Towards the fingerprinting of radiative forcing: Inhomogeneity of homogeneous greenhouse gas forcing

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Atmospheric Composition: Spectral Climate Signal
Radiative Forcing of Climate Using A-Train Data and Infrared Spectral Fingerprinting
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### Radiative Forcing by Emissions and Drivers

<table>
<thead>
<tr>
<th>Emitted Compound</th>
<th>Resulting Atmospheric Drivers</th>
<th>Radiative Forcing by Emissions and Drivers</th>
<th>Level of Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>CO₂</td>
<td>1.68 [1.33 to 2.03]</td>
<td>VH</td>
</tr>
<tr>
<td>CH₄</td>
<td>CO₂, H₂O, O₃, CH₄</td>
<td>0.97 [0.74 to 1.20]</td>
<td>H</td>
</tr>
<tr>
<td>Halo-carbons</td>
<td>O₃, CFCs, HCFCs</td>
<td>0.18 [0.01 to 0.35]</td>
<td>H</td>
</tr>
<tr>
<td>N₂O</td>
<td>N₂O</td>
<td>0.17 [0.13 to 0.21]</td>
<td>VH</td>
</tr>
<tr>
<td>CO</td>
<td>CO₂, CH₄, O₃</td>
<td>0.23 [0.16 to 0.30]</td>
<td>M</td>
</tr>
<tr>
<td>NMVOC</td>
<td>CO₂, CH₄, O₃</td>
<td>0.10 [0.05 to 0.15]</td>
<td>M</td>
</tr>
<tr>
<td>NOₓ</td>
<td>Nitrate, CH₄, O₃</td>
<td>-0.15 [-0.34 to 0.03]</td>
<td>M</td>
</tr>
<tr>
<td>Aerosols and precursors</td>
<td>Mineral dust, Sulphate, Nitrate, Organic carbon, Black carbon</td>
<td>-0.27 [-0.77 to 0.23]</td>
<td>H</td>
</tr>
<tr>
<td>Cloud adjustments due to aerosols</td>
<td></td>
<td>-0.55 [-1.33 to -0.06]</td>
<td>L</td>
</tr>
<tr>
<td>Albedo change due to land use</td>
<td></td>
<td>-0.15 [-0.25 to -0.05]</td>
<td>M</td>
</tr>
<tr>
<td>Natural</td>
<td>Changes in solar irradiance</td>
<td>0.05 [0.00 to 0.10]</td>
<td>M</td>
</tr>
</tbody>
</table>

**Total Anthropogenic RF relative to 1750**

- **2011**: 2.29 [1.13 to 3.33] (H)
- **1980**: 1.25 [0.64 to 1.86] (H)
- **1950**: 0.57 [0.29 to 0.85] (M)

**IPCC 2013**
Joint (IR+RO) fingerprinting performance

<table>
<thead>
<tr>
<th></th>
<th>RMS (IR)</th>
<th>RMS (IR+RO)</th>
<th>G.M.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>0.10</td>
<td>0.11</td>
<td>-2.73</td>
</tr>
<tr>
<td>Tₜrop</td>
<td>3.27</td>
<td>3.88</td>
<td>3.35</td>
</tr>
<tr>
<td>Tₚstrat</td>
<td>2.02</td>
<td>0.98</td>
<td>9.78</td>
</tr>
<tr>
<td>qₜrop</td>
<td>1.32</td>
<td>0.73</td>
<td>-4.99</td>
</tr>
<tr>
<td>qₚstrat</td>
<td>0.10</td>
<td>0.12</td>
<td>-0.27</td>
</tr>
<tr>
<td>Cₗow</td>
<td>3.76</td>
<td>3.66</td>
<td>0.18</td>
</tr>
<tr>
<td>Cₚmid</td>
<td>1.36</td>
<td>1.25</td>
<td>0.07</td>
</tr>
<tr>
<td>Cₚhigh</td>
<td>3.05</td>
<td>1.07</td>
<td>-1.18</td>
</tr>
</tbody>
</table>

Outline

• Homogeneous Greenhouse Gas (HGG) forcing
  – Distribution features
  – Reasons behind inhomogeneity and a regression model
  – Implications for Poleward Energy Transport (PET)

• Distinction of this work
  – Previous works were concerned with global mean value
    e.g. for CO2 forcing: \( F = F_0 \log(C/C_0) \)
    \( \Delta F \leq 10\% \) [Shi et al. 1990 ... Myhre et al. 1998 ... Byrne & Goldblatt 2014 ... IPCC AR1-5]

  – We are concerned with spatial and temporal variation
    “It is not practical to develop simplified expressions for meridionally resolved forcings.” [Byrne & Goldblatt 2014] - Is it?
2xCO$_2$ Forcing (Instantaneous Forcing)

- $F(2xCO_2)$ computed using RRTM and 5 yr 4x daily ERA-interim global atmos profiles (T, q, Cld, O3).
- CO$_2$ 380 -> 760 ppm.
- Multi-year global Mean: 2.3 W m$^{-2}$ (all-sky)
- Range of all monthly mean values: -2.5 – 5.1 W m$^{-2}$

Note there is $>300\%$ variability – in comparison to $\leq10\%$ variability in the global mean value [log formula from IPCC,...]
What causes forcing to vary?

- Consider F as resulting from change in greenhouse effect (trapping of surface emission)
  
  \[ F \propto \text{surface emission} \]
  
  \[ \Rightarrow \text{Predictor: } Ts \text{ (surface temperature)} \]

- Consider F as resulting from lifting of emission level
  
  \[ F \propto \text{atmospheric temperature change in the vertical} \]
  
  \[ \Rightarrow \text{Predictor: } \Gamma = Ts - T_{10hPa} \]

- Cloud and water vapor masking effect
  
  \[ \Rightarrow \text{Predictor: WVP (water vapor path), CRF (cloud radiative forcing =} \]
  
  \[ R_{\text{clear-sky}} - R_{\text{all-sky}}: \text{Zhang}&Huang [2014] \text{ found it is perfect for predicting } F_c - F_a \]
Statistics

- Regression model: \( F = F_0 + A^* (y-y_0)/y_0 \)
  - Solved by minimizing \( \Sigma W_i (F_i - F)^2 \), \( W_i = \cos(\text{latitude}_i) \).
- Best predictor for clear-sky forcing \( F_c : \Gamma \)

<table>
<thead>
<tr>
<th>Predictors: ( y )</th>
<th>Ts</th>
<th>( \Gamma )</th>
<th>Ts, Ta</th>
<th>Ts, Ta, WVP</th>
<th>CRF</th>
<th>( F_c, \text{CRF} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r )</td>
<td>0.91</td>
<td>0.96</td>
<td>0.91, 0.05</td>
<td>0.91, 0.05, 0.65</td>
<td>0.99</td>
<td>0.95, 0.06</td>
</tr>
<tr>
<td>( y_0 )</td>
<td>288.4</td>
<td>60.2</td>
<td>288.4, 228.2</td>
<td>288.4, 228.2, 26.30</td>
<td>18.1</td>
<td>n/a</td>
</tr>
<tr>
<td>( A )</td>
<td>12.94</td>
<td>3.13</td>
<td>15.34, -8.33</td>
<td>18.99, -8.14, -0.42</td>
<td>0.48</td>
<td>n/a</td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.82</td>
<td>0.93</td>
<td>0.96</td>
<td>0.97</td>
<td>0.99</td>
<td>0.95</td>
</tr>
<tr>
<td>( \text{err} )</td>
<td>0.48</td>
<td>0.30</td>
<td>0.23</td>
<td>0.21</td>
<td>0.04</td>
<td>0.22</td>
</tr>
<tr>
<td>( \text{GM}_p )</td>
<td>2.75</td>
<td>2.75</td>
<td>2.75</td>
<td>2.75</td>
<td>0.51</td>
<td>2.24</td>
</tr>
<tr>
<td>( \text{STD}_p )</td>
<td>0.94</td>
<td>0.93</td>
<td>1.00</td>
<td>1.08</td>
<td>0.26</td>
<td>0.96</td>
</tr>
</tbody>
</table>

GM = 2.75, STD = 1.06
Prediction model

• Clear-sky

\[
F_c = 2.75 + 18.99 \frac{T_s - 288.4}{288.4} - 8.14 \frac{T_a - 228.2}{228.2} - 0.42 \frac{WVP - 26.3}{26.3}
\]  

Eq. 1

• Clear-all-sky difference

\[
\Delta F = 0.51 + 0.48 \frac{CRF - 18.1}{18.1}
\]  

Eq. 2

• All-sky

\[
F_a = 2.24 + 18.99 \frac{T_s - 288.4}{288.4} - 8.14 \frac{T_a - 228.2}{228.2} - 0.42 \frac{WVP - 26.3}{26.3} - 0.48 \frac{CRF - 18.1}{18.1}
\]  

Eq. 3

A 1.0 W m\(^{-2}\) change in the doubling CO\(_2\) forcing can result from 15 K change in \(T_s\), or 28 K change in \(T_a\), or 63 kg m\(^{-2}\) change in \(WVP\), or 38 W m\(^{-2}\) change in \(CRF\).
Truth: Simulated by MODTRAN (a diff RT model!) from CM2 atmosphere
Prediction: Regression model (Eq. 3) + CM2 climatology (Ts, Ta, WVP and CRF)
$R^2 = 0.94$; Mean standard error = 0.2 W m$^{-2}$ (<10%)
Double-ITCZ bias disclosed by prediction – Climatology related bias detected!
Other HGG forcing

- 2xCH4 and 2xN2O forcing greatly resembles 2xCO2 forcing.
- Similar reason(s) behind forcing variation
- Same regression model may work?

Regression model (rearranged):
\[
\frac{\hat{F} - F_0}{F_0} = B \frac{y - y_0}{y_0}
\]

Fractional change in \( F_a \) is proportional to the fractional changes in the four predictor variables, with the scaling factor \( B \) being 8.5 for \( T_s \), -3.6 for \( T_a \), -0.19 for \( WVP \), and -0.21 for \( CRF \).

\( R^2 \sim 85\% \), RMS \sim 10\% of global mean.
4xCO2 forcing in CMIP5 models

- Forcing predicted from GCM climatology using regression model
  \[ F = F_0 + A \frac{y-y_0}{y_0} \]

- Implied PET calculated by integrating radiation anomaly from pole to pole [Eq. 4 of Huang & Zhang 2014]
  \[ F(\phi) = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \int_0^{2\pi} R_X(\lambda, \phi) \alpha^2 \cos \phi \, d\lambda \, d\phi \]

- Inter-model difference in forcing distribution => inter-model difference in implied PET (a factor of 2 at mid-latitudes)
• Significant correlation between forcing implied PET change and actual PET change!

• PET forcing: implied by forcing distribution

• PET overall: overall PET change in the models (assessed at the end of the abrupt4xCO2 experiment)

• Correlation shown for 35°N (typical of extratropics)
Conclusions

- This study has
  - Demonstrated strong inhomogeneity in the radiative forcing of HGGs
  - Found the key factors that cause forcing variation (and built a regression model for estimating forcing)
  - Exemplified the important implications of forcing inhomogeneity

- These initial results suggest
  - Forcing distribution pattern have fundamental and profound impacts on the dynamical and circulation responses during global warming
  - Observational determination of HGG forcing needs global coverage – CLARREO!

References
- Huang, Y. and M. Zhang (2014), The implication of radiative forcing and feedback for poleward energy transport, GRL.