FINNISH METEOROLOGICAL INSTITUTE

In terms of radiative forcing, not all black carbon emissions are equal

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Outline

1. **Background / motivation**

2. **Model set-up**

3. **Experiments**

4. **Results, part 1: impact of emission location**
   -for uniform BC emissions throughout the year

5. **Results, part 2: impact of emission season**
   - globally, for zonally uniform emissions
   - for the subarctic zone (56.84°-68.21°N), as a function of longitude

6. **Results, part 3: a reconstruction exercise**
   - how well can one recover the BC radiative forcing from the idealized experiments, for a realistic distribution of emissions?

7. **Summary & remaining questions**

1. Background / motivation

- Development of robust emission metrics to guide climate policy for short-lived climate forcers like black carbon (BC) is complicated by the fact that the atmospheric concentrations, the radiative forcing (RF), and ultimately, the climate response, depend on the location and timing of emissions

- In the present work, we study systematically one part of the problem: how does the RF associated with BC emissions depend on the latitude, longitude and season of emissions?

  - the emphasis will be on global-mean top-of-the atmosphere (TOA) BC direct RF and the RF due to BC in snow (although the methodology also allows addressing the spatial distributions of RF)

2. Model set-up

The experiments were conducted with NorESM1-Happi

- An upgraded model version from NorESM1-M used for CMIP5 (Graff et al., Earth. Syst. Dynam., 10, 569-598, 2019)

  - the upgrades include more efficient wet deposition for BC

  - for this study, diagnostic shortwave radiation calculations were added for evaluating separately the effect of BC in air and snow (also, aerosol indirect effects are diagnosed, but not discussed much here …)

- Horizontal resolution 1.9° x 2.5°

- **AMIP-style runs**; SSTs and sea ice from merged Reynolds/HadISST products (Hurrell et al., J. Climate 2008)

Model set-up: ”AEROFFL”

NorESM’s aerosol scheme (Kirkevåg et al., Geosci. Model Dev., 6, 207–244, 2013) **was run in an offline mode**

- physical and chemical processes influencing aerosol concentrations are simulated interactively, but the simulated aerosol concentrations do not influence the simulated climate

  - instead, in the atmosphere model (CAM4-Oslo), CCSM’s prescribed standard aerosols are used for integrating the model forward in time

- Similarly, while BC in snow was simulated interactively (over land, in CLM4/SNICAR, over sea ice, in CICE4), its impact was not included in the snow albedo used for climate feedback calculations

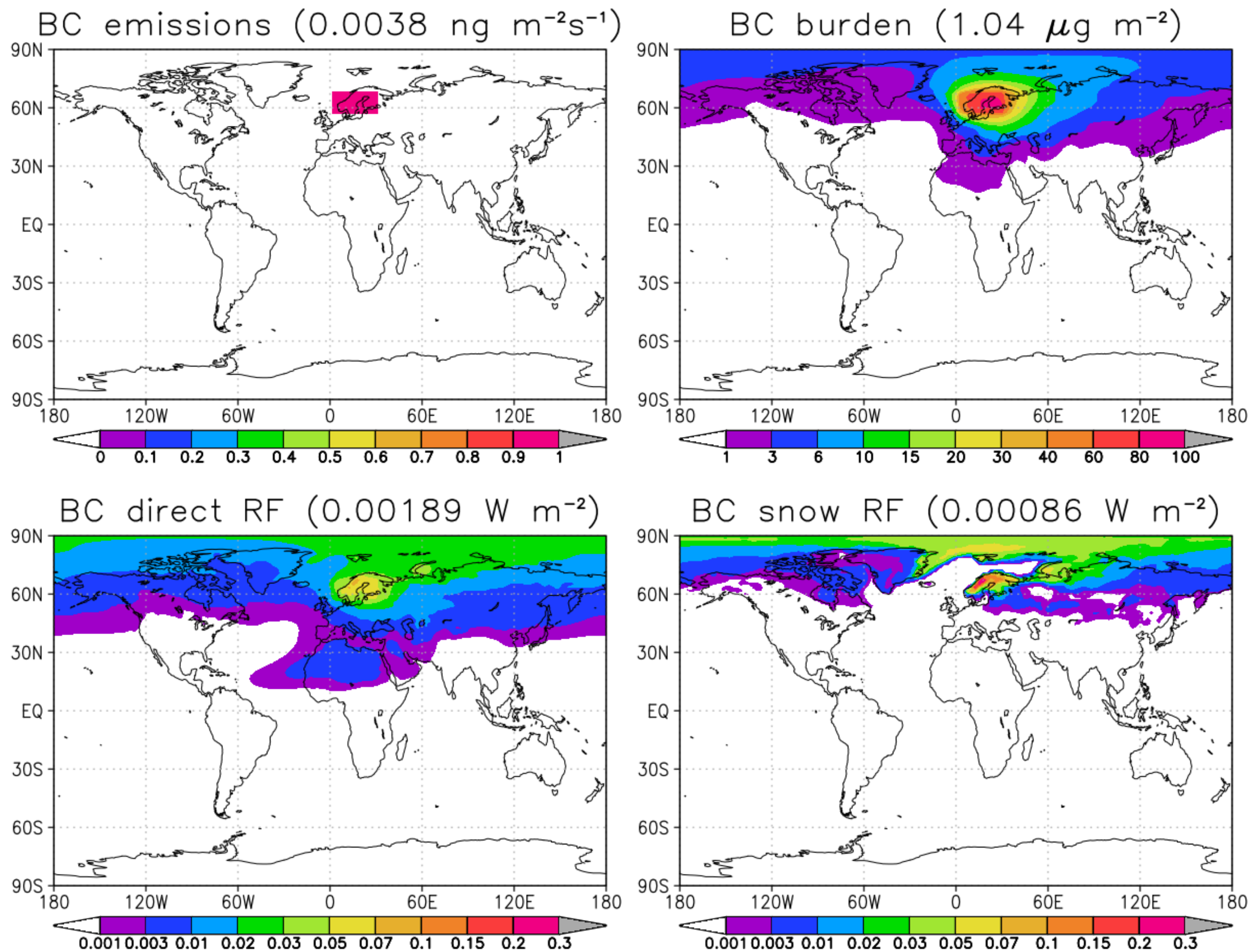
The benefit of the off-line treatment of aerosols

Meteorological conditions are repeated identically irrespective of the assumed BC emissions

$\Rightarrow$ This allows for an essentially noise-free evaluation of even very small radiative forcings!

Example: constant BC emissions (10^{-12} kg m^{-2} s^{-1}) in the Fennoscandian area (56.84-68.21°N, 1.25-31.25°E)

- global mean values given in parenthesis



Treatment of emissions

- **Greenhouse gases**
  - RCP8.5, for model years 2012-2017

- **sulphates, POM**
  - emission year fixed to 2015
  - biomass burning emissions: ”IPCC emissions”, RCP8.5
  - ”fossil fuel” emissions: ECLIPSE V6b CLE
    * 7 sectors: DOM, ENE, FLR, IND, SHP, TRA, WST
    * the AWB sector (agricultural waste burning) omitted due to likely overlap with biomass burning

- **black carbon**:
  - either as above (for sulphates & POM) …
  - or (= <u>for almost all runs!)</u> idealized emission distributions, with BC emissions constrained to a specific region / season

For the record: BC-related fields when using "real" emissions (ECLIPSE V6b CLE + IPCC RCP8.5)

- Global statistics for year 2015 emissions
  - includes both anthropogenic and natural BC

BC emissions: $5.18 \cdot 10^{-13}$ kg m^{-2} s^{-1} ⇔ 8.3 Tg yr^{-1}

BC burden: $2.78 \cdot 10^{-7}$ kg m^{-2} ⇔ 142 Gg

BC lifetime: 6.2 days

BC direct RF (TOA): 0.650 Wm^{-2}

BC snow RF (TOA): 0.033 Wm^{-2}

BC snow RF for zero emissions*: 0.0043 Wm^{-2}

(* Even in the absence of emissions, there is some BC stored in snow in regions with permanent snow, especially Greenland)

3. Experiments

- **BC emission rate set to 10^{-12} kg m^{-2} s^{-1} for specific regions (and in some cases, seasons), otherwise zero**

  - BC released to the lowest model layer (and treated as ”fossil fuel” BC, see Kirkevåg et al., GMD 2013)

- For this purpose, **the world was split into 16 latitude zones** (0.00-11.37°N, 11.37-22.74°N, 22.74-34.11°N, 34.11-45.47°N, 45.47-56.84°N, 56.84-68.21°N, 68.21-79.58°N, 79.58-90.00°N, and similarly for the southern hemisphere) and **12 longitude zones** (178.75-148.75°W, 148.75-118.75°W, …, 151.25-181.25°E)

  - for convenience, region boundaries selected so that each NorESM grid cell belongs to exactly one region

- Seasonal distribution of emissions: **either throughout the year** (ANN), **or for only one season** (DJF, MAM, JJA, SON)

Model runs conducted

- **Runs with emissions throughout the year (ANN) for all 192 lat-lon regions** (192 runs)

- Runs **for all 5 seasonal emission distributions** (ANN, DJF, MAM, JJA, SON):
  - zonally uniform emissions (16 latitude zones $\Rightarrow$ 80 runs)
  - lat-lon -resolved emissions for the ”subarctic” latitude zone (56.84-68.21°N) (48 runs, on top of ”ANN”)
  - other lat-lon-season combinations: work in progress …

- **A run with BC emissions set to zero**
  - a baseline for the ”residual” BC radiative forcing in snow (cf. slide 8)

All experiments were run for 6 years (2012-2017), and statistics were computed for 2013-2017

4) Results, part 1: impact of emission location

(for seasonally uniform emissions)

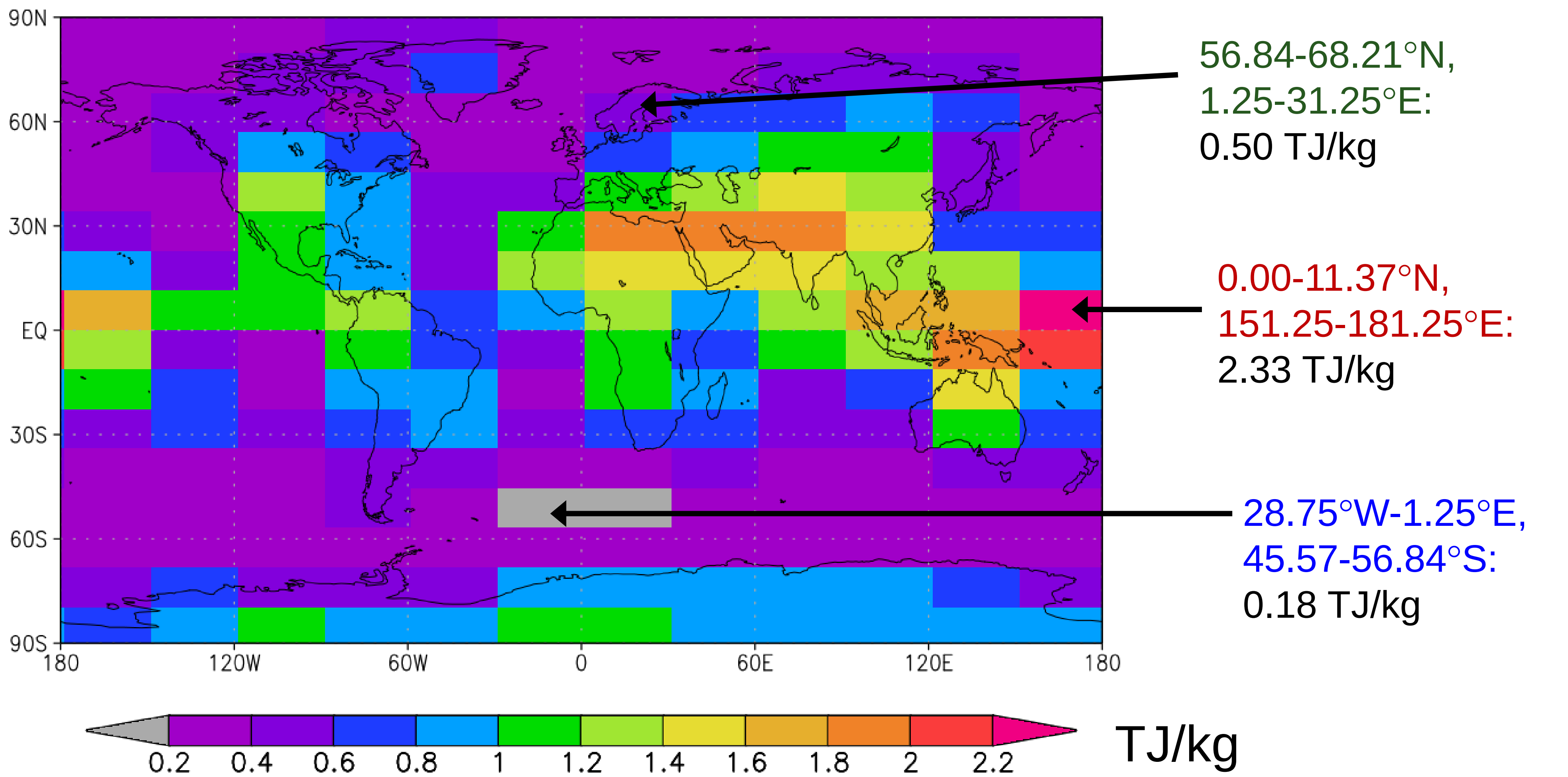
- The focus will be on BC direct radiative forcing, and the radiative forcing due to BC in snow (both defined at TOA)

- The forcings will be expressed in units of TJ kg^{-1} (the energy added to the climate system by emission of 1 kg BC). In the present case, global-mean forcings may be converted to W m^{-2} as

  Forcing [W m^{-2}] = area_fraction_of_emissions x Forcing [TJ kg^{-1}]

- BC lifetime associated with emissions in a given region is also considered (lifetime = burden / emissions, both averaged over the globe)

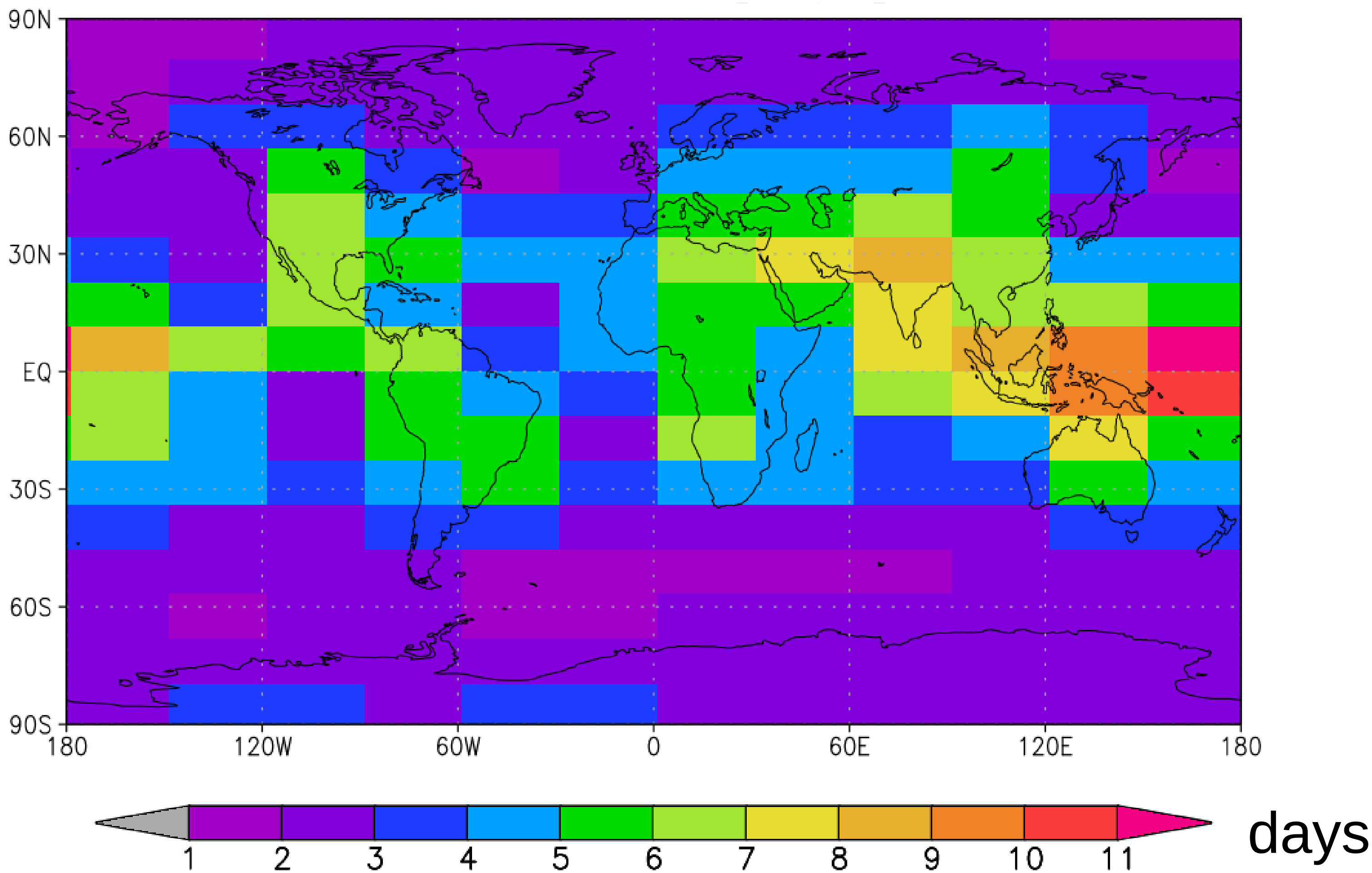
Global-mean BC direct radiative forcing at TOA



An order of magnitude variation depending on emission location

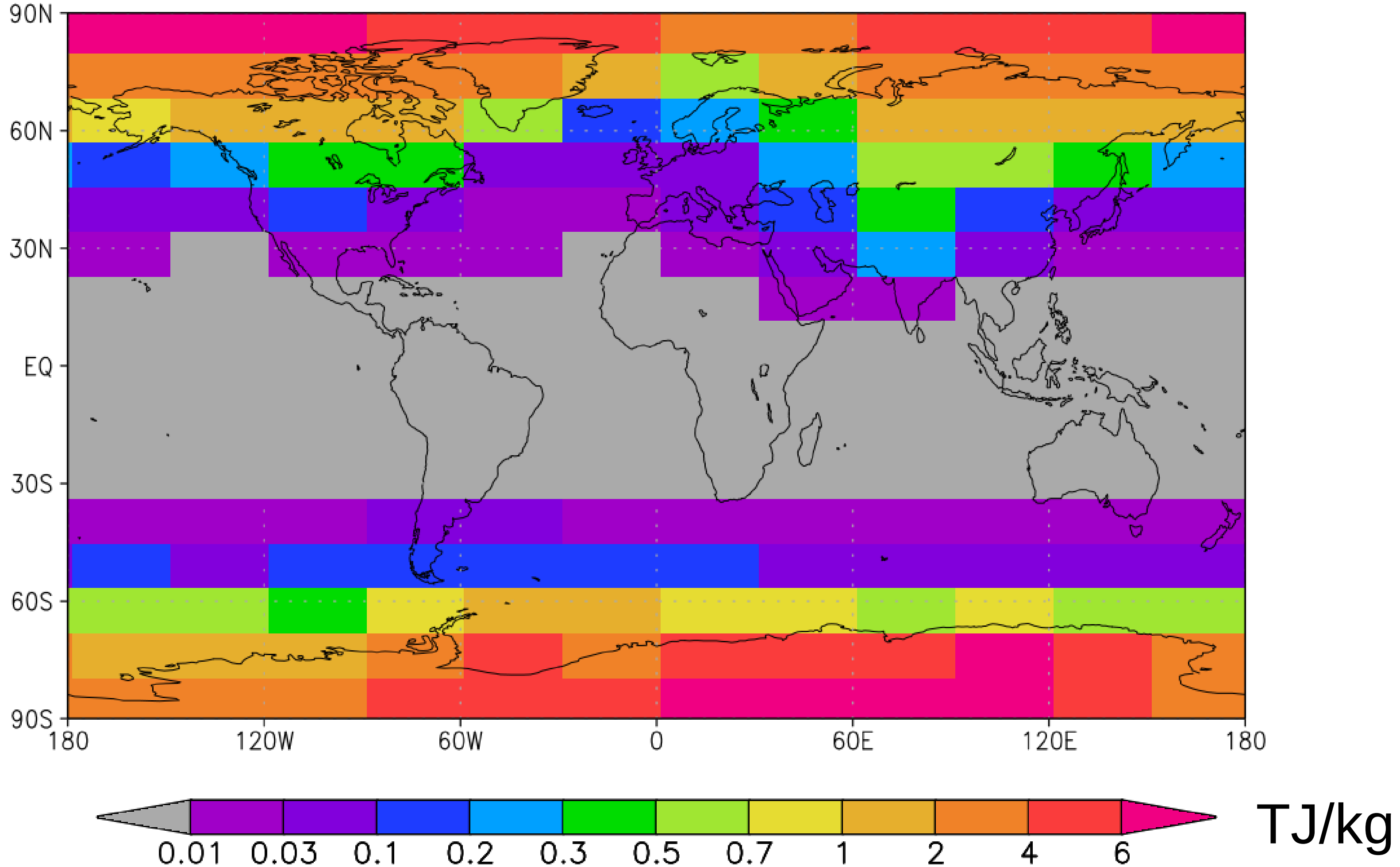
- largest values in regions of deep convection
- other factors: surface albedo, cloudiness, insolation …

BC lifetime



Varies from less than 2 to more than 11 days; explains a part of the differences seen in the BC direct radiative forcing

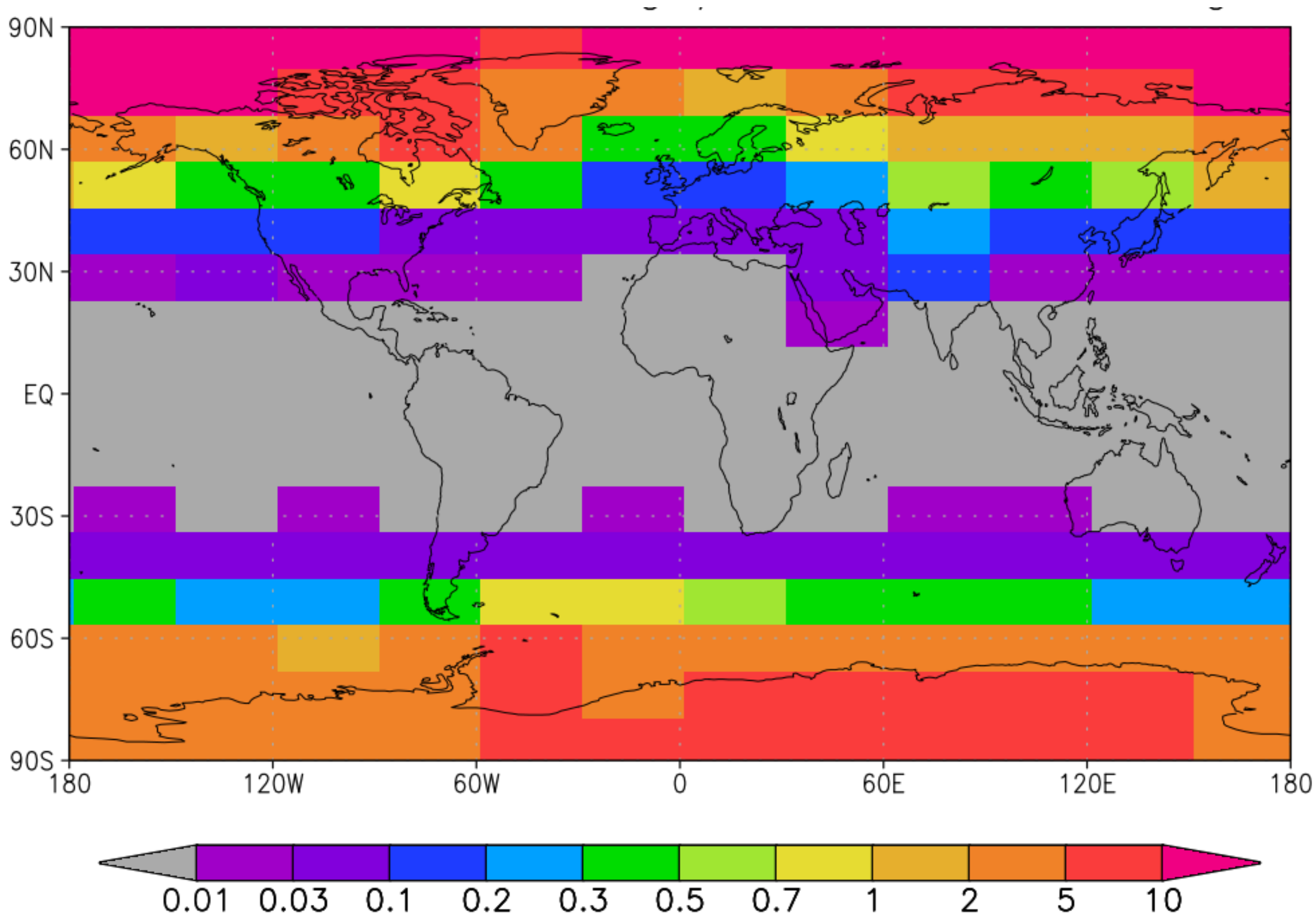
Global-mean radiative forcing due to BC in snow



Virtually zero at low latitudes, but very large in the Arctic and in the Antarctic (maxima much larger than those in DRF!)

- also note the substantial longitudinal variation, e.g. at 56.84-68.21°N

Ratio: BC snow radiative forcing / DRF



The DRF dominates for low-to-midlatitude emissions, but in the Arctic and in the Antarctic, the snow forcing is <u>much</u> larger

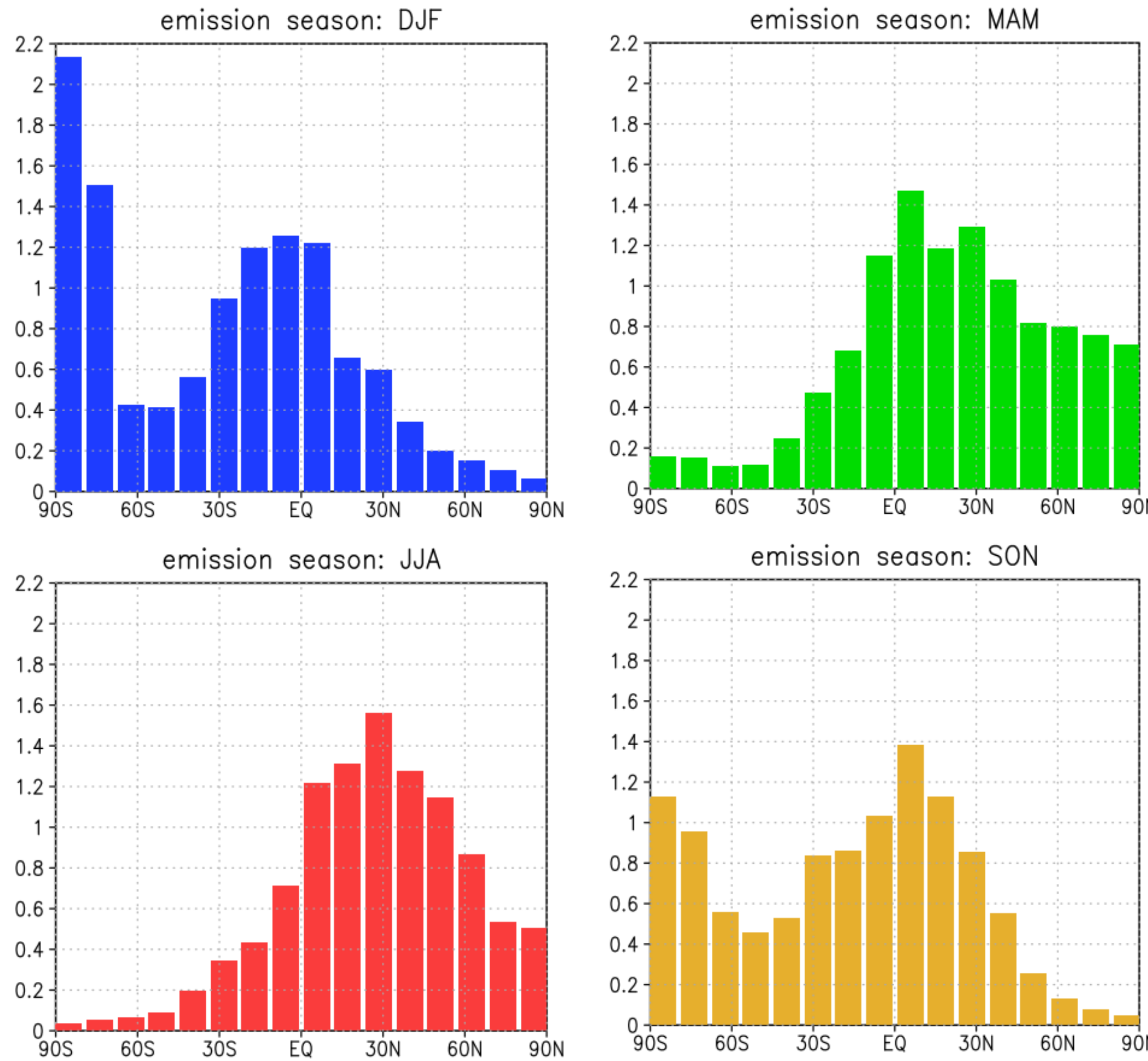
5. Results, part 2: impact of emission season

- the case with zonally uniform emissions

Global-mean BC direct radiative forcing at TOA
(units: TJ / kg)

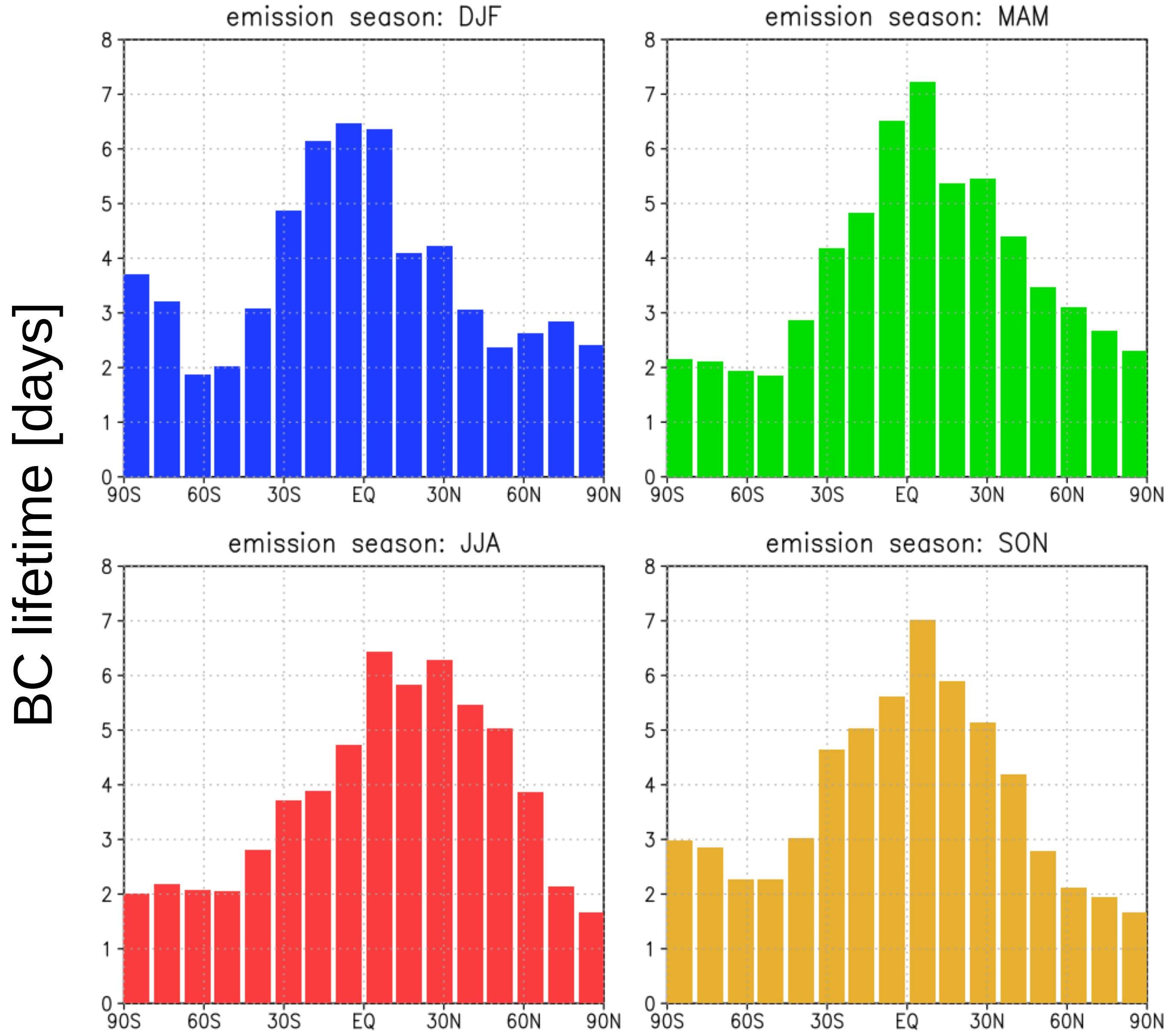
The radiative forcing associated with mid-to-high-latitude emissions largely follows the annual cycle of insolation

- although, for the Arctic BC emissions, the maximum DRF already occurs in spring (less snow and ice in summer)



BC lifetime also depends on the emission season

Especially for emissions from mid-latitude (land?) regions, the lifetime is longer for emissions in summer than winter, due to more convective conditions.



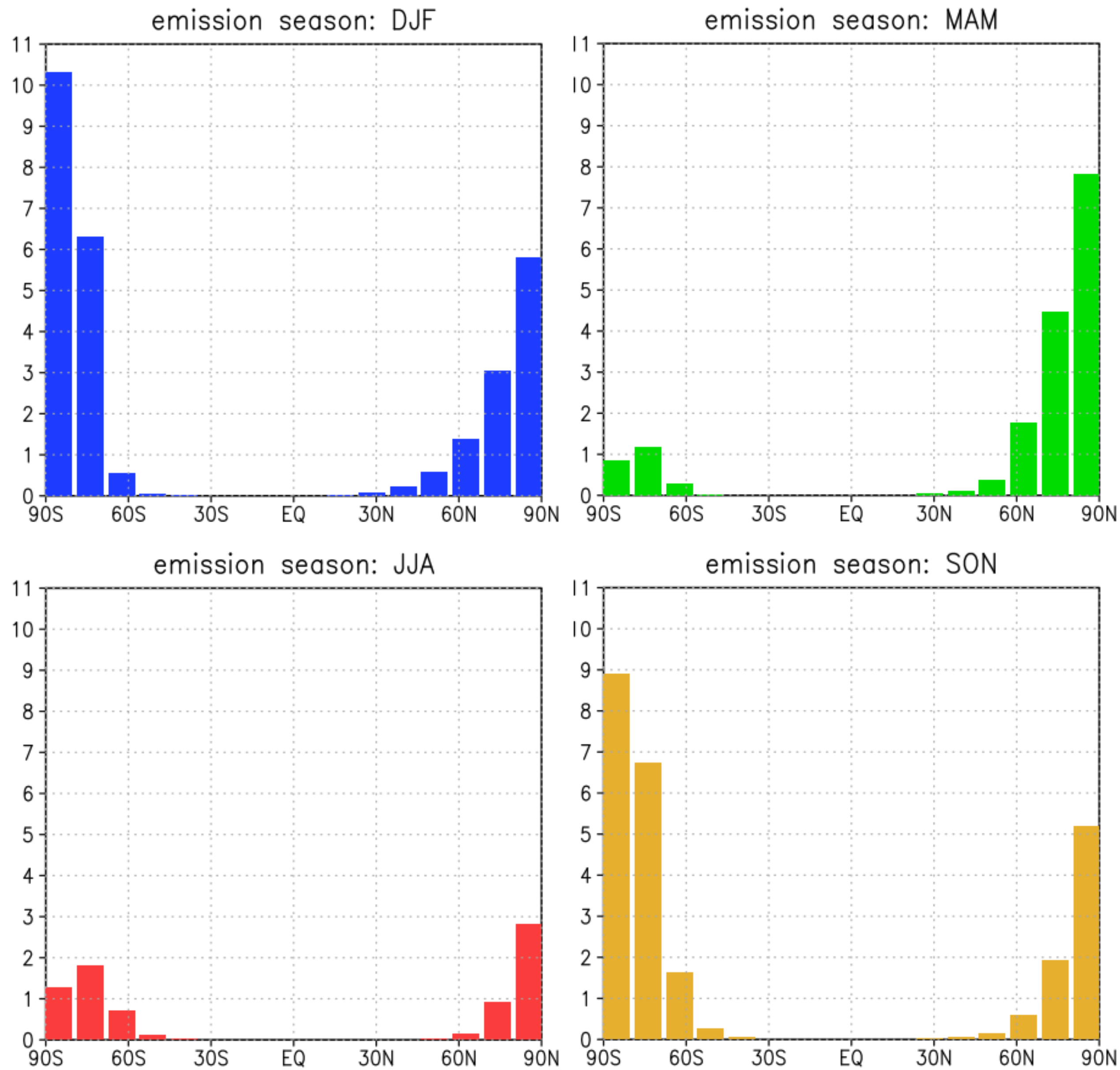
Radiative forcing due to BC in snow [TJ / kg]

The dependence on emission season is quite different from that for the DRF!

- BC accumulated in snow in the dark season can absorb solar radiation several months later!

For NH high-latitude emissions, maximum occurs in spring and minimum in summer (due to lack of snow)

For Antarctic emissions, maximum occurs in summer (permanent snow!) but the autumn and winter values are low (not obvious why …)



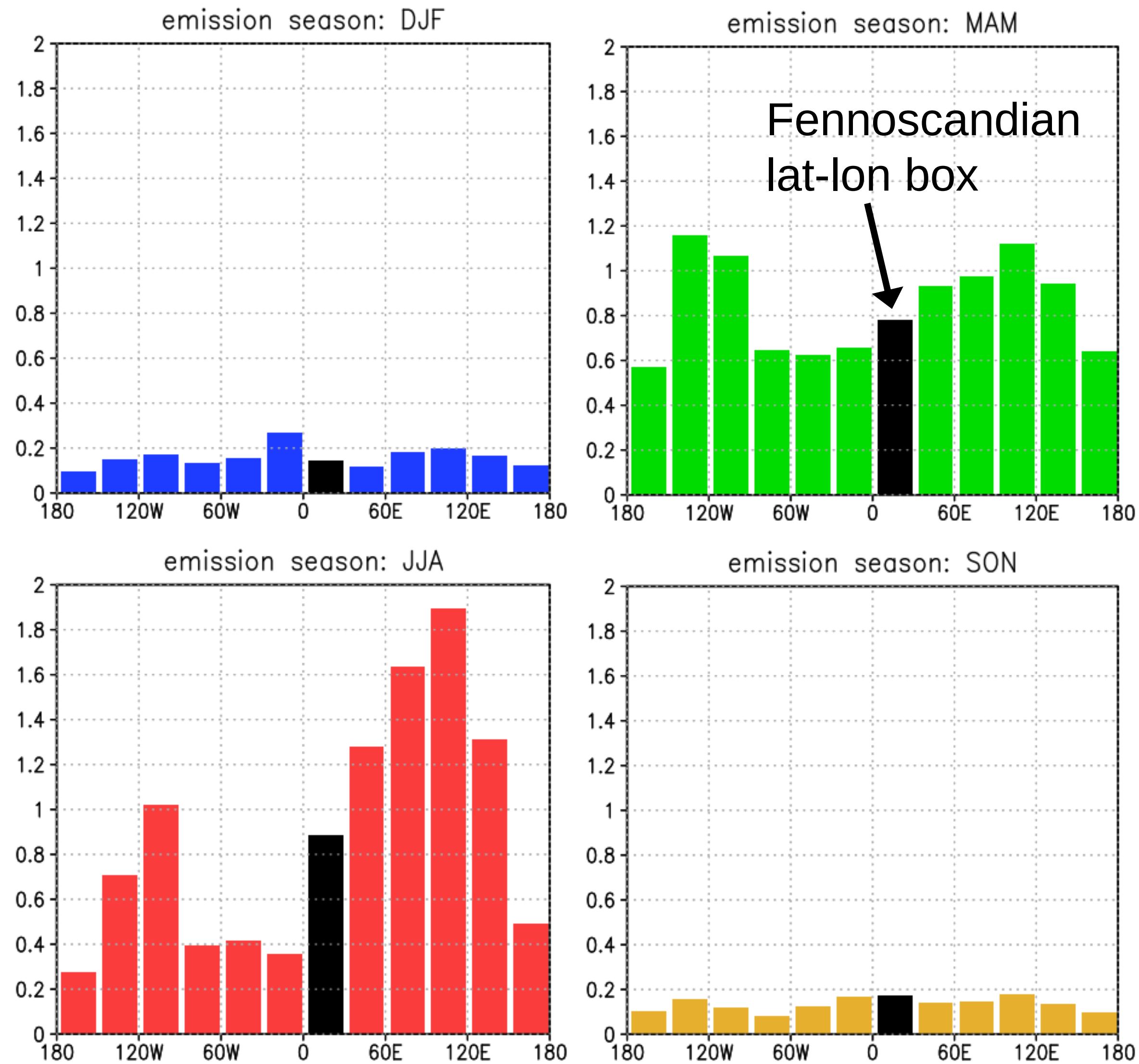
Impact of emission season

- for emissions from the subarctic zone (56.84-68.21°N)

Global-mean BC direct radiative forcing at TOA
(units: TJ / kg)

The primary contribution comes from spring & summer emissions

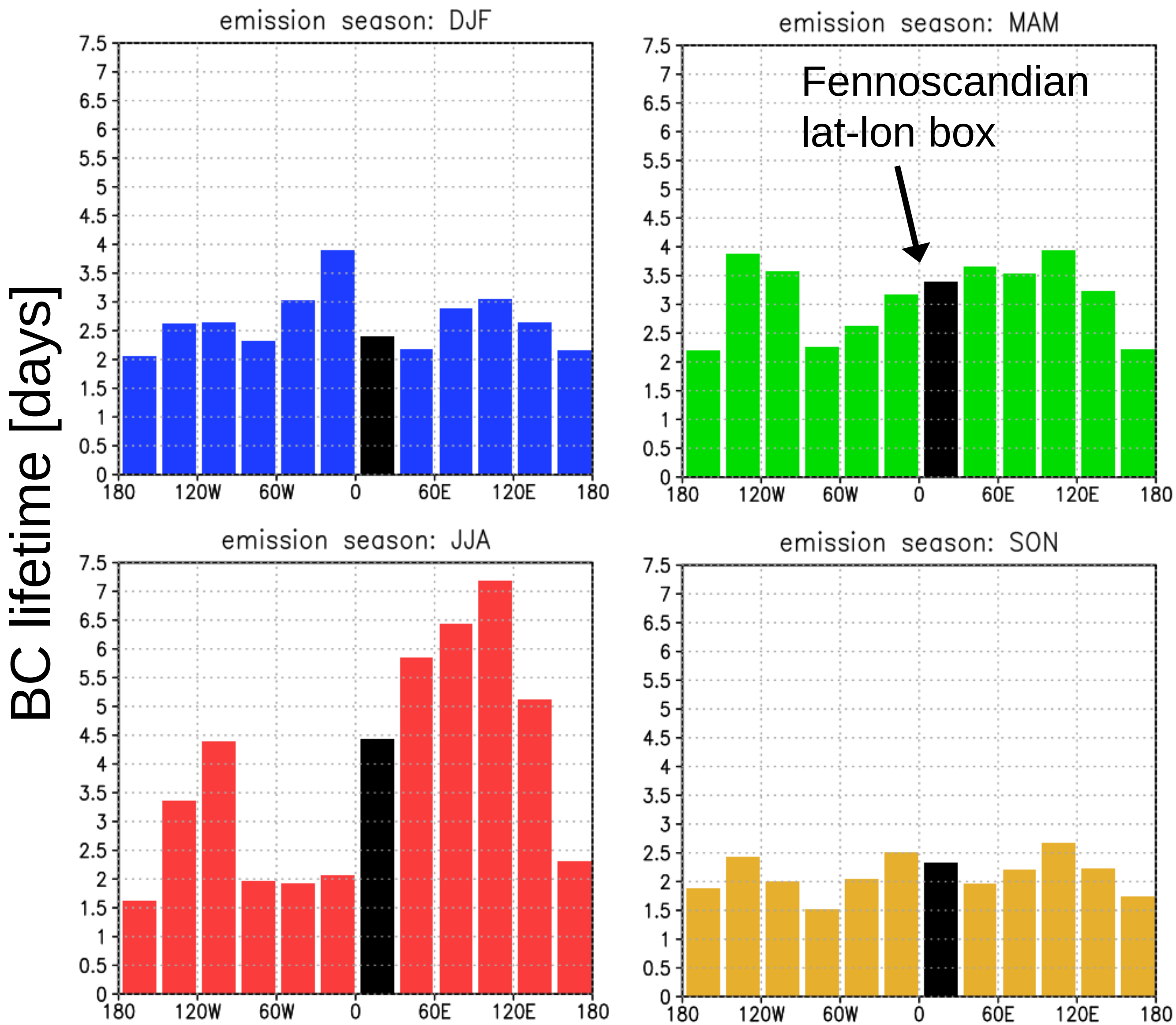
There is substantial dependence on the longitude of emissions, especially in summer.



Lifetime for BC from the subarctic zone (56.84-68.21°N)

In summer, generally longer lifetime for continental than maritime emissions

Note especially that long atmospheric lifetime contributes to the large DRF associated with summertime BC emissions from Siberia

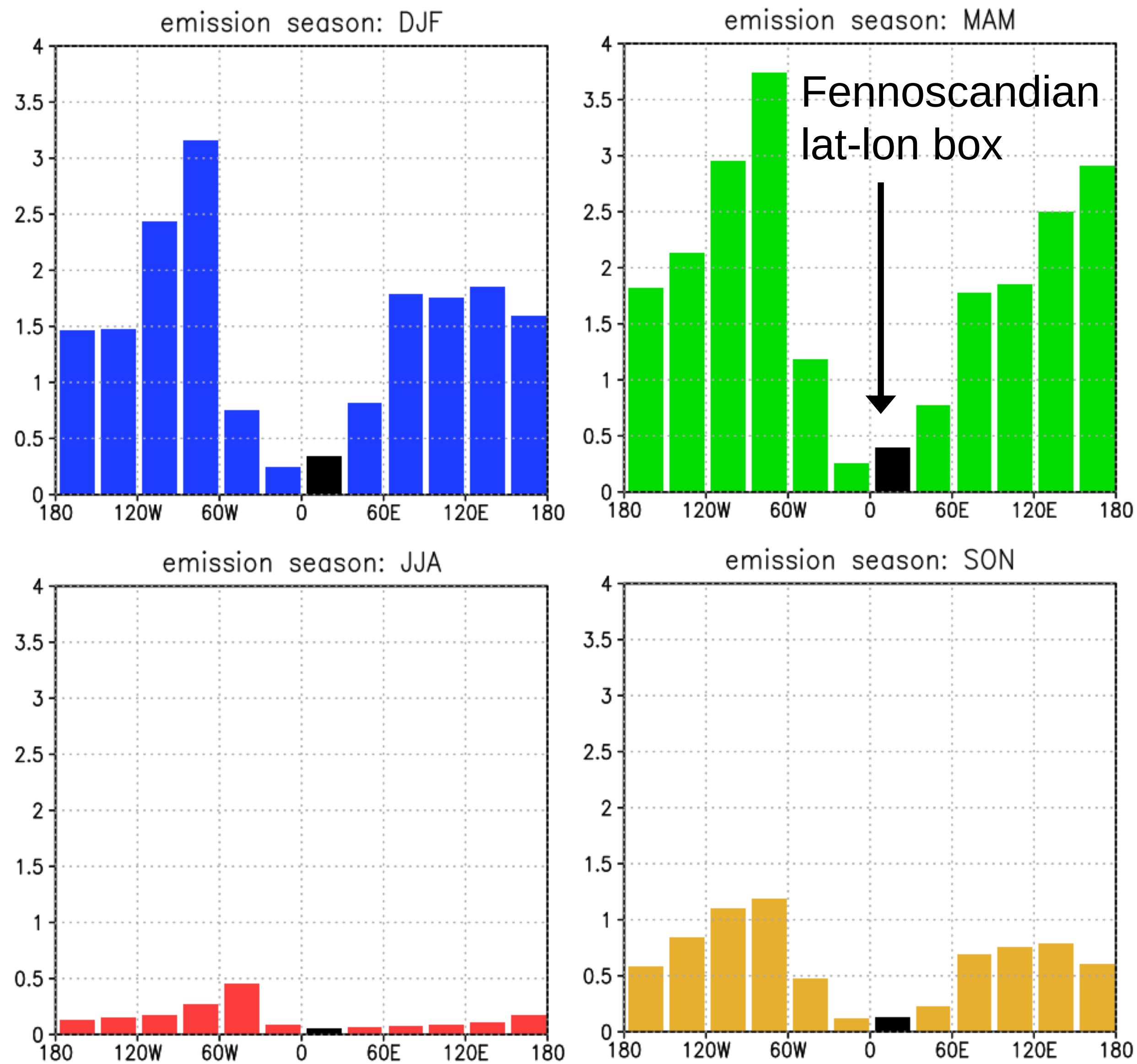


Snow radiative forcing [TJ/kg] for BC emissions from the subarctic zone (56.84-68.21°N)

Very strong dependence on longitude!

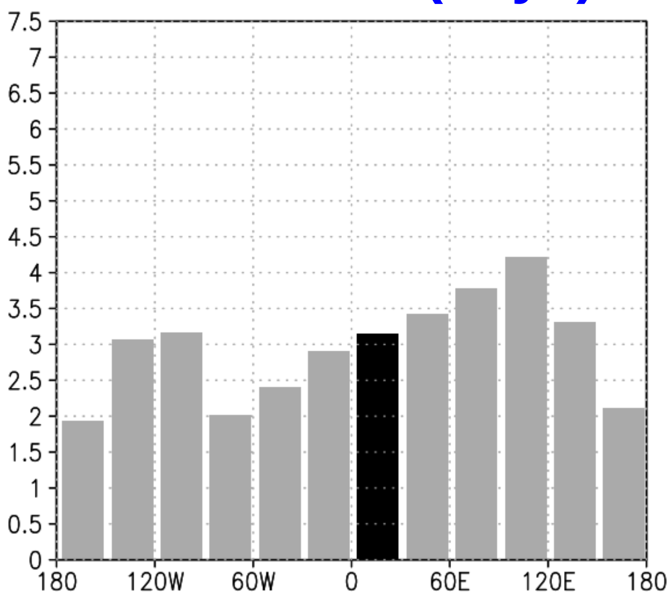
Largest values for emissions from northeastern North America and Siberia, as emissions from these regions are mostly deposited in areas where snow prevails long into spring / early summer.

Relatively small values e.g. for the Fennoscandian lat-lon box

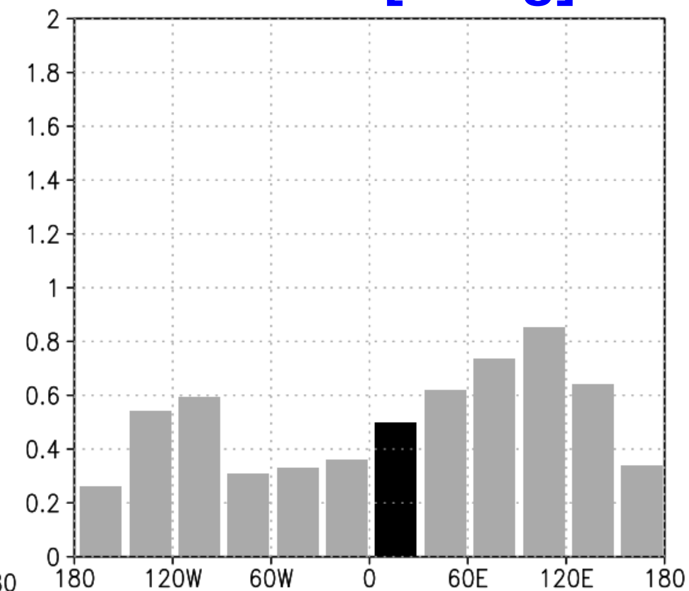


Annual-means for the subarctic zone (56.84-68.21°N)
(i.e. the case with constant emissions through the year)

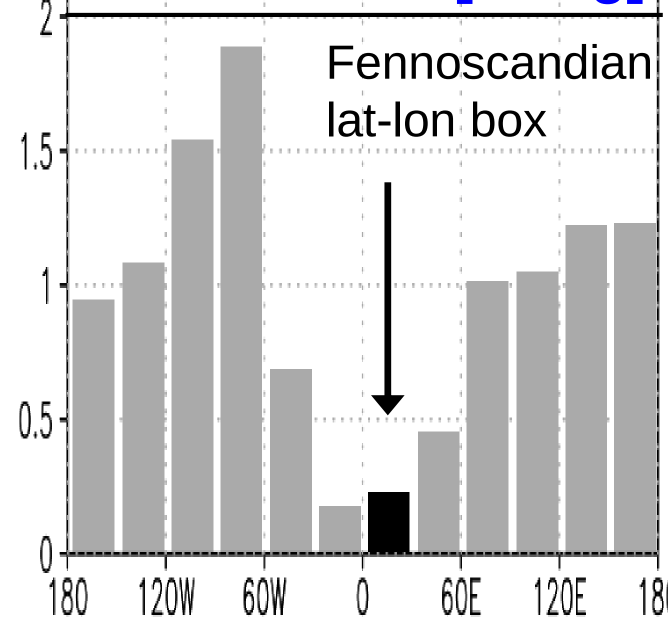
BC lifetime (days)



BC DRF [TJ/kg]



BC snow RF [TJ/kg]



There are substantial longitudinal variations

- For example, for a given emission rate, the Fennoscandian emissions are less harmful than those from e.g. Siberia (gas flaring from Russian oil industry)

At most longitudes, the BC snow RF dominates over the direct RF

- and probably more so for the climate response? BC snow RF has high efficacy!

6. Results, part 3: a reconstruction exercise

BC concentrations & radiative forcings might depend non-linearly on BC emissions

When there is a global distribution of BC emissions, is it possible to estimate (e.g.) the resulting radiative forcing as a weighted sum of forcings derived for single-region emissions?

?

The estimated radiative forcing fields were derived as:

$$\mathrm{RF}_{\mathrm{estimated}}(x,y) = \sum_{j=1}^{m} \sum_{i=1}^{n} \frac{\varepsilon_{\mathrm{real},i,j}}{\varepsilon_{\mathrm{ideal},i,\mathrm{j}}} \mathrm{RF}_{\mathrm{ideal},i,j}(x,y)$$

Here: **i** = 1…n = index for the longitude zones (n=12)

j = 1…m = index for the latitude zones (m=16)

$\varepsilon_{\mathbf{real},\boldsymbol{i},\boldsymbol{j}}$ = ”real-world” BC emission rate averaged over the lat-lon box (i,j)

$\varepsilon_{\boldsymbol{ideal},\boldsymbol{i},\boldsymbol{j}}$ = emission rate for lat-lon box (i,j) in the idealized single-region emissions experiments (=10^{-12} kg m^{-2} s^{-1})

$\mathbf{RF}_{\boldsymbol{ideal},\boldsymbol{i},\boldsymbol{j}}$= radiative forcing associated with the emission $\varepsilon_{\boldsymbol{ideal},\boldsymbol{i},\boldsymbol{j}}$

NOTE: This can also be applied to other BC-related quantities, e.g. burdens

NOTE2: A third sum could be added for the season of emissions, but it would require a full lat-lon-season matrix of the idealized emission experiments

Two cases were reconstructed

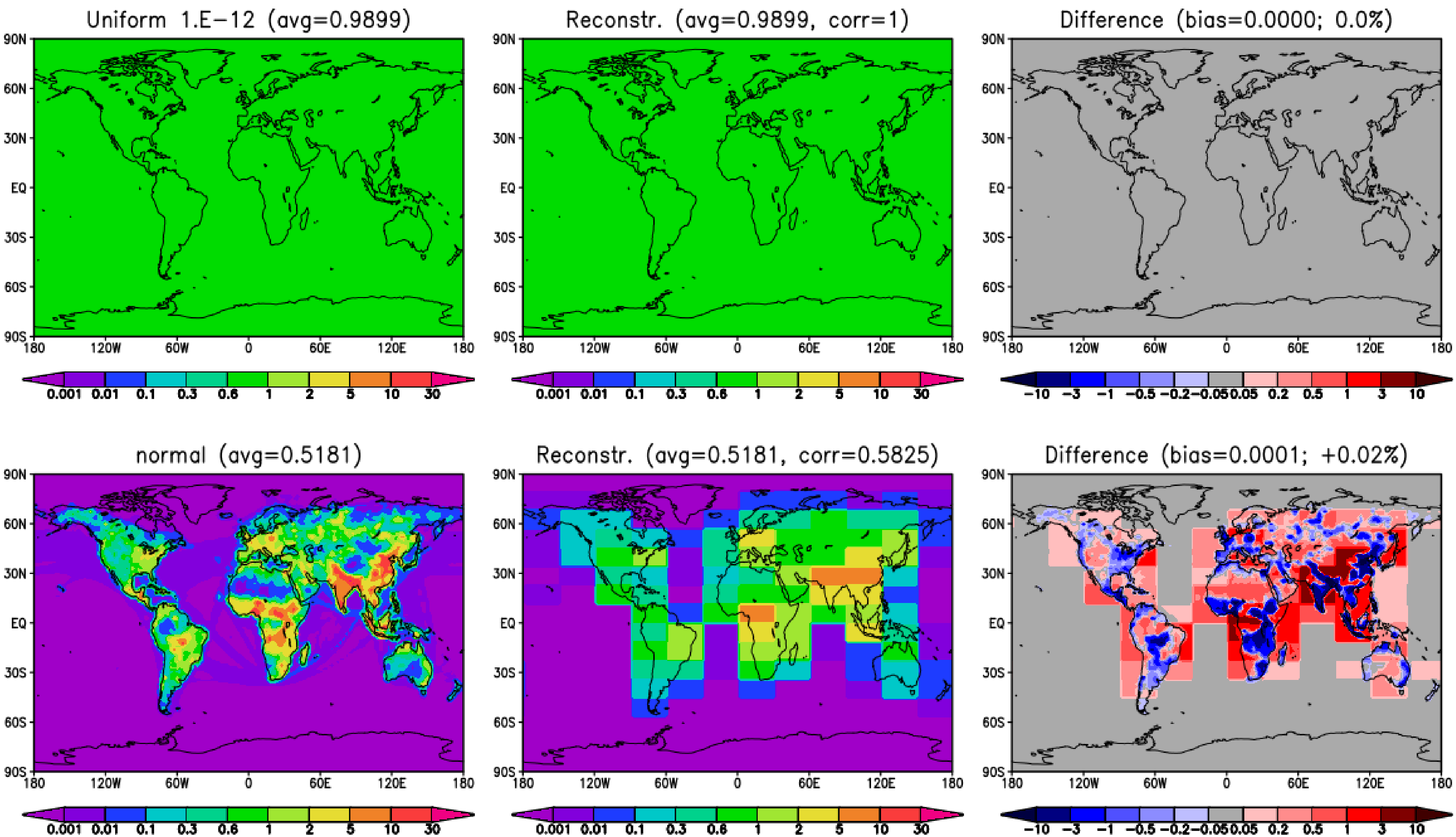
1) Uniform 1.E-12

- constant BC emission rate 10^{-12} kg m^{-2} s^{-1} everywhere
("a perfectly equal world")

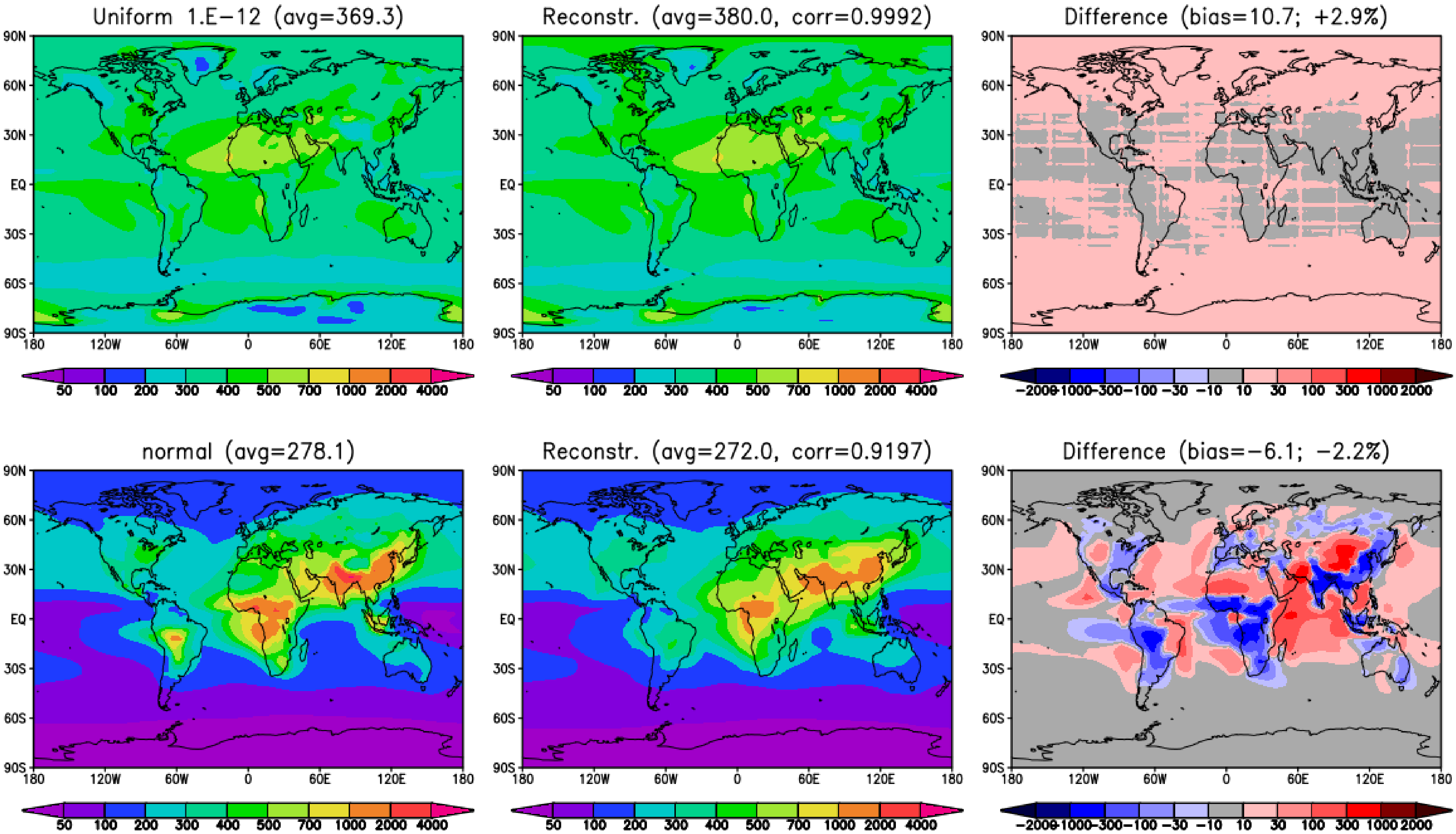
2) Normal

- an estimate of real-world emissions
= "fossil fuel" emissions from ECLIPSE V6b CLE, year 2015; biomass burning and aircraft emissions from IPCC RCP8.5

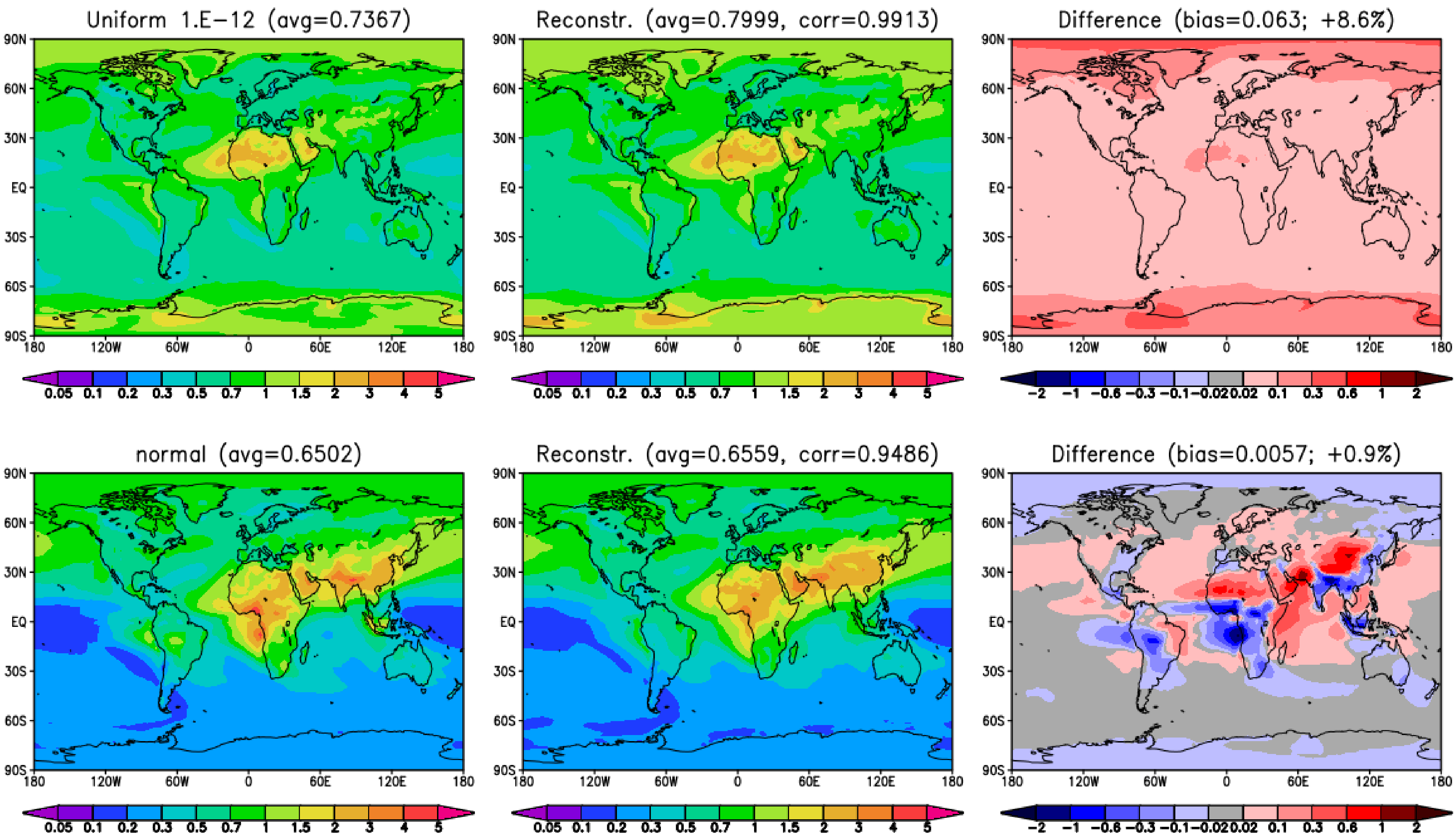
BC emissions (unit: 10^{-12} kg m^{-2} s^{-1})



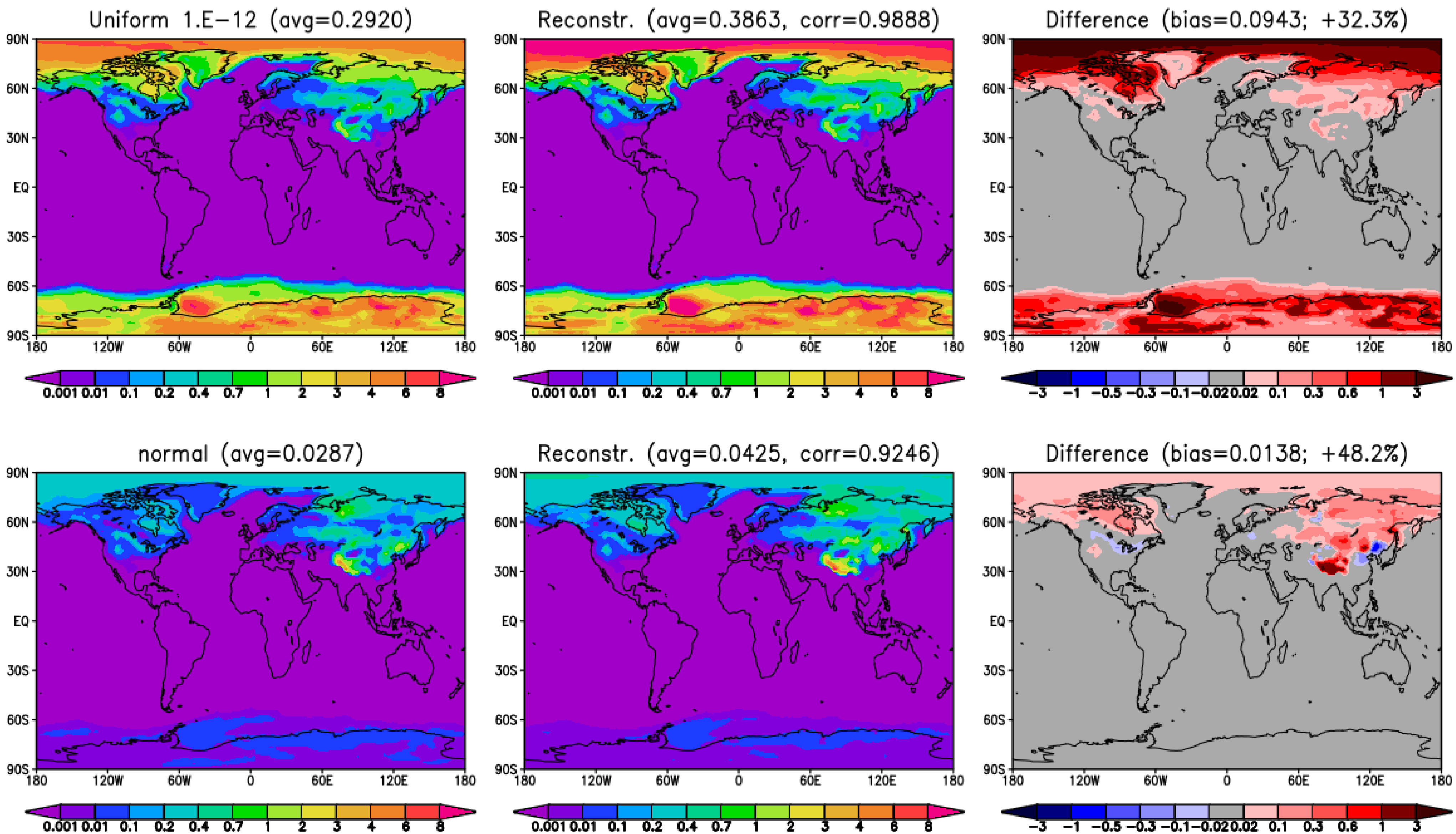
BC burden (unit: 10^{-9} kg m^{-2})



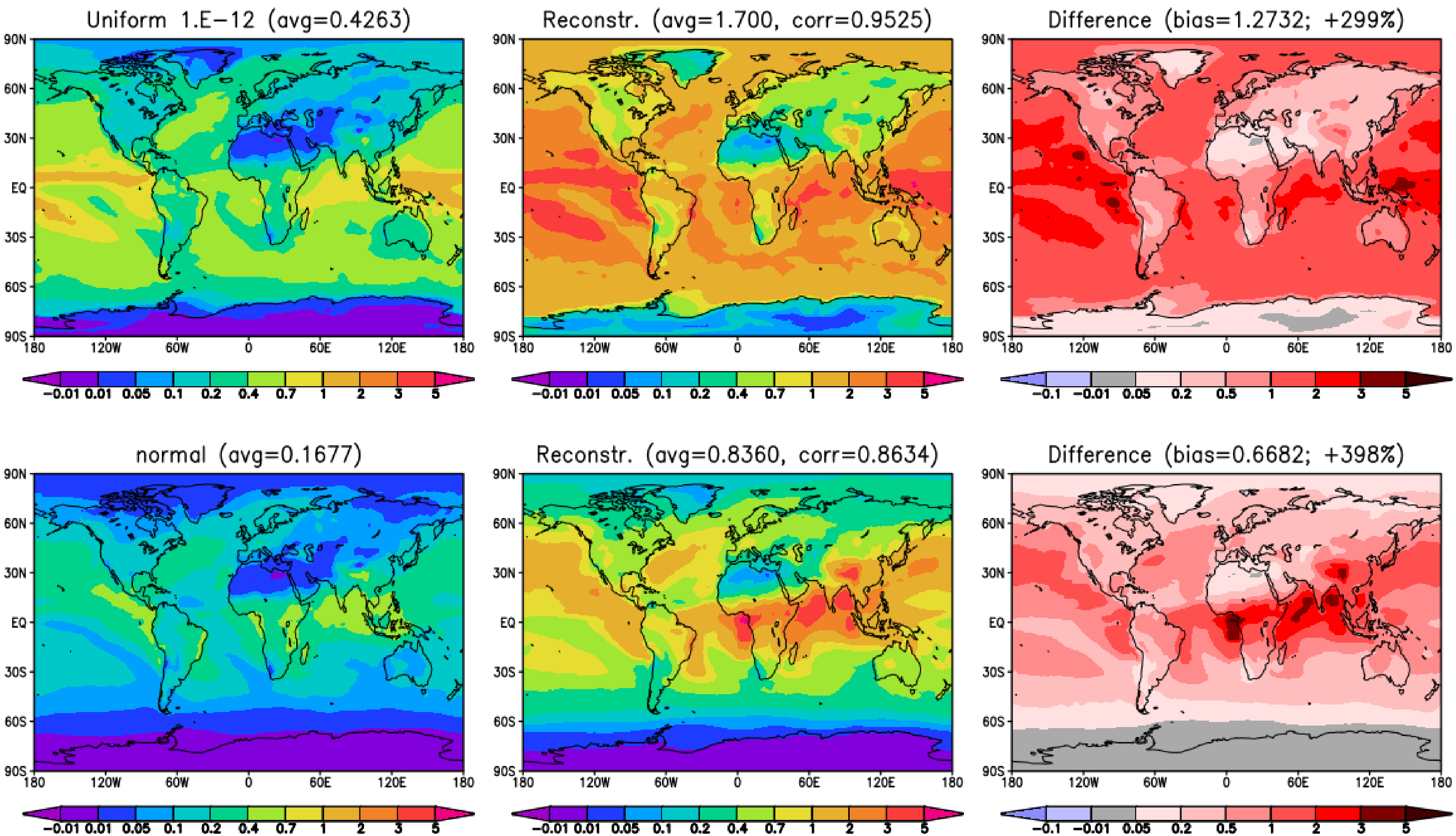
BC direct radiative forcing at TOA (W m^{-2})



TOA radiative forcing due to BC in snow (W m^{-2})



BC indirect forcing at TOA (W m^{-2})



Reconstruction exercise: findings

1) BC burdens and the direct RF are reconstructed quite well

- In fact, for the case with realistic emissions, the spatial correlations are much higher for the BC burden (0.92) and direct RF (0.95) than for emissions (0.58).

2) For the RF due to BC in snow, a positive bias exists

- Mostly less than 20% in the Arctic but ~70% in Tibet
- This occurs partly because the RF due to BC in snow increases weaker than linearly with increasing BC, for high BC concentration
- There are also some subtle effects related to how BC emissions are distributed over the ≈11.4 x 30° lat-lon boxes (typically, higher population density and more emissions in locations with less snow)
- The seasonal distribution of emissions also contributes (if the ”real-world” emissions are averaged over the year, the overall bias drops from +48 to +33%)

Reconstruction exercise: findings …

3) For the BC indirect RF, a catastrophic overestimate results!

- evidently, the indirect RF depends very non-linearly on BC concentrations!
- This suggests that the indirect RF cannot be meaningfully estimated by summing up the contributions from individual regions
- Overall, the BC indirect RF is not well-known. Interestingly, it is generally positive in NorESM1-Happi (and original NorESM1); most studies suggest a slight negative forcing (e.g., Bond et al., JGR 2013)

7. Summary

- The global-mean **direct radiative forcing caused by a given BC emission depends strongly on the location of emissions**, with variations by a factor of up to ≥ 10 (even for emissions uniform in time)

  - typically, largest burden and DRF associated with emissions in convective low-latitude locations

  - factors that also influence the DRF: availability of solar radiation; transport of BC over high-albedo surfaces (snow, ice, desert or optically thick clouds

- **The RF due to BC in snow** is minimal for low-latitude emissions, but **over high latitudes, it dominates overwhelmingly over the BC direct RF** (and even more so for the climate response?)

  - the typically short lifetime of high-latitude BC emissions reduces the DRF, but not the RF due to BC in snow

Summary (cnt'd)

- There is **substantial dependence on the longitude of emissions**

  - for example, for the Fennoscandian emissions, the BC snow RF is much smaller than that typical of the subarctic zone (56.84-68.21°N)

- **The seasonal cycle of emissions is also important**

  - The DRF associated with a given BC emission largely follows the seasonal cycle of insolation: maximum for emissions in summer and minimum for emissions in winter

  - The RF due to BC in snow is generally largest for spring emissions over the NH and for summer emissions in the Antarctic

Some remaining questions

1) ”All models are wrong”, including NorESM1-Happi
   - **how model-dependent are these results?**

2) It is well known that **for BC, the top-of-the-atmosphere radiative forcing alone is not a very good metric for the climate response**

   - yet, the climate response would be the most relevant information for developing emission metrics to guide climate policy

   - a direct evaluation of the climate response with the current lat-lon(-season) resolution of emissions would be totally unfeasible (a signal/noise nightmare!)

Thank you for your interest!

(And sorry: it is mineral dust, not black carbon …! :-)