Peter Huybers
Harvard University
August 1st

Peking University - Harvard University
2017 Graduate Summer School

Sponsored by PKU and the Harvard Global Institute

IPCC 2013 summary for policy makers on Equilibrium Climate Sensitivity

(D.2 p14)

- The equilibrium climate sensitivity quantifies the response of the climate system to constant radiative forcing on multi- century time scales. It is defined as the change in global mean surface temperature at equilibrium that is caused by a doubling of the atmospheric CO_2 concentration. Equilibrium climate sensitivity is *likely* in the range 1.5°C to 4.5°C (*high confidence*), *extremely unlikely* less than 1°C (*high confidence*), and *very unlikely* greater than 6°C (*medium confidence*)[16]. The lower temperature limit of the assessed *likely* range is thus less than the 2°C in the AR4, but the upper limit is the same. This assessment reflects improved understanding, the extended temperature record in the atmosphere and ocean, and new estimates of radiative forcing.

IPCC 2013 summary for policy makers on Equilibrium Climate Sensitivity

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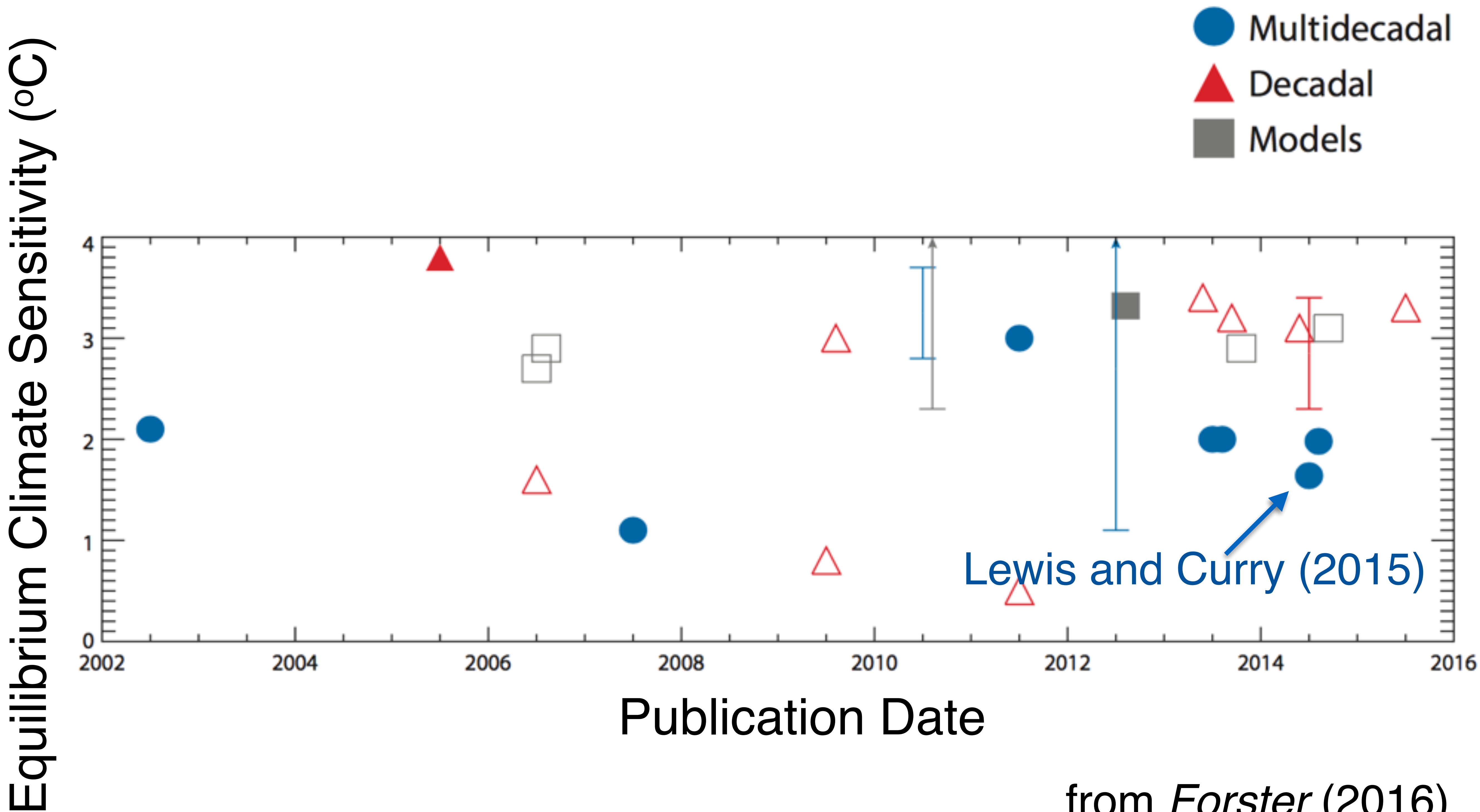
Footnote 16

No best estimate for equilibrium climate sensitivity can now be given because of a lack of agreement on values across assessed lines of evidence and studies.

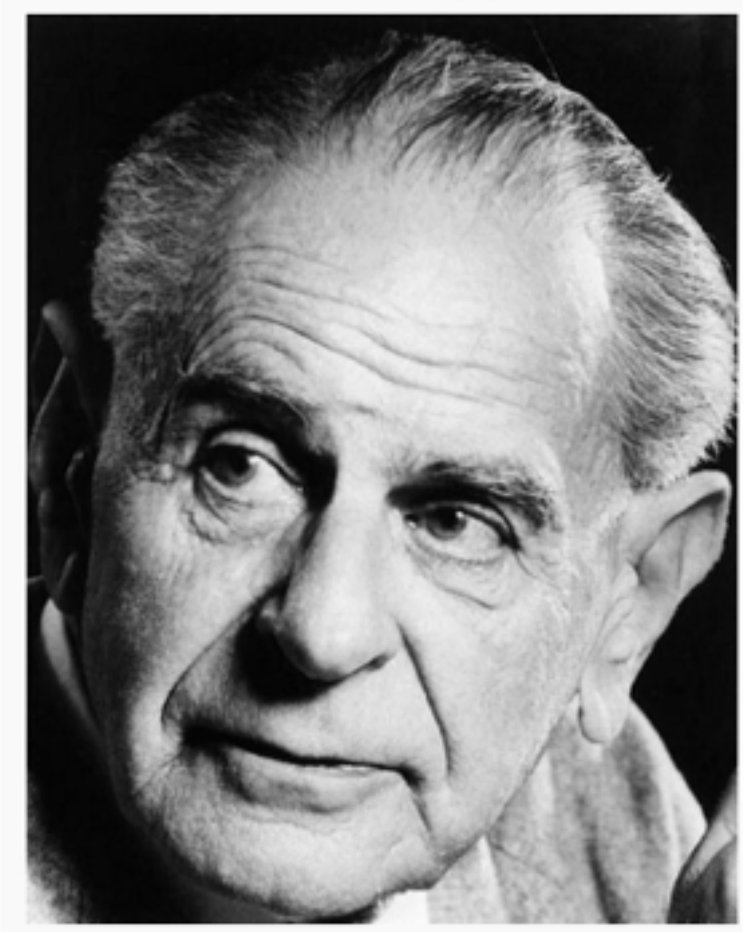
Forster (2016) summarizes the equilibrium climate sensitivities inferred from models and observations



from *Forster* (2016)

“The criterion of the scientific status of a theory is its falsifiability, or refutability, or testability.” *Karl Popper* (1963)

1. The more a theory forbids, the better it is. A theory which is not refutable by any conceivable event is non-scientific.
2. It is easy to obtain confirmations, or verifications, for nearly every theory — if we look for confirmations.
3. Every genuine test of a theory is an attempt to falsify it, or to refute it.



(Excerpted from Conjectures and Refutations by Karl R. Popper, 1963)

Lewis and Curry (2015) estimate an Equilibrium Climate Sensitivity of 1.64ºC, lower than the 2—4.5ºC range quoted earlier by the IPCC.

$$\mathrm{ECS} = F_{2\times CO2} \frac{T_{2000} - T_{1870}}{(F_{2000} - F_{1870}) - (Q_{2000} - Q_{1870})}$$

ECS: equilibrium climate sensitivity,
$F_{2\times CO2}$: forcing due to doubling of CO2 (3.71 $\mathrm{W/m^2}$),
Q_{1870}: initial heat uptake (0.15 ± 0.08 $\mathrm{W/m^2}$),
Q_{2000}: final heat uptake (0.51 ± 0.09 $\mathrm{W/m^2}$),
ΔT: warming ($0.71 \pm 0.08°\mathrm{C}$),
ΔF: change in forcing (1.98 ± 0.5 $\mathrm{W/m^2}$),

Changes are the difference between 1859-1882 and 1995-2011 averages.

‘Empirical’ estimates of Equilibrium Climate Sensitivity depend upon muliple lines of observational analysis, each uncertain.

2. Uncertain corrections

1. Anomalous?

$$\mathrm{ECS} = F_{2\times CO2}\frac{T_{2000} - T_{1870}}{(F_{2000} - F_{1870}) - (Q_{2000} - Q_{1870})}$$

5. Not actually equal

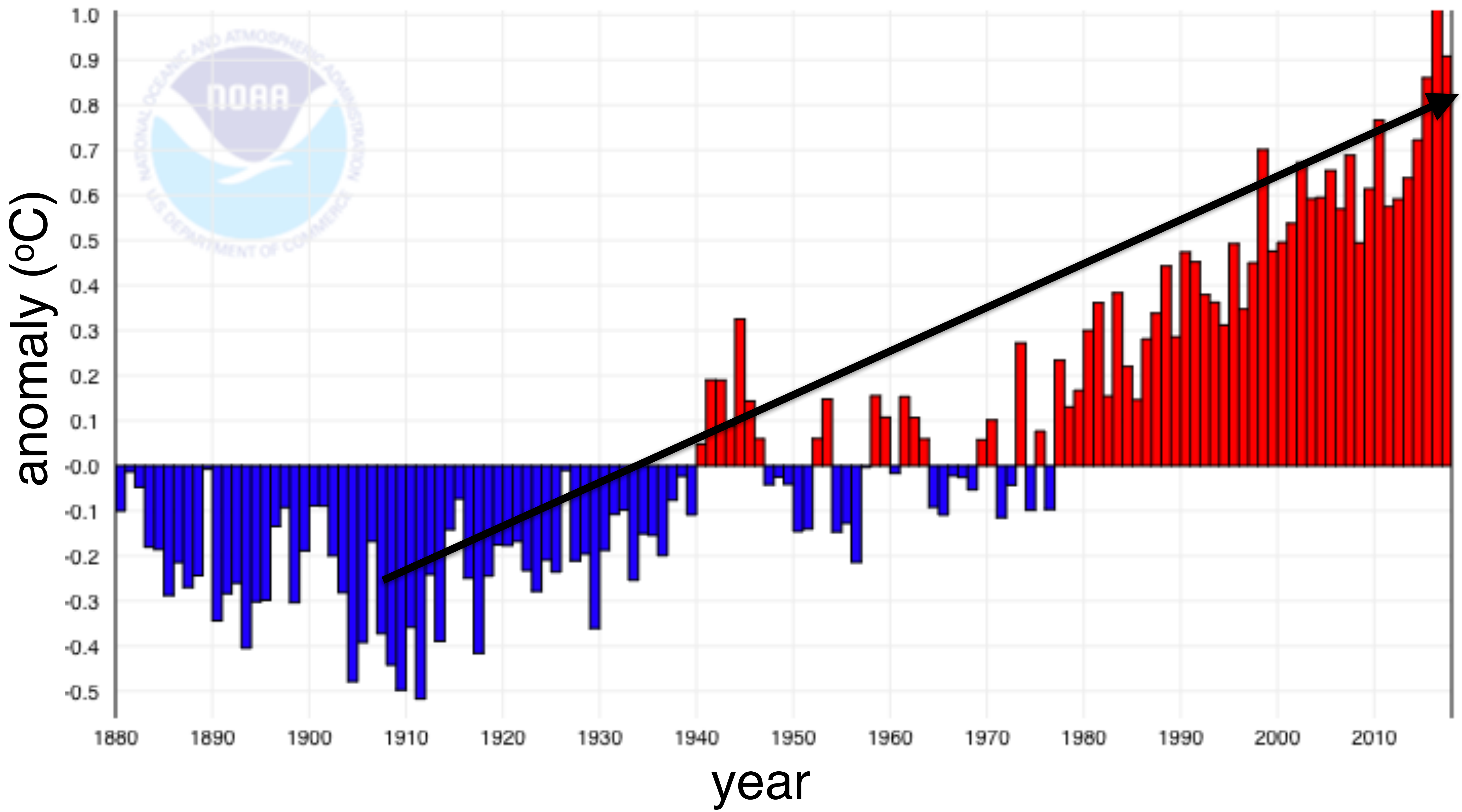
3. Incomplete sampling

4. Could it be cooling?

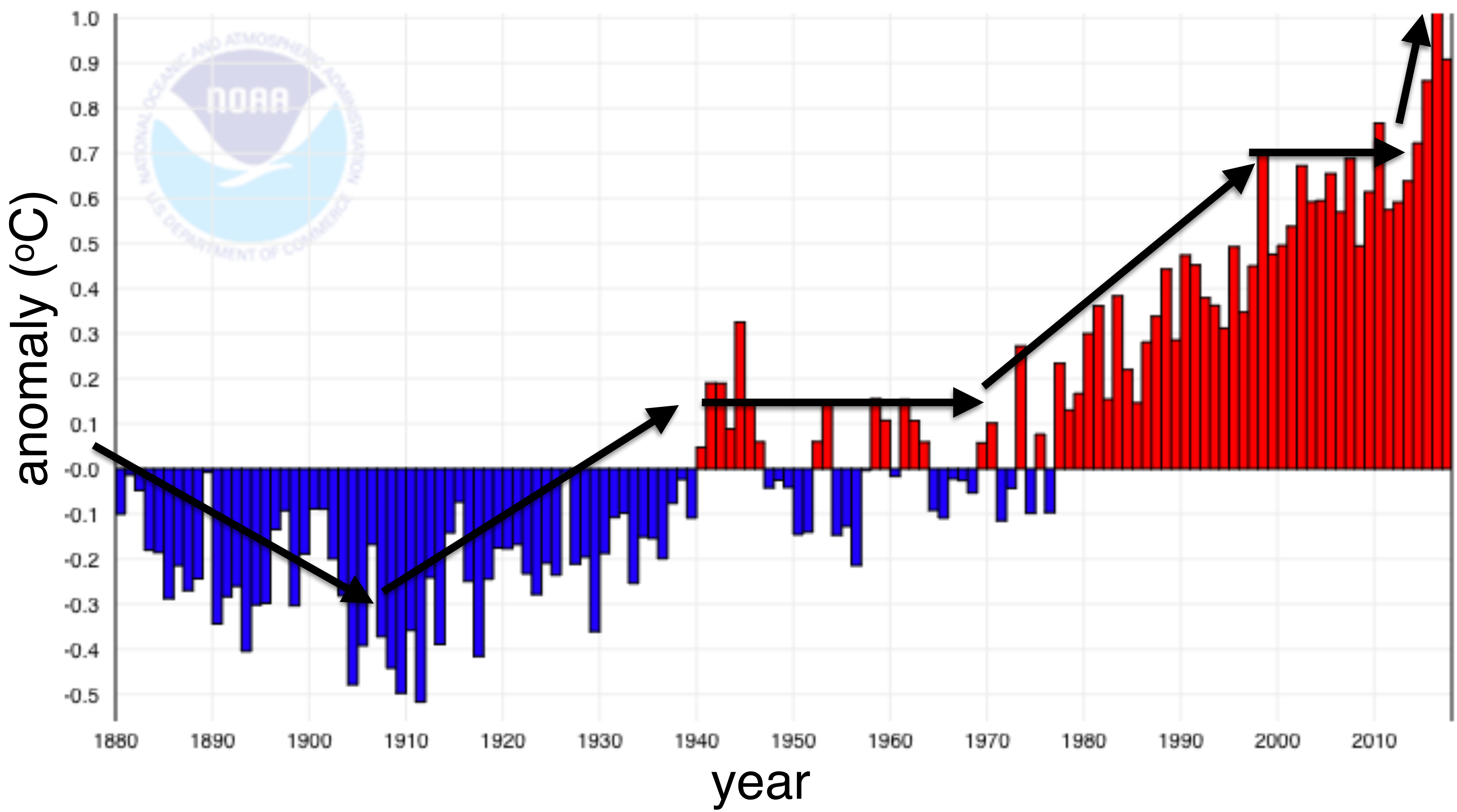
Outline

1. Recently observed versus simulated temperature trends
   (*M. Lin, 2016)*
2. Correcting historical temperature estimates
   (*C.Chan,* in prep.)
3. Seasonal constraints on today's energy imbalance
   (*K. McKinnon*, 2016)
4. Earth's energy imbalance circa 1870
   (*G. Gebbie*, in prep.)
5. Slow mode contributions to equilibrium climate sensitivity
   (*C. Proistosescu*, 2017)

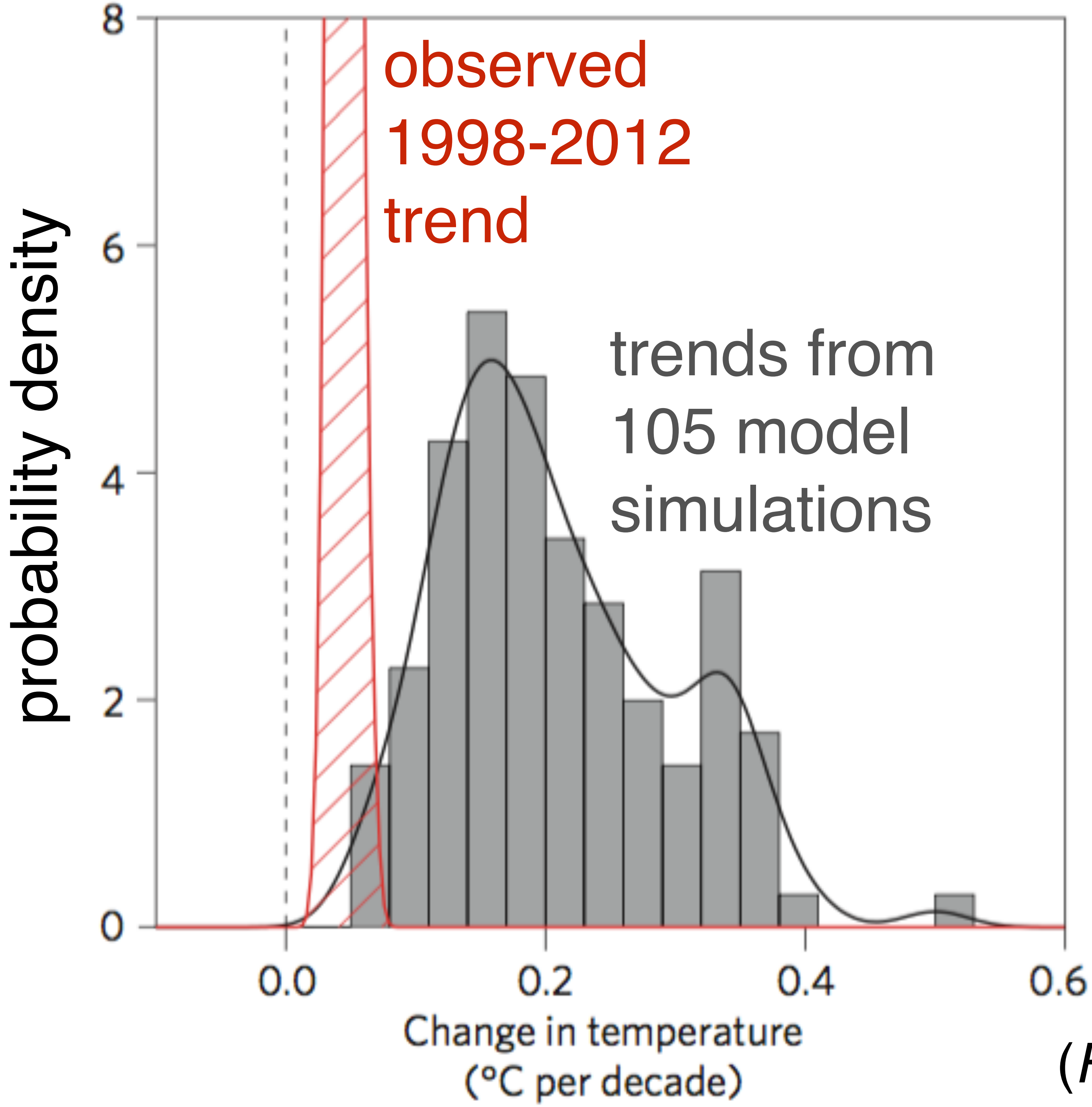
Global Land and Ocean Temperature Anomalies, January-June



Global Land and Ocean Temperature Anomalies, January-June

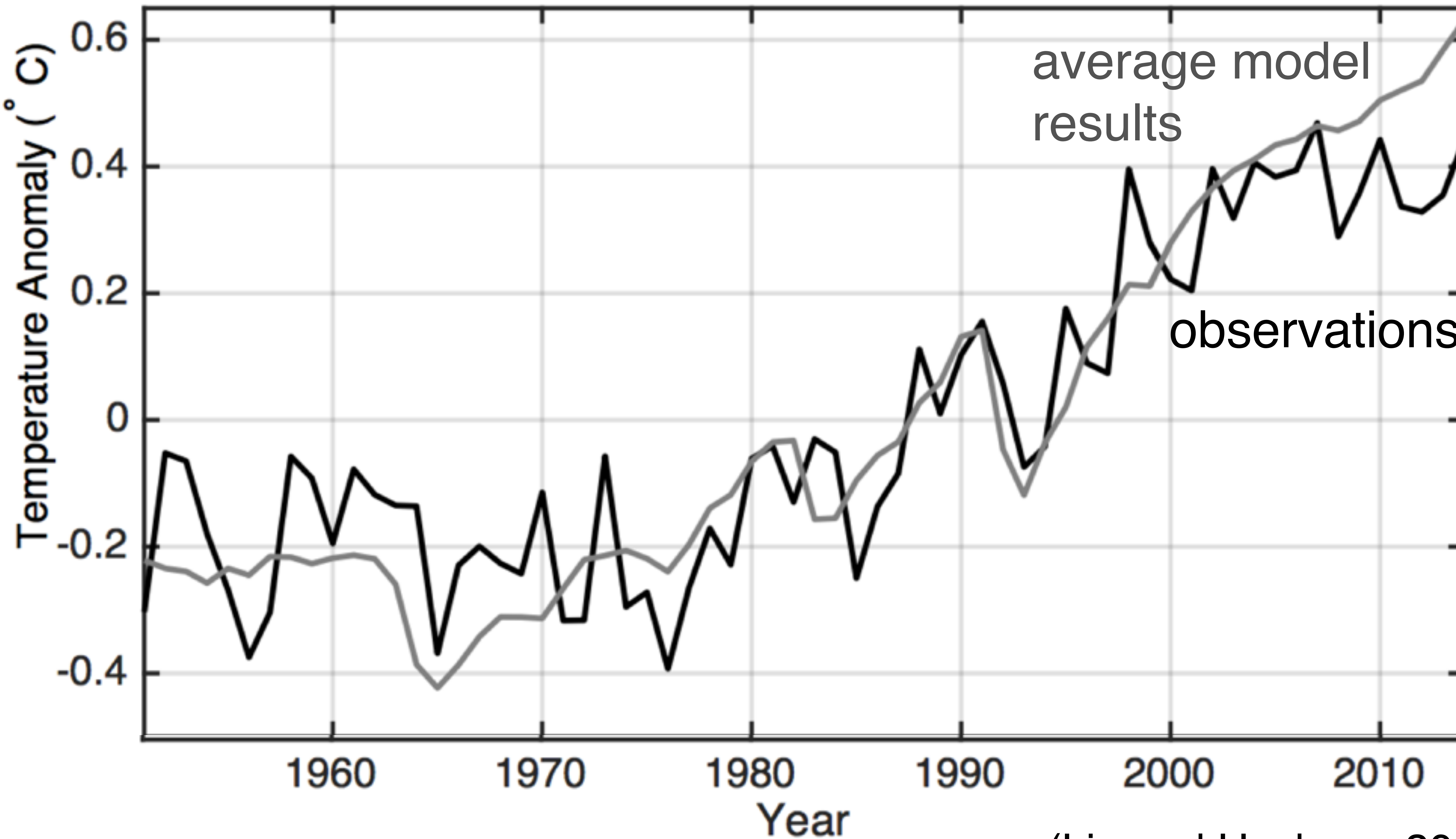


The IPCC reported that the 1998-2012 trends in observed global average temperature were significantly lower than in their collection of model results



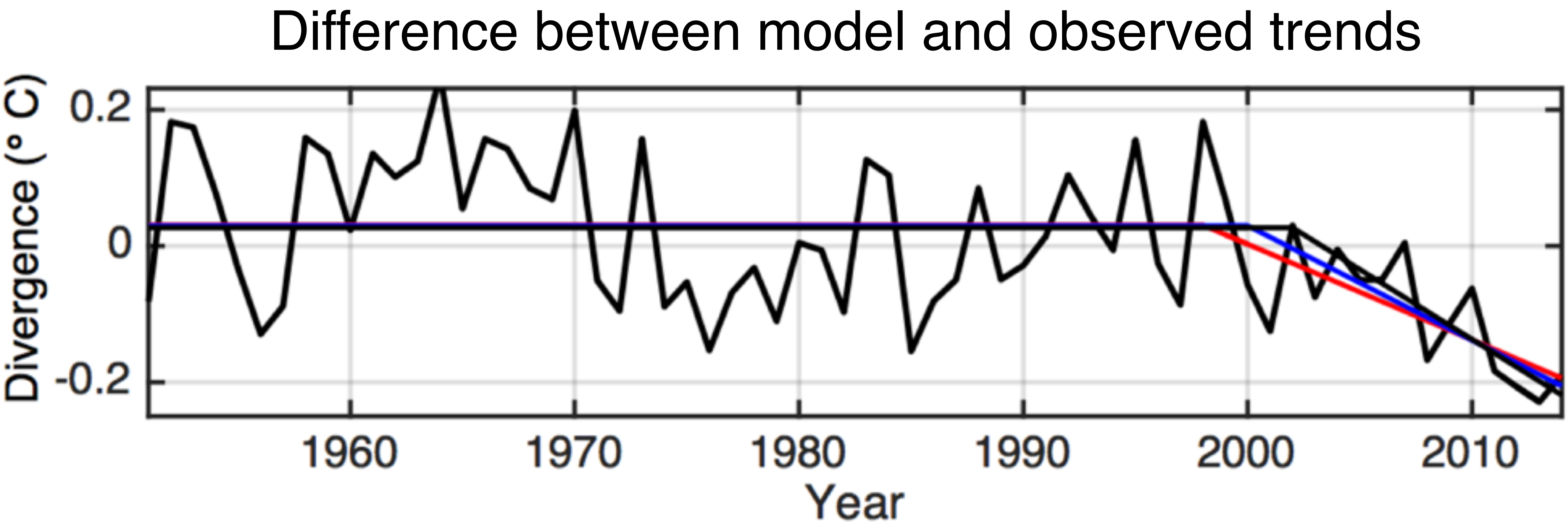
(*Fyfe et al.*, 2013)

Does the pause in Earth's temperature rise falsify the IPCC models?



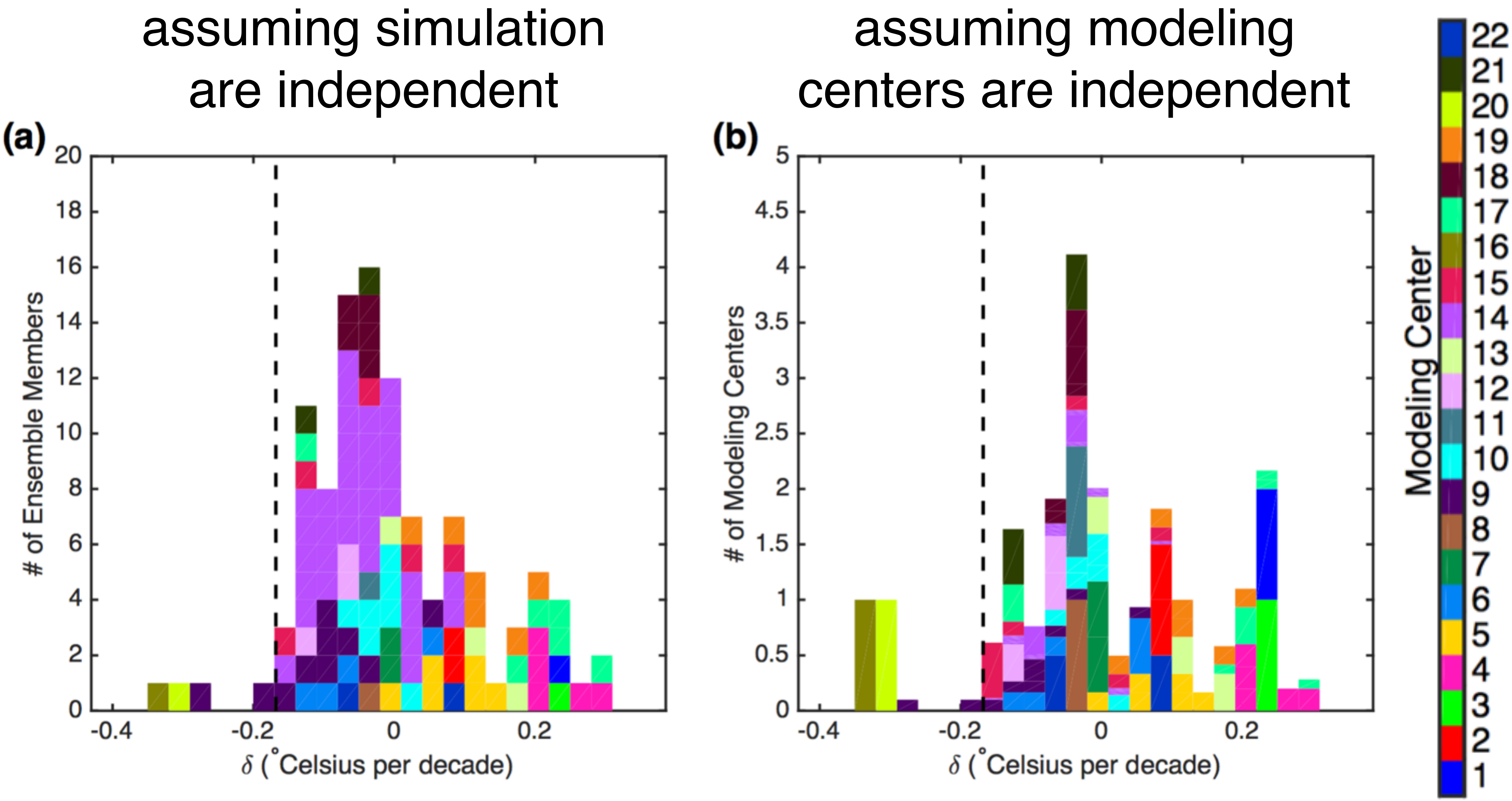
(Lin and Huybers, 2016)

Does the pause in Earth's temperature rise falsify the IPCC models?



(Lin and Huybers, 2016)

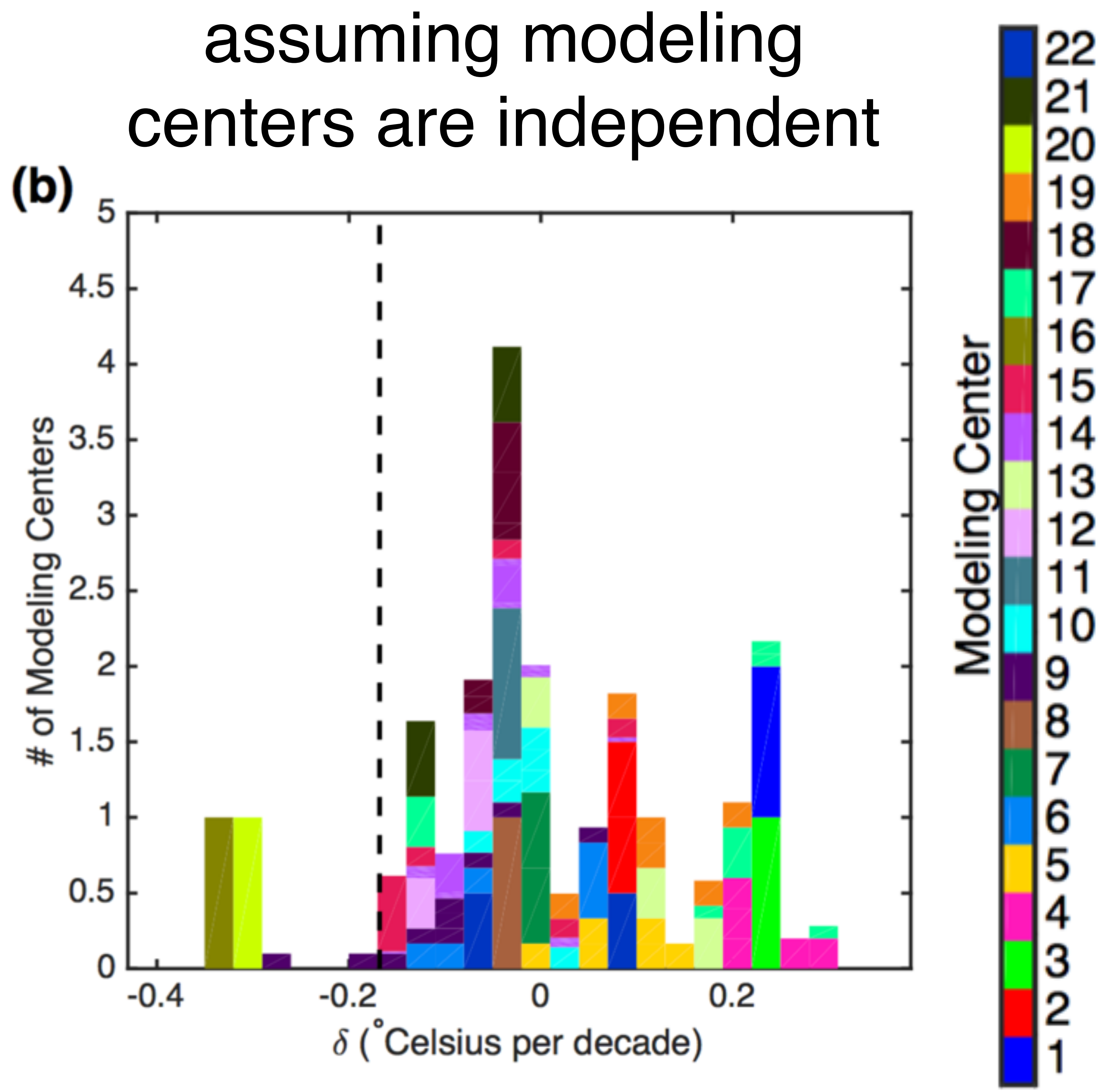
Does the pause in Earth's temperature rise falsify the IPCC models?



(Lin and Huybers, 2016)

Does the pause in Earth's temperature rise falsify the IPCC models? No, but does this improve confidence?

- The spread in model simulations, admits for the slow warming observed between 1998-2012.
- Any model-data distinction further diminishes when accounting for uncertainties in observed temperatures and that we are looking at an interval selected on the basis of having anomalously low cooling.
- In Popper's parlance, the model simulations are not falsified. Inter-decadal variability makes it difficult to falsify the models using decadal temperature trends.



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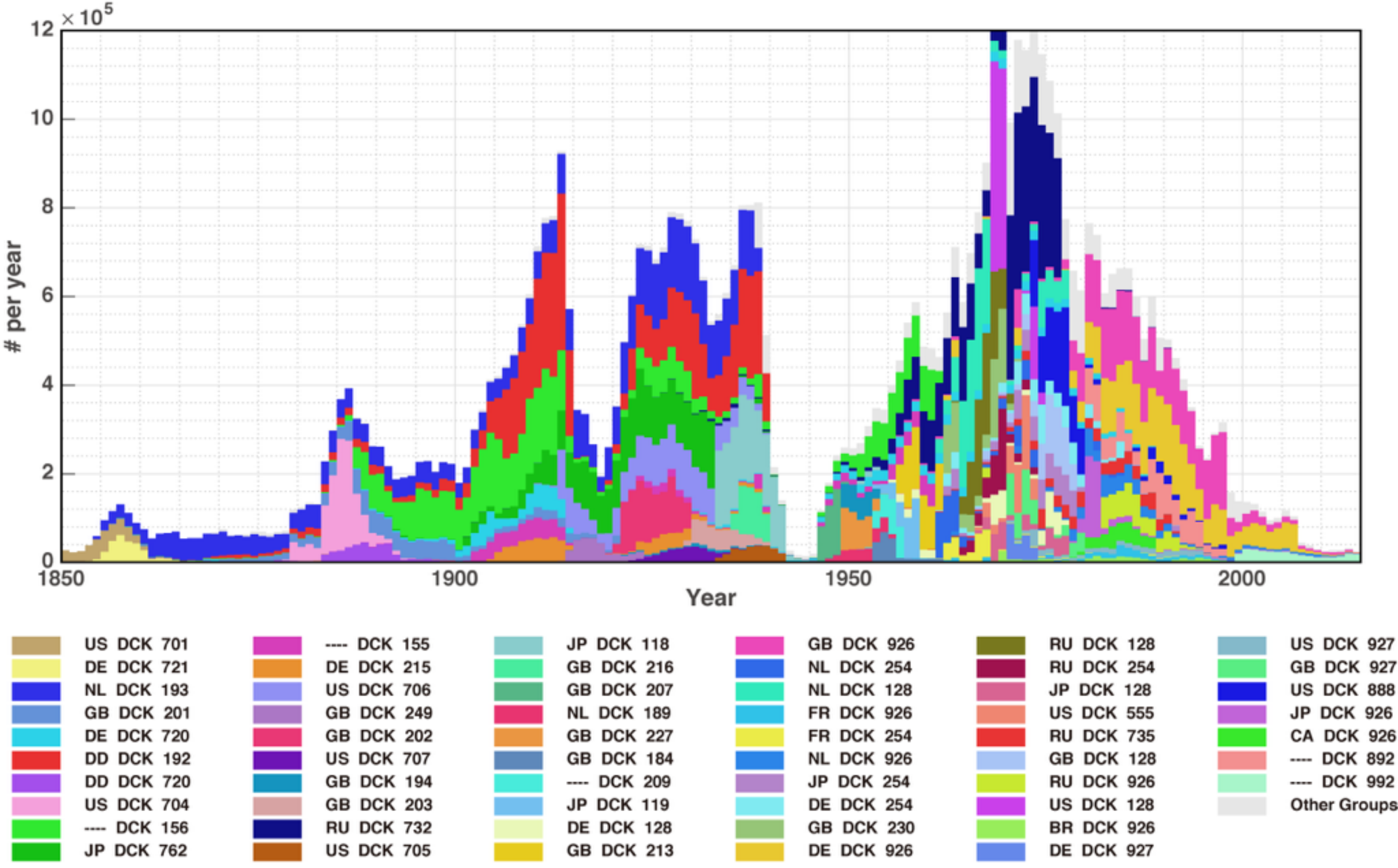
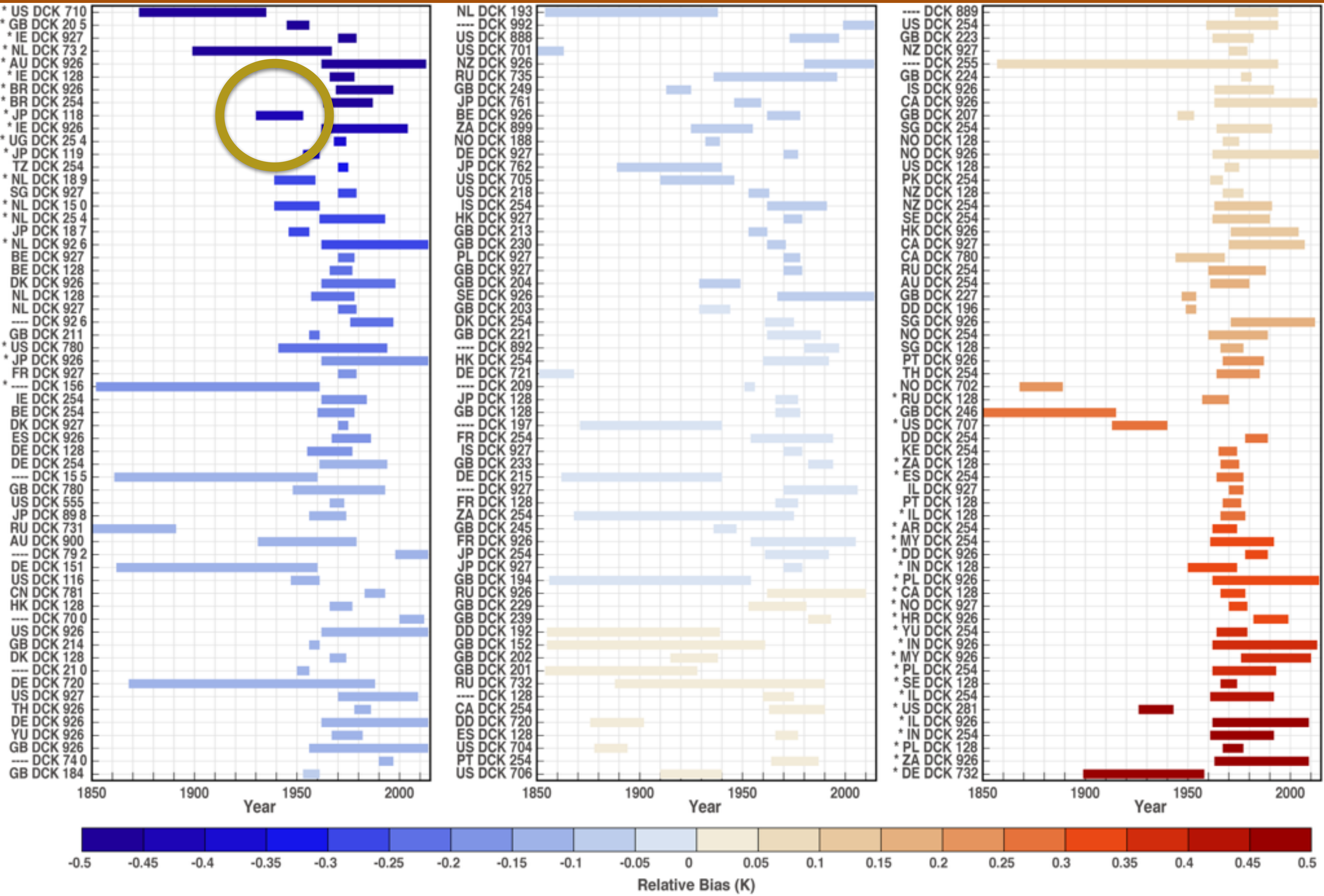
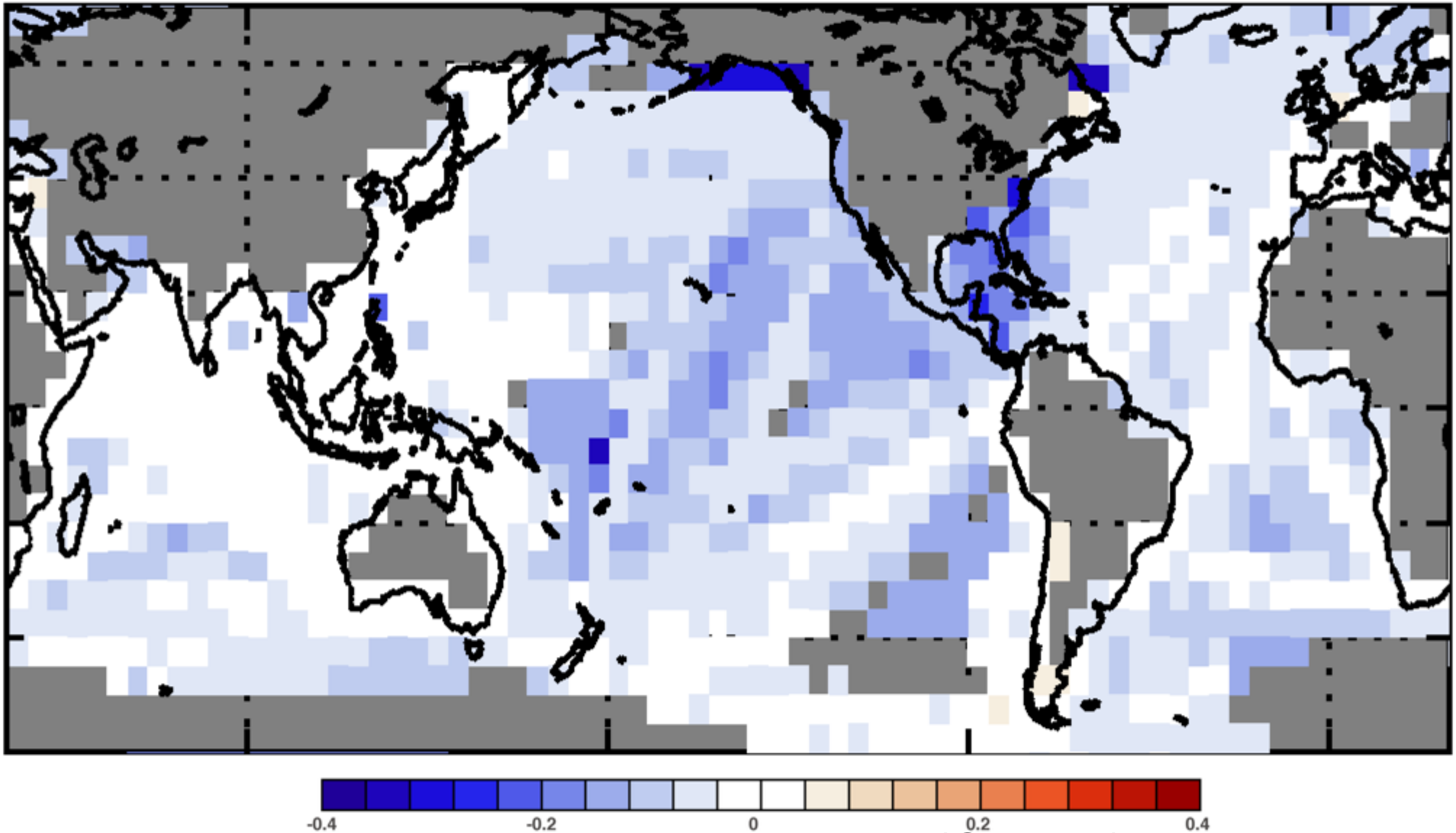
Sea Surface Temperature observations from buckets per year (International Comprehensive Ocean-Atmosphere Dataset, 2016)



Japanese measurements are anomalously cold

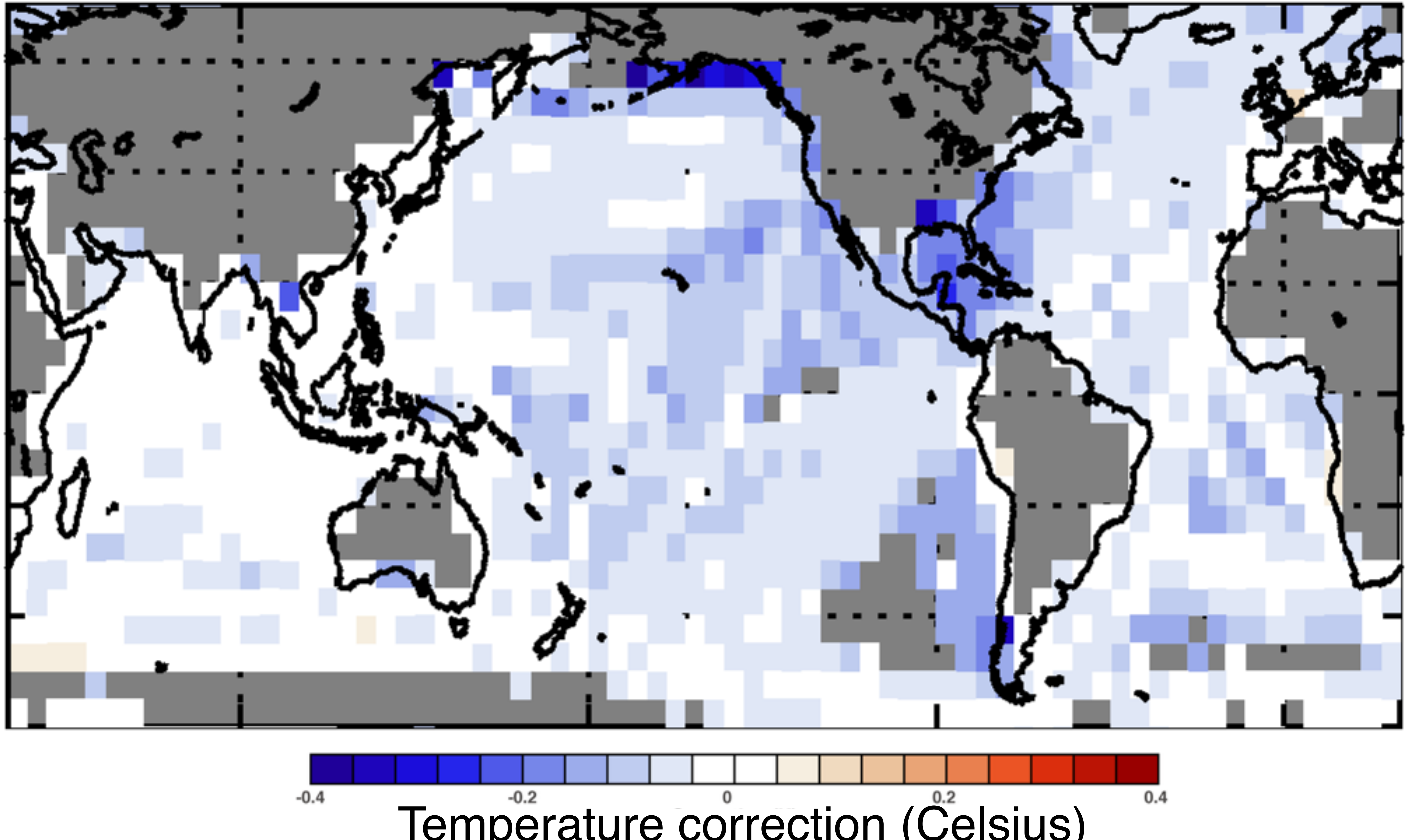


SST correction field 1931

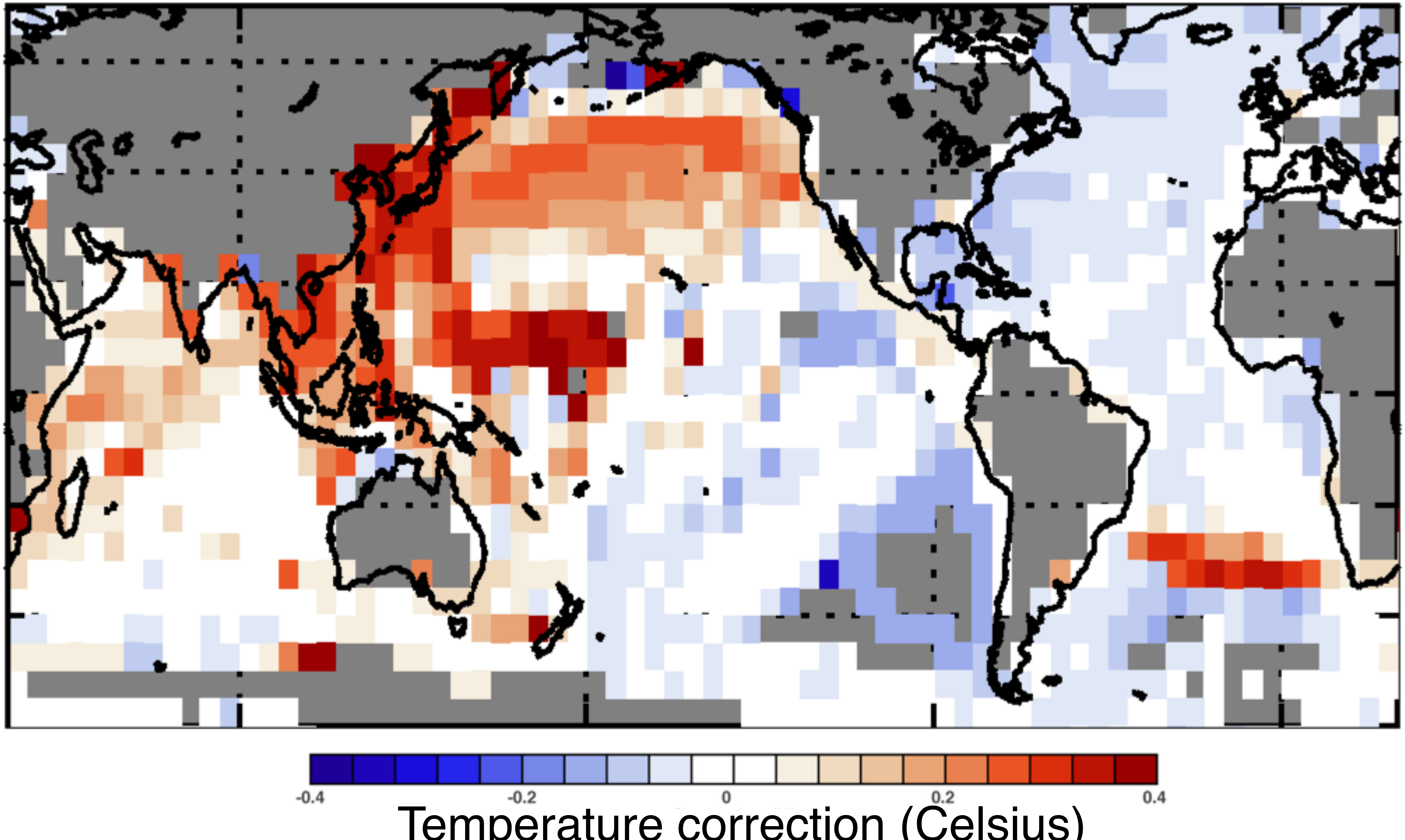


Temperature correction (Celsius)

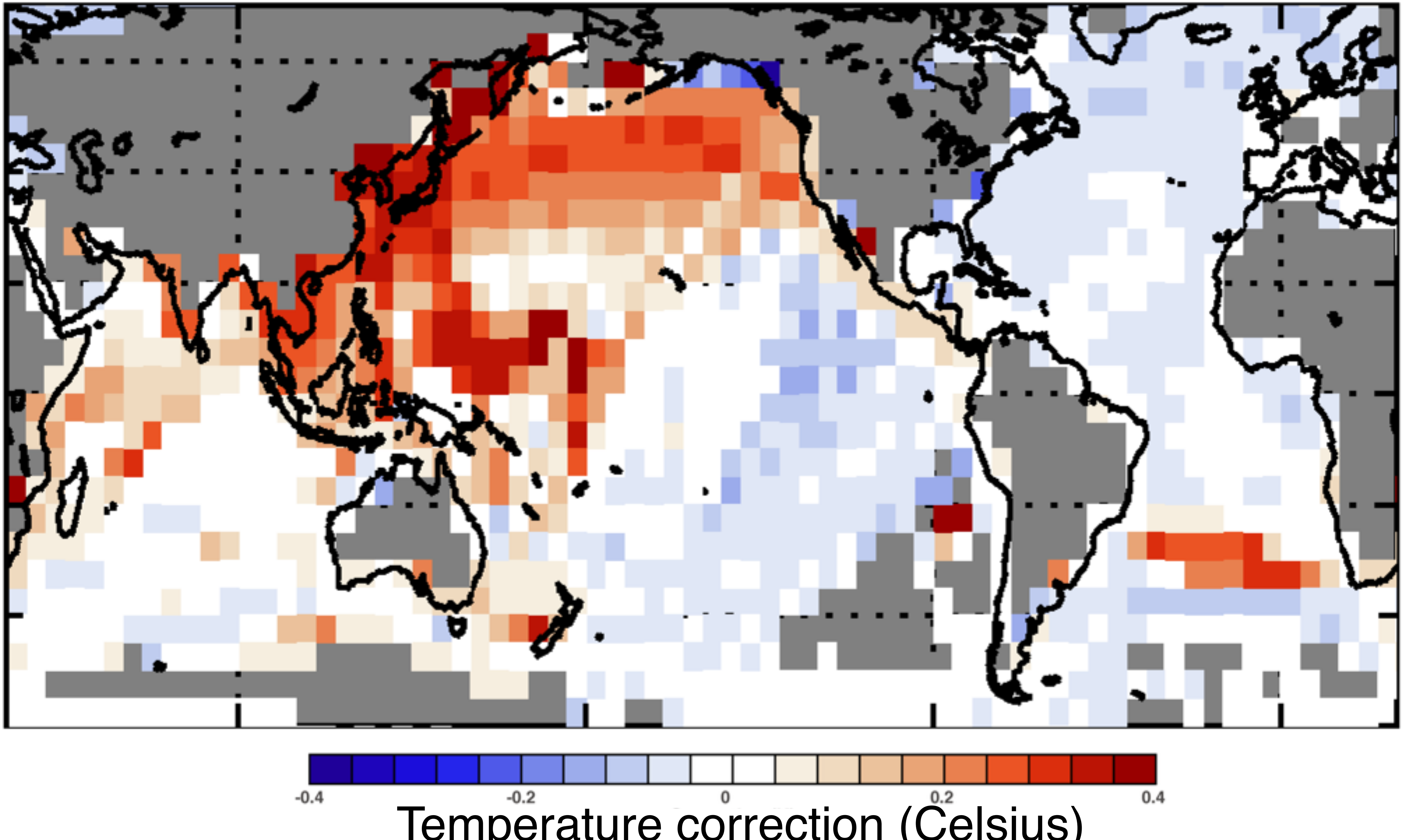
SST correction field 1932



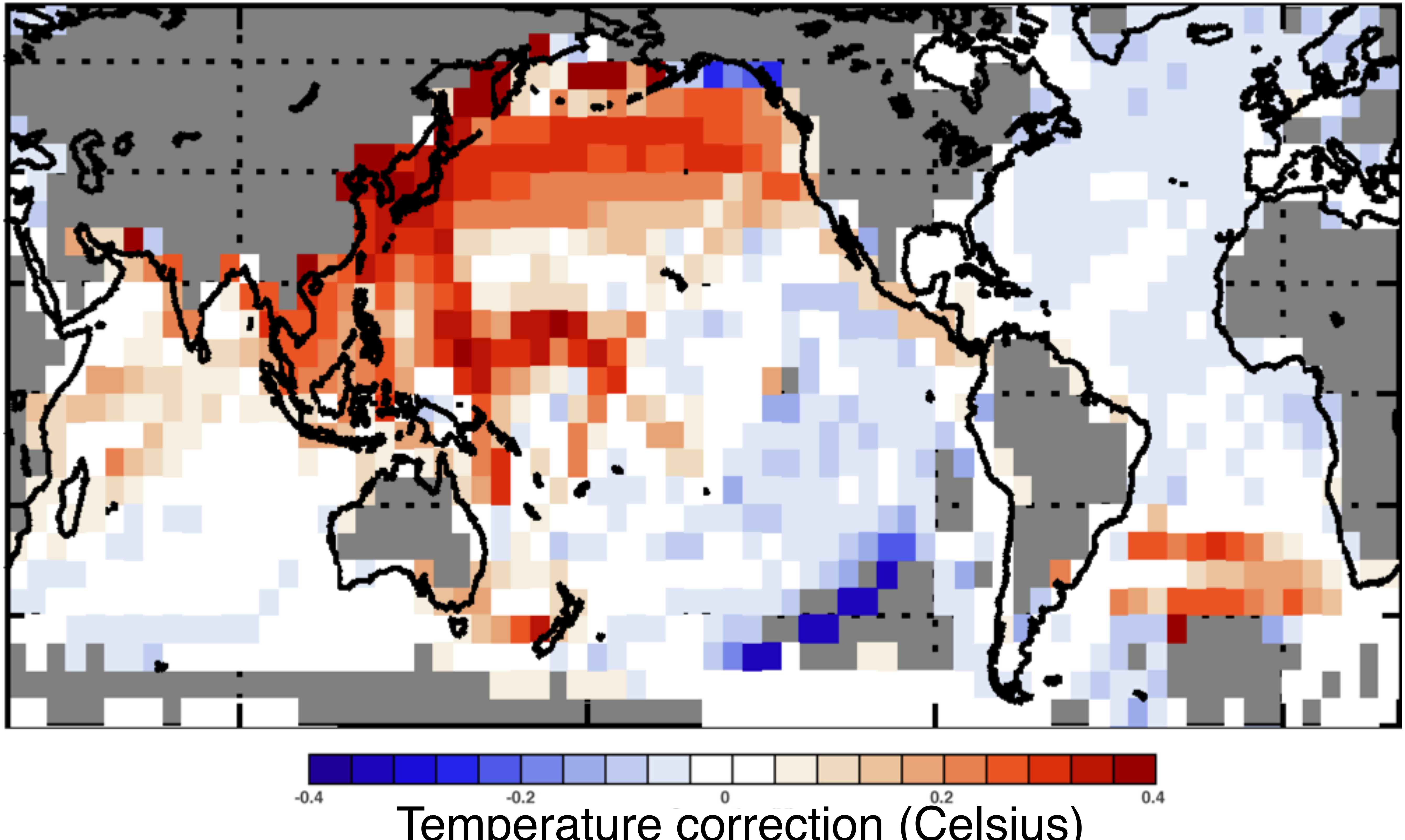
SST correction field 1933



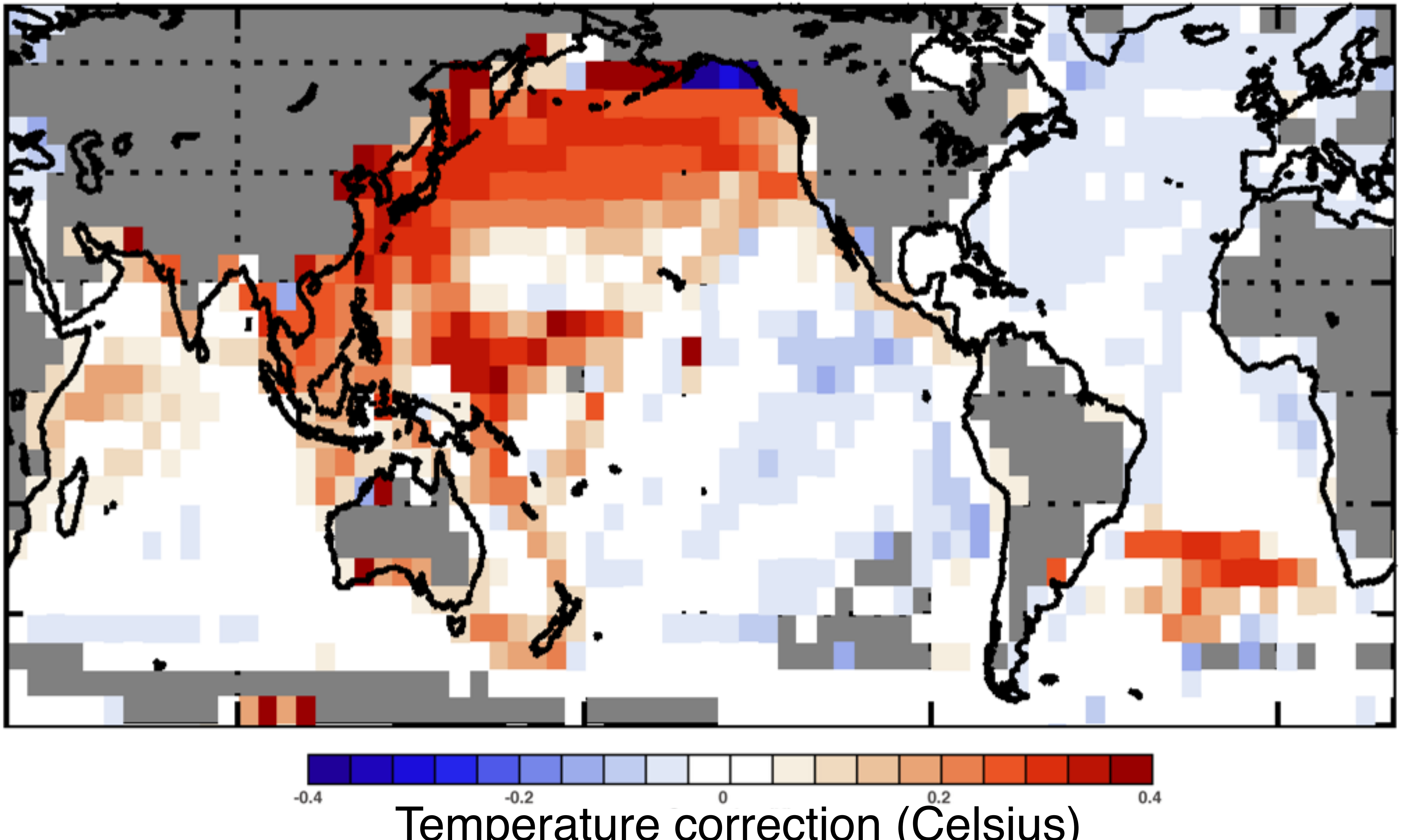
SST correction field 1934



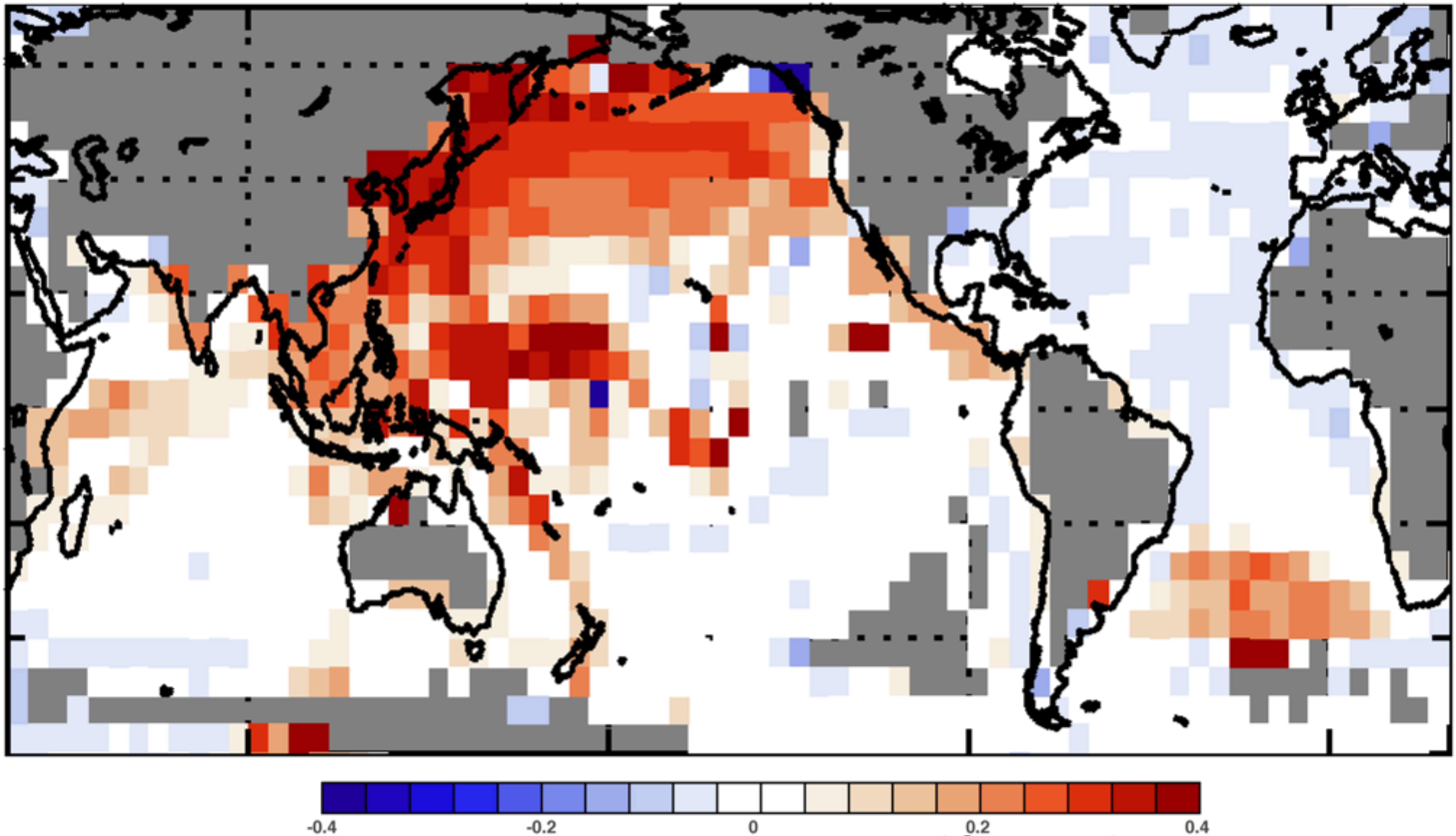
SST correction field 1935



SST correction field 1936

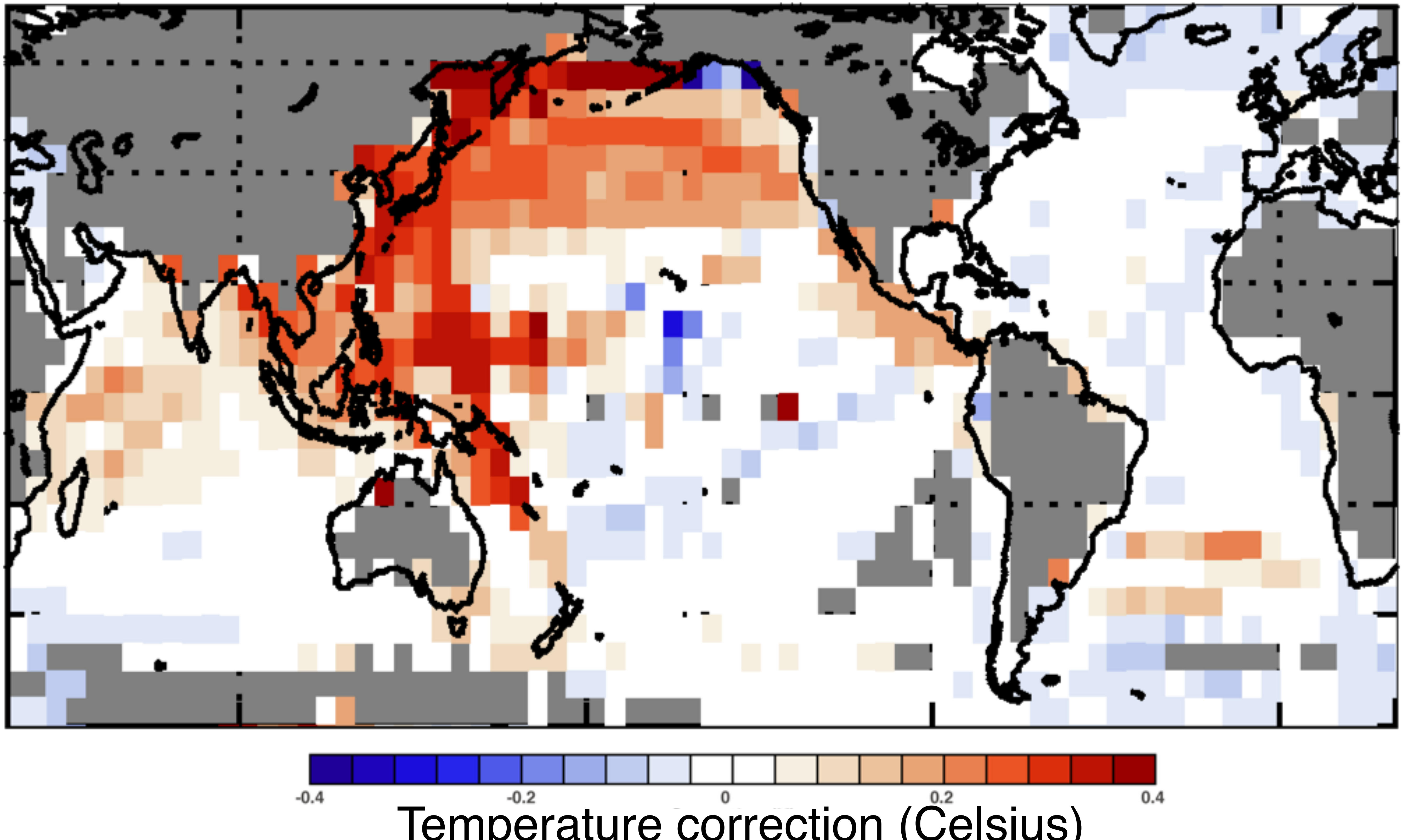


SST correction field 1937

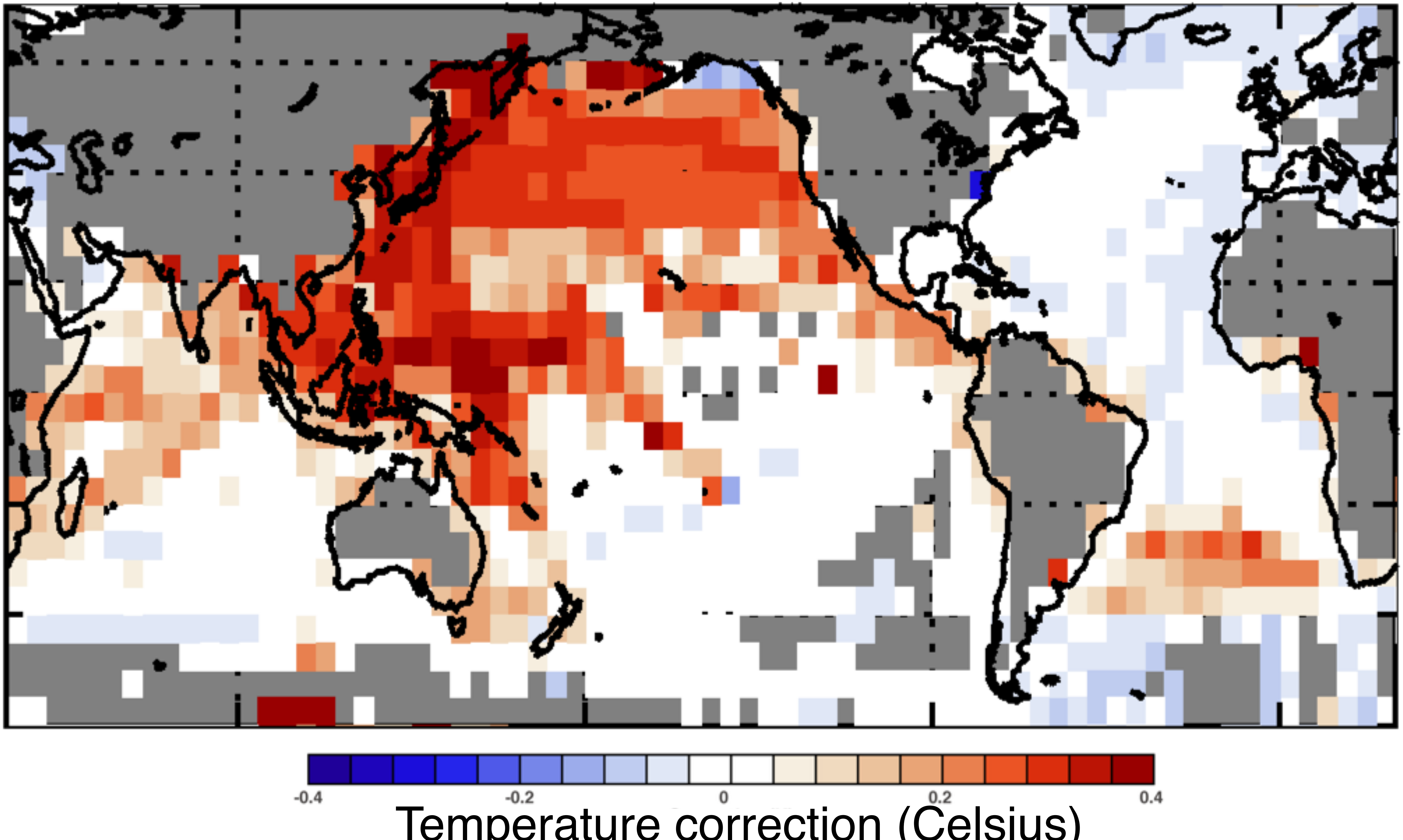


Temperature correction (Celsius)

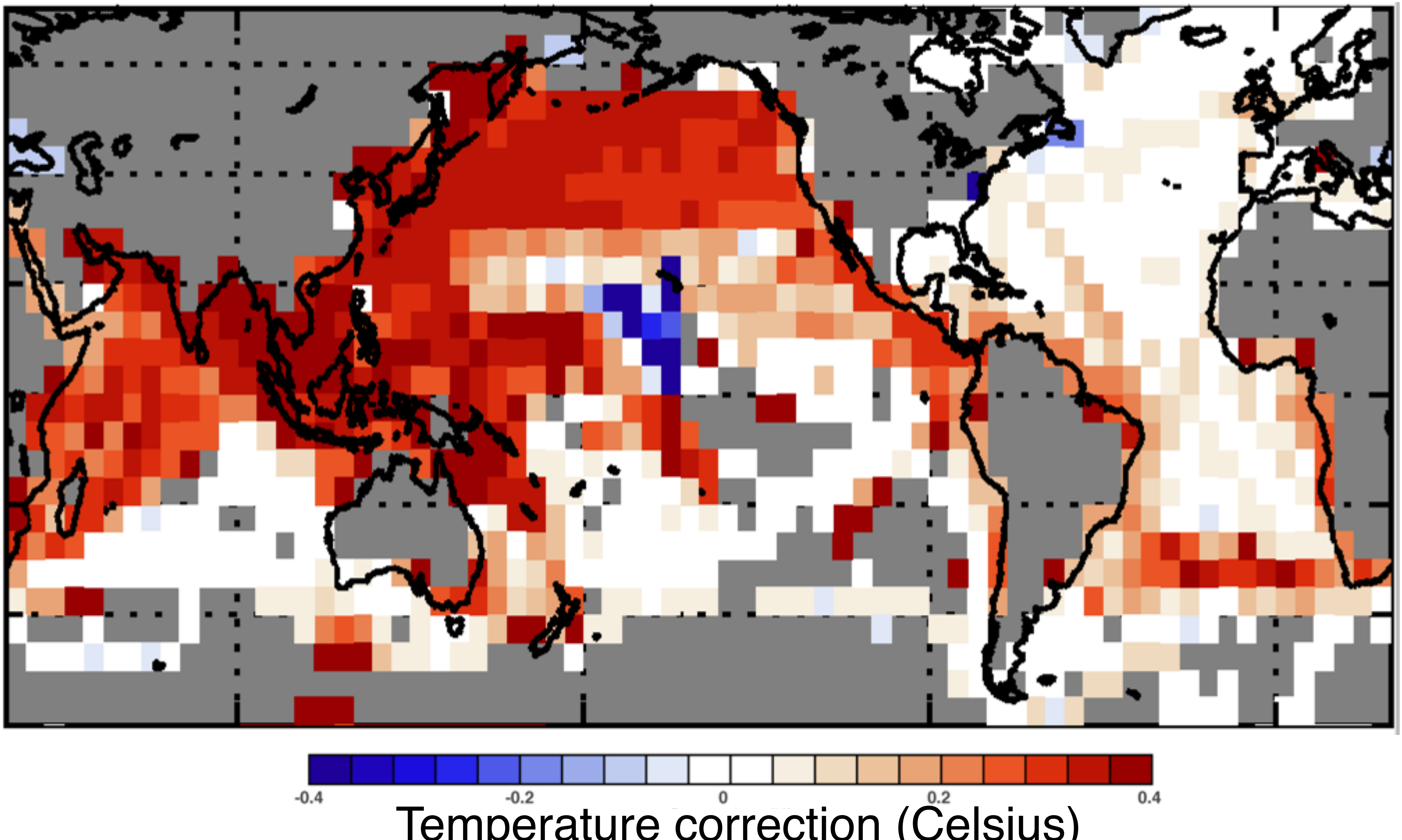
SST correction field 1938



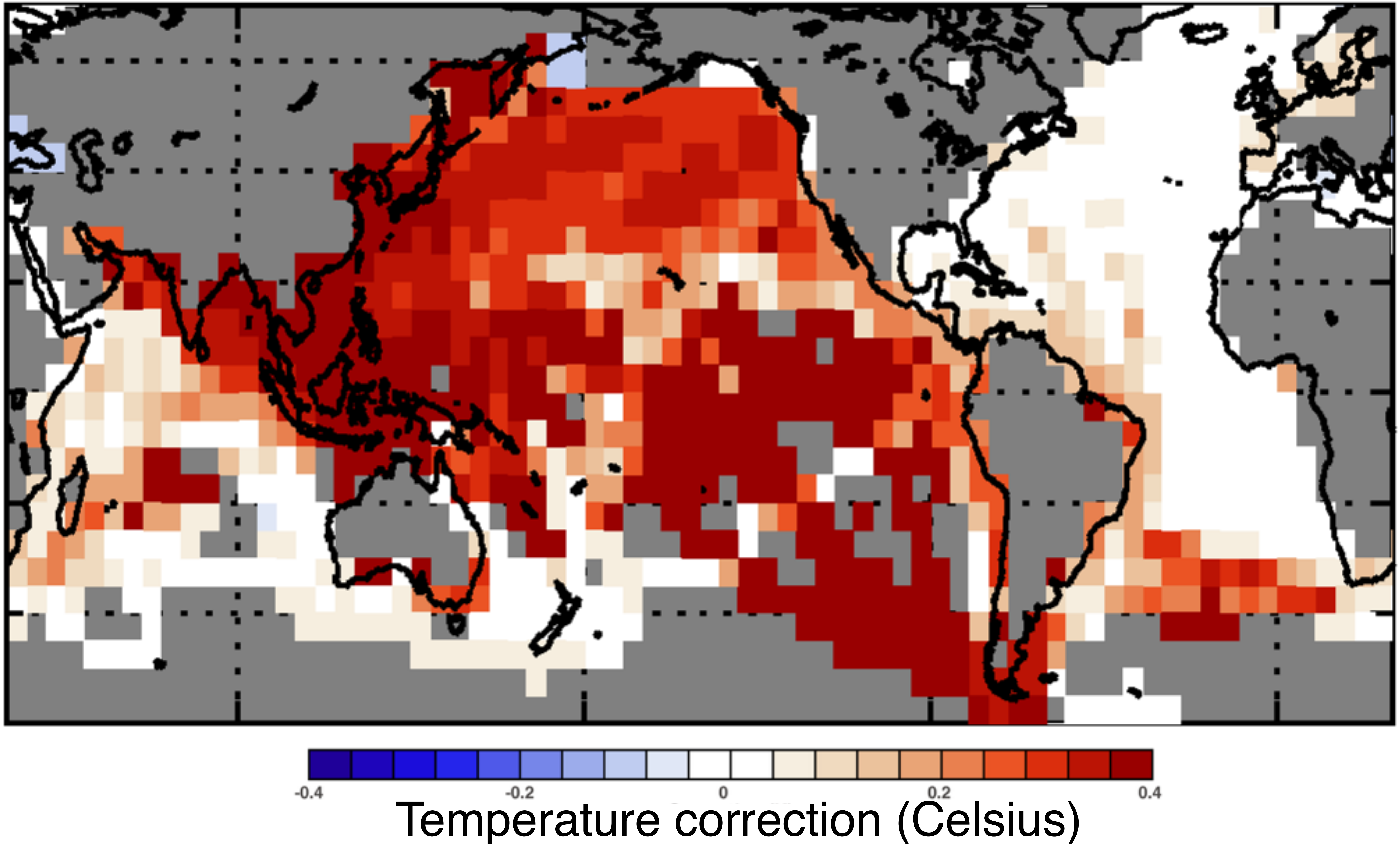
SST correction field 1939



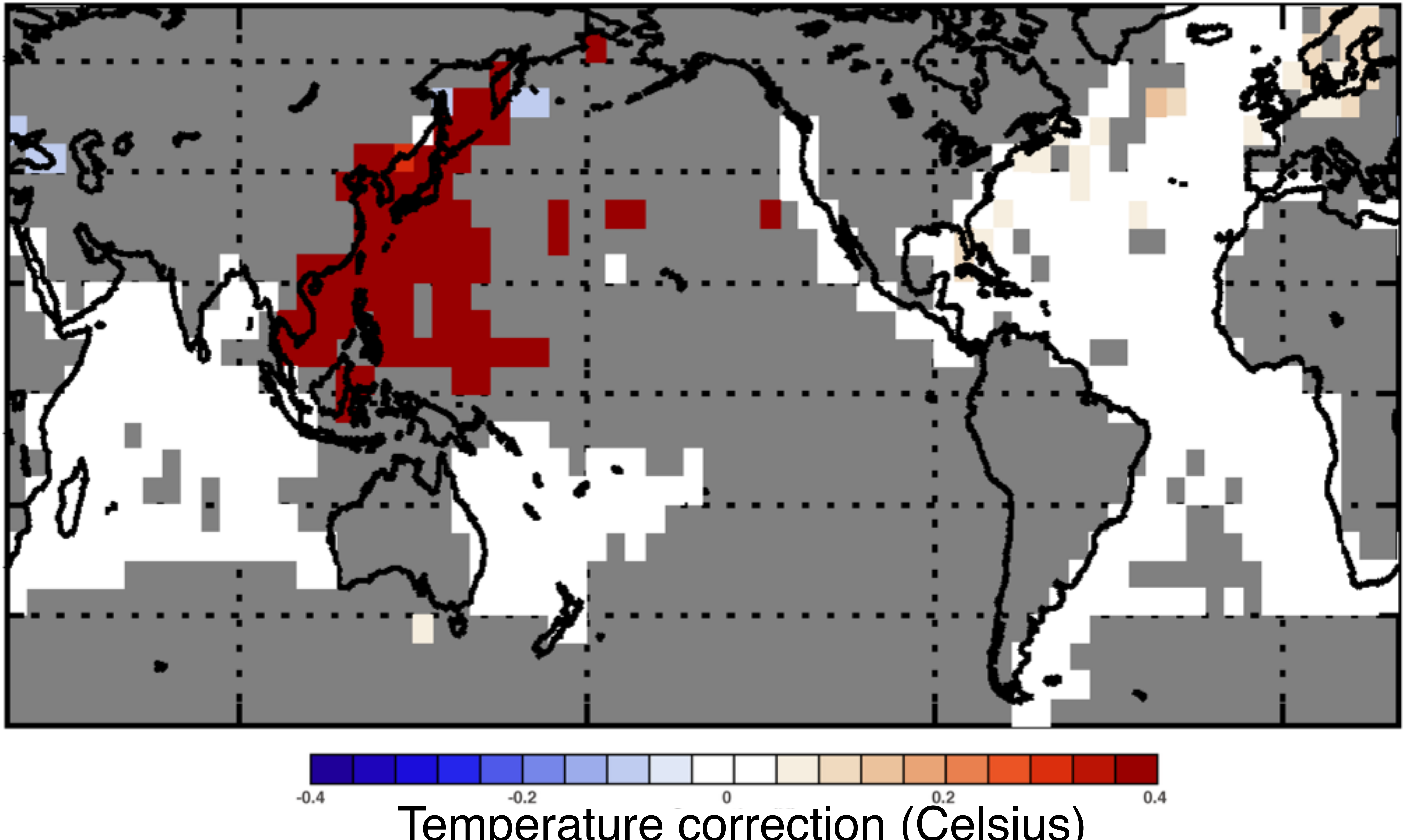
SST correction field 1940



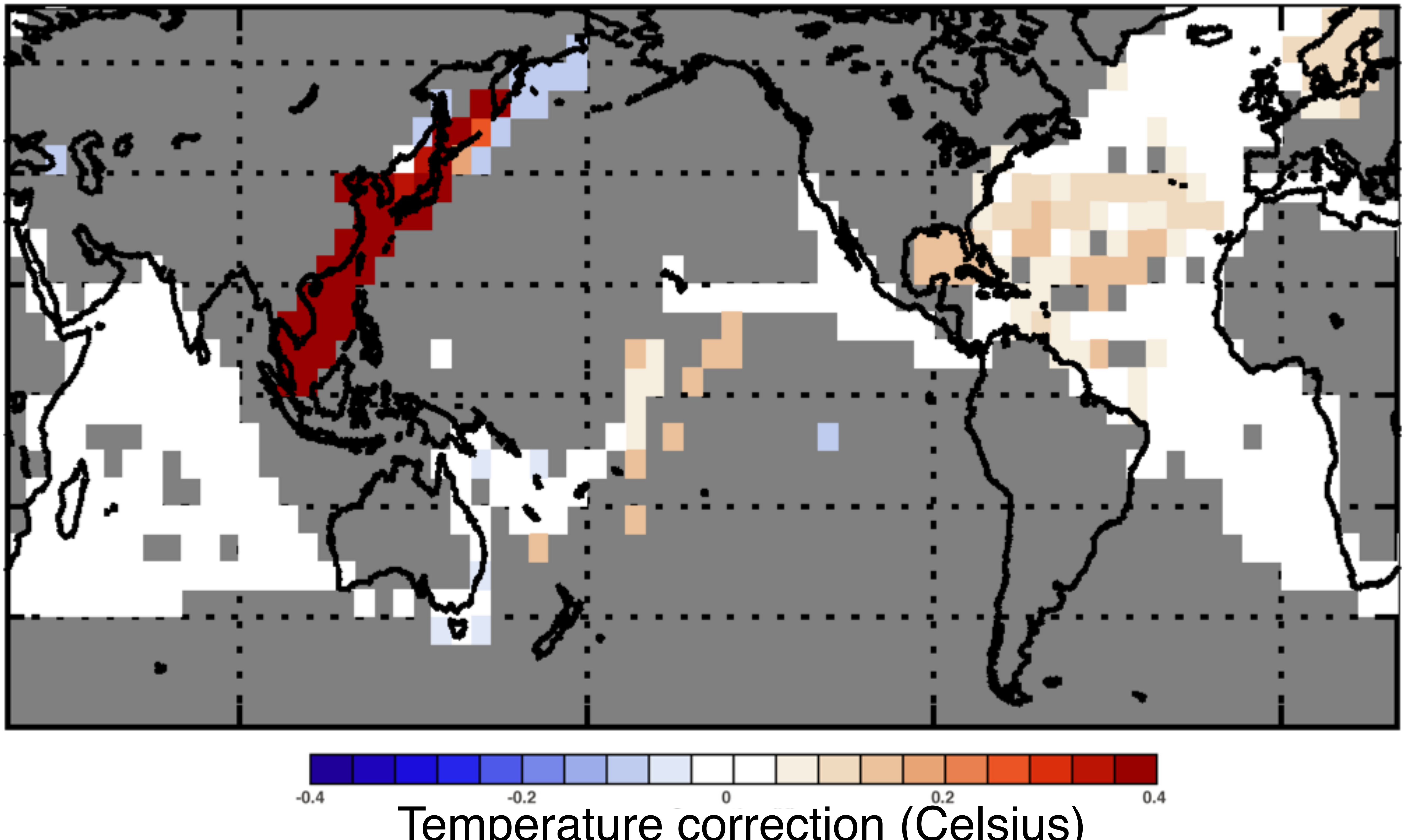
SST correction field 1941



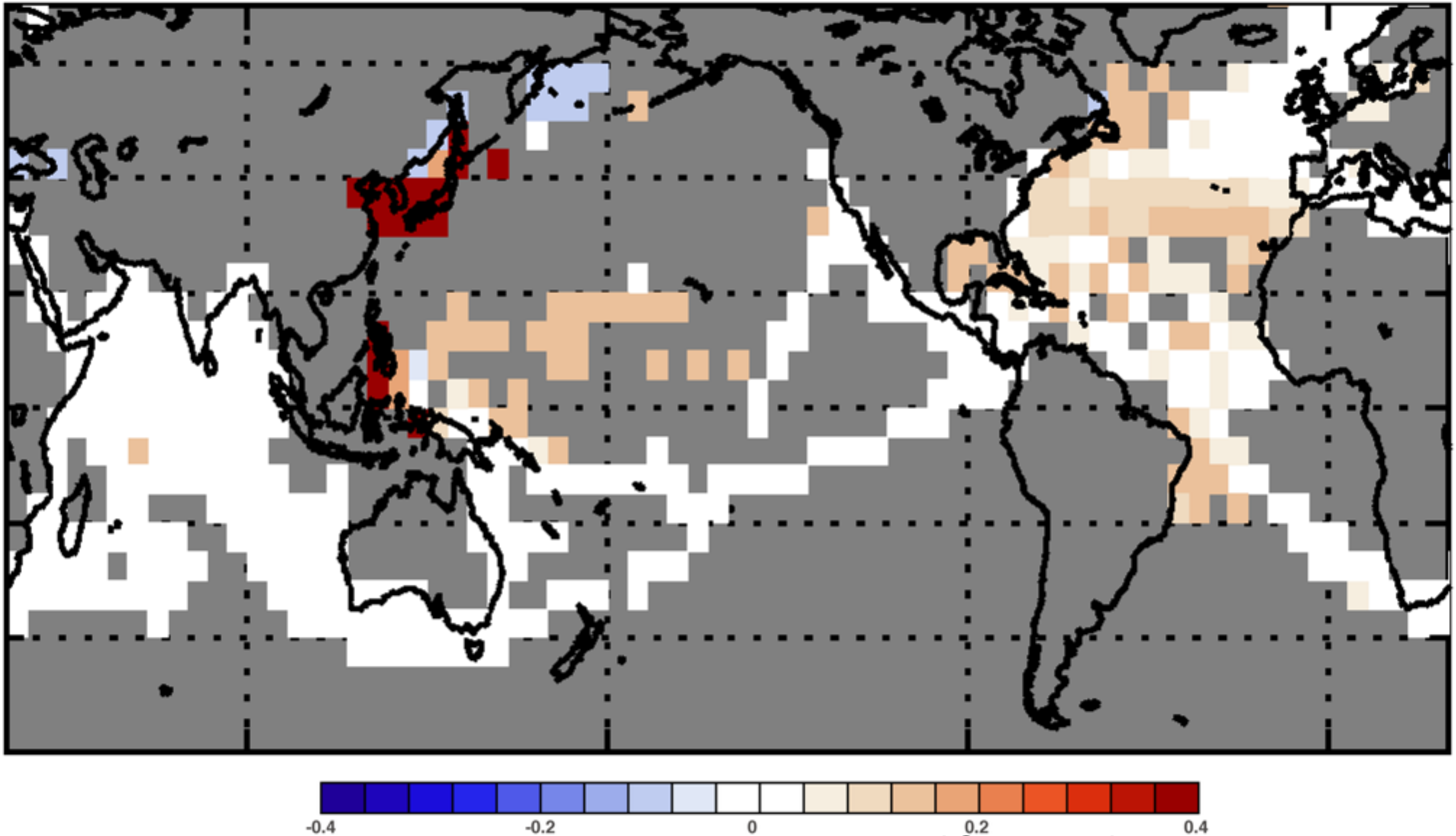
SST correction field 1942



SST correction field 1943

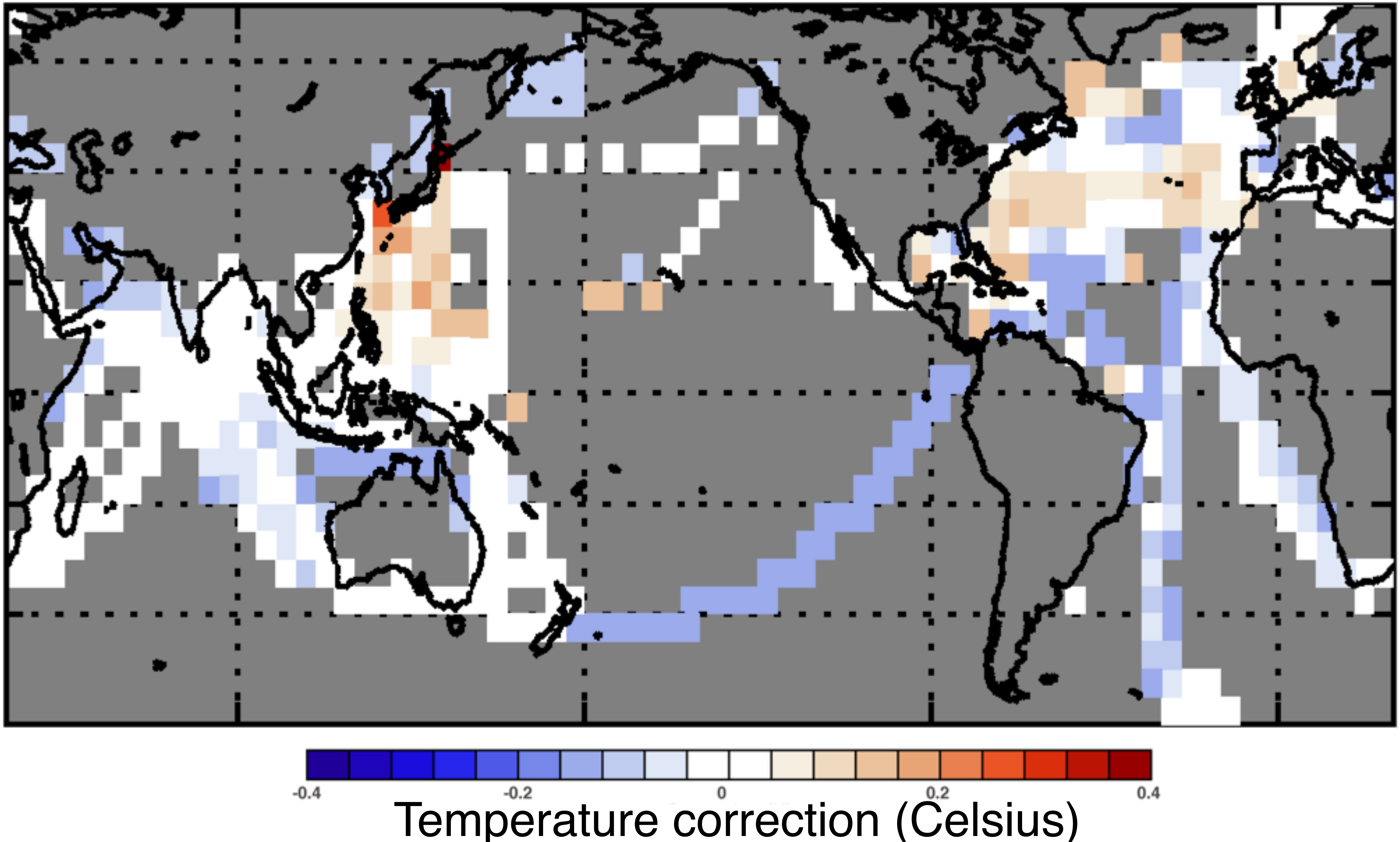


SST correction field 1944

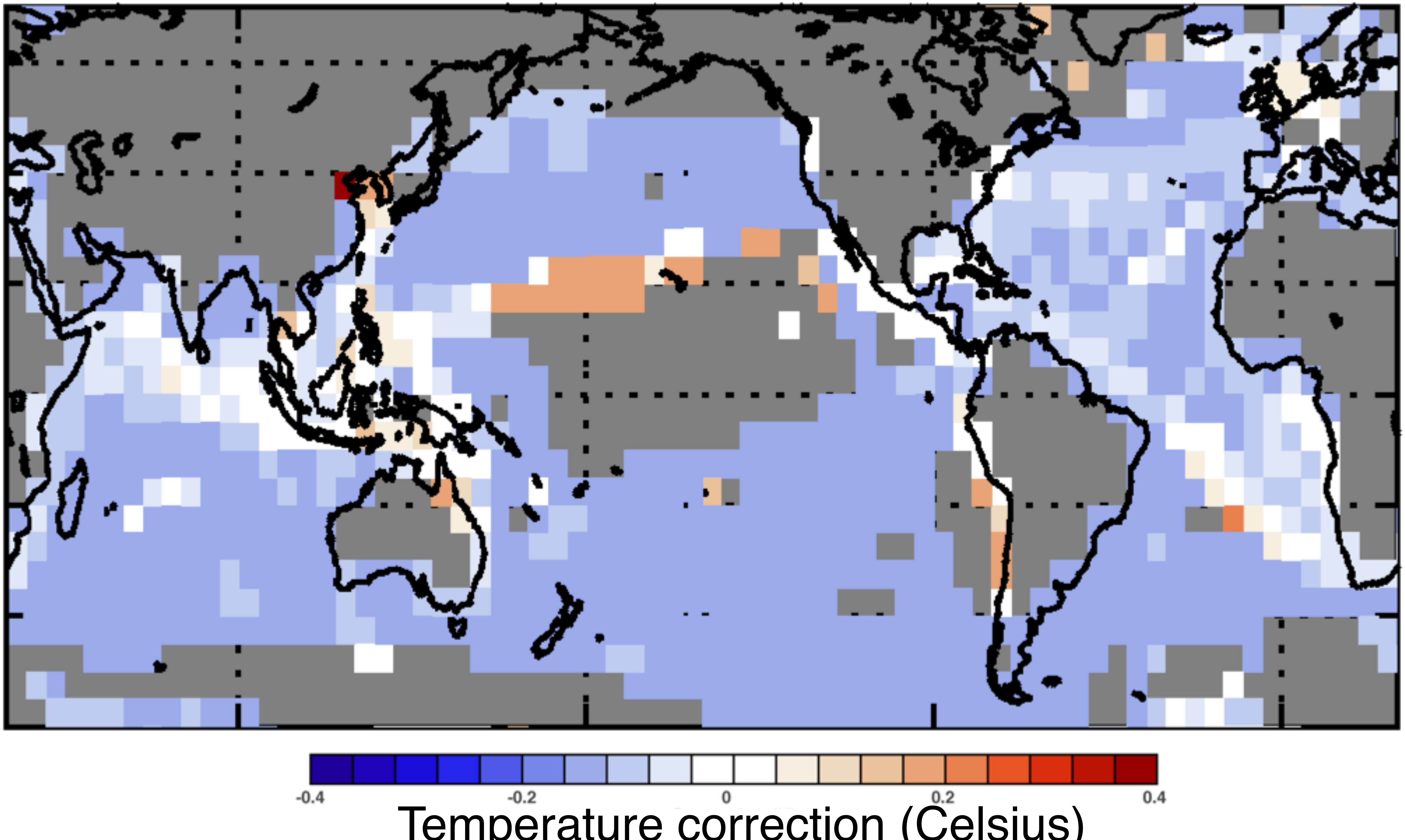


Temperature correction (Celsius)

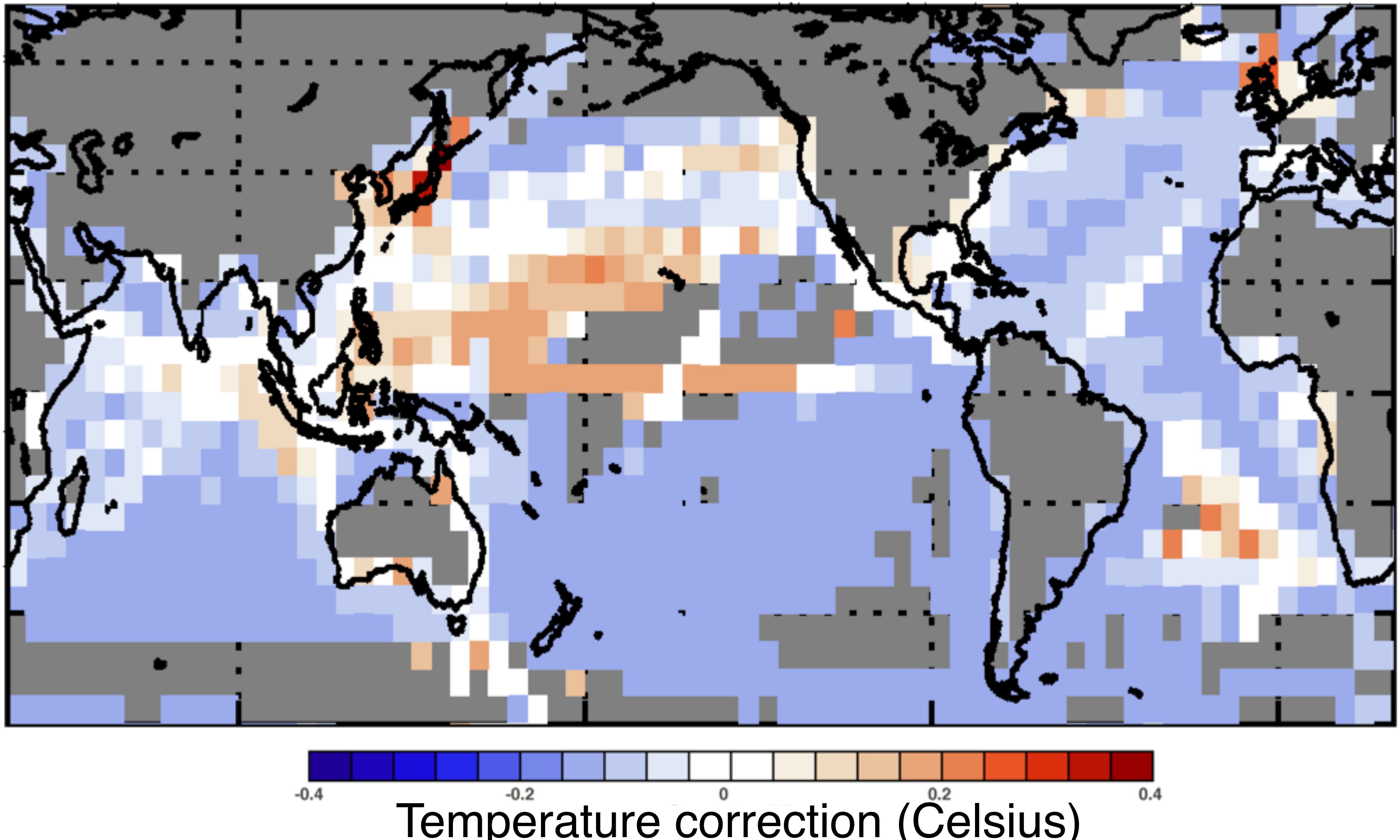
SST correction field 1945



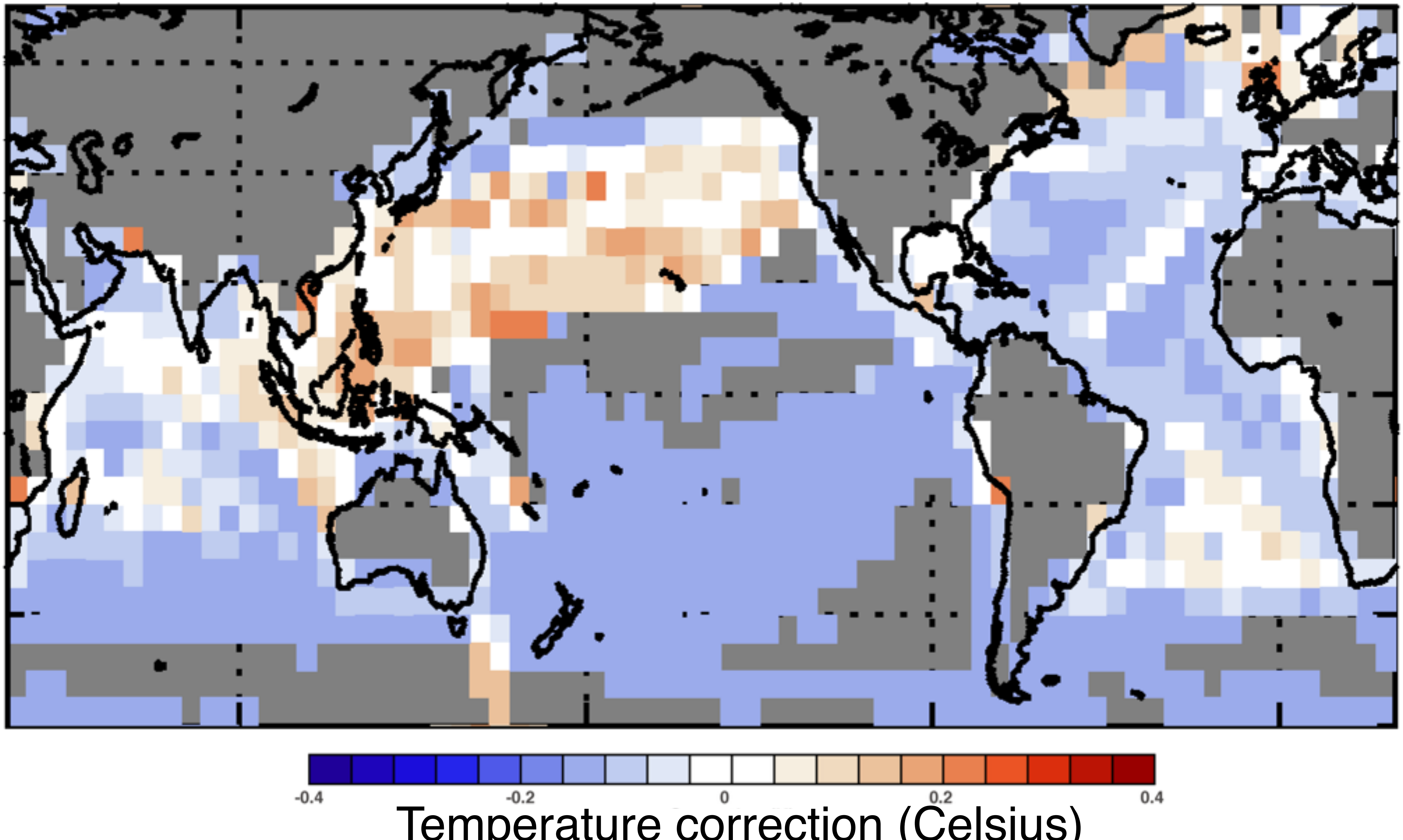
SST correction field 1946



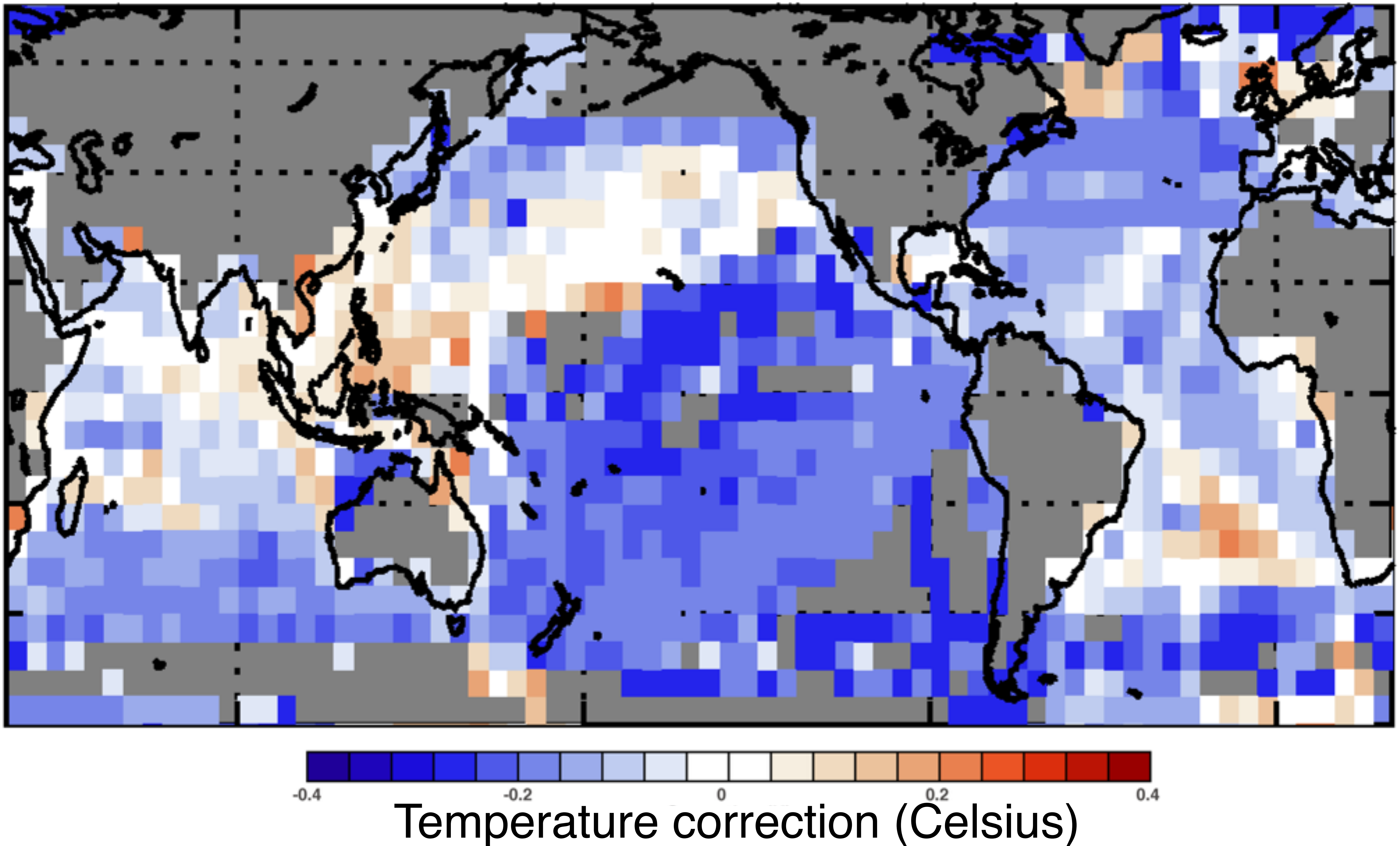
SST correction field 1947



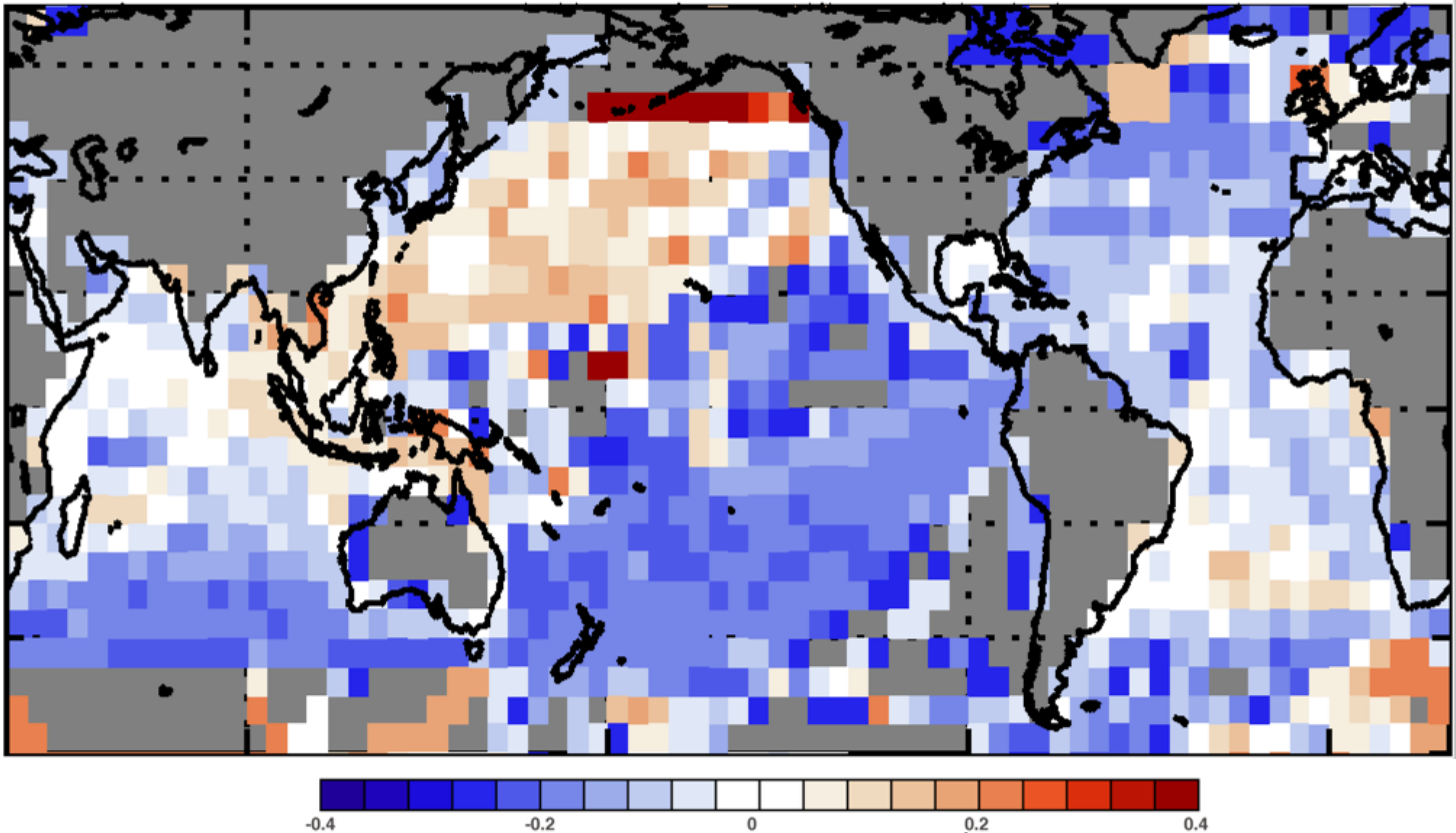
SST correction field 1948



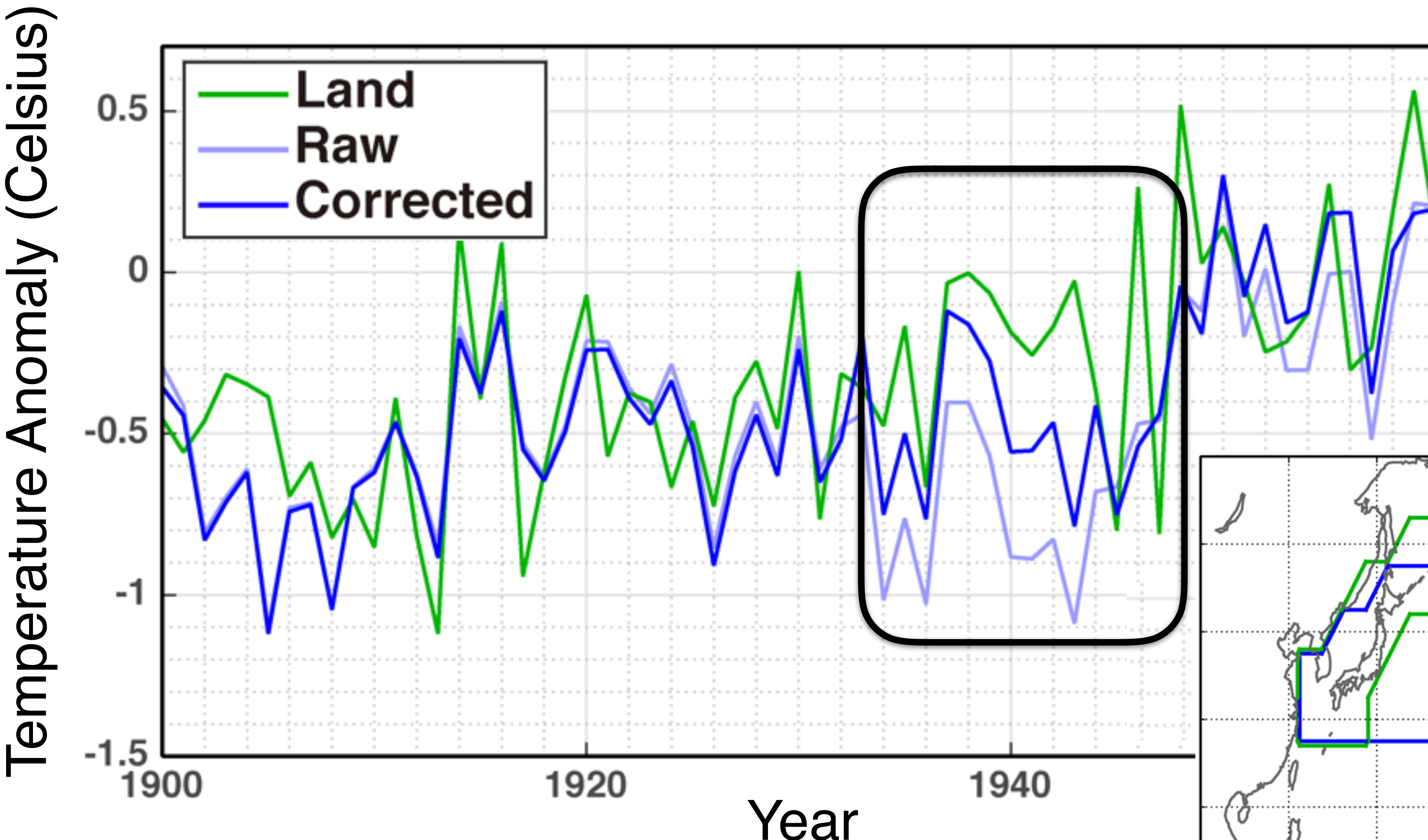
SST correction field 1949

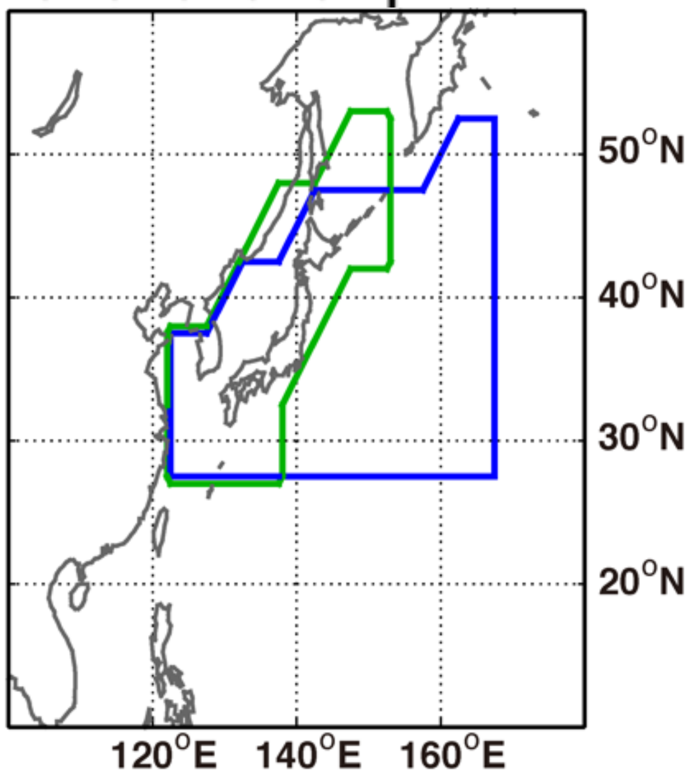


SST correction field 1950

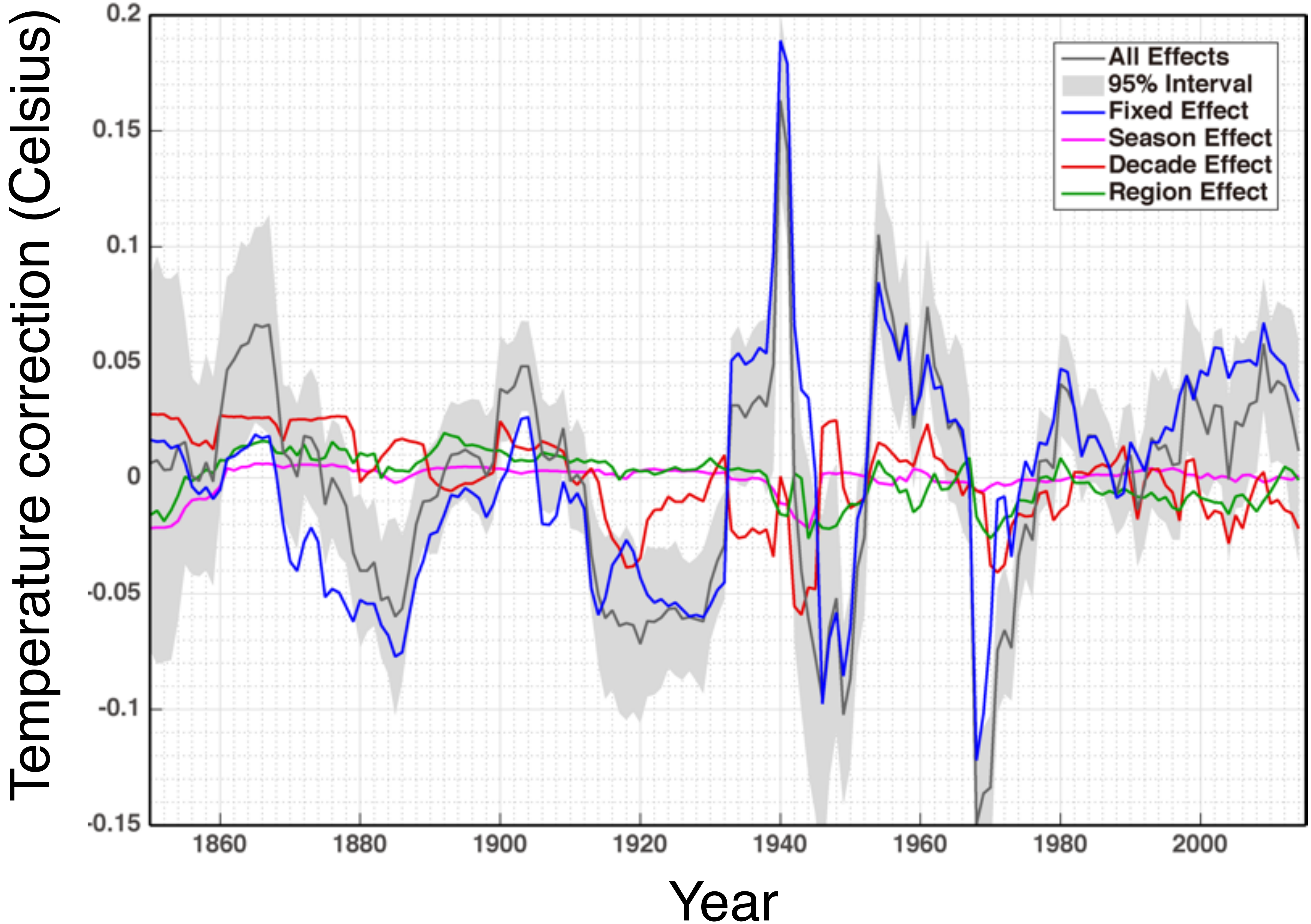


Corrected SST anomalies in the Northwest Pacific better correspond to regional land-temperature anomalies





Corrections to bucket temperature observations imply order 0.1 degree Celsius uncertainties in global SST



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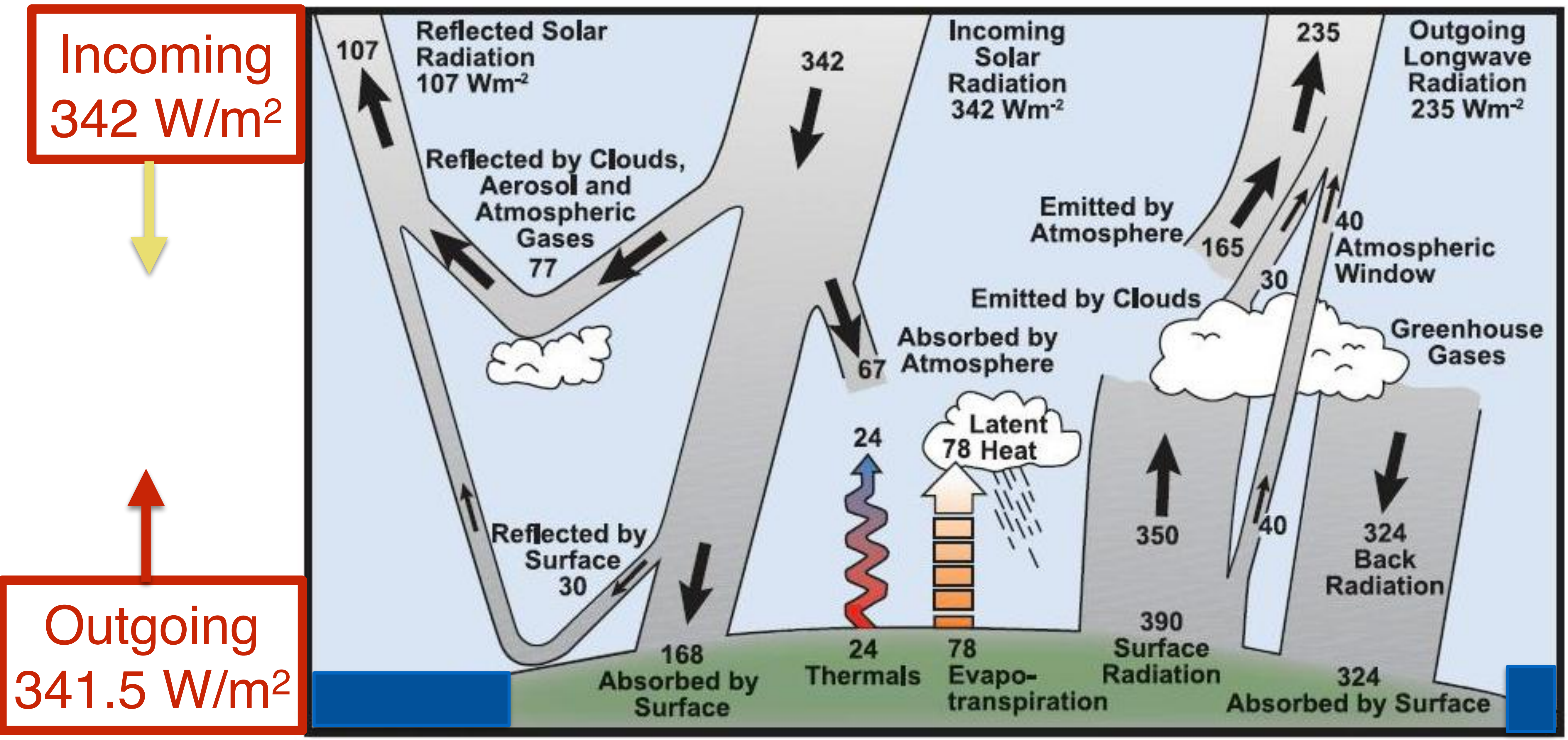
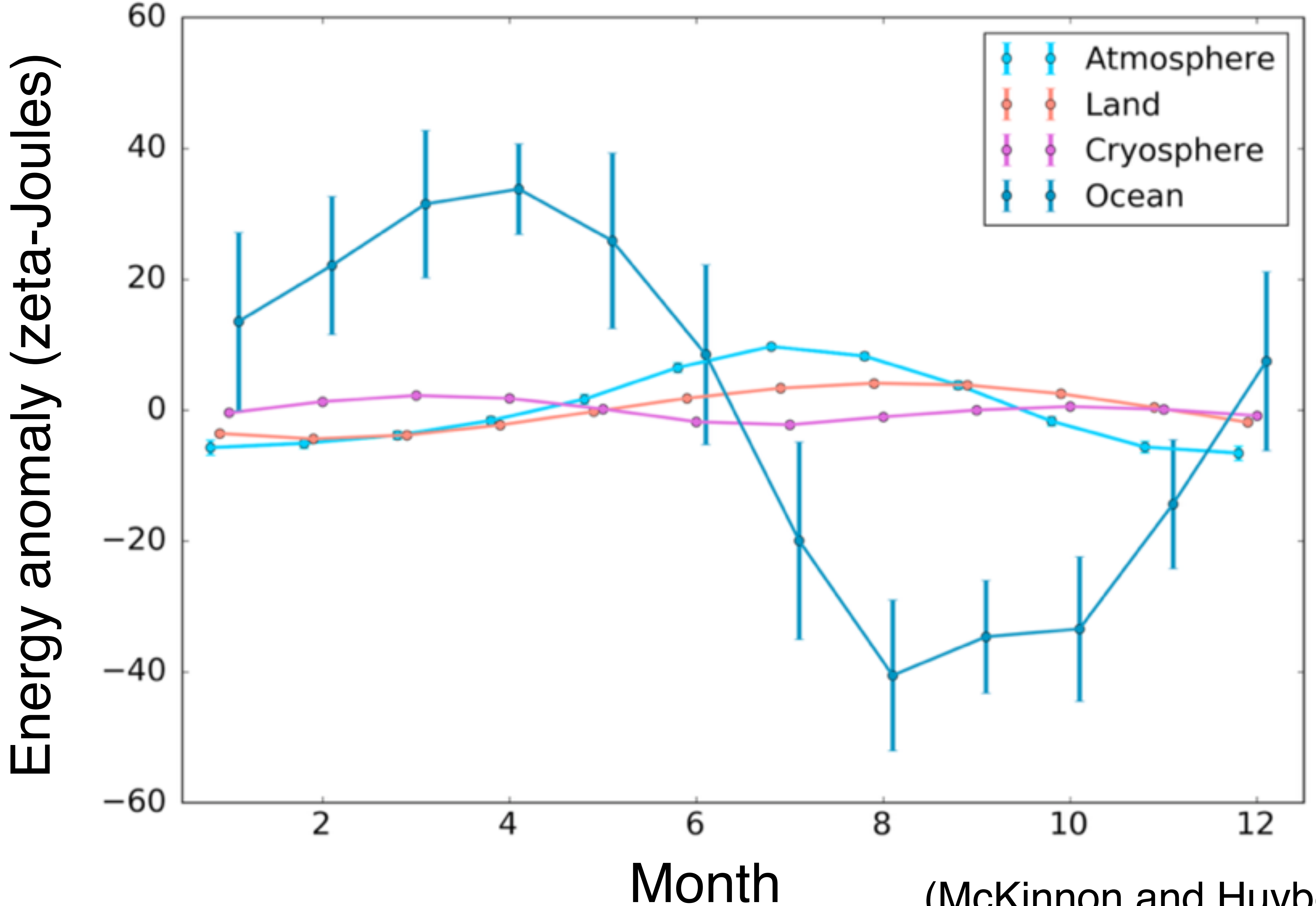
Better measurements of Earth's energy imbalance would permit for a more severe test of our models and theory.



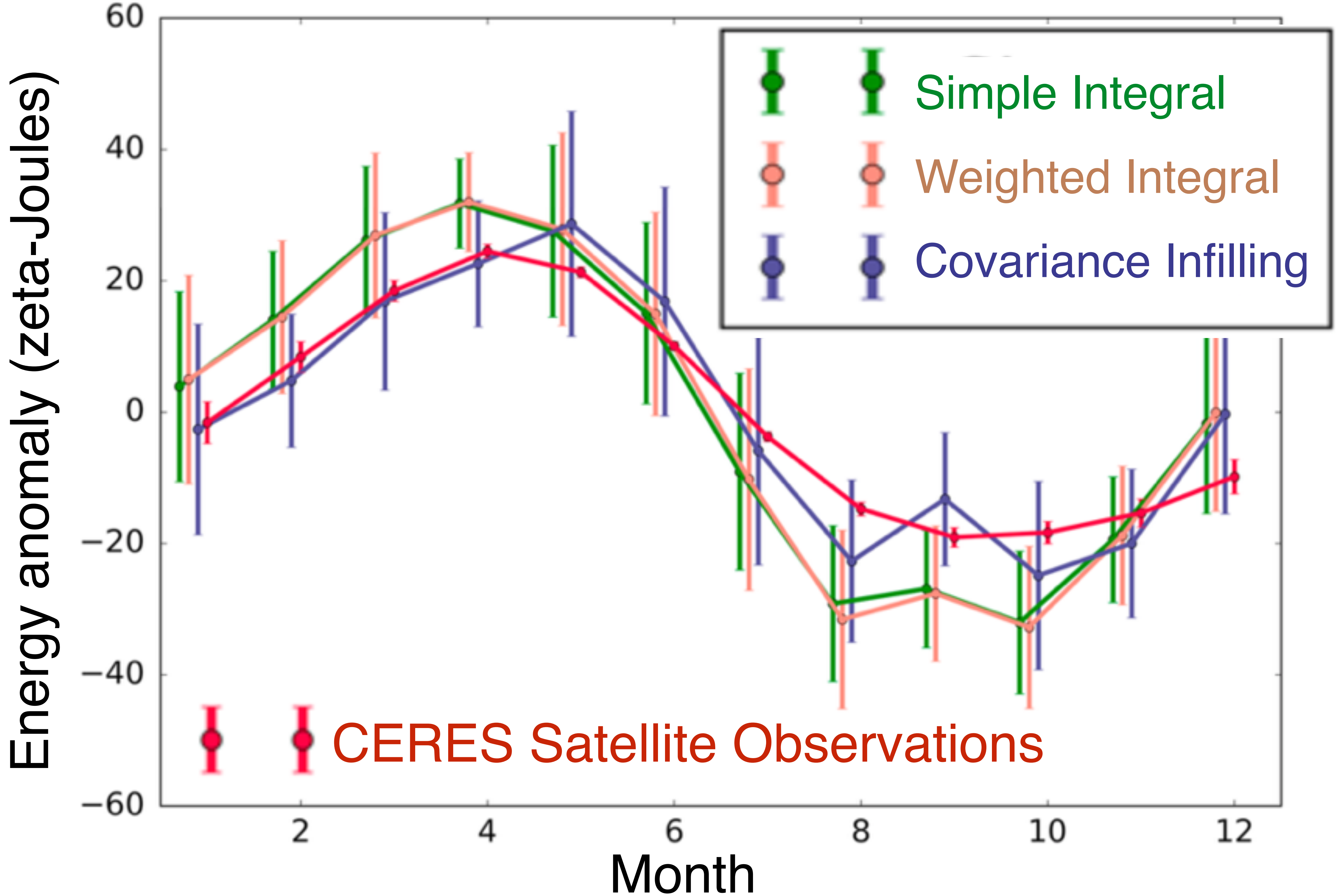
Earth's energy imbalance: heating of 0.5 +/- 0.4W/m² *Johnson* et al. (2016)

Components of seasonal variability in Earth's energy budget



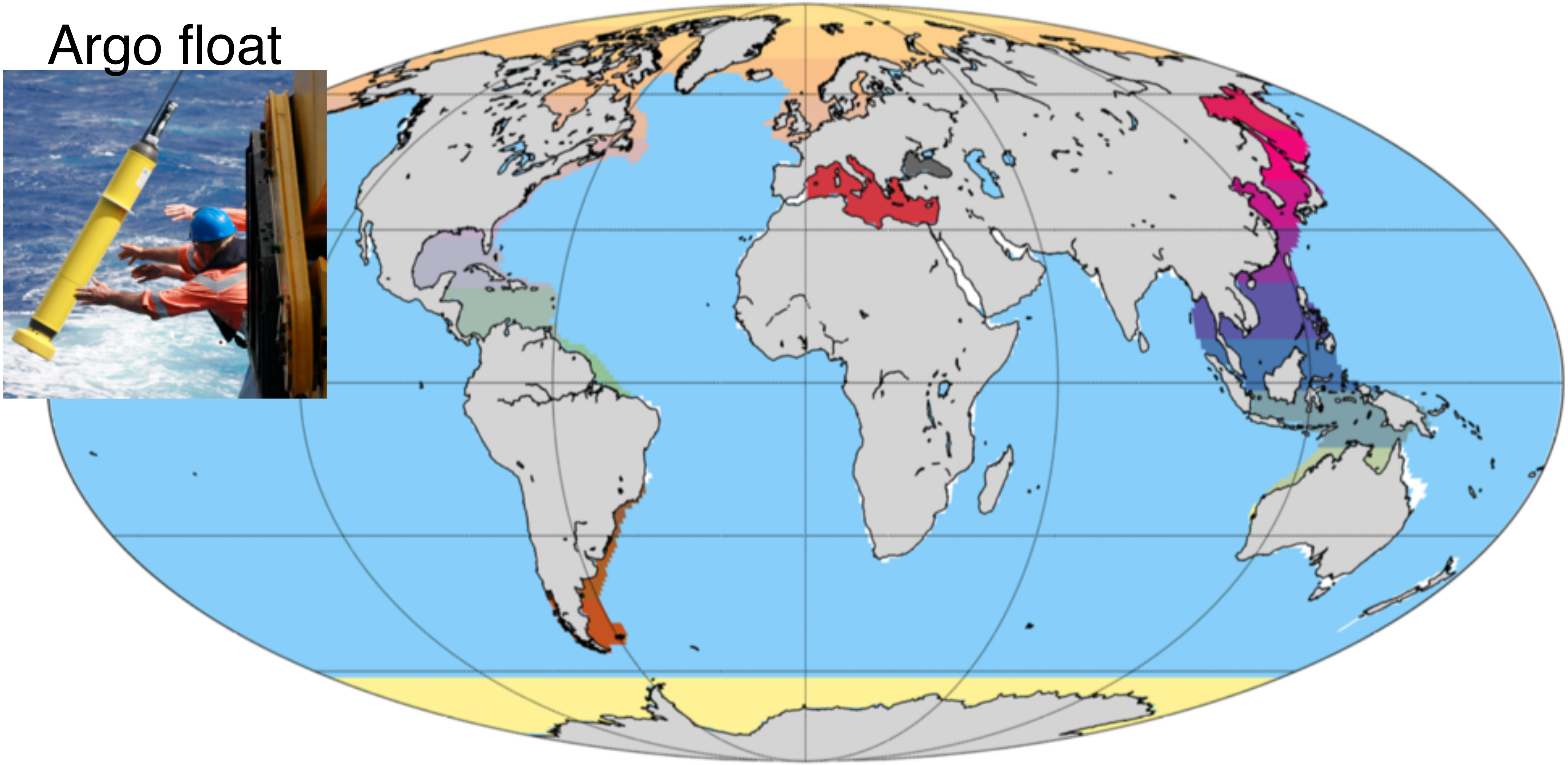
(McKinnon and Huybers, 2016)

Seasonal cycle of Earth's net energy budget compared to CERES satellite observations (Southern Hemisphere dominates)



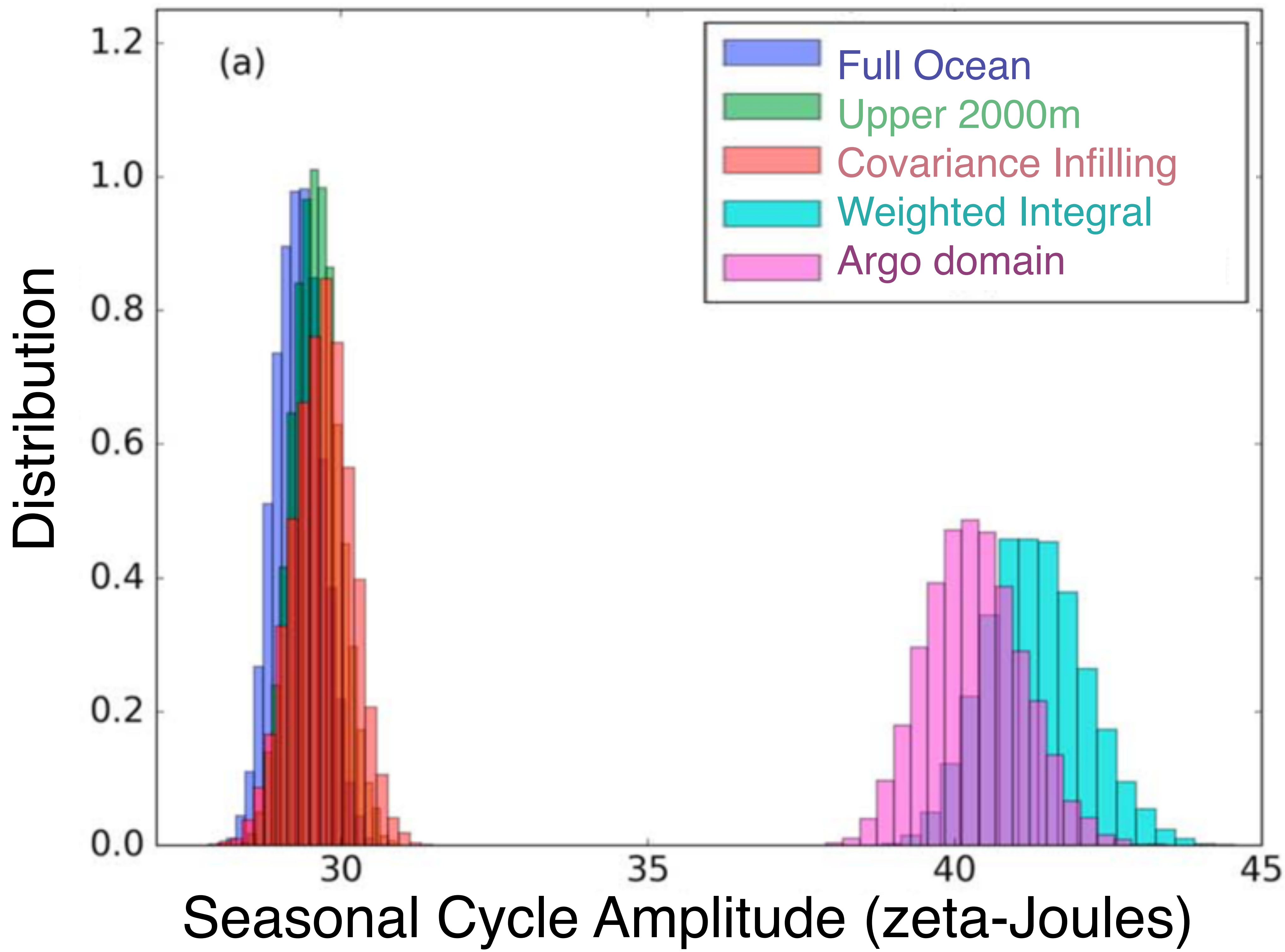
Ocean temperatures are not mapped near continental shelves and in shallow oceans (e.g., by Roemmich and Gilson, 2009)

Argo float

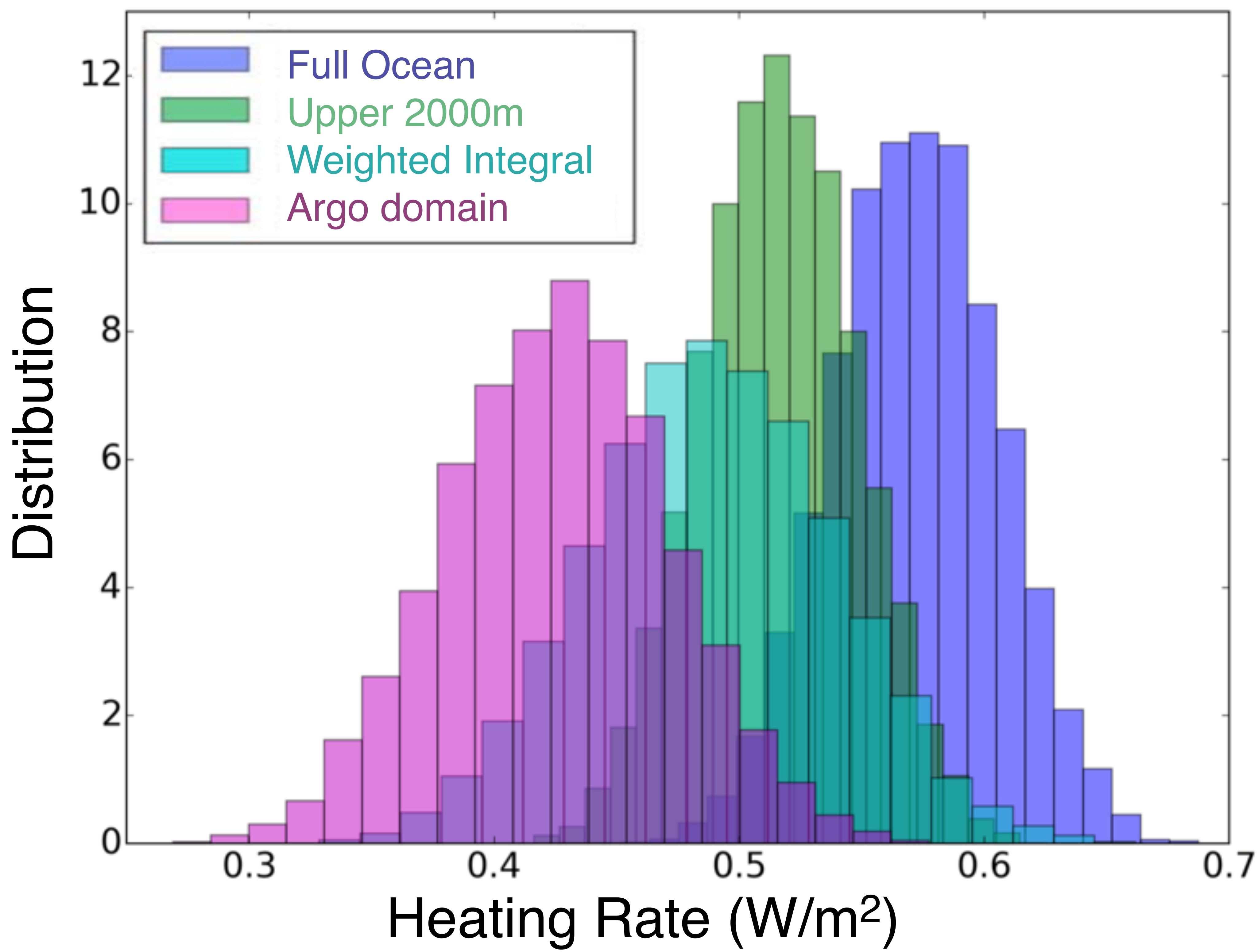


Map of where ARGO observations regularly extend (cyan), and regions grouped together for infilling (colors)

In a simulation from CESM1, the seasonal cycle in heating is accurately estimated when using covariance infilling.



Annual heating rate is 0.1 W/m² higher in CESM1 simulations when including the full domain relative to a weighted integral.



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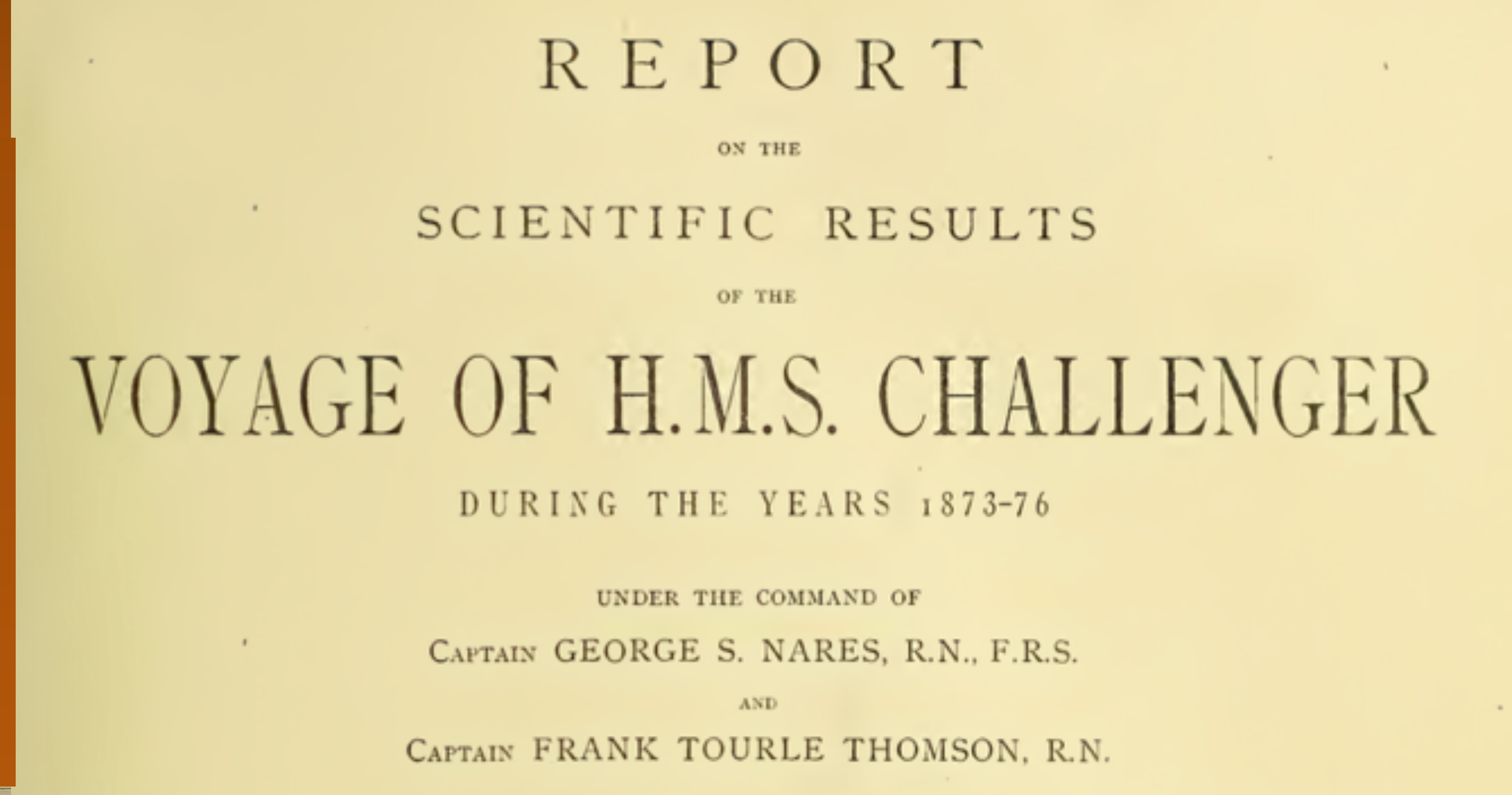
5000 temperatures observations were collected from the world's oceans, spanning from top to bottom



REPORT

ON THE

SCIENTIFIC RESULTS

OF THE

VOYAGE OF H.M.S. CHALLENGER

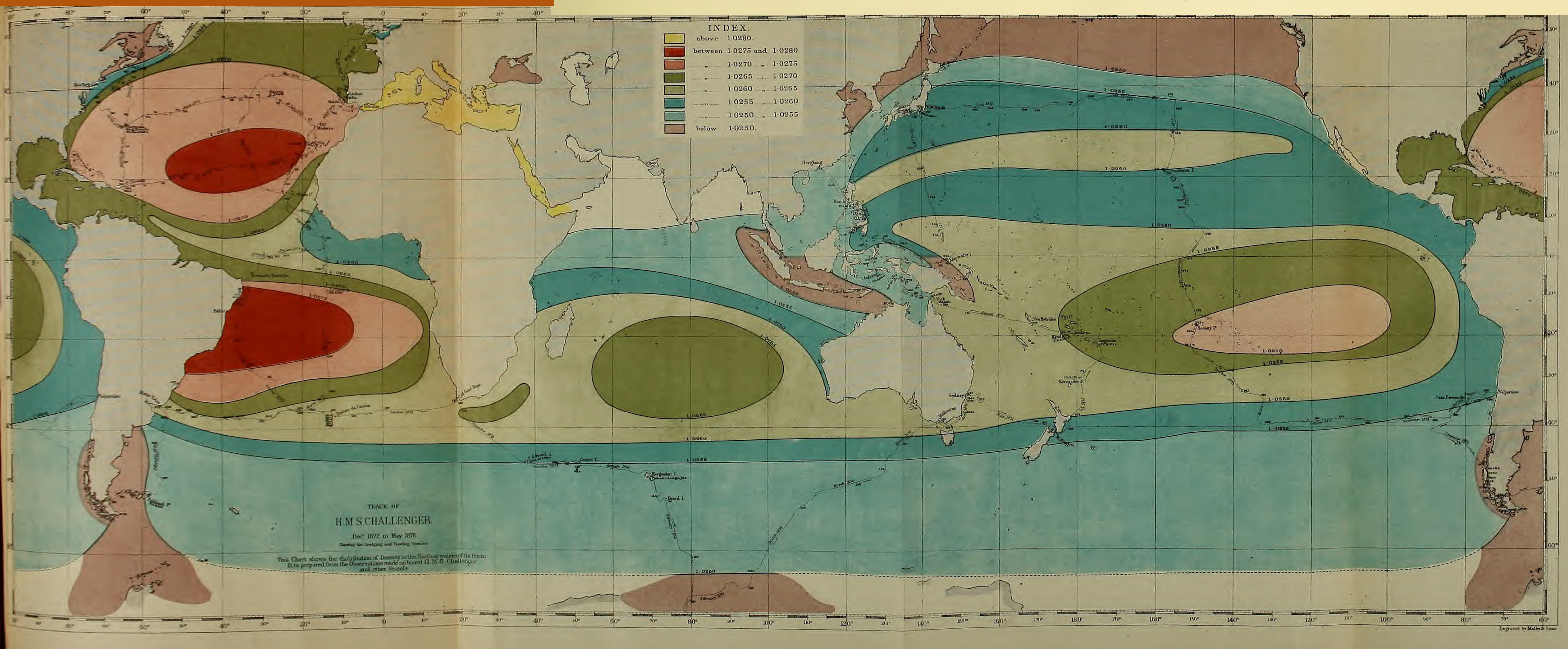
DURING THE YEARS 1873-76

UNDER THE COMMAND OF

CAPTAIN GEORGE S. NARES, R.N., F.R.S.

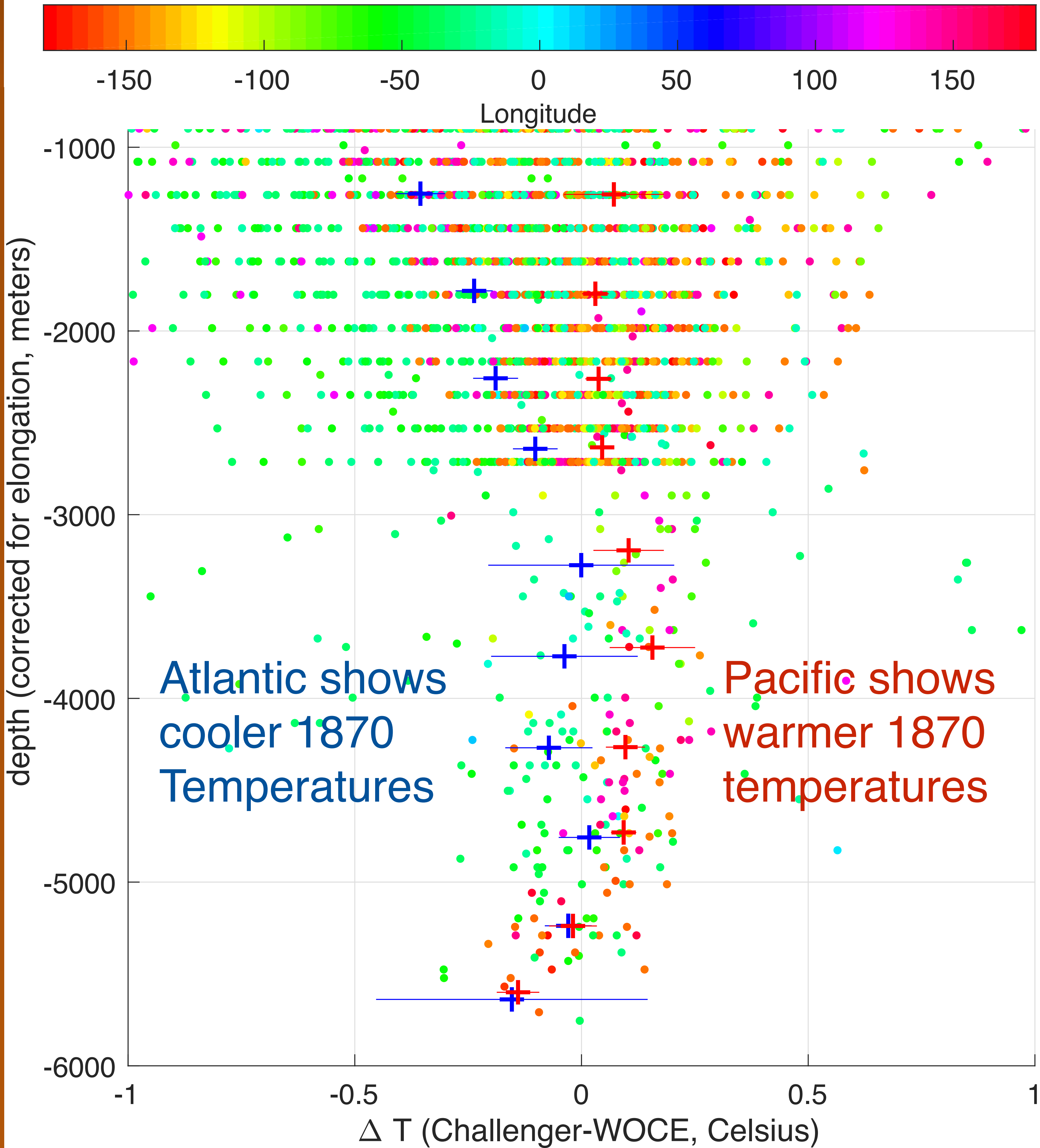
AND

CAPTAIN FRANK TOURLE THOMSON, R.N.

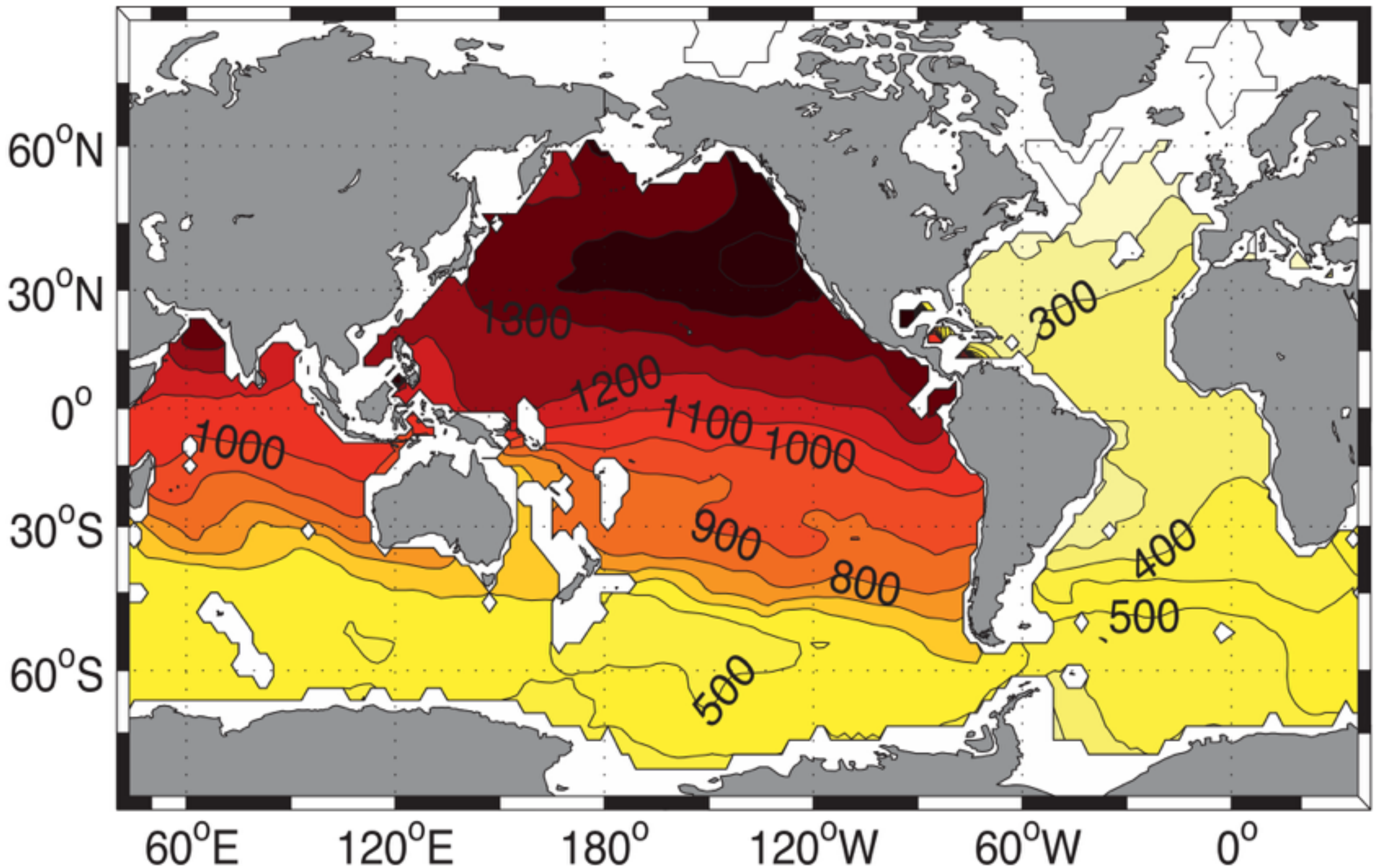


Comparing against modern observations, the Atlantic shows warming since 1870.

In contrast, the Pacific shows cooling, especially between 3-4km depth and in Northern regions.

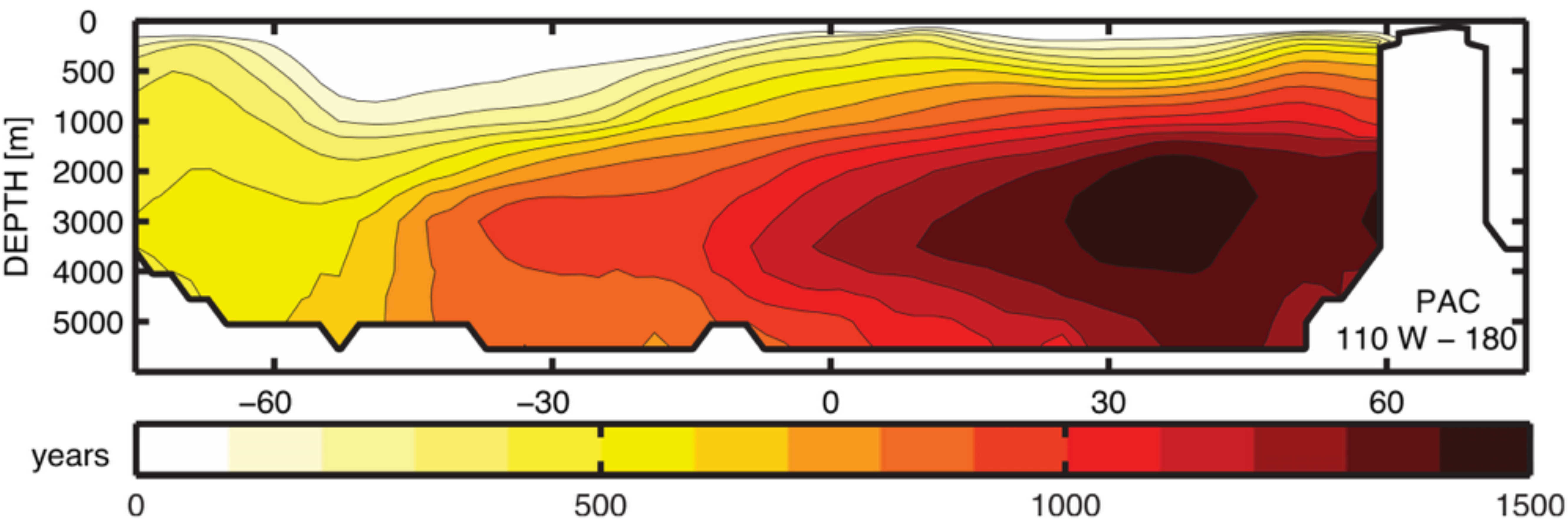


Average age of ocean waters at 2500 meters depth



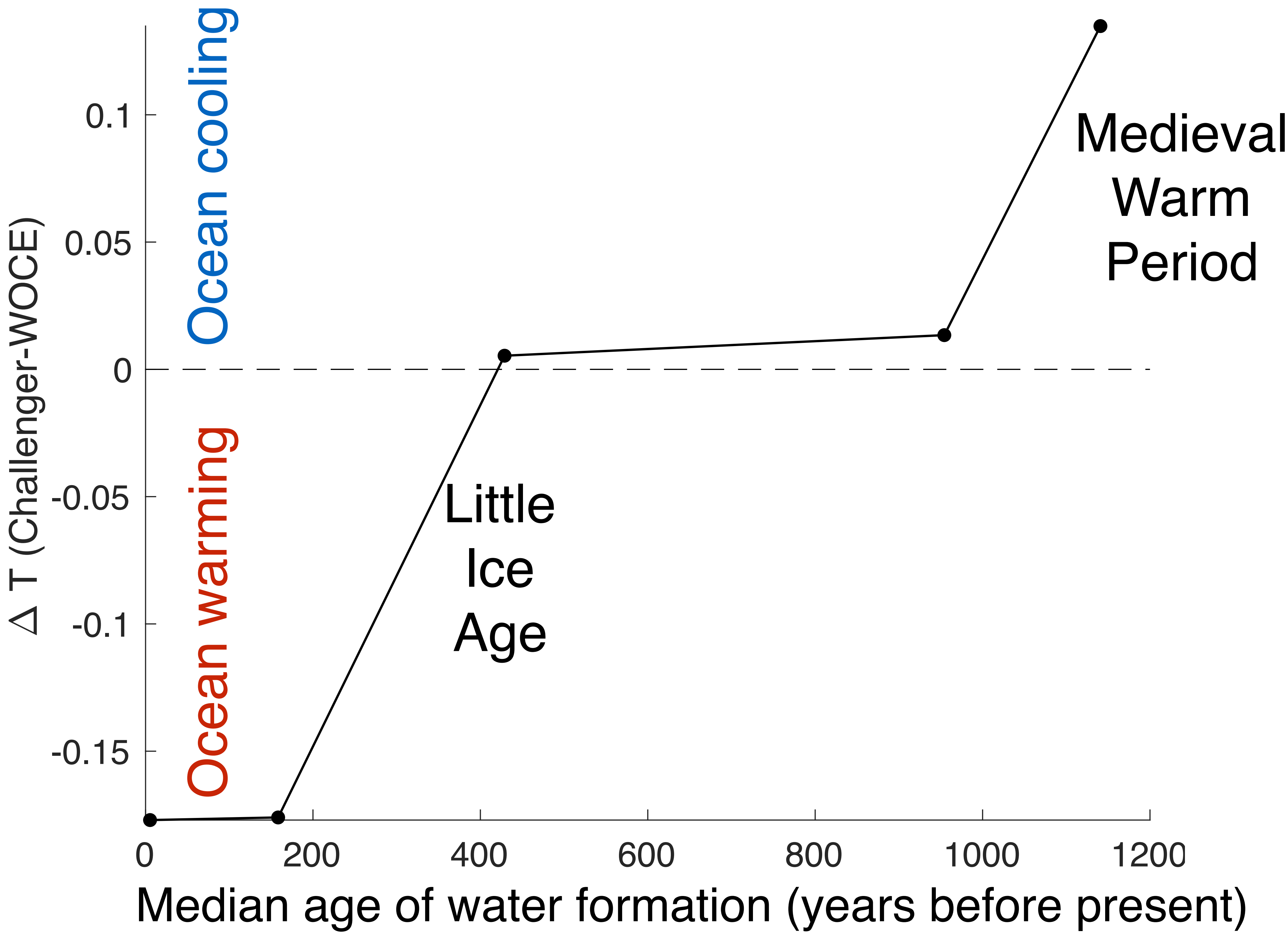
Gebbie and Huybers (2014)

Average age of ocean waters in the Pacific is greatest at 3km depth near 40 degrees North



Gebbie and Huybers (2014)

Changes in ocean temperature since 1870 indicate that waters formed during the Medieval Warm Period are still cooling, whereas those formed during the Little Ice Age are warming.



Summary so far

1. Recently observed versus simulated temperature trends are consistent.
2. Correcting historical temperature estimates implies greater temperature uncertainty.
3. Seasonal constraints on today’s energy imbalance imply greater heat uptake in marginal seas.
4. Earth’s energy imbalance circa 1870 indicates that the ocean may have been cooling.

Updating Lewis and Curry (2015), the central estimate of Equilibrium Climate Sensitivity rises from 1.6º to 2.6ºC

$$\mathrm{ECS} = F_{2\times CO2} \frac{T_{2000} - T_{1870}}{(F_{2000} - F_{1870}) - (Q_{2000} - Q_{1870})}$$

$F_{2\times CO2}$: forcing due to doubling of CO2 ($3.7\ \mathrm{W/m^2}$),
Q_{1870}: initial heat uptake ($0.15 \rightarrow -0.1 \pm 0.2\ \mathrm{W/m^2}$),
Q_{2000}: final heat uptake ($0.51 \rightarrow 0.6 \pm 0.1\ \mathrm{W/m^2}$),
ΔT: warming ($0.71 \rightarrow 0.9 \pm 0.2$°C), (see *Richardson* 2016)
ΔF: change in forcing ($1.98 \rightarrow 2.0 \pm 0.5\ \mathrm{W/m^2}$).

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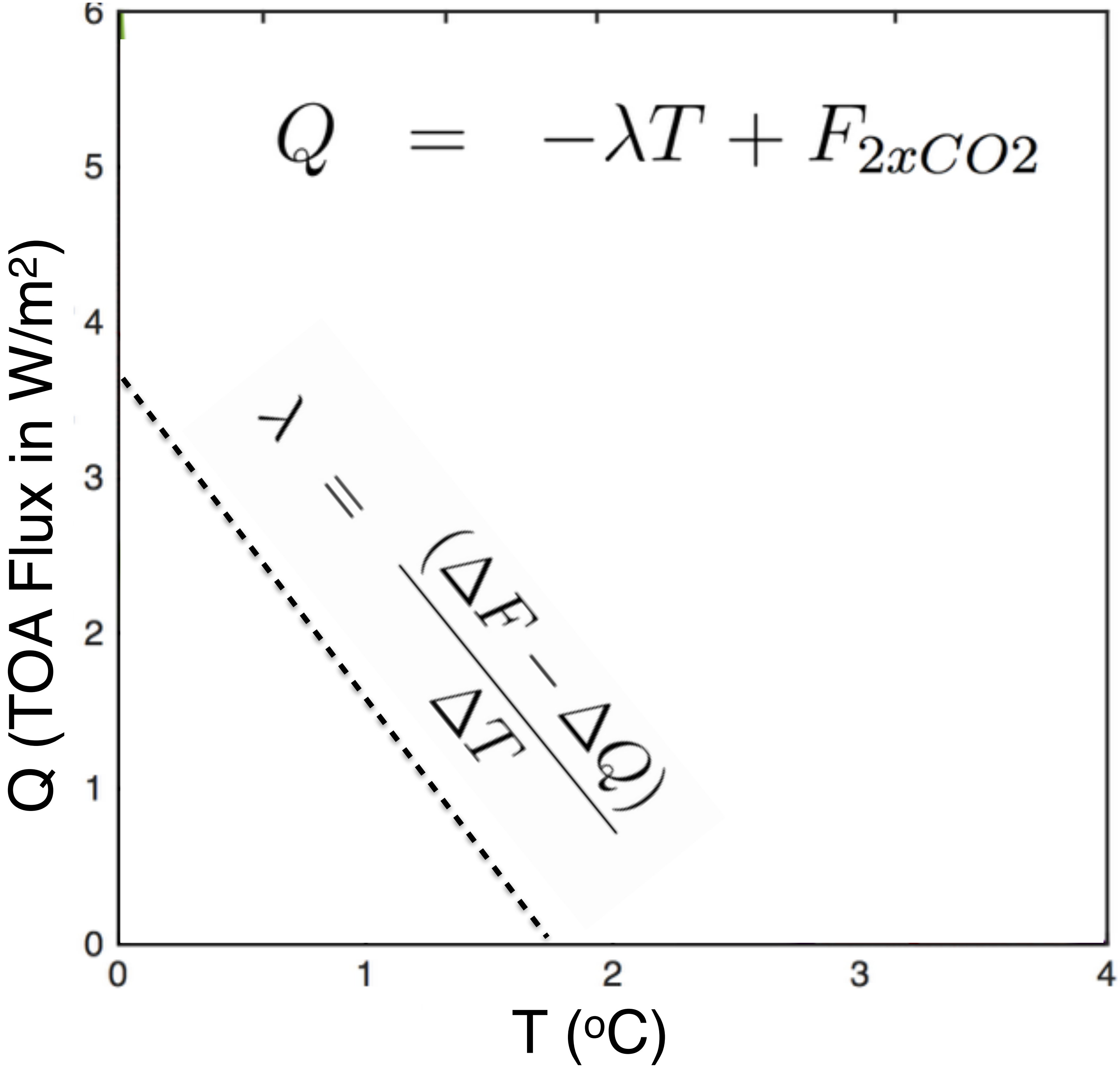
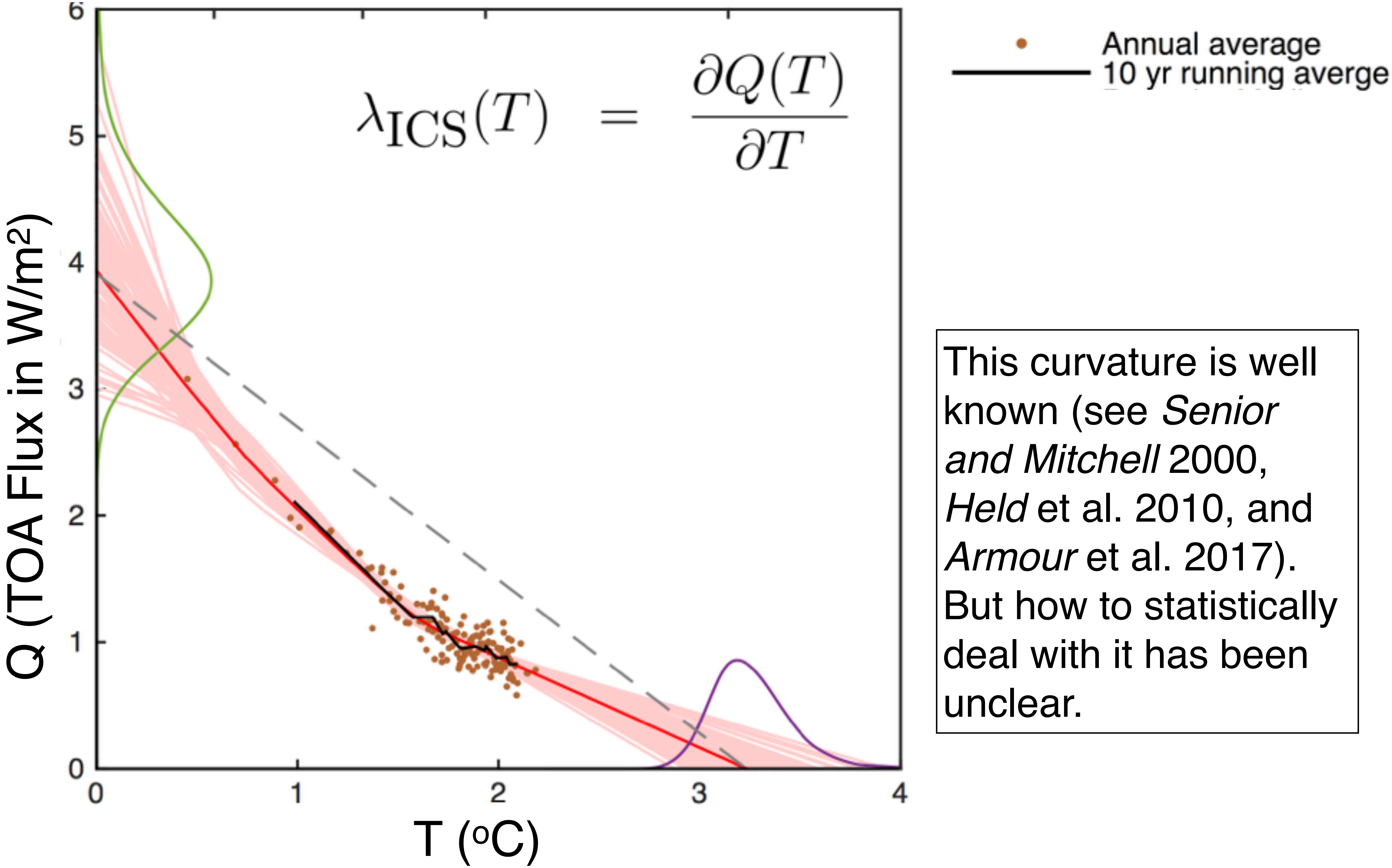
In Lewis and Curry's approach heat uptake should be a linear function of temperature…

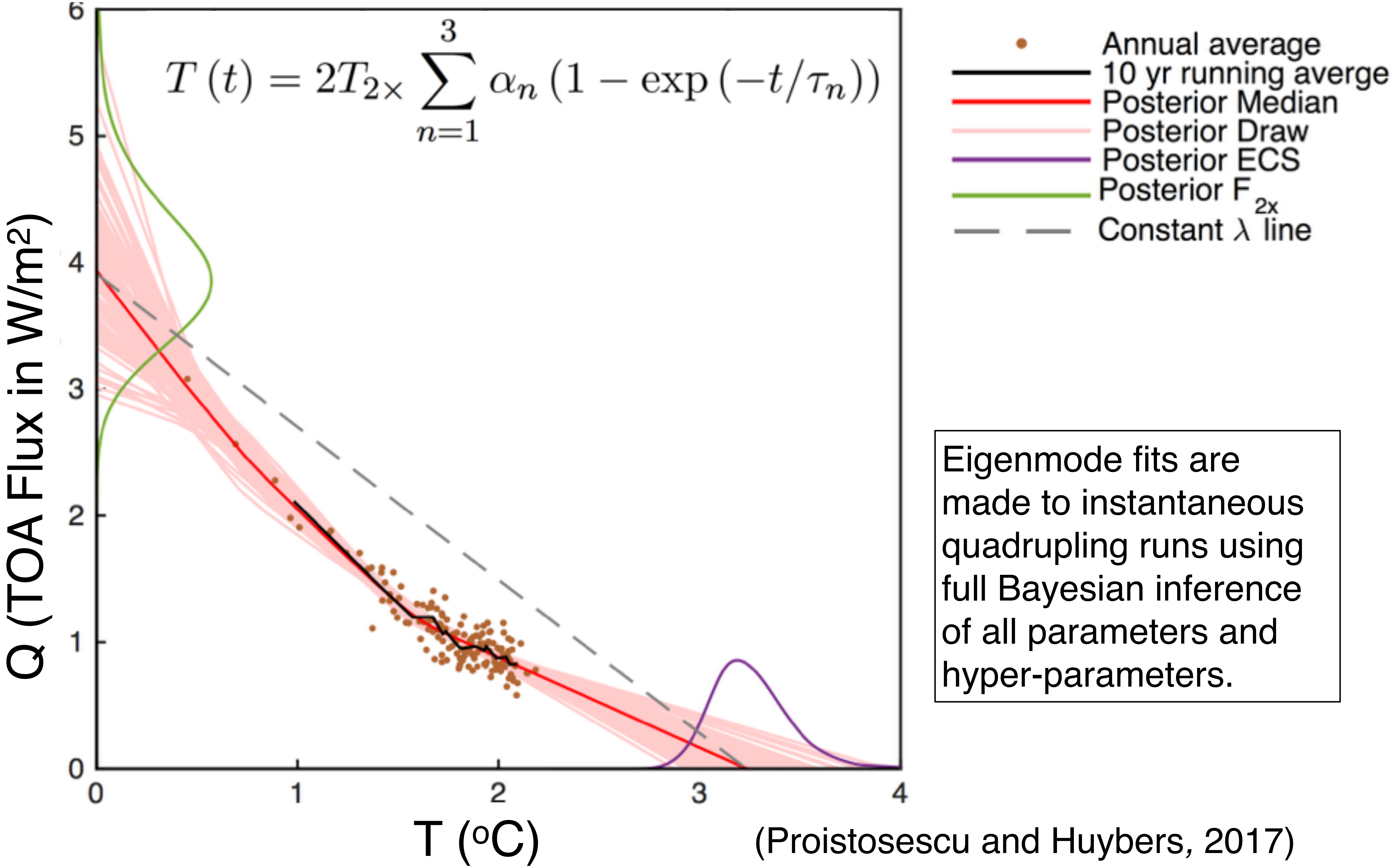


But the evolution of Q is convex with respect to T in general circulation models. Such curvature implies that historical inferences are of an Instantaneous Climate Sensitivity (ICS).



This curvature is well known (see *Senior and Mitchell* 2000, *Held* et al. 2010, and *Armour* et al. 2017). But how to statistically deal with it has been unclear.

T and Q can be well-described using three eigenmodes having annual, decadal, and centennial timescales

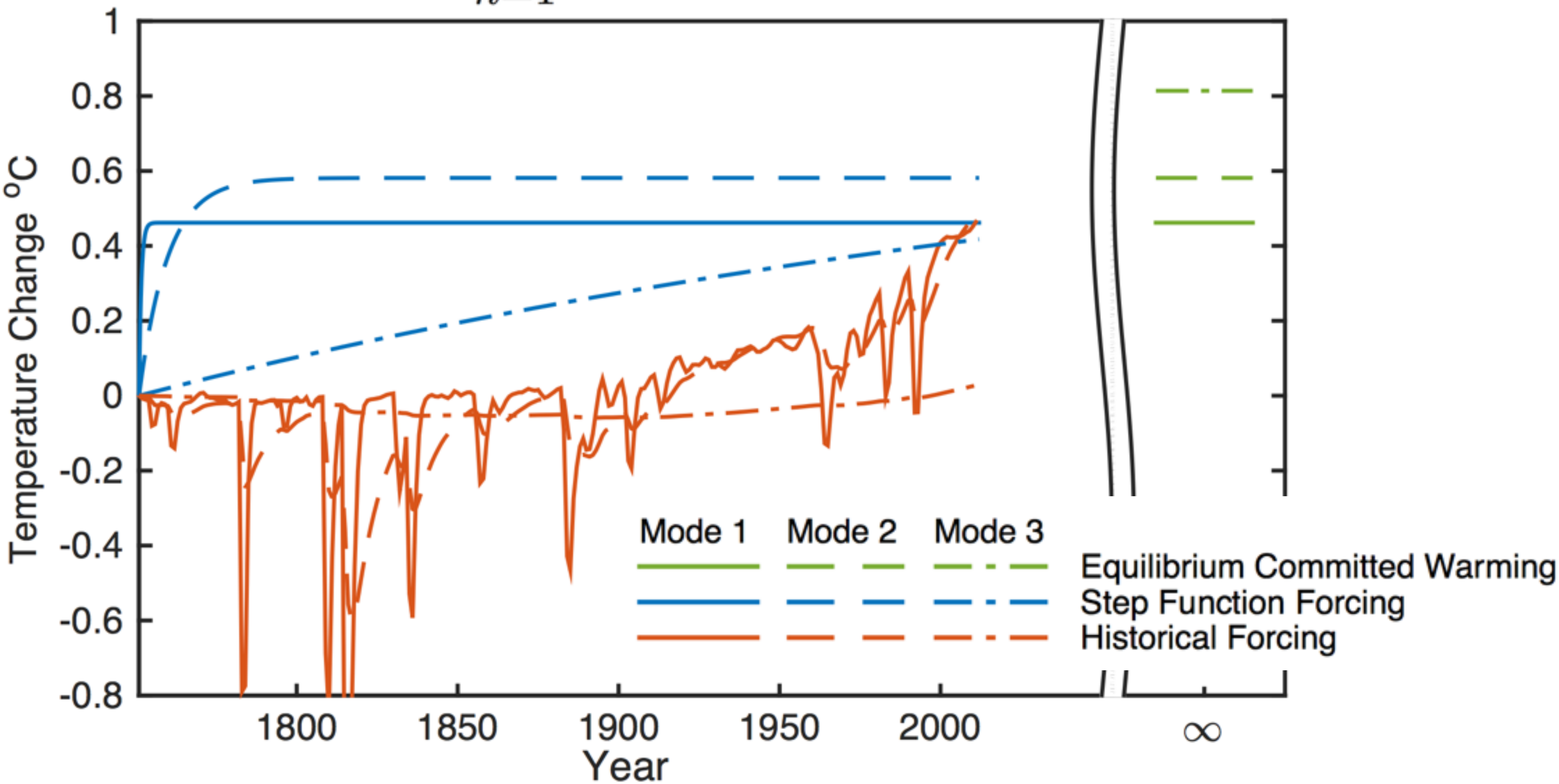


Eigenmode fits are made to instantaneous quadrupling runs using full Bayesian inference of all parameters and hyper-parameters.

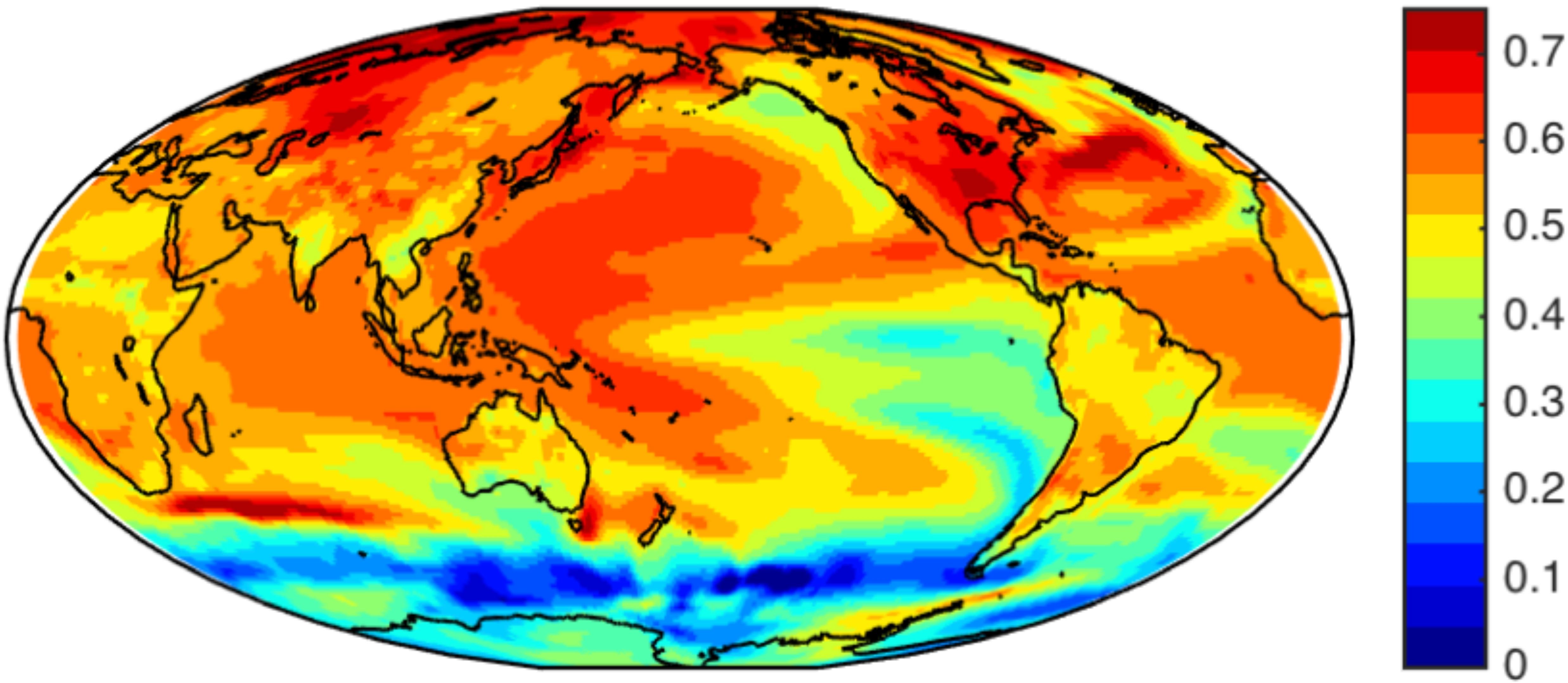
(Proistosescu and Huybers, 2017)

The centennial eignemode ultimately contributes most warming but is essentially absent from modern temperatures

$$T(t) = 2T_{2\times} \sum_{n=1}^{3} \alpha_n \left(1 - \exp\left(-t/\tau_n\right)\right)$$

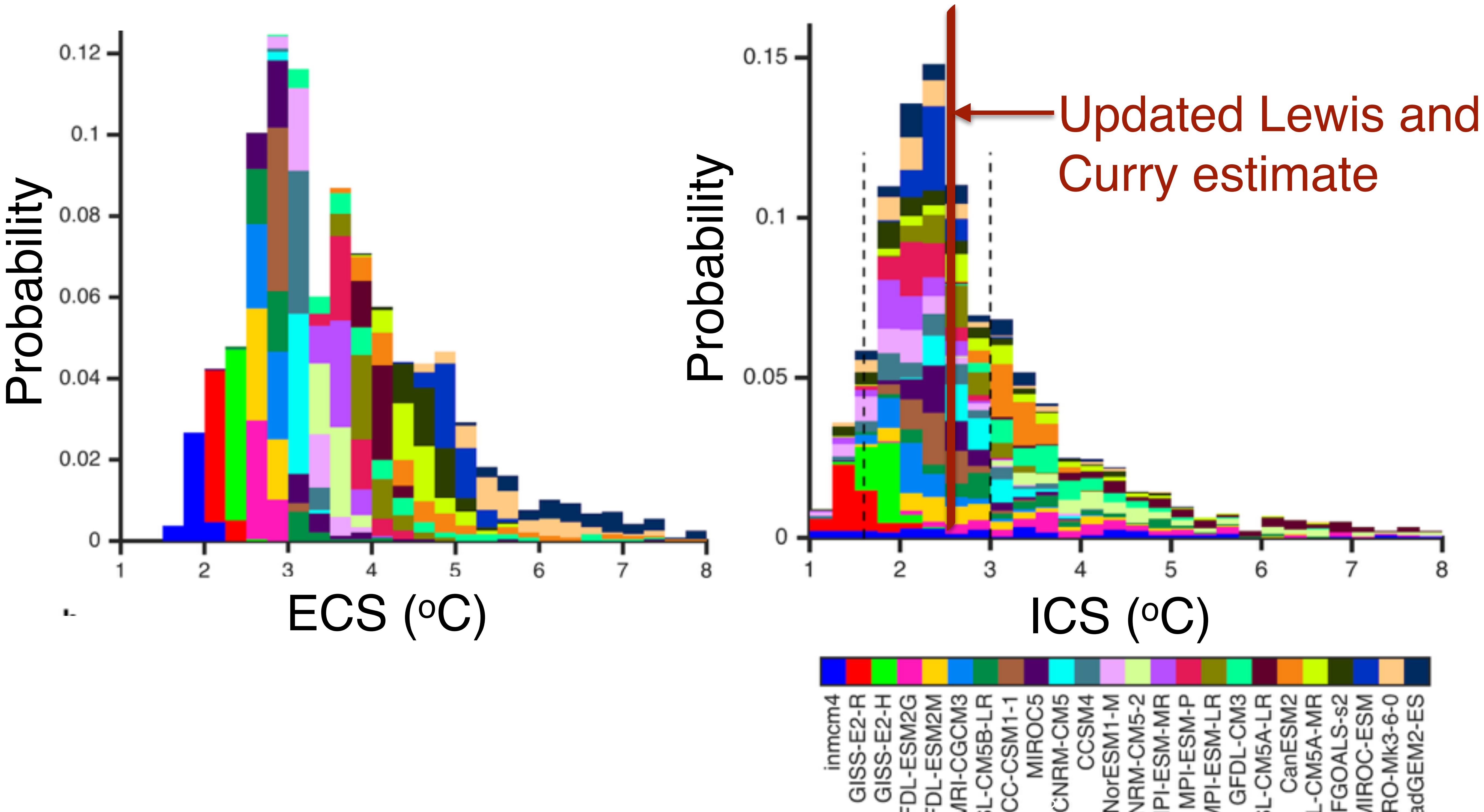


Applying historical forcing to a spatially-resolved estimate, indicates that the Eastern Equatorial Pacific and Southern Ocean are both far from their equilibrium values.



Fraction of warming realized between modern and equilibrium temperature

Historical inferences downweight slower modes of response, and inform about an Instantaneous Climate Sensitivity (ICS). CMIP5 and historical ICS values are entirely consistent.



(Proistosescu and Huybers, 2017; also see Armour 2017)

Conclusions

- Further analysis of historical observations and longterm radiative feedback responses indicates no discrepancy with simulations.
- This is not all good news for advancing climate science; we still need to find ways to meaningfully test our theories and models.
- In order to test Equilibrium Climate Sensitivity we need longterm observations for which there are two practical options.
  - Careful analysis of historical instrumental records may yield meaningful constraints, but we are still some ways off. Historical climate data is nuanced and worse than useless if interpreted badly.
  - Second, paleoclimate records may be useful not only in extending the record, but perhaps also for filling out and helping calibrate the historical period.

SST correction field 1940. Hatching indicates regions where Japanese observations are reported.