Sensitivity of the Pacific Cold Tongue and Double-ITCZ Biases to Convective Parameterization

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Simulated equatorial sea surface temperatures are too cold.
Excess rainfall in the southeast Pacific; Insufficient rainfall on the equator

Hwang and Frierson (2013)
Precipitation biases amplified when coupled.

Li and Xie (2014)
These biases are found in the CESM-LENS.
Suggested bias sources

• Extratropical controls
  - e.g. Hwang and Frierson (2013); Kay et al. (2016); Hawcroft et al. (2016)

• Coupled ocean-atmosphere feedbacks
  - e.g. Zhang et al. (2007), Liu et al. (2012)

• Inadequate convective parameterization
  - e.g. Song and Zhang (2009), Oueslati and Bellon (2015)
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If convection plays a key role in coupled tropical feedbacks related to the double-ITCZ and cold tongue biases, perturbations to convective parameterization should influence the development of these biases.
Model simulations use CESM1

**Atmosphere (2°)**
CAM5, Finite Volume
Prescribe Aerosols

**Sea Ice (1°)**
CICE4

**Ocean (1°)**
POP2

**Land (2°)**
CLM4.0
(Satellite Phenology)

**Comparison datasets**

- **GPCP** (Huffman et al., 2009)
  - Precipitation

- **SODA** (Carton and Geiss, 2008)
  - Sea surface temperature (SST)
  - Surface wind stress ($\tau$)
  - Ocean velocities
Simulation plan

Spin up model components

Ocean/Sea Ice (CORE2 Forced; Large and Yeager, 2009)

Atmosphere IC (ERA Interim)

Land (CAS Atmo. Forcing; Qian et al., 2006)

Initial conditions for coupled run taken from this point
Simulation plan

[1] Spin up model components
[2] Run stand alone models forward

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(CORE2 Forced; Large and Yeager, 2009)

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1981-01

1986-01

1991-01

Initial conditions for coupled run taken from this point
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Ocean/Sea Ice (CORE2 Forced; Large and Yeager, 2009)

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Initial conditions for coupled run taken from this point
Convective parameterizations used

CTRL (and NOSP)
- UW ShCu (Park and Bretherton, 2009)
- ZM DC (Zhang and McFarlane, 1995)

NODC
- UW ShCu (Park and Bretherton, 2009)
- ZM DC (Zhang and McFarlane, 1995)

SP
- Embedded 2D cloud-resolving model replacing moist physics (Grabowski, 2001)
Precipitation: Jan-June 1981
Convective parameterization affects meridional width of dry zone.
Convective parameterization affects meridional width of dry zone.

All simulations produce excess SE Pacific rainfall.
No consistent change in double-ITCZ bias.

Stronger double ITCZ
No consistent change in double-ITCZ bias.
100 m ΔOcean Heat Content: Jan-June 1981 mean

OCN - SODA

NODC - SODA

CTRL - SODA

SP - SODA
100 m $\Delta$Ocean Heat Content: Jan-June 1981 mean

No cold tongue bias in ocean only simulation

OCN - SODA

NODC - SODA

CTRL - SODA

SP - SODA
100 m $\Delta$Ocean Heat Content: Jan-June 1981 mean

No cold tongue bias in ocean only simulation

Cold tongue bias develops rapidly in fully coupled simulations

OCN - SODA

CTRL - SODA

NODC - SODA

SP - SODA
100 m ΔOHC: Jan-June 1981 mean

\[
\text{Cold Tongue Index} = \frac{\text{OHC}(3^\circ S: 3^\circ N, 180^\circ: 220^\circ E)}{\text{OHC}(20^\circ S: 20^\circ N, 150^\circ E: 250^\circ E)}
\]
Cold Tongue Index = \[ \text{OHC}(3^\circ S: 3^\circ N, 180^\circ: 220^\circ E) - \text{OHC}(20^\circ S: 20^\circ N, 150^\circ E: 250^\circ E) \]

More negative = Stronger cold tongue
Cold tongue index

\[
\Delta T_{\text{CI}} = W - W
\]

(a) 1981

(b) 1986

(c) 1991
SP cold tongue improves

NODC cold tongue worsens

![Graphs showing temperature changes](image)
SP cold tongue improves

NODC cold tongue worsens

Majority of bias develops in first 3 months
Ocean Heat Budget

\[ \Delta \text{Ocean heat content} \]

\[ c_{p,ocn} \rho_{ocn} \frac{dT_{ocn}}{dt} = -u \frac{\partial T}{\partial x} - v \frac{\partial T}{\partial y} - w \frac{\partial T}{\partial z} + Q_{sfc} + Q_{physics} \]

- Zonal advection
- Meridional advection
- Vertical advection
- Net surface heat flux
- Ocean physics
CTRL-OCN
\(\phi = [-3, 3] \ \theta = [180, 220]\)

Heat flux or change in heat content (W/m²)

Days from Initialization

- 1981: \(\Delta OHC\)
- 1986: \(Q_{sfc}\)
- Residual (physics)

\(-u \frac{dT}{dx}\)
\(-v \frac{dT}{dy}\)
\(-w \frac{dT}{dz}\)
CTRL cools due to zonal advection

\[
\begin{align*}
\text{Residual} & \quad \Delta OHC \\
-\frac{u}{dx} & \quad -\frac{v}{dy} \\
-\frac{w}{dz} & \quad Q_{sfc}
\end{align*}
\]
CTRL **cools** due to zonal advection
CTRL **cools** due to zonal advection.

NODC **cooler** due to enhanced upwelling.

**CTRL-OCN**

\[ \phi = [-3, 3] \theta = [180, 220] \]

Heat flux or change in heat content (W/m²)

- **1981**  
  - ΔOHC
  - \(-u \frac{dT}{dx}\)

- **1986**  
  - \(Q_{sfc}\)
  - \(-v \frac{dT}{dy}\)

- **1991**  
  - Residual (physics)
  - \(-w \frac{dT}{dz}\)
CTRL cools due to zonal advection

NODC cooler due to enhanced upwelling

\[ \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} = -\frac{1}{\rho c_p} \frac{\partial Q_{sfc}}{\partial t} + \nabla \cdot \mathbf{Q}_{\text{res}} \]

\[ Q_{sfc} \]

\[ \Delta OHC \]

\[ Q_{sfc} \] due to zonal advection

\[ \frac{\partial OHC}{\partial t} = Q_{sfc} - \frac{1}{\rho c_p} \frac{\partial Q_{sfc}}{\partial t} - \nabla \cdot \mathbf{Q}_{\text{res}} \]

\[ \begin{align*}
\Delta OHC & = Q_{sfc} - \frac{1}{\rho c_p} \frac{\partial Q_{sfc}}{\partial t} - \nabla \cdot \mathbf{Q}_{\text{res}} \\
\end{align*} \]
CTRL **cools** due to zonal advection

NODC **cooler** due to enhanced upwelling

SP **warmer** due to *reduced* zonal advection

(a) CTRL-OCN $\phi=[-3, 3] \theta=[180, 220]$

(b) NODC-CTRL $\phi=[-3, 3] \theta=[180, 220]$

(c) SP-NOSP $\phi=[-3, 3] \theta=[180, 220]$

- **● 1981** $\Delta OHC$
- **△ 1986** $Q_{sfc}$
- **■ 1991** Residual (physics)

\[
\begin{align*}
\frac{dT}{dx} - u \frac{dT}{dx} &\quad - v \frac{dT}{dy} - w \frac{dT}{dz} \\
\end{align*}
\]
Zonal wind stress:
Jan-June 1981 mean
Zonal wind stress:
Jan-June 1981 mean

Surface pressure:
Jan-June 1981 mean
Zonal wind stress:
Jan-June 1981 mean

Surface pressure:
Jan-June 1981 mean
Zonal wind stress: Jan-June 1981 mean

Surface pressure: Jan-June 1981 mean

What is going on with SP?
Zonal Velocity: Jan 1981
Zonal Velocity: Jan 1981
Zonal Velocity: Jan 1981

Surface wind decouples in SP
Convective parameterization changes...

Affect the strength of the Pacific cold tongue bias through ocean advection and zonal wind stress.

Can be related to vertical convective momentum fluxes and large scale pressure field.

Produce no consistent change in the double ITCZ bias.
Convective parameterization changes...

Produce no consistent change in the double ITCZ bias.

Affect the strength of the Pacific cold tongue bias through ocean advection and zonal wind stress.

Can be related to vertical convective momentum fluxes and large scale pressure field.
Remaining questions

Why is double-ITCZ bias insensitive to convective parameterization?

Why did CESM2’s double-ITCZ disappear?

Can we predict the bias response from AMIP-style simulations?

Does the SP cold tongue degrade with inclusion of convective momentum flux parameterization?
Longer simulation shows moderate improvement with superparameterization

**Fixed SST** simulations versus **fully coupled** simulations for **CTRL** and **NODC** (SP simulations yet to be analyzed)
100 m Ocean Heat Content: Jan-June 1981 mean
The geostrophic zonal current

\[ M_G = \frac{1}{\beta} \int_x^{x_e} \frac{d}{dy} (\nabla \times \tau) \, dx - \frac{\tau_y}{f} \]

is the zonally integrated meridional gradient of surface wind stress curl plus Ekman transport.