Medium-range Forecast Error: Air-sea Coupling, Clouds, and Scale of Meridional Propagation

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CCTM, January 2013.

Background

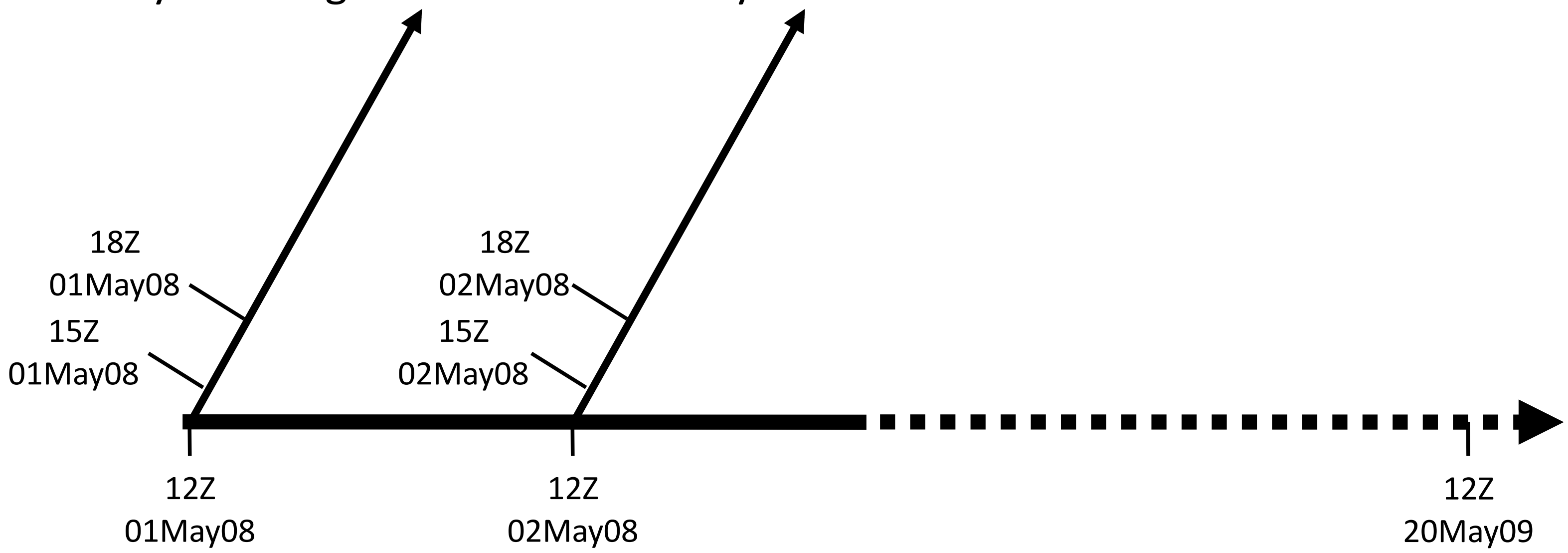
- An accurate forecast of precipitation over the South Asian monsoon region at high spatial resolution up to 10 days in advance and beyond is necessary for decision making in different areas like agriculture and water resources management.
- Although significant improvements have been made in short-range forecasting by numerical models during the past few decades (Simmons and Hollingsworth 2002; Harper et al. 2007; Kalnay et al. 1998), there still exists large errors in short-to-medium range forecasts.

✓ Since May 2008, the WCRP and the World Weather Research Programme/ The Observing System Research and Predictability Experiment (WWRP/ THORPEX) have been organizing coordinated observations, modeling and forecasting organized tropical convection with a goal to better understand its multiscale structure and interaction.

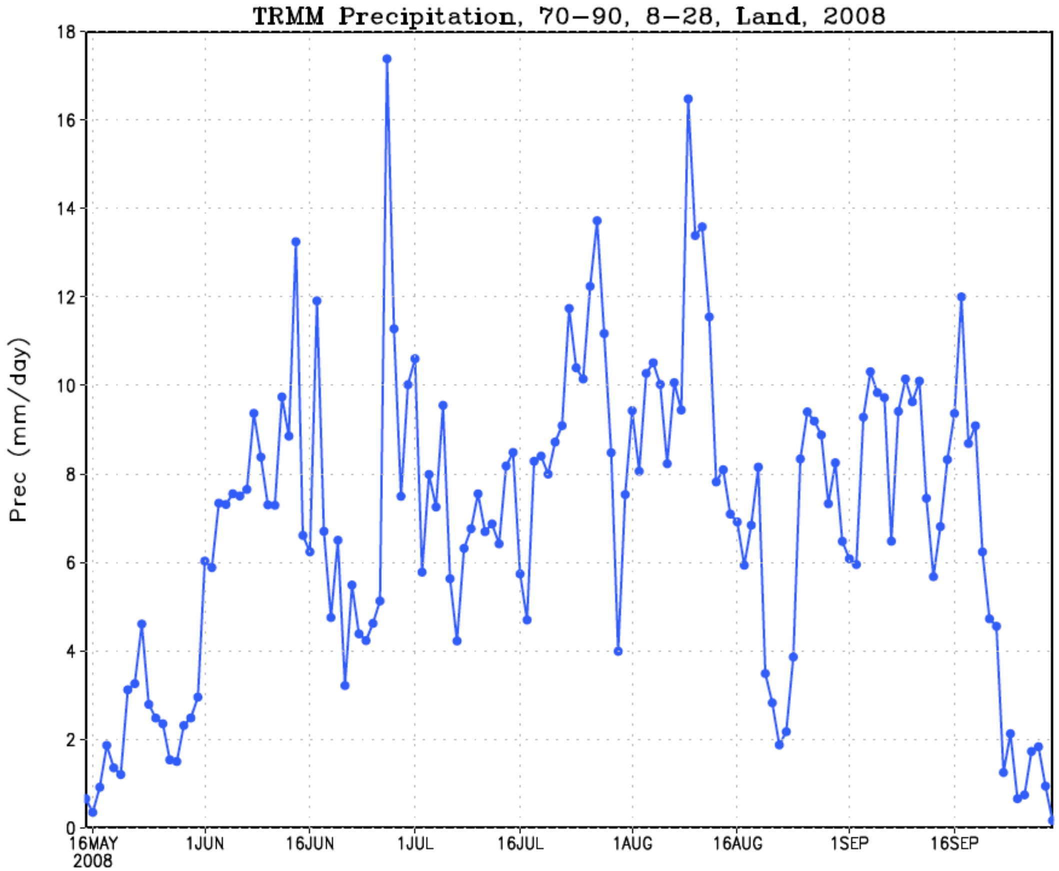
- This program is titled as the Year of Tropical Convection (YOTC).
- As a part of this program, the European Centre for Medium-Range Weather Forecasts (ECMWF) generated high-resolution model forecasts up to 240 h from May 2008 through April 2010.

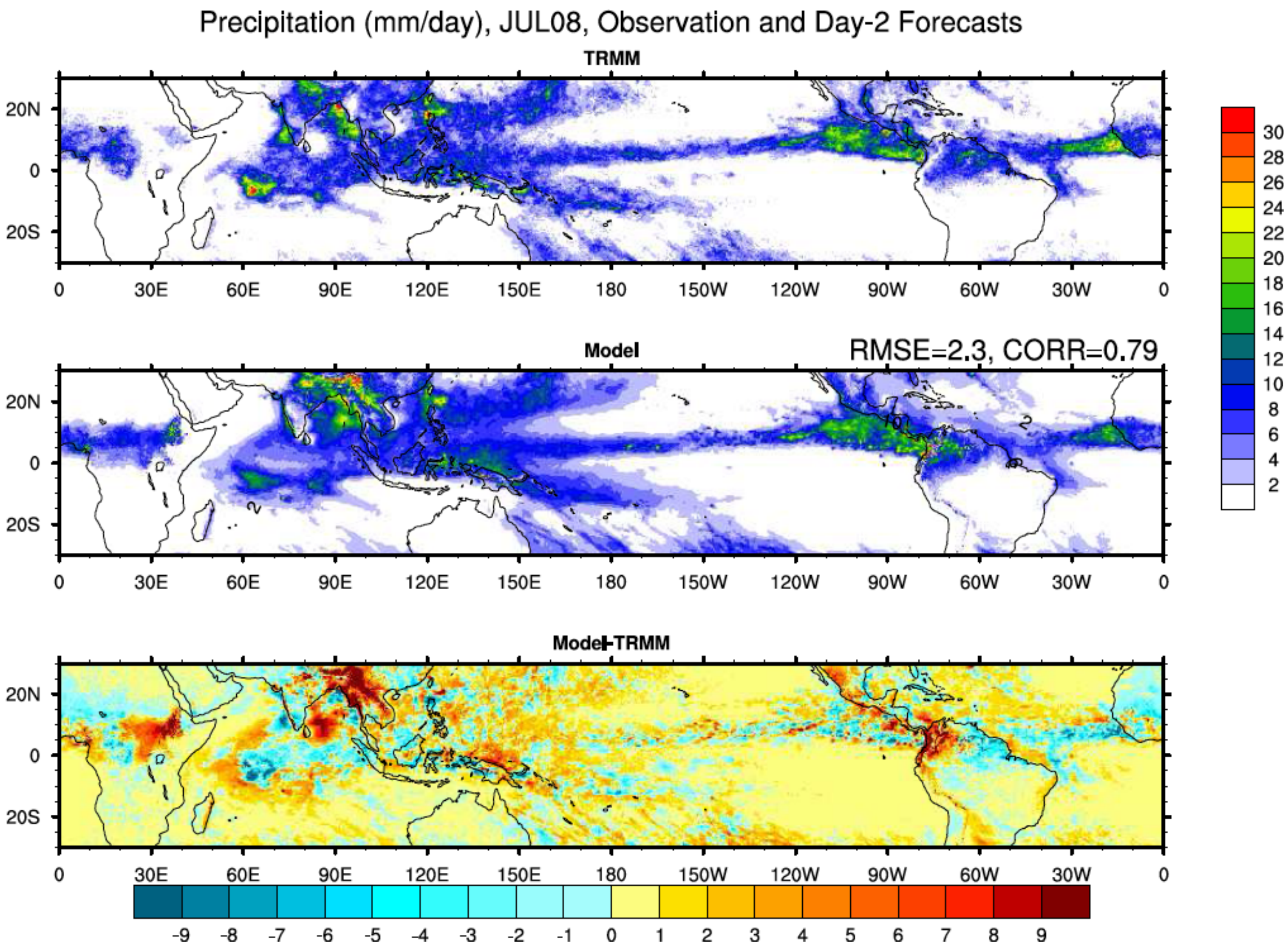
Model Forecast Details

- 3-hourly forecasts up to 96 hours, 6-hourly forecasts up to 240 hours.
- Forecasts started at 12 GMT of each day during 1 May 2008 through 20 May 2009.
- Average of 3 to 12 hour forecasts is termed as day-1 (calendar day of the forecast initial condition).
- Average of 15 to 36 hour forecasts is termed as day-2.
- Day 3 through 10 follows similarly.

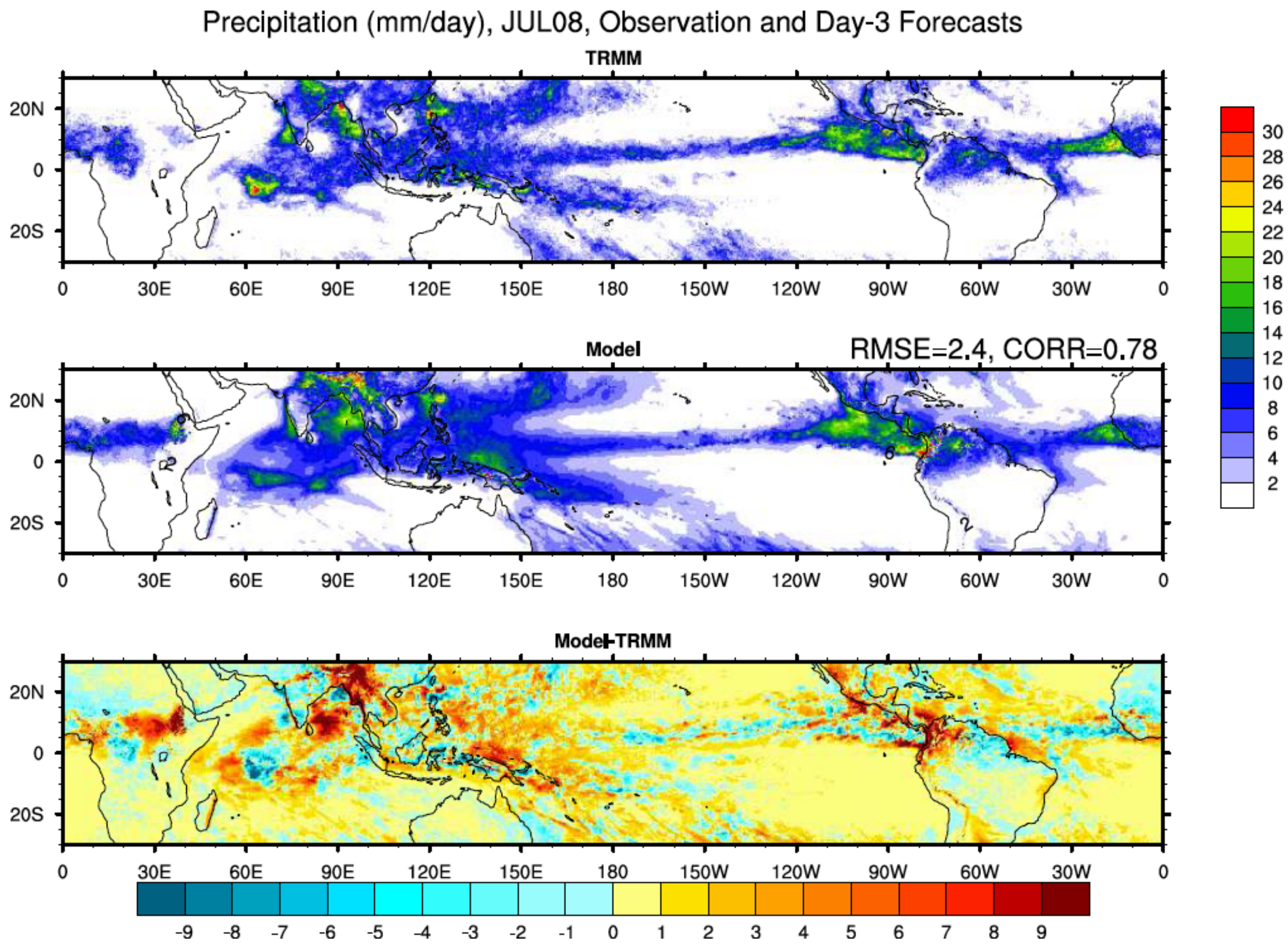


Observed Daily Precipitation over the Indian Region from TRMM Satellite Estimation

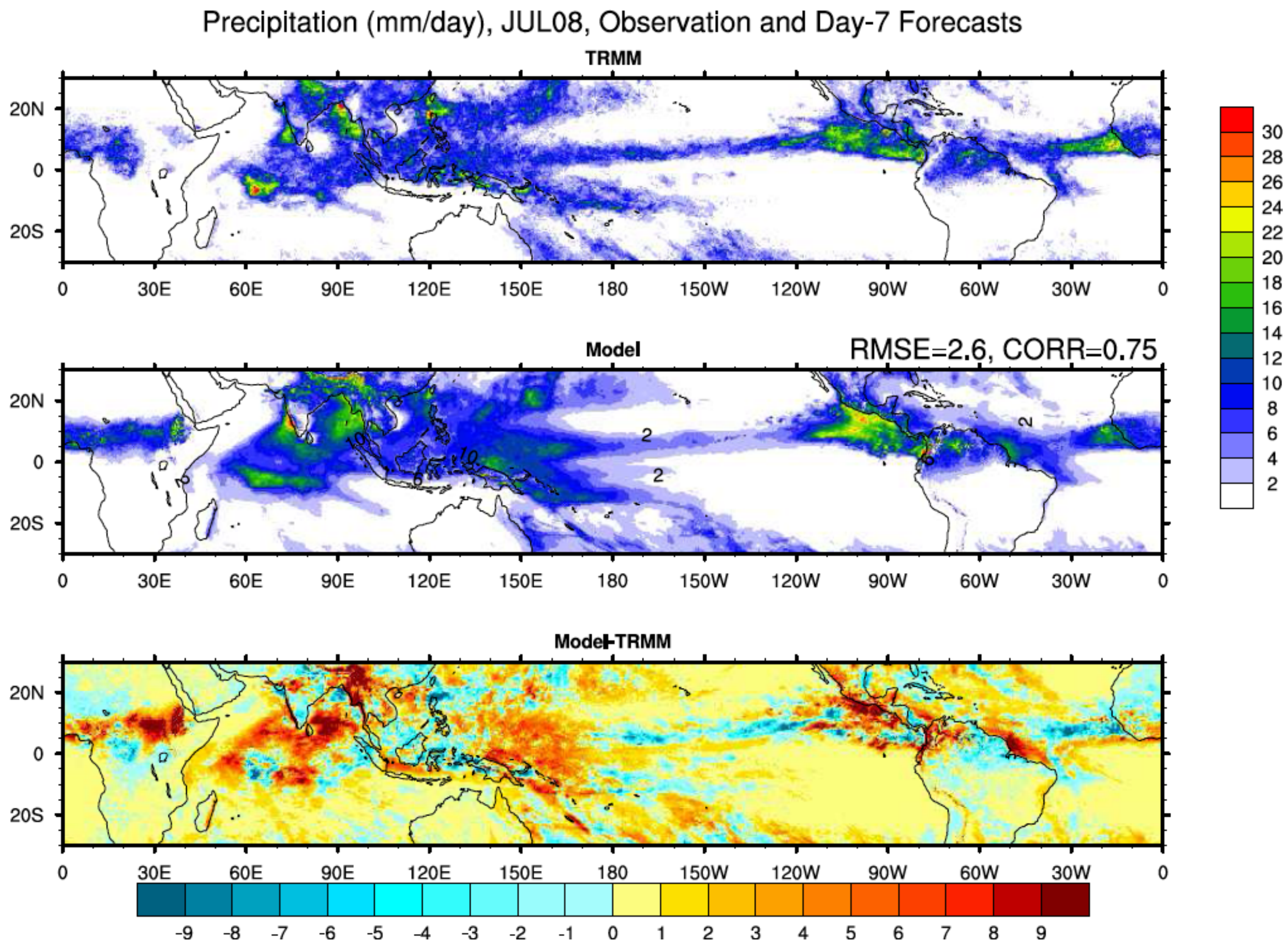




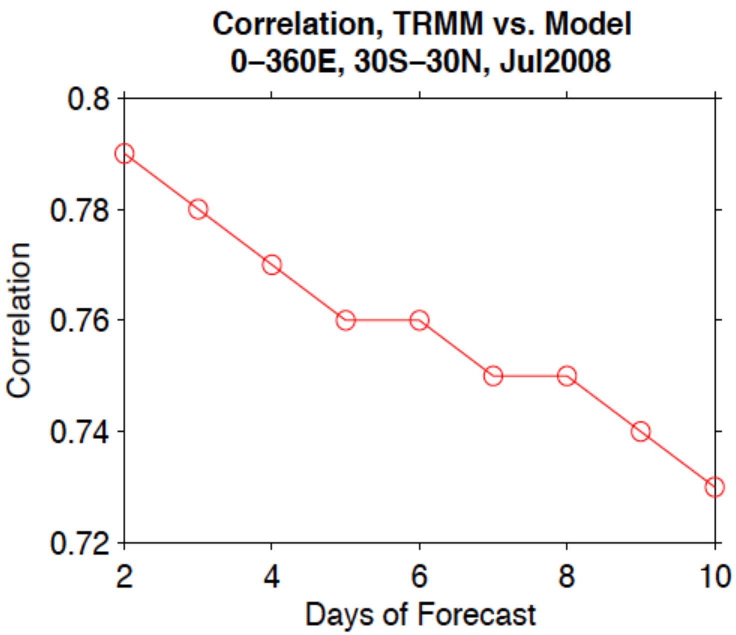
Precipitation (mm/day), JUL08, Observation and Day-2 Forecasts
TRMM
Model
RMSE=2.3, CORR=0.79
Model-TRMM
20N
0
20S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9

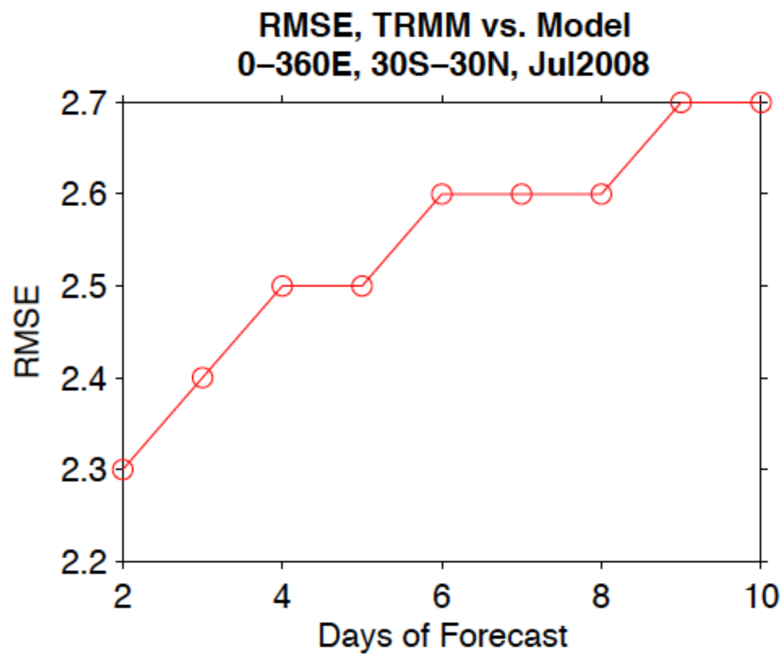


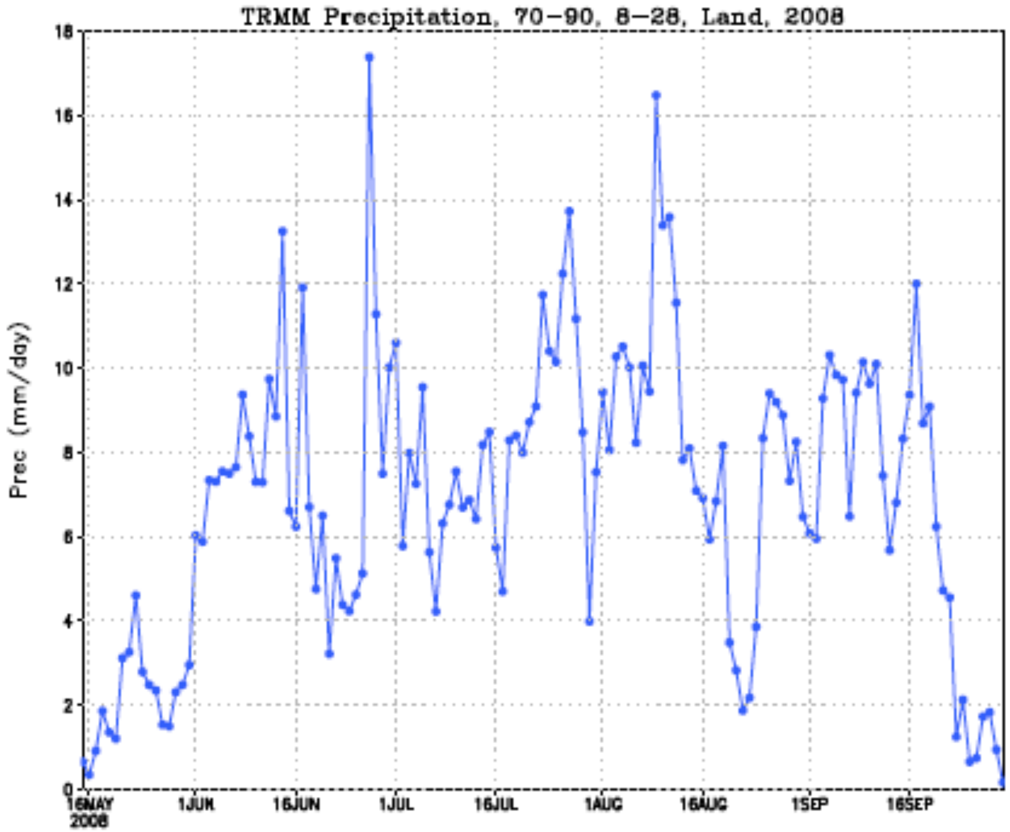
Precipitation (mm/day), JUL08, Observation and Day-3 Forecasts
TRMM
Model
RMSE=2.4, CORR=0.78
Model-TRMM
20N
0
20S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9


Precipitation (mm/day), JUL08, Observation and Day-7 Forecasts
TRMM
Model
RMSE=2.6, CORR=0.75
Model-TRMM
20N
0
20S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
-9
-8
-7
-6
-5
-4
-3
-2
-1
1
2
3
4
5
6
7
8
9

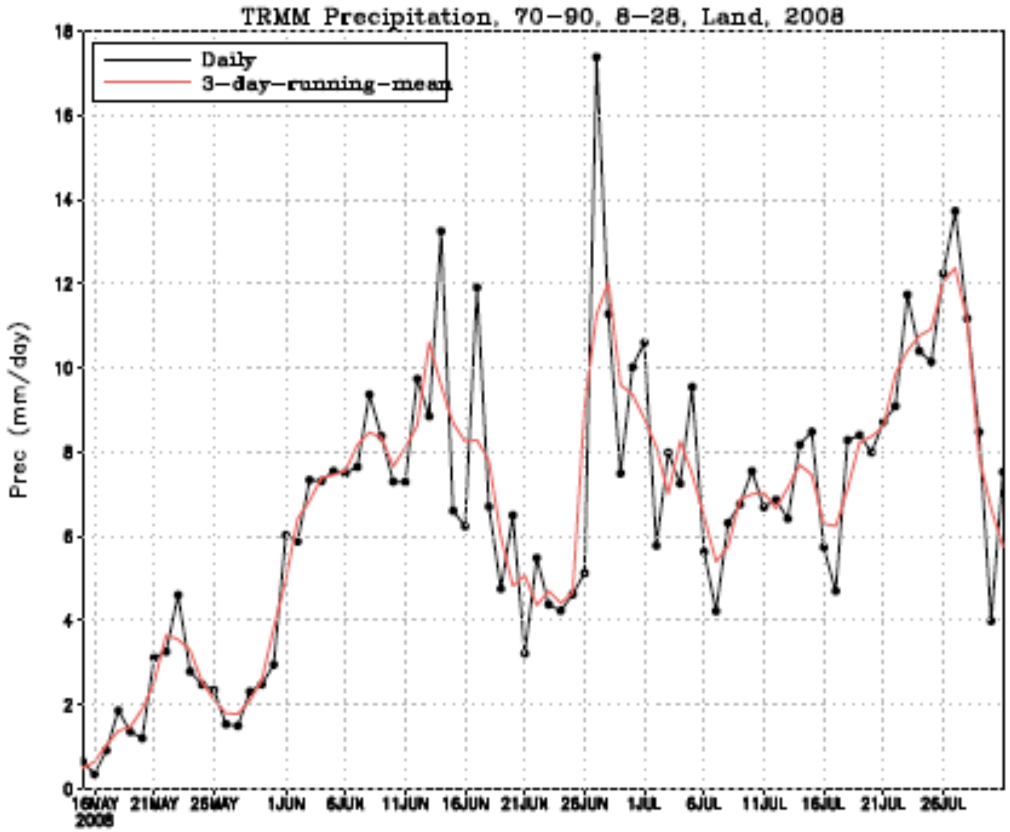
Skill Scores during July over the Tropics



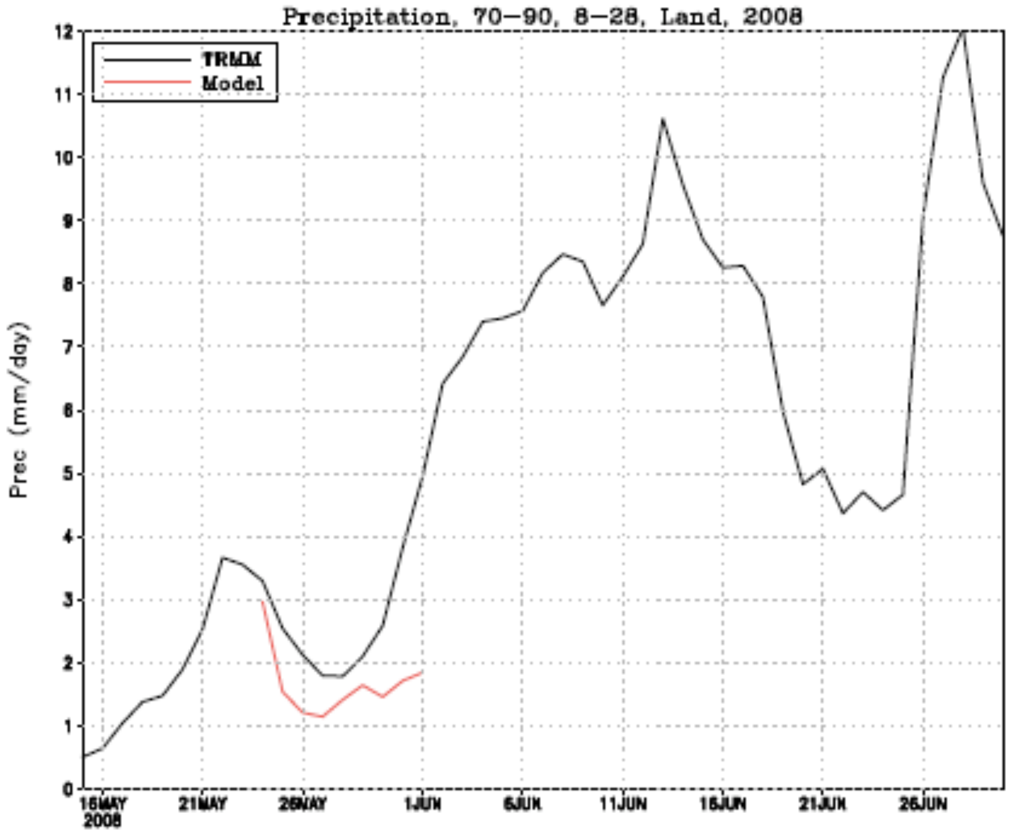




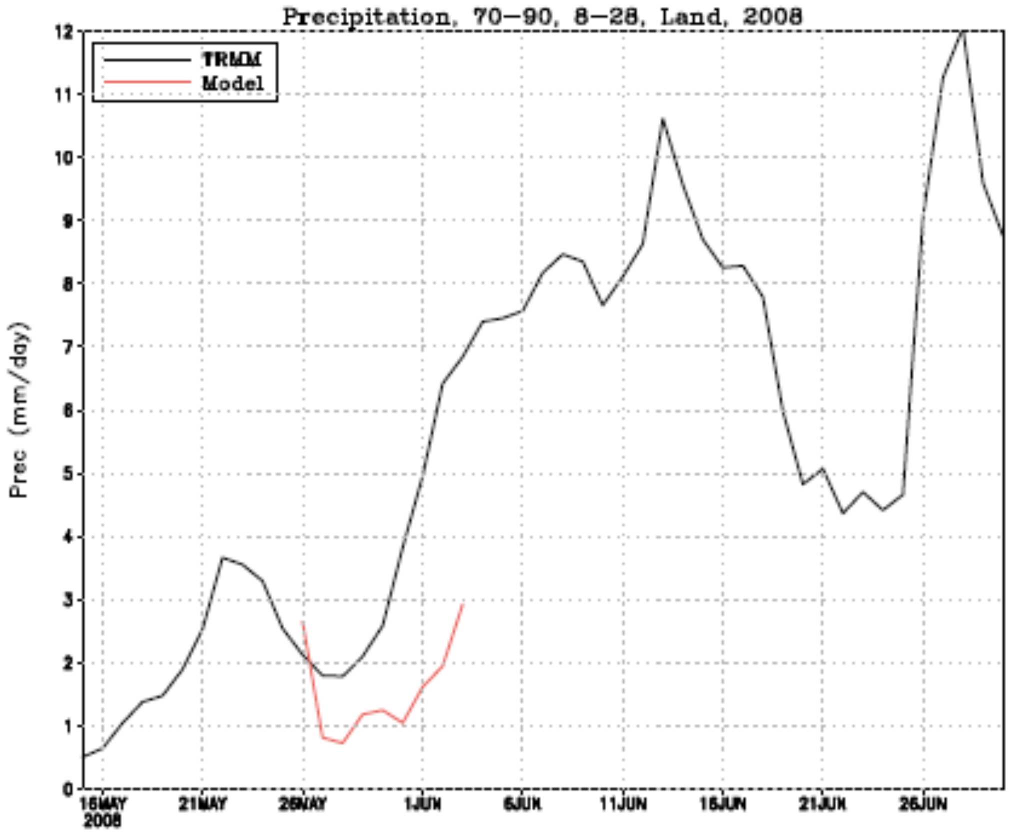
TRMM Precipitation, 70-90, 8-28, Land, 2008
Prec (mm/day)
0
2
4
6
8
10
12
14
16
18
16MAY
2008
1JUN
16JUN
1JUL
16JUL
1AUG
16AUG
1SEP
16SEP



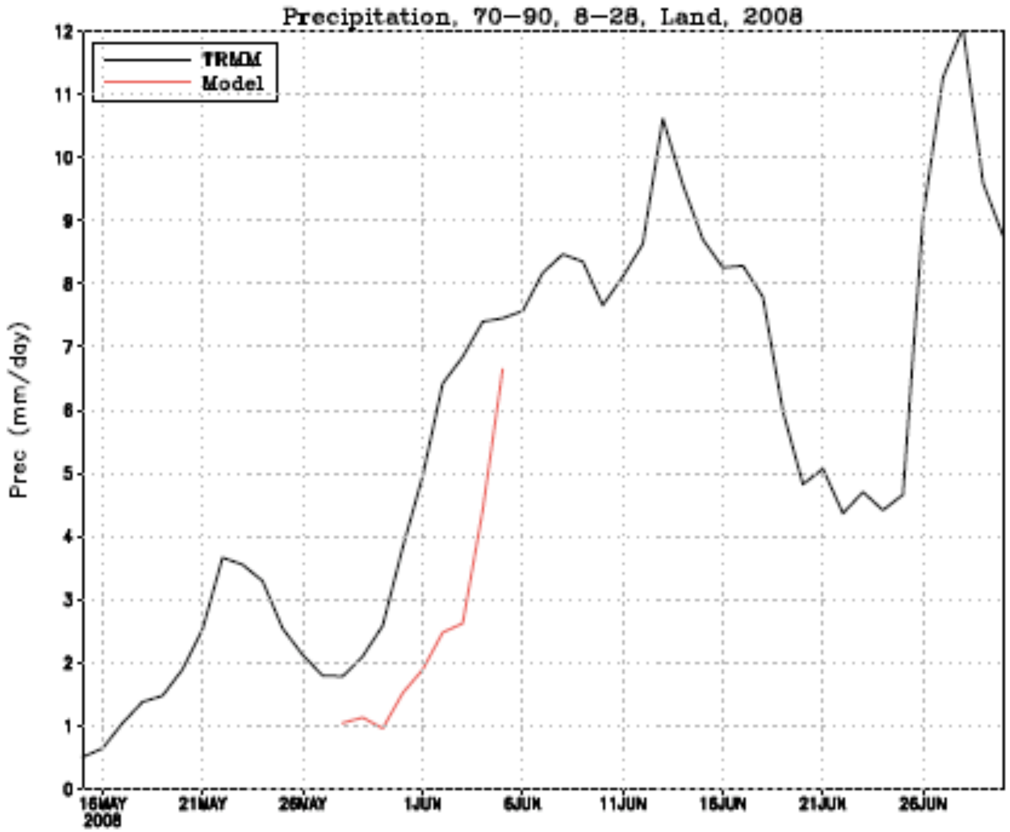
TRMM Precipitation, 70-90, 8-28, Land, 2008
Daily
3-day-running-mean
Prec (mm/day)
0
2
4
6
8
10
12
14
16
18
16MAY 2008
21MAY
26MAY
1JUN
6JUN
11JUN
16JUN
21JUN
26JUN
1JUL
6JUL
11JUL
16JUL
21JUL
26JUL



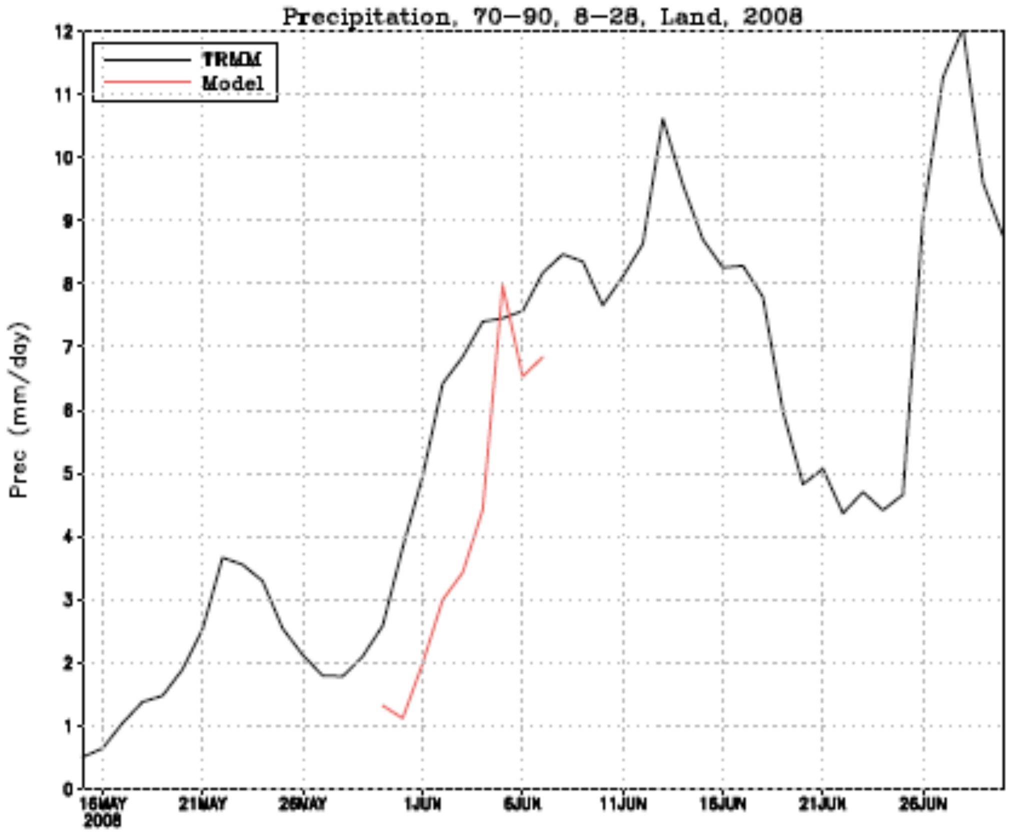
Precipitation, 70-90, 8-28, Land, 2008
TRMM
Model
Prec (mm/day)
0
1
2
3
4
5
6
7
8
9
10
11
12
16MAY
2008
21MAY
26MAY
1JUN
6JUN
11JUN
16JUN
21JUN
26JUN



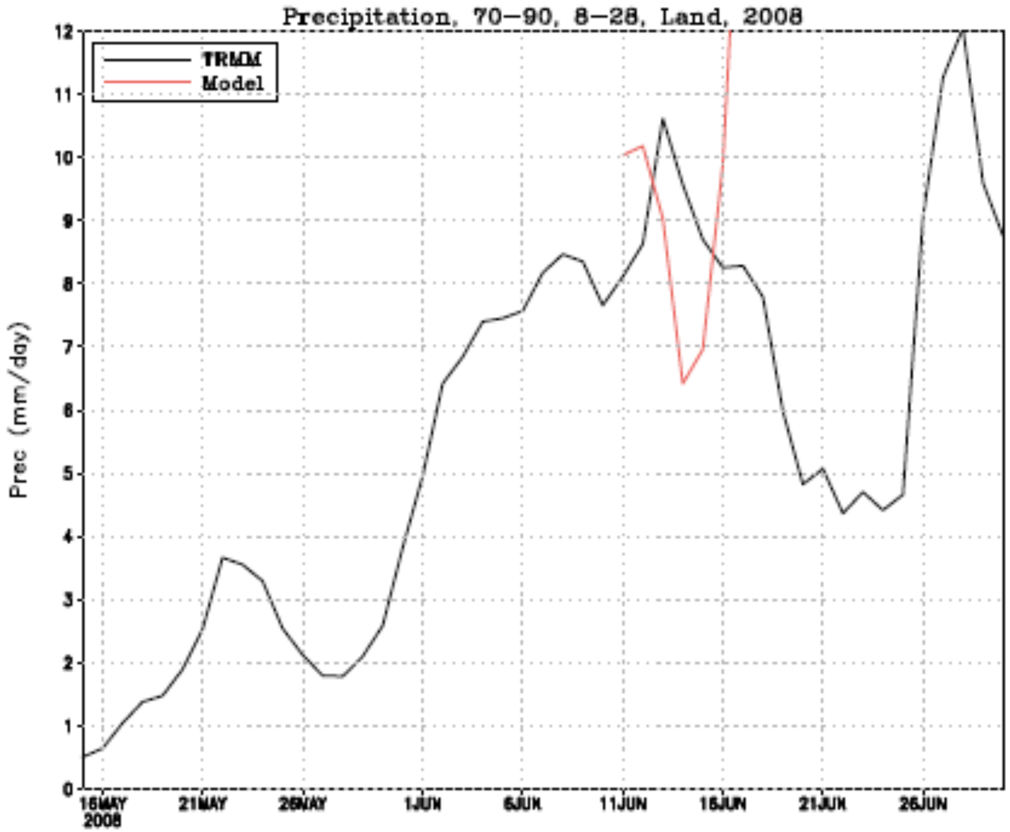
Precipitation, 70–90, 8–28, Land, 2008
TRMM
Model
Prec (mm/day)
0
1
2
3
4
5
6
7
8
9
10
11
12
16MAY
2008
21MAY
26MAY
1JUN
6JUN
11JUN
16JUN
21JUN
26JUN



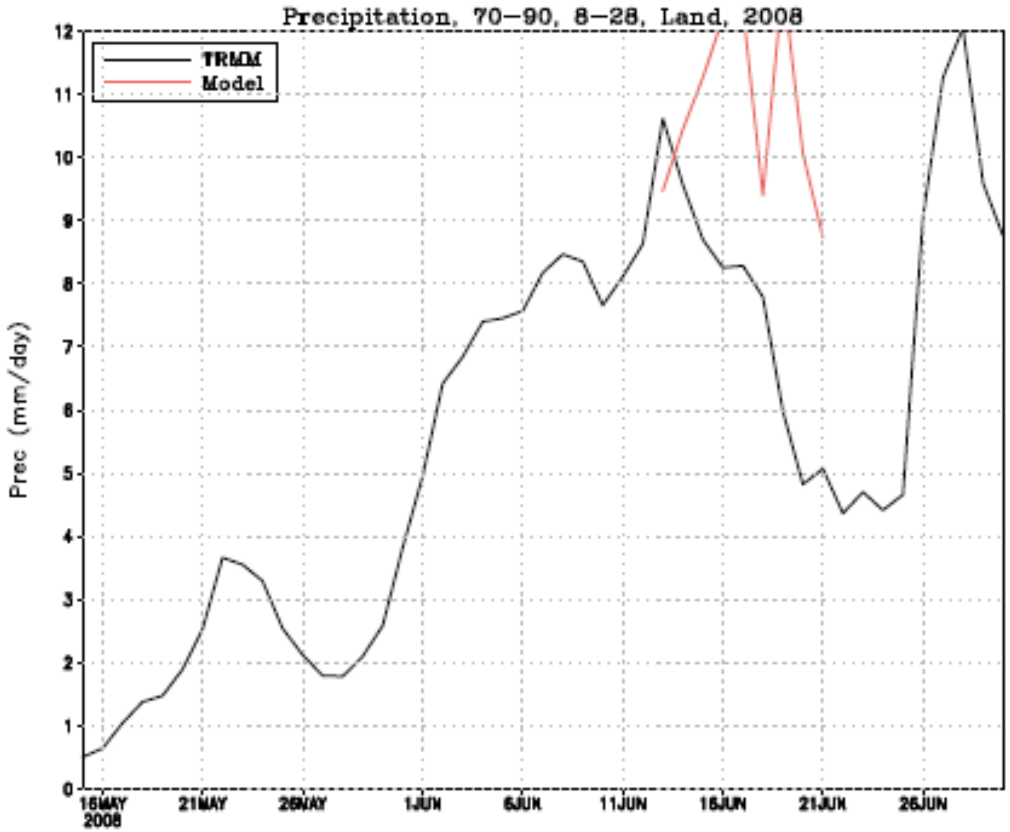
Precipitation, 70-90, 8-28, Land, 2008
TRMM
Model
Prec (mm/day)
0
1
2
3
4
5
6
7
8
9
10
11
12
16MAY
2008
21MAY
26MAY
1JUN
6JUN
11JUN
16JUN
21JUN
26JUN



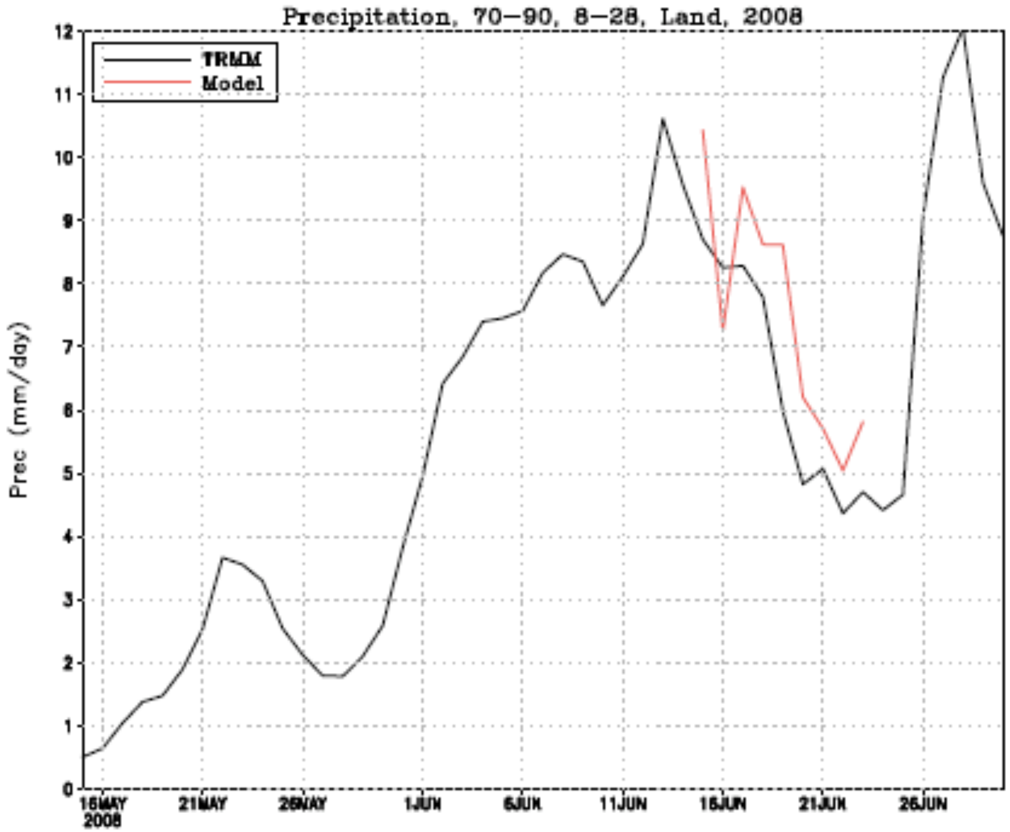
Precipitation, 70–90, 8–28, Land, 2008
TRMM
Model
Prec (mm/day)
0
1
2
3
4
5
6
7
8
9
10
11
12
16MAY
2008
21MAY
26MAY
1JUN
6JUN
11JUN
16JUN
21JUN
26JUN



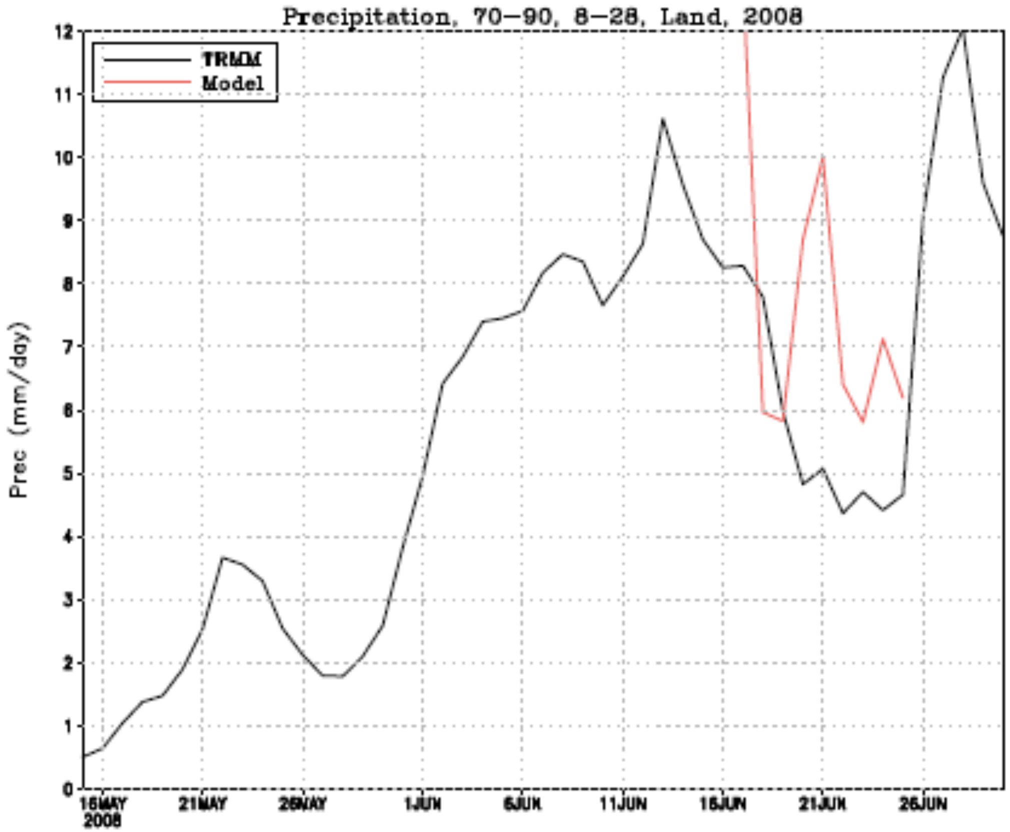
Precipitation, 70–90, 8–28, Land, 2008
TRMM
Model
Prec (mm/day)
0
1
2
3
4
5
6
7
8
9
10
11
12
16MAY
2008
21MAY
26MAY
1JUN
6JUN
11JUN
16JUN
21JUN
26JUN

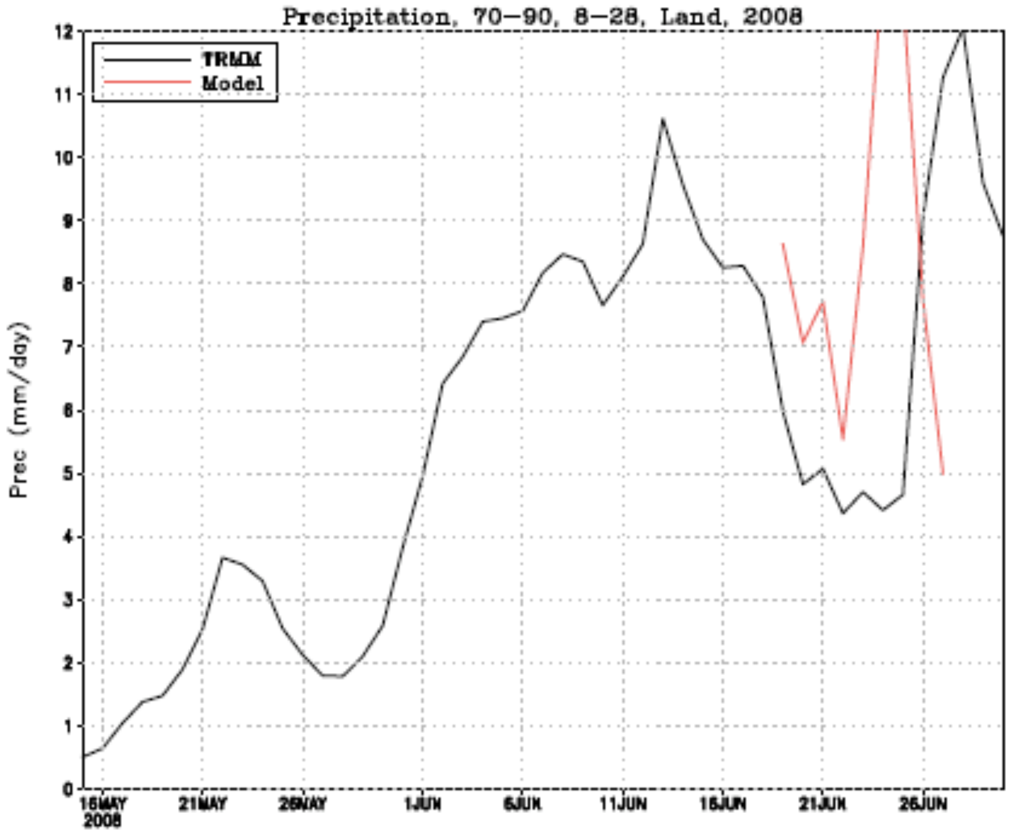


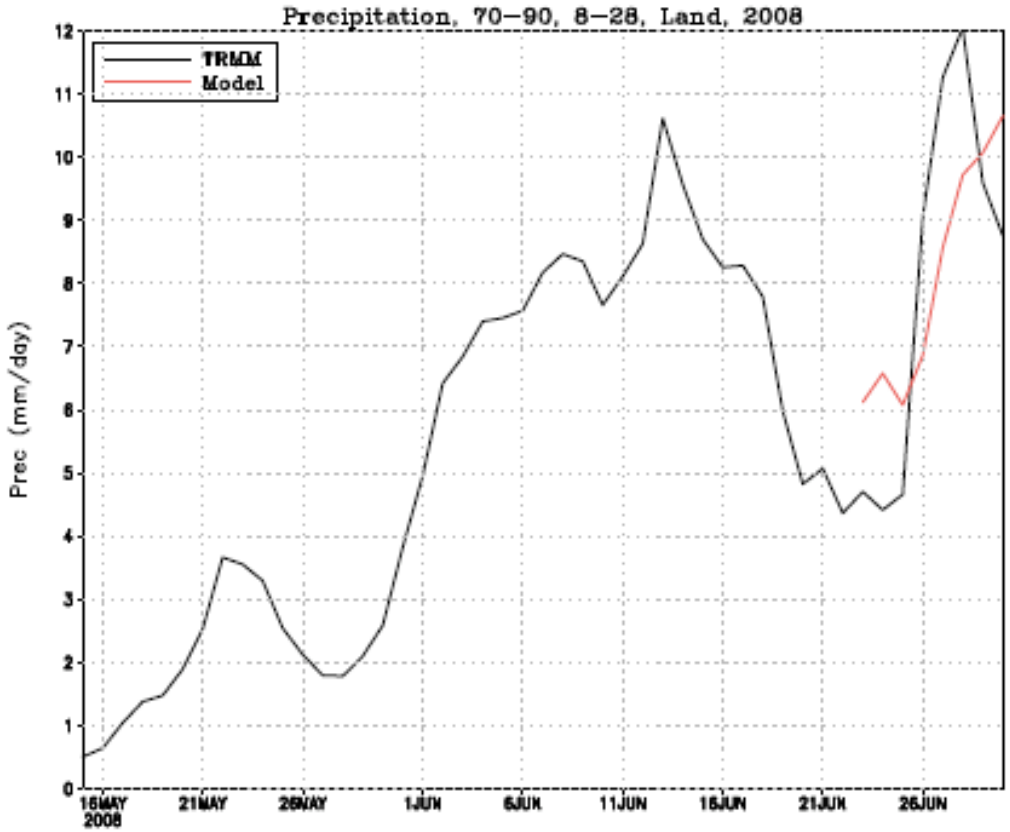
Precipitation, 70–90, 8–28, Land, 2008
TRMM
Model
Prec (mm/day)
0
1
2
3
4
5
6
7
8
9
10
11
12
16MAY
2008
21MAY
26MAY
1JUN
6JUN
11JUN
16JUN
21JUN
26JUN



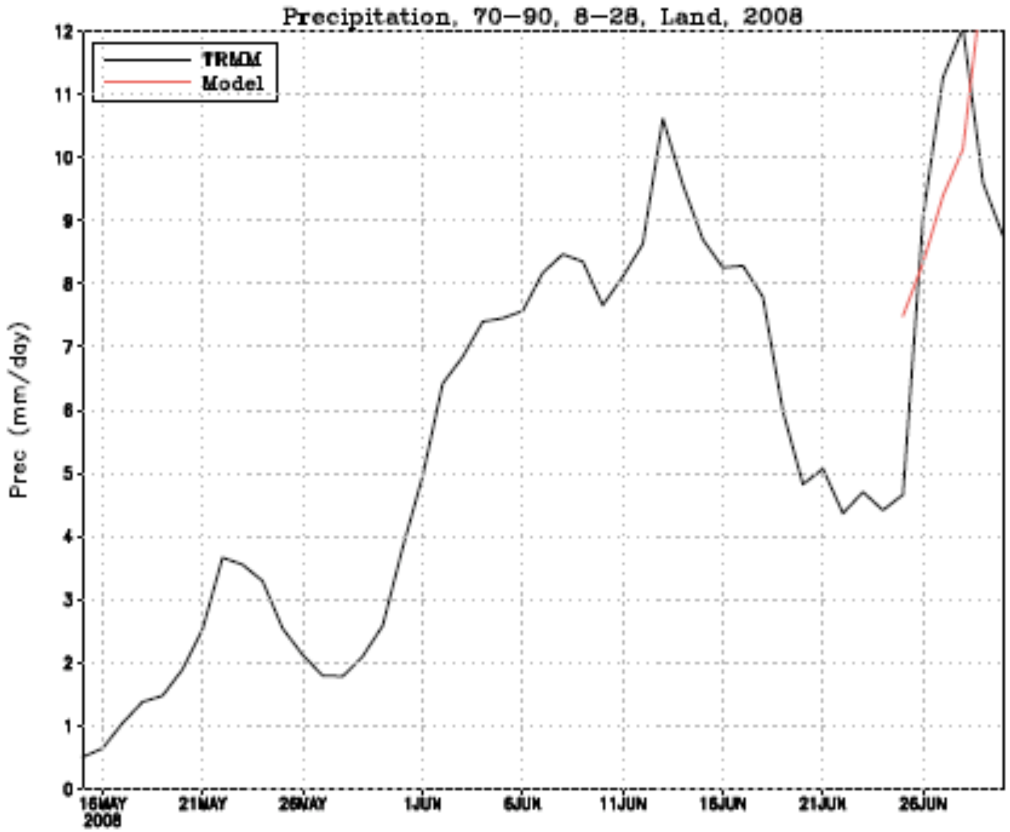
Precipitation, 70-90, 8-28, Land, 2008
TRMM
Model
Prec (mm/day)
0
1
2
3
4
5
6
7
8
9
10
11
12
16MAY
2008
21MAY
26MAY
1JUN
6JUN
11JUN
16JUN
21JUN
26JUN


Precipitation, 70–90, 8–28, Land, 2008
TRMM
Model
Prec (mm/day)
0
1
2
3
4
5
6
7
8
9
10
11
12
16MAY
2008
21MAY
26MAY
1JUN
6JUN
11JUN
16JUN
21JUN
26JUN

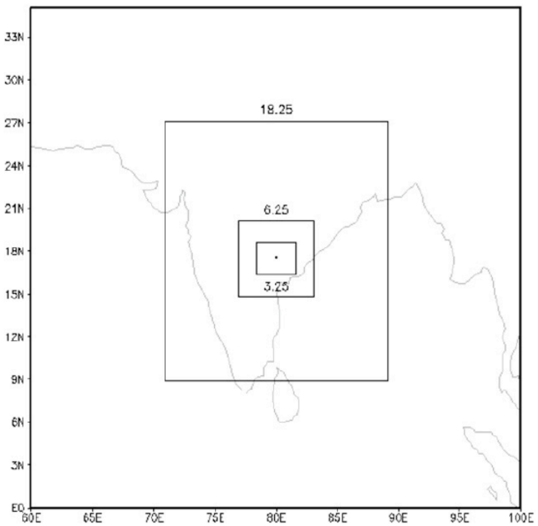

Precipitation, 70–90, 8–28, Land, 2008
TRMM
Model
Prec (mm/day)
0
1
2
3
4
5
6
7
8
9
10
11
12
16MAY
2008
21MAY
26MAY
1JUN
6JUN
11JUN
16JUN
21JUN
26JUN

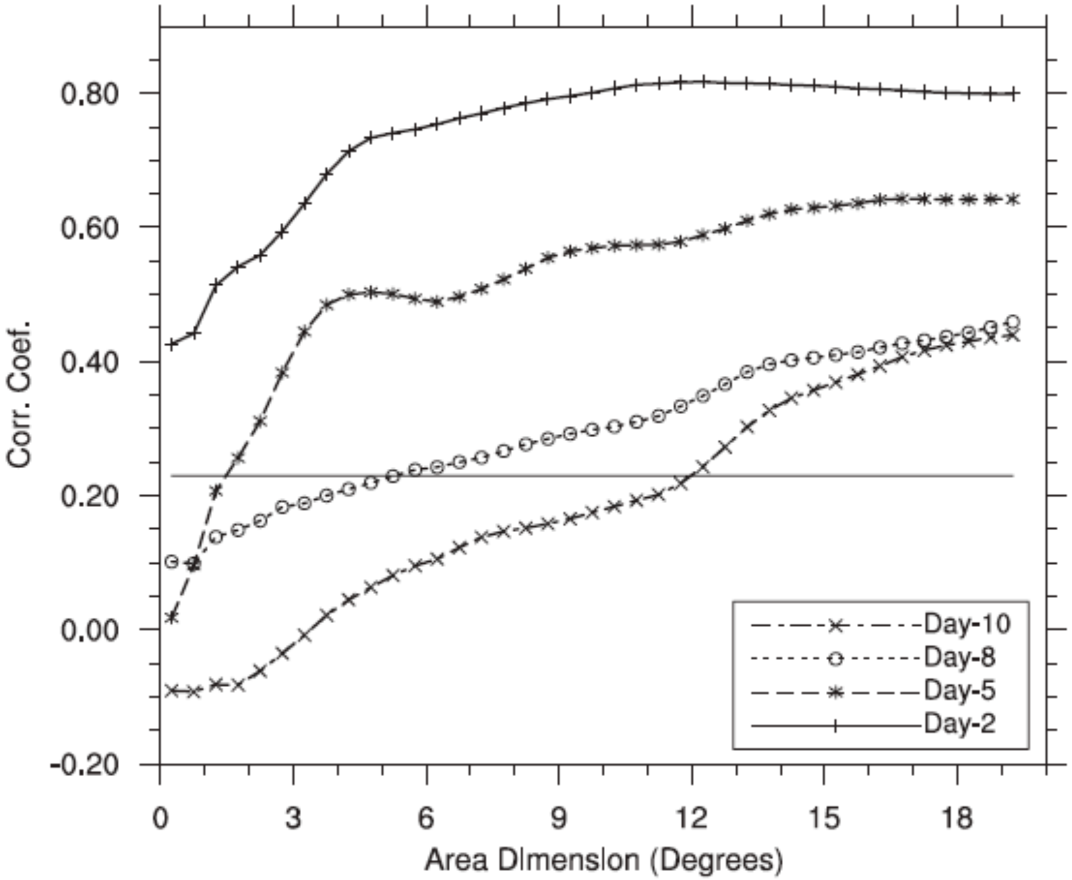


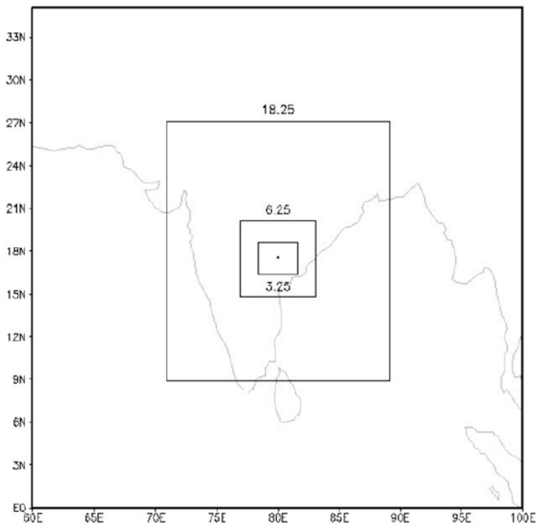
Precipitation, 70-90, 8-28, Land, 2008
TRMM
Model
Prec (mm/day)
0
1
2
3
4
5
6
7
8
9
10
11
12
16MAY
2008
21MAY
26MAY
1JUN
6JUN
11JUN
16JUN
21JUN
26JUN



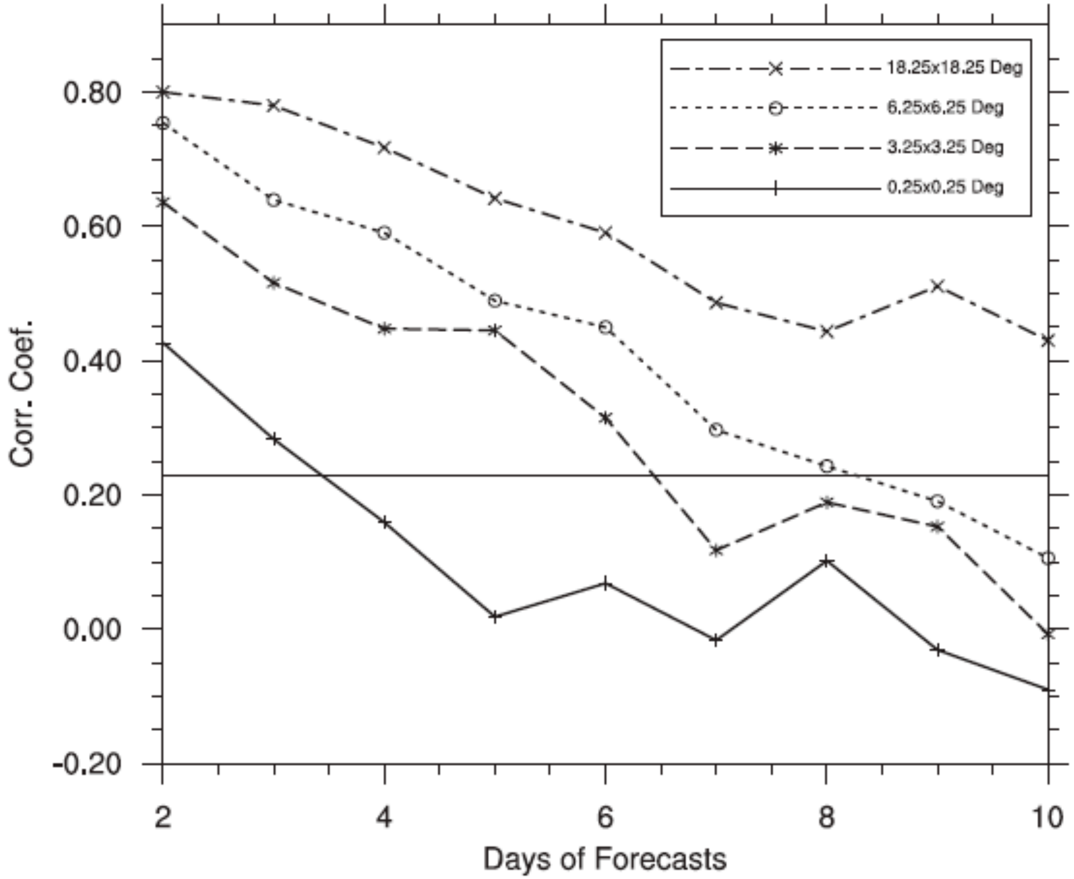
Precipitation, 70–90, 8–28, Land, 2008
TRMM
Model
Prec (mm/day)
0
1
2
3
4
5
6
7
8
9
10
11
12
16MAY
2008
21MAY
26MAY
1JUN
6JUN
11JUN
16JUN
21JUN
26JUN


18.25
6.25
3.25

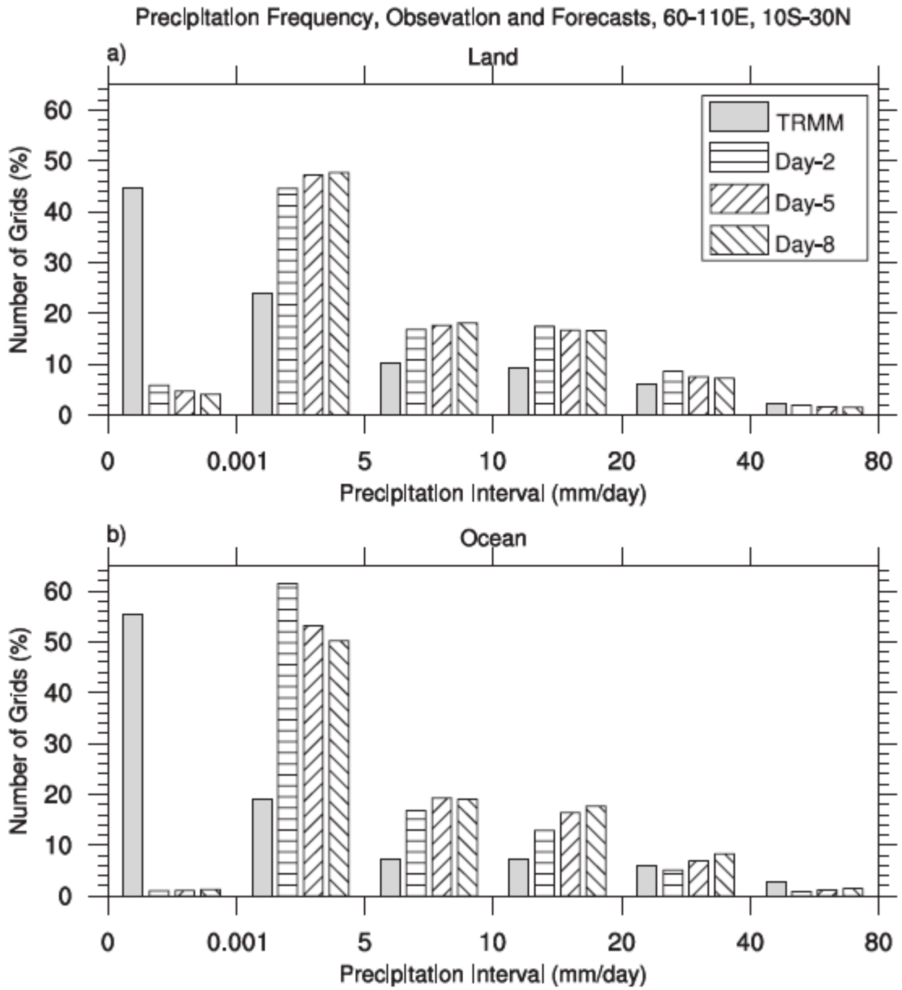

Corr. Coef.
Area Dimension (Degrees)
Day-10
Day-8
Day-5
Day-2



18.25
6.25
3.25
33N
30N
27N
24N
21N
18N
15N
12N
9N
6N
3N
EQ
60E
65E
70E
75E
80E
85E
90E
95E
100E

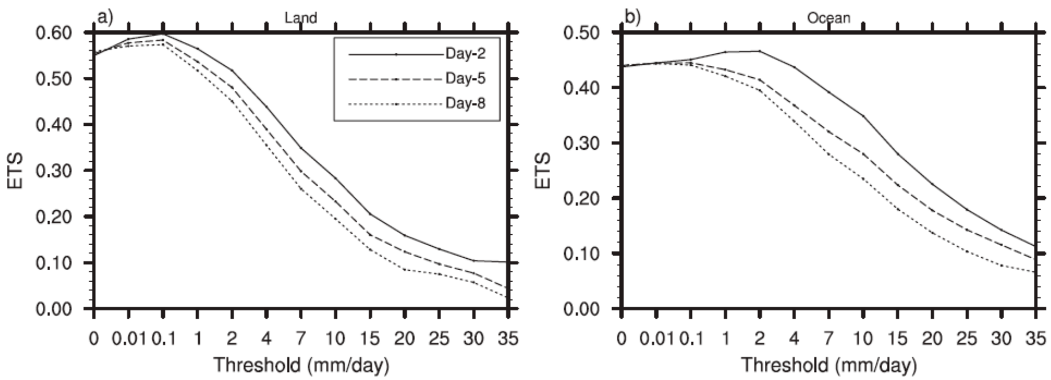


18.25x18.25 Deg
6.25x6.25 Deg
3.25x3.25 Deg
0.25x0.25 Deg
Corr. Coef.
0.80
0.60
0.40
0.20
0.00
-0.20
2
4
6
8
10
Days of Forecasts



Precipitation Frequency, Obsevation and Forecasts, 60-110E, 10S-30N
a)
Land
TRMM
Day-2
Day-5
Day-8
Number of Grids (%)
0
10
20
30
40
50
60
0
0.001
5
10
20
40
80
Precipitation Interval (mm/day)
b)
Ocean
Number of Grids (%)
0
10
20
30
40
50
60
0
0.001
5
10
20
40
80
Precipitation Interval (mm/day)

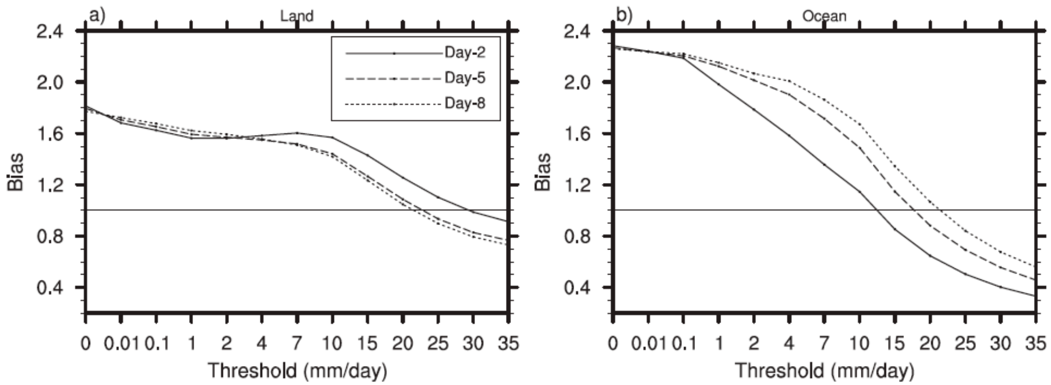
Equitable Threat Score of Precipitation Forecasts, 60-110E, 10S-30N, JJAS08



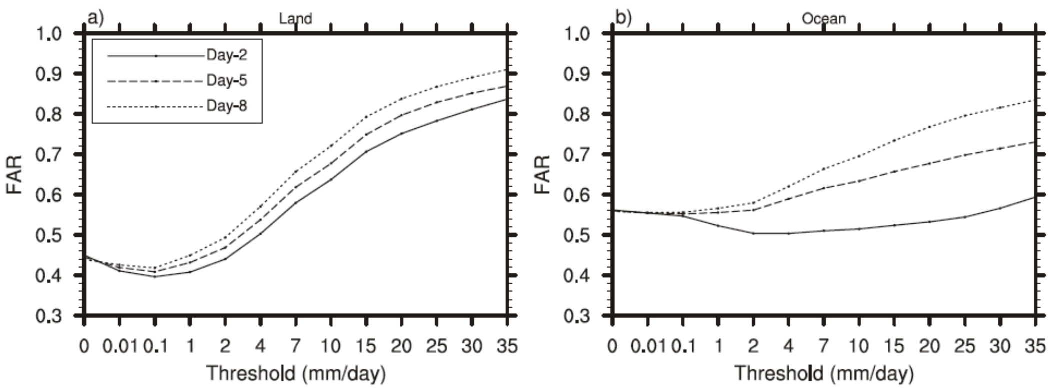
$$\mathrm{ETS} = \frac{H - E}{F + O - H - E}$$

Bias Score of Precipitation Forecasts, 60-110E, 10S-30N, JJAS08

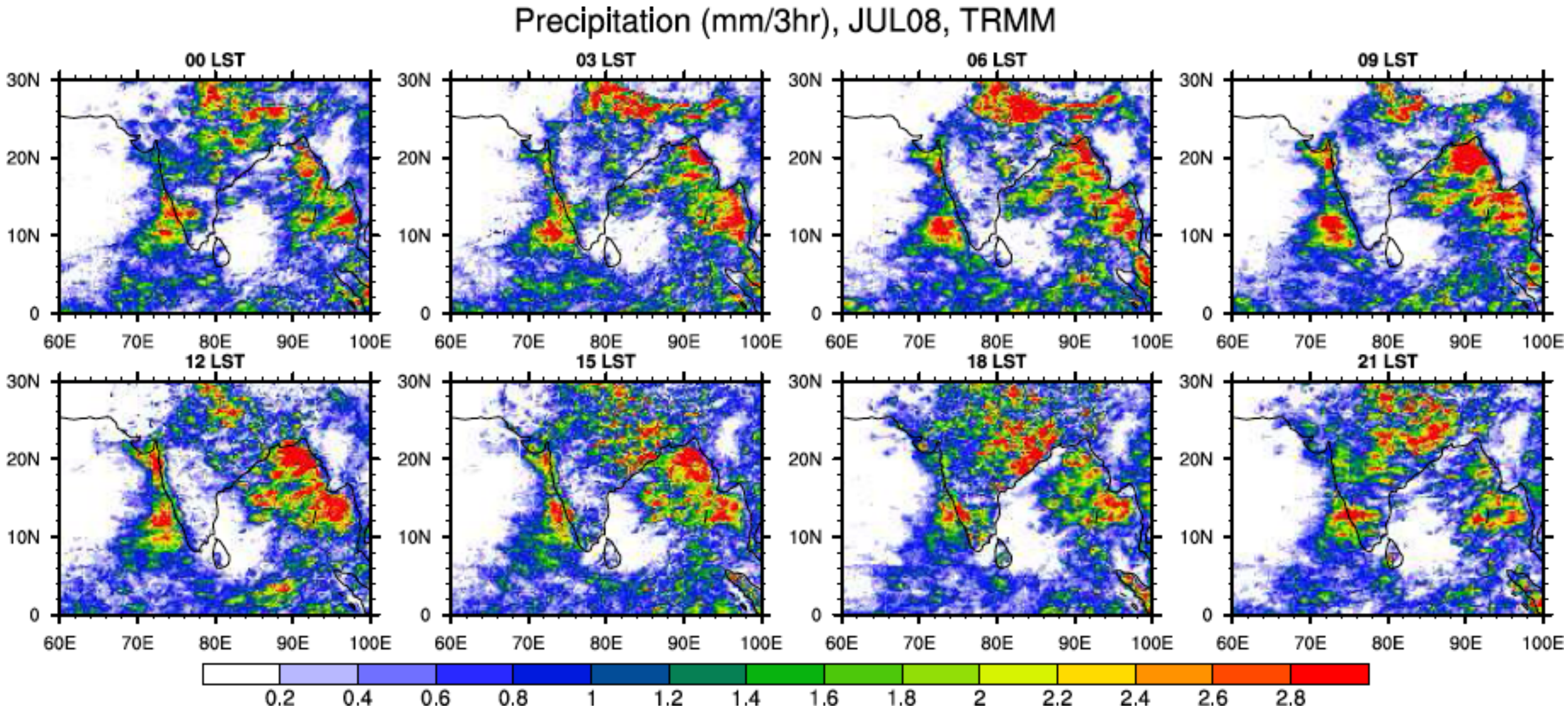
$$\mathrm{BIAS} = \frac{F}{O}$$



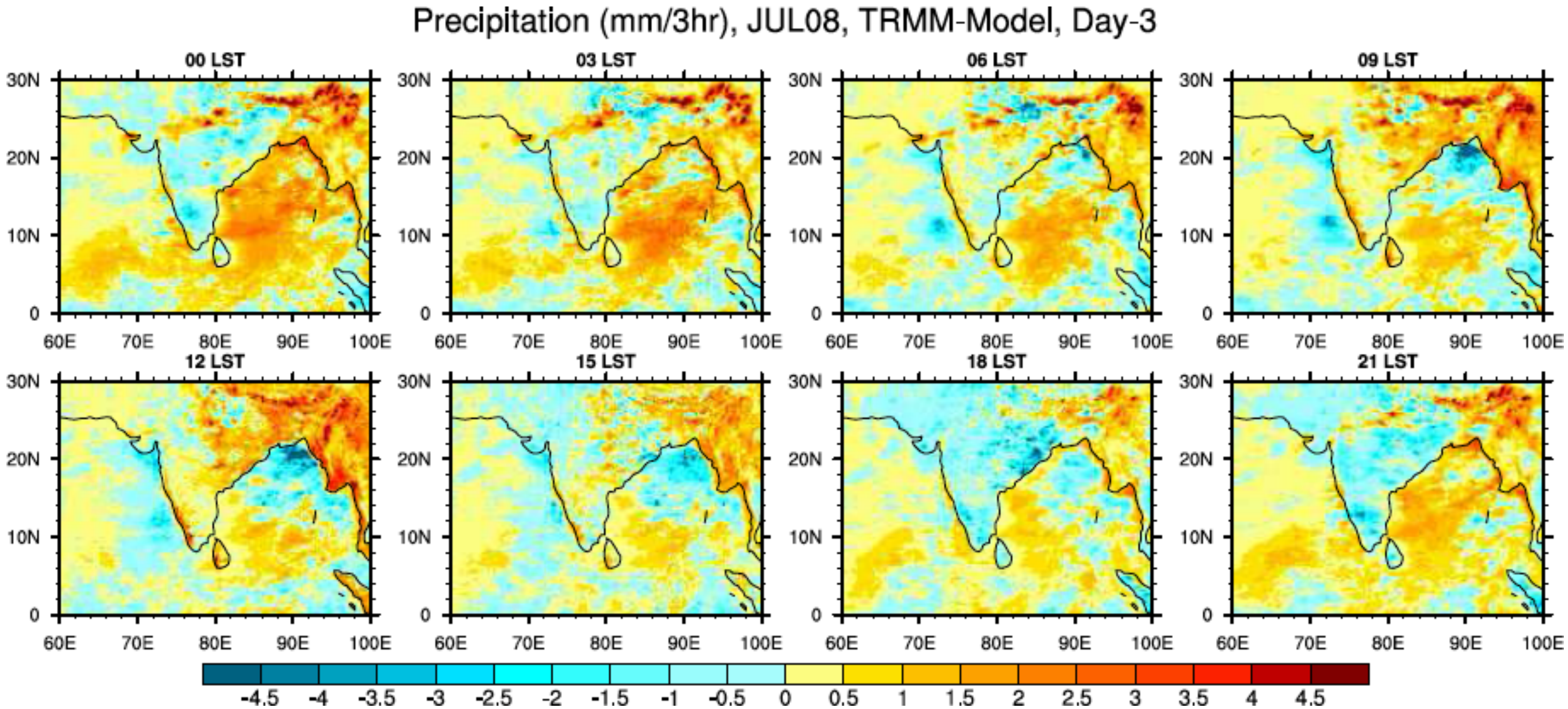
False Alarm Ratio of Precipitation Forecasts, 60-110E, 10S-30N, JJAS08

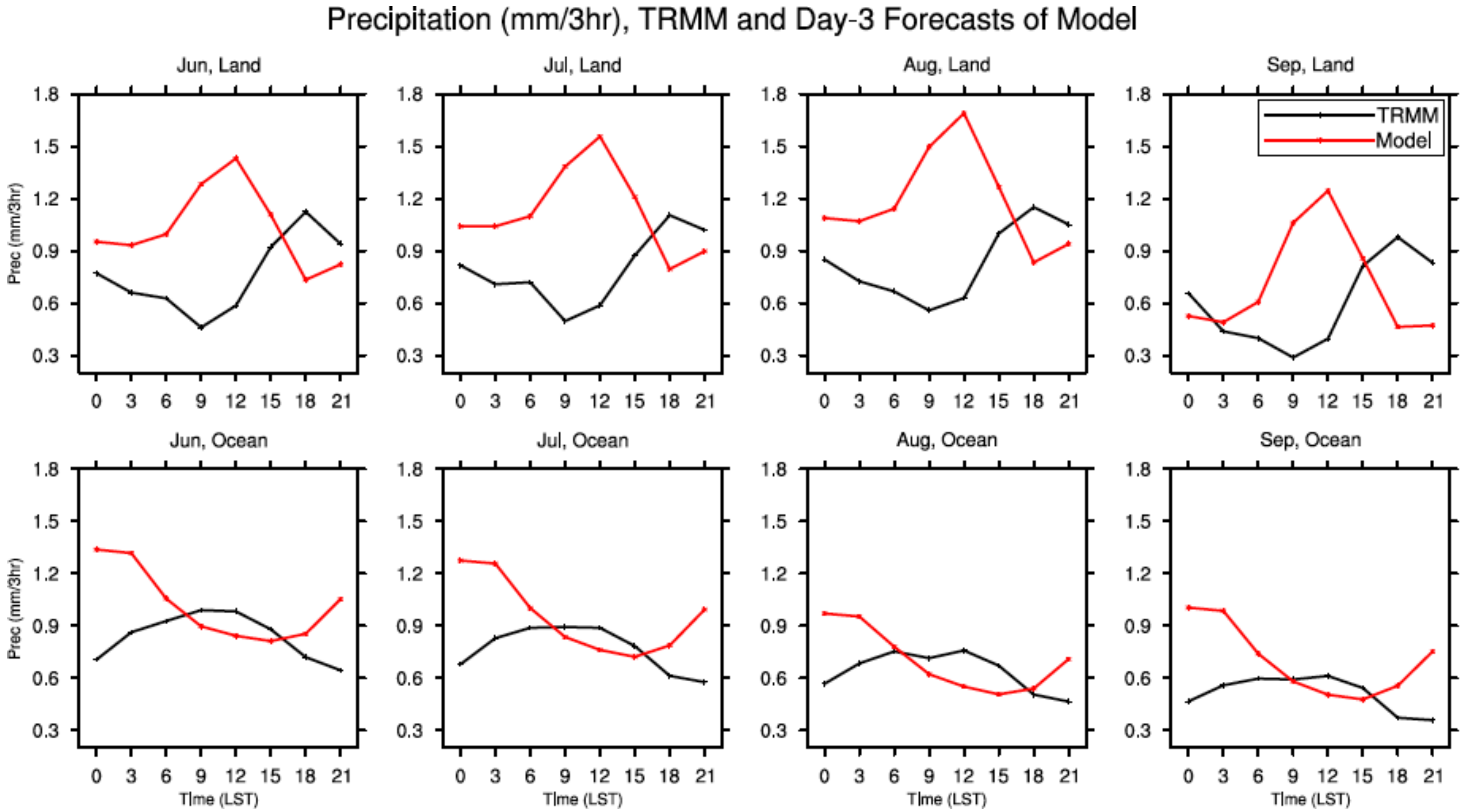


$$\mathrm{FAR} = \frac{F - H}{F}$$

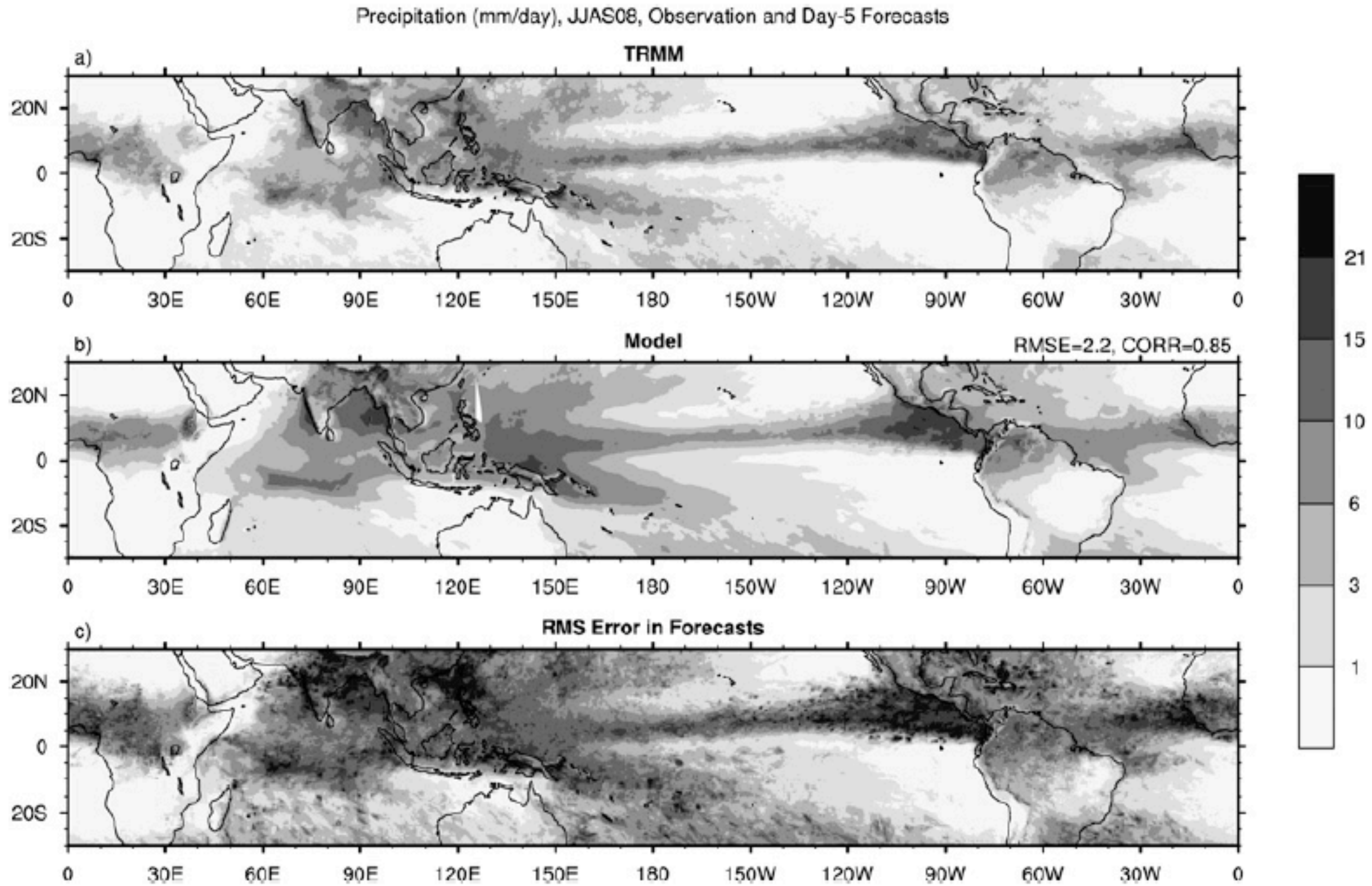


Precipitation (mm/3hr), JUL08, TRMM
00 LST
03 LST
06 LST
09 LST
12 LST
15 LST
18 LST
21 LST
30N
20N
10N
0
60E
70E
80E
90E
100E
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8

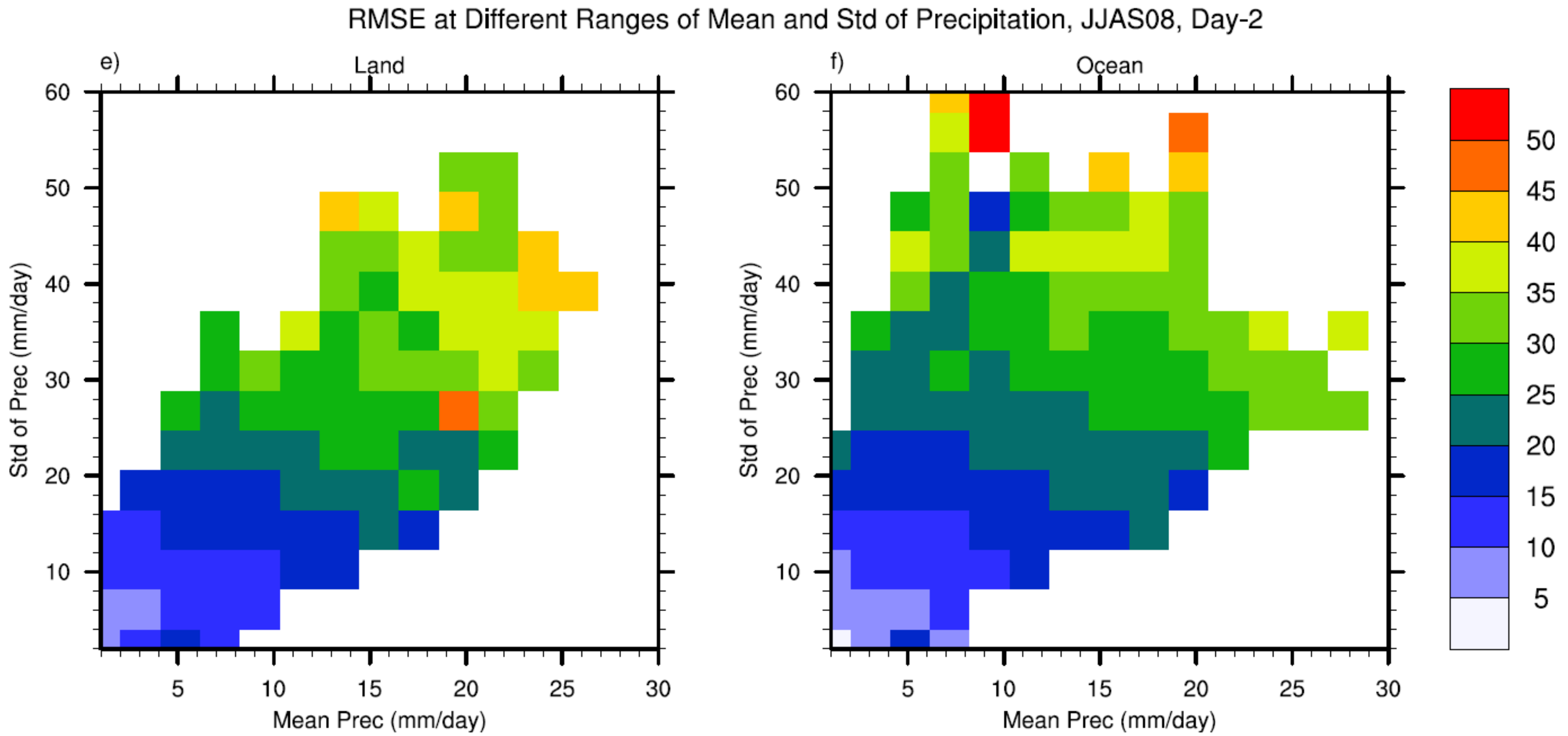

Precipitation (mm/3hr), JUL08, TRMM-Model, Day-3
00 LST
03 LST
06 LST
09 LST
12 LST
15 LST
18 LST
21 LST
30N
20N
10N
0
60E
70E
80E
90E
100E
-4.5
-4
-3.5
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5



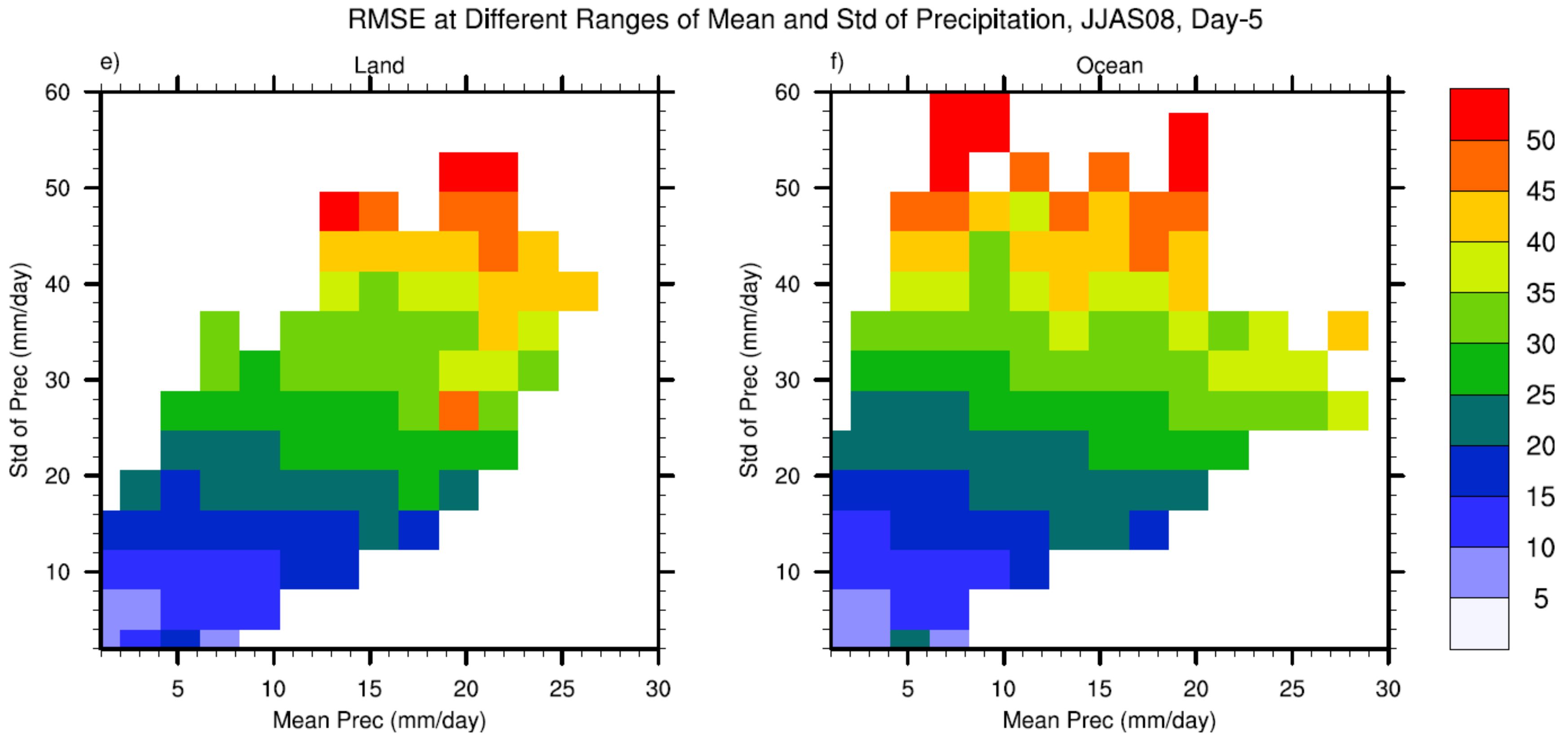
Precipitation (mm/3hr), TRMM and Day-3 Forecasts of Model
Jun, Land
Jul, Land
Aug, Land
Sep, Land
Jun, Ocean
Jul, Ocean
Aug, Ocean
Sep, Ocean
TRMM
Model
Prec (mm/3hr)
Time (LST)



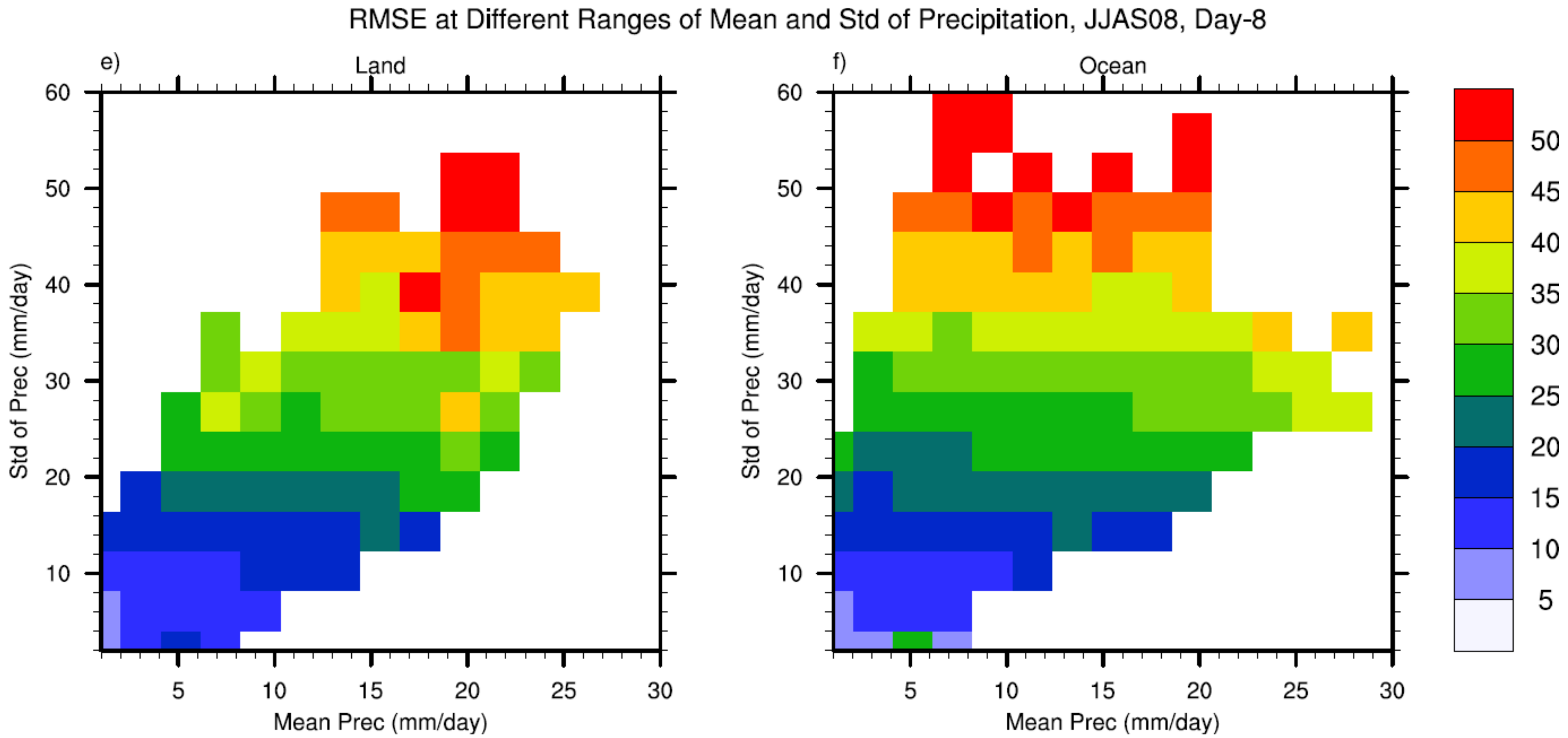
Precipitation (mm/day), JJAS08, Observation and Day-5 Forecasts
a)
TRMM
b)
Model
RMSE=2.2, CORR=0.85
c)
RMS Error in Forecasts
20N
0
20S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
21
15
10
6
3
1



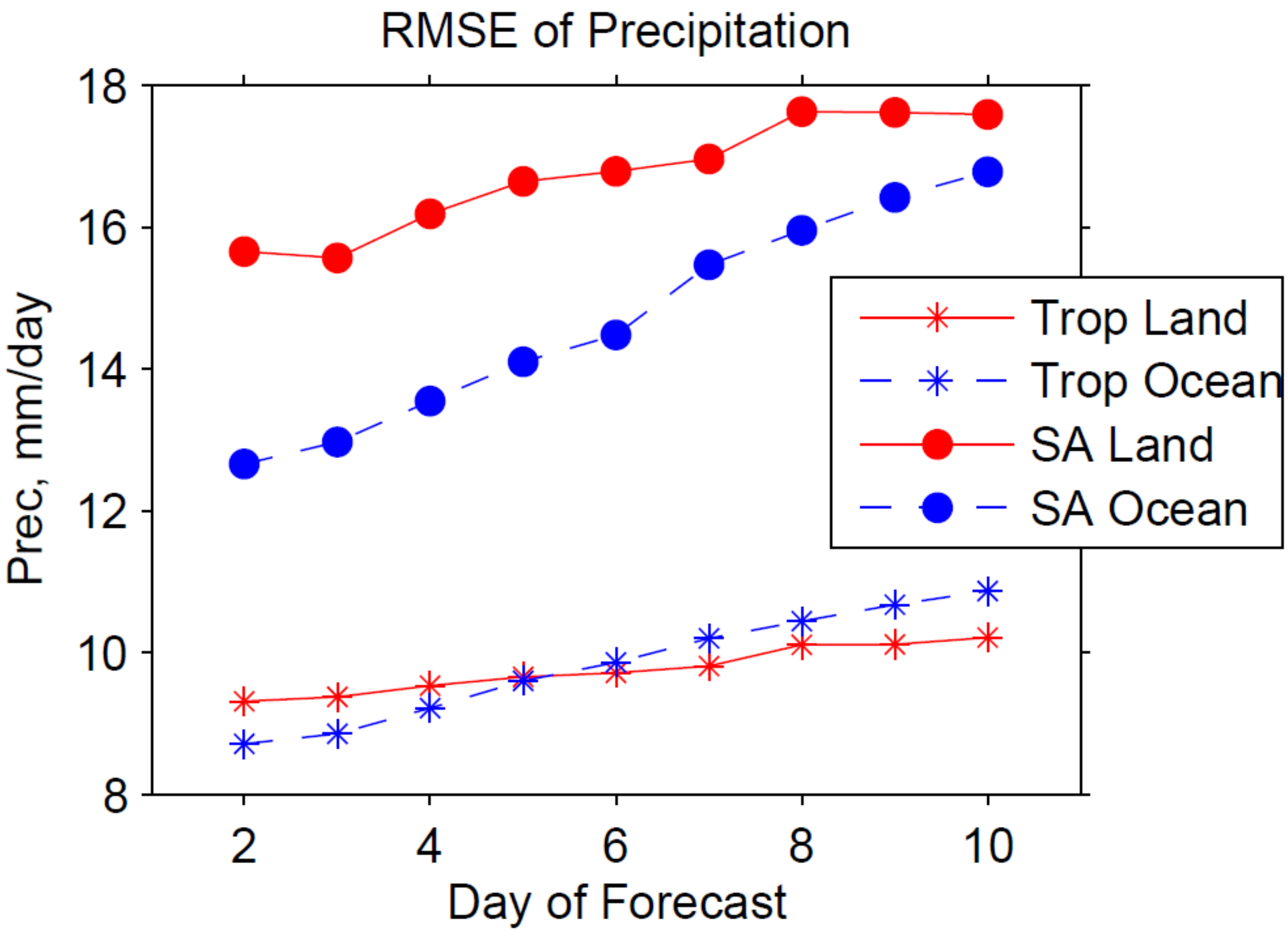
RMSE at Different Ranges of Mean and Std of Precipitation, JJAS08, Day-2
e)
Land
f)
Ocean
Std of Prec (mm/day)
Mean Prec (mm/day)
60
50
40
30
20
10
5
10
15
20
25
30
45
35



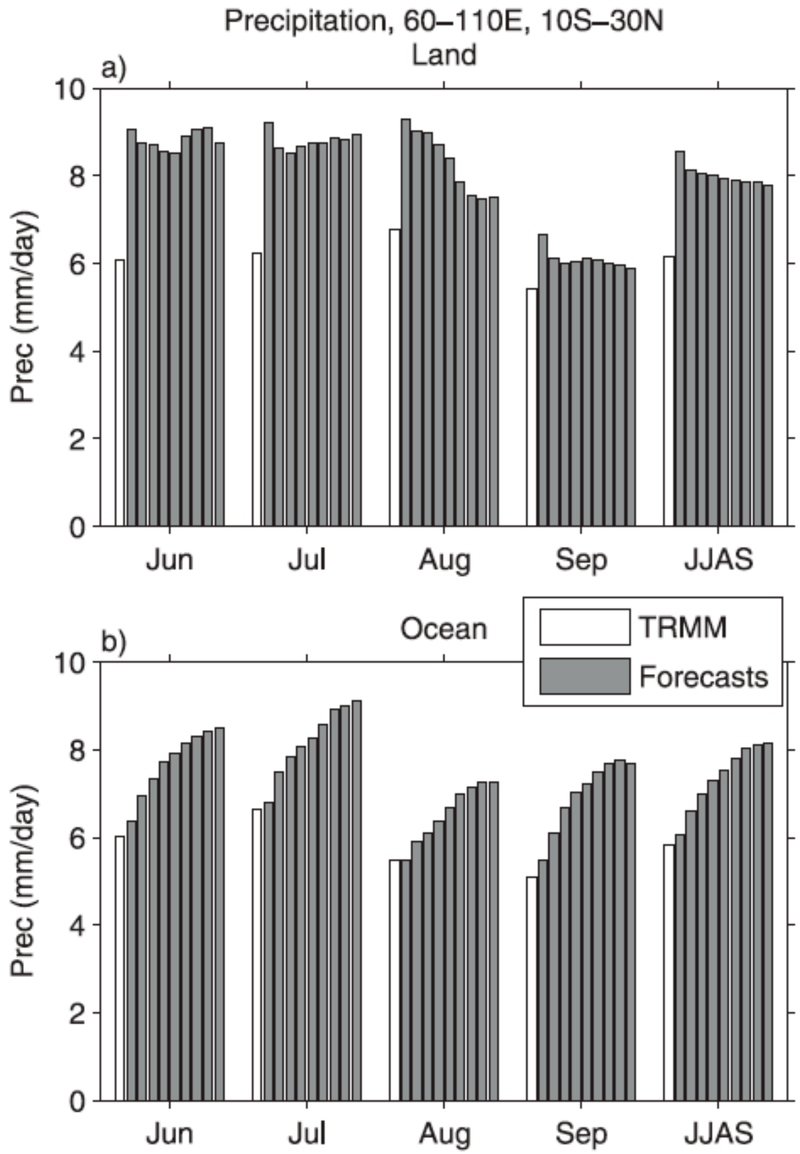
RMSE at Different Ranges of Mean and Std of Precipitation, JJAS08, Day-5
e)
Land
f)
Ocean
Std of Prec (mm/day)
Mean Prec (mm/day)
60
50
40
30
20
10
5
10
15
20
25
30
5
10
15
20
25
30
35
40
45
50

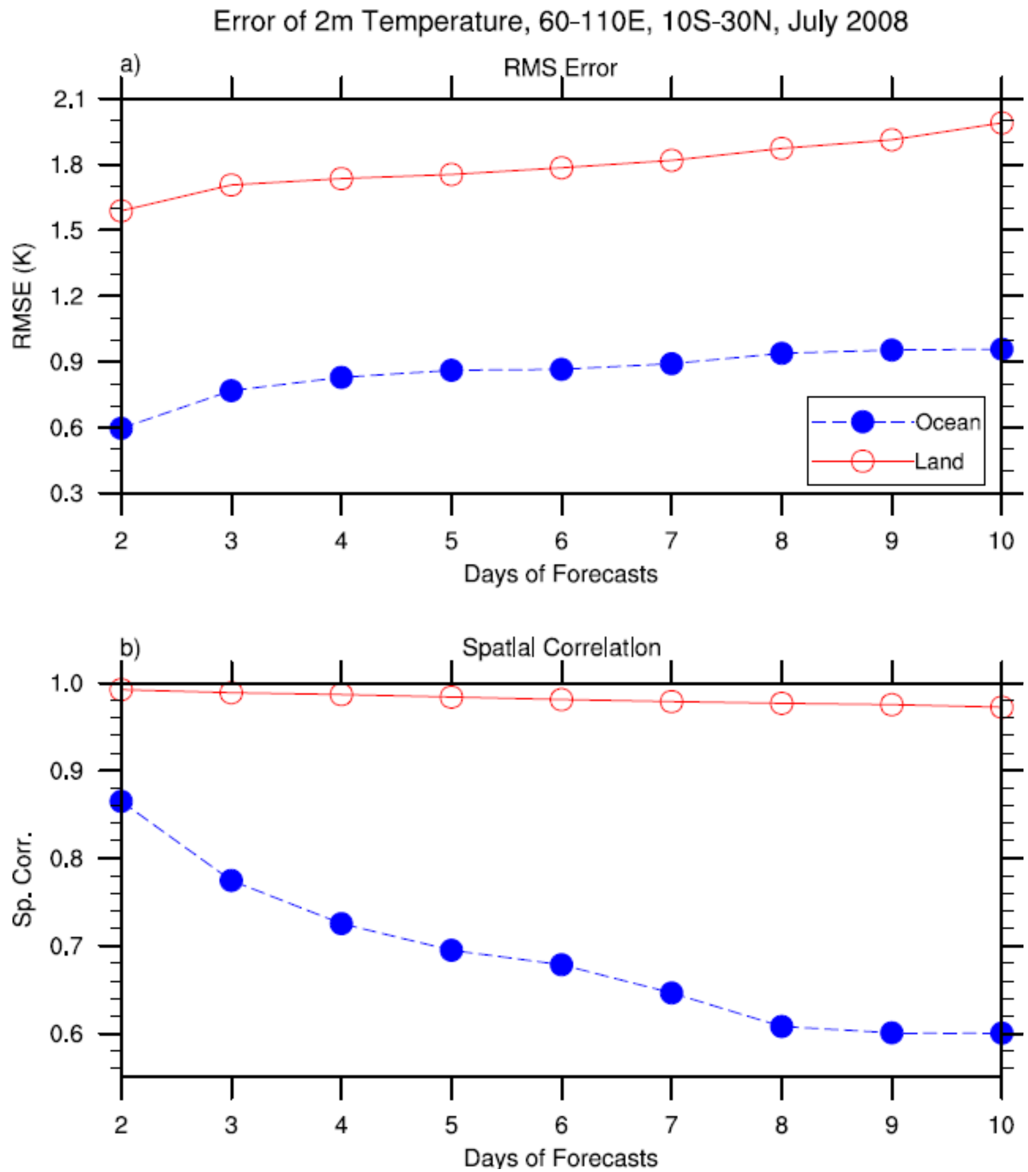


RMSE at Different Ranges of Mean and Std of Precipitation, JJAS08, Day-8
e)
Land
f)
Ocean
Std of Prec (mm/day)
Mean Prec (mm/day)
60
50
40
30
20
10
5
10
15
20
25
30
50
45
40
35
30
25
20
15
10
5

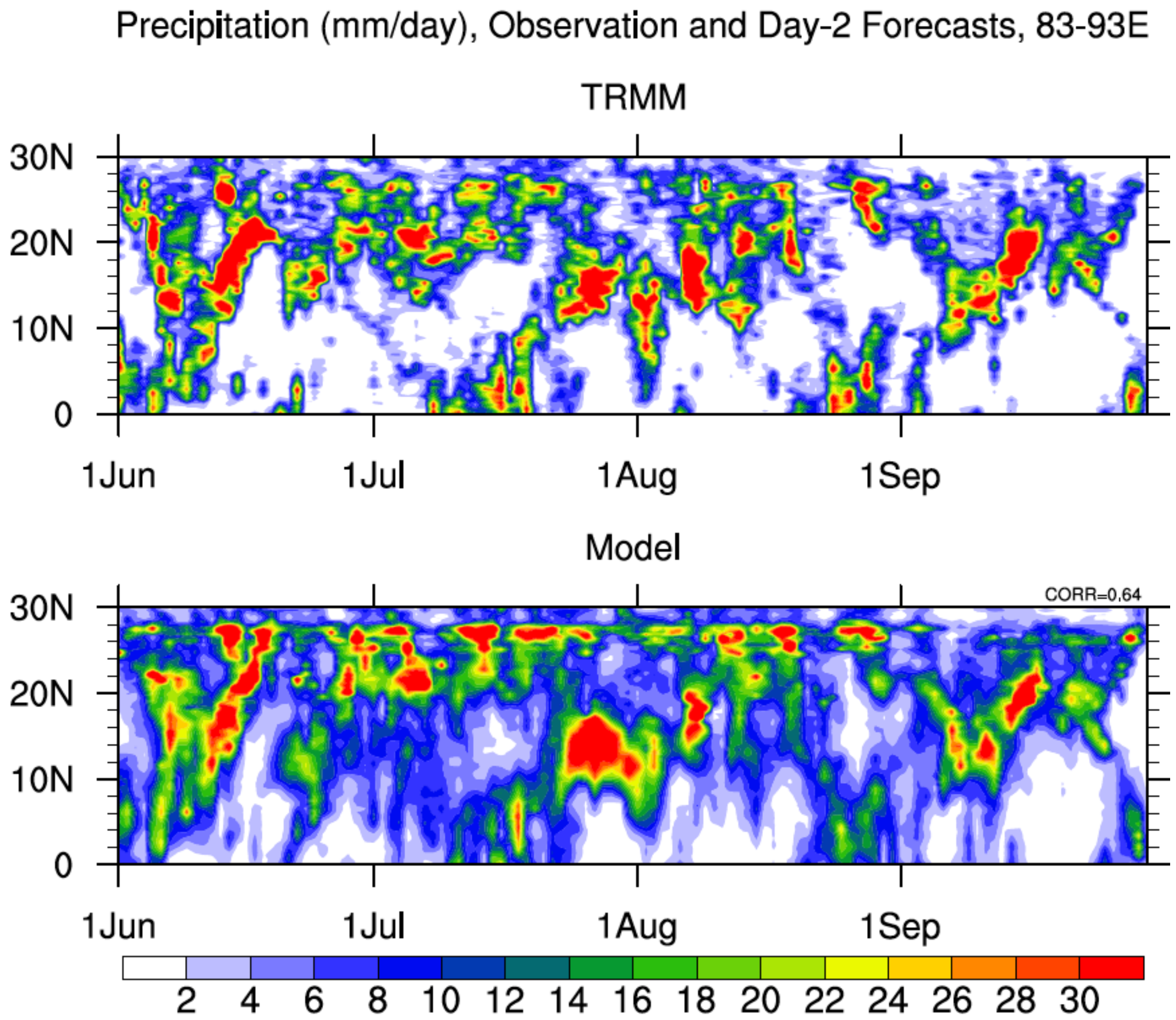


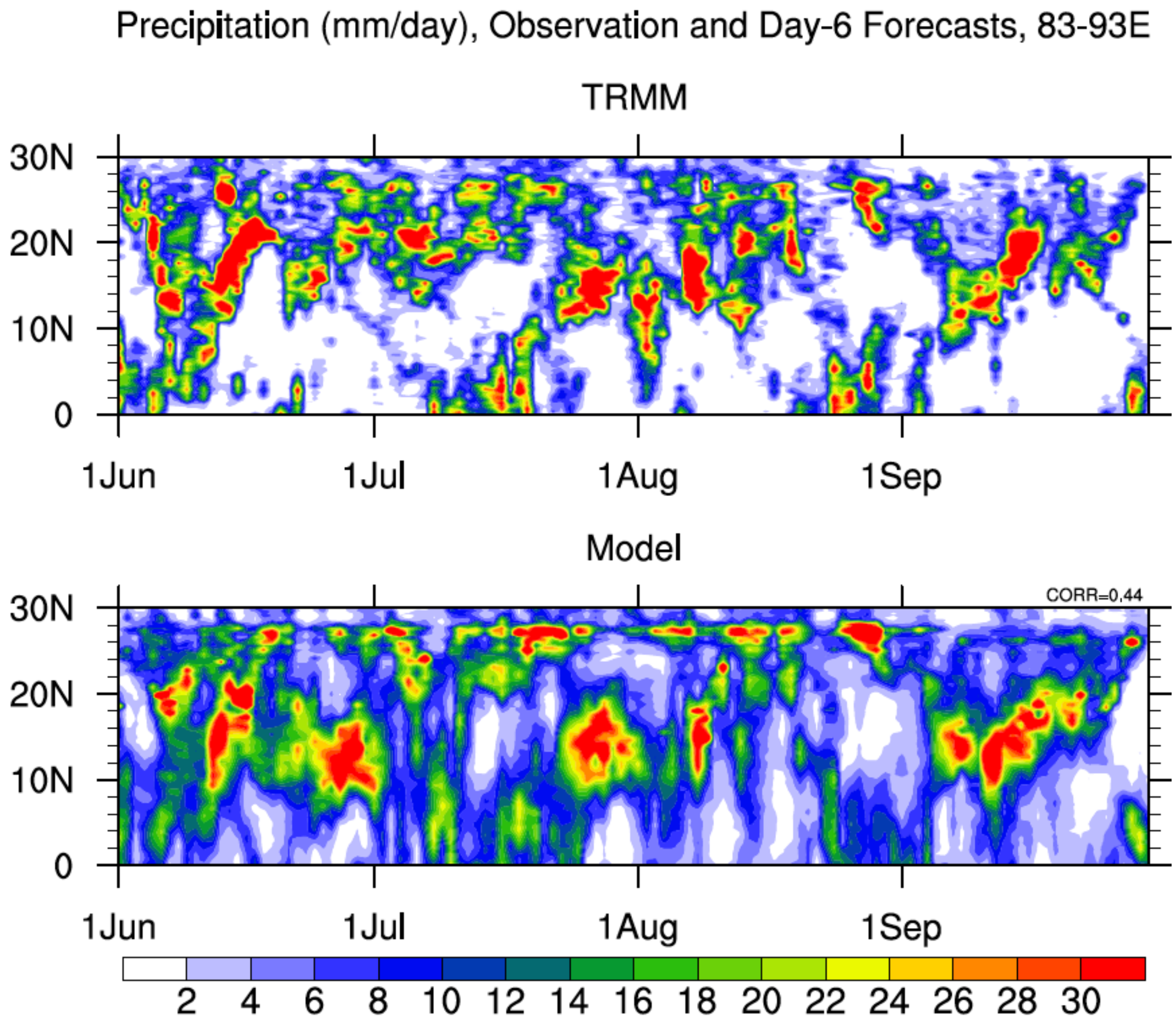
Chakraborty (2010, MWR)


Precipitation, 60–110E, 10S–30N
Land
a)
Prec (mm/day)
0
2
4
6
8
10
Jun
Jul
Aug
Sep
JJAS
Ocean
b)
TRMM
Forecasts

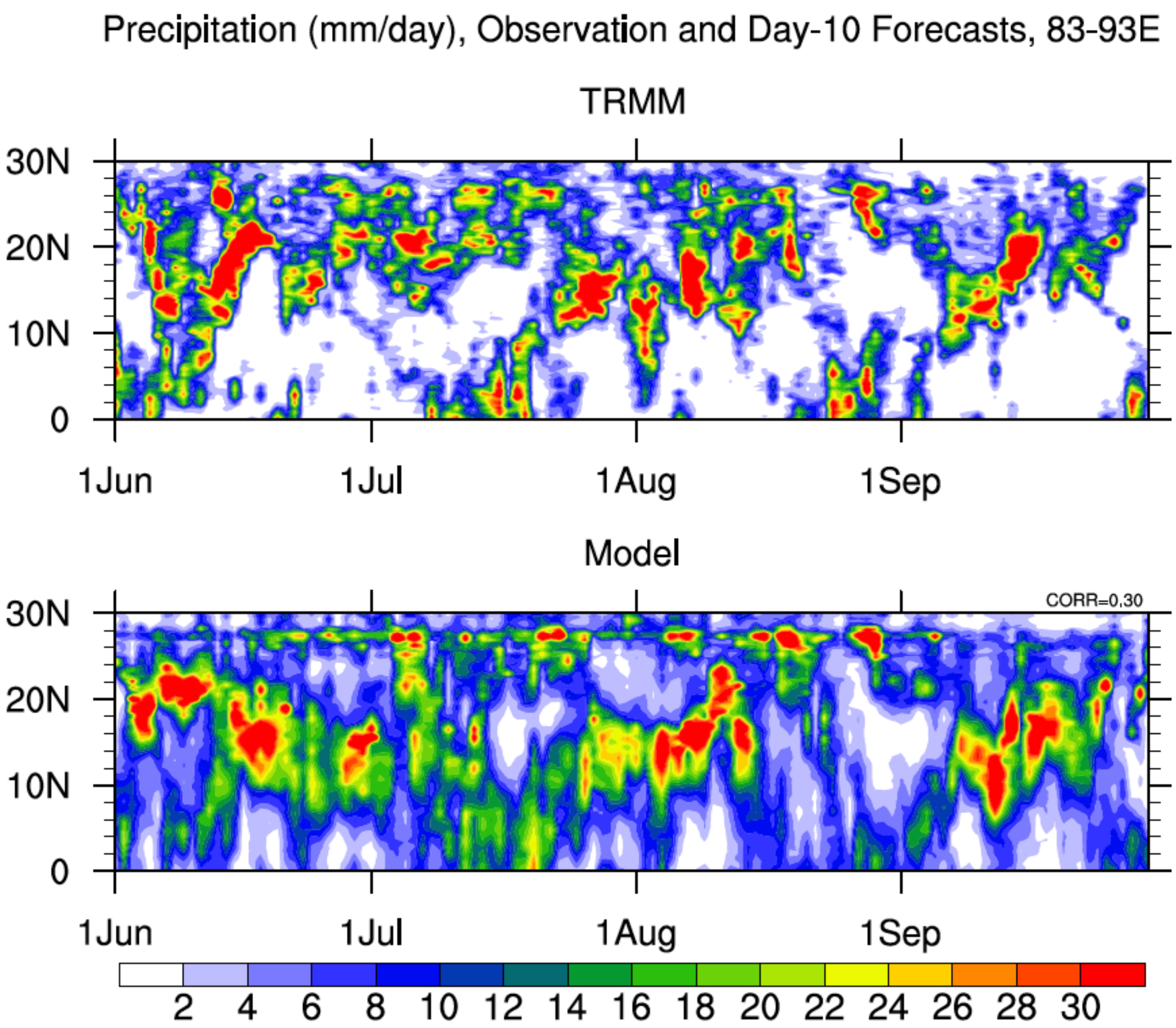


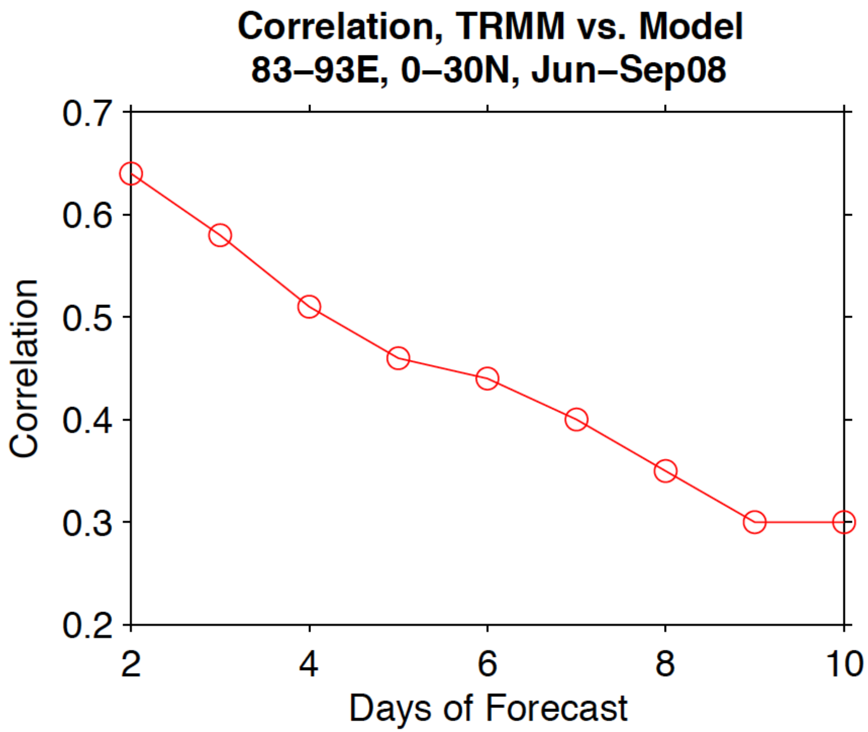
Error of 2m Temperature, 60-110E, 10S-30N, July 2008
a)
RMS Error
RMSE (K)
2.1
1.8
1.5
1.2
0.9
0.6
0.3
Ocean
Land
2 3 4 5 6 7 8 9 10
Days of Forecasts
b)
Spatial Correlation
Sp. Corr.
1.0
0.9
0.8
0.7
0.6
2 3 4 5 6 7 8 9 10
Days of Forecasts


Precipitation (mm/day), Observation and Day-2 Forecasts, 83-93E
TRMM
30N
20N
10N
0
1Jun
1Jul
1Aug
1Sep
Model
CORR=0.64
30N
20N
10N
0
1Jun
1Jul
1Aug
1Sep
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30



Precipitation (mm/day), Observation and Day-6 Forecasts, 83-93E
TRMM
30N
20N
10N
0
1Jun
1Jul
1Aug
1Sep
Model
CORR=0.44
30N
20N
10N
0
1Jun
1Jul
1Aug
1Sep
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30


Precipitation (mm/day), Observation and Day-10 Forecasts, 83-93E
TRMM
30N
20N
10N
0
1Jun
1Jul
1Aug
1Sep
Model
CORR=0.30
30N
20N
10N
0
1Jun
1Jul
1Aug
1Sep
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30


Correlation, TRMM vs. Model
83–93E, 0–30N, Jun–Sep08
0.7
0.6
0.5
0.4
0.3
0.2
Correlation
2
4
6
8
10
Days of Forecast

Spatial Scale of Meridional Propagation of Convection

Morlet Wavelet:

$$\psi_0(\eta) = \pi^{-0.25}\, e^{i\omega_0\eta}\, e^{-\eta^2/2}$$
$$= \underbrace{\sqrt{\frac{2}{\pi}}\, e^{i\omega_0\eta}}_{\text{Plain Wave}} \quad \underbrace{\frac{1}{\sqrt{2\pi}}\, e^{-\eta^2/2}}_{\text{N(0,1)}}$$

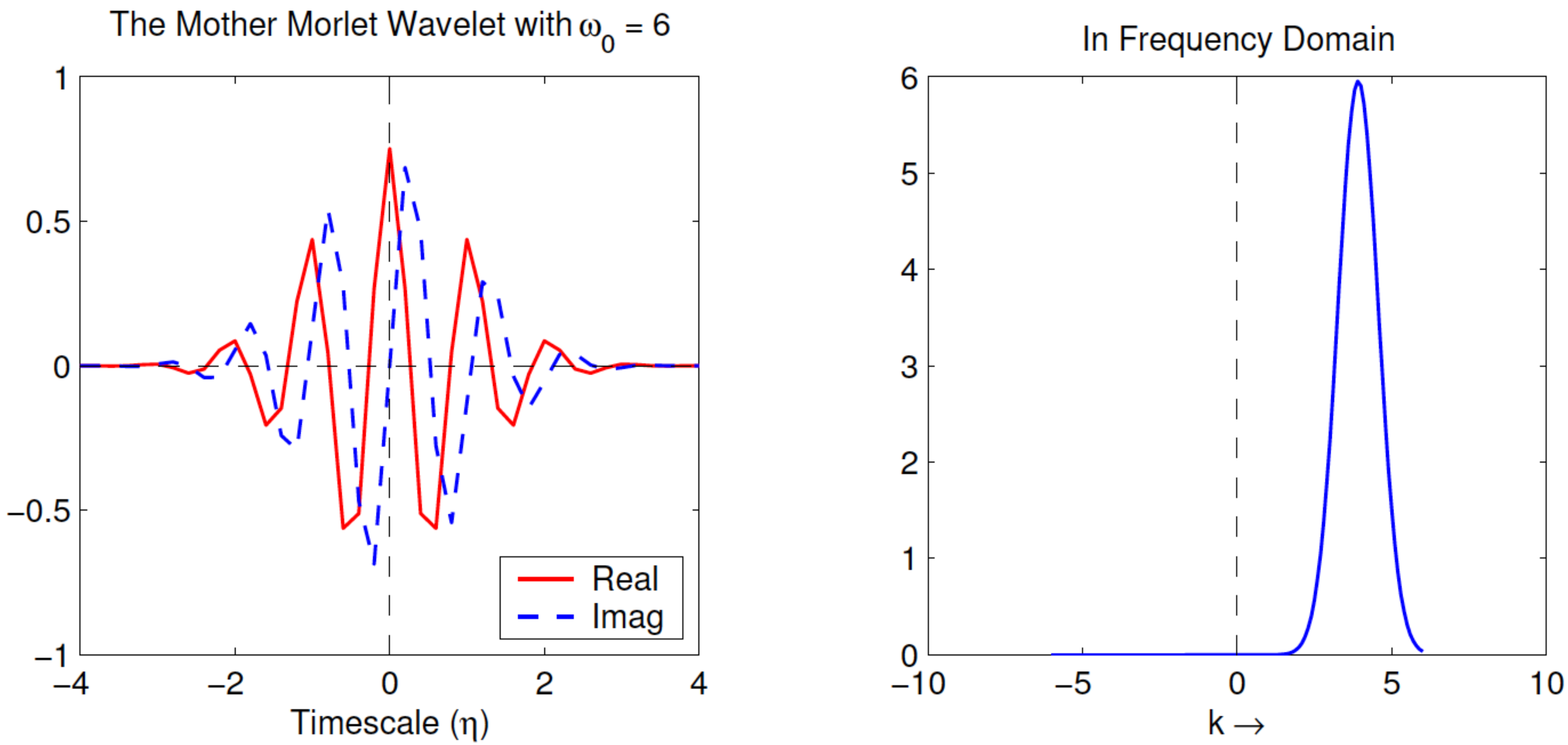
Wavelet transform of the time series **is the convolution of a scaled and translated** 98 version of this wavelet function:

$$W_n(s) = \sum_{n'=0}^{N-1} y_{n'} * \psi^* \left(\frac{(n' - n)\delta t}{s} \right)$$

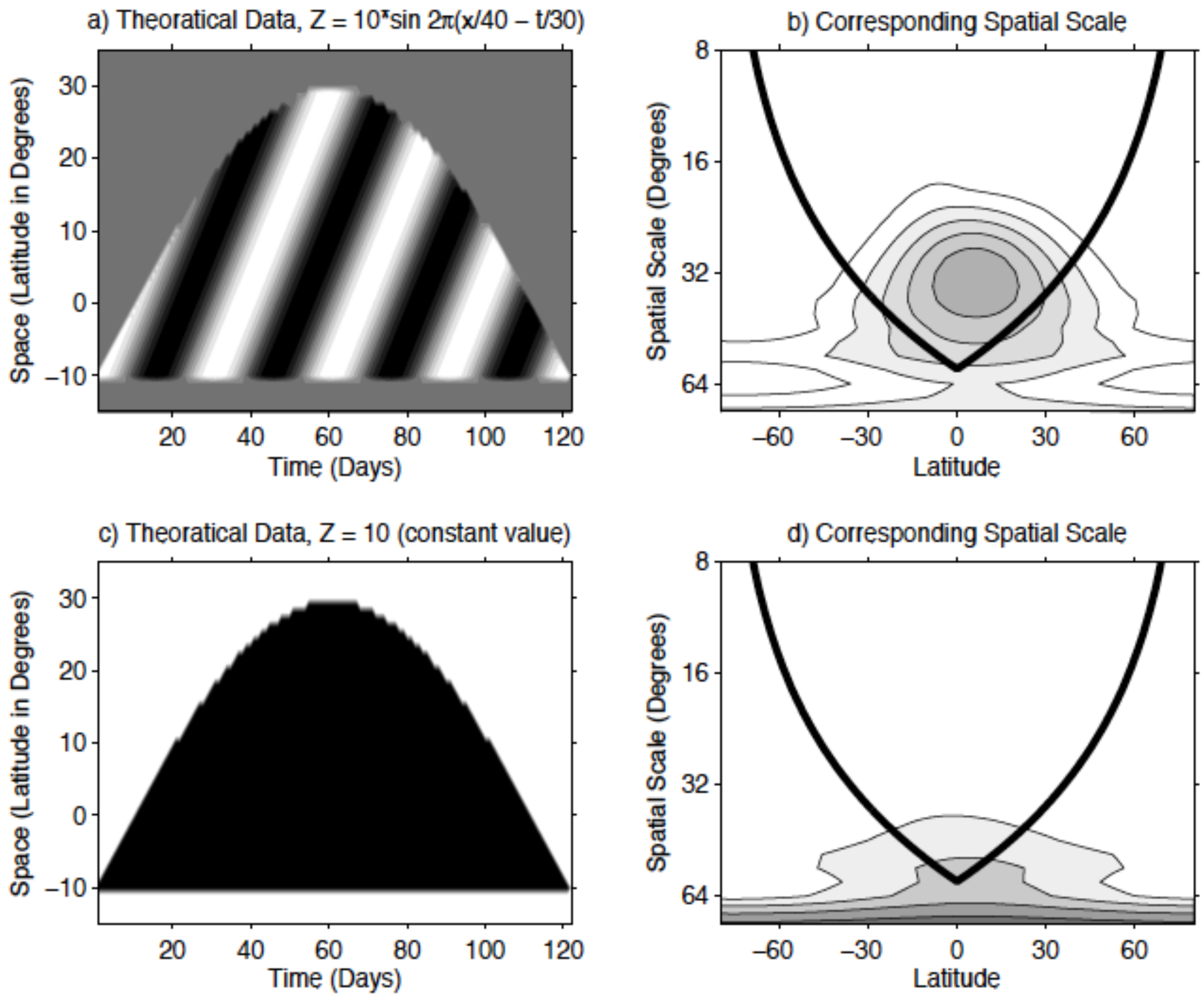
Final field after 2-dimensional wavelet analysis:

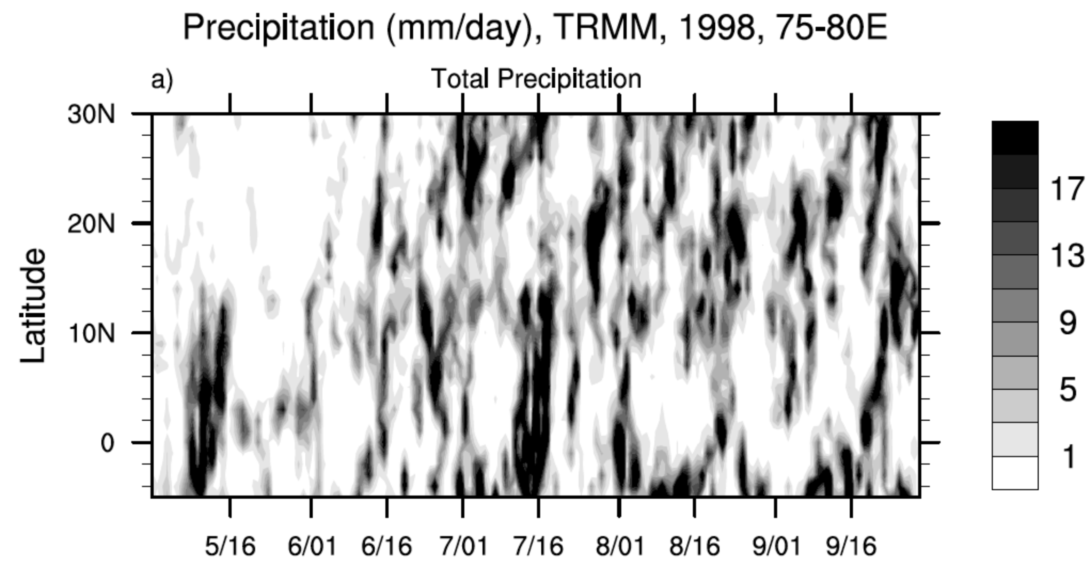
$$w(s_y, y, s_t, t) = g(s_y, y, t) * \frac{1}{\sqrt{s_t}}\, \psi_0 \left(\frac{t}{s_t} \right)$$

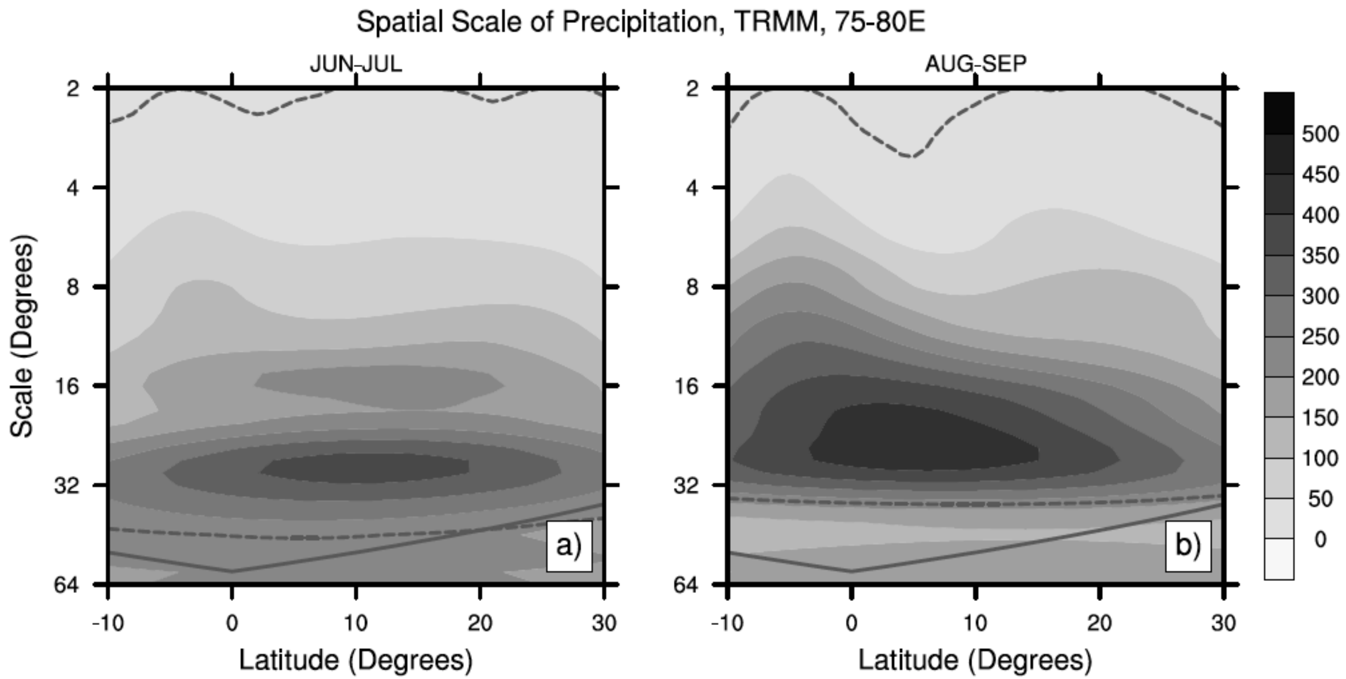
Chakraborty and Nanjundiah (2012, MWR)

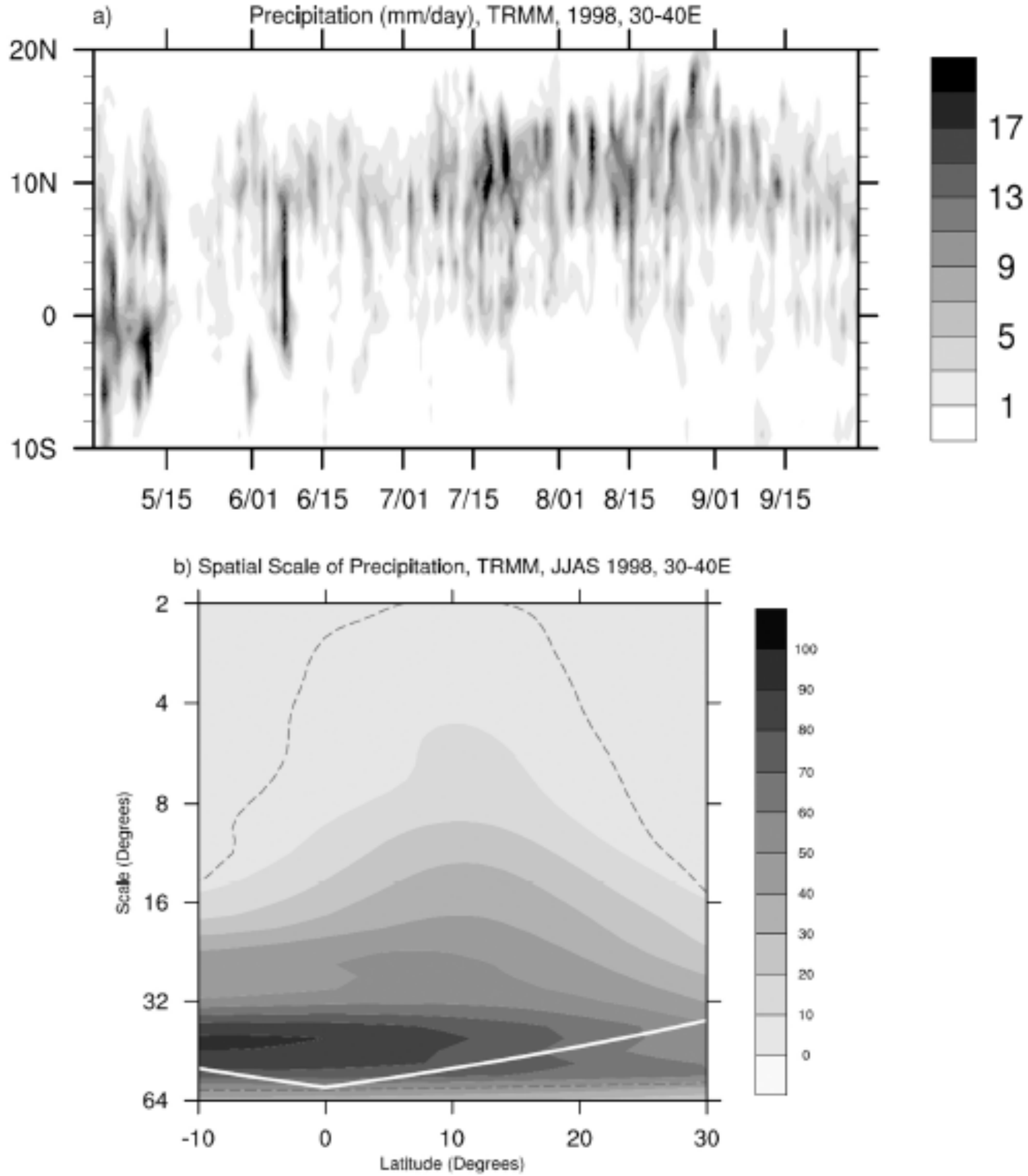


The Mother Morlet Wavelet with ω0 = 6
1
0.5
0
−0.5
−1
−4
−2
0
2
4
Timescale (η)
Real
Imag
In Frequency Domain
6
5
4
3
2
1
0
−10
−5
0
5
10
k →

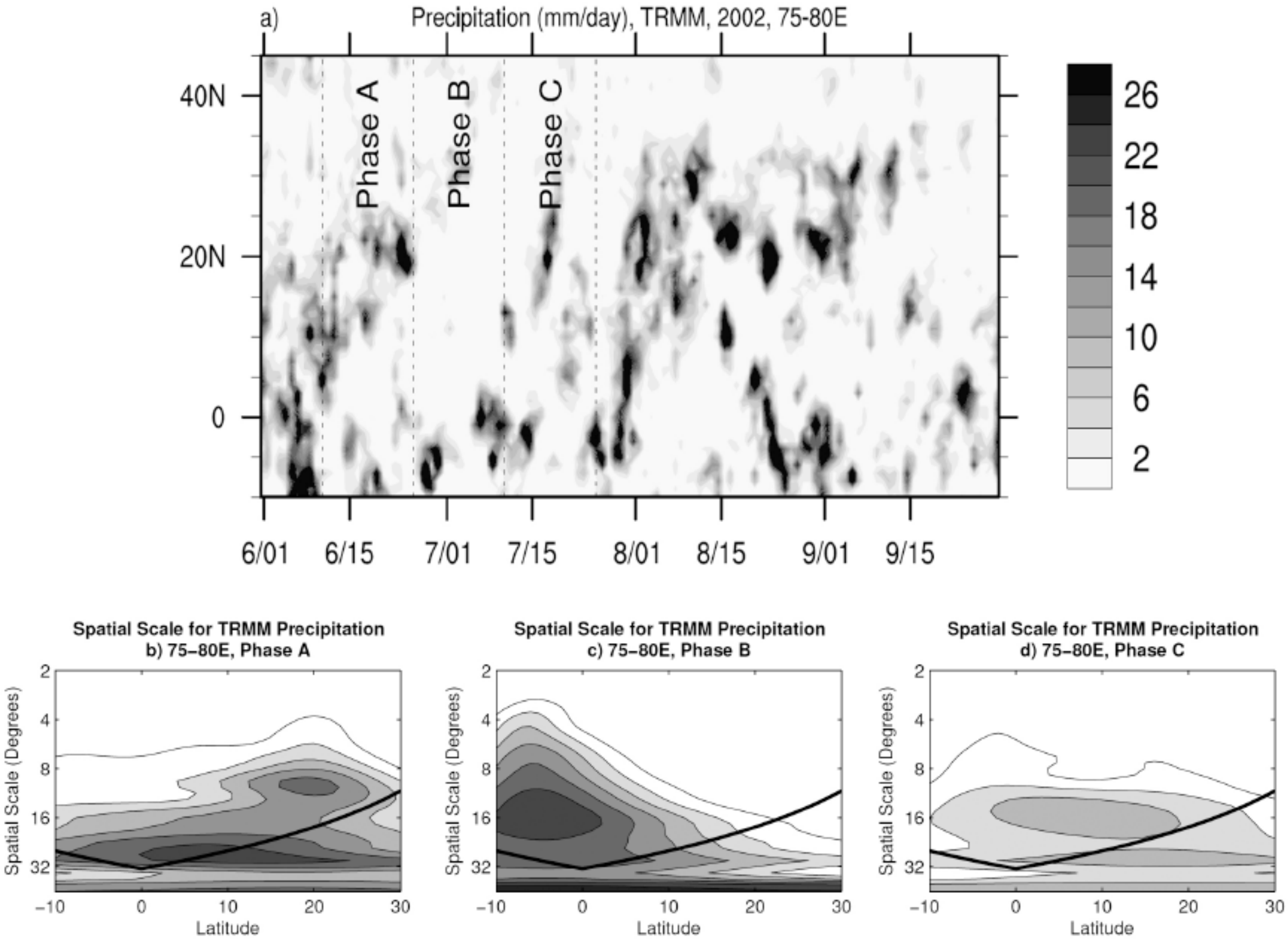

a) Theoratical Data, Z = 10*sin 2π(x/40 – t/30)
Space (Latitude in Degrees)
30
20
10
0
–10
20
40
60
80
100
120
Time (Days)
b) Corresponding Spatial Scale
Spatial Scale (Degrees)
8
16
32
64
–60
–30
0
30
60
Latitude
c) Theoratical Data, Z = 10 (constant value)
Space (Latitude in Degrees)
30
20
10
0
–10
20
40
60
80
100
120
Time (Days)
d) Corresponding Spatial Scale
Spatial Scale (Degrees)
8
16
32
64
–60
–30
0
30
60
Latitude

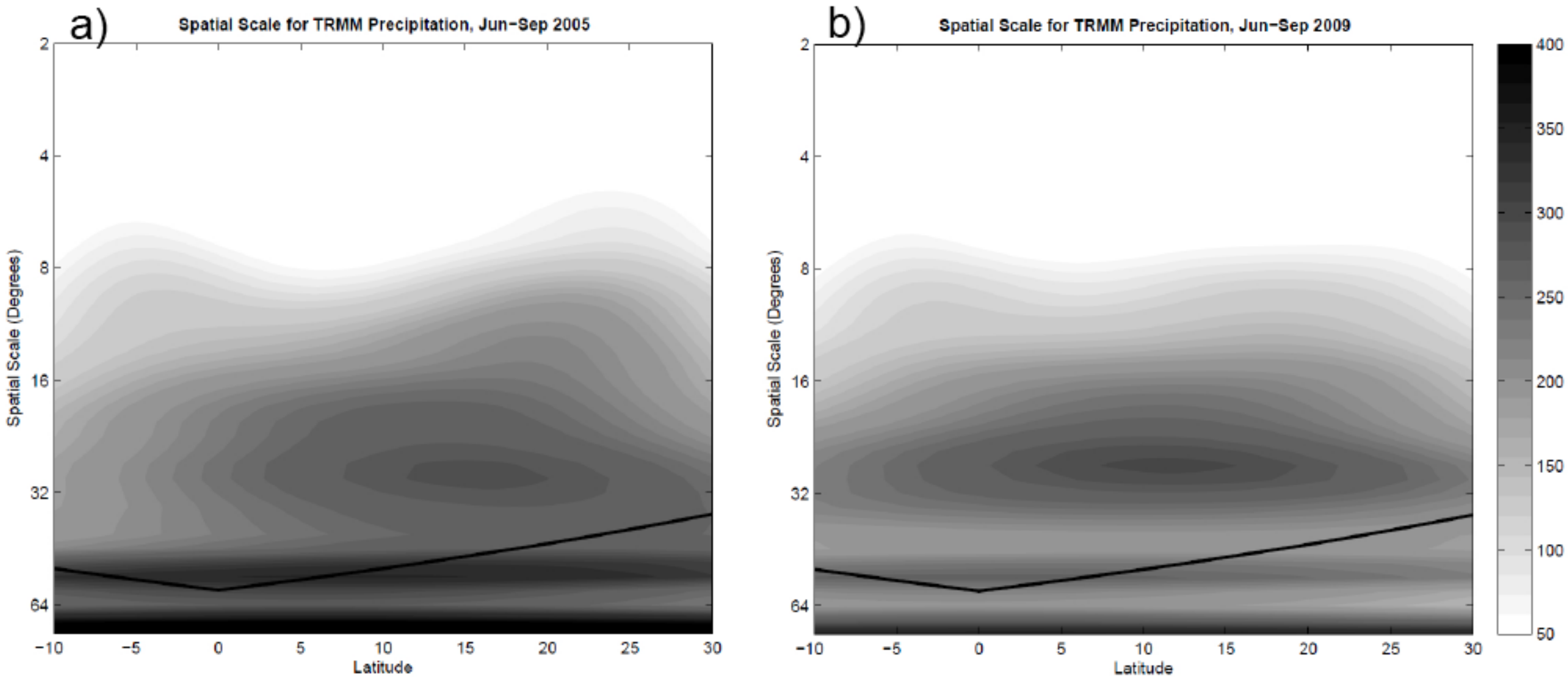

Precipitation (mm/day), TRMM, 1998, 75-80E
a)
Total Precipitation
30N
20N
10N
0
Latitude
5/16
6/01
6/16
7/01
7/16
8/01
8/16
9/01
9/16
17
13
9
5
1


Spatial Scale of Precipitation, TRMM, 75-80E
JUN-JUL
AUG-SEP
Scale (Degrees)
2
4
8
16
32
64
-10
0
10
20
30
Latitude (Degrees)
a)
b)
500
450
400
350
300
250
200
150
100
50
0

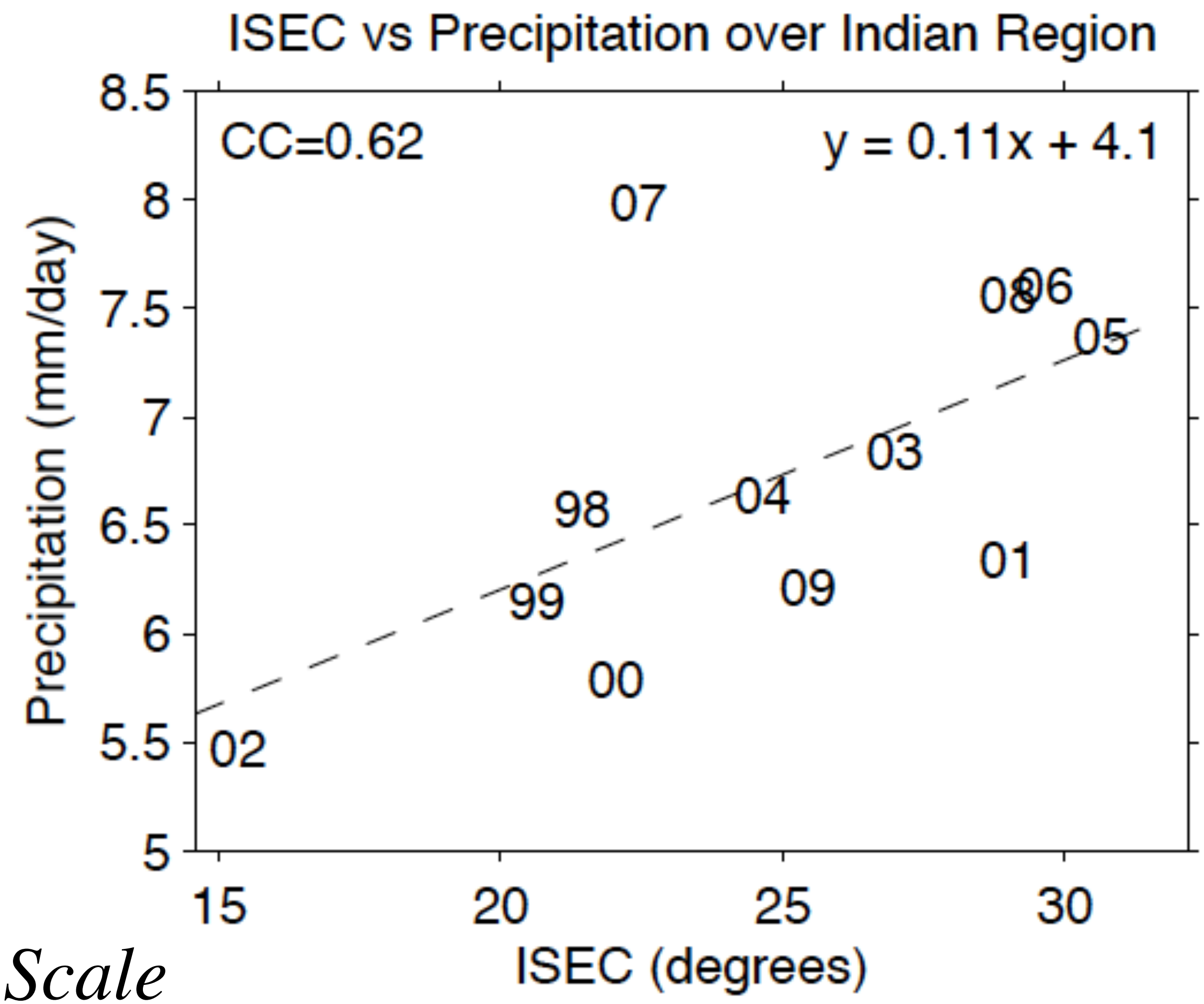


a)
Precipitation (mm/day), TRMM, 1998, 30-40E
20N
10N
0
10S
5/15
6/01
6/15
7/01
7/15
8/01
8/15
9/01
9/15
17
13
9
5
1
b) Spatial Scale of Precipitation, TRMM, JJAS 1998, 30-40E
Scale (Degrees)
2
4
8
16
32
64
-10
0
10
20
30
Latitude (Degrees)
100
90
80
70
60
50
40
30
20
10
0

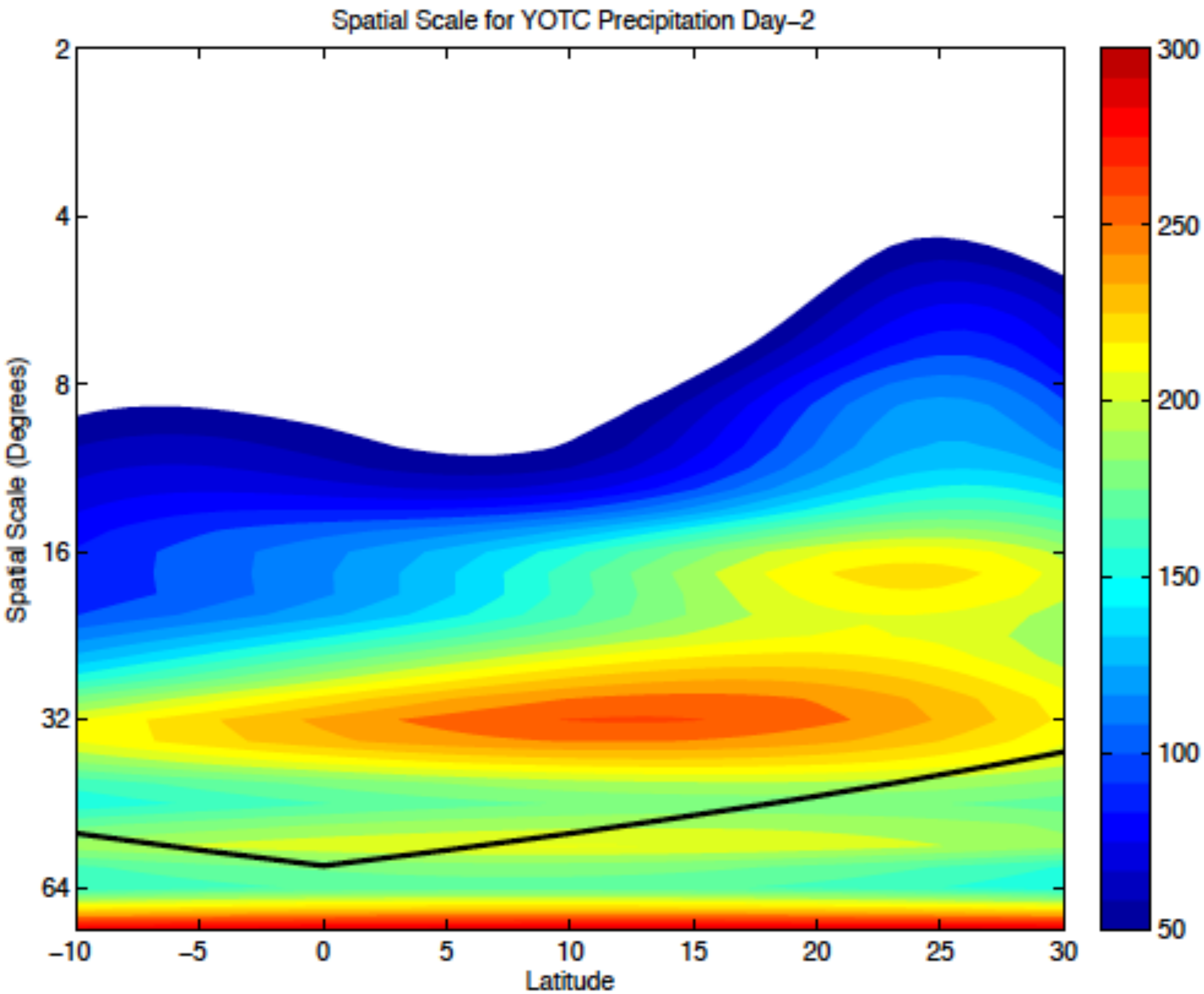

a)
Precipitation (mm/day), TRMM, 2002, 75-80E
Phase A
Phase B
Phase C
40N
20N
0
6/01
6/15
7/01
7/15
8/01
8/15
9/01
9/15
26
22
18
14
10
6
2
Spatial Scale for TRMM Precipitation
b) 75−80E, Phase A
Spatial Scale for TRMM Precipitation
c) 75−80E, Phase B
Spatial Scale for TRMM Precipitation
d) 75−80E, Phase C
Spatial Scale (Degrees)
Latitude


a)
Spatial Scale for TRMM Precipitation, Jun−Sep 2005
Spatial Scale (Degrees)
2
4
8
16
32
64
−10
−5
0
5
10
15
20
25
30
Latitude
b)
Spatial Scale for TRMM Precipitation, Jun−Sep 2009
Spatial Scale (Degrees)
Latitude
400
350
300
250
200
150
100
50

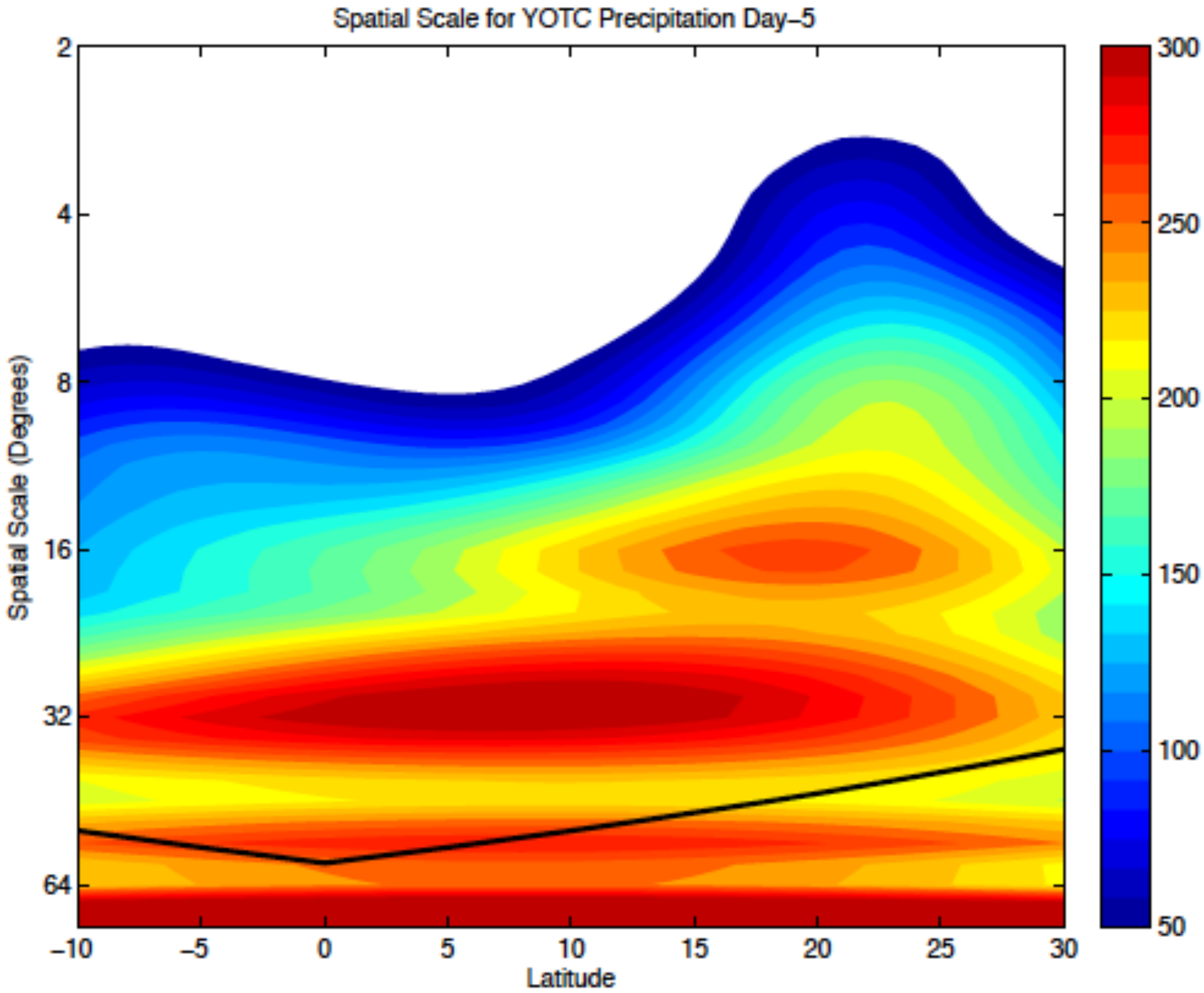
Index for the Spatial Extent of Convection



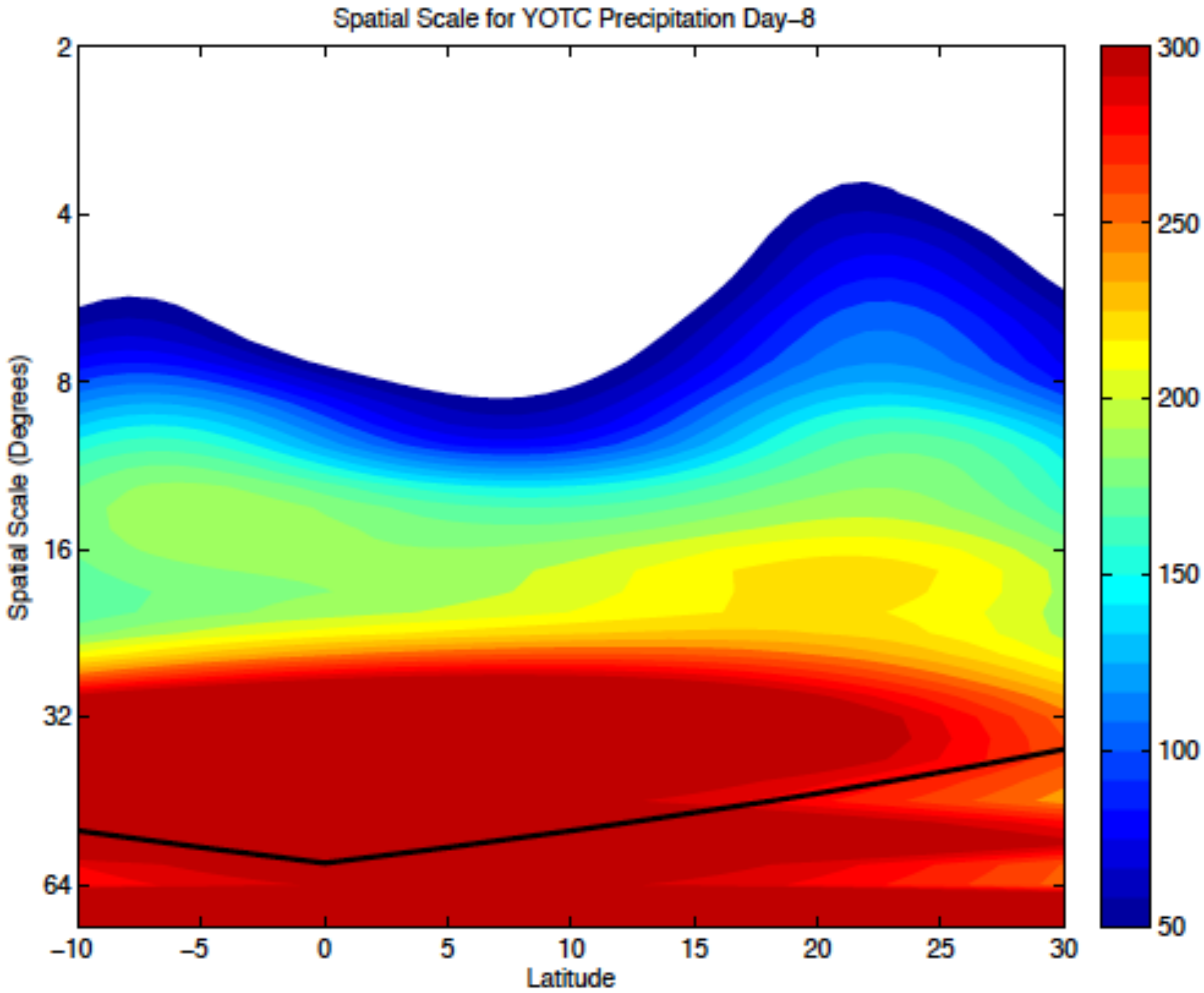
$$ISEC = Lat + \frac{Scale}{2}$$



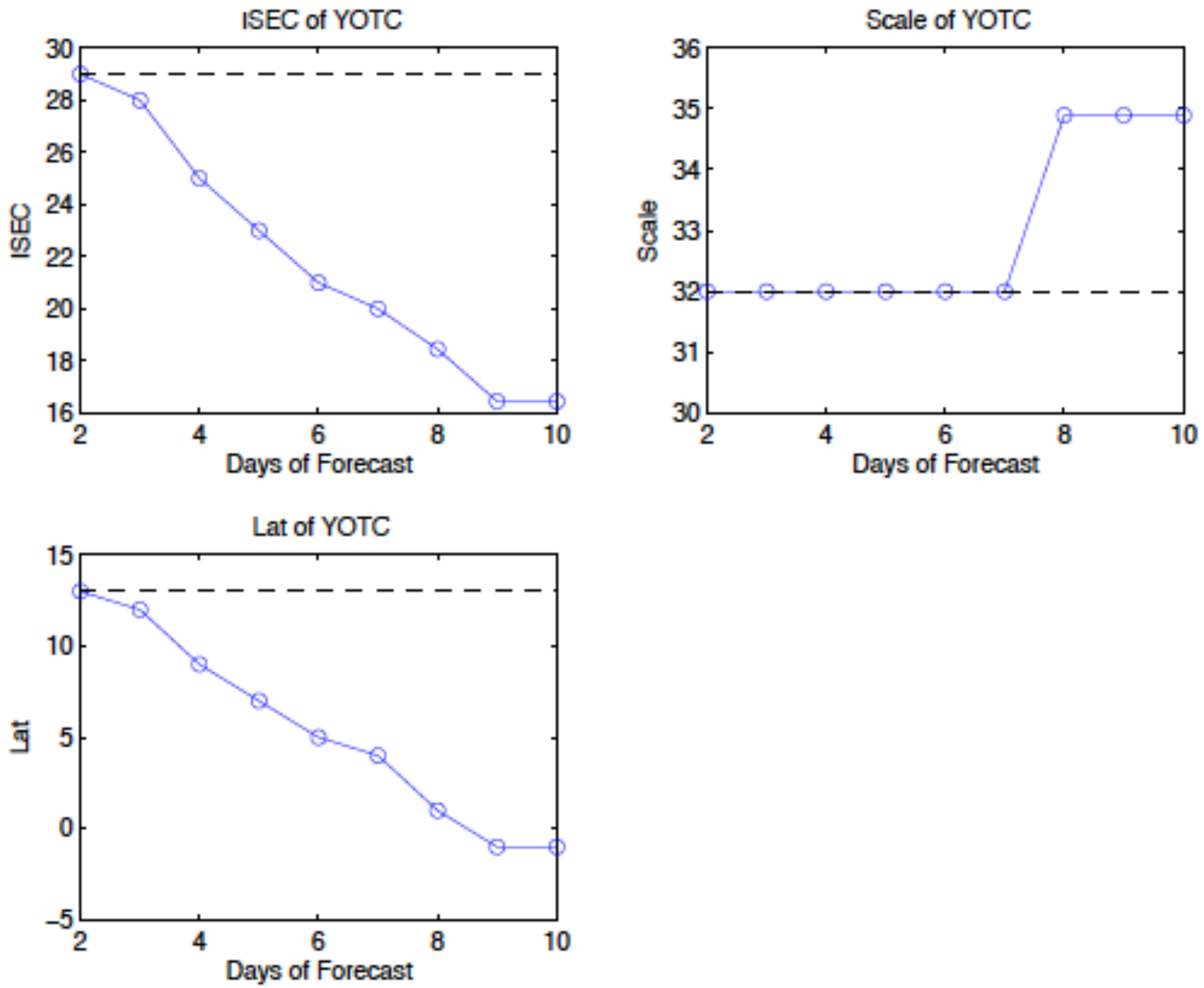
Spatial Scale for YOTC Precipitation Day−2
Spatial Scale (Degrees)
2
4
8
16
32
64
−10
−5
0
5
10
15
20
25
30
Latitude
300
250
200
150
100
50



Spatial Scale for YOTC Precipitation Day–5
Spatial Scale (Degrees)
2
4
8
16
32
64
–10
–5
0
5
10
15
20
25
30
Latitude
300
250
200
150
100
50

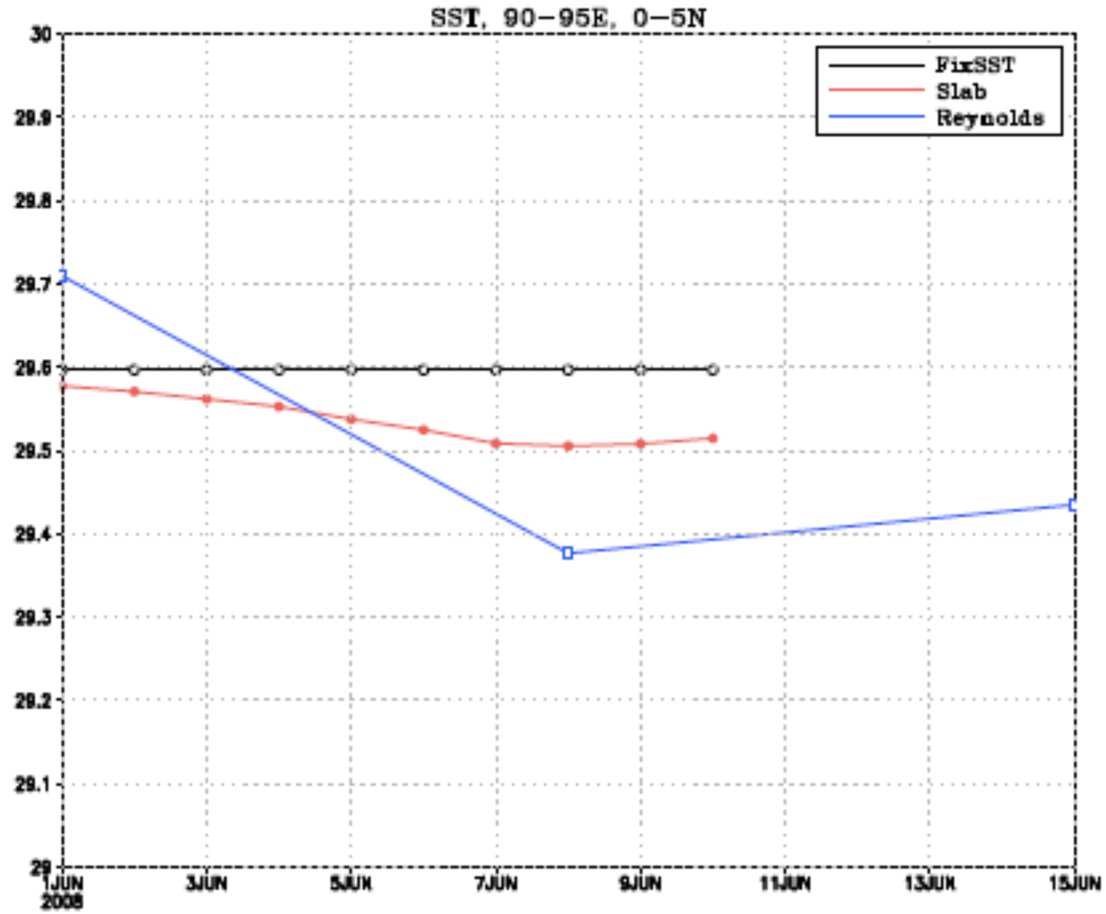


Spatial Scale for YOTC Precipitation Day–8
Spatial Scale (Degrees)
2
4
8
16
32
64
–10
–5
0
5
10
15
20
25
30
Latitude
300
250
200
150
100
50


ISEC of YOTC
ISEC
Days of Forecast
Scale of YOTC
Scale
Days of Forecast
Lat of YOTC
Lat
Days of Forecast

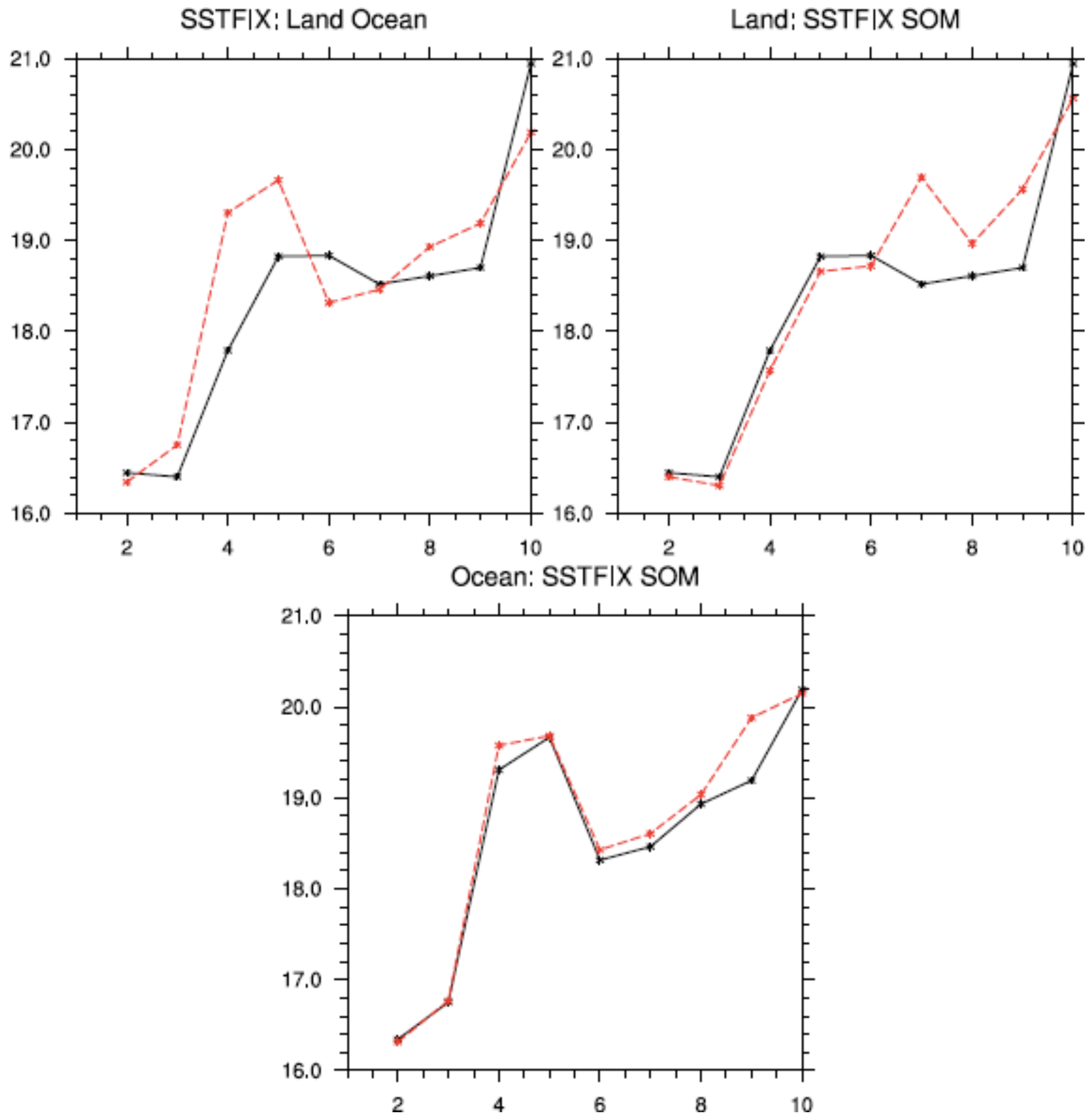
Model Details and Experiments

- Seasonal Forecast Model (SFM) with T170 resolution.
- Grid size is about 0.7 deg near the Equator.
- 10-day long forecast with fixed SST and slab ocean model.
- Slab ocean model (SOM) with climatological mixed layer depth, solar radiation transmission (based on Ohlmann and Siegel 2000) depends on clouds and angle of zenith angle (chlorophyll).
- 10-day long experiments were performed from end of May through June of 2008, starting at 00 GMT of every day.

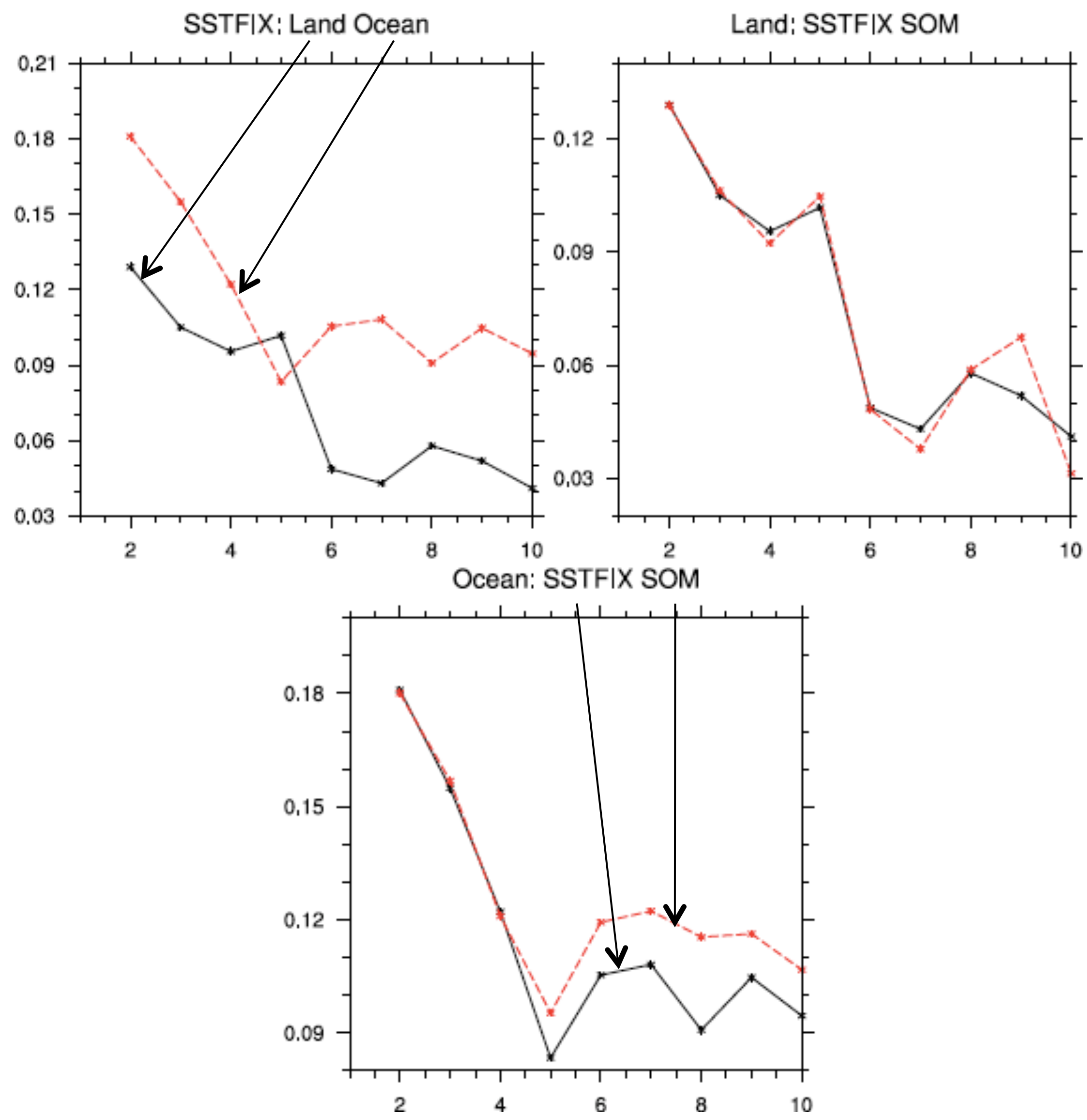


SST, 90−95E, 0−5N
FixSST
Slab
Reynolds
30
29.9
29.8
29.7
29.6
29.5
29.4
29.3
29.2
29.1
29
1JUN
2008
3JUN
5JUN
7JUN
9JUN
11JUN
13JUN
15JUN

RMS Error in Precipitation over South Asian Monsoon Region



Spatial Correlation in Precipitation over South Asian Monsoon Region



1) ECMWF model generally overestimates precipitation over tropical land and ocean for days 2 through 10 of forecasts.
2) Over the south Asian region, forecasted precipitation over the ocean is higher for longer lead time.
3) Rate of growth of error is larger over ocean as compared to that over land. This is probably due to lack of two-way air-sea interaction in the model.
4) Preliminary experiments suggest that at longer lead time skill over ocean can be improved with a slab ocean model coupled to the GCM.
5) An atmospheric model coupled with a slab ocean model seems to improve the medium range forecast skill.

A typical diagnostic cloud scheme

- o Radiation code of the model allows cloud to form at any layer.
- o Cloud amount is determined from the relative humidity.
- o If layer mean (mass weighted) relative humidity exceeds a specified threshold value cloud is present in that grid at that layer.
- o The cloud amount is

$$cc = \left(\frac{rh - rh_c}{1 - rh_c}\right)^2$$

where rh_c is the threshold relative humidity:

Cloud type	rh_c
High	0.40
Middle	0.45
Low	0.70

⇨ High cloud amount is corrected using the convective precipitation (if non-zero):

$$cc_h = 4(0.247 + 0.126 \ln P - 0.3)^2$$

where P is precipitation in mm.

- Earlier cloud schemes used relative humidity (RH) threshold criteria for estimating cloud amount.
- Modifications to those schemes used other parameters like stability and vertical velocity as modifiers to RH based cloud fraction.

Prognostic Cloud Scheme

- Clouds and precipitation are tightly coupled to each other in nature.
- However, in large-scale global general circulation models (GCM), clouds are treated separately with precipitation.

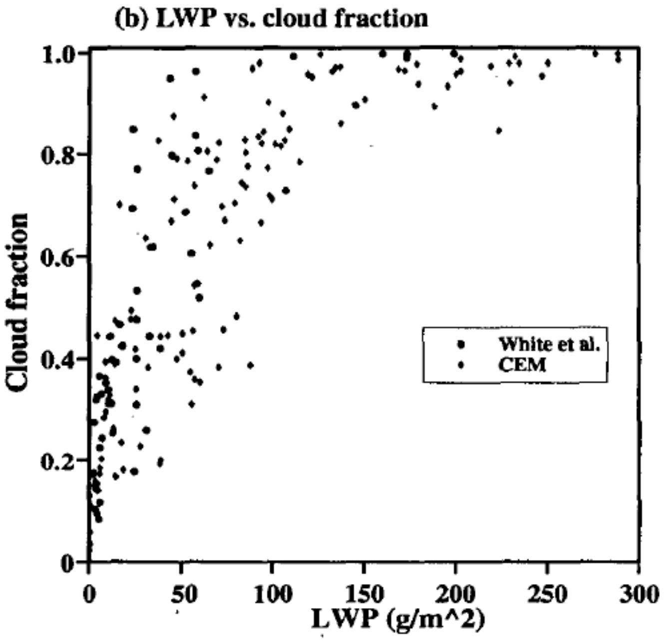
- A prognostic cloud scheme includes and predicts cloud fractions and cloud liquid/ice water mixing ratio as prognostic variables.
- The cloud optical properties are interactive in such schemes.
- Moreover, prognostic cloud schemes can contain all important cloud microphysical processes such as autoconversion, accretion and cloud/rain water evaporation.

➢ Mass balance equation for cloud-water/ice content:

$$\frac{d}{dt}\int \rho_w dV = S_w - D_w$$

Cloud Scheme in GFS

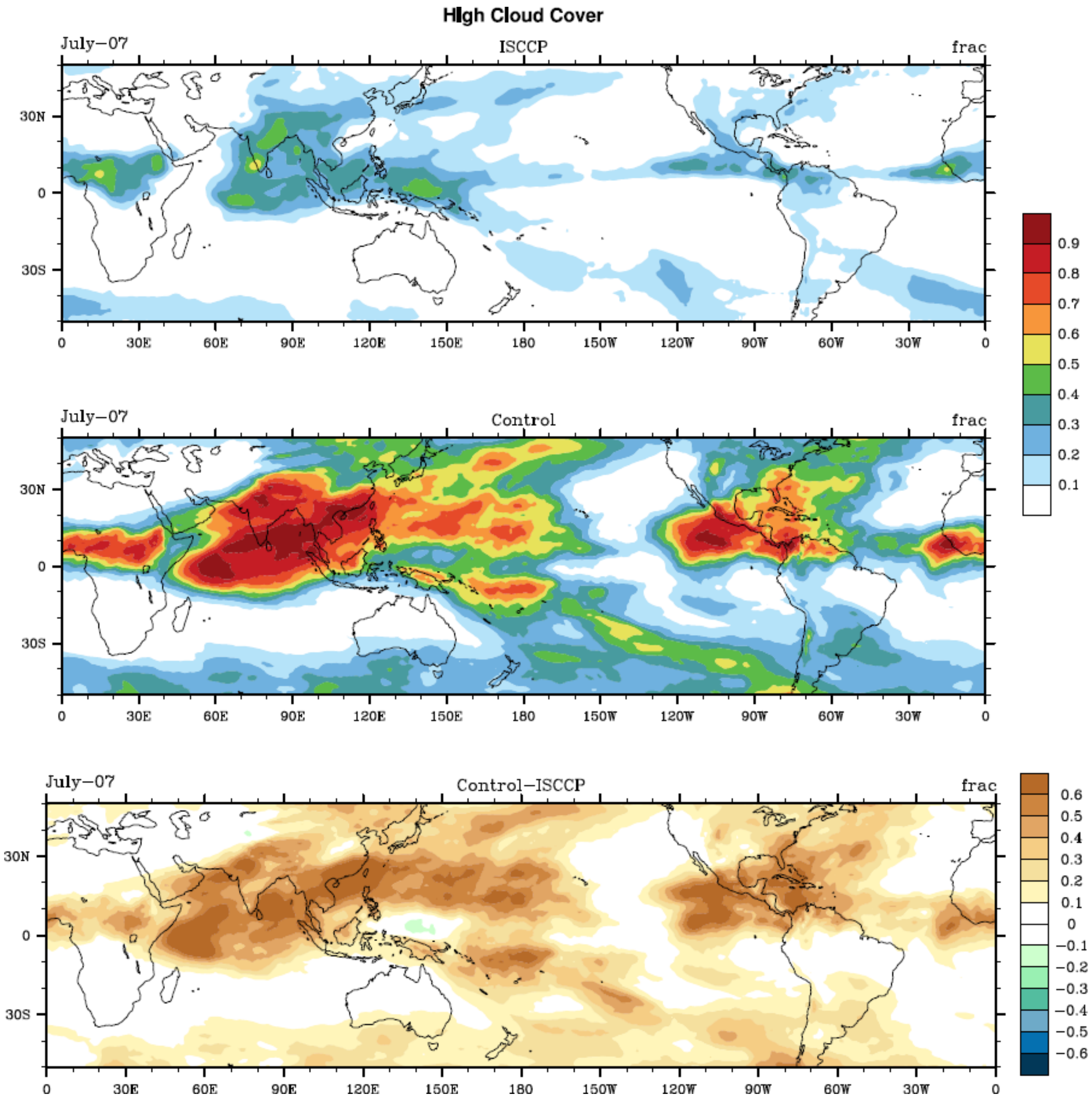
- The new version (v2) of the global forecast system (GFS) model uses a prognostic cloud scheme.
- The scheme is based on Zhao and Carr (1997), Xu and Randall (1996), and Moorthi et al (2001).
- Cloud fraction is calculated using cloud liquid and ice water mixing ratio (q_l + q_i) and relative humidity (RH).

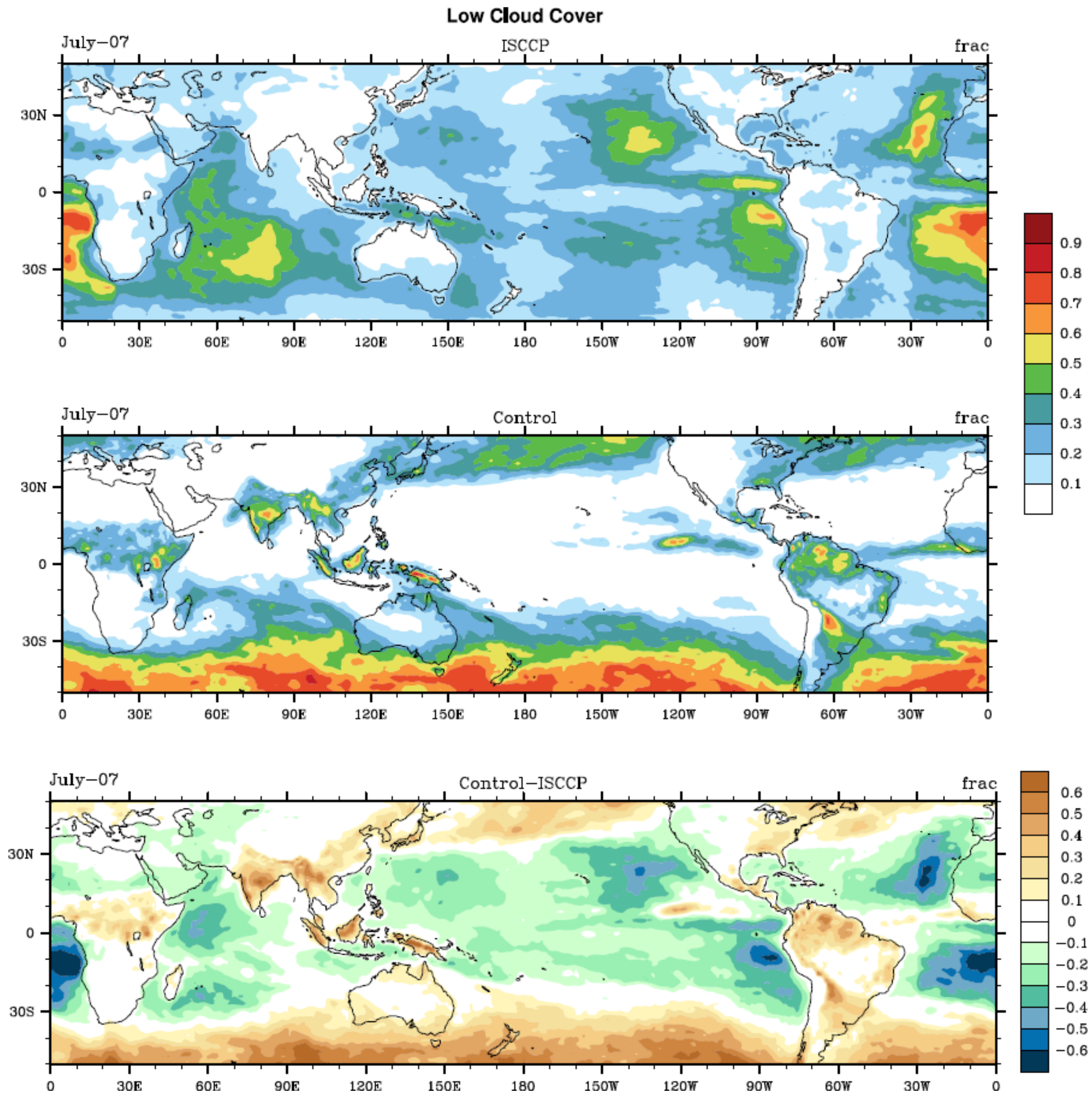


$$CC = RH^{0.25}\left(1 - \exp\left(-\frac{2000(q_l + q_i)}{((1 - RH)q_s)^{0.25}}\right)\right)$$

Model and Experimental Setup

1. Global Forecast System (GFS) model was used.
2. Resolution: T190 which corresponds to 0.64x0.64 degree in horizontal.
3. Model has 64 vertical hybrid sigma-pressure level.
4. Model was integrated for 35 days from 27 June 2007.
5. Initial condition from NCEP final analysis (FNL).
6. SST boundary condition prescribed from Reynolds weekly mean data.

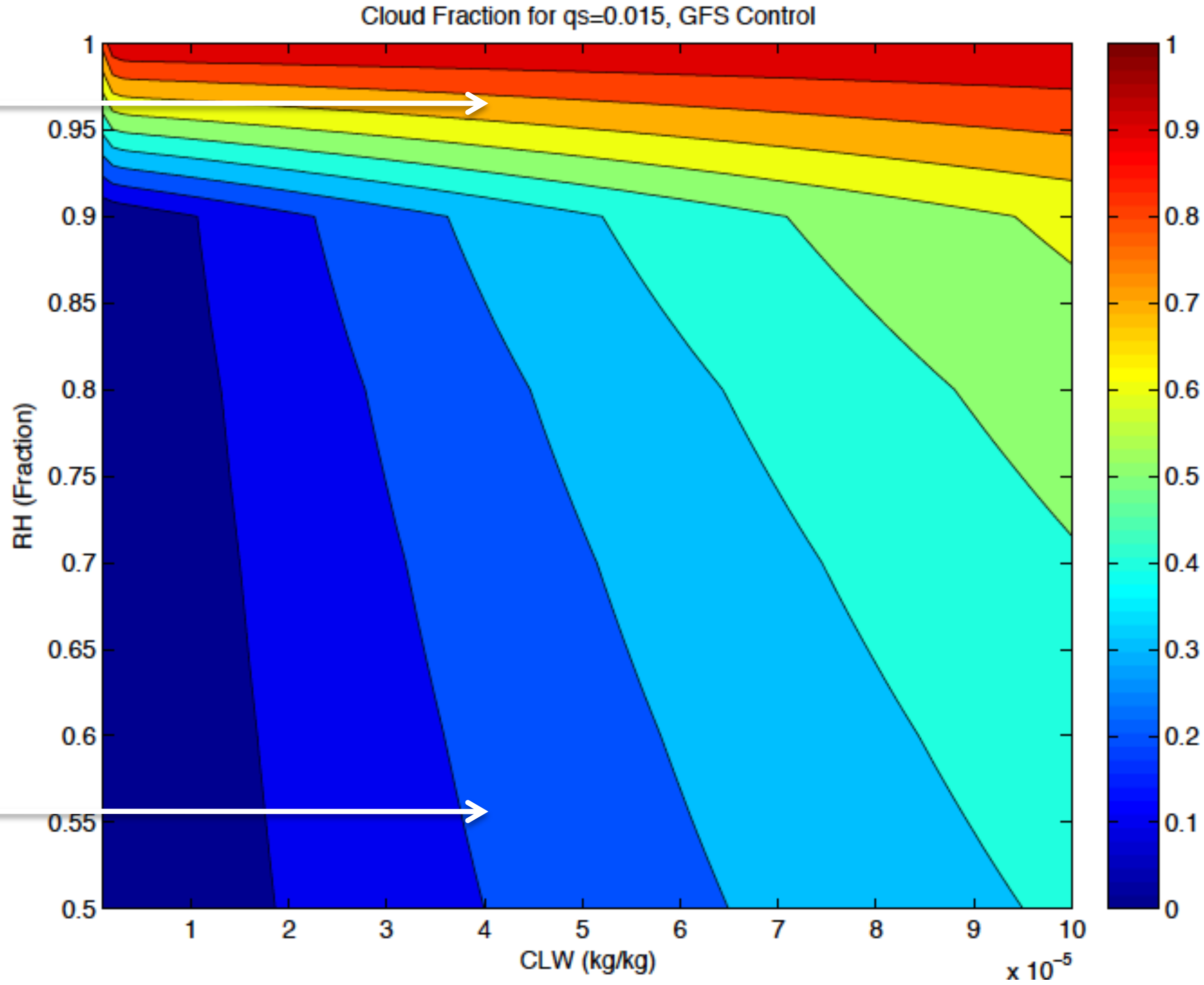

High Cloud Cover
July−07
ISCCP
frac
30N
0
30S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
July−07
Control
frac
July−07
Control−ISCCP
frac
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
−0.4
−0.5
−0.6



Low Cloud Cover
July−07
ISCCP
frac
30N
0
30S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
July−07
Control
frac
July−07
Control−ISCCP
frac
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
−0.4
−0.5
−0.6

Synthetic Cloud Fraction in GFS Control

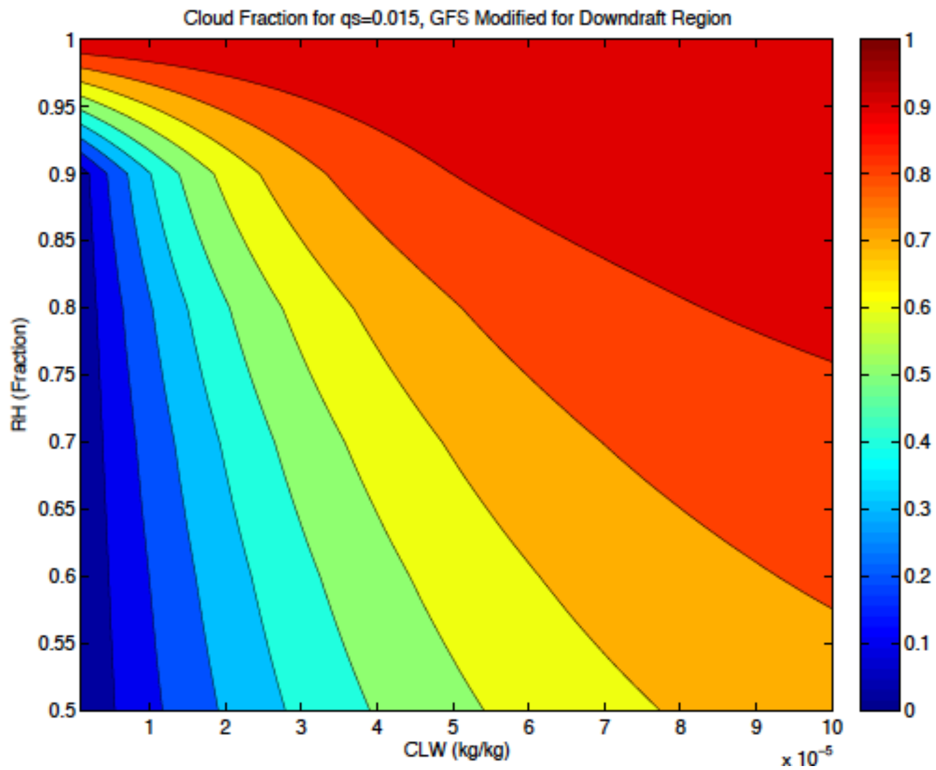
Less sensitive to CLW at high RH



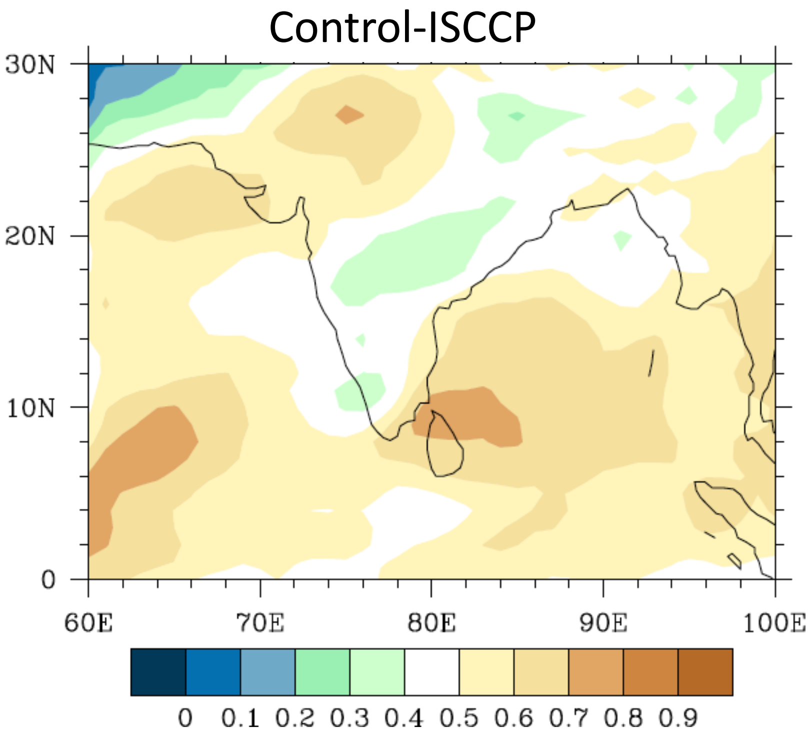
More sensitive to CLW at low RH

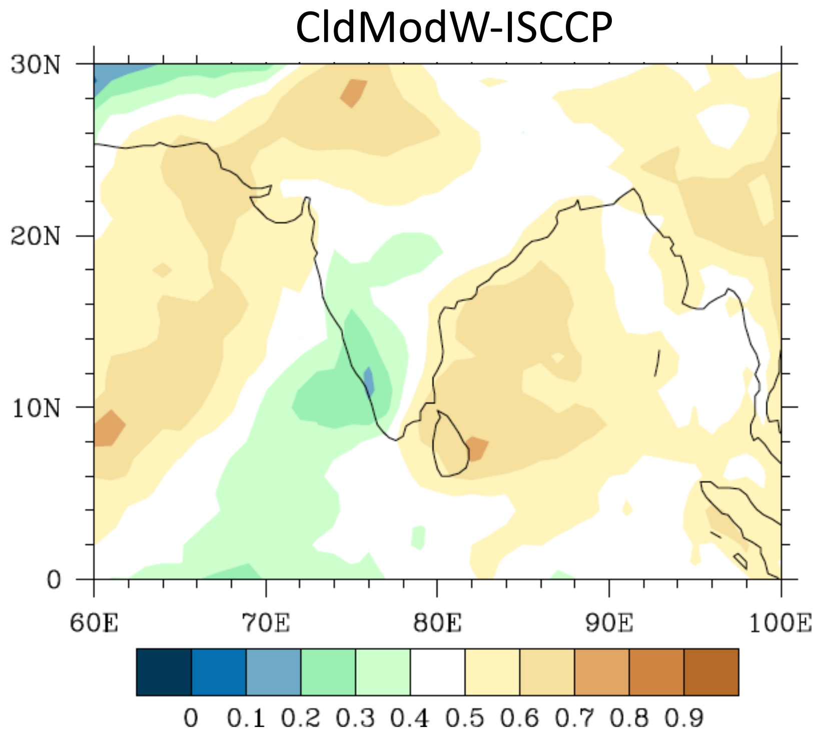
Synthetic cloud fraction in GFS Modified Scheme

1. Modified in the cloud scheme for more sensitivity to CLW in low RH regime.
2. Introduced vertical velocity criteria for calculation of low cloud fraction.

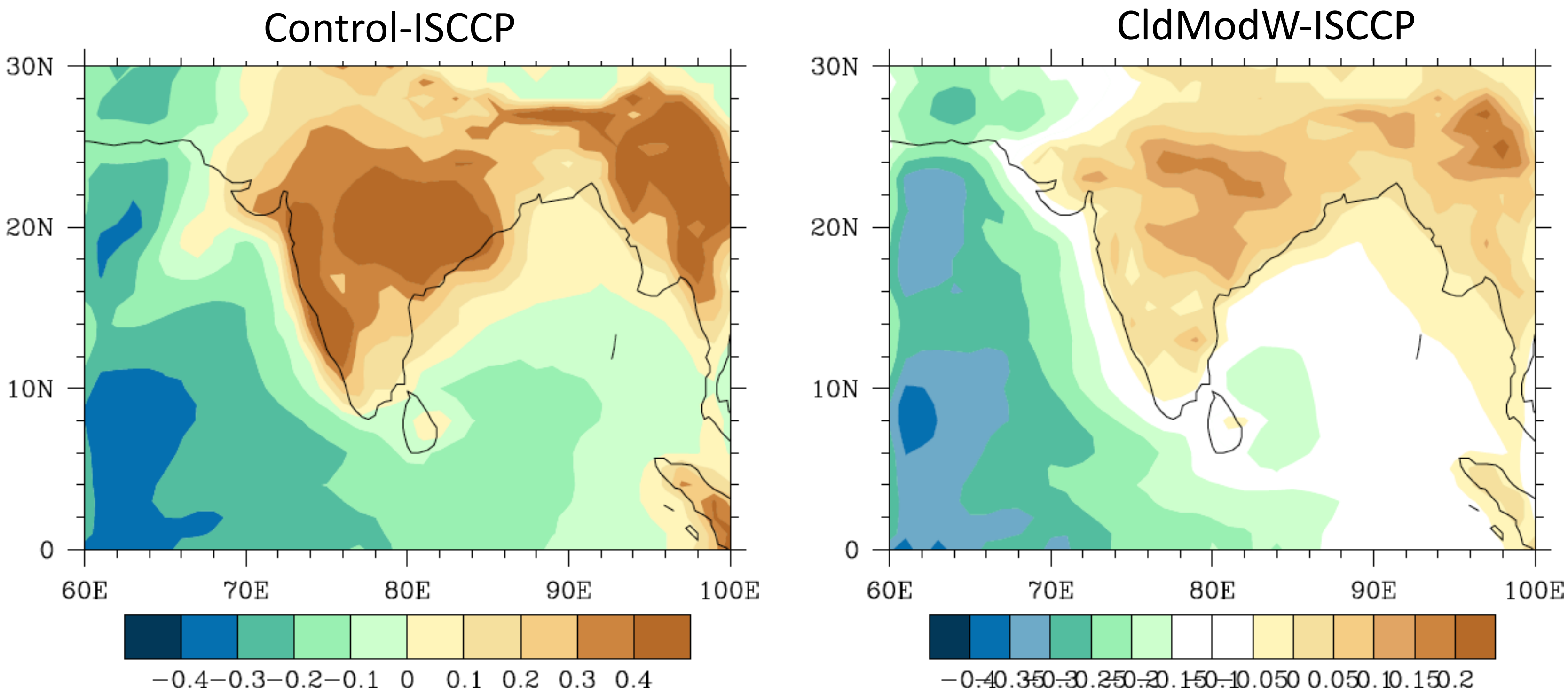


Error in High Cloud Cover, Jul07

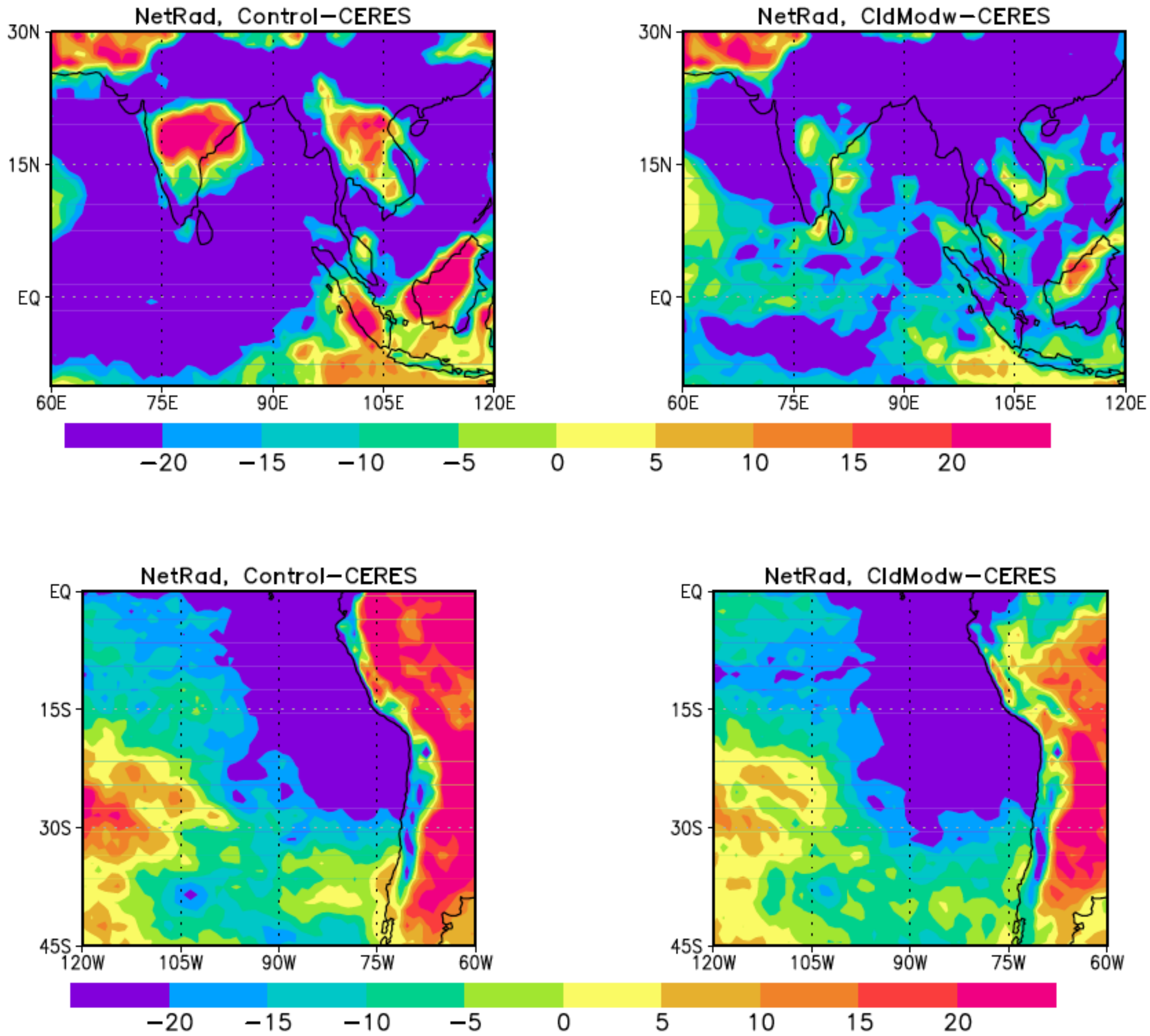


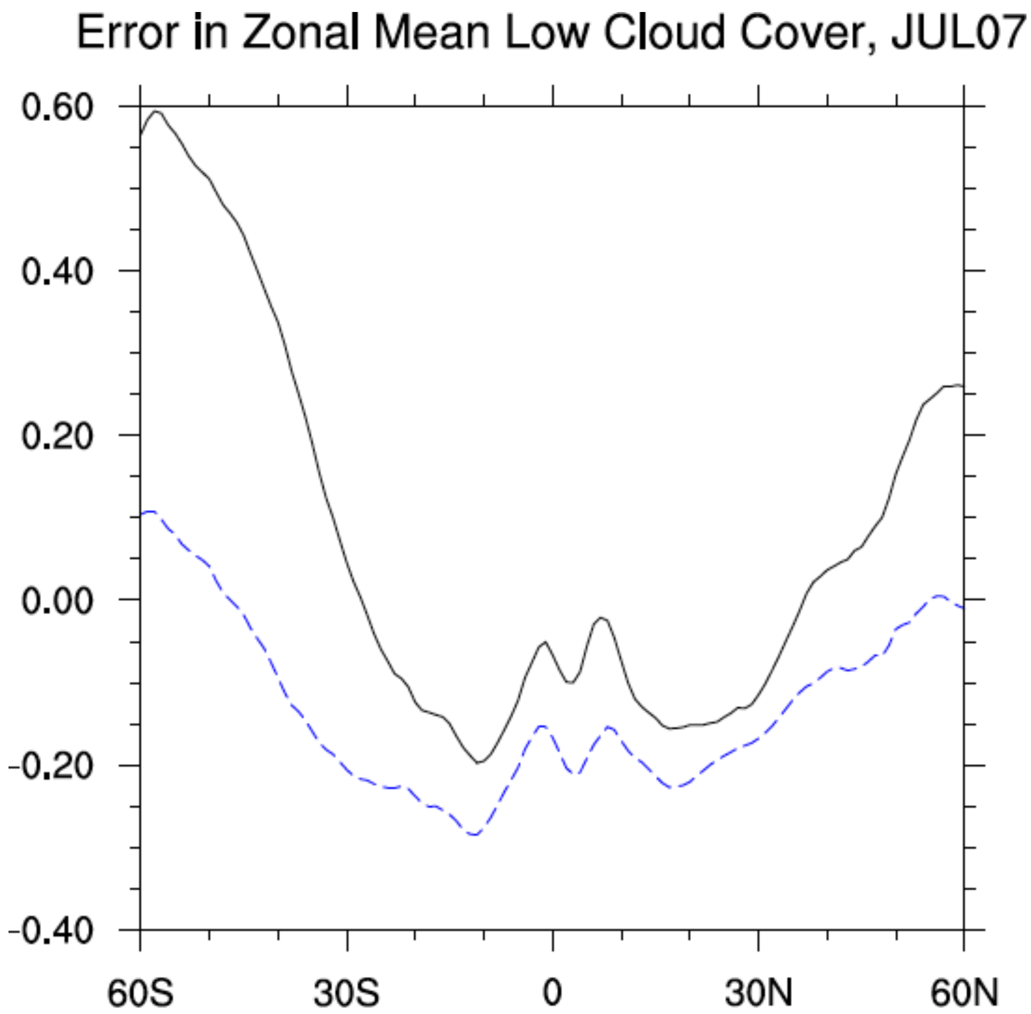


Error in Low Cloud Cover, Jul07



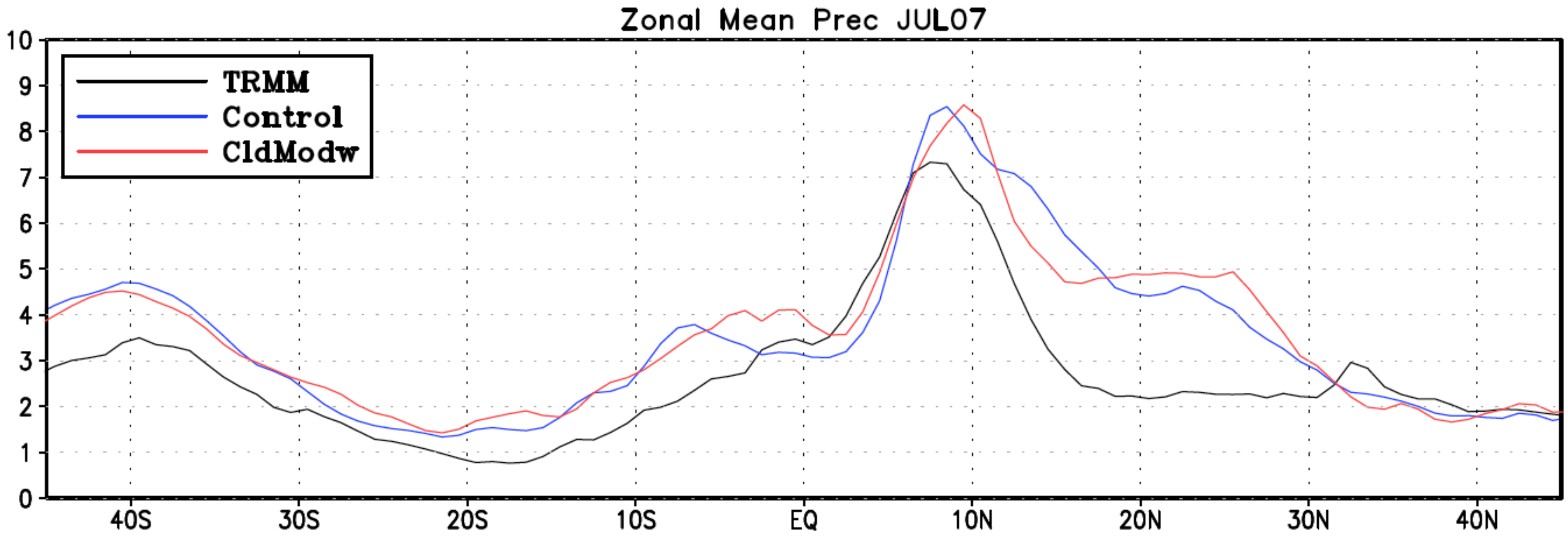
Error in TOA Net Radiation



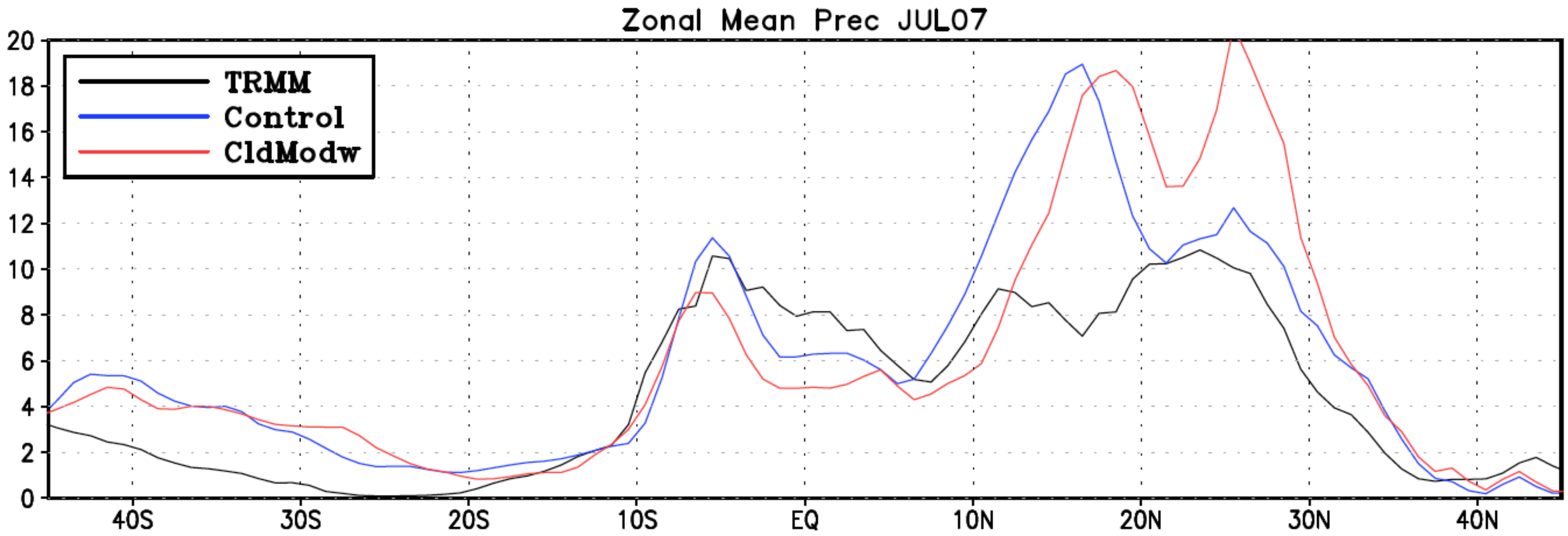


Error in Zonal Mean Low Cloud Cover, JUL07
0.60
0.40
0.20
0.00
-0.20
-0.40
60S
30S
0
30N
60N

Prec, 0-360E Mean



Prec, 70-100E Mean



Conclusions

1. Current GFS model has large error in simulating cloud covers.
2. These errors are propagated to error in radiation budget.
3. It is possible to correct some of those errors by modification in cloud parameterization scheme.
4. Such improvements can improve monsoon forecast by the model.
5. More observations in cloud microphysical scale required for better development of parameterization scheme.

Thank You