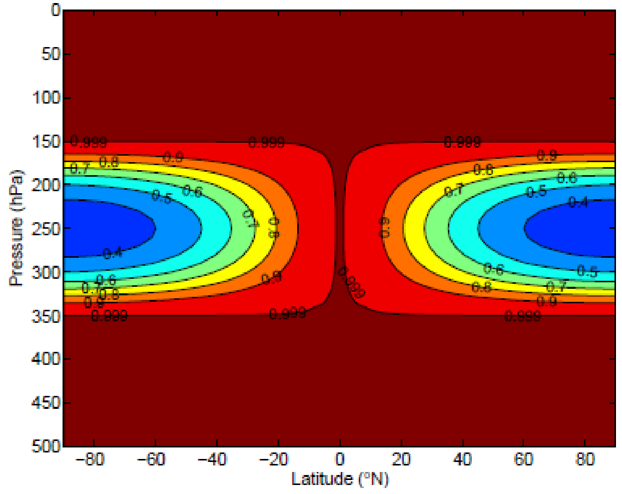
- **47r3** (current) has longstanding biases: middle atmosphere too warm and polar lower stratosphere too cold
- **48r1** (2023): HLO trained on latest CAMS ozone improves mesosphere; other bias changes mitigated with SLVF vertical filtering scheme
- **49r1** (2024): ecCKD uses improved solar spectrum with less UV, removing middle-atmosphere warm bias; better spectroscopy reduces polar lower stratosphere cold bias

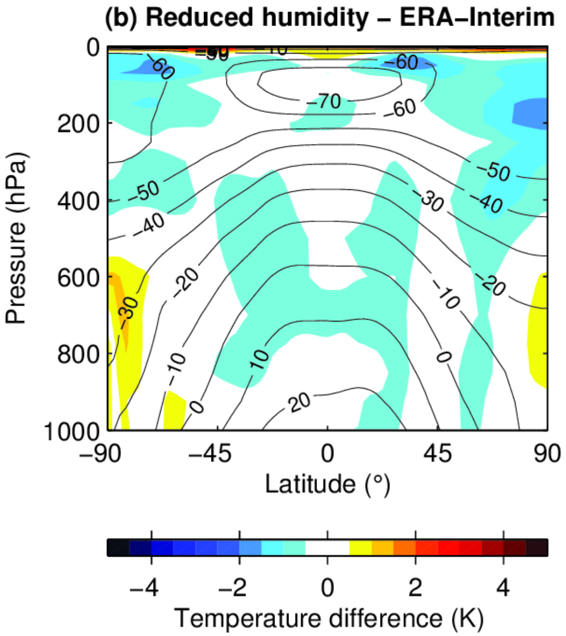


Other cause of the polar lower stratosphere cold bias: much too moist!









- Up to 5 K too cold
- Problem in IFS for at least 25 years
- Common to most/all global models

- Water vapour bias compared to MLS (%)
- Erroneous transport of water vapour from troposphere, emits too strongly in longwave

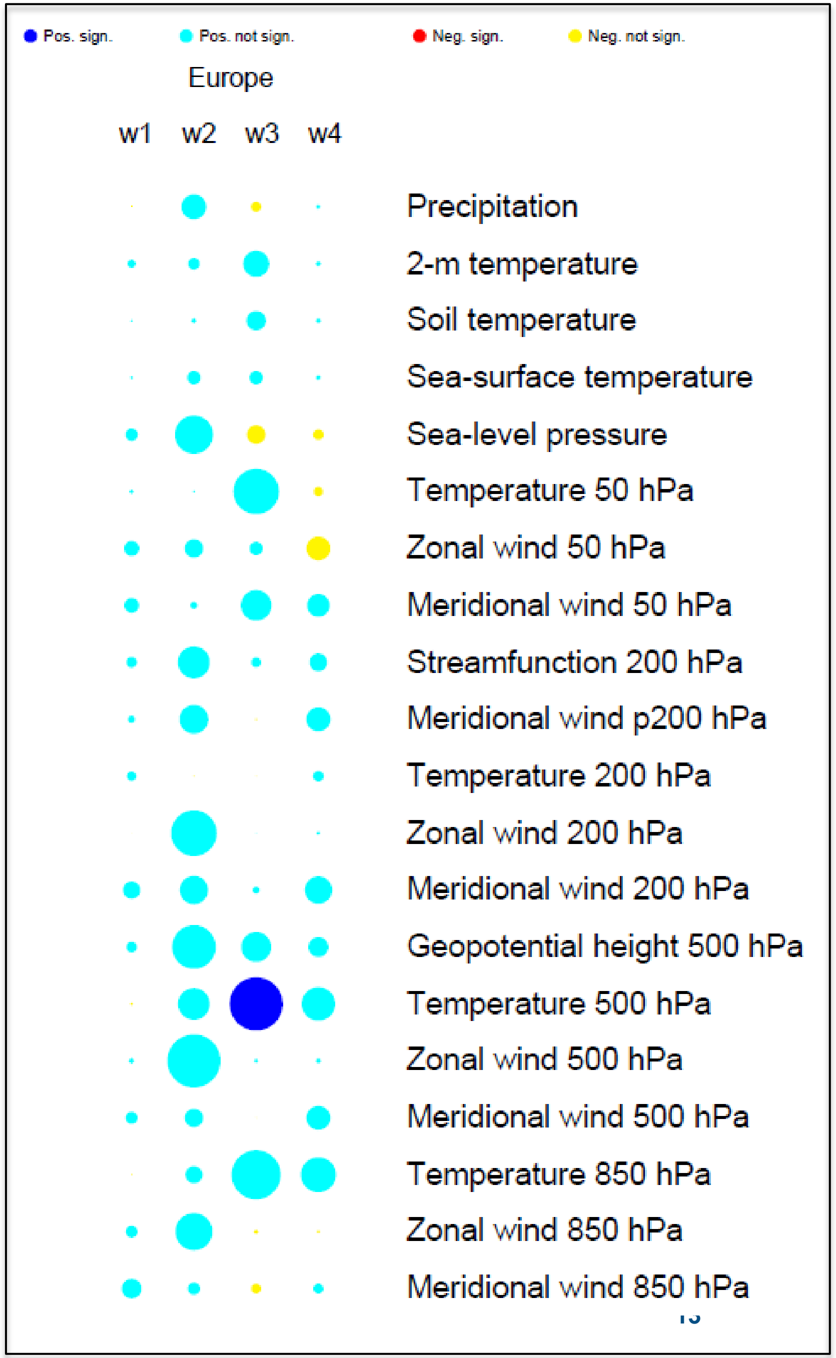
- What if we artificially reduce humidity seen by radiation?
- *Just for experimental purposes, not operations!*

- Cold bias removed!

Impact of removing polar cold bias

Frederic Vitart

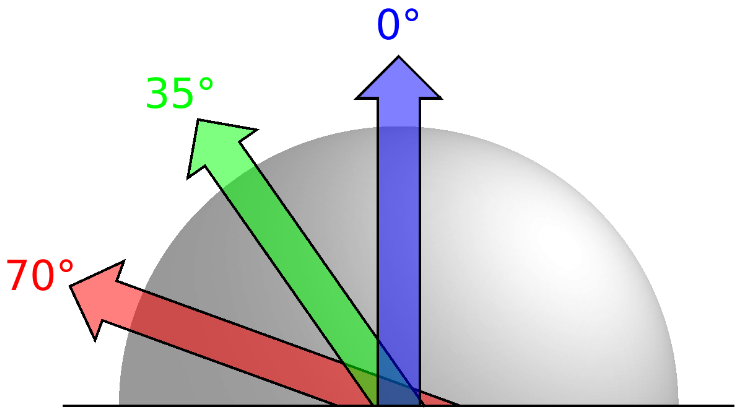
- Monthly forecast experiment artificially reducing humidity seen by radiation leads to *improvement in troposphere monthly forecast skill* (good example of radiation interacting with other processes)
- What's the dynamical mechanism? Does the cold bias act as a barrier impeding the influence of the stratosphere on the troposphere?
- *Hope to gain some of this effect from ecCKD gas optics, while improved water vapour transport is tackled by others*

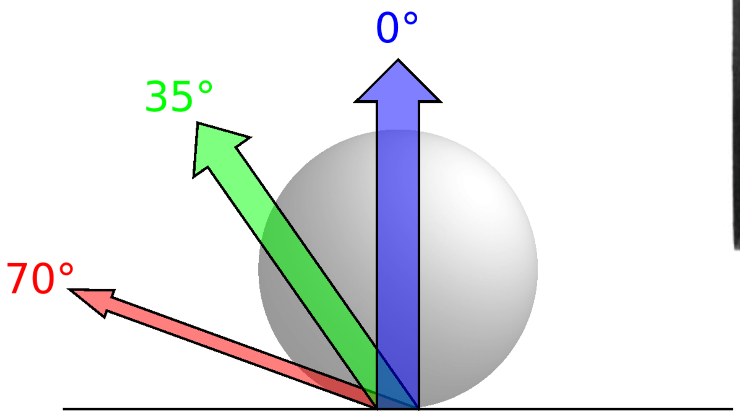


Blue is an improvement!

Beyond two streams for the propagation of diffuse radiation

- Invented by Schuster (1905) – surely we can afford to do better 116 years layer?
- How should the discrete zenith angles be chosen for most accuracy?
- Consider isotropic emission or scattering from a flat surface:





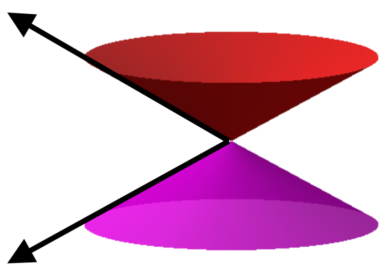
- If radiance field is isotropic, suggests radiation evenly distributed in $\mu = \cos\theta$ space
- Sykes (1951) therefore suggested we should discretize μ in each hemisphere using Gauss-Legendre quadrature
- One angle per hemisphere has μ_1=1/2 so θ_1=60°

- But Lambert's Cosine Law says that energy from an isotropically emitting horizontal surface is proportional to μ
- Therefore we expect the most representative angle to be skewed to larger μ, or smaller θ

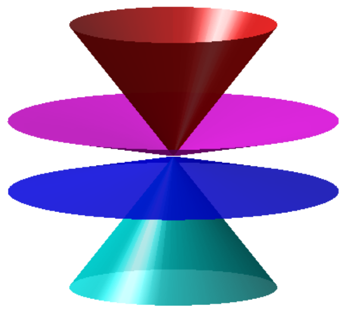
What discrete angles best approximate the transmittance of a layer?

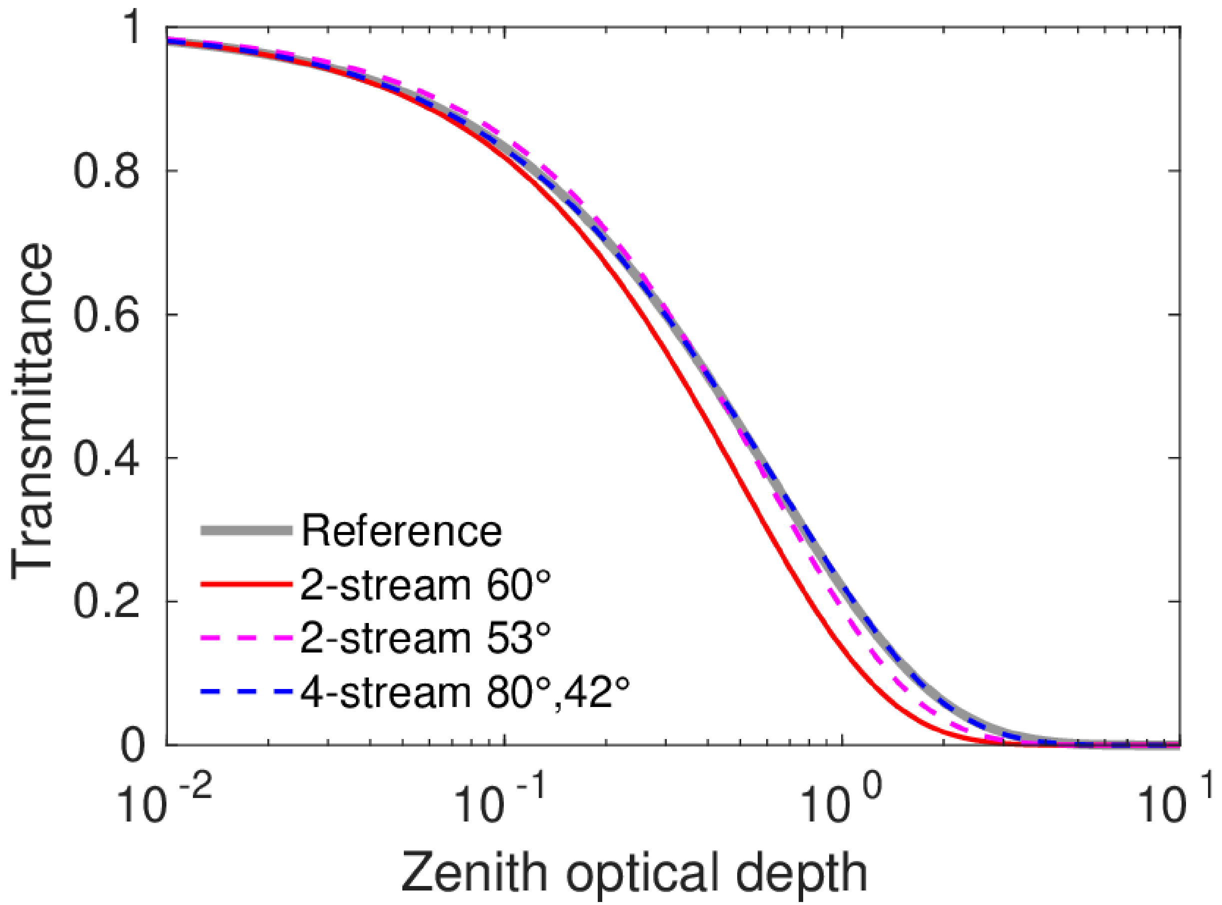
- **Reference transmittance** $T = 2\int_0^1 \exp(-\tau/\mu)\,\mu\,d\mu$
- Two stream approximation: $T \approx \exp(-\tau/\mu_1)$
- "Hemispheric mean" value of 60° significantly underestimates transmittance
- Elsasser (1942) suggested 53° is a better fit to the curve, and this is used in most longwave schemes worldwide, but still overestimates transmittance of low optical depth layers, and underestimates transmittance for high optical depth
- *4 streams better but with what angles & weights?*

2 streams



4 streams





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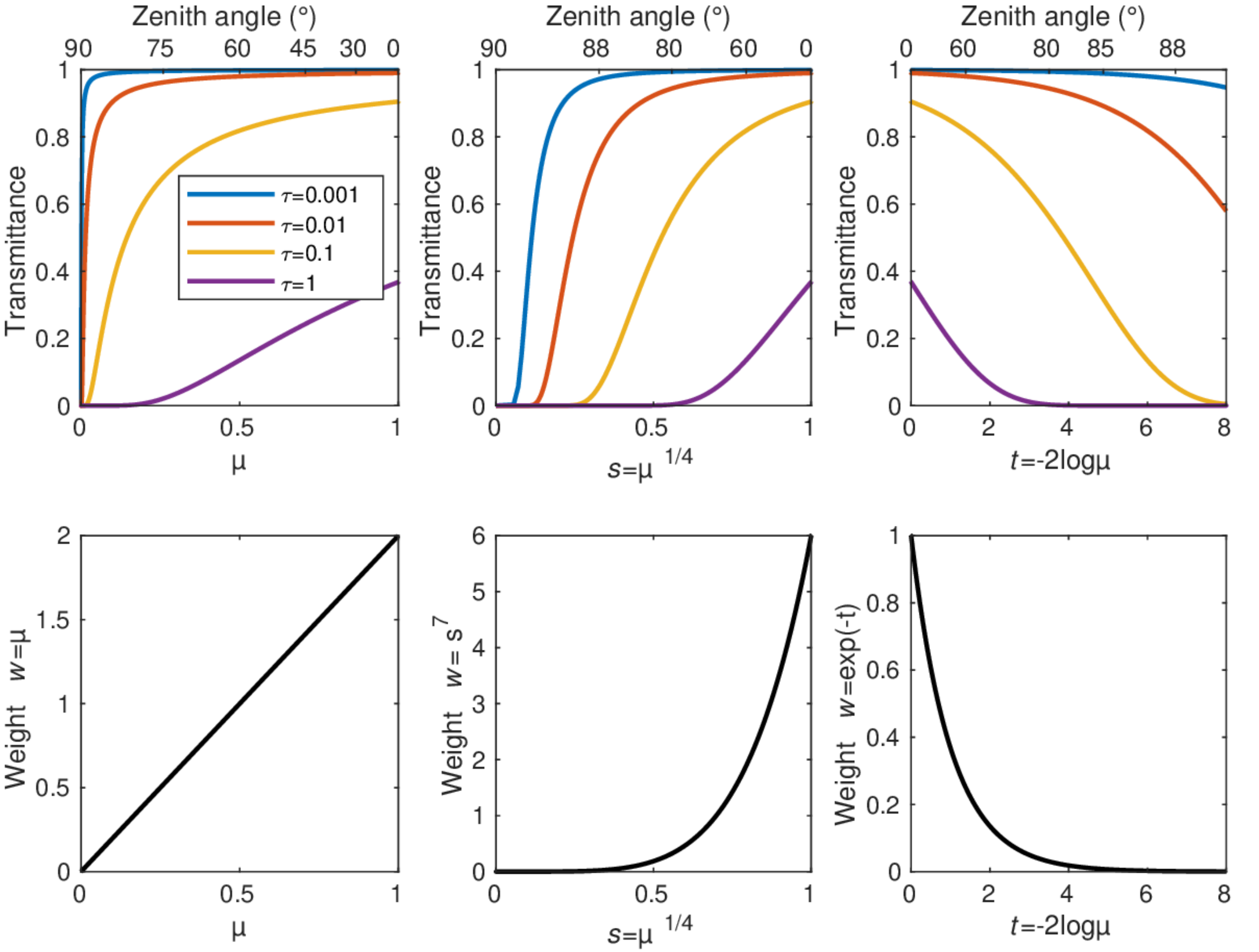
What is the best Gaussian quadrature scheme for choosing angles?

- We want to approximate a weighted integral $\int_a^b W(x)f(x)dx$ by $\sum_{i=1}^{N} w_i f(x_i)$
- Gaussian quadrature provides the optimal nodes x_i & weights w_i, and is *exact* if $f(x)$ is a polynomial of degree $\leq 2N-1$
- Sykes used **Gauss-Legendre** quadrature, but:
  - ➢ This incorrectly assumes $W = 1$
  - ➢ Transmittance function not well fitted by a polynomial near the horizon ($\mu = 0$)
- Alternative: change of variables to make transmittance function smoother (see also Li 2000), e.g.:
  - ➢ Use $s = \mu^{1/4}$ resulting in weight $W = s^7$: use **Gauss-Jacobi** quadrature
  - ➢ Use $t = -2\log\mu$ resulting in $W = \exp(-t)$: use **Gauss-Laguerre** quadrature
- Both suggest θ_1~53° for 2 streams (N=1)!



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Longwave evaluation with realistic clear-sky profiles

- 50 CKDMIP "evaluation" profiles
- No clouds so no scattering: computationally straightforward
- 2-stream θ_1=60°: large errors in fluxes and heating rates
- 2-stream θ_1=53°: improved fluxes but heating rates still biased – CO_2 cooling in upper stratosphere and mesosphere is too weak
- For 4 streams: "optimized" Gauss-Laguerre much more accurate than Gauss-Legendre

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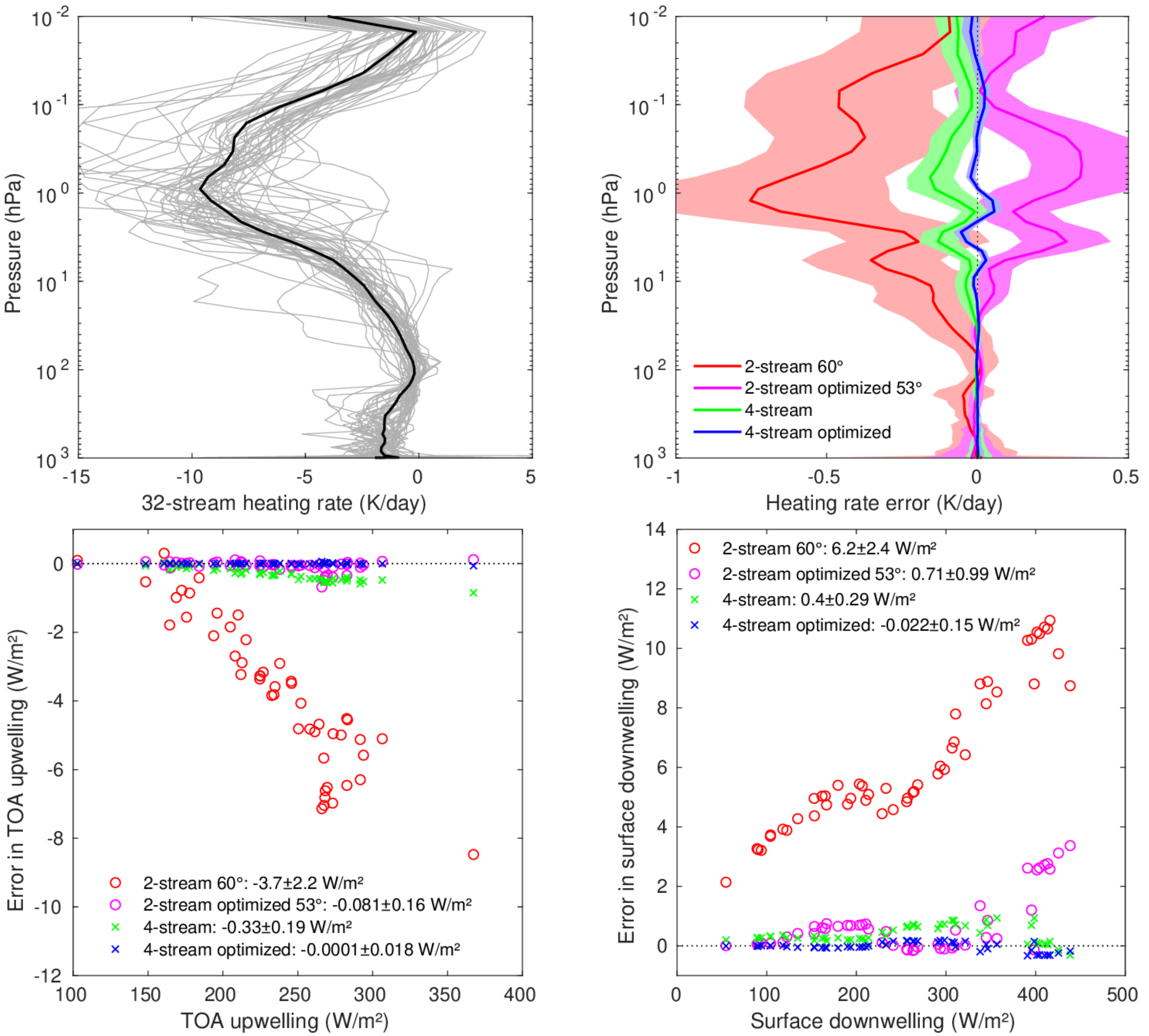
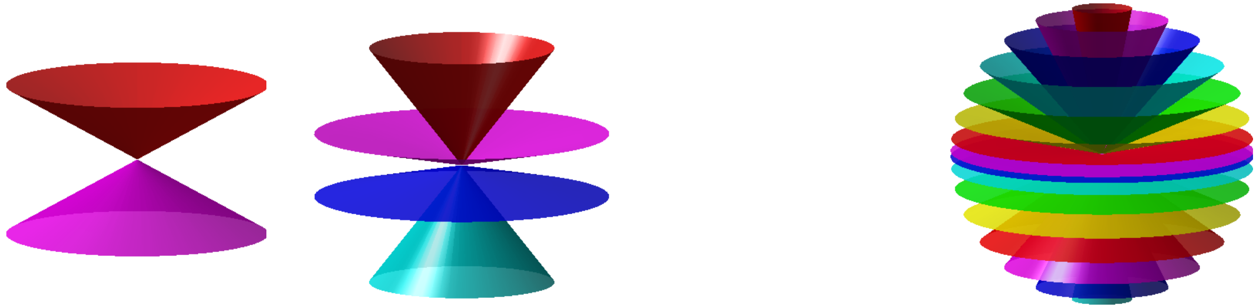
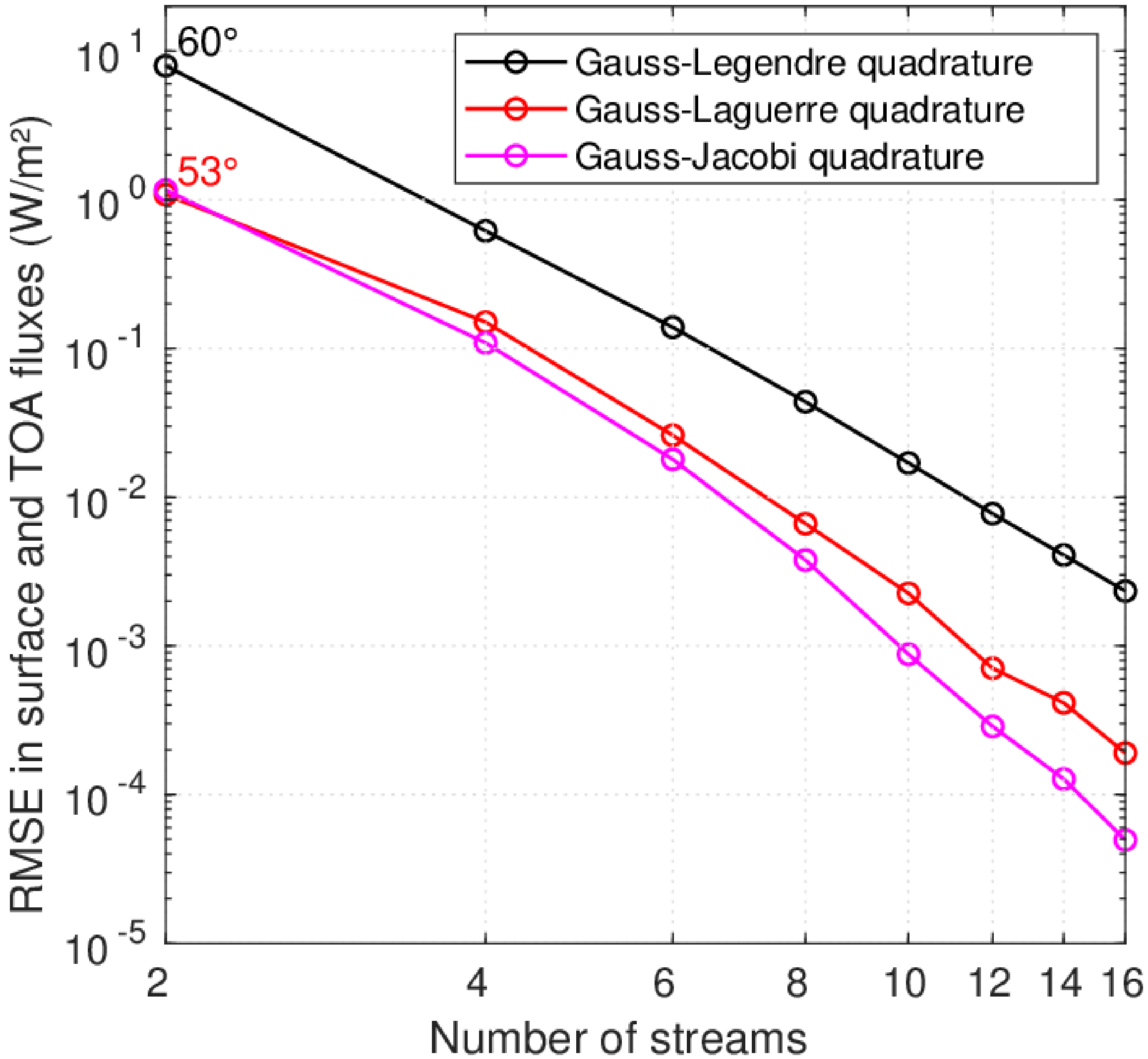


What about more streams?

- Evaluate on same CKDMIP profiles
- Alternative quadrature schemes at least EIGHT times more accurate than Gauss-Legendre for same number of streams!
- Gauss-Jacobi slightly better than Gauss-Laguerre
- Fourth-order convergence, so no need for more than 4 streams in an NWP context
- LESSON: always re-examine very old assumptions!





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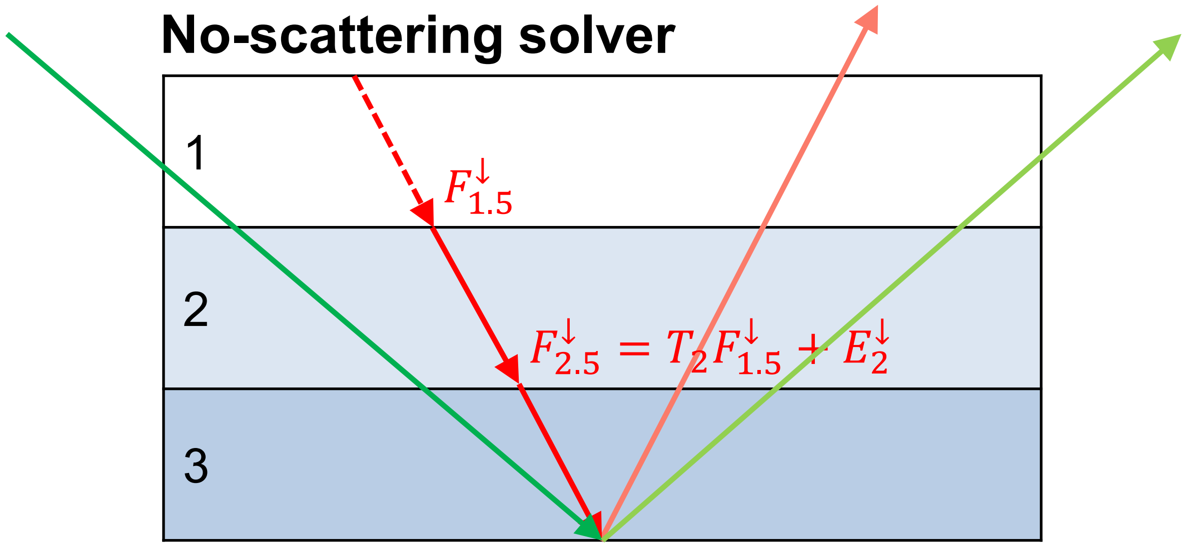
Modelling multi-stream, multi-layer longwave radiative transfer

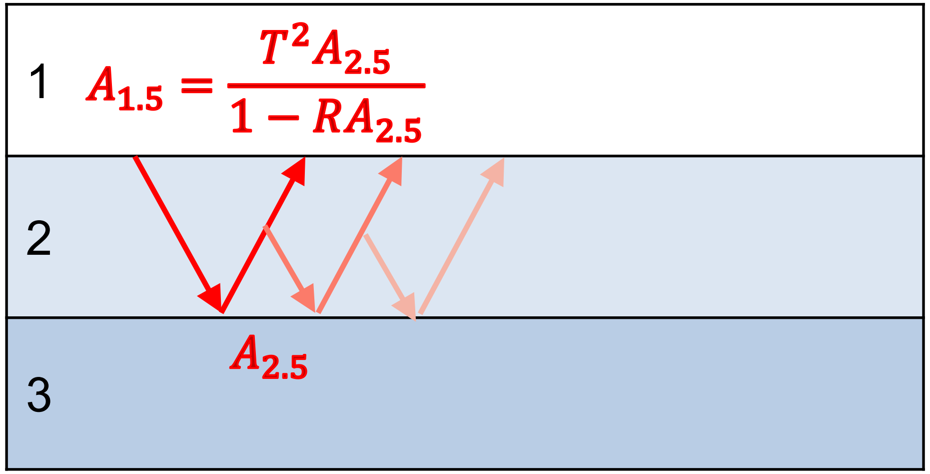
No-scattering solver



Surface reflection and emission

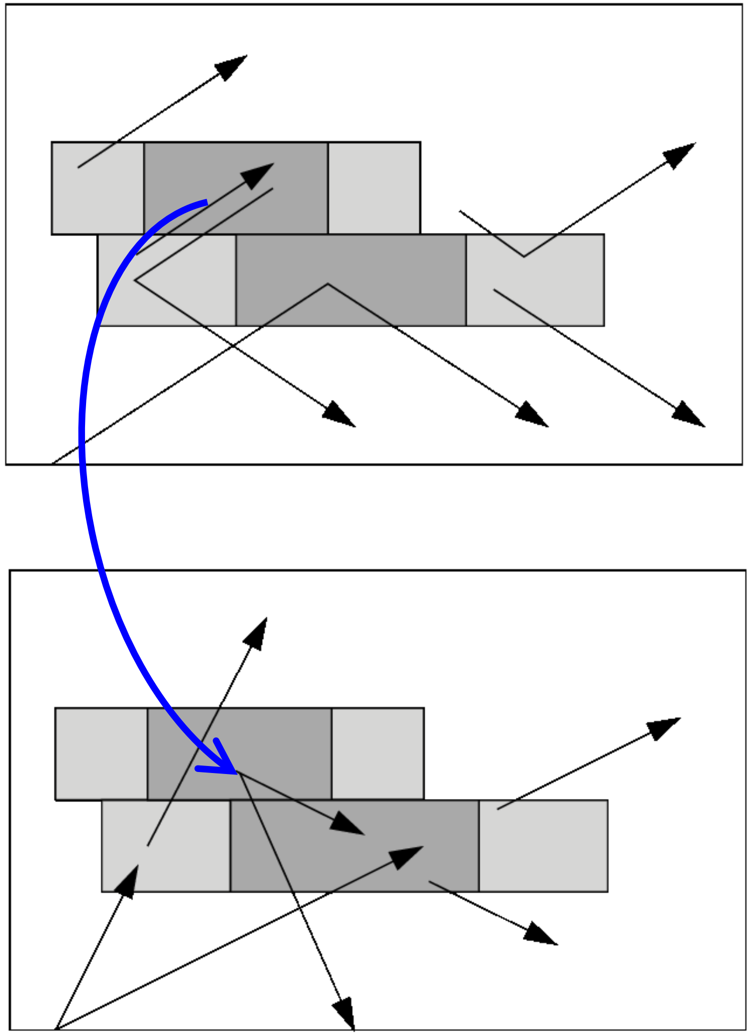
- Work down then up through atmosphere using transmission *T* and emission *E* in each layer (used for calculations on previous slide)
- Cost increases linearly with number of streams: O(*N*)

Scattering solver



- Work up through layers computing albedo of entire atmosphere below, then down to compute fluxes
- ecRad uses this method and incorporates cloudy regions in some layers ("Tripeclouds" solver)
- With 2*N* streams, replace each scalar by an *N*×*N* matrix, but matrix multiplication goes as O(N^3) so 4 streams is ~8x more expensive than 2 streams!

How can we make this more affordable?



- Perform a standard two-stream "Tripleclouds" solve, with scattering, to obtain a first estimate of the distribution of fluxes using the two-stream approximation

- Then use the 2+4 idea of Fu et al. (1997): cast four rays through the domain, including attenuation and emission along the way as in the no-scattering case, but use the Tripleclouds fluxes to add the contribution of scattering into the beam
- Sum the 2 upward and 2 downward beams to get a better estimate of the flux profiles

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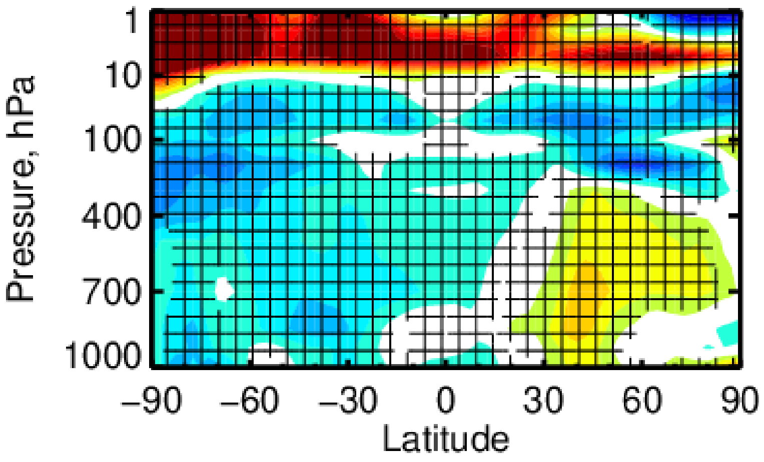
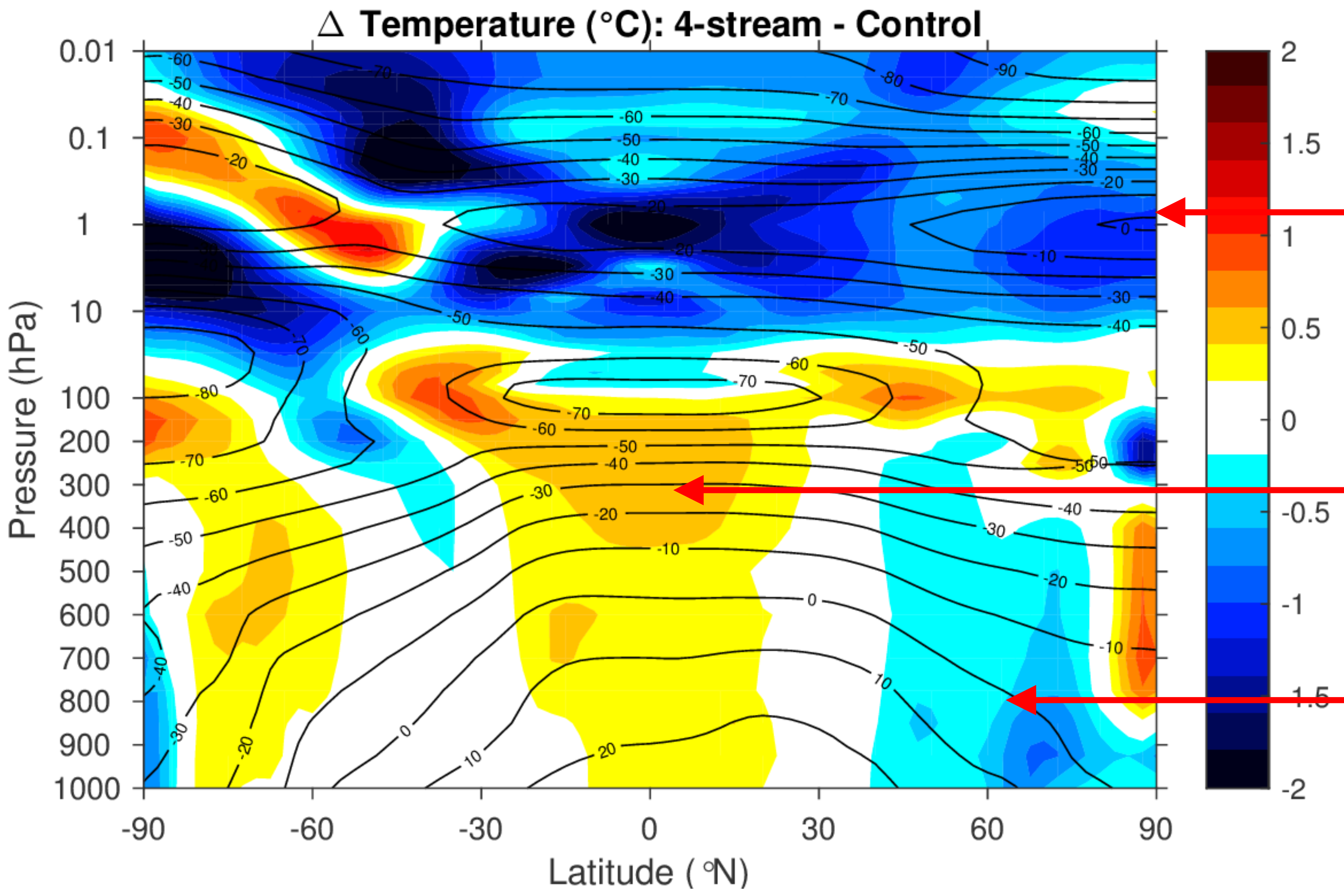
Impact on model climate (preliminary!)

- Ensemble of 4x 1-year free-running 60-km resolution simulations
- JJA average shown here, control is 2-stream with 53°

JJA 7-day forecast bias (±2K)





- Cooling of upper stratosphere and mesosphere by up to 2 K (consistent with offline results)
- Warming of upper tropical troposphere by around 0.5 K
- Cooling of the summer northern hemisphere troposphere, *countering a long-standing bias!*

Summary

- Much scope for improving radiation performance via improved inputs and boundary conditions
  - Prognostic ozone improves stratospheric predictive skill but what are the mechanisms and how can we extend the timescale of impact?
  - How can we improve stratosphere-troposphere coupling, e.g. by improving mean temperature structure?
  - Aerosols, clouds, land-surface albedo and urban areas are also being actively investigated at ECMWF
- Faster gas optics schemes (e.g. ecCKD and ACRANEB) offer the possibility to invest more computational resource into more accurate solvers, e.g. more than two streams
  - Sykes (1951) method still widely used to select discrete angles, but we can do much better!
  - Four-stream longwave solver (using Fu's 2+4 stream approach coupled to Tripleclouds) changes temperature bias structure in interesting ways, and also increases radiative coupling between nearby layers
  - Two-stream method potentially incurs larger errors in shortwave calculations of cloud reflectance when the sun is low in the sky – can we explicitly model the wide-angle forward scattering lobe in the scattering phase function of clouds, without the expense of a full four-stream solver?
  - Or consider representing 3D effects? Could also increase complexity further, then emulate the behaviour cheaply using a Neural Network (see Mat's talk)