An estimate of equilibrium climate sensitivity from interannual variability

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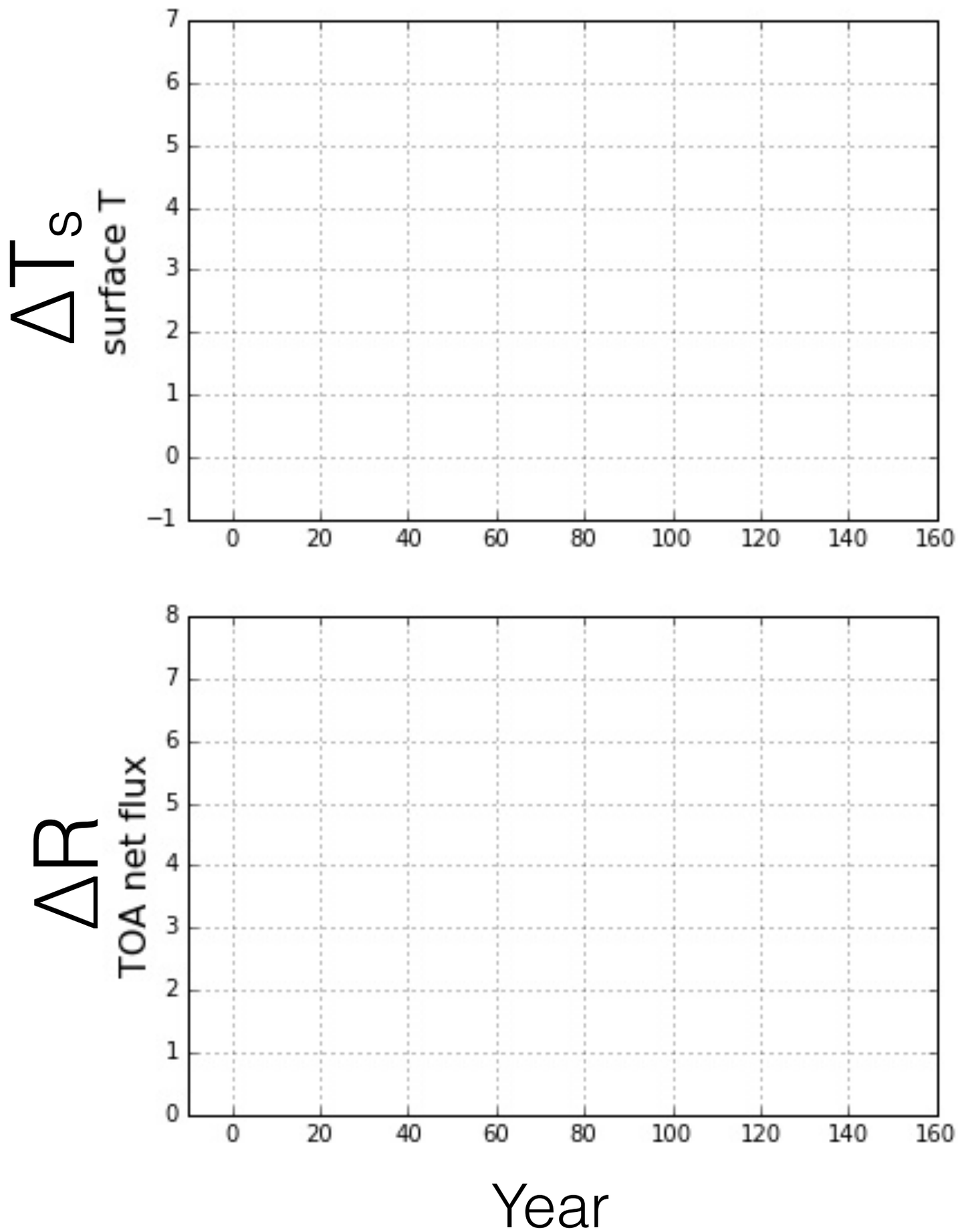
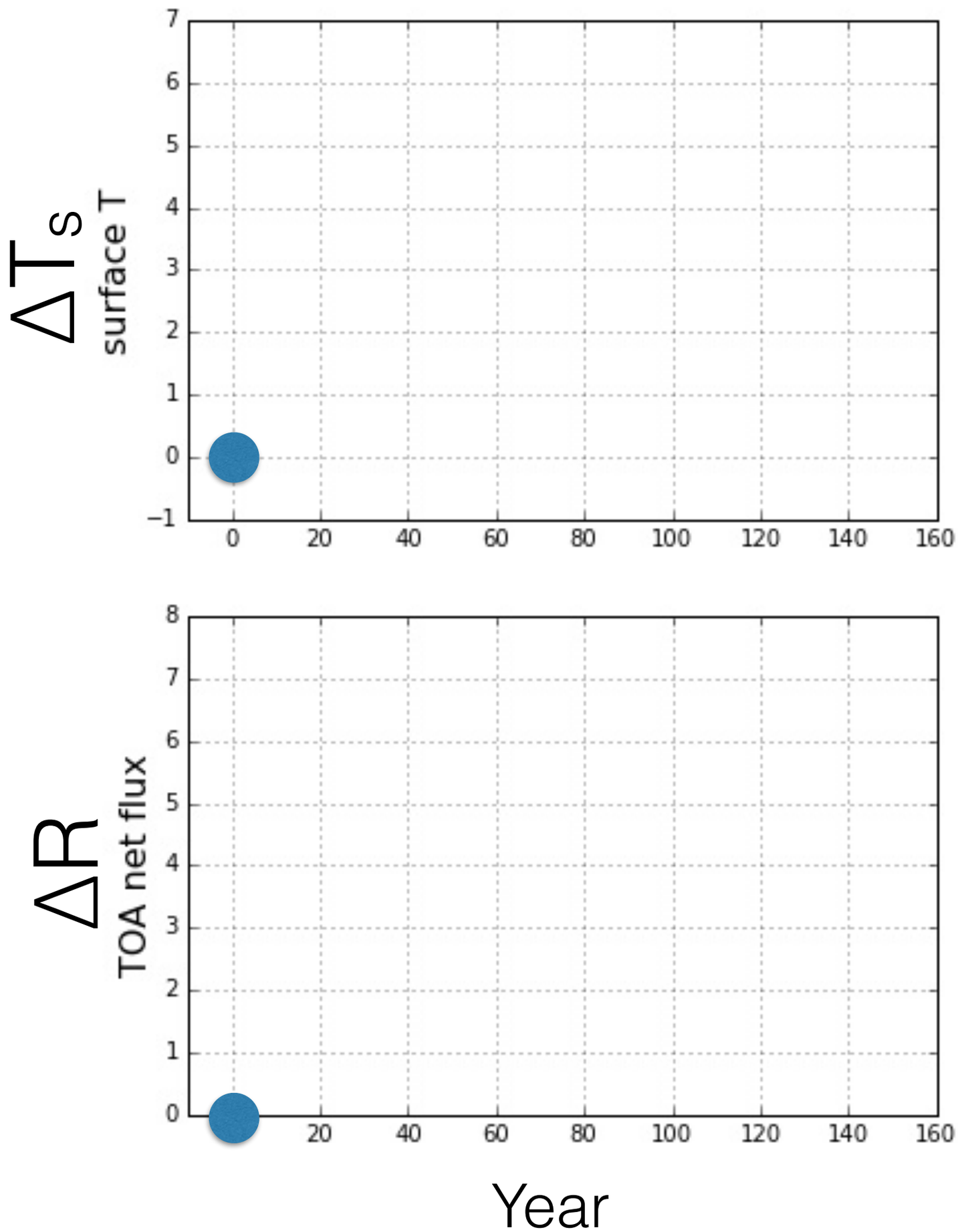


abrupt 4xCO2
GFDL-CM3



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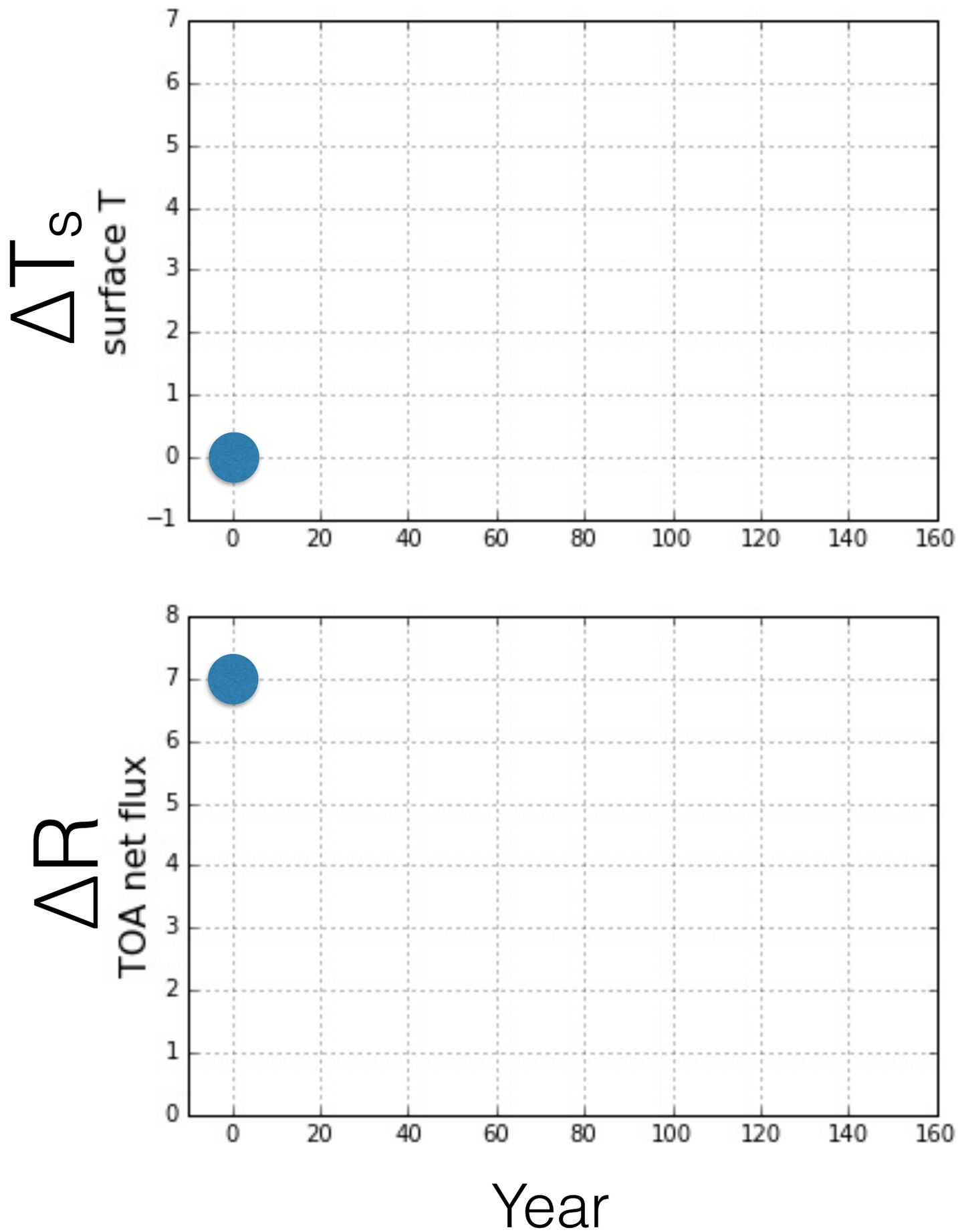

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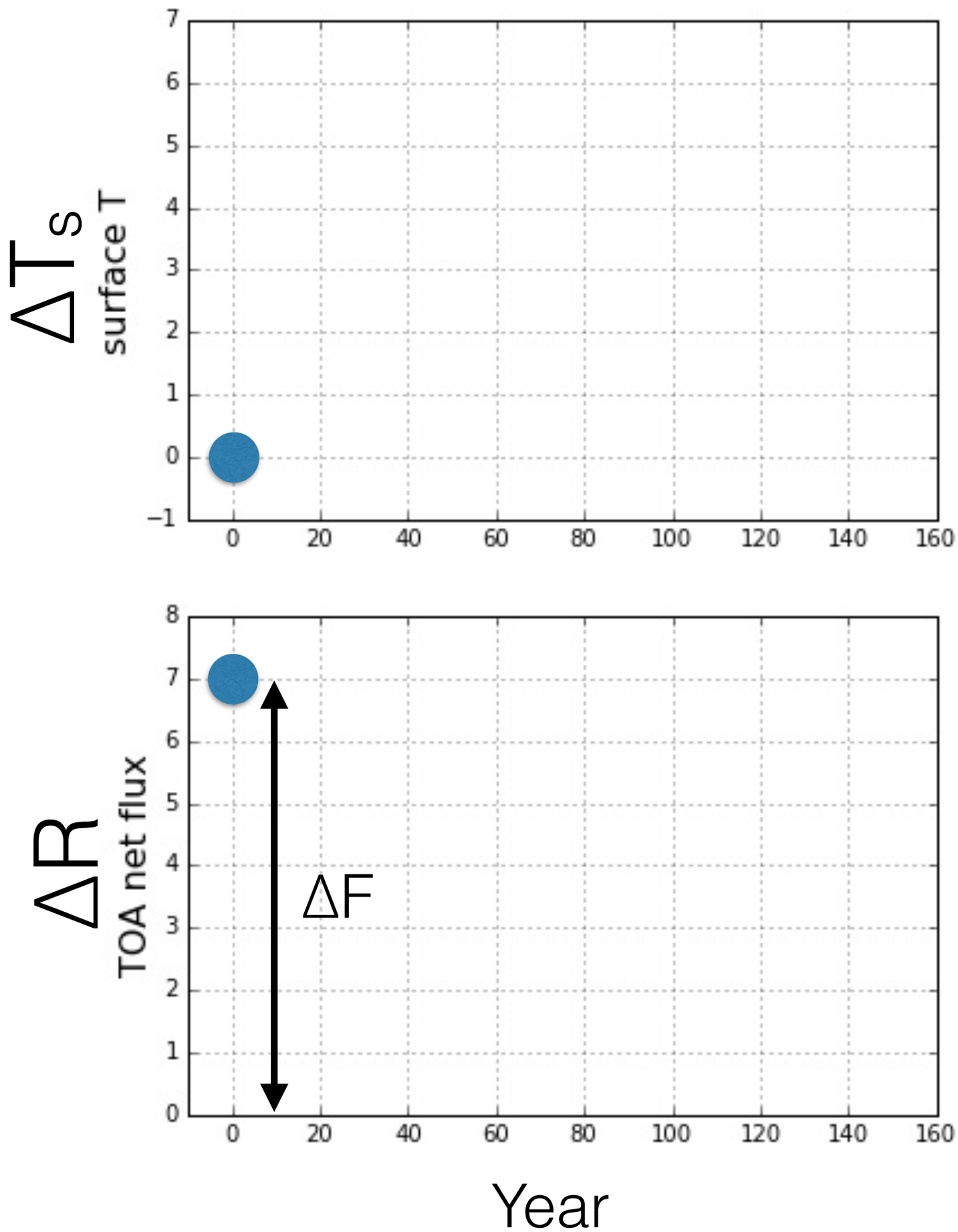

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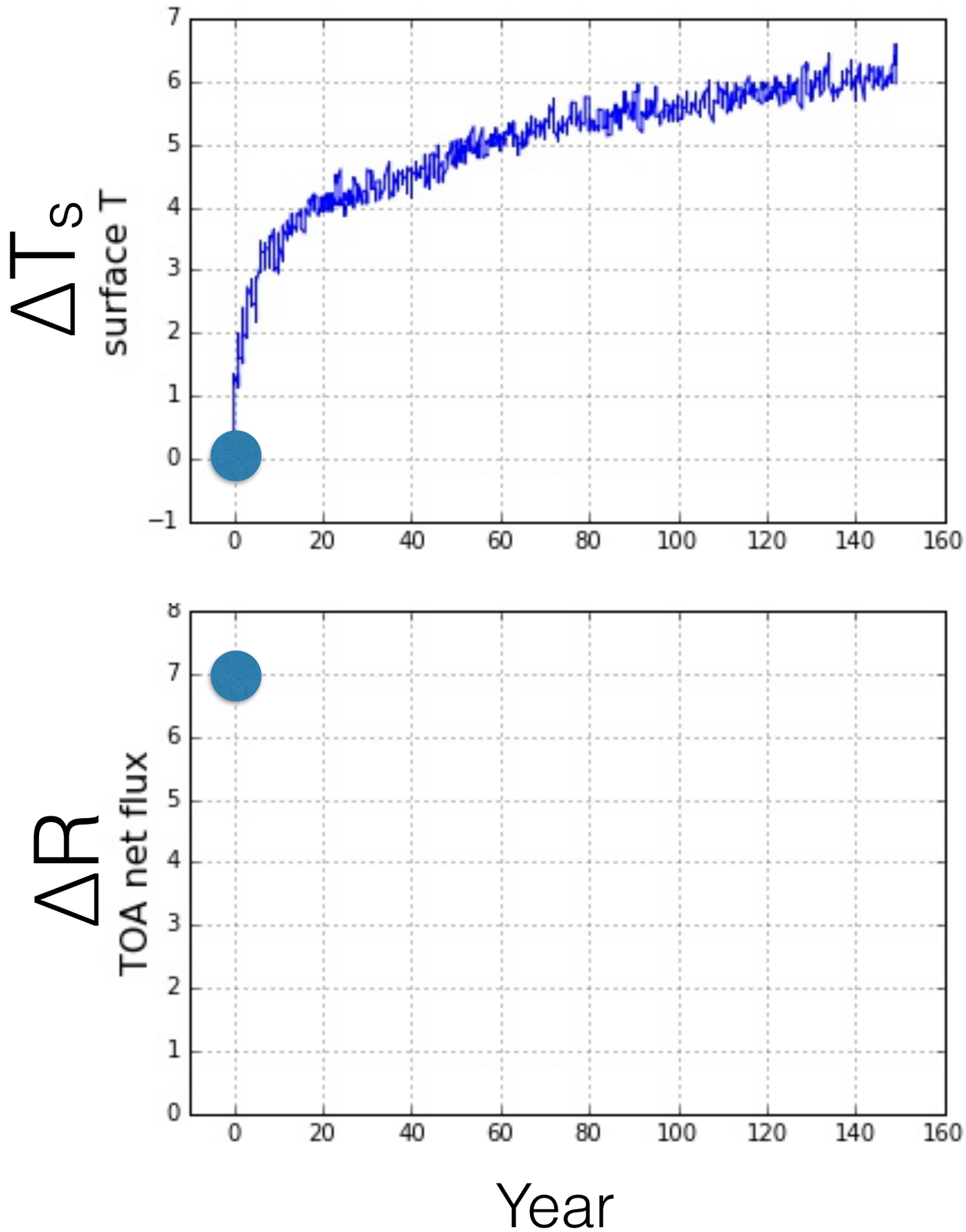

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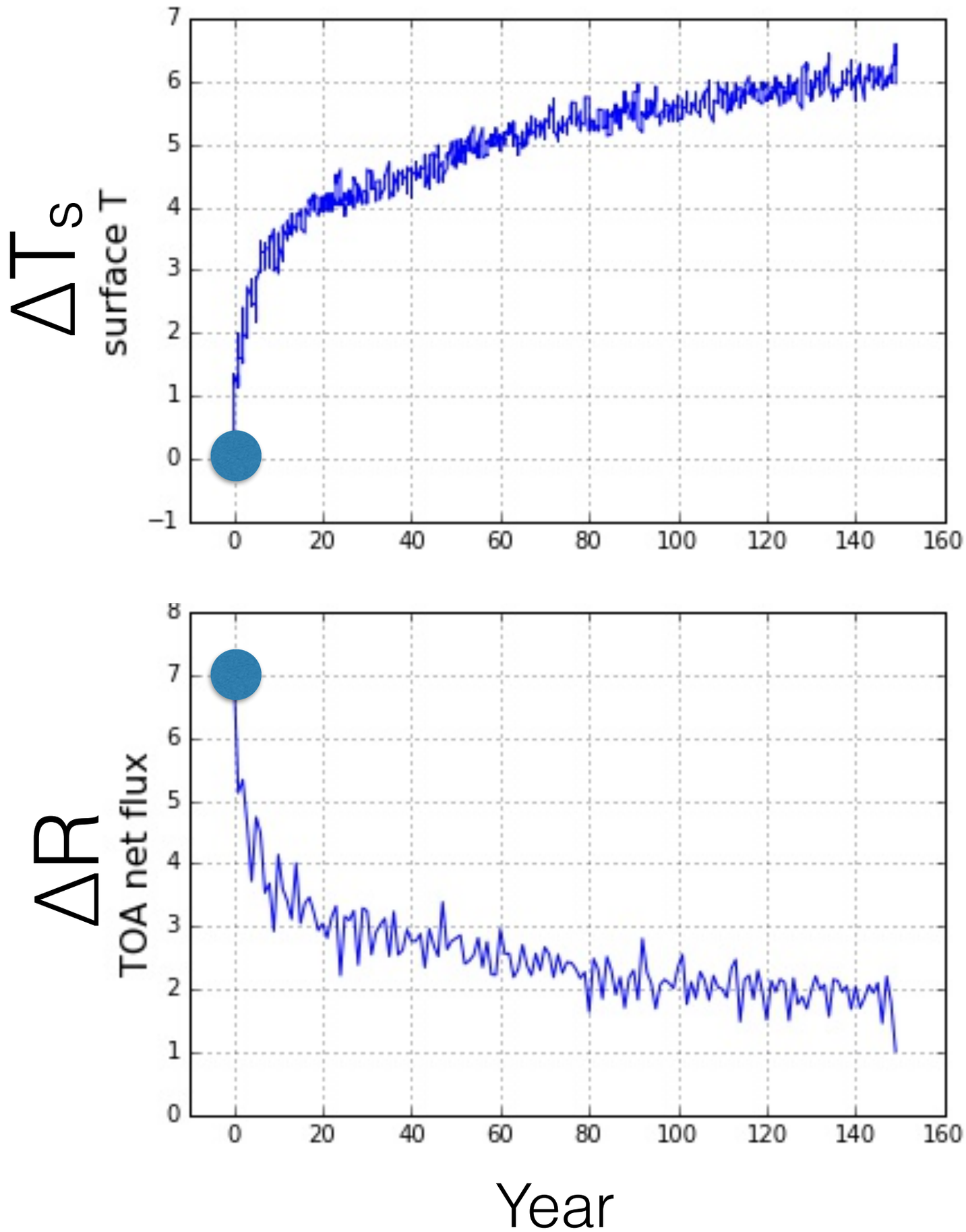

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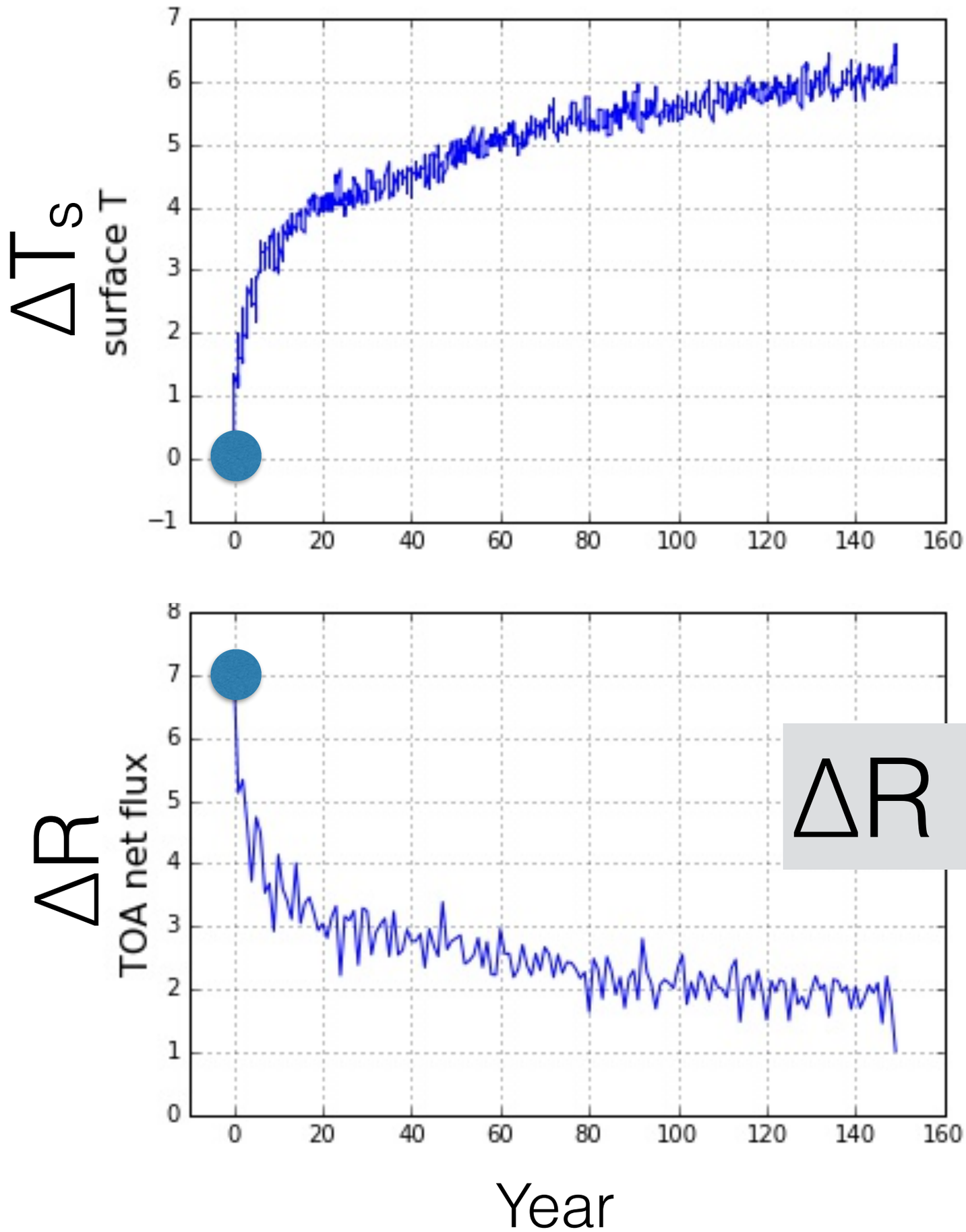

abrupt 4xCO2
GFDL-CM3

$$\Delta R = \Delta F + \lambda \Delta T_s$$

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$$\Delta R = \Delta F + \lambda \Delta T_S$$

solve for this

$$\Delta R = \Delta F + \lambda \Delta T_S$$

solve for this

$$\mathrm{ECS} = -\frac{F_{2\times CO_2}}{\lambda}$$

$$\Delta R = \Delta F + \lambda \Delta T_S$$

solve for this

$$\Delta R = \Delta F + \lambda \Delta T_S$$

CERES

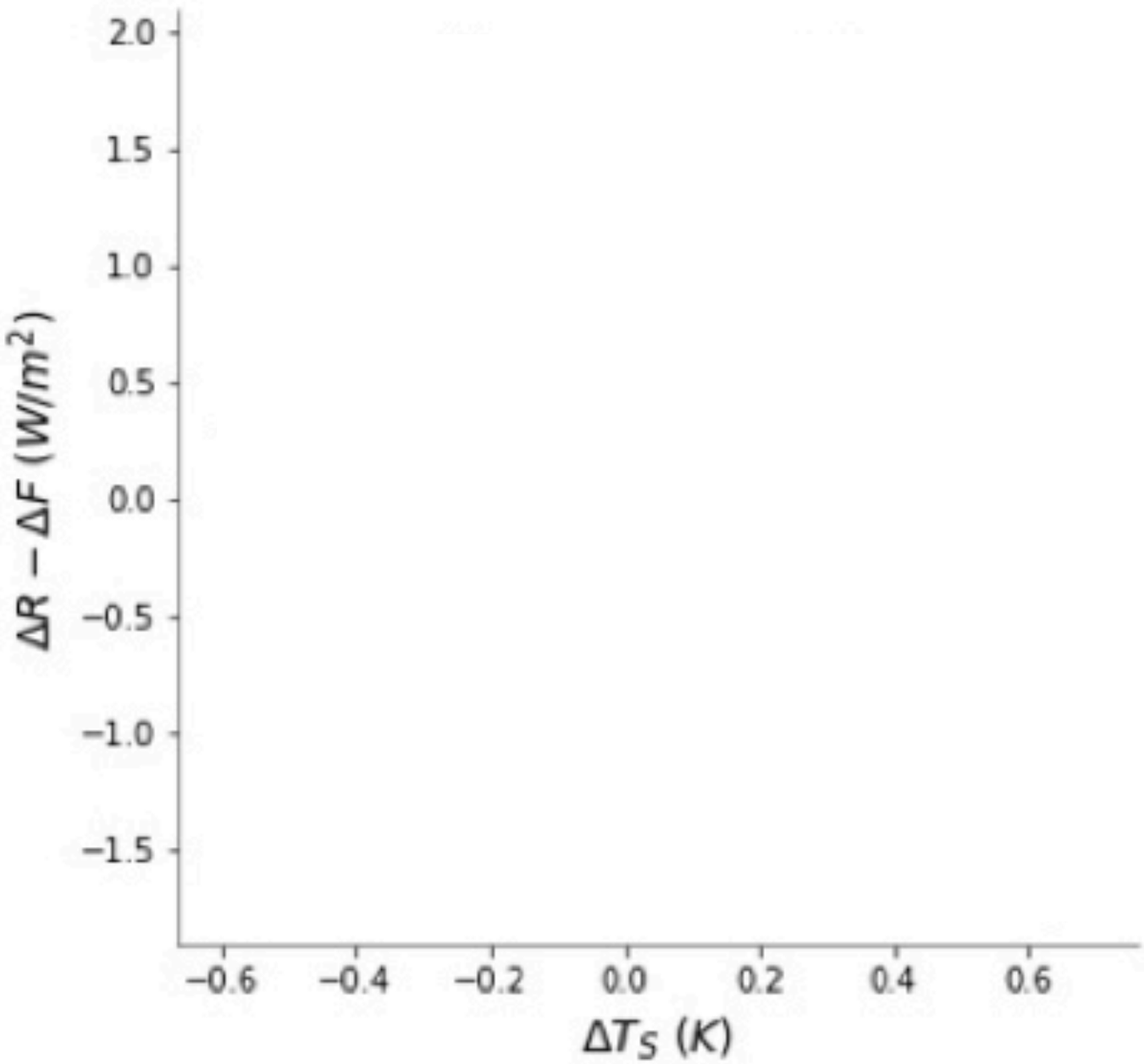
updated AR/5

solve for this

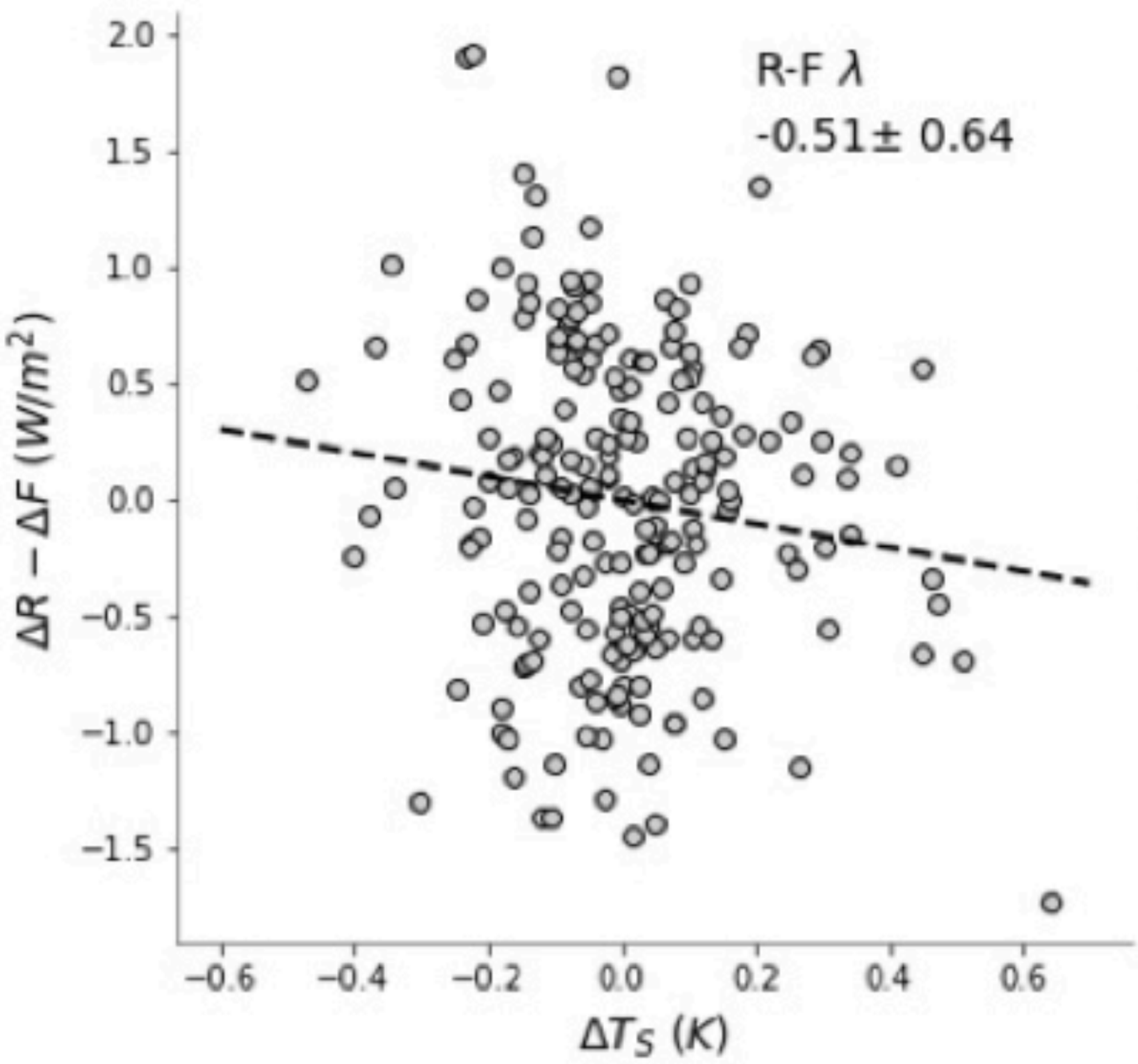
ERA-interim

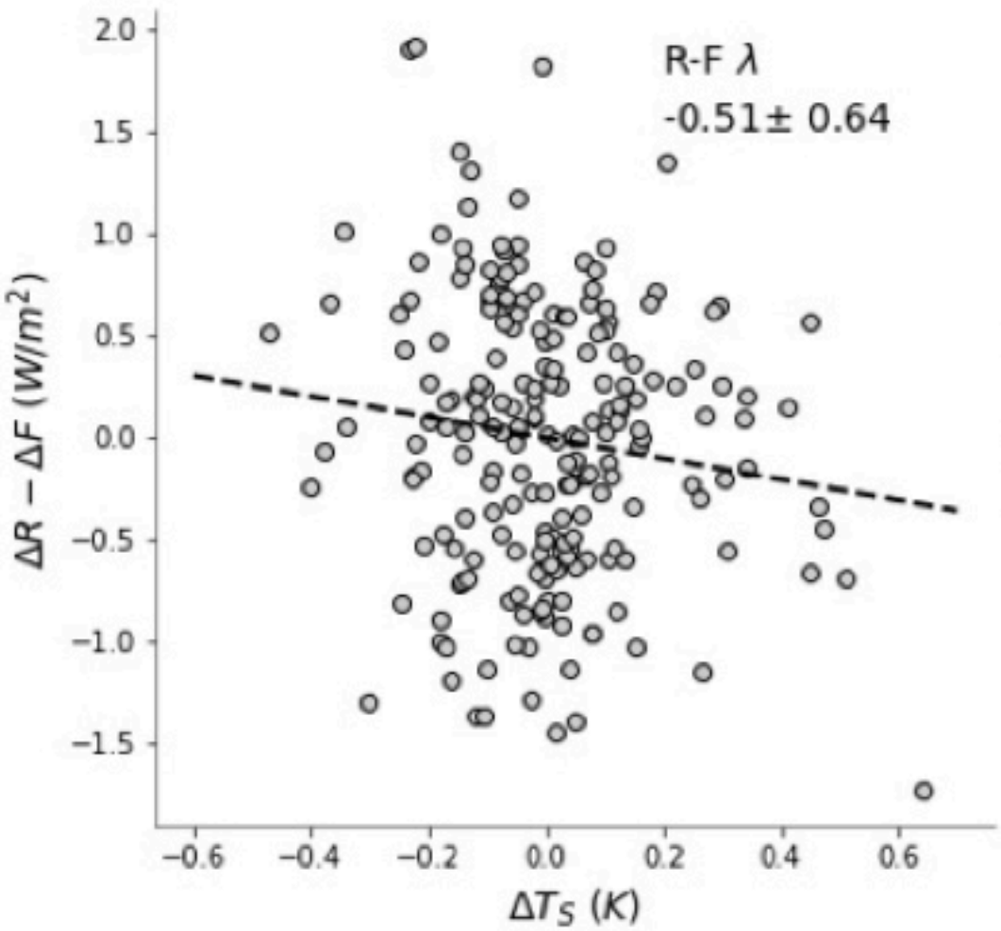
analysis covers 2000-2017

$$\Delta R - \Delta F = \lambda \Delta T_S$$

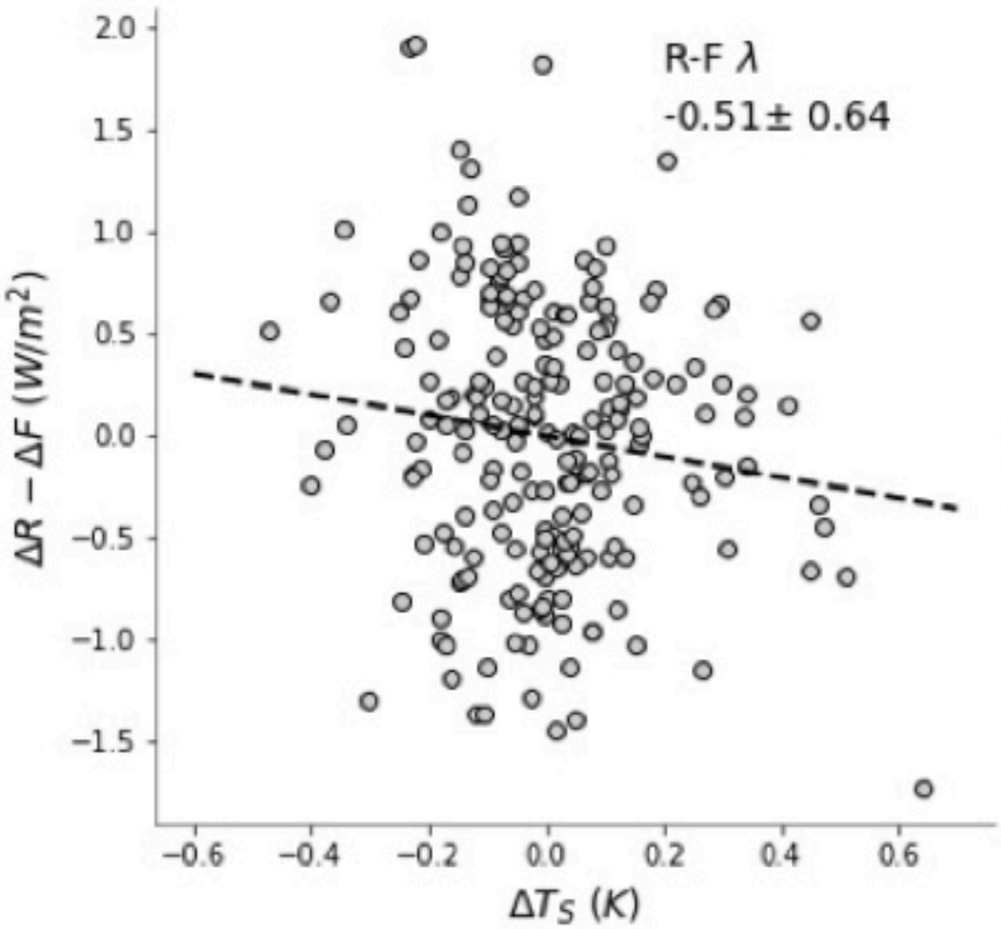


$$\Delta R - \Delta F = \lambda \Delta T_S$$



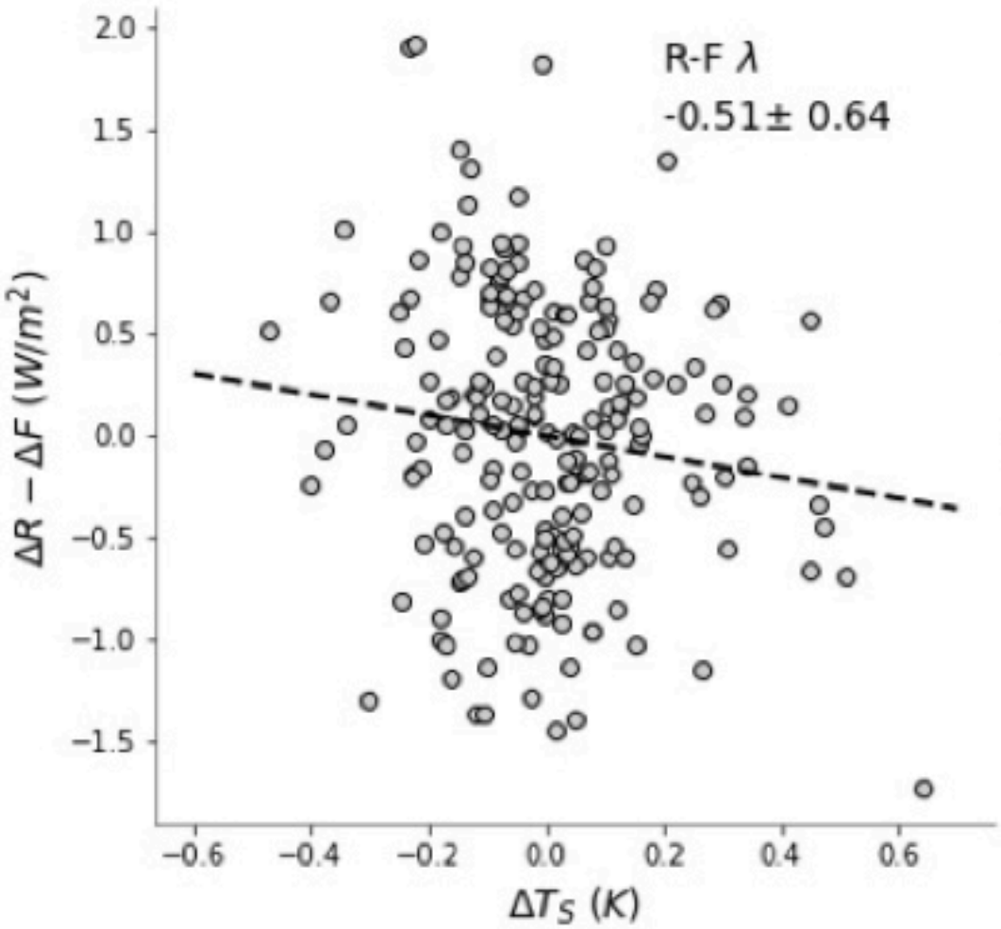

R-F λ
-0.51± 0.64
$\Delta R - \Delta F$ (W/m^2)
ΔT_S (K)
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6

$$\lambda_{iv}$$



$$\mathrm{ECS} = -\frac{F_{2\times CO_2}}{\lambda_{2\times CO_2}}$$

λ_{iv}



$$\mathrm{ECS} = -\frac{F_{2\times CO_2}}{\lambda_{2\times CO_2}}$$

???

$$\lambda_{iv}$$

$$\lambda_{2\times CO_2,est} = \lambda_{iv,obs}\left(\frac{\lambda_{2\times CO_2}}{\lambda_{iv}}\right)$$

$$\lambda_{2\times CO_2,est} = \lambda_{iv,obs}\left(\frac{\lambda_{2\times CO_2}}{\lambda_{iv}}\right)$$

Measured by CERES

$$\lambda_{2\times CO_2,est} = \lambda_{iv,obs}\left(\frac{\lambda_{2\times CO_2}}{\lambda_{iv}}\right)$$

Measured by CERES

estimated from
CMIP5 model runs

Traditional energy balance framework

$$\mathrm{ECS} = -\frac{F_{2\times CO_2}}{\lambda_{iv,obs}}\left(\frac{\lambda_{iv}}{\lambda_{2\times CO_2}}\right)$$

Traditional energy balance framework

$$\mathrm{ECS} = -\frac{F_{2\times CO_2}}{\lambda_{iv,obs}}\left(\frac{\lambda_{iv}}{\lambda_{2\times CO_2}}\right)$$

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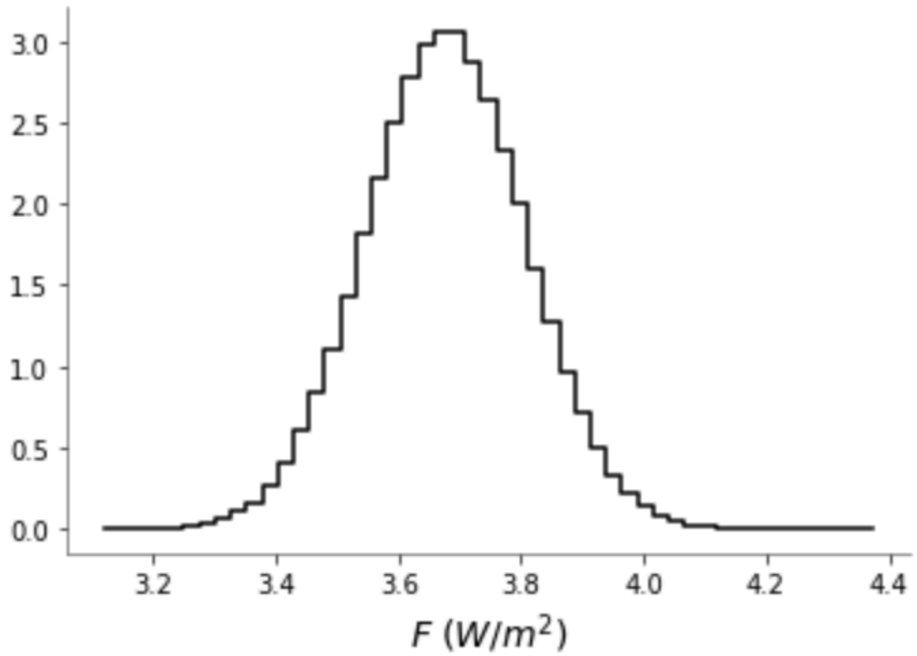

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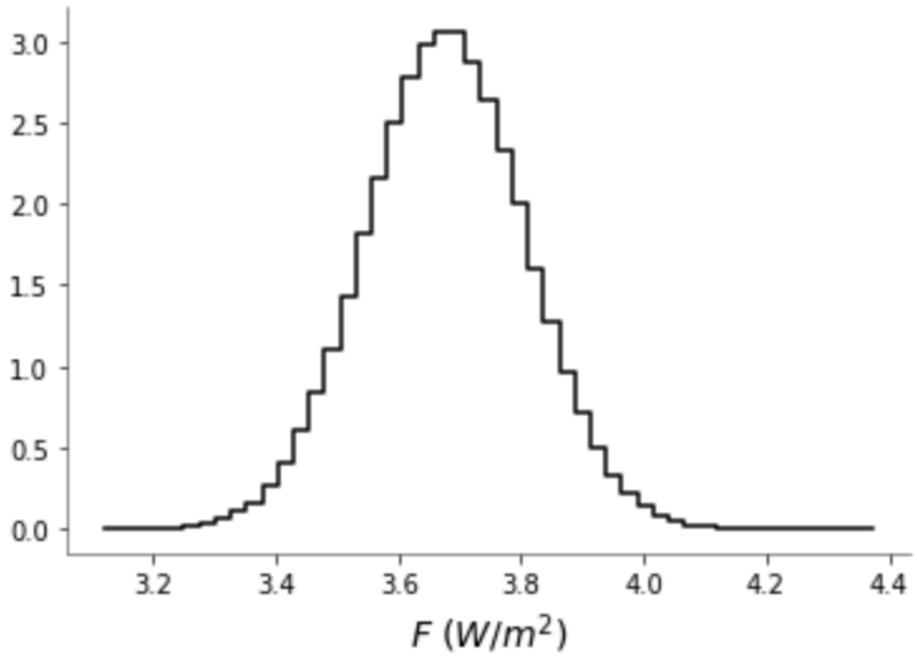

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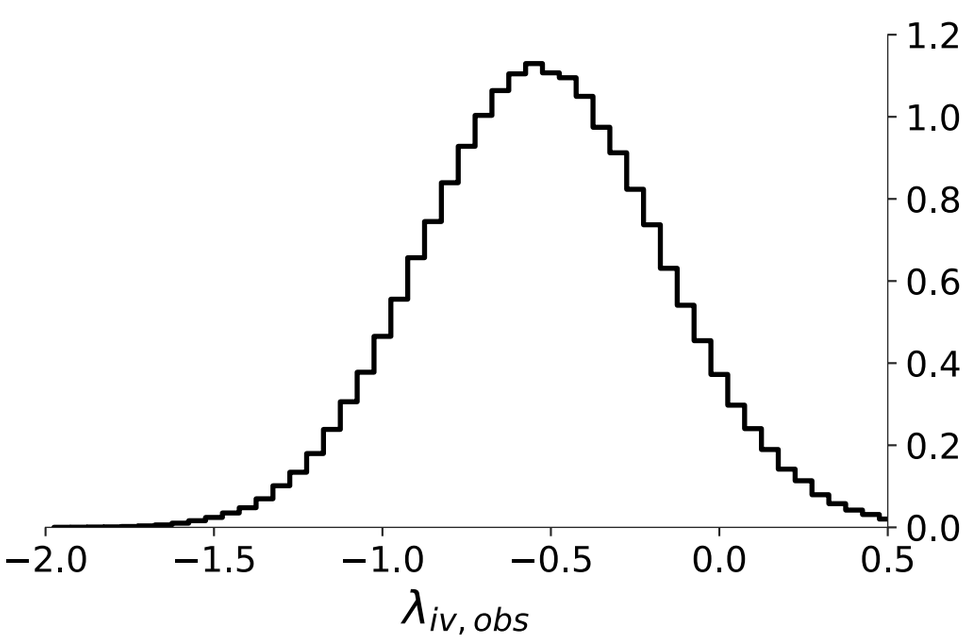
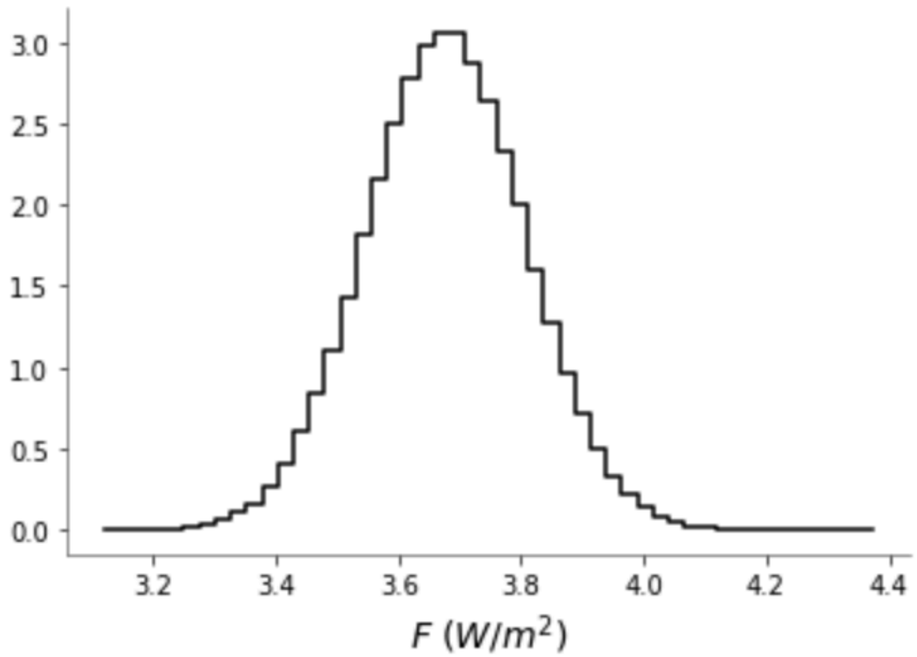
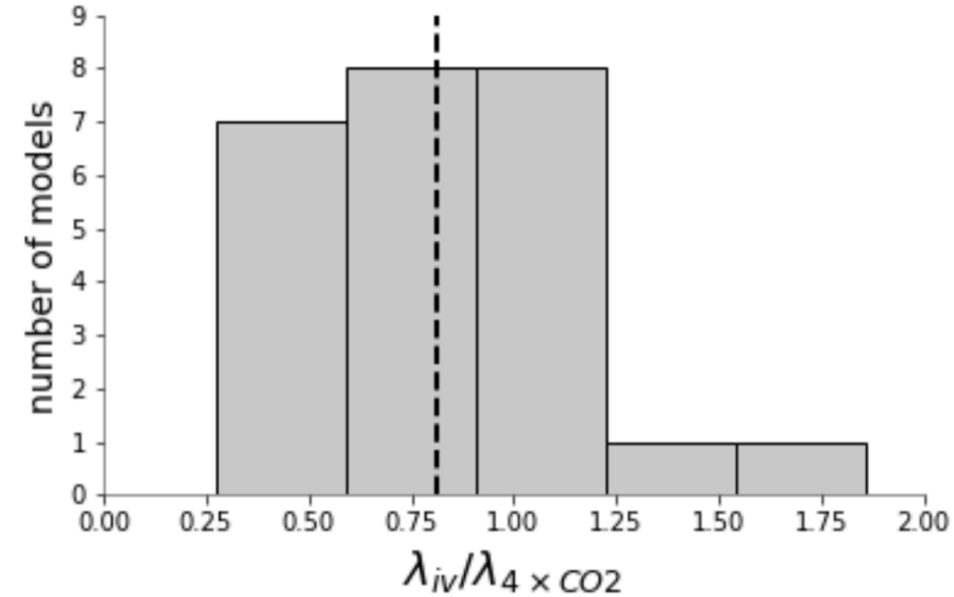
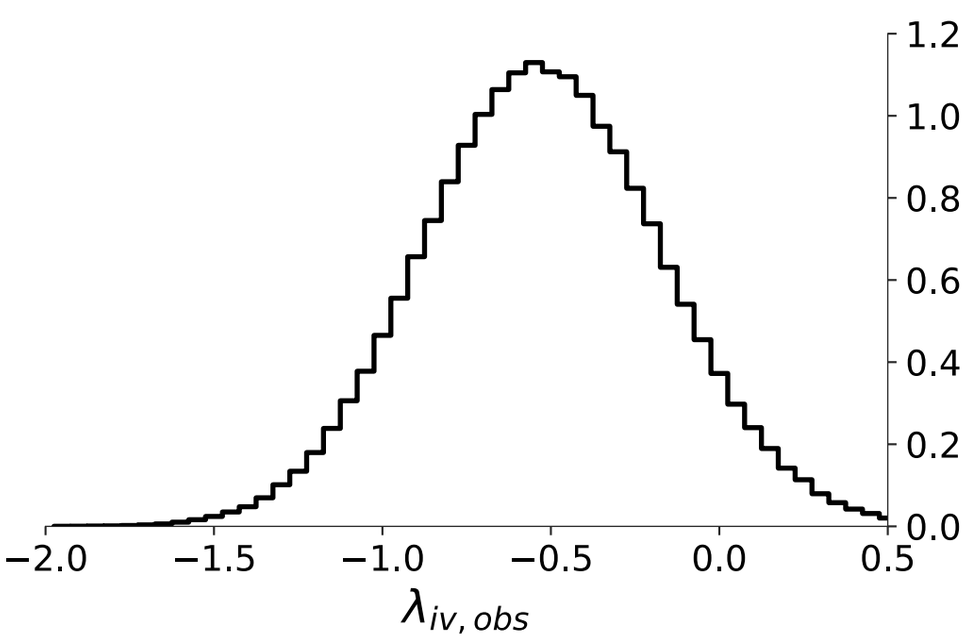
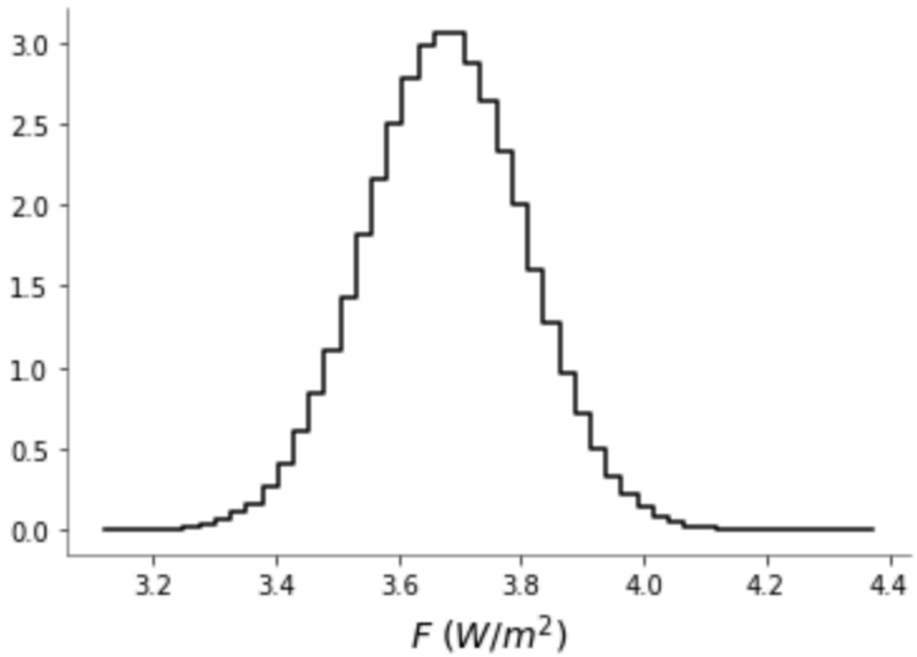


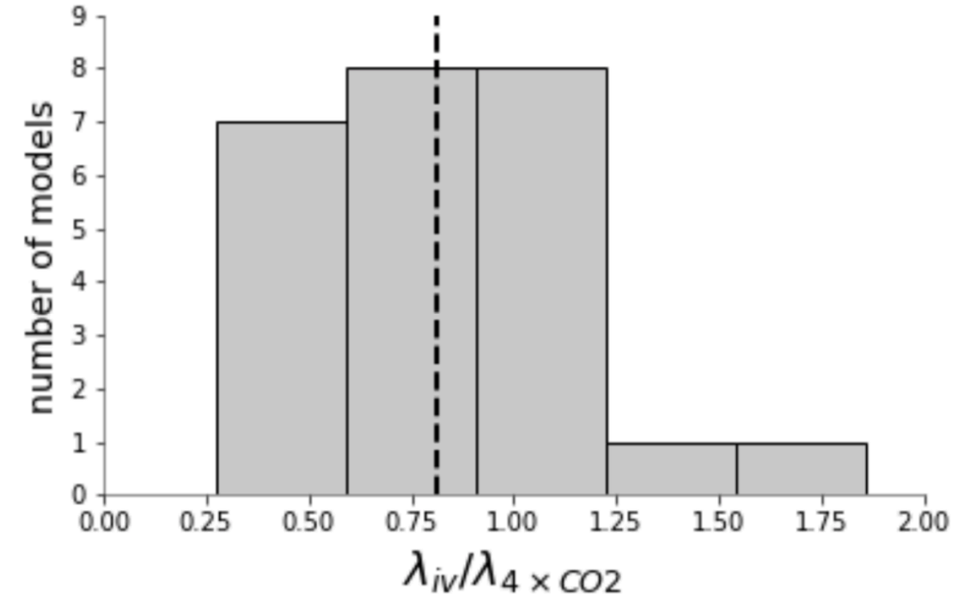




$$\mathrm{ECS} \approx -\frac{F_{2\times CO_2}}{\lambda_{iv,obs}}\left(\frac{\lambda_{iv}}{\lambda_{4\times CO_2}}\right)$$







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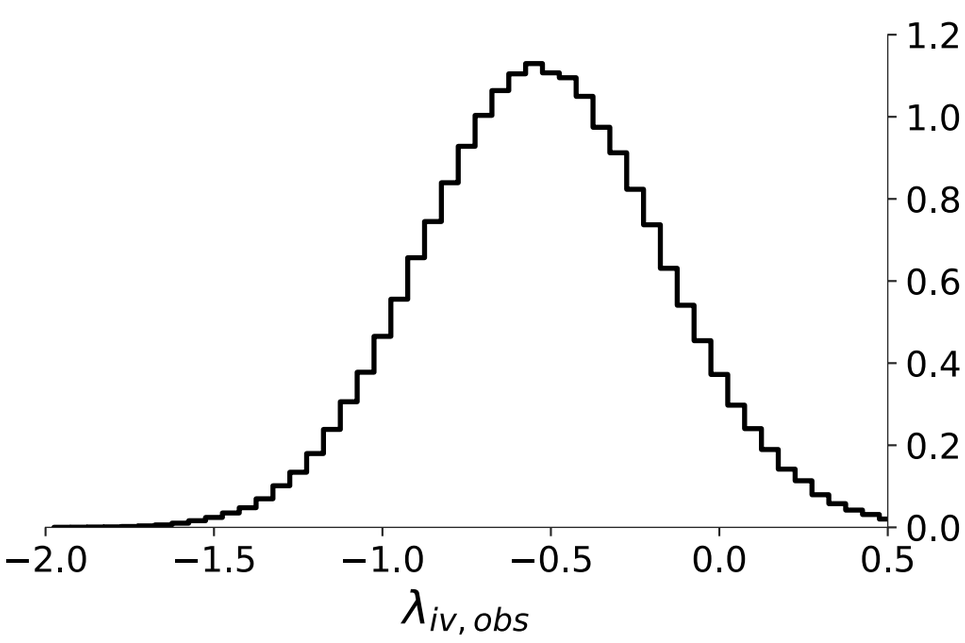
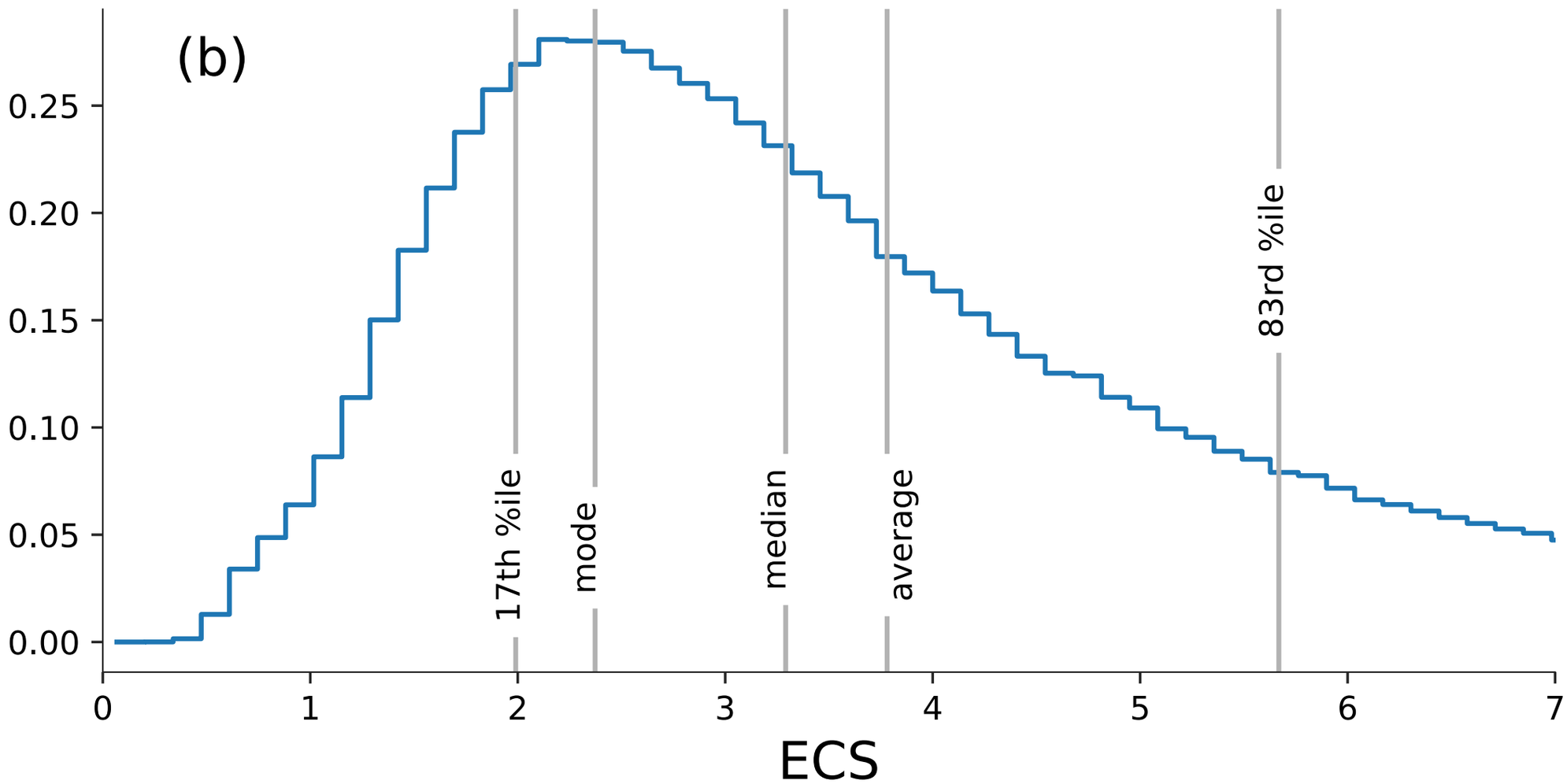
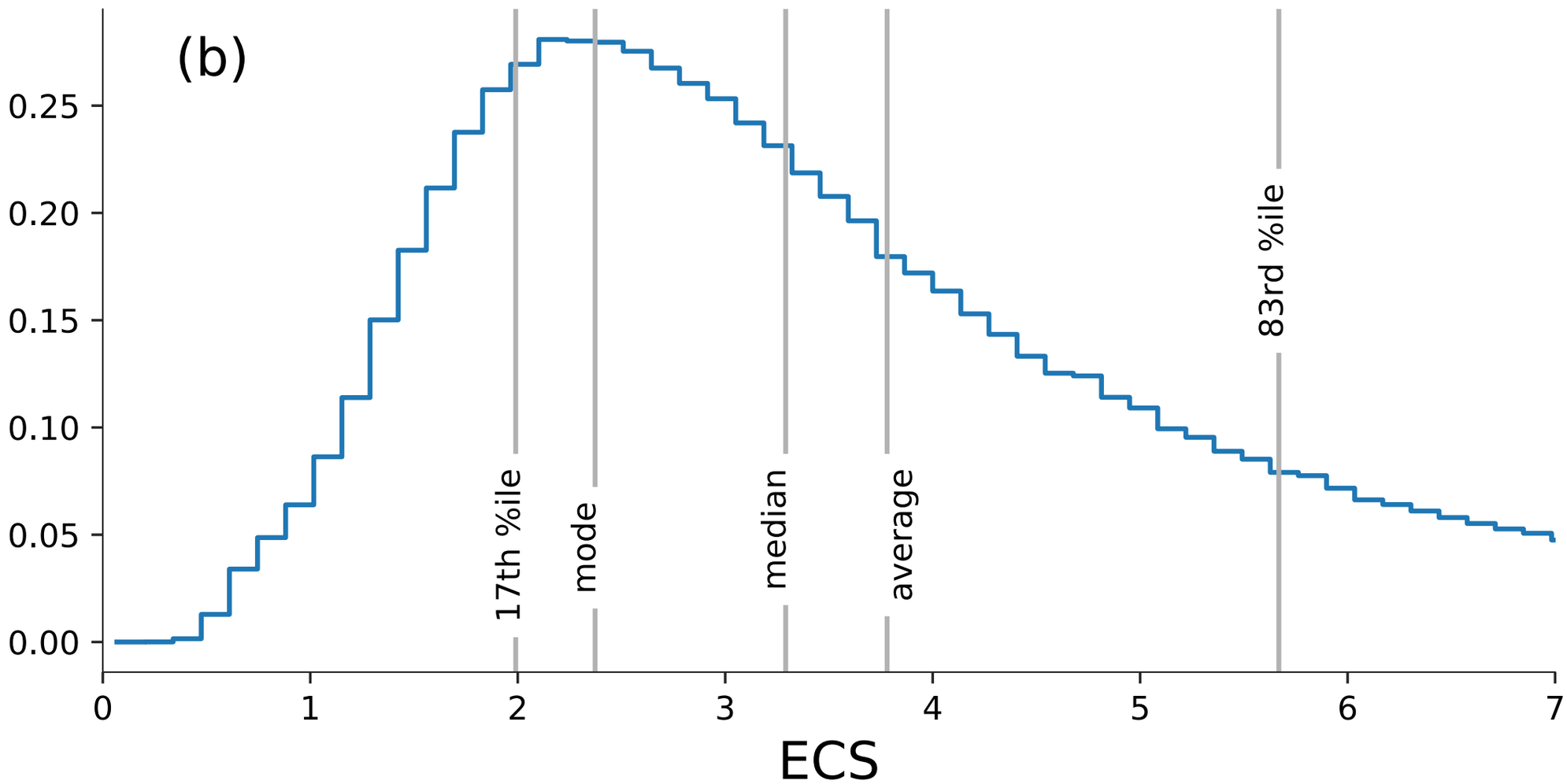


Monte Carlo: take 500,000 samples of each distribution and calculate 500,000 estimates of ECS

ECS

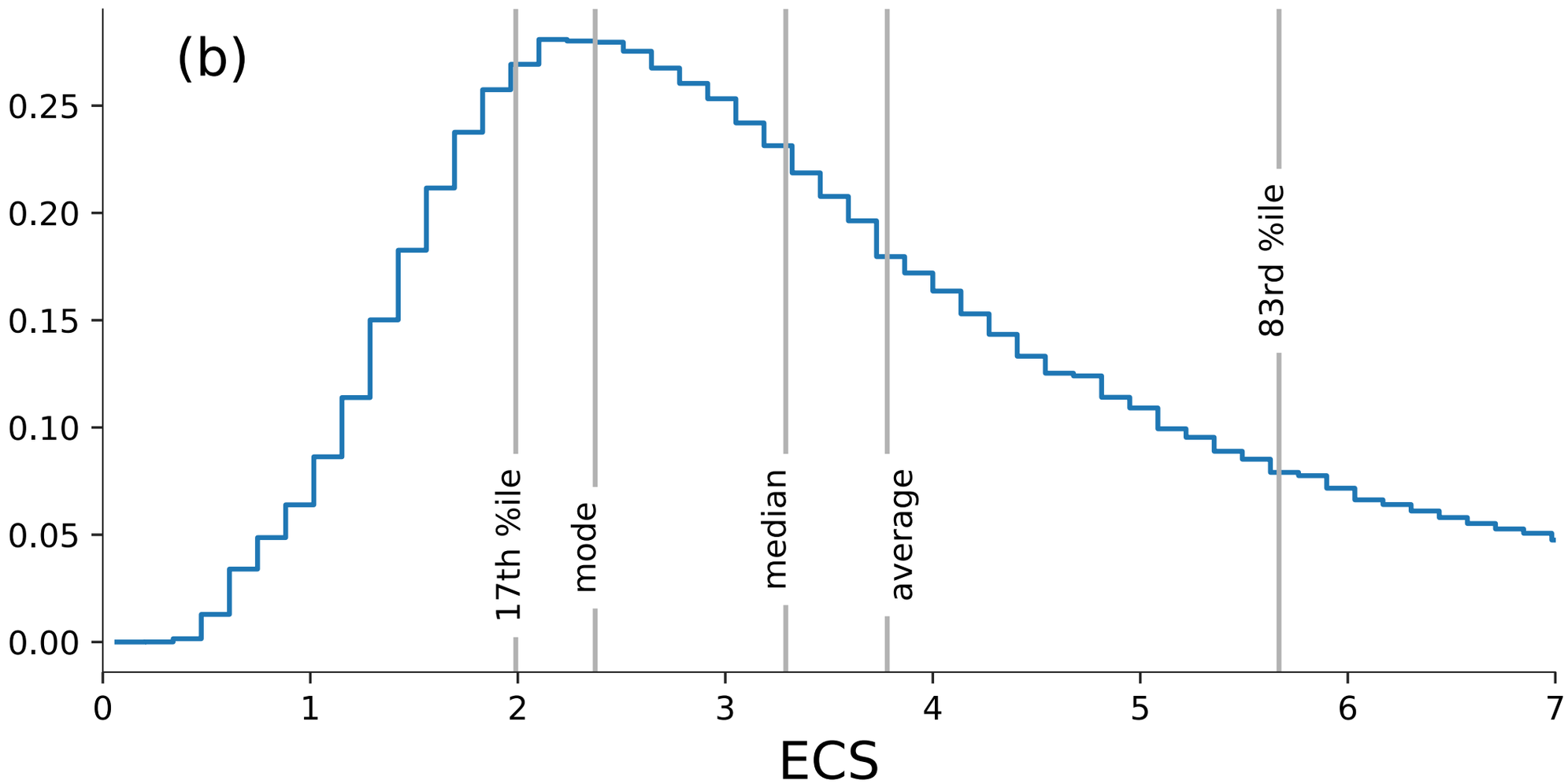

(b)
0.25
0.20
0.15
0.10
0.05
0.00
0
1
2
3
4
5
6
7
ECS
17th %ile
mode
median
average
83rd %ile

ECS



likely range: 2.0-5.7 K
median: 3.3 K

Problems: 1) not great constraint; 2) $\lambda_{iv,obs}$ can vary



likely range: 2.0-5.7 K
median: 3.3 K

revised framework

$$R = F + \Theta \Delta T_A$$

Dessler, Mauritsen, Stevens: The influence of internal variability on Earth's energy balance framework and implications for estimating climate sensitivity, Atmos. Chem. Phys., 2018.

revised framework

$$R = F + \Theta \Delta T_A$$

500-hPa <u>tropical</u> temperatures

Dessler, Mauritsen, Stevens: The influence of internal variability on Earth's energy balance framework and implications for estimating climate sensitivity, Atmos. Chem. Phys., 2018.

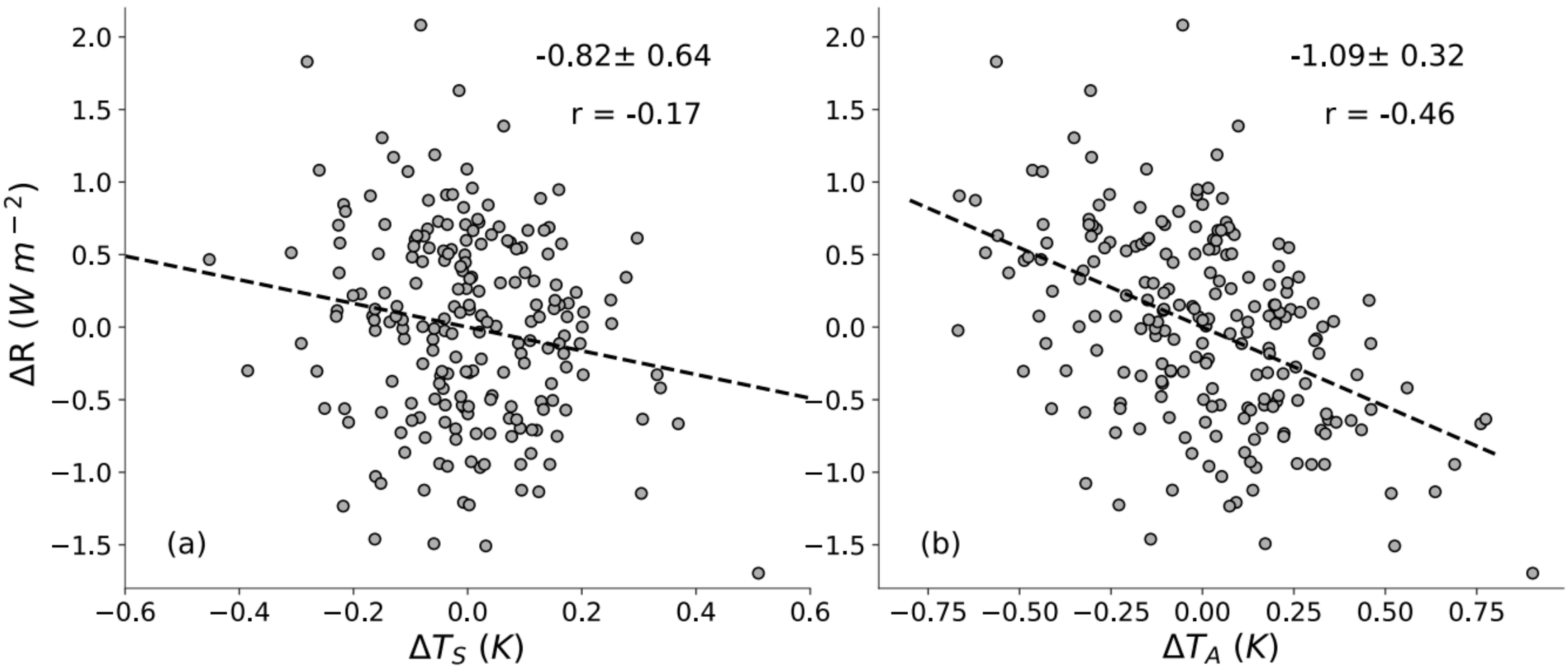
revised framework

$$R = F + \Theta \Delta T_A$$

Converts change in T_A to flux; replaces λ

500-hPa <u>tropical</u> temperatures

Dessler, Mauritsen, Stevens: The influence of internal variability on Earth's energy balance framework and implications for estimating climate sensitivity, Atmos. Chem. Phys., 2018.



CERES Ed. 4 TOA fluxes & ERA-interim temperatures

monthly avg. detrended anomalies

ΔT_s = global avg. surface temperature

ΔT_A = tropical avg. 500-hPa temperature

revised framework

$$R = F + \Theta \Delta T_A$$

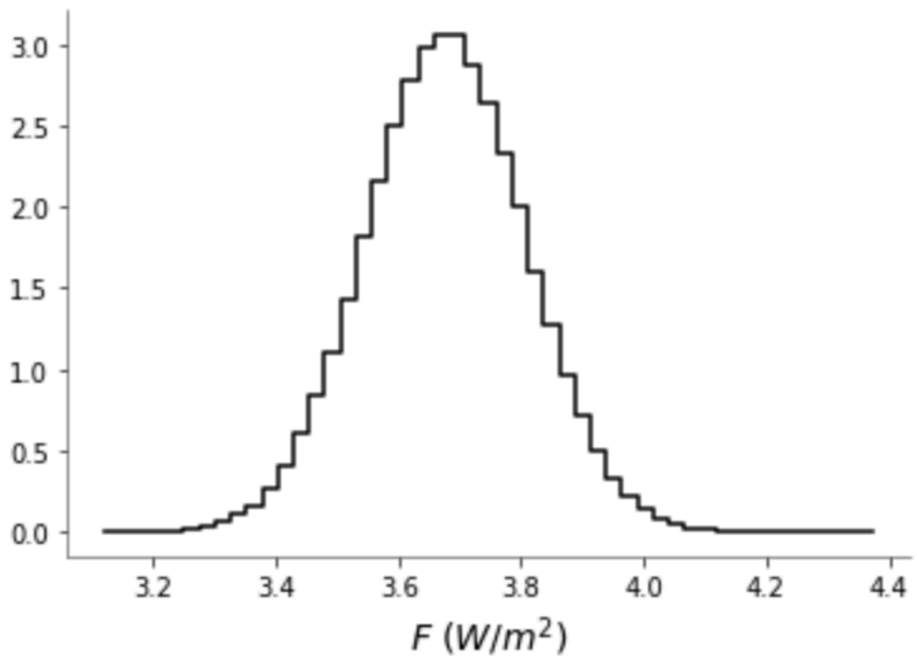
$$\mathrm{ECS} \approx -\frac{F_{2\times CO_2}}{\Theta_{iv,obs}} \left(\frac{\Theta_{iv}}{\Theta_{4\times CO_2}} \right) \left(\frac{\Delta T_S}{\Delta T_A} \right)$$

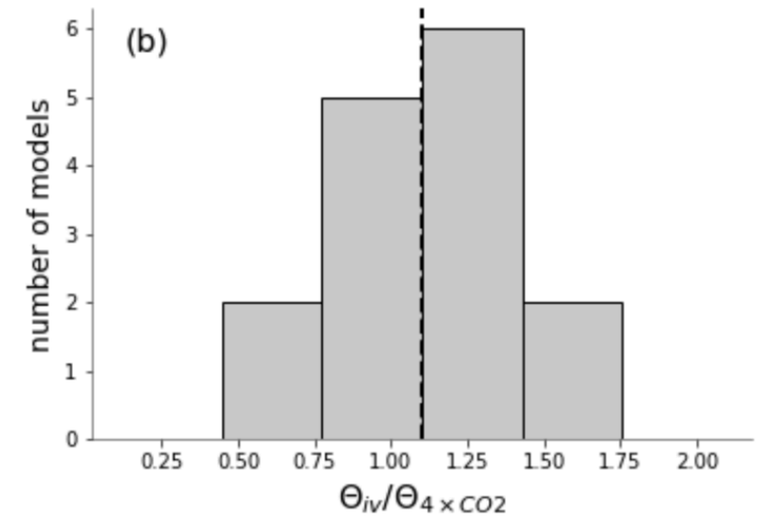
revised framework

$$R = F + \Theta \Delta T_A$$

$$\mathrm{ECS} \approx \boxed{-\frac{F_{2\times CO_2}}{\Theta_{iv,obs}} \left(\frac{\Theta_{iv}}{\Theta_{4\times CO_2}} \right)} \left(\frac{\Delta T_S}{\Delta T_A} \right)$$

ΔT_A





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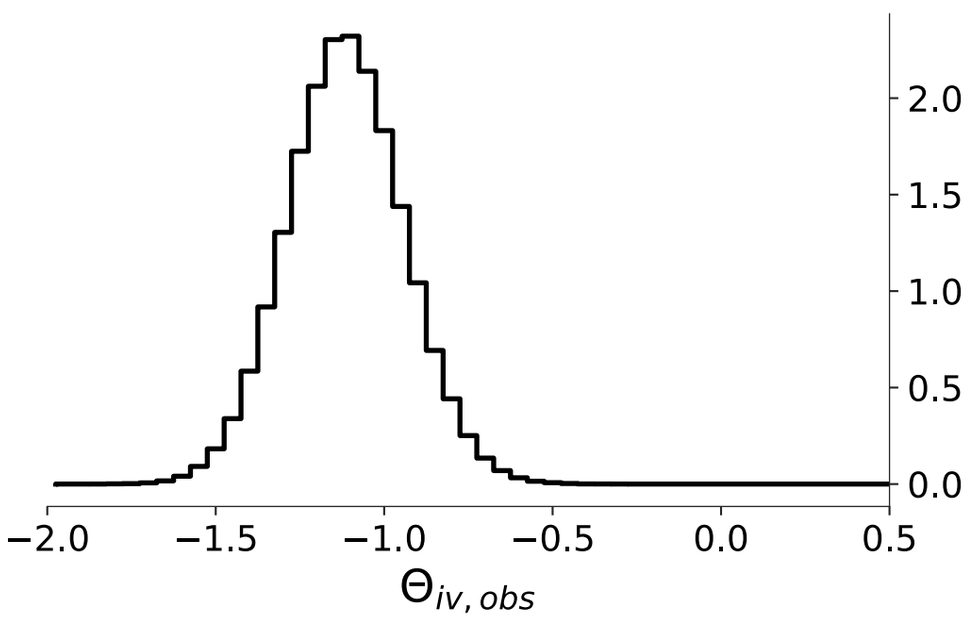

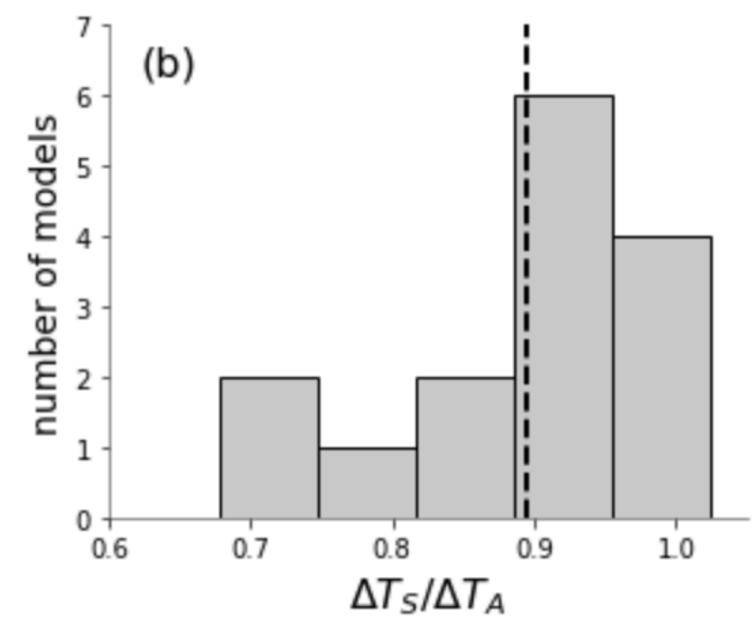

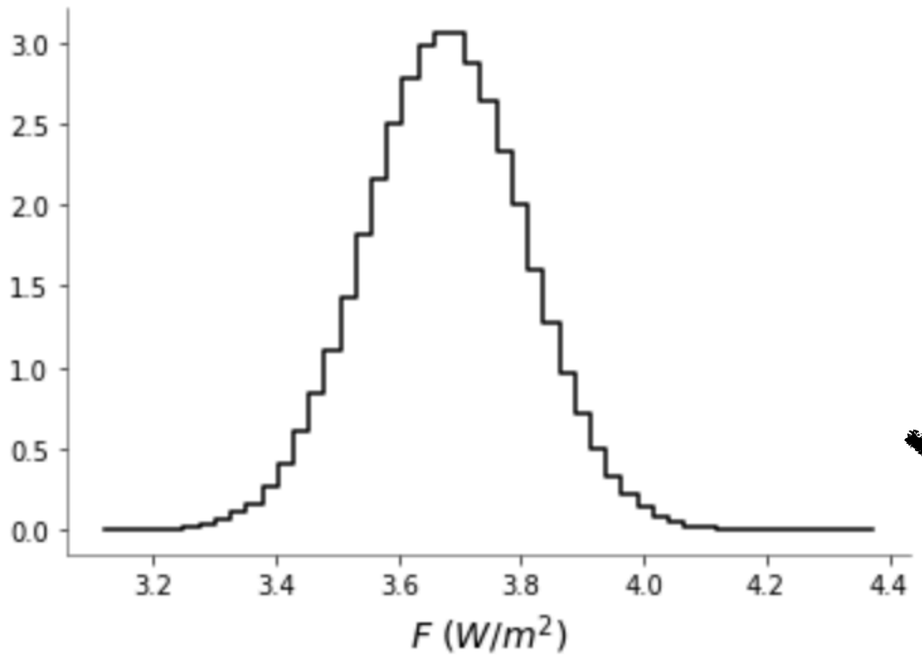

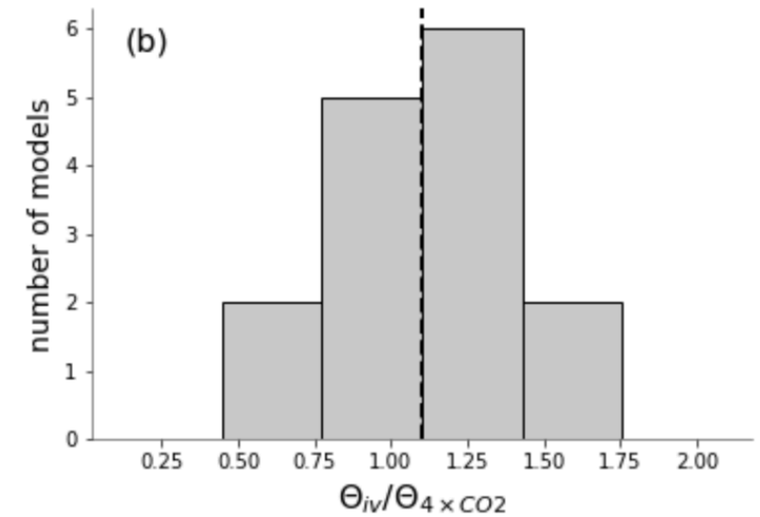

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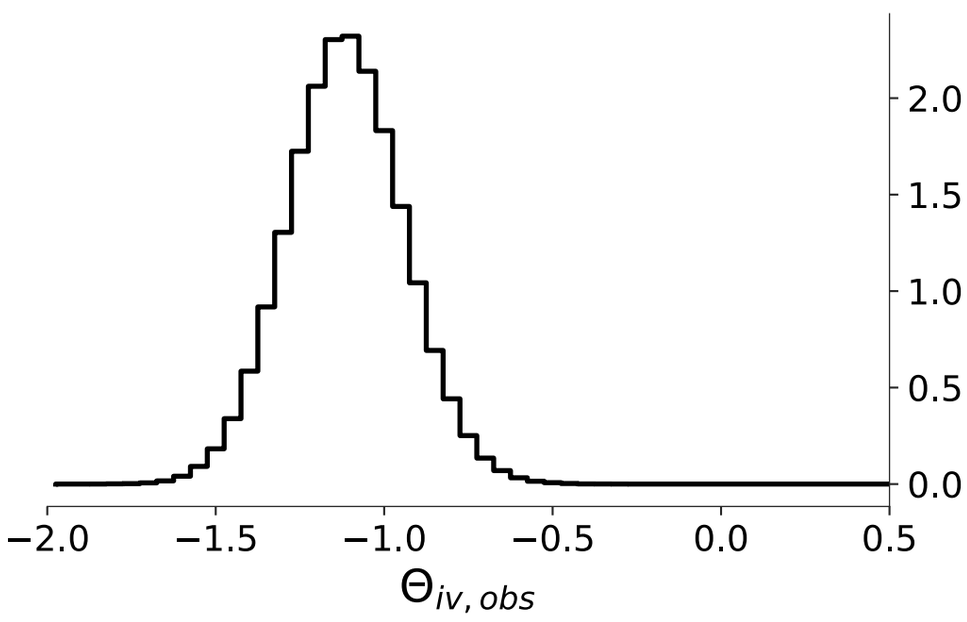
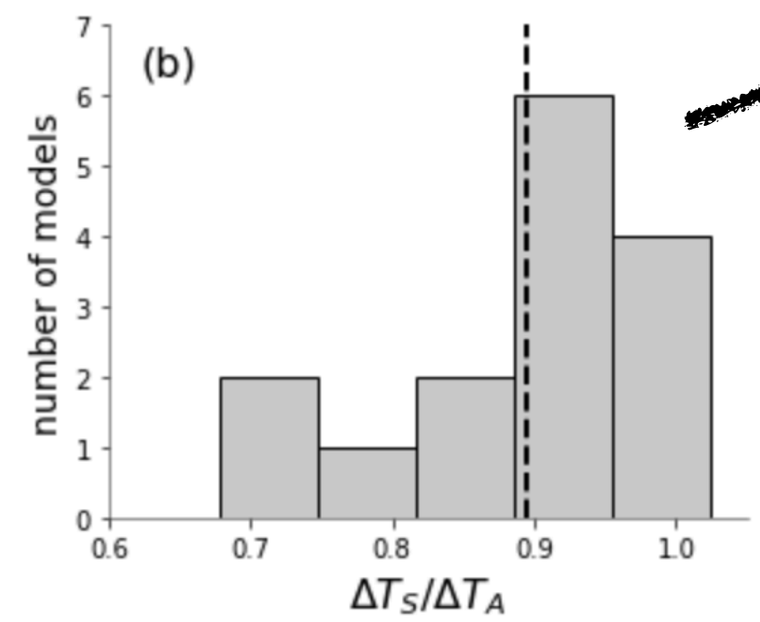
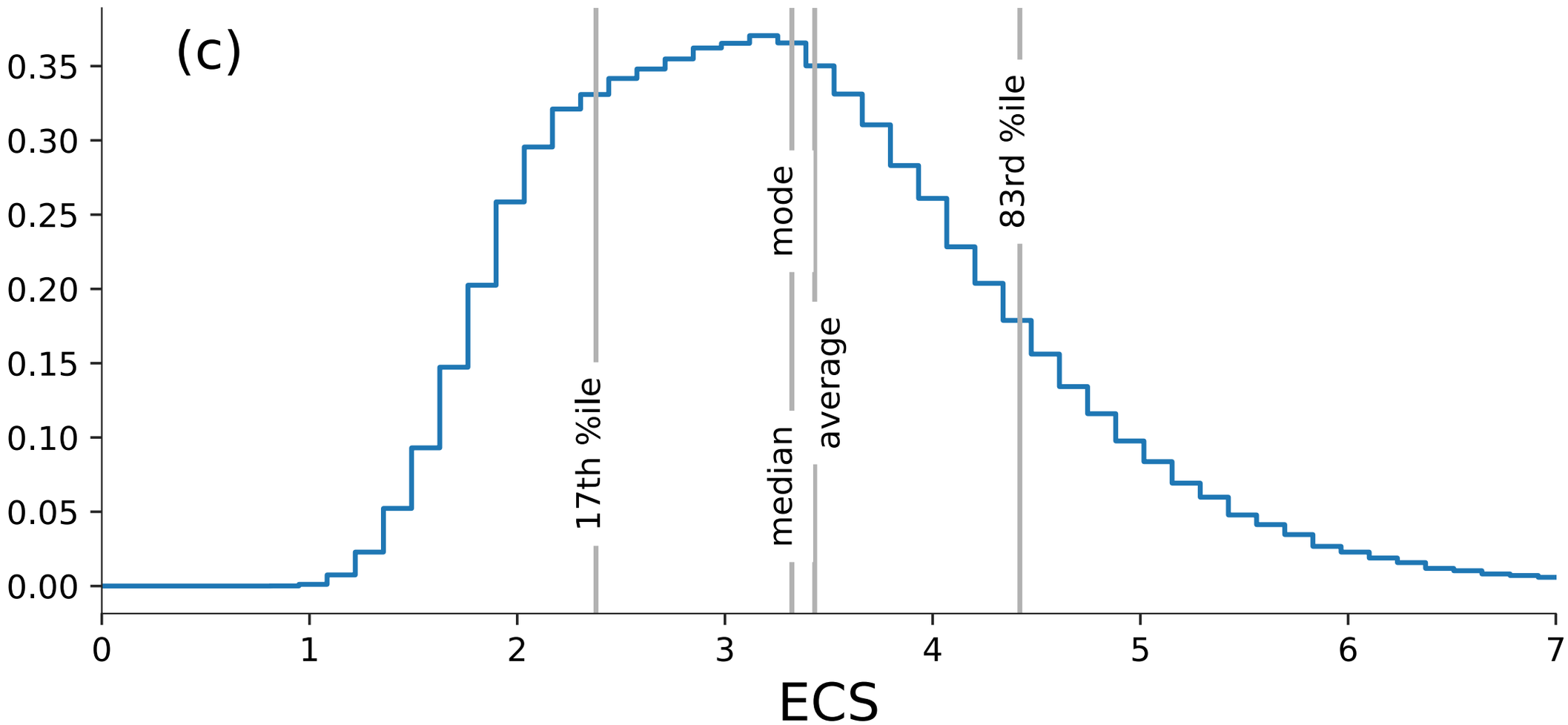
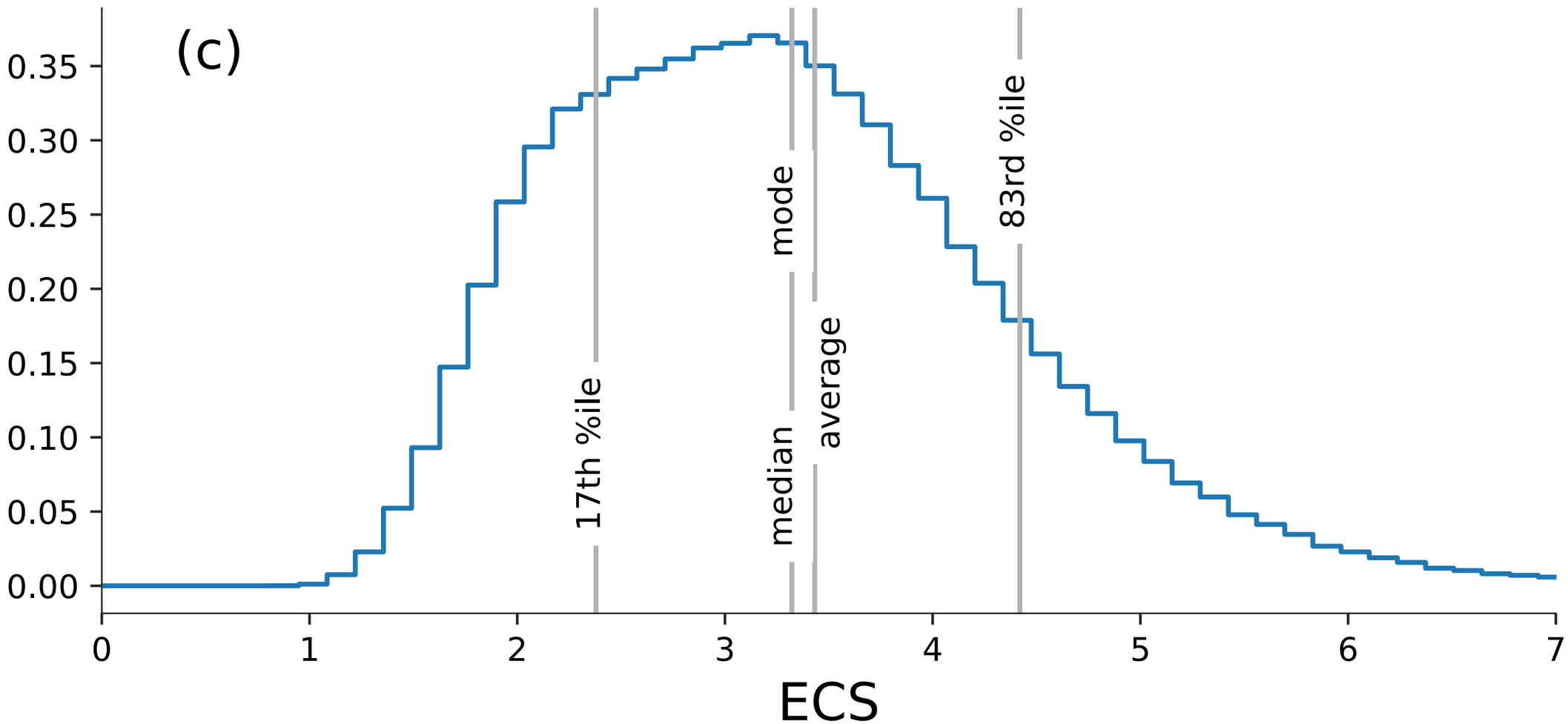




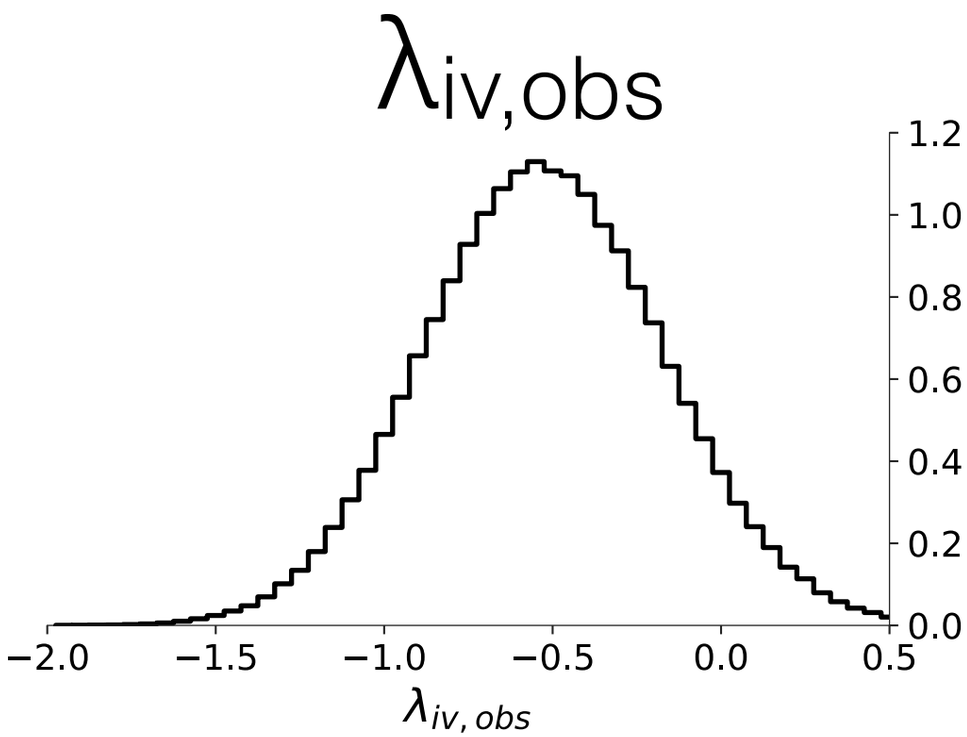
ECS

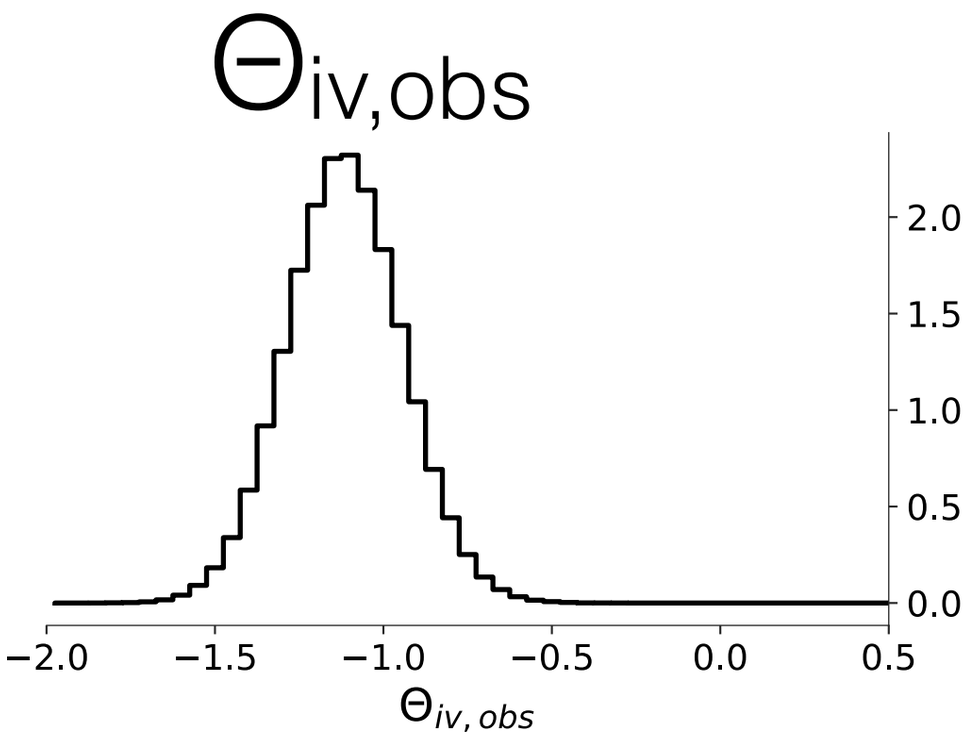

(c)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
1
2
3
4
5
6
7
ECS
17th %ile
median
mode
average
83rd %ile

ECS



likely range: 2.4-4.5 K
median: 3.3 K





Also, λ_{iv} has larger interdecadal variability than Θ_{iv}

$$\mathrm{ECS} \approx -\frac{F_{2\times CO_2}}{\Theta_{iv,obs}} \left(\frac{\Theta_{iv}}{\Theta_{4\times CO_2}} \right) \left(\frac{\Delta T_S}{\Delta T_A} \right)$$

$$\mathrm{ECS} \approx -\frac{F_{2\times CO_2}}{\Theta_{iv,obs}} \boxed{\left(\frac{\Theta_{iv}}{\Theta_{4\times CO_2}}\right)} \left(\frac{\Delta T_S}{\Delta T_A}\right)$$

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40%

$$\mathrm{ECS} \approx -\frac{F_{2\times CO_2}}{\Theta_{iv,obs}} \boxed{\left(\frac{\Theta_{iv}}{\Theta_{4\times CO_2}}\right)} \left(\frac{\Delta T_S}{\Delta T_A}\right)$$

40%

We can compare Θ_{iv} in the models to observations

$$\mathrm{ECS} \approx -\frac{F_{2\times CO_2}}{\Theta_{iv,obs}} \boxed{\left(\frac{\Theta_{iv}}{\Theta_{4\times CO_2}}\right)} \left(\frac{\Delta T_S}{\Delta T_A}\right)$$

40%

We can compare Θ_{iv} in the models to observations

… error in ratio requires error in numerator that is not reflected in the denominator …

Test with MPI-ESM 1.2

	ECS	Θ_{iv}	Θ_{4xCO2}	**ratio**
“iris”				
standard				
high ECS				

Thanks to T. Mauritsen and D. Jimenez for the model runs

Test with MPI-ESM 1.2

	ECS	Θ_{iv}	Θ_{4xCO2}	**ratio**
“iris”				
standard	3.0			
high ECS				

Thanks to T. Mauritsen and D. Jimenez for the model runs

Test with MPI-ESM 1.2

	ECS	Θ_{iv}	Θ_{4xCO2}	**ratio**
“iris”	2.6			
standard	3.0			
high ECS				

Thanks to T. Mauritsen and D. Jimenez for the model runs

Test with MPI-ESM 1.2

	ECS	Θ_{iv}	Θ_{4xCO2}	**ratio**
“iris”	2.6			
standard	3.0			
high ECS	5.2			

Thanks to T. Mauritsen and D. Jimenez for the model runs

Test with MPI-ESM 1.2

	ECS	Θ_{iv}	Θ_{4xCO2}	**ratio**
“iris”	2.6	-1.29		
standard	3.0	-0.98		
high ECS	5.2	-0.57		

Thanks to T. Mauritsen and D. Jimenez for the model runs

Test with MPI-ESM 1.2

	ECS	Θ_{iv}	Θ_{4xCO2}	**ratio**
“iris”	2.6	-1.29	-1.23	
standard	3.0	-0.98	-1.04	
high ECS	5.2	-0.57	-0.63	

Thanks to T. Mauritsen and D. Jimenez for the model runs

Test with MPI-ESM 1.2

	ECS	Θ_{iv}	Θ_{4xCO2}	**ratio**
“iris”	2.6	-1.29	-1.23	0.96
standard	3.0	-0.98	-1.04	1.06
high ECS	5.2	-0.57	-0.63	1.10

Thanks to T. Mauritsen and D. Jimenez for the model runs

$$\mathrm{ECS} \approx -\frac{F_{2\times CO_2}}{\Theta_{iv,obs}} \boxed{\left(\frac{\Theta_{iv}}{\Theta_{4\times CO_2}}\right)} \left(\frac{\Delta T_S}{\Delta T_A}\right)$$

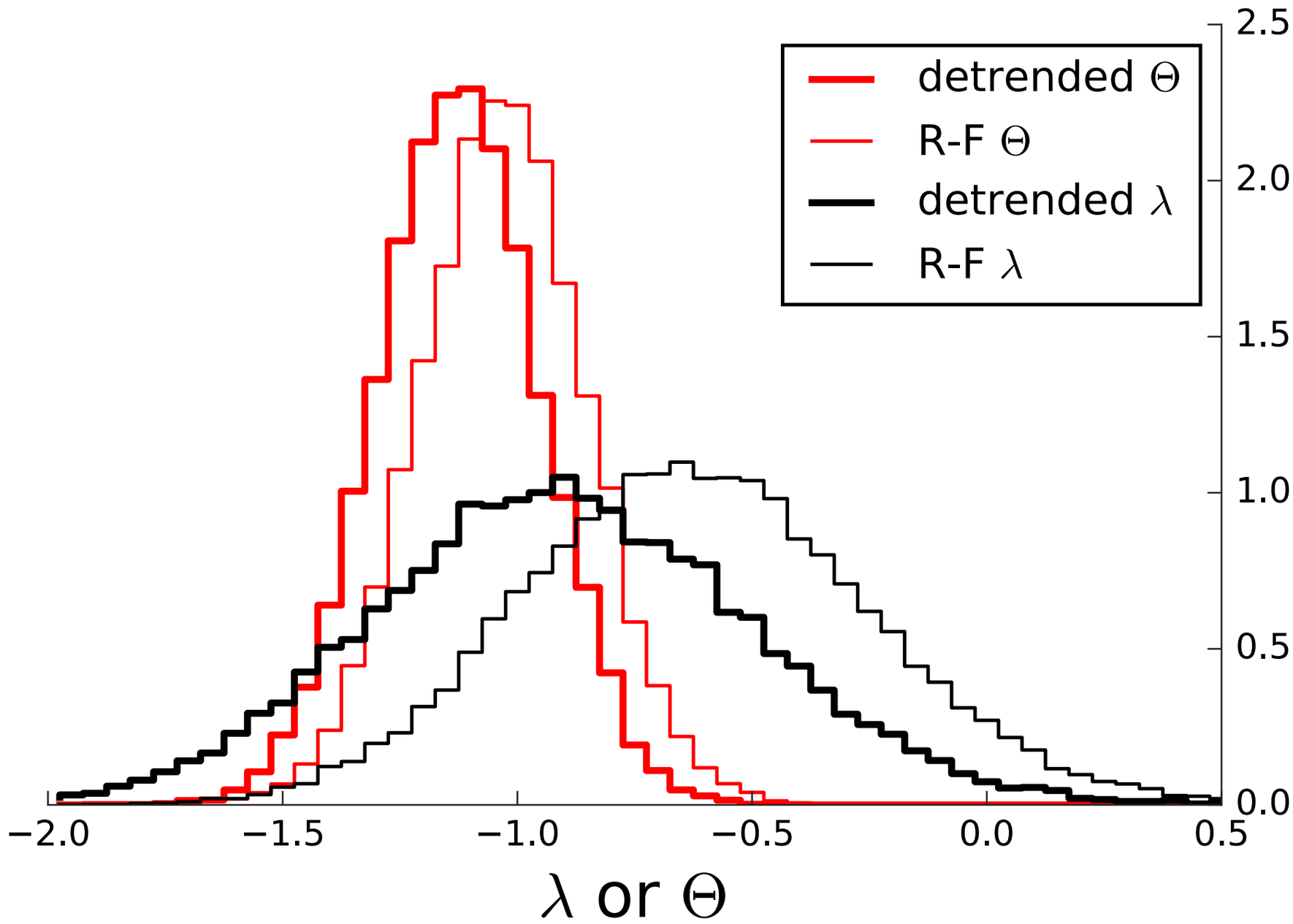
$$\mathrm{ECS} \approx -\frac{F_{2\times CO_2}}{\Theta_{iv,obs}} \boxed{\left(\frac{\Theta_{iv}}{\Theta_{4\times CO_2}}\right)} \left(\frac{\Delta T_S}{\Delta T_A}\right)$$

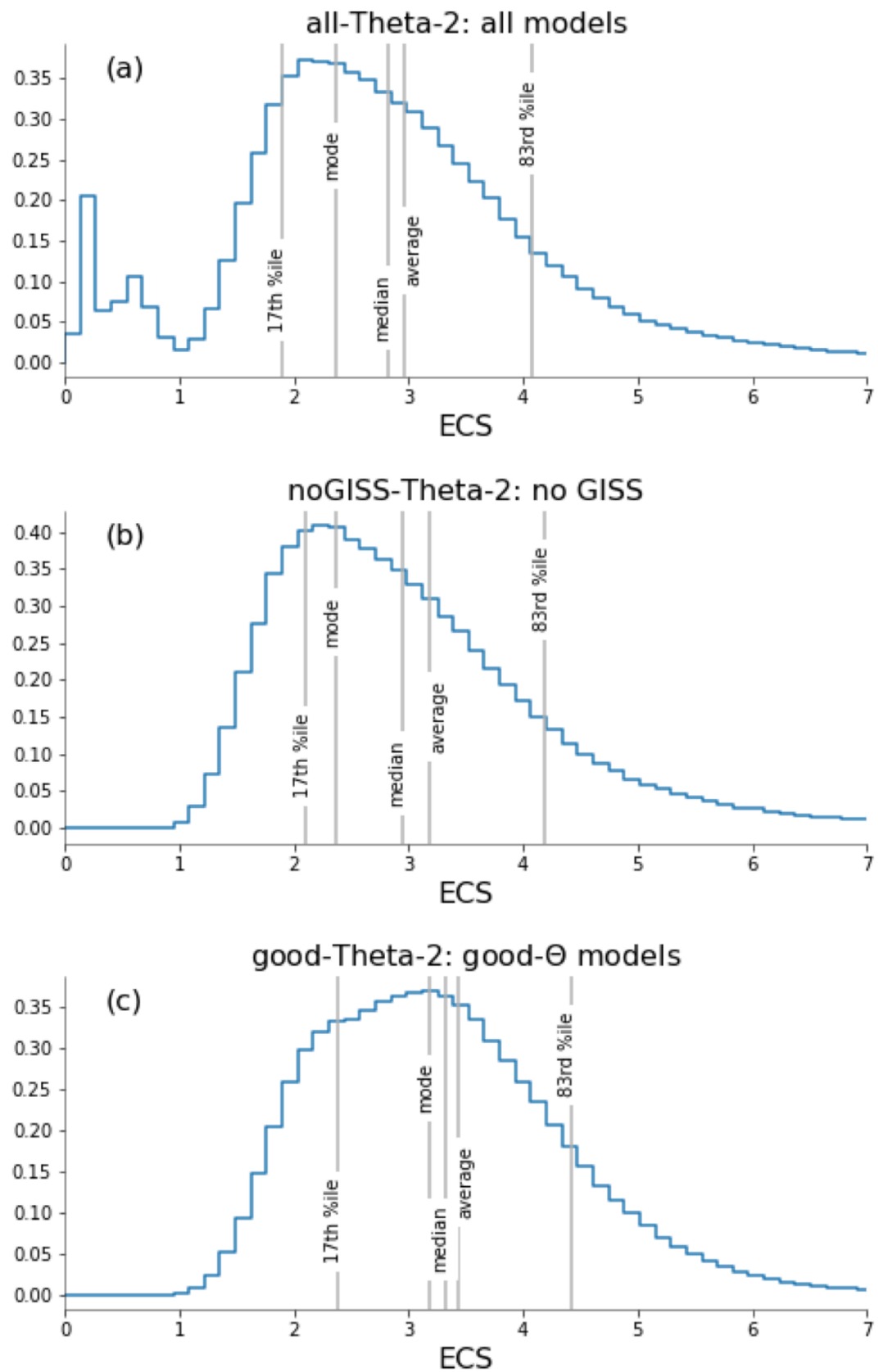
This is a believable model-derived quantity

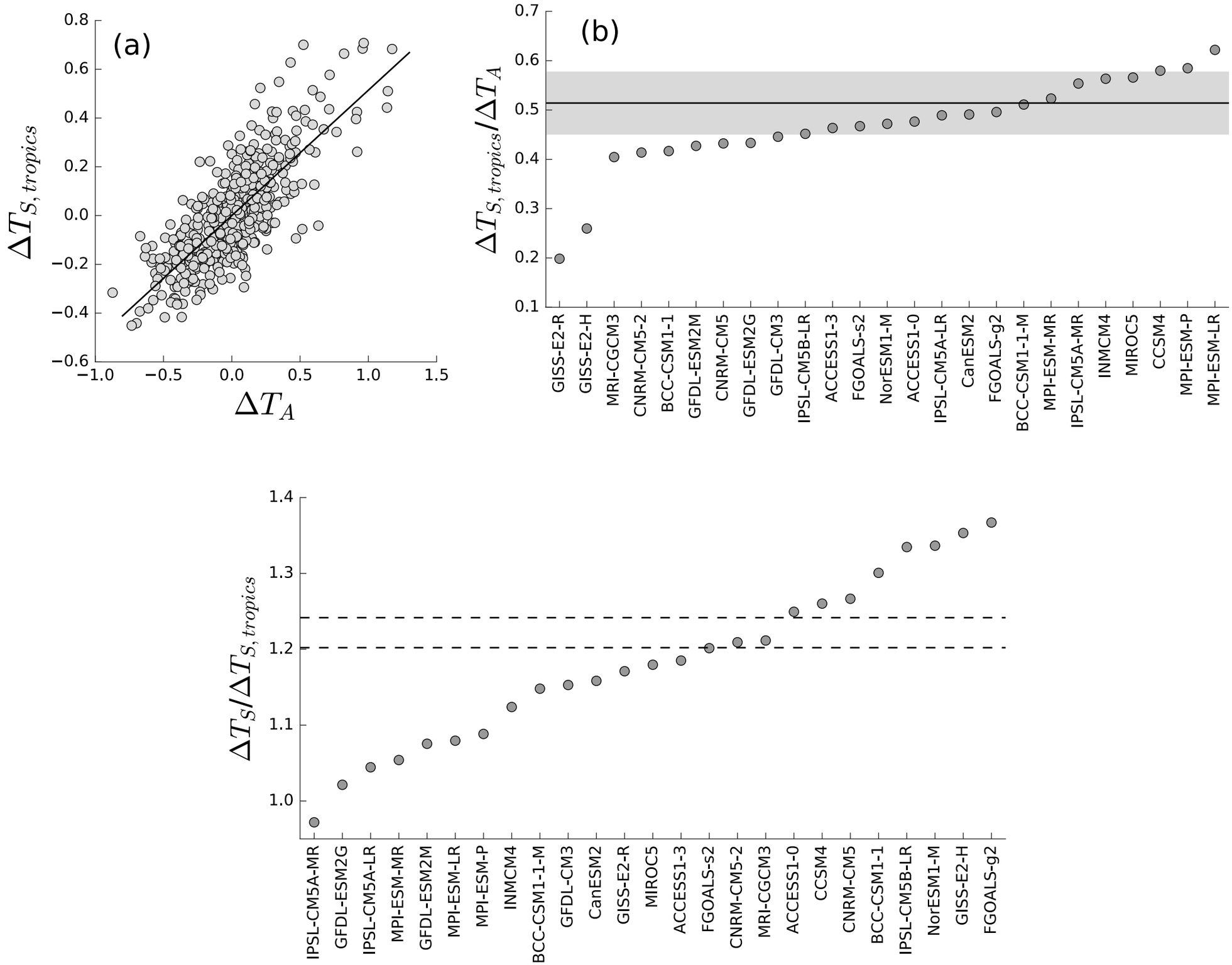
Conclusions

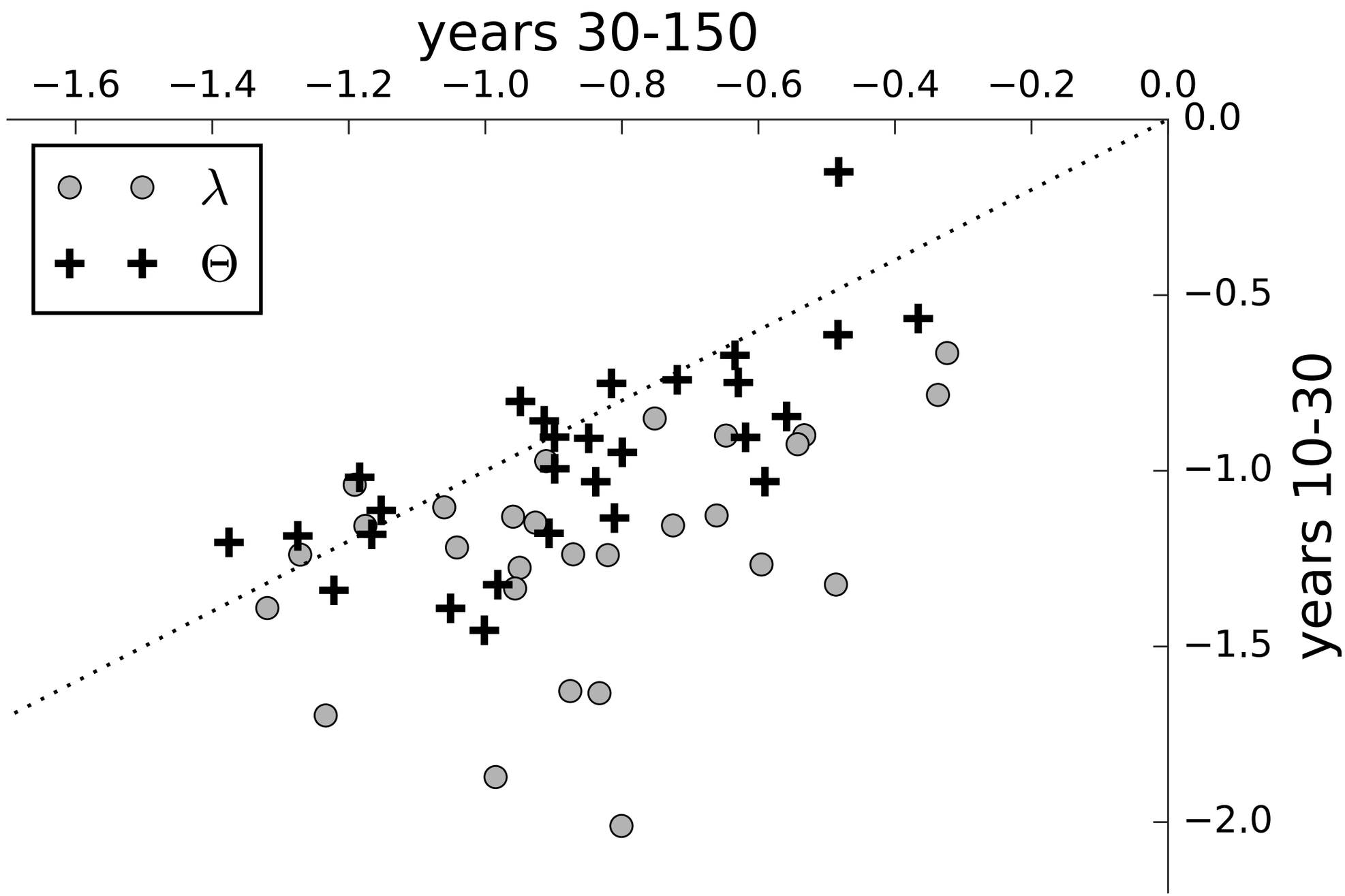
- Using interannual variability, we estimate ECS is *likely* 2.4-4.5 K
- We see no evidence of low ECS (1.5-2 K) suggested by estimates based on the 20th century record
- Key parameter is the ratio $\Theta_{iv}/\Theta_{4xCO2}$
- Pre-print: https://eartharxiv.org/4et67/

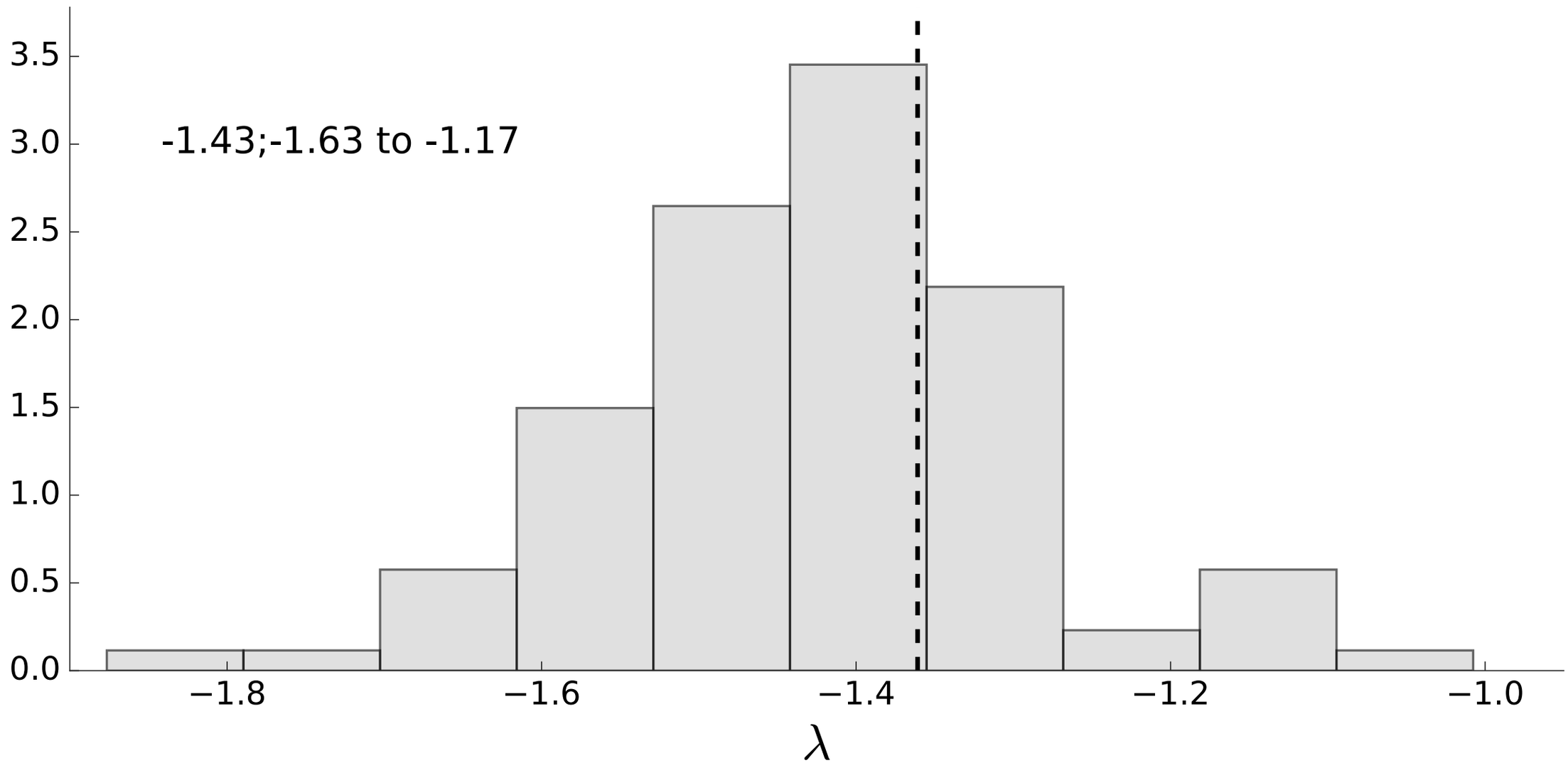
backup slides


detrended Θ
R-F Θ
detrended λ
R-F λ
2.5
2.0
1.5
1.0
0.5
0.0
−2.0
−1.5
−1.0
−0.5
0.0
0.5
λ or Θ


all-Theta-2: all models
(a)
17th %ile
mode
median
average
83rd %ile
ECS
noGISS-Theta-2: no GISS
(b)
17th %ile
mode
median
average
83rd %ile
ECS
good-Theta-2: good-Θ models
(c)
17th %ile
mode
median
average
83rd %ile
ECS

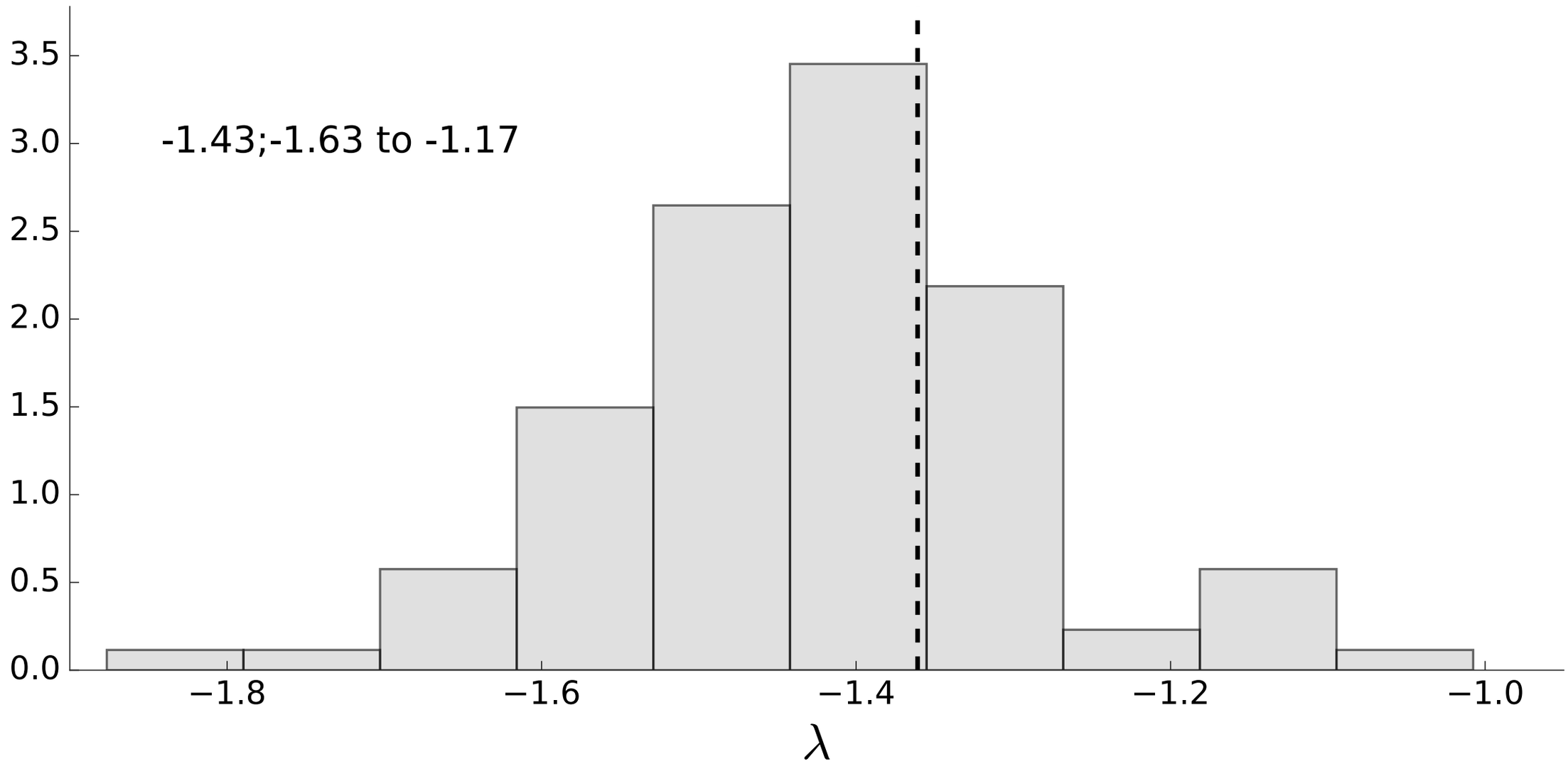

(a)
$\Delta T_{S,tropics}$
ΔT_A
(b)
$\Delta T_{S,tropics}/\Delta T_A$
GISS-E2-R
GISS-E2-H
MRI-CGCM3
CNRM-CM5-2
BCC-CSM1-1
GFDL-ESM2M
CNRM-CM5
GFDL-ESM2G
GFDL-CM3
IPSL-CM5B-LR
ACCESS1-3
FGOALS-s2
NorESM1-M
ACCESS1-0
IPSL-CM5A-LR
CanESM2
FGOALS-g2
BCC-CSM1-1-M
MPI-ESM-MR
IPSL-CM5A-MR
INMCM4
MIROC5
CCSM4
MPI-ESM-P
MPI-ESM-LR
$\Delta T_S/\Delta T_{S,tropics}$
IPSL-CM5A-MR
GFDL-ESM2G
IPSL-CM5A-LR
MPI-ESM-MR
GFDL-ESM2M
MPI-ESM-LR
MPI-ESM-P
INMCM4
BCC-CSM1-1-M
GFDL-CM3
CanESM2
GISS-E2-R
MIROC5
ACCESS1-3
FGOALS-s2
CNRM-CM5-2
MRI-CGCM3
ACCESS1-0
CCSM4
CNRM-CM5
BCC-CSM1-1
IPSL-CM5B-LR
NorESM1-M
GISS-E2-H
FGOALS-g2


years 30-150
−1.6
−1.4
−1.2
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
0.0
−0.5
−1.0
−1.5
−2.0
years 10-30
λ
Θ

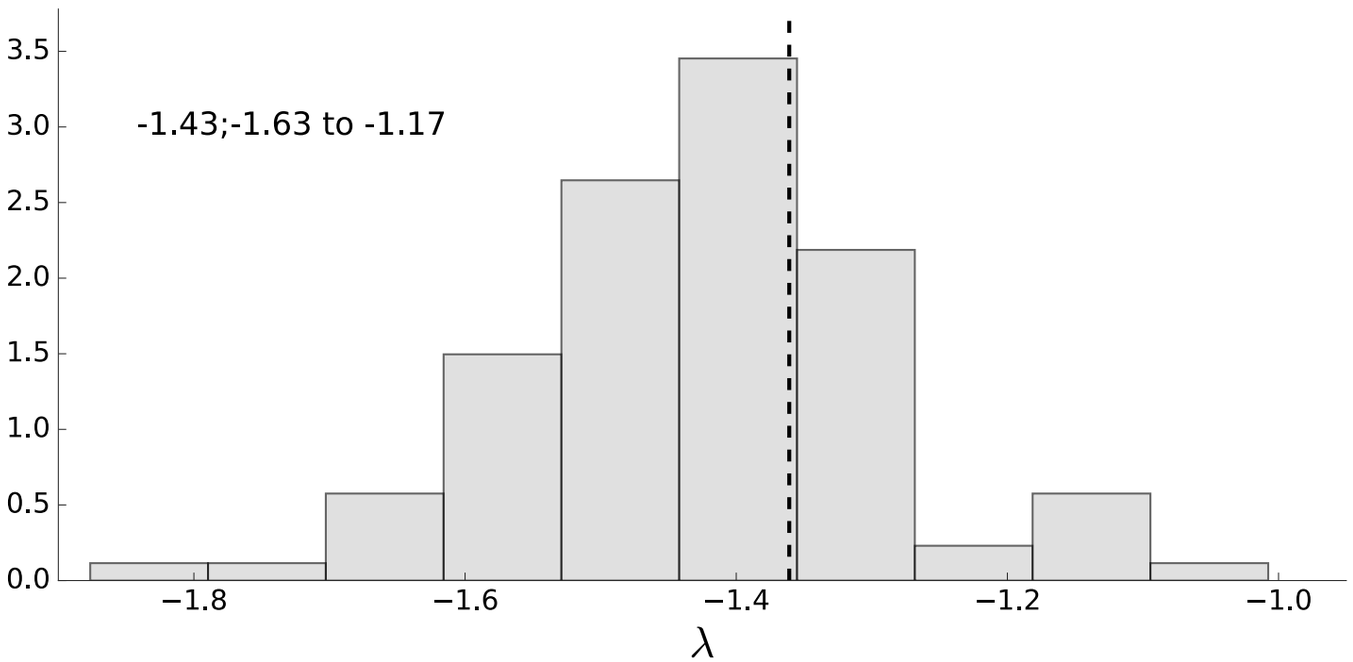


W/m²/K

internal variability

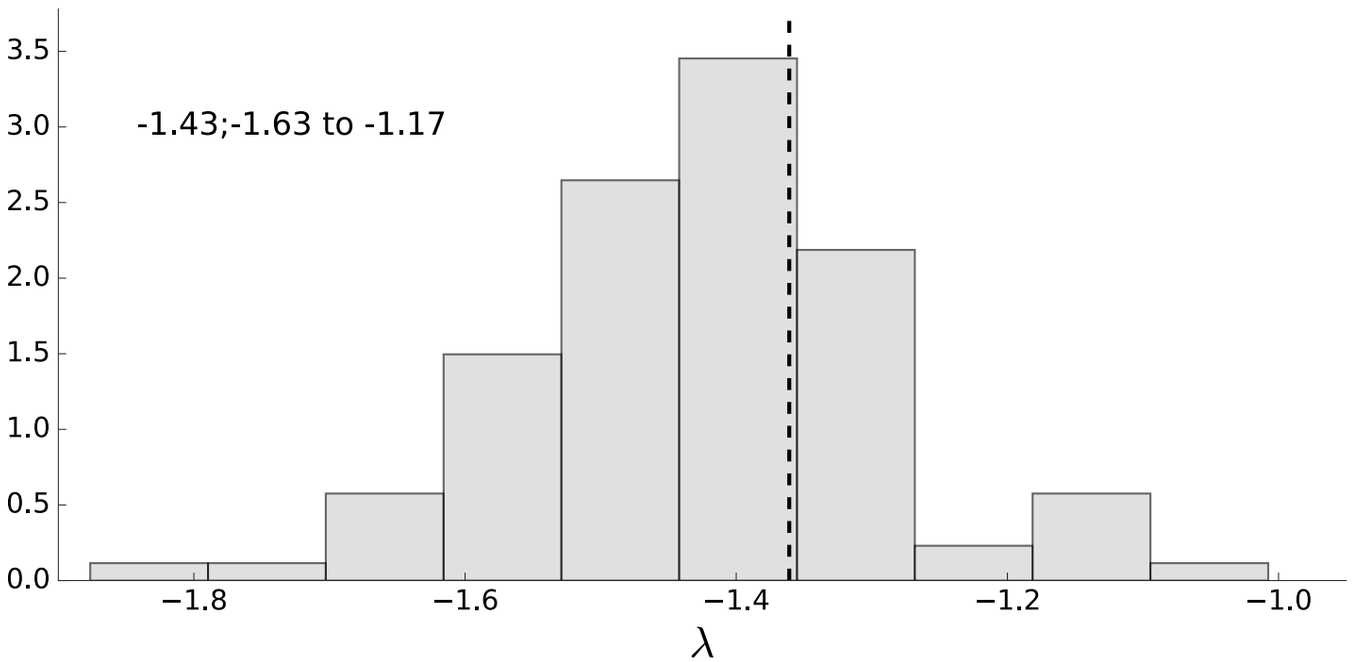


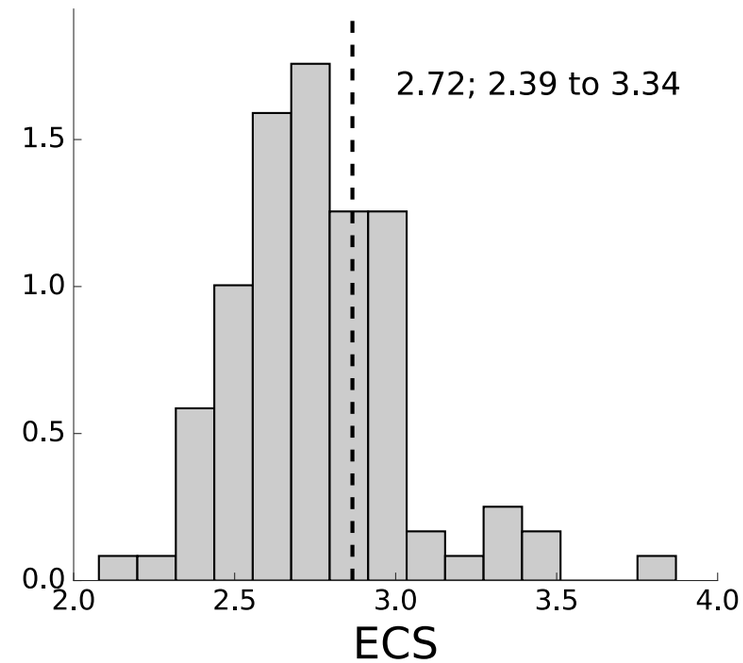
W/m²/K



$$\lambda = \frac{\Delta(R - F)}{\Delta T_S}$$

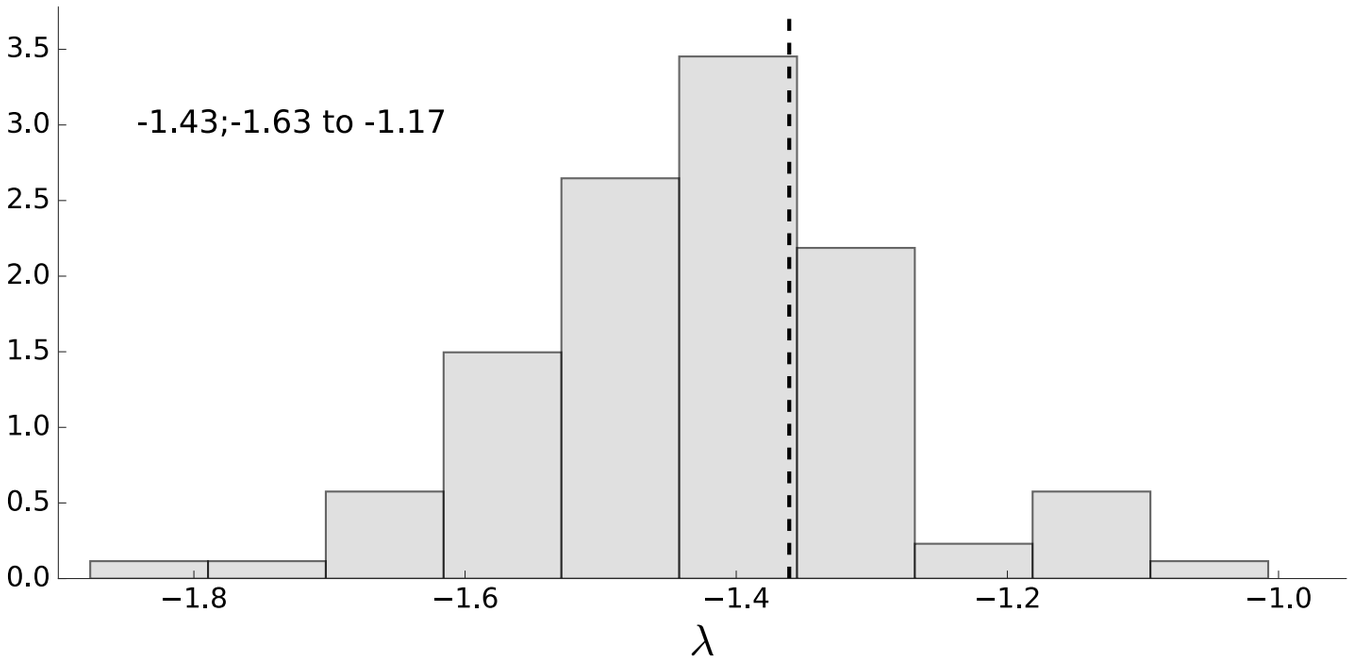
$$\mathrm{ECS} = -\frac{F_{2\times CO_2}}{\lambda}$$

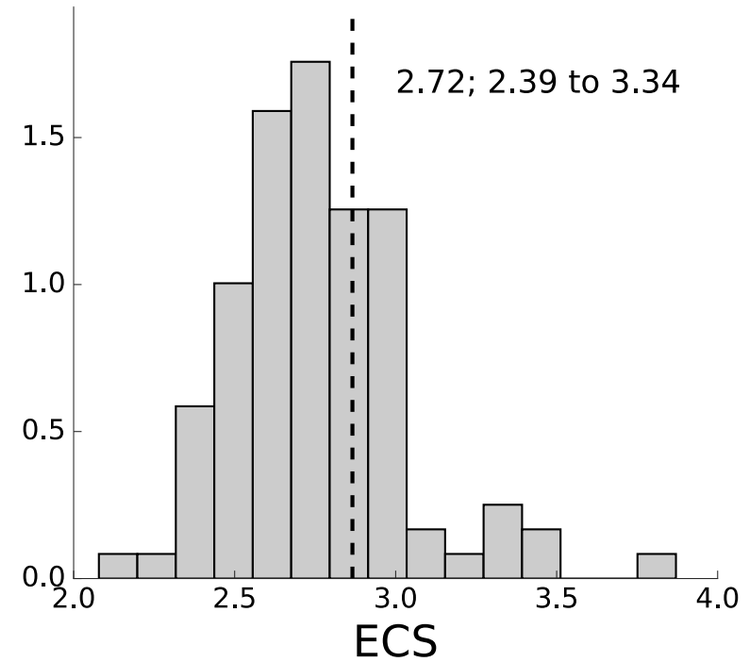




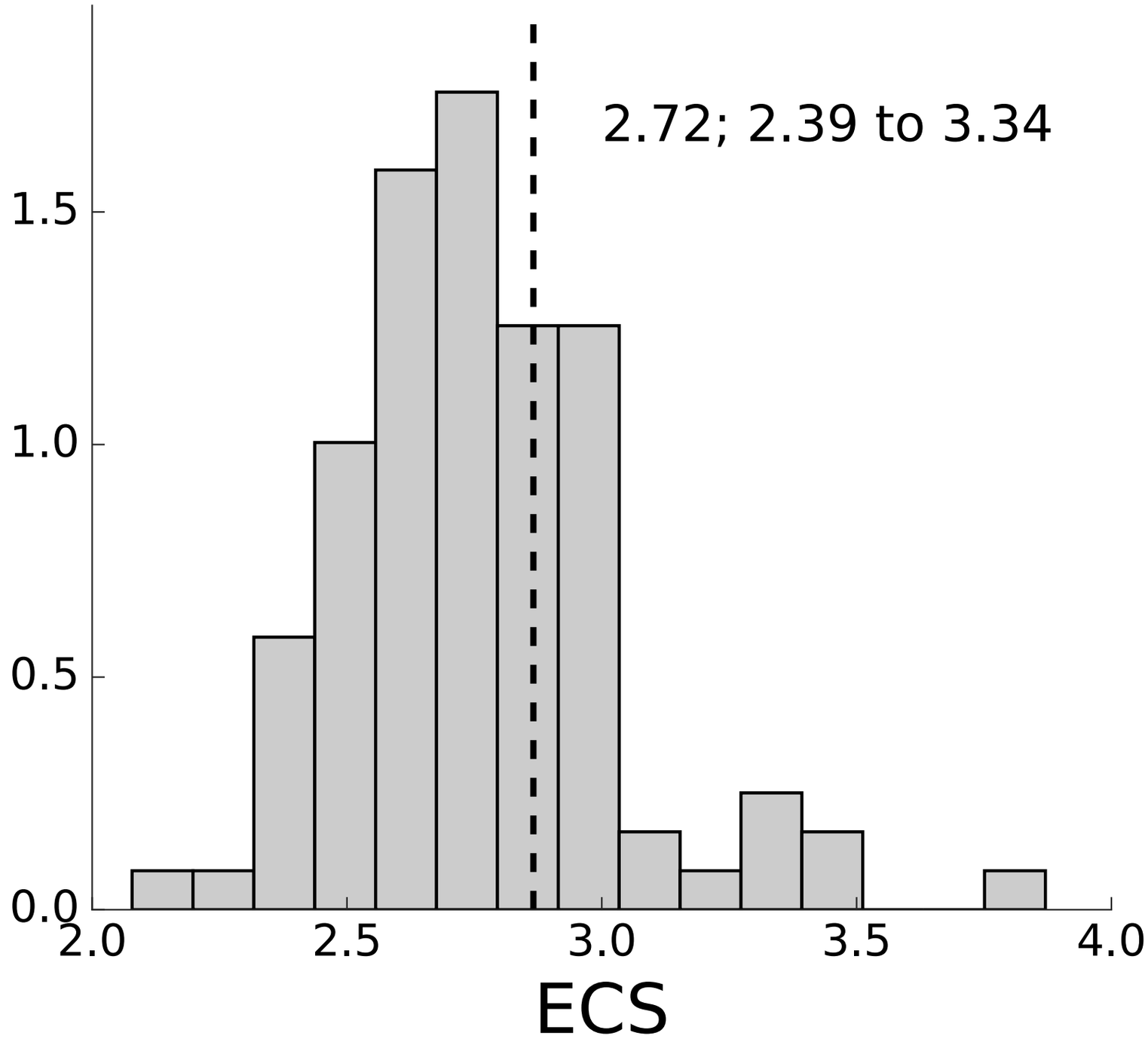
$$\lambda = \frac{\Delta(R - F)}{\Delta T_S}$$

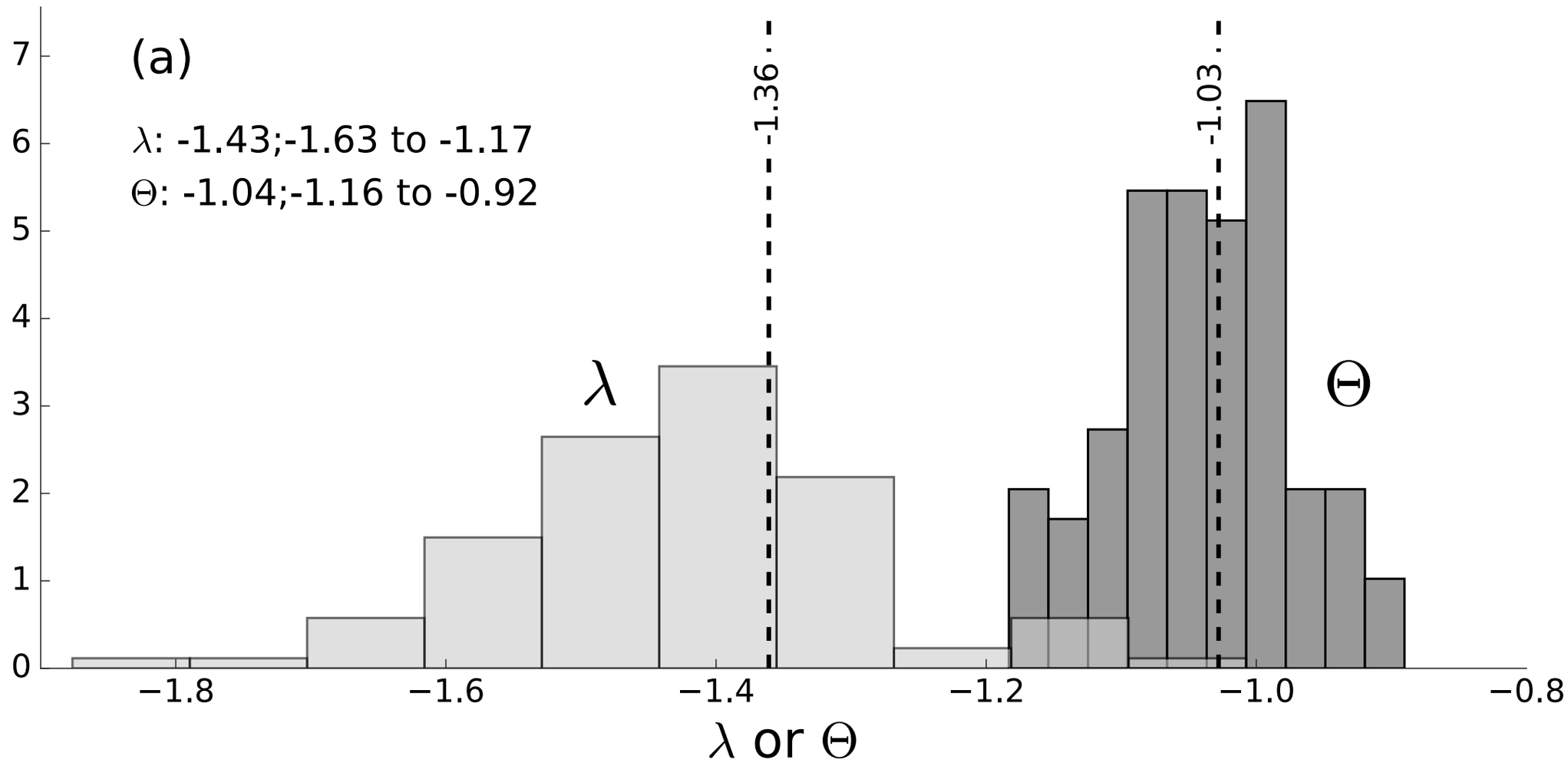
$$\mathrm{ECS} = -\frac{F_{2\times CO_2}}{\lambda}$$


-1.43;-1.63 to -1.17
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−1.8
−1.6
−1.4
−1.2
−1.0
λ


2.72; 2.39 to 3.34
1.5
1.0
0.5
0.0
2.0
2.5
3.0
3.5
4.0
ECS

−1.0

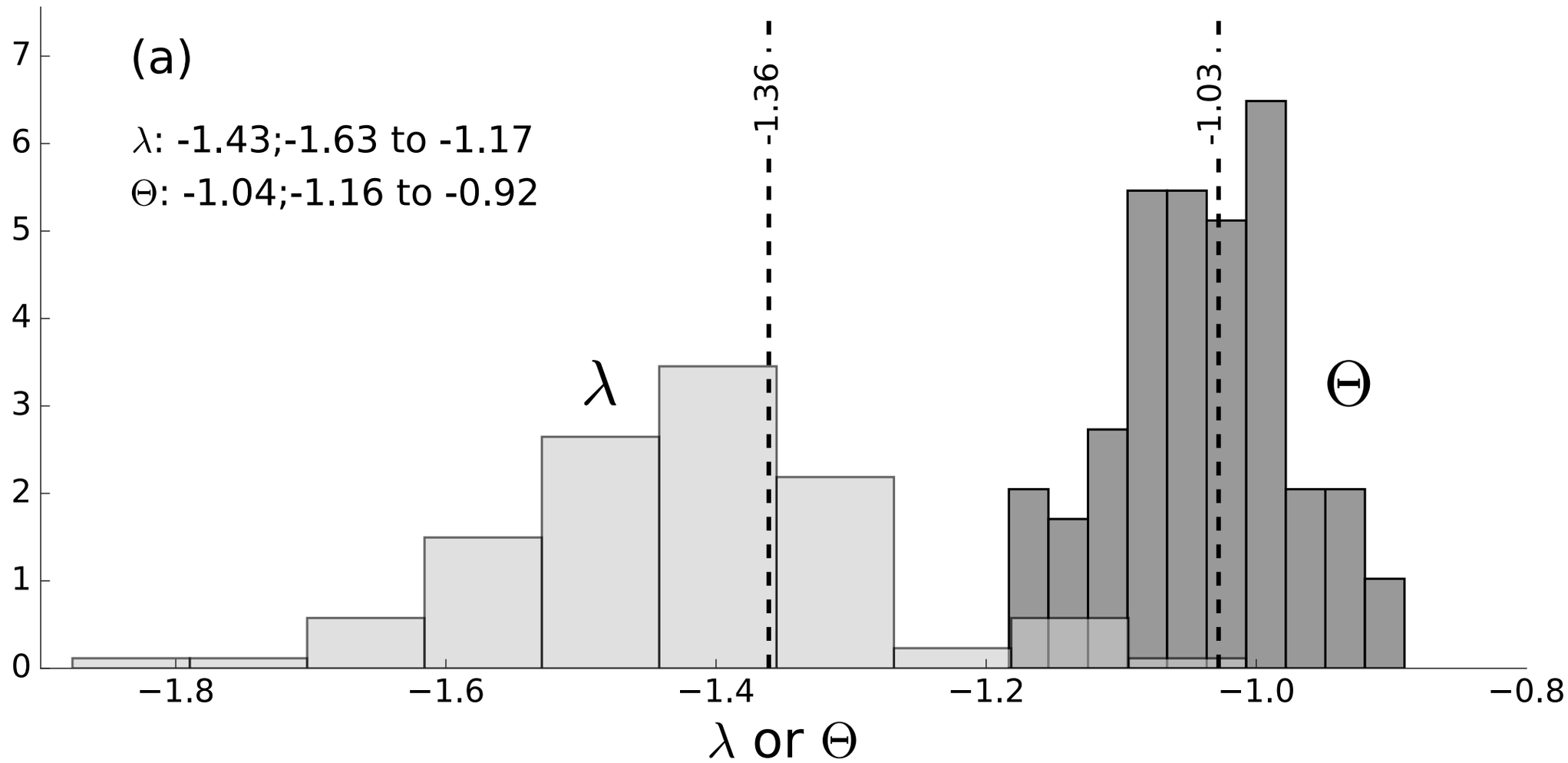

2.72; 2.39 to 3.34
1.5
1.0
0.5
0.0
2.0
2.5
3.0
3.5
4.0
ECS



$$\lambda = \Delta(R\text{-}F)/\Delta T_S$$

$$\Theta = \Delta(R\text{-}F)/\Delta T_A$$

confirmed in CMIP5 control runs



$$\lambda = \Delta(R\text{-}F)/\Delta T_S$$

$$\Theta = \Delta(R\text{-}F)/\Delta T_A$$

Table 1. ECS values from the λ runs

Summary of the statistics of the ECS distributions derived using Eq. 4. "%<2" and "%>4.5" gives the percent of ECS values that are below 2 K or above 4.5 K. Units are in K, except for "%<2" and "%>4.5", which are in percent.

run	**mean**	**mode**	**median**	**5-95%**	**17-83%**	**%<2**	**%>4.5**
all-Lambda-1	4.63	2.98	4.23	1.7-8.8	2.5-7.0	6	32
all-Lambda-2	3.78	2.44	3.29	1.4-7.9	2.0-5.7	15	26
all-Lambda-1-f	4.43	2.71	3.99	1.6-8.7	2.3-6.7	8	30
all-Lambda-1-f_20-150	4.59	2.85	4.19	1.6-8.9	2.4-7.0	7	31
good-Lambda-1	4.20	2.71	3.73	1.6-8.4	2.3-6.3	9	28
good-Lambda-2	3.66	2.31	3.19	1.4-7.7	1.9-5.4	16	24
good-Lambda-1-f_20-150	4.18	2.71	3.72	1.4-8.5	2.2-6.4	10	28
good-Lambda-1-f	3.98	2.44	3.48	1.4-8.3	2.1-6.0	12	25

Names containing "all" or "good" include all models or just the ones whose λ_{iv} agrees with the CERES observations, respectively. The names with "-1" or "-2" use $\lambda_{iv,obs}$ derived using estimates of forcing (the R-F calculations) and the detrended calculations, respectively. The names including "-f" use forcing from the CMIP5 abrupt 4x CO_2 runs (see Sect. S2). The names including "-f_20-150" calculate F_{2xCO2} and λ_{4xCO2} from years 20-150 of the abrupt $4xCO_2$ runs (see Sect. S2).

Table 2. ECS values from the Θ runs
Same as Table 1, but derived using Eq. 6.

run	**mean**	**mode**	**median**	**5-95%**	**17-83%**	**%<2**	**%>4.5**
all-Theta-1	3.33	2.58	3.14	0.7-6.2	2.1-4.6	15	19
all-Theta-2	2.96	2.31	2.82	0.7-5.4	1.9-4.1	20	11
all-Theta-1-corr	3.36	2.58	3.13	0.8-6.5	2.0-4.8	16	20
all-Theta-1-f	3.11	2.44	2.91	0.7-6.0	1.9-4.4	21	16
all-Theta-1-f_20_150	2.98	2.31	2.75	0.6-5.8	1.8-4.3	24	14
good-Theta-1	3.56	2.58	3.33	2.0-5.9	2.4-4.7	6	20
good-Theta-2	3.43	3.12	3.33	1.9-5.3	2.4-4.4	6	15
good-Theta-1-corr	3.58	2.44	3.33	1.9-6.2	2.3-4.8	7	21
good-Theta-1-f	2.81	2.17	2.65	0.5-5.1	1.8-3.9	25	10
good-Theta-1-f_20-150	2.71	2.03	2.51	0.4-5.0	1.7-3.8	30	9
noGISS-Theta-1	3.56	2.58	3.28	1.9-6.3	2.3-4.8	8	21
noGISS-Theta-2	3.18	2.31	2.94	1.7-5.5	2.1-4.2	13	12

Names follow the same convention as Table 1. The names including "noGISS-" include all models except the two GISS models. In the "-corr" calculations, each Monte Carlo value of ECS uses values of $\Delta T_S/\Delta T_A$ and $\Theta_{iv}/\Theta_{4xCO2}$ from the same model.

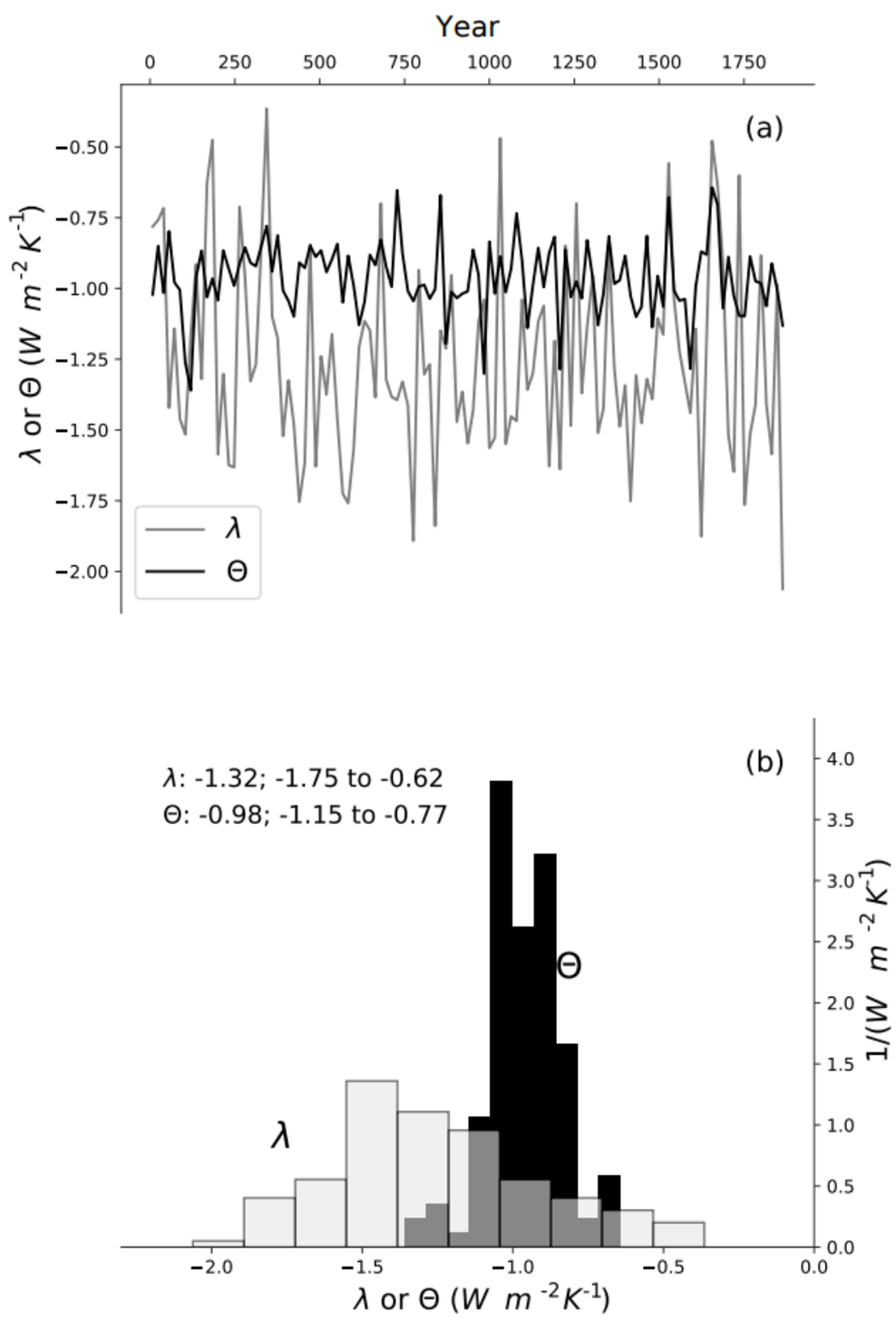


Figure 6. **(a)** Time series of λ (gray) and Θ (black) estimated in a 17-year sliding window of a 2000-year control run of the MPI-ESM1.1. **(b)** PDFs of the time series in **(a)**. Median and 5–95 % confidence interval for each distribution are displayed on the plot.