The LLNL Climate UQ Project

Brief Overview and Preliminary Results

Lawrence Livermore National Laboratory, P. O. Box 808, Livermore, CA 94551

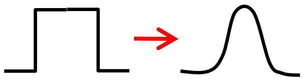
This work performed under the auspices of the U.S. Department of Energy by
Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

UCRL-LLNL-PRES-423404

Climate UQ Teams

- UQ Project Lead
  - Richard Klein (LLNL, U.C. Berkeley)
- Climate Team
  - Curt Covey (climate lead)
  - Donald Lucas (modeling and analysis)
  - John Tannahill (software architecture and development)
  - Yuying Zhang (observations and analysis)
  - Others (Peter Gleckler, Steve Klein)
- UQ and Computation Teams
  - David Domyancic, Scott Brandon (LLNL UQ Pipeline)
  - Gardar Johannesson (curse of dimensionality, design of experiments)
  - Carol Woodward, Jeff Hittinger (numerical errors, adjoints)
  - Others (Charles Tong, …)

Climate Model UQ Goals

- Phase One
  - 12-year CAM + AMIP runs (ver 3.6.73, phys 3.5.1, 1.9 x 2.5)
  - Exploratory sensitivity and uncertainty studies
    - Start with 21 uncertain target parameters (top hat parameter PDFs)
    - Rank order parameters (most-to-least influential)
    - Characterize linear versus non-linear/interaction responses
  - Variable selection, dimensional reduction (DR) and adaptive sampling refinement (ASR)
- Phase Two
  - Parameter calibration ensemble 
    - Use ASR to target important regions of parameter space for ensemble runs
    - Use observational data to constrain uncertain parameters: traditional reanalysis datasets, passive sensor cloud data (ISCCP, MODIS), active sensor cloud data (CloudSat, CALIPSO)
- Phase Three
  - UQ runs using CAM (calibrated) + SlabOcean (CCSM)
  - 2 x CO2 runs
  - Quantify climate sensitivity PDF and determine confidence bounds on the PDF

CAM/UQ study logistics

- CAM particulars:
  - CAM version 3.6.73, with a few local modifications
  - 2 degree, AMIP, cam3_5_1 physics, run for 12 simulated years
  - 21 input parameters of interest explored
  - 192 tasks/run X 2 cpu's per task = 384 cpu's/run
- atlas platform:
  - 1072 batch nodes X 8 cpu's/node = 8,576 batch cpu's
- Typical CAM/UQ study particulars:
  - 11 concurrent CAM runs X 384 cpu's/run = 4,224 cpu's for CAM
  - 4,224 cpu's for CAM + 1 UQ Pipeline node = 4,232 cpu's total
  - 16 hour job length
- MOAT1 study throughput:
  - 220 runs took ~9.5 days
  - Code was executing ~60% of that time

Climate Model Uncertainty Quantification

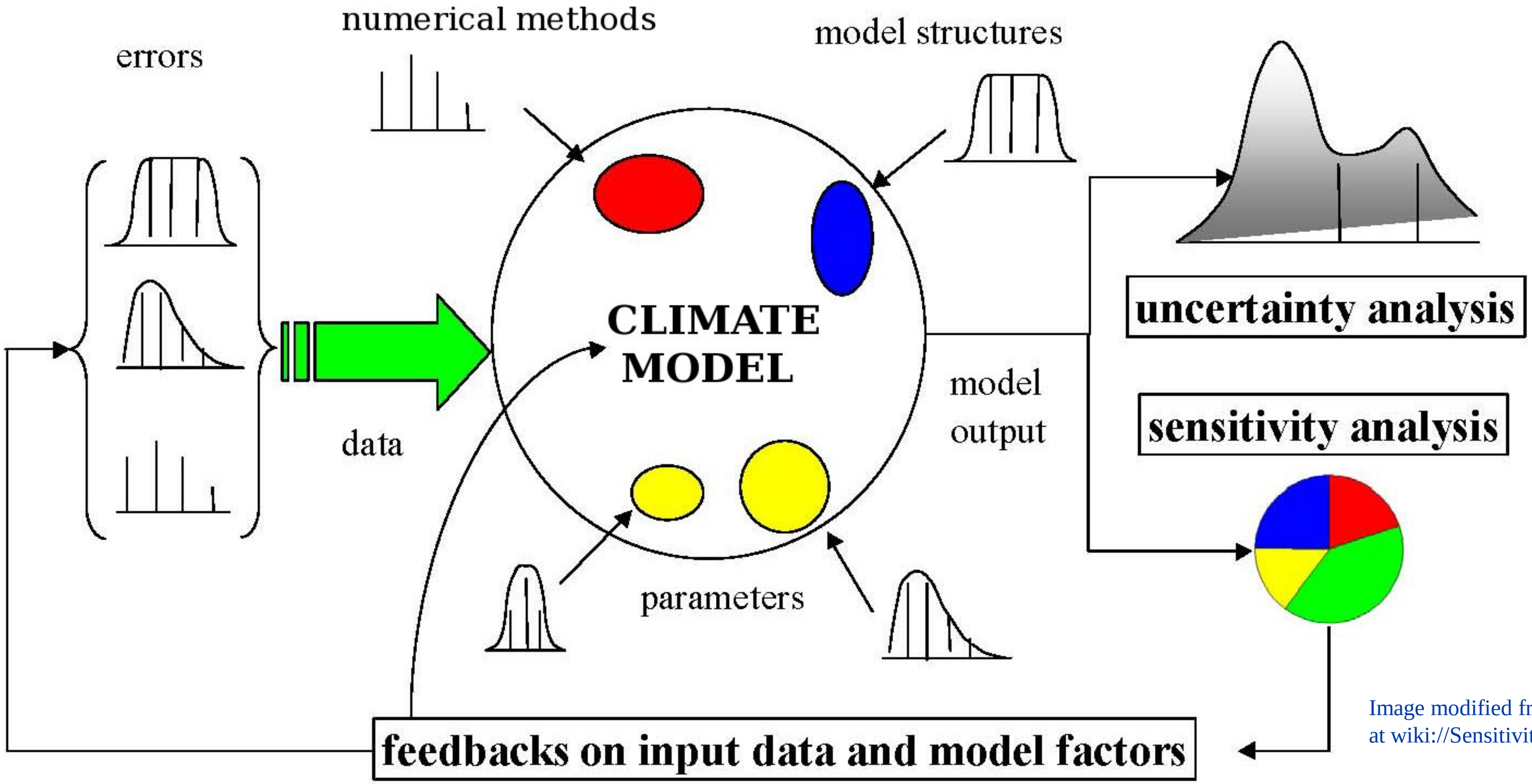


Image modified from A. Saltelli at wiki://Sensitivity_Analysis

UQ PIPELINE

Automated UQ

Parameter estimation

Variance decomposition

Stochastic expansions

Dimensional reduction

Latin Hypercube

Adaptive sampling

Climate Model UQ Studies

Group	Model(s)	# params	# runs	Types of runs	Ref.
QUMP	HadAM+SM	29	53 (2 x 26 + 1)	AMIP + 1,2 x CO2 OAT	Murphy et al (2004)
CPN	HadAM+SM	10	multi-10^3 (~3^{10})	AMIP + 1,2 x CO2	Piani et al (2005); Knutti et al (2006)
CPN	HadCM	74	>50,000 (but << 3^{74})	Same as QUMP below	Frame et al (2009)
QUMP	HadAM+SM +CM+RCM + CMIP3/IPCC	31 + extra	280 + 17 + 16	AMIP + 1,2 x CO2 +coupled ocn + biogeochem	UK Climate Projections (summer 2009, papers to follow)
UT Austin	CAM3.1	6	518	2-yr AMIP + 1,2 x CO2	Jackson et al. (2008)
Sanderson	CAM3.1	4	81	AMIP + 1,2 x CO2	Sanderson CCSM Workshop 2009
LLNL	CAM3.6.73	21	~500 and counting	12-yr AMIP OAT+MOAT (next: LHS + 1,2 x CO2)	Work began Oct. 2009

21 Parameters in Initial UQ Studies

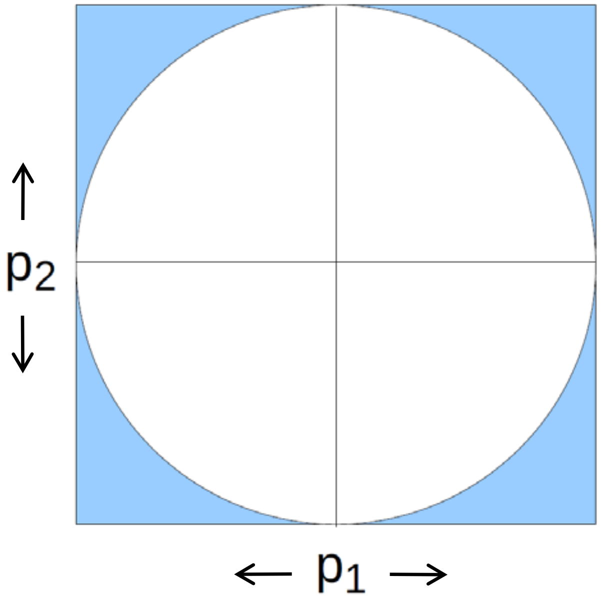
	Variable Name	Description	Nmlist Prefix	File Name	Source*
1	rhminh	Minimum RH for high stable cloud formation	cldfrc_	cloud_fraction.F90	J
2	rhminl	Minimum RH for low stable cloud formation	cldfrc_	cloud_fraction.F90	J+S
3	rliqice	Liquid drop size over sea ice	cldopt_	pkg_cldoptics.F90	R
4	rliqland	Liquid drop size over land	cldopt_	pkg_cldoptics.F90	R
5	rliqocean	Liquid drop size over ocean	cldopt_	pkg_cldoptics.F90	R
6	ice_stokes_fac	Ice Stokes factor scaling fall speed	cldsed_	pkg_cld_sedimnent.F90	S
7	capnc	Cloud particle # dens. over cold land/ocean	cldwat_	cldwat.F90	R
8	capnsi	Cloud particle # dens. over sea ice	cldwat_	cldwat.F90	R
9	capnw	Cloud particle # dens. over warm land	cldwat_	cldwat.F90	R
10	conke	Stratiform precip. evaporation efficiency	cldwat_	cldwat.F90	J
11	icritc	Threshold for cold ice autoconversion	cldwat_	cldwat.F90	S
12	icritw	Threshold for warm ice autoconversion	cldwat_	cldwat.F90	S
13	r3lcrit	Crit. radius where liq. conversion begins	cldwat_	cldwat.F90	R
14	ricr	Critical Richardson # for boundary layer	hbdiff_	hb_diff.F90	K/B
15	c0/shallow	Shallow convec. precip. efficiency parameter	hkconv_	hk_conv.F90	J
16	cmftau	Time scale for consump. rate of shallow CAPE	hkconv_	hk_conv.F90	K/B
17	alfa	Initial cloud downdraft mass flux	zmconv_	zm_conv.F90	J
18	c0/deep	Deep convec. precip. efficiency parameter	zmconv_	zm_conv.F90	J
19	dmpdz	Parcel fractional mass entrainment rate	zmconv_	zm_conv.F90	S
20	ke	Environmental air entrainment rate	zmconv_	zm_conv.F90	J
21	tau	Time scale for consump. rate of deep CAPE	zmconv_	zm_conv.F90	J

* J = Jackson et al. (2008) J Clim 21: 6698; R = P. Rasch (2009) suggestion; S = Sanderson (2009) talk at CCSM Workshop; SK = S. Klein + D. Bader (2009) suggestion

Traditional One-At-a-Time (OAT)

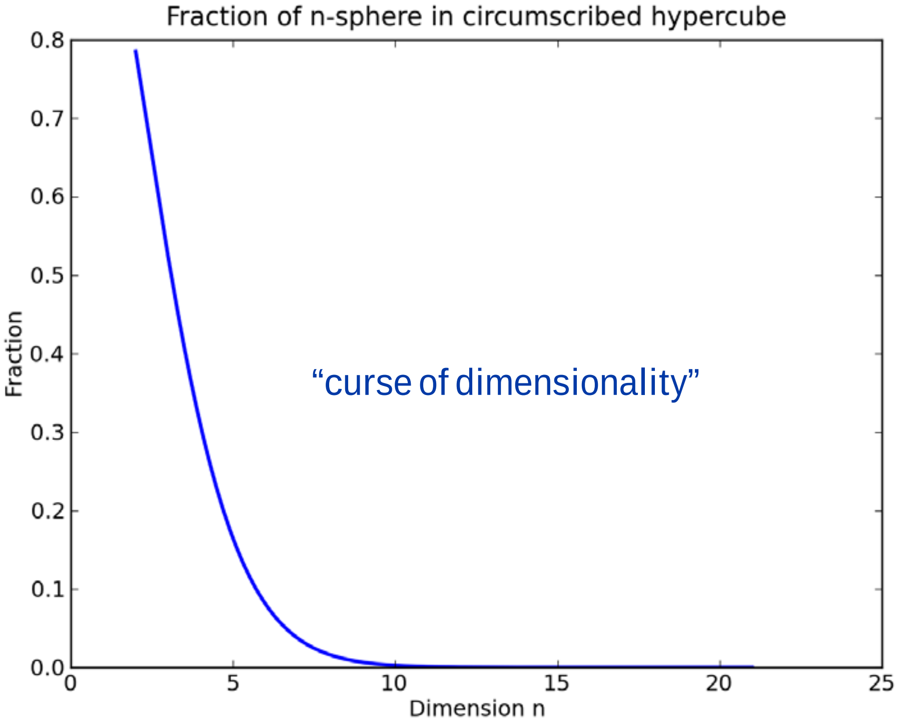
- Easy to implement
- Low computational cost

  Order ~ $2N_p + 1$
  43 CAM runs
- Misses corner regions (i.e. neglects joint effects)



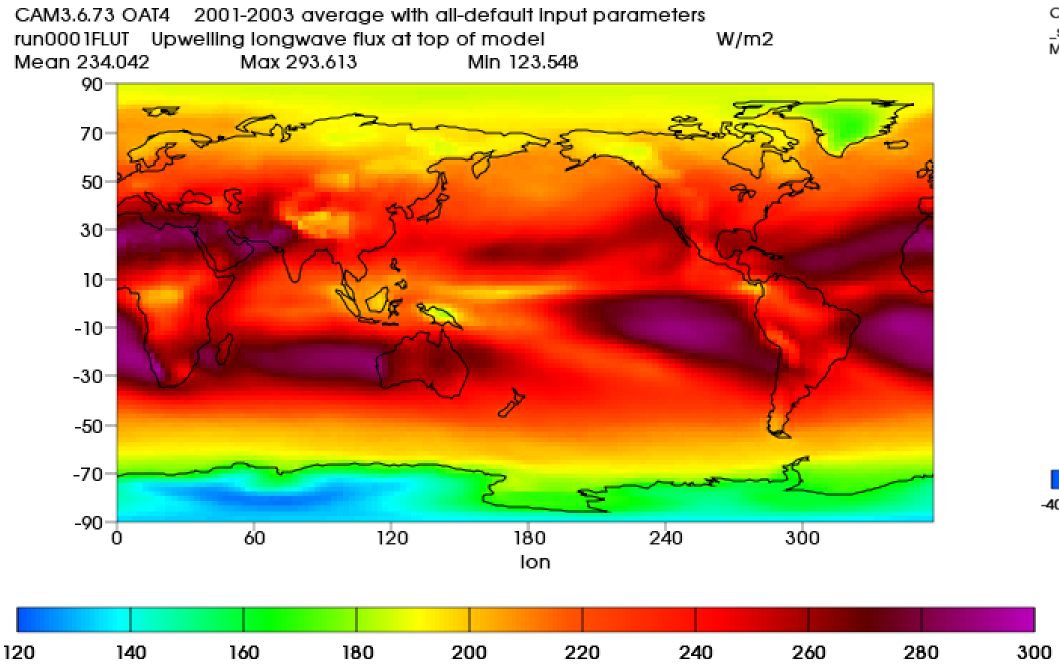
In 21 Dimensions

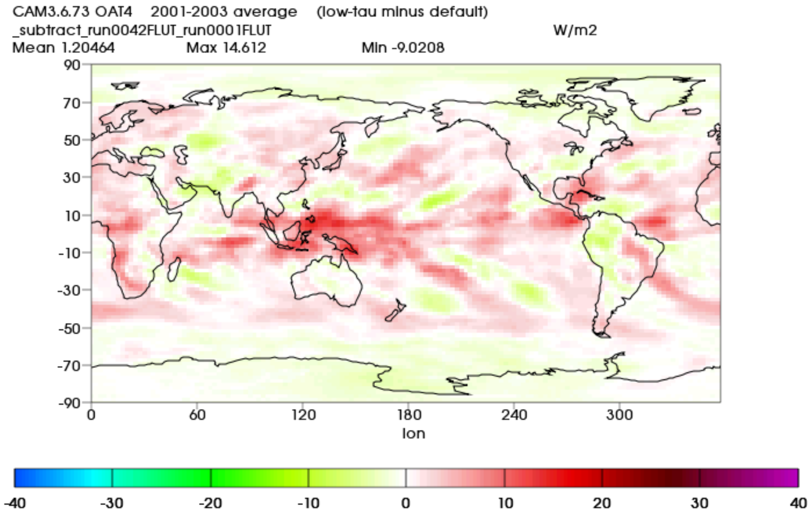
- Over 2 million corners (2^N)
- Fraction ≈ 6.7×10^{-9}

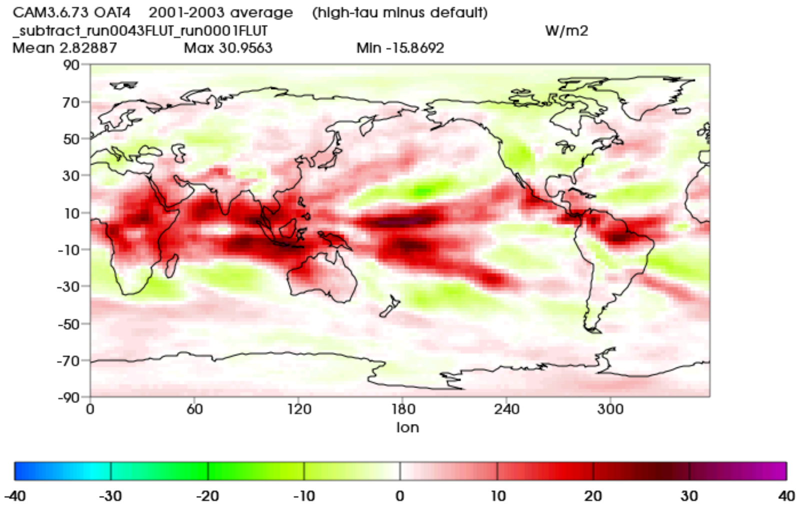


"curse of dimensionality"

Sample Output From Initial OAT Run

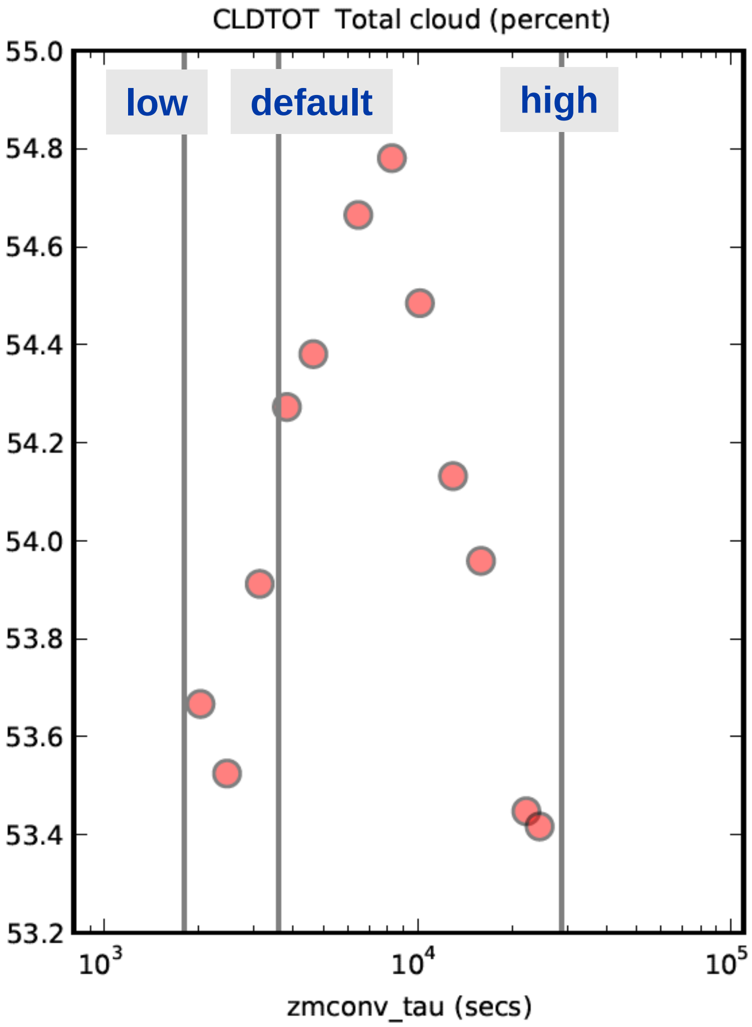


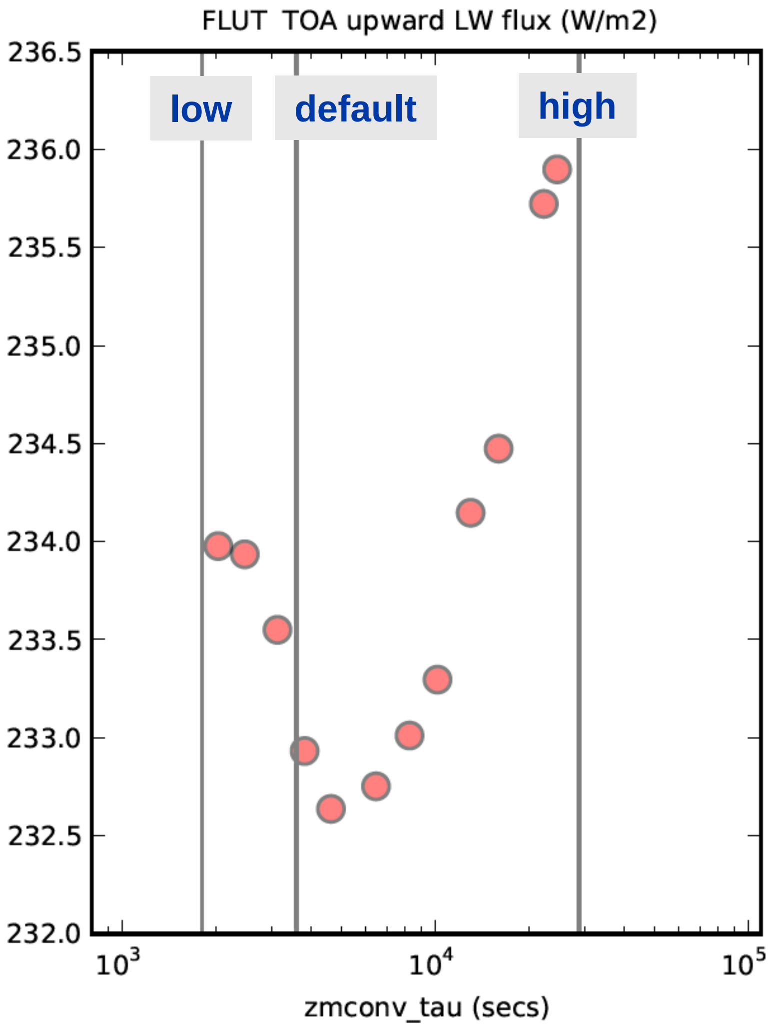




Nonlinear Responses Detected With OAT

10 random samples (LHS) generated for the tau parameter in Zhang-McFarlane convection





Morris One-At-a-Time (MOAT)

- Suggested by M. D. Morris (ORNL) in *Technometrics* (1991)
- *M*ulti-path One-At-a-Time

  Sample along multiple paths and build up statistics of sensitivities throughout parameter space

- Easy to implement
- Relatively low computational cost

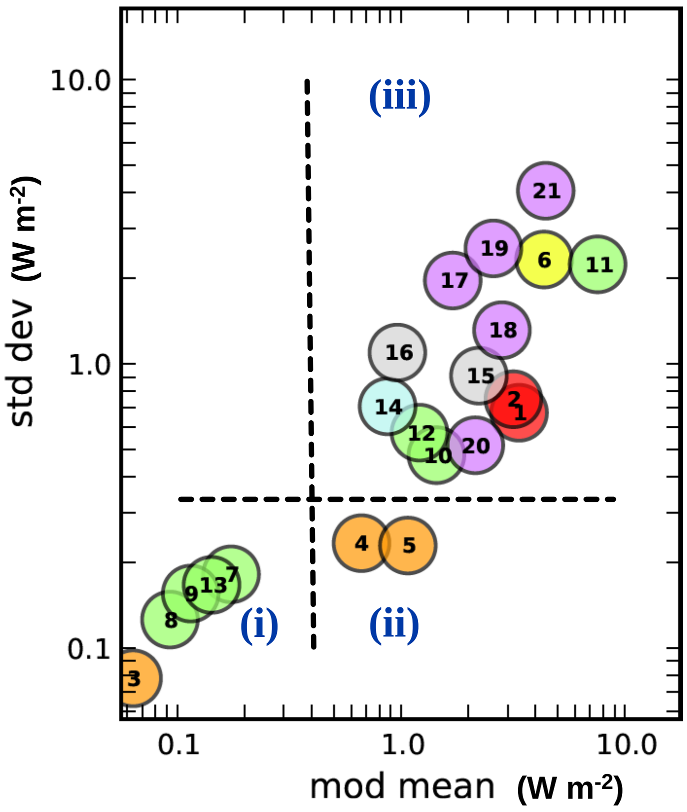
  $N_{runs} = M\ (N_p + 1)$

  M = number of MOAT paths (usually 10-20)

  220 to 440 CAM runs

- ***Screen*** and ***rank*** important parameters with linear or non-linear effects

Example MOAT Screening Diagram



(i) Not important

(ii) Important and linear

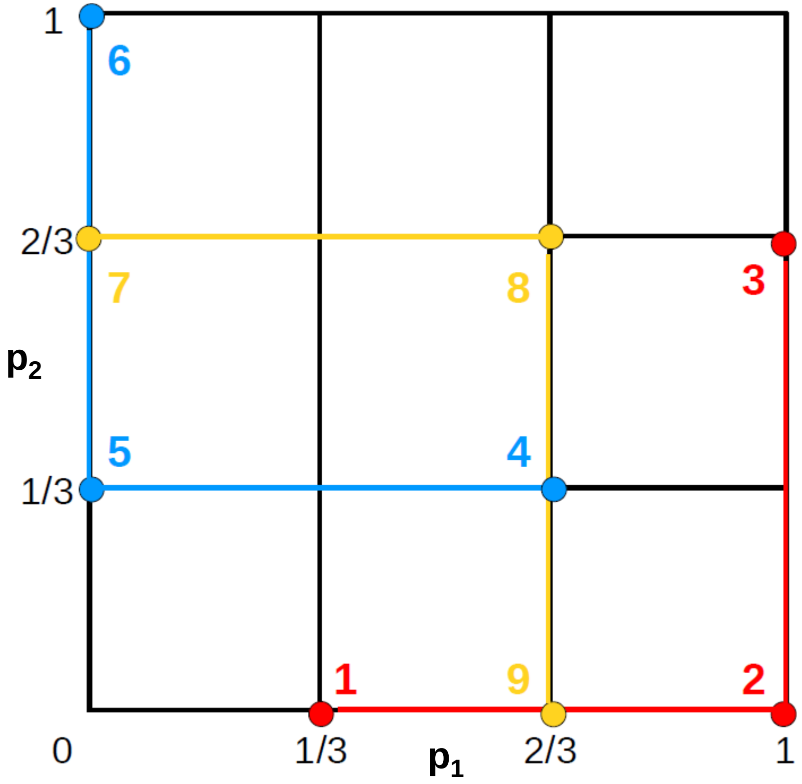
(iii) Important and non-linear

Sensitivity of the global average upwelling longwave flux (FLUT) at the top of model to 21 parameters in CAM

Red	cldfrc
Orange	cldopt
Yellow	cldsed
Green	cldwat
Blue	hbdiff
Gray	hkconv
Violet	zmconv

Morris One-At-a-Time (MOAT)

Example: Two Parameter, Three Path Study



path	run	p_1	p_2	
1	1	1/3	0	$d_{1,1}$
1	2	1	0	$d_{1,2}$
1	3	1	2/3	
2	4	2/3	1/3	$d_{2,1}$
2	5	0	1/3	$d_{2,2}$
2	6	0	1	
3	7	0	2/3	$d_{3,1}$
3	8	2/3	2/3	$d_{3,2}$
3	9	2/3	0	

$$\mu_1^* = (|d_{1,1}| + |d_{2,1}| + |d_{3,1}|)/3$$

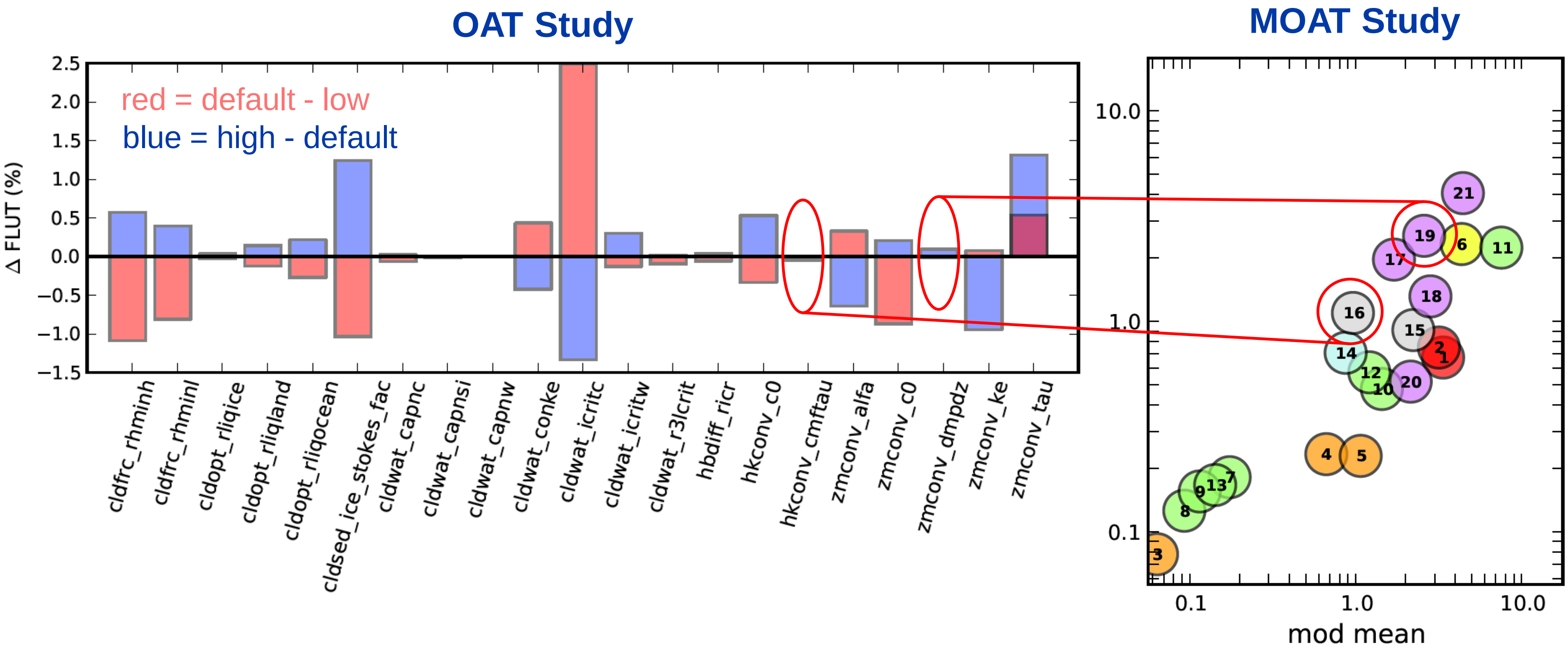
$$d_{i,j} = \frac{\Delta \text{ output}}{\Delta \text{ input}}$$ (path *i*, parameter *j*)

$$\mu_j^* = \text{avg}(|d_{i,j}|),\ \sigma_j = \text{stddev}(d_{i,j})$$

(1) Normalize p’s on [0,1]
(2) Chop into regular lattice
(3) Choose random start point
(4) Step in p_1 direction
(5) Step in p_2 direction
(6) Go back to step (3)

OAT vs MOAT

The sensitivity of global annual average FLUT to changes in 21 parameters



OAT Study

MOAT Study

- **OAT study suggests that FLUT is *not* sensitive to zmconv_dmpdz and hkconv_cmftau**
- **MOAT study indicates that these are important parameters!**

MOAT Parameter Screening Plots

MOAT Parameter Legend

1 = cldfrc_rhminh

2 = cldfrc_rhminl

3 = cldopt_rliqice

4 = cldopt_rliqland

5 = cldopt_rliqocean

6 = cldsed_ice_stokes_fac

7 = cldwat_capnc

8 = cldwat_capnsi

9 = cldwat_capnw

10 = cldwat_conke

11 = cldwat_icritc

12 = cldwat_icritw

13 = cldwat_r3lcrit

14 = hbdiff_ricr

15 = hkconv_c0

16 = hkconv_cmftau

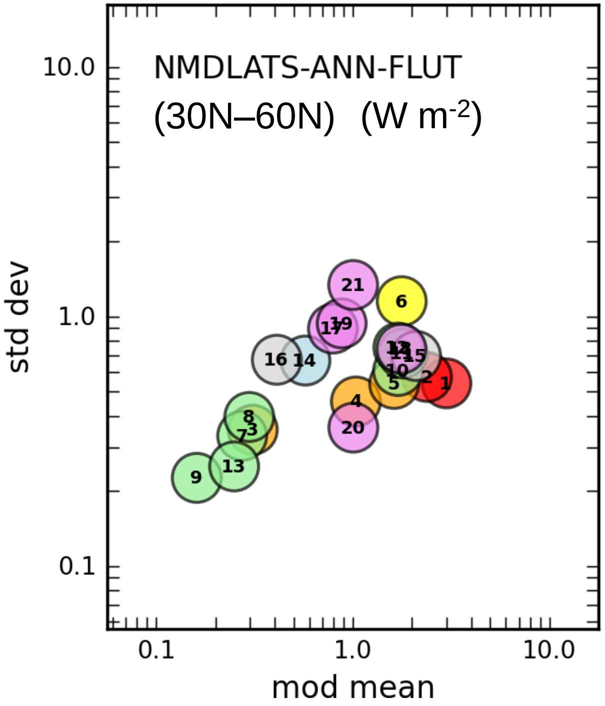
17 = zmconv_alfa

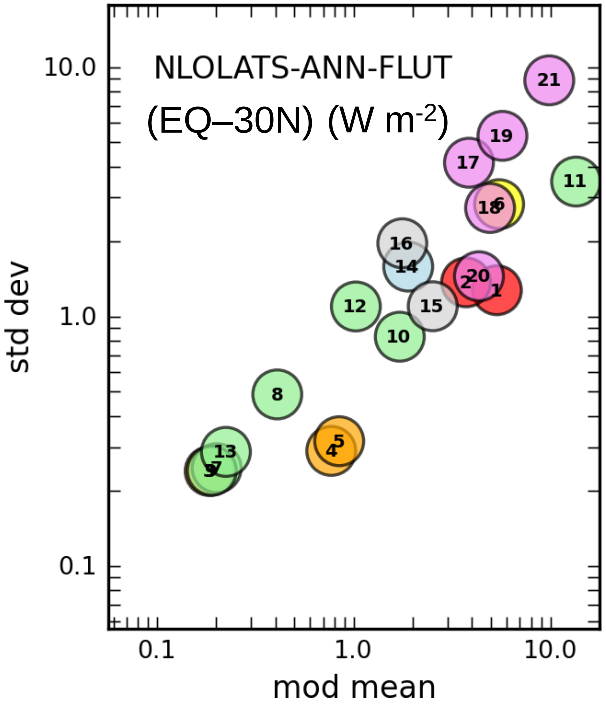
18 = zmconv_c0

19 = zmconv_dmpdz

20 = zmconv_ke

21 = zmconv_tau



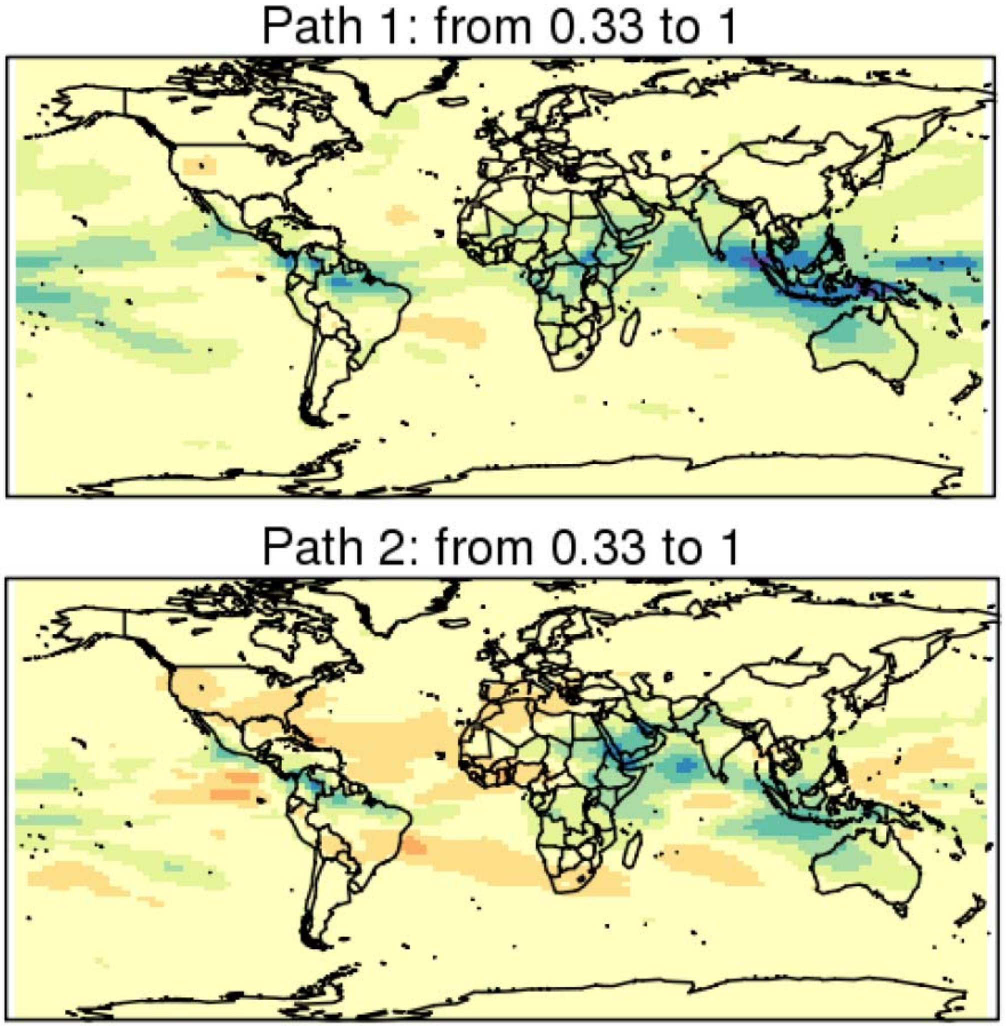


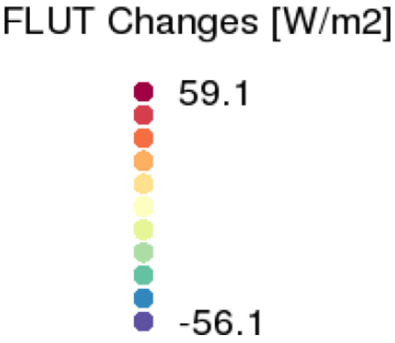
- **Initial MOAT screening plots (e.g. sensitivity of FLUT to the 21 parameters)**
- **Are there distinct parameter clusters? (dimensional reduction)**
- **Is the rank order robust for different time-space averages?**

Responses For Different MOAT Paths

Maps of ∆FLUT for the same ∆zmconv_tau, but at different points in the parameter space

The response of FLUT differs in magnitude and sign!

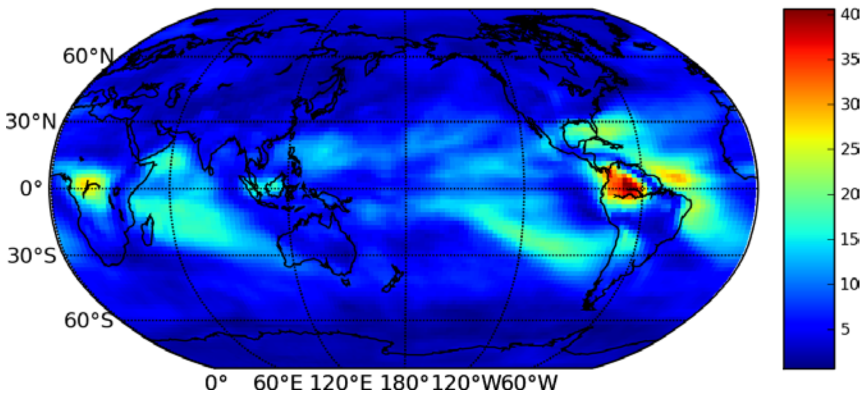




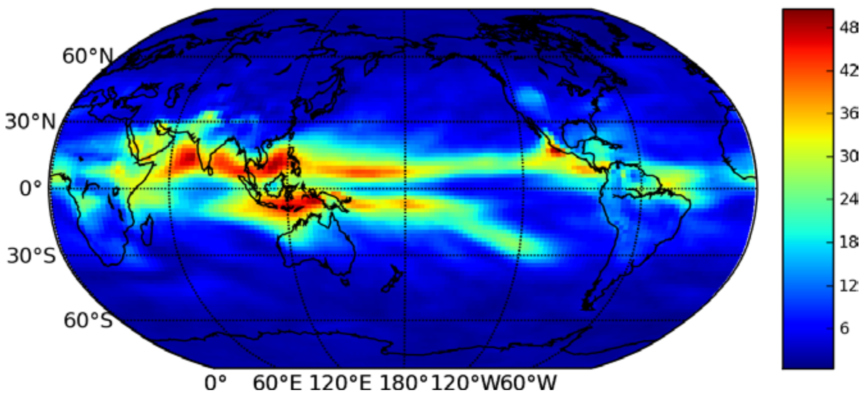
MOAT Sensitivity Maps

- **Each sensitivity map is constructed from 20 runs (2 runs per MOAT path)**
- **Responses vary in space and time and are nonlinear (stddev)**

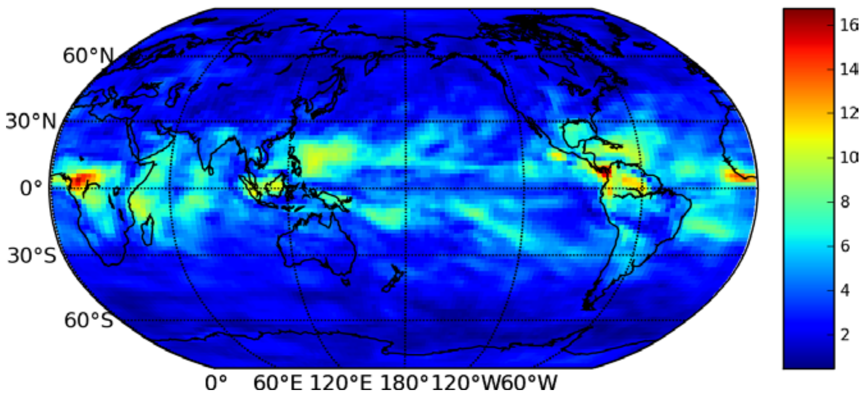
mean |ΔFLUT/Δcldfrc_rhminl| (W m^{-2})



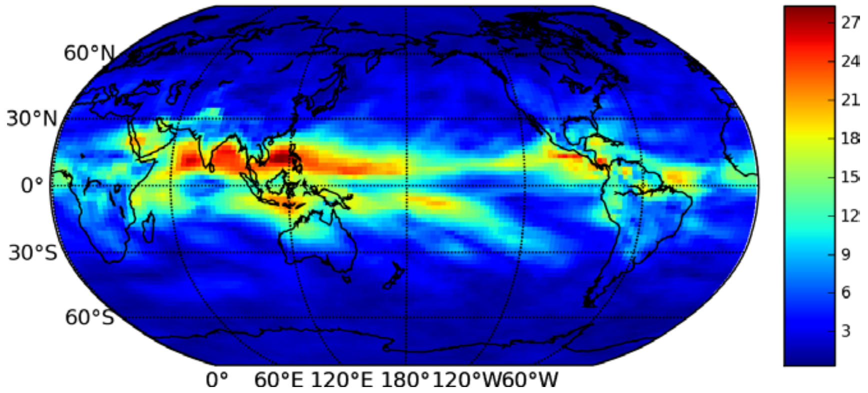
mean |ΔFLUT/Δzmconv_tau| (W m^{-2})



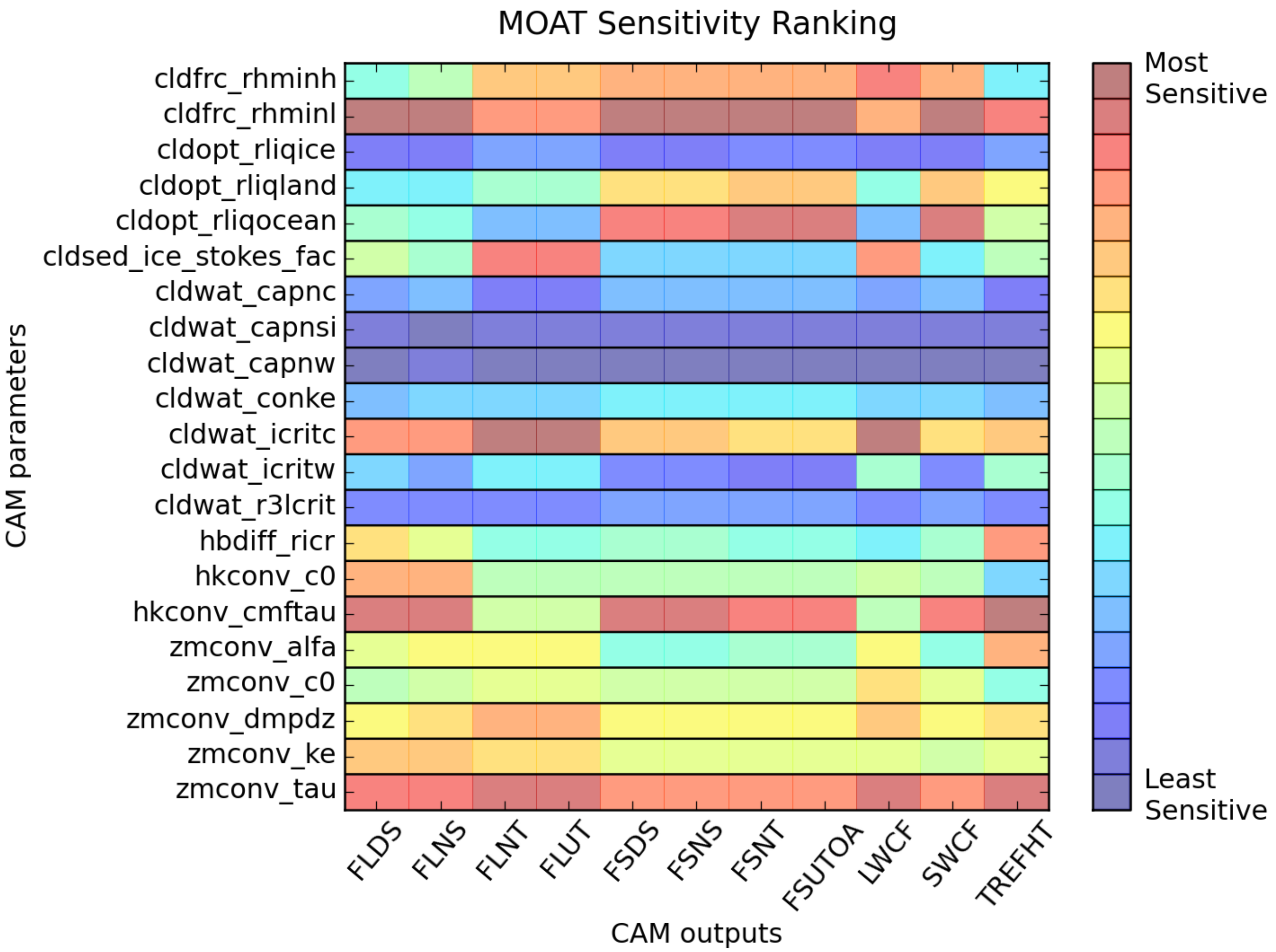
stddev |ΔFLUT/Δcldfrc_rhminl| (W m^{-2})



stddev |ΔFLUT/Δzmconv_tau| (W m^{-2})



MOAT Rank Order



- **Grid point mean sensitivities (10 paths, 220 CAM runs)**
- **Area-weighted spatial average of mean sensitivities**
- **Rank order by magnitude (1 to 21)**
- **Red (blue) bands indicate consistently high (low) sensitivities**
- **Initial analysis highlights 5 or 6 parameters that may be dropped for future UQ studies**

Next Steps

- Near term
  - Additional MOAT runs to assess ‘convergence’
  - Preliminary decomposition of variance (i.e. uncertainty)

    $V(Y) = (V_1 + V_2 + \ldots) + (V_{12} + V_{13} + \ldots) + (V_{123} + \ldots) + \ldots$
    - Test robustness using an alternate method
  - Apply dimensional reduction, develop adaptive sampling refinement
- Mid-term
  - Assemble and apply observational database
  - Define model-observation metrics
  - Constrain model parameters using *smart* ensemble
- Long term
  - 2xCO2 and formal UQ on climate sensitivity