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Feedback Attributions of the Climate Difference in the Muted and the Accelerated Warming Periods

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1. Data and methodology

Most of the data used in this study are obtained from the latest European Centre for Medium-range Weather Forecasts (ECMWF) Re-Analysis Interim (ERA-Interim; Uppala *et al.* 2008; Dee *et al.* 2011). The time series of the annual mean CO2 concentration from 1984 to 2013 is downloaded from the Earth System Research Laboratory website (http://www.esrl.noaa.gov/gmd/ccgg/trends/).

We have adopted the same package of a climate feedback-response analysis method (CFRAM) analysis reported in Deng *et al.* (2012) and Sejas *et al.* (2014) to attribute the near-surface temperature anomalies (STAs) shown in Fig. 1c to external forcing and various climate feedback processes (radiative and non-radiative feedback processes, shown in Equation (1)), based on the energy balance.

$$\Delta \mathrm{T}_{M+1} = \left(\frac{\partial \vec{\mathrm{R}}}{\partial \vec{\mathrm{T}}}\right)^{-1}_{M+1} \left\{ \begin{array}{c} \Delta\vec{\mathrm{S}}^{(\mathrm{solar})} + \Delta\vec{\mathrm{R}}^{(CO2)} + \Delta\vec{\mathrm{S}}^{(\alpha)} + \left(\Delta\vec{\mathrm{S}}^{(\mathrm{w})} - \Delta\vec{\mathrm{R}}^{(\mathrm{w})}\right) + \left(\Delta\vec{\mathrm{S}}^{(\mathrm{c})} - \Delta\vec{\mathrm{R}}^{(\mathrm{c})}\right) \\ + \left(\Delta\vec{\mathrm{S}}^{(\mathrm{O}^3)} - \Delta\vec{\mathrm{R}}^{(\mathrm{O}^3)}\right) + \Delta\vec{\mathrm{Q}}^{LH} + \Delta\vec{\mathrm{Q}}^{SH} + \Delta\vec{\mathrm{Q}}^{ocn\_dyn+storage} + \Delta\vec{\mathrm{Q}}^{atm\_dyn} \end{array} \right\} \quad (1)$$

2. Results

The decade of 1984-95 is regarded as the accelerated warming period whereas the decade of 2002-13 corresponds to a weaker warming period. This work examines the mean state difference between the two periods (Fig. 1). The key features of the mean state in 2002-13 in reference to that in the accelerated warming period are (i) a La Niña like pattern over the tropical Pacific, (ii) a pronounced polar warming amplification pattern in the northern extratropics, and (iii) cold temperature anomalies over the Southern Ocean sandwiched by the dominance of warm temperature anomalies in the north and

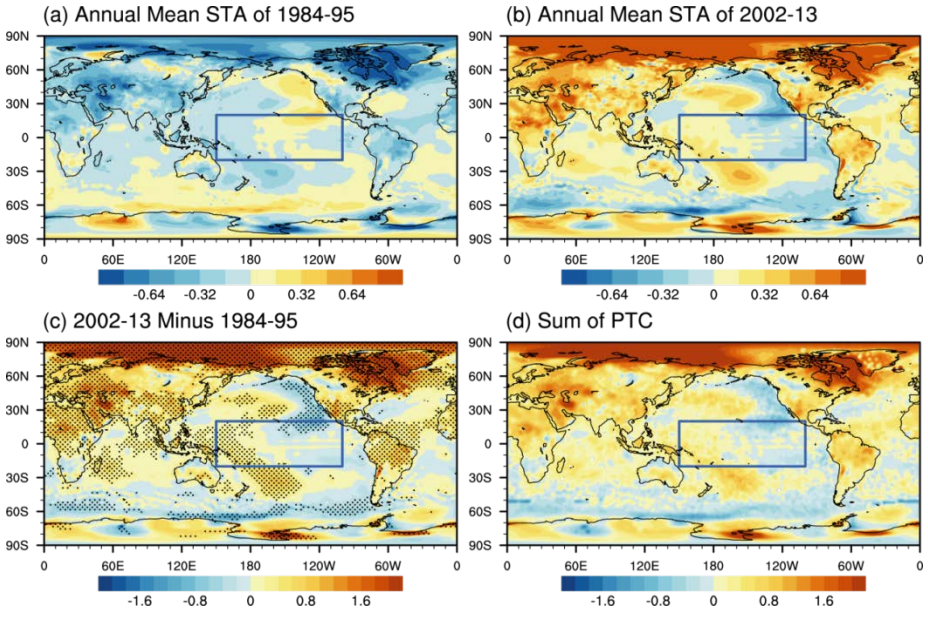

Fig. 1 Annual mean STAs of the period of (a) 1984-95, and (b) 2002-13, (Unit: K). (c) The difference in SAT between the two periods (Unit: K). And (d) the sum of CFRAM-derived partial temperature changes due to individual processes. The dotted areas indicate values achieving 0.1 level of statistical significance. The blue box outlines the tropical Pacific region (20°S-20°N, 150°-100°W), one of the three key regions discussed in the text.

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south in the southern extratropics.

A climate feedback-response analysis method is applied to attribute the changes in the climatological mean surface temperature between the two periods to various dynamic and thermodynamic processes (Fig. 2). The La Niña like pattern is associated with the strengthening of the Walker Circulation over the tropical Pacific. Increase of low level clouds, reduction of atmospheric water vapor, and increase of surface latent heat fluxes are the main processes contributing to the cooling in the eastern tropical Pacific. Surface processes contribute positively to the spatial pattern of the mean state difference in both the northern and southern extratropics. The atmospheric dynamic processes contribute positively to the difference in the northern extratropics, but negatively to the difference in the southern extratropics, responsible for the greater warming over the northern extratropics than the southern extratropics (Fig. 3; Note that the term labeled as "Others" is for the sum of partial STAs due to differences in solar radiation, CO_2, and ozone between the two periods whereas the "Sum" is the PAP coefficient obtained from the sum of all CFRAM-derived STAs. Bars with dots overlay the corresponding bars labeled with "Sum", indicating that the sum of all CFRAM-derived STAs indeed approximates to observed STAs.).

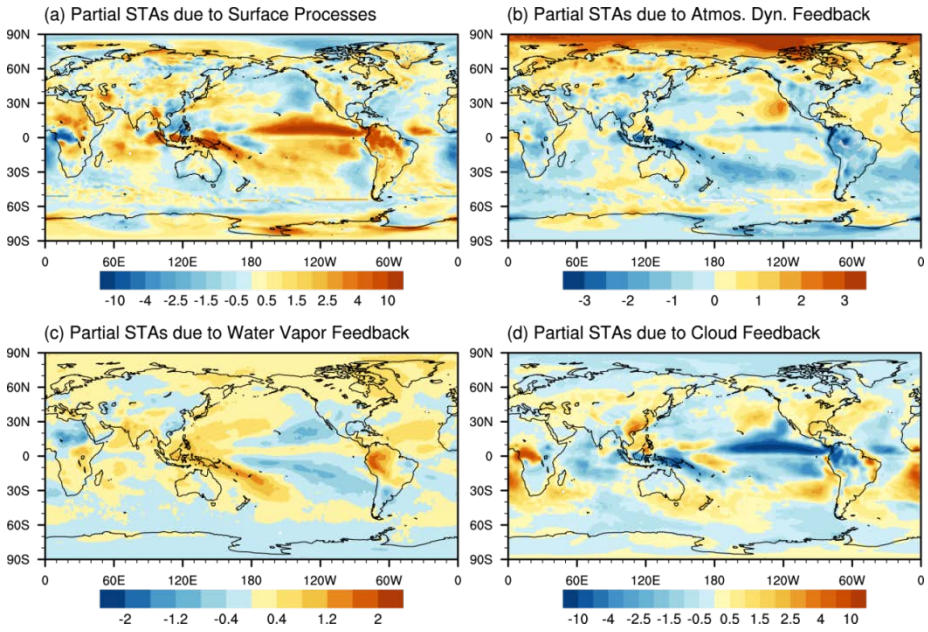

Fig. 2 Partial STAs (units: K) due to the (a) surface processes (including surface sensible heat flux, surface latent heat flux, and the oceanic dynamic process plus ocean/land heat storage term), (b) atmospheric dynamic processes, (c) water vapor feedback, and (d) cloud feedback.

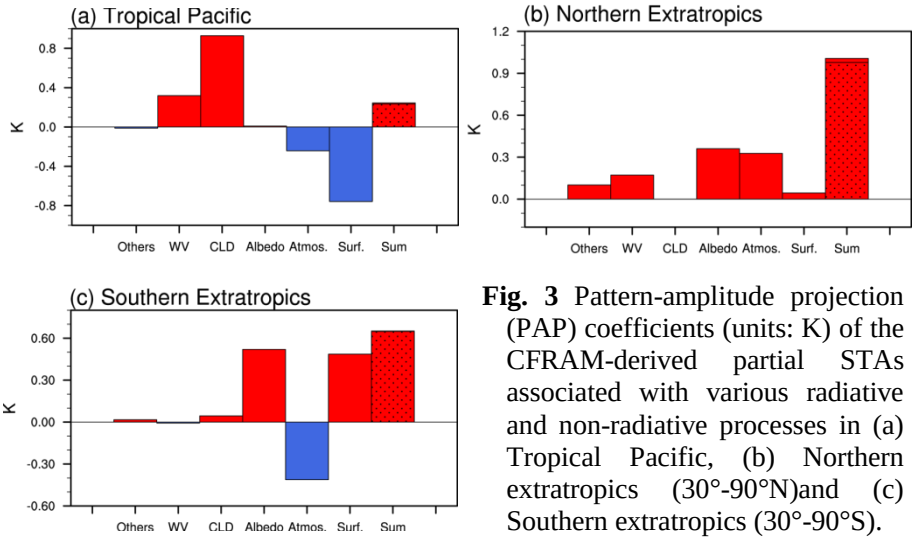

Fig. 3 Pattern-amplitude projection (PAP) coefficients (units: K) of the CFRAM-derived partial STAs associated with various radiative and non-radiative processes in (a) Tropical Pacific, (b) Northern extratropics (30°-90°N)and (c) Southern extratropics (30°-90°S).

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