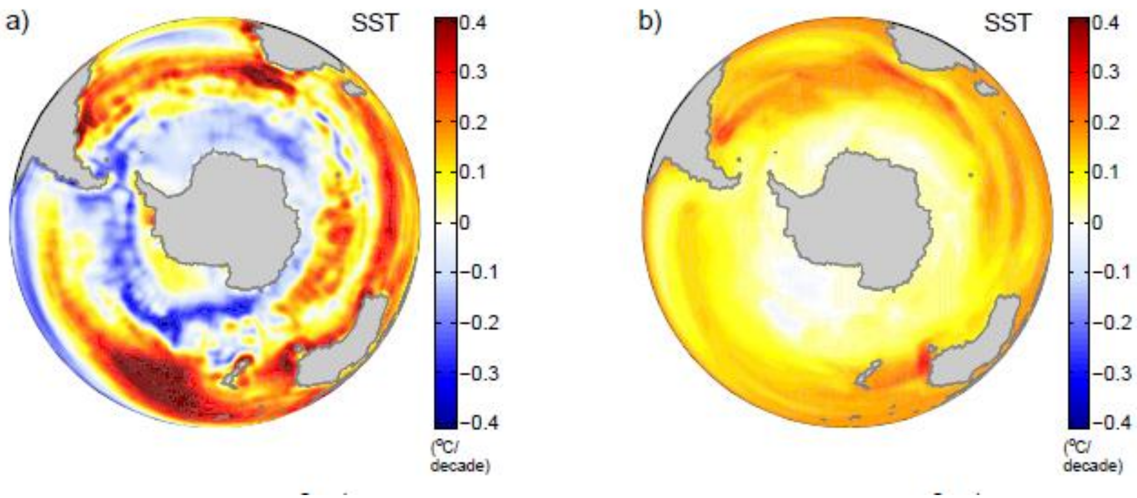
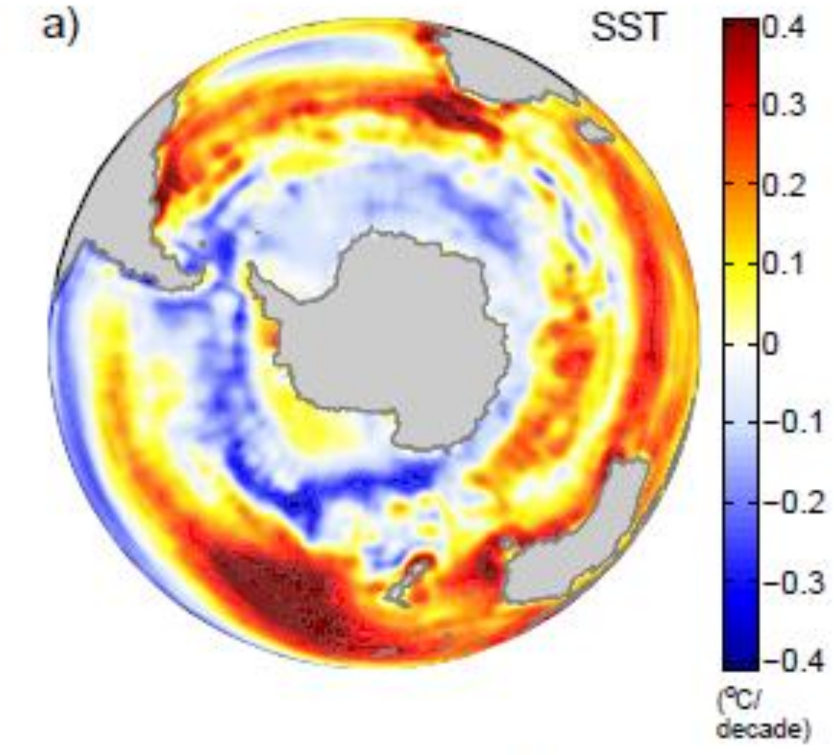
Understanding historical Southern Ocean trends in observations and simulations



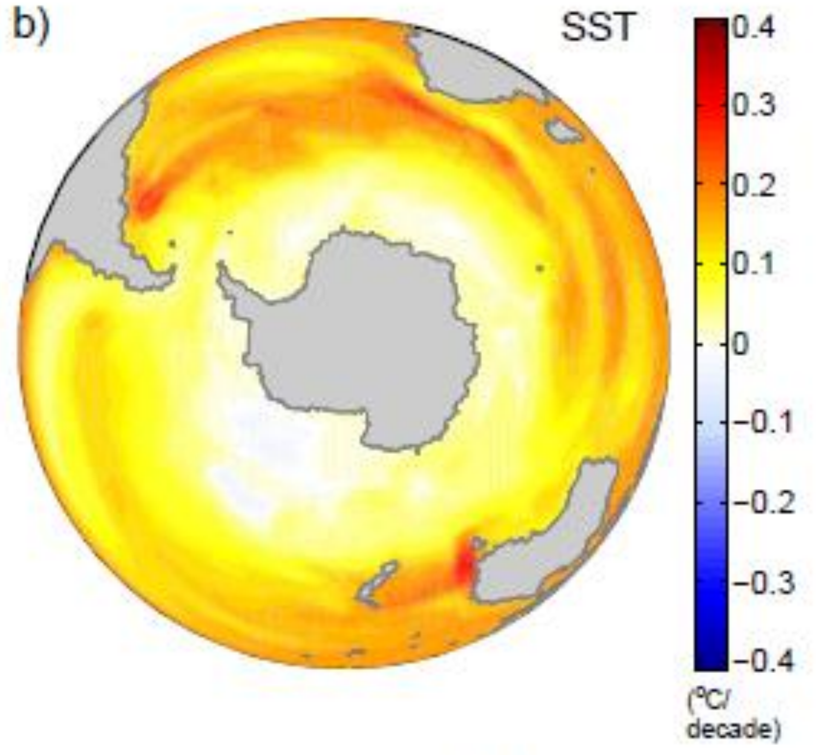
Yavor Kostov

MIT, U. of Oxford

Understanding historical Southern Ocean trends in observations and simulations

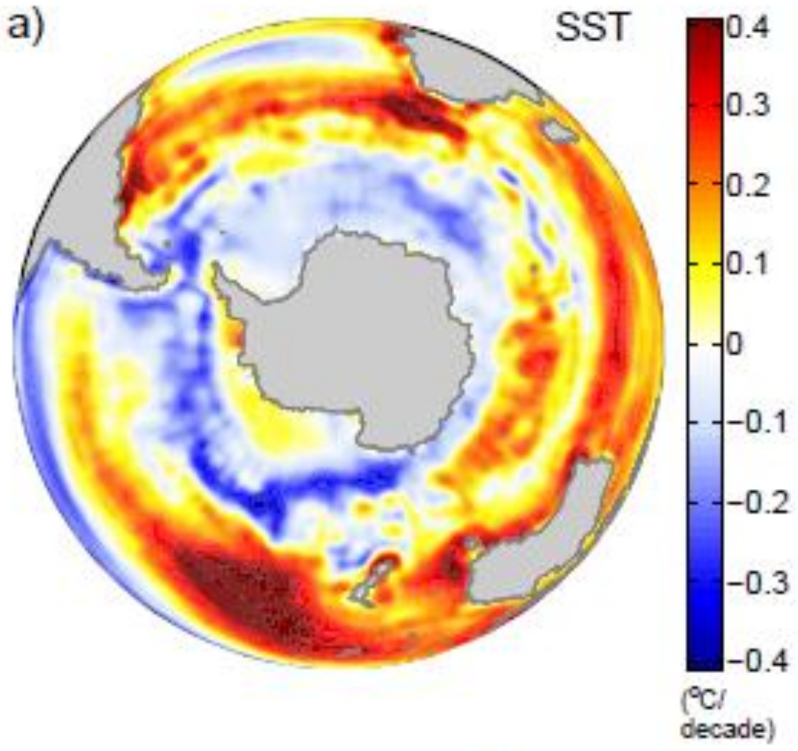


<u>Observations</u>:
NOAA Reynolds Optimum Interpolation
SST Trend 1982-2014



<u>CMIP5 Historical Simulations:</u>
SST Trend 1982-2014

The role of SAM and greenhouse gas forcing?



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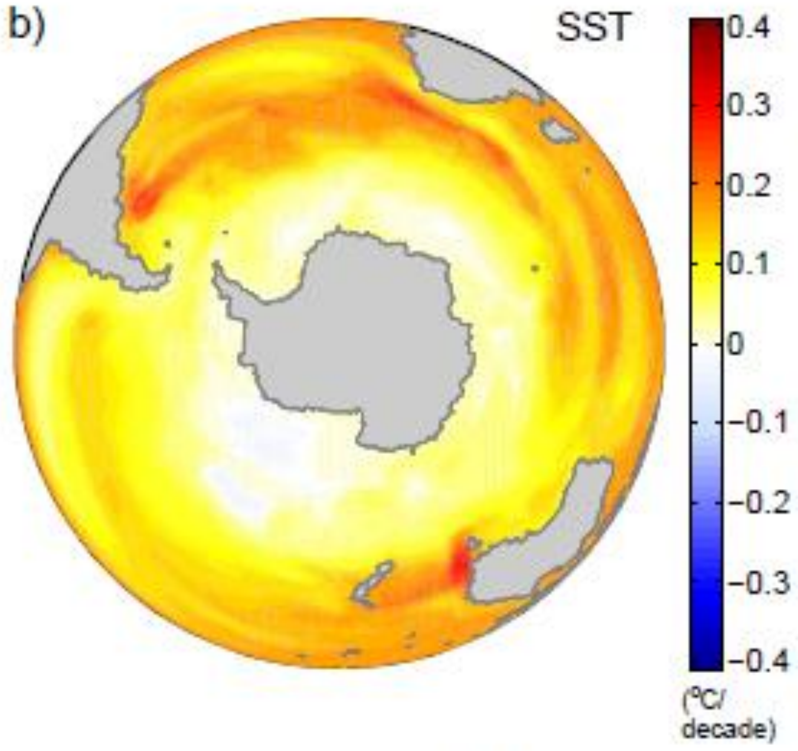
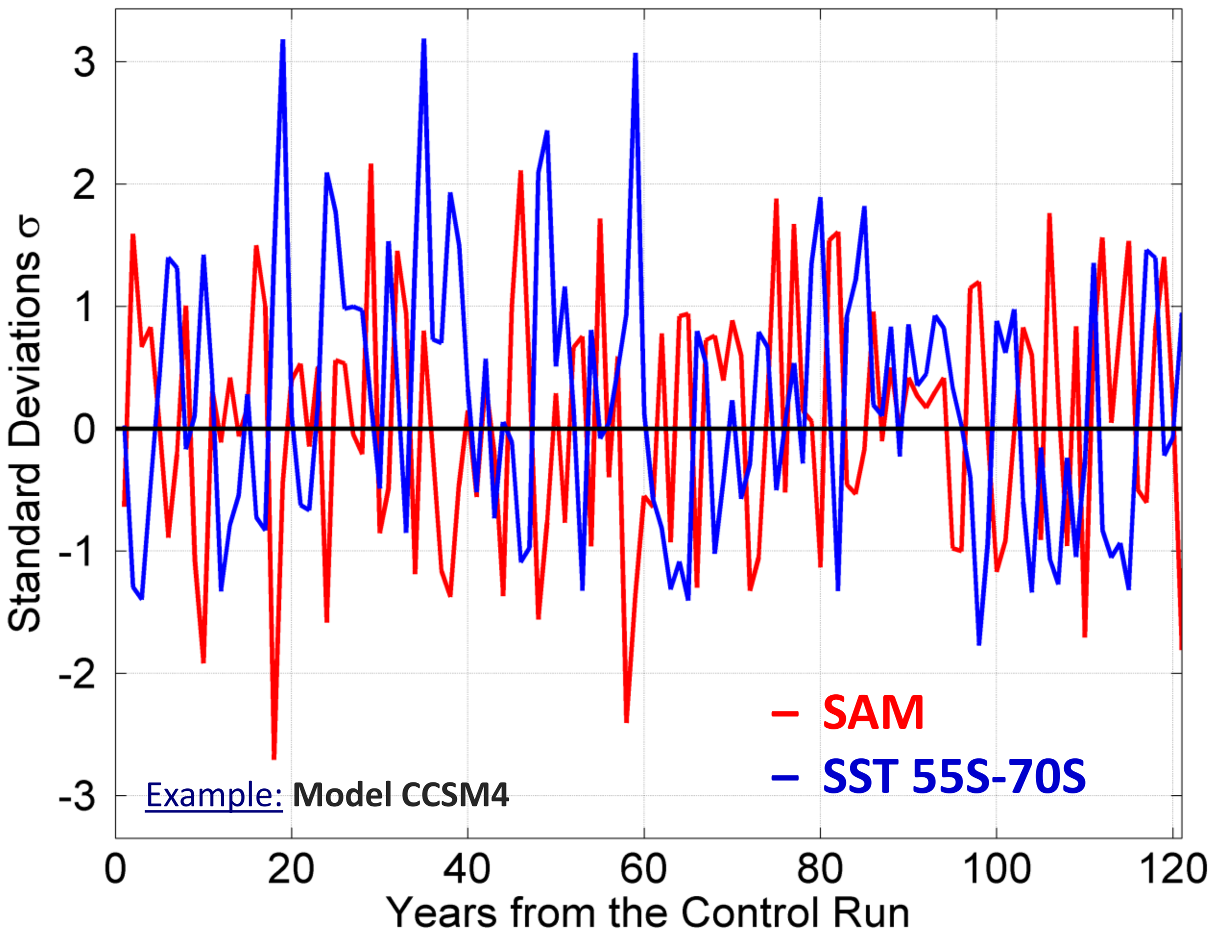


<u>CMIP5 Historical Simulations:</u>
SST Trend 1982-2014

SOUTHERN OCEAN RESPONSE FUNCTIONS TO SAM

Kostov et al. (2016) Fast and slow responses of Southern Ocean sea surface temperature to SAM in coupled climate models. *Climate Dynamics*. Published Online. DOI: 10.1007/s00382-016-3162-z

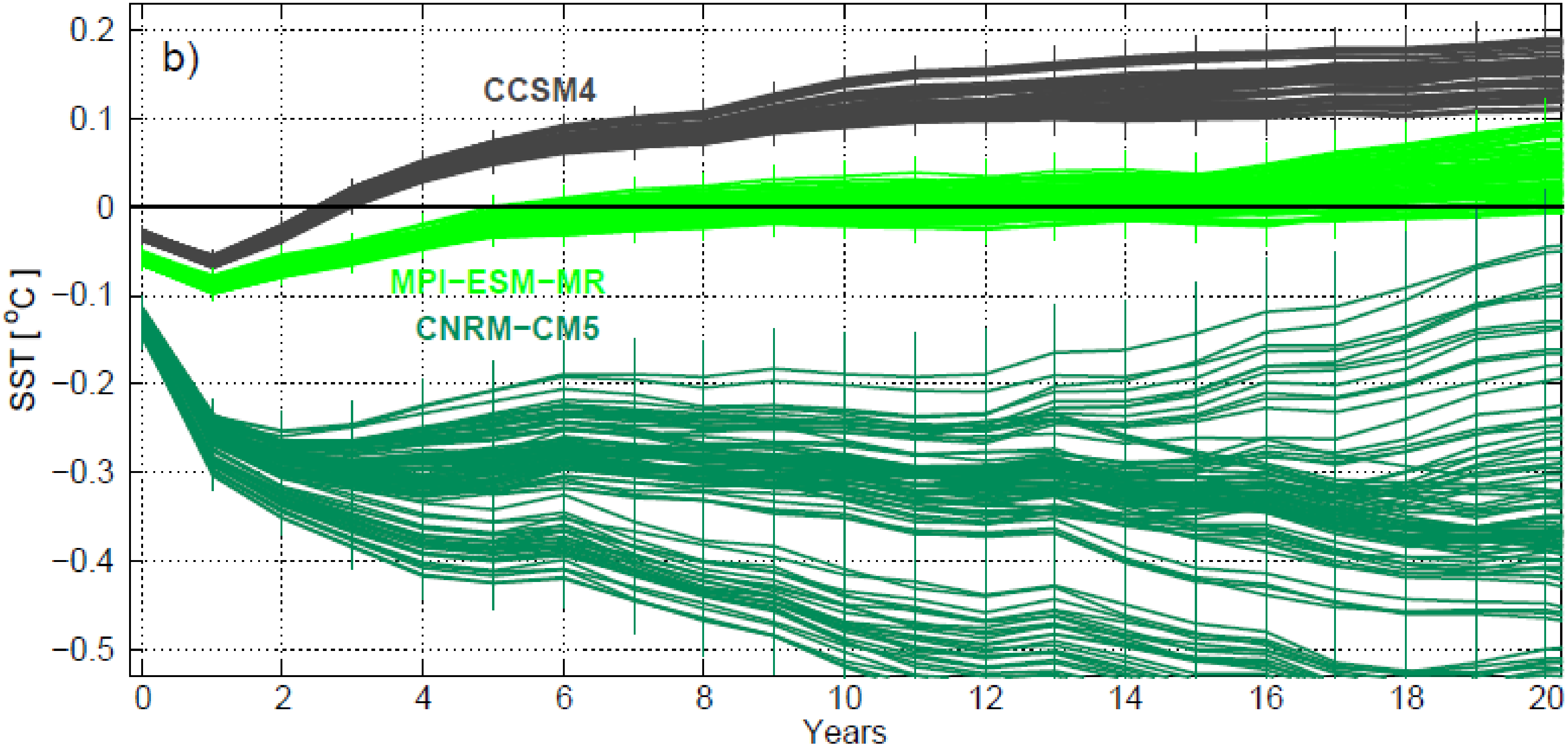
How does Southern Ocean SST respond to SAM on different timescales?



We first estimate the **impulse** response function $G(\tau)$ from the control runs

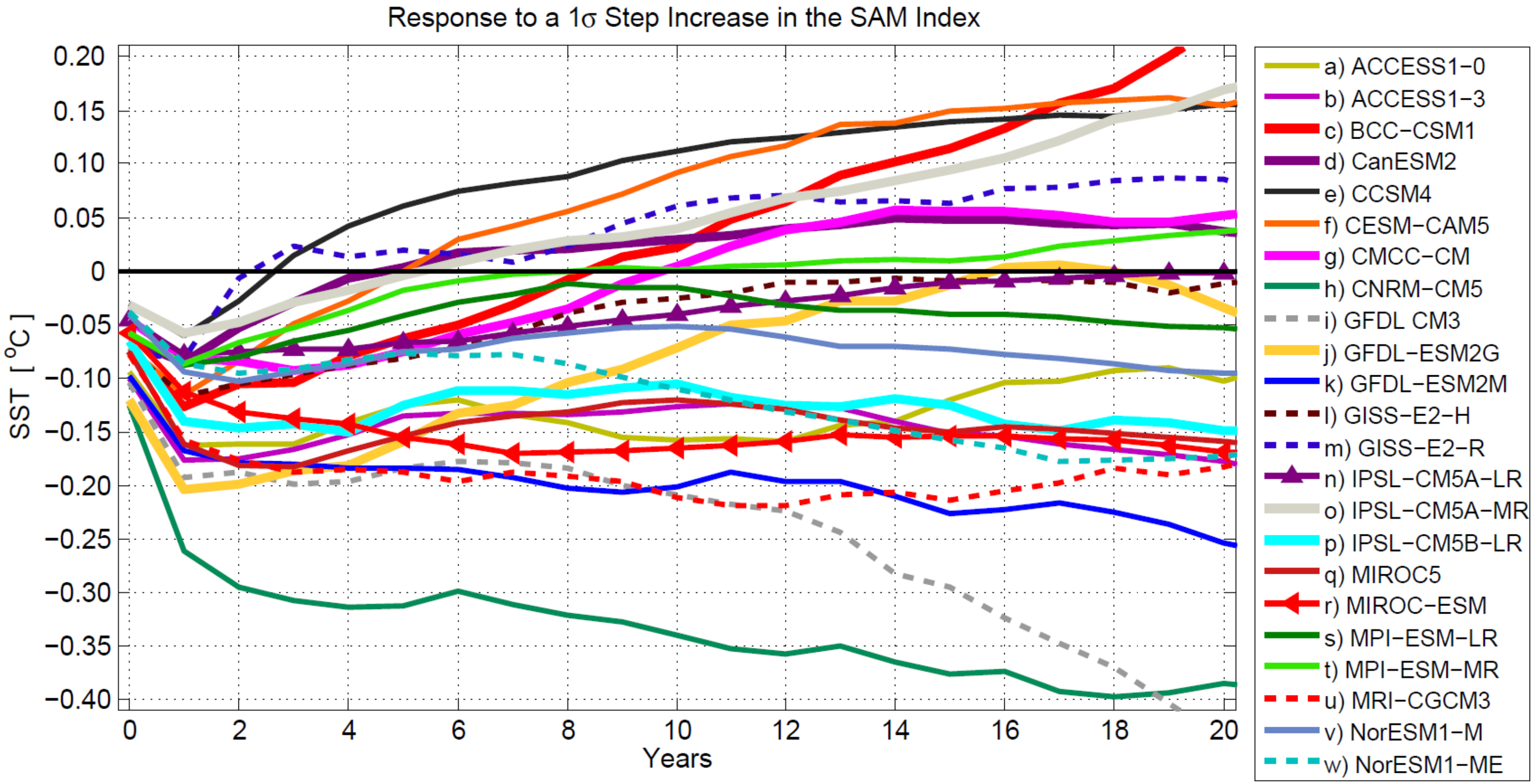
$$SST(t) = \int_0^{+\infty} G(\tau)\, SAM(t-\tau)d\tau + \varepsilon \approx \int_0^{\tau_{max}} G(\tau)\, SAM(t-\tau)d\tau + \varepsilon$$

Southern Ocean Step Response Functions to a SAM-like Pattern



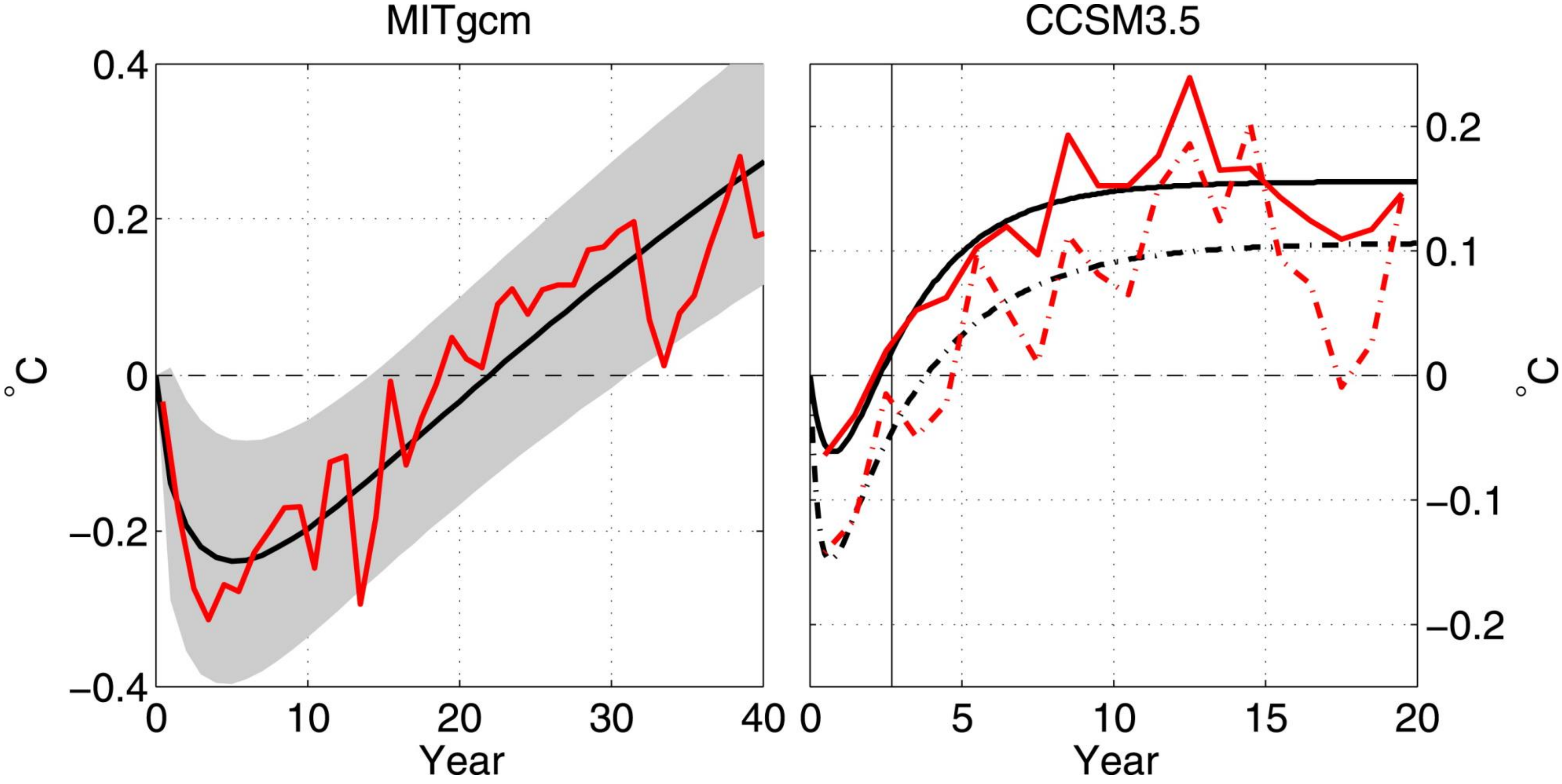
Kostov et al. (2016), *Submitted*

Southern Ocean Step Response Functions to a SAM-like Pattern



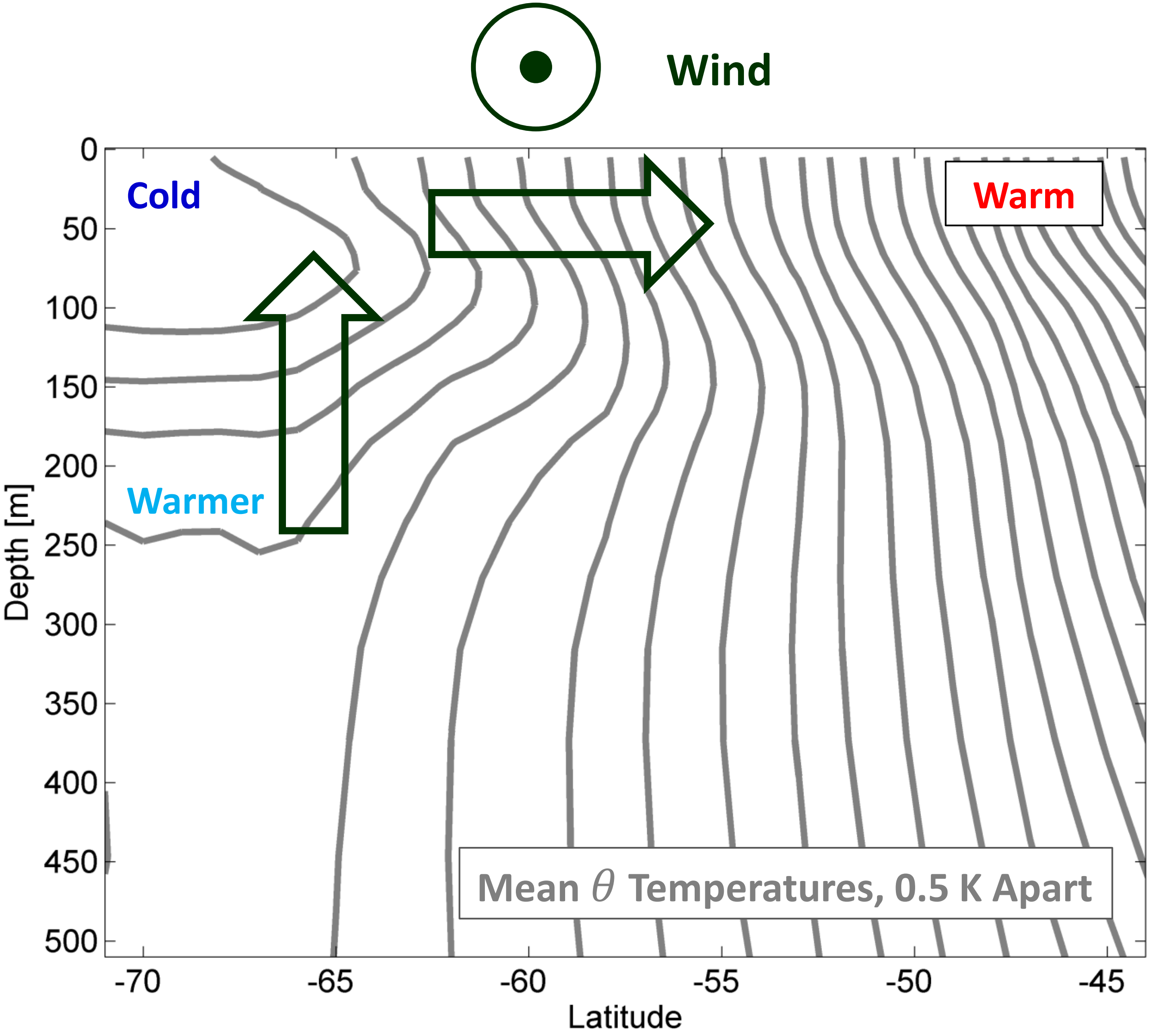
Kostov et al. (2016), *Climate Dynamics.* **Published Online**

Two-timescale response to a SAM-like pattern under ozone depletion

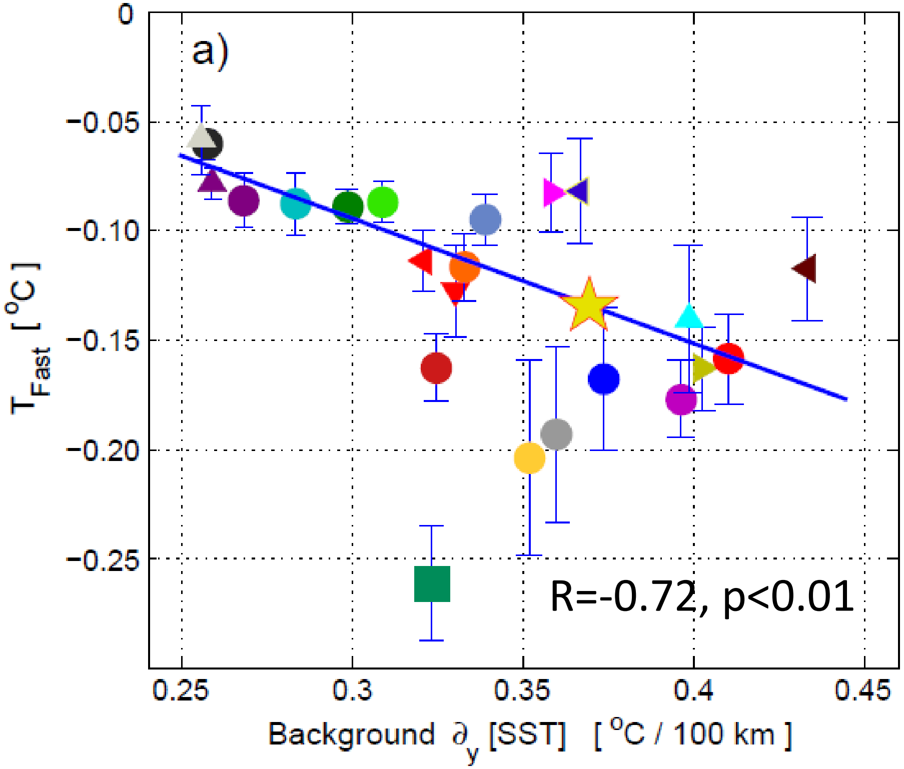


Ferreira et al. (2015)

Mechanism of the two-timescale response



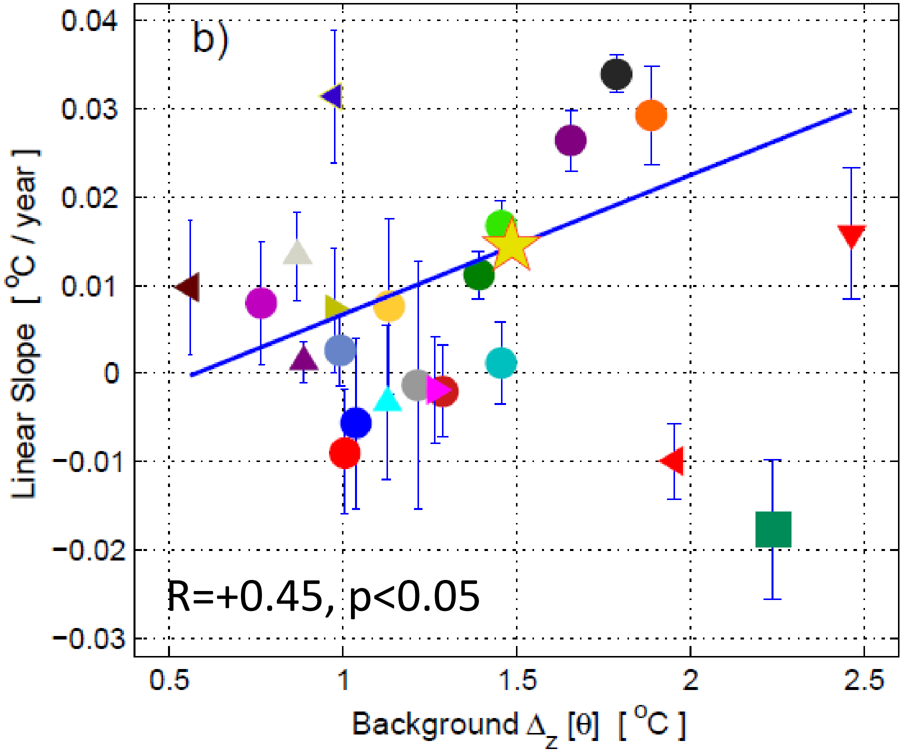
Also, seee Purich et al. (2016)



Weighted linear least squares regressions

The Year 1 cooling response to SAM is negatively correlated with the meridional gradient of climatological SST.

Real World Estimate ☆



The slope of the slow warming response is positively correlated with the vertical contrast in Southern Ocean potential temperature.

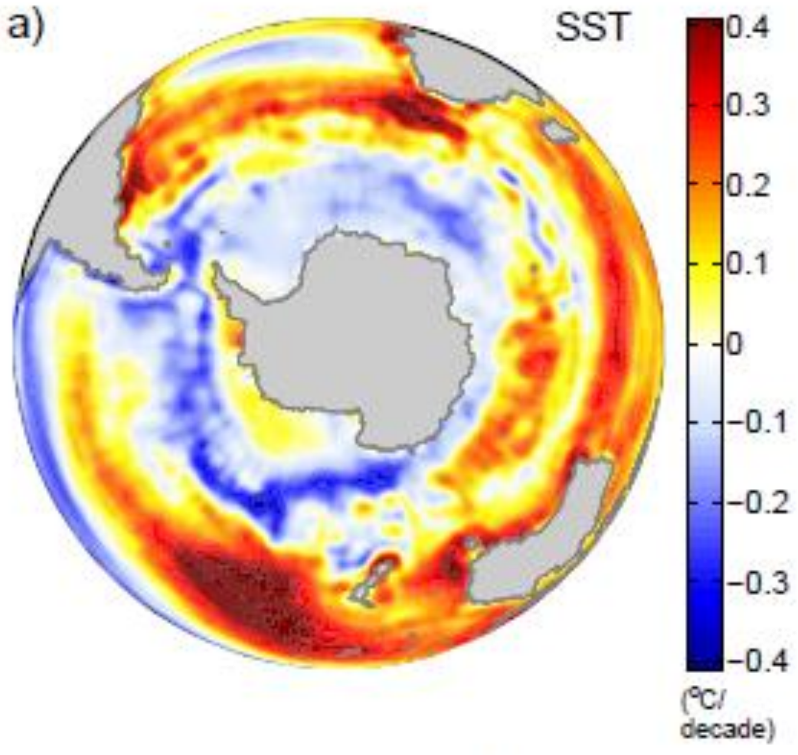
More complicated than the fast response.

Kostov et al. (2016), *Climate Dynamics.*
Published Online

APPLICATION

Work in Prep.

Understanding historical Southern Ocean trends in observations and simulations



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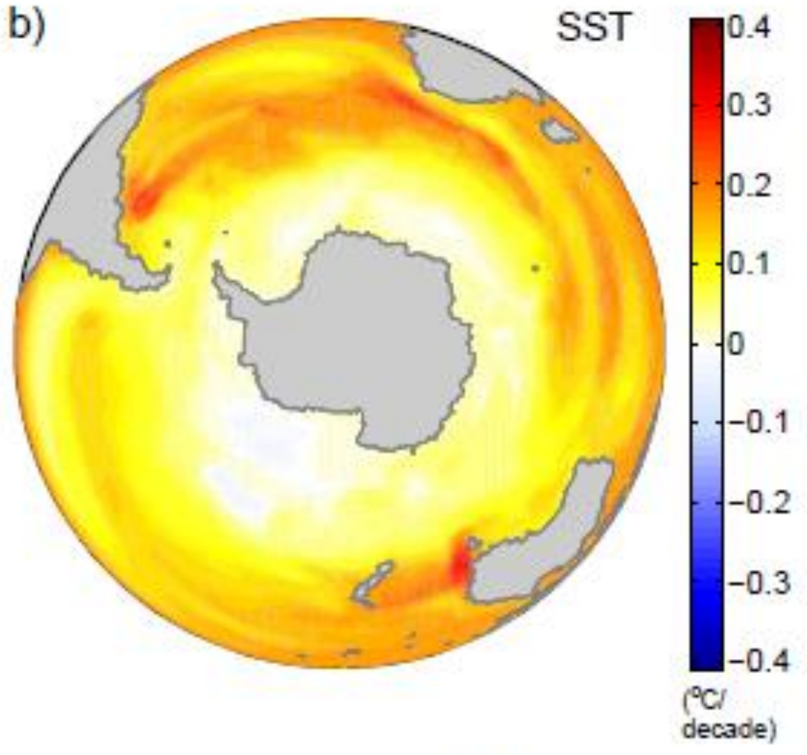
SST Trend 1982-2014



CMIP5 Historical Simulations:
SST Trend 1982-2014

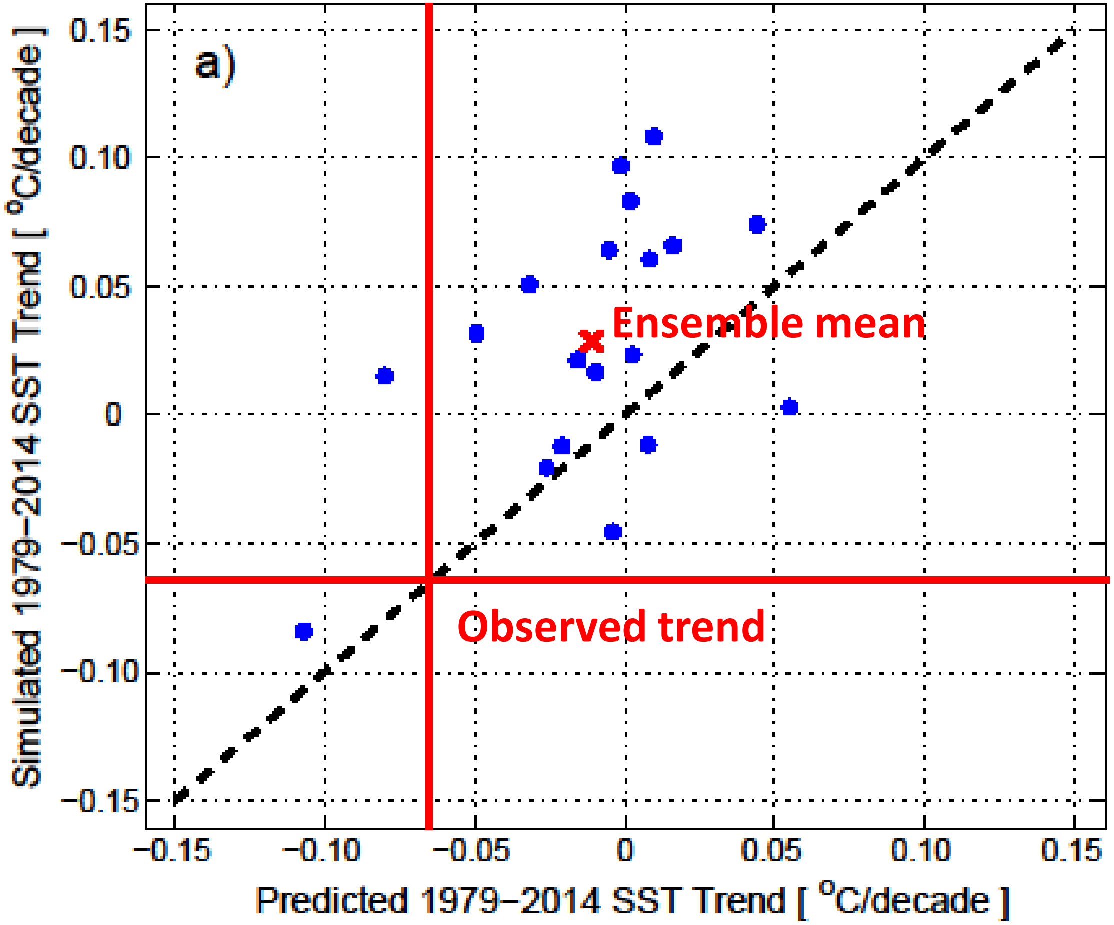
Convolving the Step Response S with the Evolution of Historical Forcing F_{hist}

Given a history of observed forcing, we can estimate the historical response via the convolution

$$SST_{hist}\,(t) = \int_0^t S(\tau)\left(\left.\frac{dSAM_{hist}}{dt}\right]_{(t-\tau)}\right)d\tau$$

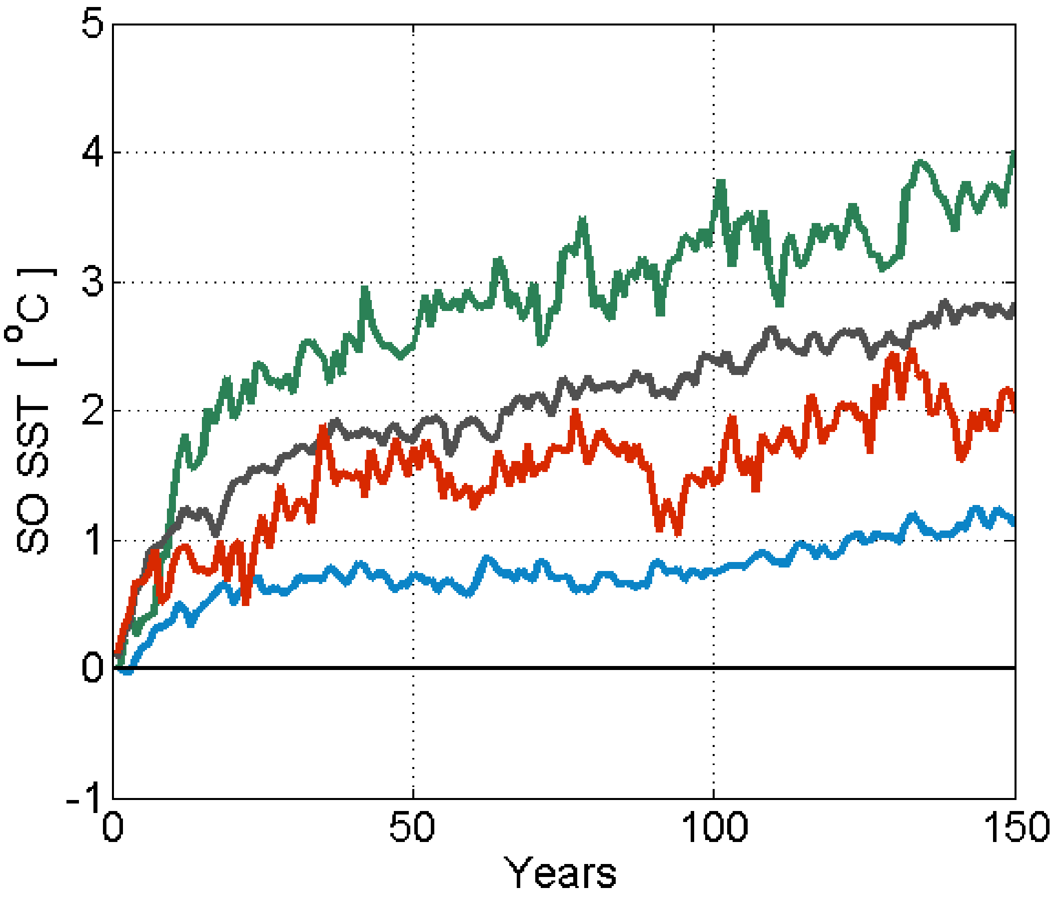
The historical SST response at time t.

Convolutions of the SAM CRFs



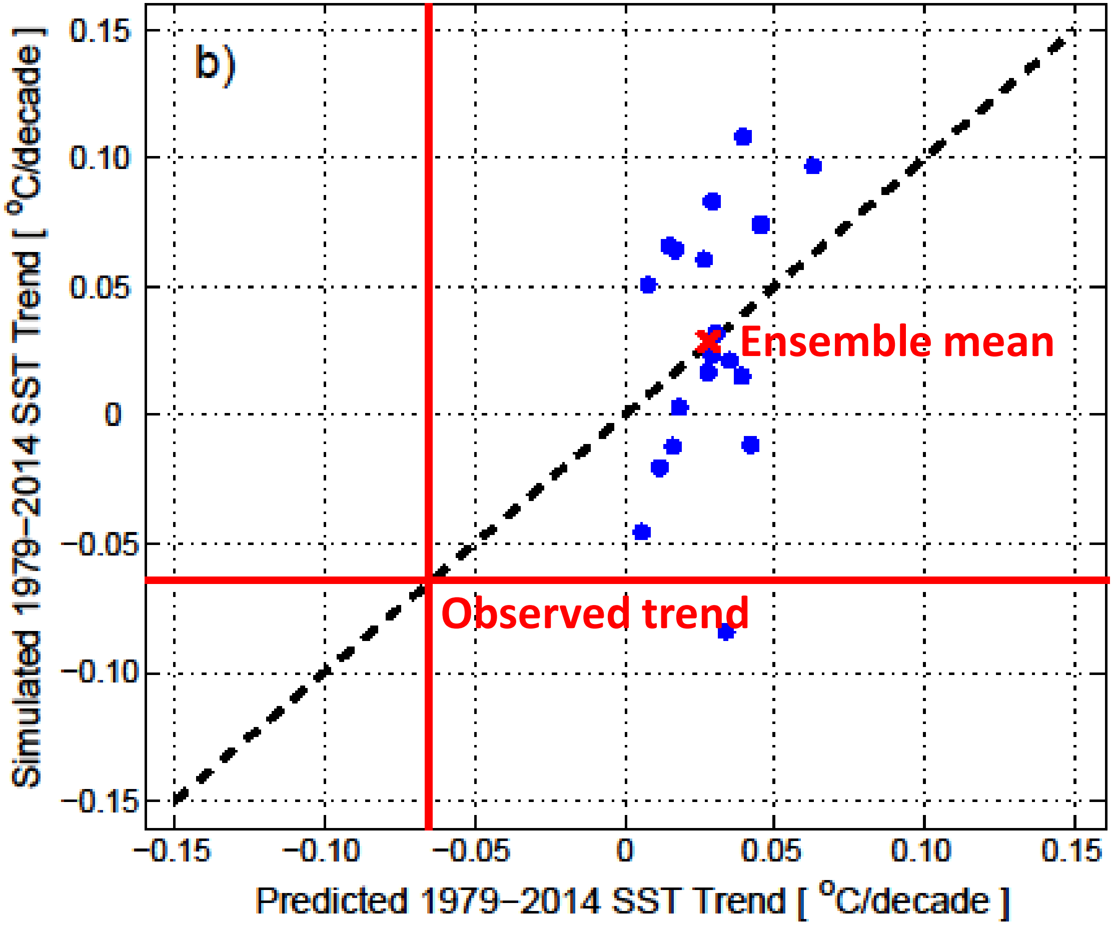
- Capture some of the intermodel spread;
- Underestimate the warming in historical simulations

CMIP5 CRFs to Greenhouse Gas Forcing



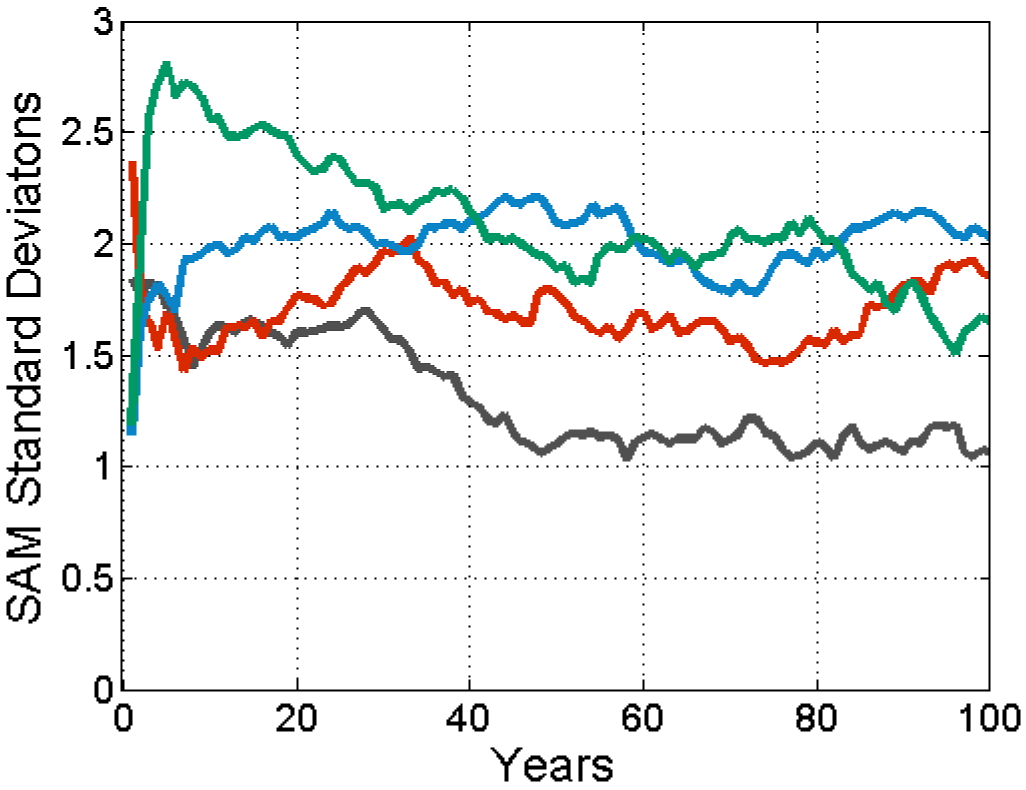
- Based on CMIP5 abrupt CO2 quadrupling experiments;
- Constitute step responses functions of SO SST to TOA radiative forcing.

Convolutions of the GHG CRFs



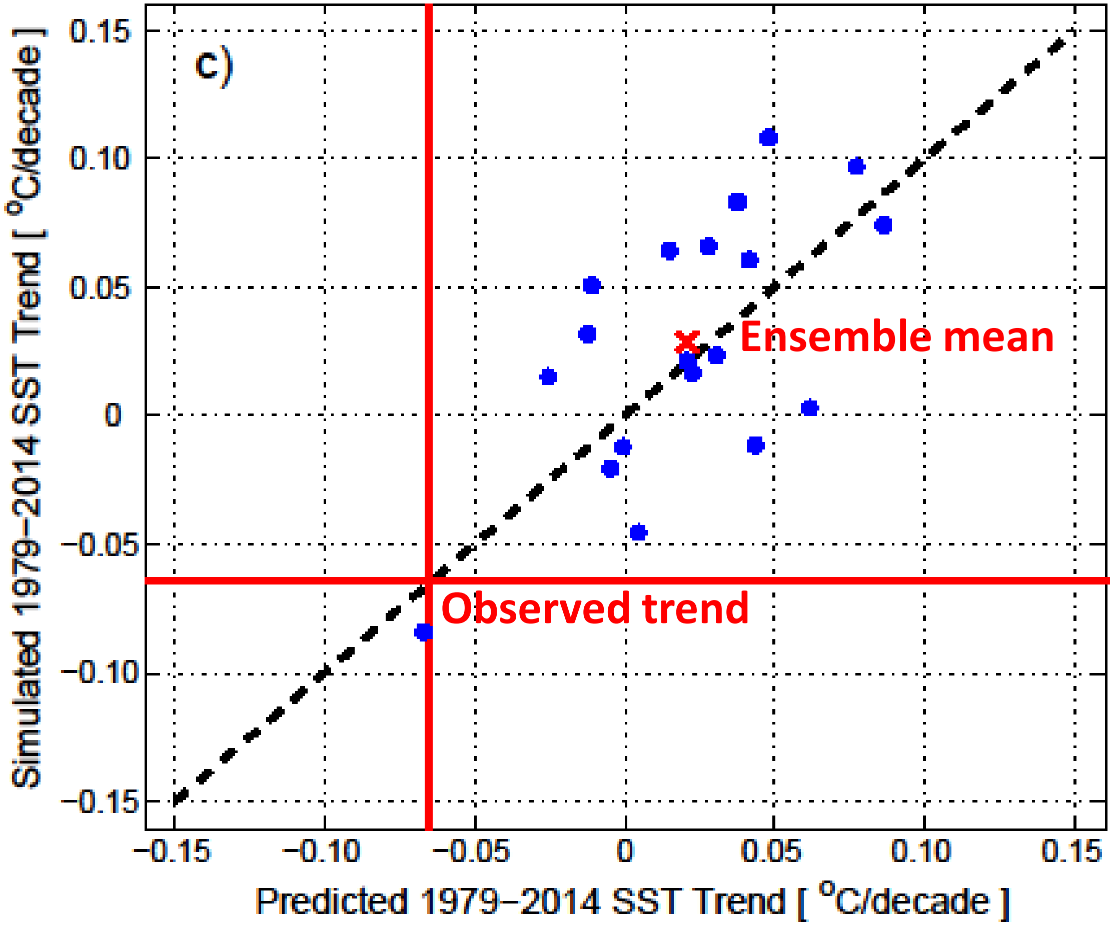
- The ensemble mean reconstruction shows realistic warming;
- The GHG convolution does not reproduce individual model responses.

Impact of GHG forcing on the SAM cannot be neglected



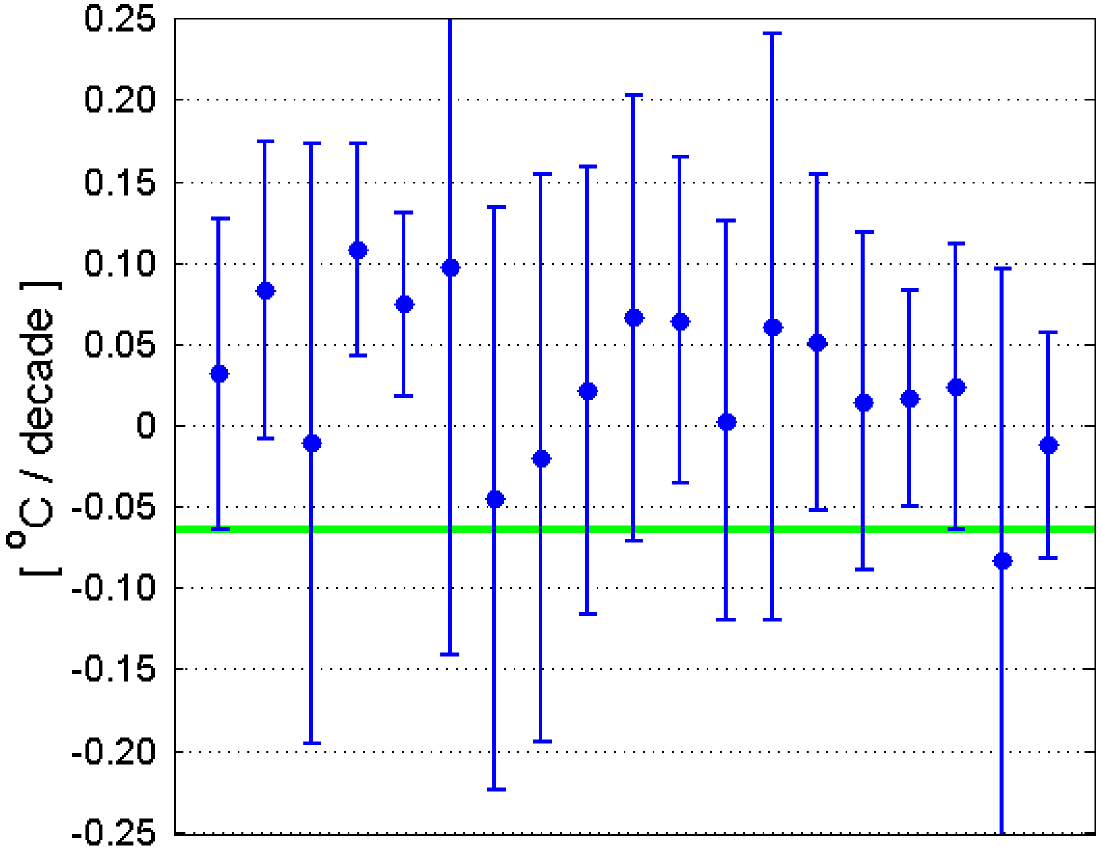
- Based on CMIP5 abrupt CO2 quadrupling experiments;
- Constitute step responses functions of SAM to TOA radiative forcing.

Combined GHG and SAM Convolutions



- Reproduces the ensemble mean response;
- Capture some of the intermodel spread.

A Southern Ocean warming bias in the CMIP5 historical simulations

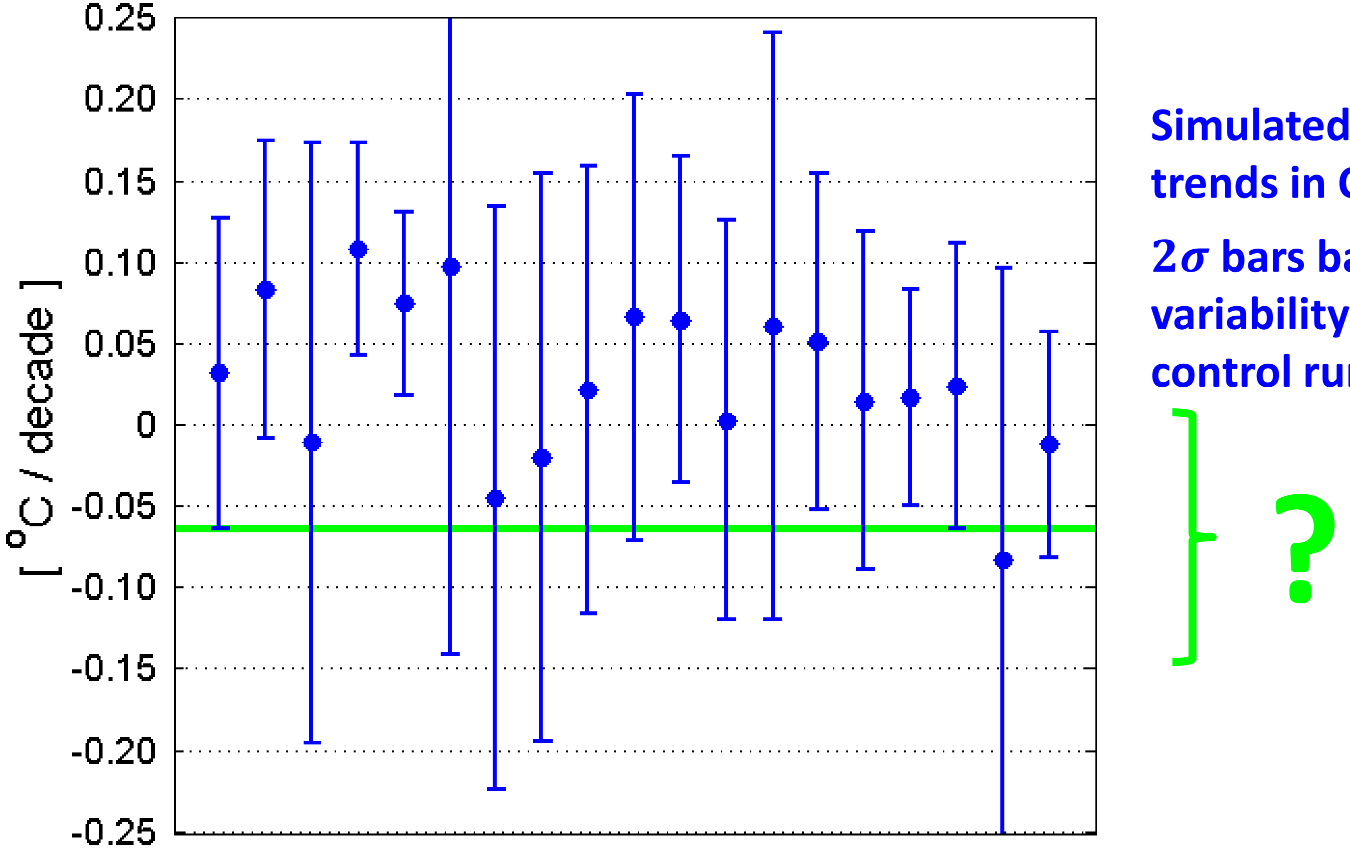


Simulated historical trends in CMIP5 ;

2σ bars based on variability in the control runs.

Observed trend NOAA Reynolds OI

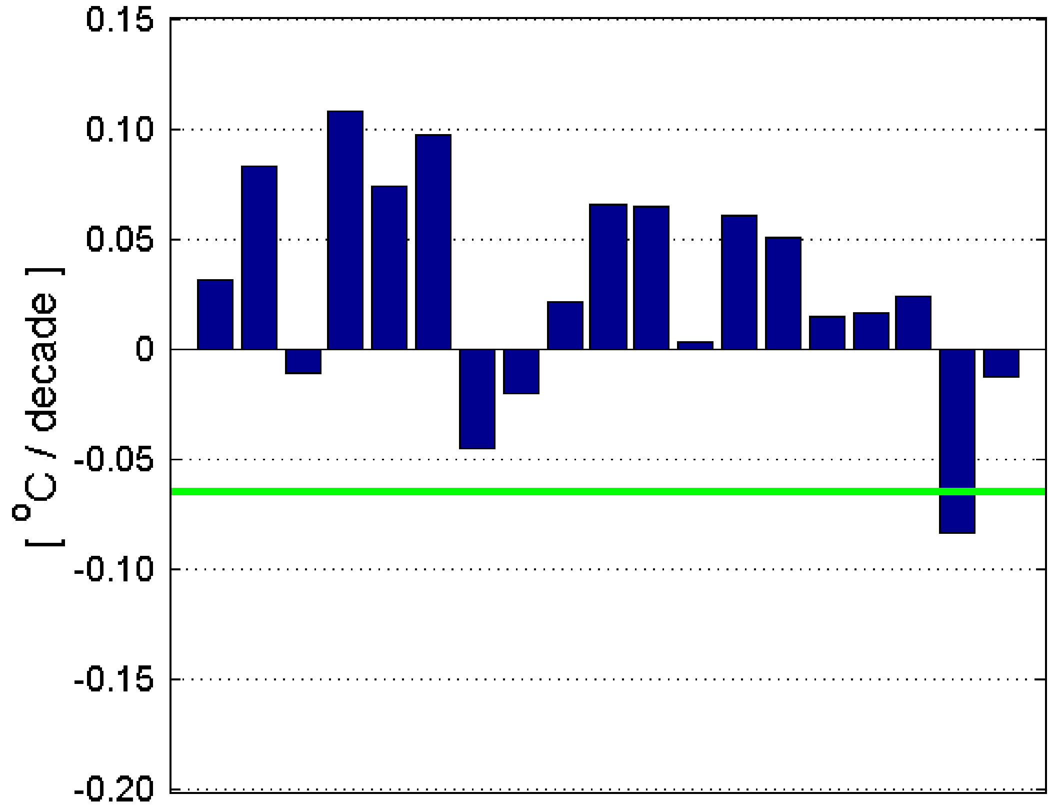
A Southern Ocean warming bias in the CMIP5 historical simulations



Simulated historical trends in CMIP5 ;

2σ bars based on variability in the control runs.

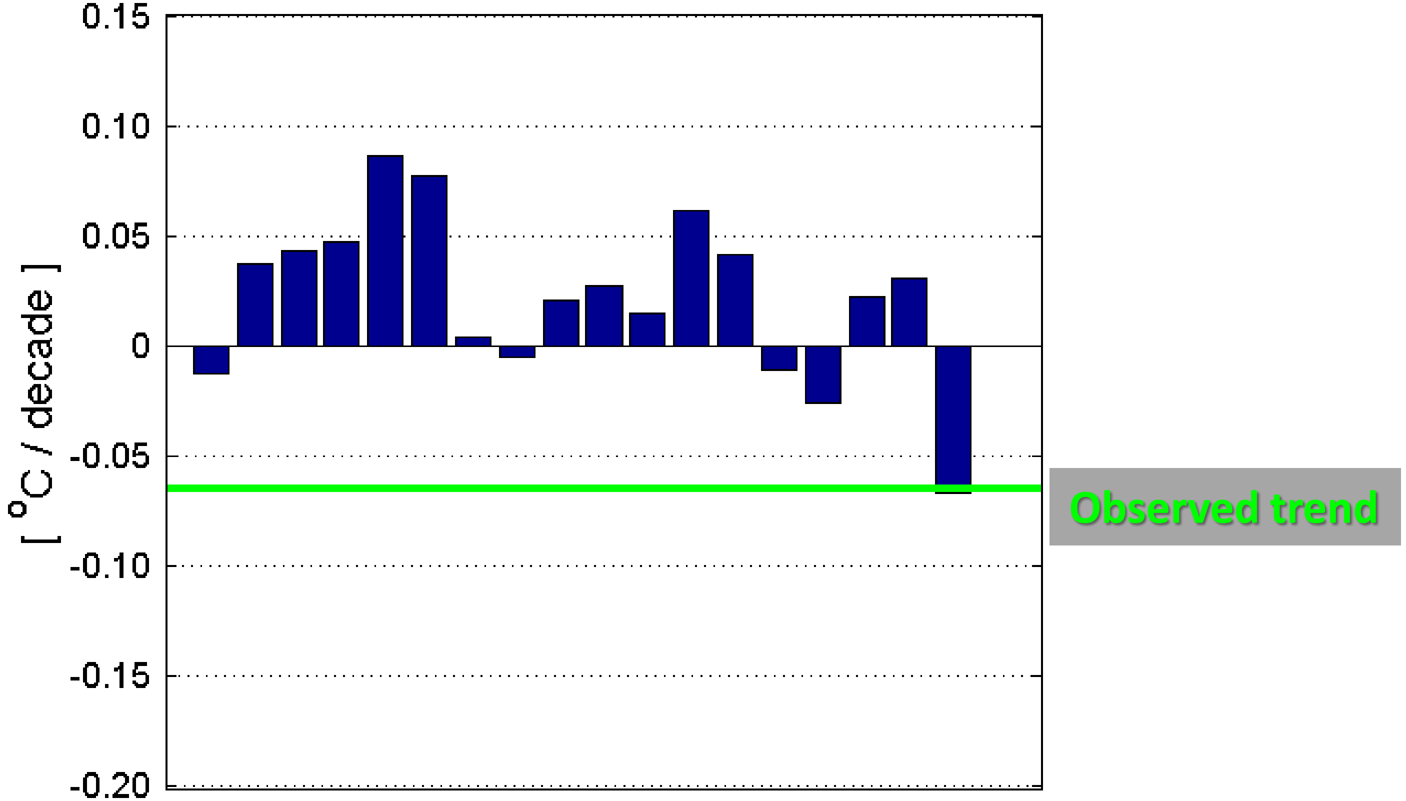
A Southern Ocean warming bias in the CMIP5 historical simulations



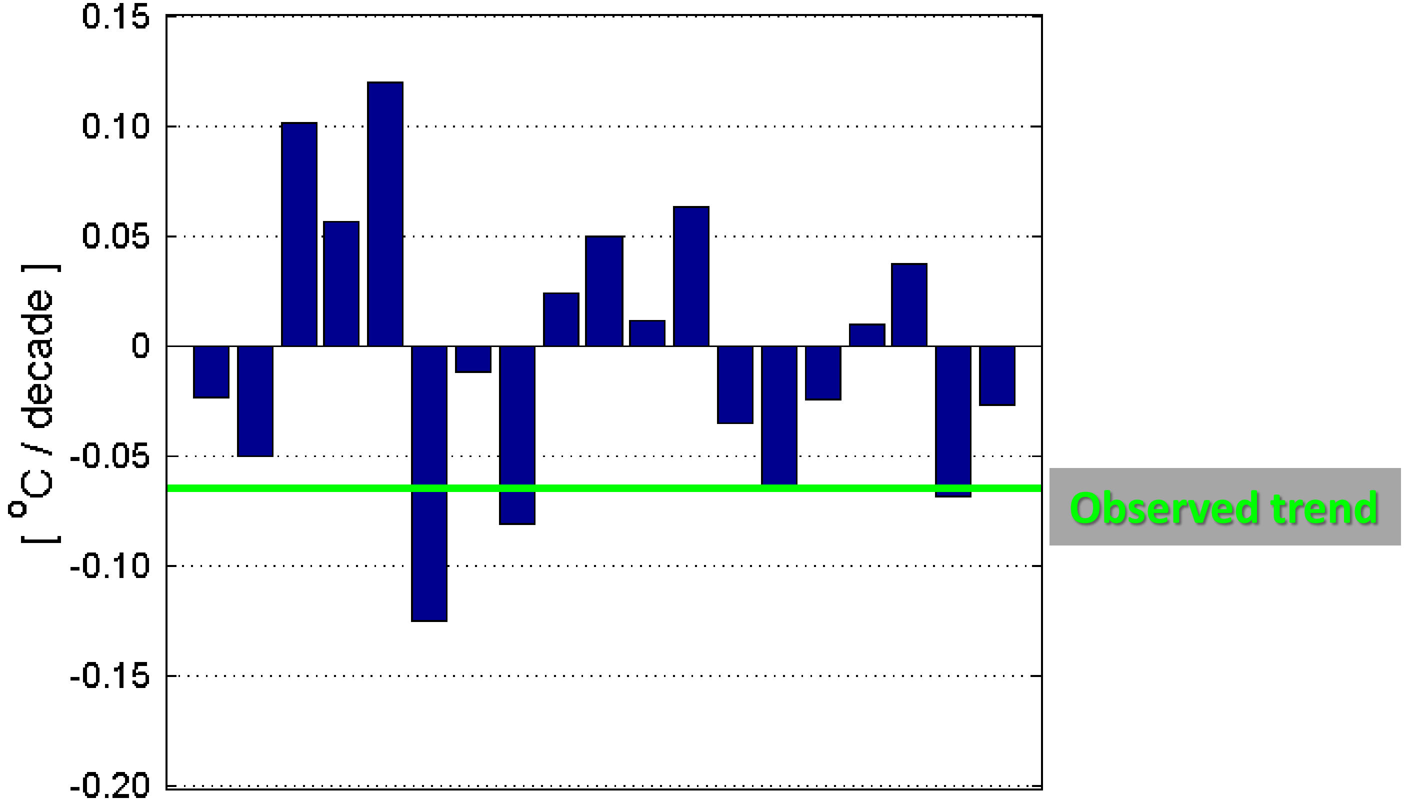
CMIP5 Trends from historical simulations

Observed trend

A Southern Ocean warming bias in **our <u>reconstruction</u> of** the CMIP5 historical simulations



Convolving the CMIP5 with the **observed** SAM and GHG trends



- Most models are expected to show more SO cooling under realistic SAM trends (taken from HadSLP2r);
- Several models expected to warm more under stronger SAM.

Conclusions

- Historical Southern Ocean SST trends: SAM and GHG forcing.

- Many coupled global climate models exhibit a two-timescale response of the Southern Ocean to SAM. The fast cooling regime transitions to a slow warming response.

- The SST response to SAM: wind-driven transport redistributing the background heat content.

- To reproduce the observed Southern Ocean cooling trends, models need both realistic SAM anomalies and realistic ocean stratification.

Future directions:

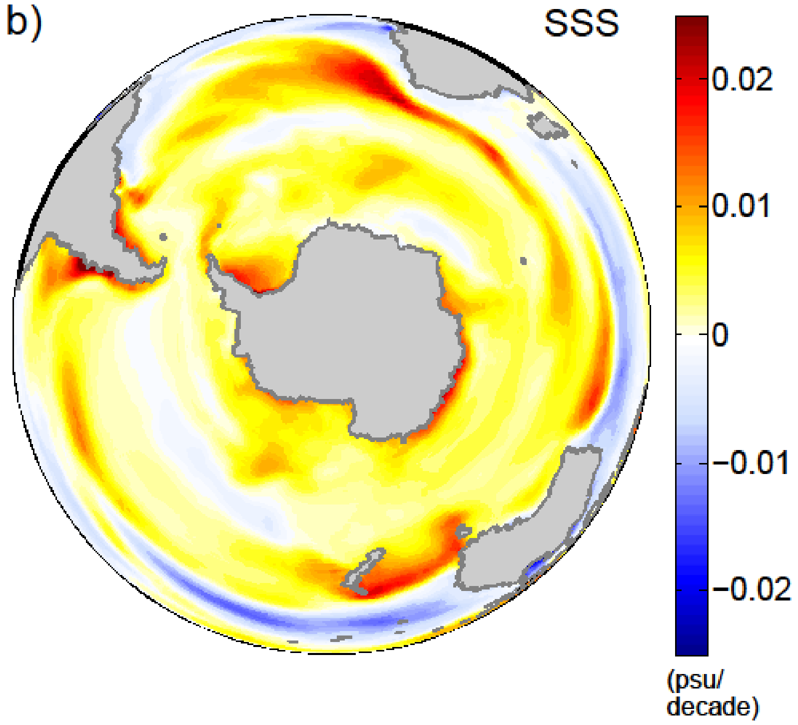
- Bias-correction of the model step response functions to SAM;
- Taking into account seasonality:

A positive trend in DJF SAM triggers a stronger cooling (e.g., Purich et al., 2016)

It is surprising that annual mean reconstructions work relatively well.

Ensemble Mean Composite of 30-year Trends in Sea Surface Salinity (SSS)

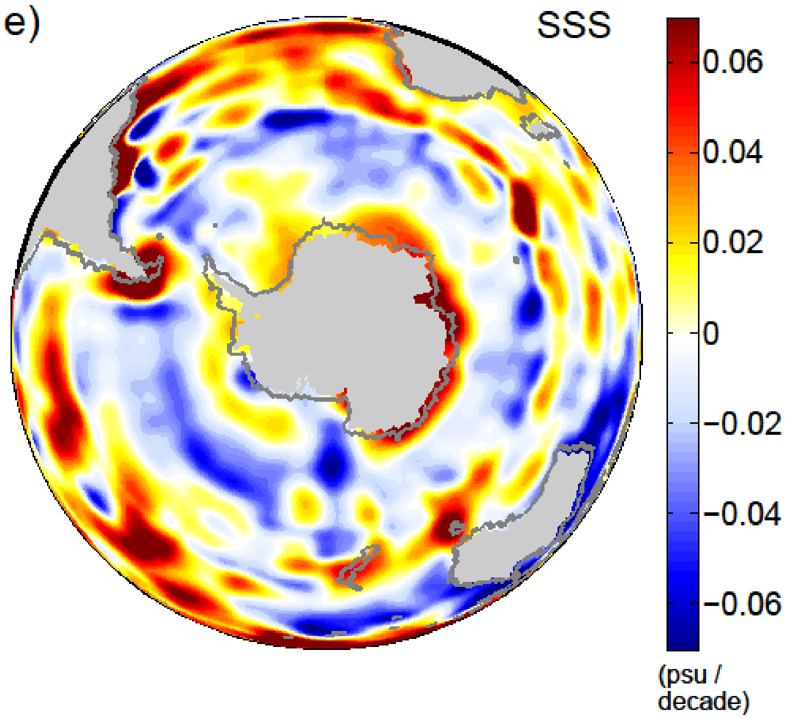
- Salinification at the surface;
- Different from studies which suggest that freshening plays an important role for setting the surface cooling trends (e.g., Bitanja et al., 2013);
- Under positive SAM trends, we see cooling without freshening.



Salinification
(**<u>Not</u>** freshening)

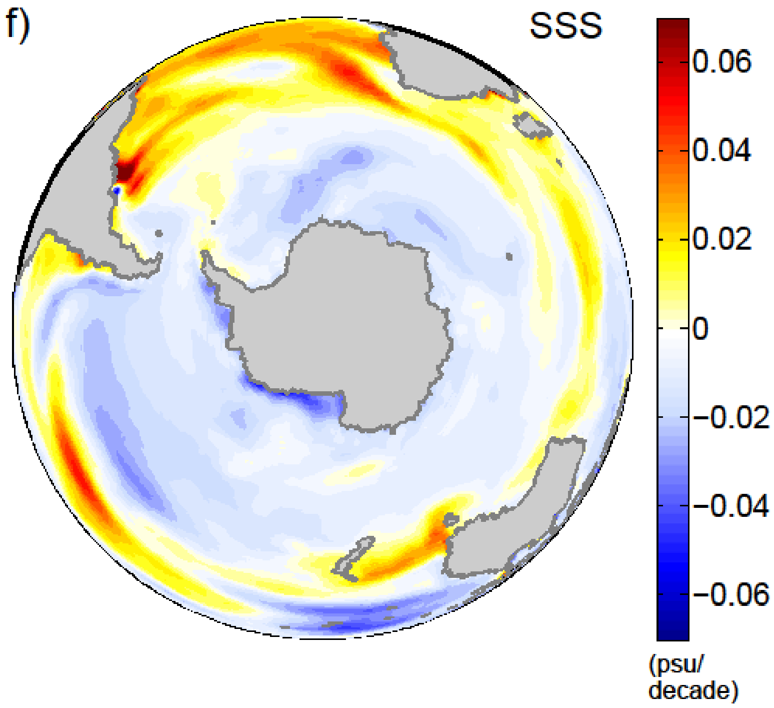
Observed Southern Ocean Freshening

- The Hadley EN4 dataset shows Southern Ocean freshening between 1979 and 2013.

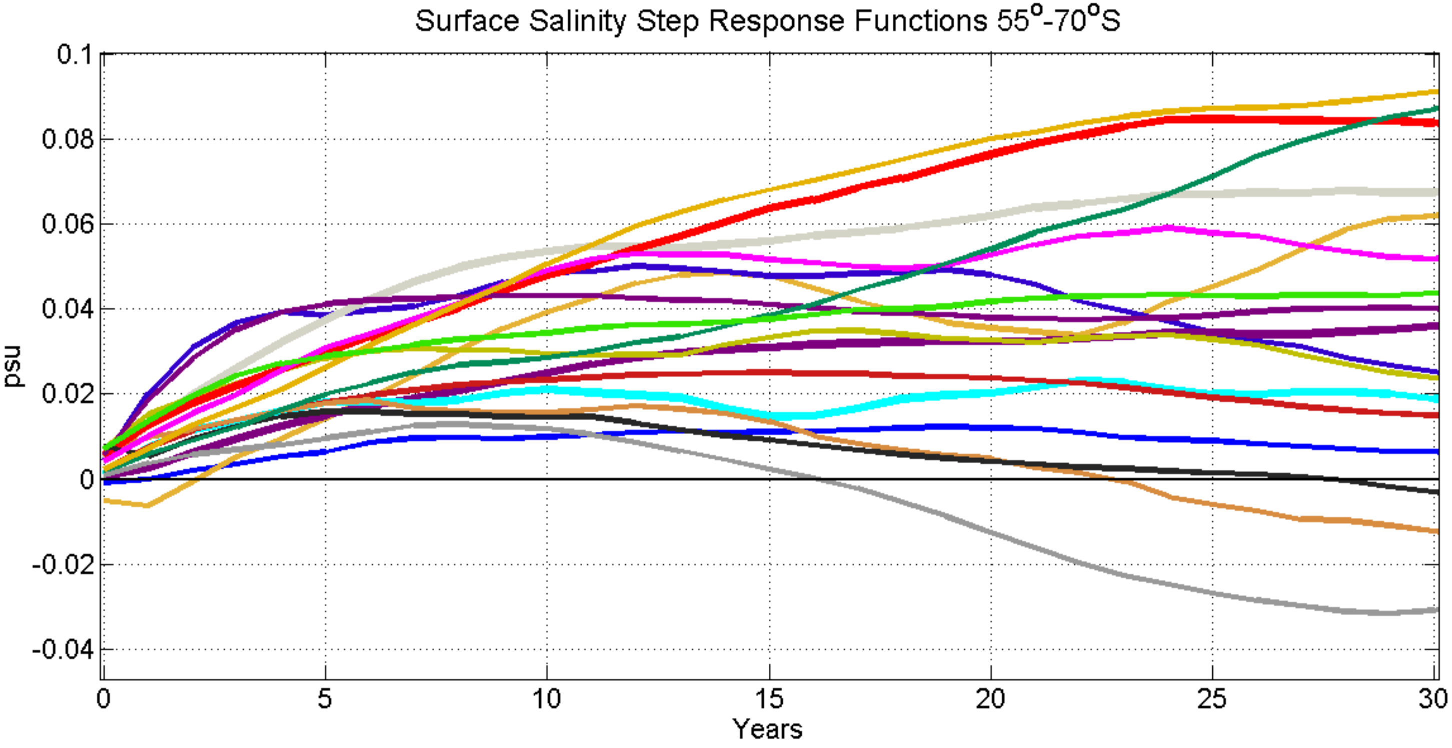


Ensemble mean of the 1979-2014 simulated trends in Sea Surface Salinity (SSS)

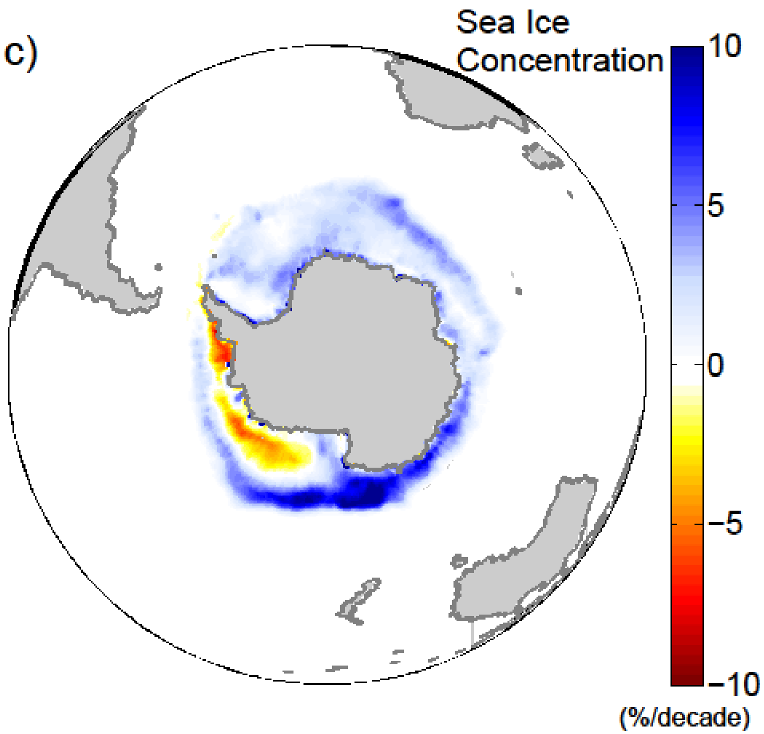
- Historical CMIP5 do show freshening trends;
- Weaker than the observed freshening;



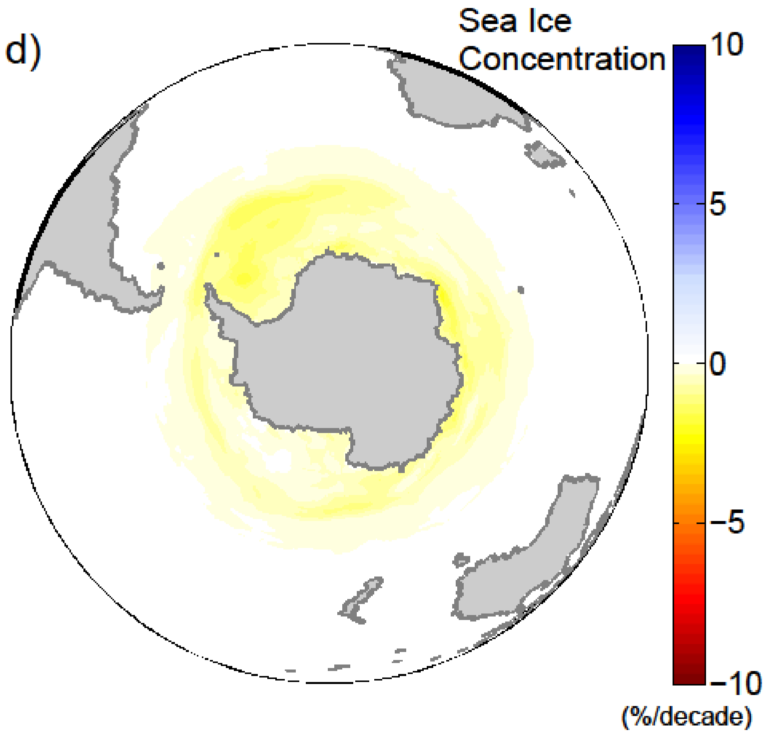
Southern Ocean Salinity CRFs



Observed Vs Simulated Sea Ice Trends



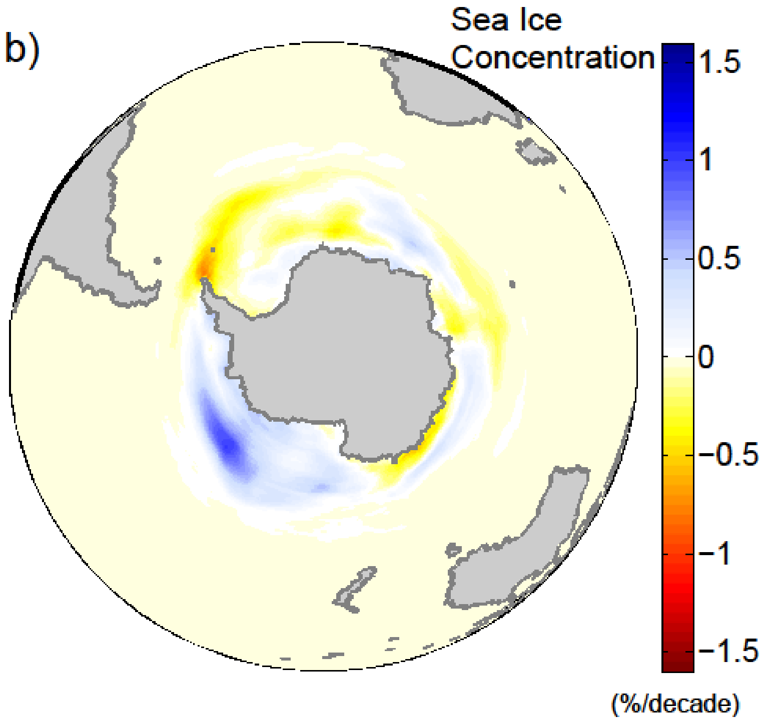
Observations
(NOAA Reynolds 1982-2014)



CMIP5 Simulations
(1979-2014)

Ensemble mean sea ice concentration trends in SAM-based composites

- The SAM-based composites show weak sea ice expansion on the Pacific side of the Southern Ocean;
- In each model the pattern of sea ice concentration trends is negatively correlated with the pattern of SST trends.



Extracting the Response to Impulse Forcing from Unforced Control Experiments

$$\boldsymbol{Y} = \boldsymbol{X}\boldsymbol{g} + \boldsymbol{\varepsilon}$$

$\Rightarrow$ We estimate $\widehat{\boldsymbol{g}} = (\boldsymbol{X}^T\boldsymbol{X})^{-1}\boldsymbol{X}^T\boldsymbol{Y}$ and residuals $\boldsymbol{\varepsilon}$

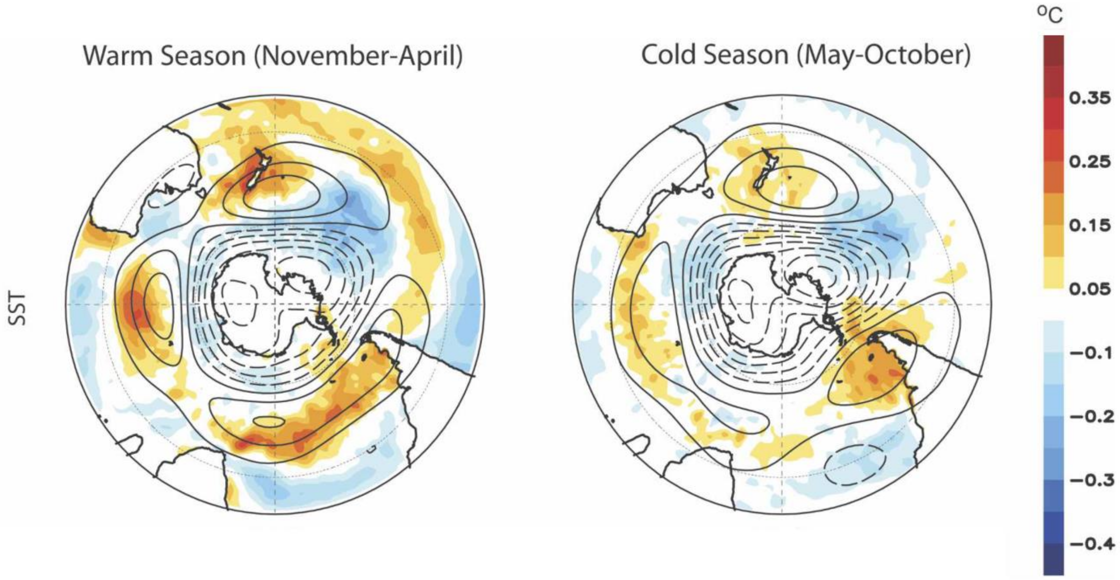
We calculate uncertainties for each estimated $\widehat{g}_i$.

- The covariance matrix

$$\left(\frac{\hat{\boldsymbol{\varepsilon}}^T\hat{\boldsymbol{\varepsilon}}}{Length(\boldsymbol{Y}) - n}\right)(\boldsymbol{X}^T\boldsymbol{X})^{-1}$$

gives us the uncertainties for each estimate $\widehat{g}_i$.

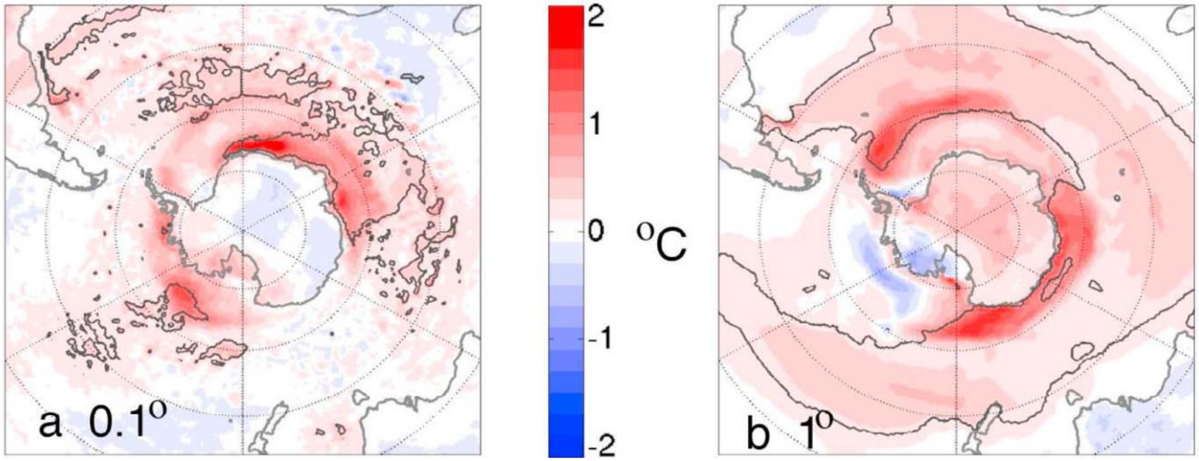
What is the impact of SAM-like wind trends on the Southern Ocean SST trends?



COOLING

Ciasto and Thompson (2008)

Northward transport of colder water; Surface heat fluxes



WARMING

Bitz and Polvani (2012)

Annual means in CCSM3.5

Upwelling of warmer water

Idealized GHG Trend

Assume: The historical GHG concentration grows exponentially from 280 ppm in 1855 to a 480 ppm **CO2-equivalent** in 2014 (160 years).

→ TOA forcing due to GHGs grows linearly.

Rescaling the historical forcing trend
by the abrupt 4xCO2 forcing:

$$F_{GHGtrend} = \left(\frac{\ln(480) - \ln(280)}{\ln(4 \times 280) - \ln(280)}\right)\frac{1}{160\ years}$$

$$= \left(\frac{\ln(480/280)}{\ln(4)}\right)\frac{1}{160\ years}$$

Assume all model-specific deviations from this trend are an error term.

NOAA AGGI

Extracting the Response to Impulse Forcing from Unforced Control Experiments

Least-squares regression of the lagged SST and wind (SAM) timeseries gives the coefficients g_i, where

$$SST(t) \approx \sum_{i=0}^{\tau_{max}} g_i\, u(t-i) + \varepsilon$$

can be written in matrix notation as

$$\boldsymbol{Y} = \boldsymbol{X}\boldsymbol{g} + \boldsymbol{\varepsilon}$$

⇒ We estimate $\widehat{\boldsymbol{g}} = (\boldsymbol{X}^T\boldsymbol{X})^{-1}\boldsymbol{X}^T\boldsymbol{Y}$

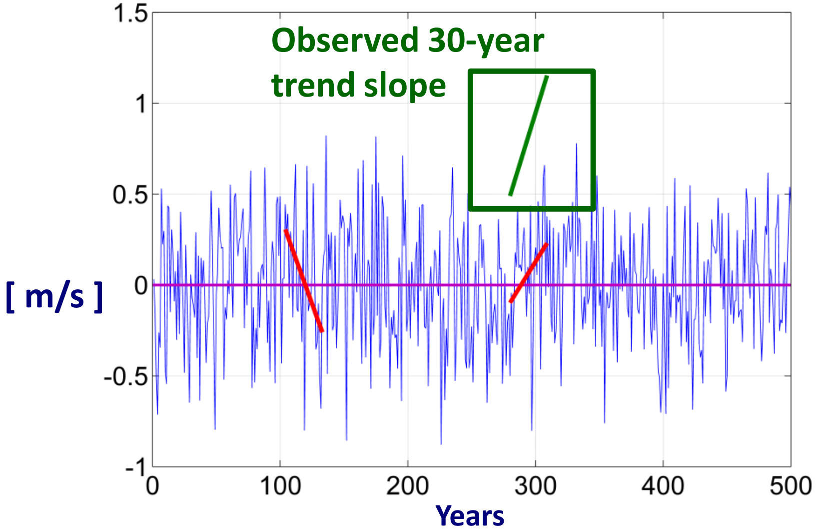
We also calculate uncertainties for each estimated $\widehat{g_i}$ based on the residual of each regression fit.

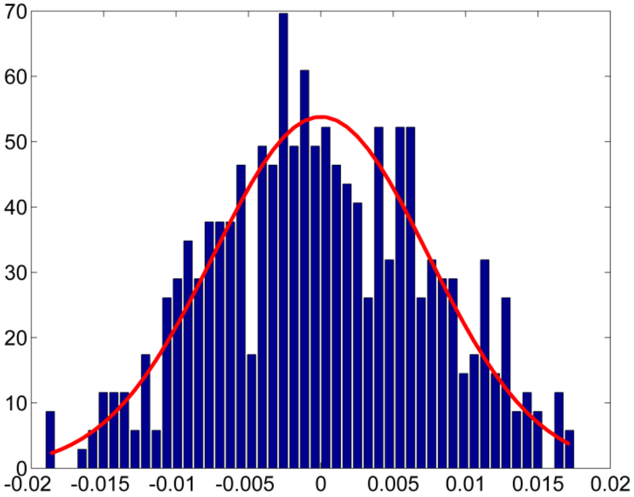
VERIFICATION

Compositing periods of strong SAM-like wind trends in the CMIP5 control runs

Example: **Model ACCESS1-0**

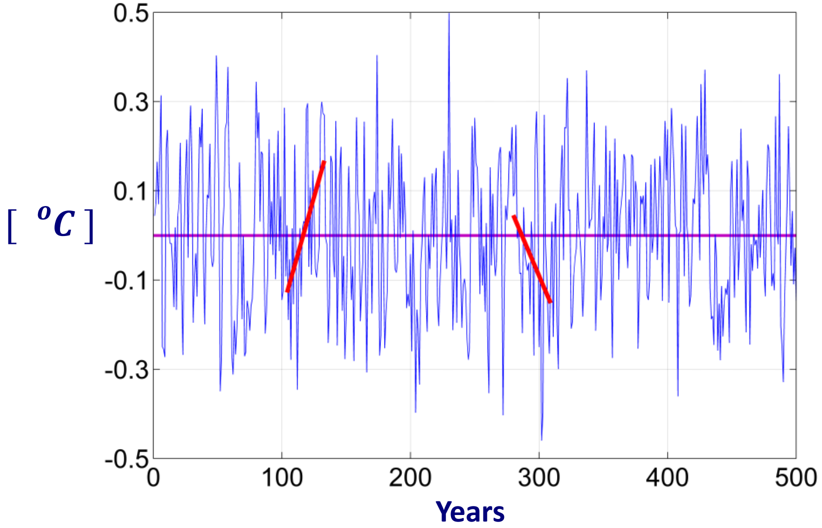
Anomaly in the Maximum Zonal Average Surface Westerlies



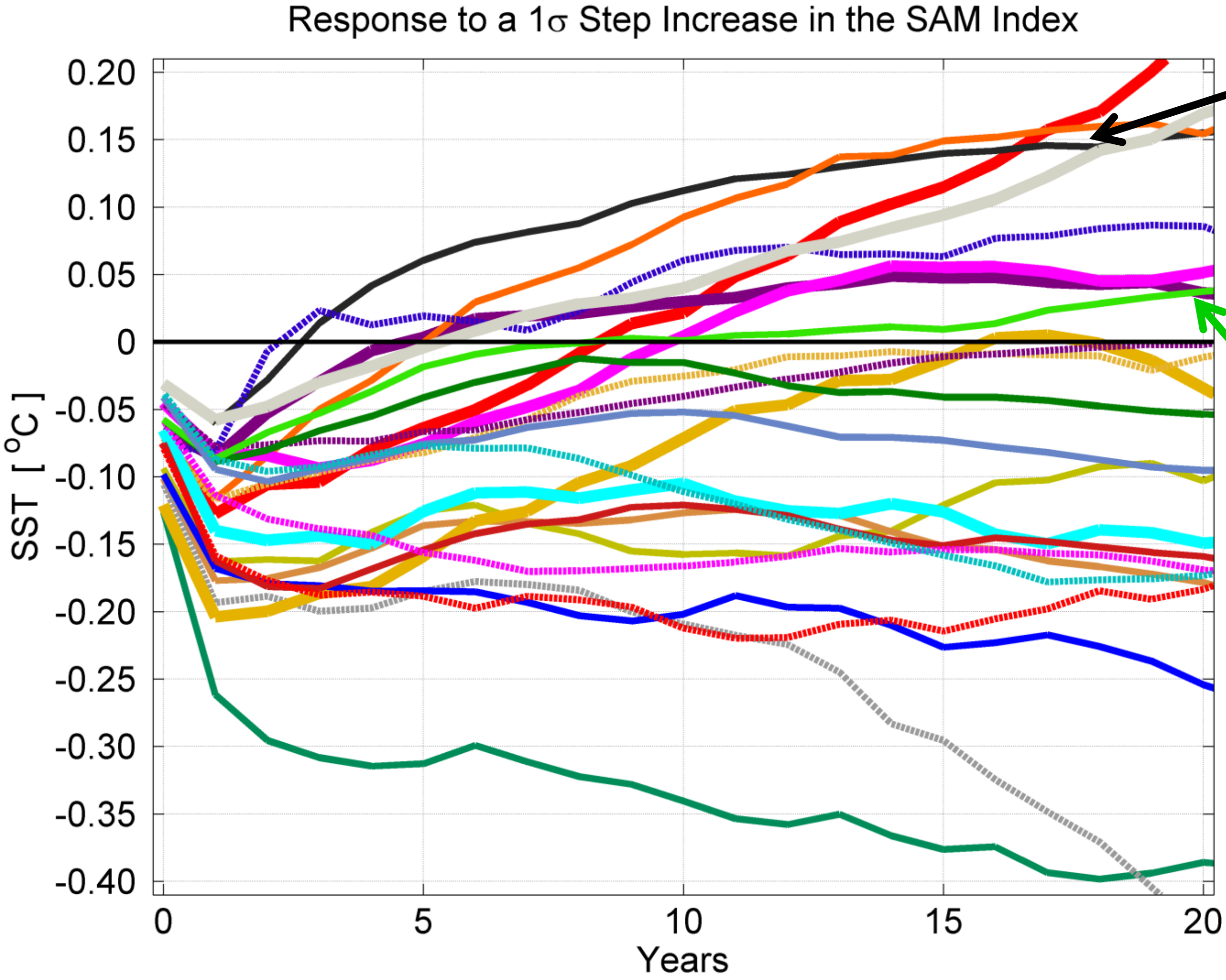


Distribution of 30-year wind trends
Model ACCESS1-0

Zonally Averaged Annual Mean SST Anomaly 55S to 70S



- Sample 30-year periods of $\pm 2\sigma$ SAM-like wind trends;
- Composite the contemporaneous 30-year SST and OHC trends;
- Rescale by the last 30-year wind trend from ERA-I reanalysis.

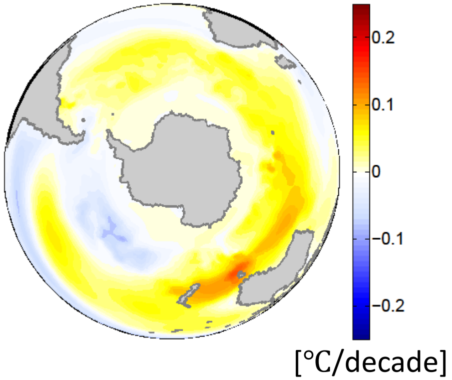

Response to a 1σ Step Increase in the SAM Index

SST response functions (55°-70°S)

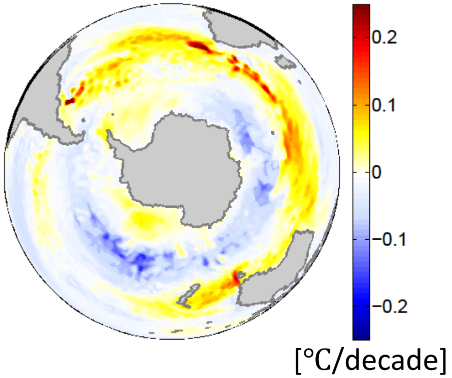
Vs.

Composited 30-year SST trends
from periods of extreme 30-year trends in the SAM index.

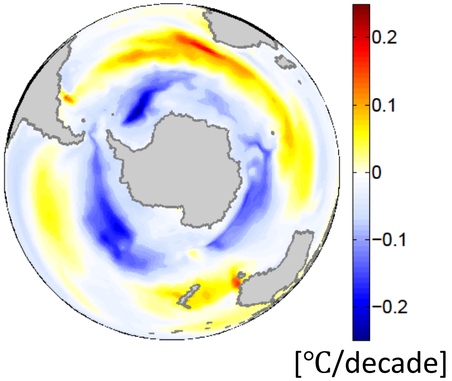
CCSM4



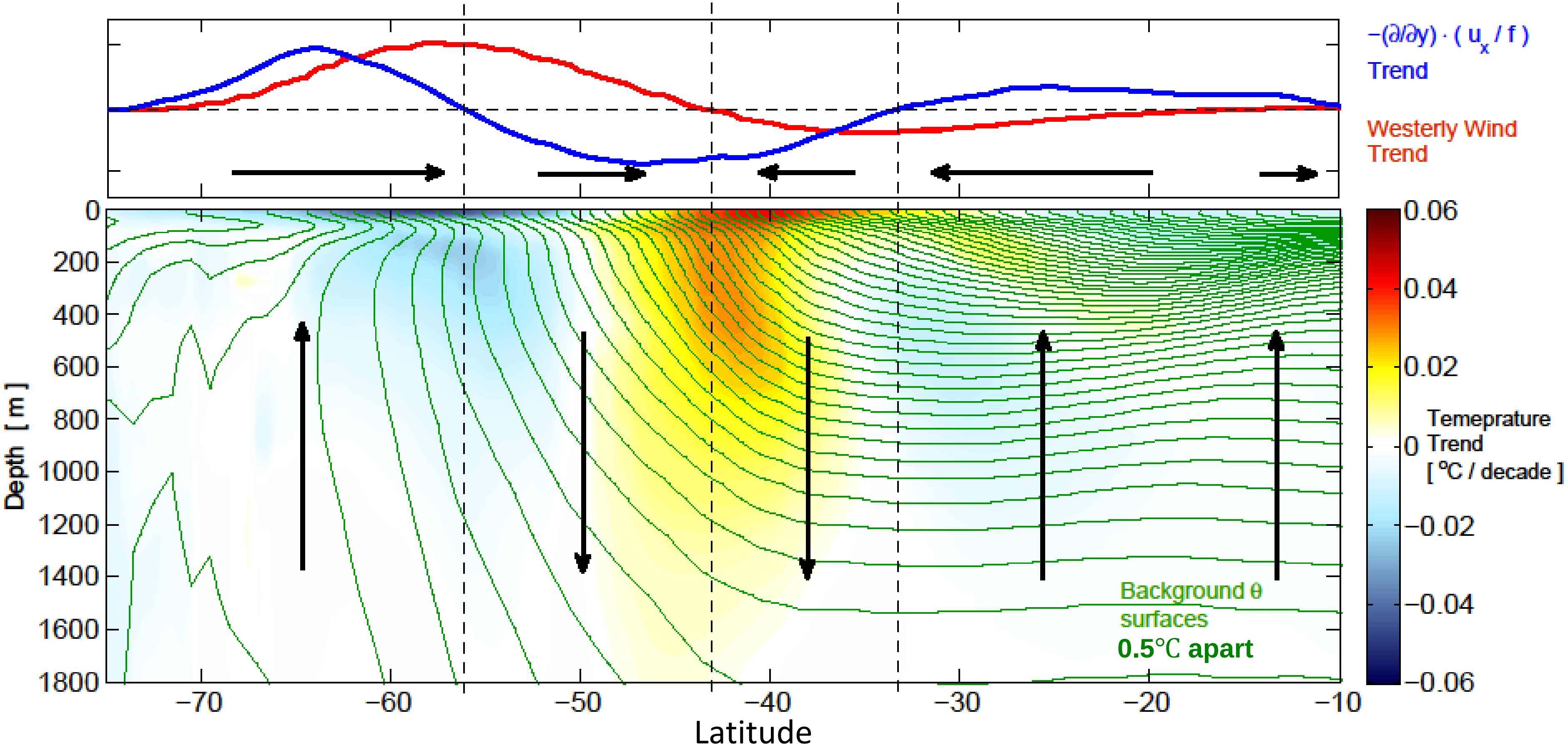
MPI ESM MR



CNRM CM5



Ensemble Mean Composite of Ocean Potential Temperature Trends



Easily interpreted in terms of the wind-driven circulation acting on the background temperature gradients.

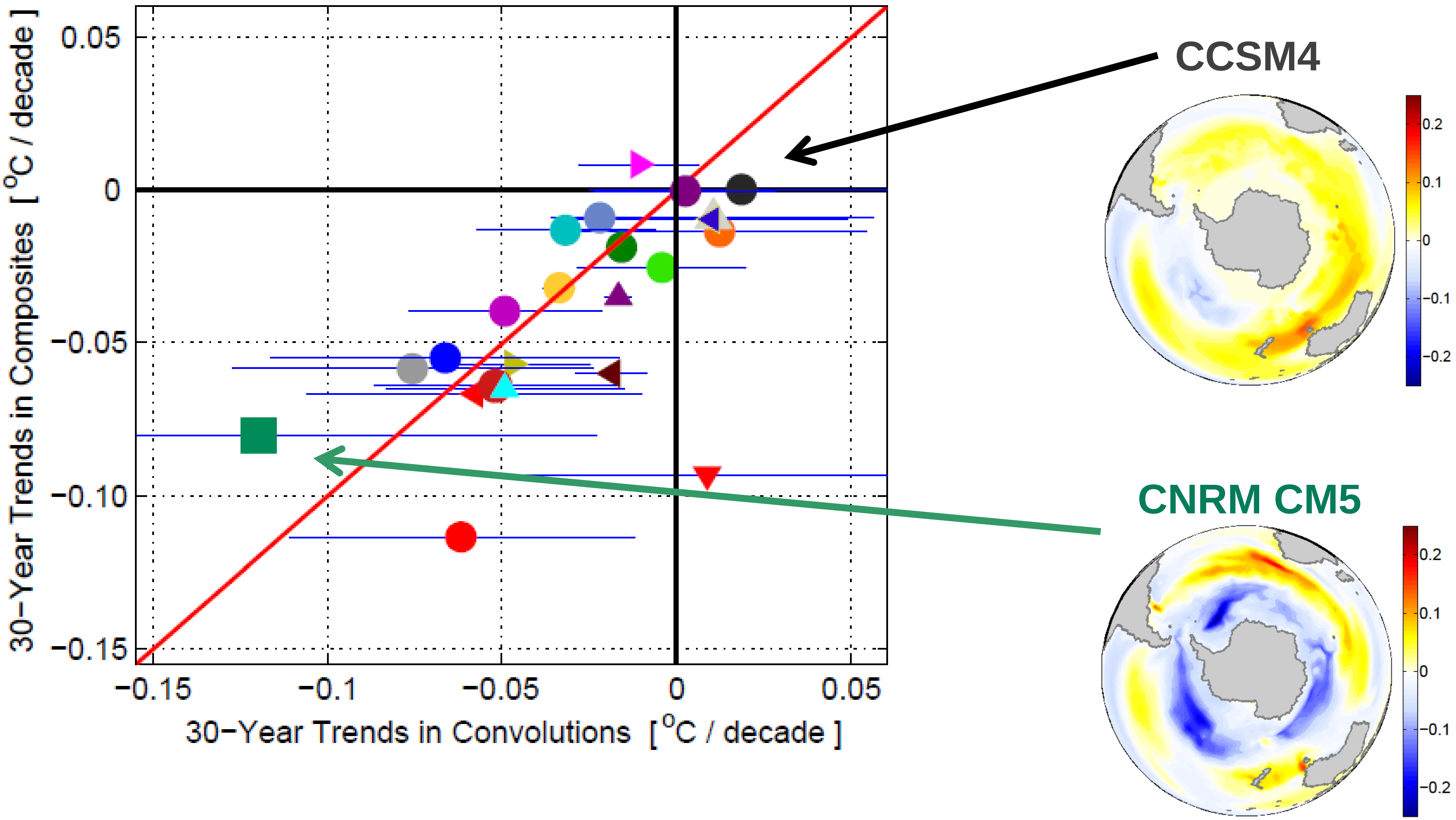
Convolving the Step Response S with the Evolution of Historical Forcing F_{hist}

Given a history of observed forcing, we can estimate the historical response via the convolution

$$SST_{Compos}\,(t) = \int_{0}^{t} S(\tau)\left(\frac{dSAM_{Compos}}{dt}\bigg]_{(t-\tau)}\right)d\tau$$

The composited SST response at time t.

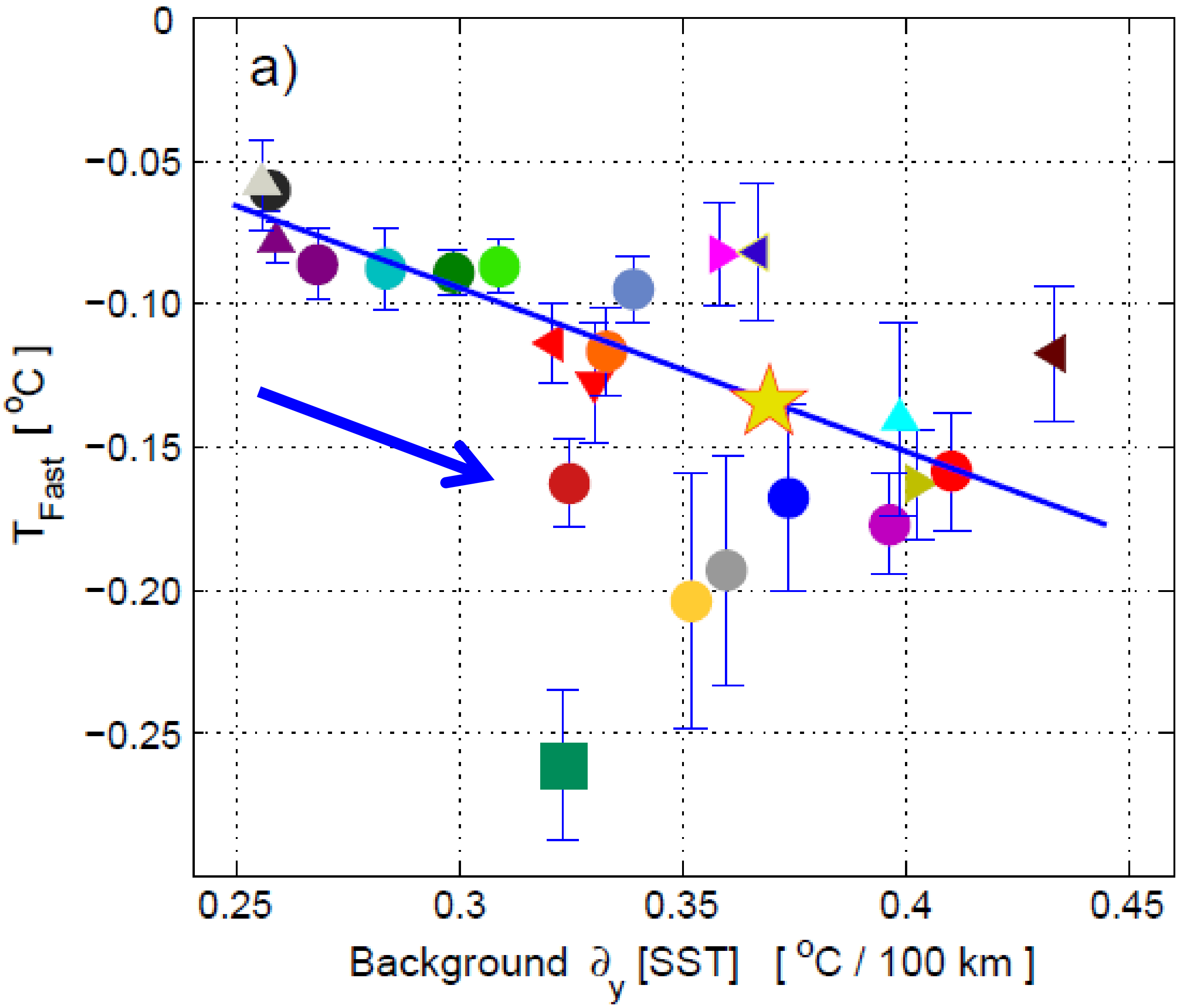
Using step response functions to recover the composited SST trends



CCSM4

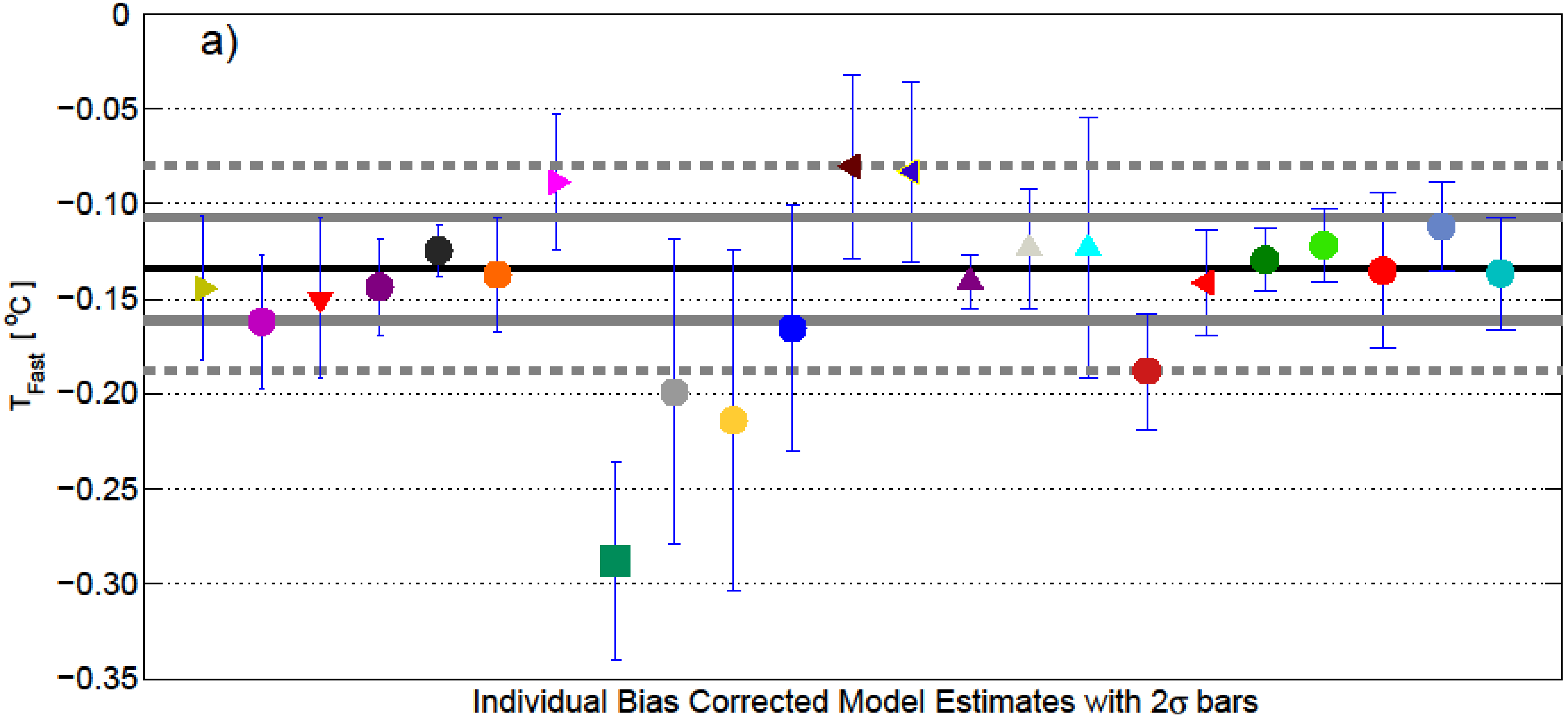
CNRM CM5

Bias Correction of the Fast Response (See DeAngelis 2015)

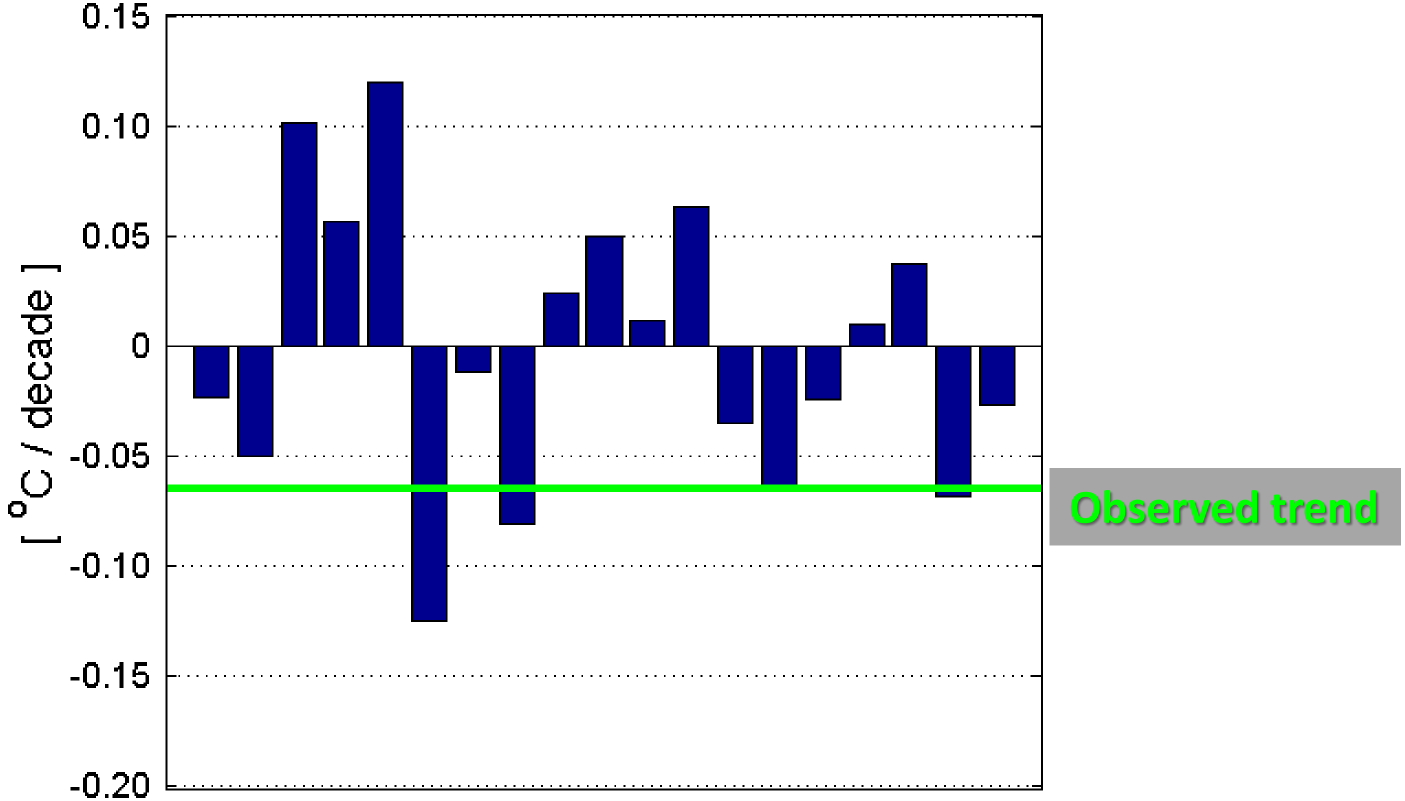


Real World ☆

Bias corrected Year 1 Fast Response



Convolving the CMIP5 with the **observed** SAM and GHG trends



- Most models are expected to show more SO cooling under realistic SAM trends (taken from HadSLP2r);
- Several models expected to warm more under stronger SAM.

Bias Correcting the Fast Response using climatology of meridional SST gradients