Arctic temperature response to changes in emissions of short-lived climate forcers

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AMAP organization and charge

• Report (published in late 2015) motivated to understand Arctic climate impacts and mitigation opportunities associated with emissions of short-lived climate forcers (including aerosols, ozone, methane) from different regions and sectors.

• Report focuses on temperature impacts. Key modeling results from the report are described by Sand et al (2015, Nature Climate Change).

• In no way do these studies undercut the importance of CO₂ as the main anthropogenic driver of Arctic climate change.
Forcing agents considered

- Black carbon (BC)
- Organic carbon (OC)
- Sulfate (via SO$_2$ emission precursor)
- Ozone (via NO$_x$, CO, VOC emission precursors)
Models applied in the assessment

• CESM 1.1.1 (CAM5.2 with MAM7 aerosols)
  – Aerosol direct+snow/ice RF
• CanAM 4.2
  – Aerosol direct+indirect+snow/ice RF
• NorESM (Cam-Oslo aerosol module)
  – Aerosol direct+indirect RF
• Oslo-CTM2
  – $O_3$ direct RF
• SMHI-MATCH
  – Aerosol direct + $O_3$ direct RF
The direct effect

The indirect effect

The 'semi-direct' effect

The snow/ice darkening effect

$\Delta T > 0$

$\Delta T < 0$

$\Delta T > 0$

$\Delta T > 0$

SW

LW

$\frac{d\theta}{dz}$

$\Delta T > 0$
Small perturbations, large variability

http://www.doctordisruption.com/
Estimating temperature response

- Emissions provided by European ECLIPSE project
- Explicit calculations of radiative forcing conducted with each model, using ECLIPSEv4a emissions
- Use of regional temperature sensitivity factors (Shindell and Faluvegi, 2009; Flanner, 2013) enables efficient evaluation of temperature impacts associated with small radiative forcings

<table>
<thead>
<tr>
<th>Forcing Location</th>
<th>Atmospheric BC</th>
<th>Ozone</th>
<th>Scattering Aerosol</th>
<th>BC in snow and ice</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°S - 28°S</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.18</td>
</tr>
<tr>
<td>28°S - 28°N</td>
<td>0.31</td>
<td>0.13</td>
<td>0.16</td>
<td>0.93</td>
</tr>
<tr>
<td>28°N - 60°N</td>
<td>0.15</td>
<td>0.05</td>
<td>0.17</td>
<td>0.45</td>
</tr>
<tr>
<td>60°N - 90°N</td>
<td>VR³</td>
<td>0.07</td>
<td>0.31</td>
<td>1.06</td>
</tr>
</tbody>
</table>

*VR indicates use of vertically-resolved forcing.*
Importance of vertical BC distribution

Radiative efficiency of BC increases with altitude

Arctic equilibrium temperature response in CESM with uniform BC layers aloft (left), in the lower troposphere (center), and in snow and sea-ice (right) (Flanner, 2013).
Different transport pathways to Arctic

AMAP report (2015)
Arctic $\Delta T$ calculation

Arctic $\Delta T$ caused by each emitted component ($c_E$) from each region ($r$) and sector ($s$): Sum the contributions from all forcing mechanisms ($c_F$) associated with that component, operating in different latitudinal zones ($j$):

$$\Delta T(c_E, r, s) = \sum_{F} \sum_{j=1}^{4} RF(j, c_F, r, s) \times RCS(j, c_F)$$

For BC within the Arctic atmosphere, we also consider the altitudinal dependence ($z$) of BC forcing and associated surface temperature response expected for BC at that altitude (right):

$$\Delta T(c_E, r, s) = \sum_{z} RF(z, c_F, r, s) \cdot RCS(z, c_F)$$
Black Carbon emissions

1) domestic
2) energy/industry/waste
3) Transport
4) agricultural waste burning
5) forest fires
6) flaring
Emissions regions

- Canada
- United States
- Nordic Countries
- Russia
- South East Asia
- Non-Arctic Europe
One example: BC emissions from flaring oil/gas

3% of global BC emiss
33% > 60°N
66% > 66°N

AMAP BC&O₃ report, 2015
One example: BC emissions from flaring in Russia
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Arctic surface temperature change

1) domestic
2) energy/industry/waste
3) Transport
4) agricultural waste burning
5) forest fires
6) flaring

Sand et al. (2015)
‘Bang for the gram’

Sand et al. (2015)
Total Arctic $\Delta T_{eq}$ from all global emissions

- All SLCFs considered: $-0.44 \ (-1.02 \text{ to } -0.04) \ K$
- BC in atmosphere and snow: $+0.48 \ (0.33 \text{ to } 0.66) \ K$
- OC: $-0.18 \ (-0.30 \text{ to } +0.03) \ K$
- SO$_4$\: $-0.85 \ (-1.29 \text{ to } -0.57) \ K$
- O$_3$: $+0.05 \ (+0.04 \text{ to } +0.05) \ K$
- Arctic 1900–2015 $\Delta T$: about 2.0 K
- Arctic 1900–2005 $\Delta T$ due to all non-GHG forcing agents: about $-1.0 \ K$ (Fyfe et al, 2013)
Future mitigation potential

• A global emissions scenario was designed that is beneficial for both **air quality** and **short-term climate impacts** (and thus most likely to be politically feasible)
  – Scenario includes large reductions in BC-rich sources
  – Mitigation actions begin in 2015, completed by 2030

• Climate impacts assessed out to 2050, using model-mean $\Delta T_{eq}$’s and impulse response functions (Boucher and Reddy, 2008):

$$\Delta T_A(t) = \sum_{r,s,c_E} \int_{t_e=2015}^{t} \Delta E(c_E, r, s, t_e) \times RCS_{n}(c_E, r, s) \times IRF_N(t - t_e) \, dt_e$$

$$\text{IRF}(t) = \sum_{j=1}^{2} \frac{c_j}{\tau_j} \exp \left( -\frac{t_j}{\tau_j} \right)$$

• Transient climate response compared with that of a baseline (“current legislation”) emissions scenario, both with RCP6.0 $\text{CO}_2$
Mitigated Arctic warming by 2050

- Total reduction in Arctic warming: 0.2 K (including warming from coincident reductions in cooling agents)
- For comparison: Difference in 2050 Arctic temperature between RCP2.6 and RCP8.5 scenarios: 0.5 K
Mitigation measures produce a small, but statistically significant reduction in 2050 Arctic sea ice loss in all 4 participating models.

Explicitly simulated temperature changes agree to within ~20% of those calculated with the RCS technique.
Model Evaluation

- Simulated Arctic aerosol distributions from ECLIPSE models evaluated extensively by Eckhardt et al (ACP, 2015)
- Decent model-mean, annual-mean agreement, but many models (including CESM) simulate too little surface BC during winter/spring and too much during summer
- All models simulate too little BC at Tiksi
Conclusions: SLCF impacts on the Arctic

Using global transport models with advanced aerosol-radiation-cloud and aerosol-radiation-snow schemes and climate sensitivity factors we find:

1. **Domestic emissions** from **Asia** *warm* the Arctic, mostly via *remote* forcing
   - Russian *gas flaring* also *warms*, mostly via *local* BC deposition on snow
2. The **Energy+Industry+Waste** sector *cools* the Arctic via high SO$_2$ emissions
3. Russian and Nordic emissions are low, but could be cost-effective targets because the Arctic is most sensitive to emissions from these regions
4. All current BC emissions *warm* the Arctic by about 0.5 K
   - All SO$_2$ emissions *cool* the Arctic by about $-0.85$ K
5. A feasible, but aggressive emission mitigation scenario could reduce 2050 surface temperatures in the Arctic by 0.2 K ($\pm 0.17$)
6. Substantial uncertainties originate from RCS factors and cloud-indirect effects
Thanks!

AMAP: a Working Group of the Arctic Council; a cooperation between the 8 Arctic countries, indigenous peoples and observing countries and international organizations.

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