Energetic and precipitation responses in the Sahel to sea surface temperature perturbations

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Motivations

Severe uncertainty in rainfall response to anthropogenic warming

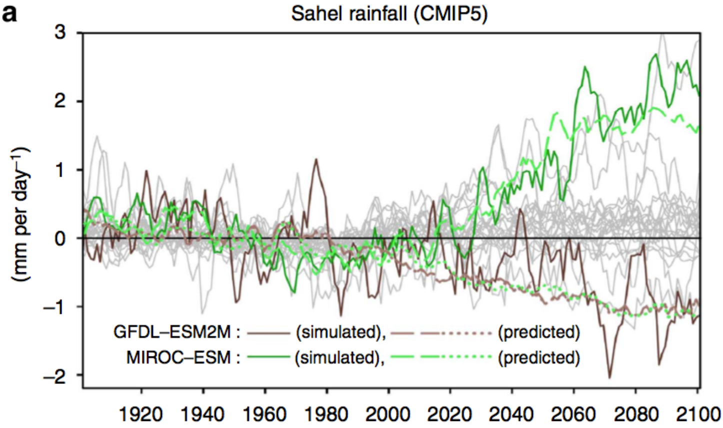
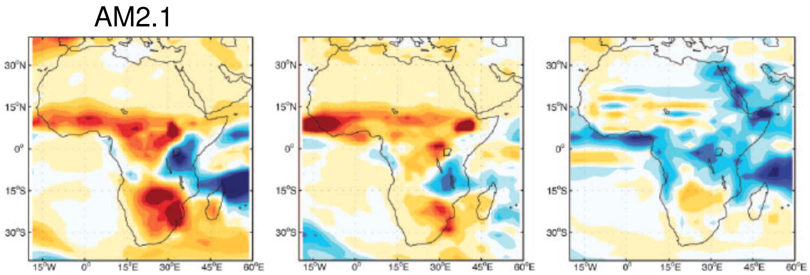


Fig. 1a, *Park et al 2015* | Sahel P in RCP8.5 runs

Motivations

GFDL AM2.1: uniform 2 K SST warming $\rightarrow$ massive Sahel drying. Plausible?



JAS δP in 3 AGCMs in +2K experiments

Fig. 5 of *Held et al 2005* | Warm colors=drying.

So for AM2.1 at least, full coupled response controlled by atmosphere response to mean SST warming

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GFDL AM2.1: Mean SST warming dries Sahel via enhanced Sahara-Sahel MSE difference

Other models: MSE gradient-based drying mechanism robust & linked to climatological convective depth

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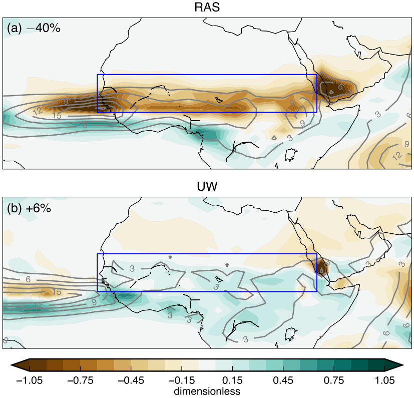
RAS vs. UW

Replacing AM2.1 convection scheme causes drying to disappear entirely



JAS δP in +2 K runs.
Top: default, RAS.
Bottom: UW convection.

Default: Relaxed Arakawa Schubert (RAS)

Replacement: U. Washington (UW), *Bretherton et al. 2004*
As configured for HiRAM

UW designed for shallow convection: more quiescent
Whereas RAS very active

RAS vs. UW

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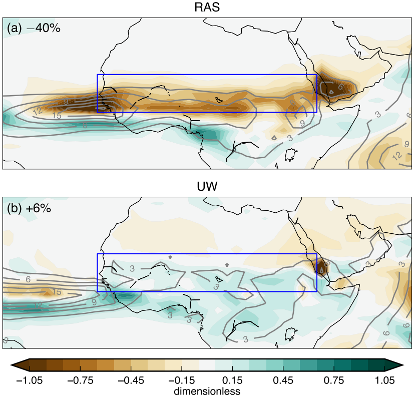


JAS δP in +2 K runs.
Top: default, RAS.
Bottom: UW convection.

Focus on differences in large-scale control climate

Rather than convective processes themselves

MSE budget | Column integral: Energetic forcing balanced by circulation diverging MSE

$$\overline{F}_{\mathrm{net}} \approx \left\{\overline{\mathbf{u}}\cdot\nabla\overline{h}\right\} + \left\{\overline{\omega}\partial_p\overline{h}\right\}$$

Canonical tropical convection zone balance: $\overline{F}_{\mathrm{net}} \approx \left\{\overline{\omega}\partial_p\overline{h}\right\}$

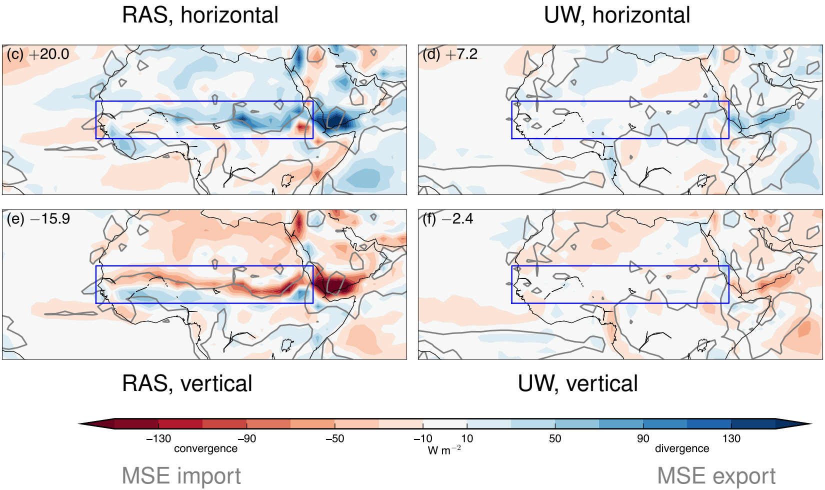
Forcing drives deep moist convection, c.f. *Neelin and Held 1987*

Sahel control simulation: $\overline{F}_{\mathrm{net}} \approx \left\{\overline{\mathbf{u}}\cdot\nabla\overline{h}\right\}$

Forcing balanced primarily by northerly advection of dry, low-MSE Saharan air

MSE budget

+2 K: large RAS advection response; less impact on UW



MSE budget

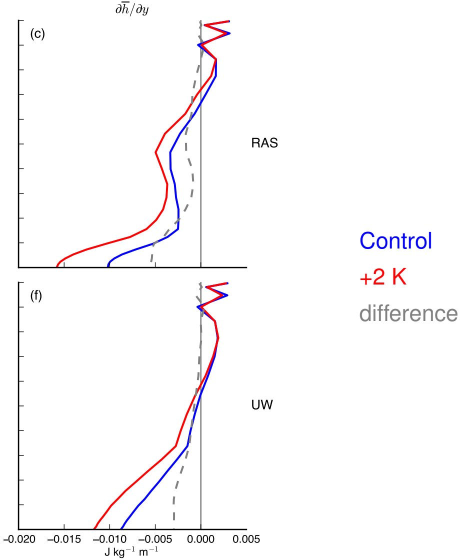
Sahel-Sahara MSE difference increases, which dries the Sahel

Enhances drying influence of Saharan inflow

Effectively “upped-ante” mechanism of Chou & Neelin

More so and over greater depth in RAS than UW

Especially in mid- to upper-troposphere



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GFDL AM2.1: Mean SST warming dries Sahel via enhanced Sahara-Sahel MSE difference

Other models: MSE gradient-based drying mechanism robust & linked to climatological convective depth

Do Sahel drying mechanisms in AM2.1 extend to other models?

7 GFDL model variants

AM2.1, AM2.1-UW, AM2.5, AM3, c90-AM3, HiRAM, c48-HiRAM

10 CMIP5 models

Those that ran “amip” and “amip4K”

Uniform SST perturbation: +2 K for GFDL; +4 K for CMIP5

But still δP still mismatch after normalizing

Other models

Do Sahel drying mechanisms in AM2.1 extend to other models?

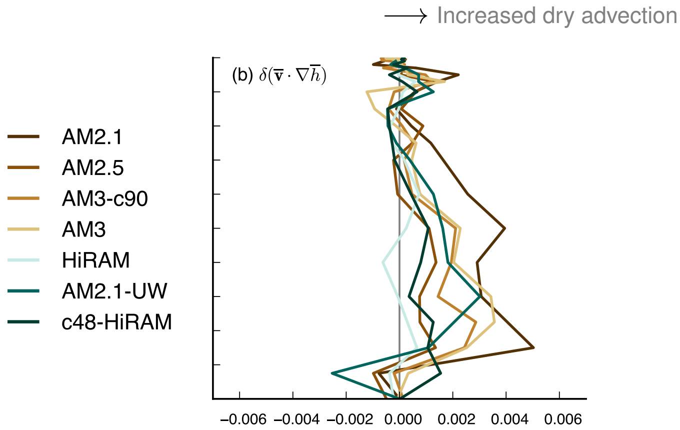
Sahel JAS rainfall reduction in 14 of 17 models!

3 outliers = GFDL variants using UW

And northerly dry advection enhanced in all

GFDL

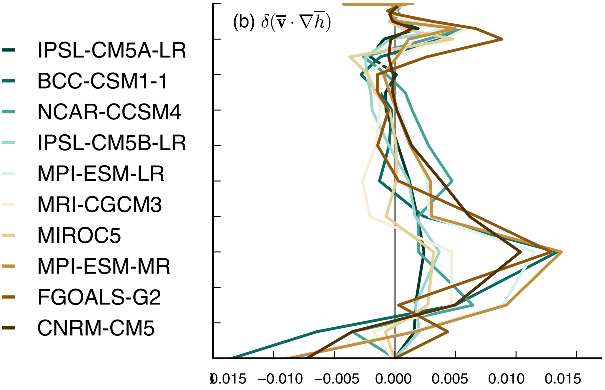
Saharan dry air advection into Sahel increases in ∼all models



Colors correspond to Sahel δP: drying → wettening

CMIP5

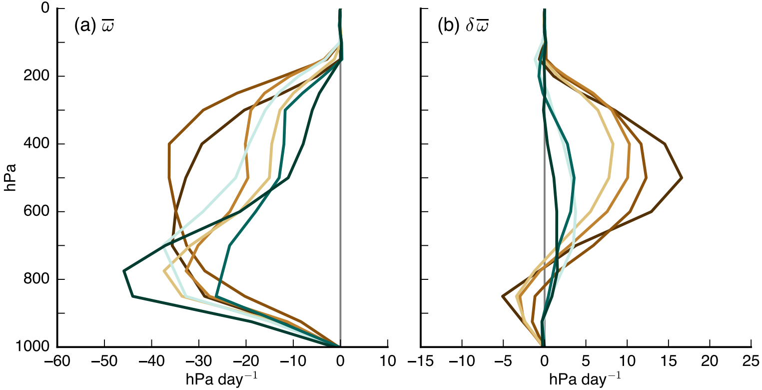
Saharan dry air advection into Sahel increases in ∼all models



Not shown: again largely driven by the increase MSE difference

GFDL

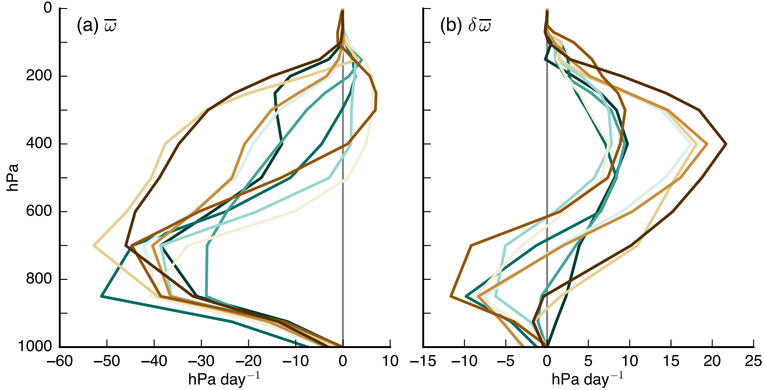
Ascent profile shallows in all models and relates to control convective depth



Sahel (left) control, (right) anomalous ω in GFDL models, same coloring as before

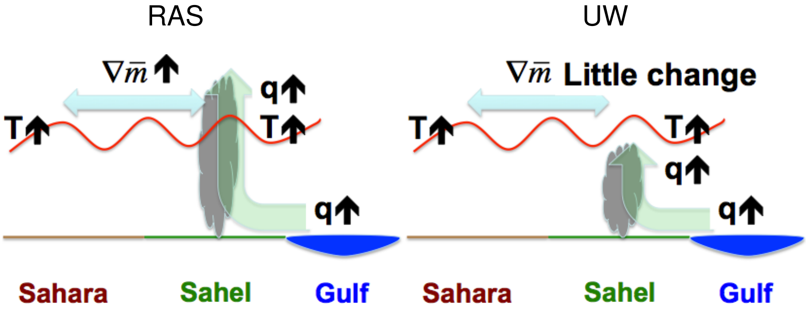
CMIP5

Qualitatively the same as for GFDL but with more scatter



Sahel (left) control, (right) anomalous ω for CMIP5, same coloring as before

Our claim | Deeper convection in RAS enhances Sahel-Sahara MSE difference more

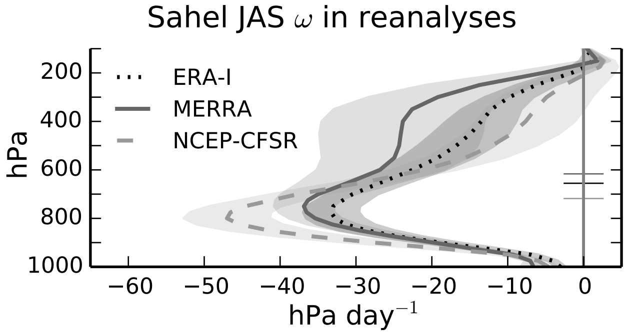


Schematic courtesy of Yi Ming | Notation: $\bar{m}$ is MSE

Ocean warming and moistening communicated
to free troposphere by convection

Thus Sahel-Sahara MSE increase sensitive to convective depth

Reanalyses | Sahel ascent profiles in three reanalyses are predominantly bottom-heavy



Non-negligible scatter; would like to understand better

Potential contamination by convection scheme, by our arguments

All separated from GFDL and CMIP5 top-heavy outliers

And those are among the worst drying models!

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Other models: MSE gradient-based drying mechanism robust & linked to climatological convective depth

AMS request

Greatest obs need: better understanding of discrepancies among reanalyses

"Reanalyses MIP"?

I.e. run different reanalysis models w/ identical obs. data

And run each reanalysis product with the input data of the others

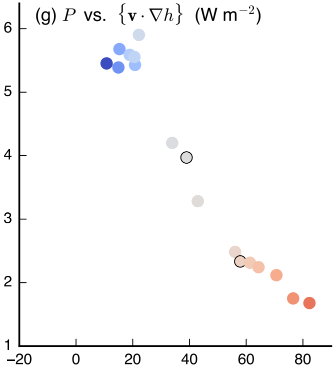
(Not sure if this is feasible from technical standpoint)

Where to find this stuff

Email	`shill@atmos.ucla.edu`
Website	`http://people.atmos.ucla.edu/shill/`
Sahel AM2.1 δP	In revision, *J. Climate*
Sahel models/obs	Eventual submission somewhere
PhD thesis	On my website

begin extra slides

Wide SST range | Study roles of large-scale circ. vs. physics by varying δSST



Sahel (vertical axis) P and (horizontal axis) $\overline{\mathbf{u}} \cdot \nabla \overline{h}$ in AM2.1 with uniform δSST from -15 to +10 K. Control and +2 K outlined.

RAS: P, P_{conv}, P_{ls}, E, and $P - E$ decrease $\sim$monotonically w/ SST

Only P shown here

UW: P, P_{conv}, and E increase; P_{ls}, and $P - E$ decrease w/ SST

Not shown

So P_{conv} is key discrepancy

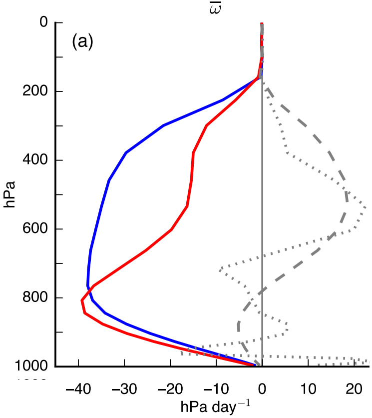
And that UW E increases more rapidly than P

Ascent

RAS: increased horizontal divergence balanced by anomalous subsidence

Anomalous subsidence drives anomalous MSE convergence by divergent flow

I.e. shallows convection and balances increased dry advection



Control | +2 K | difference

Ascent

RAS: increased horizontal divergence balanced by anomalous subsidence

Leading order perturbation budget in free troposphere:

$$\overline{\mathbf{u}}\cdot\delta\nabla\overline{h} + (\delta\overline{\omega})\partial_p\overline{h} \approx 0$$

Rearrange:

$$\delta\overline{\omega} \approx -\frac{\overline{\mathbf{u}}\cdot\delta\nabla\overline{h}}{\partial_p\overline{h}}$$

Numerator positive all levels; $\partial_p\overline{h} = 0$ at $\sim$650 hPa (not shown)

Thus descent above, ascent below 650 hPa

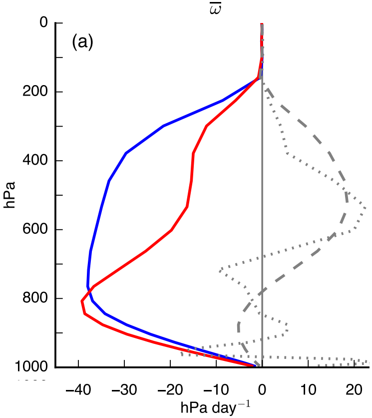
Ascent | RAS: more horizontal MSE divergence, less MSE divergence via subsidence

Dotted curve:

$$\delta\overline{\omega} \approx -\frac{\overline{\mathbf{u}}\cdot\delta\nabla\overline{h}}{\partial_p\overline{h}}$$

Sinking in free troposphere, ascent in boundary layer

Amounts to major shallowing of ascent profile



Ascent

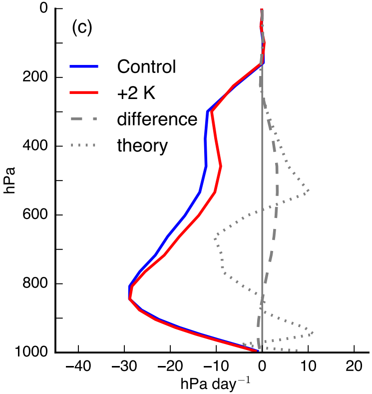
UW: anomalous free tropospheric descent, but more modest than RAS

Same qualitative response, despite weaker magnitude

Sinking overcome by moistening influences of ocean warming

Diagnostic for $\delta\overline{\omega}$ from RAS doesn't work

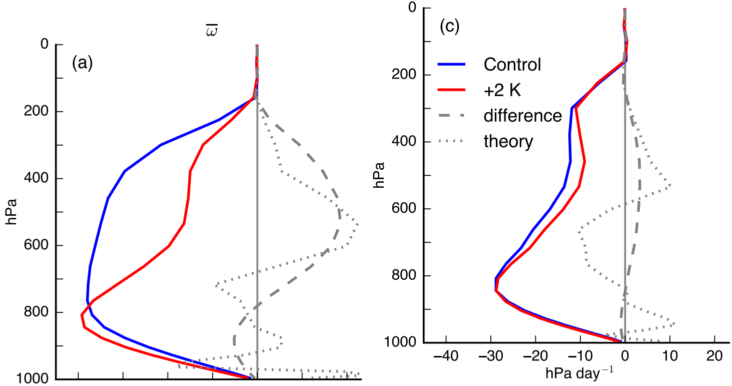
Neglects forcing term; more important in UW



RAS vs. UW

Deeper convection in RAS enhances Sahel-Sahara MSE difference more

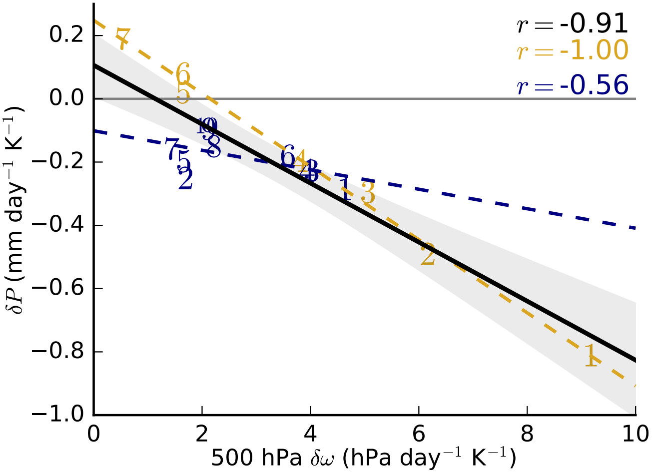
RAS UW



Exacerbated by moist static stability effect

Little UW convection reaches mid-troposphere where most prone to suppression

Combined | $\delta\overline{\omega}$ correlated with $\delta\overline{P}$ perfectly for GFDL, insignificantly for CMIP5



GFDL models | CMIP5 models | combined