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

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Motivation:
ENSO response under global warming is still uncertain!

Enso dynamics in climate models still show severe deficits!

Adapted and updated from IPCC AR4 (2007)
El Niño/Southern Oscillation

Normal Conditions

Convective Circulation

Equator

Thermocline

120° E  80° W

El Niño Conditions

Thermocline

120° E  80° W
The positive Bjerknes Feedback and negative heat flux feedback

Sea Surface Temperature over eastern Pacific

Zonal Wind over western Pacific

Convective Circulation

Normal Conditions

El Niño Conditions

Thermocline depth in eastern Pacific

Zonal Wind

U10+

SST+

Thermocline

Z20+
The positive Bjerknes Feedback and negative heat flux feedback

- **Sea Surface Temperature** over eastern Pacific
- **Zonal Wind** over western Pacific
- **Convective Circulation**
- **Thermocline depth** in eastern Pacific
- **Heat flux** over western and eastern Pacific
  - $Q_{net}^-$

**Normal Conditions**

**El Niño Conditions**

- **U10+**
- **SST+**
- **Z20+**
The positive Bjerknes Feedback and negative heat flux feedback

Zonal Wind over western Pacific

U10+

SST+

Sea Surface Temperature over eastern Pacific

Heat flux over western and eastern Pacific

Qnet-

Thermocline depth in eastern Pacific

Z20+
Motivation: Underestimated Atmospheric Feedbacks in CMIP3 and CMIP5

Most CMIP3 and CMIP5 models underestimate Wind-SST feedback and Heat flux-SST feedback. Is there error compensation?

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

Observations

c = -0.48

Bellenger et al. (2014)
Motivation: Underestimated Atmospheric Feedbacks in CMIP3 and CMIP5

Observations

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

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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!

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 Niño 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 Niño events, and cools during La Niña 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 anomalies. 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 SST.

**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 SST.

**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 SST. This feedback plays an important role for CP El Niño 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 SST.

**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 Niño events.

**Multiplicative Noise:** As the warm pool expands eastward during a developing El Niño, 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 Niño 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 Niño and La Niña 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.

*Timmermann et al. (2018)*
Motivation: How can models have a realistic ENSO amplitude with strongly underestimated wind feedbacks?
ENSO Hoevmoeller composites
(normalised with Niño3.4 SST)

std(Niño3.4) = 0.82

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?

\[ \text{std(Niño3.4)} = 0.98 \]
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

- 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

Mauritsen et al. (2012)
ECHAM5 experiments:
Perturbed physics vs. mean state

Zonal wind feedback

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
In respect of the SST bias, it is important to look at relative SST (area mean SST removed)
SST bias of STRONG, MEDIUM and WEAK SST bias in the Nino4 region controls ENSO atmospheric feedbacks

SST bias vs. atm. 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
In **WEAK** the rising branch of the Walker Circulation is too far in the west

Bayr et al. (2017), Clim Dyn
Convective response shifts to the west from STRONG to WEAK
Convective response shifts to the west from **STRONG** to **WEAK**
Wind-driven or short wave-driven ocean-atmosphere coupling?

CMIP5

\[ r^2 = 0.61 \]

KCM

\[ r^2 = 0.69 \]

Reanalysis

BCCR CM2.0

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

Bayr et al., in prep.
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

Dommengst (2010)
Bayr et al. (2017), Clim Dyn

ENSO Composites in Obs and CMIP5

SST

U10

W at 500 hPa

Qnet

SW

Obs

STRONG

MEDIUM

WEAK
Error Compensation

Bayr et al., in prep.
Error Compensation

Integrated heat fluxes (=> “offline” slab ocean)

Underestimated heat flux damping!

Underestimated wind forcing!

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

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**positive feedbacks**

(a) Zonal Advection Feedback

(b) Ekman Feedback

(c) Thermocline Feedback

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**negative feedbacks**

(d) Dynamical Damping

(e) Thermal Damping

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**sum of pos. and neg. feedbacks**
Influence of atmospheric feedbacks on ENSO phase locking

CMIP5

KCM

$r^2 = 0.46$

$r^2 = 0.29$

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

Bayr et al. (2017), Clim Dyn
Influence of atmospheric feedbacks on ENSO asymmetry

Bayr et al. (2017), Clim Dyn

CMIP5

KCM

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

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!
ENSO is a coupled ocean-atmosphere phenomena!

Question: Which positive feedback couples ocean and atmosphere?
ENSO dynamics in climate models

**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!

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

- Wind-SST feedback
  - strong positive
  - medium neutral
  - weak negative

- Shortwave-SST feedback
  - small strong negative
  - medium neutral
  - large positive
Thank you for your attention!

No cold SST bias

Large cold SST bias

too westward
Walker
Circulation

too weak wind feedback is compensated
by positive shortwave feedback!

strong wind feedback

SW-

negative shortwave feedback

U10+

SST+

SW+

positive shortwave feedback

weak wind feedback

U10+

SST+

weak thermocline feedback/
ocean dynamical heating

strong thermocline feedback/
ocean dynamical heating

Z20+

Z20+
References

