On the use of spectral kernels

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Spectral kernel application

• Kernel (scaling) method
  – Spectral kernels
  – Radiative effect of water vapor

• Implication for radiative forcing in general
  – Curve of growth (spectroscopy) explanation vs. Radiative transfer explanation

Reference
Zonal mean (equa. to pole) spectral kernels

Water vapor clear-sky

ker_up_clear_h2o, lat band 1

lat band 2

lat band 3

lat band 4

lat band 5

lat band 6

lat band 7

lat band 8

lat band 9

W m\(^{-2}\) / cm\(^{-1}\) / ΔX
Zonal mean (equa. to pole) spectral kernels

Water vapor all-sky

ker_up_h2o, lat band 1

lat band 2

lat band 3

lat band 4

lat band 5

lat band 6

lat band 7

lat band 8

lat band 9
Model-simulated vs. Kernel-analyzed dOLR

- Example: Interannual variation
- kernel method
\[ \Delta R_x = \left( \frac{dR}{dX} \right) \Delta X \]

Truth Simul.
Bias \( K_{\text{LINEAR}} \)
Bias \( K_{\text{LOG}} \)
Bias Hybrid

W m\(^{-2}\)

[Bani Shahabadi and Huang, 2014, J.G.R.-Atmos.]
Model-simulated vs. Kernel-analyzed spectral dOLR

- Interannual tropical mean change
- Kernel method
  \[ \Delta R_x = \left( \frac{dR}{dX} \right) \Delta X \]

Concerning H2O:

- Linear scaling: \[ \Delta X = \Delta (q) \]
- Log-scaling: \[ \Delta X = \Delta (\log(q)) \]

[Bani Shahabadi and Huang, 2014, J.G.R.-Atmos.]
Log behaviour, i.e., reduced sensitivity, can be understood as inter-layer and intra-layer effects.

\[ \Delta R = \sum_i \frac{\partial R}{\partial q^i} \Delta q^i + \frac{1}{2} \sum_i \frac{\partial^2 R}{\partial q^i \partial q^i} (\Delta q^i)^2 + \sum_{i \neq j} \frac{\partial^2 R}{\partial q^i \partial q^j} \Delta q^i \Delta q^j \]

[1\textsuperscript{st} vs. 2\textsuperscript{nd}-order kernel]

[Bani Shahabadi and Huang, 2014, J.G.R.-Atmos.]
1\textsuperscript{st} vs. 2\textsuperscript{nd}-order kernel

- Case: uniform 2xH2O
- Inter-layer > intra-layer for H2O band
- Inter-layer offsets intra-layer

\[
\Delta R = \sum_i \frac{\partial R}{\partial q^i} \Delta q^i
\]

\[
+ \frac{1}{2} \sum_i \frac{\partial^2 R}{\partial q^i \partial q^i} (\Delta q^i)^2
\]

\[
+ \sum_{i \neq j} \frac{\partial^2 R}{\partial q^i \partial q^j} \Delta q^i \Delta q^j
\]
Hybrid scaling

Best performance can be obtained through:

- Absorption band: log-scaling
- Window: linear-scaling

[Shahabadi and Huang, 2014, J.G.R.-Atmos.]
Logarithmic relationship holds even for monochromatic radiance!

Monochromatic!

Truth:
\[ \Delta R(8x) = R(8x) - R(1x) \]
Calculated using LBL RT model

Log scaling:
\[ \Delta R(8x) = \Delta R(1.1x) * \log(8)/\log(1.1) \]
Linear scaling:
\[ \Delta R(8x) = \Delta R(1.1x) * (8-1)/0.1 \]
Logarithmic relationship

Radiative forcing [W m^{-2}] calculated using R.T. model by perturbing atmospheric CO_{2} concentration (q).

- Log relationship can be verified with any RT model
- Log estimation formula widely adopted
  - $F = F_0 \log(q/q_0)$
  [IPCC AR1,2,3,...; Wikipedia, ...]
Cause of logarithmic relationship
Answer 1: it is due to spectroscopy

Saturation of an absorption line

Radiative forcing $\propto$ increased absorption $\propto$ saturation from line center to wing: “curve of growth” theorem [Goody&Yung 1989]; from band center to wing [Pierrehumbert 2010]

The log relationship applies to spectrally integrated (broadband) radiation flux.

Realclimate.org
Counterevidence: Logarithmic relationship holds even for monochromatic radiance!

CO₂ case.

Truth:
ΔR(8x) = R(8x) – R(1x)
Calculated using LBL RT model

Log scaling:
ΔR(8x) = ΔR(1.1x) * log(8)/log(1.1)

Linear scaling:
ΔR(8x) = ΔR(1.1x) * (8-1)/0.1
Example: Radiance at 300 cm$^{-1}$

W calculated using LBLRTM and a standard profile

Cause of logarithmic relationship

Answer 2: it is due to radiative transfer

- Emission layer displacement model

Solution to non-scattering
R.T. Eq. can be generalized as:

\[ R = \sum \{ W_i * B_i \} \]

- \( W_i \): weighting function for layer \( i \), a function of optical depth \( \tau \) measured from TOA to layer \( i \).

- \( B_i \): Planck function of layer temperature \( T_i \).
Solution to non-scattering
R.T. Eq. can be generalized as:
\[ R = \Sigma \{ W_i * B_i \} \]

Perturbation of absorber amount \((\alpha x q)\) equivalently displaces all the contributing layers to higher altitudes.

As \( W = W(\tau) \) and \( \tau \propto q \), each emission layer is displaced from \( \tau \) to \( \tau' = \tau/\alpha \).

Given \( T = T_0 - z*\Gamma \), it can be shown \( B \propto \log(\tau) \), and thus \( B(\tau') - B(\tau) \propto \log(\alpha) \)

[Huang and Bani Shahabadi, J. Atmos. Sci., under review]
Summary

• Spectral kernels are developed and ready for climate diagnoses
  – Log- and linear-scaling suit different spectral regions
  – Wise to apply hybrid scaling

• Why logarithmic in the absorption band?
  Log-dependence:
  – Holds for monochromatic radiance (not only broadband flux)
  – Results from radiative transfer (not only spectroscopy)
    “Emission layer displacement model”
  Key conditions:
    saturated absorption;
    lapse rate;
    coherent dX -> fingerprint configuration