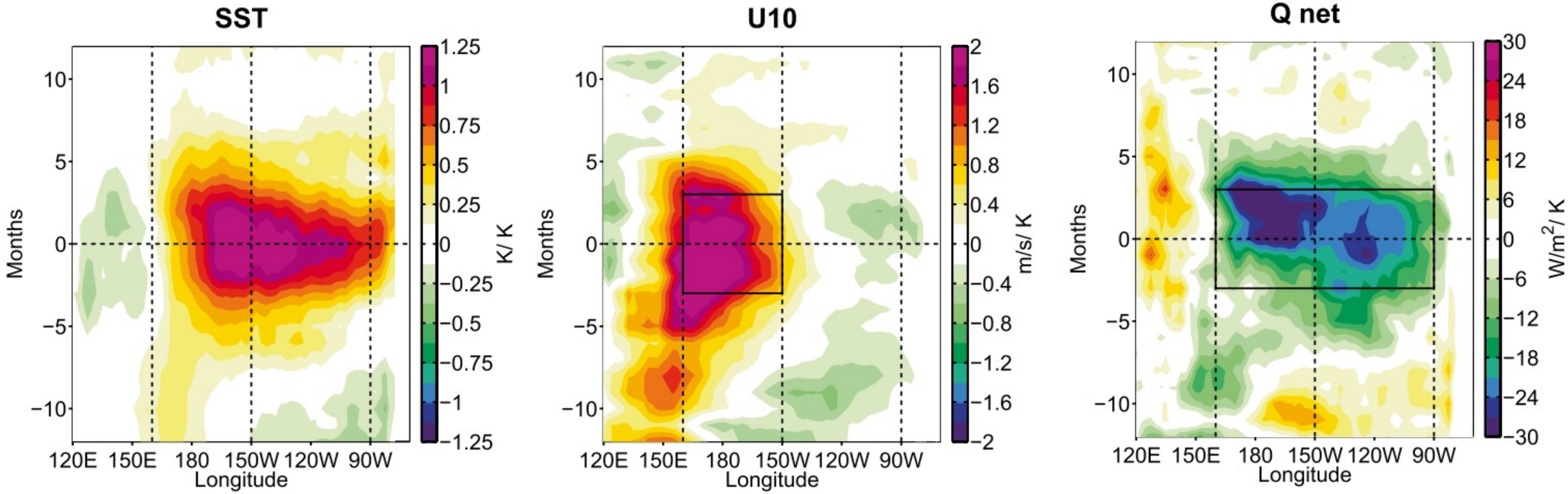
The role of atmospheric feedbacks in ENSO simulation and projection



Tobias Bayr, Mojib Latif, Dietmar Dommenget, Christian Wengel,
Joke Lübbecke, Annika Drews, Goratz Beobide-Arsuaga and Wonsun Park

Overview

- Motivation
- Atmospheric feedbacks
- Error compensation
- Outlook on new project

What drives ENSO in climate models?

Dogs wags tail

or

Tail wags dog

Wind-driven ENSO dynamics:

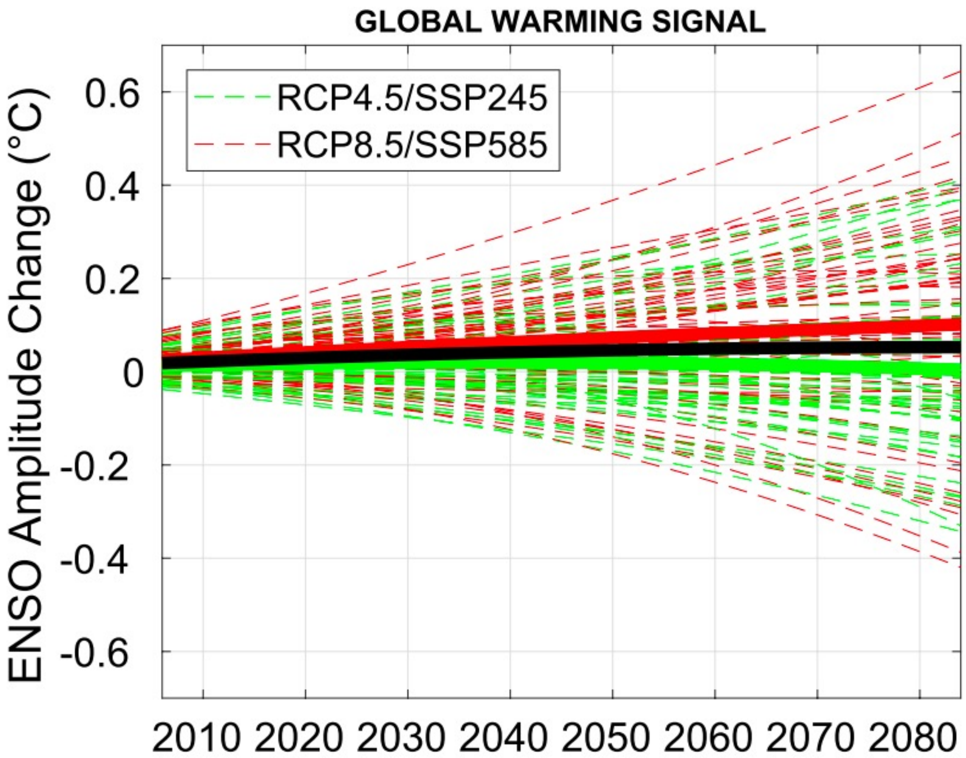
Bjerknes, thermocline, zonal advective,

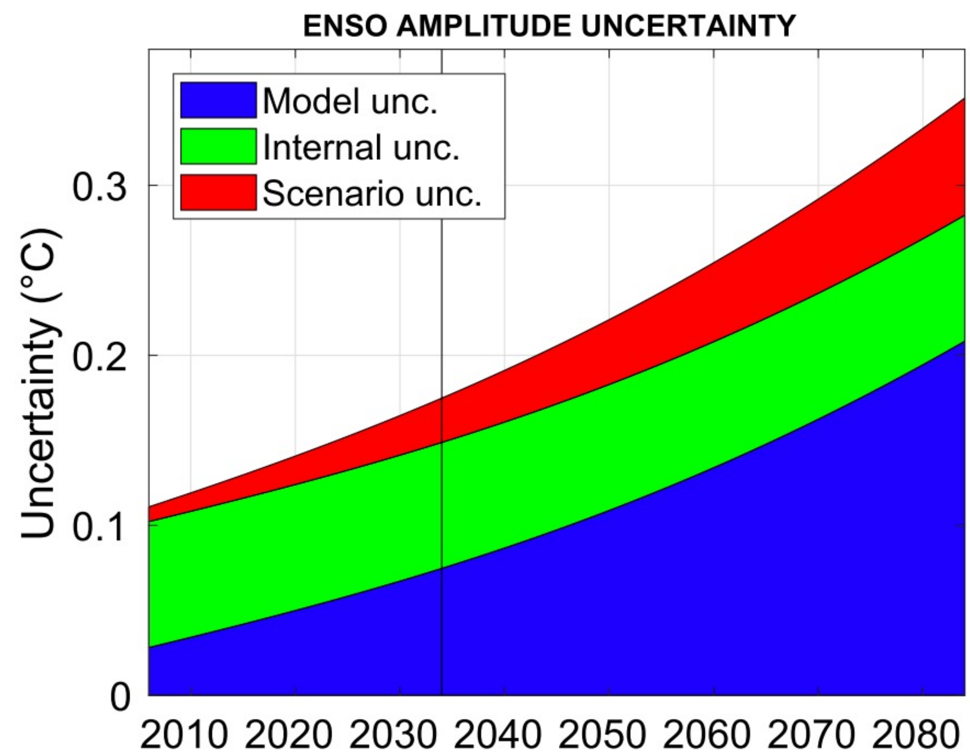
Ekman feedbacks drive ENSO

Heat flux-driven ENSO dynamics:

Short wave-SST feedback drives ENSO

Motivation:
ENSO response under global warming is still uncertain!





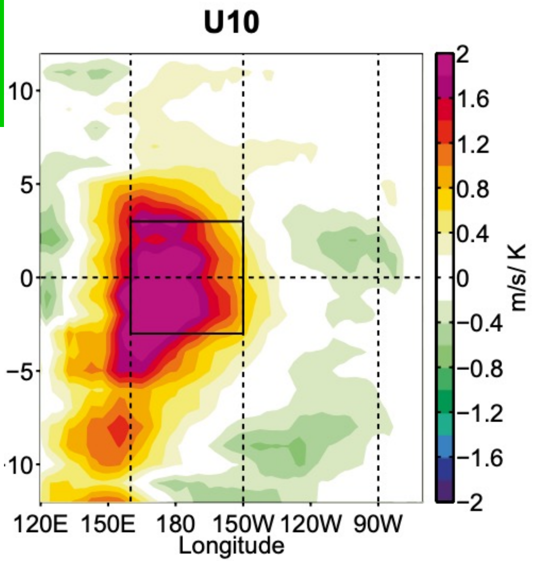
Beobide-Arsuaga et al. (2021)

Mostly due to large model uncertainty!

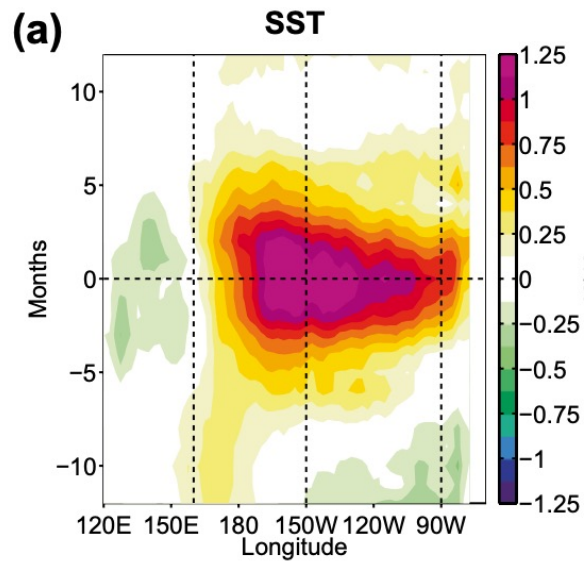
El Niño in observations

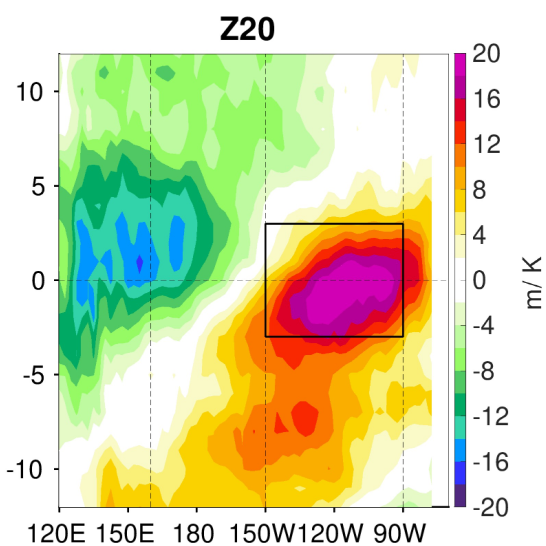
positive and negative atmospheric feedbacks

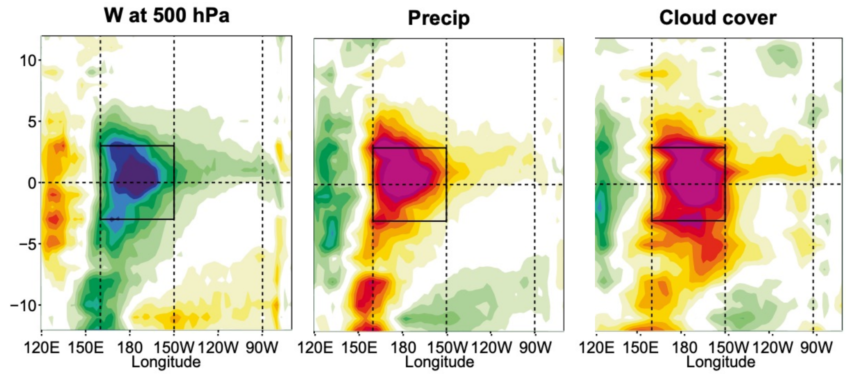
Dogs wags tail

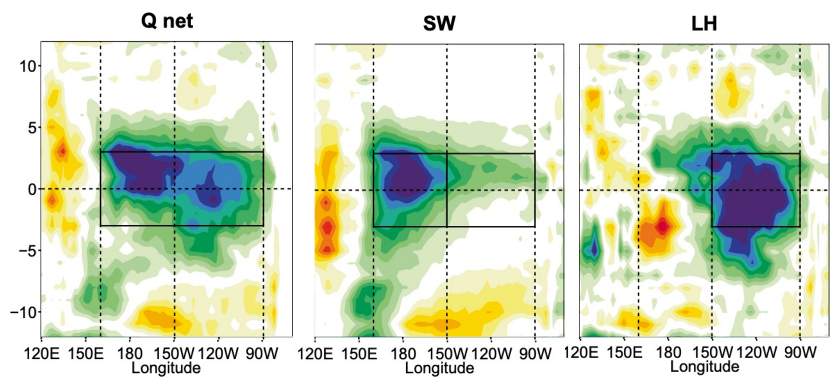


positive
wind-SST
feedback



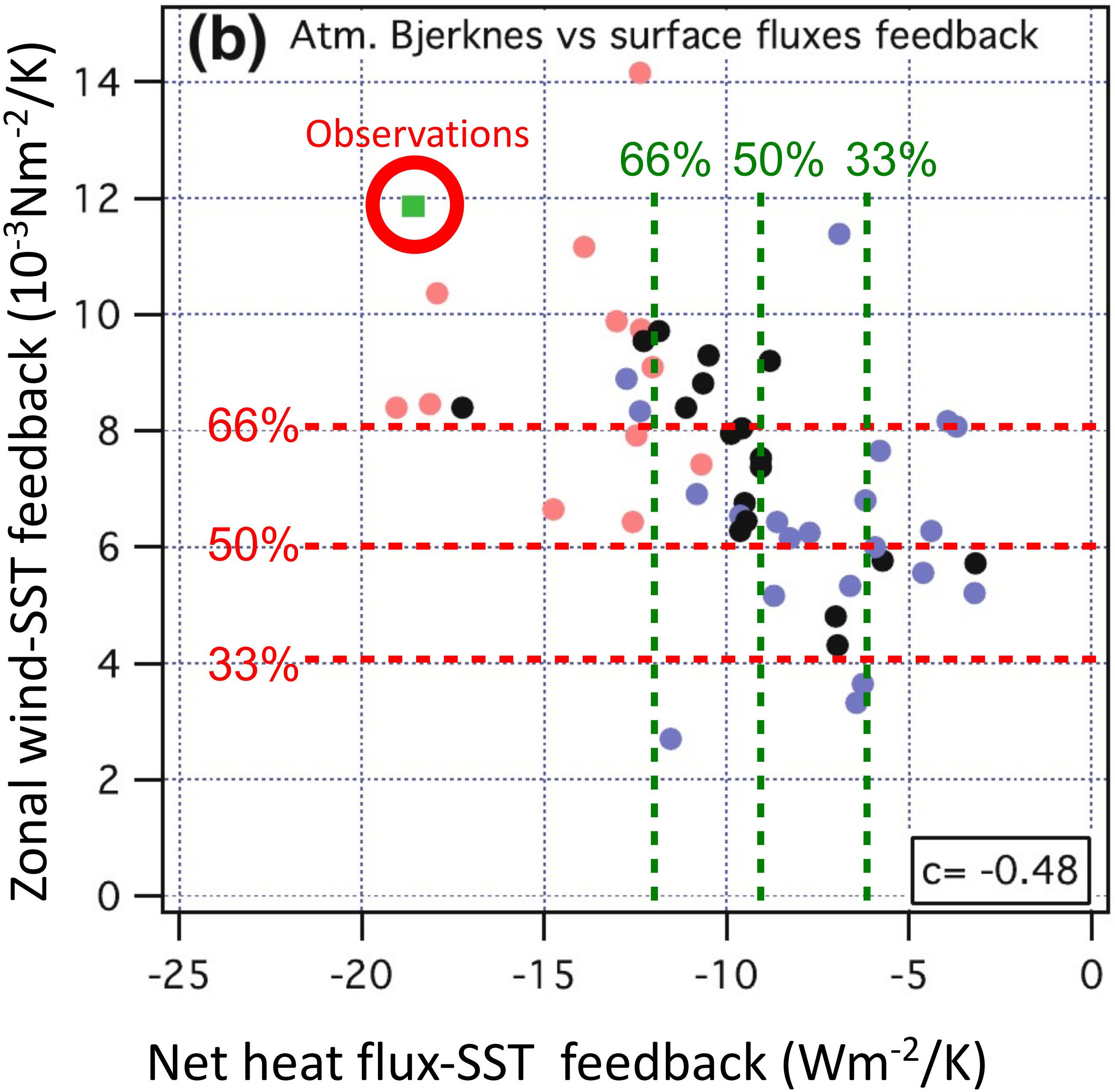






negative heat flux feedback

Motivation: Underestimated Atmospheric Feedbacks in CMIP3 and CMIP5



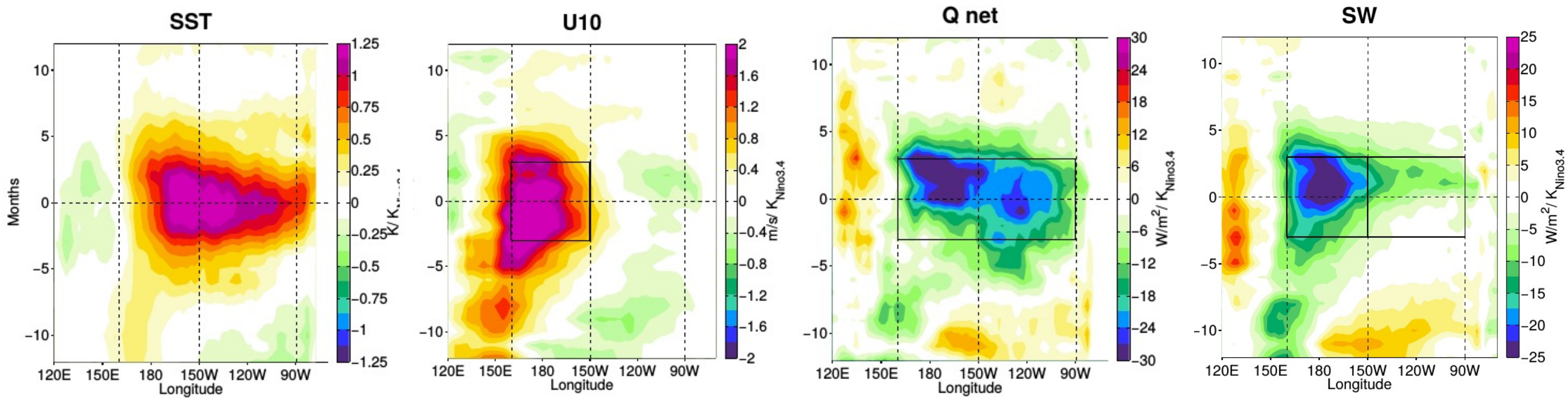
Most CMIP3 and CMIP5 models underestimate Wind-SST feedback and Heat flux-SST feedback => Compensating Error?

Red: convective in Nino3
Black: conv./sub. in Nino3
Blue: subsiding in Nino3

Bellenger et al. (2014)

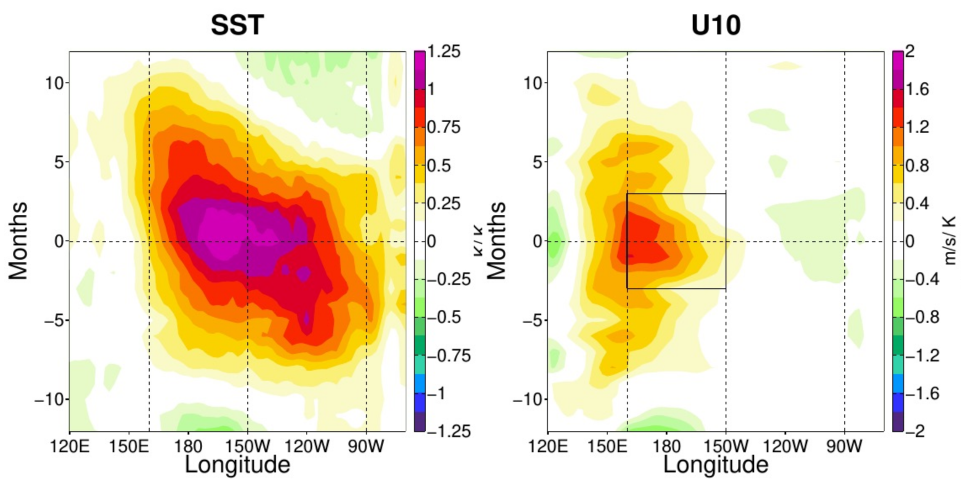
ENSO Hoevmoeller composites
(normalised with Niño3.4 SST)

Observations



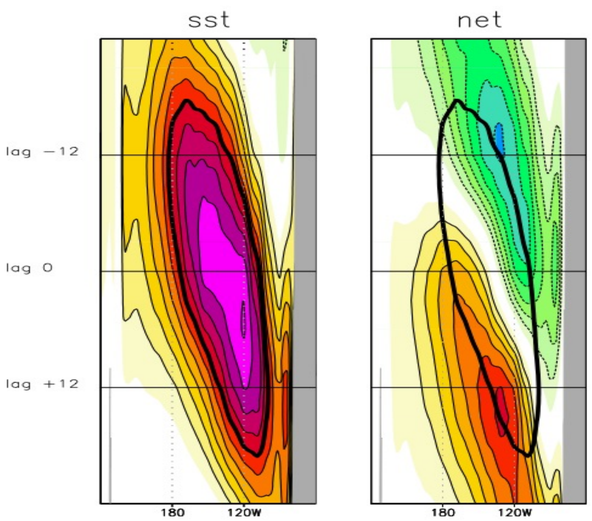
std(Niño3.4) = 0.82

CMCC-CESM



std(Niño3.4) = 1.31

Heat flux driven El Niño



Tail wags dog

El Niño-like SST variability
in ECHAM5 Slab ocean run with
a strong equatorial cold bias

=> in absence of ocean
dynamics
=> interaction of heat fluxes
with heat capacity of ocean

Positive SW feedback drives heat flux El Niño!

Dommenget (2010)

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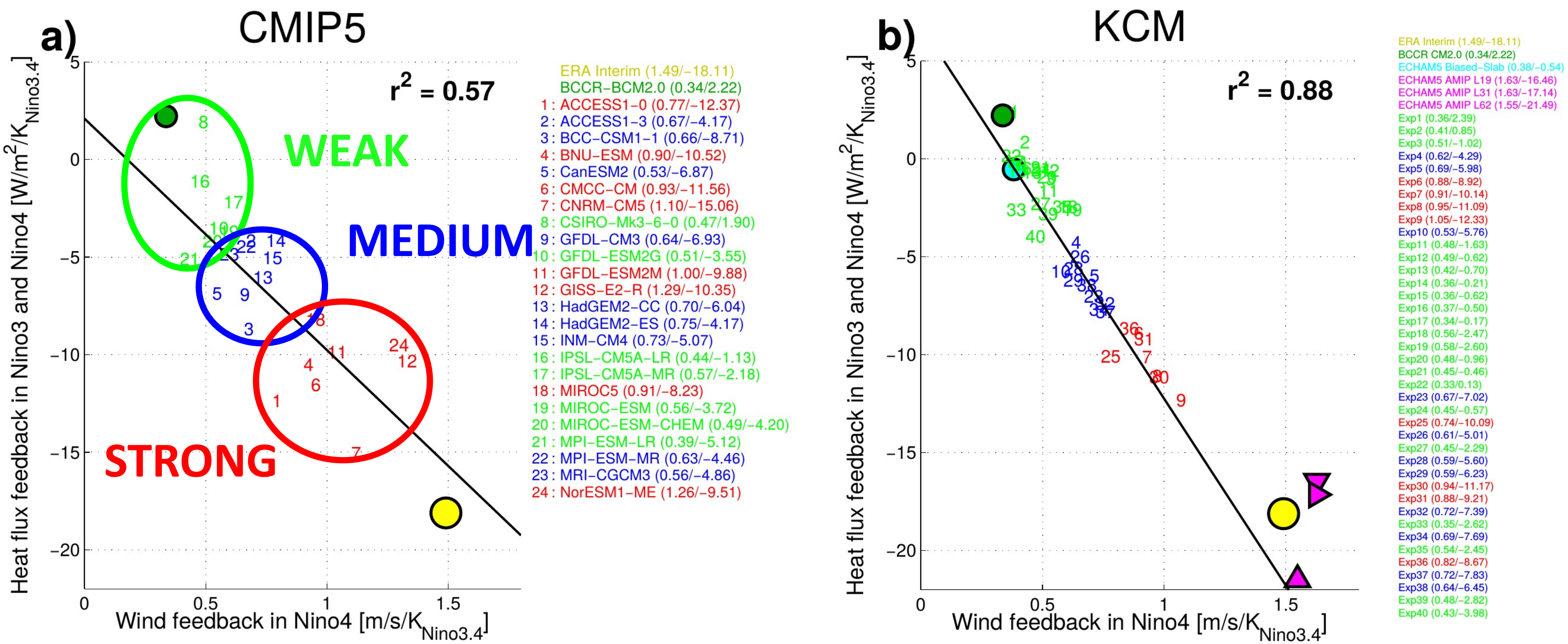
Multi model ensemble of CMIP5 and perturbed physics ensemble of KCM

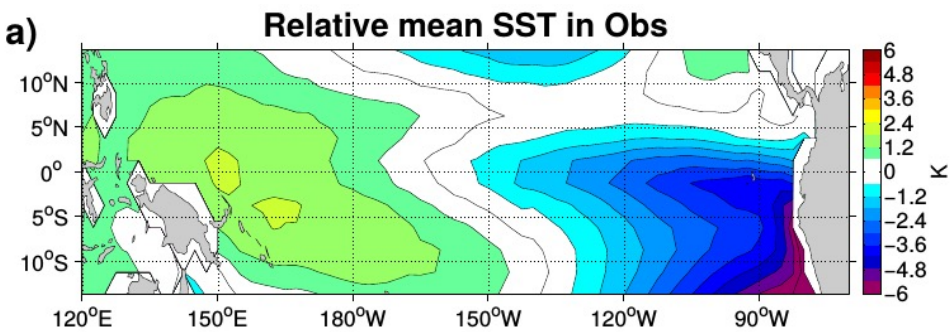
Zonal wind vs. net heat flux feedback in



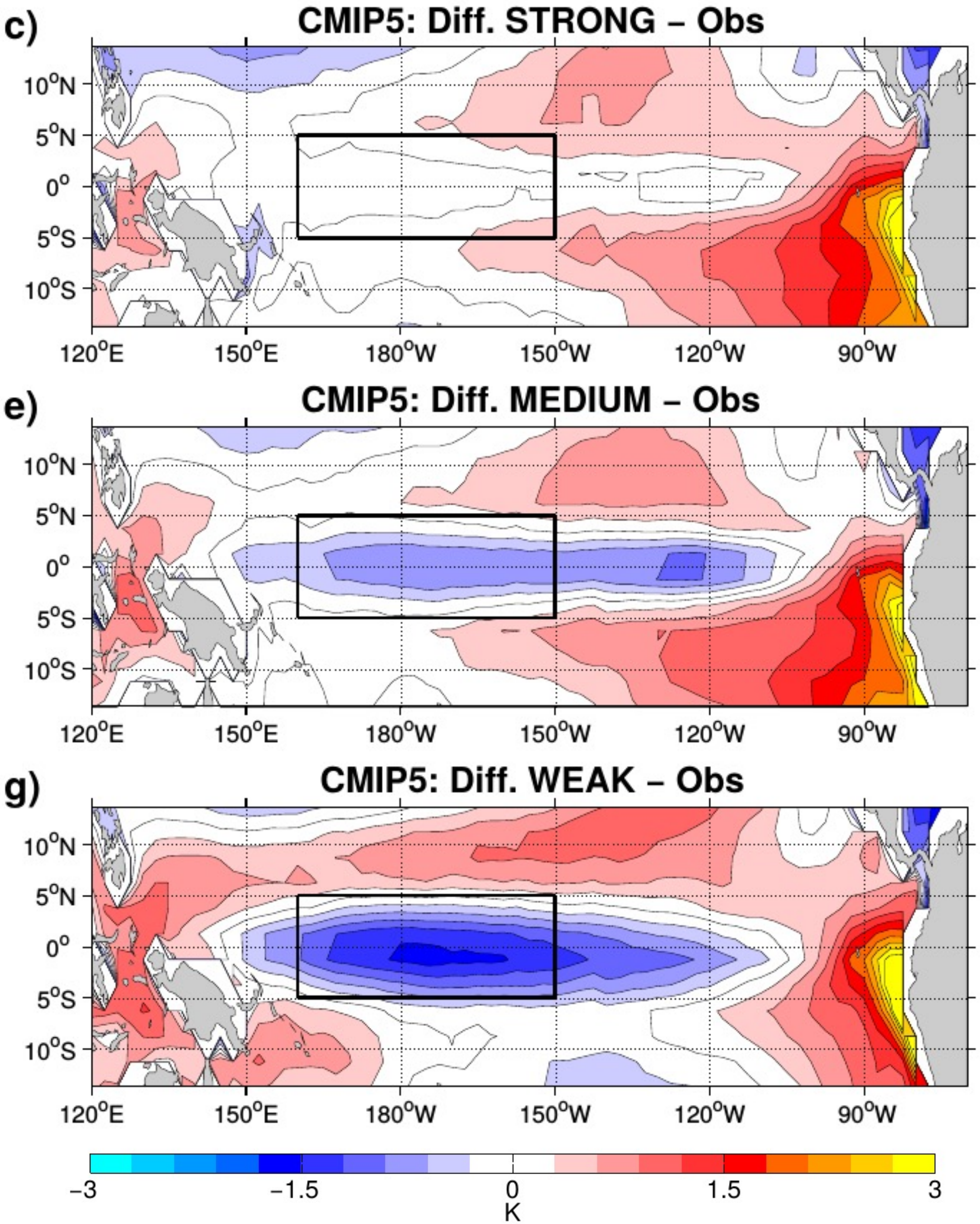
It is possible to reproduce the spread in atmospheric feedback of CMIP5 models with a perturbed physics ensemble of one model!

Bayr et al. (2018)

SST bias of STRONG, MEDIUM and WEAK



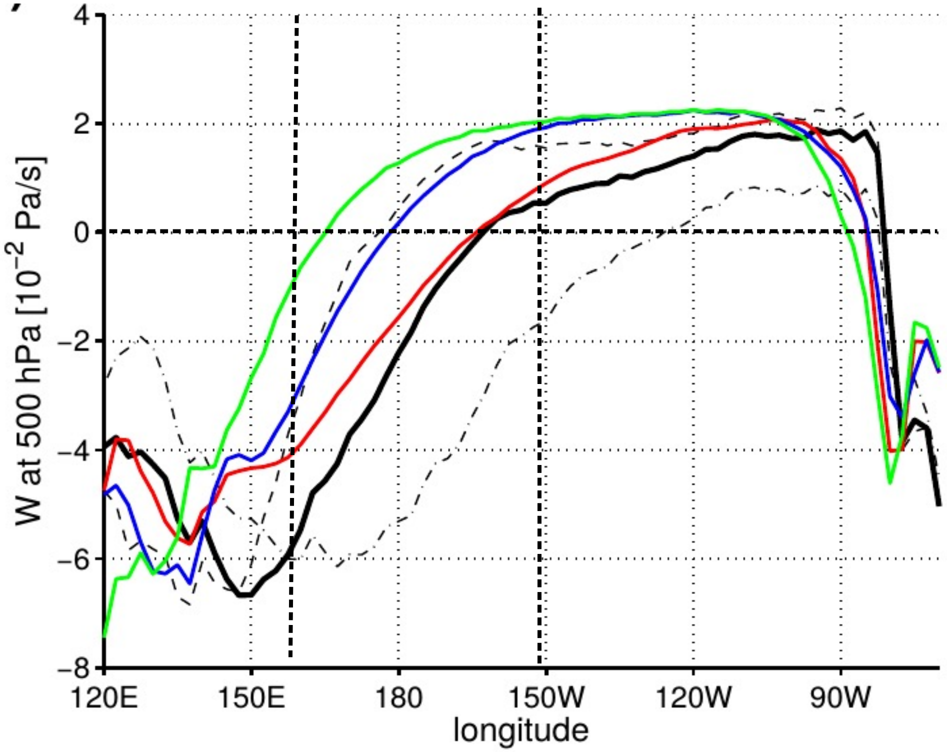
SST bias in the Niño4 region controls ENSO atmospheric feedbacks!



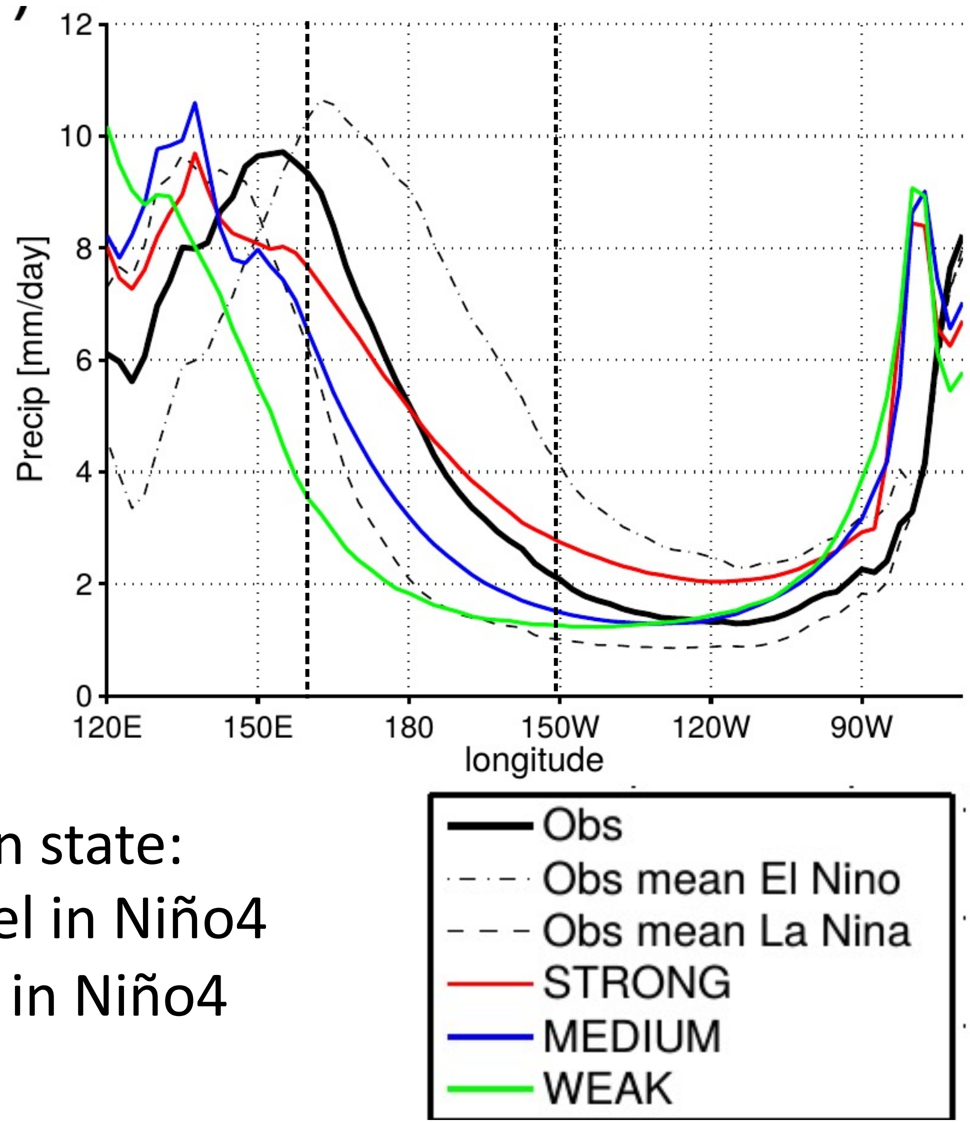
Bayr et al. (2018)

Mean state of Observations, STRONG, MEDIUM and WEAK

Equatorial vertical wind at 500 hPa



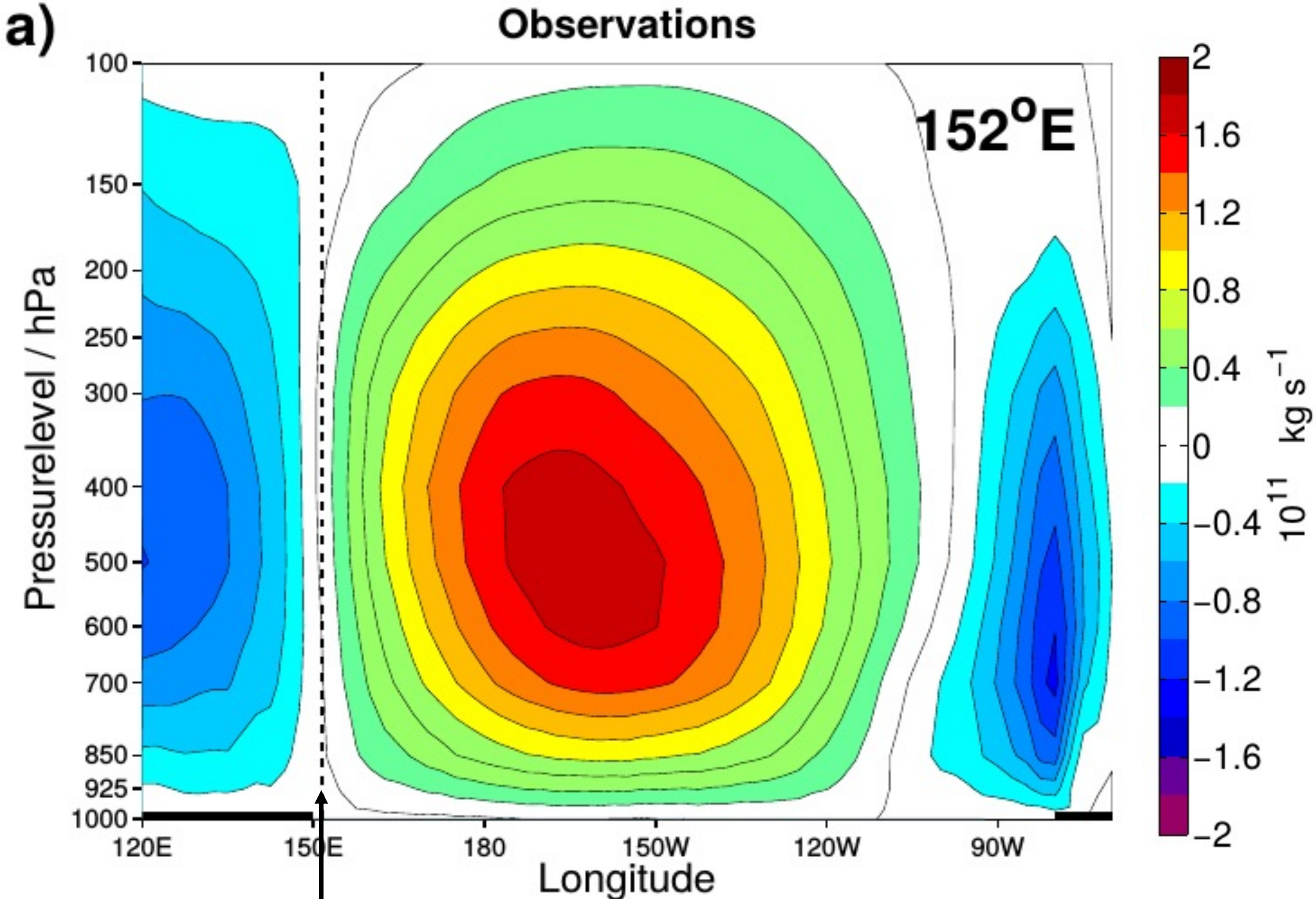
Equatorial precipitation



- WEAK is in a La Niña-like mean state:
- Descending air at 500 hPa level in Niño4
- Underestimated precipitation in Niño4

Bayr et al. (2018)

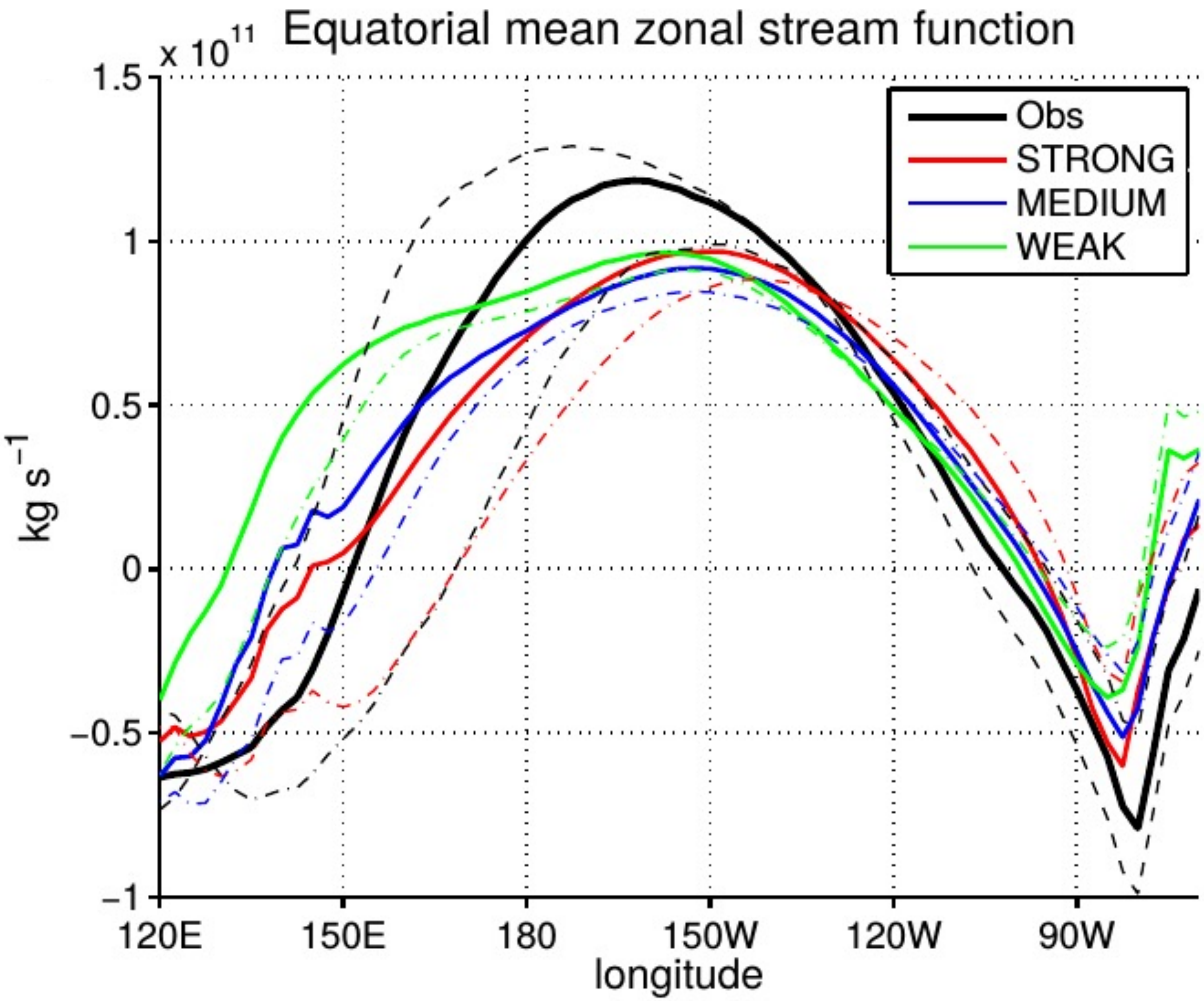
Walker Circulation & feedback strength

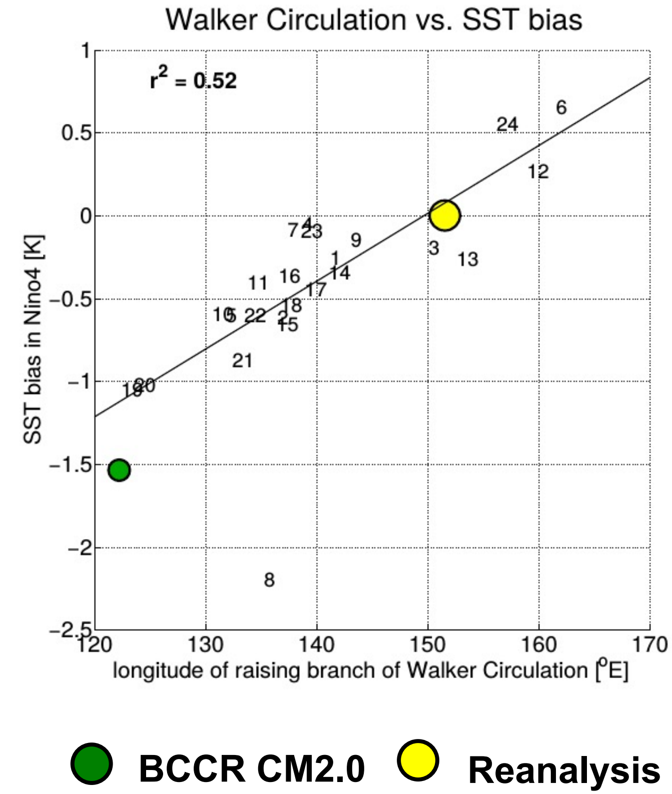


Rising branch of the Walker Circulation
= region of strongest convection

Bayr et al. (2018)

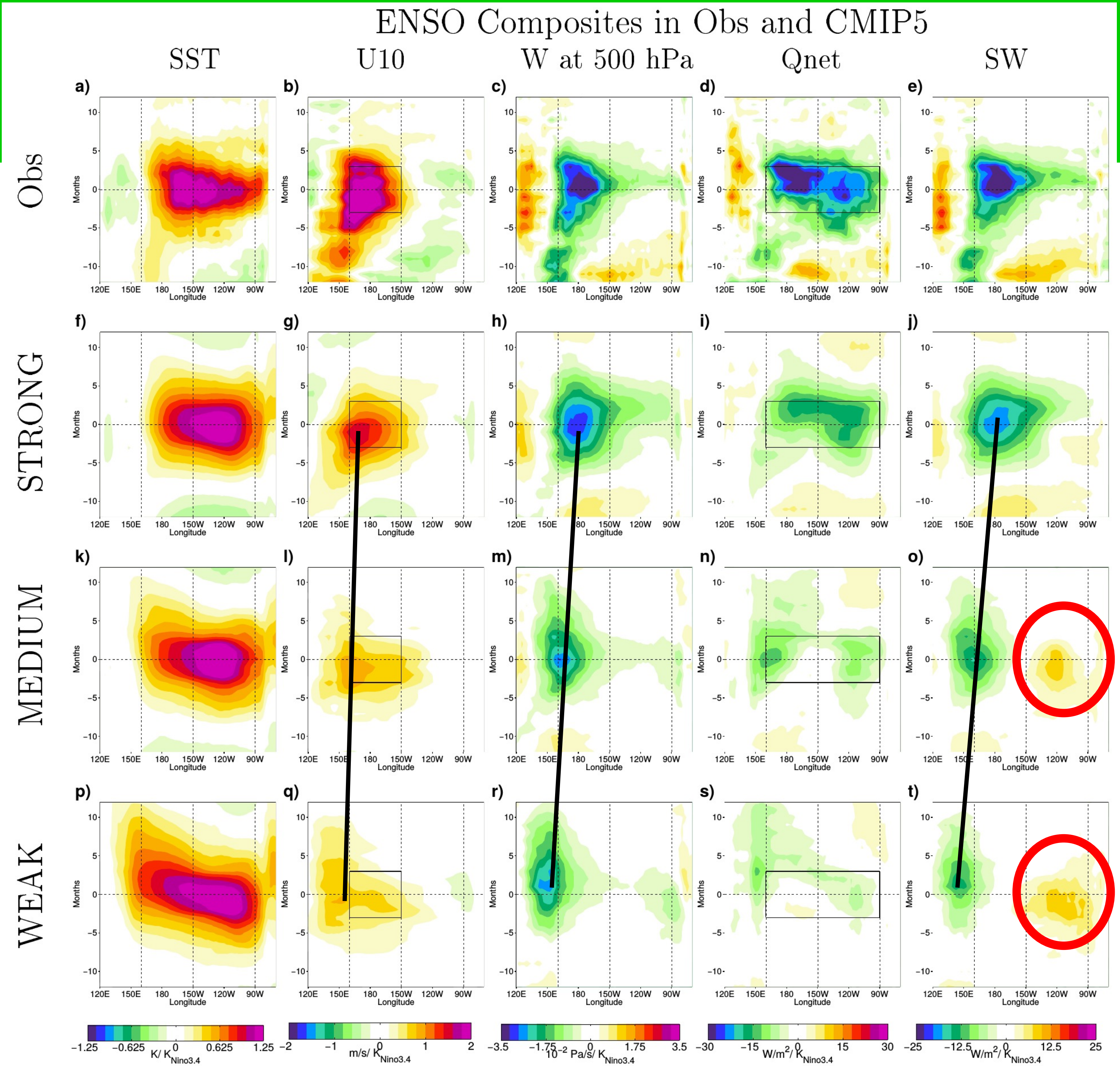
Walker Circulation & feedback strength





In WEAK the rising branch of the Walker Circulation is too far in the west

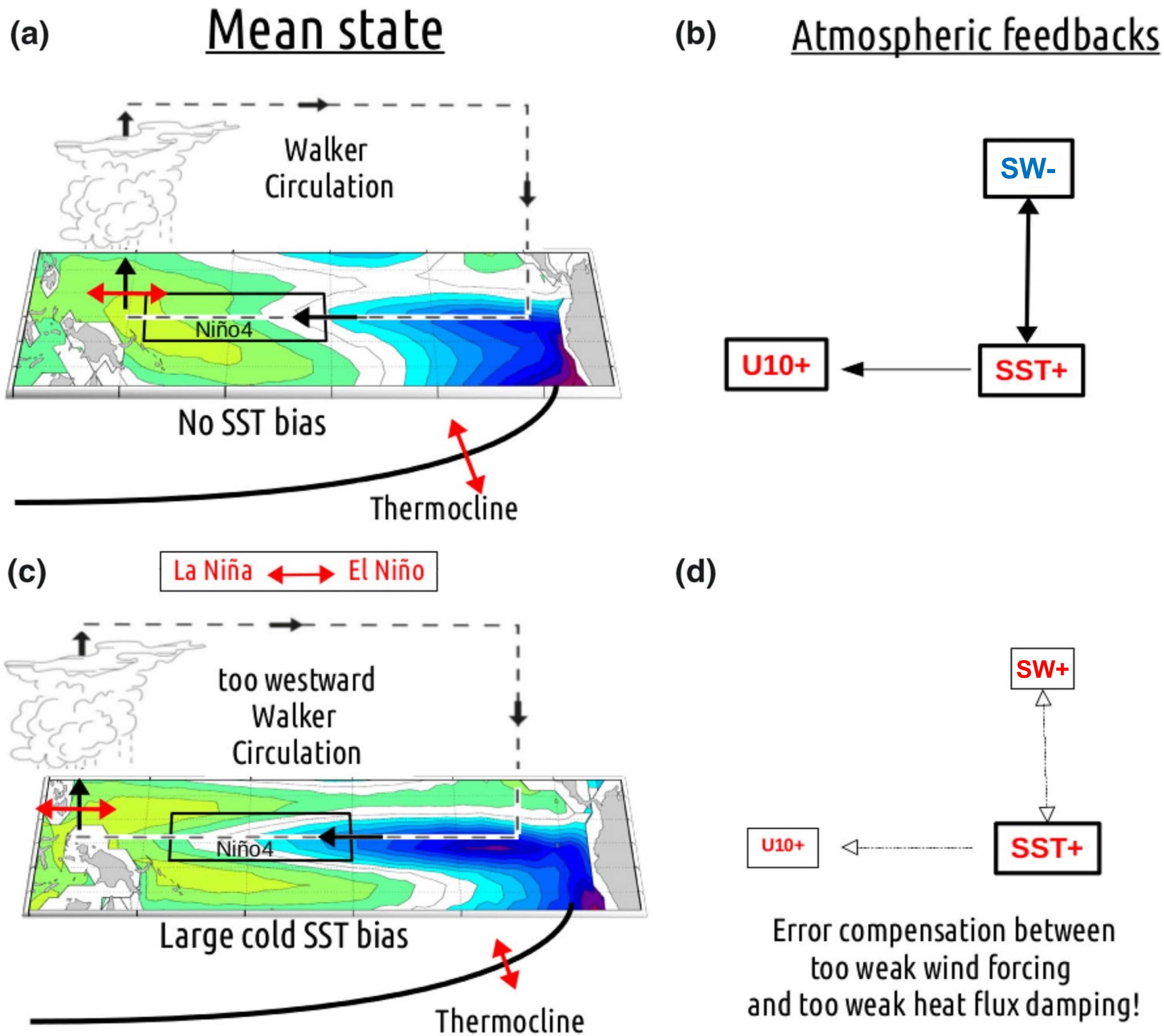
Bayr et al. (2018)



Convective response shifts to the west from STRONG to WEAK

Bayr et al. (2018)

The effect of the cold bias on ENSO atmospheric feedbacks

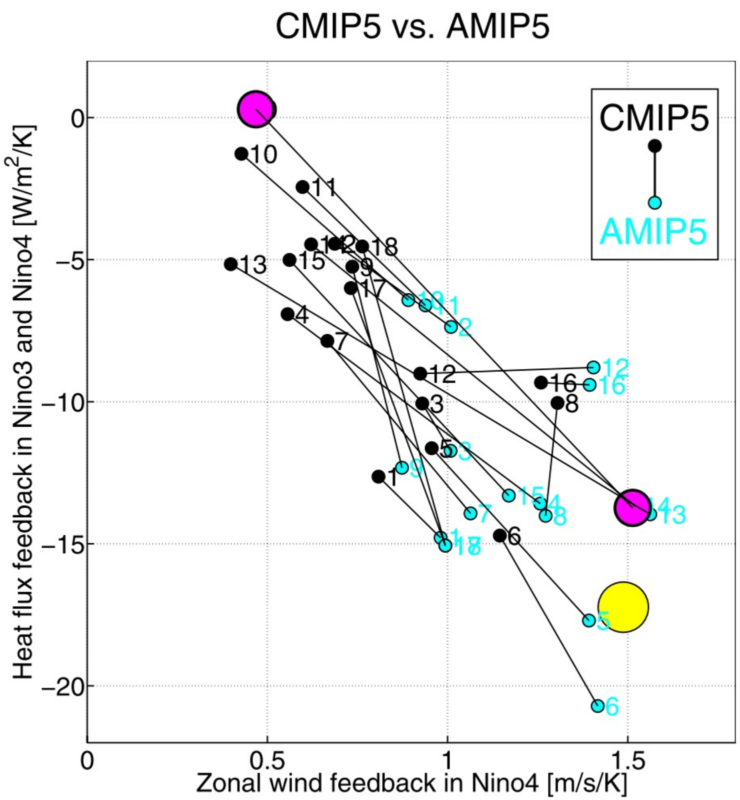


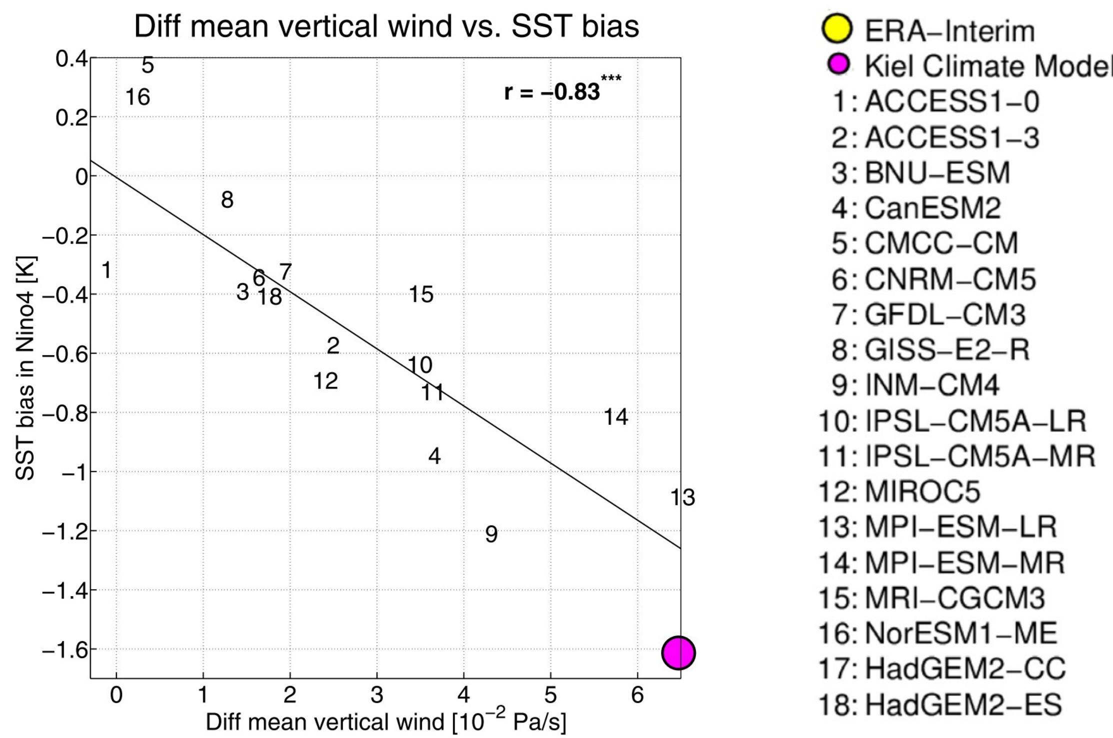
wind-driven ENSO dynamics

Hybrid wind-driven and short wave-driven ENSO dynamics

Bayr et al. (2019)

Weakening of atmospheric feedbacks from AMIP5 to CMIP5





Most CMIP5 models have weaker atmospheric feedbacks than the AMIP5 models
=> Cold bias evolves in many coupled climate models due to model biases that are amplified via ocean-atmosphere coupling

Bayr et al. (2020)

Overview

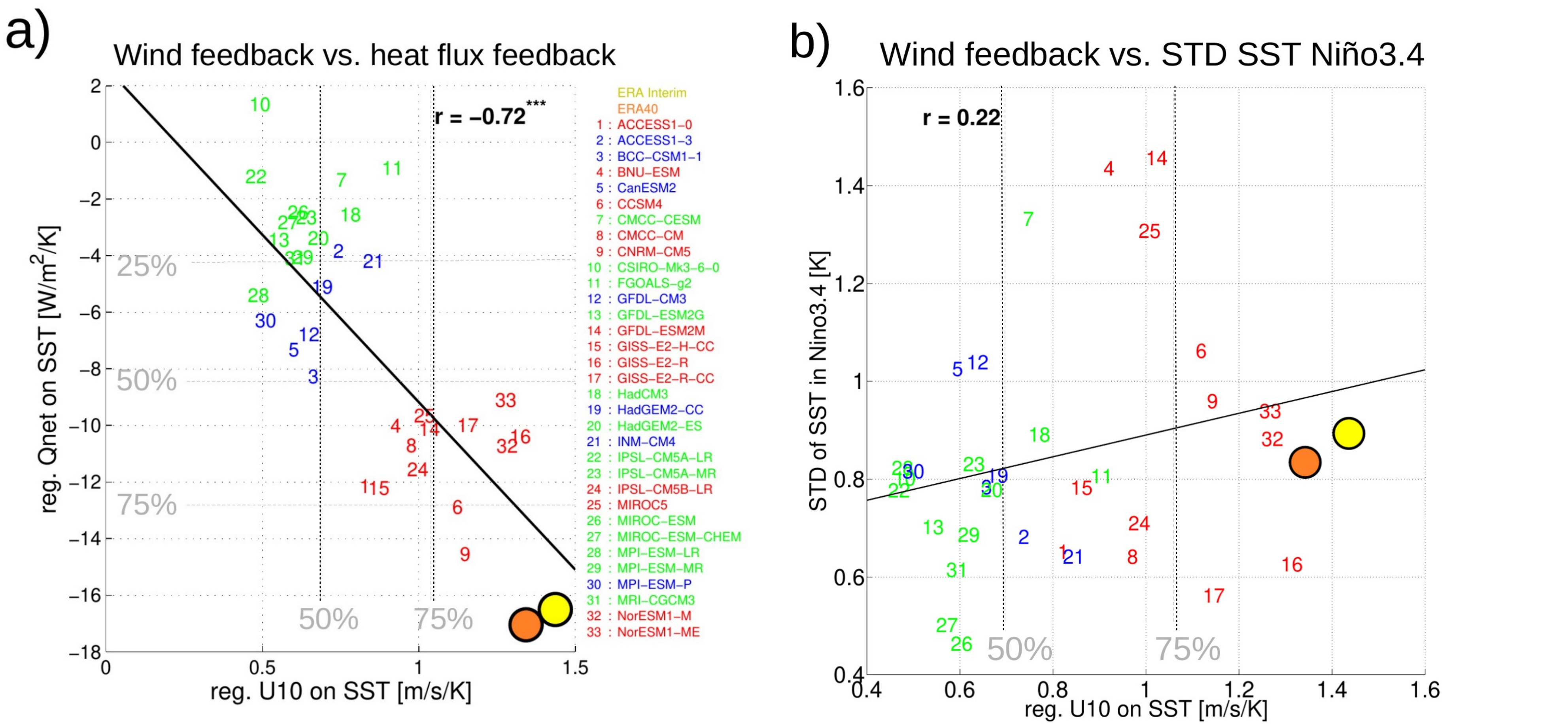
Motivation

Atmospheric feedbacks

Error compensation

Outlook on new project

Error Compensation of ENSO Atmospheric Feedbacks in CMIP5



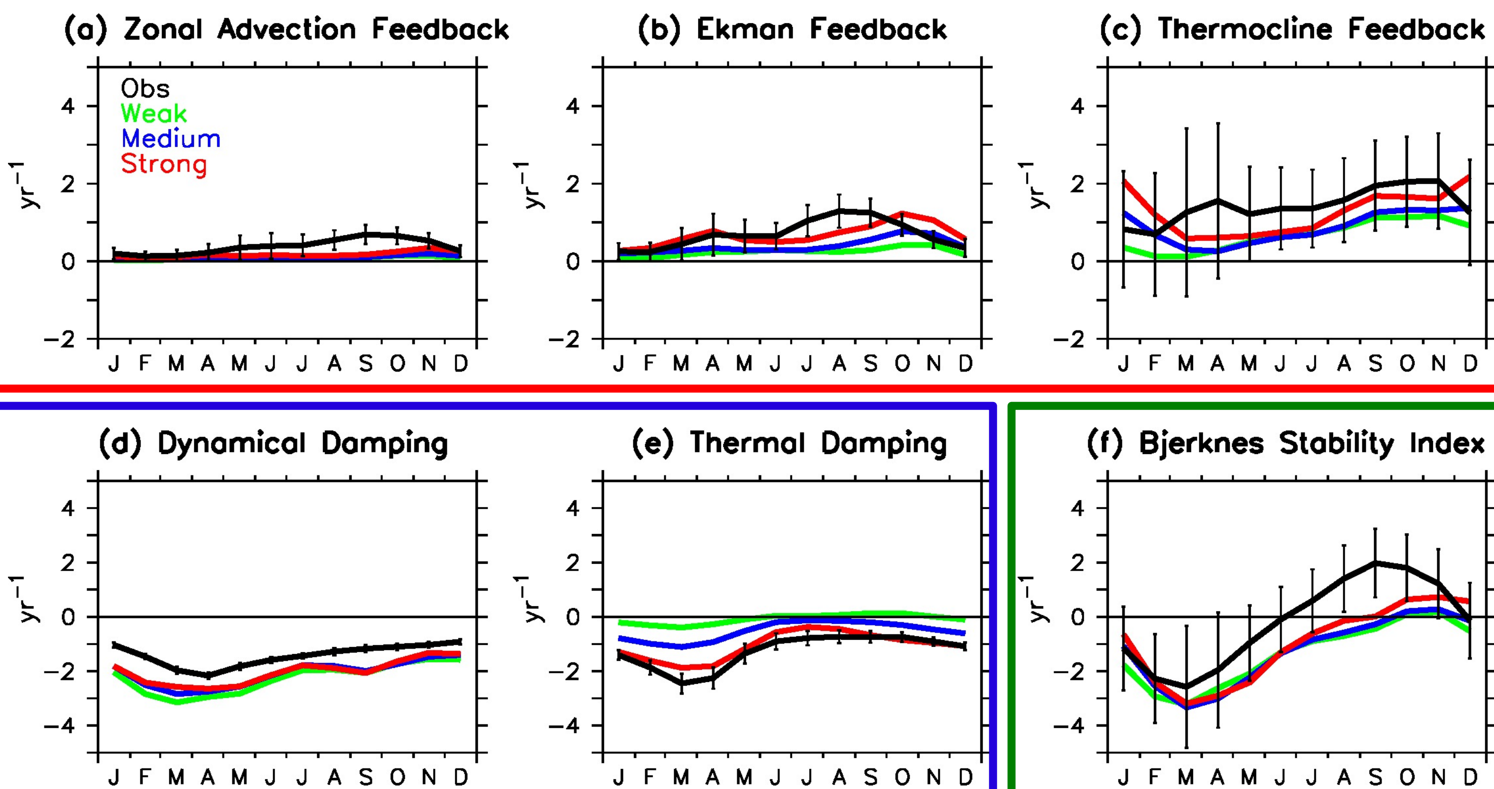
How can models with a strongly underestimated wind-SST feedback have a realistic ENSO amplitude?

=> error compensation between underestimated wind-SST and heat flux-SST feedback

Bayr et al. (2019)

Error compensation of too weak positive and negative feedbacks

positive feedbacks



negative feedbacks

sum of pos. and neg. feedbacks

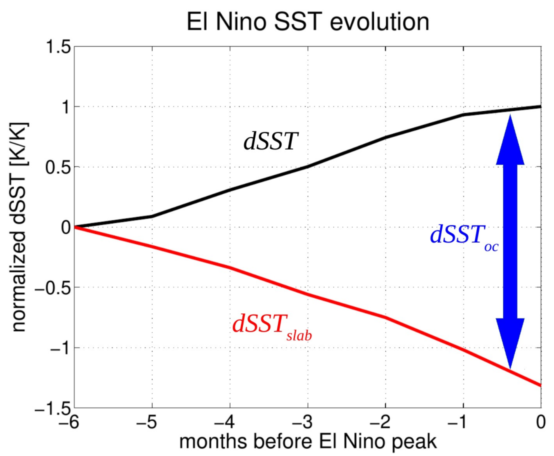
Bayr et al. (2019)

The overall Bjerknes Stability Index is not to different in the 3 sub-ensembles due to error compensation between too weak positive and negative feedbacks.

The Offline Slab Ocean SST Method

$$dSST_{slab} = \frac{1}{c_p \cdot \rho} \int_{t=-6}^{t=0} \frac{Q_{net}}{H} dt$$

- with c_p = 4000 J kg^{-1} K^{-1} (specific heat capacity of sea water),
  ρ = 1024 kg m^{-3} (average density of sea water),
  t = 0 (maximum of ENSO event),
  H: temporally and spatially varying mixed layer depth (MLD)



$$dSST \approx dSST_{oc} + dSST_{slab}$$

- SST change is caused by ocean dynamics ($dSST_{oc}$) and atmospheric heat fluxes ($dSST_{slab}$)

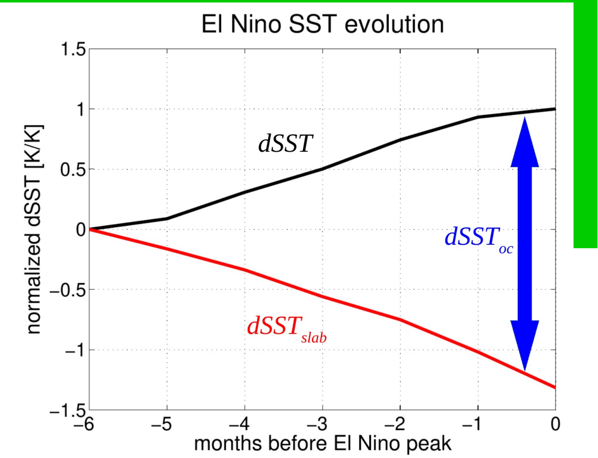
$$\Rightarrow dSST_{oc} \approx dSST - dSST_{slab}$$

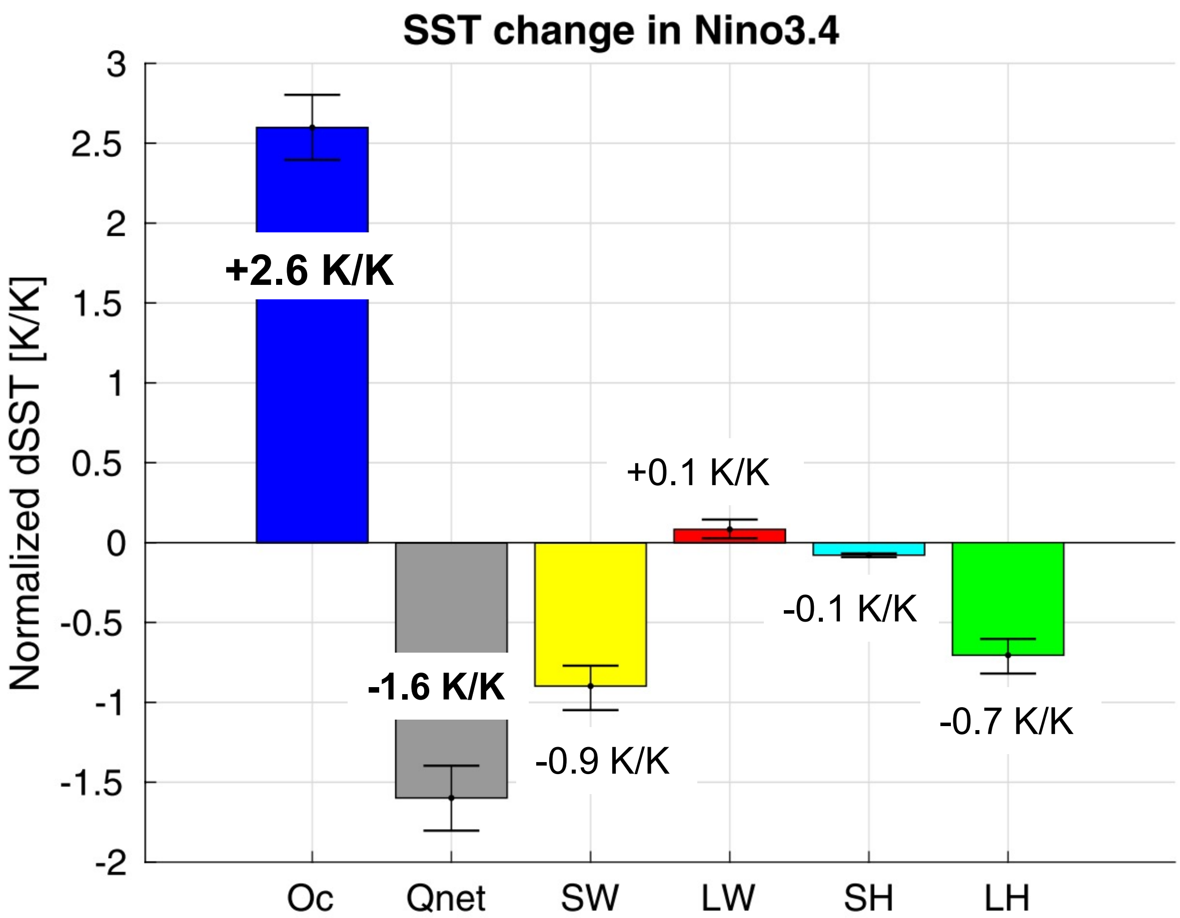
- We can estimate $dSST_{oc}$ when we know $dSST_{slab}$!

- Advantage: Easy and fast to compute as one only needs the SST, the heat fluxes and MLD!

Bayr et al. (2020)

dSST ~ $dSST_{oc} + dSST_{slab}$

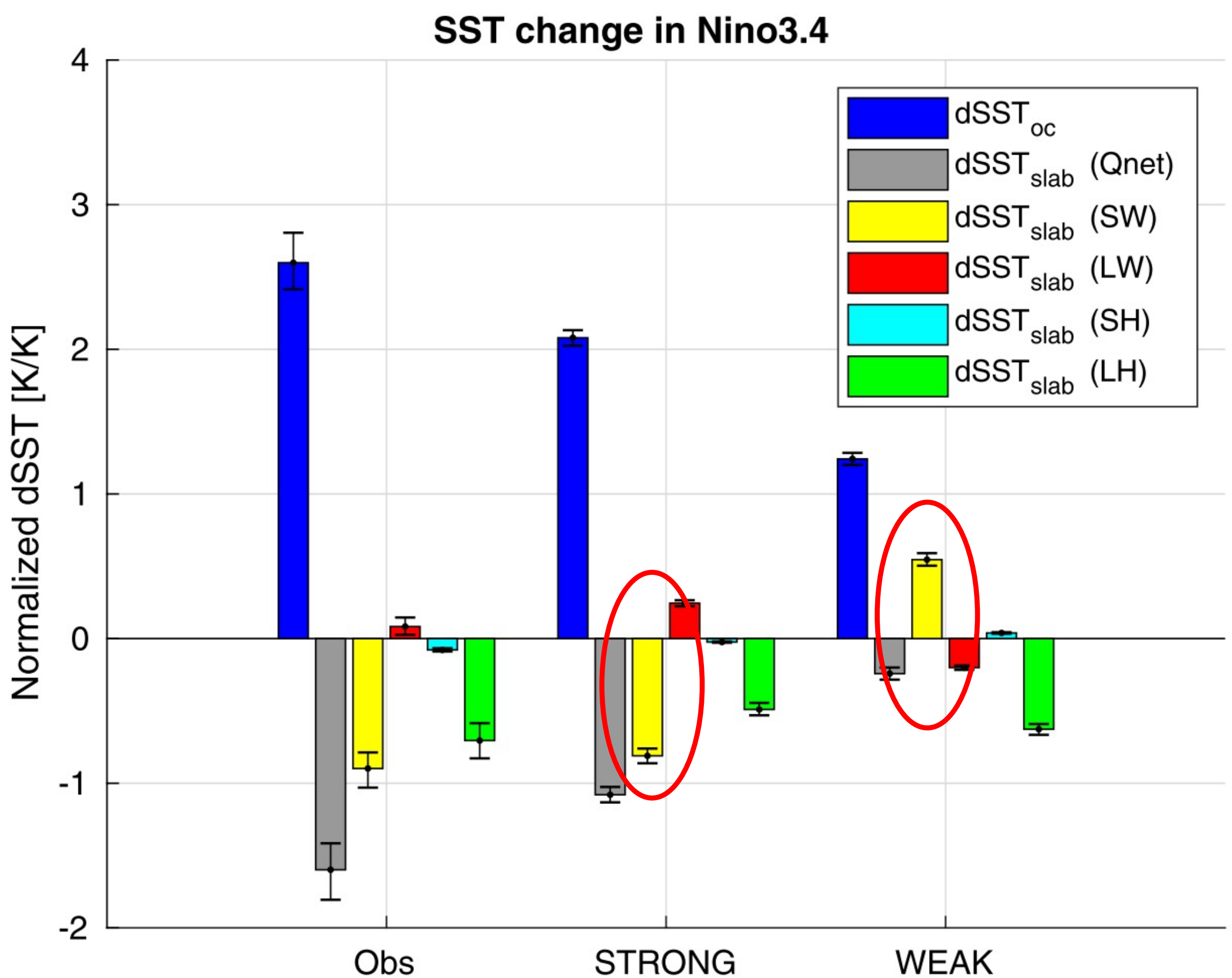




Bayr et al. (2020)

In reanalysis +1 K of SST warming during El Nino is damped by -1.6 K of heat fluxes
=> +2.6 K of warming by anomalous ocean circulation is needed to get +1K of SST warming

Slab Ocean SST in CMIP5 sub-ensembles with STRONG and WEAK ENSO atmospheric feedbacks

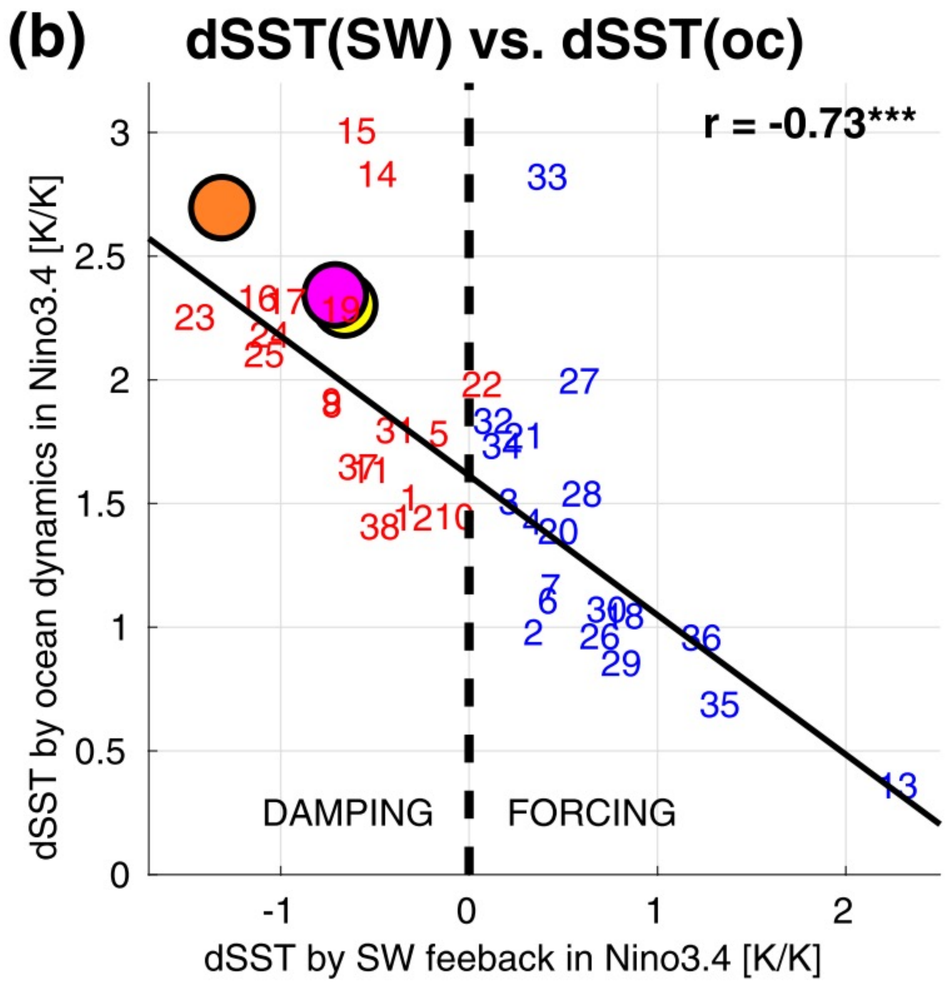


Bayr et al. (2020)

A weaker forcing by ocean dynamics is compensated by a positive SW feedback!

SST change by ocean dynamics vs. SST change by SW feedback

Dogs wags tail



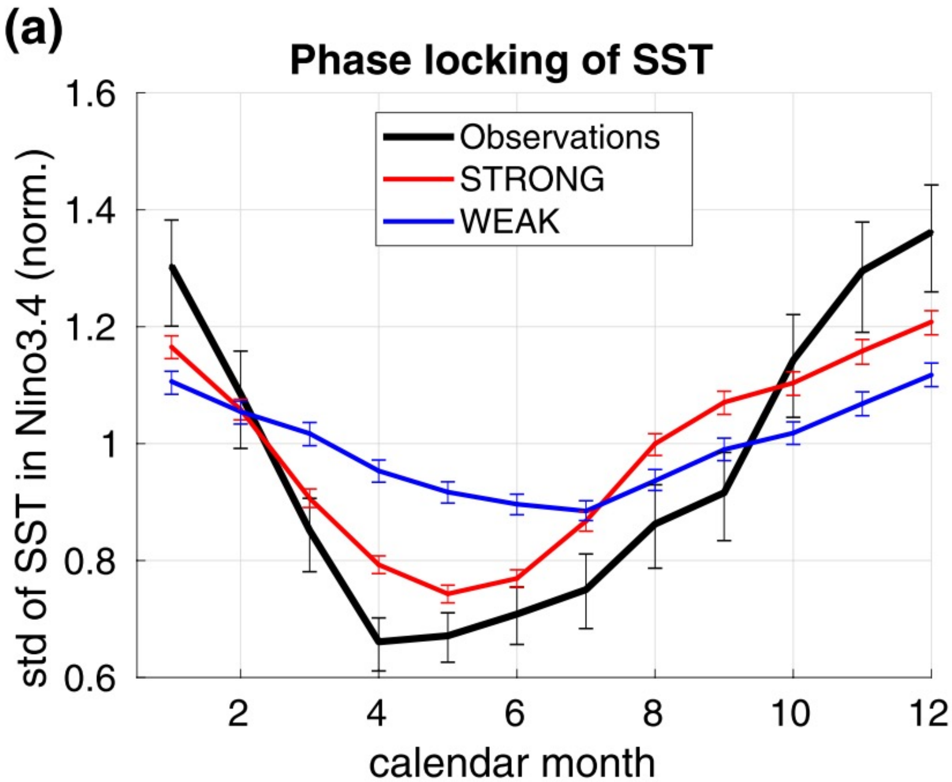
Tail wags dog

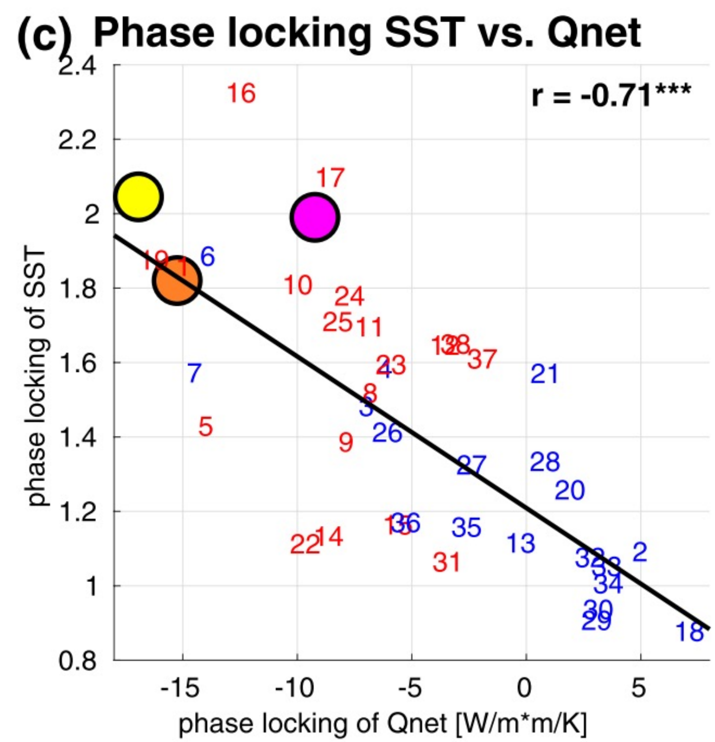
In the most biased models contributes a positive SW feedback by the same amount to the SST change as the ocean dynamics!

=> Hybrid of wind-driven and SW-driven ENSO dynamics!

Bayr et al. (2020)

Atmospheric feedbacks & ENSO phase locking



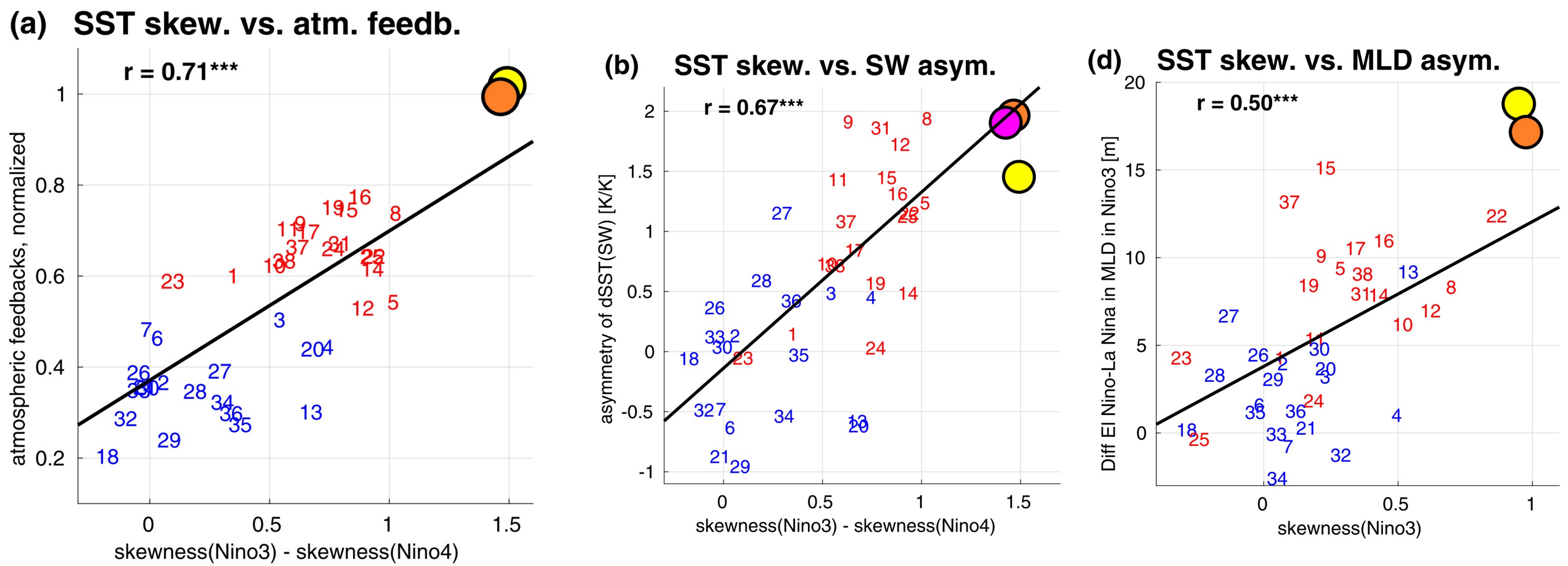


Better phase locking in models with stronger atmospheric feedbacks

=> Wind, SW and LH feedback contribute to ENSO phase locking

Bayr et al. (2020)

Atmospheric feedbacks & ENSO asymmetry



Climate models with stronger ENSO atmospheric feedbacks tend to simulate the ENSO asymmetry better

=> Wind, SW and LH feedback contribute to ENSO asymmetry (LH via asymmetry in mixed layer depth)

Bayr et al. (2020)

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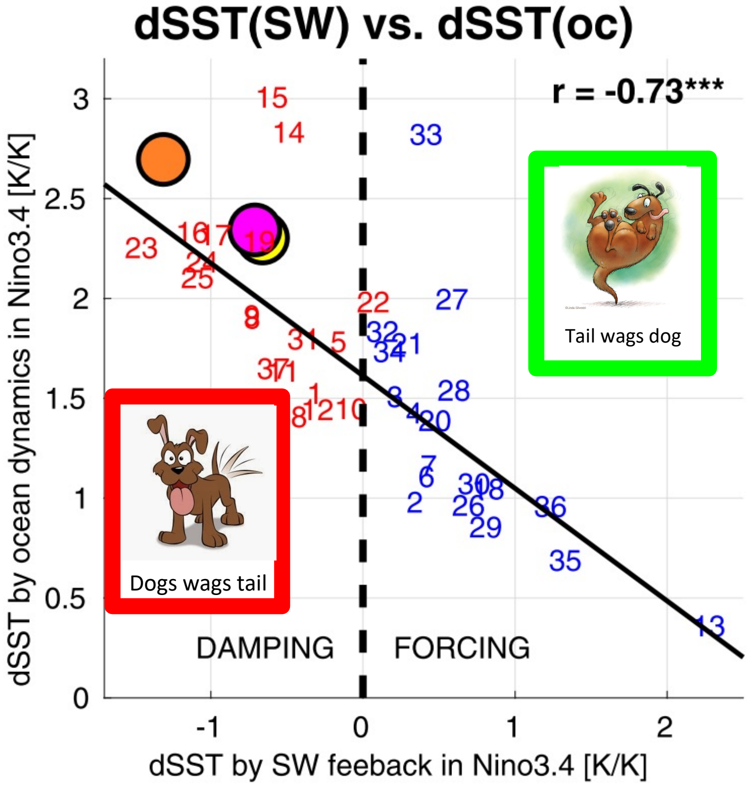
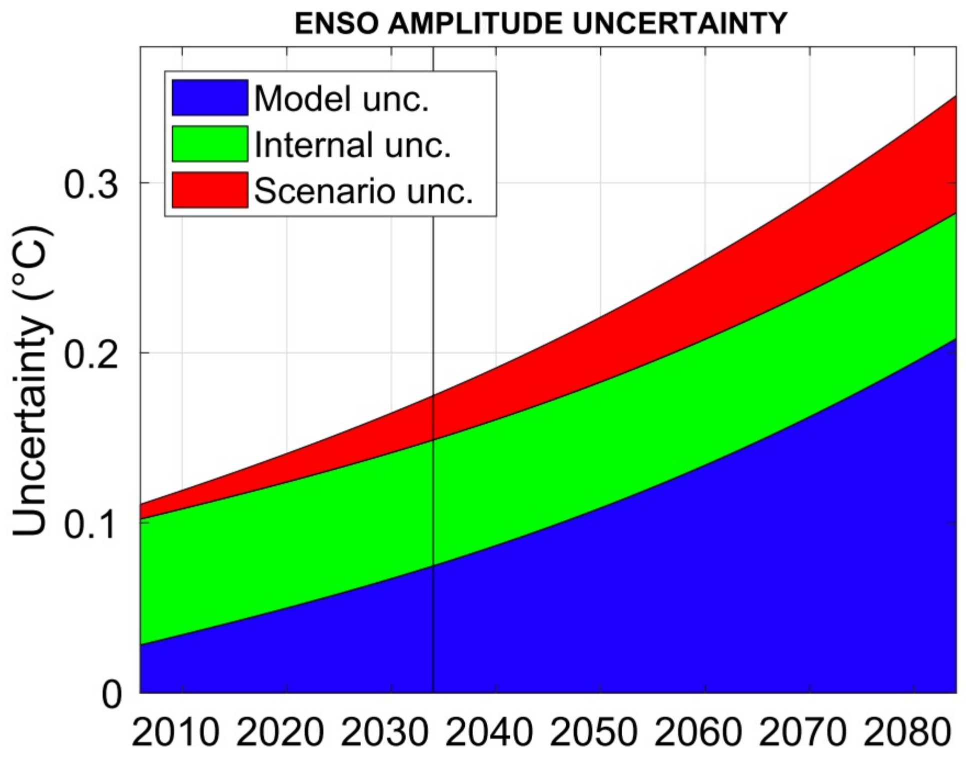
Outlook on new project

What is my new project about?

Influence of Model Bias on ENSO Projection for the 21st Century (IMBE21C)



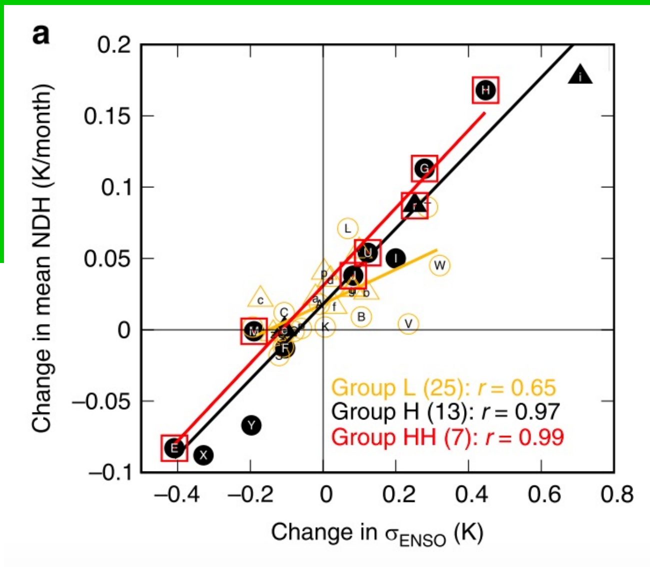
Bayr et al. (2020)



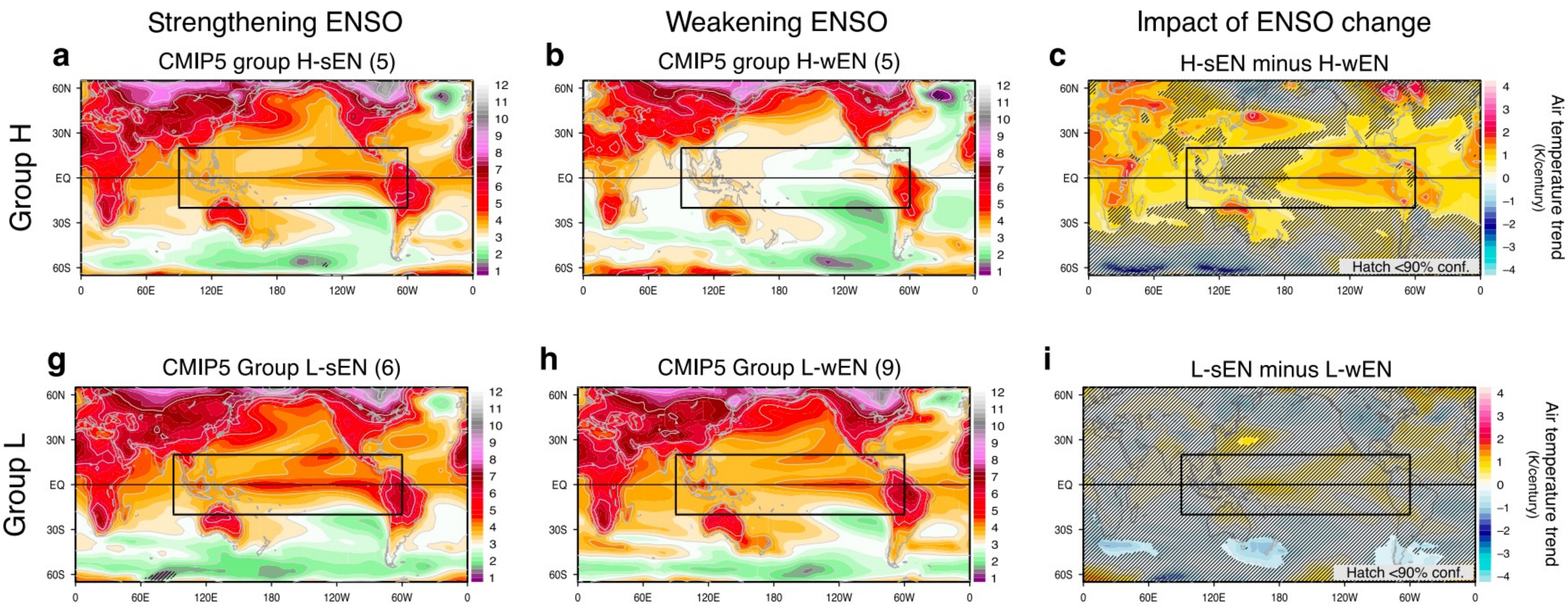
Beobide-Arsuaga et al. (2021)

Which influence have the biased ENSO dynamics on ENSO global warming projections?

Global warming projection in "good" and "bad" ENSO models



"Good" ENSO models with an El Nino-like warming show a stronger warming than models with a La Nina-like warming!



"Bad" ENSO models show not such a difference!

Hayashi et al. (2020)

Influence of Model Bias on ENSO Projection for the 21st Century (IMBE21C)

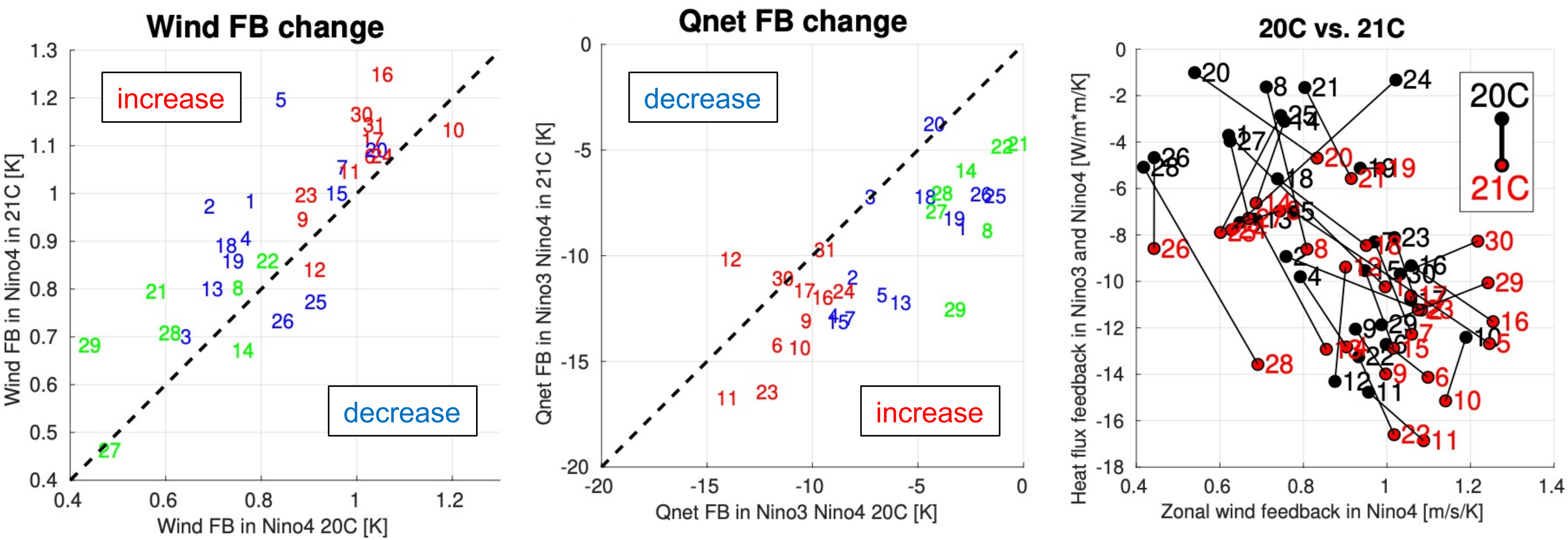
Already answered questions from proposal:

- Quantify the model bias in ENSO dynamics in CMIP5 models (Bayr et al. 2020)
- Which are the largest uncertainties in ENSO global warming projections? (Beobide-Arsuaga et al. 2021)

Open research questions:

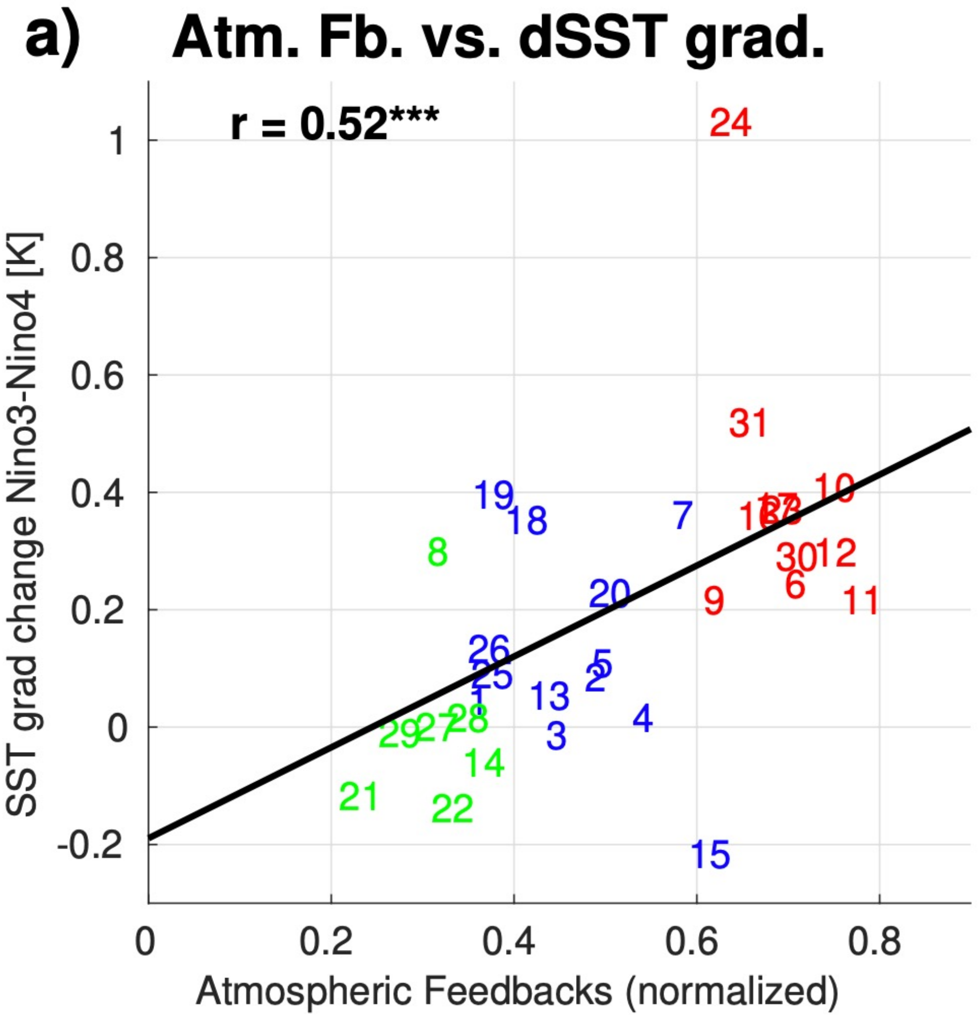
- How will ENSO atmospheric feedbacks change under global warming and why?
- Which influence has the atmospheric feedback strength on ENSO global warming projection?
- Is there a difference in ENSO atmospheric feedbacks between CMIP5 and CMIP6 models?
- …

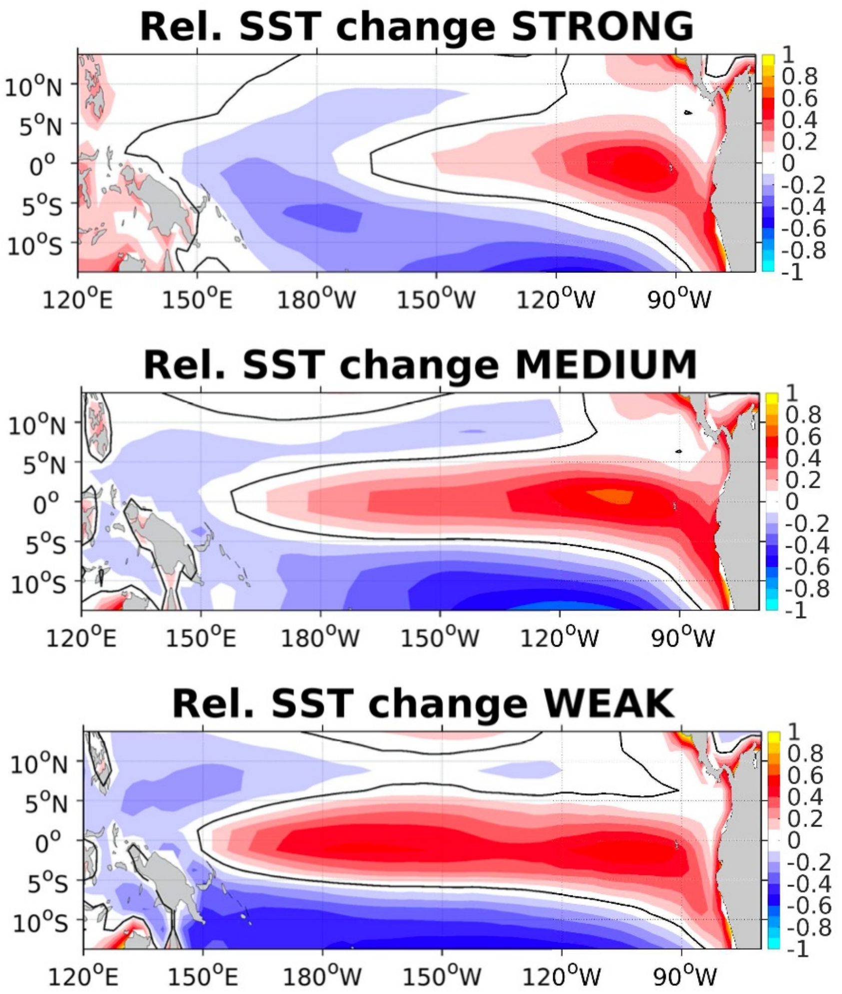
Preliminary results: Atmospheric feedback change in global warming projections



- Both atmospheric feedbacks become stronger under global warming in most CMIP5 models
- But there is no strong relation between the change in wind feedback and the change in heat flux feedback

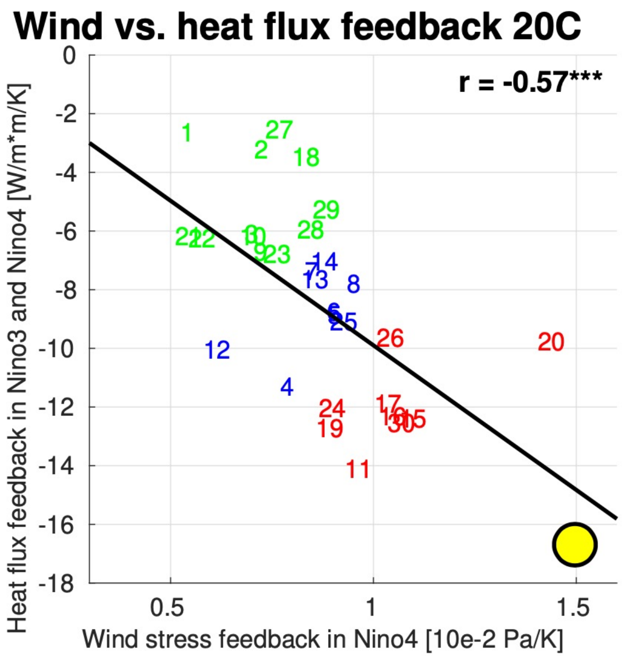
Influence of atmospheric feedback strength on ENSO global warming projections

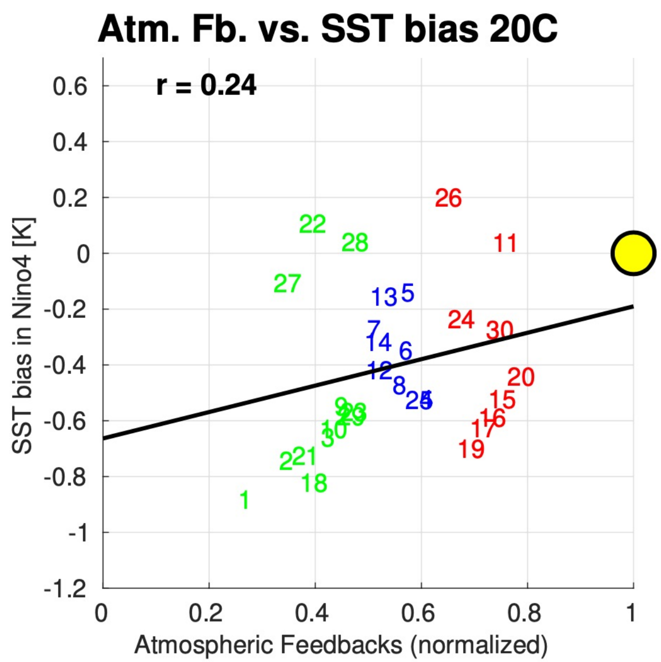


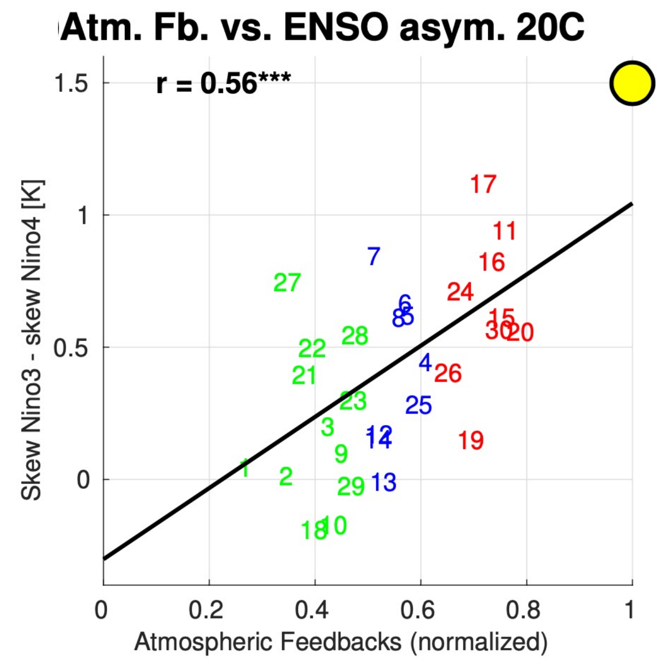


Models with STRONG atmospheric feedbacks simulate a weakening of the SST gradient, while models with WEAK atmospheric feedbacks a more uniform equatorial warming

Atmospheric feedbacks in CMIP6







- Underestimated atmospheric feedbacks and error compensation is also present in the CMIP6 models
- But seems not to be so strongly related to the cold bias in Nino4
- ENSO asymmetry is also strongly related to the atmospheric feedback strength in CMIP6

Take home massage:

Two types of ENSO dynamics exist in many climate models!

Dogs wags tail

~~or~~

and

Tail wags dog

Wind-driven ENSO dynamics:

explains observed ENSO

but is partly absent in many CGCMs

Heat flux-driven ENSO dynamics:

due to equatorial cold bias,

is partly present in many CGCMs

Take home massage:

Many climate models have ENSO variability for the wrong reasons!

Climate Models with

STRONG

MEDIUM

WEAK

atmospheric feedbacks

Dogs wags tail

Dogs wags tail

Tail wags dog

Dogs wags tail

Tail wags dog

Cold SST bias in Niño4

small — medium — large

Wind-SST feedback

strong — medium — weak

Shortwave-SST feedback

negative — neutral — positive

Summary

- To improve simulated ENSO it is important to improve the mean state in climate models
  - Cold SST bias in Niño4 region shifts rising branch of the Walker Circulation to the west (up to 30°)
  - Zonal wind and heat flux feedback are too weak as convective response too far west
  - There is a gradual change and a error compensation !
- Strong atmospheric feedbacks enhance important ENSO properties like seasonal phase looking and asymmetry between El Niño and La Niña

Outlook on new project

Open research questions:

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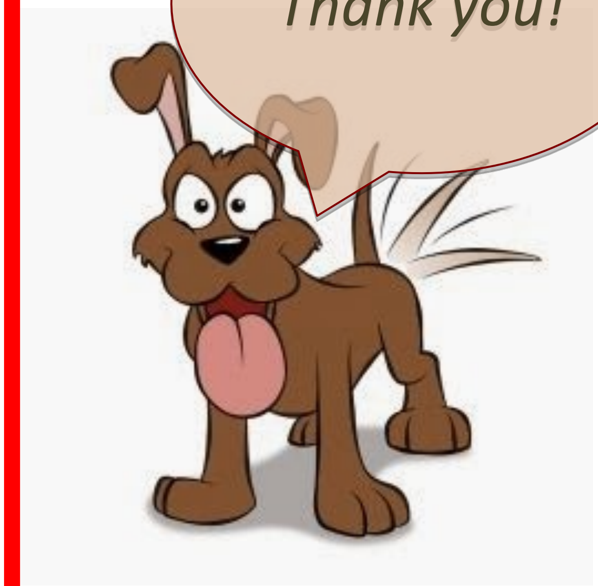
- …?

ENSO dynamics in climate models



Dogs wags tail

and

Tail wags dog

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