The influence of anthropogenic aerosols on the Aleutian Low

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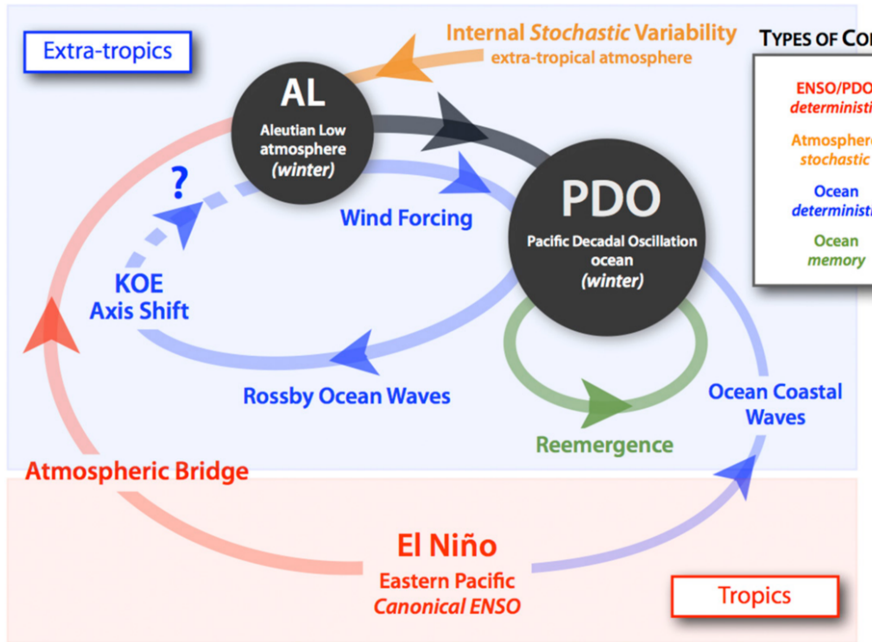
1. MOTIVATION: Research has suggested that regional changes in anthropogenic aerosols can influence the Pacific Decadal Oscillation (PDO), a major mode of climate variability, through modulation of the Aleutian Low. This study aims to improve understanding of the mechanisms through which anthropogenic aerosols can affect the Aleutian Low.

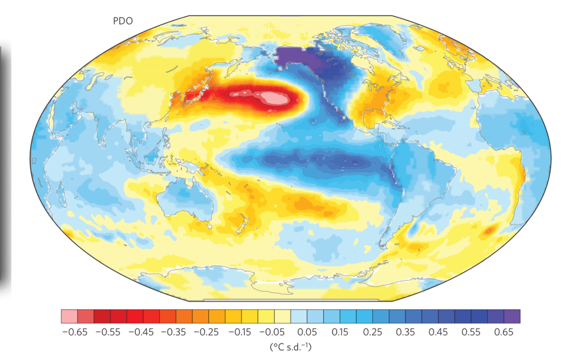
2. SUMMARY: We analyse changes to the Aleutian Low in boreal winter in an ensemble of climate models forced with idealised global and regional black carbon (BC) and sulphate aerosol perturbations. We show a robust weakening of the Aleutian Low forced by a global 10-fold increase in BC in both coupled and prescribed SST experiments. We investigate the mechanisms through which BC emissions influence the Aleutian Low by forcing a linearised steady-state primitive equation model with diabatic heating anomalies. We find that direct aerosol heating over India and China generates Rossby wave trains that propagate north-east into the North Pacific. The response to a global 5-fold increase in sulphate aerosol and a regional 10-fold increase in sulphate aerosol over Asia shows poor consistency across models, with a mean response that does not project onto the Aleutian Low.

3. METHODOLOGY:

i) Climate model data: 11 models from the Precipitation Driver and Response Model Intercomparison Project. The models ran experiments with idealised global and regional step perturbations of sulphate and black carbon aerosol with 2 configurations – a fully coupled ocean-atmosphere (100 years) and a fixed ocean (run > 15 years). Each model specifies sulphate and black carbon as concentrations or emissions. ***Abbreviated experiment names: BCx10 = Global black carbon x 10, BCx10a = Black carbon x10 (Asia only), Sulx5 = Global sulphate x 5, Sulx10a = Sulphate x10 (Asia only), Sulx10e = Sulphate x10 (Europe only).*** *Some figures also show a double CO_2 experiment for comparison* ***(CO2x2)****.*

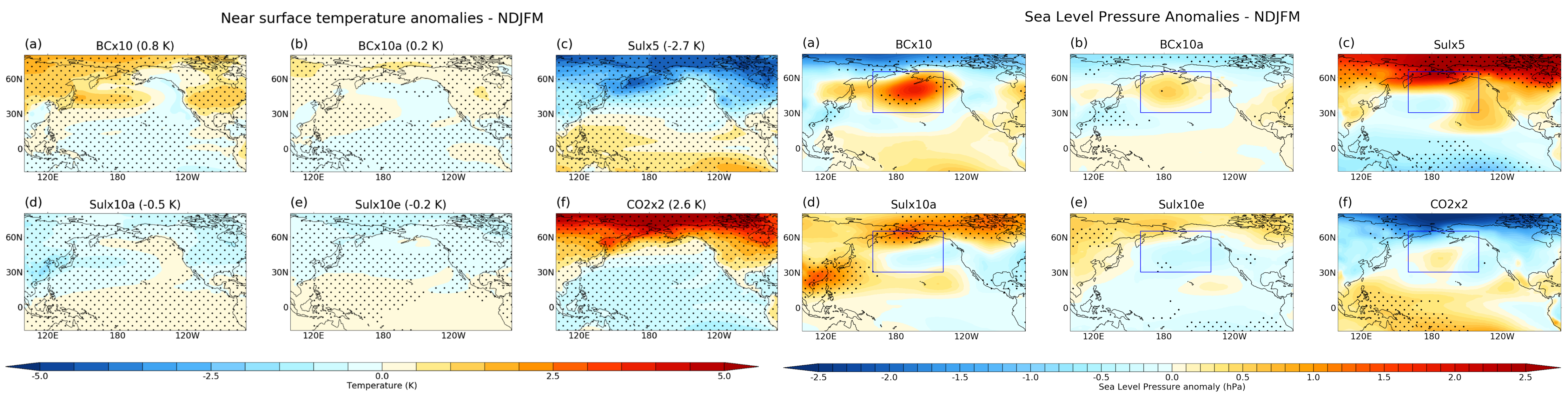
ii) Linear stationary wave model (LUMA): linearized steady-state primitive equation model. Diabatic heating anomalies associated with a) PDRMIP precipitation anomalies (BC & sulphate) and b) instantaneous heating due to absorbing BC aerosol derived from an offline radiative transfer model. Note the linear model should only be qualitatively compared to the climate models owing to the method for solving the linear operator.



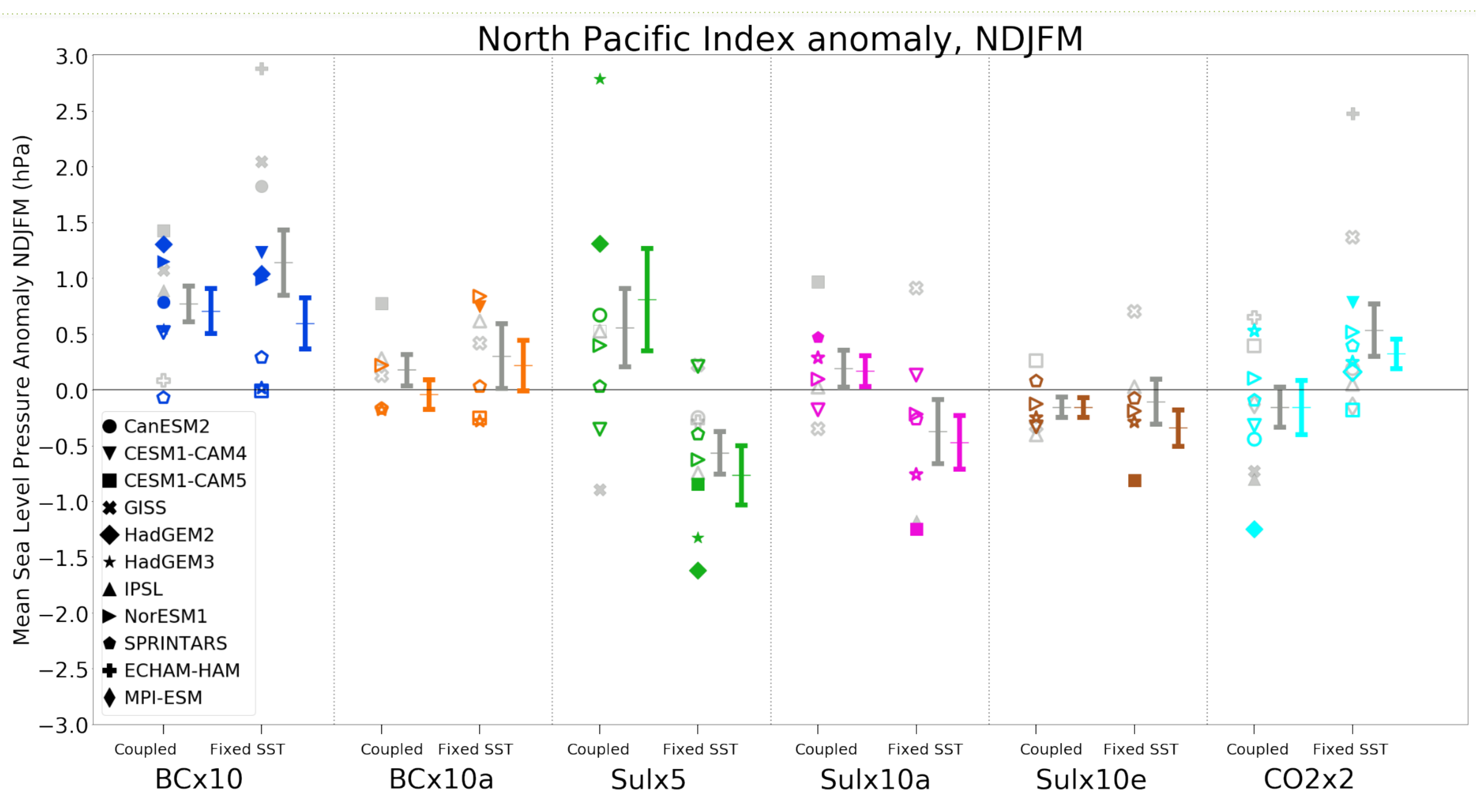


Left: Schematic of the mechanisms that play a role in the evolution of the Pacific Decadal Oscillation (PDO). Note the (precursory) relationship of Aleutian Low to the PDO. Taken from *Newman et al. (2016)*. ***Top:*** PDO expressed as the leading EOF of monthly SST anomalies in the North Pacific (taken from *Trenberth et al. (2014)*).

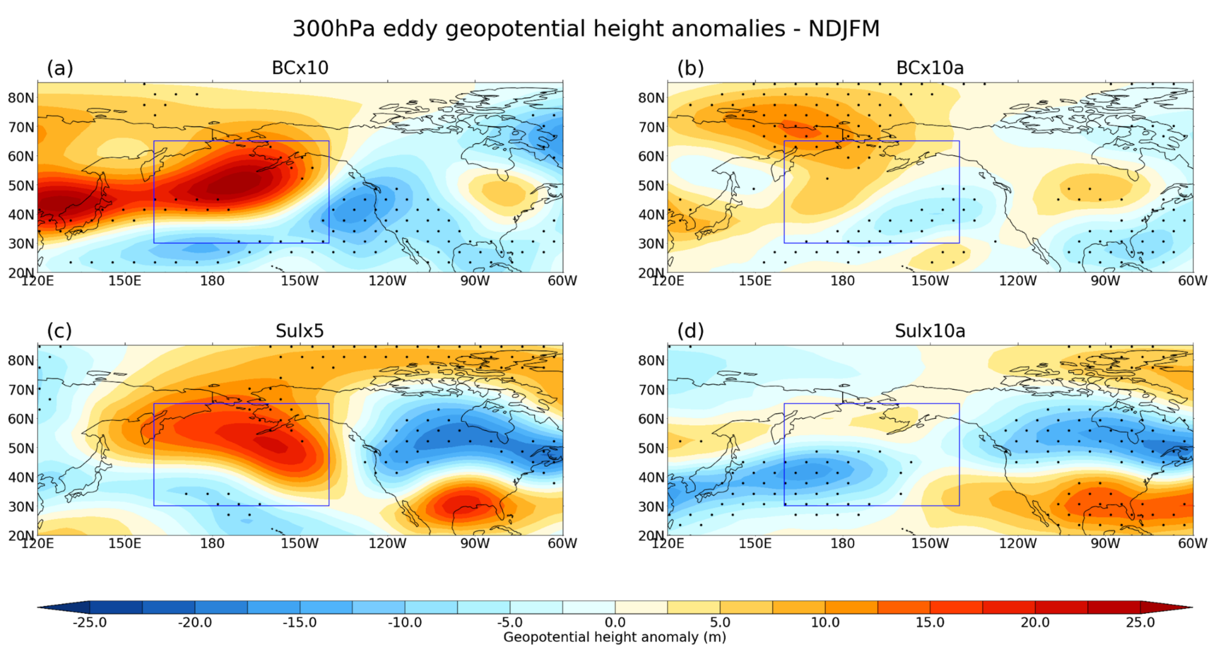
4. ANALYSIS OF CLIMATE MODELS:



Above left: Multi-model mean (MMM) NDJFM near surface temperature anomalies in the coupled experiments (global mean has been subtracted). Stippling shows where all models agree on sign of anomaly. ***Above right***: same as above left instead with sea level pressure anomalies. Box defines the North Pacific Index (NPI) region. ***Below***: MMM NDJFM 300 hPa eddy geopotential height anomalies across four of the global and regional aerosol perturbation experiments.



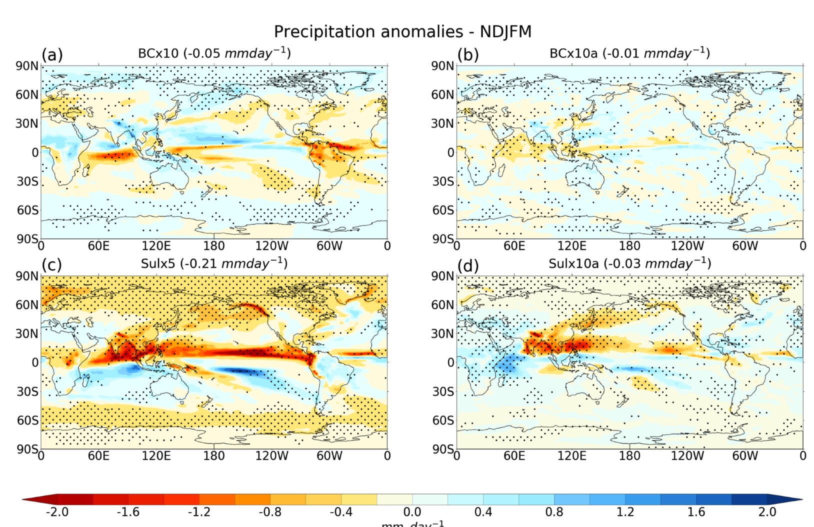
Above: NPI anomaly averaged for NDJFM for each contributing model. Shown are values from coupled and fixed SST experiments. Coloured symbols indicate models used to create input fields for LUMA. Filled symbols represent differences significant at the 95% confidence level, and vice versa for open symbols. Whiskers show MMM ± 1 standard error for each experiment.



Key findings:

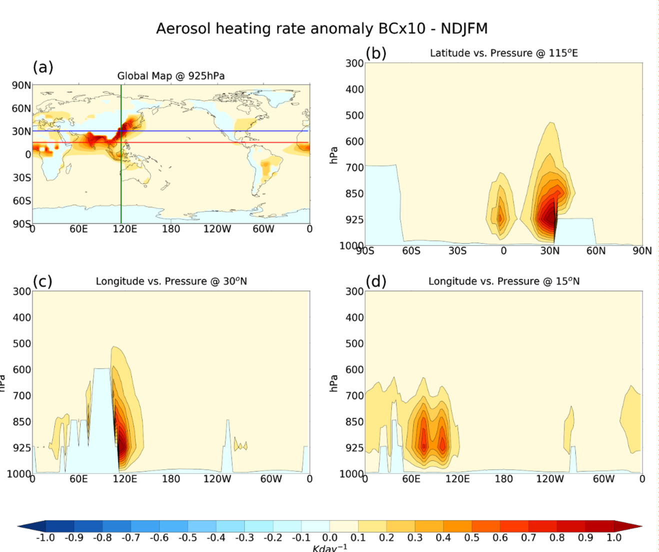
- Robust weakening of the Aleutian Low due to 10-fold increase in global black carbon – similar response in fixed SST experiment indicates small role for ocean feedbacks.
- Weaker but less robust weakening of Aleutian Low for regional black carbon increase in Asia.
- Response to 5-fold increase in global sulphate aerosol and 10-fold increase in sulphate aerosol over Asia do not project strongly onto climatological Aleutian Low – fixed SST experiments indicate a larger role for ocean feedbacks.

5. CALCULATING DIABATIC HEATING ANOMALIES:

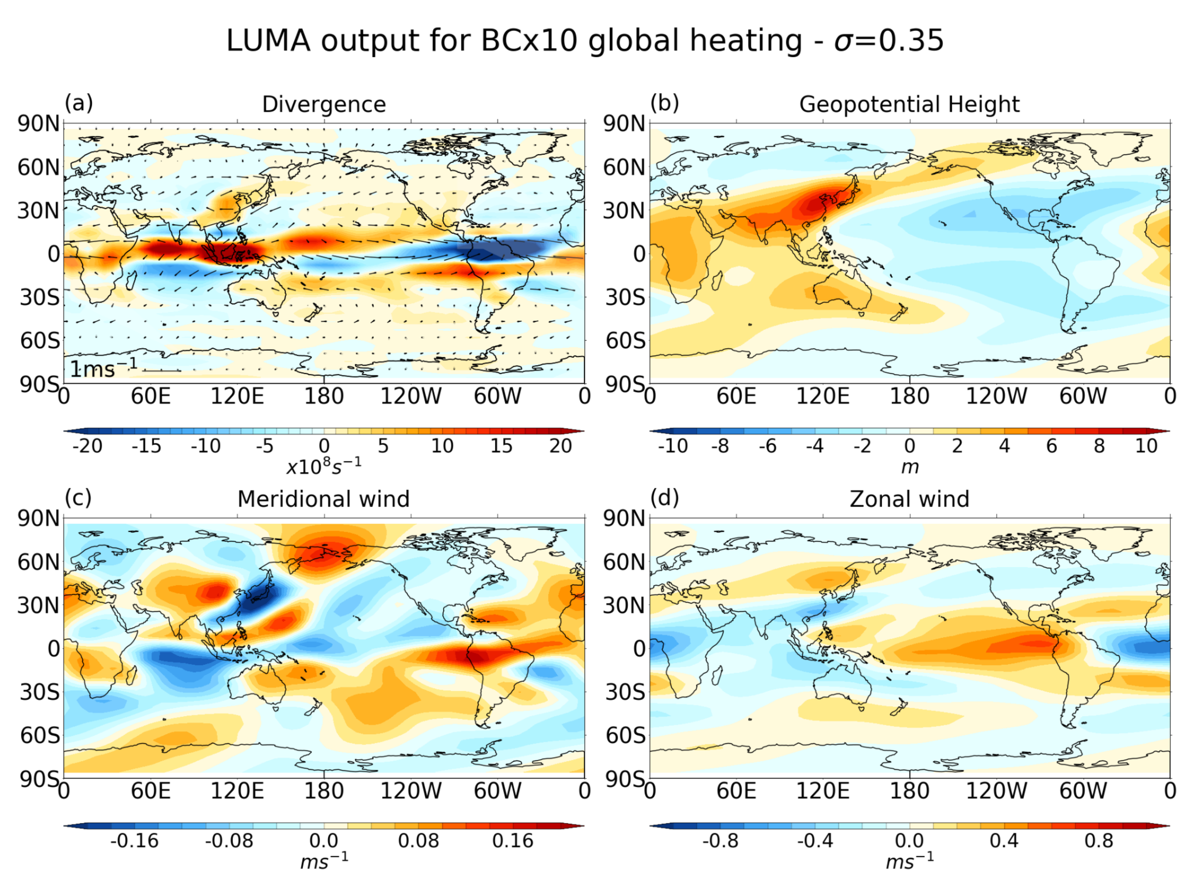


Below: NDJFM heating rate anomalies (K day^{-1}) due to MMM BCx10 aerosol perturbation. (a) Global distribution at 925 hPa. Green, blue and red transects relate to the vertical heating profiles in b, c and d, respectively. (b,c,d) Longitude-pressure transects showing instantaneous heating rates due to the BC aerosols.

Above: NDJFM MMM precipitation (mm day^{-1}) anomalies in four coupled aerosol perturbation experiments. Stippling shows where all models agree on sign of anomaly. The global mean precipitation anomaly is shown in the header. Precipitation is converted to an estimated tropospheric column aveage latent heating anomaly by multiplying with $(g\ L\ \rho_w\ 10^{-5})/[C_p(P_0 - 125)]$, where L is the latent heat of condensation, g is gravity, ρ_w is the density of water, C_p is the specific heat of air at constant pressure and P_0 is a reference surface pressure. The heating is distribution vertically using a Gaussian profile centred at 550 hPa.



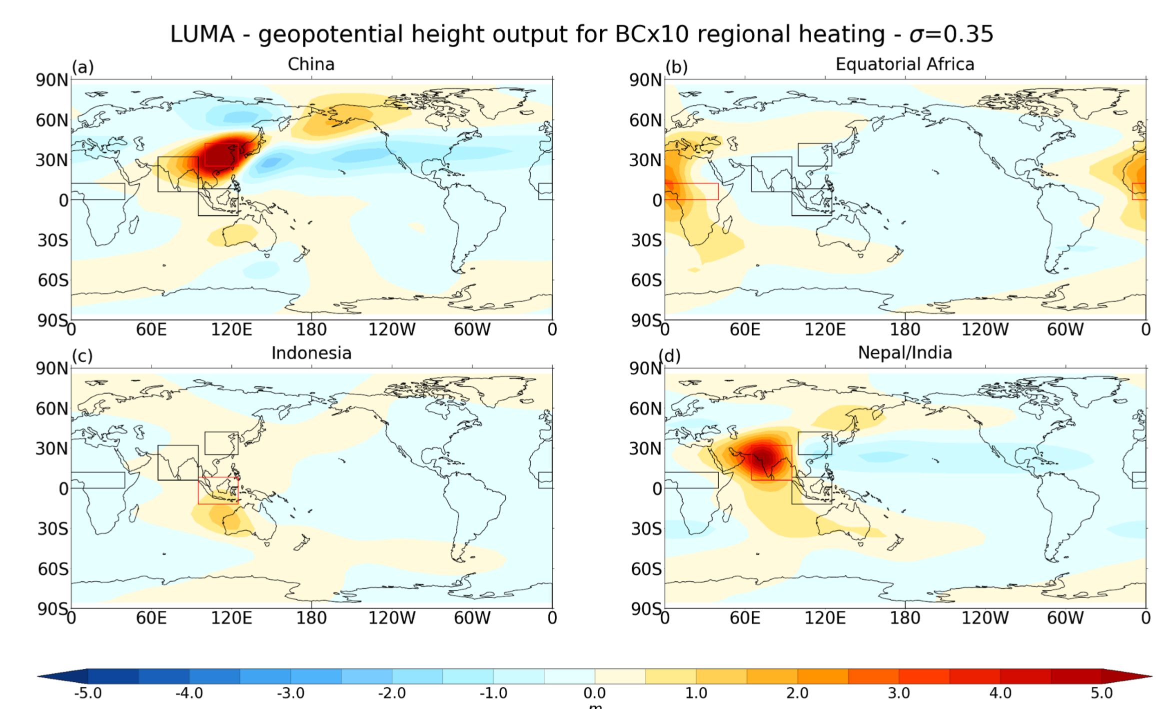
6. STATIONARY WAVE MODEL:



Upper left: LUMA steady-state response (σ=0.35) to diabatic heating anomalies from the NDJFM global atmospheric absorption and precipitation for the BCx10 experiment.

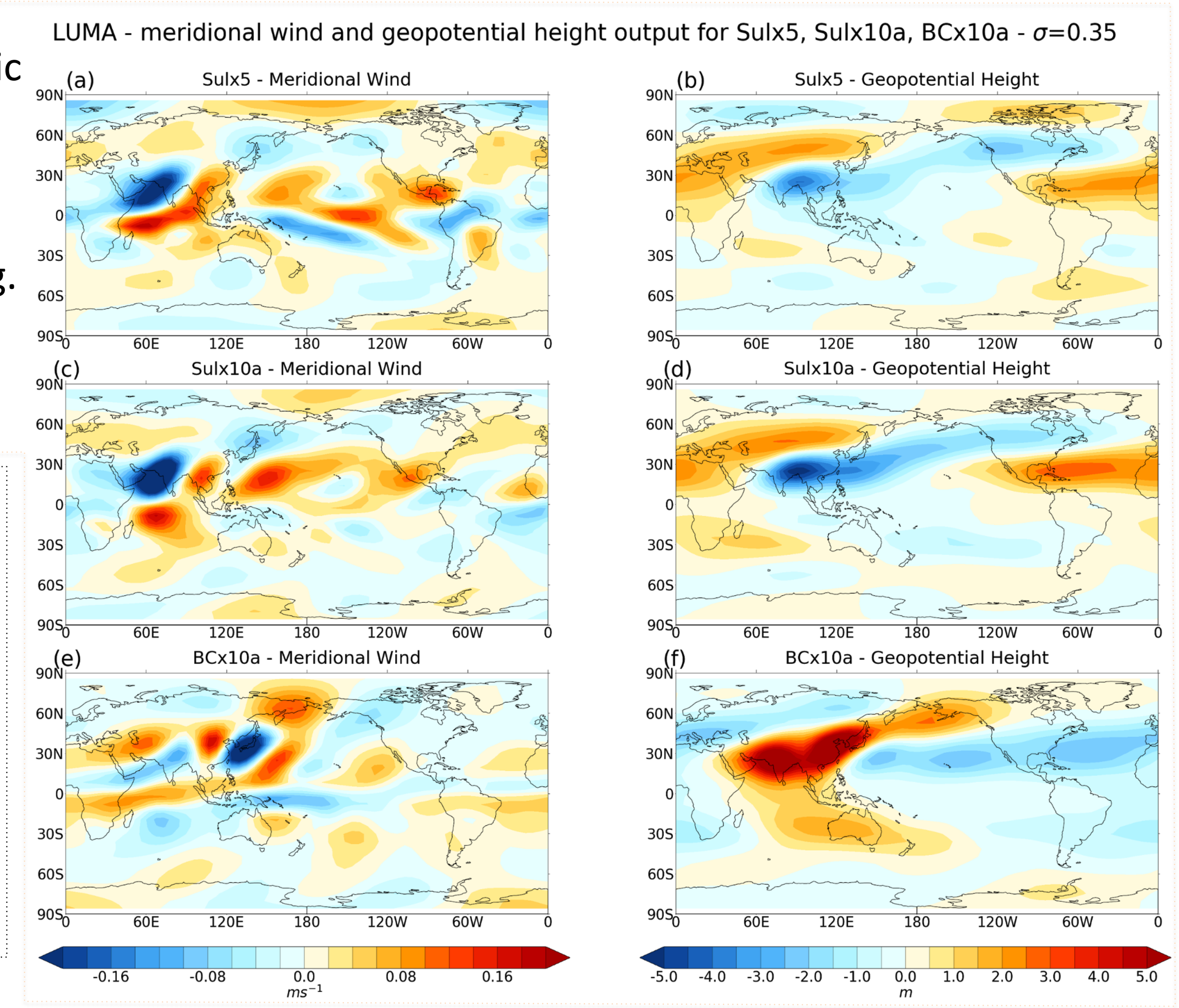
Lower left: LUMA steady-state geopotential height anomalies (σ=0.35) due to regional diabatic heating from the BCx10 experiment.

Lower right: LUMA steady-state responses (σ=0.35) due to diabatic heating from NDJFM precipitation responses in the (a,b) Sulx5, (c,d) Sulx10a and NDJFM mean precipitation and atmospheric absorption in the BCx10a (e,f) experiments.



Key findings:

- Diabatic heating over China and India are important for the North Pacific stationary wave response to BCx10 through generation of anomalous Rossby wave sources (not shown).
- The direct radiative effect from the absorbing aerosol is a more important source of diabatic heating than the anomalous latent heating.
- The linear model does not reproduce pattern to Sulx5 and BCx10a – responses are less consistent.



7. CONCLUSIONS: Our results show that black carbon can modulate the strength of the Aleutian Low through the excitation of anomalous Rossby wave source regions, and induce surface temperature anomalies in the North Pacific that resemble the PDO. In response to sulphate aerosol forcing, we do not see a consistent impact on the Aleutian Low across models, which contrasts with the studies by Smith et al. (2016) and Oudar et al. (2018) who showed that the increase in aerosols over Asia during 1998-2012 tends to weaken the Aleutian Low in simulations with coupled climate models.

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