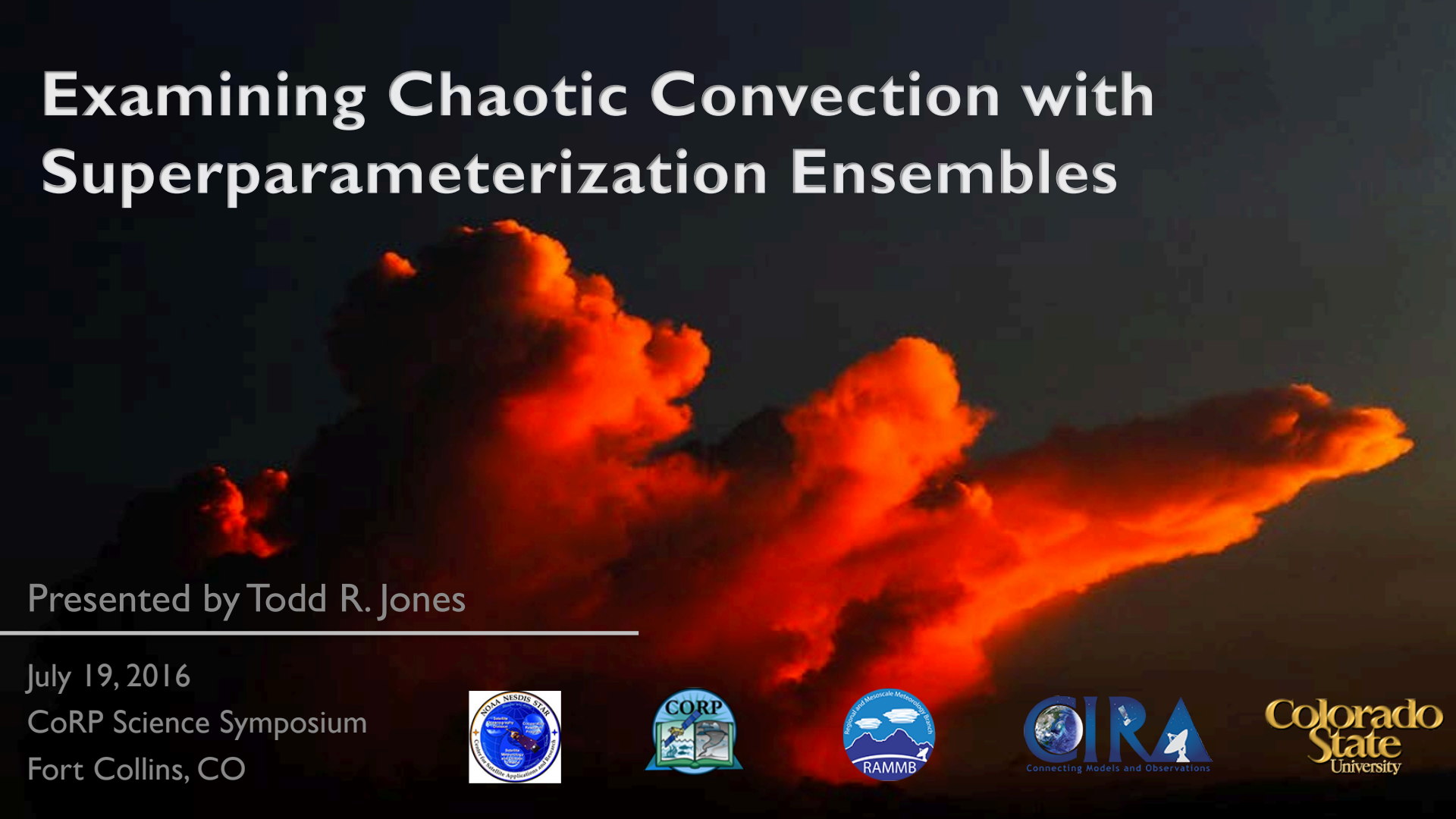
Examining Chaotic Convection with Superparameterization Ensembles



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July 19, 2016

CoRP Science Symposium

Fort Collins, CO

Forecasting with GCMs

Large Scale

Small Scale

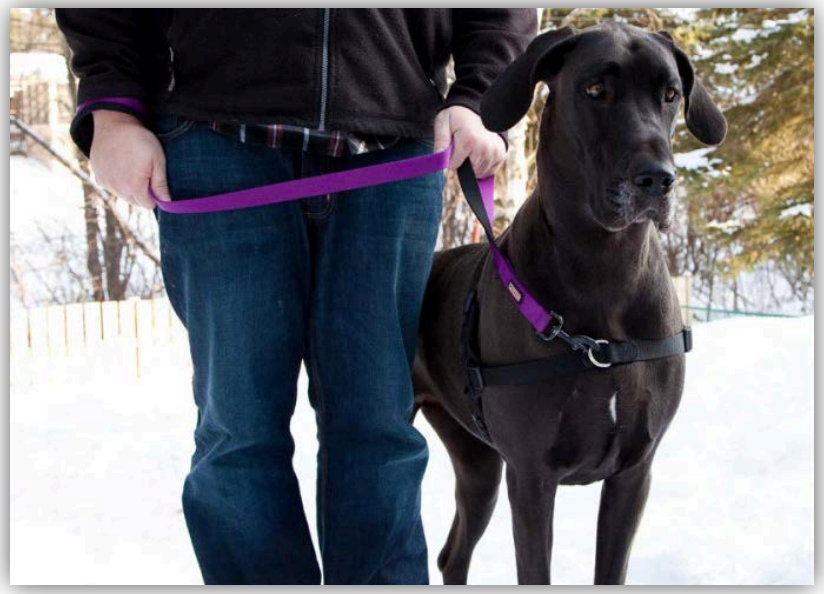
Advective Forcing

Heating & Drying

Parameterized

Convection
Microphysics
Radiation
Turbulence

Deterministic



Expected Values
- something like -
Ensemble Means

Non-Deterministic

Individual Realizations
with
Sensitive Dependence on Initial Conditions

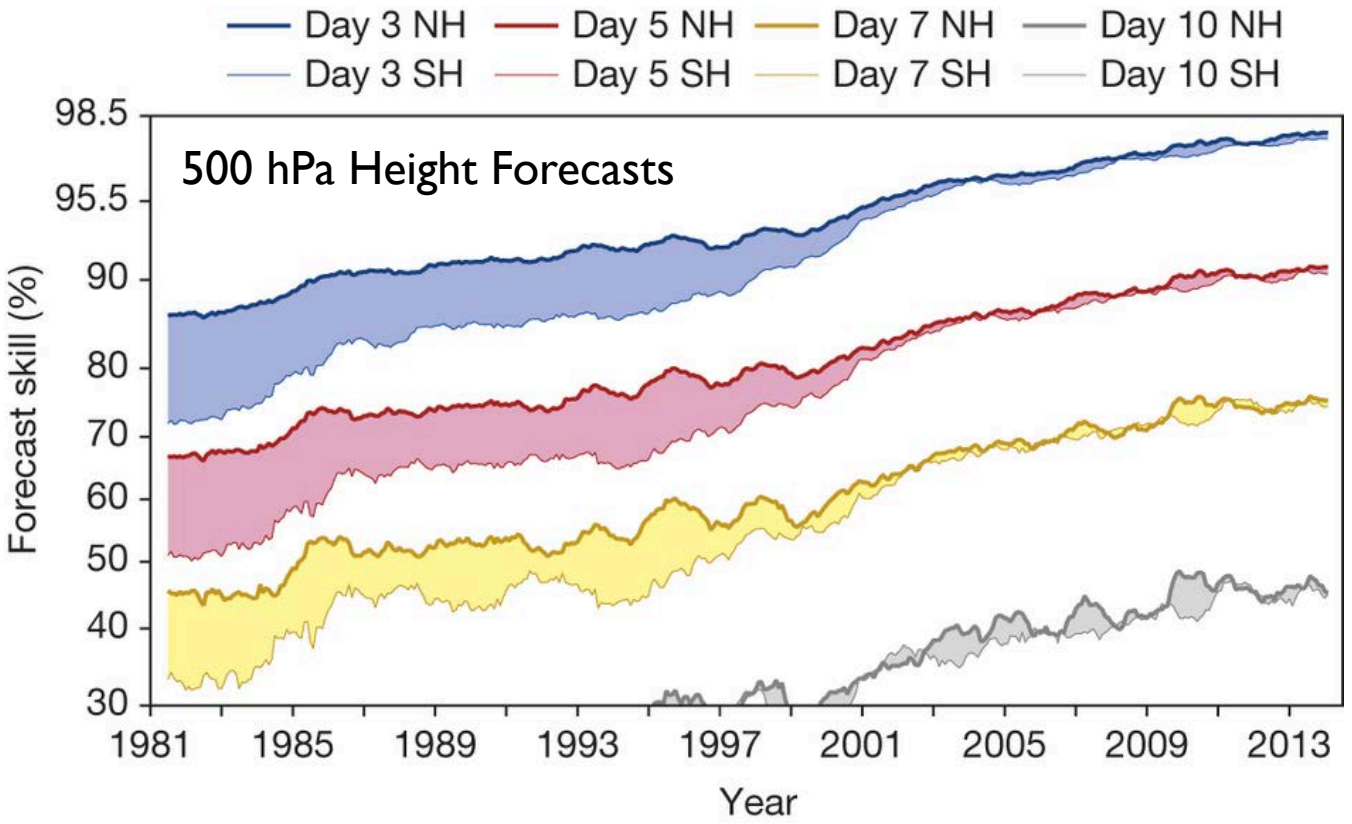
Limits of Convective Parameterizations

- Issues with SDIC, sample size, false scale separation, memory and time scales limit deterministic parameterizability.
- Real physical tendencies have a significant chaotic component.
  - They are only partially predictable.
  - Grid cell averaged precipitation is **intrinsically uncertain**.
- We confront this by providing the solution wandering space:
  - Ensembles
  - Stochastic parameterization
  - Superparameterization
    - Non-deterministic due to SDIC on the convective scale

Limits of Convective Parameterizations

- Many deterministic parameterizations yield convection that acts too quickly.
  - Poor timing and extremes
- A lack of high-frequency, small-scale variability in GCM precipitation and physical tendency fields may limit their ability to simulate low-frequency, large-scale aspects of climate variability.
  - Poor intraseasonal variability, MJO, QBO

Large-scale feature are improving.

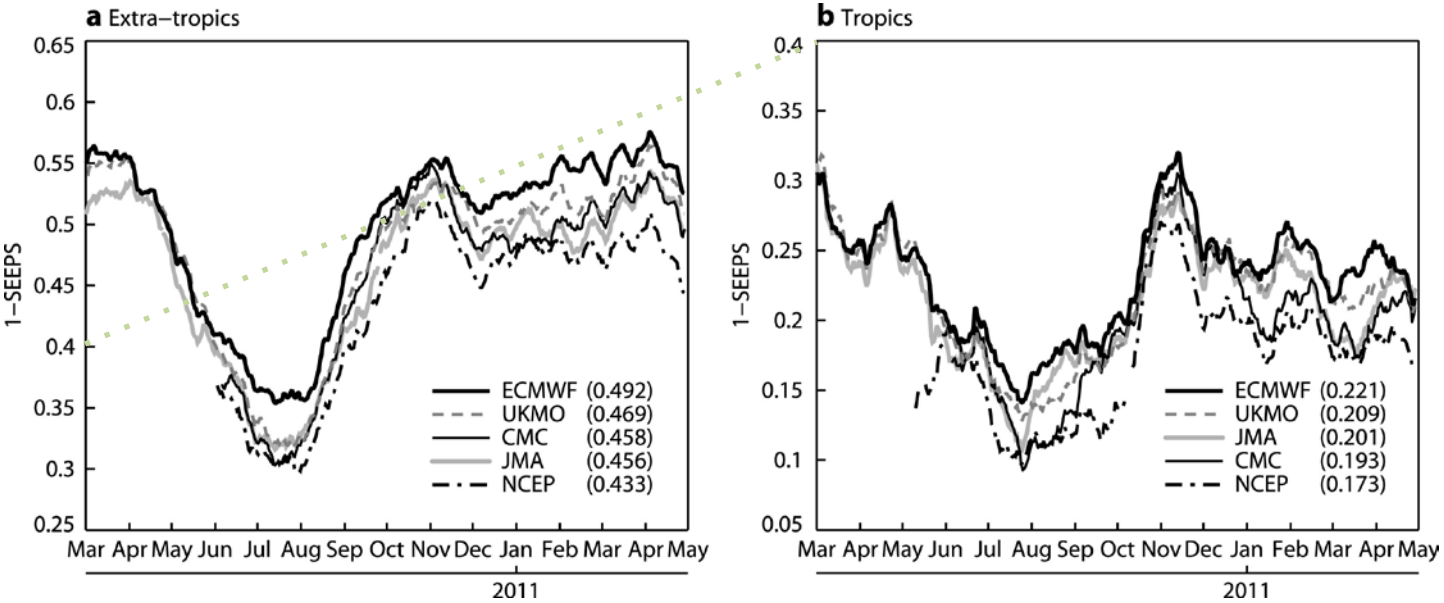


Values > 60 indicate useful forecasts.

Bauer et al., Nature, 2015

Precipitation forecasting is quite difficult…

Better Skill



Haiden et al., MWR, 2012

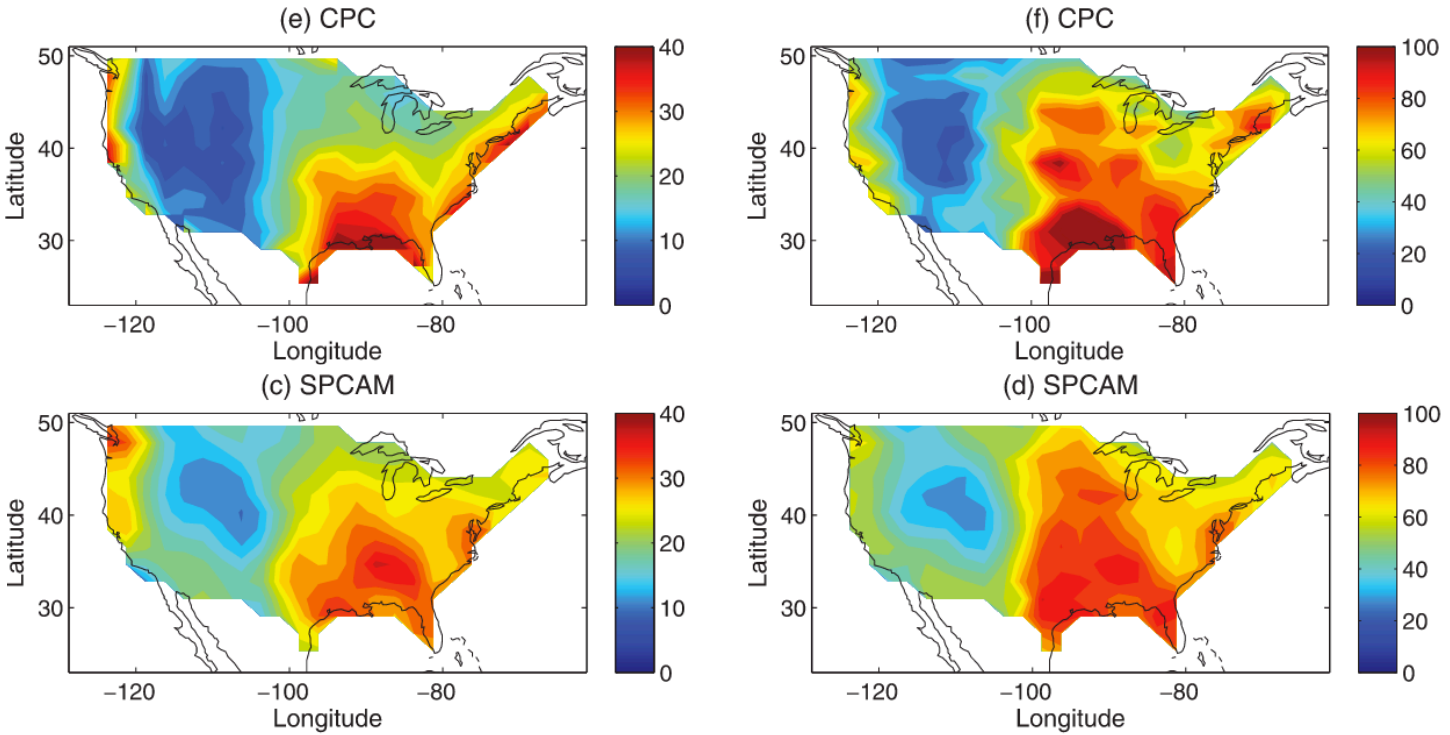
…particularly intense precipitation.

95th percentile, daily

99.5th percentile, 3-hourly

Obs

SP-CAM



Li et al., JAMES, 2012

We Wonder…

- Does the large-scale need to feel "jagged," stochastic tendencies?
- Is it possible for a smoothed, more deterministic tendency to yield the same gains?
- Can we explore the range of possible realizations at the same time?

Superparameterization

CAM

Advective Forcing →

← Heating & Drying

Parameterized

Convection
Microphysics
Radiation
Turbulence

SP-CAM

Advective Forcing →

← Heating & Drying

Advective Forcing →

← Heating & Drying

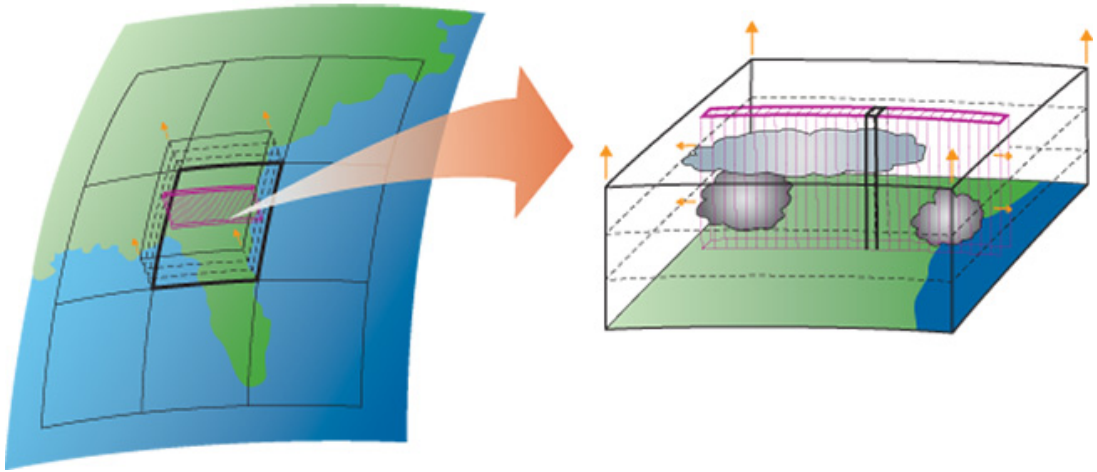
Parameterized

Microphysics
Radiation
Turbulence

2.5° × 1.9°

32 × 4-km curtain

Superparameterization

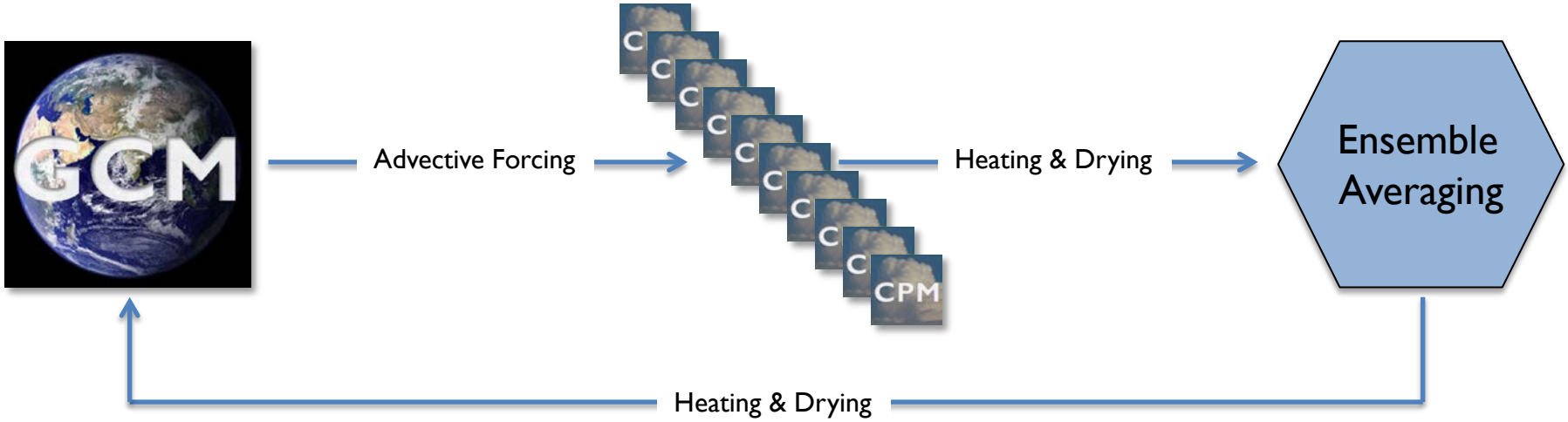


Solves equations of motion - No closure assumption - No triggers
Mesoscale organization - Convective memory - SDIC

Computationally Expensive

More Deterministic, Multiple Realizations

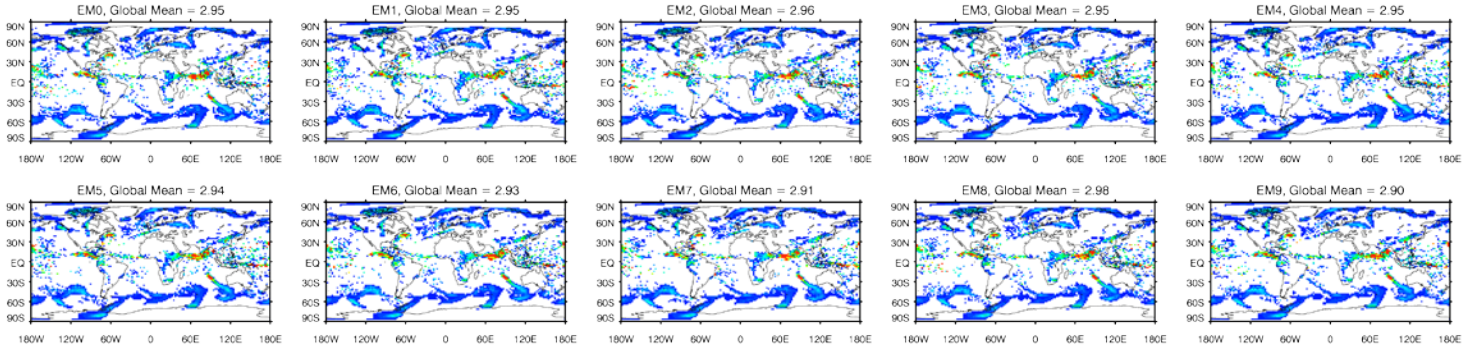
MP-CAM

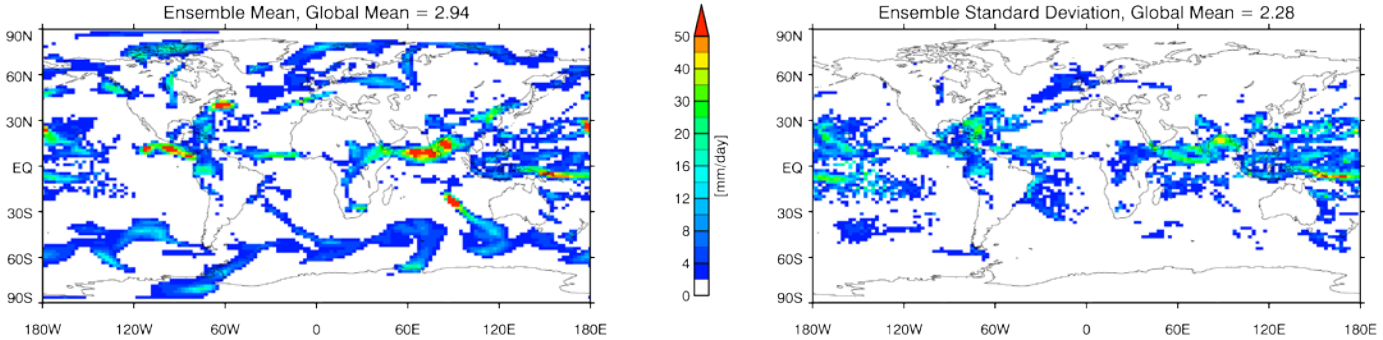


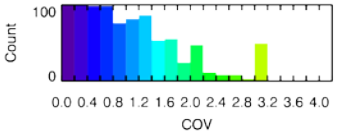
See the same GCM state - Slightly different initial conditions - Running independently

Experimental Design

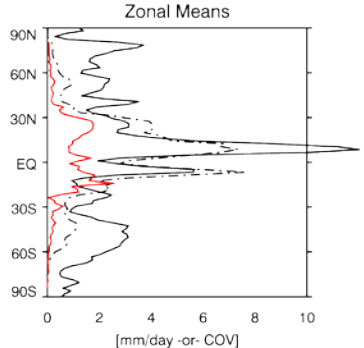
- CAM-FV with 2.5°×1.9° longitude-latitude grid
- Climatological SSTs
- SP-CAM, 30 years
  - 32×4-km curtain, oriented N-S
- MP-CAM, ~23 years
  - 10 clone CPMs
  - 4 years of 3-hourly data
  - 2 days every GCM time step
- SP-CAM Ensemble "Forecast," 10 days

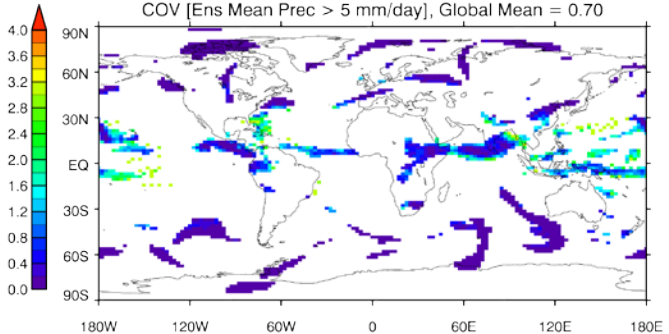


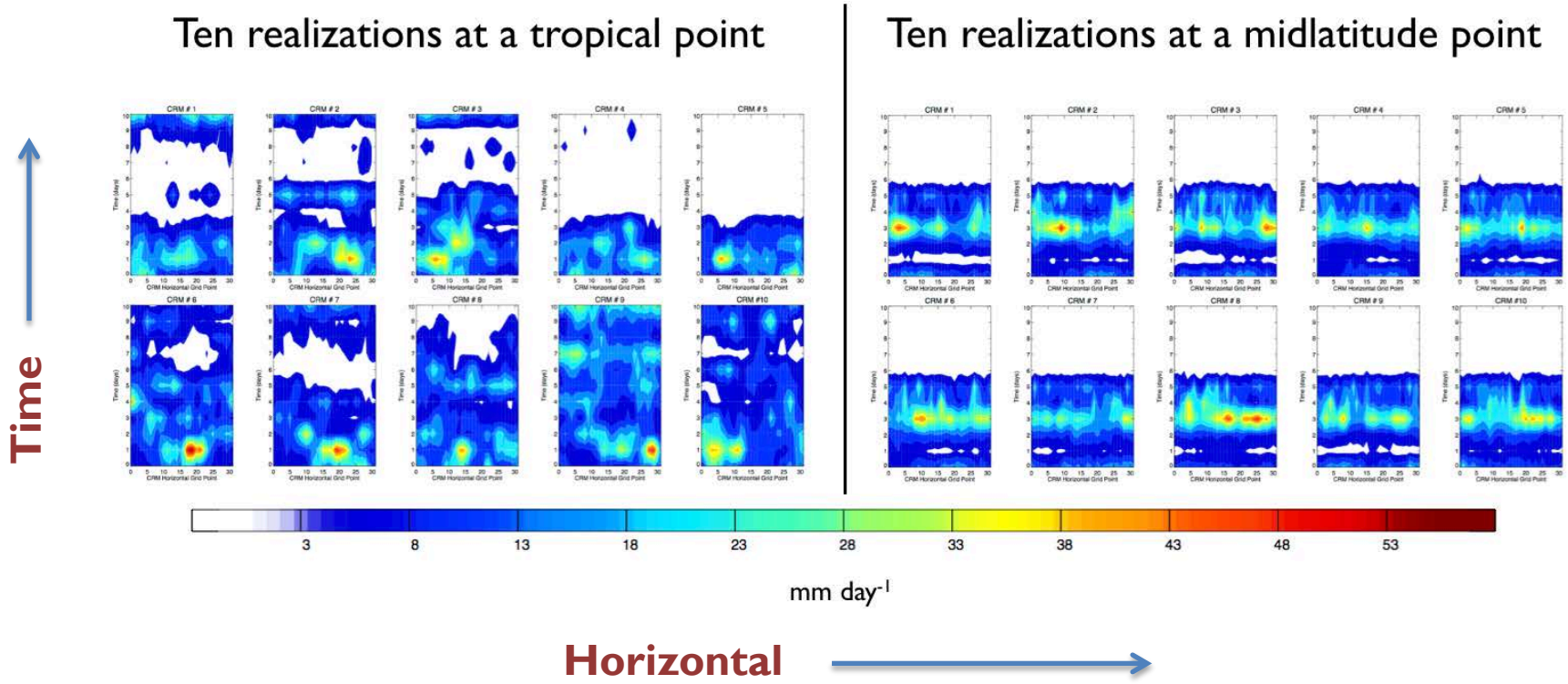




Single Day
Oct 3
Precipitation






Ten realizations at a tropical point
Ten realizations at a midlatitude point
Time
CRM # 1
CRM # 2
CRM # 3
CRM # 4
CRM # 5
CRM # 6
CRM # 7
CRM # 8
CRM # 9
CRM #10
3
8
13
18
23
28
33
38
43
48
53
mm day-1
Horizontal

A more deterministic superparameterization

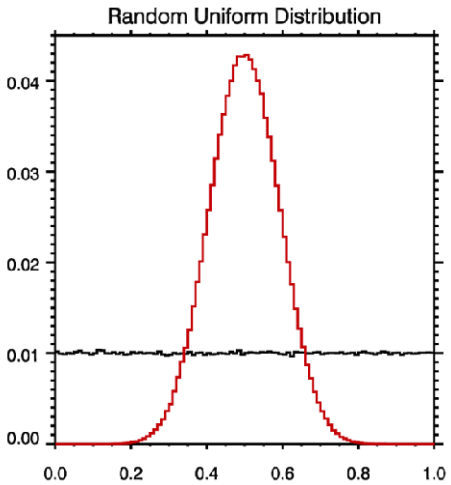
Did we really create one?

A more deterministic superparameterization

Standard deviations of averages are smaller than standard deviations of individual time series.

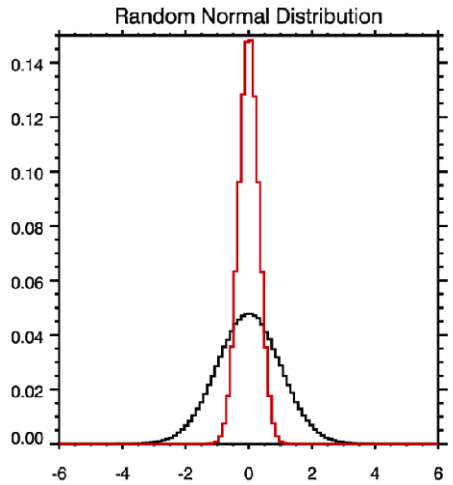
$$\sigma_{\overline{x}} = \frac{\sigma}{\sqrt{n}}$$

PDFs with 10 random time series



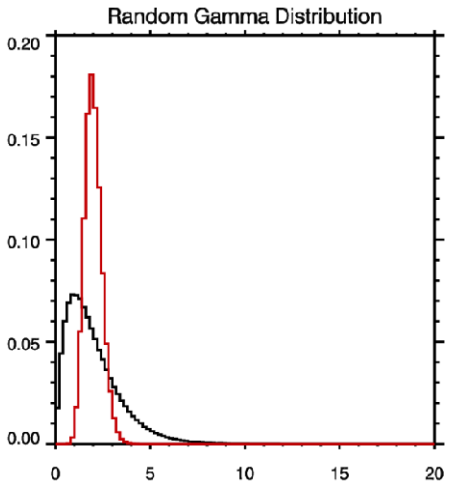
$\sigma = 0.289, \sigma_{\bar{x}} = 0.091$

$\sigma/\sigma_{\bar{x}} = 3.160$



$\sigma = 1.001, \sigma_{\bar{x}} = 0.317$

$\sigma/\sigma_{\bar{x}} = 3.162$

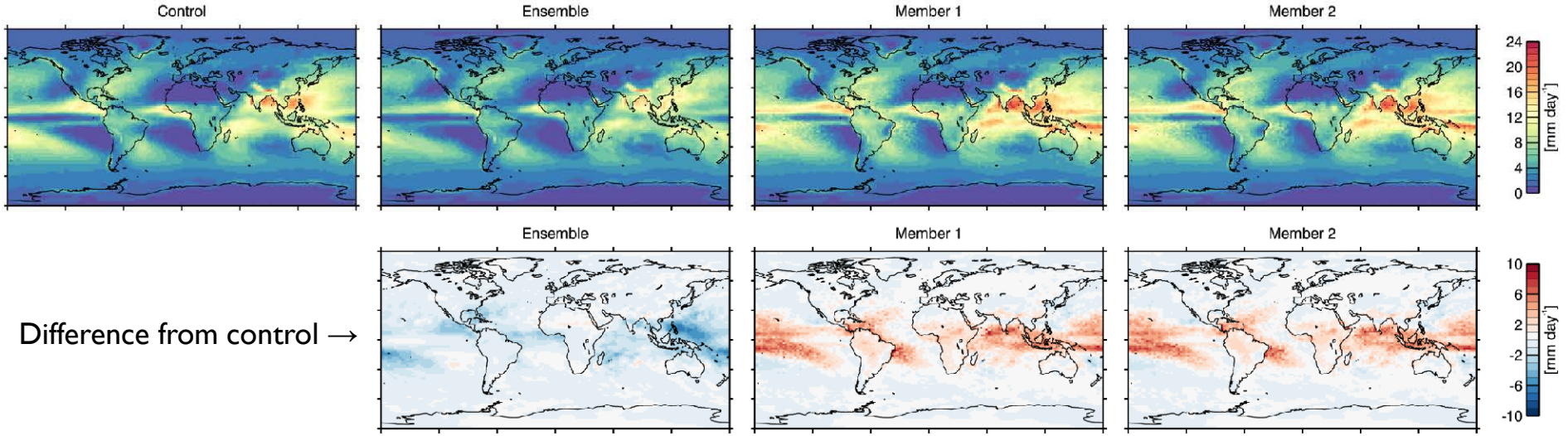


$\sigma = 1.416, \sigma_{\bar{x}} = 0.447$

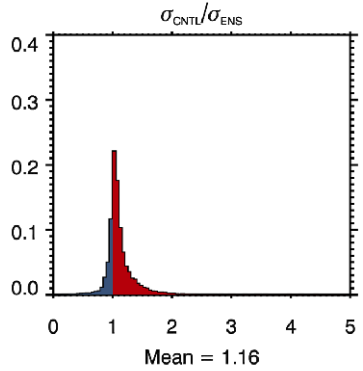
$\sigma/\sigma_{\bar{x}} = 3.166$

…But our data is not random…

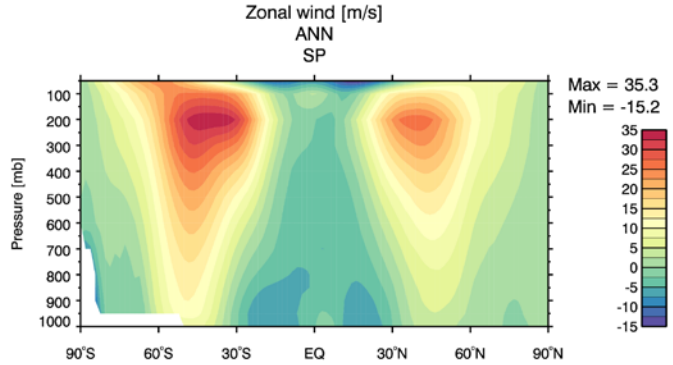
Standard deviation of local time series

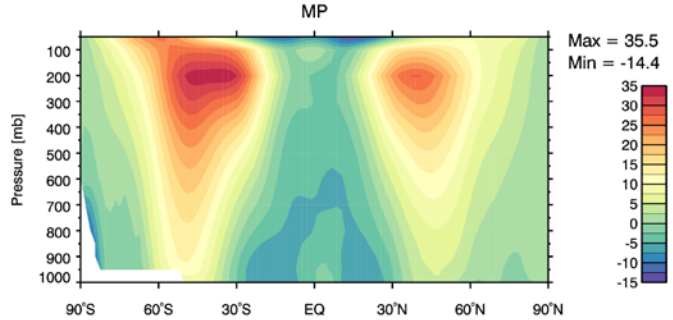


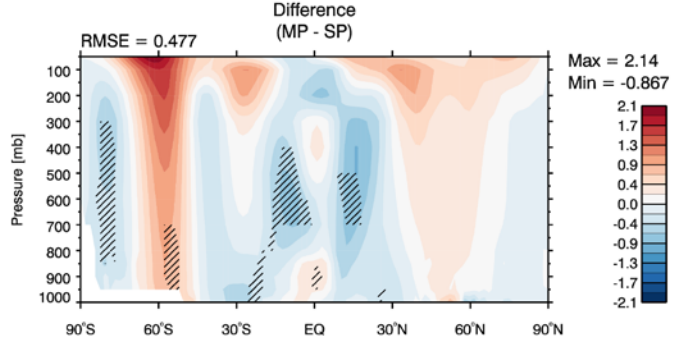
Difference from control →

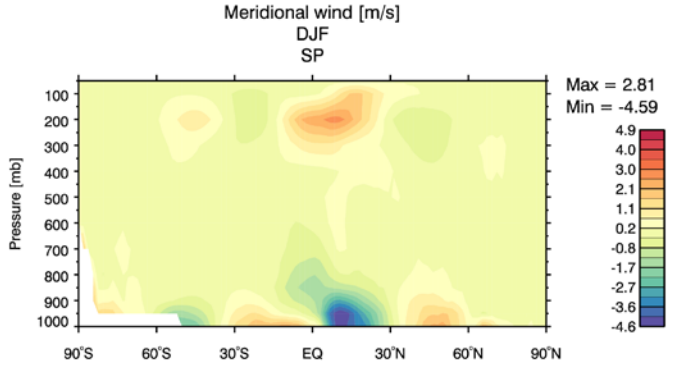


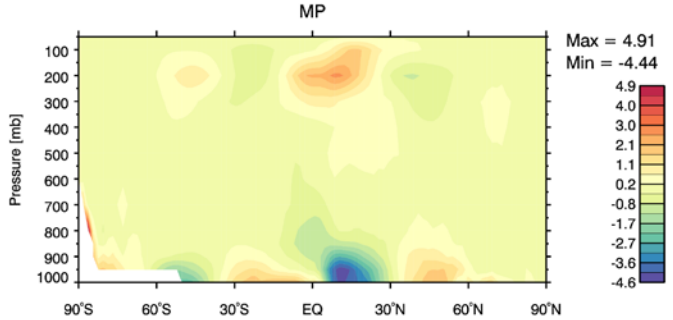
How do the climates of SP and MP differ?

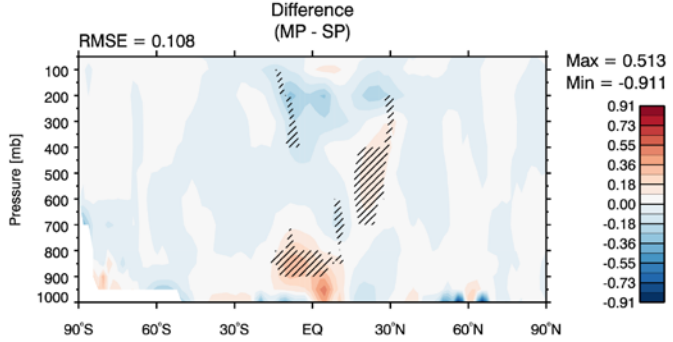

Zonal wind [m/s]
ANN
SP
Max = 35.3
Min = -15.2
Pressure [mb]
100
200
300
400
500
600
700
800
900
1000
90°S
60°S
30°S
EQ
30°N
60°N
90°N
35
30
25
20
15
10
5
0
-5
-10
-15

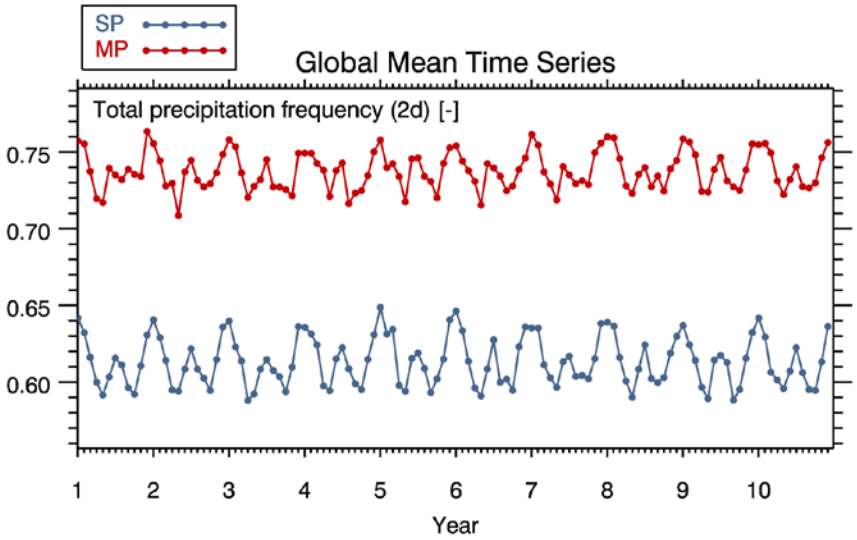

MP
Max = 35.5
Min = -14.4
Pressure [mb]
100
200
300
400
500
600
700
800
900
1000
90°S
60°S
30°S
EQ
30°N
60°N
90°N
35
30
25
20
15
10
5
0
-5
-10
-15

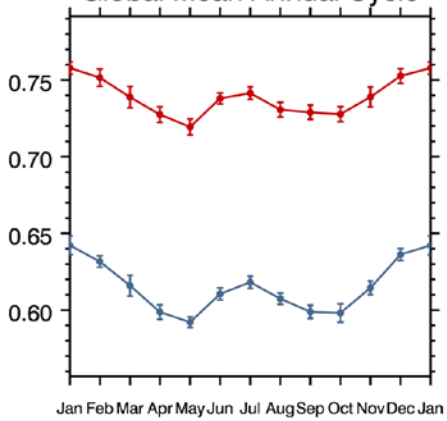

Difference
(MP - SP)
RMSE = 0.477
Max = 2.14
Min = -0.867
Pressure [mb]
100
200
300
400
500
600
700
800
900
1000
90°S
60°S
30°S
EQ
30°N
60°N
90°N
2.1
1.7
1.3
0.9
0.4
0.0
-0.4
-0.9
-1.3
-1.7
-2.1

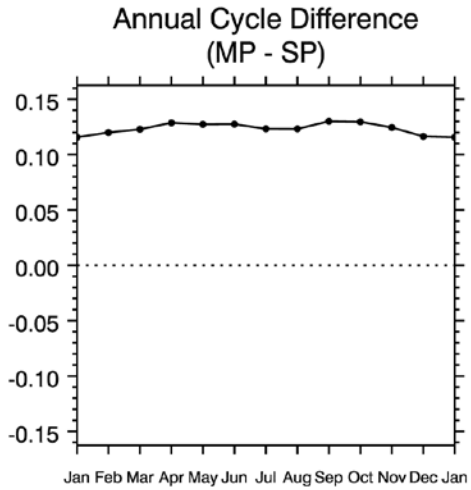

Meridional wind [m/s]
DJF
SP
Max = 2.81
Min = -4.59
Pressure [mb]
100
200
300
400
500
600
700
800
900
1000
90°S
60°S
30°S
EQ
30°N
60°N
90°N
4.9
4.0
3.0
2.1
1.1
0.2
-0.8
-1.7
-2.7
-3.6
-4.6


MP
Max = 4.91
Min = -4.44
Pressure [mb]
100
200
300
400
500
600
700
800
900
1000
90°S
60°S
30°S
EQ
30°N
60°N
90°N
4.9
4.0
3.0
2.1
1.1
0.2
-0.8
-1.7
-2.7
-3.6
-4.6

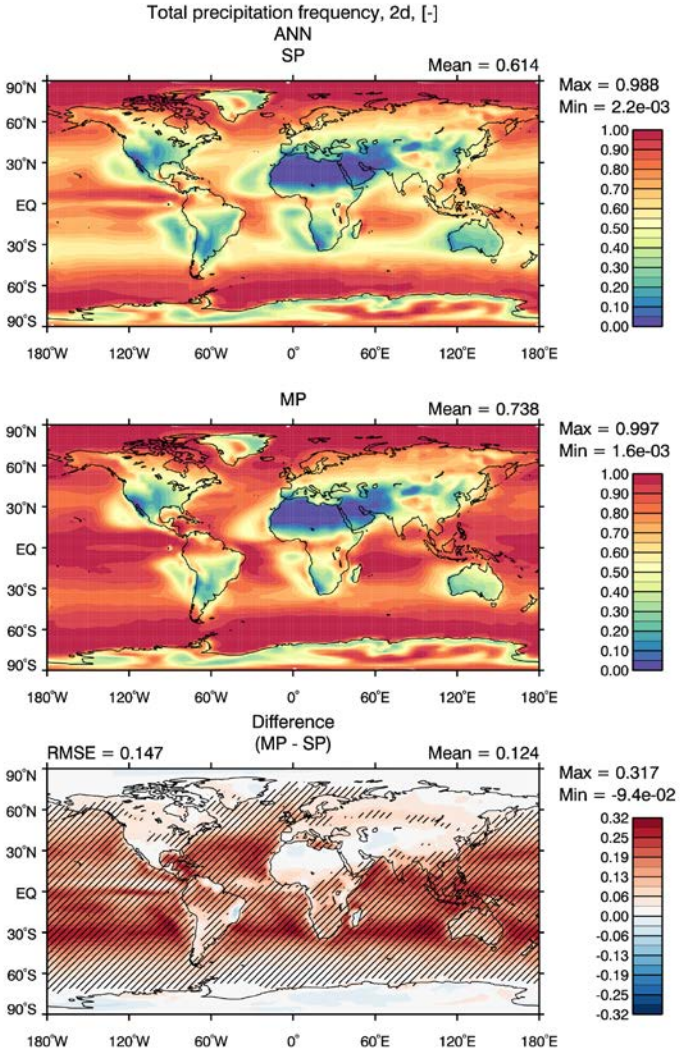

Difference
(MP - SP)
RMSE = 0.108
Max = 0.513
Min = -0.911
Pressure [mb]
100
200
300
400
500
600
700
800
900
1000
90°S
60°S
30°S
EQ
30°N
60°N
90°N
0.91
0.73
0.55
0.36
0.18
0.00
-0.18
-0.36
-0.55
-0.73
-0.91

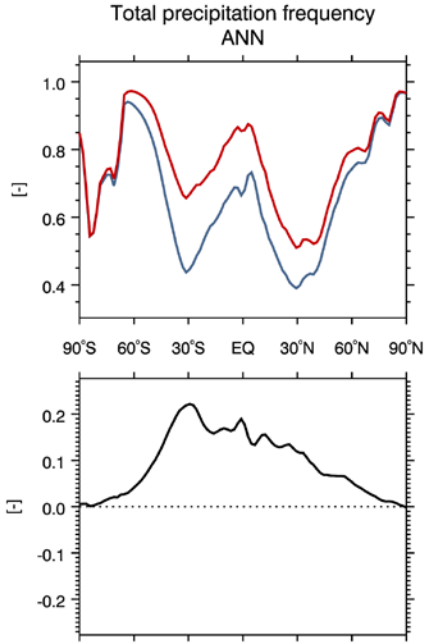

SP
MP
Global Mean Time Series
Total precipitation frequency (2d) [-]
0.75
0.70
0.65
0.60
1
2
3
4
5
6
7
8
9
10
Year

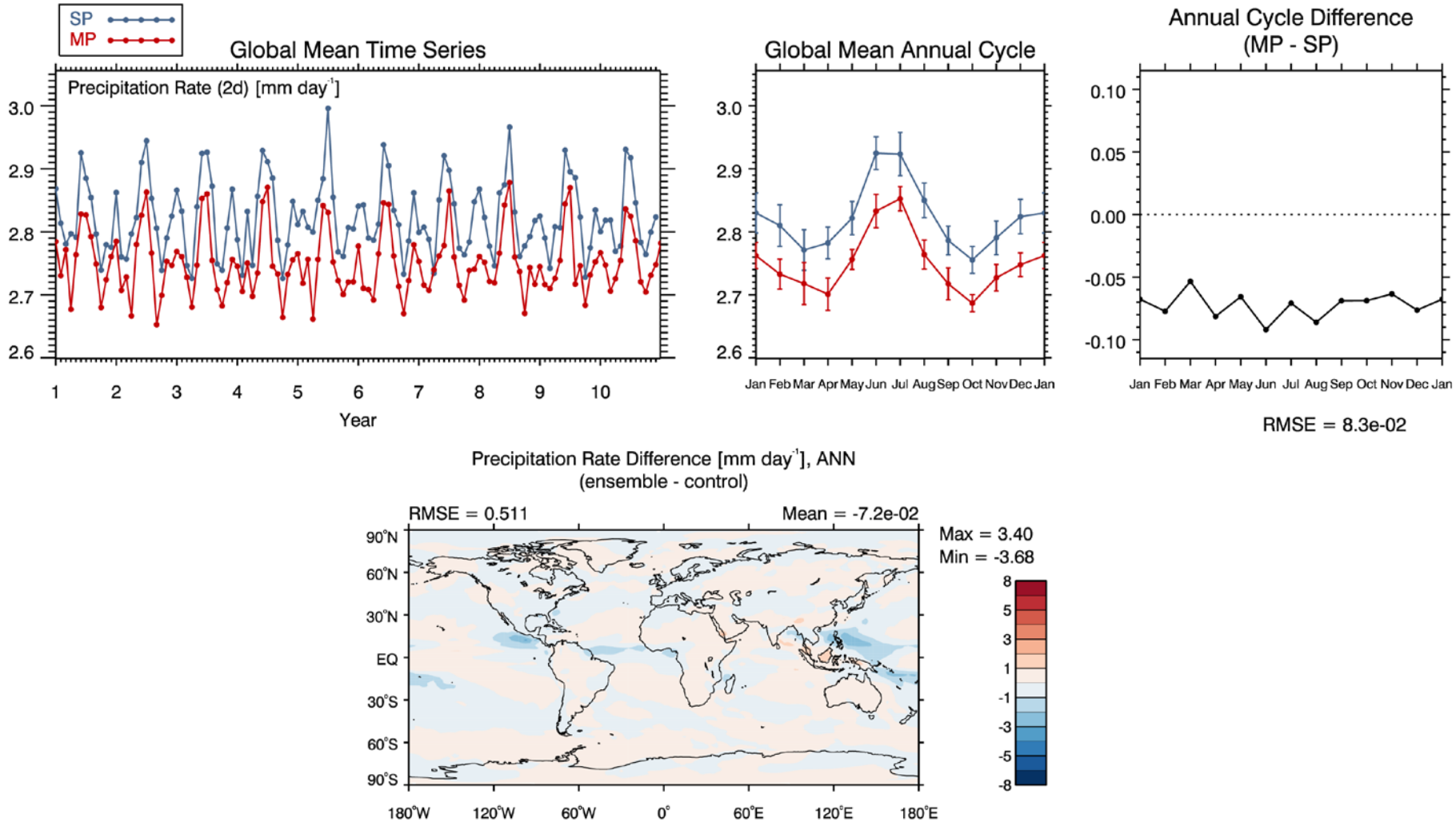

Global Mean Annual Cycle
0.75
0.70
0.65
0.60
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan

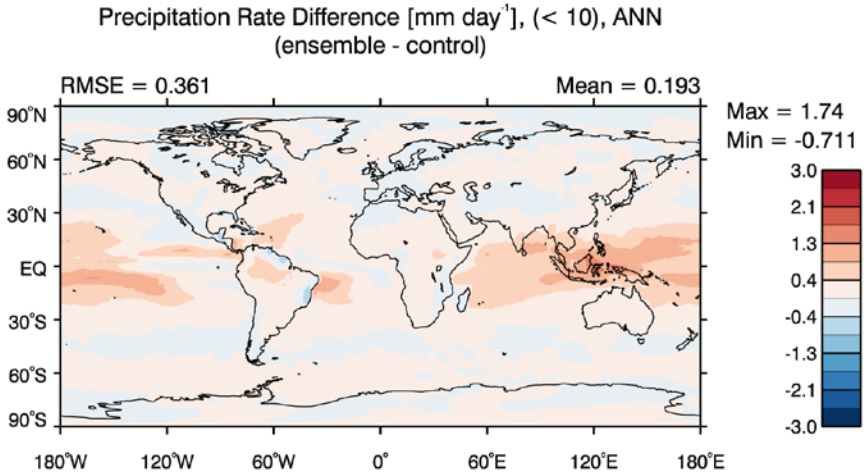

Annual Cycle Difference
(MP - SP)
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan

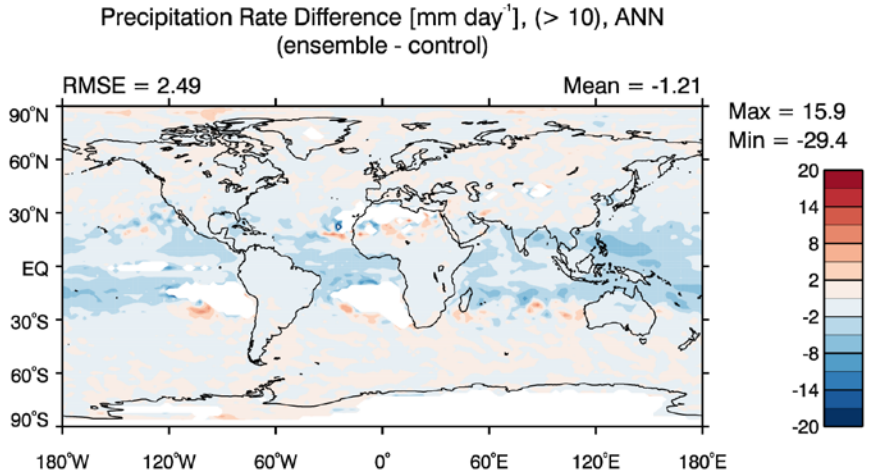
RMSE = 0.125

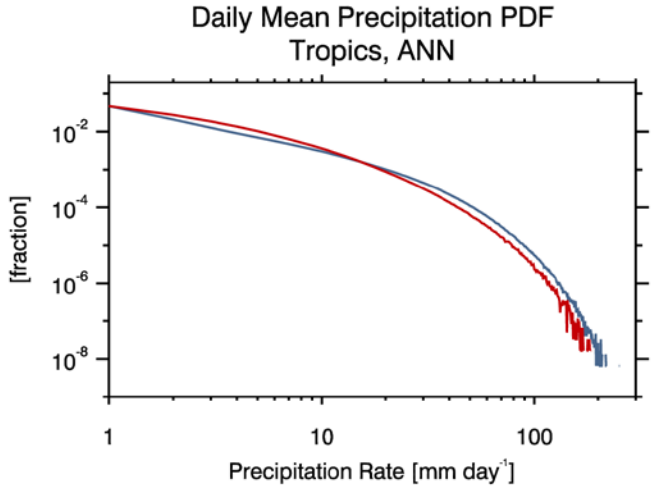

Total precipitation frequency, 2d, [-]
ANN
SP
Mean = 0.614
Max = 0.988
Min = 2.2e-03
MP
Mean = 0.738
Max = 0.997
Min = 1.6e-03
Difference
(MP - SP)
RMSE = 0.147
Mean = 0.124
Max = 0.317
Min = -9.4e-02
90°N
60°N
30°N
EQ
30°S
60°S
90°S
180°W
120°W
60°W
0°
60°E
120°E
180°E
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.32
0.25
0.19
0.13
0.06
0.00
-0.06
-0.13
-0.19
-0.25
-0.32


Total precipitation frequency
ANN
[-]
1.0
0.8
0.6
0.4
90°S
60°S
30°S
EQ
30°N
60°N
90°N
0.2
0.1
0.0
-0.1
-0.2

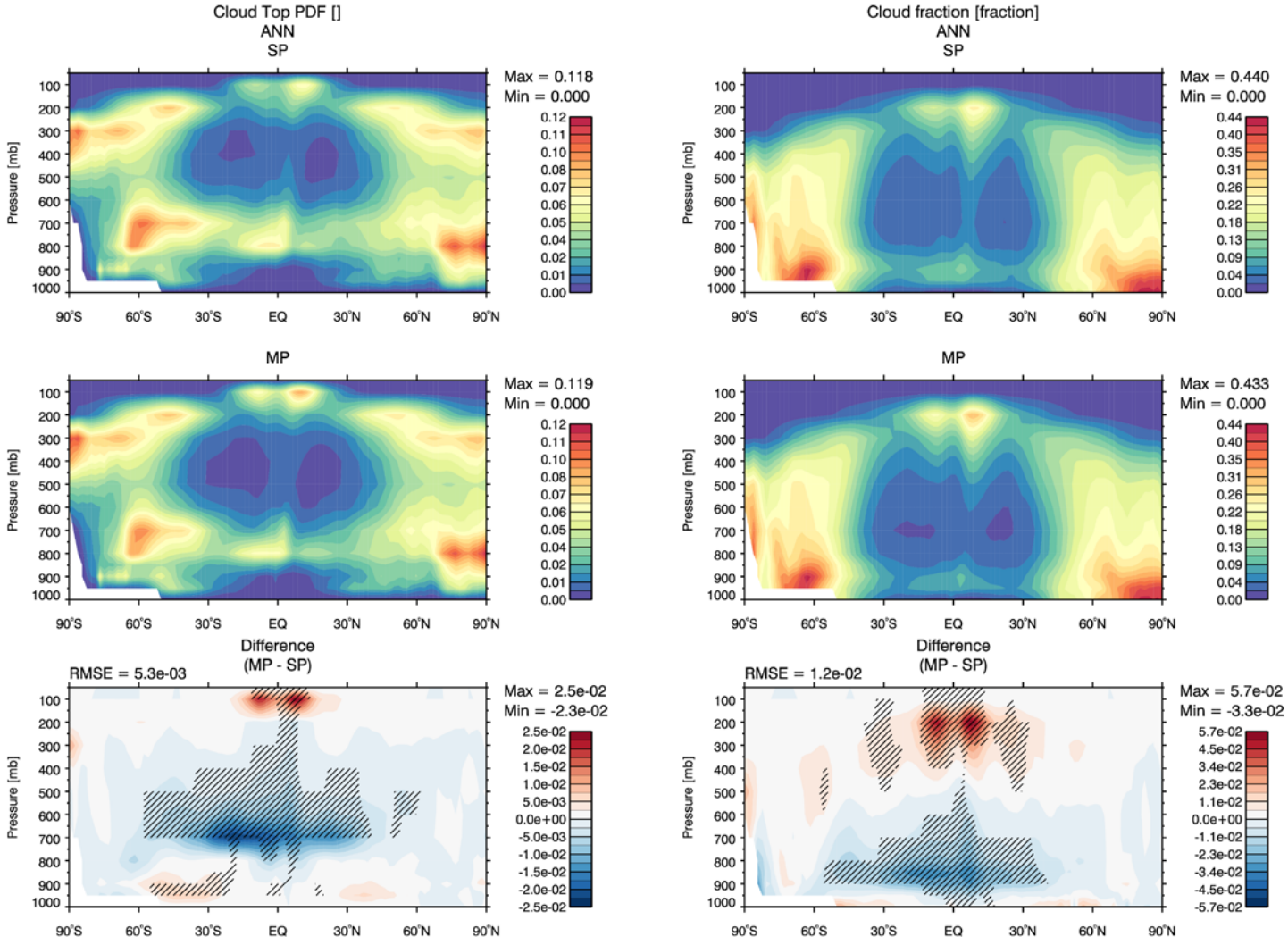

SP
MP
Global Mean Time Series
Precipitation Rate (2d) [mm day-1]
3.0
2.9
2.8
2.7
2.6
1
2
3
4
5
6
7
8
9
10
Year
Global Mean Annual Cycle
3.0
2.9
2.8
2.7
2.6
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan
Annual Cycle Difference
(MP - SP)
0.10
0.05
0.00
-0.05
-0.10
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan
RMSE = 8.3e-02
Precipitation Rate Difference [mm day-1], ANN
(ensemble - control)
RMSE = 0.511
Mean = -7.2e-02
Max = 3.40
Min = -3.68
90°N
60°N
30°N
EQ
30°S
60°S
90°S
180°W
120°W
60°W
0°
60°E
120°E
180°E
8
5
3
1
-1
-3
-5
-8

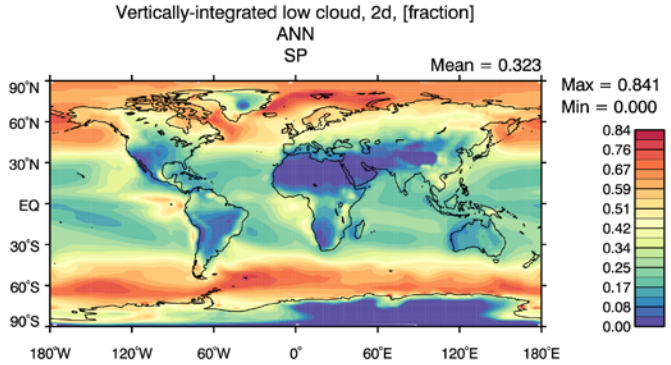


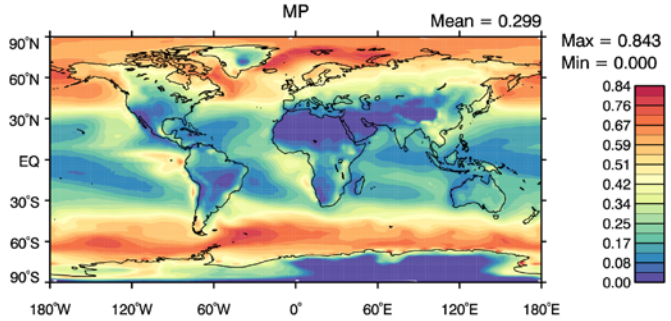


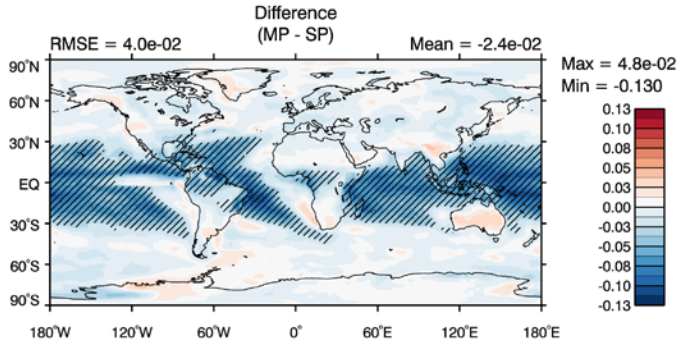


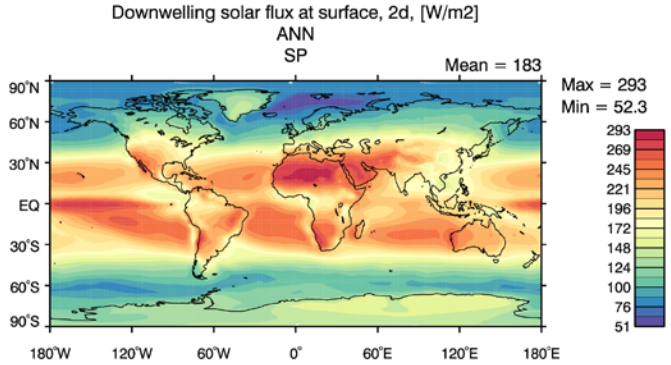
- More frequent precipitation
- Increased light precipitation
- Decreased heavy precipitation

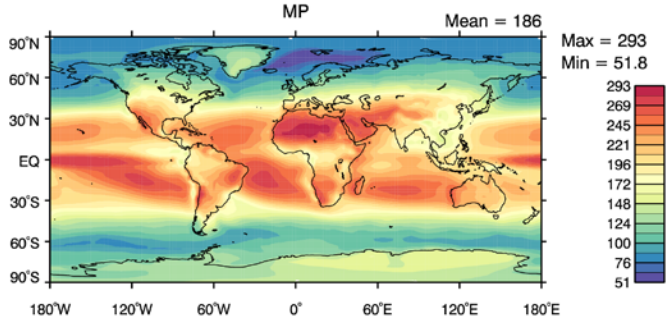

Cloud Top PDF []
ANN
SP
Max = 0.118
Min = 0.000
Cloud fraction [fraction]
ANN
SP
Max = 0.440
Min = 0.000
MP
Max = 0.119
Min = 0.000
MP
Max = 0.433
Min = 0.000
Difference
(MP - SP)
RMSE = 5.3e-03
Max = 2.5e-02
Min = -2.3e-02
Difference
(MP - SP)
RMSE = 1.2e-02
Max = 5.7e-02
Min = -3.3e-02
Pressure [mb]
100
200
300
400
500
600
700
800
900
1000
90°S
60°S
30°S
EQ
30°N
60°N
90°N
0.12
0.11
0.10
0.08
0.07
0.06
0.05
0.04
0.02
0.01
0.00
0.44
0.40
0.35
0.31
0.26
0.22
0.18
0.13
0.09
0.04
0.00
2.5e-02
2.0e-02
1.5e-02
1.0e-02
5.0e-03
0.0e+00
-5.0e-03
-1.0e-02
-1.5e-02
-2.0e-02
-2.5e-02
5.7e-02
4.5e-02
3.4e-02
2.3e-02
1.1e-02
0.0e+00
-1.1e-02
-2.3e-02
-3.4e-02
-4.5e-02
-5.7e-02

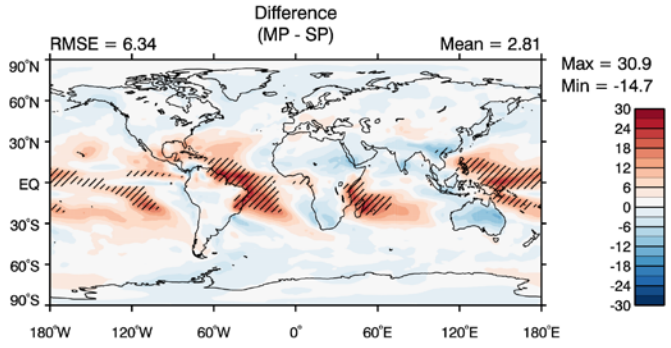

Vertically-integrated low cloud, 2d, [fraction]
ANN
SP
Mean = 0.323
Max = 0.841
Min = 0.000
0.84
0.76
0.67
0.59
0.51
0.42
0.34
0.25
0.17
0.08
0.00
90°N
60°N
30°N
EQ
30°S
60°S
90°S
180°W
120°W
60°W
0°
60°E
120°E
180°E

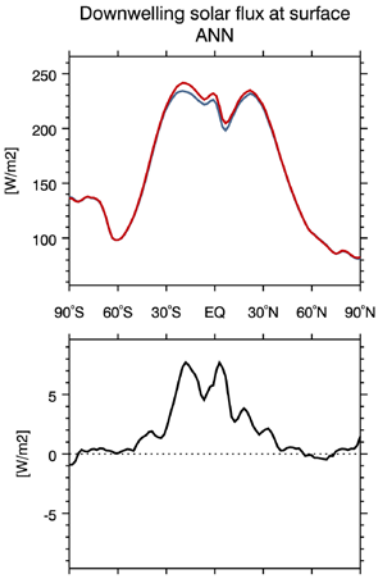

MP
Mean = 0.299
Max = 0.843
Min = 0.000
0.84
0.76
0.67
0.59
0.51
0.42
0.34
0.25
0.17
0.08
0.00
90°N
60°N
30°N
EQ
30°S
60°S
90°S
180°W
120°W
60°W
0°
60°E
120°E
180°E

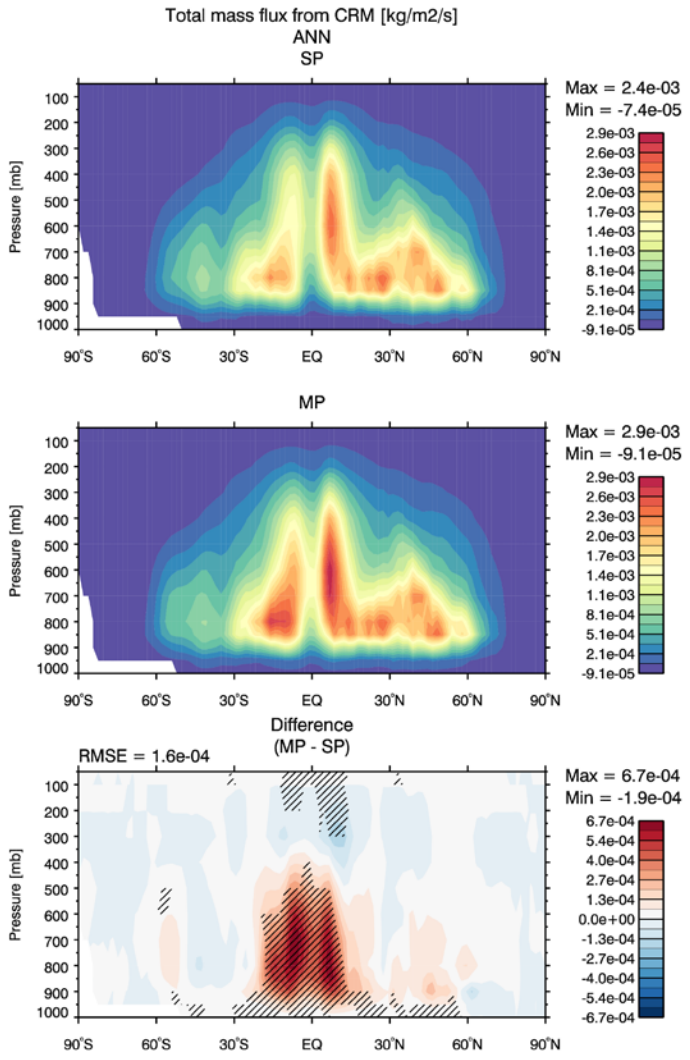

Difference
(MP - SP)
RMSE = 4.0e-02
Mean = -2.4e-02
Max = 4.8e-02
Min = -0.130
0.13
0.10
0.08
0.05
0.03
0.00
-0.03
-0.05
-0.08
-0.10
-0.13
90°N
60°N
30°N
EQ
30°S
60°S
90°S
180°W
120°W
60°W
0°
60°E
120°E
180°E

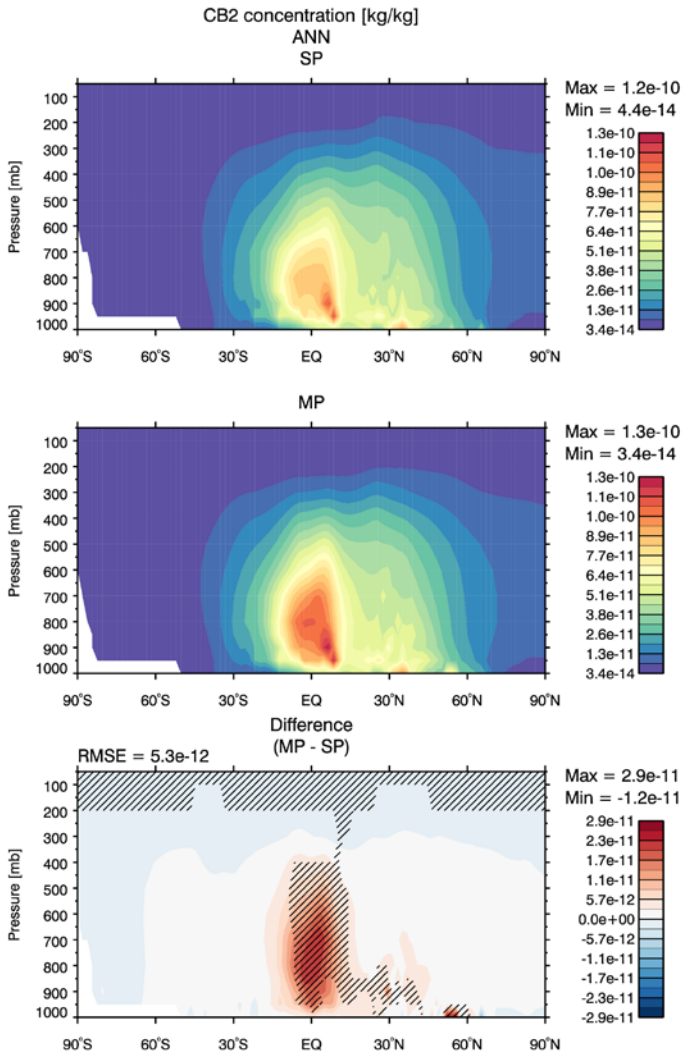

Downwelling solar flux at surface, 2d, [W/m2]
ANN
SP
Mean = 183
Max = 293
Min = 52.3
293
269
245
221
196
172
148
124
100
76
51
90°N
60°N
30°N
EQ
30°S
60°S
90°S
180°W
120°W
60°W
0°
60°E
120°E
180°E

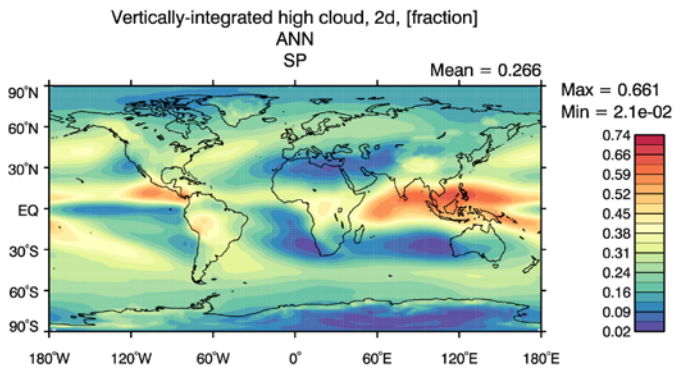

MP
Mean = 186
Max = 293
Min = 51.8
293
269
245
221
196
172
148
124
100
76
51
90°N
60°N
30°N
EQ
30°S
60°S
90°S
180°W
120°W
60°W
0°
60°E
120°E
180°E

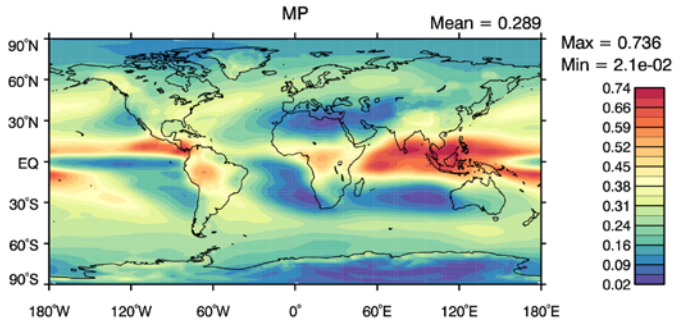

Difference
(MP - SP)
RMSE = 6.34
Mean = 2.81
Max = 30.9
Min = -14.7
30
24
18
12
6
0
-6
-12
-18
-24
-30
90°N
60°N
30°N
EQ
30°S
60°S
90°S
180°W
120°W
60°W
0°
60°E
120°E
180°E

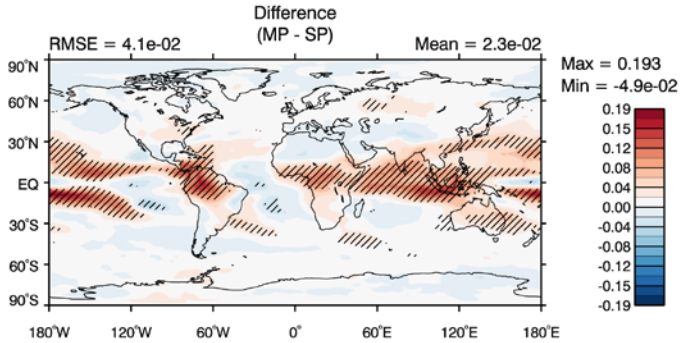

Downwelling solar flux at surface
ANN
[W/m2]
250
200
150
100
90°S
60°S
30°S
EQ
30°N
60°N
90°N
[W/m2]
5
0
-5

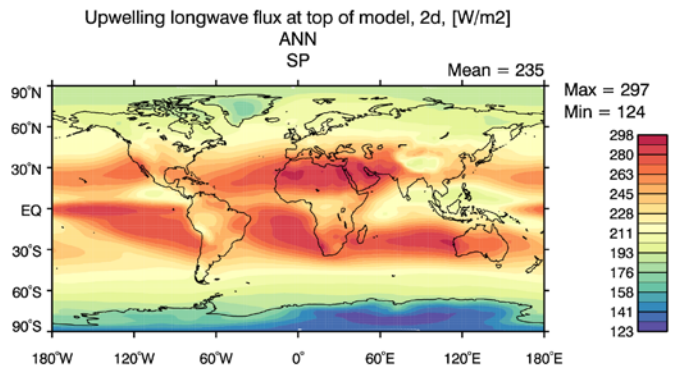

Total mass flux from CRM [kg/m2/s]
ANN
SP
Max = 2.4e-03
Min = -7.4e-05
2.9e-03
2.6e-03
2.3e-03
2.0e-03
1.7e-03
1.4e-03
1.1e-03
8.1e-04
5.1e-04
2.1e-04
-9.1e-05
Pressure [mb]
100
200
300
400
500
600
700
800
900
1000
90°S
60°S
30°S
EQ
30°N
60°N
90°N
MP
Max = 2.9e-03
Min = -9.1e-05
2.9e-03
2.6e-03
2.3e-03
2.0e-03
1.7e-03
1.4e-03
1.1e-03
8.1e-04
5.1e-04
2.1e-04
-9.1e-05
Difference
(MP - SP)
RMSE = 1.6e-04
Max = 6.7e-04
Min = -1.9e-04
6.7e-04
5.4e-04
4.0e-04
2.7e-04
1.3e-04
0.0e+00
-1.3e-04
-2.7e-04
-4.0e-04
-5.4e-04
-6.7e-04

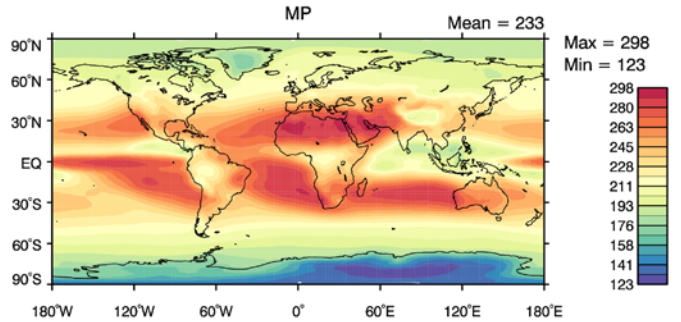

CB2 concentration [kg/kg]
ANN
SP
Max = 1.2e-10
Min = 4.4e-14
1.3e-10
1.1e-10
1.0e-10
8.9e-11
7.7e-11
6.4e-11
5.1e-11
3.8e-11
2.6e-11
1.3e-11
3.4e-14
Pressure [mb]
100
200
300
400
500
600
700
800
900
1000
90°S
60°S
30°S
EQ
30°N
60°N
90°N
MP
Max = 1.3e-10
Min = 3.4e-14
1.3e-10
1.1e-10
1.0e-10
8.9e-11
7.7e-11
6.4e-11
5.1e-11
3.8e-11
2.6e-11
1.3e-11
3.4e-14
Difference
(MP - SP)
RMSE = 5.3e-12
Max = 2.9e-11
Min = -1.2e-11
2.9e-11
2.3e-11
1.7e-11
1.1e-11
5.7e-12
0.0e+00
-5.7e-12
-1.1e-11
-1.7e-11
-2.3e-11
-2.9e-11

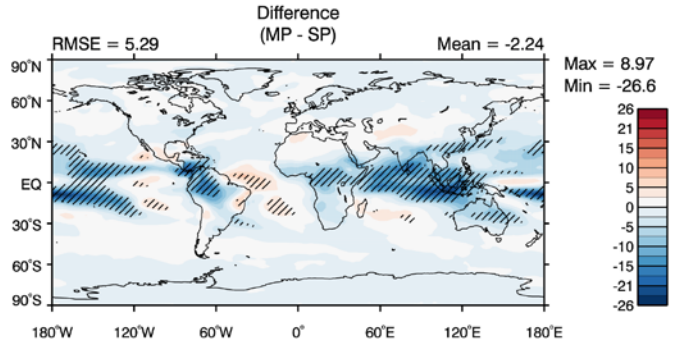

Vertically-integrated high cloud, 2d, [fraction]
ANN
SP
Mean = 0.266
Max = 0.661
Min = 2.1e-02
0.74
0.66
0.59
0.52
0.45
0.38
0.31
0.24
0.16
0.09
0.02
90°N
60°N
30°N
EQ
30°S
60°S
90°S
180°W
120°W
60°W
0°
60°E
120°E
180°E

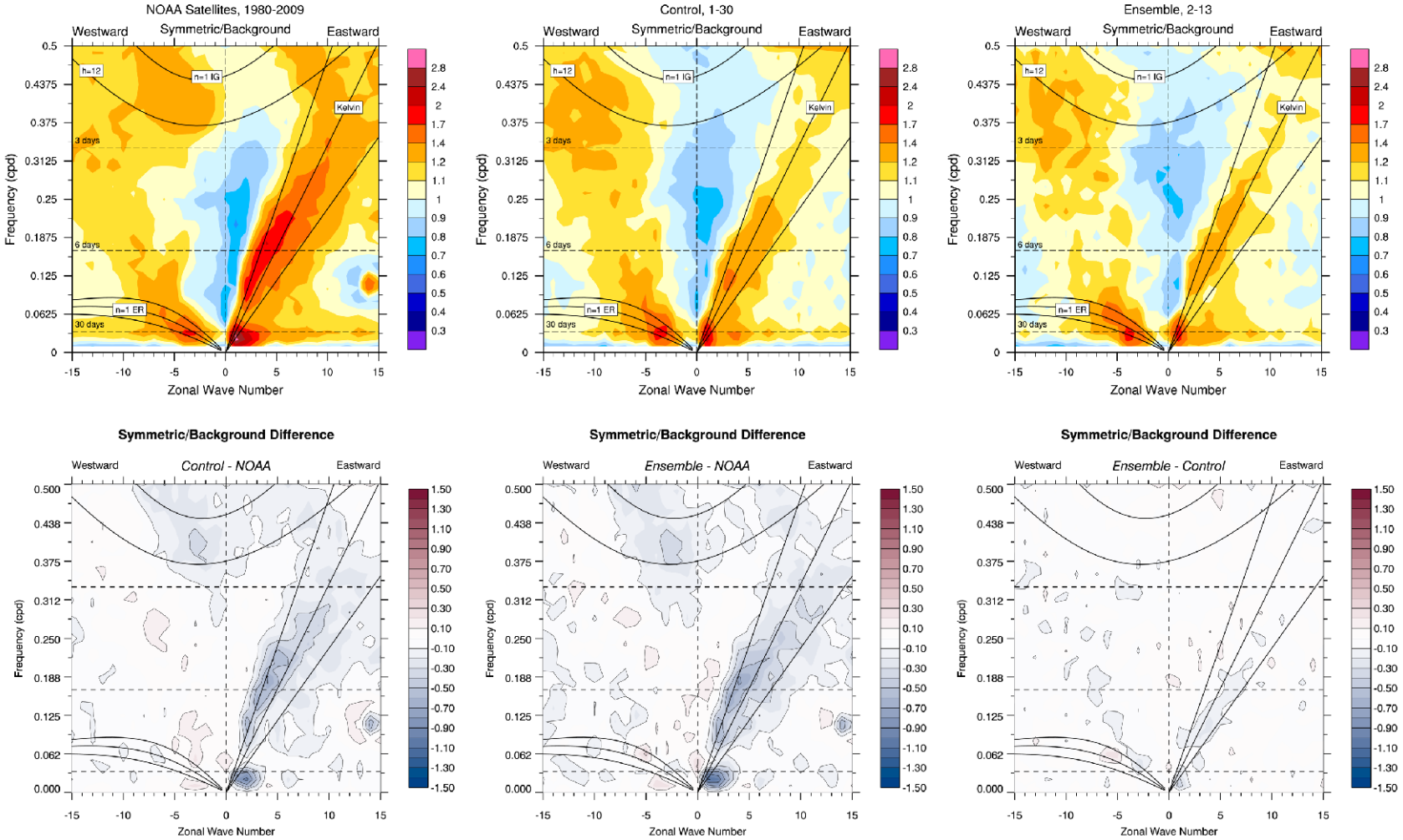

MP
Mean = 0.289
Max = 0.736
Min = 2.1e-02
0.74
0.66
0.59
0.52
0.45
0.38
0.31
0.24
0.16
0.09
0.02
90°N
60°N
30°N
EQ
30°S
60°S
90°S
180°W
120°W
60°W
0°
60°E
120°E
180°E


Difference
(MP - SP)
RMSE = 4.1e-02
Mean = 2.3e-02
Max = 0.193
Min = -4.9e-02
0.19
0.15
0.12
0.08
0.04
0.00
-0.04
-0.08
-0.12
-0.15
-0.19
90°N
60°N
30°N
EQ
30°S
60°S
90°S
180°W
120°W
60°W
0°
60°E
120°E
180°E


Upwelling longwave flux at top of model, 2d, [W/m2]
ANN
SP
Mean = 235
Max = 297
Min = 124
298
280
263
245
228
211
193
176
158
141
123
90°N
60°N
30°N
EQ
30°S
60°S
90°S
180°W
120°W
60°W
0°
60°E
120°E
180°E


MP
Mean = 233
Max = 298
Min = 123
298
280
263
245
228
211
193
176
158
141
123
90°N
60°N
30°N
EQ
30°S
60°S
90°S
180°W
120°W
60°W
0°
60°E
120°E
180°E


Difference
(MP - SP)
RMSE = 5.29
Mean = -2.24
Max = 8.97
Min = -26.6
26
21
15
10
5
0
-5
-10
-15
-21
-26
90°N
60°N
30°N
EQ
30°S
60°S
90°S
180°W
120°W
60°W
0°
60°E
120°E
180°E


NOAA Satellites, 1980-2009
Control, 1-30
Ensemble, 2-13
Westward
Symmetric/Background
Eastward
h=12
n=1 IG
Kelvin
3 days
6 days
n=1 ER
30 days
Frequency (cpd)
Zonal Wave Number
Symmetric/Background Difference
Control - NOAA
Ensemble - NOAA
Ensemble - Control

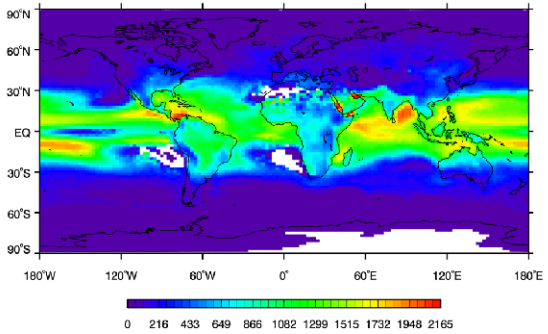
Locating Strong, Unpredictable Convection

- Exploring, and potentially exploiting, the range of possible realizations using identical large-scale states.
- Use spread measures as indicators of predictability
  - Coefficient of variation (standard deviation/mean, noise/signal)
  - Proportional variability (mean ratio of all combinations of data pairs)
- Look for associated large-scale properties
  - Since we can better predict the large-scale, perhaps we can predict potential predictability.

Locating Strong, Unpredictable Convection

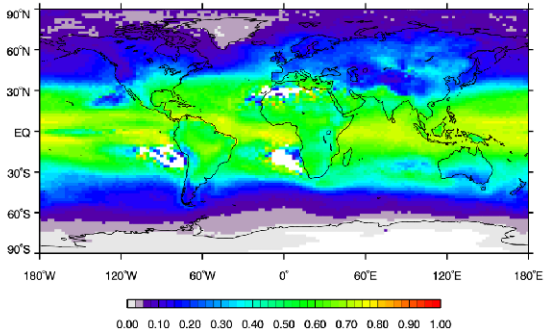
Data: 3648 days

Pseudoadiabatic convective available potential energy [J/kg]



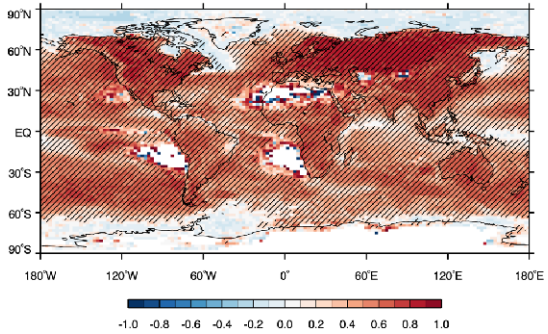
ANN, precip > 5 mm day^{-1}

Proportional Variability



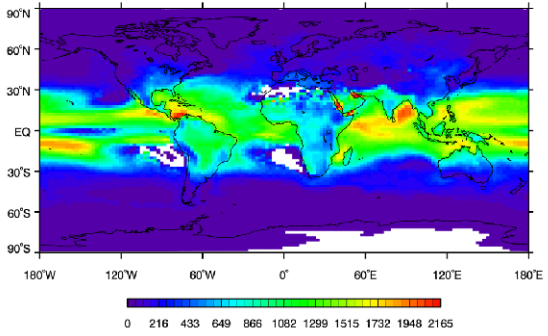
$r_{S/T}$ = 0.788, r_S = 0.907, r_{GMT} = 0.465, r_{GMT95} = 0.511

Local Temporal Correlation (sig @ 95%)



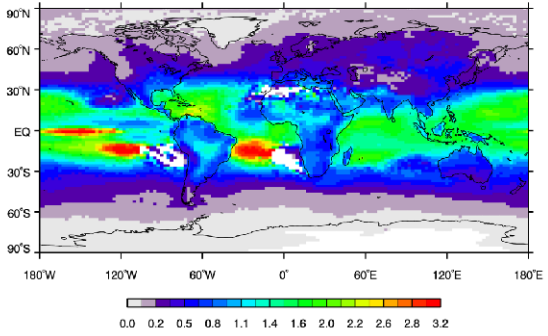
Data: 3648 days

Pseudoadiabatic convective available potential energy [J/kg]



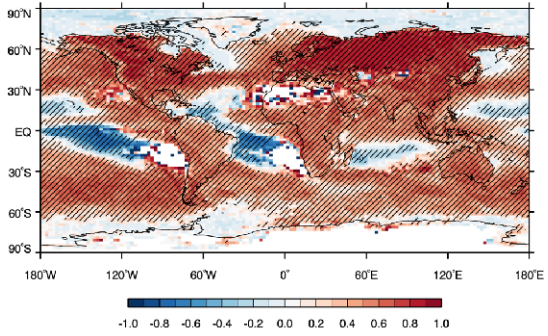
ANN, precip > 5 mm day^{-1}

COV



$r_{S/T}$ = 0.716, r_S = 0.842, r_{GMT} = 0.366, r_{GMT95} = 0.430

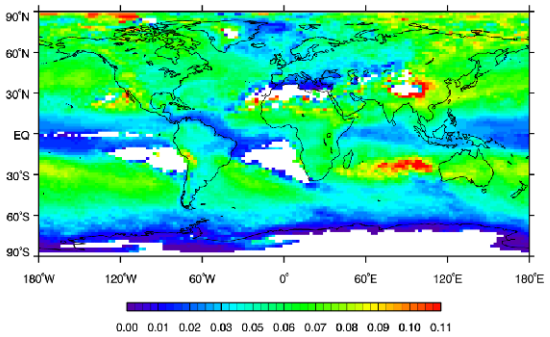
Local Temporal Correlation (sig @ 95%)



Locating Strong, Unpredictable Convection

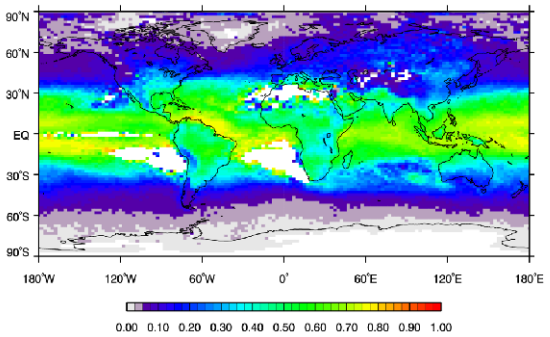
Data: 2133 days

Grid box averaged cloud liquid amount [g kg^{-1}], 600 mb



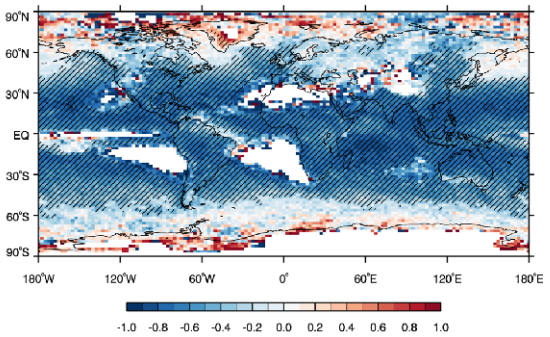
ANN, precip > 10 mm day^{-1}

Proportional Variability



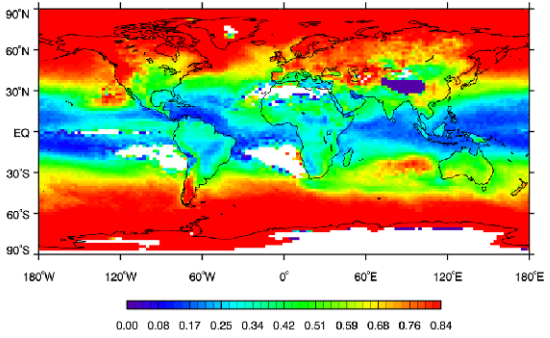
$r_{S/T}$ = -0.445, r_S = -0.083, r_{GMT} = -0.452, r_{GMT95} = -0.576

Local Temporal Correlation (sig @ 95%)



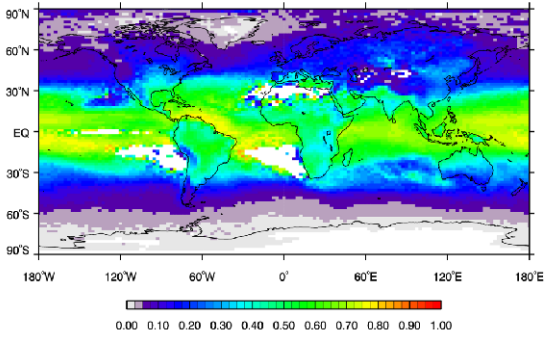
Data: 3648 days

Vertically-integrated low cloud [fraction]



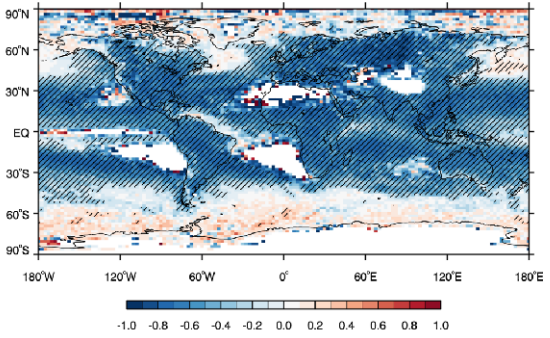
ANN, precip > 10 mm day^{-1}

Proportional Variability



$r_{S/T}$ = -0.803, r_S = -0.931, r_{GMT} = -0.413, r_{GMT95} = -0.528

Local Temporal Correlation (sig @ 95%)



Quasi-Conclusions

- Deterministic parameterizations produce weaker, more frequent precipitation.
- This leads to more high cloud, weaker OLR, and lower precipitation amounts.
- Deterministic parameterizations may be able to represent intraseasonal variability. (Even while degrading some statistics)
- Spread around the response is not simply proportional to the mean, has spatial structure, and is associated with L-S features.
- We have useful tools to explore these issues.