Addressing Biases in Earth System Models: Role of Atmospheric Boundary Layer Processes

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Background

- Atmospheric boundary layer (BL) mediates the exchanges of the atmosphere with the surface that provides energy, water, and biogeochemical fluxes.

- In Earth system models (ESMs), parameterizations must work together – BL parameterization and its interactions with parameterizations of convection and cloud microphysics is a major source of uncertainty in ESMs.

- ESMs are built from bottom-up, but metrics to measure model skill and system behaviors are mostly top-down (e.g., TOA energy balance, large-scale circulation) – How to ensure process fidelity in ESMs?

- Detailed observations used to develop and evaluate parameterizations are often not used to constrain their behaviors in ESMs because of scale mismatch.

- Practical examples of addressing model biases related to BL processes in E3SM.
Dry bias in tropical west Pacific

- Convective gustiness may be important in regions dominated by convection and weak resolved winds – tropical west Pacific is such a region
- Positive feedback between gustiness and evaporation may amplify precipitation response

JJA precip bias in E3SM (mm/day)

JJA resolved wind speed (m/s)

Enhancement of surface fluxes by disturbed PBL

Parameterization developed based on LES and TOGA COARE

(Harrop et al. 2017)

(Redelsperger et al. 2000)
Diagnosing model response to the missing process

Gustiness parameterization developed based on LES and TOGA COARE data

Normalized Gross Moist Stability (NGMS) predicted the amplified response of precipitation to evaporation changes due to convective gustiness

The above lend confidence to how the dry bias is addressed
Low bias in coastal stratocumulus

- Skewness in vertical velocity is an important variable in the CLUBB parameterization.

Coastal Sc SWCF bias: 40W/m$^2$

Skewness differs for different cloud regimes

(Ma et al., in preparation)

Golaz et al. (2002)
Effects of tuning for skewness of Sc

Adjust a few parameters to enhance turbulence and reduce skewness in coastal SC regions

Key adjusted parameters related to skewness and turbulence fluxes

\[
\frac{\partial w}{\partial t} = -w \frac{\partial w}{\partial z} + 2w \frac{\partial w^2}{\partial \theta_0} - C_s \left(2w^2 \frac{\partial w}{\partial z} + 2w \frac{\partial w}{\partial \theta_0} \right) + \frac{2}{3} C_s \left(w \frac{\partial w^3}{\partial \theta_0} - w^3 \frac{\partial \theta_0}{\partial z}\right) - C_1 \left(-3w^2 \frac{\partial w}{\partial z} + 3w \frac{\partial w^2}{\partial \theta_0}\right) + (K_w + \nu) \frac{\partial^2 w}{\partial z^2}
\]

\[
\frac{\partial \theta}{\partial t} = -w \frac{\partial \theta}{\partial z} + \frac{\partial \theta^2}{\partial \theta_0} - w \frac{\partial \theta^2}{\partial z} - \frac{\partial \theta}{\partial \theta_0} + \frac{\partial q}{\partial \theta_0} - \frac{\partial q}{\partial z} - C_1 \left(-q \frac{\partial \theta}{\partial z} + q \frac{\partial \theta^2}{\partial \theta_0}\right) + (K_\theta + \nu_q) \frac{\partial^2 \theta}{\partial z^2}
\]

\[
\frac{\partial w'}{\partial t} = -w' \frac{\partial w'}{\partial z} + 2w' \frac{\partial w'^2}{\partial \theta_0} - C_s \left(2w^2 \frac{\partial w'}{\partial z} + 2w \frac{\partial w'}{\partial \theta_0} \right) + \frac{2}{3} C_s \left(w \frac{\partial w'^3}{\partial \theta_0} - w^3 \frac{\partial \theta_0}{\partial z}\right) - C_1 \left(-3w^2 \frac{\partial w'}{\partial z} + 3w \frac{\partial w'^2}{\partial \theta_0}\right) + (K_{w'} + \nu_{w'}) \frac{\partial^2 w'}{\partial z^2}
\]

\[
\frac{\partial \theta'}{\partial t} = -w' \frac{\partial \theta'}{\partial z} + \frac{\partial \theta'^2}{\partial \theta_0} - w' \frac{\partial \theta'^2}{\partial z} - \frac{\partial \theta'}{\partial \theta_0} + \frac{\partial q'}{\partial \theta_0} - \frac{\partial q'}{\partial z} - C_1 \left(-q' \frac{\partial \theta'}{\partial z} + q' \frac{\partial \theta'^2}{\partial \theta_0}\right) + (K_{\theta'} + \nu_{q'}) \frac{\partial^2 \theta'}{\partial z^2}
\]

(Subset of CLUBB equations from Bogenschulte et al. 2013)
Convective gustiness over land

- Gustiness parameterization reduces dry bias over tropical western Pacific and Amazon and improves surface winds in the cold tongue – expected benefits for ENSO

Precipitation bias in old model

Change in P between new and old model (CLUBB tuning + gustiness)

Also improves surface winds in the cold tongue
Questions

What impacts do boundary layer processes have on weather, sub-seasonal to seasonal, and climate prediction?
- BL processes have large impacts on: regional precipitation (e.g., dry bias in tropical west Pacific and Amazon), cloud feedback and aerosol indirect forcing (e.g., stratocumulus), TOA energy balance (from -0.11 W/m² to 1.12 W/m²) and climate sensitivity

What limitations, with respect to boundary layer processes, exist in weather, sub-seasonal to seasonal, and climate prediction models?
- How to develop confidence in the BL processes of your models when there are many tuning knobs potentially leading to similar model outcomes?
- How to isolate biases from multiple processes that are strongly coupled (e.g., BL with clouds, convection, surface processes)?
What observational efforts would be most beneficial in addressing these limitations in numerical models?

- Both observations and LES simulations are useful for continued development of BL parameterizations, with a stronger focus on unifying representations of strongly interactive processes (turbulence, cloud microphysics, shallow and deep convection)
- Develop long term observations of the interactive processes in regions with common biases in climate models and ESMs
- Explore innovative use of observations and LES (e.g., short forecast experiments, model-data fusion, machine learning, UQ)