Prognosing momentum fluxes in CAM

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AMWG meeting

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Outline of talk

- There are two drawbacks of using downgradient diffusion to model momentum fluxes.
- Where in the equations does the physics of upgradient fluxes reside?
- Single-column simulations show that prognosis of momentum fluxes is able to produce upgradient fluxes.
- When the momentum fluxes are prognosed, global simulations exhibit minor improvements.

The version of CLUBB in CAM6 parameterizes momentum fluxes using simple down-gradient diffusion:

$$\overline{u'w'} = -K \frac{\partial \overline{u}}{\partial z}$$

In CAM6's atmosphere, CLUBB's eddy diffusivity is active even in shallow convection.

Use of downgradient diffusion for momentum fluxes has two drawbacks:

1. Downgradient diffusion lacks flexibility. This makes it difficult to tune.

2. Downgradient diffusion cannot model upgradient fluxes.

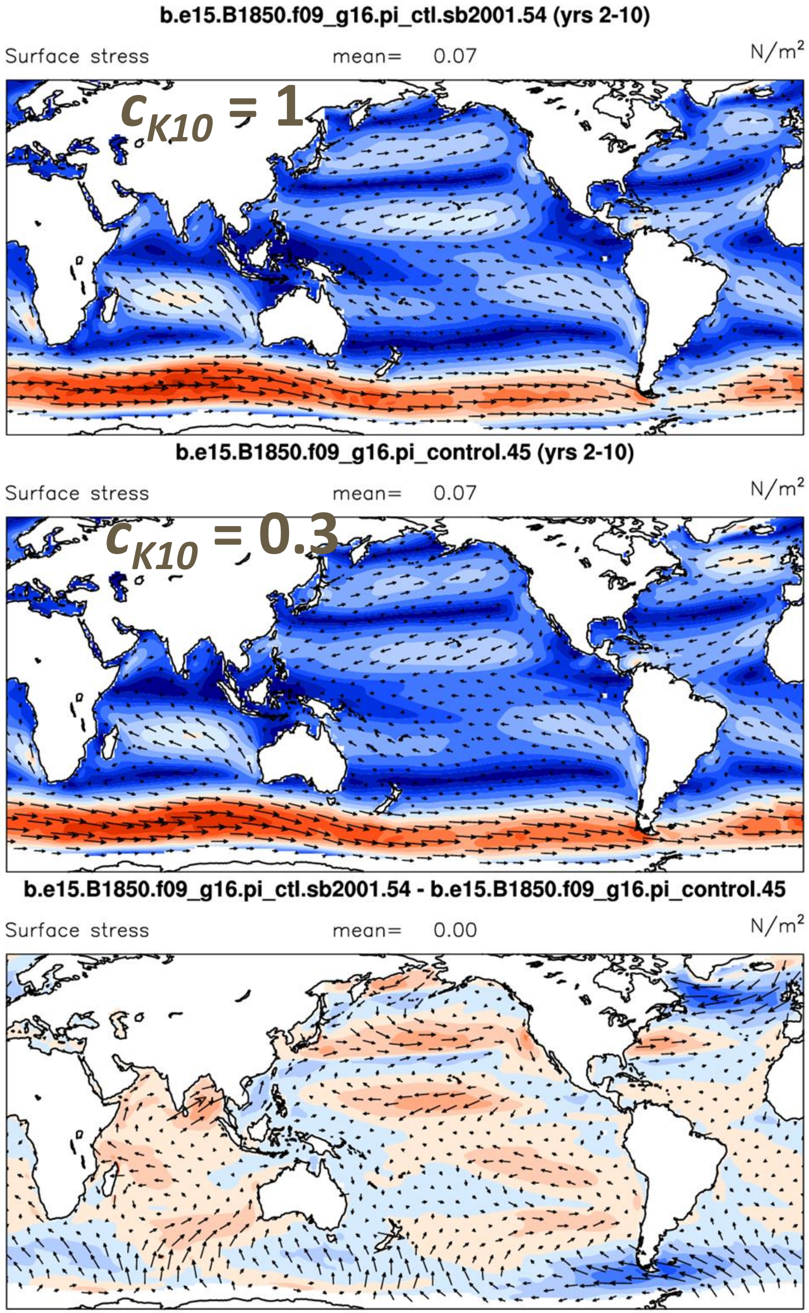
Drawback 1: Downgradient diffusion is simple, but inflexible

$$K = c_{K10} L \sqrt{\mathrm{tke}}$$

c_{K10} is the only obvious tunable parameter.

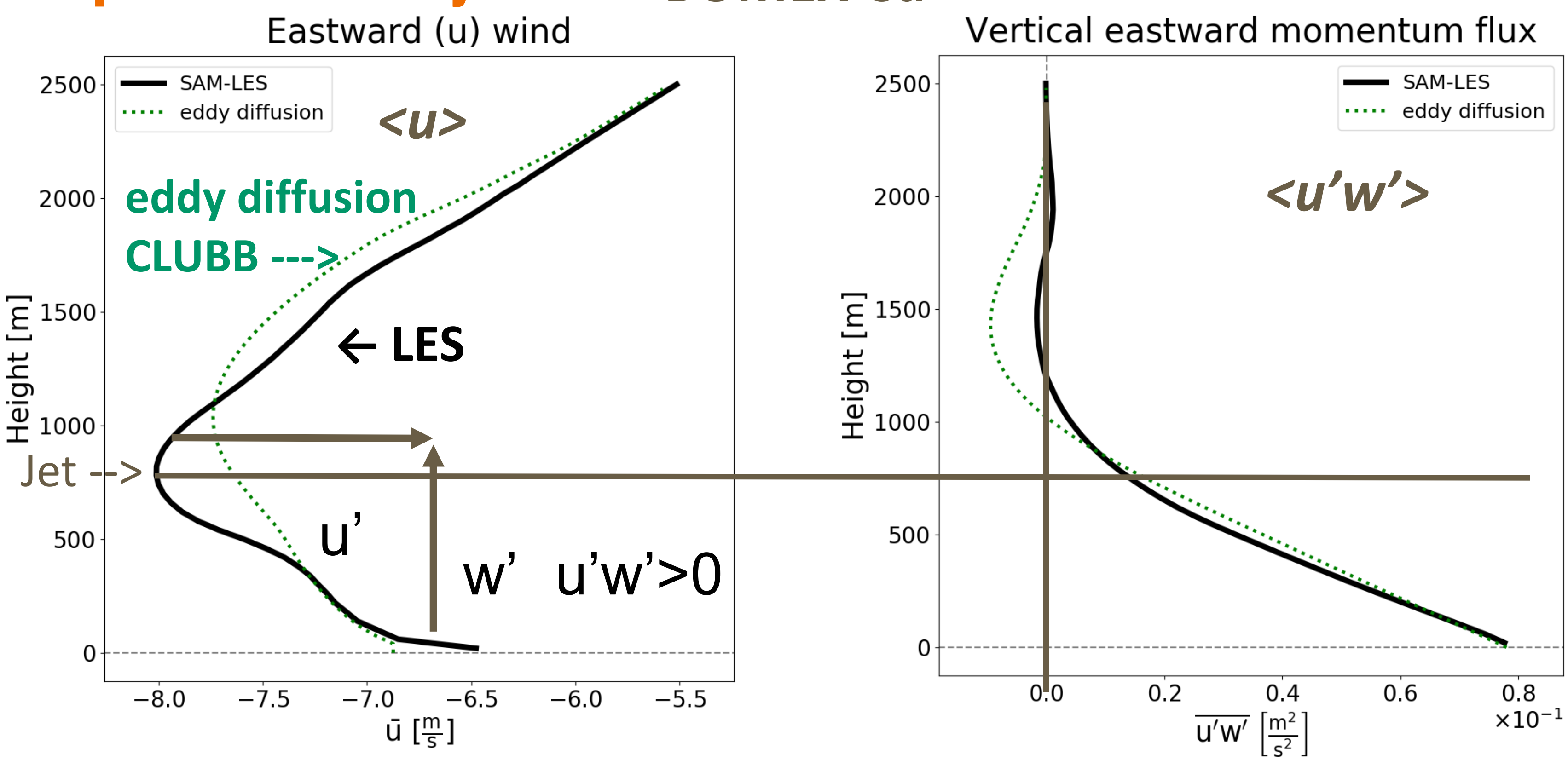
With downgradient diffusion, it is difficult to simultaneously tune the surface pressure and oceanic surface wind stress

Although increasing c_{K10} from 0.3 to 1.0 leads to “much improved skill scores for SLP, changes to subtropical surface stresses cause the sea surface temperatures to drop to unreasonable levels.” (P. Bogenschutz)



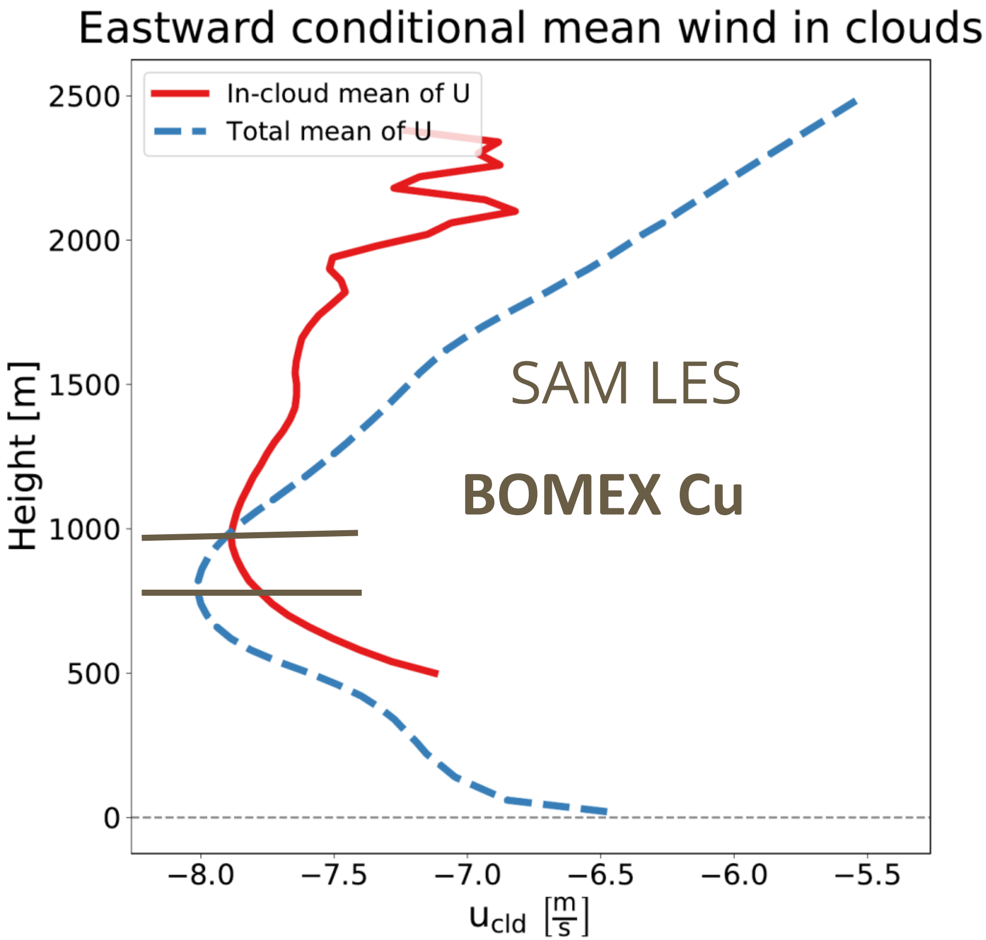
Drawback 2: Momentum fluxes in nature are sometimes upgradient if there is non-local vertical transport in the presence of a jet

BOMEX Cu



A plume rising from the surface will deposit counter-gradient momentum aloft.

The cloud is brought toward the environmental wind at all altitudes, but the flux is upgradient because of lifting above the jet max



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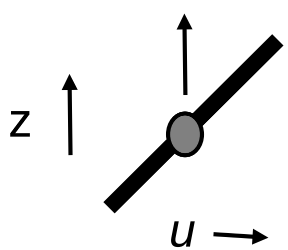
Where does the physics of upgradient transport reside?

$$\frac{\partial \overline{u'w'}}{\partial t} = \underbrace{-\overline{w'^2}\frac{\partial \bar{u}}{\partial z}}_{\text{Turb Prod}} \underbrace{+(1-C_5)\frac{g}{\theta_{vs}}\overline{u'\theta'_v}}_{\text{Buoy Prod}} \underbrace{-\frac{C_4}{\tau}\overline{u'w'}}_{\text{Pressure}} \underbrace{-\frac{\partial \overline{w'^2u'}}{\partial z}}_{\text{Turb Transport}}$$



pressure pushes parcel back to environment wind value, u'=0, with time scale tau

turb transport is a flux of flux:

$w'^2u' = w'(u'w')$

. . . in the buoyancy production and turbulent transport (flux-of-flux) terms:

To see this, drop the time tendency term and re-arrange:

$$\overline{u'w'} = \underbrace{-\frac{\tau}{C_4}\overline{w'^2}\frac{\partial \bar{u}}{\partial z}}_{\text{Eddy Diff}} \underbrace{+\frac{\tau}{C_4}(1-C_5)\frac{g}{\theta_{vs}}\overline{u'\theta_v'}}_{\text{Buoy Prod}} \underbrace{-\frac{\tau}{C_4}\frac{\partial \overline{w'^2 u'}}{\partial z}}_{\text{Turb Transport}}$$

The turbulent production term leads to downgradient diffusion, with diffusivity *K = tau* <*w'*^{2}>/*C*$_4$.

The flux-of-flux term leads to non-local transport, as in mass-flux schemes:

$$\frac{\partial \rho \sigma \overline{u}^{\mathrm{up}}}{\partial t} = -\frac{\partial M \overline{u}^{\mathrm{up}}}{\partial z} + E\overline{u} - D\overline{u}^{\mathrm{up}} + \text{Pressure force}$$

The vertical derivative connects layers at different altitudes. This functional form is different than simple corrections for non-local transport (e.g., Holtslag).

The flux-of-flux term is large only when the turbulence is skewed, as in cumulus layers

By use of CLUBB's PDF shape, the flux of flux can be approximated as

$$\overline{w'^2 u'} = \text{Constant} \frac{\overline{w'^3}}{\overline{w'^2}} \overline{u'w'}$$

Here, <*w'*^{3}/*w'*^{2}> is a convective velocity scale that transports <*u'w'*>.

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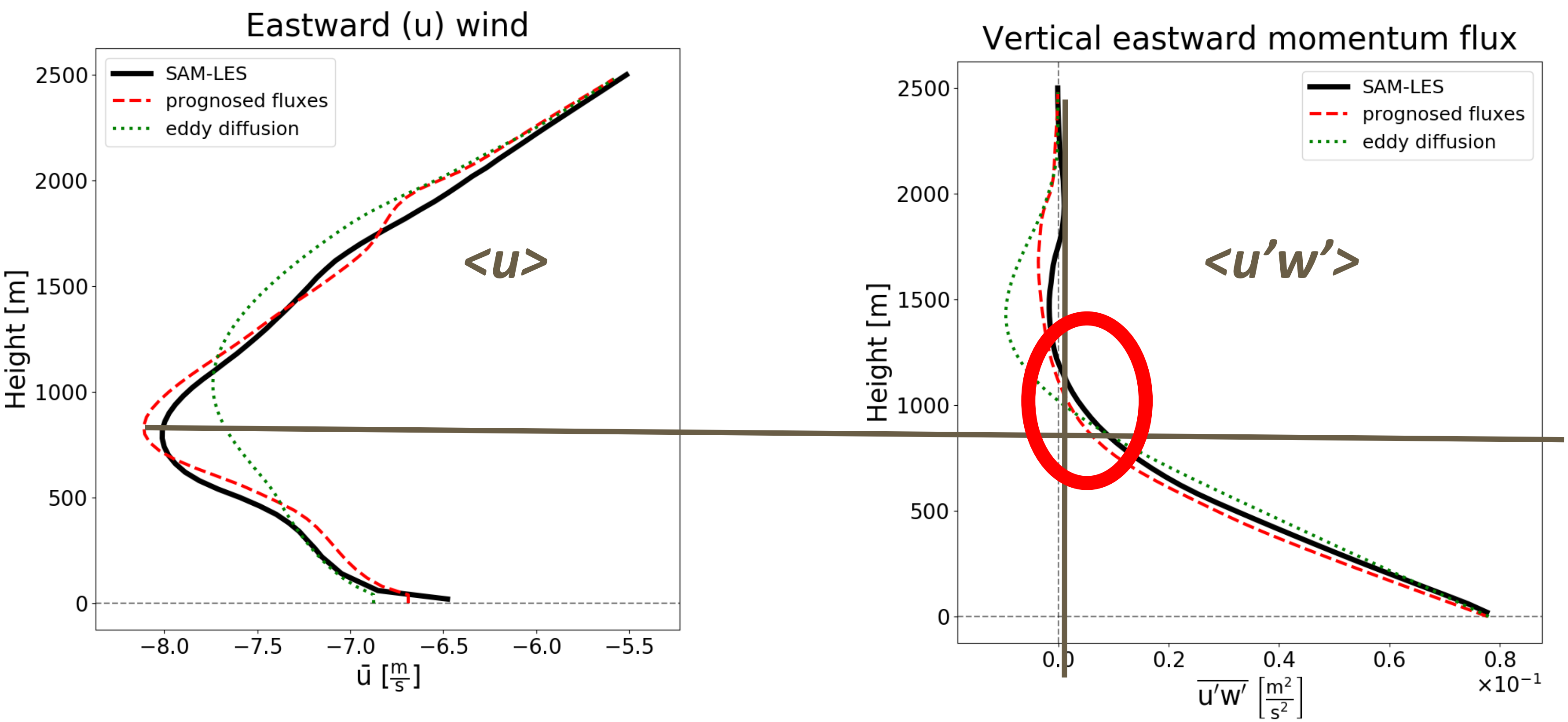
The solution we have implemented is to prognose momentum fluxes

The extra cost in CLUBB above and beyond diagnosing momentum fluxes is zero (!), because CLUBB already calculates the scalar fluxes, and the LU-decomposition from that calculation can be re-used.

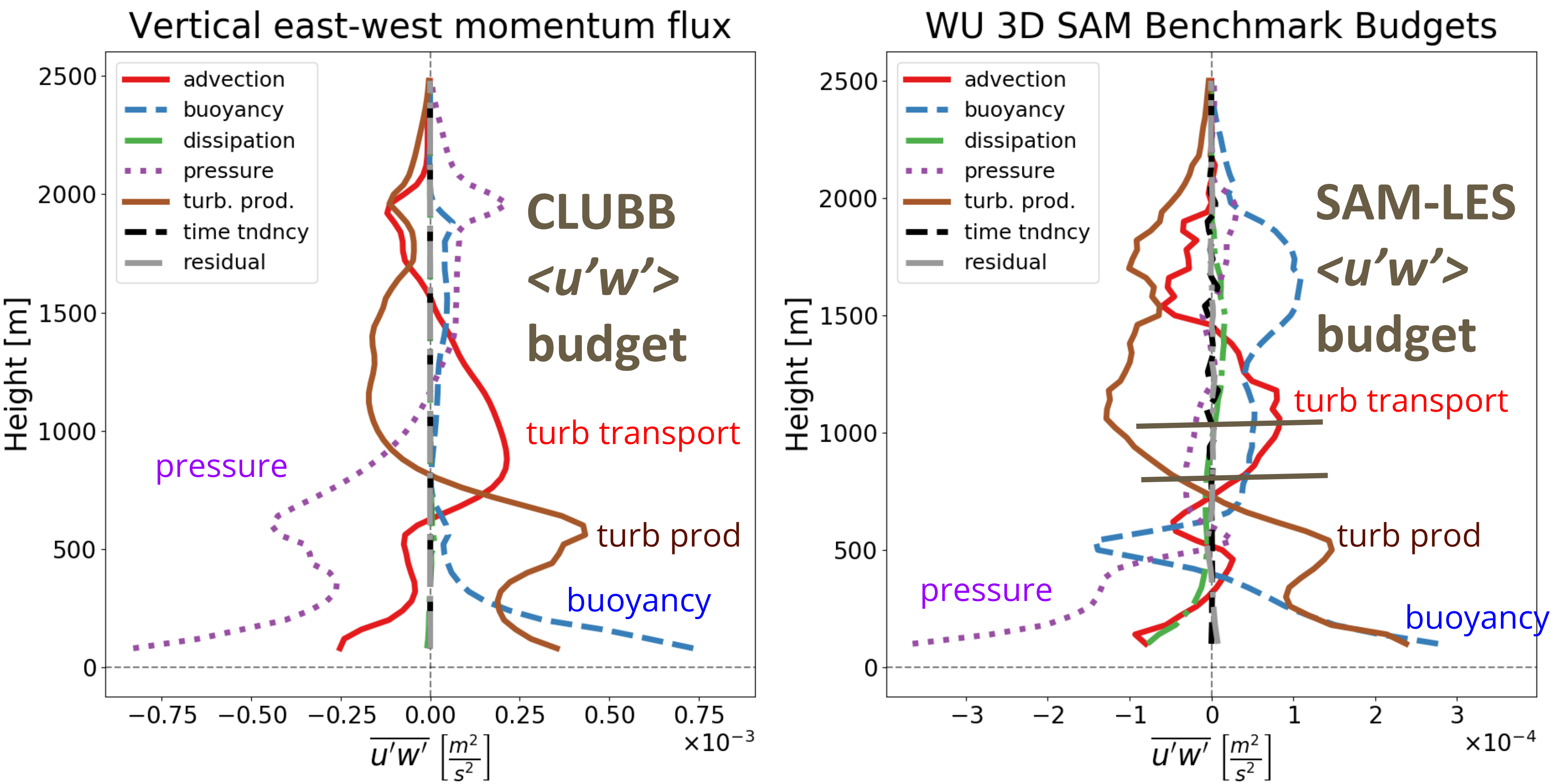
$$\left(\qquad\qquad\right)\left(u'w'\right) = \left(\qquad\right)$$

Prognosing momentum fluxes is capable of producing a region of upgradient flux in the BOMEX shallow cumulus case:

CLUBB single-column simulation of BOMEX Cu



The <*u'w'*> budget terms in BOMEX look qualitatively reasonable



$$\frac{\partial \overline{u'w'}}{\partial t} = \underbrace{-\overline{w'^2}\frac{\partial \bar{u}}{\partial z}}_{\text{Turb Prod}} \underbrace{+(1-C_5)\frac{g}{\theta_{vs}}\overline{u'\theta'_v}}_{\text{Buoy Prod}} \underbrace{-\frac{C_4}{\tau}\overline{u'w'}}_{\text{Pressure}} \underbrace{-\frac{\partial \overline{w'^2u'}}{\partial z}}_{\text{Turb Transport}}$$

Retaining the buoyancy and flux-of-flux terms allows more flexibility in tuning

$$\overline{u'w'} = \underbrace{-\frac{\tau}{C_4}\overline{w'^2}\frac{\partial \bar{u}}{\partial z}}_{\text{Eddy Diff}} \underbrace{+\frac{\tau}{C_4}(1 - C_5)\frac{g}{\theta_{vs}}\overline{u'\theta'_v}}_{\text{Buoy Prod}} \underbrace{-\frac{\tau}{C_4}\frac{\partial \overline{w'^2u'}}{\partial z}}_{\text{Turb Transport}}$$

Adjusting C_4 is kind of like adjusting the eddy diffusivity coefficient $1/c_{K10}$. But parameters in the buoyancy term can change the behavior near the lower surface.

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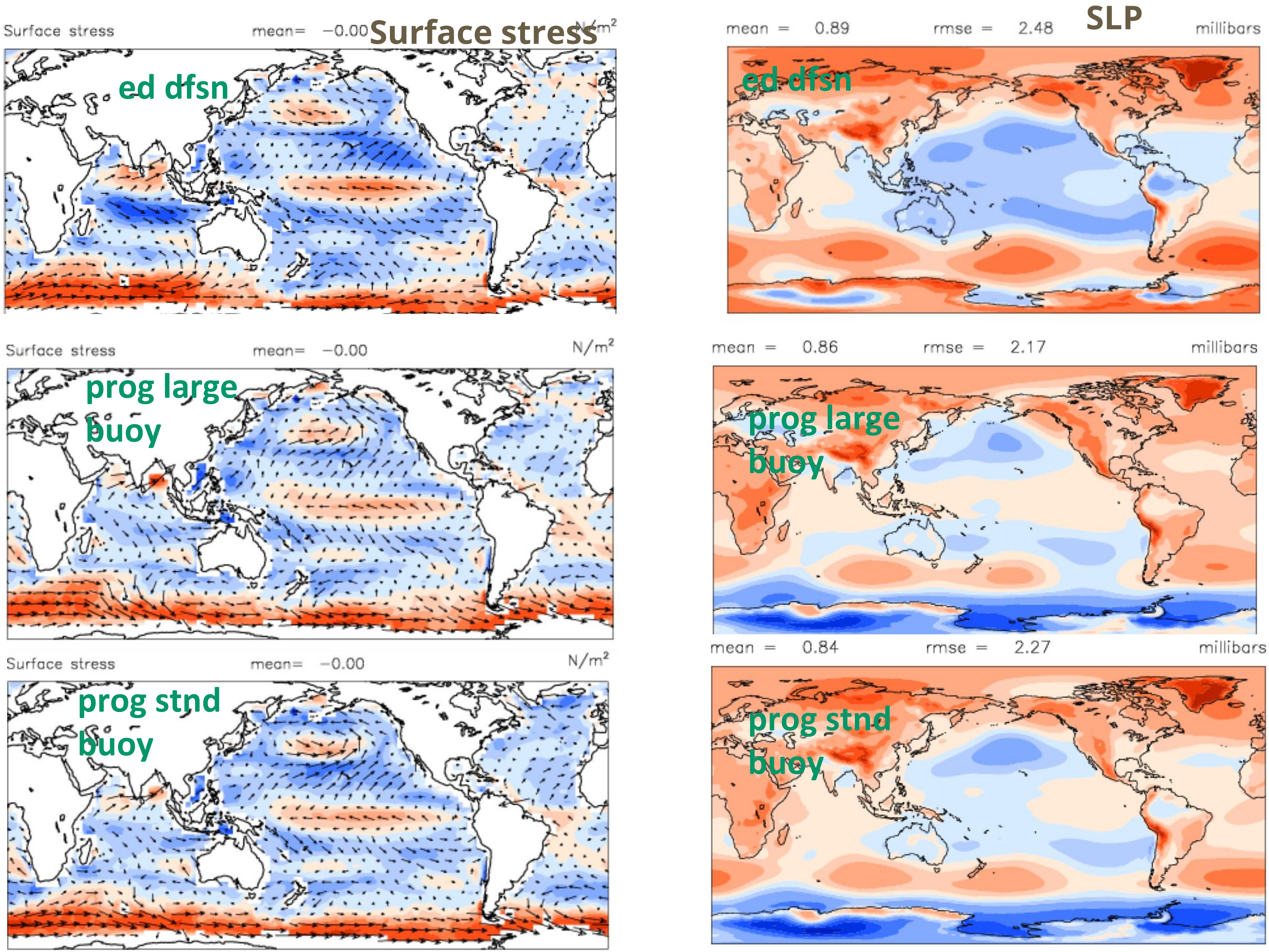
Does prognosing momentum fluxes improve global simulations?

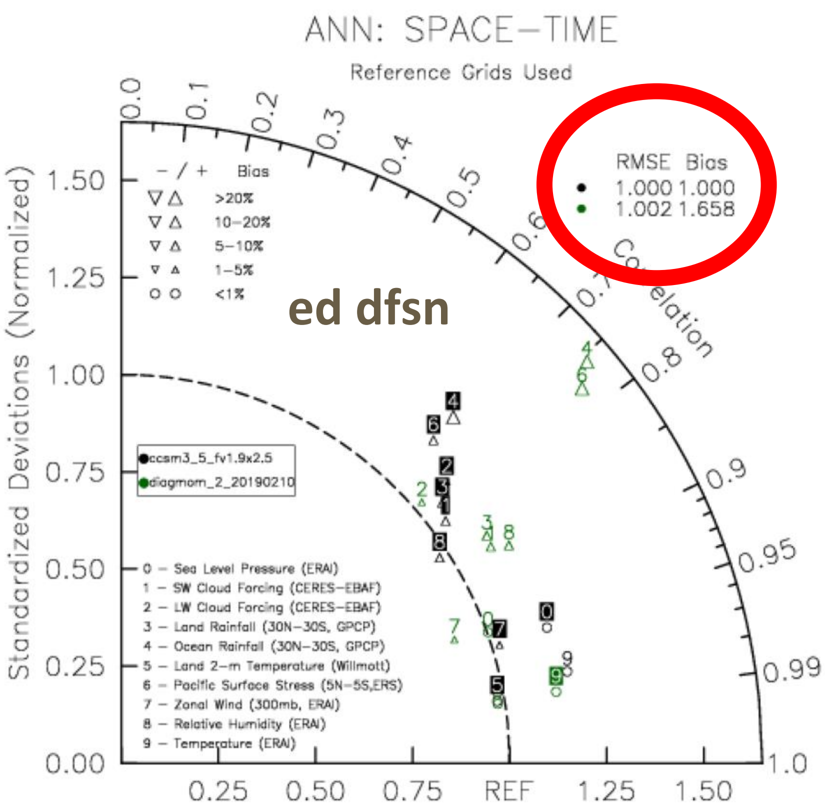
Do the extra tuning parameters provide more flexibility?

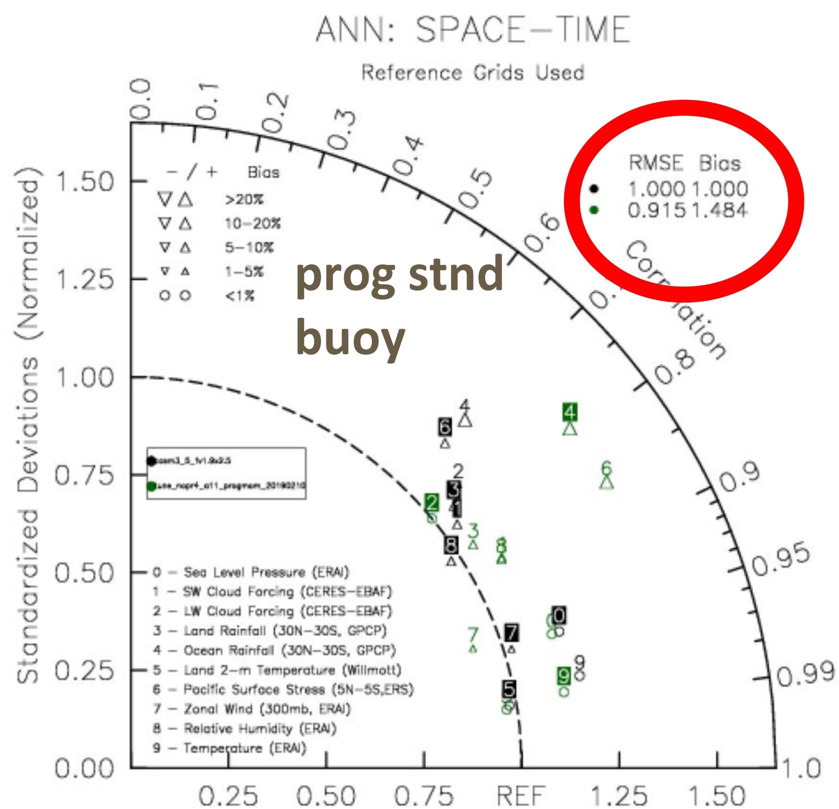
We'll show some 5-year, 2° CAM-CLUBB-SILHS simulations.

The simulations have prescribed SST, and the Zhang-McFarlane deep convective scheme is shut off.


Surface stress
SLP
Surface stress
mean= −0.00
N/m²
ed dfsn
Surface stress
mean= −0.00
N/m²
prog large buoy
Surface stress
mean= −0.00
N/m²
prog stnd buoy
mean = 0.89
rmse = 2.48
millibars
ed dfsn
mean = 0.86
rmse = 2.17
millibars
prog large buoy
mean = 0.84
rmse = 2.27
millibars
prog stnd buoy

With prognosed momentum fluxes, the Taylor score is a little better





Conclusions

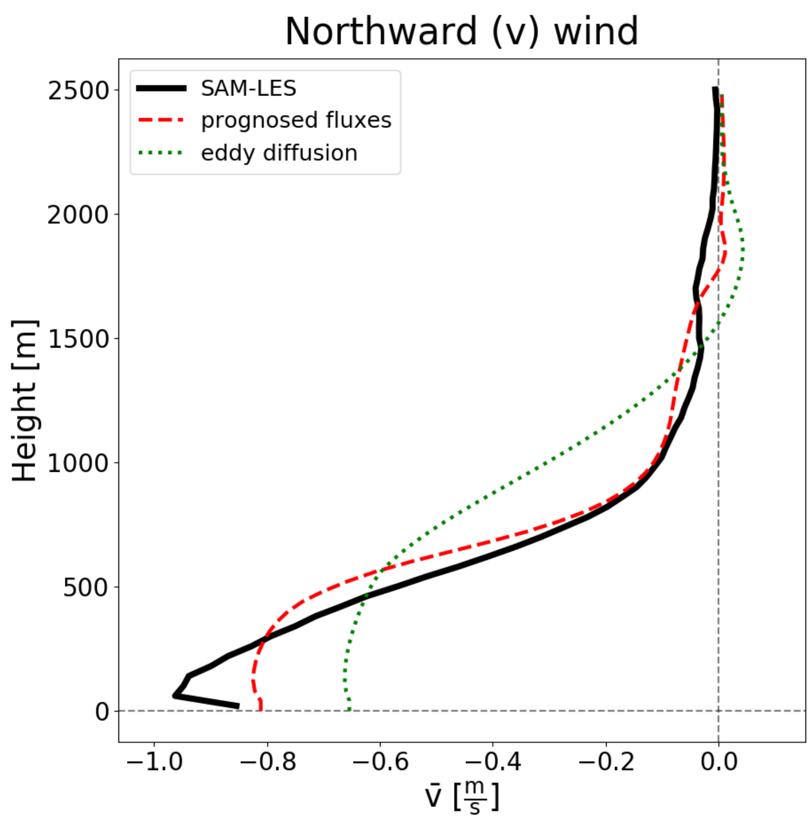
1. Momentum fluxes can be upgradient in nature.

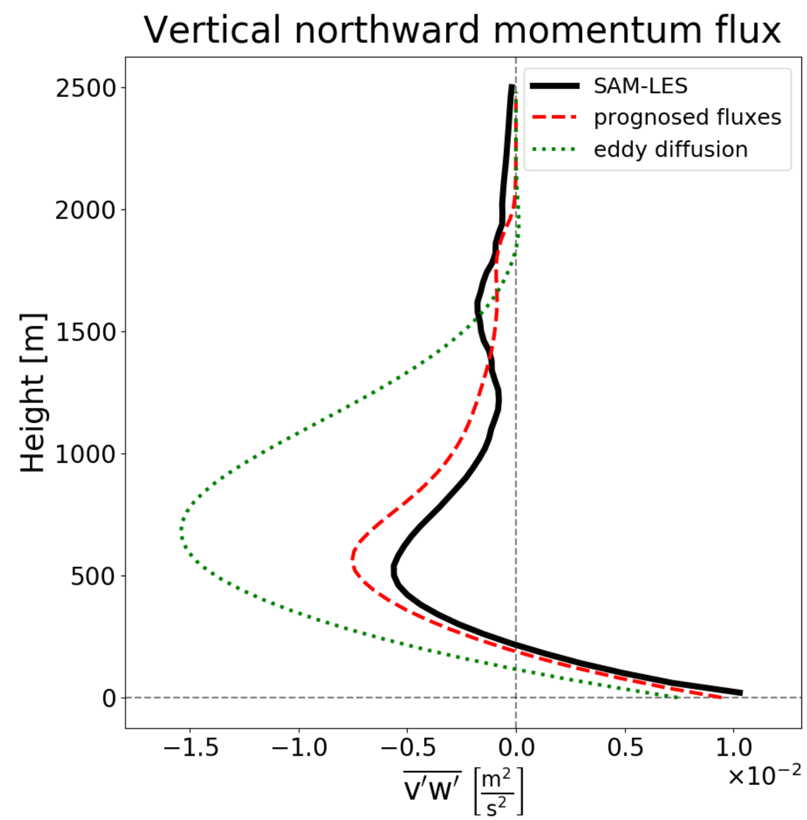
2. Momentum fluxes can be prognosed in CLUBB at no additional cost

3. Prognostic momentum fluxes lead to a bit more flexibility and accuracy

Thanks for your time!

The meridional wind is also improved . . .





The zonal wind in the DYCOMS2 RF01 stratocumulus case is a little better mixed: