Final report for DOE Early Career Award # DE-SC0012152

By Mike Pritchard

This summarizes technical highlights from the DOE Early Career Project entitled "**Understanding the Roles of Cloud Microphysics and Land Surface Coupling Feedbacks in Multi-Scale Predictions of Central US Summer Hydroclimate"** led by PI Mike Pritchard at the University of California spanning July 2014-2020. The project's original aims were to investigate trade-offs of cloud superparameterization such as the effects of microphysical assumptions on mesoscale convective systems (Section I) and the representation of land-atmosphere coupling under explicit convection (Section II). Under the same broader theme of water cycle dynamics, superparameterization, and land interaction, the project evolved to further investigate the climate dynamics of irrigation, vegetation and streamflow (Section III), the dynamics of the Madden-Julian Oscillation (Section IV), as well as the use of modern machine learning to replace traditional sub grid approaches for climate simulation (Section V). Twenty peer-reviewed journal publications were produced as a result of this project (Section VI).

I. Trade-offs of cloud superparameterization for climate simulation:

Much of this research project applies cloud "superparameterization (SP)", which is a multi-scale atmospheric modeling approach that embeds thousands of moist turbulence-permitting cloud-resolving models (CRMs) within global climate models, to replace the traditional error-prone approximations (or "parameterizations") of unresolved convection and clouds. SP is not without its own limiting idealizations so one focus has attempted to clarify its trade-offs for practical issues of weather and climate simulation. For example, in **Pritchard et al. (2014)** it was revealed that an interesting trade-off of using limited extent CRMs is to artificially limit the efficiency of vertical mixing in tropical deep convection regions, controlled by the room available for compensating subsidence to balance deep updrafts. In **Yu and Pritchard (2015),** together with a UCI PhD student S. Yu, new research revealed a surprising sensitivity to increasing the frequency of communication between the cloud-resolving and planetary-resolving scale regimes -- stiffer communication drives a lower tropical gross moist stability and thus juicier precipitation extremes (Fig. 1).

New tuning knobs on convective organization and mysterious dynamics revealed by superparameterized time-step sensitivity tests.

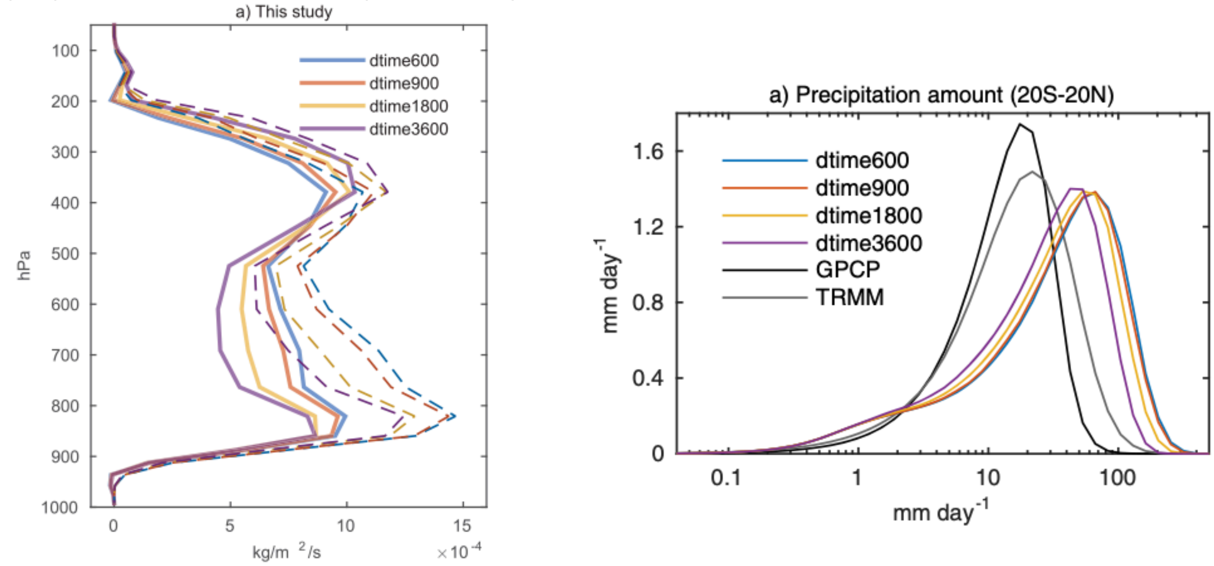

Fig. 1: Response of (left) the convective mass flux in the deep tropics vs. (right) the rainfall amount distribution to varying the multi-scale coupling frequency alone in a superparameterized climate simulation (Yu and Pritchard, 2015).

This has raised new questions about the emergent dynamics of superparameterized climate models, worthy of future work, and meanwhile has become a useful new tuning knob for developers, including those currently involved in the DOE's Exascale Computing Project (ECP).

One interesting aspect of SP simulations is that they can produce storms reminiscent of Central US summertime mesoscale convective systems. Mesoscale convective systems (MCSs) bring the central US up to 70% of its warm-season precipitation, making them a crucial source of moisture for a sensitive agricultural region. Reproducing MCSs in global models has been challenging because the physics straddle the divide between global, meso-scale, and cloud-scale dynamics. The superparameterized (SP) Community Atmosphere Model (CAM) can produce spontaneous eastward propagating convective envelopes in the central US but the signal has not been microphysically tuned. In **Elliot et al. (2016)** we tested varying potential tuning parameters, including model horizontal grid size and cloud microphysical parameters, and examined how they influenced the representative convective intensity statistics (longwave cloud forcing and precipitation rate) of seasonal MCS composites. To establish a natural background variability baseline, we performed a five-summer reference run of constant grid size and microphysical parameterization. We found that the interannual and intraseasonal variability in MCS-like storm intensity dominates any sensitivities in single-season test simulations (Fig. 2). Based on the level of internal variability in the MCS signal that we quantify for the first time, *we predict ensembles* *that include hundreds of independent MCS will be needed to detect or tune unconstrained microphysical sensitivities* of superparameterized MCS. This emphasizes the importance of simulation experiment designs that leverage *long time series* of observed cloud statistics such as at ARM SGP, as opposed hindcasts that target individual intense observing periods, if SP simulations are to be meaningfully constrained by data.

Surprising amounts of internal variability obscure microphysical sensitivities of super-parameterized Central US Mesoscale Convective Systems (MCS)

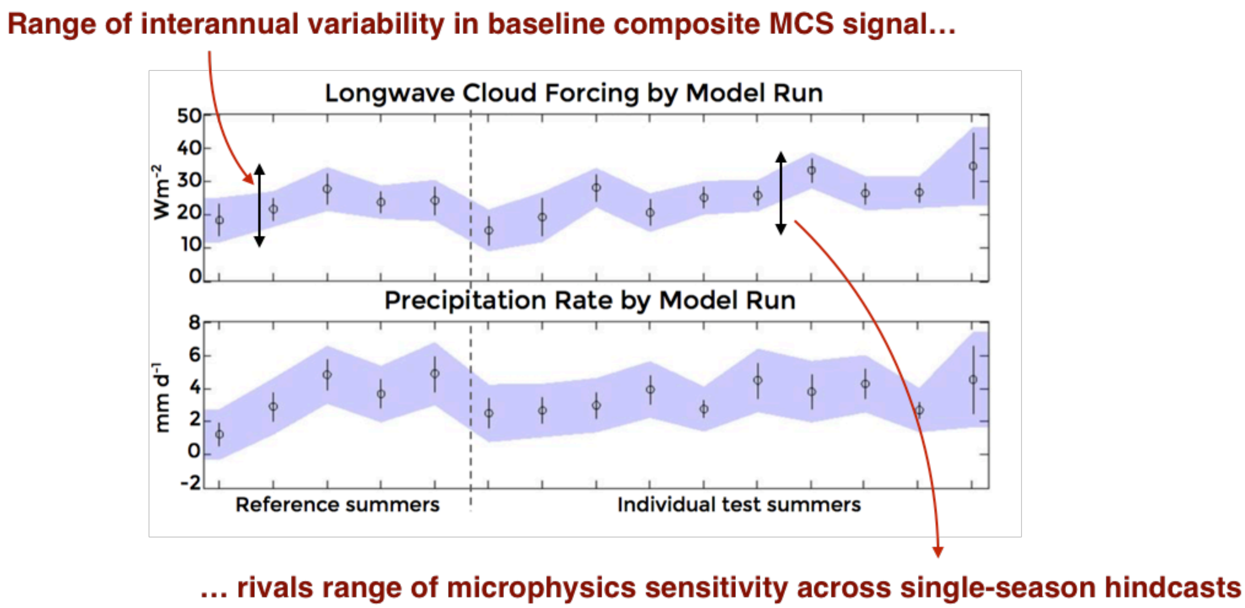

Fig. 2: Results summarizing the single-season tests that varied microphysical parameters (right) relative to a control simulations holding microphysics fixed but sampling internal variability, illustrating the noise level discovered to obscure meaningful composite tuning of superparameterized MCS (**Elliot et al. 2016**).

While this is discouraging for the tuning of fine-scale regional climate features, there is much to be detected on larger scales. Capturing realistic global present-day rainfall intensity is critical for understanding the sensitivity of rainfall to climate change and improving confidence in future projections. In **Kooperman et al. (2016a)** we demonstrate that explicitly resolving convection with superparameterization (SP) improves the representation of rainfall intensity, including both moderate and extreme rates, especially in regions of organized convection. We justify this conclusion by performing the most in-depth analysis yet of the effects of SP on rainfall, spanning three versions of the conventional (CAM) and superparameterized (SPCAM) Community Atmosphere Model, and validated against two satellite global gridded rainfall products (GPCP 1DD and TRMM 3B42). This helps discriminate robust effects of superparameterization that emerge across multiple versions for the first time.

We find that the *moderate rainfall rates* (which are not a typical focus of this sort of analysis, but which deliver the most accumulated rain) are systematically too weak in all versions of CAM and do not improve with horizontal resolution. However, SPCAM is able to capture the intensity of the amount mode, as well as extreme rates, observed by TRMM 3B42 in regions of tropical wave, Madden-Julian Oscillation, ITCZ, and monsoon activity. Importantly, unlike CAM, this happens without sensitivity to horizontal resolution, illustrating an intrinsic *scale-awareness* of the SP algorithm (Fig. 3).

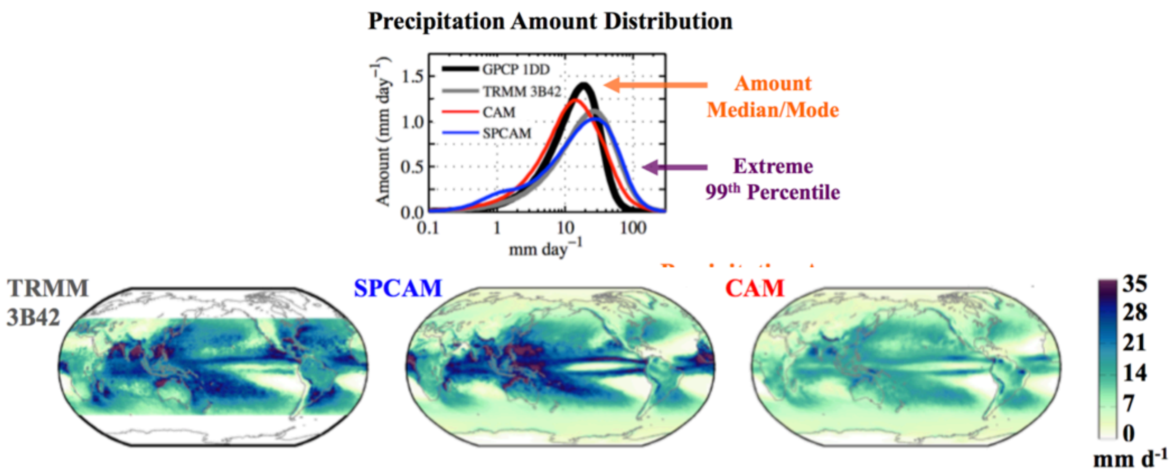

Fig. 3: (top) Global amount distribution of rainfall in (red) conventional vs. (blue) superparameterized climate simulations compared to two observational products. (Bottom) geographic structure of the amount mode. From **Kooperman et al. (2016a**).

Kooperman et al. (2016b) builds off that result by further mapping out the climate change of the rainfall distribution, and how it is modified through the use of explicit convection, in three simulation pairs. The results emphasize how *moderate rainfall rates* (which are not a typical focus of this sort of analysis) are strikingly impacted by climate change when explicit convection is used, especially in geographic action centers in the tropics where monsoons and tropical waves are important modulators of the frequency distribution. Maps of the climate change of the "rain amount mode" (the rain rate that delivers most accumulated precipitation) are shown to be especially revealing in this regard.

Kooperman et al. (2018) build further on this work by attempting to clarify the discrepancies between conventionally vs. superparameterized climate simulations' response to climate change, again exploiting the median of the rainfall "amount distribution". This turns out to be clarifying and reveals some otherwise hidden trade-offs. One discovery is a strong stationarity -- to both changes in resolution and surface temperature -- of the parameterized component of the total rainfall amount median. Meanwhile, separating just the large-scale component of rainfall in CAM reveals median statistics that are curiously consistent with benchmark superparameterized calculations, both in the response to forced surface warming, as well as in the value of the amount median in present climate. We expect these findings to help inform broader goals in the community to develop satisfying, scale-insensitive parameterizations of deep convection in coarse resolution climate simulations, and to help model some new best practices for a complementary approach to statistically separate large-scale from parameterized rainfall.

II. Effects of explicit convection on land-atmosphere coupling.

In **Sun and Pritchard (2016)** we report the first in-depth analysis of the effect of explicit convection (superparameterization; SP) on global land-atmosphere coupling. This work was highlighted as a "feature article" on *JAMES'* website. Our results show that SP improves the geographic pattern of the "terrestrial segment" of land-atmosphere coupling, with better validation against rainfall-assimilating land reanalysis. SP also globally reduces the diurnal Triggering Feedback Strength (TFS) – that is, a morning soil water anomaly is less prone to triggering afternoon rainfall when SP is used compared to the conventionally parameterized CAM. This improves validation against the North American Regional Reanalysis (Fig. 4). Using a new set of metrics that we call the Planetary Boundary Layer Feedback Strength (PFS), we illustrate that a key effect of SP is to tighten the connection between rainfall triggering and the responses of PBL properties such as Lifted Condensation Level and PBL height to surface flux anomalies. This highlights that despite its distortion of TFS the conventional CAM produces realistic PFS, suggesting the parameterization problem is perhaps more solvable than it might appear, given a better triggering formulation.

Superparameterization reduces diurnal land-atmosphere coupling and improves its regional structure over the US.

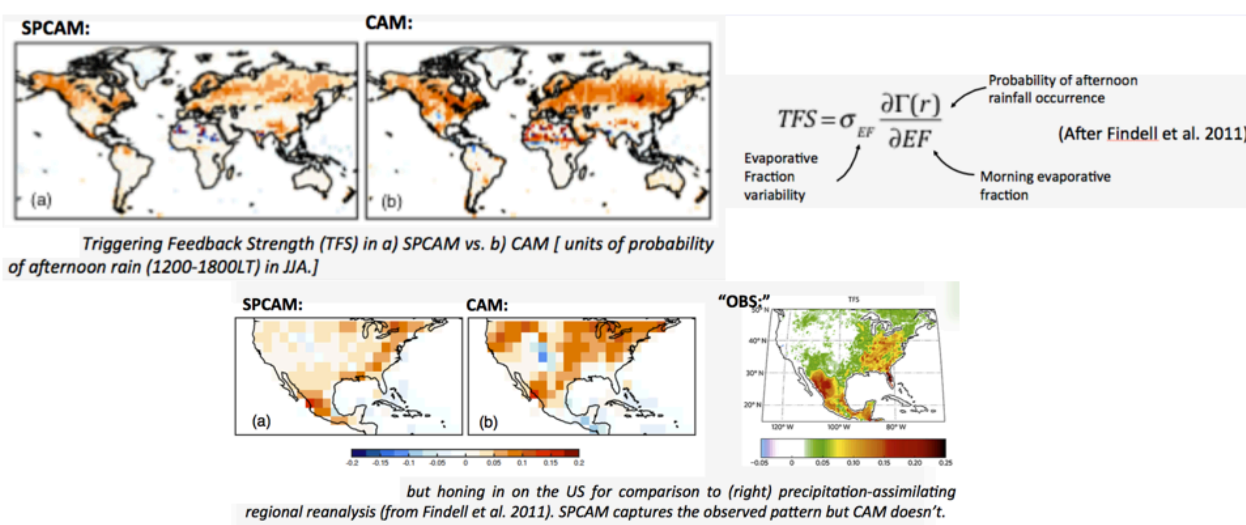

Fig. 4: Analysis of the land-coupling strength as measuring probabilistically via the "Triggering Feedback Strength" in conventional (CAM) vs. superparameterized (SPCAM) simulations. Results show SP reduces the land-atmosphere coupling especially in the Central US. From **Sun and Pritchard (2016)**.

In **Qin et al. 2018** we build on these results as the first to attempt a "GLACE-type" experiment with a superparameterized climate model (i.e. a classic test in which soil moisture is artificially prescribed to isolate L-A coupling strength). The results confirm our preliminary finding in Sun and Pritchard (2016), that hydrologic L-A coupling is strongly muted by SP – not only on subdaily timescales, but also on synoptic. Second, a timescale sensitivity analysis shows that in contrast no strong effect of SP on L-A coupling can be found on seasonal or longer timescales. Along with **Sun and Pritchard (2018),** Qin et al. looks at the thermal coupling pathway for the first time, identifying two interesting subregions. Over Arabia, SP shuts down unrealistically strong thermal coupling in CAM; this is traced to SP's effects on mean precipitation, which realistically shifts this location from a transitional coupling regime to a dry zone, where little coupling is expected. In the Southwest US, SP does the opposite by *enhancing* thermal coupling. Interestingly, in tracing the origin of these dynamics **Qin et al. 2018** reveals a previously unrecognized effect of SP is to systematically increase the surface Bowen Ratio. This result is verified across multiple version pairs of SPCAM/CAM and revealed to be a robust consequence of SP, with impacts worth considering for the representation of surface temperature extremes.

<u>III. Irrigation, vegetation and streamflow climate dynamics.</u>

Global climate models have begun to incorporate explicit treatments of irrigation in their land surface models, but different approaches have led to disagreement on the ability of irrigation to modulate the local and non-local hydroclimate. In **Fowler and Pritchard (2018)**, we use the irrigation scheme of CLM4 coupled with CAM5 to assess the impact of Indian irrigation on precipitation. Through a novel application of 60 hindcast ensembles initialized on 3 different days, we have identified a series of robust non-local rainfall changes that stem from the addition of irrigation but are highly sensitive to initial synoptic conditions. These patterns are primarily observable on short lead times (e.g., 8-14 days after the simulation is initialized), though a few signals persist through the full 45-day period and indicate sub-seasonal and potentially climatic impacts of irrigation. These findings suggest that the current collection of long, free-running climate simulations with irrigation might reveal increased agreement on the role of irrigation on precipitation if they were clustered by synoptic state. Analysis of local surface variables within the heavily irrigated region of northwestern India reveals a few limitations of the irrigation scheme in CLM4. Most notably, we find that a large fraction of the water being applied to the surface is lost to surface runoff rather than infiltrating the surface. Water that *is* able to enter the soil column tends to drain through the upper soil column too quickly. This behavior likely limits the response of transpiration to irrigation, given that the bulk of crop roots reside in the upper 11 cm of the soil column while irrigation seems to primarily impact 1 m moisture levels. Realistic applications of irrigation water, as contained in the CLM4 scheme, therefore might not lead to realistic responses of the land surface and/or overlying atmosphere.

In **Kooperman et al. (2017)** we began new collaborative work focusing on forest physiological-climate interactions. Most earth system models used by the Intergovernmental Panel on Climate Change (IPCC) project increases in rainfall across tropical Asia, and neutral or drying trends across lowland South America. The cause of this pattern is not well understood, and many previous researchers have explored climate change effects on sea surface temperatures and changes in ocean and atmospheric circulation as possible drivers. Here researchers from our team, terrestrial eco-hydrologistis at UC Irvine and U. of Georgia, along with collaborators from LBL, ORNL, NCAR, and U. of Washington, show that much of this pattern can be traced back to the way forests respond to rising atmospheric CO_2. Water loss by plants is regulated by tiny holes on the bottom of leaves (stomata) that open or close in response to changing environmental conditions. Our best understanding of the way these stomata function suggests they will become more restricted as carbon dioxide levels in the atmosphere increase. As this occurs, the plants will become more efficient at using available water in soils, but will evaporate less moisture into the air, causing the land surface to heat up and changing the way energy from the sun is transmitted back into the atmosphere. This work, published in *Nature Climate Change*, indicates that these changes in surface energy fluxes can have a dominant role in changing future patterns of rainfall across the tropics. This work highlights the importance of improving our understanding of forest responses to rising CO_2 as a means to reduce uncertainties in climate projections of future drought stress. In summary, applying a simulation design in which CO_2 increases were isolated over individual continents in the Community Earth System Model (CESM), we demonstrate that contrasts in regional circulation, moisture flux, and stability anomalies arise over each continent from declines in stomatal conductance and transpiration. Our analysis indicates that South American forests may be more vulnerable to rising CO_2 than Asian or African forests (Fig. 5)

The profound effects of tropical leaf pores' response to CO_2 on rainfall.

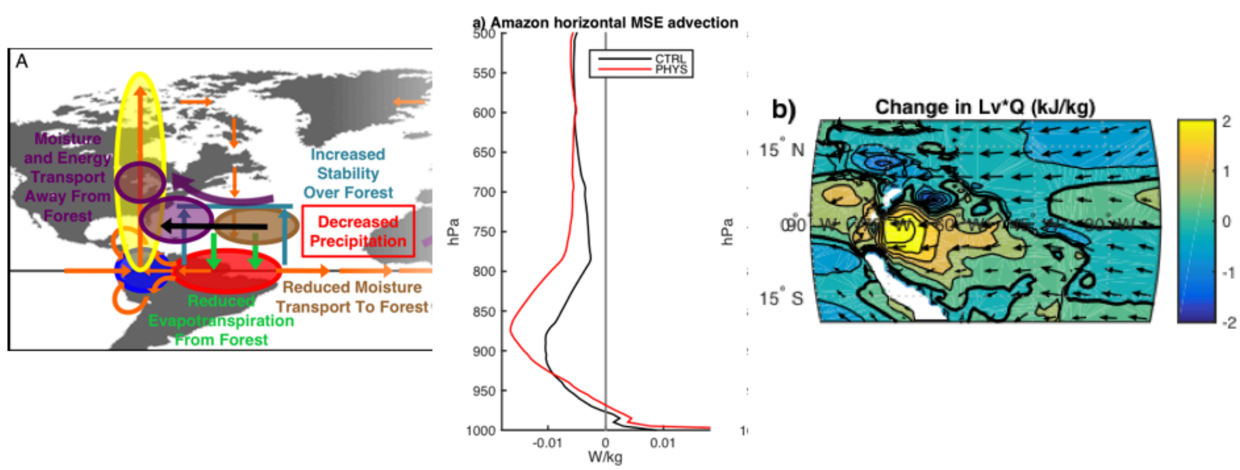

Fig. 5: (Left) schematic showing the reponse of the regional water cycle to rainforest stomatal closure, indicating a reduction of rainfall over the Amazon and an increase over the Andes. These dynamics are associated with (middle) an increase in lateral vapor advection leading to (right) a building up moist static energy over the Andes. From **Kooperman et al. (2017)**.

In **Langenbrunner et al. (2018)** we performed an in-depth investigation into the underlying atmospheric dynamics that mediate the above responses and assessed their robustness to finely resolved regional climate simulations. The results highlighted an interesting causal pathway (Fig.

6) in which the parameterized planetary boundary layer turbulence plays a major role. Stomatal closure of the rainforest is felt by the atmosphere as a shift in the Bowen ratio from latent towards sensible heat fluxes, driving a deepening of the PBL but also a stability-mediated increase in the efficieny of vapor transport above the PBL. Once there, it is easily flushed by the Andean low-level jet in ways that starve the local forest of column moist static energy, and thus rainfall.

Why does the Amazon dry itself at high CO2?

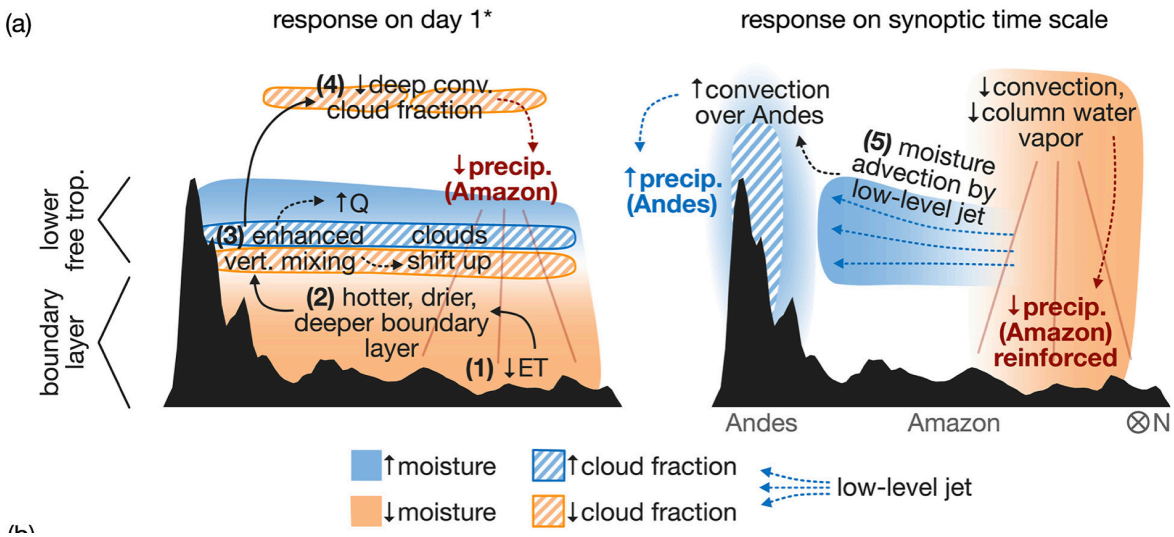

Fig. 6: Schematic summarizing the results of high-resolution regional climate simulations subject to surface forcing via a prescribed stomatal closure leading to planetary boundary layer responses that, coupled to advection, explain the Amazonian rainfall reduction and Andean rainfall increases. From **Langenbrunner et al. (2018)**, *Earth's Future*.

Building further on the downstream impacts from the above work, in **Kooperman et al. (2018)** we identified a strong control between the plant physiological response to CO2 and river runoff. The implications for global streamflow were elucidated in detail by us in **Fowler et al. (2019)**, and published in *Nature Climate Change*. This was achieved by linking a climate model capable of isolating physiological effects to a hydrodynamic streamflow model. The results were quite provocative – stomata are a stronger control on streamflow than radiative effects of CO2 for vast regions of the planet equatorward of 35 degrees latitude (Fig. 7).

Plant physiology is a main control of future river flow equatorward of 30 degrees latitude.

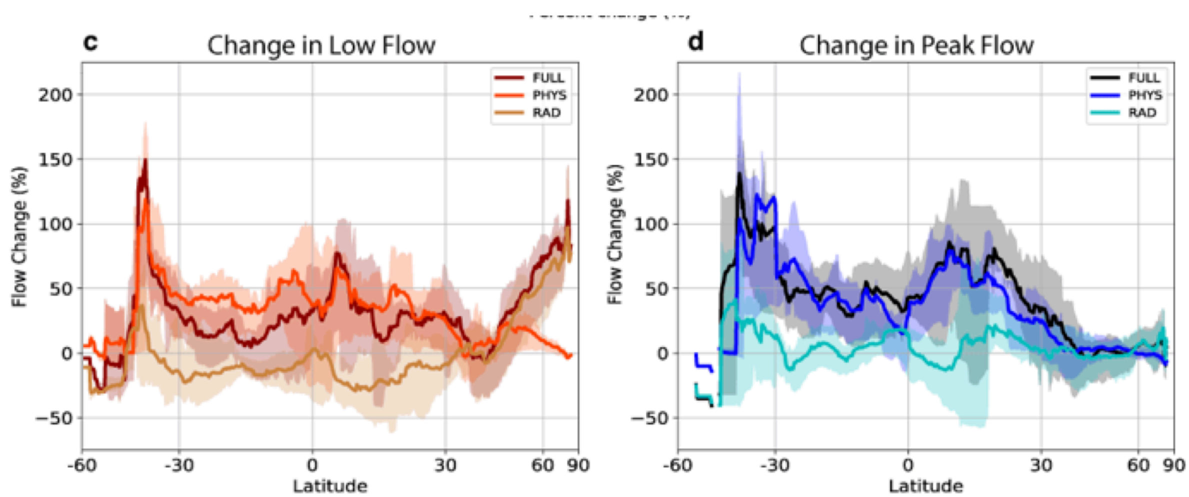

Fig. 7: Response of global streamflow as a function of latitude to the full effects of increased CO_2 (FULL) vs. its atmosphere radiative component (RAD) alone and (PHYS) plant-physiological component. Equatorward of 35 degrees latitude, rainforest physiology is the primary control on simulated streamflow changes. From **Fowler et al. (2019)**, *Nature Climate Change.*

IV. Dynamics of the Madden-Julian Oscillation:

Now that it is possible to simulate the Madden Julian Oscillation (MJO) signal explicitly such as in superparameterized global atmospheric models, hypotheses about what controls observed relationships between sea surface temperatures (SSTs) and the MJO can be explored. In **Benedict et al. (2015)** we use idealized simulations with the superparameterized (SP)CAM to explore how the "Indian Ocean Dipole (IOD)" SST pattern can disrupt the MJO — a hypothesis based on an observed MJO/IOD relationship. We show SPCAM can capture this MJO disruption but that it does not occur due to local dynamics over the Indian Ocean as one might expect (Fig. 8). Rather, the disruption dynamics are concentrated in the Central Pacific and seem to be indirectly associated with an El Nino-IOD relationship. This has implications for understanding the future of the MJO based on the future pattern of SSTs.

Confronting hypothesis that Indian ocean SST dipoles disrupt long-range propagation of the Madden—Julian Oscillation (MJO).

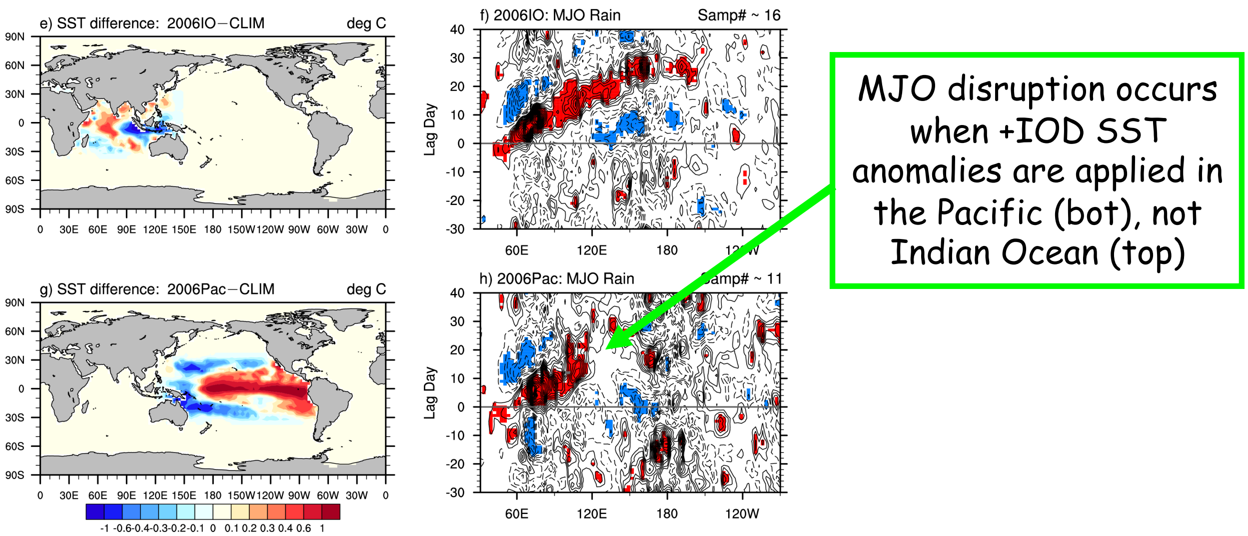

Fig. 8: (Right) composite MJO propagation measured in SPCAM in response to (left) SST perturbations including (top) the local effect of the Indian-Ocean Dipole vs. (bottom) its correlation to Pacific SST anomalies, showing the latter are more critical to disrupting MJO propagation.

Idealized simulations can be equally useful for testing hypotheses of basic MJO dynamics. In **Pritchard and Yang (2016),** we measured the sensitivity of the Madden-Julian Oscillation (MJO) across a broad range of temperatures (1°C-35°C) using a superparameterized global climate model in an unusual basic state – nocturnal, aquaplanet, and with globally homogenous sea surface temperatures. Large ensemble simulations were possible thanks to a new algorithm that can speed up the computational efficiency of superparmaterized simulations by a factor of 2-4 (**Jones et al. 2015**) by exploiting a known timescale separation between fast eddies and the rate at which they evolve the horizontal mean state of a limited domain LES. An MJO-like signal was found to be resilient in all simulations even in cold climates with SST < 15 (Fig. 9), despite reversed background meridional moist static energy gradients. This result was used to interrogate ideas related to the growing consensus for a "moisture mode" view of MJO dynamics, especially the idea that the MJO is propagated by horizontal advection of column moist static energy. Inconsistent with this view, the simulated "cold MJO" survives reversal of meridional moisture gradients in the basic state and a striking role for horizontal MSE advection in its eastward propagation energy budget cannot be detected. These findings could suggest a tight relation between the MJO and classic equatorial waves, which would tend to challenge moisture mode views of MJO dynamics that assume horizontal moisture advection as the MJO's propagator. Overall the results are relevant to understanding the controversial physics of the Madden-Julian Oscillation, which has been a decades long challenge in climate simulation and the global water cycle.

Discovering a "cold MJO" on a uniform sea surface temperature aquaplanet with implications for moisture mode theory.

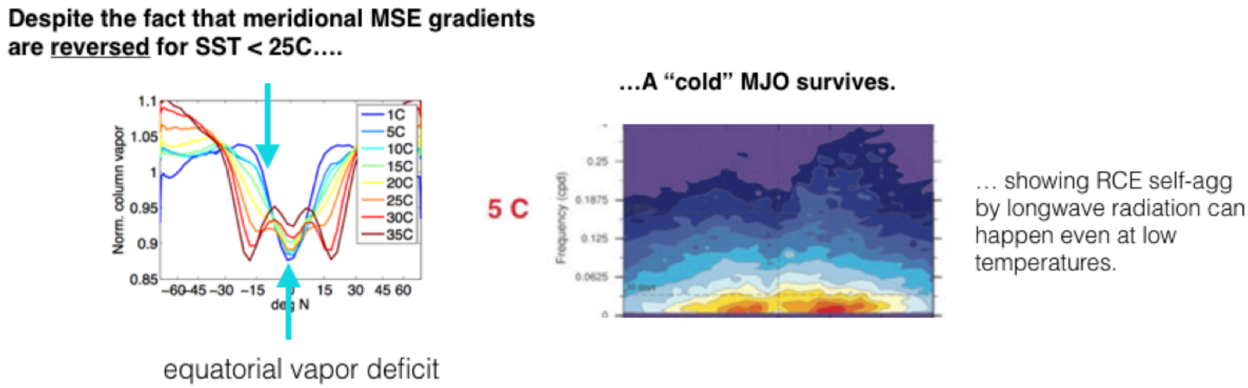

Fig. 9: (left) Integrated vapor as a function of latitude in response to extreme SST variations on a uniform temperature aquaplanet, and (right) co-existence of a MJO-like signal even at cold SSTs in which it might not be expected from moisture-mode theory. From **Pritchard and Yang (2016).**

While the above studies focused on the underlying dynamics of the MJO, in the final phases of this project we also investigated the linkage between the MJO and tropical cyclogenesis in **Fowler et al. (2020)**, *GRL*. We used quasi-explicit empirical TC downscaling tools developed at MIT to sidestep traditional sample size limitations. The results reveal a region of the South China Sea that is especially prone to MJO-induced tropical cyclone genesis. This is relevant to understanding how humans may be impacted by changing TC statistics as the MJO amplifies with climate warming and its convective envelope spreads farther into the Pacific Ocean.

V. Machine learning for process emulation.

An unexpected outgrowth of this project has been to explore the potential of modern deep neural network algorithms (i.e. machine learning) as a computationally efficient emulator of the expensive but fundamentally advantageous approaches of superparameterization. This concept was proved by us in **Gentine et al. (2018)** where even short multi-month integrations from global cloud-resolving models form a sufficiently large dataset to successfully train a deep neural network that captures the essence of the high-resolution cloud physics lacking in standard parameterization schemes. Work led by the group in **Rasp et al. (2018**) then demonstrated such a deep learning parameterization, trained on SP, is capable not only of producing robust, multi-year climate simulations exhibiting benefits of explicit convection (Fig. 10) but also can spontaneously achieve column energy conservation and some limited out-of-sample generalization. In August 2020, the PI wrote a blog post for the E3SM newsletter chronicling the progress and outlook on this rapidly developing topic.

Deep learning to represent subgrid processes in climate model:

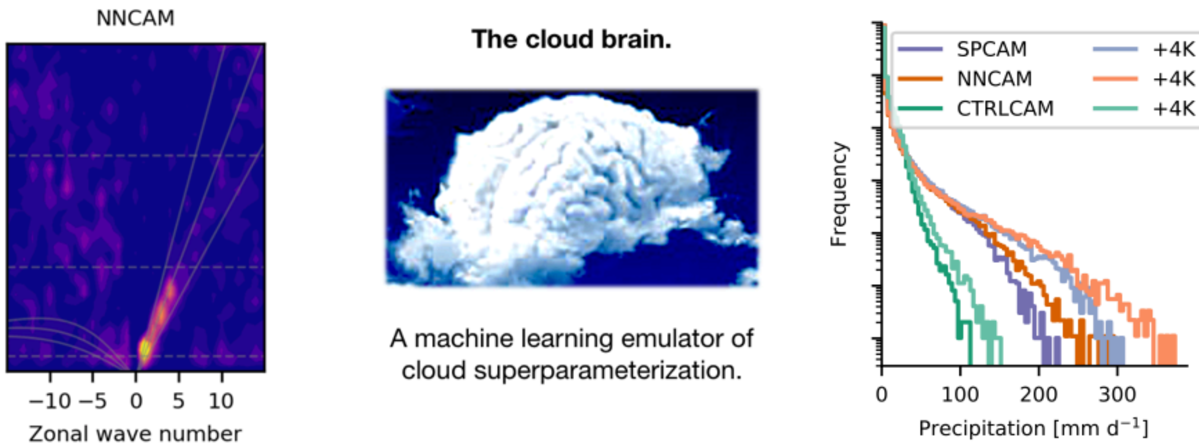

Fig. 10: (Left) Our neural network emulator replacing cloud superparameterization producing a similar equatorial wave signal-to-noise relationship in Wheeler-Kiladis spectra, at a fraction of cost and even (right) analogous precipitation statistics. Reproduced from **Rasp et al. (2018)**, *PNAS*.

VI. Summary of products – peer-reviewed journal articles (20).
Listed in reverse chronological order.

* denotes led by Pritchard's group; underlined are: PI-advised (P)ostdoc, (G)raduate student, (U)ndergraduate.

* Fowler, M. (G) and **M. Pritchard**, Regional MJO modulation of West Pacific tropical cyclones driven by multiple transient controls, *Geophysical Research Letters*, 47 (11), 2020. [link]

* Fowler, M. (G), G. Kooperman, J. T. Randerson and **M. Pritchard**. The effect of plant-physiological responses to rising CO_2 on global streamflow, *Nature Climate Change*, 9, 2019. [link]

* Langenbrunner, B. (P), **M. S. Pritchard**, G. Kooperman and J. Randerson. Why does Amazon precipitation decrease when tropical forests respond to increasing CO_2?, *Earth's Future*, 2019. [link]

Levine. P., M. Xu, F. M. Hoffman, Y. Chen, **M. S. Pritchard** and J. T. Randerson. Soil moisture variability intensifies and prolongs Amazon temperature and carbon cycle response to El Niño-Southern Oscillation, *J. Climate*, 32, 2018. [link]

Kooperman, G., M. Fowler (G), F. Hoffman, C. Koven, K. Lindsay, **M. Pritchard**, A. Swann and J. Randerson. Plant-physiological responses to rising CO_2 modify daily runoff intensity with implications for global-scale flood risk assessment, *Geophys. Res. Lett.*, 2018. [link]

* Sun, J. (P) and **M. S. Pritchard**. Effects of explicit convection on land surface air temperature and land-atmosphere coupling in the thermal feedback pathway, *J. Adv. Model. Earth Sys.*, 2018. [link]

Rasp, S. (Visiting G), **M. S. Pritchard**, and P. Gentine. Deep learning to represent sub-grid processes in climate models, *PNAS*, 2018. [link]

Gentine, P., **M. S. Pritchard**, S. Rasp (Visiting G), G. Reinaudi and G. Yacalis (G). Could machine learning break the convection parameterization deadlock?, *Geophys. Res. Lett.*, 45, 2018. [link]

Kooperman, G. K, Y. Chen, F. M. Hoffman, C. D. Koven, K. Lindsay, **M. S. Pritchard**, A. L. S. Swann, and J. T. Randerson, 2018. Forest response to rising CO_2 drives zonally asymmetric rainfall change over tropical land, *Nature Climate Change*, 8, 434–440, 2018. [link]

* Kooperman, G. J. (P), **M. S. Pritchard**, M. S., T. A. O'Brien and B. W. Timmermans. Rainfall from resolved rather than parameterized processes better represents the present-day and climate change response of moderate rates in the community atmosphere model. *J. Adv. Model. Earth Syst.*, 10, 2018. [link]

* Qin, H. (G), **M. S. Pritchard**, G. J. Kooperman (P) and H. Parishani (P), 2018. Global Effects of SuperParameterization on Hydro-Thermal Land–Atmosphere Coupling on Multiple Timescales, *J. Adv. Model. Earth Syst.*, 10, 2018. [link]

* Fowler, M. (G), **M. S. Pritchard** and G. J. Kooperman (P). Assessing the impact of Californian and Indian irrigation on precipitation in the irrigation-enabled Community Earth System Model, *J. Hydromet.*,19(2), 427-443, 2018. [link]

* Kooperman, G. J (P)., **M. S. Pritchard**, M. A. Burt, M. D. Branson, and D. A. Randall. Impacts of cloud superparameterization on projected daily rainfall intensity climate changes in multiple versions of the Community Earth System Model, *J. Adv. Model. Earth Syst.*, 8, 2016. [link]

* Sun, S. (P) and **M. S. Pritchard**. Effects of explicit convection on global land-atmosphere coupling in the superparameterized CAM, *J. Adv. Model. Earth Syst.*, 8, 1248–1269, 2016. [link]

* Elliott, E. J. (U), S. Yu (G), G. Kooperman (P), H. Morrison , M. Wang and **M. S. Pritchard**. Sensitivity of summer ensembles of superparameterized US mesoscale convective systems to cloud resolving model microphysics and grid configuration, *J. Adv. Model. Earth Syst.*, 2016. [link]

* **Pritchard, M. S**. and D. Yang. Response of the superparameterized Madden-Julian Oscillation to extreme climate and basic state variation challenges a moisture mode view. *J. Climate*, 29, 4995-5008, 2016. [link]

* Kooperman, G. J. (P), **M. S. Pritchard**, M. A. Burt, M. D. Branson, and D. A. Randall. Robust effects of cloud super-parameterization on simulated daily rainfall intensity statistics across multiple versions of CESM. *J. Adv. Model. Earth Syst.*, 8, 2016. [link]

Benedict, J. J., **M. S. Pritchard**, and W. D. Collins. Sensitivity of MJO propagation to a robust positive Indian Ocean dipole event in the superparameterized CAM, *J. Adv. Model. Earth Syst.*, 7, 1901–1917, 2015. [link]

* Yu, S. (G) and **M. S. Pritchard**. The effect of large-scale model time step and multiscale coupling frequency on cloud climatology, vertical structure, and rainfall extremes in a superparameterized GCM, *J. Adv. Model. Earth Syst.*, 7, 1977–1996, 2015. [link]

Jones, C., C. S. Bretherton and **M. S. Pritchard**. Mean-state acceleration of cloud-resolving model simulations. *J. Adv. Model. Earth Syst.*, 07, 2015. [link]