Convection scheme, cloud, and stability effects on Sahel rainfall response to uniform warming

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Summary

Sahel JAS δP in GFDL AGCMs forced w/ $+2$ K SST warming spans a wide range. Drying occurs in models whose convection schemes use threshold condensate removal for precipitation. Warming only the Indo-Pacific Warm Pool induces Sahel drying.

I. Introduction: Towards constraining future Sahel δP

GCM projections of Sahel δP vary widely
E.g. Biasutti (2013)

Held et al. (2005): Same for $+2$ K SST warming in AGCMs
Despite much simpler perturbation

AGCM $+2$ K spread persists today
Figure 1: three modern GFDL AGCMs

Role of clouds and convective parameterizations under-studied
Known to affect tropical δP

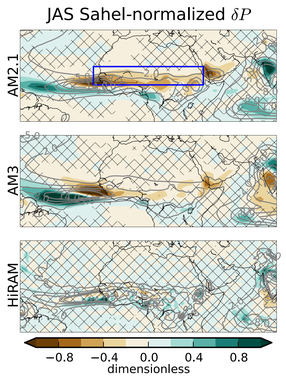

Figure 1 : JAS δP in uniform $+2$ K SST experiment, normalized by the model's climatological Sahel JAS P. Hatching = not significant at 95% level. Sahel = land points within blue box.

II. Methods: Simple δSST experiments in GFDL AGCMs

Uniform $+2$ K SST warming runs in GFDL AGCMs: AM2.1, AM3, HiRAM
Models run 30, 20, and 15 yrs, respectively after 1 yr spin-up

Control is observed climatological SST annual cycle
Present-day atmospheric composition in all runs

III. Results: Intense AM2.1 drying and warming

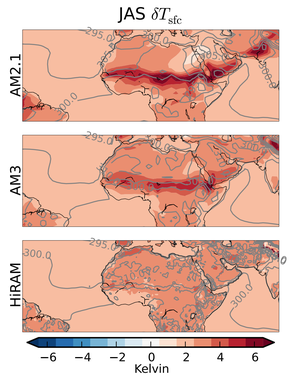

Figure 2 : $+2$ K experiment JAS surface air temperature response, units Kelvin. No hatching: significant everywhere.

	Control			$+2$ K Response		
	P	P_{conv}/P	P/E	δP	$\delta P_{\text{conv}}/P$	$\delta P/E$
AM2.1	3.63	0.85	1.61	−1.39	−0.07	−0.42
AM3	2.65	0.94	1.19	−0.31	−0.01	−0.05
HiRAM	3.86	0.40	1.85	+0.04	+0.03	−0.06

Table 1 : Sahel JAS control and $+2$ K response values of precipitation (P, mm day^{-1}), convective precipitation fraction (P_{conv}/P, unitless) and ratio of precipitation to evaporation (P/E, unitless).

IV. Results: Cloud-mediated collapse of convection in AM2.1 only

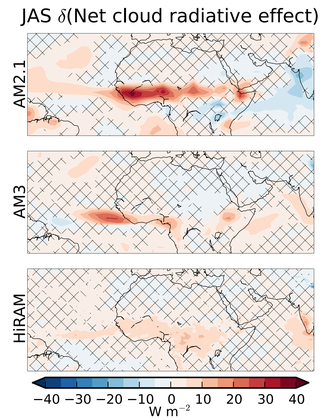

Figure 3 : $+2$ K experiment JAS net cloud radiative effect response, signed positive into the atmosphere, units W m^{-2}.

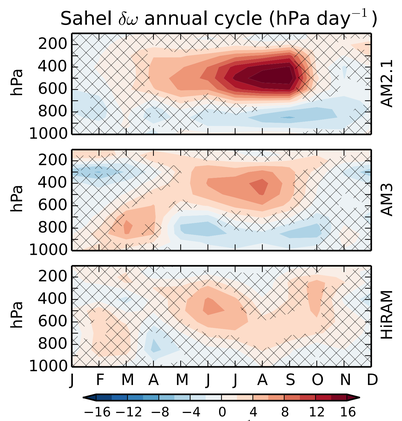

Figure 4 : $+2$ K experiment annual cycle of pressure velocity, ω, response, signed positive downwards, units hPa day^{-1}.

	Control						$+2$ K Response					
	Net	SW	LW	δNet	δSW	δLW
AM2.1	−7.1	−38.1	31.0	+9.5	+13.7	−4.2
AM3	4.6	−27.8	32.5	−0.3	+4.5	−4.8
HiRAM	−17.7	−45.7	27.9	+3.3	+2.3	+1.0

Table 2 : Sahel JAS control and $+2$ K response values of net, SW, and LW cloud radiative effect, signed positive into the atmosphere, units W m^{-2}.

AM2.1 drop in Sahel SW cloud shading (Figure 3)
Partly offset by reduced LW trapping (Table 2)

Yet *reduced* evap (not shown): moisture-limited regime
Surface must warm (Figure 2) to regain energy balance via SH and LW fluxes

Intense subsidence response in AM2.1 (Figure 4)
Coincides with intense convective mass flux, relative humidity, and cloud amount reductions (not shown)

V. Results: Convection microphysics determines Sahel δP in AM4 prototypes

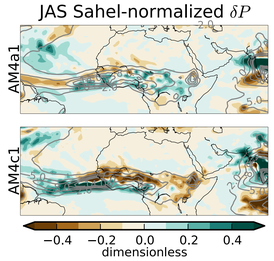

Figure 5 : As in Figure 1 but for the AM4a1 and AM4c1 models. Note omission of statistical hatching and narrower colorbar value range.

GFDL's next AGCM, AM4, currently under development
Two prototypes; differ only in convection parameters

Key difference: condensate removal mechanism for P_{conv}
AM4a1: threshold condensate removal (c.f. AM3 and HiRAM);
AM4c1: fractional removal (c.f. AM2.1)

Sahel: AM4c1 dries intensely, AM4a1 not at all in $+2$ K runs (Figure 5 and Table 3)
Aligning precisely with AM2.1/AM3/HiRAM behavior

Despite much weaker cloud response in AM4c1 vs. AM2.1
So cloud response an amplifying, not root, cause of drying

	Control						$+2$ K Response					
	P	P_{conv}/P	P/E	CRE_{net}	CRE_{SW}	CRE_{LW}	δP	$\delta P_{\text{conv}}/P$	$\delta P/E$	$\delta\text{CRE}_{\text{net}}$	$\delta\text{CRE}_{\text{SW}}$	$\delta\text{CRE}_{\text{LW}}$
AM4a1	3.57	0.68	1.65	−3.4	−29.1	25.7	−0.05	+0.01	−0.04	+0.1	+4.0	−3.9
AM4c1	2.86	0.66	1.62	−5.6	−35.2	28.6	−0.49	+0.01	−0.19	+0.5	+3.6	−3.1

Table 3 : Combined fields from Table 1 and Table 2, but for the AM4a1 and AM4c1 models.

VI. Results: AM2.1 $+2$ K in warm pool only also dries Sahel

Prior literature: "remote v. local" stability framework (e.g. Giannini et al., 2013)
Stabilized by remote convection-induced warming aloft, de-stabilized by local thermodynamic moistening

Extra experiment in AM2.1: $+2$ K only in Indo-Pacific Warm Pool
Presumably communicated to whole tropics by deep convection there

Sahel response in all fields mimics that of full $+2$ K run (Figure 6)
Albeit centered more over eastern Sahel and slightly smaller magnitude

Corroborates remote stabilization ideas
But suggests "local" cloud response is also partly remotely forced

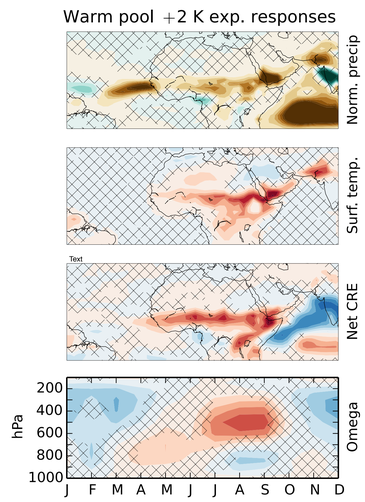

Figure 6 : AM2.1 warm pool-only $+2$ K experiment response of (top to bottom) same fields (and color scales) as those in Figures 1–4, respectively.

VII. Discussion: Implications for constraining future Sahel rainfall

Does real-world convection follow threshold or fractional behavior?
In other words: Should we believe AM2.1's intense drying?

Why is Sahel response so sensitive to condensate treatment?
Why does SW cloud forcing breakdown in AM2.1?
Still lacking mechanistic understanding.

Zhao (2014): threshold P schemes yield high climate sensitivity
Sahel δP sensitivity the inverse. Why?

Role for observations, e.g. cloud forcing via satellites?
Need to constrain condensate and cloud forcing properties

VIII. References

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IX. Acknowledgments

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