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

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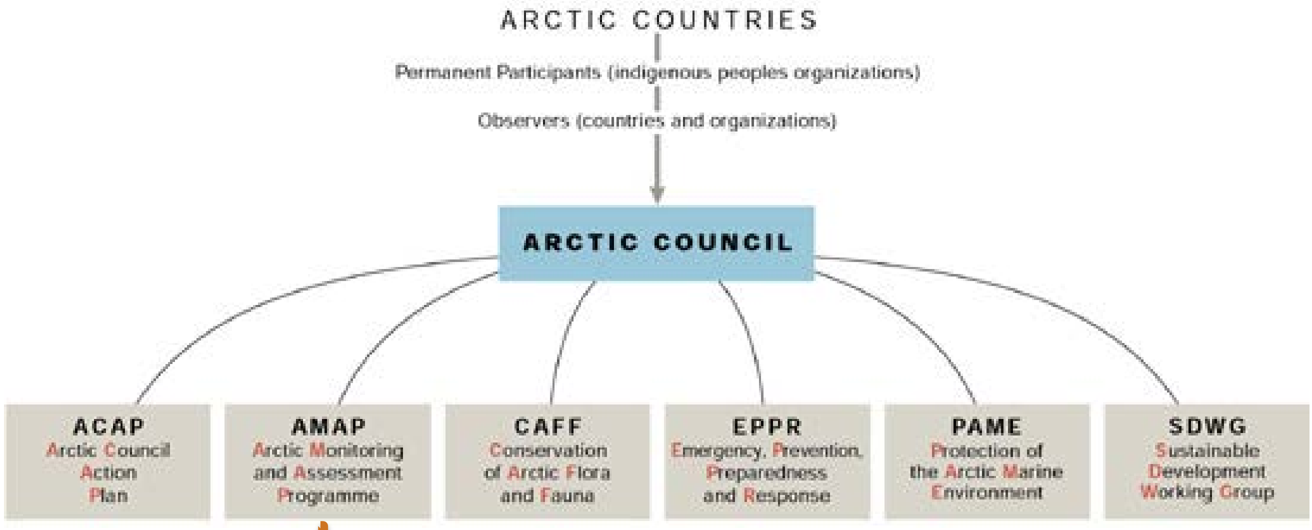
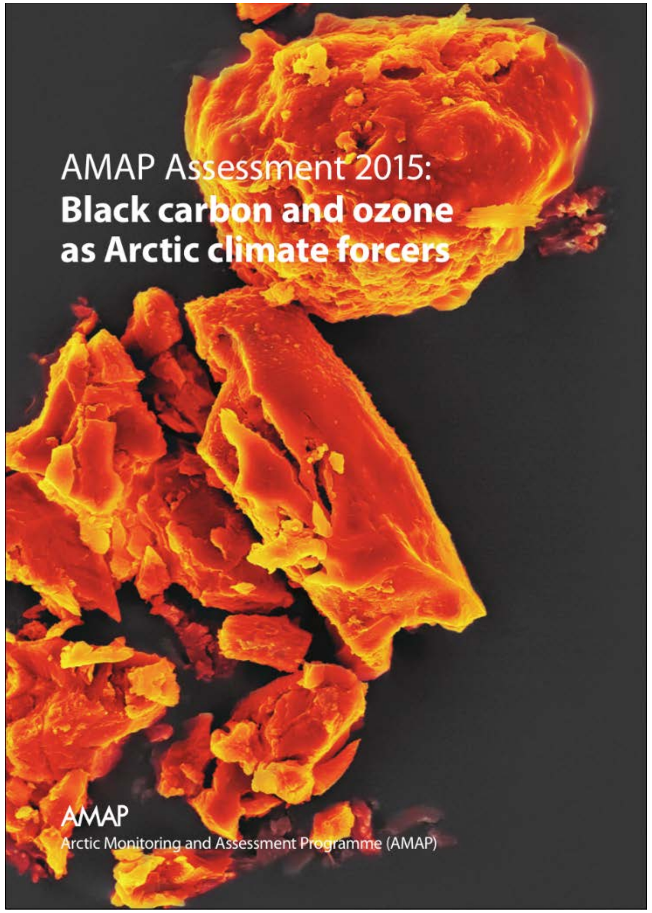
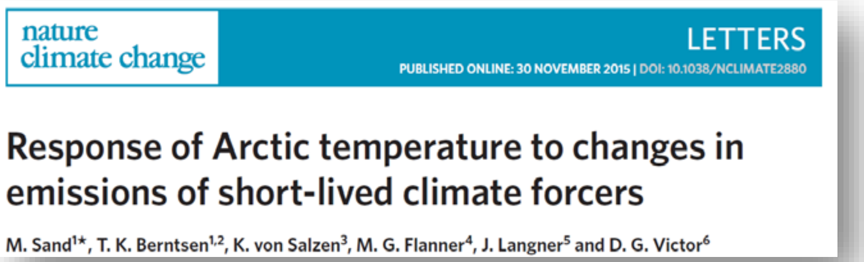
AMAP organization and charge





- 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 CO_2 as the main anthropogenic driver of Arctic climate change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Response of Arctic temperature to changes in emissions of short-lived climate forcers

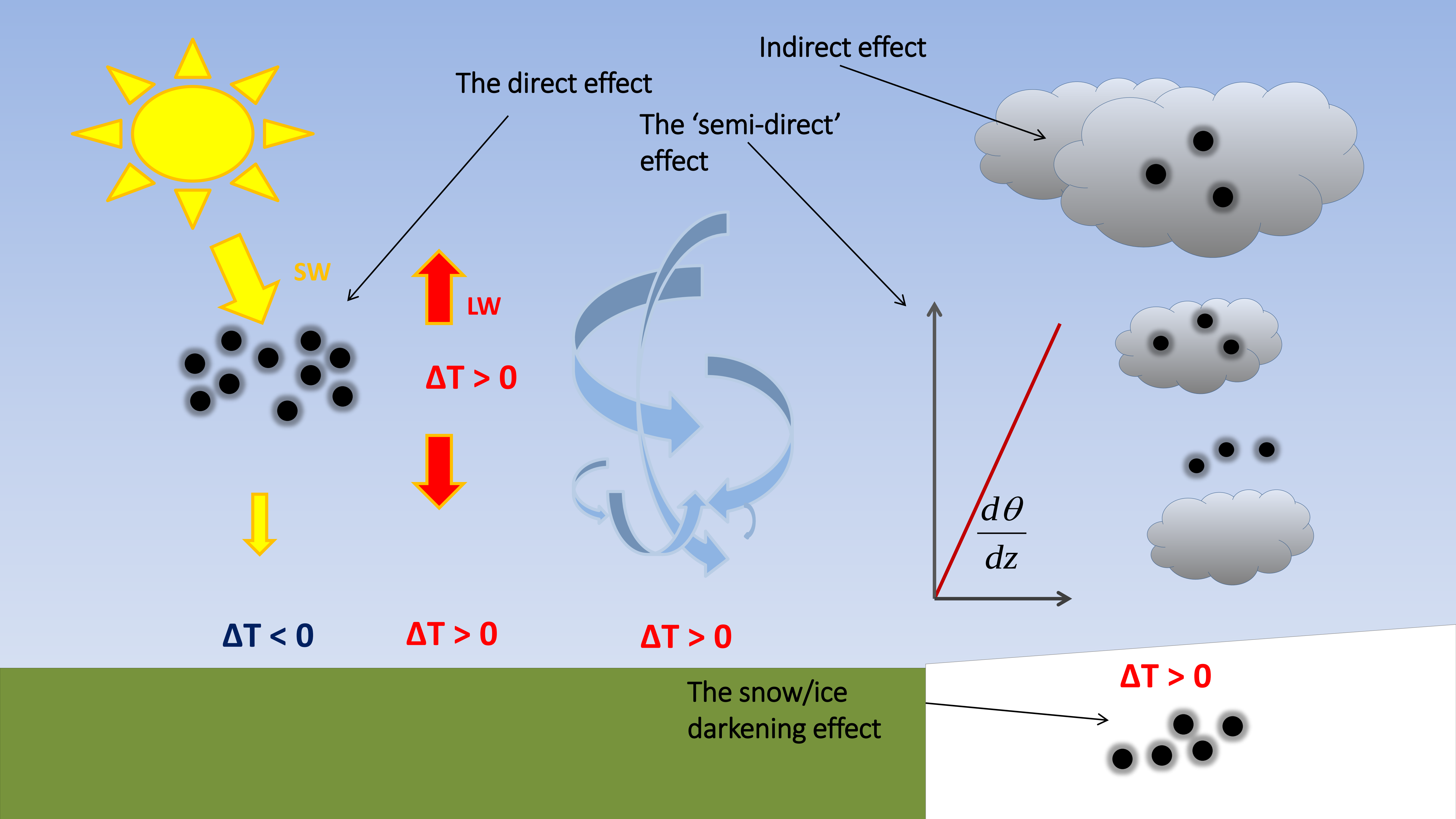
M. Sand[1*], T. K. Berntsen[1,2], K. von Salzen[3], M. G. Flanner[4], J. Langner[5] and D. G. Victor[6]

Forcing agents considered

- Black carbon (BC)
- Organic carbon (OC)
- Sulfate (via SO_2 emission precursor)
- Ozone (via NO_x, CO, VOC emission precursors)

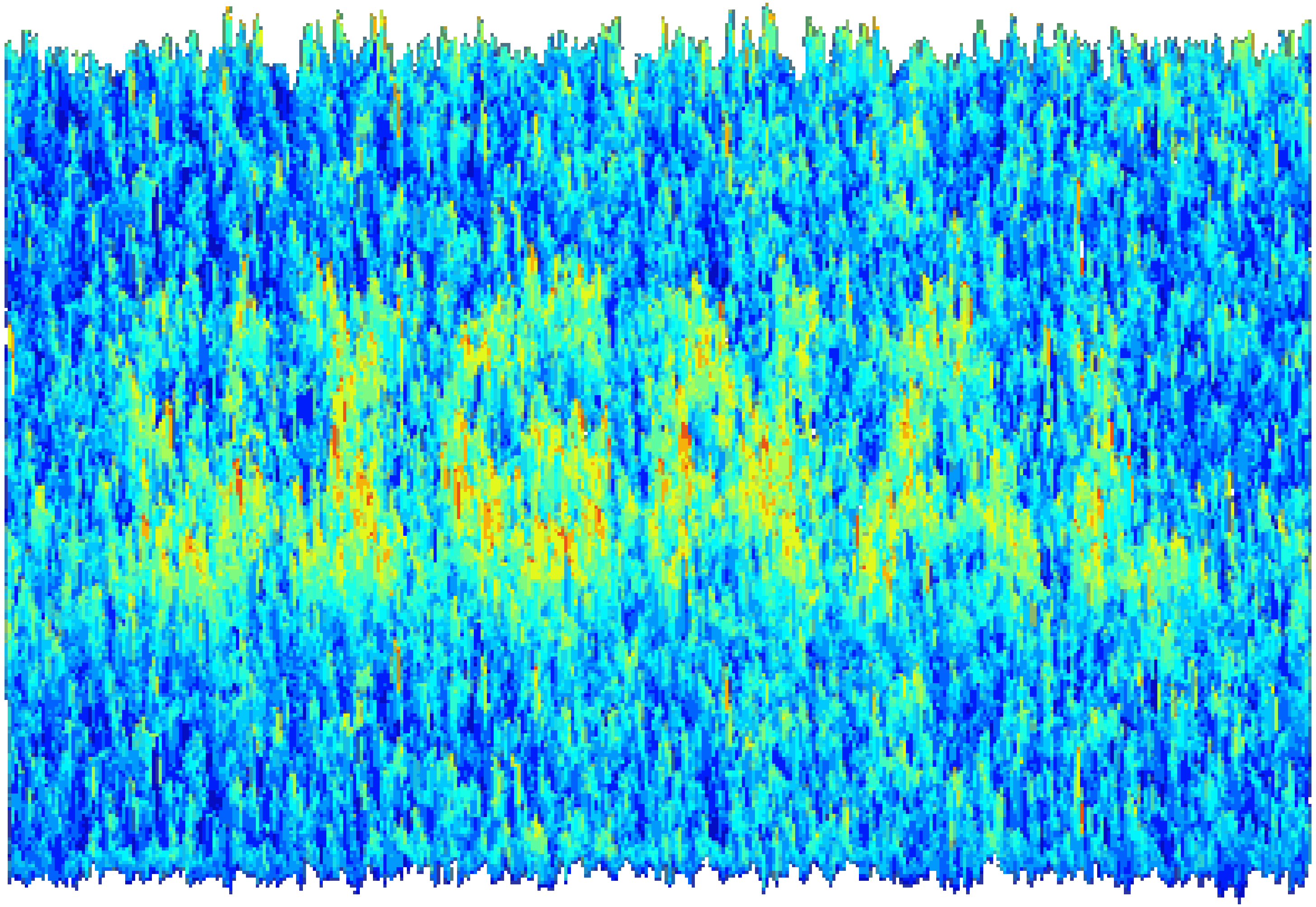
Models applied in the assessment

- 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



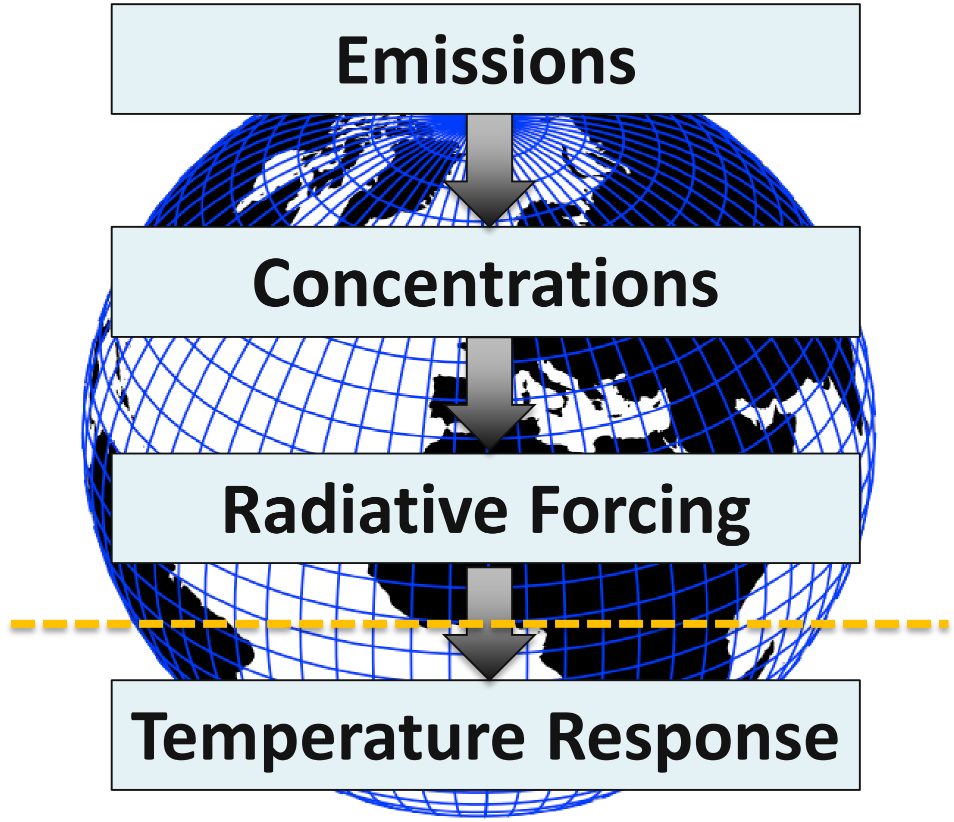
Indirect effect
The direct effect
The 'semi-direct' effect
SW
LW
ΔT > 0
$\frac{d\theta}{dz}$
ΔT < 0
ΔT > 0
ΔT > 0
The snow/ice darkening effect
ΔT > 0

Small perturbations, large variability



http://www.doctordisruption.com/

Estimating temperature response

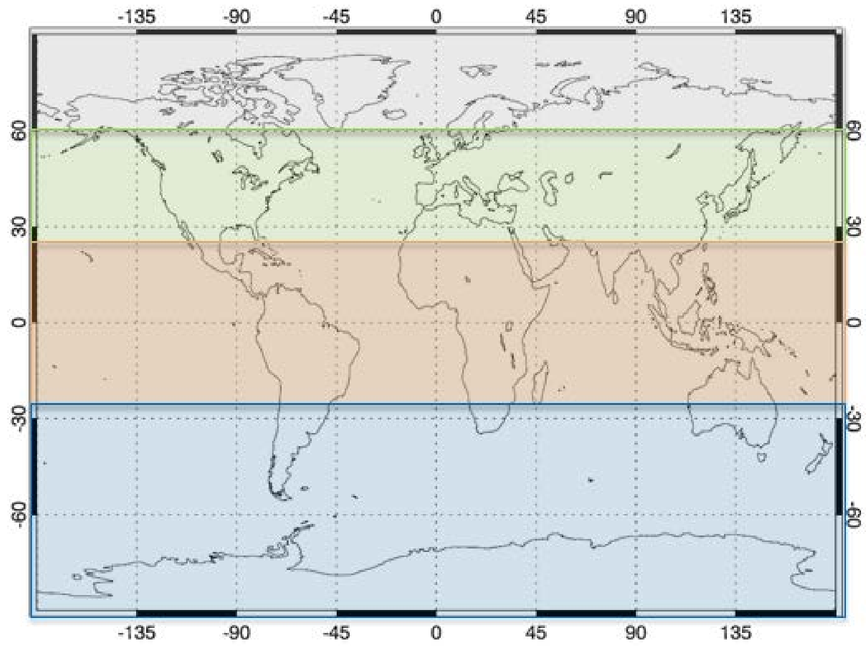


- Emissions provided by European ECLIPSE project
- Explicit calculations of radiative forcing conducted with each model, using ECLIPSEv4a emissions
- Use of **regional temperature sensitivity factors** (*Shindell and Faluvegi, 2009; Flanner, 2013*) enables efficient evaluation of temperature impacts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

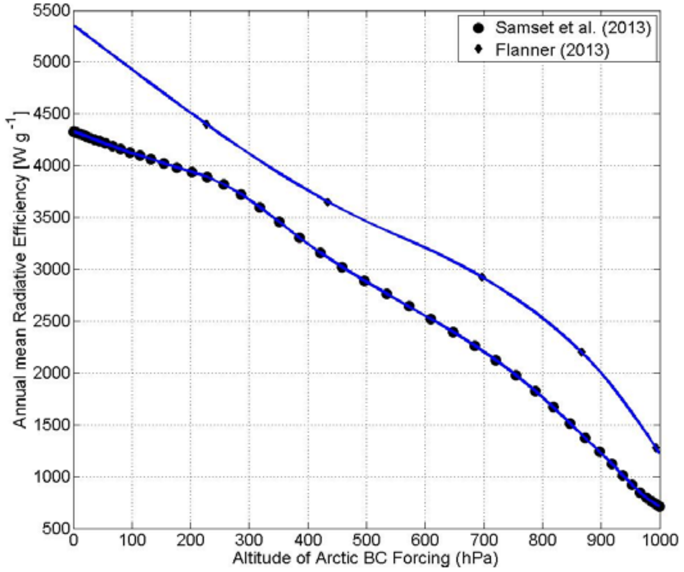
Table S3. Arctic climate sensitivity factors in units of K/(W/m^2)

	Forcing Agent			
Forcing Location	**Atmospheric BC**	**Ozone**	**Scattering Aerosol**	**BC in snow and ice**
90°S - 28°S	0.06	0.06	0.06	0.18
28°S - 28°N	0.31	0.13	0.16	0.93
28°N - 60°N	0.15	0.05	0.17	0.45
60°N - 90°N	VR[a]	0.07	0.31	1.06

[a] VR indicates use of vertically-resolved forcing.

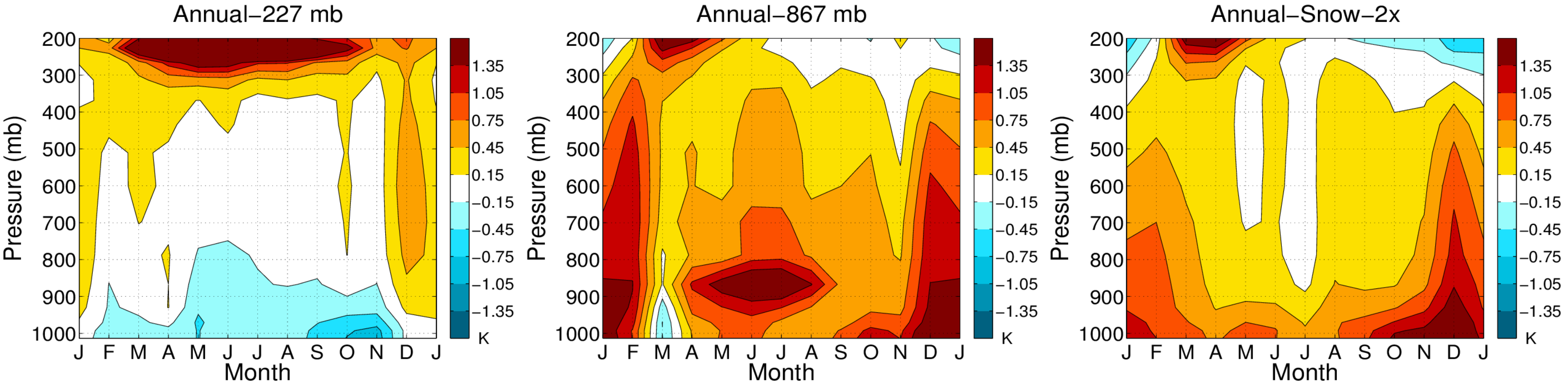


Importance of vertical BC distribution

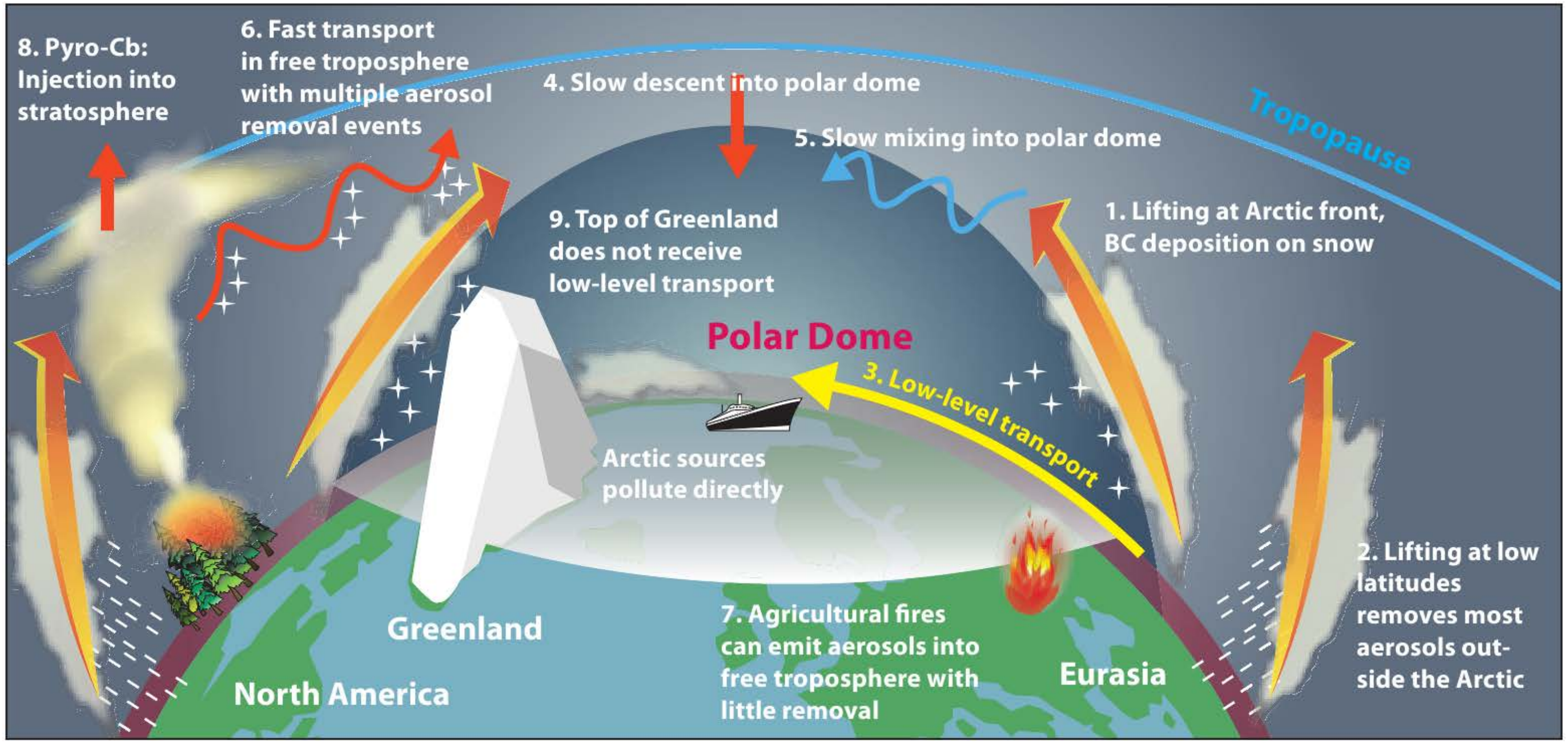


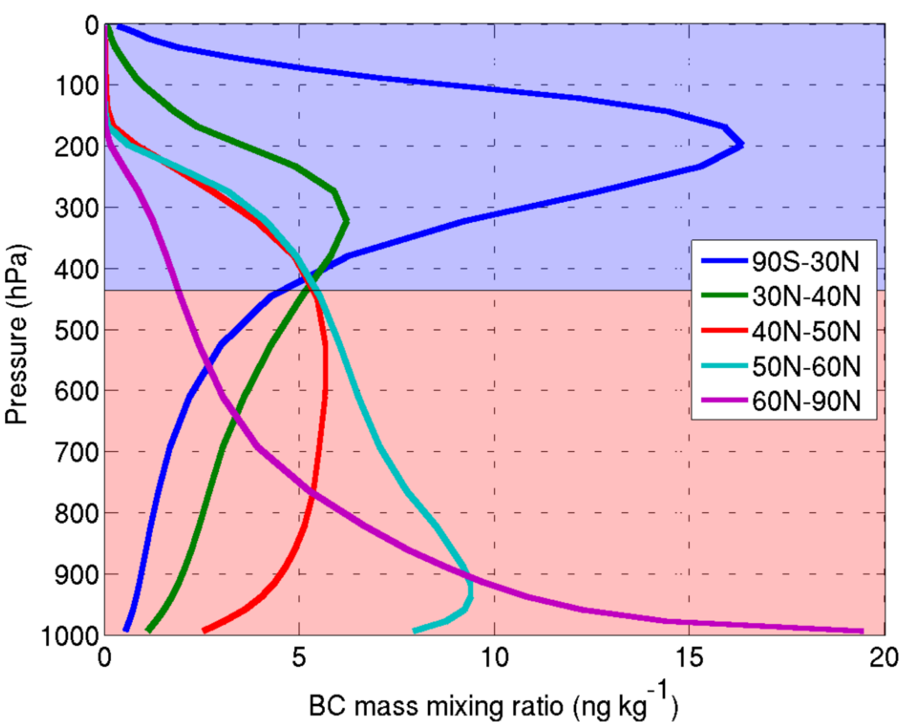
Radiative efficiency of BC increases with altitude

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)

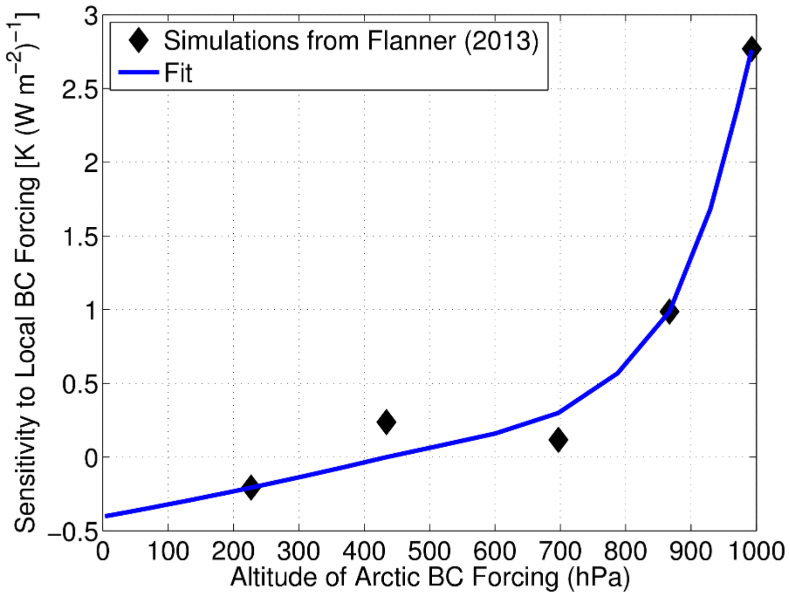
Arctic ΔT calculation

Arctic ΔT 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):

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

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):

$$\Delta T(c_E, r, s) = \sum_z \mathrm{RF}(z, c_F, r, s) \cdot \mathrm{RCS}(z, c_F)$$



Emissions sectors

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

Emissions regions

Canada

United States

Nordic Countries

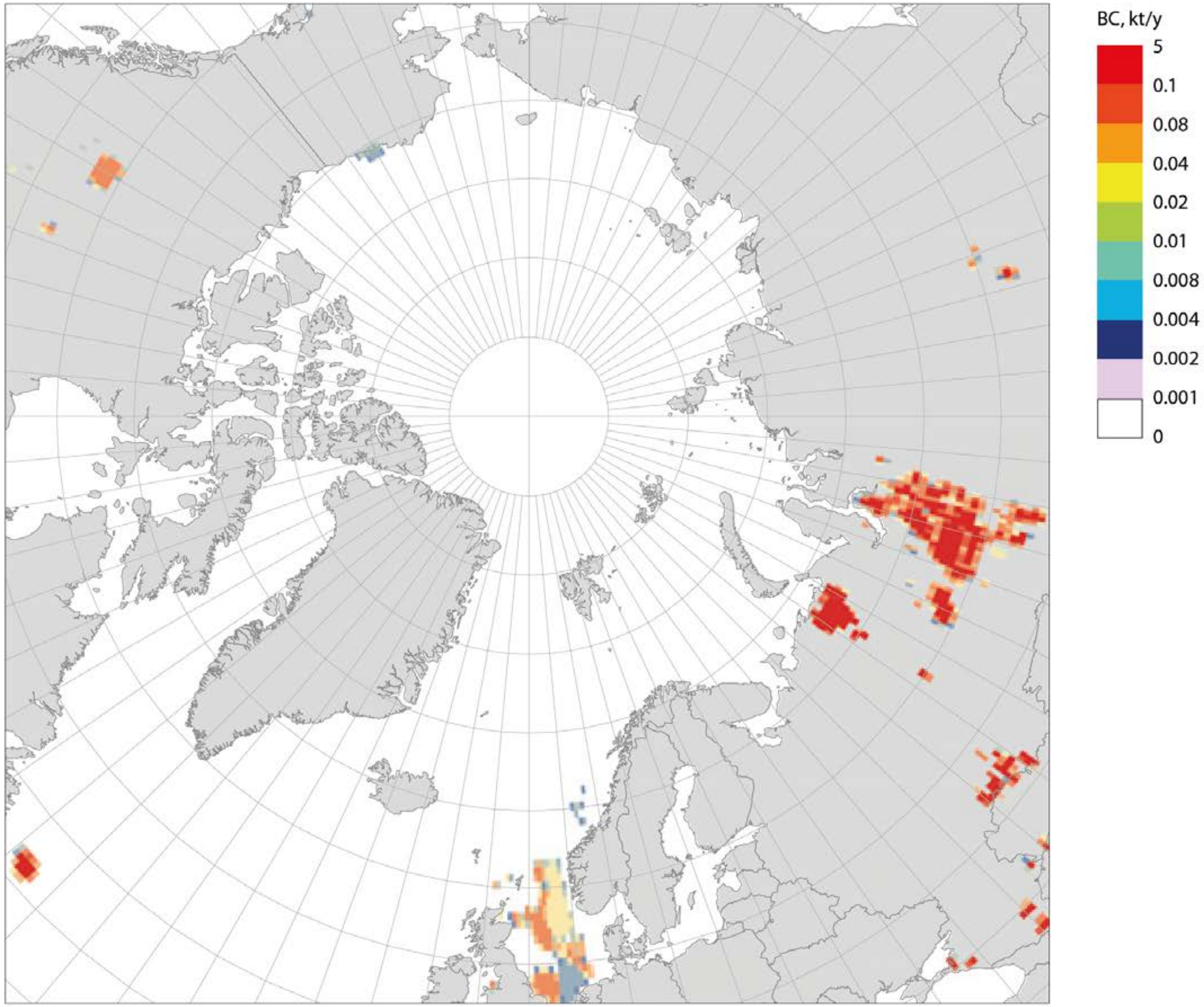
Russia

South East Asia

Non-Arctic Europe

One example: BC emissions from flaring oil/gas

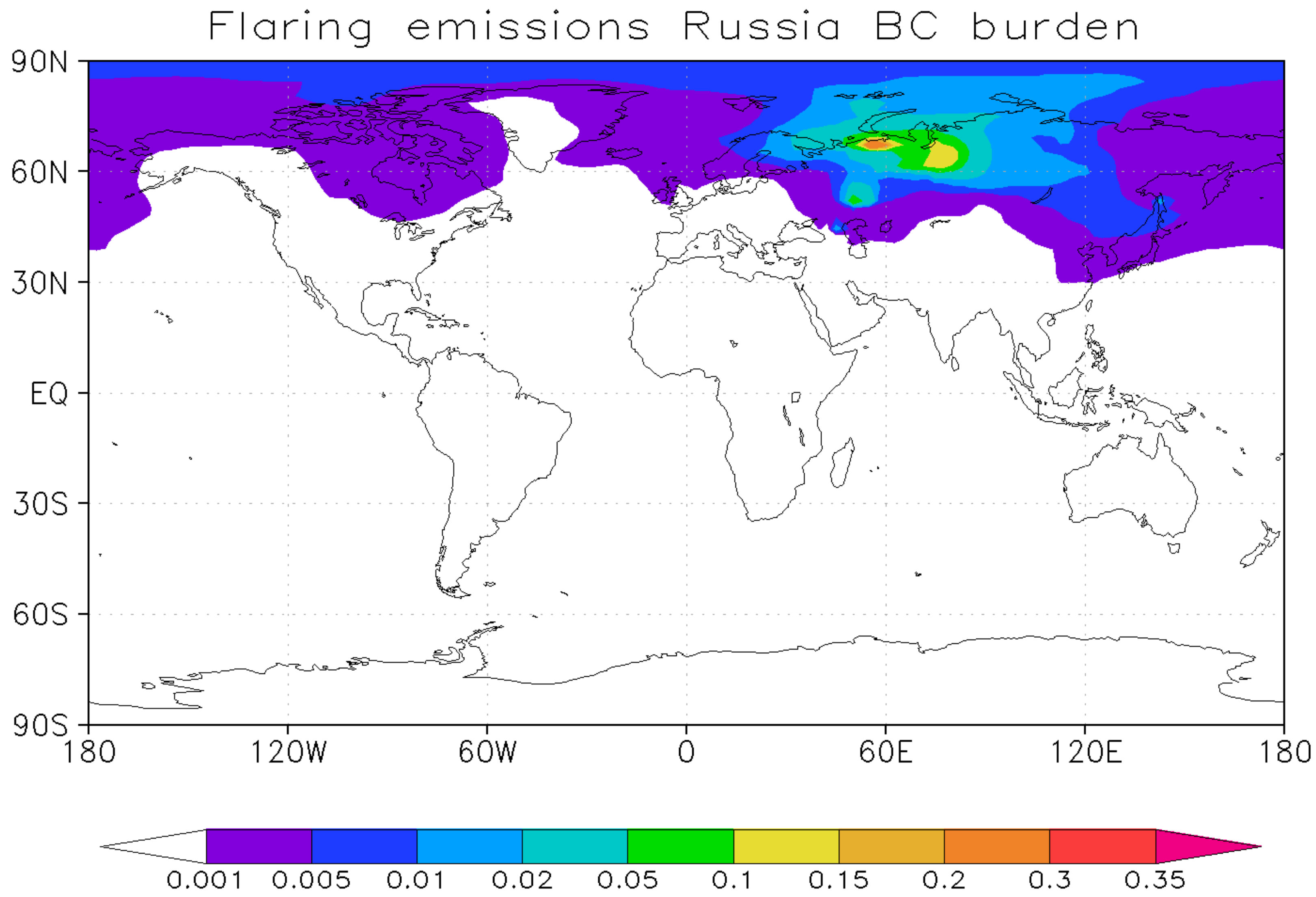
3% of global BC emiss
33% > 60°N
66% > 66°N



AMAP BC&O_3 report, 2015

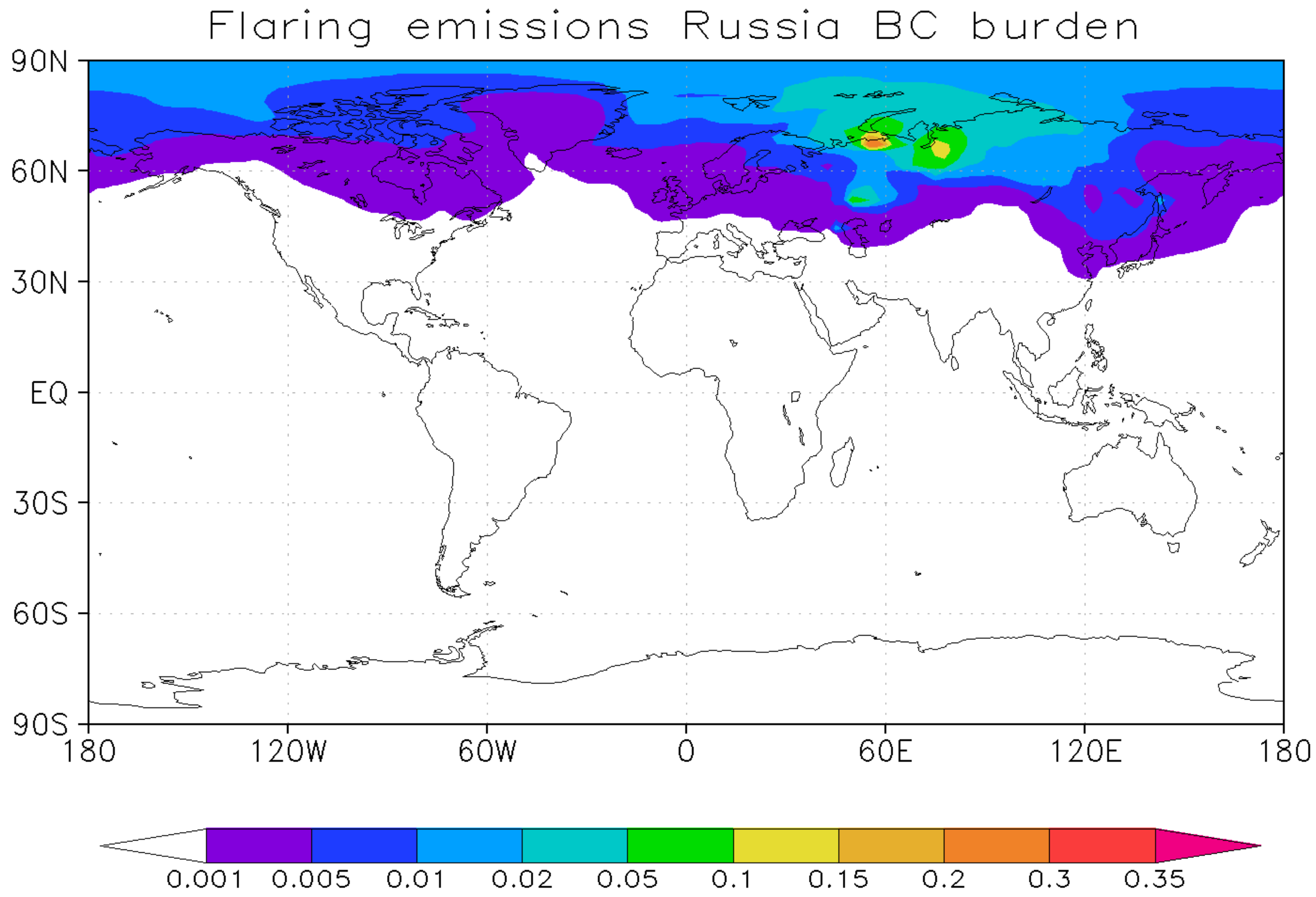
One example: BC emissions from flaring in Russia

JANUARY



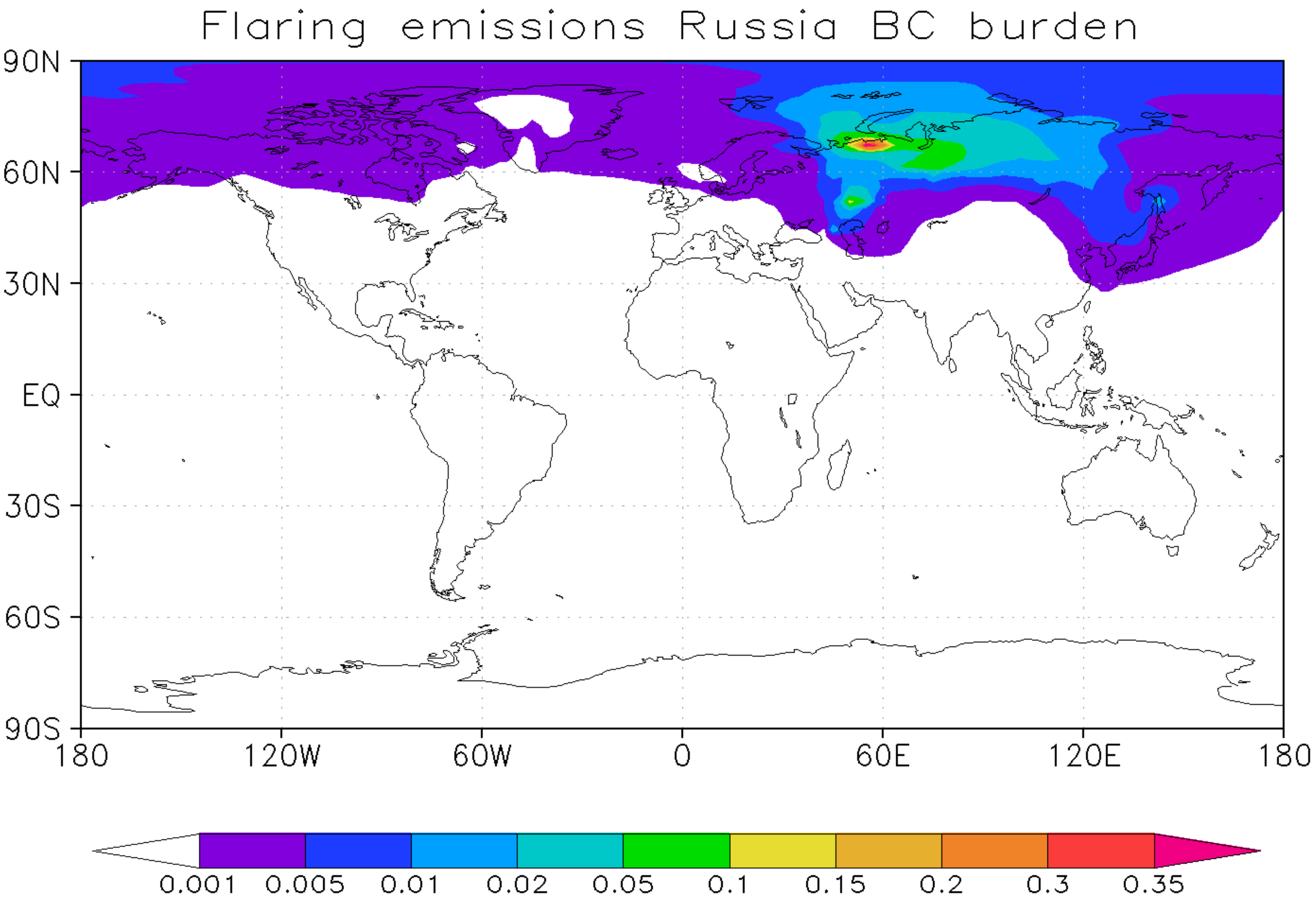
One example: BC emissions from flaring in Russia

FEBUARY



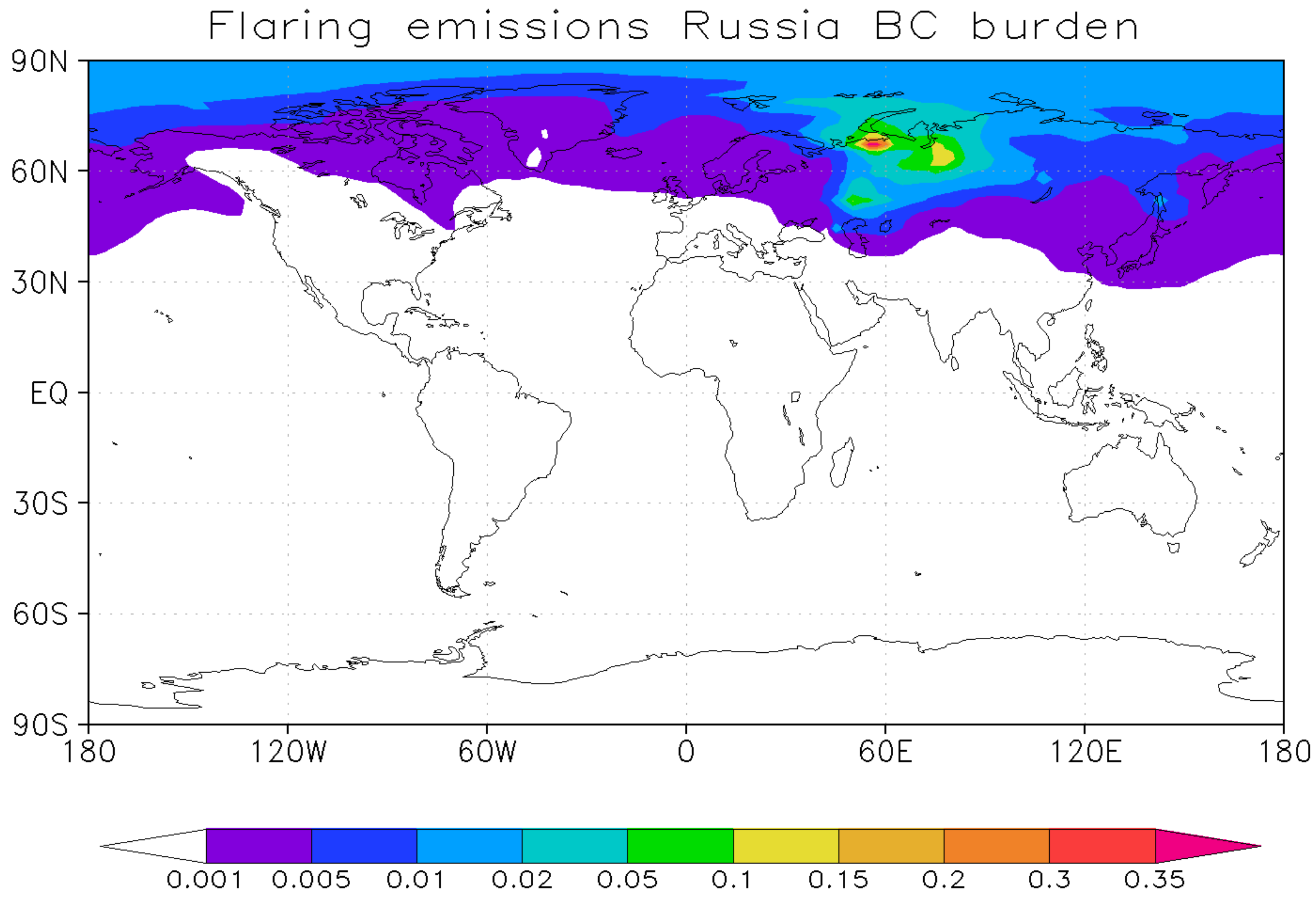
One example: BC emissions from flaring in Russia

MARCH



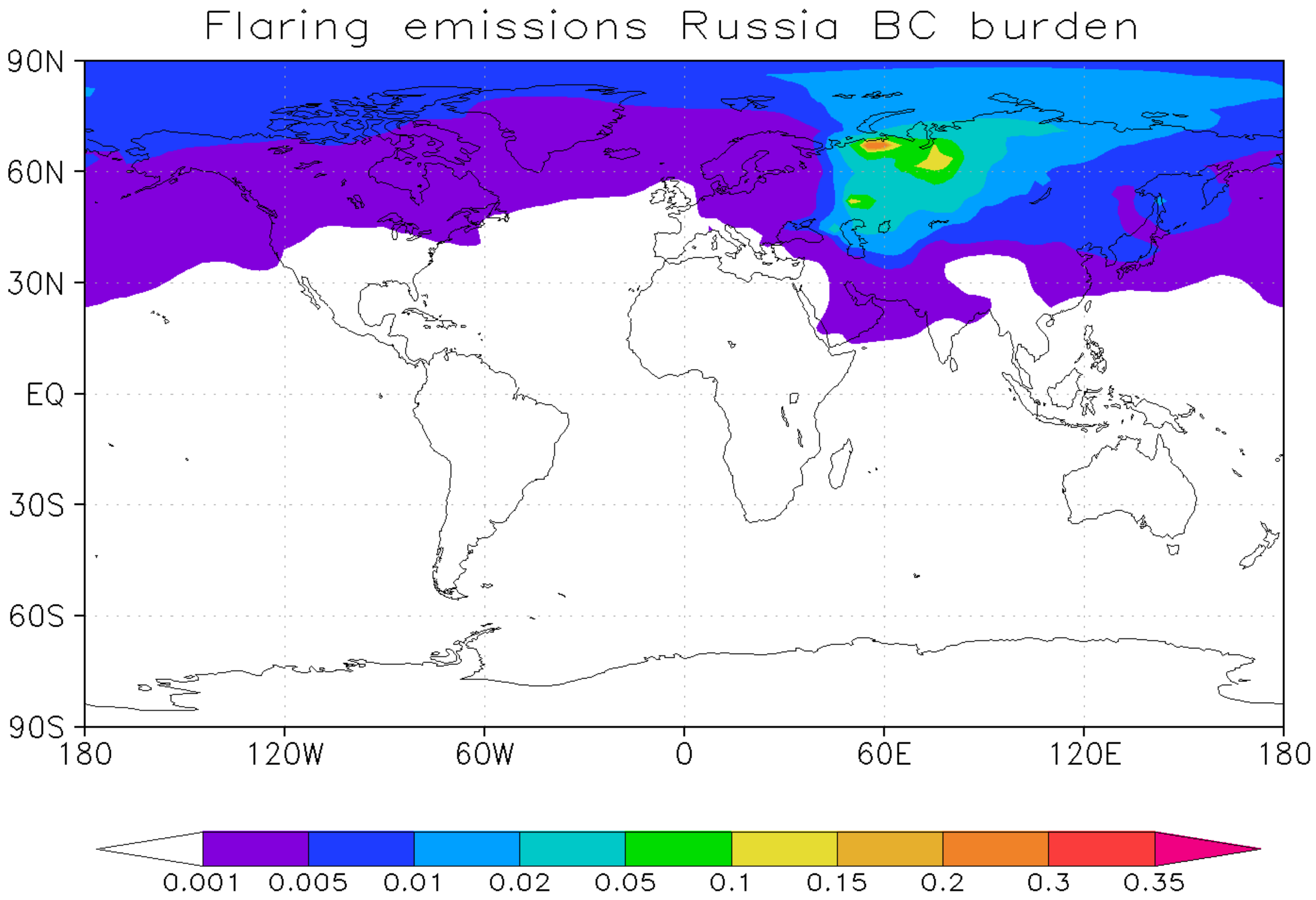
One example: BC emissions from flaring in Russia

APRIL



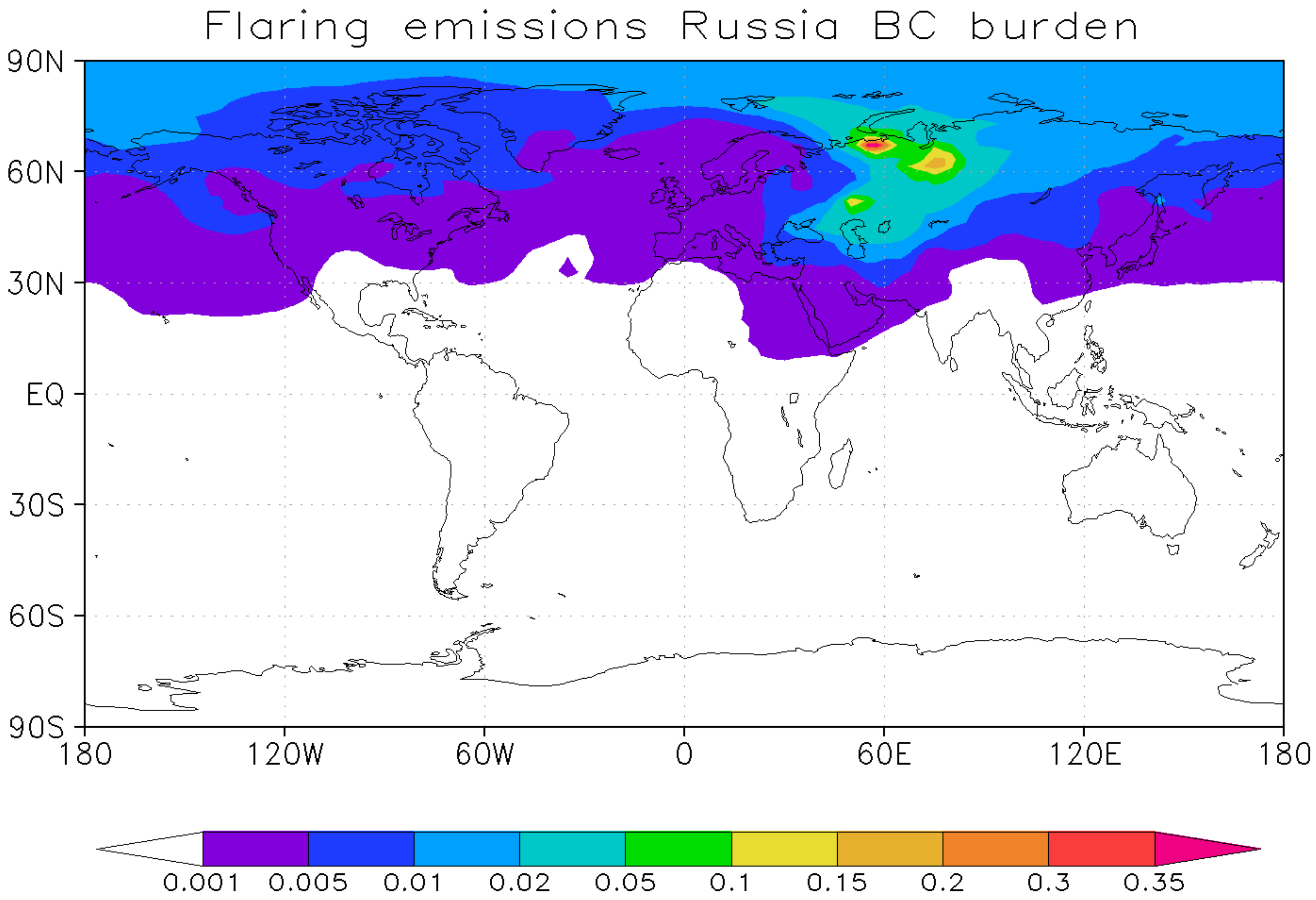
One example: BC emissions from flaring in Russia

MAY



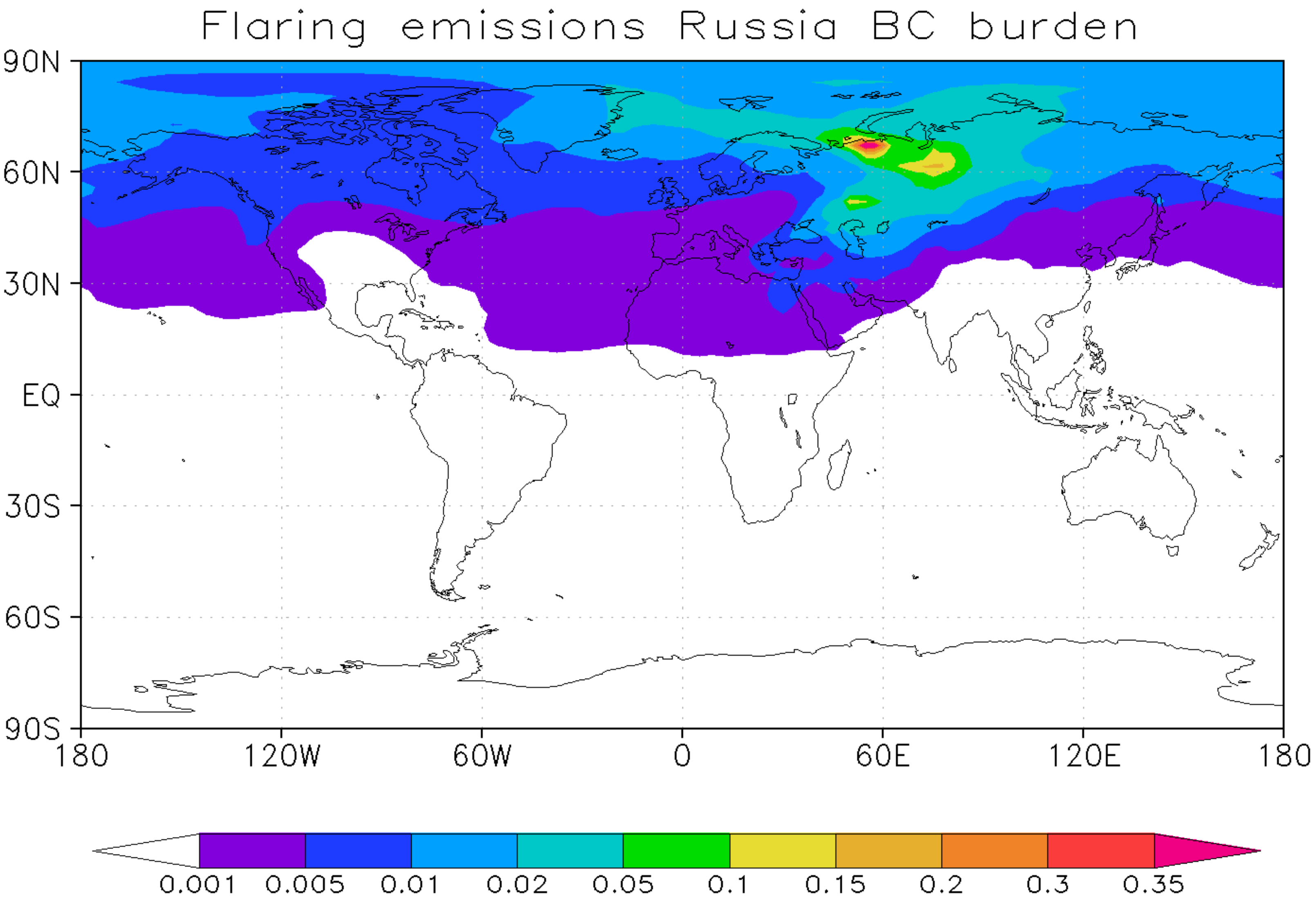
One example: BC emissions from flaring in Russia

JUNE



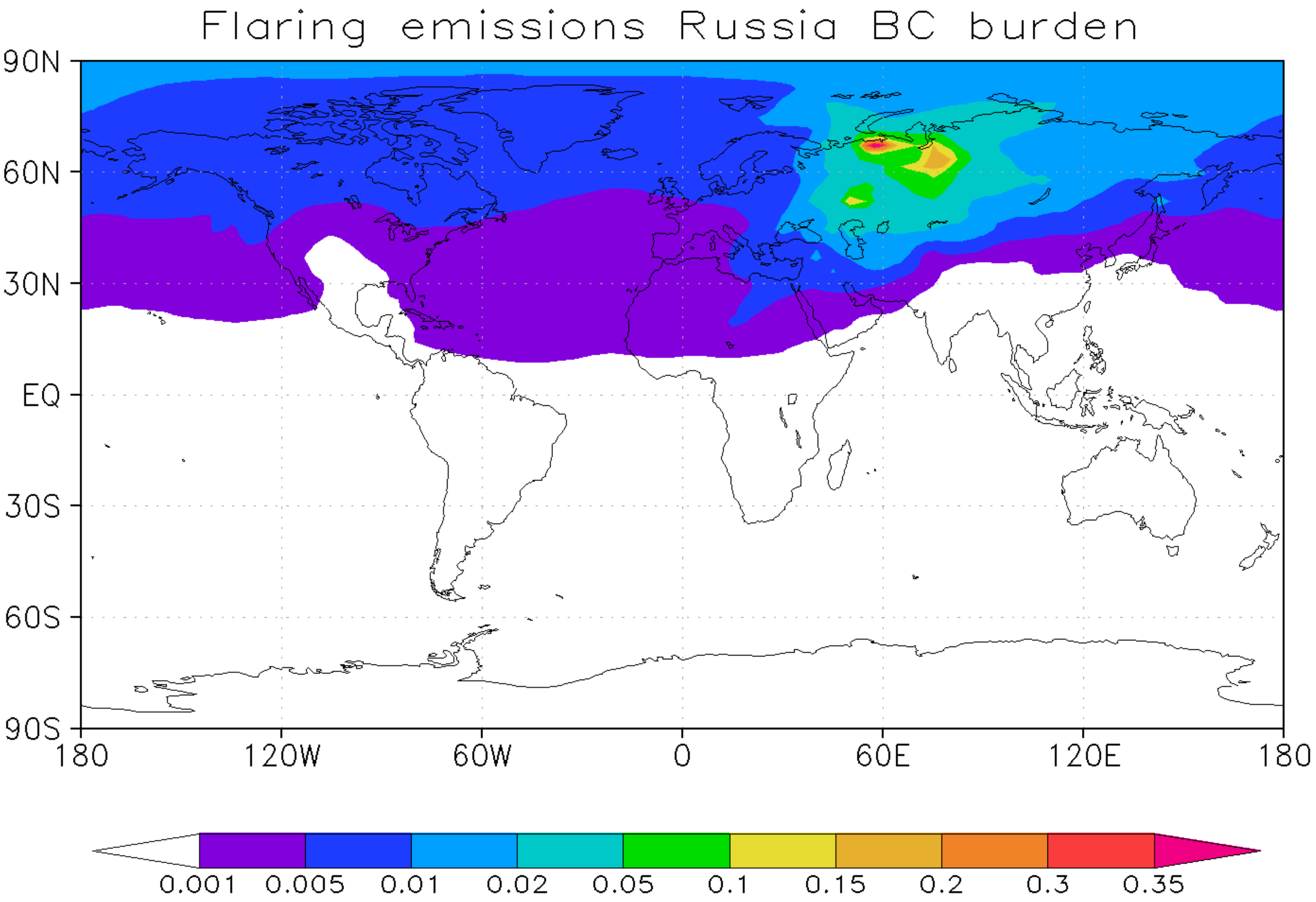
One example: BC emissions from flaring in Russia

JULY



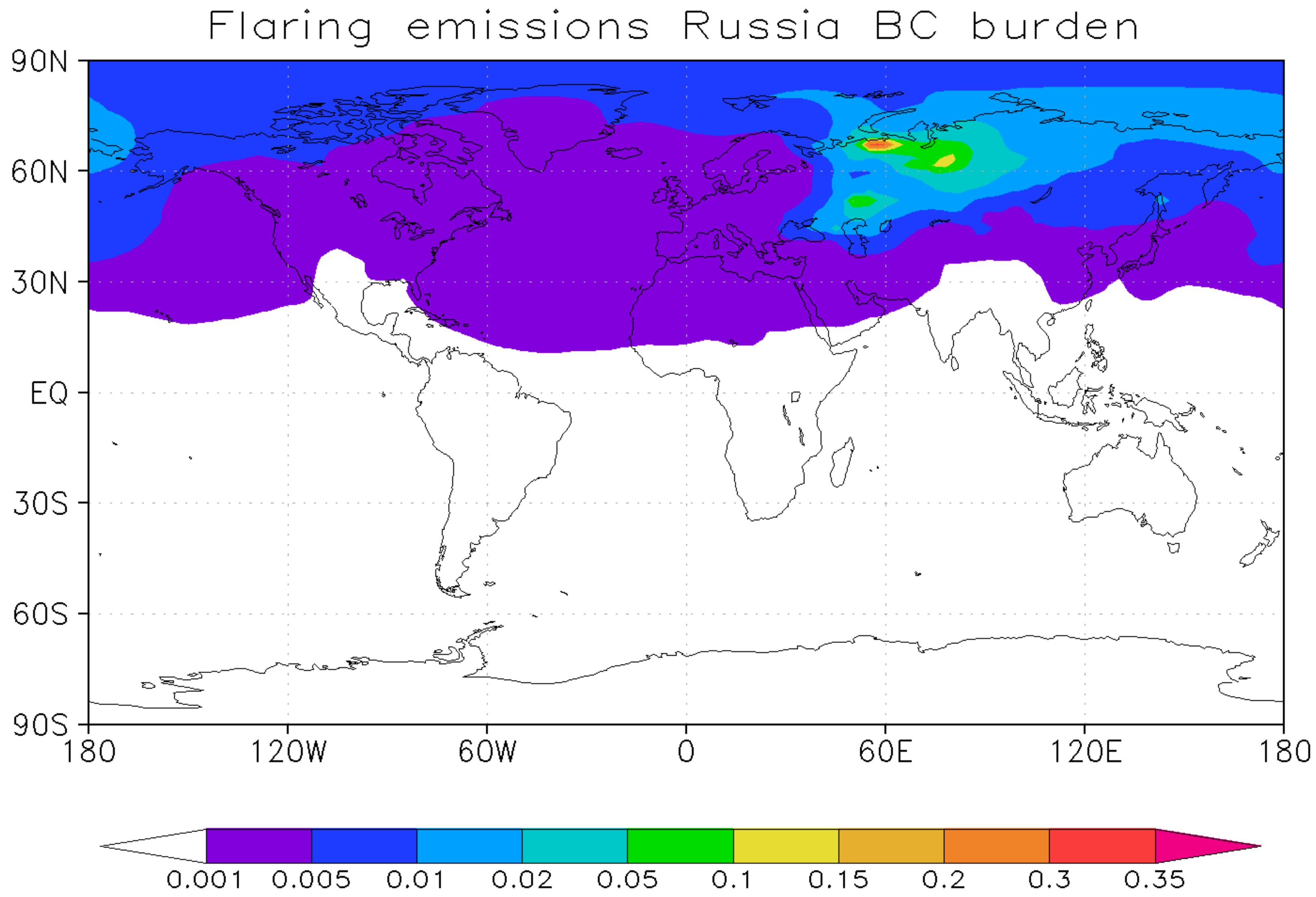
One example: BC emissions from flaring in Russia

AUGUST



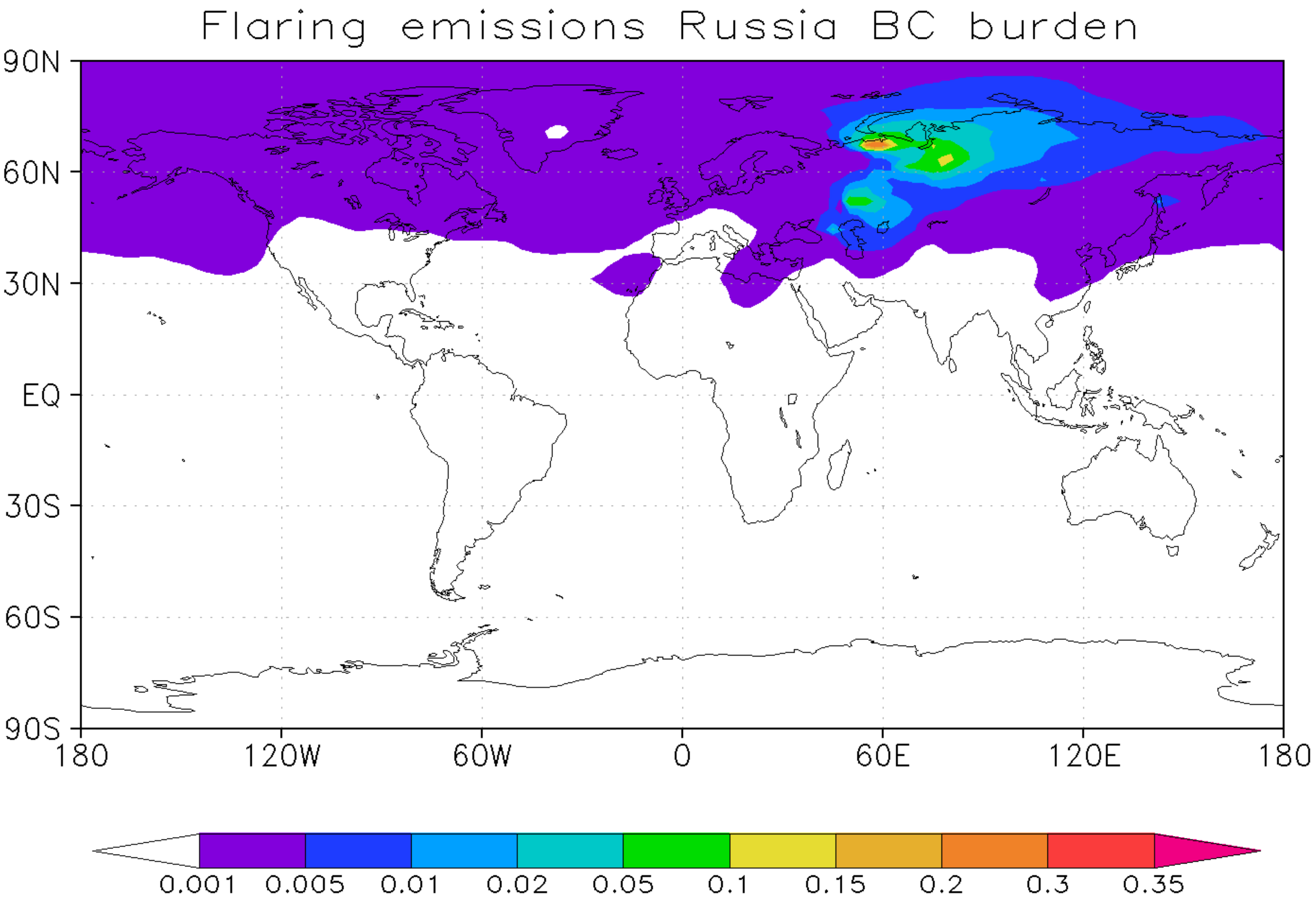
One example: BC emissions from flaring in Russia

SEPTEMBER



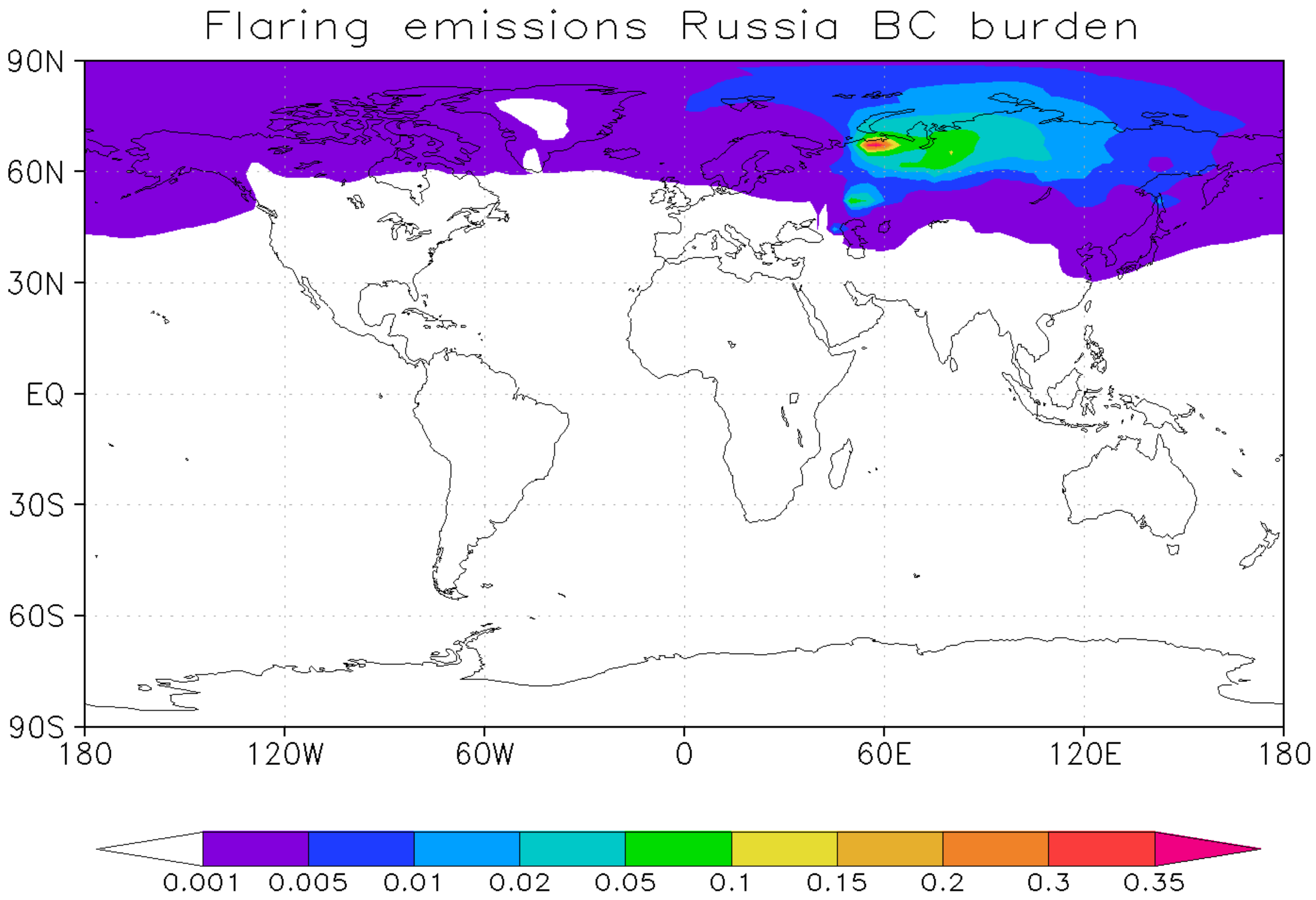
One example: BC emissions from flaring in Russia

OCTOBER



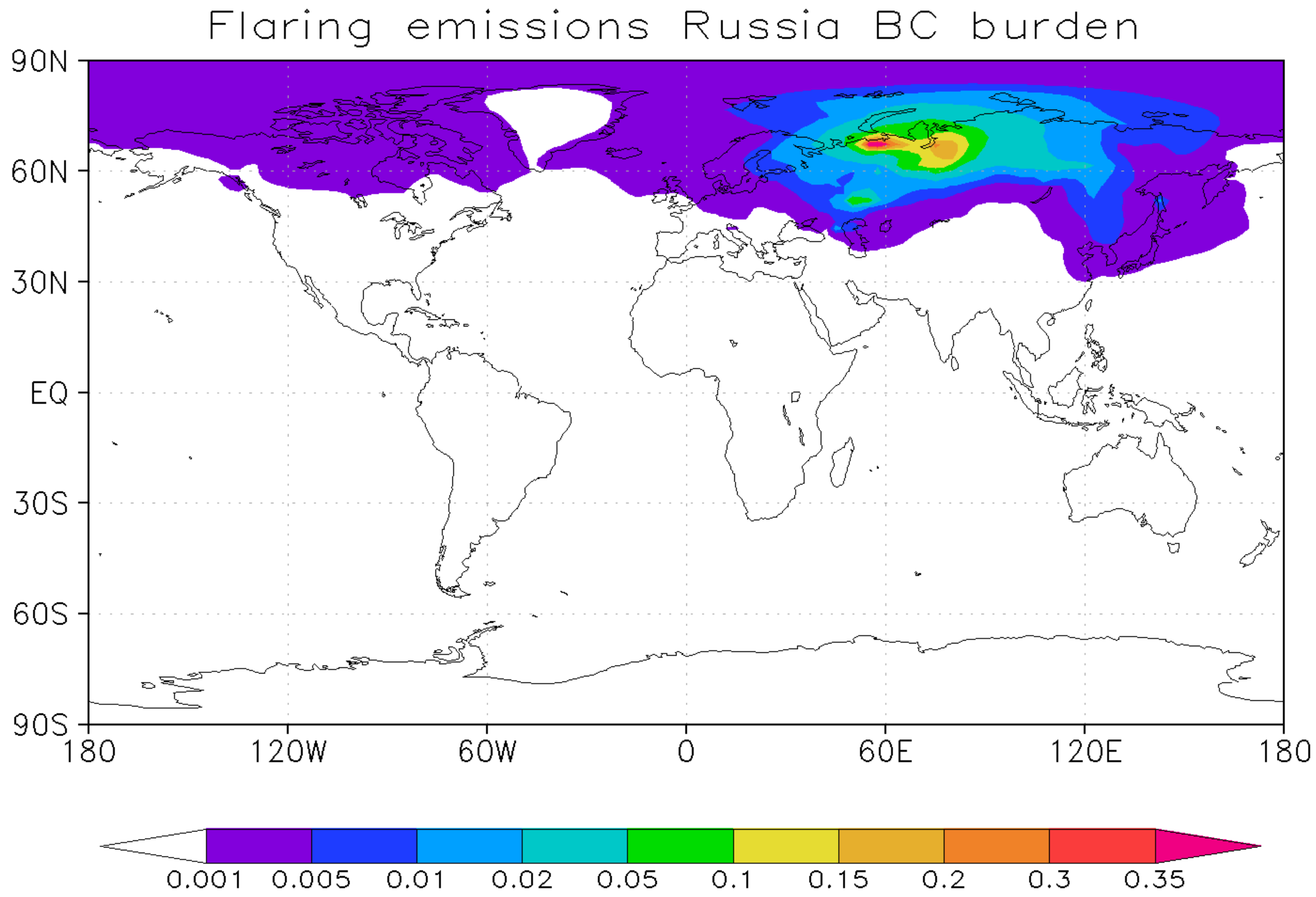
One example: BC emissions from flaring in Russia

NOVEMBER

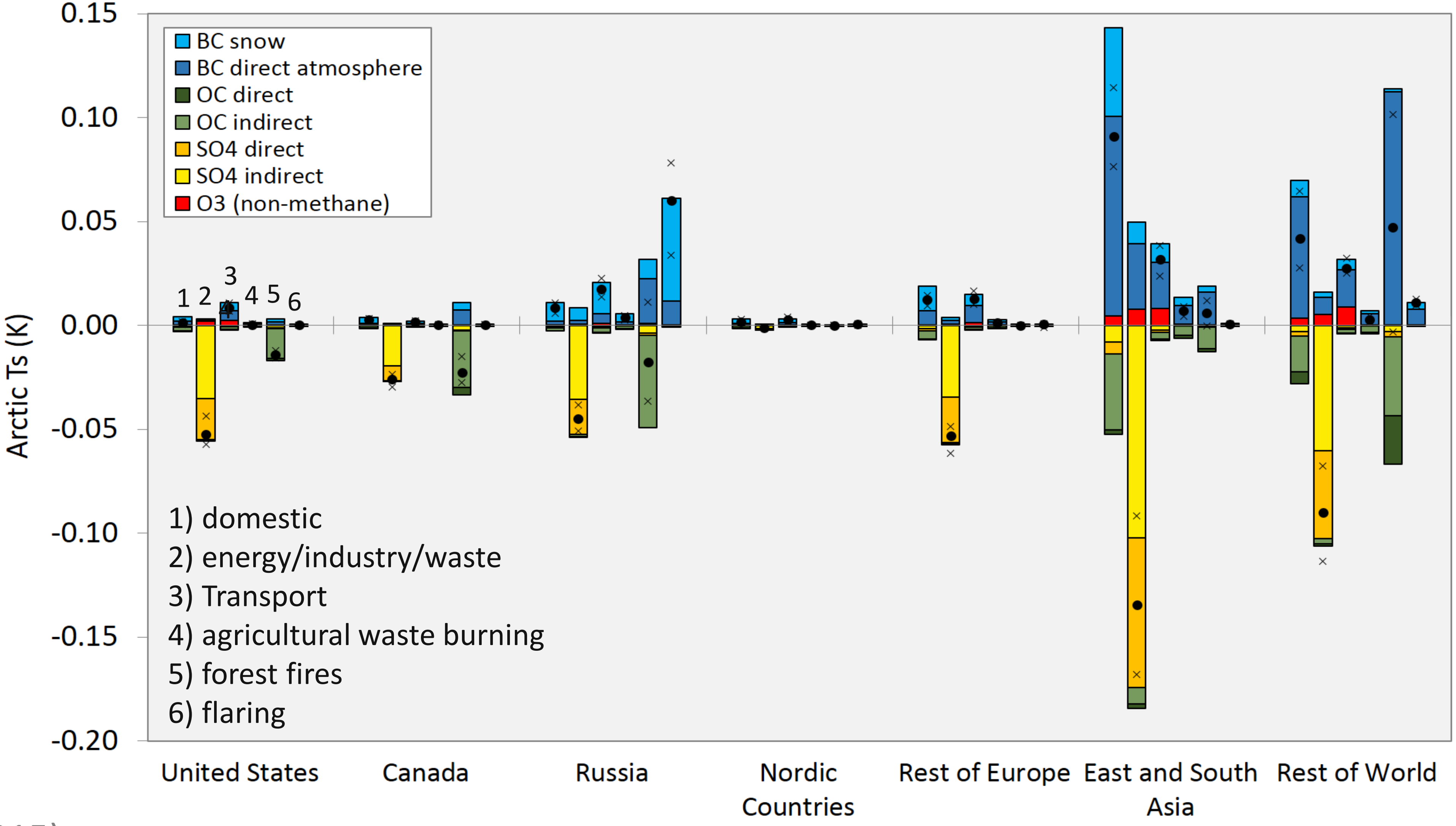


One example: BC emissions from flaring in Russia

DECEMBER

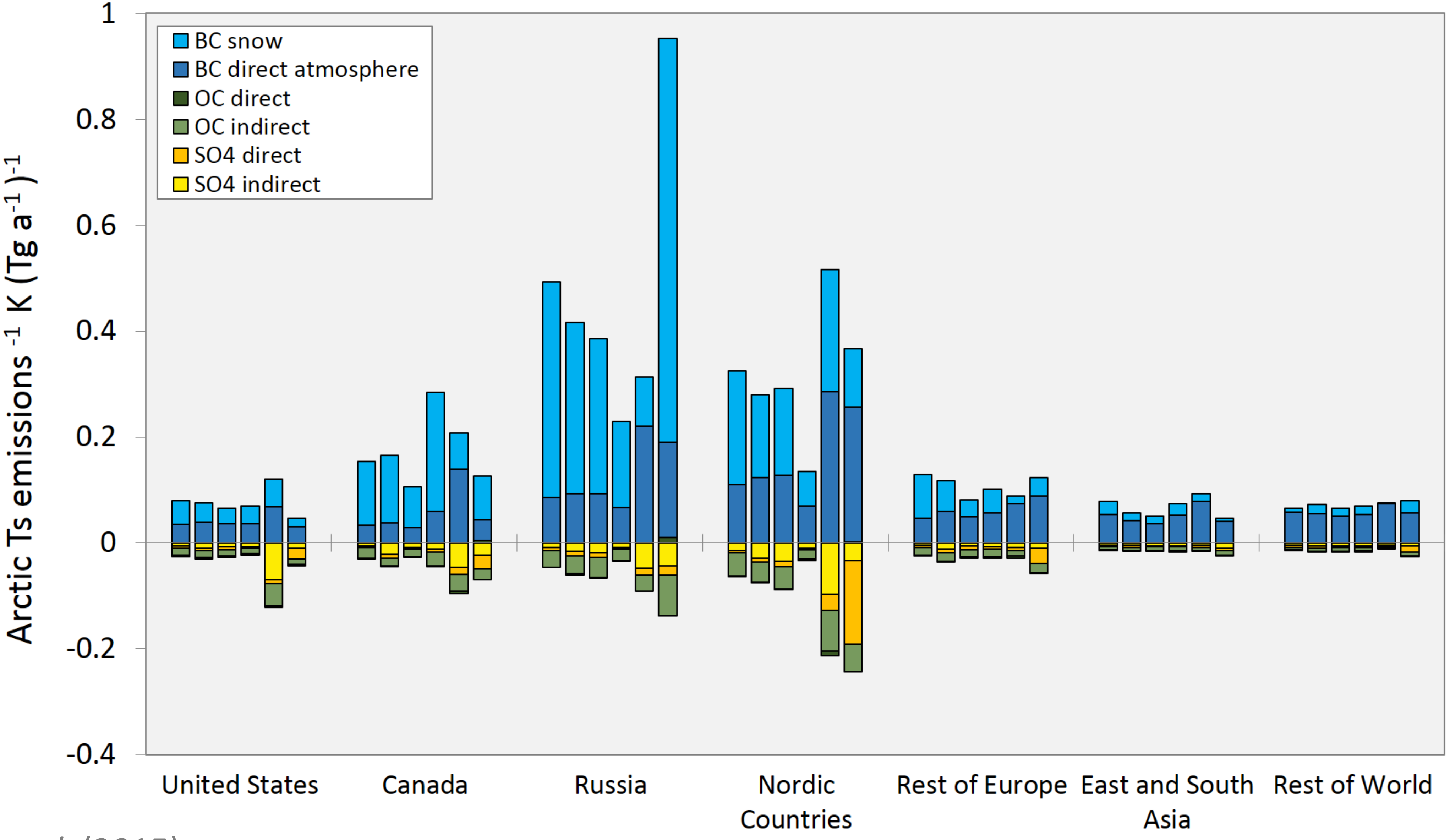


Arctic surface temperature change



Sand et al. (2015)

‘Bang for the gram’



Sand et al. (2015)

Total Arctic ΔT_{eq} from all global emissions

- All SLCFs considered: −0.44 (−1.02 to −0.04) K
- BC in atmosphere and snow: +0.48 (0.33 to 0.66) K
- OC: −0.18 (−0.30 to +0.03) K
- SO_4: −0.85 (−1.29 to −0.57) K
- O_3: +0.05 (+0.04 to +0.05) K
- Arctic 1900–2015 ΔT: about 2.0 K
- Arctic 1900–2005 ΔT due to all non-GHG forcing agents: about −1.0 K (*Fyfe et al*, 2013)

Future mitigation potential

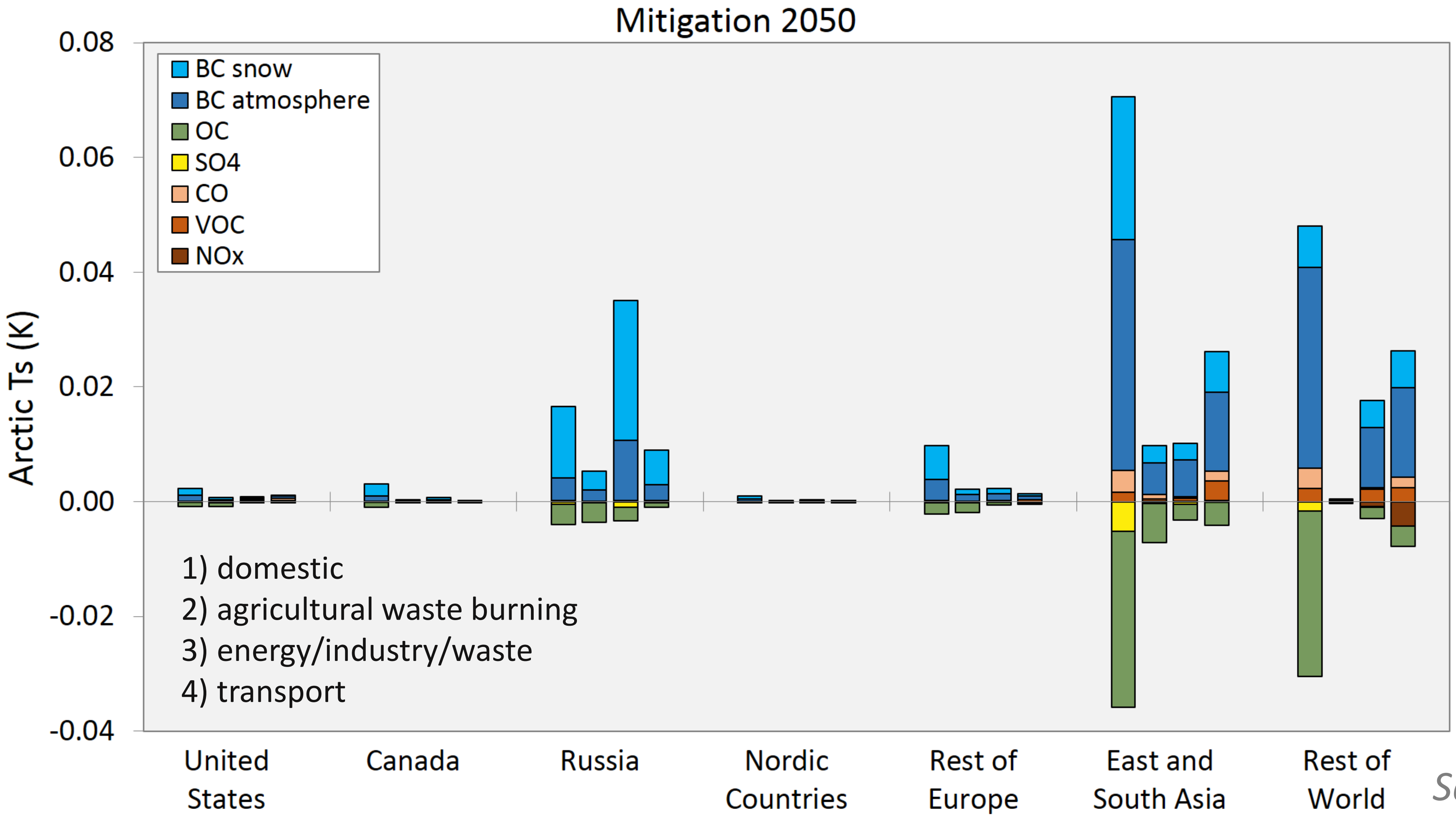
- A global emissions scenario was designed that is beneficial for both **air quality** and **short-term climate impacts** (and thus most likely to be politically feasible)
  - Scenario includes large reductions in BC-rich sources
  - Mitigation actions begin in 2015, completed by 2030
- Climate impacts assessed out to 2050, using model-mean ΔT_{eq}'s and impulse response functions (*Boucher and Reddy*, 2008):

$$\Delta T_A(t) = \sum_{r,s,c_E} \int_{t_e=2015}^{t} \Delta E(c_E, r, s, t_e) \times \mathrm{RCS_n}(c_E, r, s) \times \mathrm{IRF}_N(t - t_e)\, \mathrm{d}t_e$$

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

- Transient climate response compared with that of a baseline ("current legislation") emissions scenario, both with RCP6.0 CO_2

Mitigated Arctic warming by 2050



Sand et al., (2015)

- 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

Transient sea ice changes

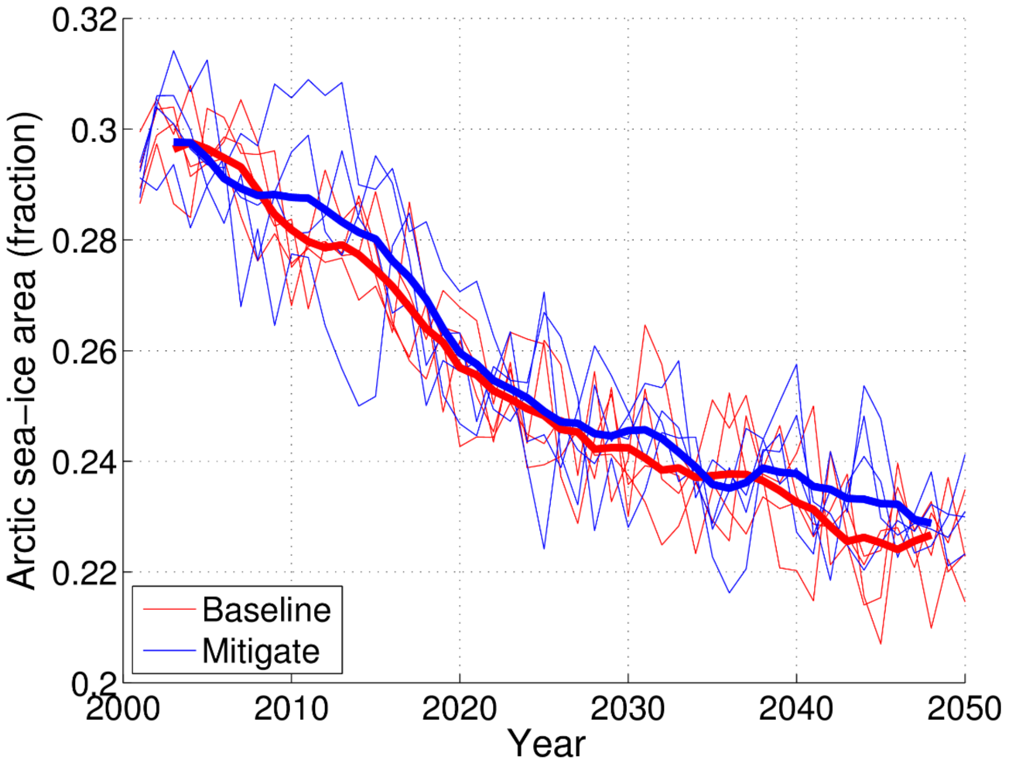
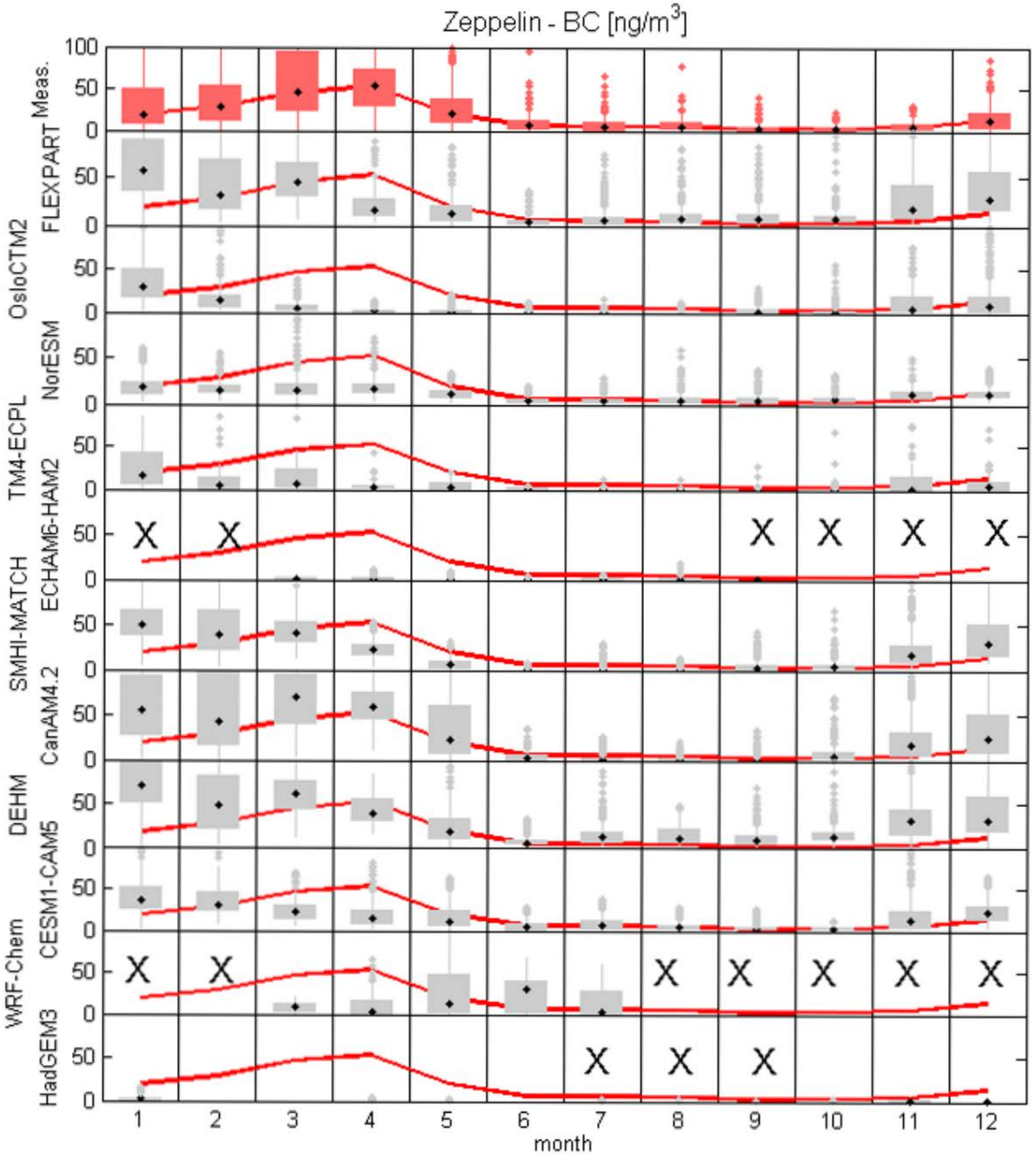


Table 11.1 Differences in the ensemble-mean climate states (MITIGATE – BASELINE) averaged over 2041–2050. Changes significant at p=0.05 are shown in bold.

	Model	Direct forcing from aerosols+CH_4+O_3 (W/m^2)	Surface air temperature (°C)	Sea-ice area (km^2)	Net cloud radiative effect (W/m^2)
Global	CESM (CAM5)	**-0.57**[a]	+0.05	+8.8×10^4	**+0.60**
	NorESM		**-0.20**	**+4.4×10^5**	
	CESM (CAM4)		**-0.24**	**+5.0×10^5**	
	HadGEM		**-0.29**	**+9.5×10^5**	
Arctic (60–90°N)	CESM (CAM5)	**-0.40**[b]	**-0.29**	**+1.6×10^5**	**+0.60**
	NorESM		**-0.42**	**+2.3×10^5**	
	CESM (CAM4)		**-0.58**	**+2.8×10^5**	
	HadGEM		**-0.49**	**+2.9×10^5**	

- 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 (± 0.17)
6. Substantial uncertainties originate from RCS factors and cloud-indirect effects

Thanks!

AMAP
Arctic Monitoring and Assessment Programme

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

www.amap.no