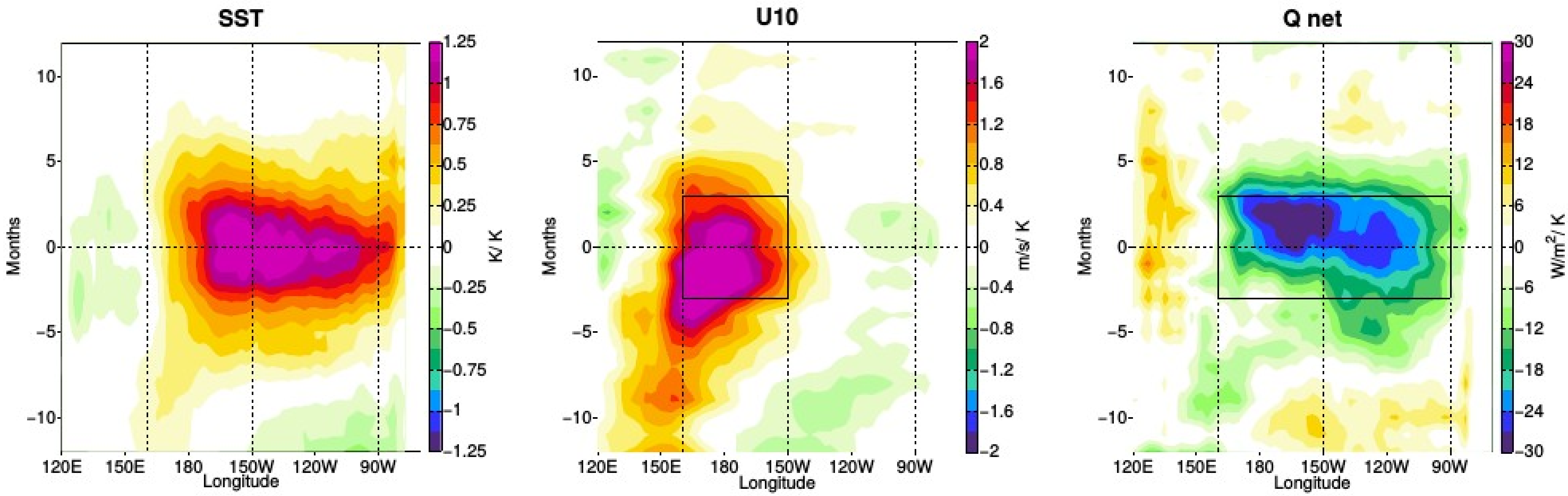
The mean state dependence of ENSO atmospheric feedbacks and ENSO dynamics in climate models



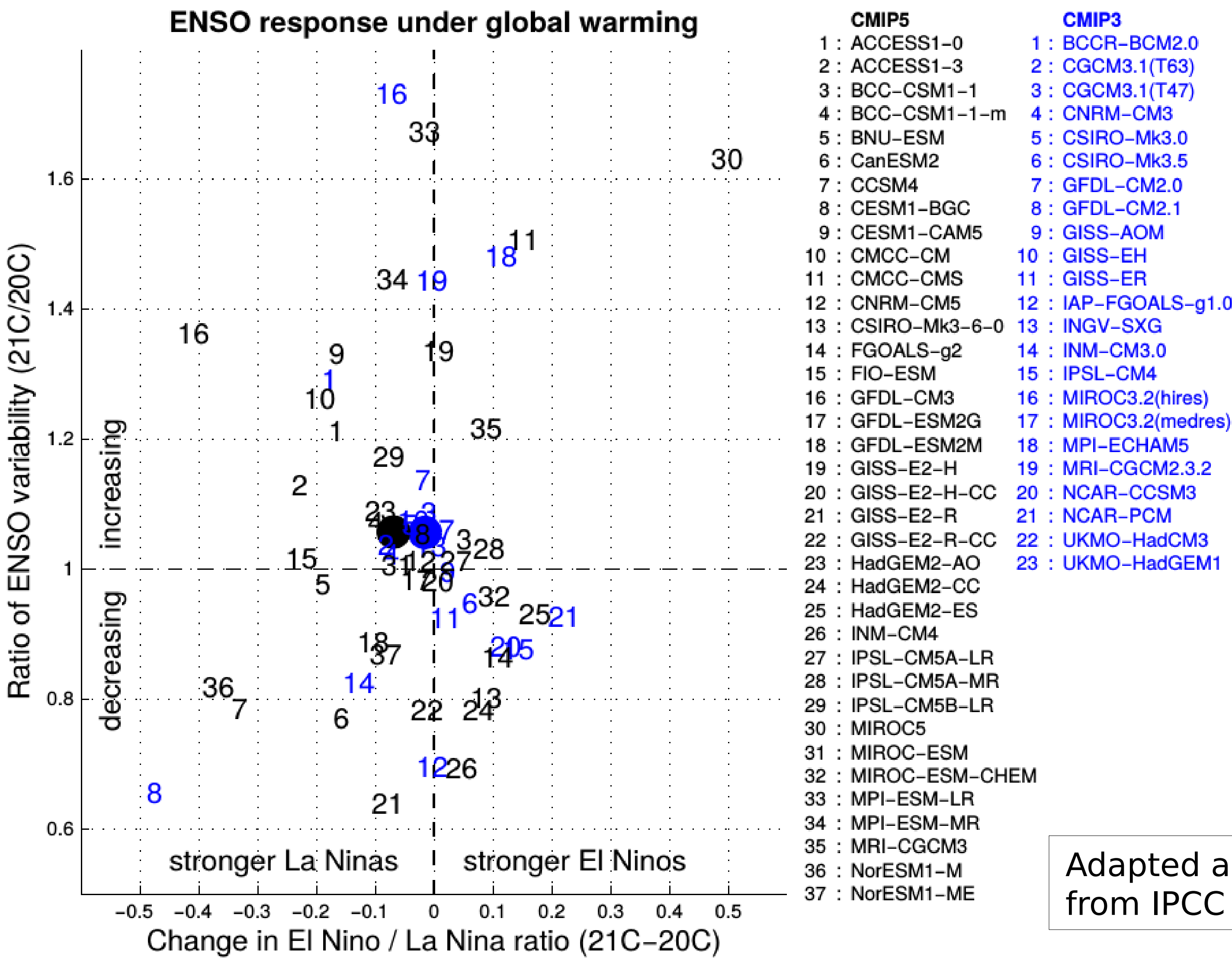
Tobias Bayr, Mojib Latif, Dietmar Dommenget, Christian Wengel, Joke Lübbecke,

Jan Harlaß and Wonsun Park

GEOMAR Kiel, Germany

GEOMAR

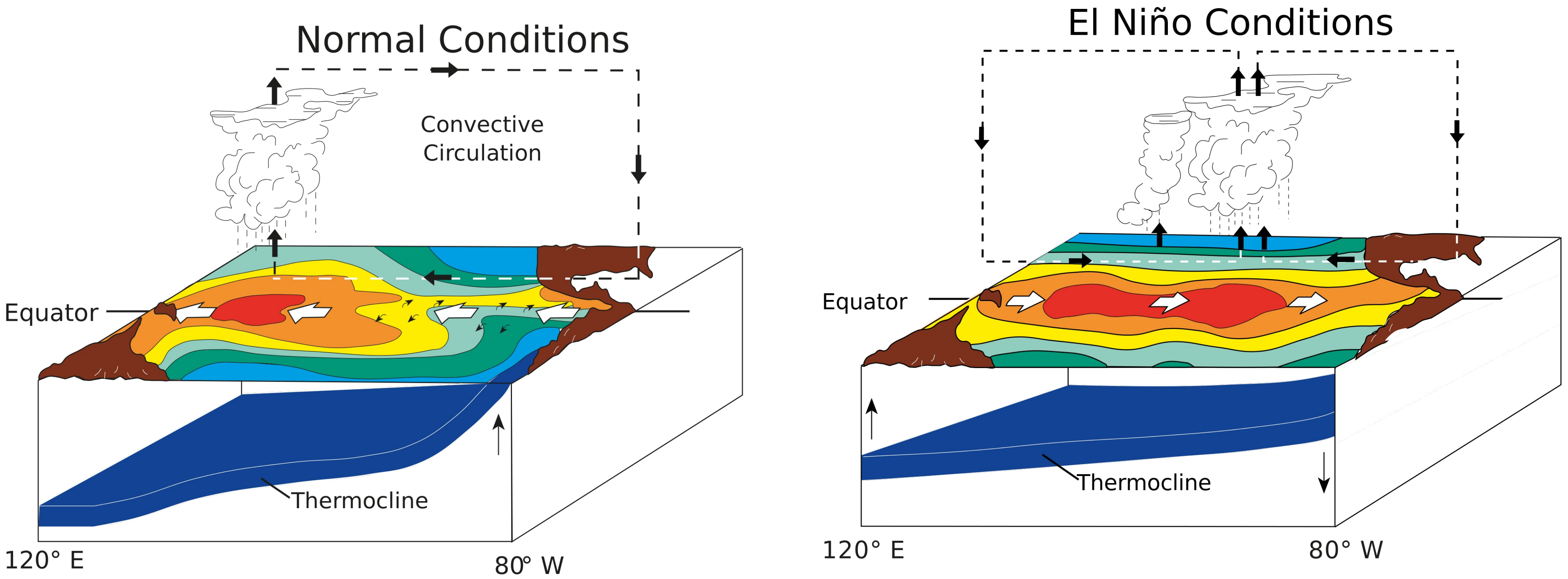
Motivation:
ENSO response under global warming is still uncertain!



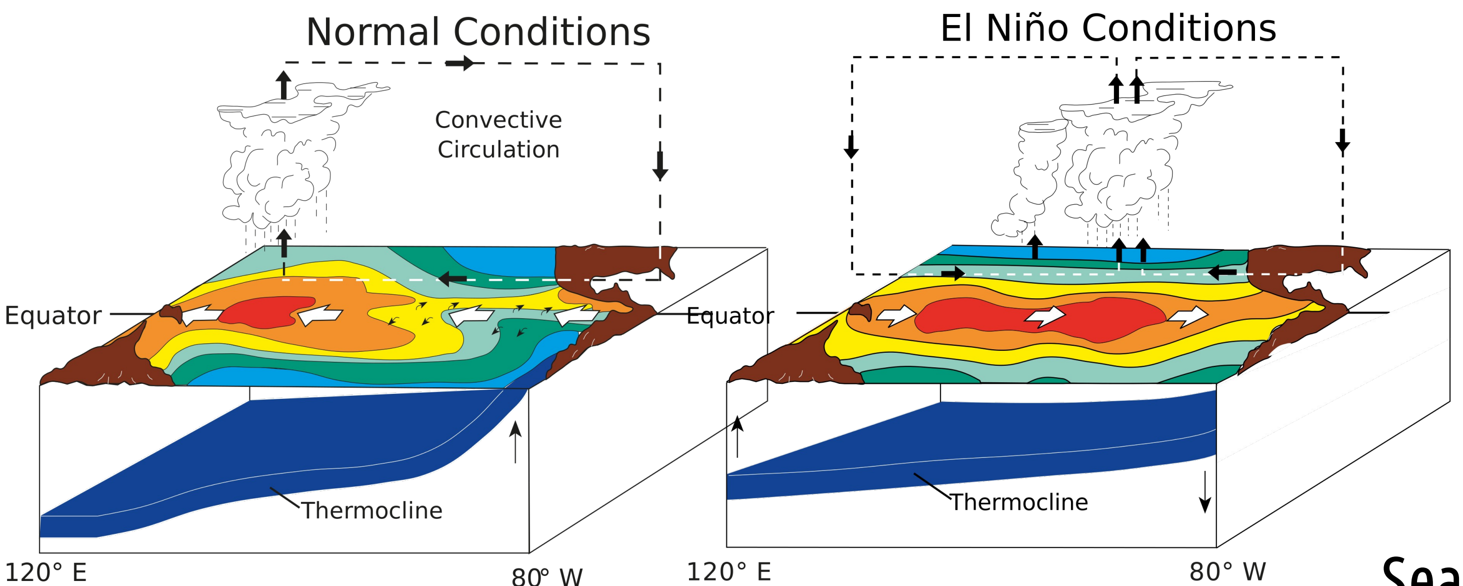
Adapted and updated from IPCC AR4(2007)

ENSO dynamics in climate models still show severe deficits!

El Niño/Southern Oscillation



The positive Bjerknes Feedback and negative heat flux feedback



Zonal Wind
over western Pacific

U10+

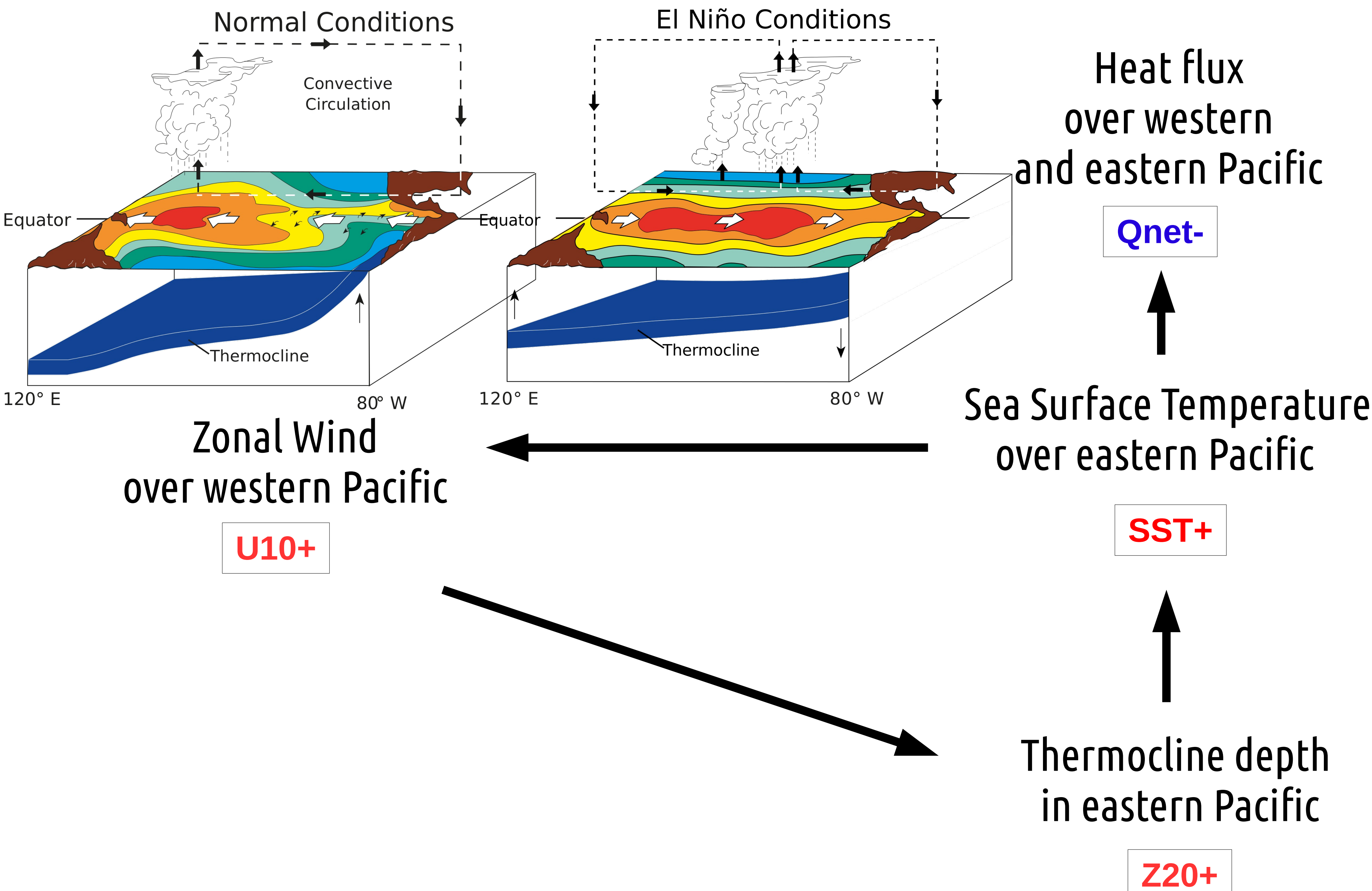
Sea Surface Temperature
over eastern Pacific

SST+

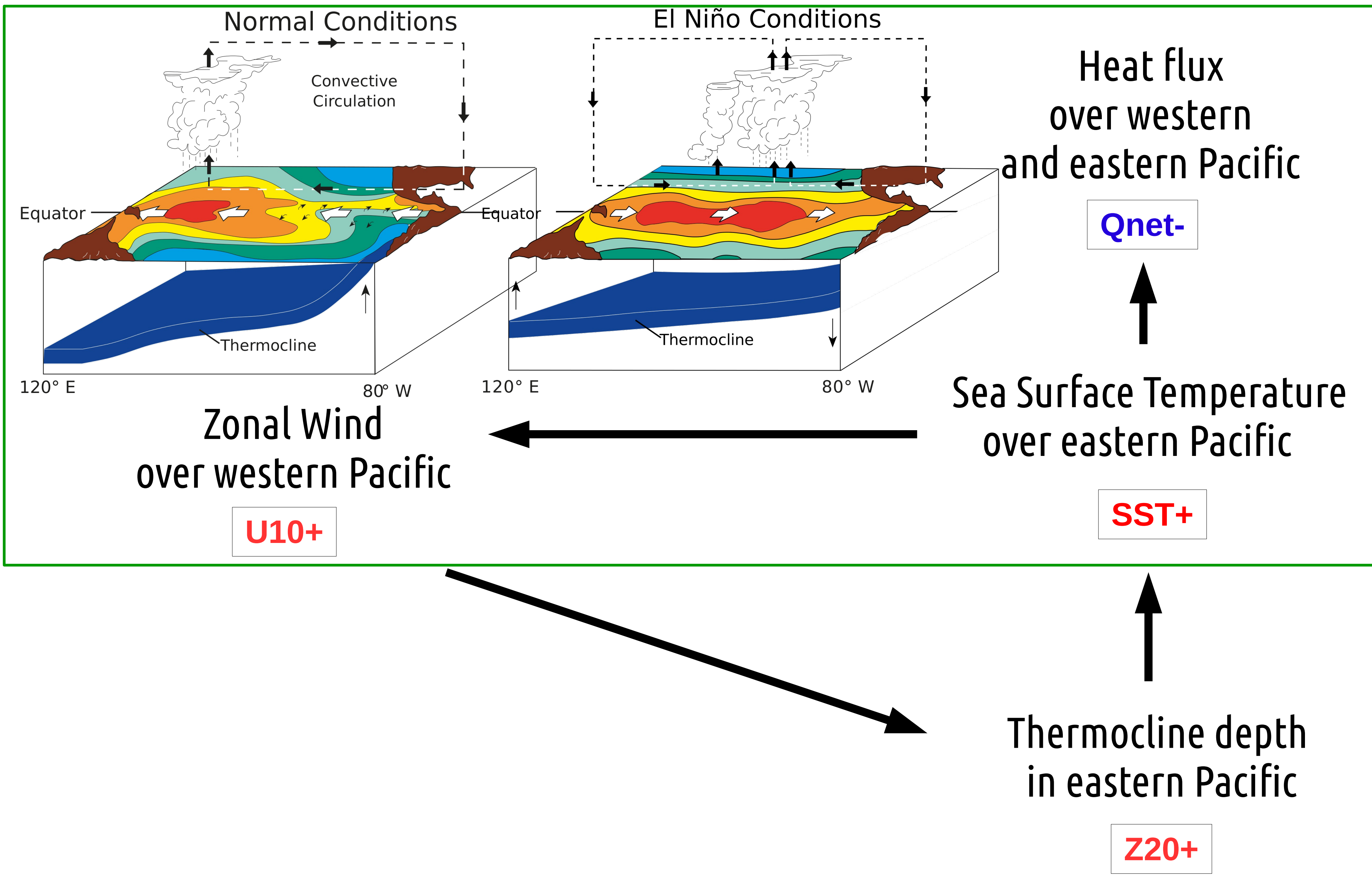
Thermocline depth
in eastern Pacific

Z20+

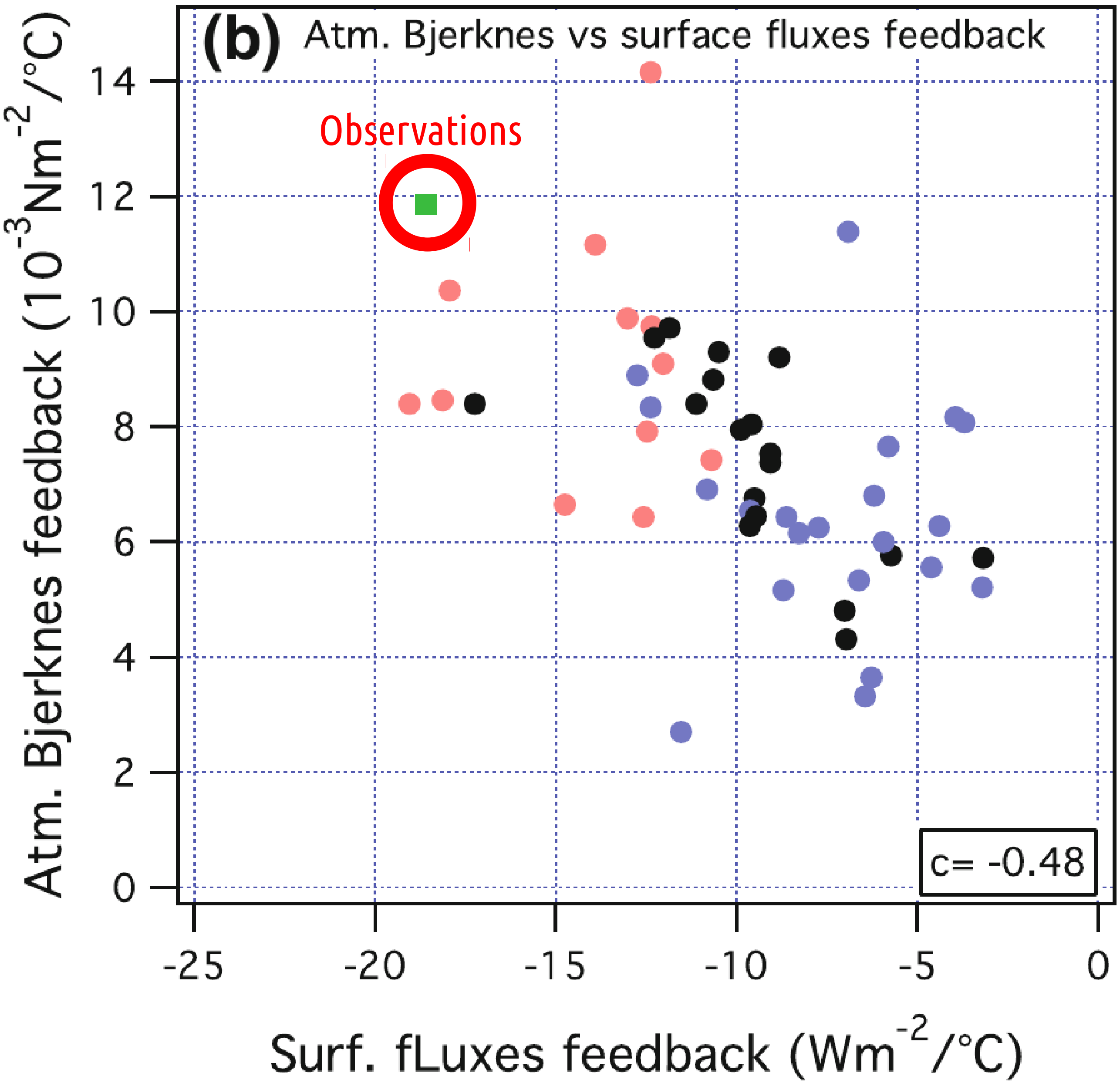
The positive Bjerknes Feedback and negative heat flux feedback



The positive Bjerknes Feedback and negative heat flux feedback



Motivation: Underestimated Atmospheric Feedbacks in CMIP3 and CMIP5



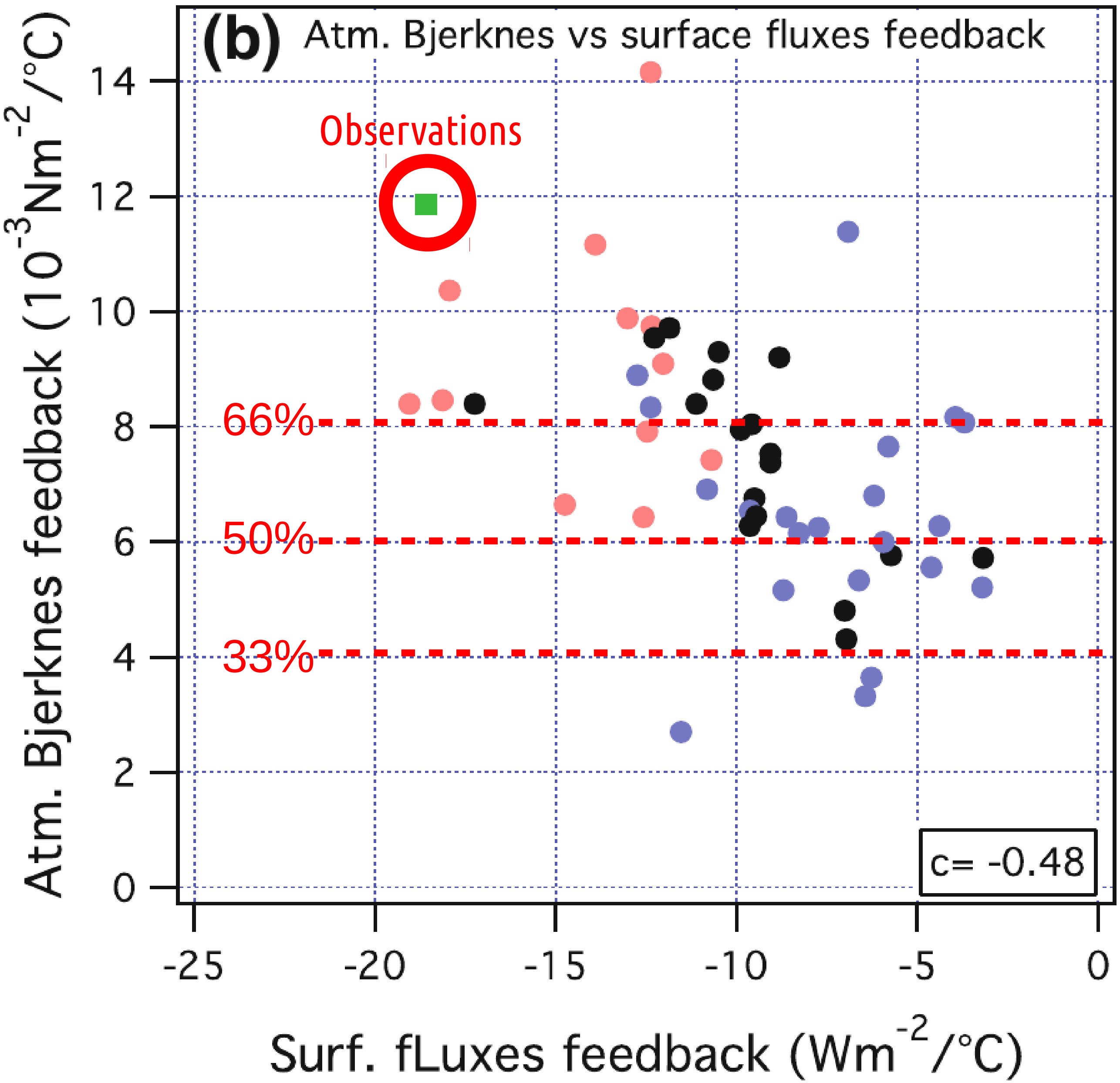
Most CMIP3 and CMIP5 models underestimate Wind-SST feedback and Heat flux-SST feedback

=> Error Compensation?

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

Bellenger et al. (2014)

Motivation: Underestimated Atmospheric Feedbacks in CMIP3 and CMIP5



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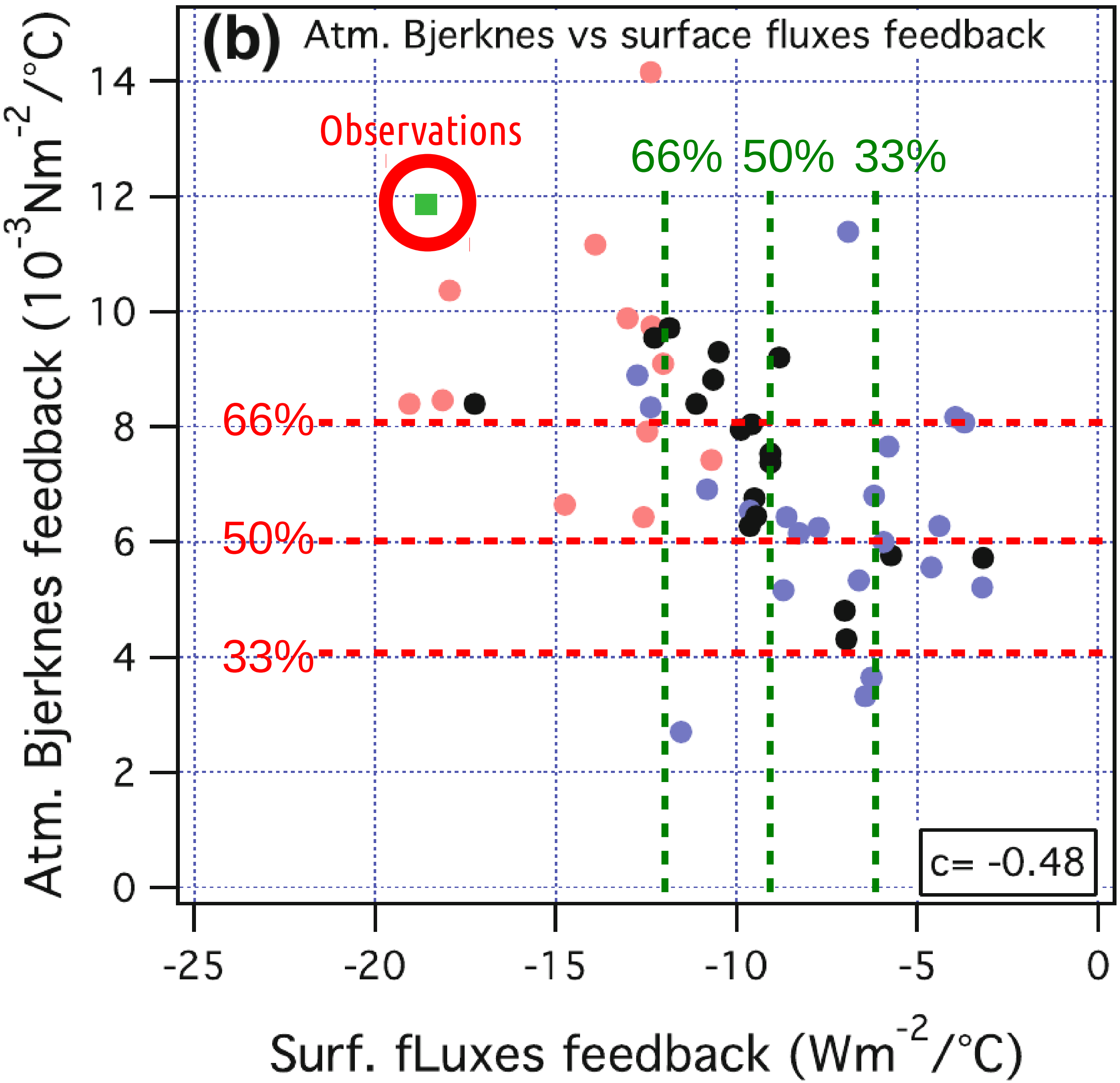
Motivation: Underestimated Atmospheric Feedbacks in CMIP3 and CMIP5



Most CMIP3 and CMIP5 models underestimate Wind-SST feedback and Heat flux-SST feedback

=> Error Compensation?

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

Bellenger et al. (2014)

Motivation:

In 9 out of 13 processes relevant for ENSO mentioned in our draft the surface winds play an important role!

Timmermann et al. (2018)

Box 1 | Processes Relevant for ENSO

Walker Circulation: Zonally-oriented atmospheric circulation cell with surface easterly (trade) winds over the central Pacific, rising air and intense rainfall over the west Pacific, westerly winds at high altitudes over the central Pacific, and sinking dry air over the east Pacific.

Western Pacific Warm Pool: A western tropical Pacific region with SST exceeding 28°C. Atmospheric deep convection frequently occurs over the Warm Pool, feeding the ascending branch of the Walker Circulation. The Warm Pool's seasonal north-south migrations play an important role in equatorial air-sea coupling, and in terminating El Nino events.

Eastern Pacific Cold Tongue: An eastern equatorial Pacific region characterized by wind-driven upwelling of cold subsurface waters. The Cold Tongue warms considerably during Eastern Pacific (EP) El Nino events, and cools during La Nina events. The subsiding branch of the atmospheric Walker Circulation is located over the Cold Tongue.

Bjerknes feedbacks: Positive (reinforcing) ENSO feedbacks along the equator, in which a weakened equatorial zonal SST gradient serves to weaken the trade winds, which in turn further weaken the zonal SST gradient due to thermocline feedbacks, Ekman feedbacks, and zonal-advective feedbacks (see below). The Bjerknes feedbacks, which can also work in reverse, are seasonally modulated and are strongest during boreal summer.

Equatorial Kelvin Wave: Eastward propagating oceanic internal wave that displaces the interface (thermocline) between warm surface waters and cold subsurface waters. Westerly equatorial wind anomalies generate downwelling Kelvin waves, which deepen the thermocline in the eastern Pacific and thus reduce the efficiency of cooling by climatological upwelling in the eastern Pacific. The opposite occurs for easterly wind aomalies. Kelvin waves need about 2 months to propagate across the equatorial Pacific.

Thermocline feedback: Positive feedback in which a warm equatorial SSTA weakens the equatorial trade winds, which relaxes the zonal tilt of the thermocline, which leads to warmer upwelled water slightly to the east. This leads to growth and eastward expansion of the original warm SSTA.

Ekman feedback: Positive feedback in which a warm equatorial SSTA weakens the equatorial trade winds, which weakens the wind-driven upwelling of cold deep water, which warms the SST slightly farther west. This leads to growth and westward expansion of the original warm SSTA.

Zonal-advective feedback: Positive feedback in which a warm equatorial SSTA weakens the equatorial trade winds, which weakens the easterly surface currents emerging from the equatorial cold tongue, which warms the SST slightly farther west. This leads to growth and westward expansion of the original warm SSTA. This feedback plays an important role for CP El Nino events.

Sverdrup transport: A warm eastern equatorial SSTA tends to weaken the trade winds more at the equator than off-equator. This generates cyclonic wind stress curl, which enhances the poleward transport (equatorial discharge) of upper-ocean heat. The opposite (recharge) occurs in response to a cold SSTA.

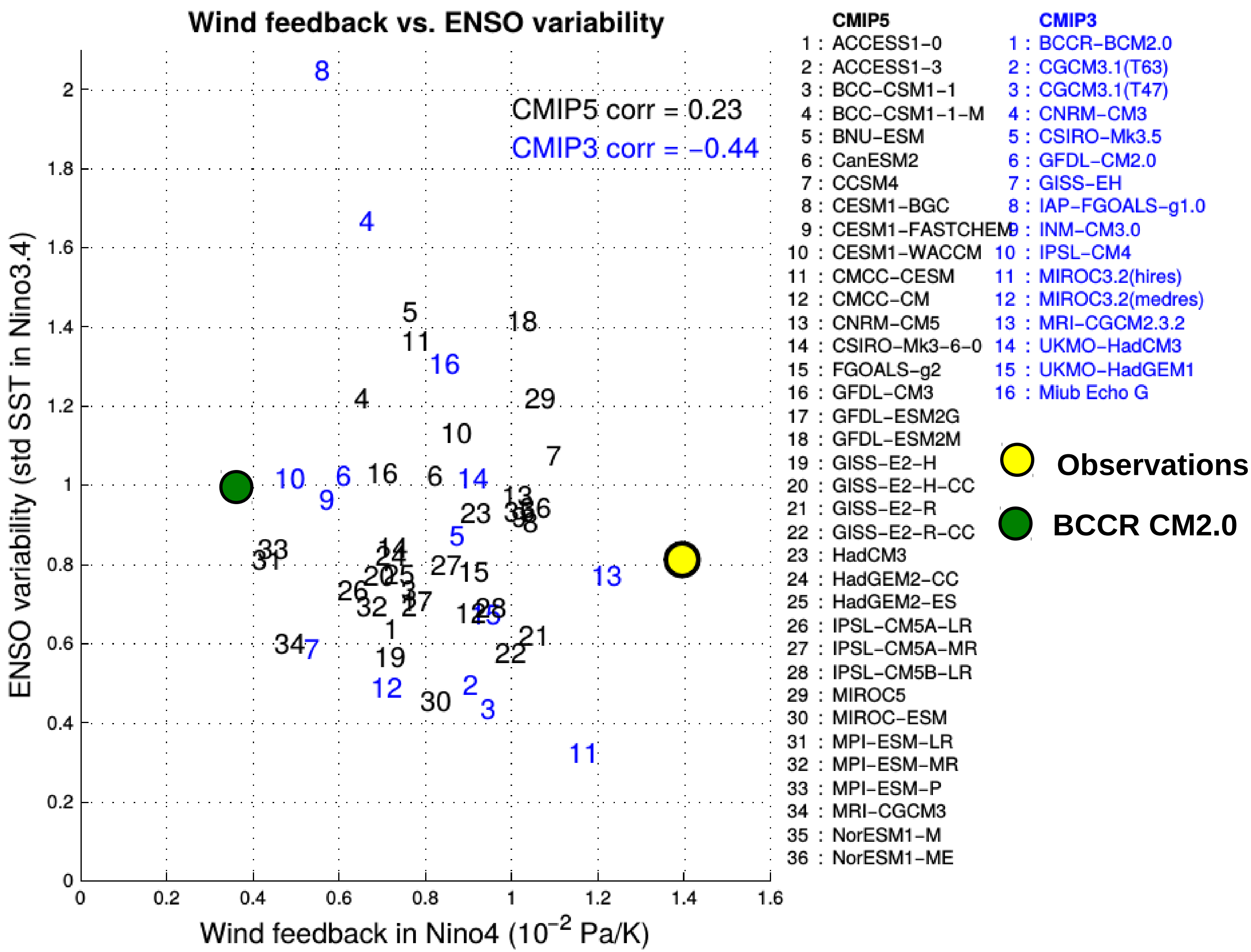
Westerly Wind Event: Low pressure weather systems in the western and central Pacific, that are often associated with an equatorial westerly wind anomaly which generate downwelling Kelvin waves and help to expand the warm pool front eastward. WWEs play a central role in triggering large El Nino events.

Multiplicative Noise: As the warm pool expands eastward during a developing El Nino, the activity of WWEs typically increases.

Combination Tones / C-mode: Enhanced spectral energy on timescales of 9 months and 15-18 months, generated by the nonlinear modulation of ENSO by the seasonal cycle, and vice versa. This interaction plays an important part in the seasonal turnaround of El Nino events, in the generation of the Indian Ocean Dipole Mode, and in establishing the linkage between ENSO and the East Asian Monsoon system.

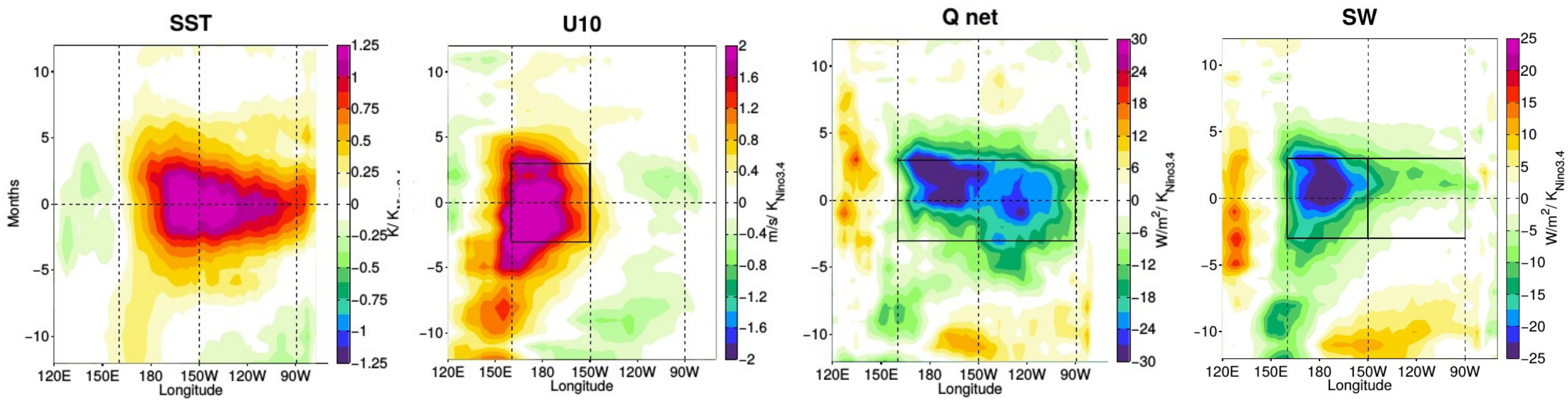
ENSO skewness: Amplitude asymmetry of El Nino and La Nina events. The histogram of eastern tropical Pacific SSTA is non-Gaussian, with warm anomalies reaching greater extremes than cold anomalies -- a clear indication of nonlinearity in the ENSO cycle.

Motivation: How can models have a realistic ENSO amplitude with strongly underestimated wind feedbacks ?



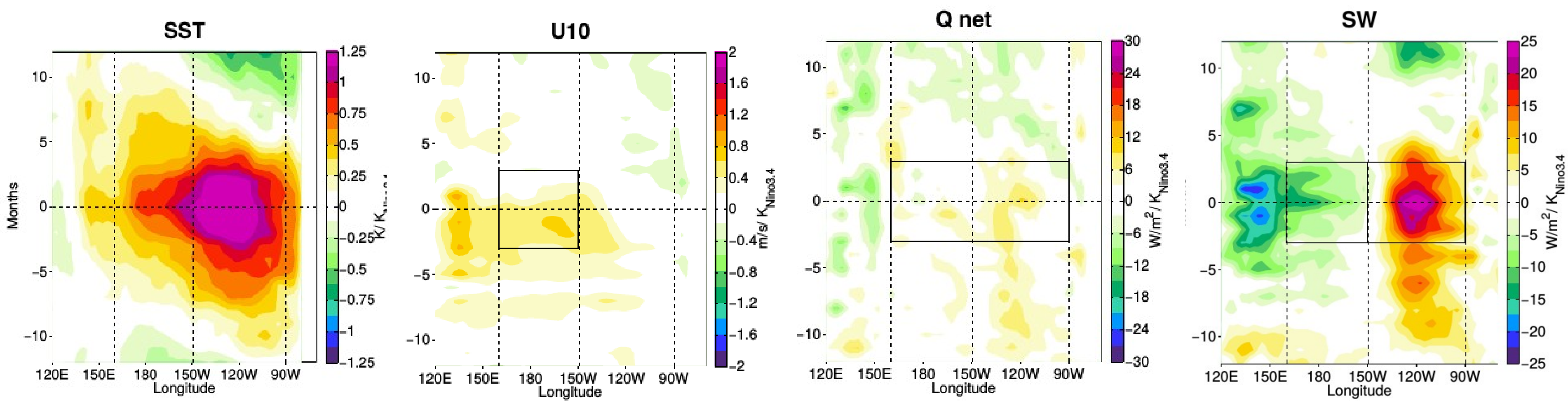
ENSO Hoevmoeller composites
(normalised with Niño3.4 SST)

Observations



std(Niño3.4) = 0.82

BCCR BCM2.0



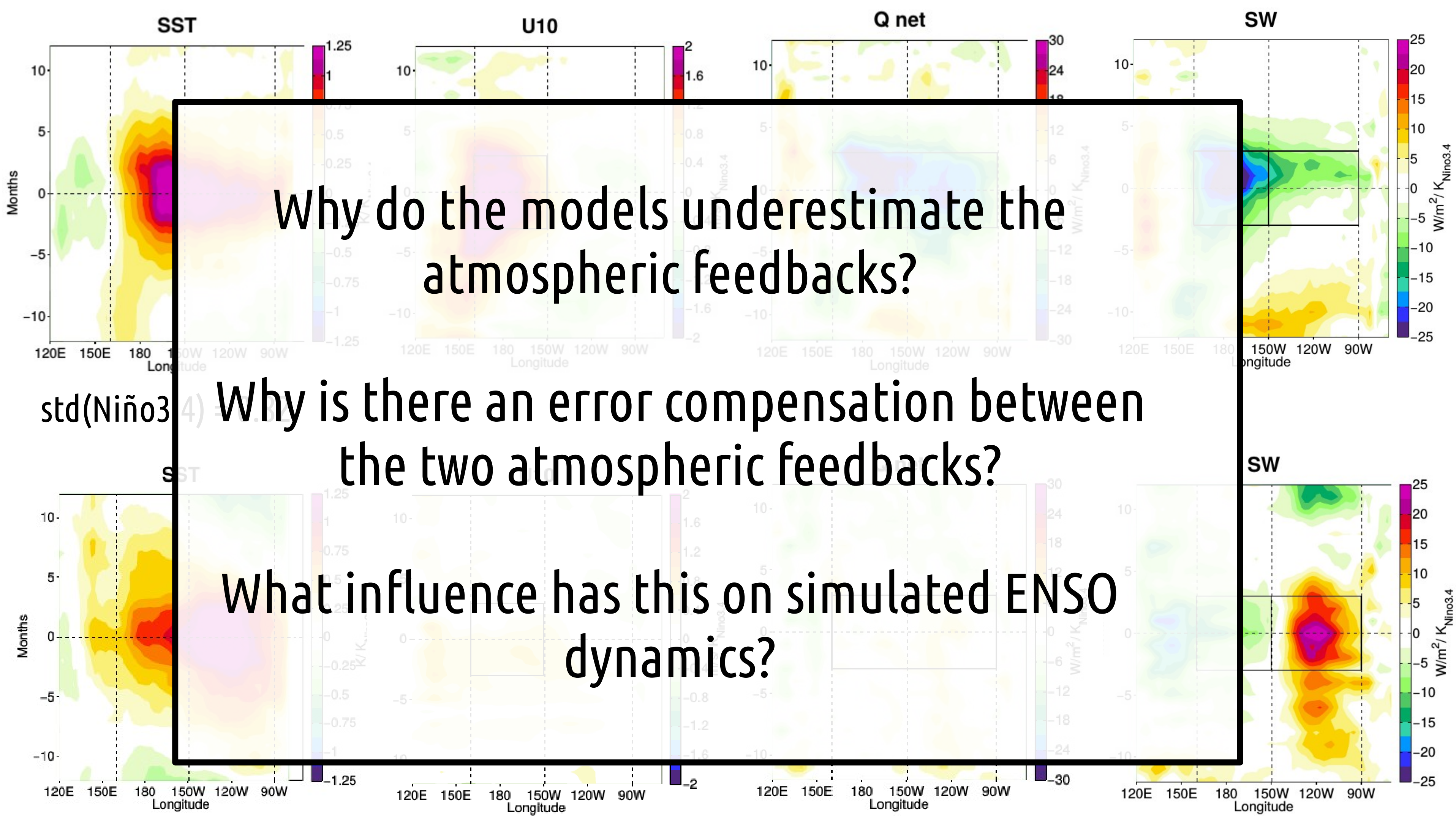
std(Niño3.4) = 0.98

ENSO Hoevmoeller composites

(normalised with Niño3.4 SST)

Observations

BCCR BCM2.0



std(Niño3.4) = 0.98

Why do the models underestimate the atmospheric feedbacks?

Why is there an error compensation between the two atmospheric feedbacks?

What influence has this on simulated ENSO dynamics?

Data of Obs, CMIP5 and KCM

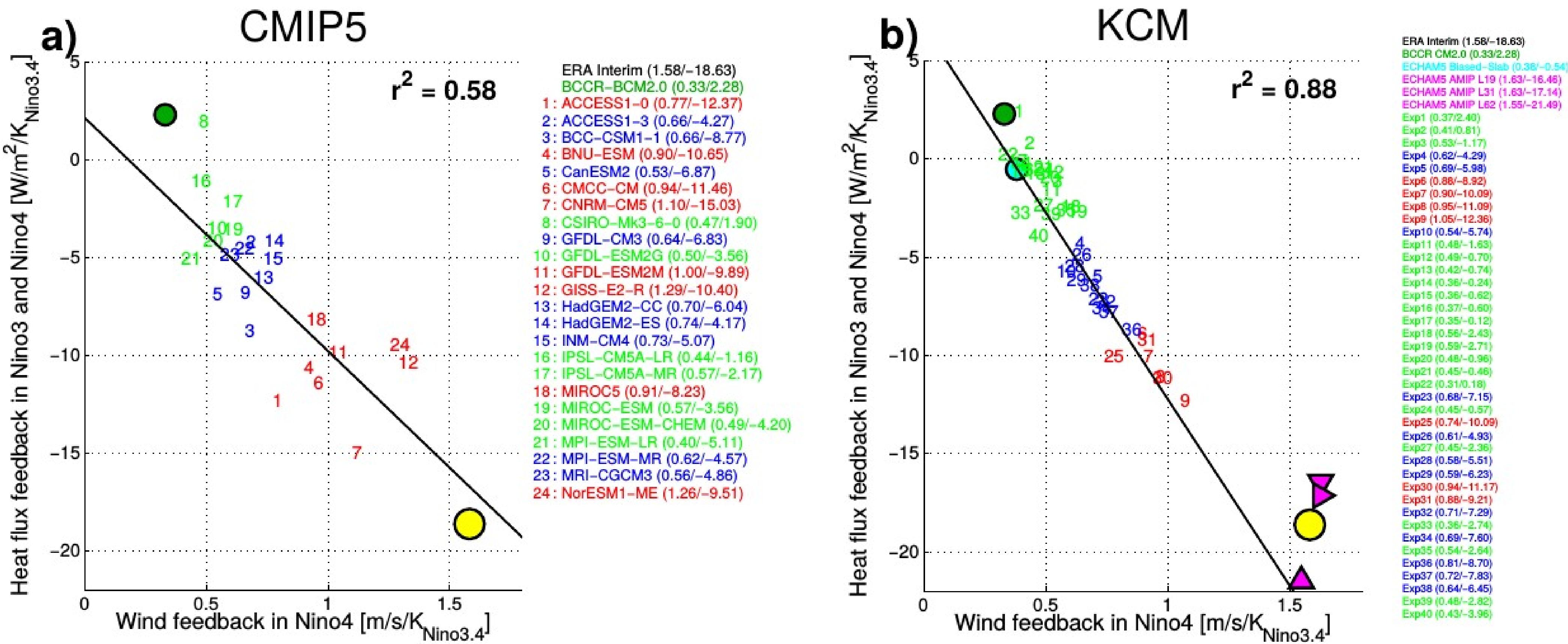
- Observations and reanalysis data:
  HadISST, ERA40, ERA Interim and SODA reanalysis

- Multimodel ensemble of 24 models of CMIP5 data base, historical simulations (1900-1999)

- Perturbed physics ensemble of the Kiel Climate Model (KCM) 1.4.0 with
  - ECHAM5 with T42 (2.8°x2.8°)
  - Nemo Orca2 (~2°x2°)
  - 40 different sets of convection parameters (= tuning parameters) based on Mauritsen et al. (2012) => 40 different mean states

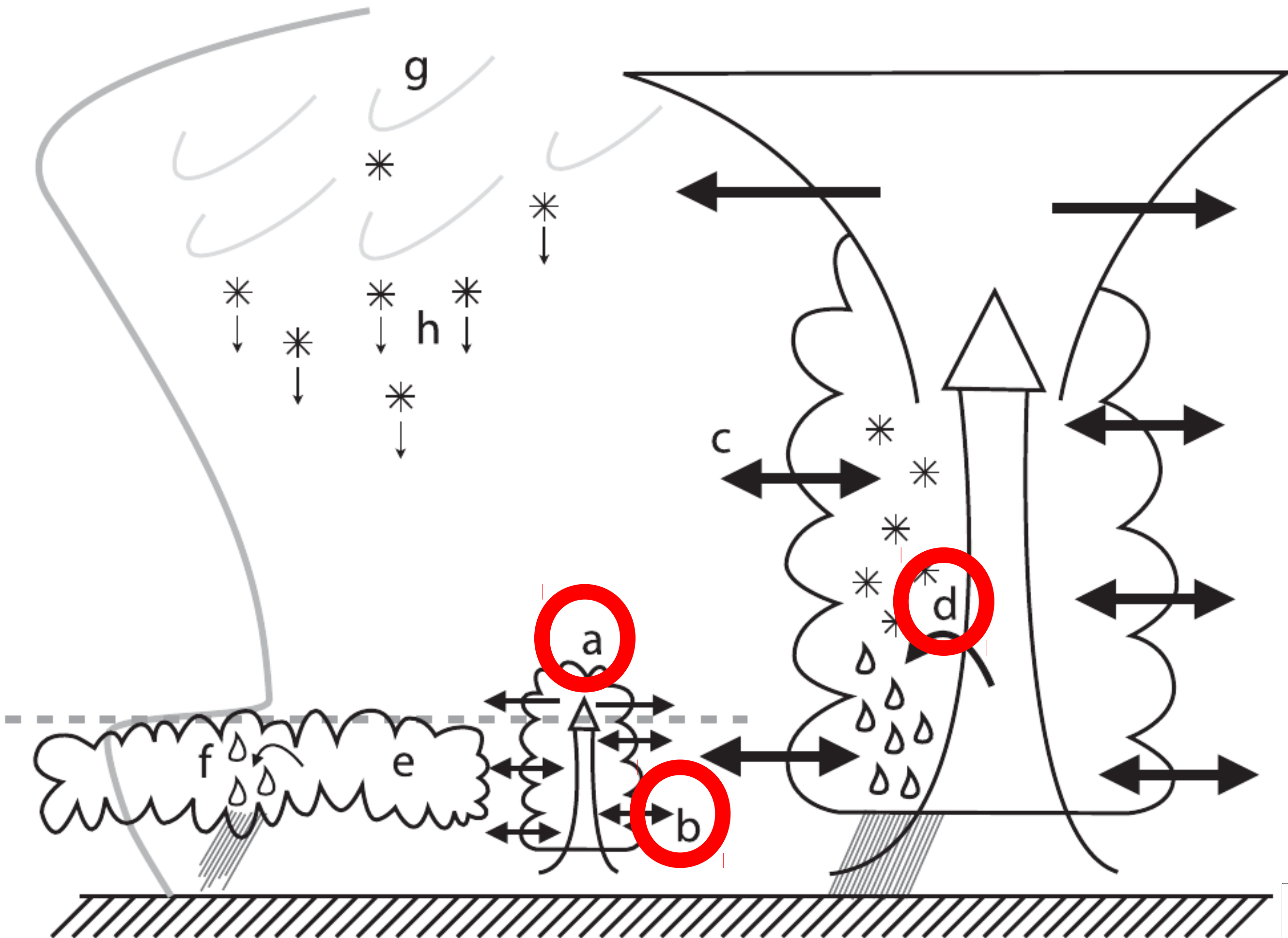
Multi model ensemble of CMIP5 and perturbed physics ensemble of KCM

Zonal wind vs. net heat flux feedback in



Bayr et al. (2017), Clim Dyn

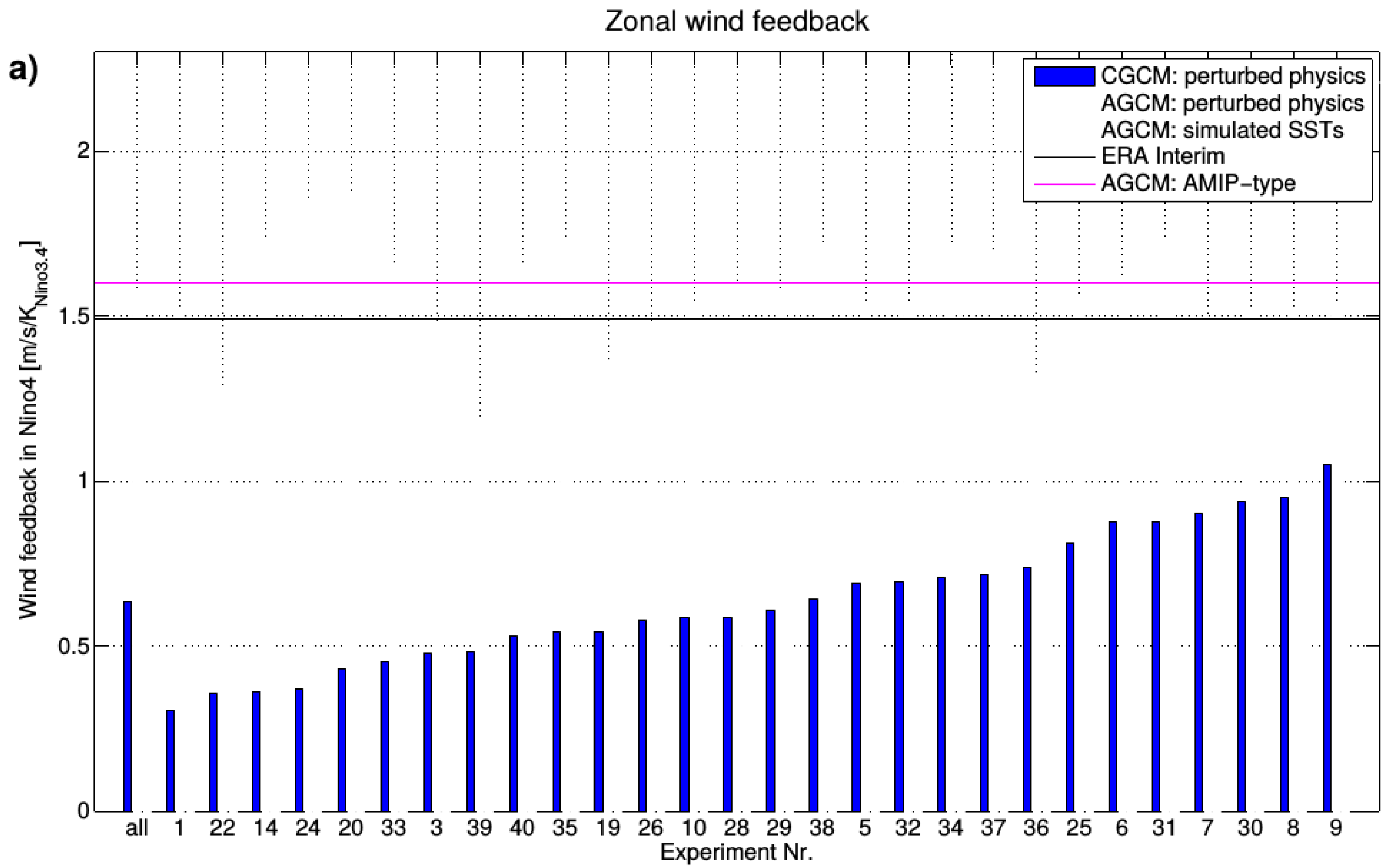
“Tuning” parameters in convection parametrisation



Mauritsen et al. (2012)

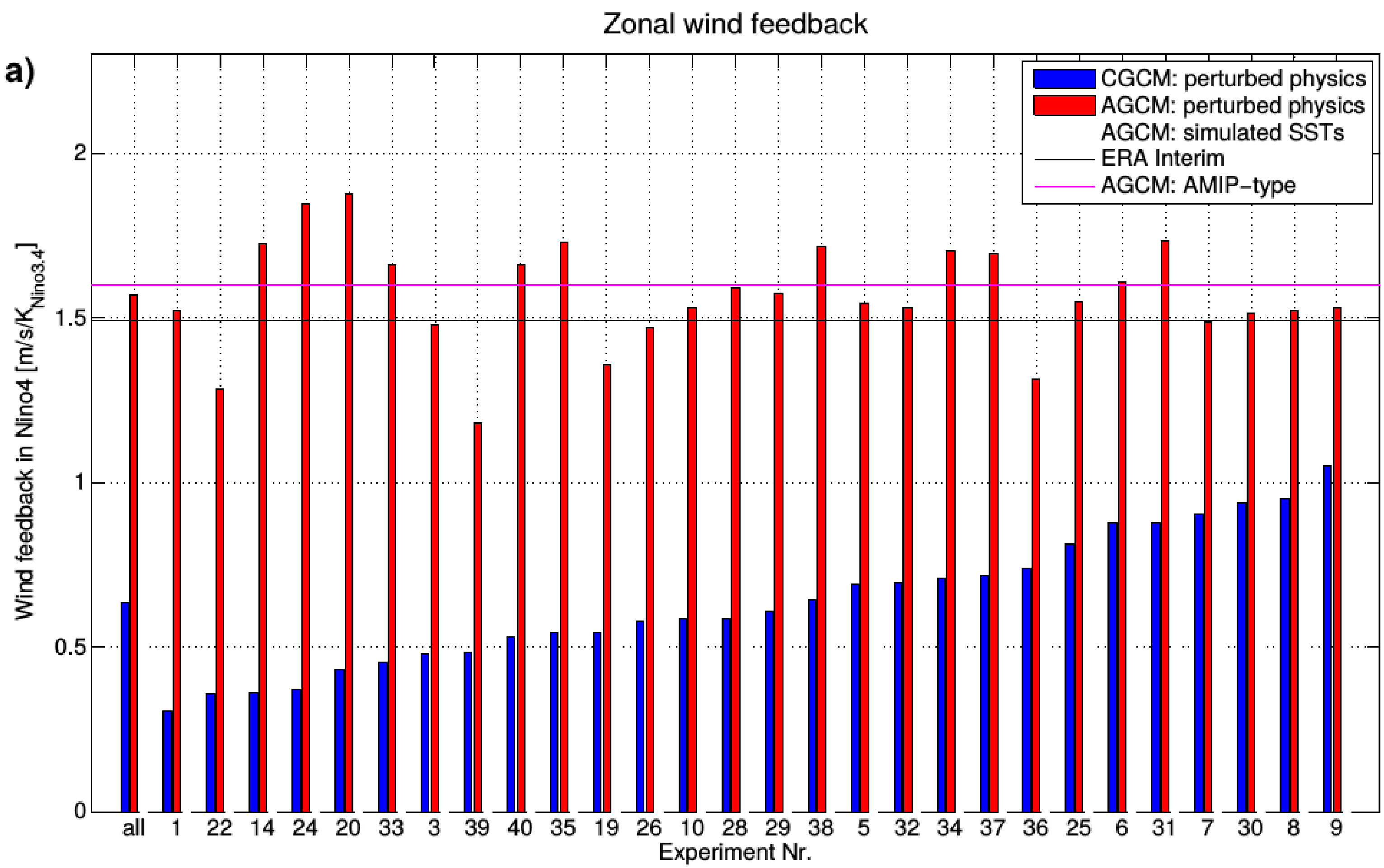
a) convective cloud mass-flux above the level of non-buoyancy
b) entrainment rate for shallow convection
d) convective cloud conversion rate from cloud water to rain

ECHAM5 experiments:
Perturbed physics vs. mean state



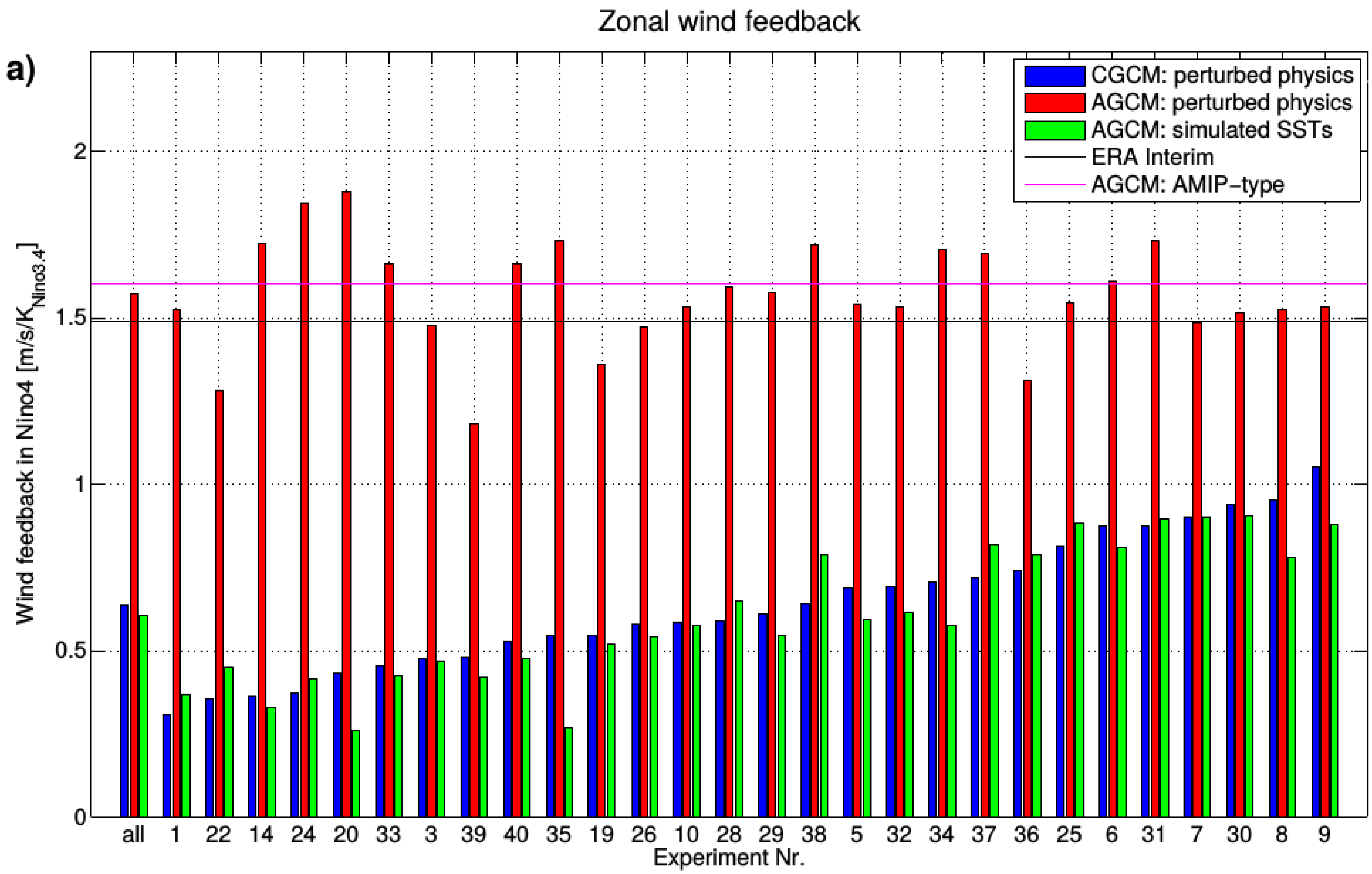
Coupled experiments

ECHAM5 experiments:
Perturbed physics vs. mean state



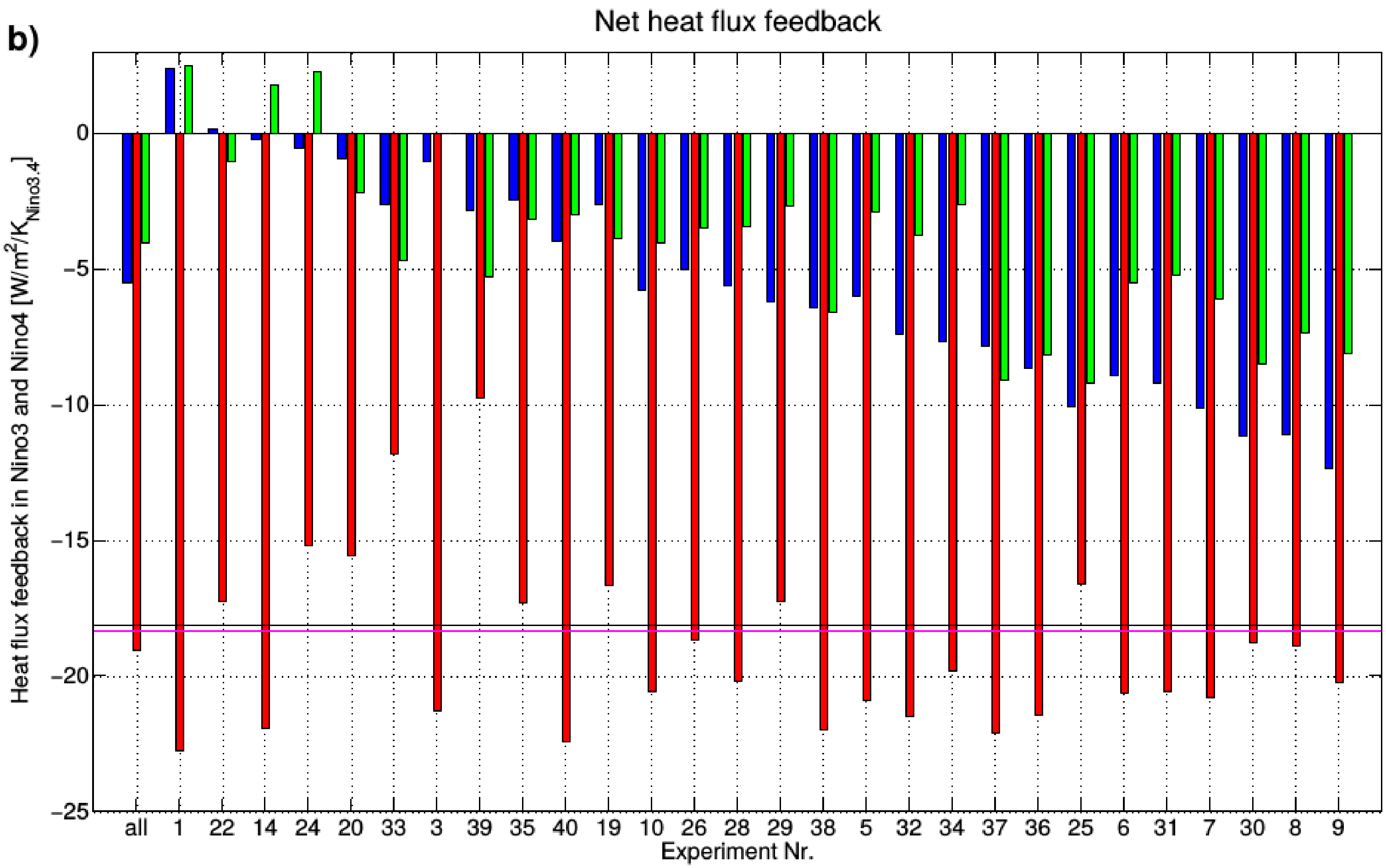
- Perturbed physics have only weak influence on atmospheric feedbacks

ECHAM5 experiments:
Perturbed physics vs. mean state



- Perturbed physics have only weak influence on atmospheric feedbacks
- Different mean states explain underestimated atmospheric feedbacks

ECHAM5 experiments:
Perturbed physics vs. mean state

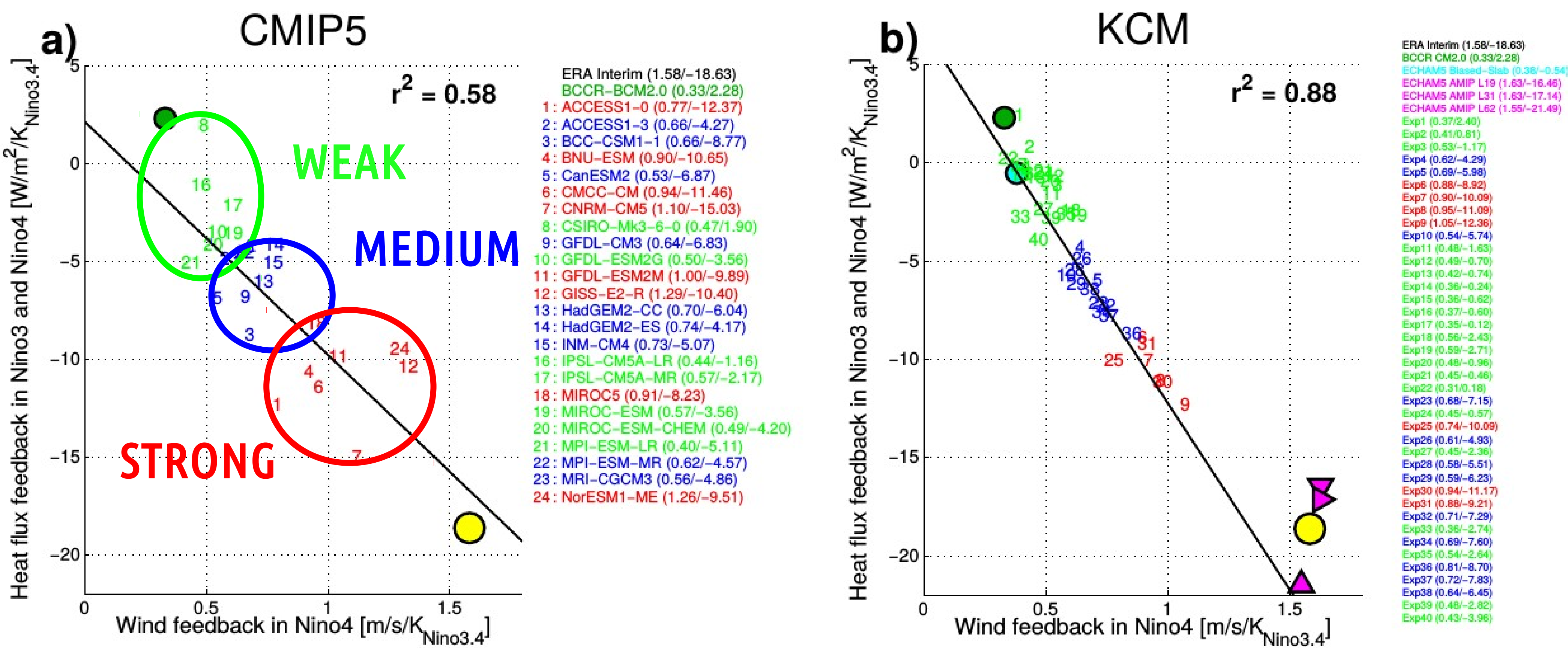


The same for net heat flux feedback:
mean state determines feedback strength!

=> error compensation between both feedbacks!

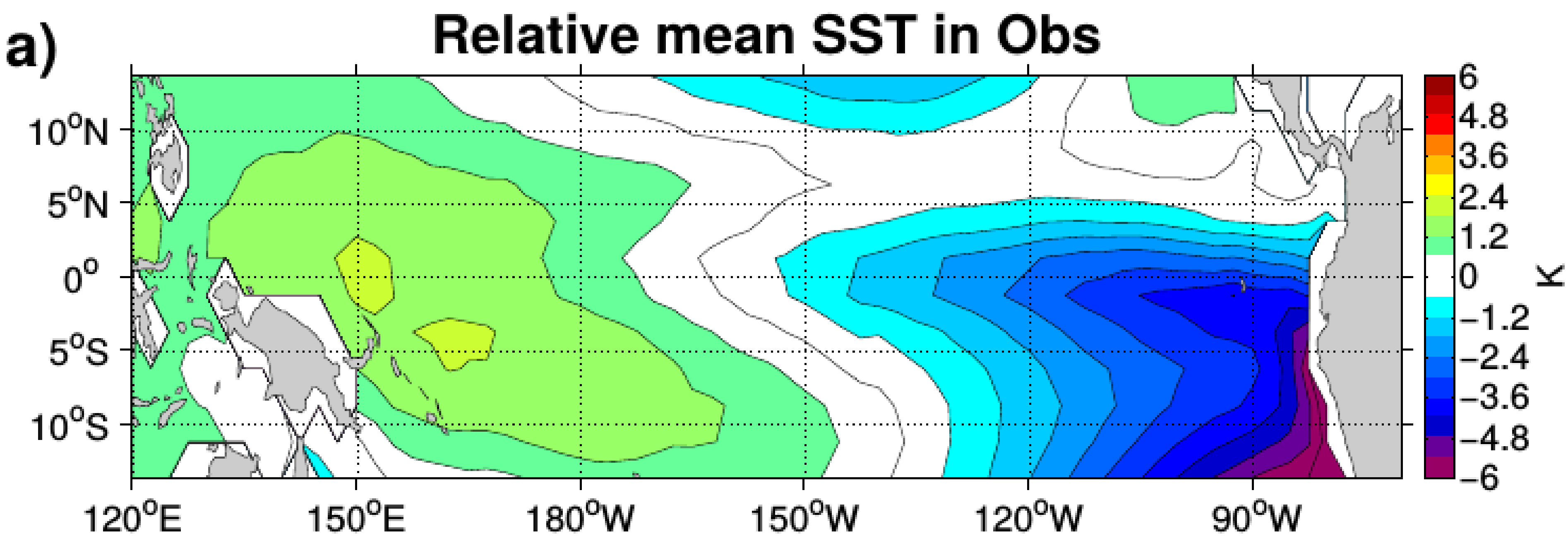
Multi model ensemble of CMIP5 and perturbed physics ensemble of KCM

Zonal wind vs. net heat flux feedback in



Bayr et al. (2017), Clim Dyn

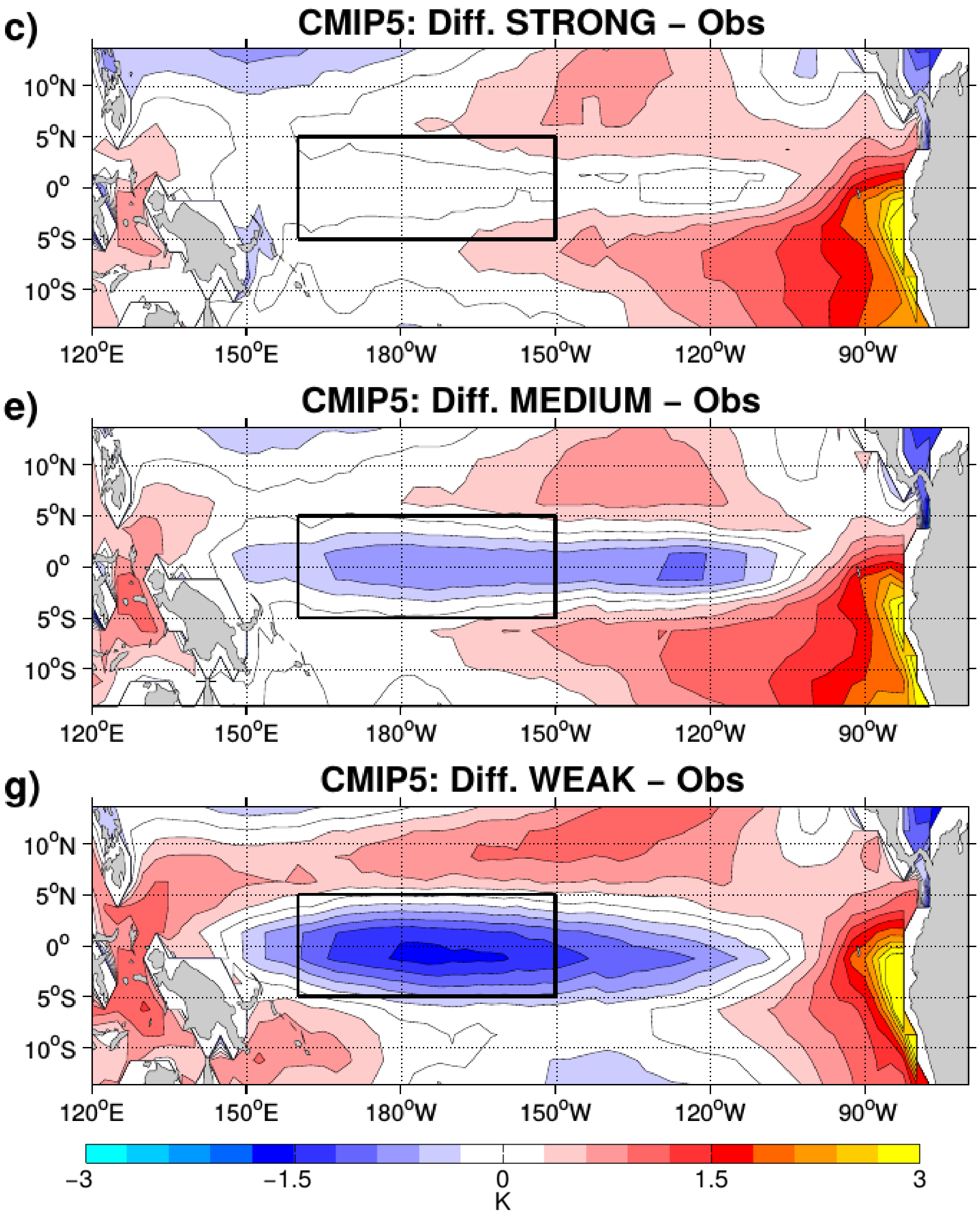
Relative SST & SST bias



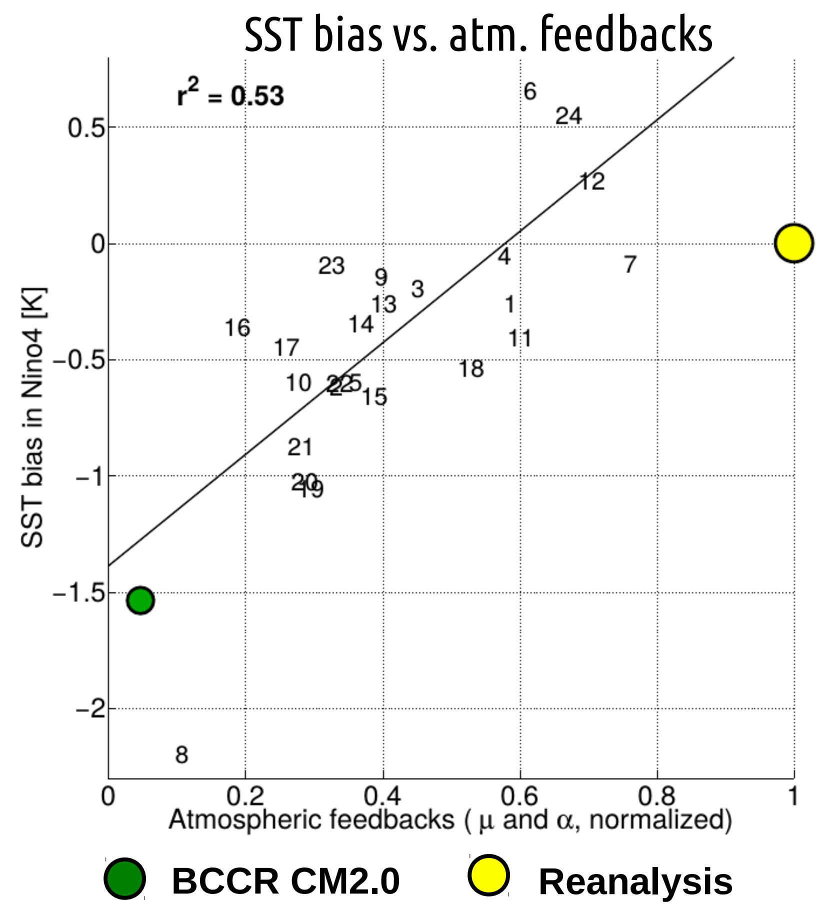
In respect of the SST bias, it is important to look at relative SST (area mean SST removed)

Bayr et al. (2017), Clim Dyn

SST bias of STRONG, MEDIUM and WEAK

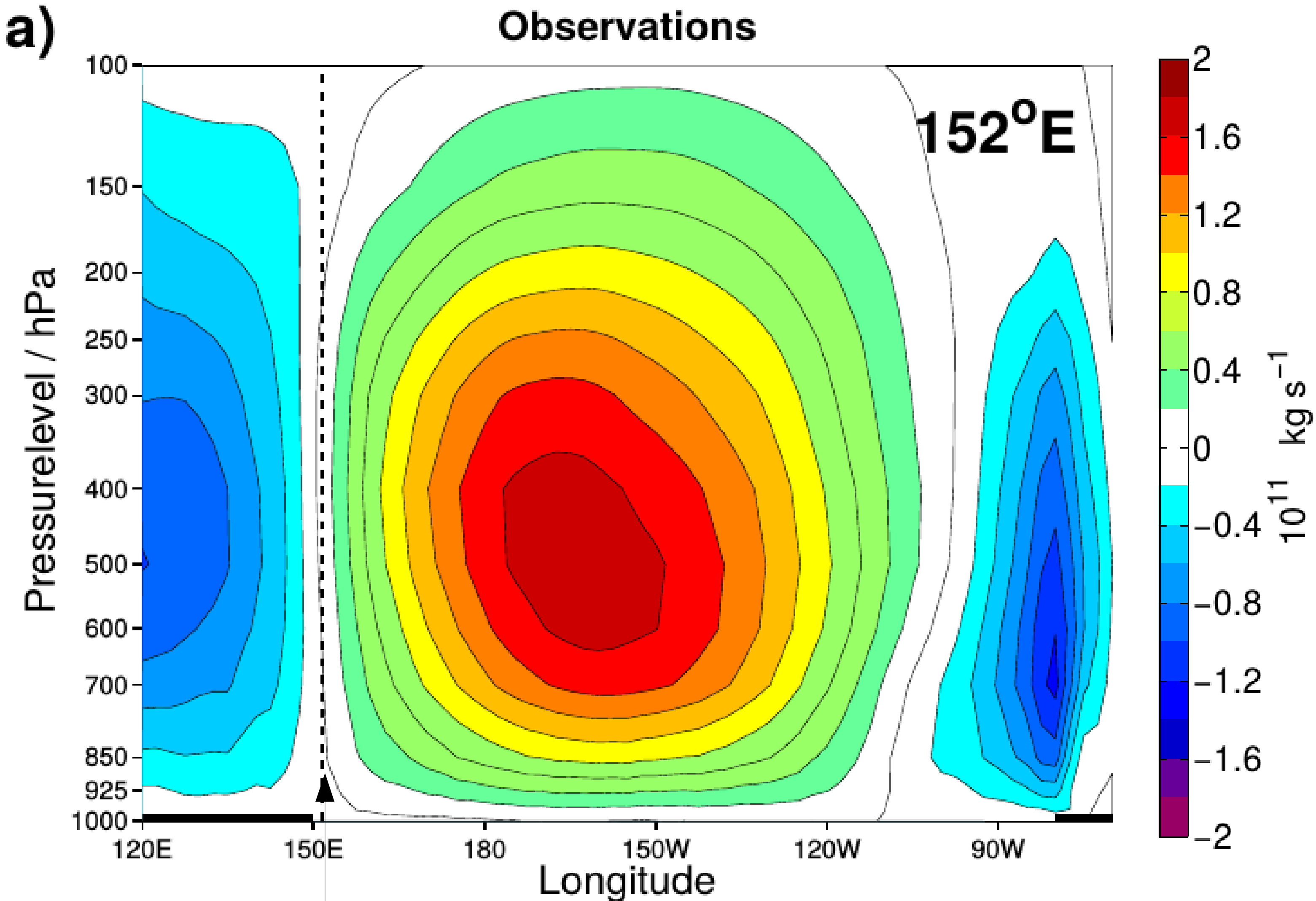


SST bias in the Nino4 region controls ENSO atmospheric feedbacks



Bayr et al. (2017), Clim Dyn

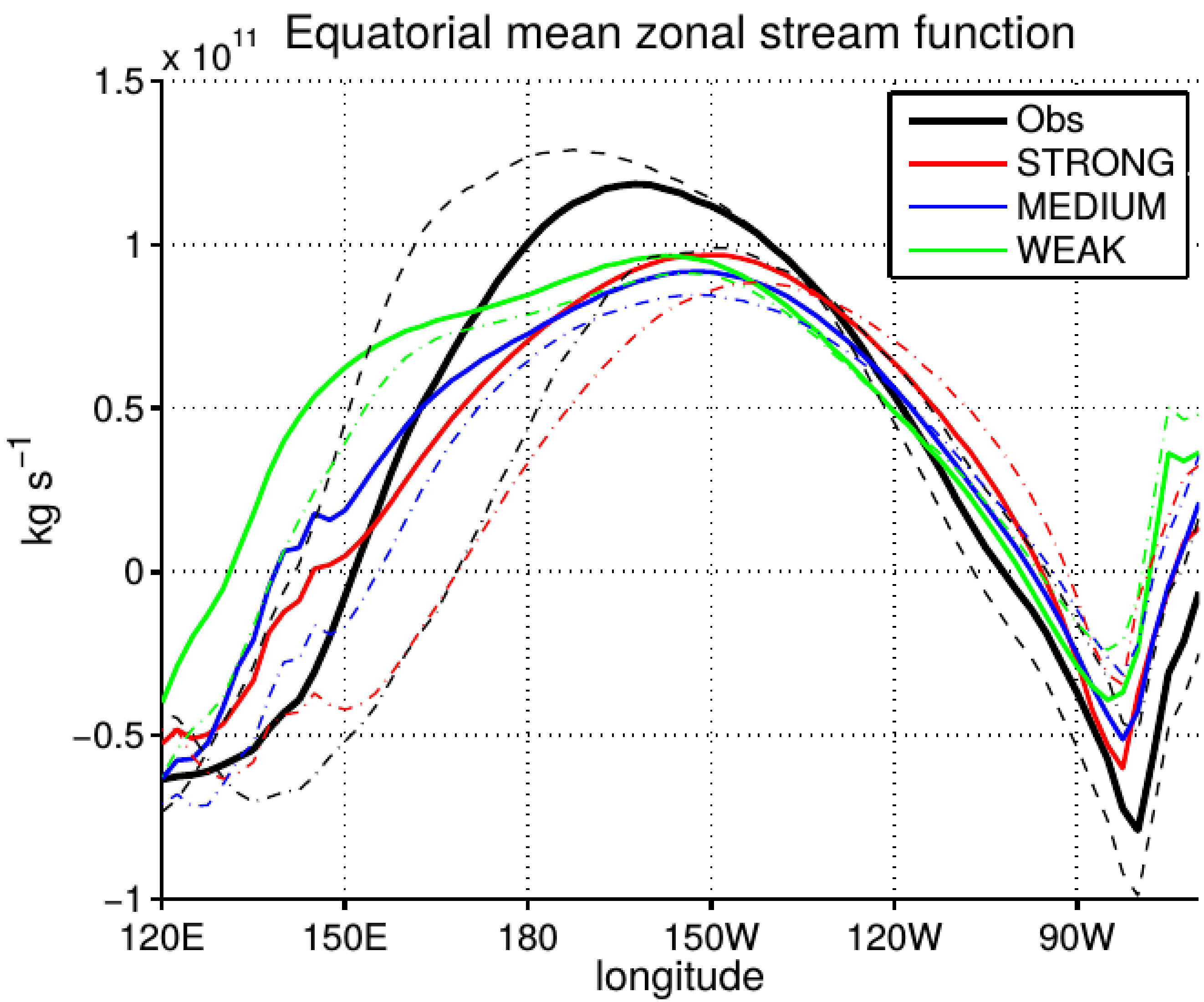
Walker Circulation & feedback strength

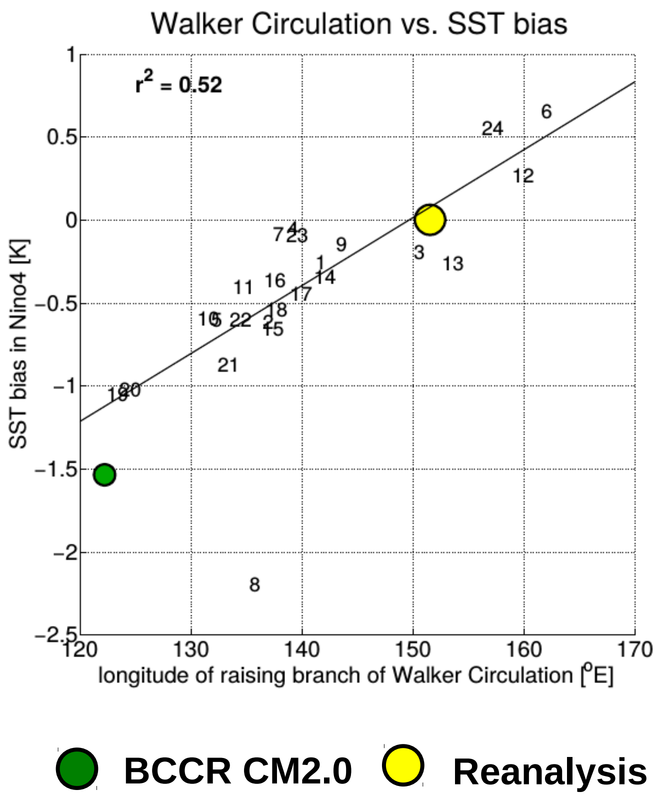


Rising branch of the Walker Circulation
= region of strongest convection

Bayr et al. (2017), Clim Dyn

Walker Circulation & feedback strength

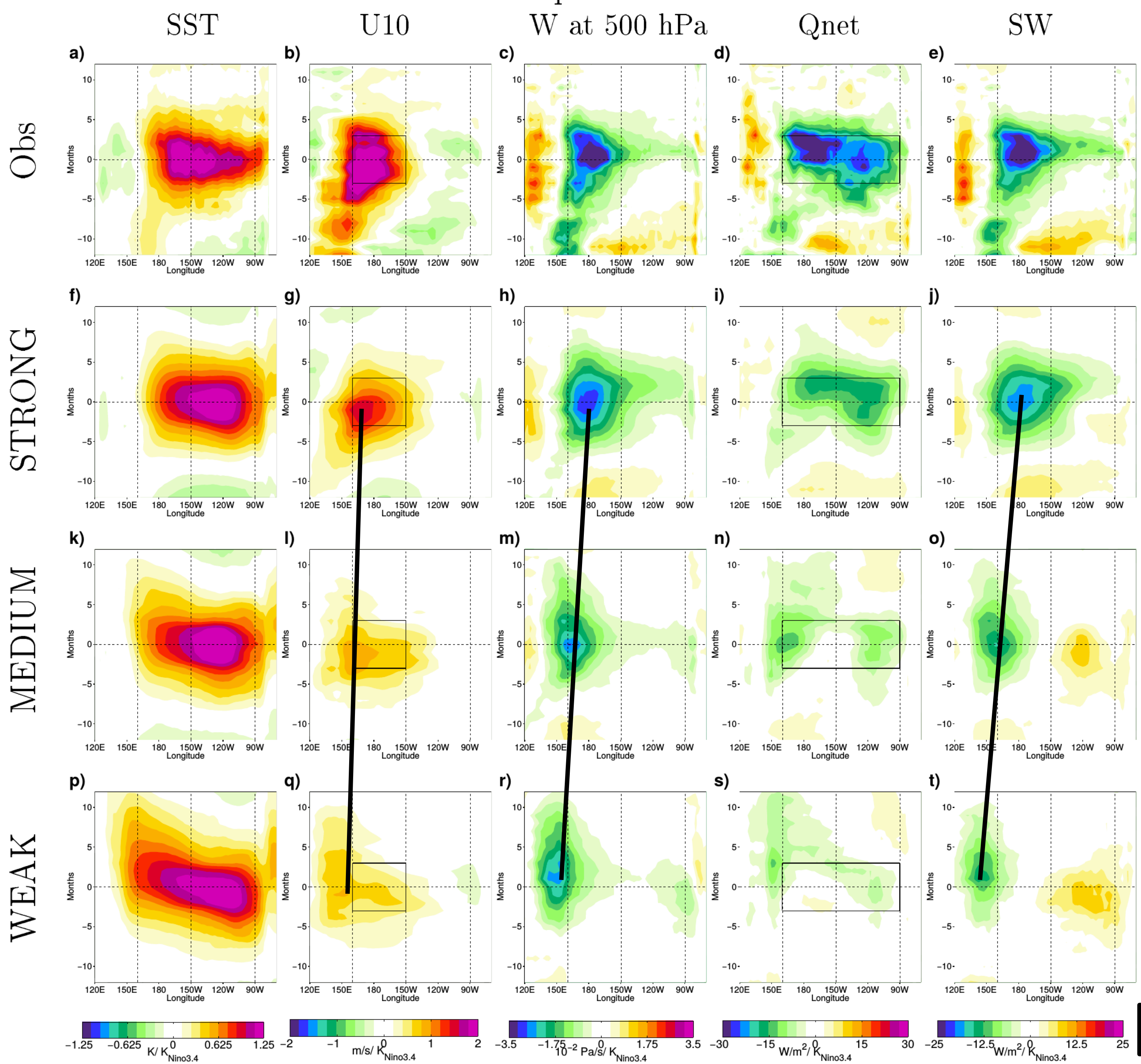




In WEAK the rising branch of the Walker Circulation is too far in the west

Bayr et al. (2017), Clim Dyn

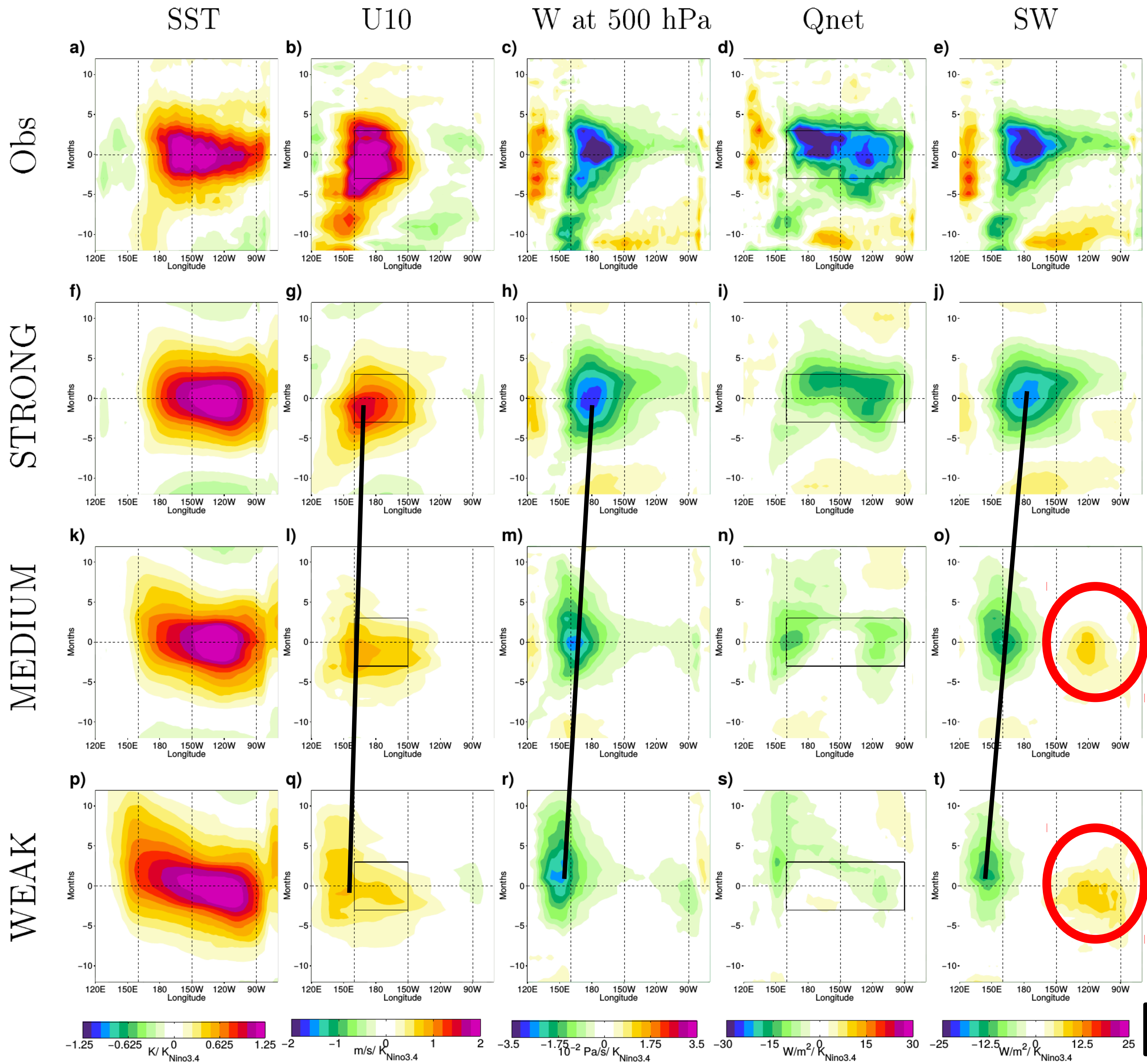
ENSO Composites in Obs and CMIP5



Convective response shifts to the west from STRONG to WEAK

Bayr et al. (2017), Clim Dyn

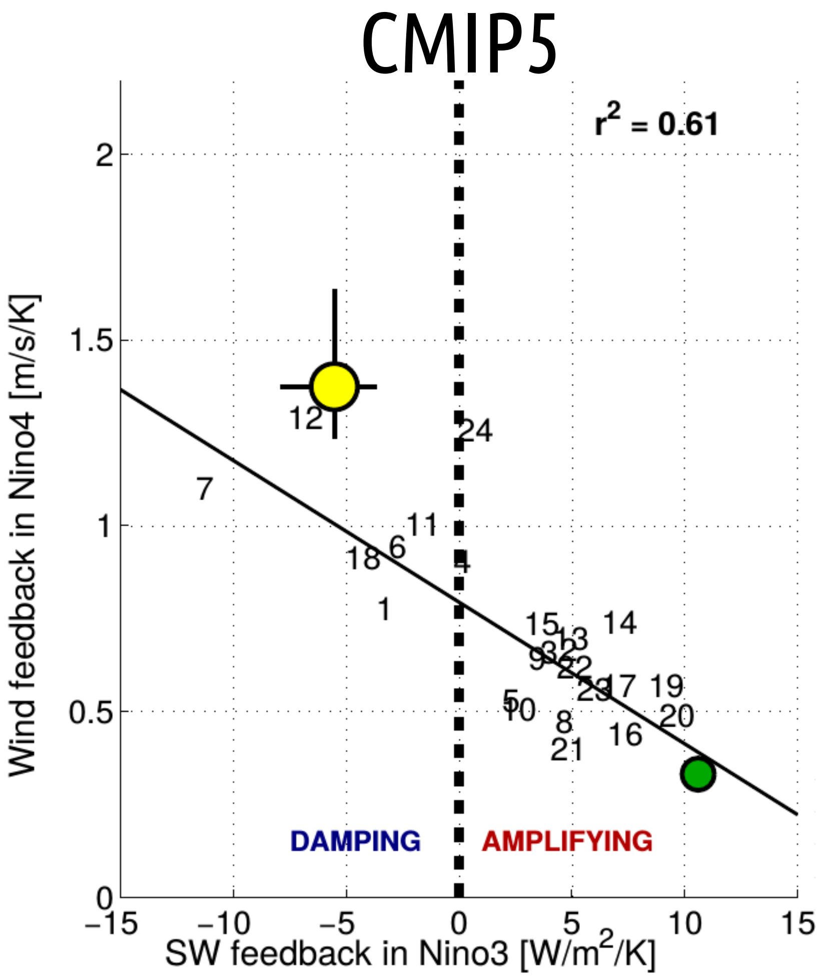
ENSO Composites in Obs and CMIP5

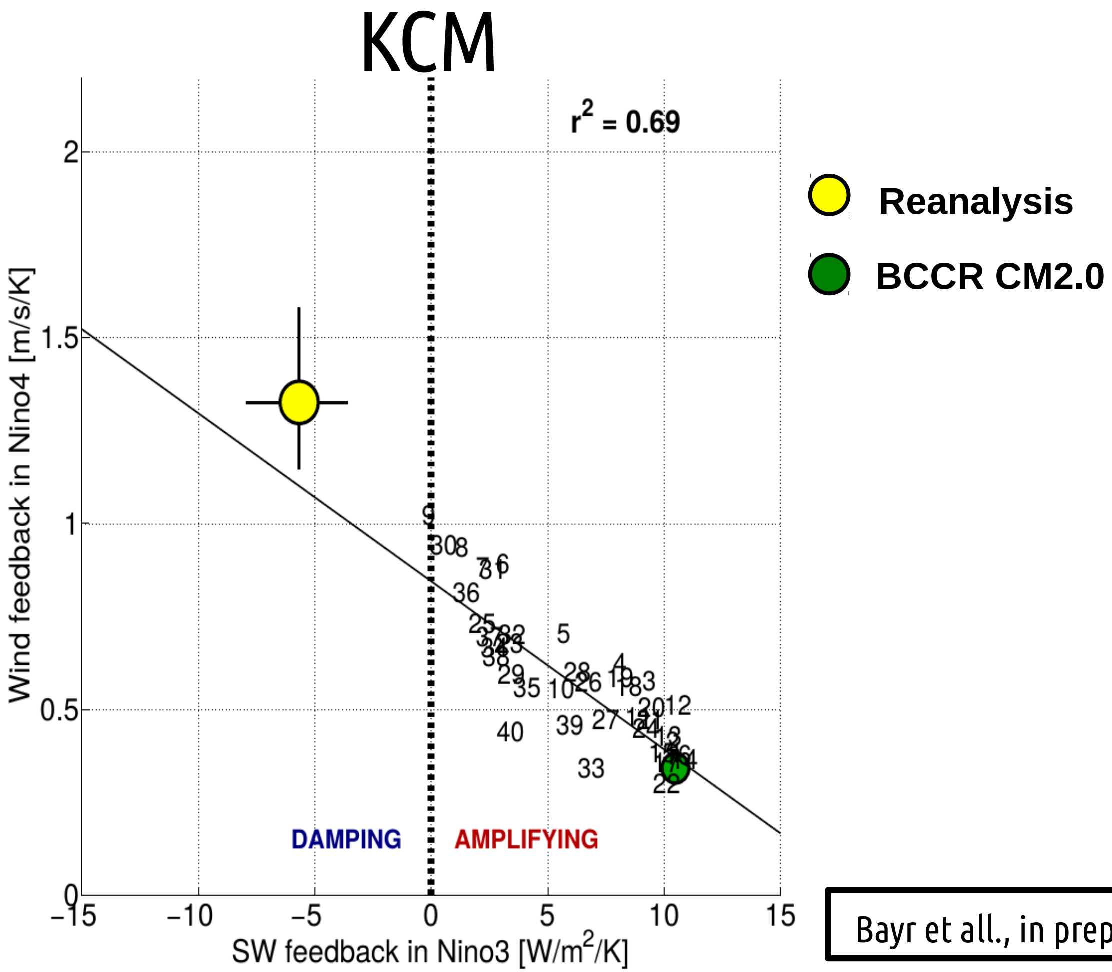


Convective response shifts to the west from STRONG to WEAK

Bayr et al. (2017), Clim Dyn

Wind-driven or short wave-driven ocean-atmosphere coupling?



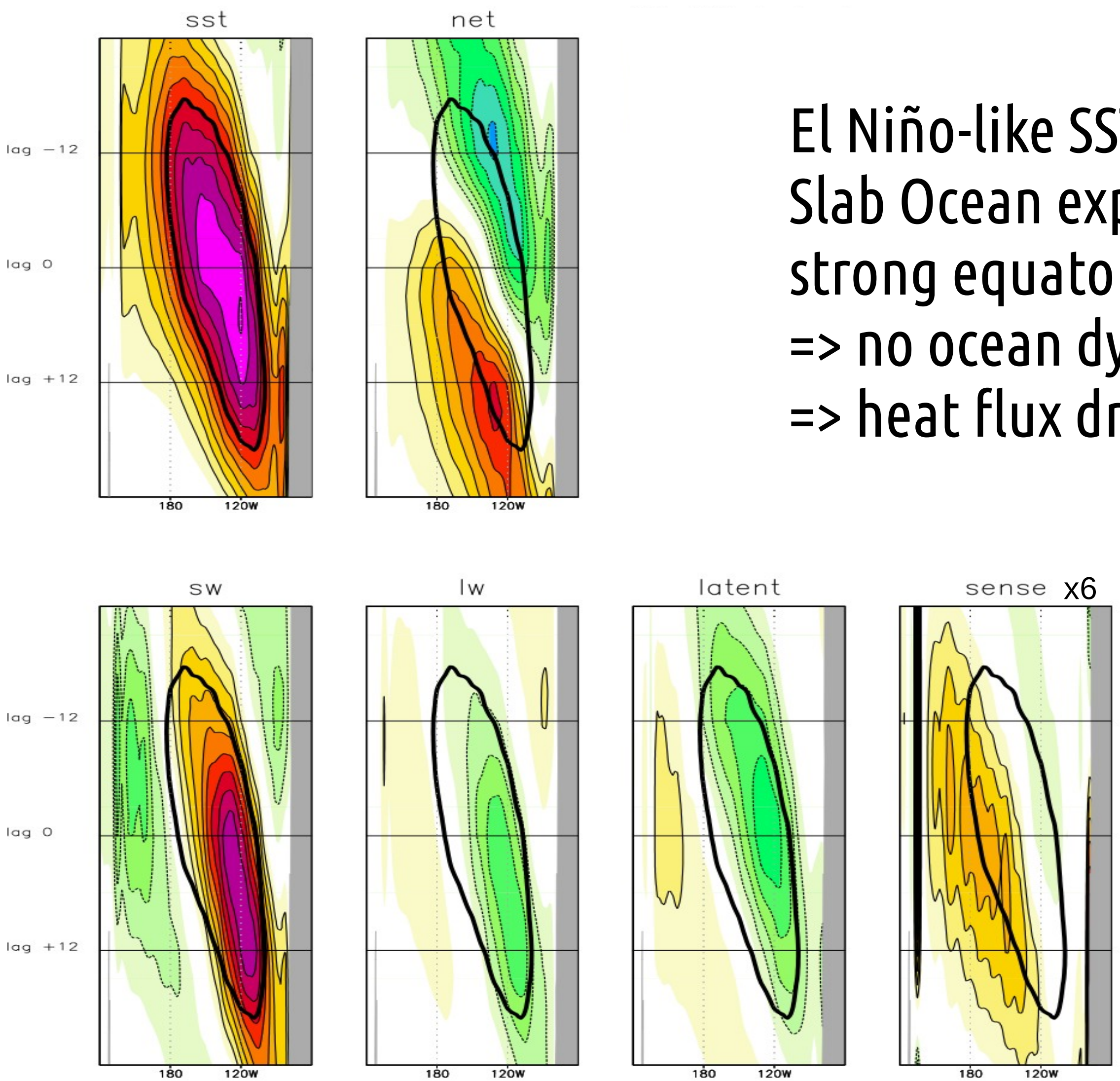


Bayr et all., in prep.

gradual shift in ENSO dynamics!

=> a continuum of possible ENSO dynamics exists in the climate models!

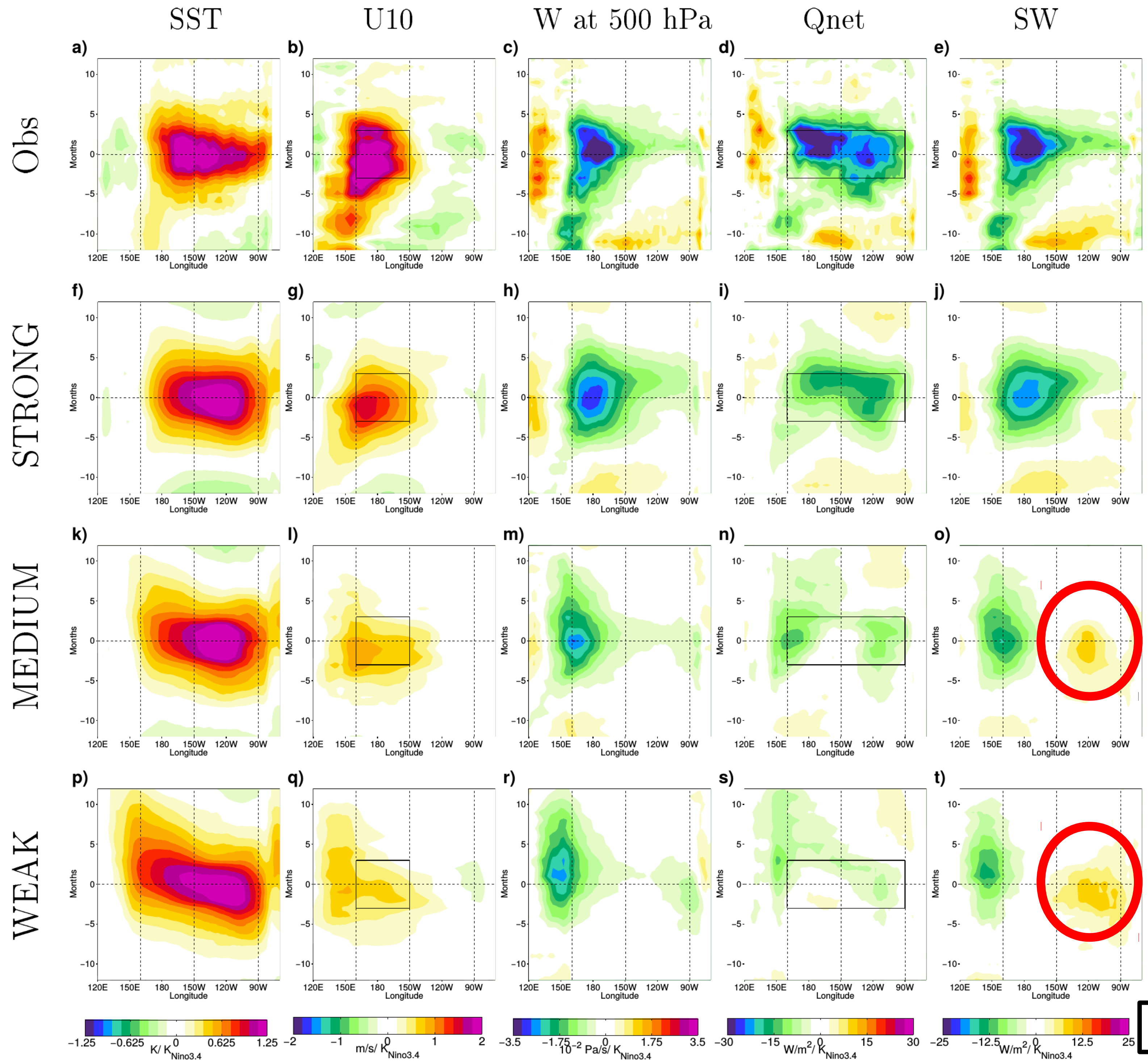
Heat Flux El Niño (or Slab Ocean El Niño)



El Niño-like SST variability in a Slab Ocean experiment with strong equatorial cold SST bias
=> no ocean dynamics
=> heat flux driven

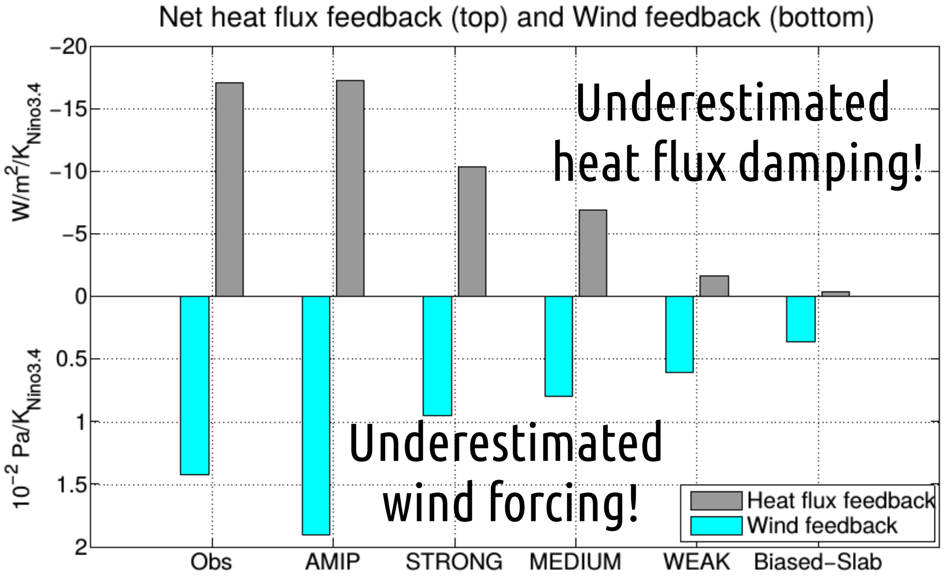
Dommenget (2010)

ENSO Composites in Obs and CMIP5



Bayr et al. (2017), Clim Dyn

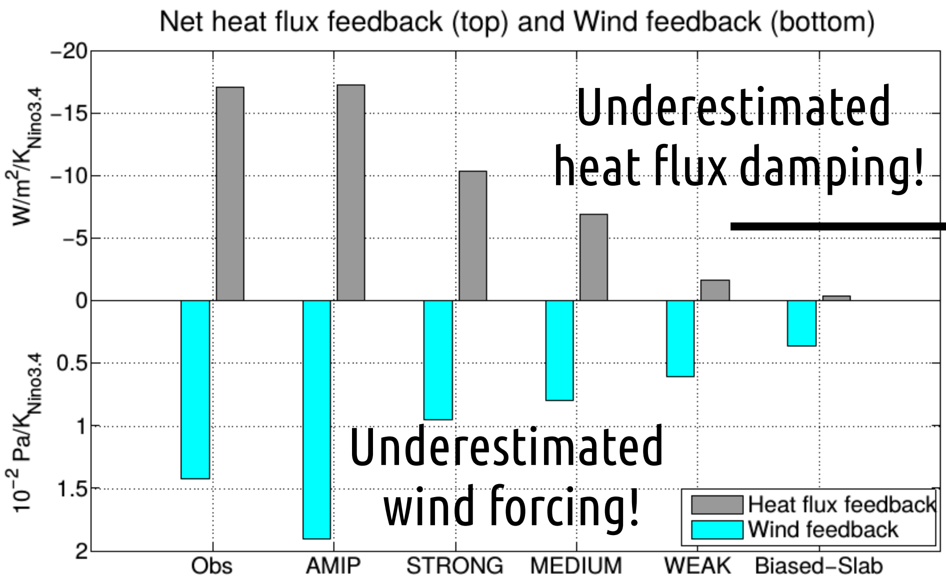
Error Compensation

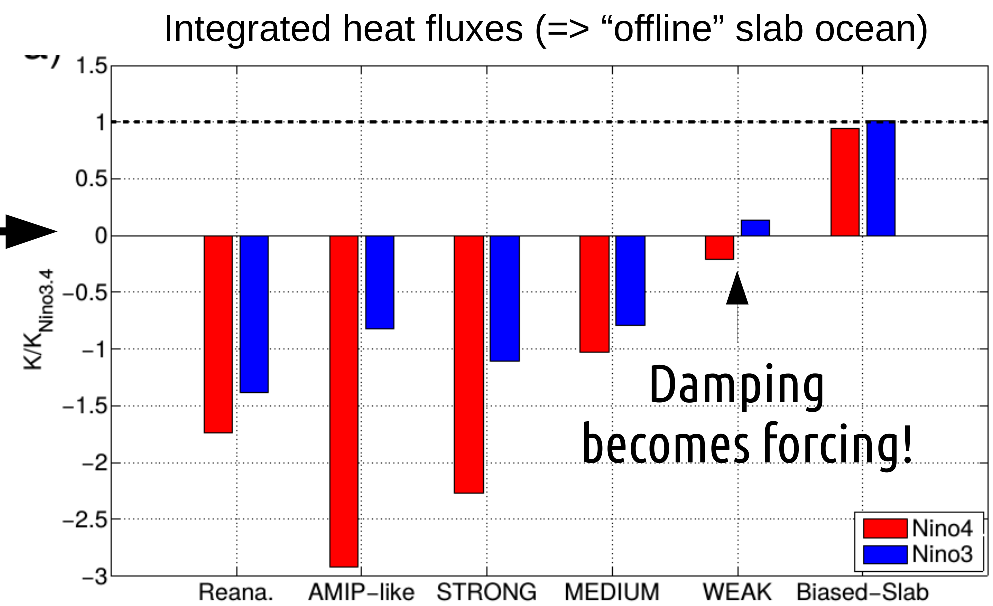


Bayr et al. , in prep.

Error Compensation

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





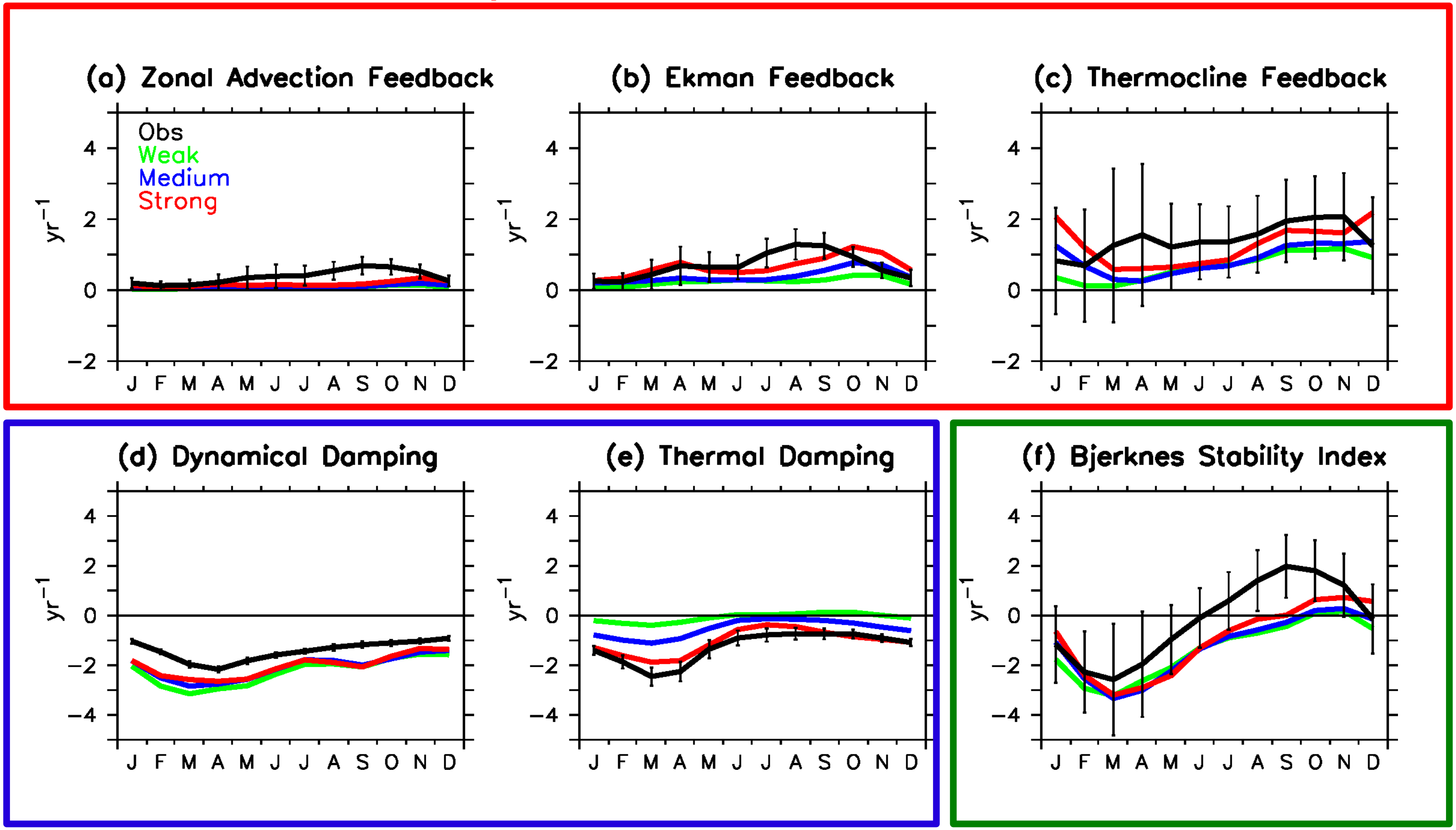
Reanalysis: ~2.5K of subsurface warming by ocean dynamics are needed to generate 1K of SST warming

=> This becomes less from STRONG to WEAK

Bayr et al. , in prep.

The Bjerknes Stability Index: positive and negative ENSO feedbacks

positive feedbacks

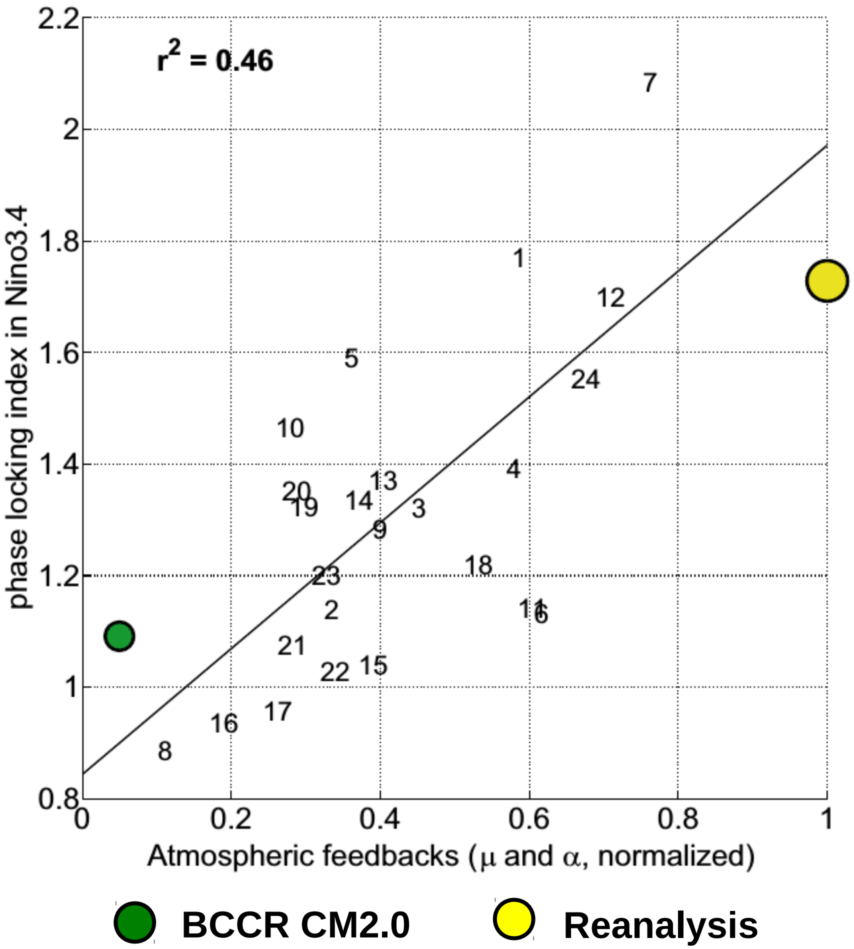


negative feedbacks

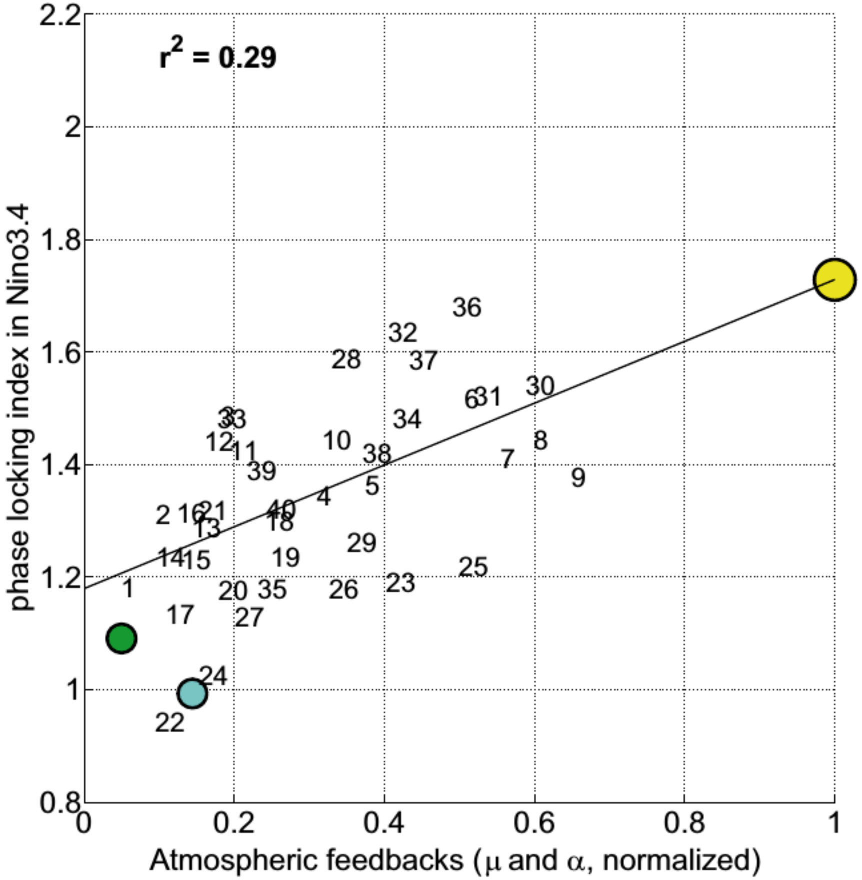
sum of pos. and neg. feedbacks

Influence of atmospheric feedbacks on ENSO phase locking

CMIP5



KCM

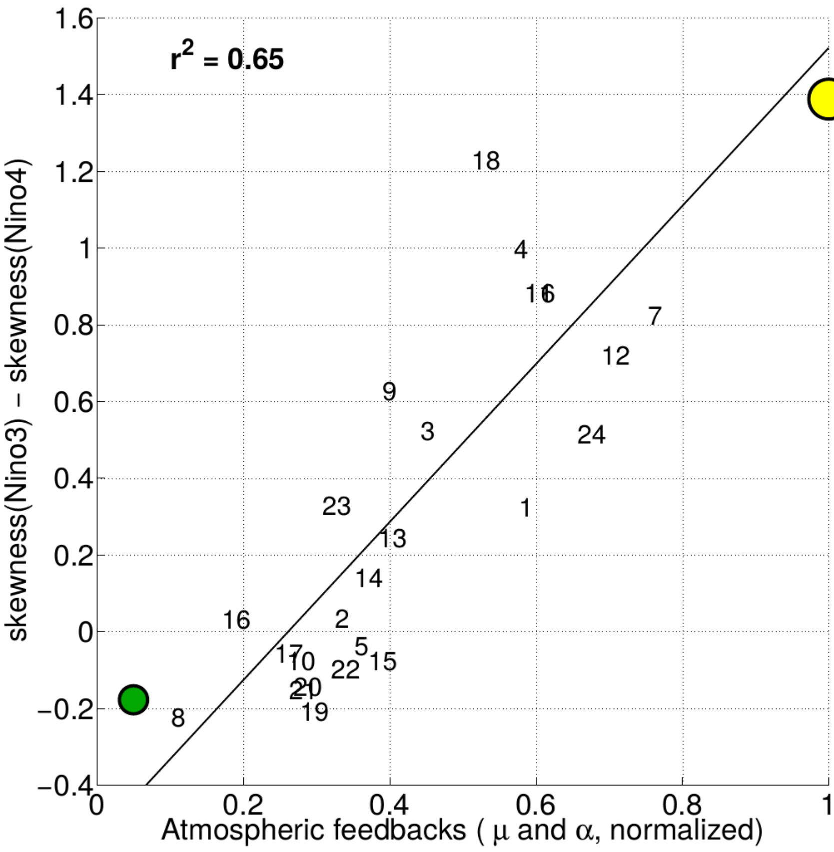


Stronger atm. feedbacks lead to a more realistic ENSO phase locking!

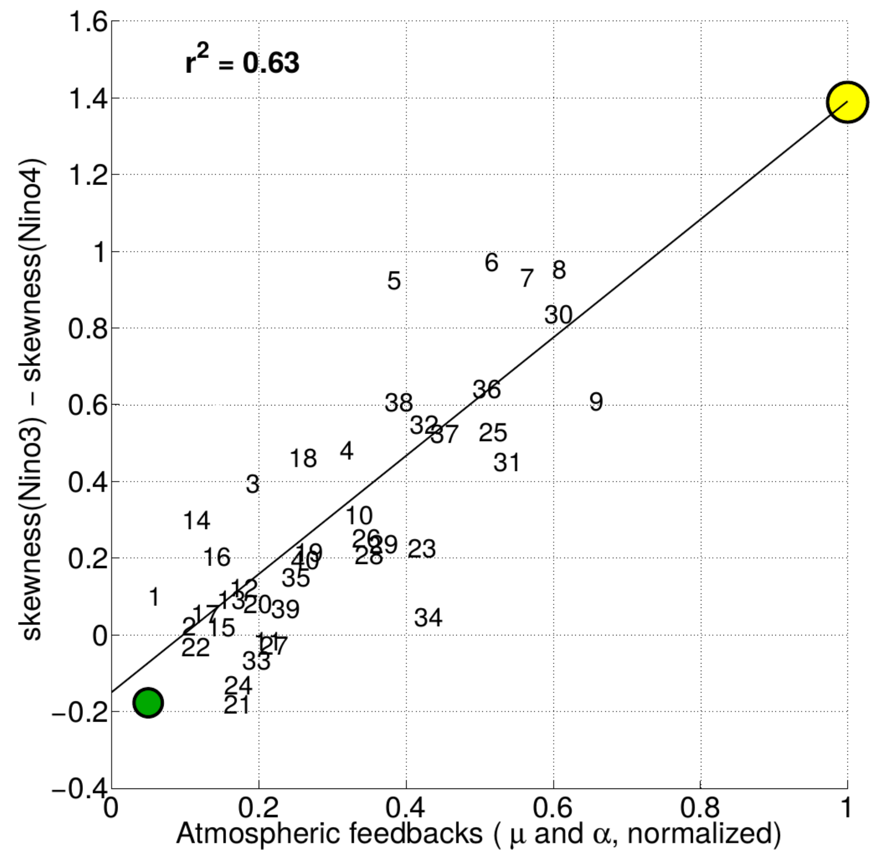
Bayr et al. (2017), Clim Dyn

Influence of atmospheric feedbacks on ENSO asymmetry

CMIP5



KCM



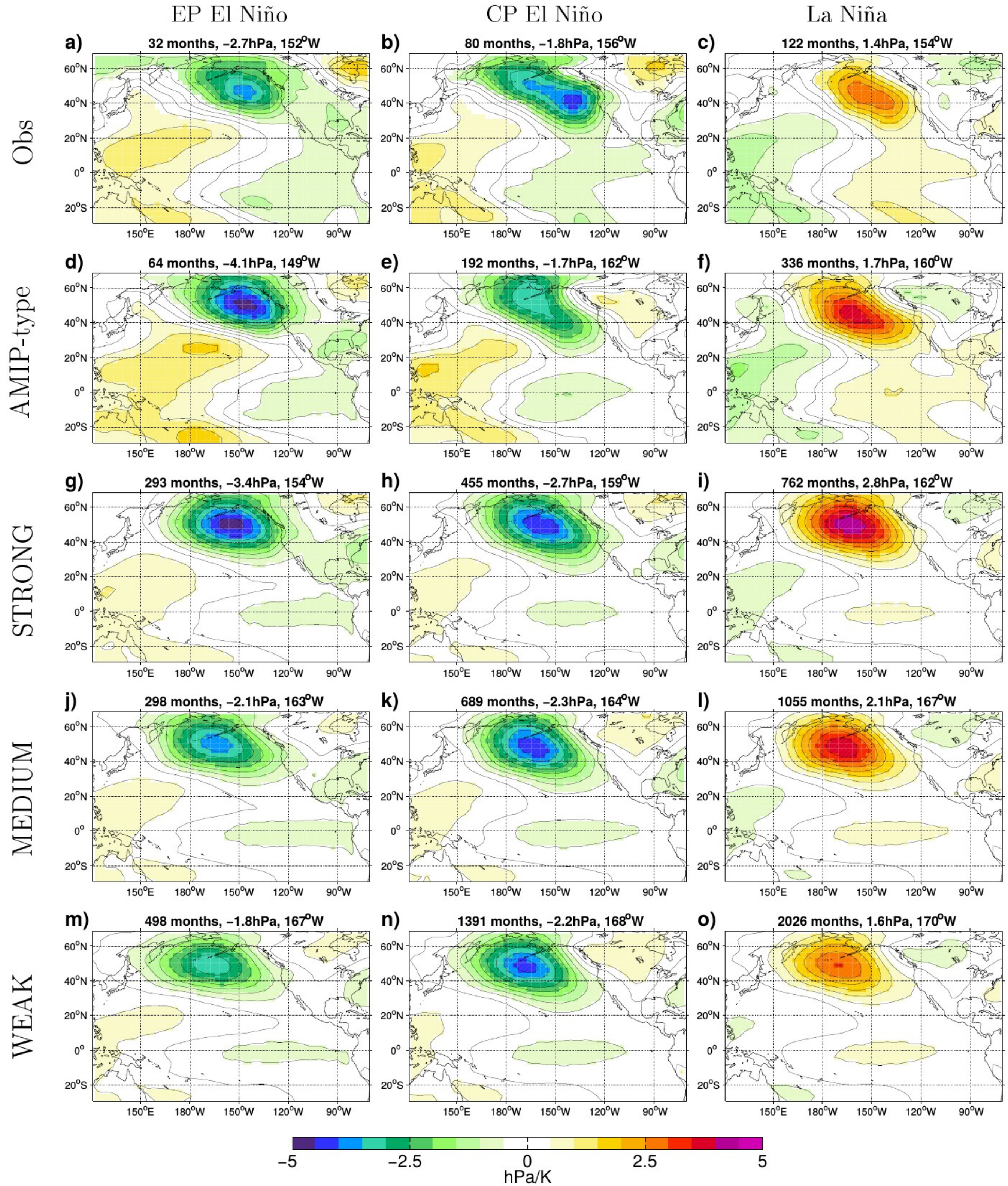
BCCR CM2.0 **Reanalysis**

Stronger atm. feedbacks lead to a more realistic ENSO asymmetry!

Bayr et al. (2017), Clim Dyn

Influence of atmospheric feedbacks on ENSO teleconnections:

SLP over the North Pacific

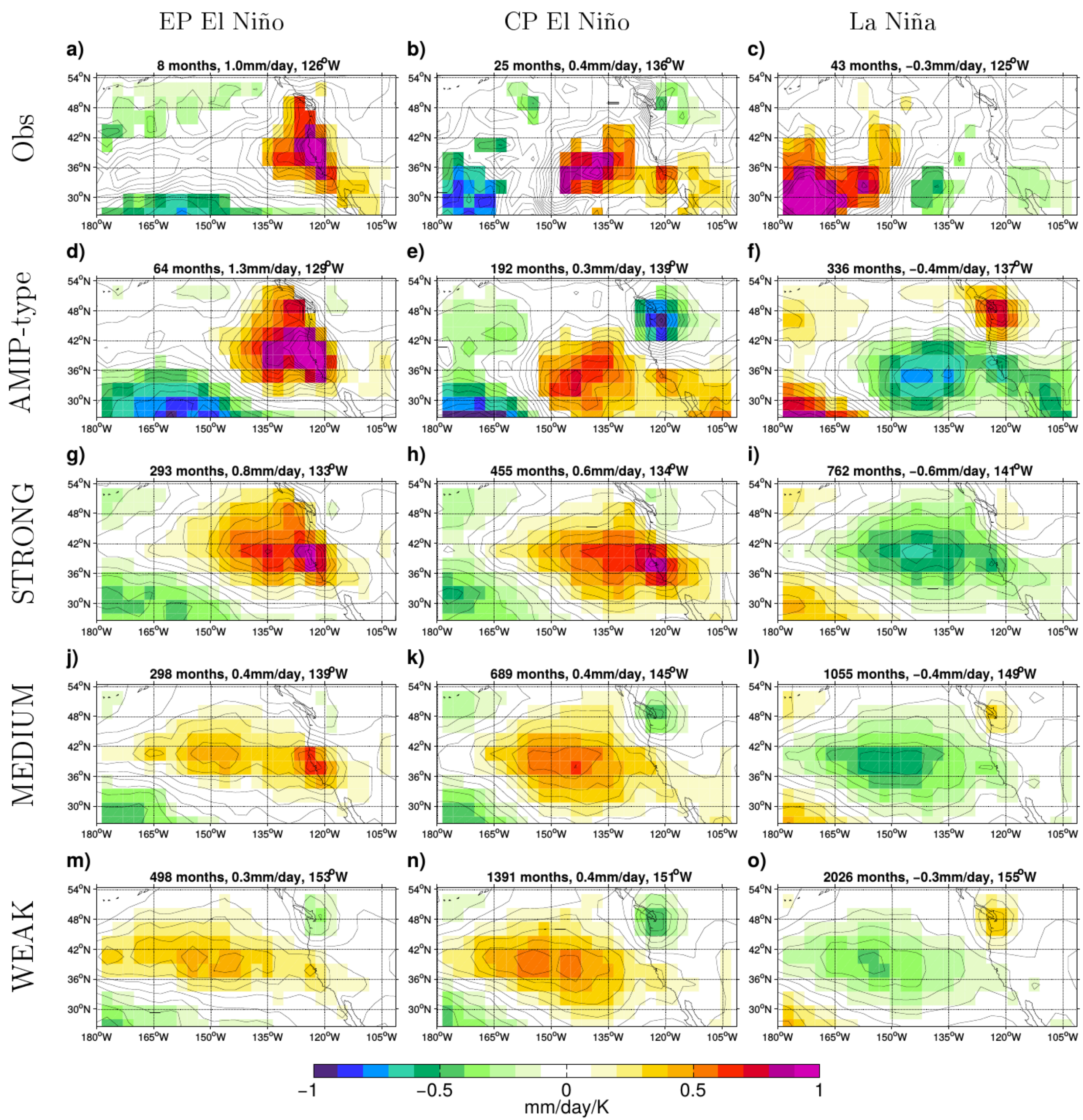


SLP response becomes weaker and more westward from STRONG to WEAK

Domeisen et al., in prep.

Influence of atmospheric feedbacks on ENSO teleconnections:

Precip over California



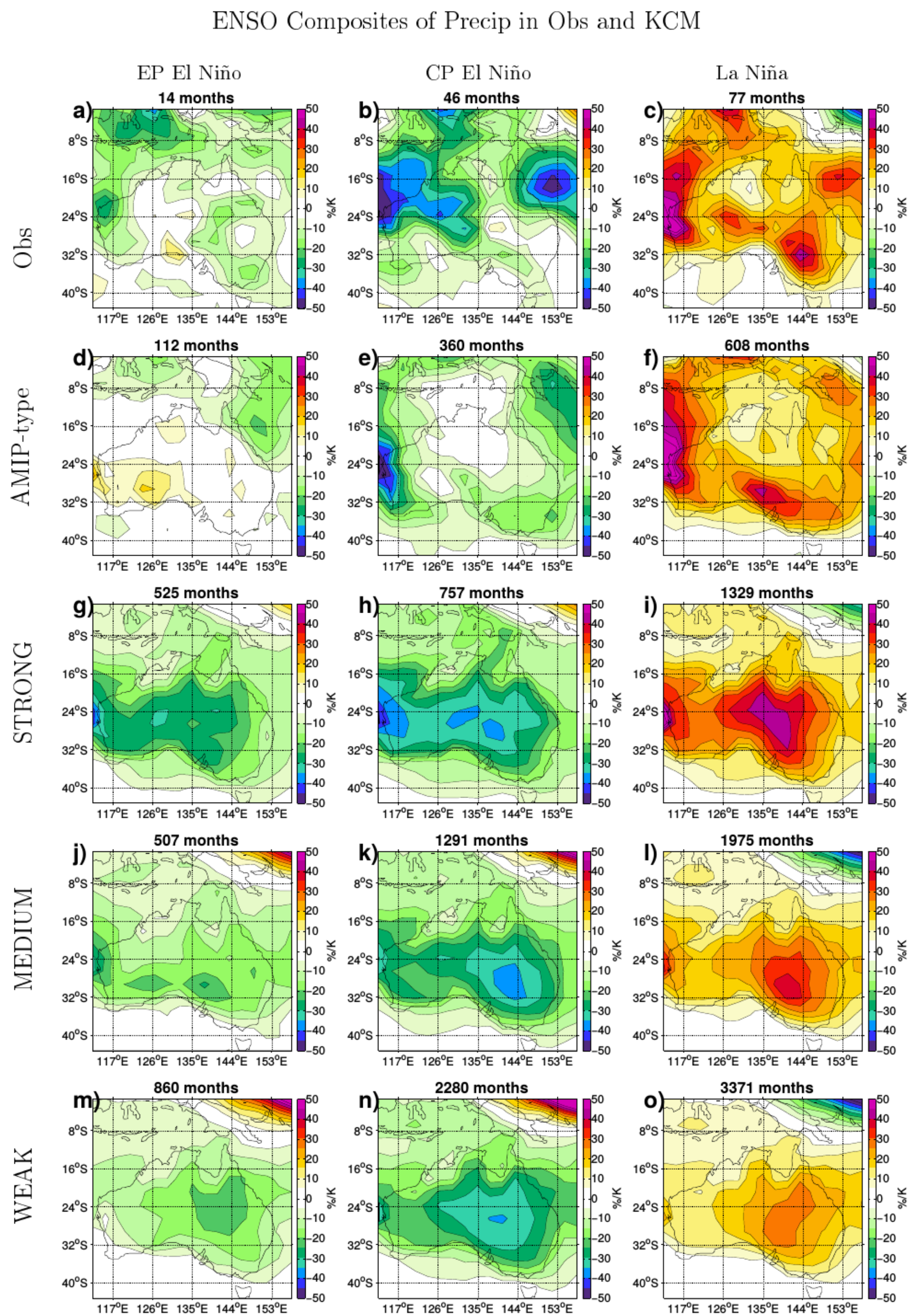
precip response becomes weaker and more westward from STRONG to WEAK

Domeisen et al., in prep.

Influence of atmospheric feedbacks on ENSO teleconnections:

ONDJFM Precip over Australia

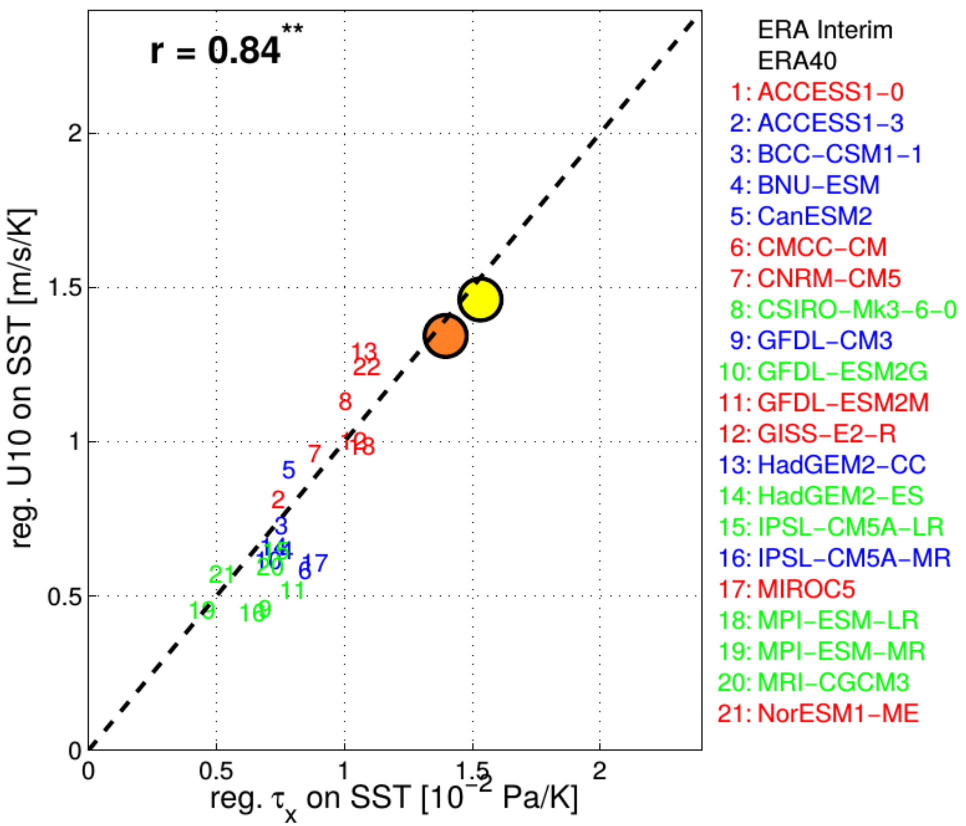
precip response becomes weaker and more westward from STRONG to WEAK



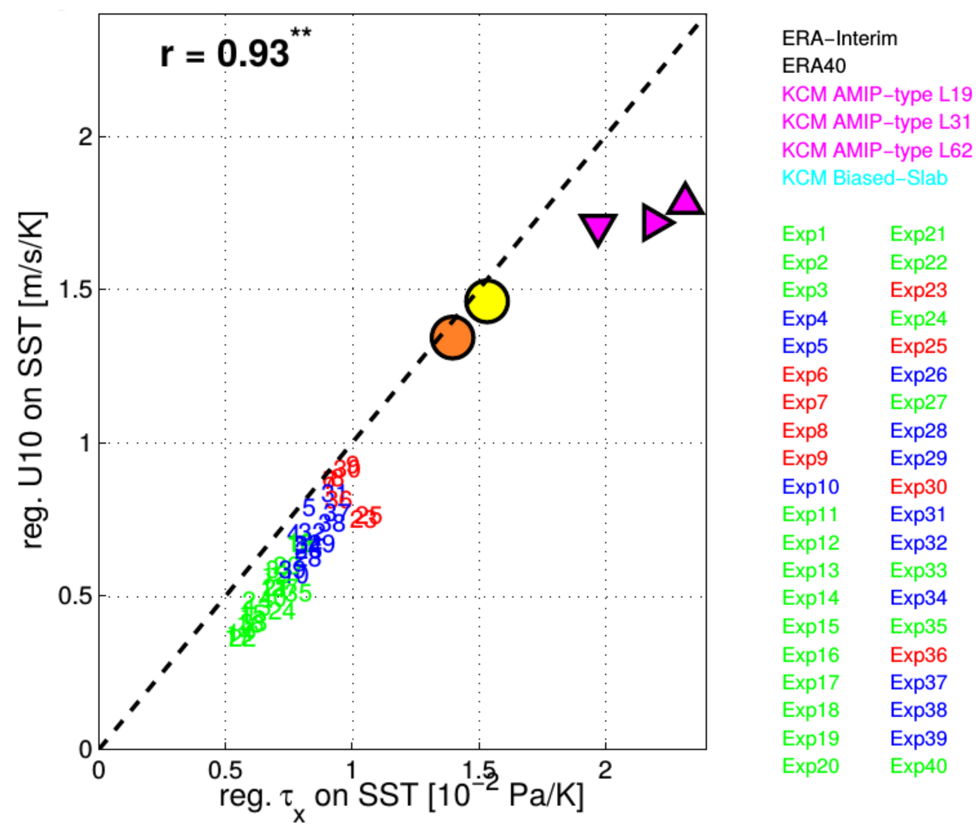
Open questions

10m wind vs. wind stress

CMIP5



KCM



Why is there such a huge difference between 10m wind and wind stress in the CMIP5 models?

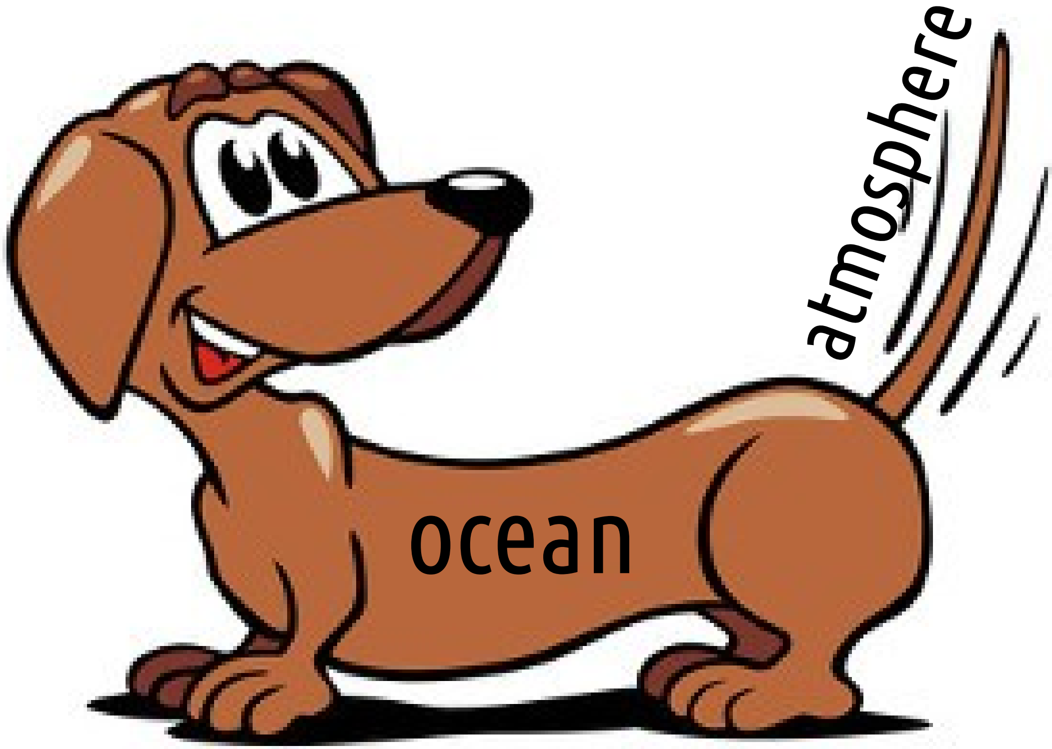
Summary

Why do the models underestimate the atmospheric feedbacks?
The cold SST bias shifts the rising branch of the Walker Circulation to the west

Why are there an error compensation between the two atmospheric feedbacks?
The wind and the short-wave feedback both depend on the position of the rising branch of the Walker Circulation

What influence has this on simulated ENSO dynamics?
This shifts ENSO dynamics from a wind-driven mode into a partly short-wave-driven mode => the models do the right thing for the wrong reasons!

Dog and Tail



ENSO is a coupled ocean-atmosphere phenomena!
Question: Which positive feedback couples ocean and atmosphere?

ENSO dynamics in climate models

Dogs wags tail

or

Tail wags dog

Bjerknes feedback:

Wind-SST feedback drives ENSO

Heat flux El Niño:

Shortwave feedback drives ENSO

Take home massage:

Two types of ENSO dynamics exist in many climate models!

Dogs wags tail

~~or~~ and

Tail wags dog

Bjerknes feedback:

explains observed ENSO

but is partly absent in CGCMs

Heat flux El Niño:

due to equatorial cold bias,

is partly present in CGCMs

Take home massage:

Many climate models have ENSO variability for the wrong reasons!

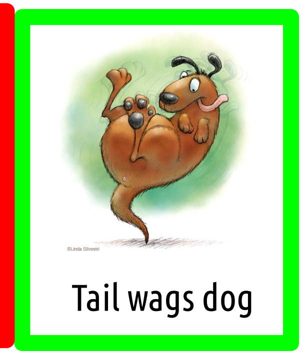
Climate Models with

STRONG

MEDIUM

WEAK

atmospheric feedbacks



Cold SST bias in Niño4

small | medium | large

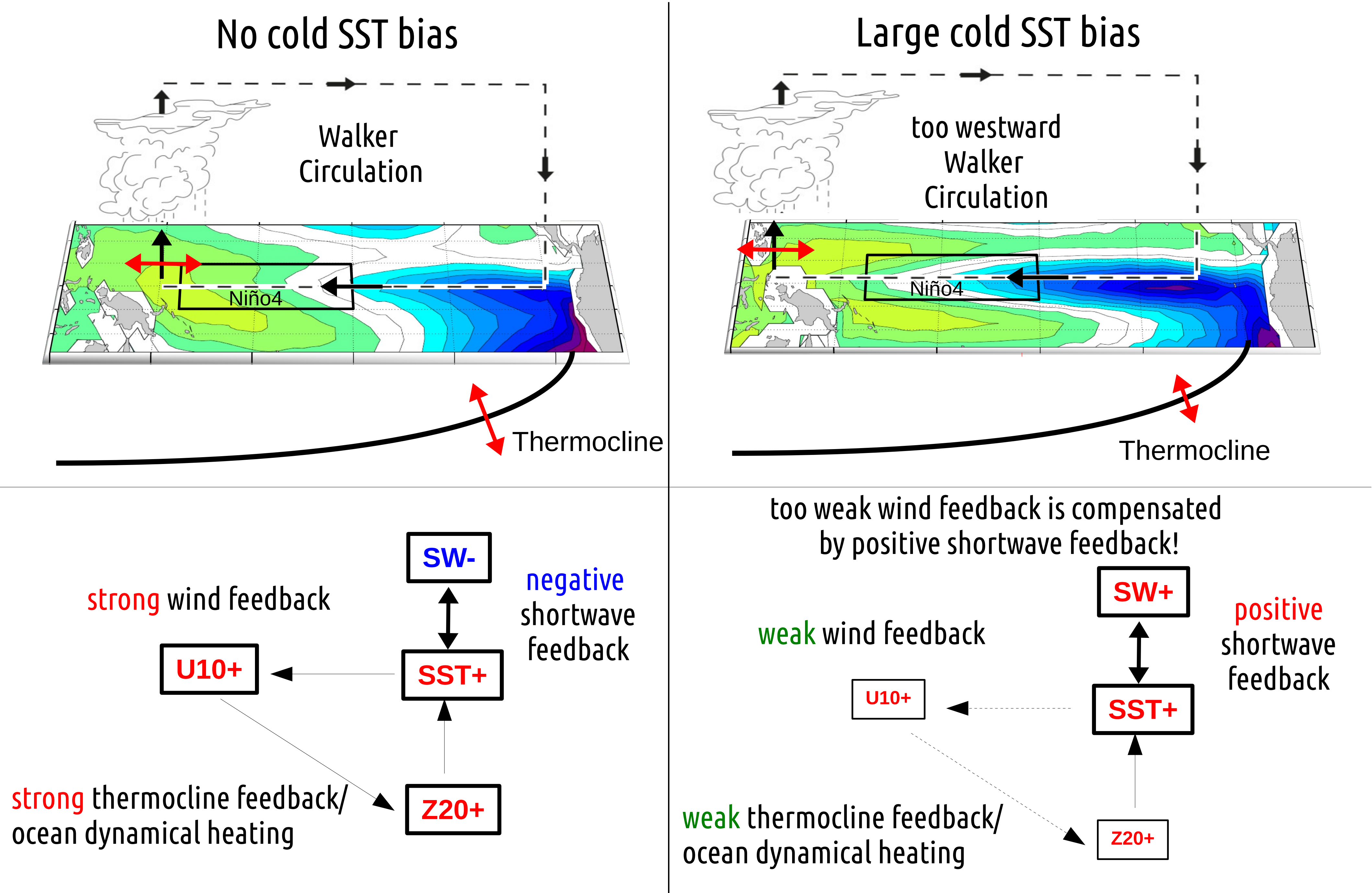
Wind-SST feedback

strong | medium | weak

Shortwave-SST feedback

negative | neutral | positive

Thank you for your attention!



References

Bayr, T., M. Latif, D. Dommenget, C. Wengel, J. Harlaß, and W. Park, 2017: Mean-State Dependence of ENSO Atmospheric Feedbacks in Climate Models. *Clim. Dyn.*, doi:10.1007/s00382-017-3799-2.

Bellenger, H., E. Guilyardi, J. Leloup, M. Lengaigne, and J. Vialard, 2014: ENSO representation in climate models: From CMIP3 to CMIP5. *Clim. Dyn.*, **42**, 1999–2018, doi:10.1007/s00382-013-1783-z.

Dommenget, D., 2010: The slab ocean El Niño. *Geophys. Res. Lett.*, **37**, L20701, doi:10.1029/2010GL044888.