Towards constraining Sahel rainfall responses to global mean temperature changes*

Spencer Hill, Yi Ming, and Isaac Held

with thanks to Ming Zhao and Leo Donner

*choose your own paleo-implication adventure

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2. Fixed relation between overturning strength and ITCZ position ($\phi_{\rm ITCZ} = a\Psi_{\max}$)
3. Constant efficiency of energy transport (a.k.a. gross moist stability Γ)

#3: see *Hill, Ming, and Held 2015*, J. Climate

"Stable get stabler", but modeling evidence inconclusive

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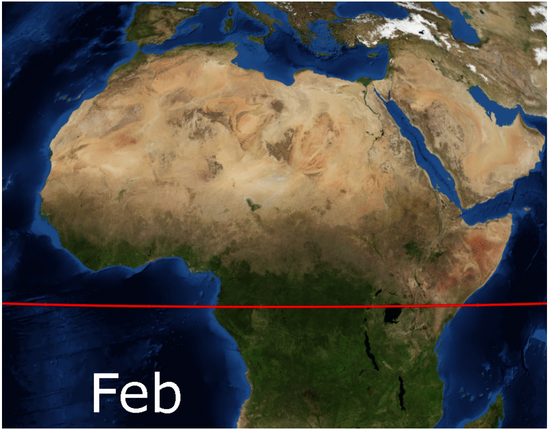
The Sahel Transition between the Sahara and equatorial Africa



Wikipedia: *The Arabic word “sahil” literally means "shore, coast", describing the appearance of the vegetation found in the Sahel as being akin to that of a coastline delimiting the sand of the Sahara.*

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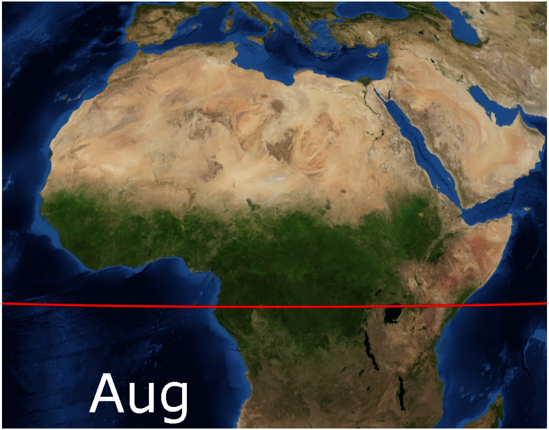

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Problem Severe 20th century drought,
severe 21st century uncertainty

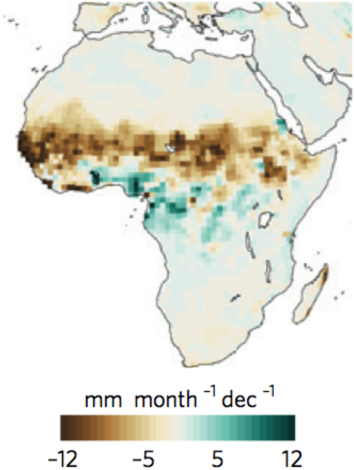

Fig 3(b) of *Bony et al 2015* & Fig. 1(a) of *Park et al 2015*

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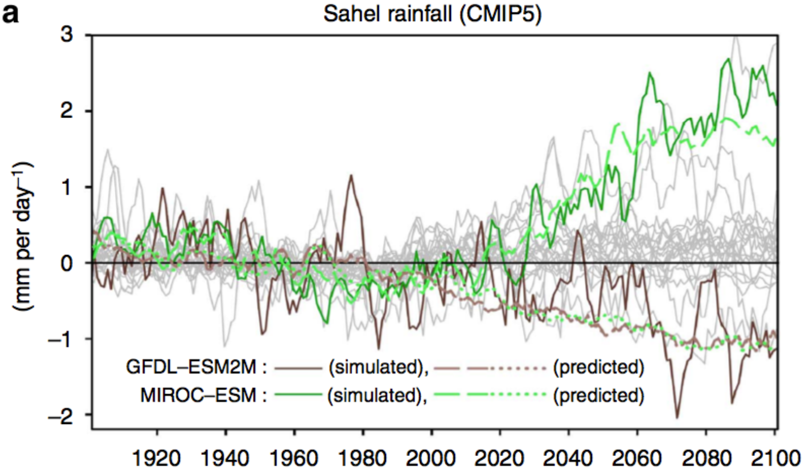
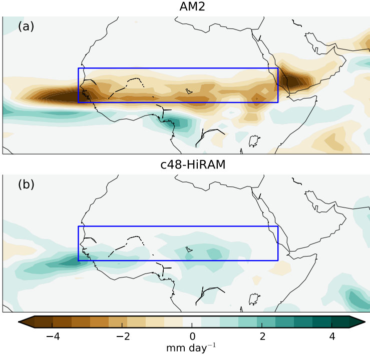


Fig 3(b) of *Bony et al 2015* & Fig. 1(a) of *Park et al 2015*

Simpler Uniform δSST: just as uncertain but much less studied



July-August-September δP in $+2$ K simulations in two GFDL AGCMs

Mean warming: most robust SST signal
"Global warming"

Coupled models using AM2 as atmospheric component: future drying almost entirely due to +2K
C.f. *Held et al 2005*

Our approach Brute force: model-by-model MSE & q budget analysis

$$h \equiv c_p T + gz + L_v q, \quad \{\} \equiv \int_0^{p_{\mathrm{sfc}}} \frac{\mathrm{d}p}{g}$$

$$\overline{F}_{\mathrm{net}} = \{\overline{h\nabla \cdot \mathbf{v}}\} + \{\overline{\mathbf{v}\nabla \cdot h}\},$$
$$\overline{E} - \overline{P} = \{\overline{q\nabla \cdot \mathbf{v}}\} + \{\overline{\mathbf{v}\nabla \cdot q}\}$$

Focus on AM2.1: dry end member of CMIP

If falsified, spread reduced appreciably

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Constraints from obs Can compare interannual variability in AMIP runs with +2K and obs

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Land role Aridity constrains surface and atmospheric dynamics

Any land region: $\overline{P} \geq \overline{E}$ and $\overline{R}_{\mathrm{sfc}} + L_v\overline{E} + \overline{H} \approx 0$
Thus $\overline{F}_{\mathrm{net}} \approx \overline{R}_{\mathrm{TOA}}$

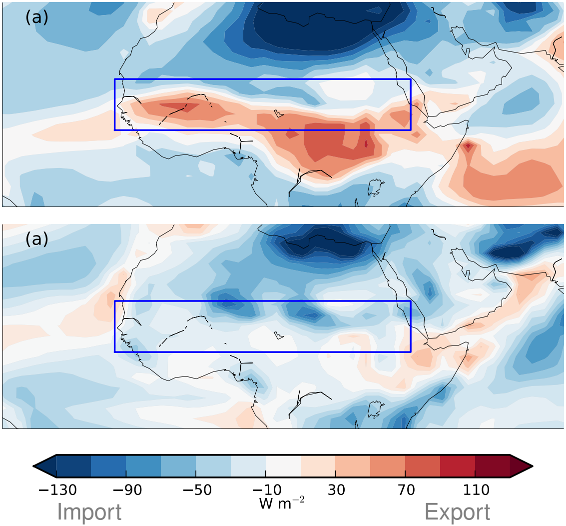
Moisture-limited E regime
$\overline{E} = \beta\overline{P}$, β - constant

Flow from Sahara dominates advection
$\overline{v} \cdot \nabla\overline{h} \approx \overline{v}\frac{\partial\overline{h}}{\partial y}$

$$\overline{R}_{\mathrm{TOA}} = \{\overline{h}\nabla \cdot \overline{\mathbf{v}}\} + \{\overline{v}\frac{\partial\overline{h}}{\partial y}\},$$

$$(\beta - 1)\overline{P} = \{\overline{q}\nabla \cdot \overline{\mathbf{v}}\} + \{\overline{v}\frac{\partial\overline{q}}{\partial y}\}$$

Energy Weak MSE divergence by convection compensated by dry advection



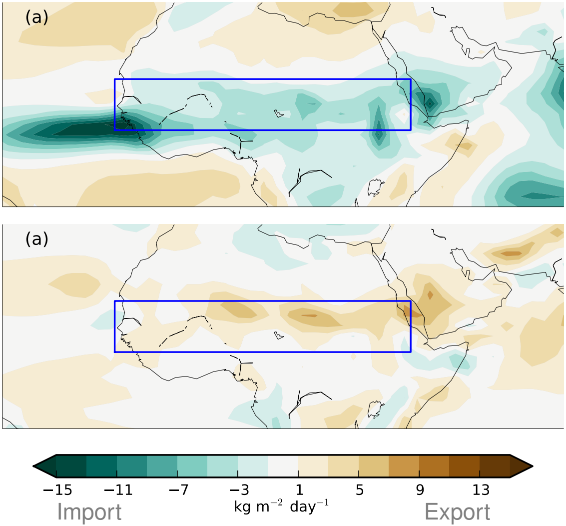
$\overline{h}\nabla\cdot\overline{\mathbf{v}}$

8.7 W m^{-2}

$\overline{\mathbf{v}}\cdot\nabla\overline{h}$

36.7 W m^{-2}

Moisture Strong convective convergence partly offset by dry advection



$\overline{q}\nabla \cdot \overline{\mathbf{v}}$

-3.66

mm day^{-1}

$\overline{\mathbf{v}} \cdot \nabla\overline{q}$

1.91

mm day^{-1}

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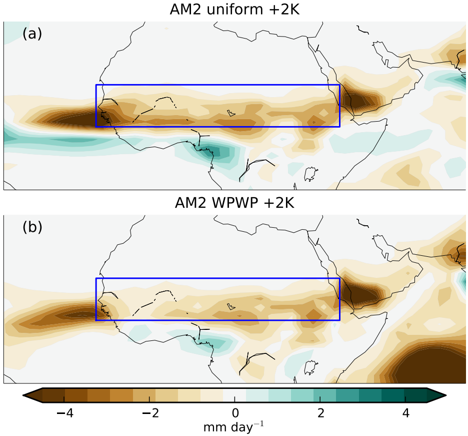
Stabilization Drying mostly due to warming aloft driven by West Pacific warming



JAS δP

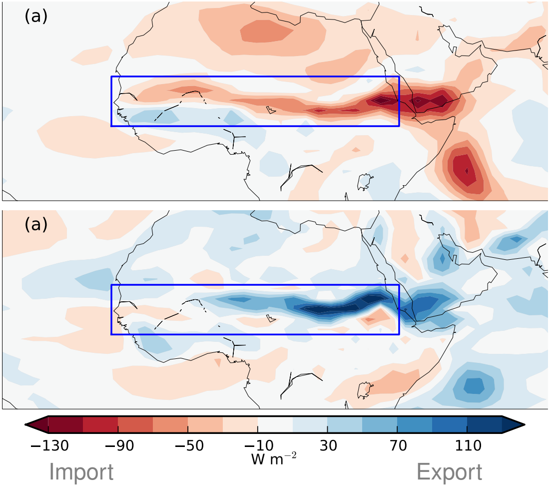
Add'l AM2.1 run: +2K in Indo-Pacific Warm Pool

Sahel drying ~80% of uniform +2K drying

Enhanced convection + WTG = inc. stability

Convective Q-E

δEnergy Upped ante mechanism acting on dry-side convective margin



$\delta\{\overline{h}\nabla \cdot \overline{\mathbf{v}}\}$

-21.2

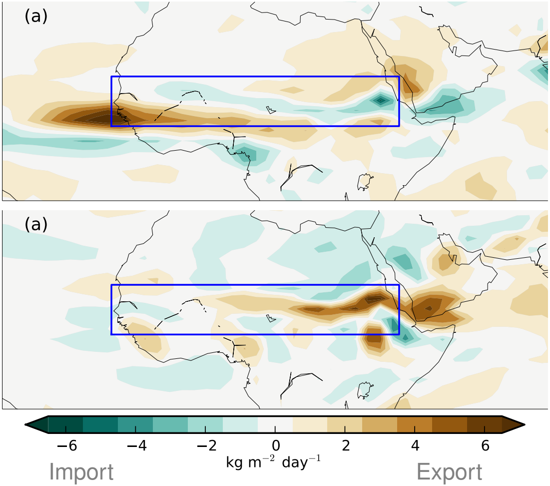
Wm^{-2}

$\delta\{\overline{\mathbf{v}} \cdot \nabla\overline{h}\}$

+22.8

W m^{-2}

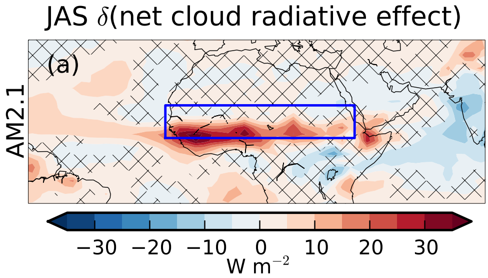
δMoisture Both suppressed convergence and enhanced dry advection yield drying



$\delta\{\overline{q}\nabla\cdot\overline{\mathbf{v}}\}$
+0.62
mm day^{-1}

$\delta\{\overline{\mathbf{v}}\cdot\nabla\overline{q}\}$
+0.61
mm day^{-1}

Clouds Reduced cloud SW shading amplifies drying through MSE budget



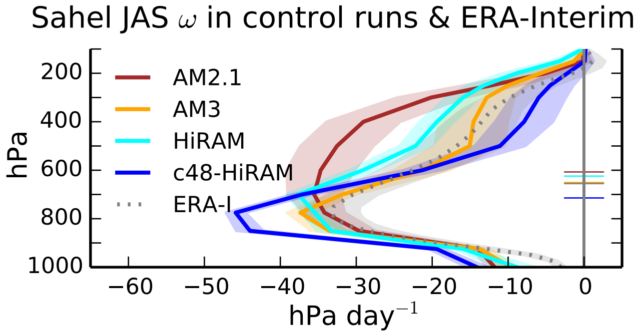
Reinforces direct suppression of convective MSE export

Advection has to compensate more strongly: more drying

Clear sky OLR increase exactly cancels: $\delta R_{\mathrm{TOA}} \approx 0$

This is likely coincidental, i.e. not a constraint

Omega Control ascent profile modulates impact of upper-tropospheric stabilization

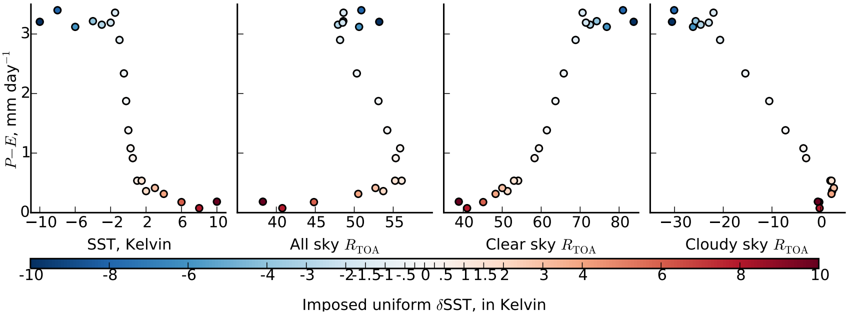


Shading = $\pm 1\sigma$; horiz. dashes = centroid

Top-heavy ascent: convection more suppressed by warming aloft

c48-HiRAM: very shallow, so doesn't "feel" stabilization

δSST $P - E$ response saturates above $\sim \pm 2$ K SST perturbation



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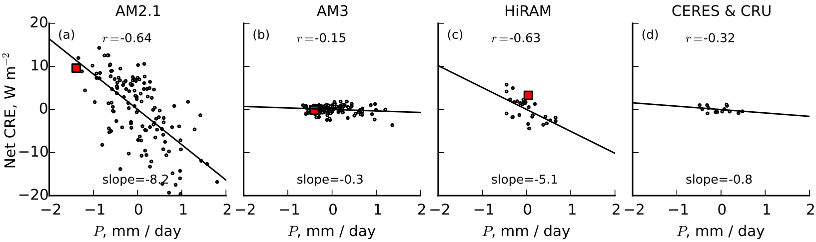
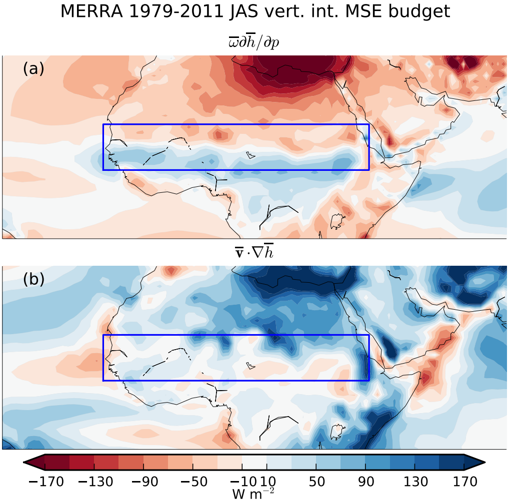
Clouds +2 K responses match interannual variability and thus can compare v. obs



Black dot = 1 yr in AMIP run/obs. Red square: +2 K response

MERRA All MSE budget terms smaller but same sign as AM2



$\{\overline{h}\nabla\cdot\overline{\mathbf{v}}\}$

1.1 W m^{-2}

$\{\overline{\mathbf{v}}\cdot\nabla\overline{h}\}$

28.6 W m^{-2}

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Discussion & outstanding questions

What determines the climatological budgets & velocity profiles?

Convection scheme? Resolution? Land model?

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Testing model projections: need process-level diagnostics
Requires characterizing mean state and variations

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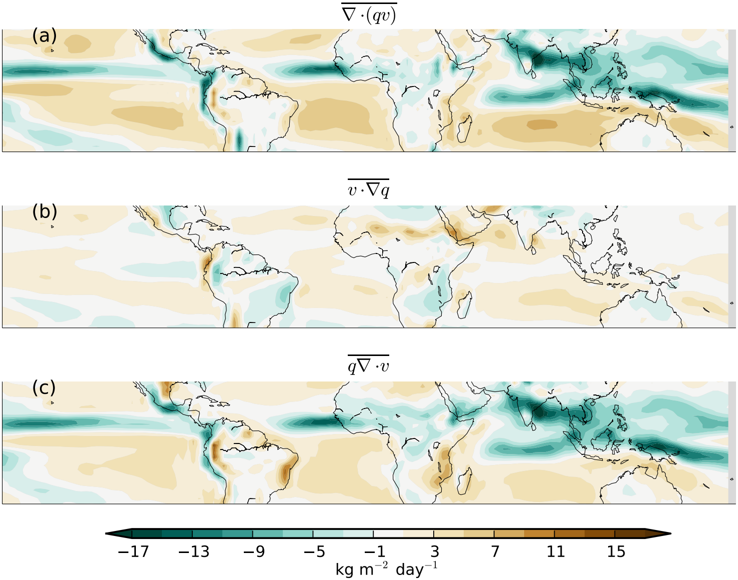
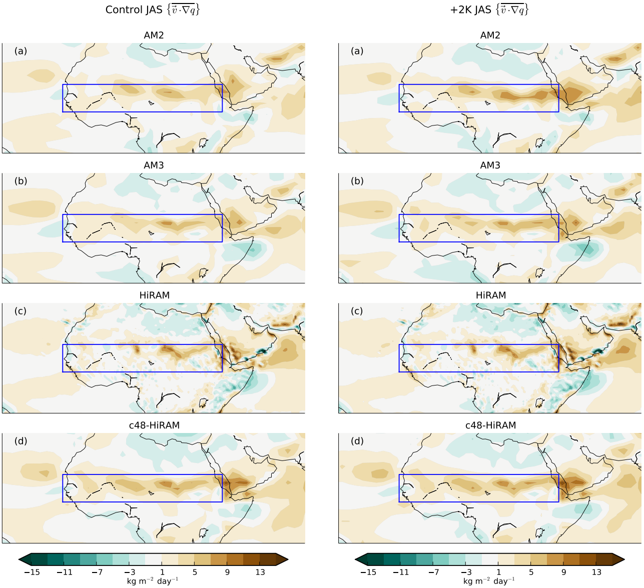
Contact: **spencerh@princeton.edu**

Zonal mean: *Hill, Ming, and Held 2015* J. Climate
Sahel: Manuscript(s) in preparation

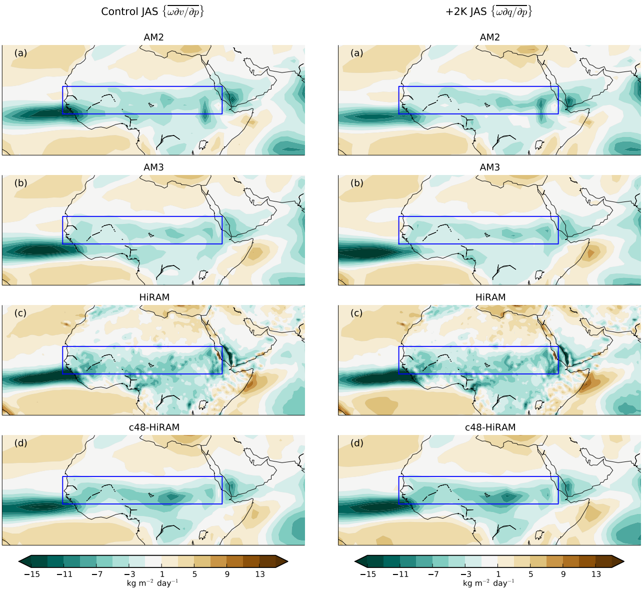
AM2.1 moisture budget decomposition



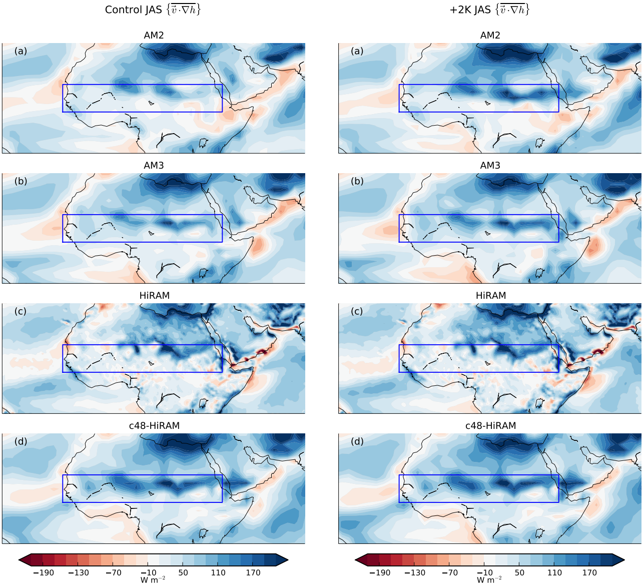
Control and +2K horizontal moisture advection



Control and +2K vertical moisture advection



Control and +2K horizontal MSE advection



Control and +2K vertical MSE advection