A Predictive Theory for the Degree of Arctic Amplification

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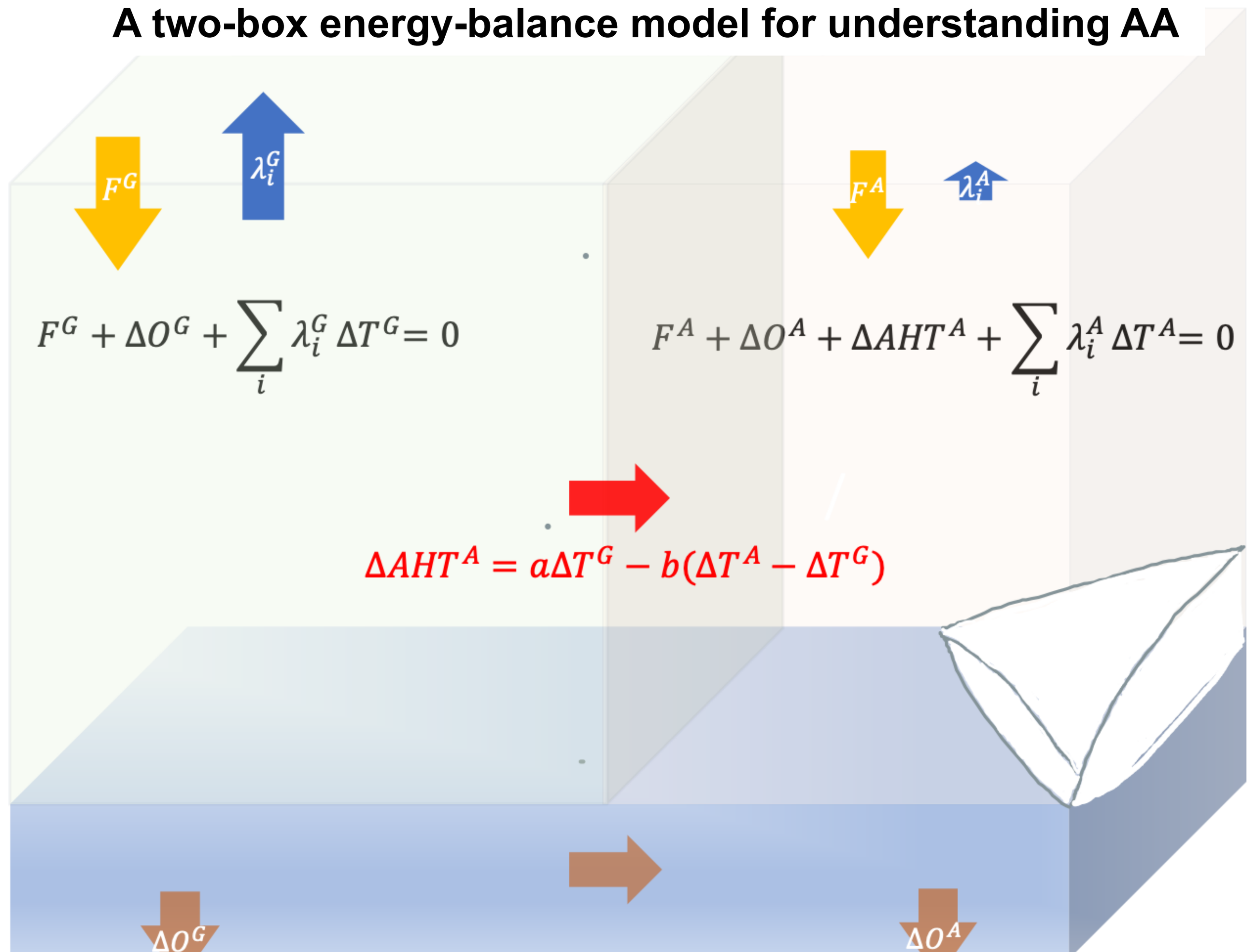
By conceptualizing AA using a two-box energy-balance model that deciphers atmospheric heat transport, we derive a theoretical formula that links the degree of Arctic Amplification to its controlling factors.

Abstract

While substantial progress has been made regarding its underlying physics, a predictive understanding of the degree of Arctic Amplification (AA) is lacking. Here, from a two-box energy-balance model, we reveal the functional relationship between the degree of AA and its controlling parameters. AA–1 is proportional to the increasing rate of AHT with global uniform warming plus the forcing-normalized difference between the Arctic and global feedbacks, and inversely proportional to the decreasing rate of AHT with AA minus the Arctic feedback. The formula captures the varying degree of AA in individual climate models under different warming scenarios and attributes the variation to specific physical factors. More importantly, the formula conveys a concise, nonlinear picture of how essential physics mutually determine the degree of AA. It articulates the intricate role of AHT, highlighting the partial derivatives to temperature instead of absolute change as key parameters for understanding AA. It reveals that the effect of lapse rate feedback, a widely recognized major contributor to AA, is closely offset by the effect of water vapor feedback.

A two-box energy-balance model for understanding AA



A theoretical formula between AA and its key parameters

Energy balance equations for the Arctic and the global mean,

$$\text{Arctic:}\quad F^A + \Delta O^A + \Delta AHT + \textstyle\sum_i \lambda_i^A \Delta T^A = 0, \qquad (1)$$

$$\text{Global:}\quad F^G + \Delta O^G + \textstyle\sum_i \lambda_i^G \Delta T^G = 0, \qquad (2)$$

ΔAHT is formulated a function of global mean warming ΔT^G and enhanced Arctic warming $\Delta T^A - \Delta T^G$ as

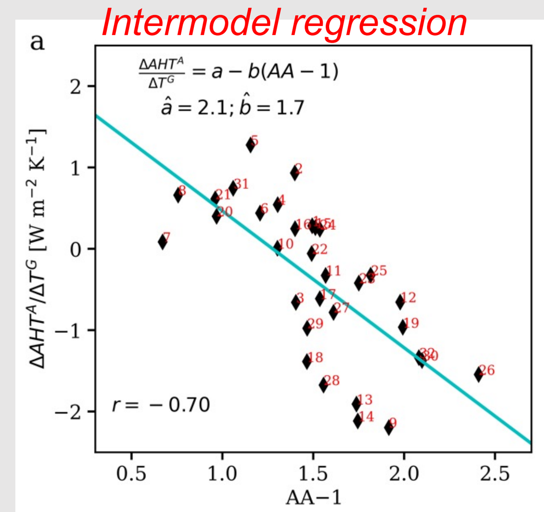
$$\Delta\Delta AHT \cong a\Delta T^G - b(\Delta T^A - \Delta T^G). \qquad (3)$$

that is

$$\Delta AHT/\Delta T^G \cong a - b(AA - 1). \qquad (4)$$

This formulation is supported by both

Intermodel regression



Theoretical formula of AHT

$$AHT \sim D\delta h$$

$$\Delta\delta h = L_v \delta\left(\frac{\partial q}{\partial T}\right)\Delta T^G + \left(L_v \frac{\partial q^A}{\partial T} + C_p\right)(\Delta T^A - \Delta T^G)$$

$$a \sim \frac{L_v^2 \delta q}{R_v T^2} \qquad b \sim D\left(\frac{L_v^2 q^A}{R_v T^2} + C_p\right)$$

ΔO is formulated a feedback to the temperature change,

$$\Delta O = -\lambda_O \Delta T, \qquad (5)$$

Eqs. 1-5 form a two-box energy-balance model, in which the Arctic and the globe experience their respective forcing and feedbacks and interact with each other through AHT . **This two-box model yields a theoretical solution for the degree of AA as,**

$$AA \equiv \frac{\Delta T^A}{\Delta T^G} = 1 + \frac{a + \lambda^A - \gamma\lambda^G}{b - \lambda^A} \equiv I^{AA}, \qquad (6)$$

$\gamma \equiv \frac{F^A}{F^G}$ is the ratio in radiative forcing between the Arctic and the globe

$\lambda^A \equiv \sum \lambda_i^A$ and $\lambda^G \equiv \sum \lambda_i^G$ are the sums of the Arctic and global feedbacks (Planck, albedo, lapse rate, water vapor, cloud, and ocean)

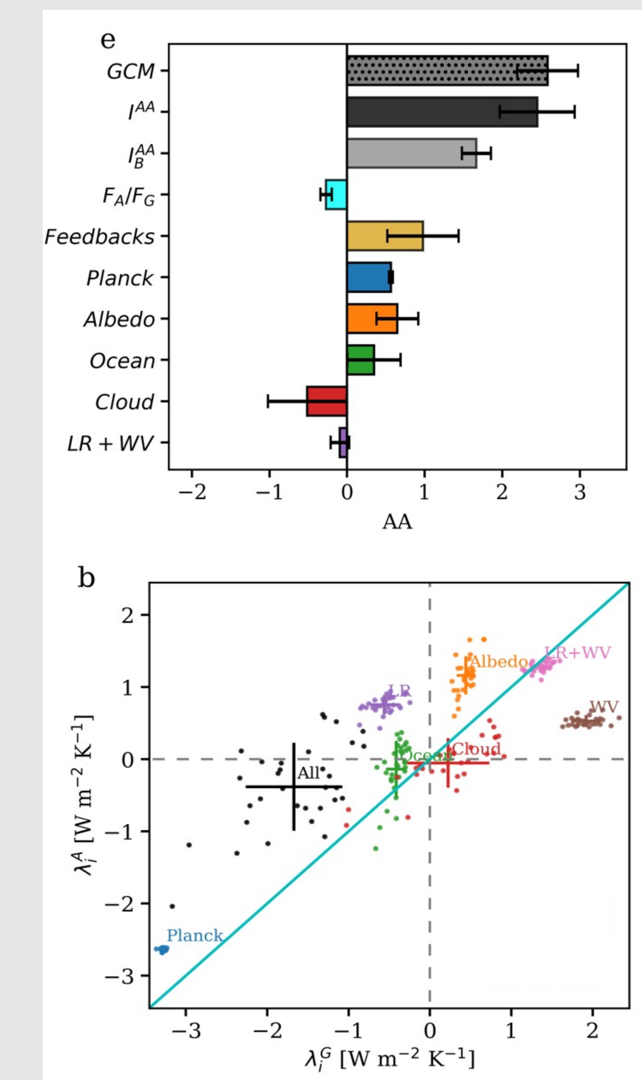
$a \equiv \frac{\partial AHT}{\partial T^G}$ measure the increasing rate of AHT with global uniform warming

$b \equiv \frac{\partial AHT}{\partial (T^A - T^G)}$ measures the decreasing rate of AHT with enhanced Arctic warming

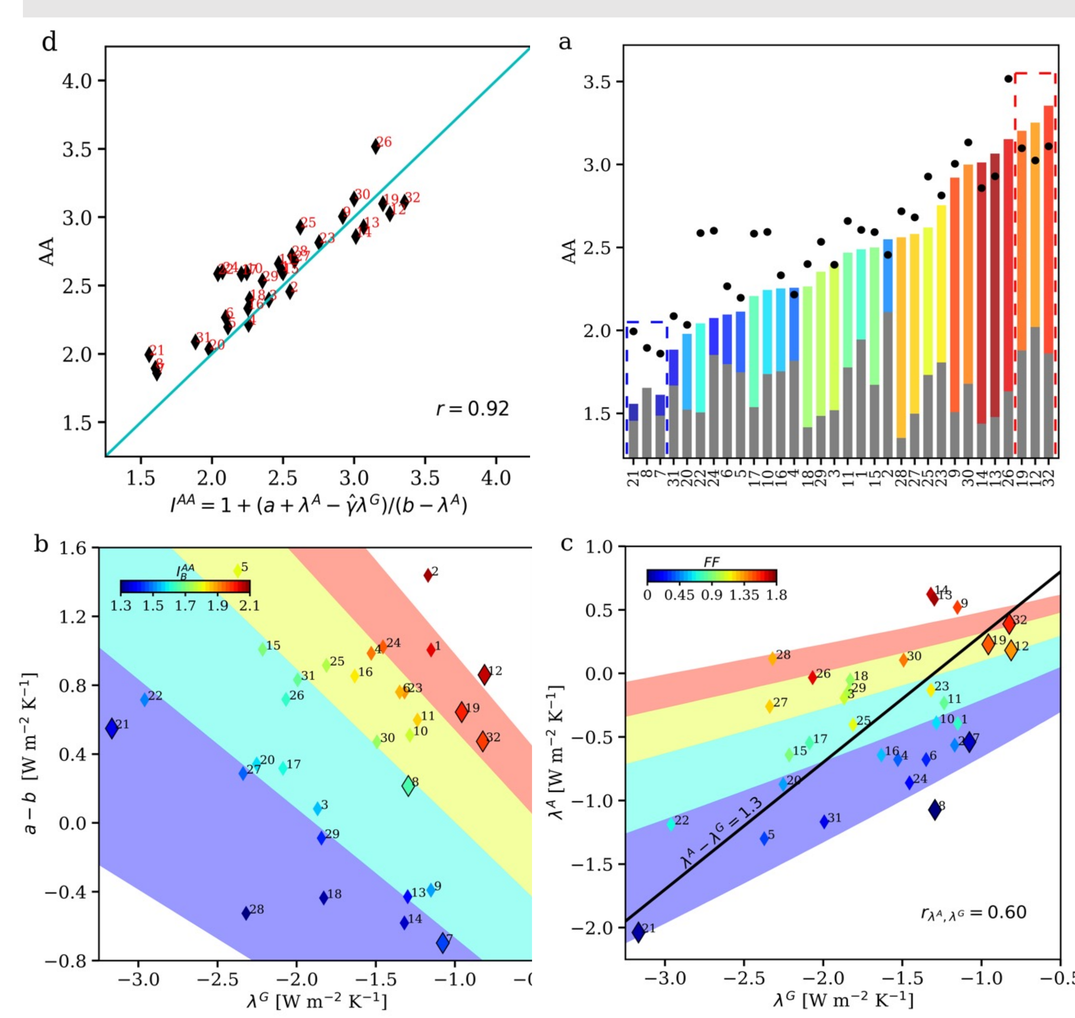
How the degree of AA emerges from essential physics

$$I^{AA} = 1 + \frac{a + \lambda^A - \gamma\lambda^G}{b - \lambda^A}$$

- A baseline AA, $I_B^{AA} = 1 + \frac{a}{b - \lambda^G}$, exists even with spatially uniform radiative forcing ($\gamma = 1$) and feedbacks ($\lambda^A = \lambda^G$).
- Weaker radiative forcing in the Arctic relative to the globe reduces AA ($\gamma \equiv \frac{F^A}{F^G} < 1$)
- Less negative (or even positive) climate feedback in the Arctic amplifies AA ($\lambda^A > \lambda^G$)
- The Planck, albedo and ocean feedbacks increase the degree of AA respectively by 0.62±0.03, 0.71±0.30 and 0.40±0.39, while the cloud feedback decreases AA by 0.60±0.63.
- Positive contribution of the lapse-rate feedback is fully if not overly compensated by negative contribution of the water-vapor feedback.



Understand the variation and outliers of AA among models



- Our theory capture the degree of AA in individual models (r=0.92)
- The variation can be understood from the variation in the baseline AA (I_B^{AA} , 1.3~2.1) and in the effect of differential forcing and feedbacks (*FF*, 0~1.8).
- I_B^{AA} is larger if $a - b$ is larger and λ^G is weaker (less negative).
- *FF* is larger when λ^G is weaker (less negative) but $\lambda^A - \lambda^G$ is higher (more positive)

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