

Background & Motivation

Nuclear explosions can cause acute and prolonged local damage with extreme societal and health consequences at the locations of detonation.

In regional nuclear conflict scenarios, in addition to local damage, firestorms triggered at targeted urban and industrial centers could inject a great amount of black carbon (BC) and particulate organic matter (POM) into the upper troposphere – lower stratosphere (UTLS) and cause global climate effects^{1,2}. Climate modeling studies have shown that the injected carbonaceous aerosol could

- Heat the upper atmosphere by increasing absorption of solar radiation aloft^{3,4}
- Cool the Earth's surface and reduce precipitation in the long term^{2,3,4,5}
- Deplete stratospheric ozone by disrupting stratospheric chemistry^{6,7}

A wide range of plausible BC emissions, from 20 to 290 Tg, could arise as a result of a full-scale nuclear exchange involving USA and Russia⁸.

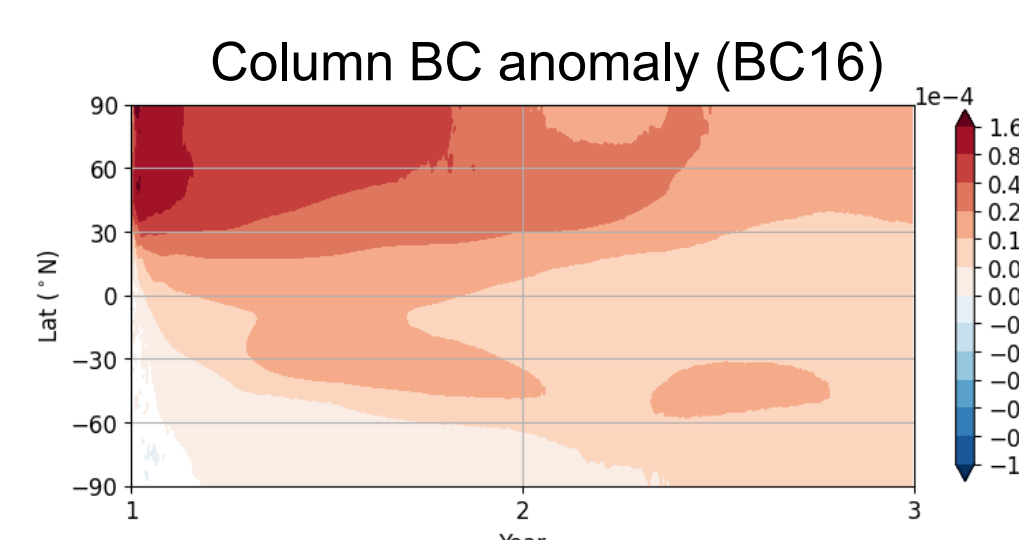
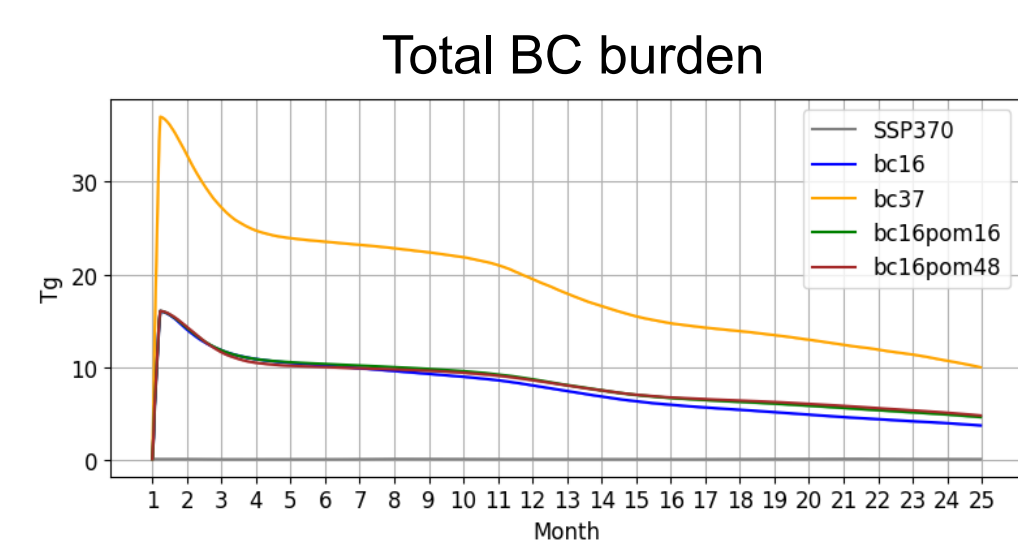
However, these climate modeling studies typically consider 100-150 Tg of BC injection, with relatively few studies exploring the climate response to relatively limited BC injections (about 20 Tg; still large compared to PyroCbs in recent major wildfire events⁹), leaving key aspects of their climate impact poorly understood.

Here, we investigate the climate response to BC/POM emission in relatively limited-forcing scenarios (16 Tg of BC injection and 0-48 Tg of POM injection).

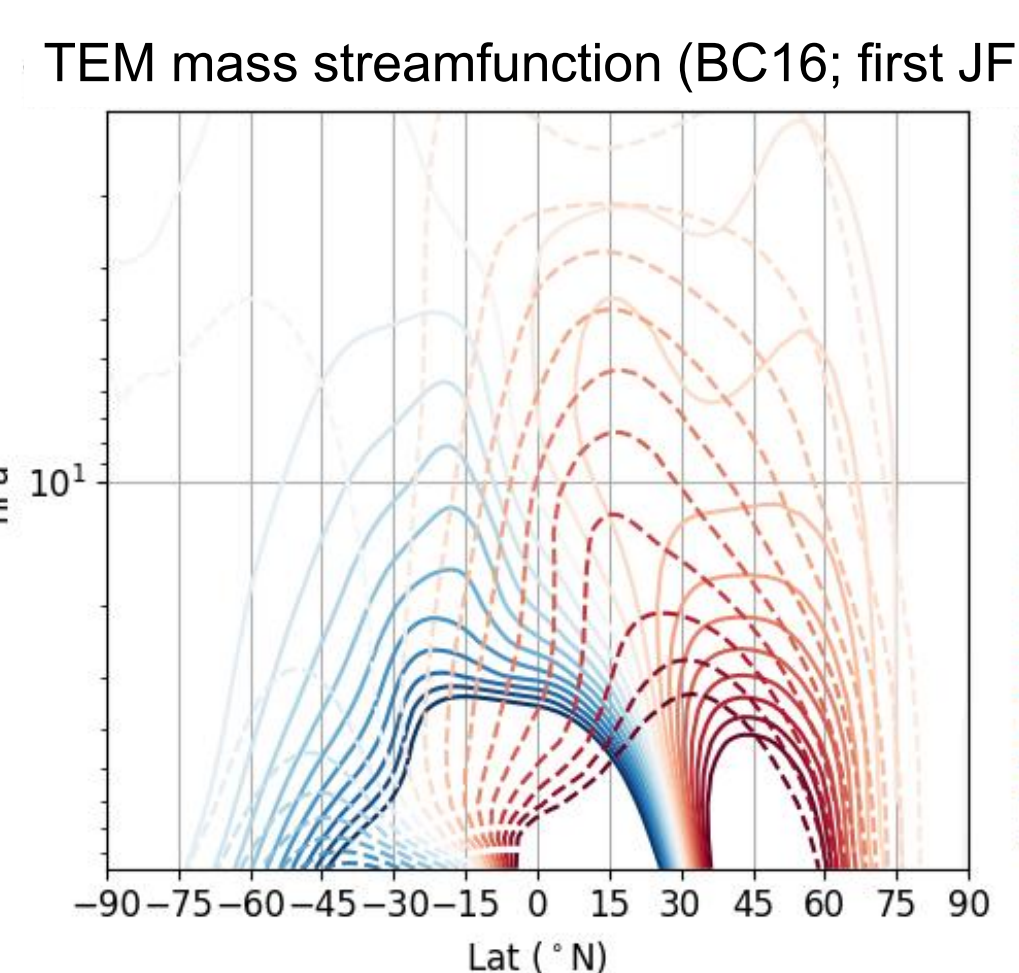
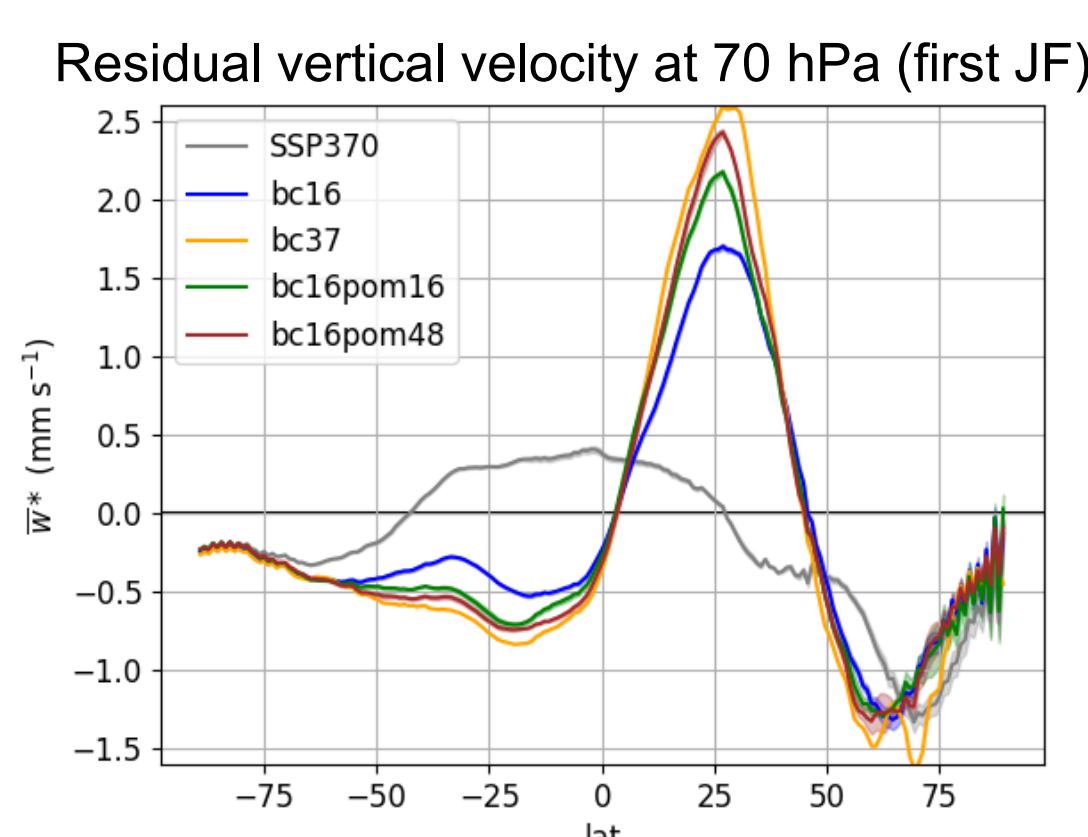
The hope is that the modeling results could aid citizens and policymakers in having well-informed conversation regarding nuclear disarmament.

Methods

- Community Earth System Model version 2 (CESM2)¹⁰ with the Whole Atmosphere Community Climate Model (WACCM6)¹¹
- Injection of BC and POM between 150 to 300 hPa over USA and Russian at a constant rate over 1 week from January 1st, 2015, under SSP3-7.0
- 4 cases with injections of 16 Tg BC (10 members), 16 Tg BC + 16 Tg POM (5 members), 16 Tg BC + 48 Tg POM (5 members), and 37 Tg BC (1 member)
- 10 members of SSP3-7.0 without injection as control
- Initial effective radii of 0.1 μm for BC and 0.4 μm for POM to represent an aged smoke population²



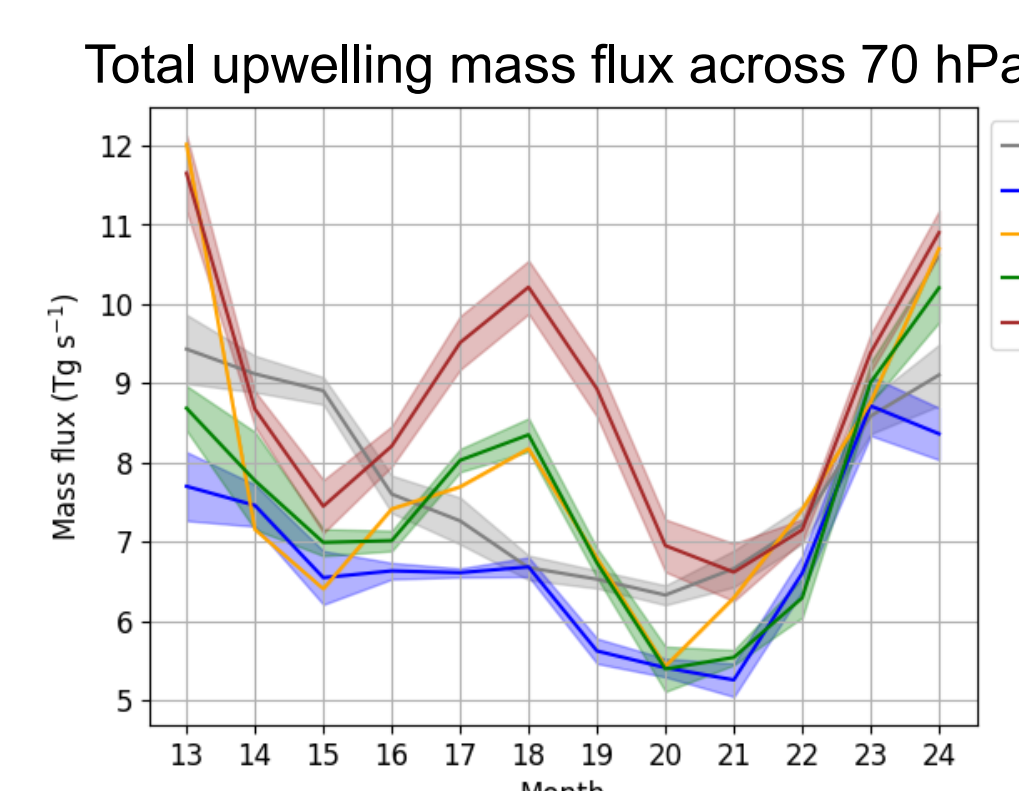
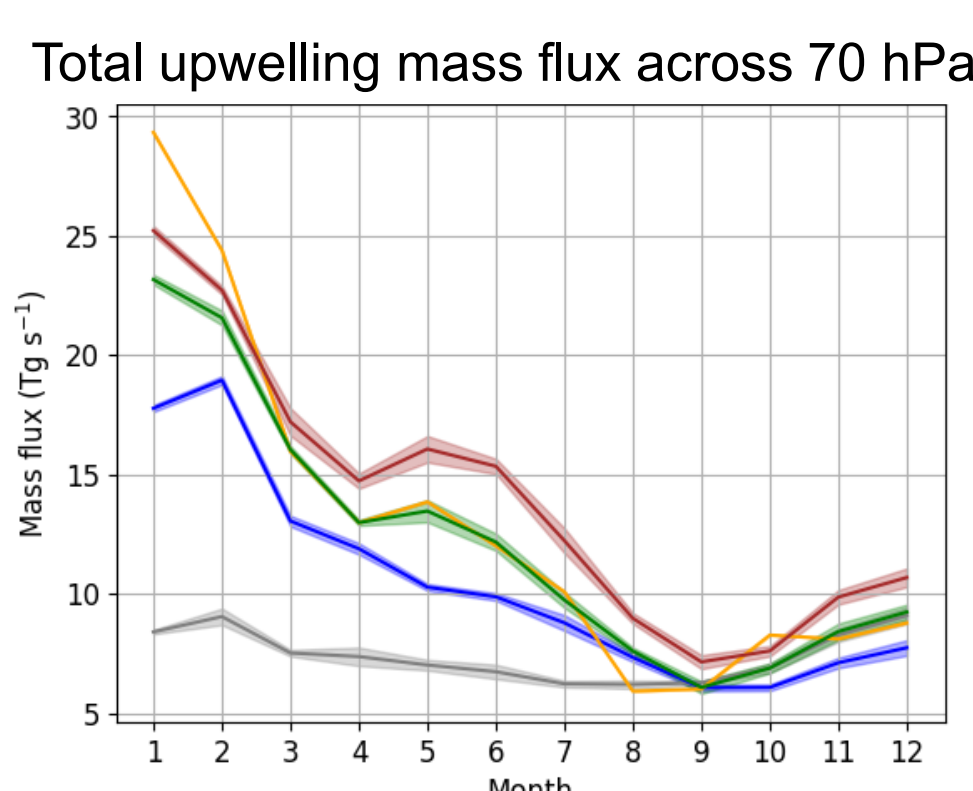
Key finding 1: Structural changes of the BDC



$$\bar{w}^* \equiv \bar{w}_a + (\bar{v}\theta'/\theta_{0z})_y$$

- In the first JF, the upwelling branch of the Brewer-Dobson Circulation (BDC) has experienced a cross-equatorial shift and an increase in strength.
- Climatologically upwelling latitudes in the SH have become downwelling.
- Implication: The net mass flux across 70 hPa has changed from an SH-to-NH direction to a NH-to-SH direction.

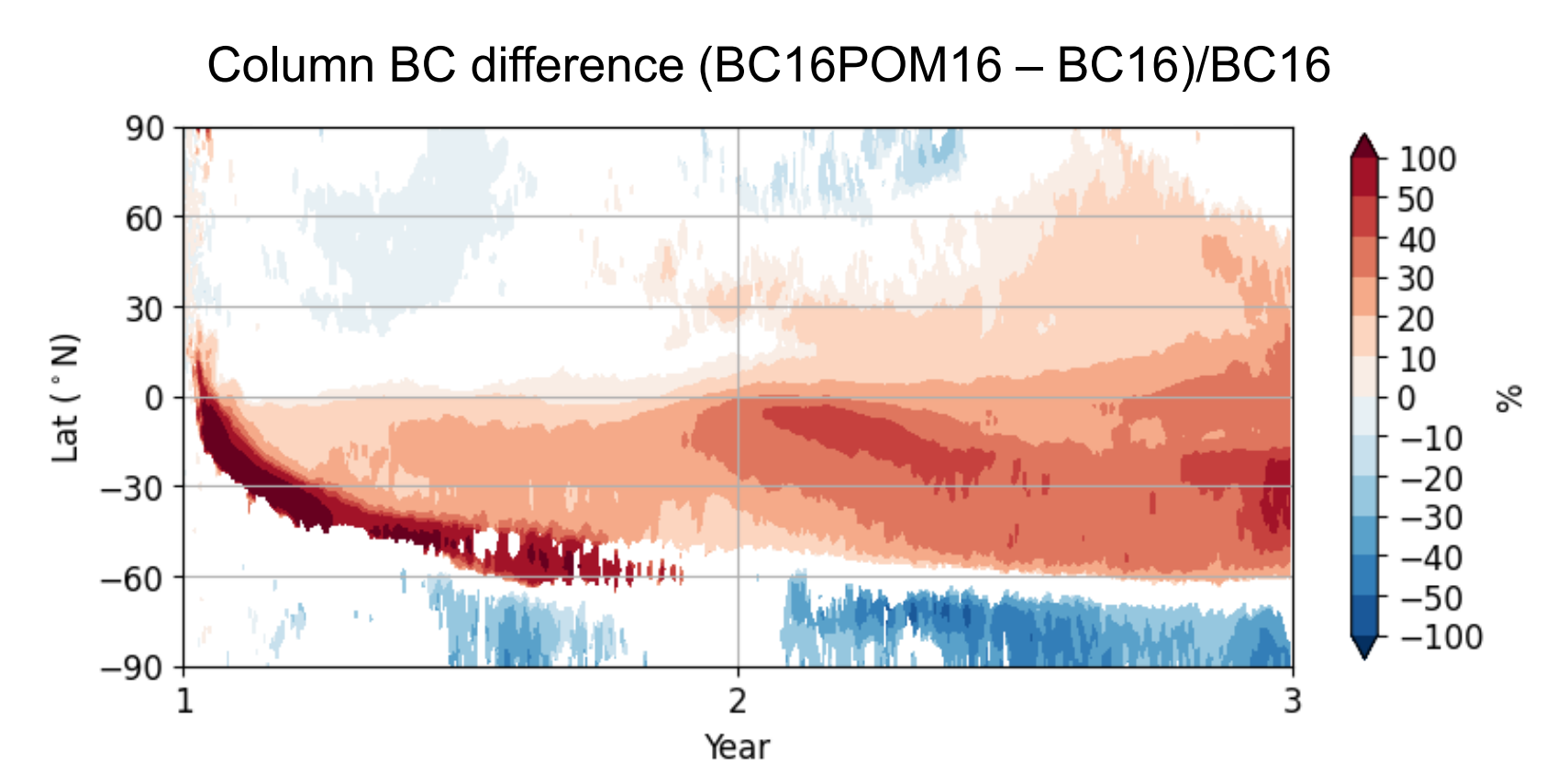
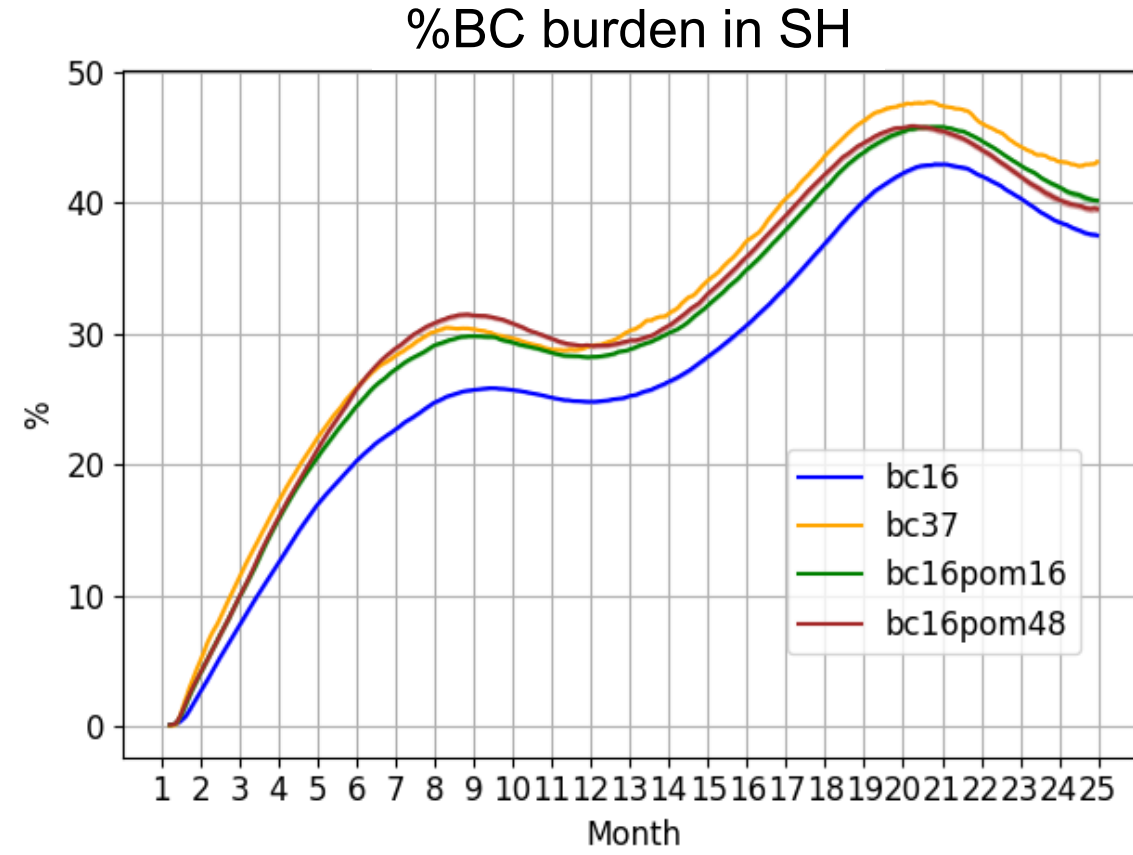
Key finding 2: Changes in the annual march of the BDC's strength



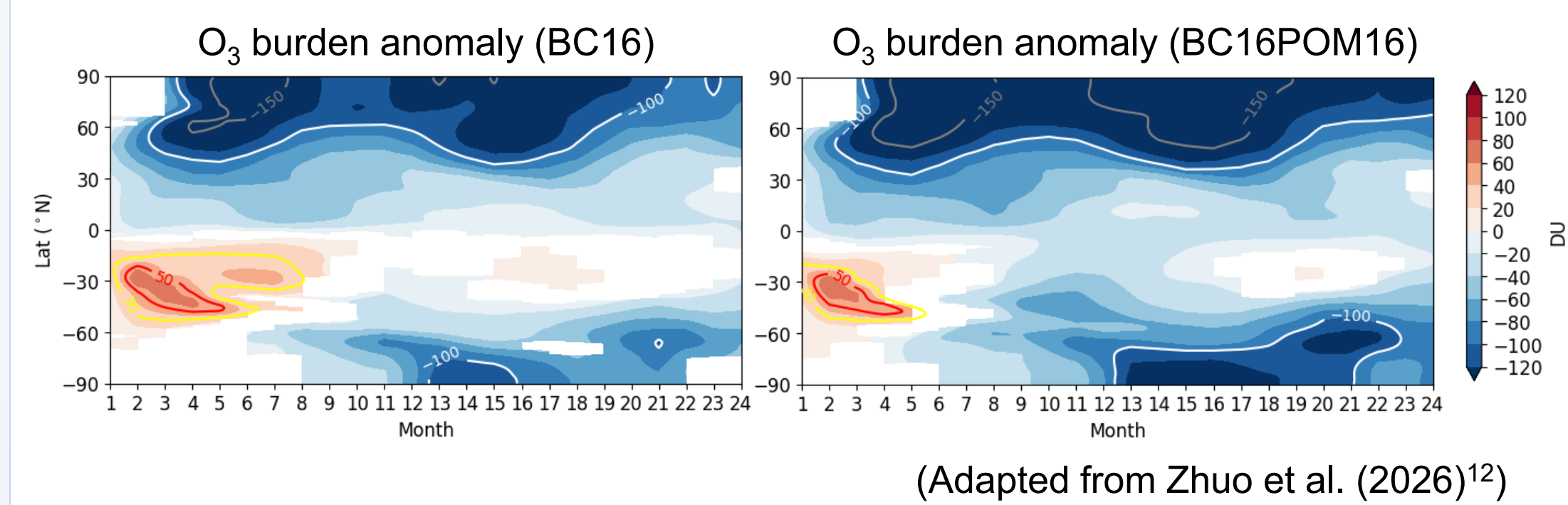
$$\text{upward mass flux} = 2\pi \int_{\bar{w}^* > 0} \bar{w}^* \rho_0 a^2 \cos \phi d\phi$$

- The BDC is strengthened until the end of the first year.
- After the first year: overall weakening for the BC-only case
- A secondary peak in June → a change in the annual march of the BDC's strength

Key finding 3: BC burden in the SH increases with the increasing BDC's strength



- The greater the increase in the BDC's strength in the first year, the greater the fraction of BC burden that enters the SH

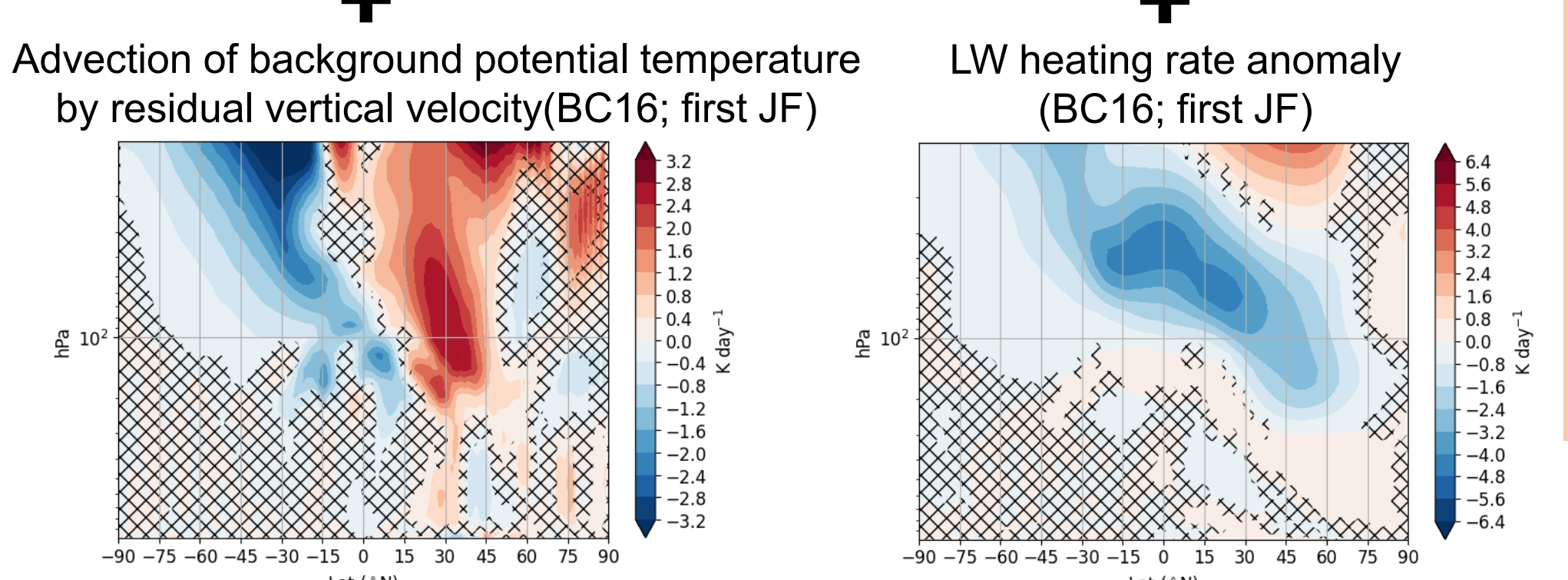
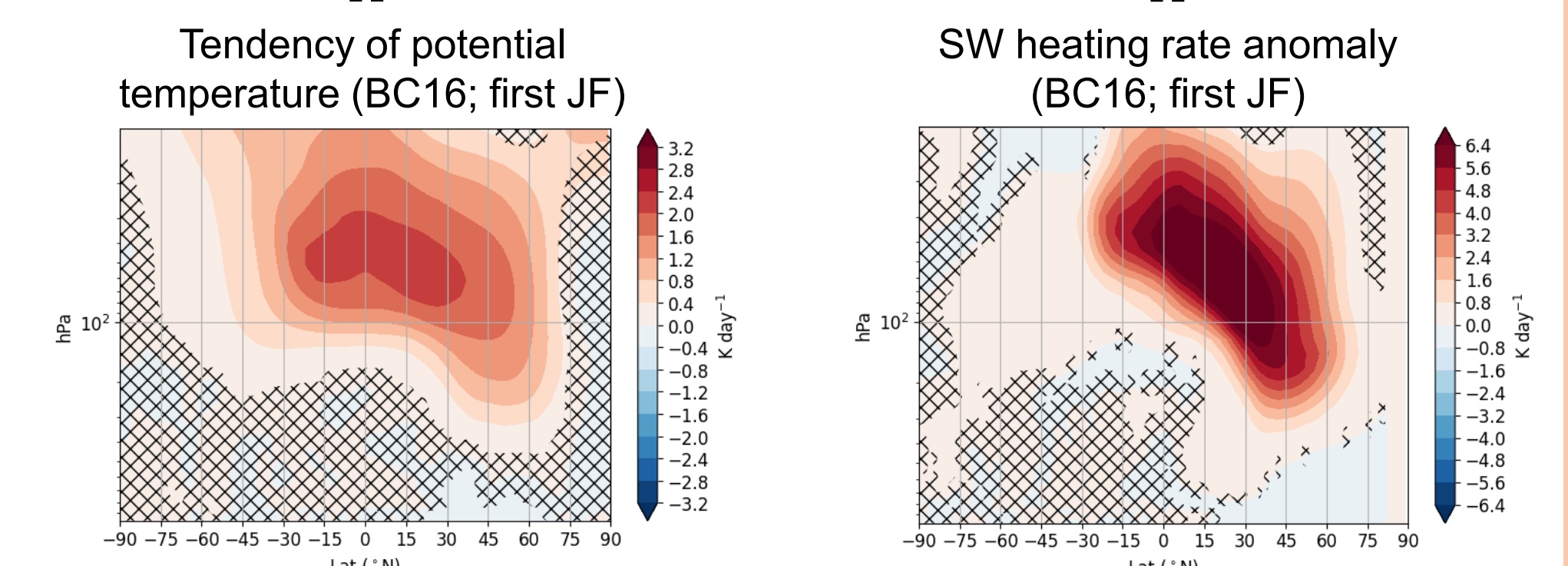
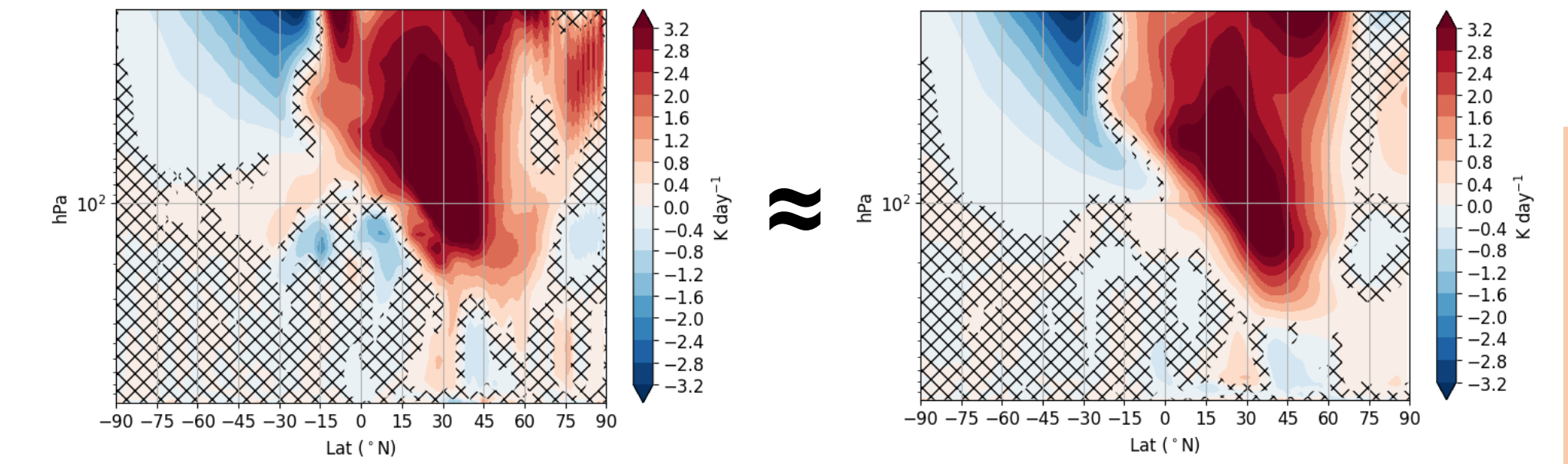


(Adapted from Zhuo et al. (2026)¹²)

- Together with additional POM, this ultimately leads to greater ozone depletion in the SH.

Decomposing the Thermodynamic Equation

Diabatic heating rate anomaly (calculated from dynamics; BC16; first JF) $\approx$ Diabatic heating rate anomaly (radiative model output; BC16; first JF)



$$\bar{\theta}_t + \bar{w}^* \theta_{0z} - \bar{Q} = 0$$

- The diabatic heating rate calculated using output dynamical variables (winds and potential temperature fields) is in good agreement with the diabatic heating rate output from the radiative model.
- The diabatic heating rate anomaly is mainly a balance between SW heating ("forcing") and LW cooling ("response").
- Part of the LW cooling in the SH is a relaxation to adiabatic heating, which itself is a response to the circulation change

Summary

- Following an extratropical injection of BC and POM into the UTLS in the NH, the BDC has experienced a structural change that favours NH-to-SH transport in the first two months after being forced by intense local diabatic heating.
- The BDC is strengthened early in the simulations, and the annual march of the BDC's strength has undergone changes that result in a secondary peak in June.
- With greater increase in the BDC's intensity in the first year, a larger portion of BC enters the SH, which contributes to ozone depletion in the SH.

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