THERMODYNAMIC CONSTRAINTS ON THE ITCZ

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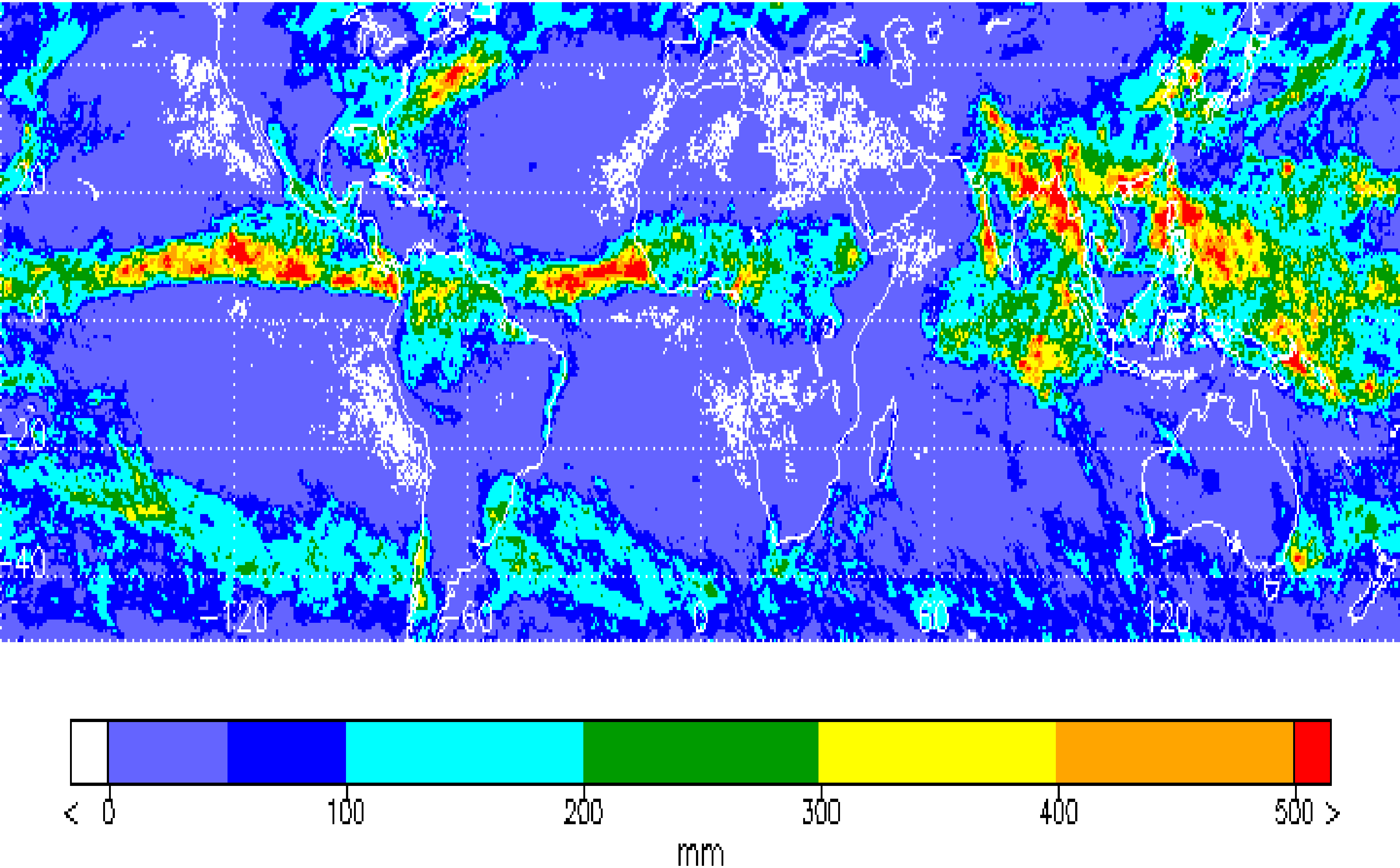
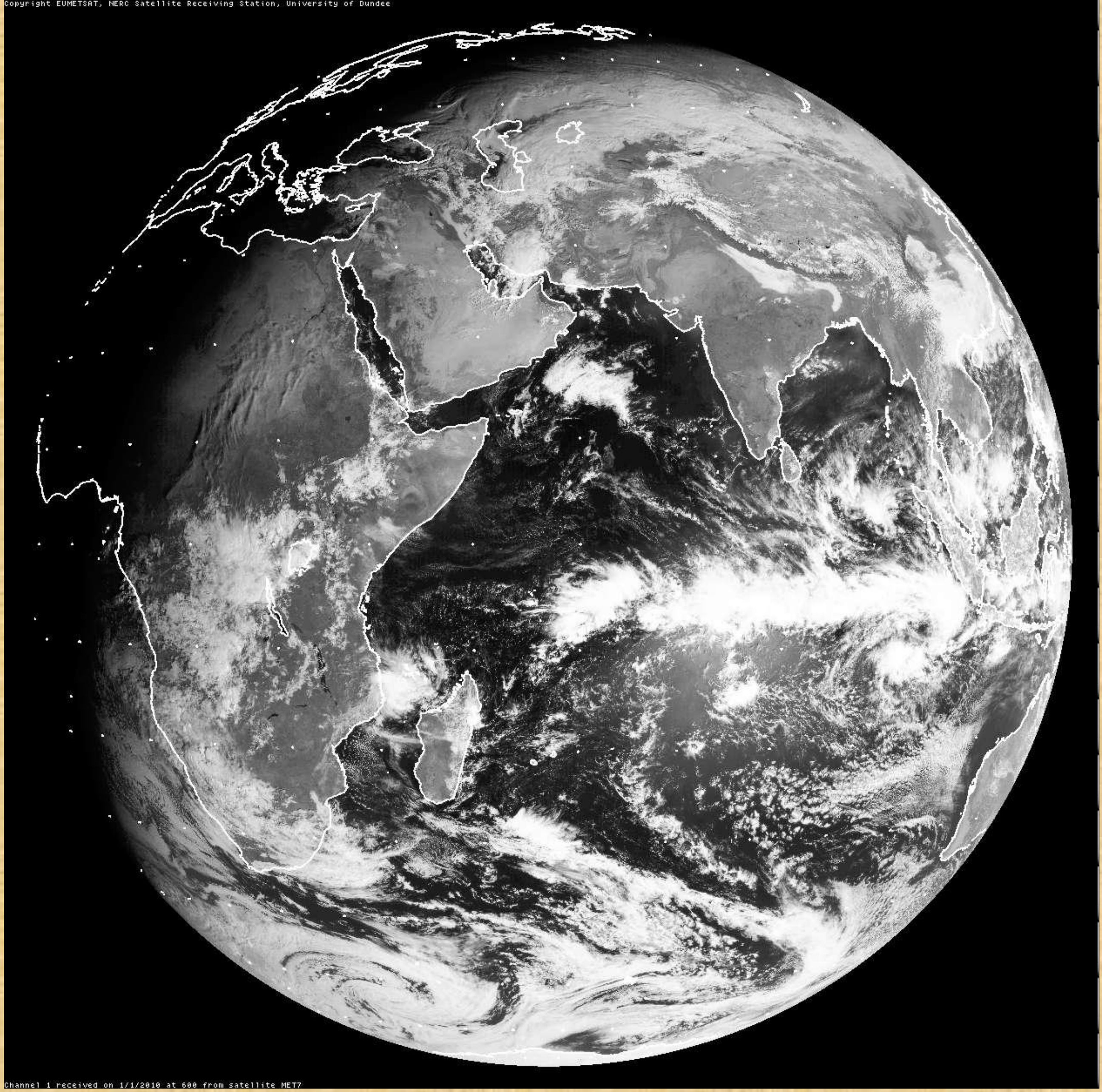
3B43 TRMM and others combined monthly accumulated surface rainfall



For Date From 2001/07/01 TO 2001/08/01



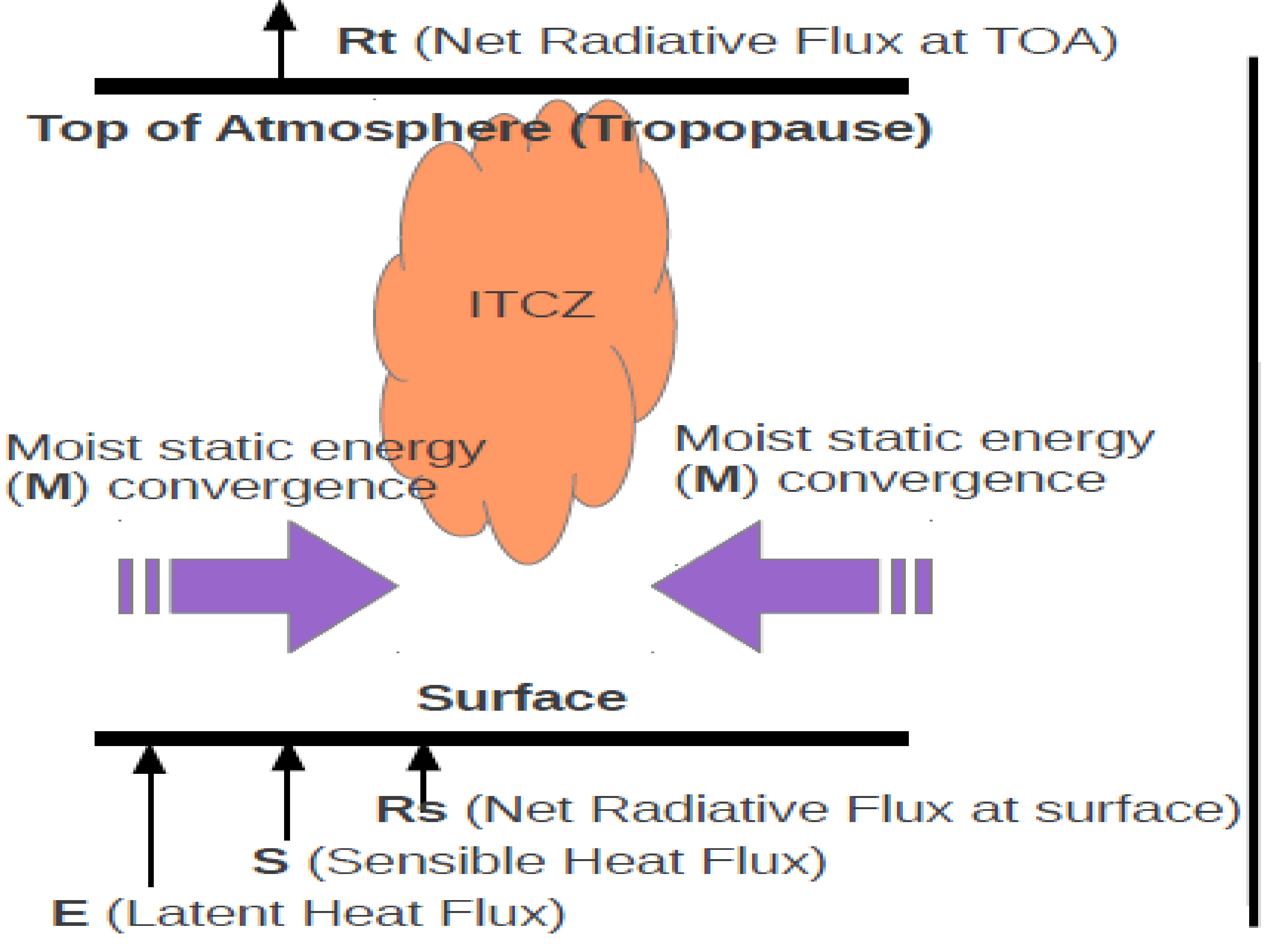
ITCZ on 1 January 2010

ZEROTH ORDER MODEL OF ITCZ

LINDZEN &NIGAM,1987

GILL 1980

NEELIN &HELD,1987


Rt (Net Radiative Flux at TOA)
Top of Atmosphere (Tropopause)
ITCZ
Moist static energy (M) convergence
Moist static energy (M) convergence
Surface
Rs (Net Radiative Flux at surface)
S (Sensible Heat Flux)
E (Latent Heat Flux)

ENERGY CONSERVATION EQUATION

$$\int \omega \, [\partial m/\partial p^*] \, \partial p^* = [F_B - F_T]$$

MOISTURE CONSERVATION EQUATION

$$\int \omega \, [\partial q/\partial p^*] \, \partial p^* = [E - P]$$

F_B & F_T Heat fluxes at bottom & top

E = Evaporation P = Precipitation

m=moist static energy=$C_pT+gZ+Lq$

$$P = E + \{F_B - F_T\} / \{GMS\}$$

$$GMS = \delta - 1$$

GROSS MOIST STABILITY

Where

P = Precipitation

E = Evaporation

F_B = Energy Flux at the Bottom

F_T = Energy Flux at the Top

$$\delta = -\{\int \omega [\partial s/\partial p]\, \partial p\}/\{\int \omega L [\partial q/\partial p]\, \partial p\}$$

$$GMS = \{\int \omega [\partial m/\partial p]\, \partial p\} / \{\int \omega L [\partial q/\partial p]\, \partial p\}$$

$$GMS = \delta - 1$$

Sign of GMS controlled by the value of δ

if δ is above 1 , GMS is positive.

$$\delta = -\{\int \omega [\partial s/\partial p]\, \partial p\} / \{\int \omega L [\partial q/\partial p]\, \partial p\}$$

$$P = E + \{Q_{NET}\} / \{\delta - 1\}$$

P = RAINFALL

E= EVAPORATION

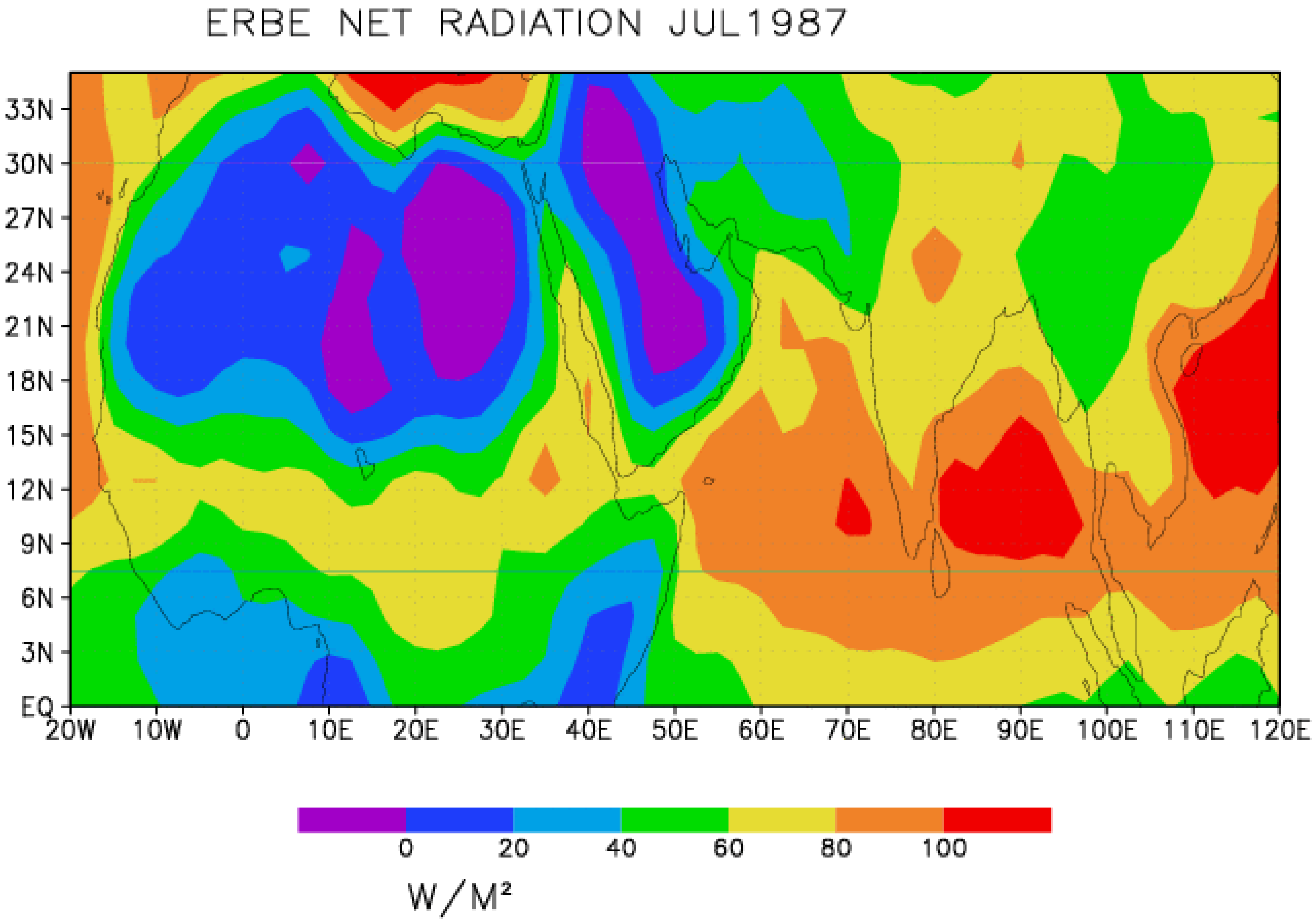
$Q_{div} = Q_{net}$ (for land)

Q_{NET} = NET RADIATION AT TOA

δ= VERTICAL STABILITY > 1

$$Q_{NET} = S(1 - \alpha) - F^{\uparrow}$$

Therefore, $(P-E) > 0$ if $Q_{NET} > 0$


ERBE NET RADIATION JUL1987
33N
30N
27N
24N
21N
18N
15N
12N
9N
6N
3N
EQ
20W
10W
0
10E
20E
30E
40E
50E
60E
70E
80E
90E
100E
110E
120E
0
20
40
60
80
100
W/M²

A Simple Expression for δ

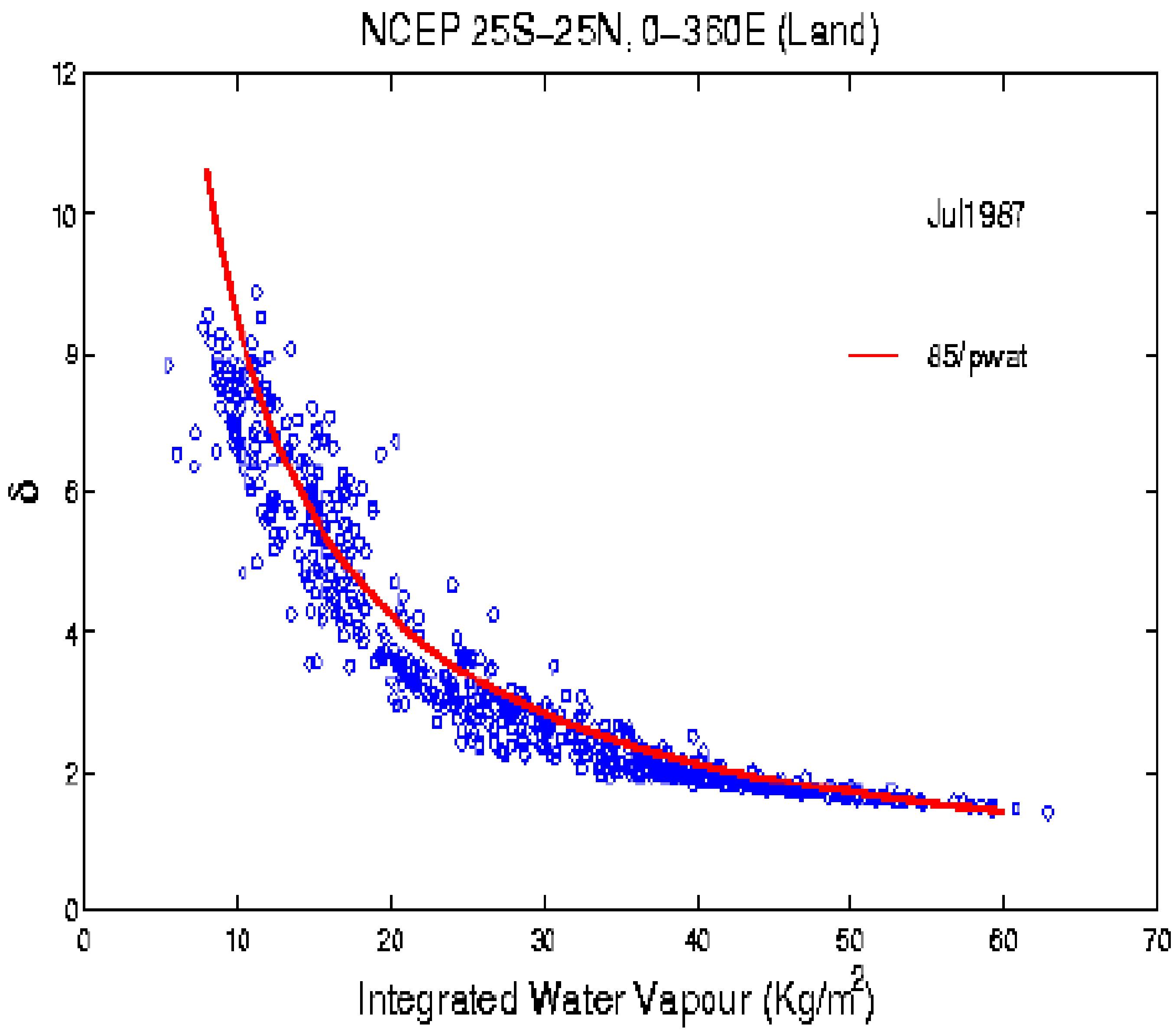
$$\omega(p) = 4\omega_m \, p/p_o \, [\, 1 - p/p_o \,]$$

$$T = T_o - \Gamma z$$

$$q(p^*) = q_O \{ p^* \}^{\lambda}$$

$$\delta = c / p_W$$

Figure 1


NCEP 25S-25N, 0-360E (Land)
Jul1987
85/pwat
S
Integrated Water Vapour (Kg/m^2)
0
2
4
6
8
10
12
0
10
20
30
40
50
60
70

$$P = E + \{Q_{NET}\} / \{C/P_W - 1\}$$

P = RAINFALL

E = EVAPORATION

Q_{NET} = NET RADIATION AT TOA

C = VERTICAL PROFILE PARAMETER

P_W = INTEGRATED WATER VAPOR

$$P - E = \{ S(1 - \alpha) - F^{\uparrow} \} / \{C/pwat - 1\}$$

S = Incoming Solar Radiation at the top

varies depending upon sun-earth geometry

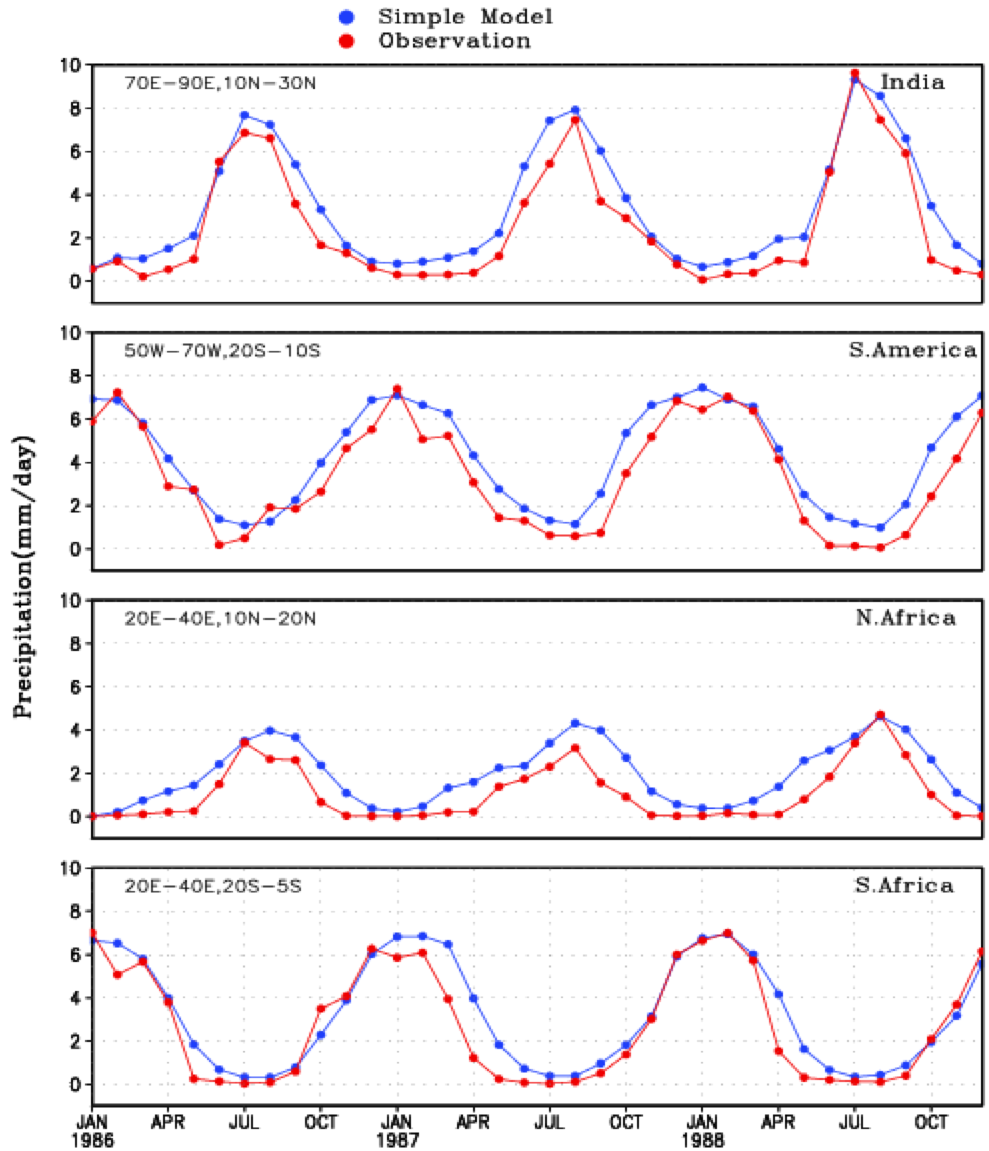
α = albedo , depends upon surface type

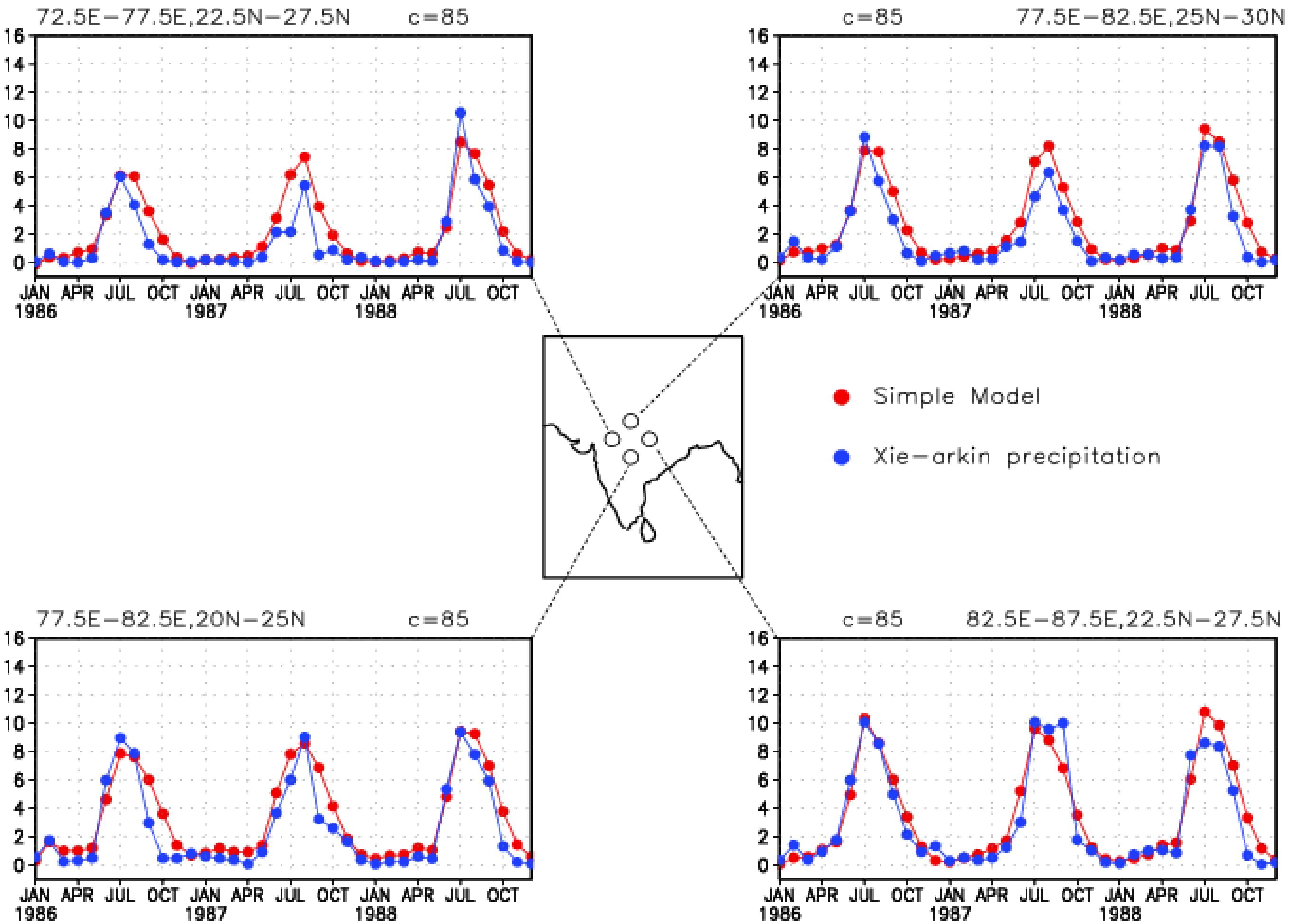
$F^{\uparrow}$= Outgoing Longwave Radiation

depends upon surface temp, water vapor & clouds

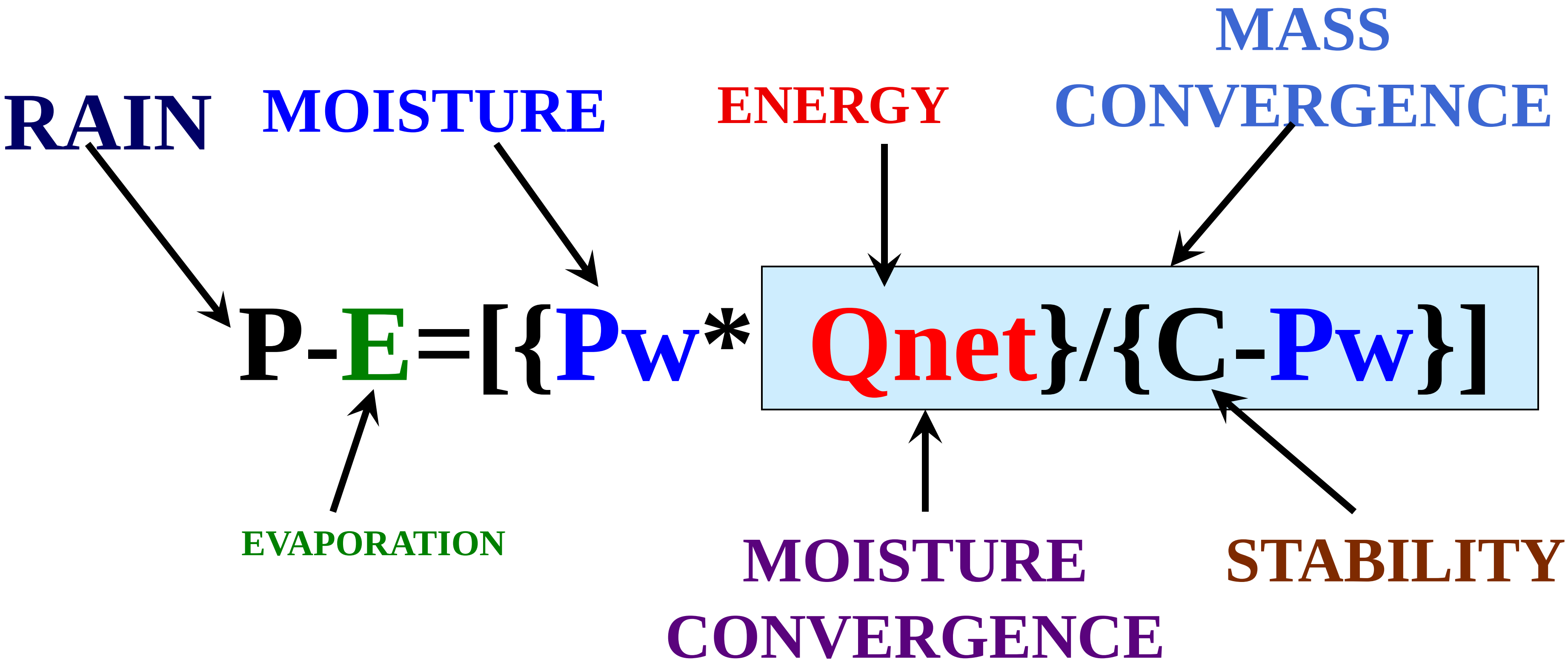
pwat= Integrated water vapour

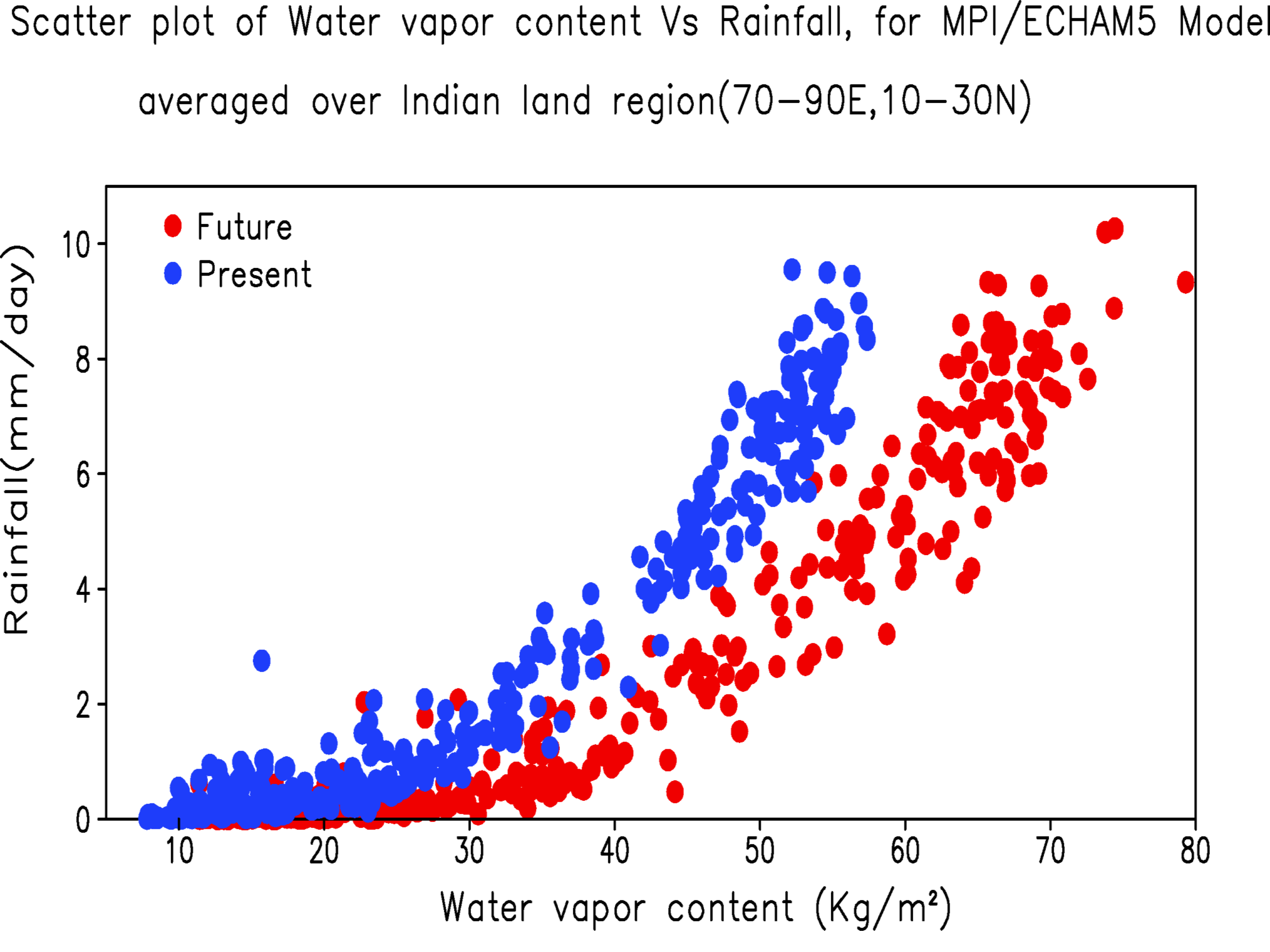
depends upon SST, and vertical motion


Simple Model
Observation
70E−90E,10N−30N
India
50W−70W,20S−10S
S.America
20E−40E,10N−20N
N.Africa
20E−40E,20S−5S
S.Africa
Precipitation(mm/day)
JAN 1986
APR
JUL
OCT
JAN 1987
APR
JUL
OCT
JAN 1988
APR
JUL
OCT



72.5E-77.5E,22.5N-27.5N c=85
c=85 77.5E-82.5E,25N-30N
77.5E-82.5E,20N-25N c=85
c=85 82.5E-87.5E,22.5N-27.5N
JAN APR JUL OCT JAN APR JUL OCT JAN APR JUL OCT
1986 1987 1988
Simple Model
Xie-arkin precipitation


RAIN
MOISTURE
ENERGY
MASS
CONVERGENCE
P-E=[{Pw* Qnet}/{C-Pw}]
EVAPORATION
MOISTURE
CONVERGENCE
STABILITY


Scatter plot of Water vapor content Vs Rainfall, for MPI/ECHAM5 Model
averaged over Indian land region(70-90E,10-30N)
Future
Present
Rainfall(mm/day)
0
2
4
6
8
10
10
20
30
40
50
60
70
80
Water vapor content (Kg/m²)

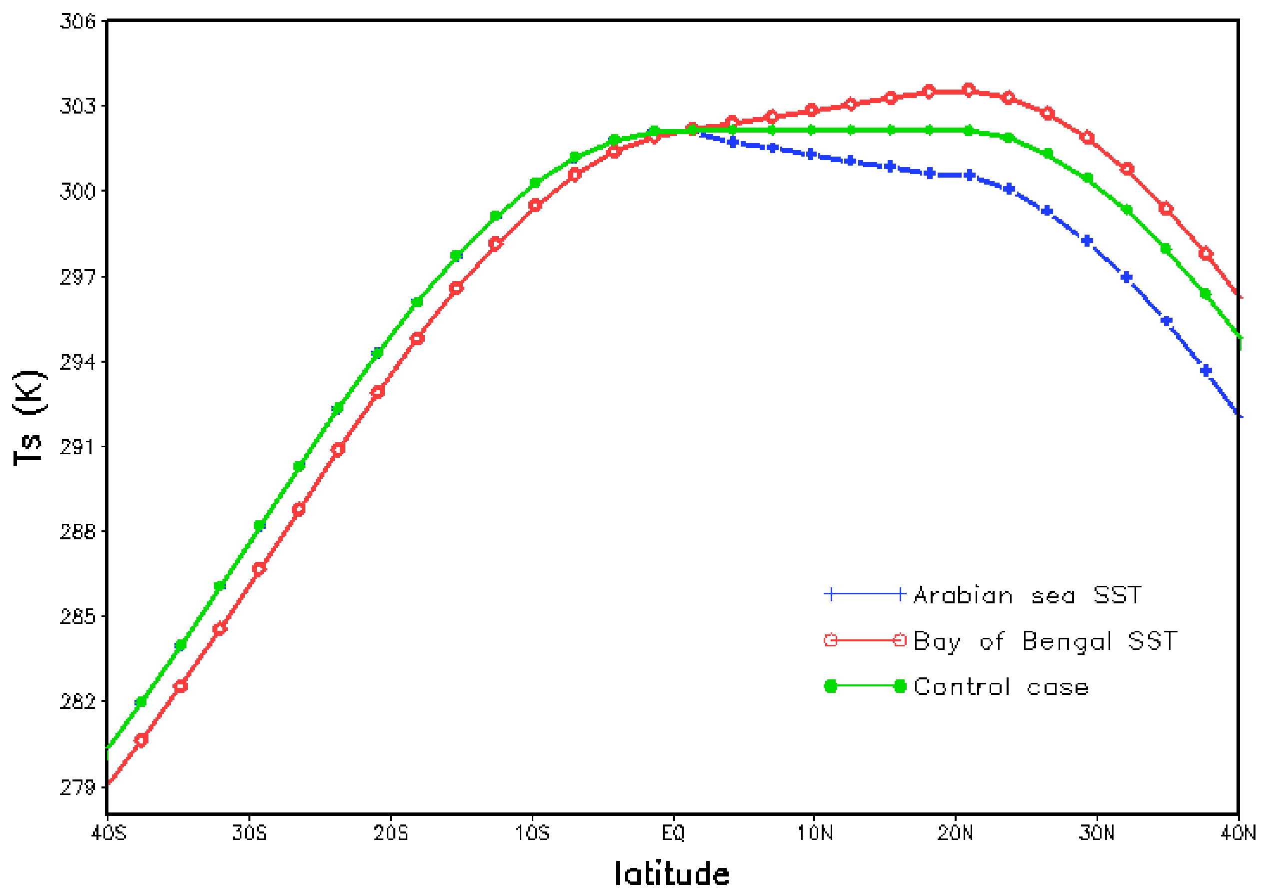
General circulation model :
Community Atmopshere Model 3.1

Feature	Detail	comments
CAM 3.1	Aqua-planet	Zonally symmetric
Resolution	T - 42	Eulerian
Levels	26	Hybrid co-ordinates
Deep convection	Zhang and McFarlane (1995)	Plume ensemble
Shallow convection	Hack (1994)	
Boundary conditions	Analytical SST profile	BoB, Ara, Flat
Convective relaxation time- τ (Tau)	Rate of CAPE consumption	1 hr (Default), 12 hr

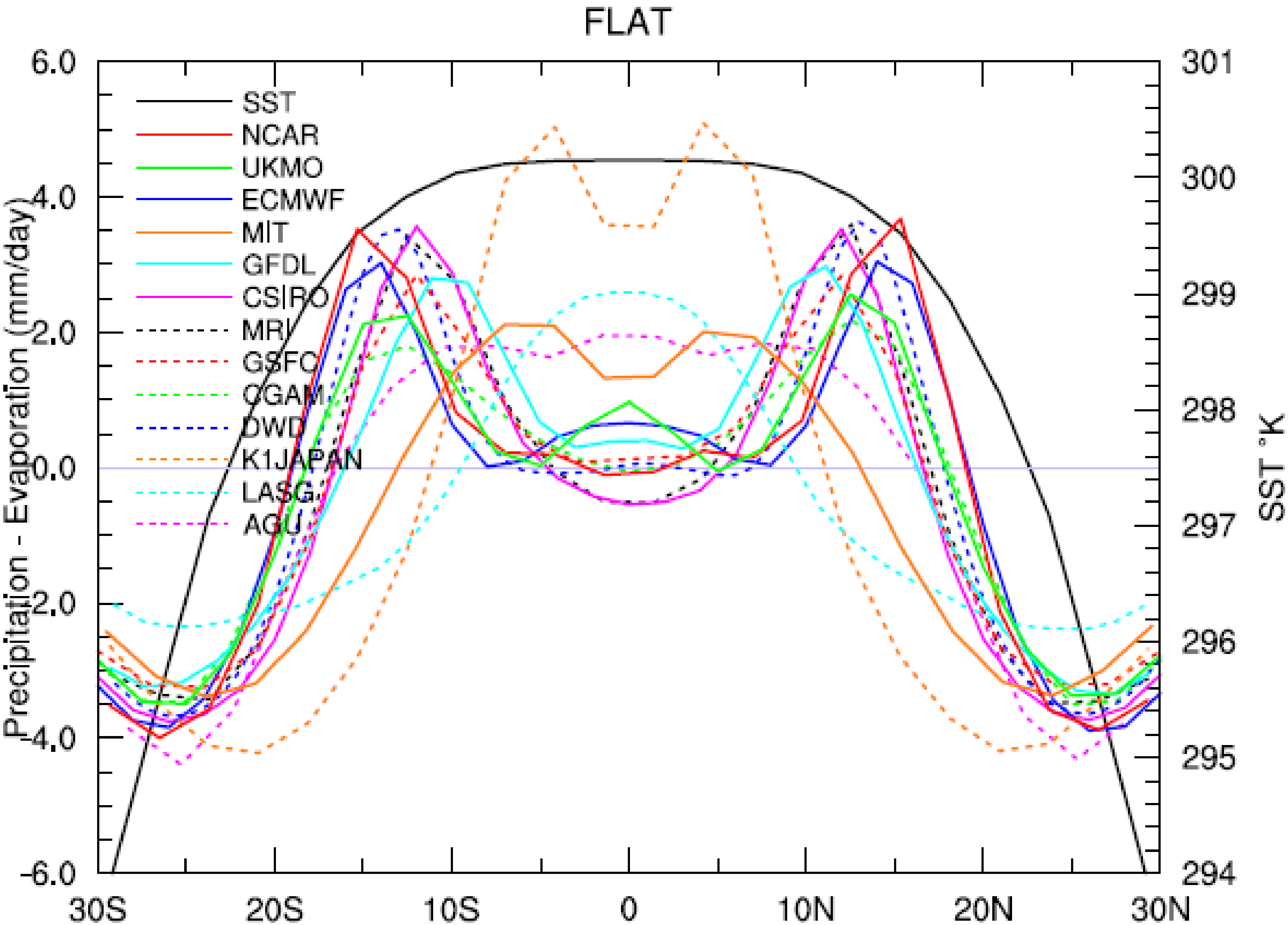
Rate of CAPE change due to convection is assumed to be proportional to cloud base mass flux Mb, given by

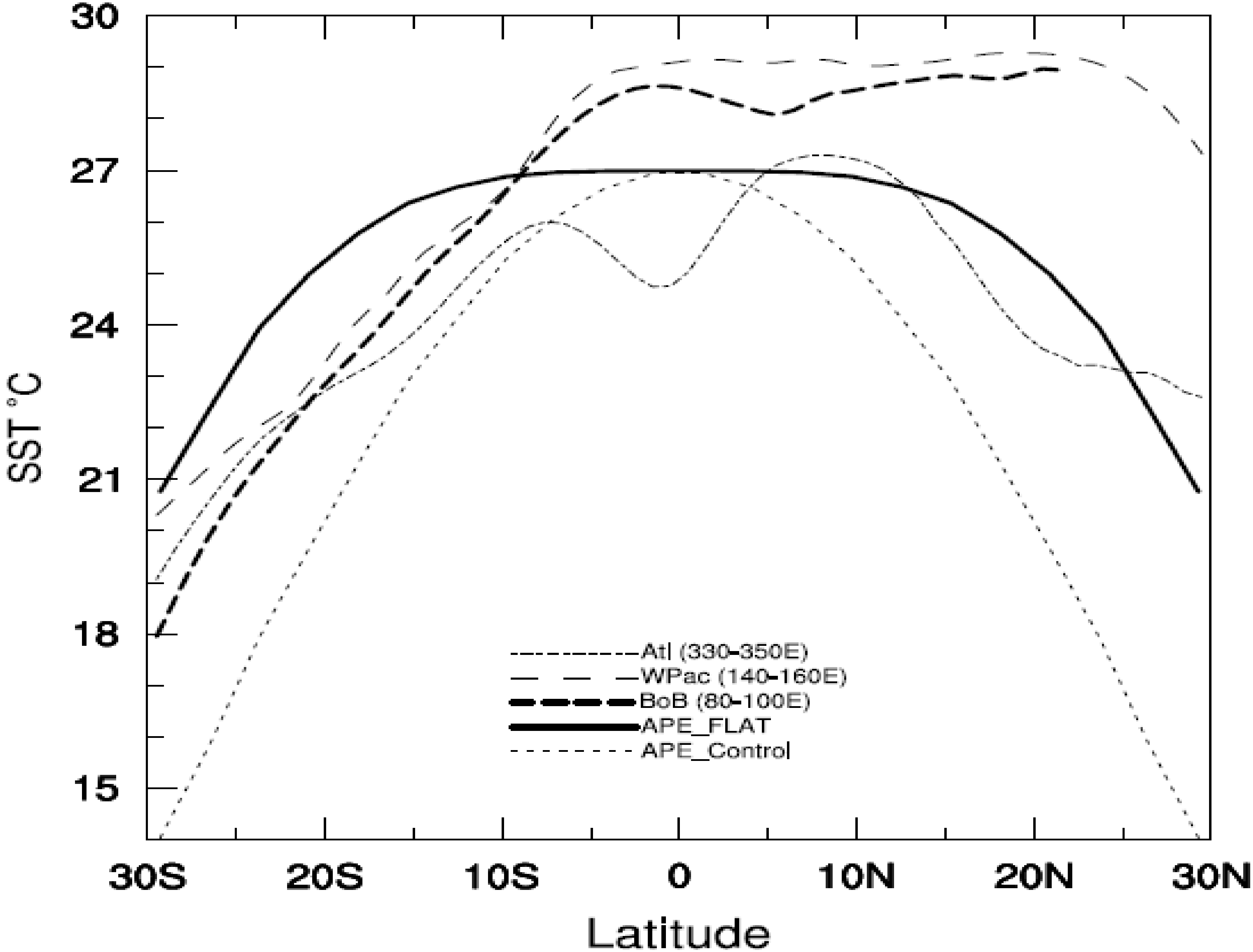
$$\frac{dA}{dt} = -Mb * F + Large\ scale\ forcing$$

$$Mb = \frac{A}{\tau * F} : A = CAPE\ , F = CAPE\ consump.\ rate$$

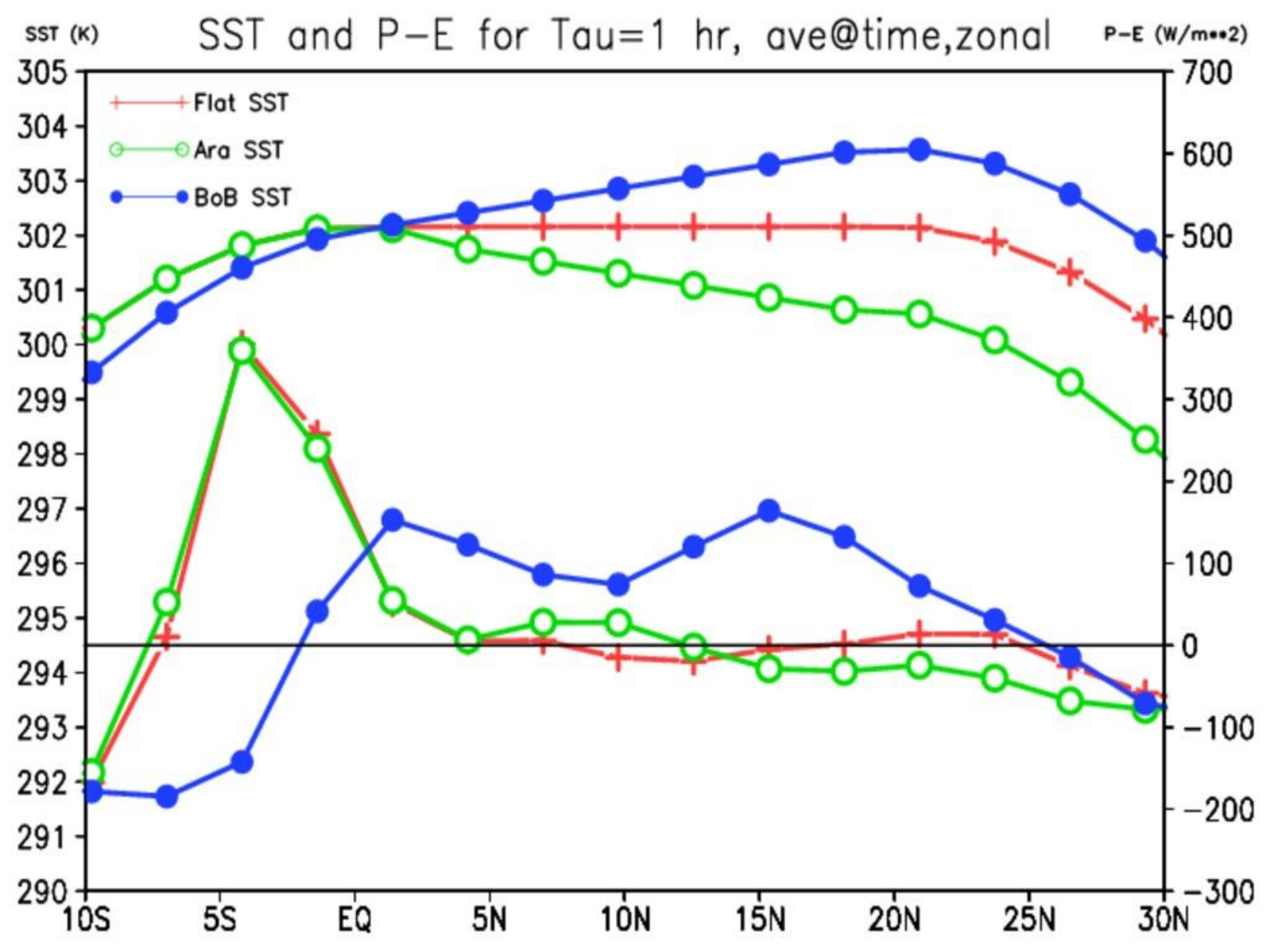


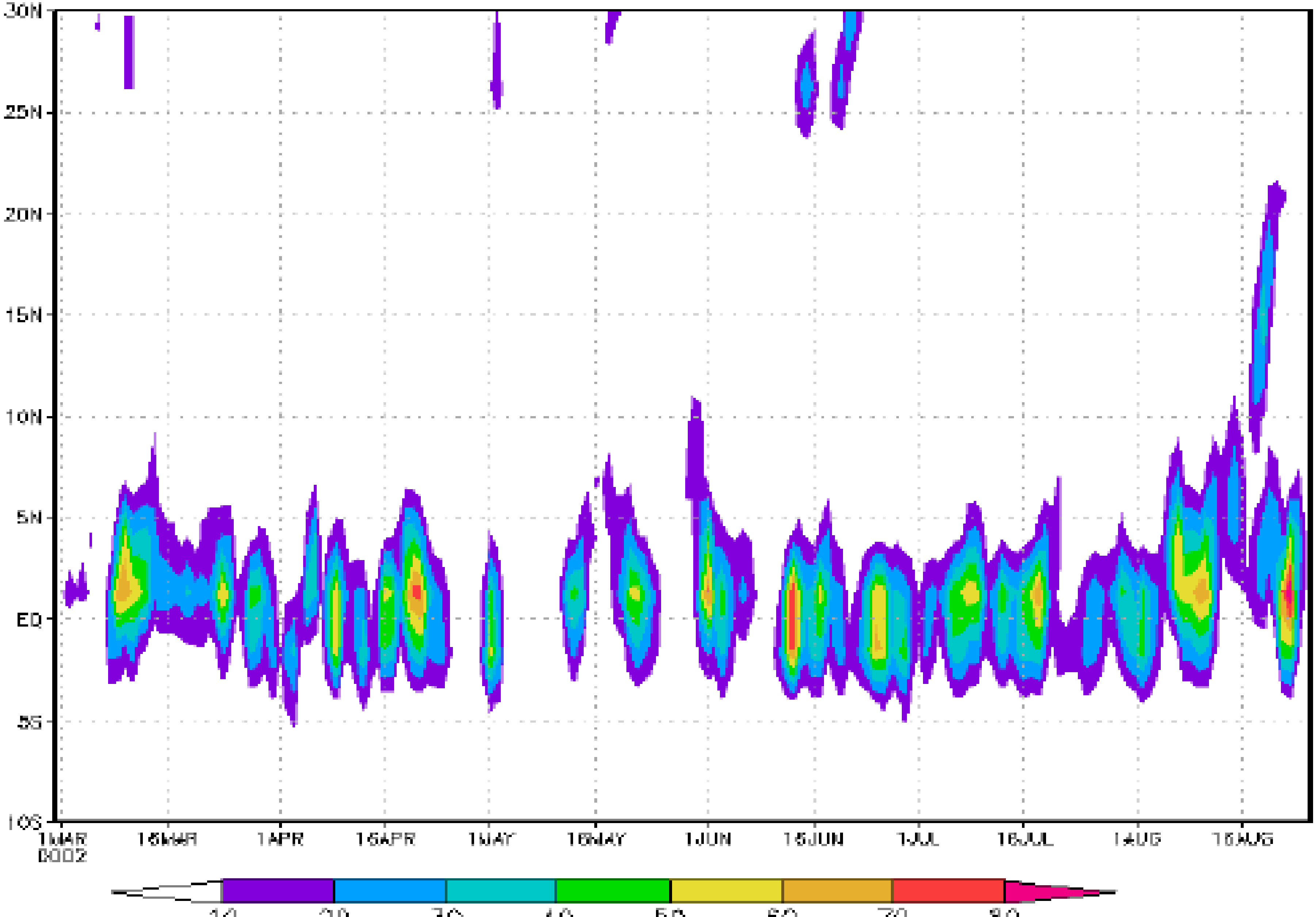
306
303
300
297
294
291
288
285
282
279
Ts (K)
40S
30S
20S
10S
EQ
10N
20N
30N
40N
latitude
Arabian sea SST
Bay of Bengal SST
Control case


FLAT
SST
NCAR
UKMO
ECMWF
MIT
GFDL
CSIRO
MRI
GSFC
CGAM
DWD
K1JAPAN
LASG
AGU
Precipitation - Evaporation (mm/day)
SST °K
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
301
300
299
298
297
296
295
294
30S
20S
10S
0
10N
20N
30N

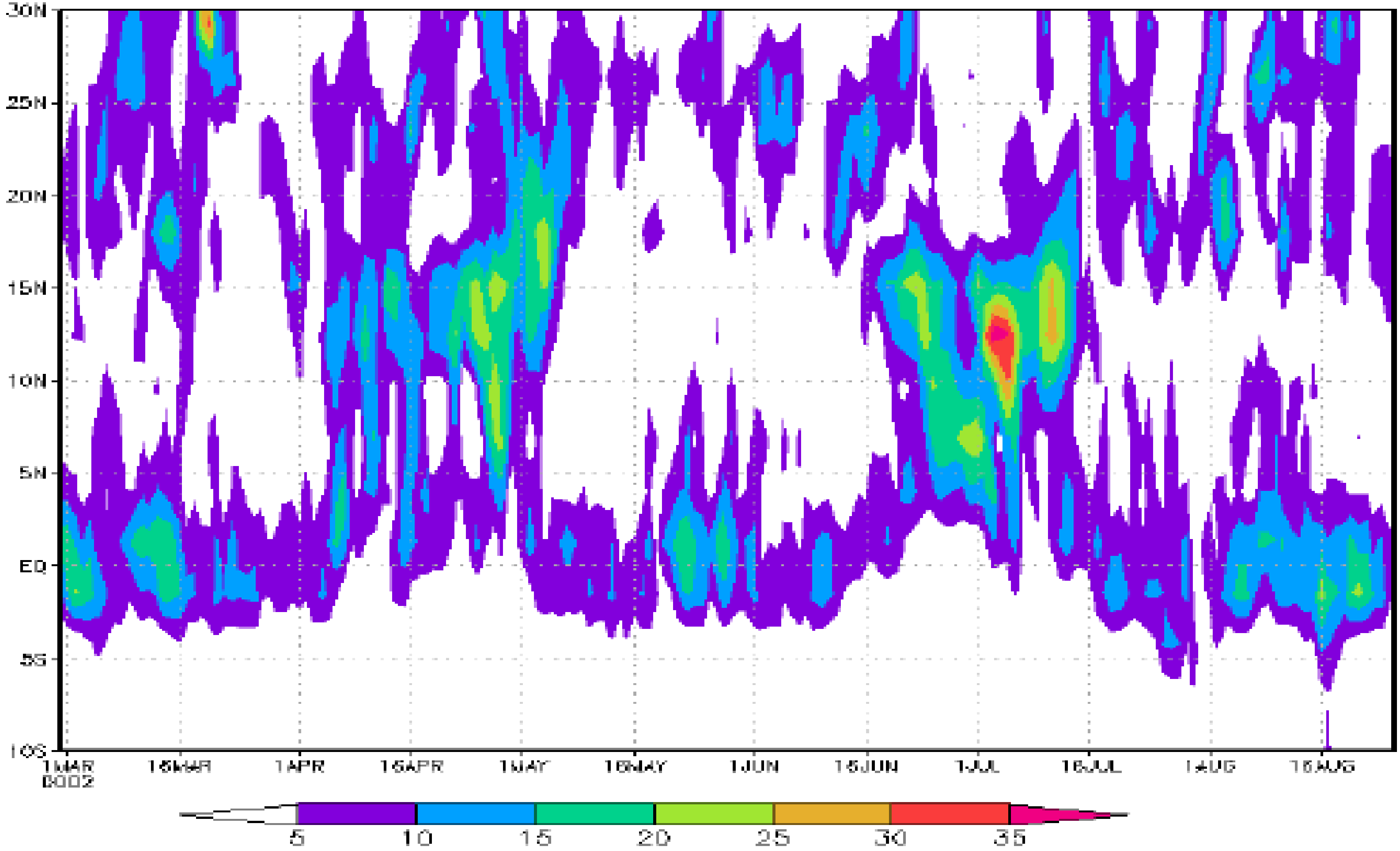


30
27
24
21
18
15
SST °C
30S
20S
10S
0
10N
20N
30N
Latitude
Atl (330-350E)
WPac (140-160E)
BoB (80-100E)
APE_FLAT
APE_Control

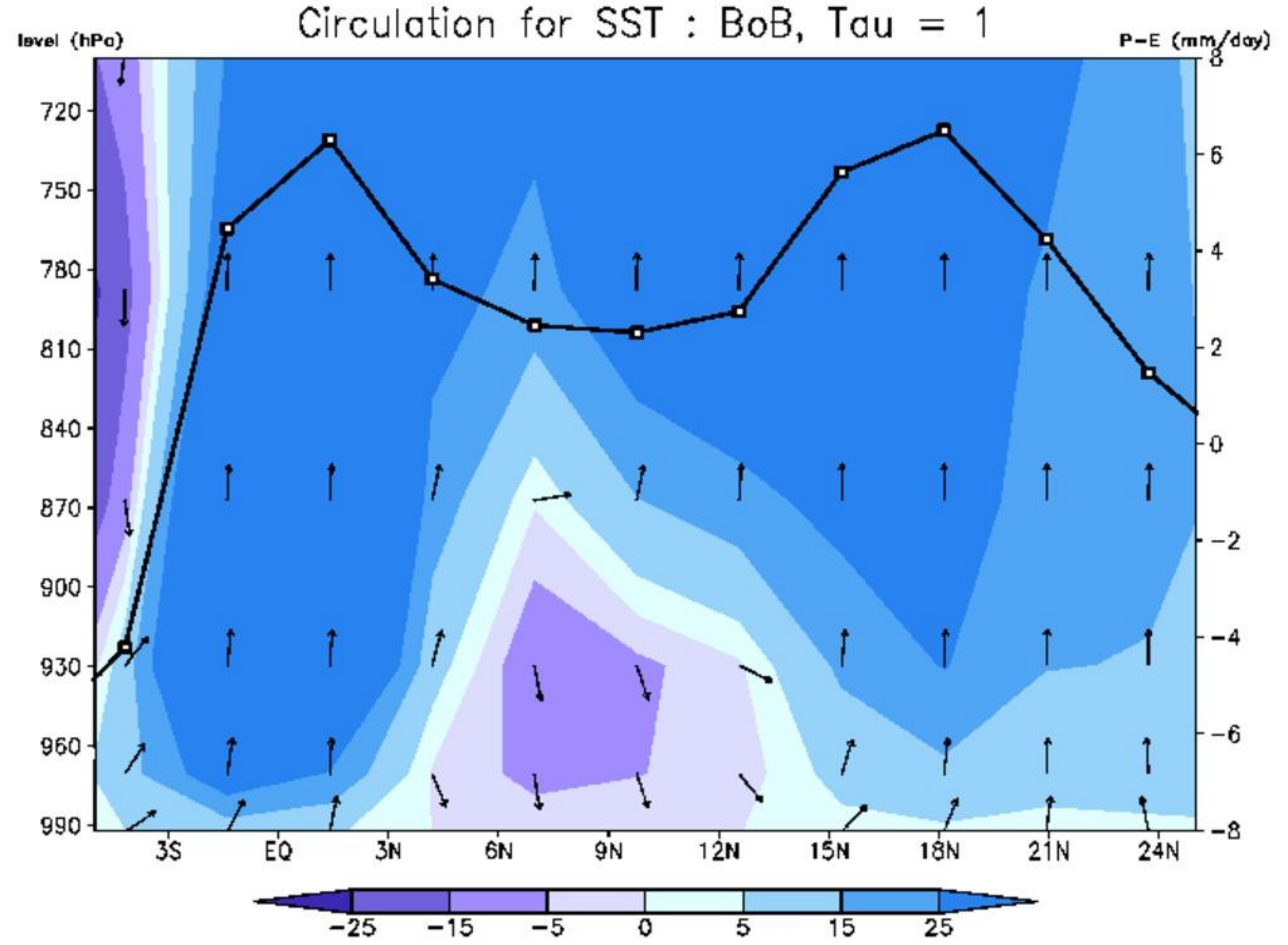

SST and P-E for Tau=1 hr, ave@time,zonal
SST (K)
P-E (W/m**2)
Flat SST
Ara SST
BoB SST
305
304
303
302
301
300
299
298
297
296
295
294
293
292
291
290
700
600
500
400
300
200
100
0
−100
−200
−300
10S
5S
EQ
5N
10N
15N
20N
25N
30N



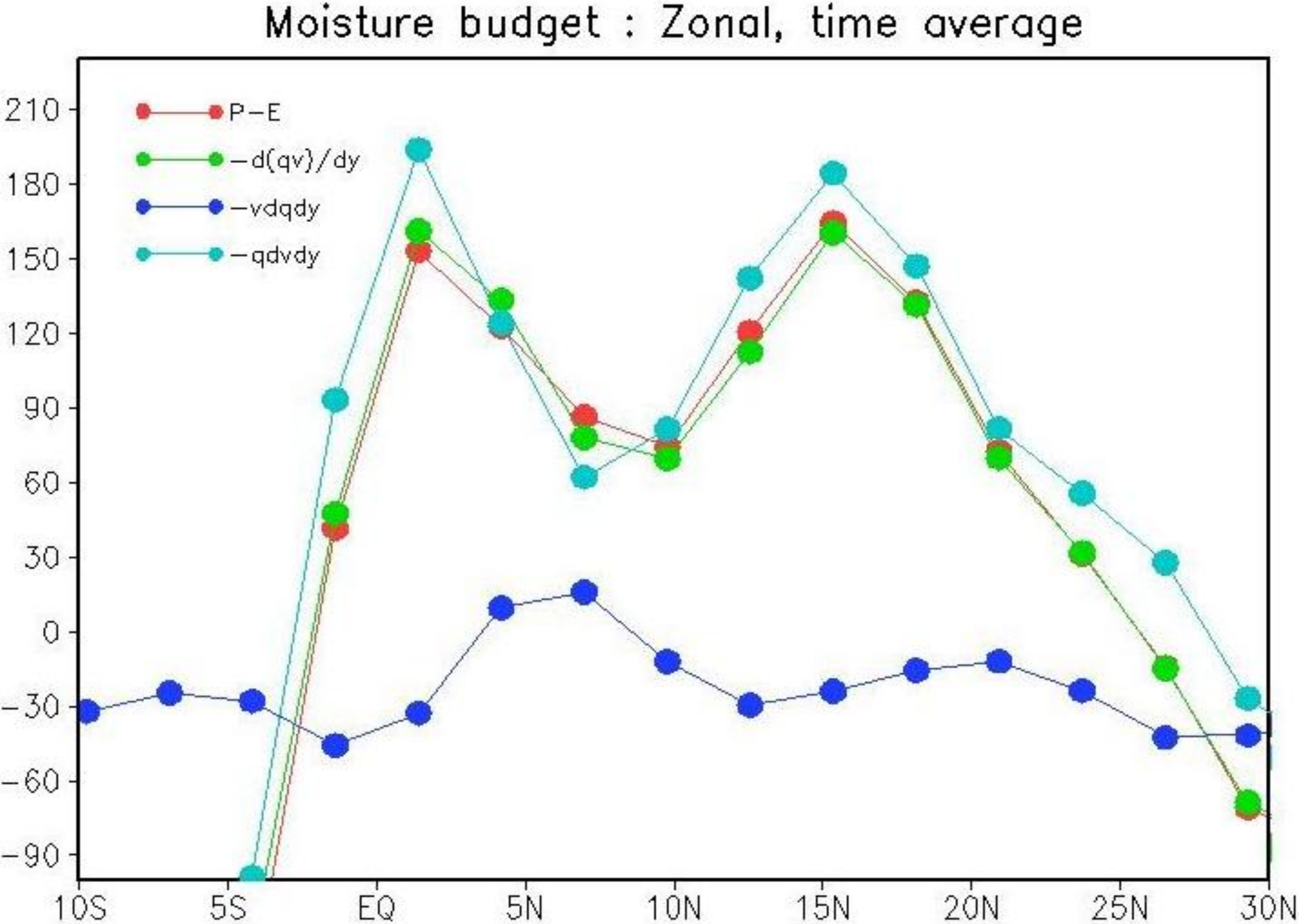
(a) Arabian sea like SST distribution

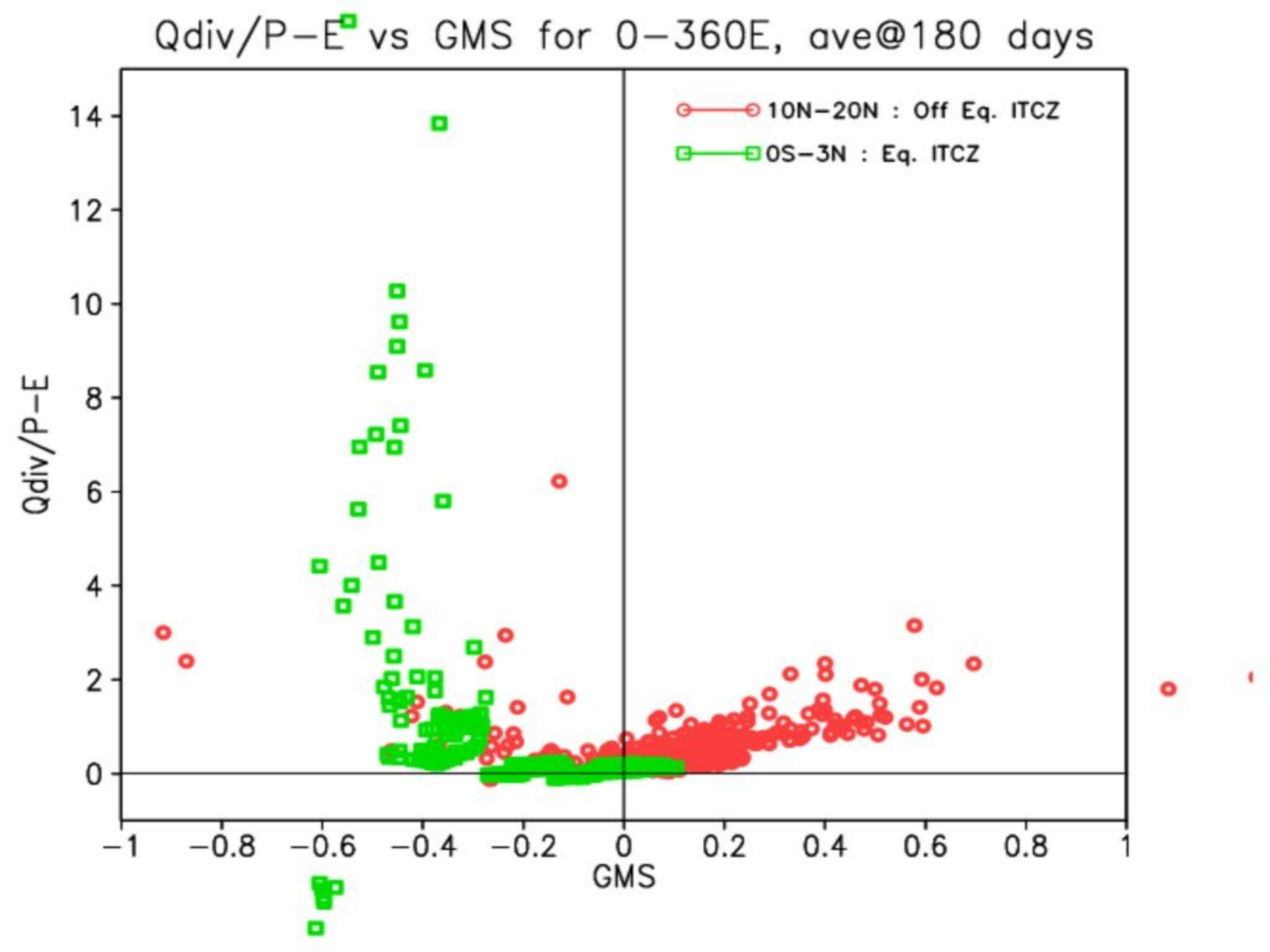

30N
25N
20N
15N
10N
5N
EQ
5S
10S
1MAR
2002
16MAR
1APR
16APR
1MAY
16MAY
1JUN
16JUN
1JUL
16JUL
1AUG
16AUG
5
10
15
20
25
30
35

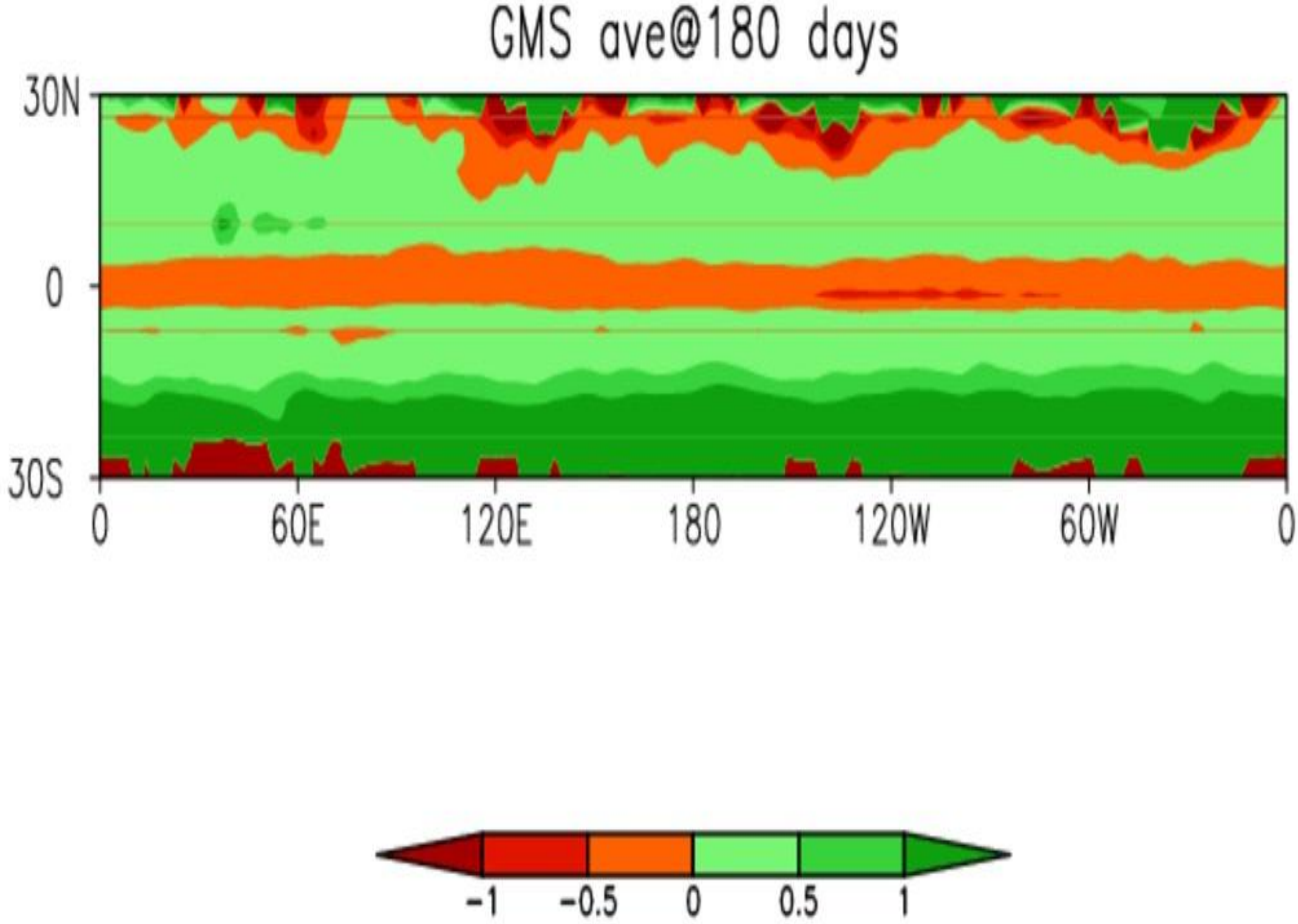
(a) τ = 1Hr

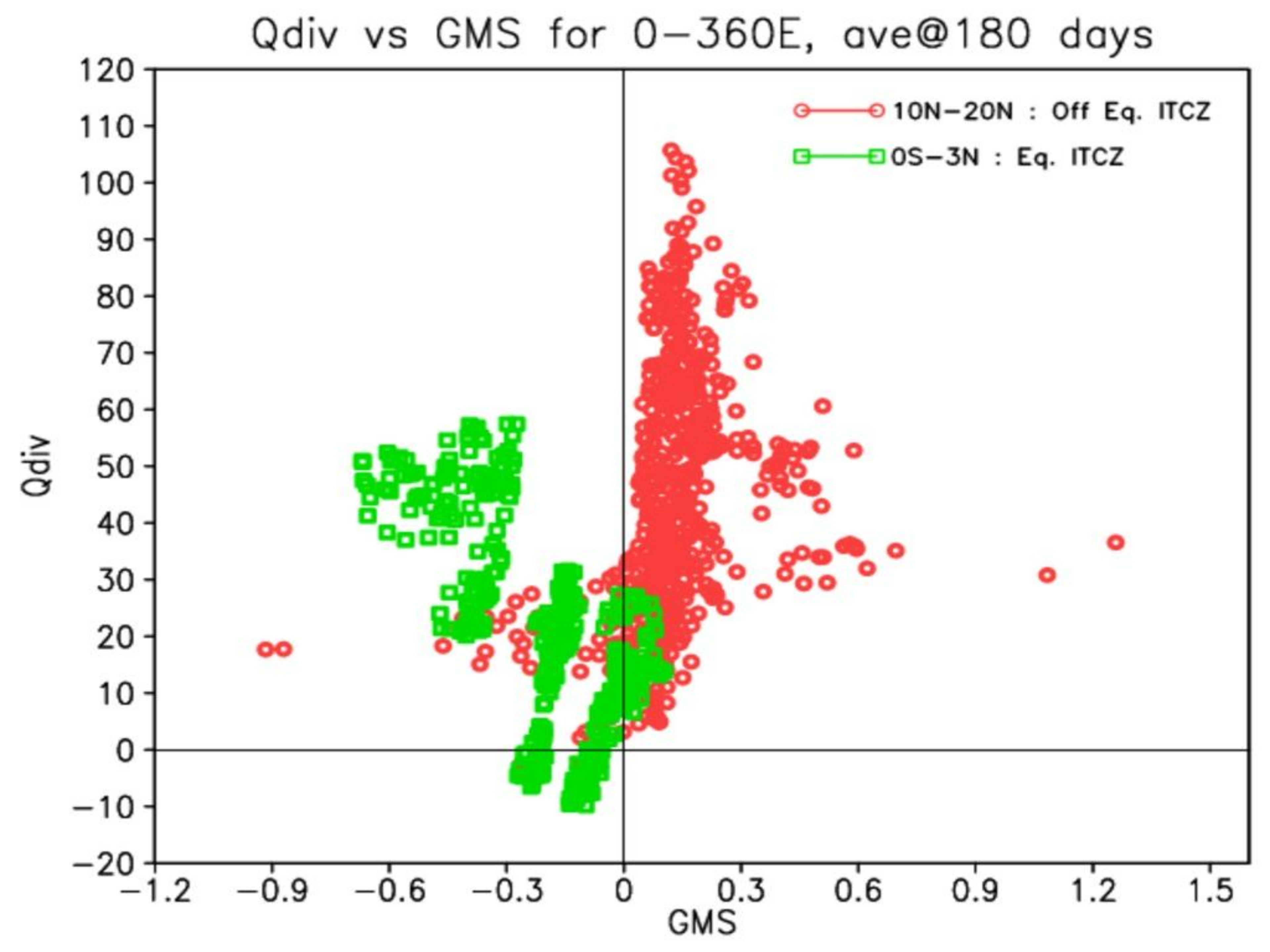


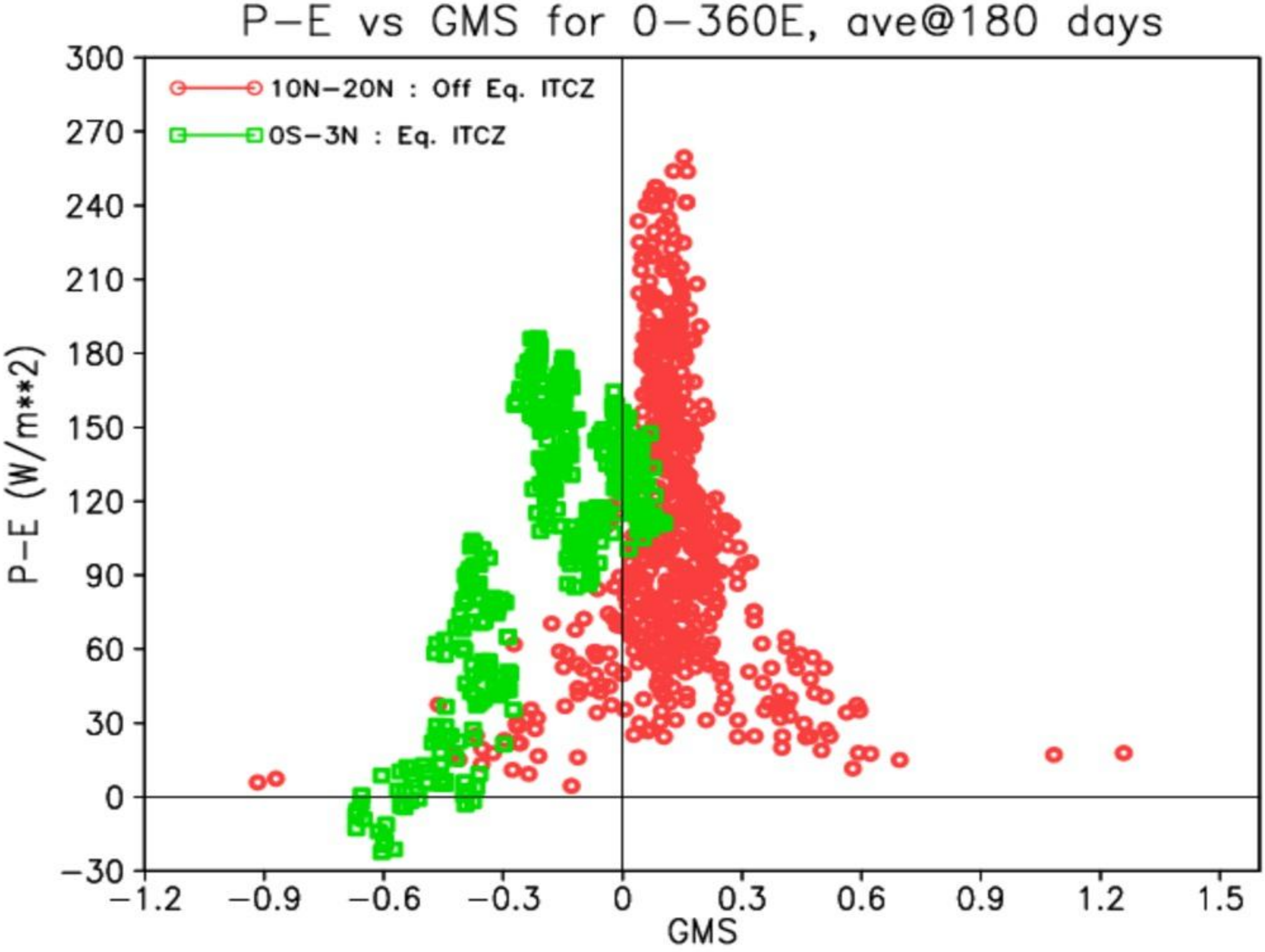
Circulation for SST : BoB, Tau = 1
level (hPa)
P-E (mm/day)
720
750
780
810
840
870
900
930
960
990
8
6
4
2
0
−2
−4
−6
−8
3S
EQ
3N
6N
9N
12N
15N
18N
21N
24N
−25
−15
−5
0
5
15
25


Moisture budget : Zonal, time average
P−E
−d(qv)/dy
−vdqdy
−qdvdy
210
180
150
120
90
60
30
0
−30
−60
−90
10S
5S
EQ
5N
10N
15N
20N
25N
30N

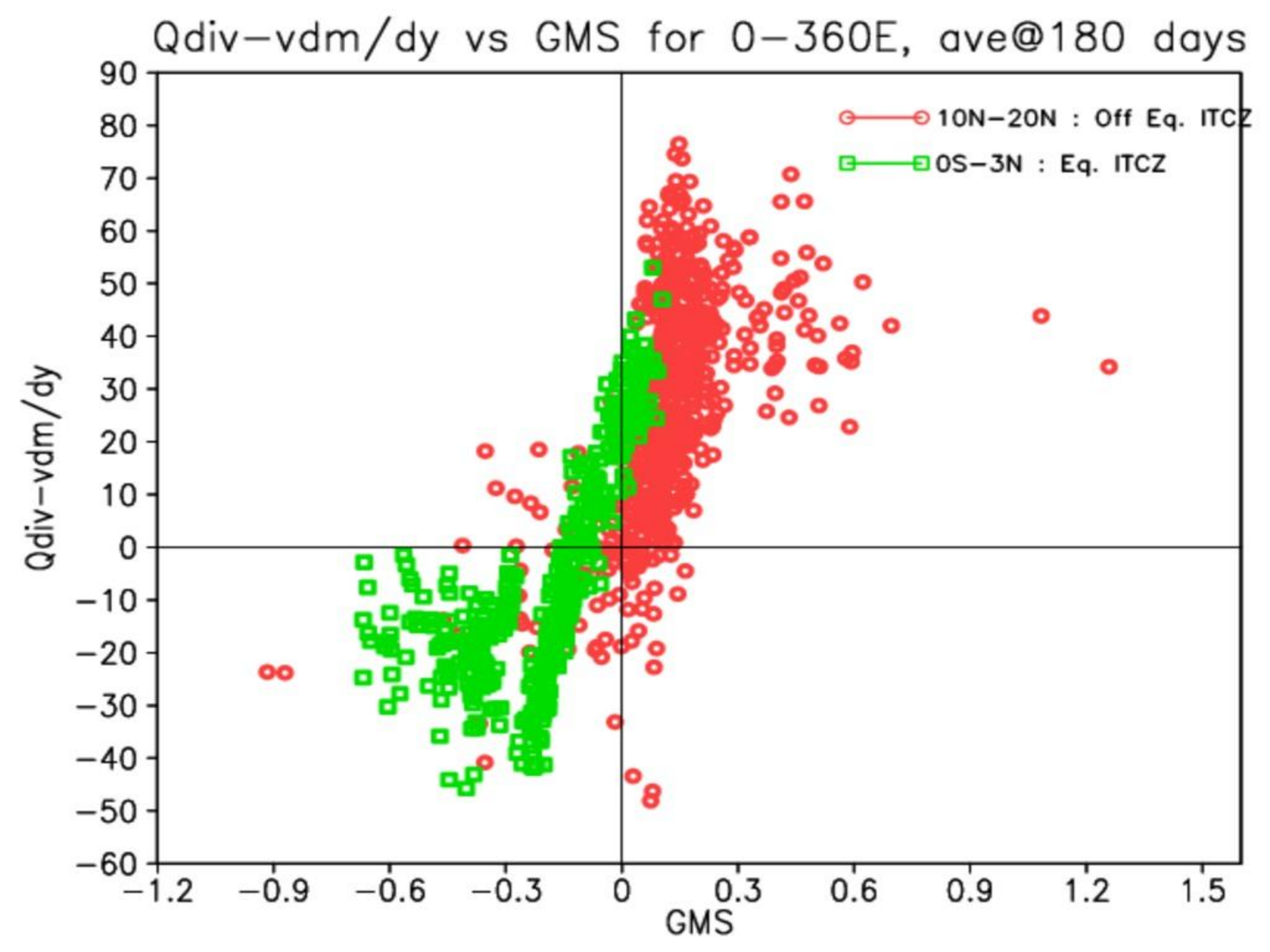

Qdiv/P-E vs GMS for 0-360E, ave@180 days
10N-20N : Off Eq. ITCZ
0S-3N : Eq. ITCZ
Qdiv/P-E
GMS
14
12
10
8
6
4
2
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

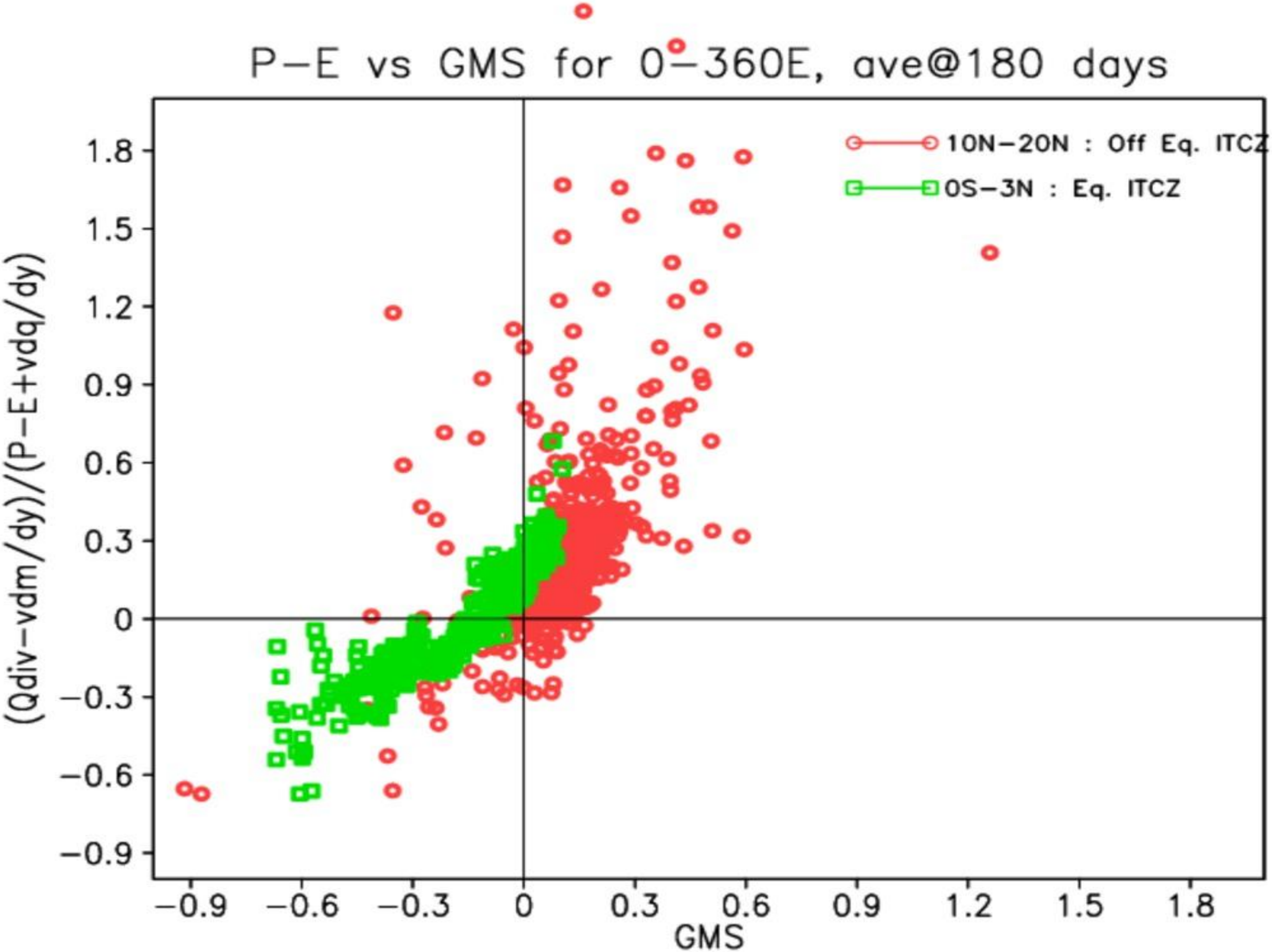

GMS ave@180 days
30N
0
30S
0
60E
120E
180
120W
60W
0
−1
−0.5
0
0.5
1


Qdiv vs GMS for 0-360E, ave@180 days
10N-20N : Off Eq. ITCZ
0S-3N : Eq. ITCZ
Qdiv
GMS
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-1.2
-0.9
-0.6
-0.3
0
0.3
0.6
0.9
1.2
1.5

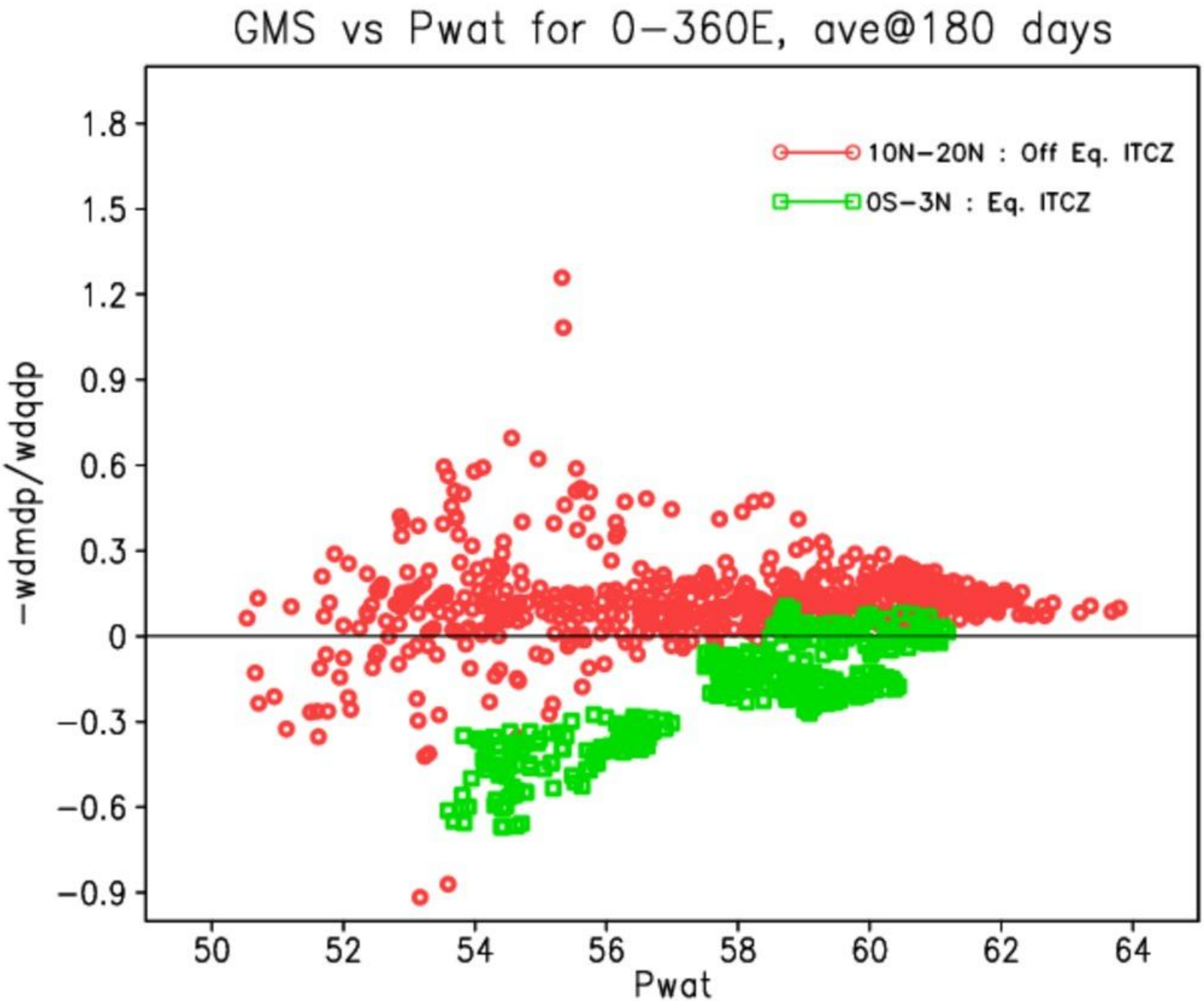


P−E vs GMS for 0−360E, ave@180 days
10N−20N : Off Eq. ITCZ
0S−3N : Eq. ITCZ
P−E (W/m**2)
GMS
300
270
240
210
180
150
120
90
60
30
0
−30
−1.2
−0.9
−0.6
−0.3
0
0.3
0.6
0.9
1.2
1.5

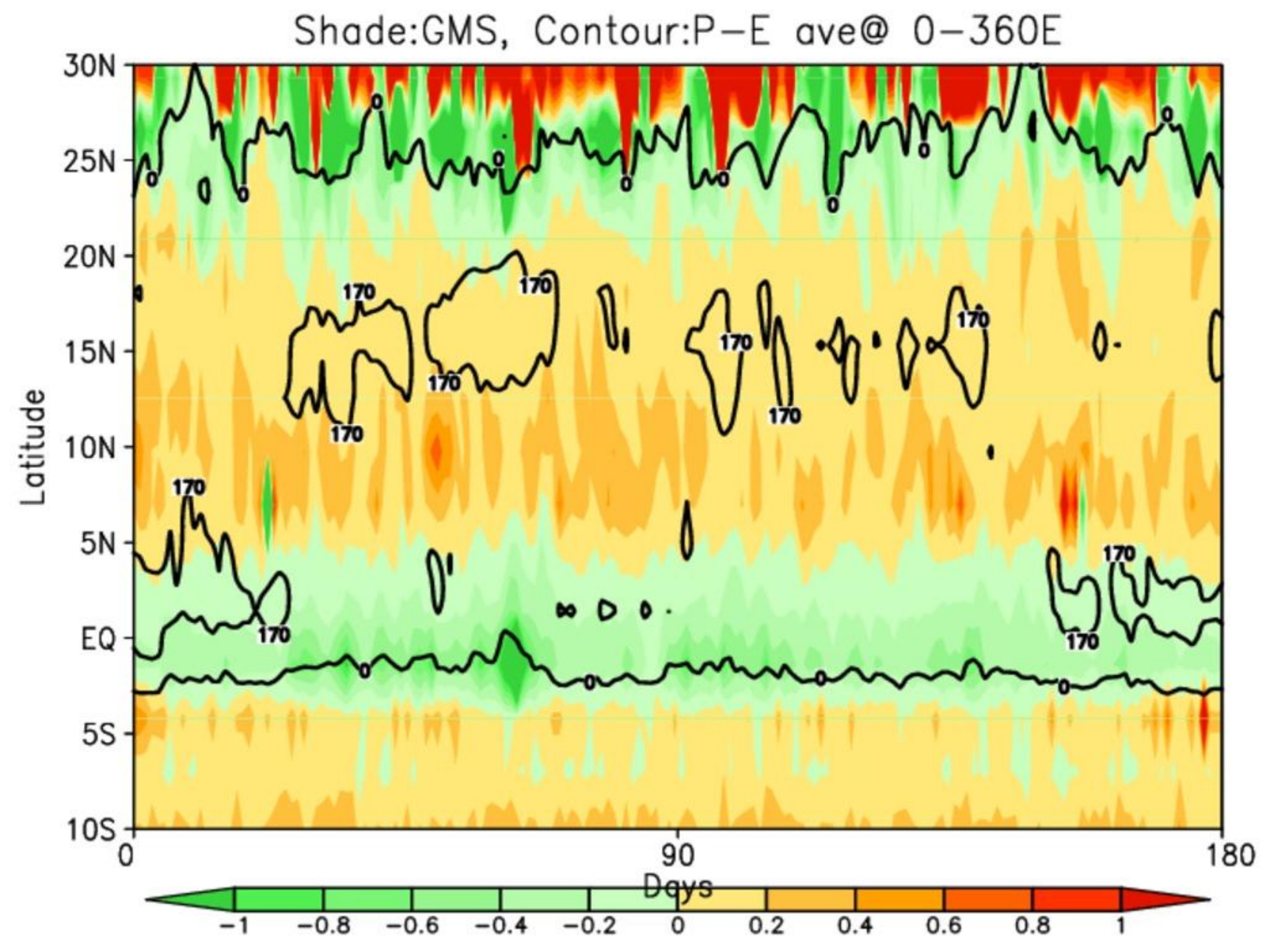

Qdiv−vdm/dy vs GMS for 0−360E, ave@180 days
10N−20N : Off Eq. ITCZ
0S−3N : Eq. ITCZ
Qdiv−vdm/dy
90
80
70
60
50
40
30
20
10
0
−10
−20
−30
−40
−50
−60
−1.2
−0.9
−0.6
−0.3
0
0.3
0.6
0.9
1.2
1.5
GMS



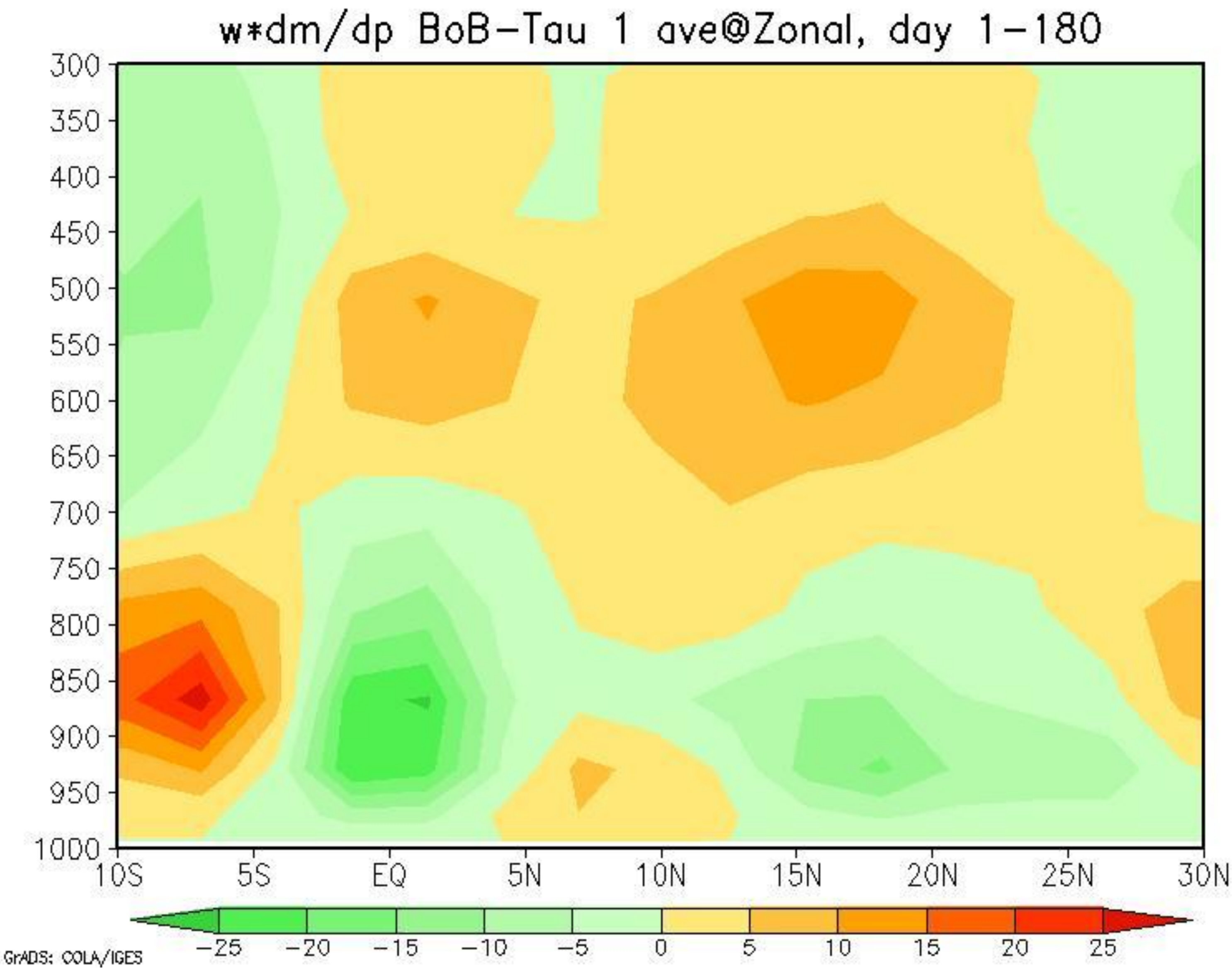
P−E vs GMS for 0−360E, ave@180 days
10N−20N : Off Eq. ITCZ
0S−3N : Eq. ITCZ
(Qdiv−vdm/dy)/(P−E+vdq/dy)
GMS
1.8
1.5
1.2
0.9
0.6
0.3
0
−0.3
−0.6
−0.9
−0.9
−0.6
−0.3
0
0.3
0.6
0.9
1.2
1.5
1.8

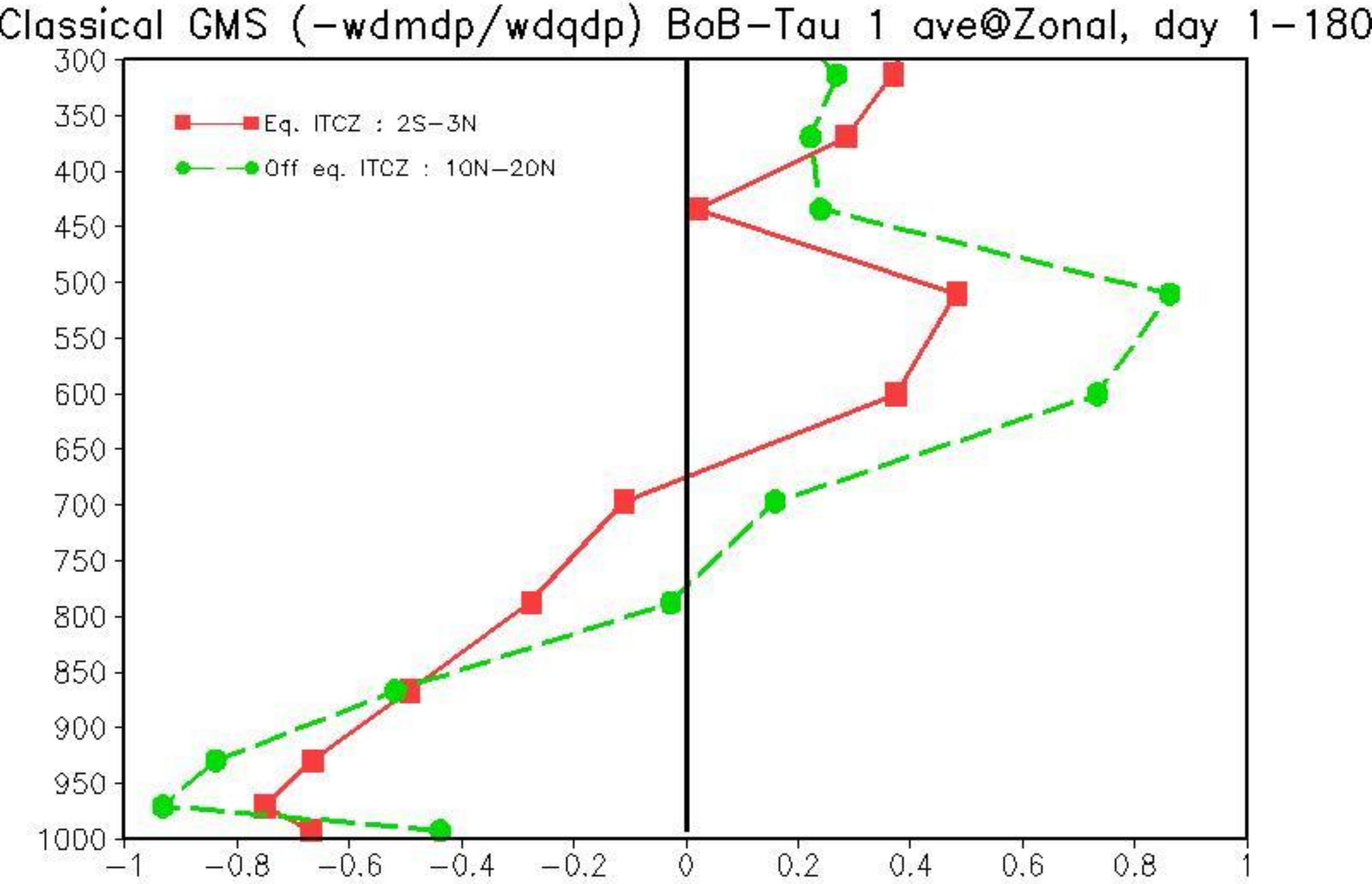


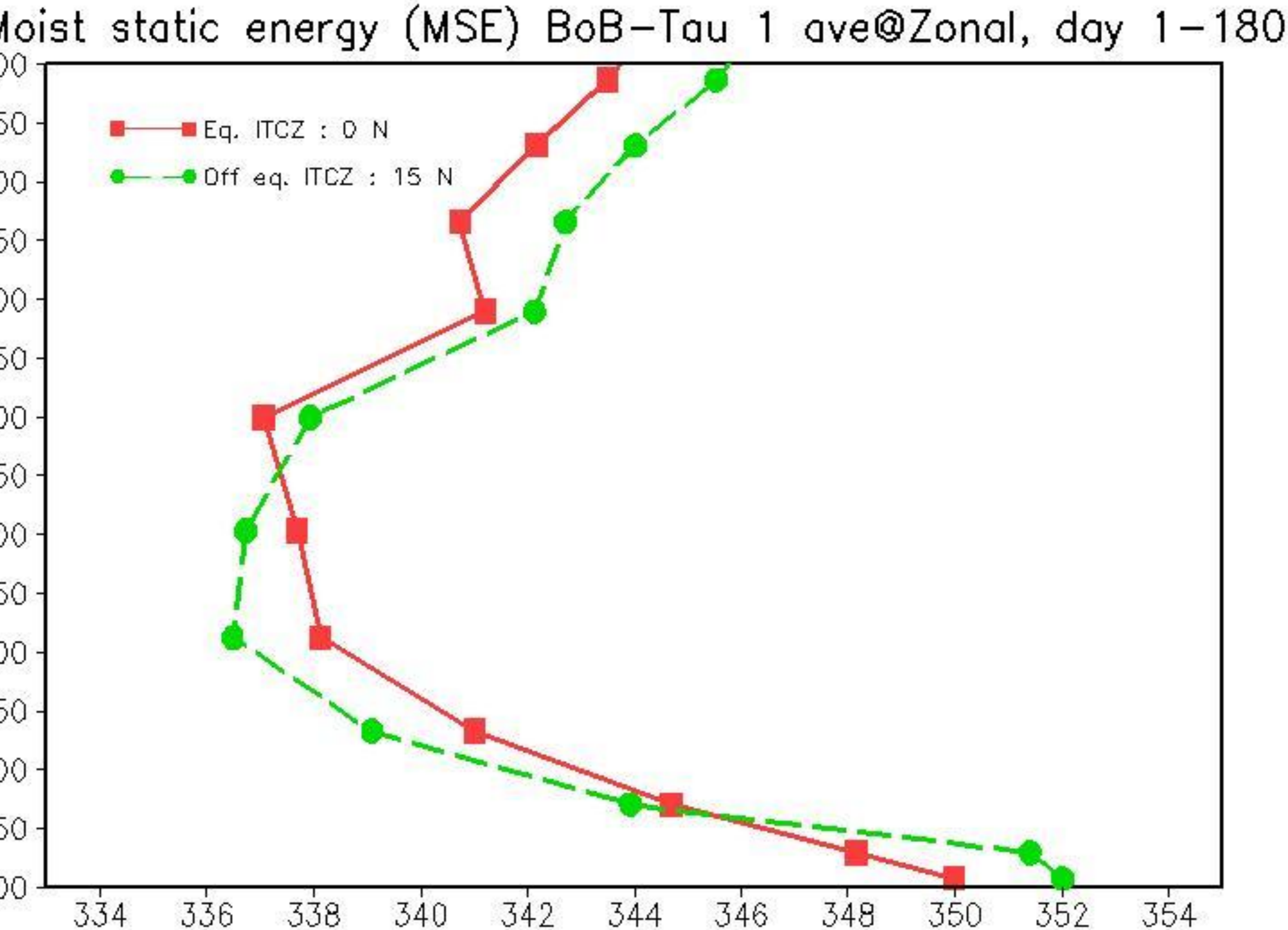
GMS vs Pwat for 0-360E, ave@180 days
10N-20N : Off Eq. ITCZ
0S-3N : Eq. ITCZ
-wdmdp/wdqdp
Pwat
1.8
1.5
1.2
0.9
0.6
0.3
0
-0.3
-0.6
-0.9
50
52
54
56
58
60
62
64

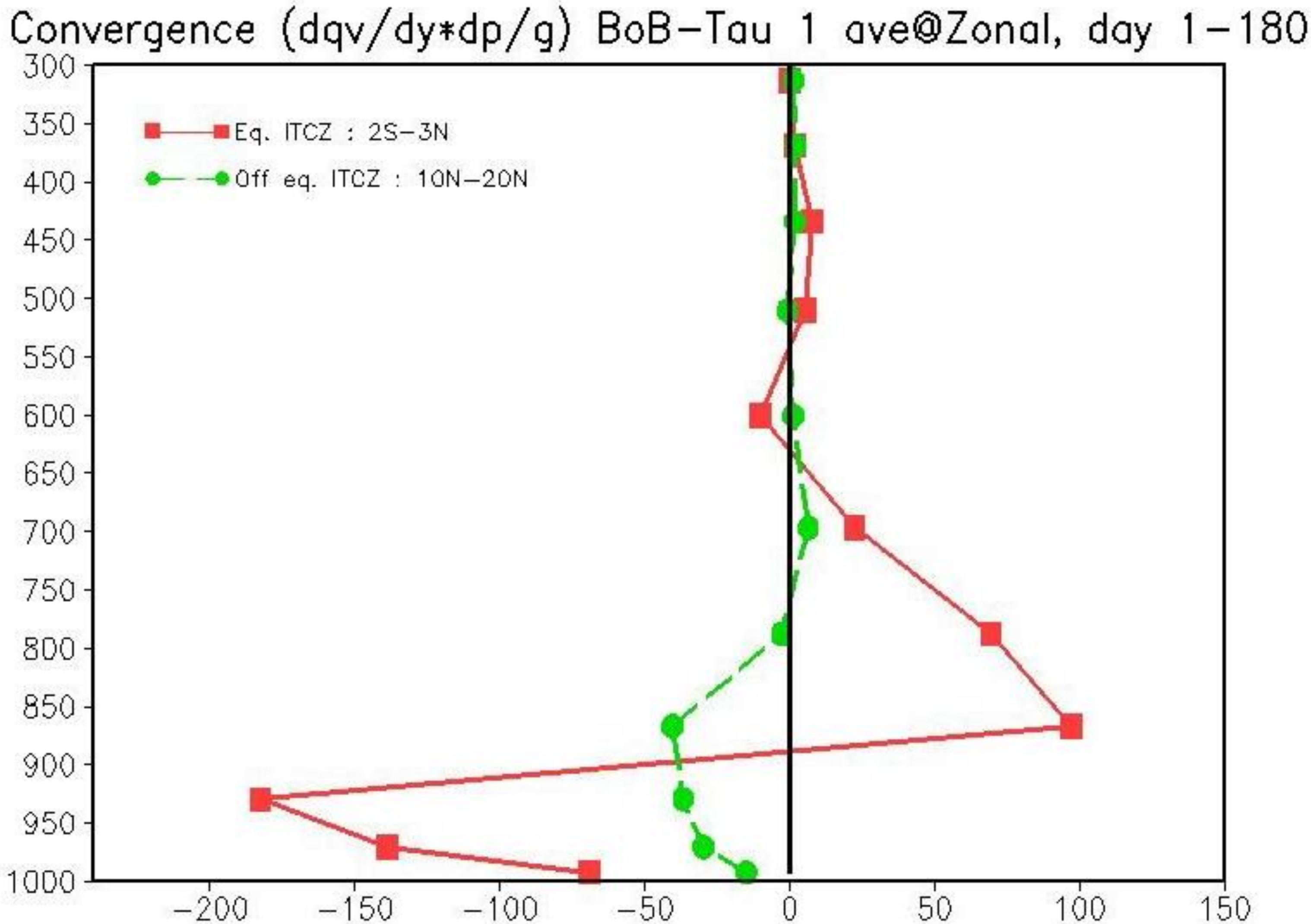


Shade:GMS, Contour:P−E ave@ 0−360E
30N
25N
20N
15N
10N
5N
EQ
5S
10S
Latitude
0
90
180
Days
170
0
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1

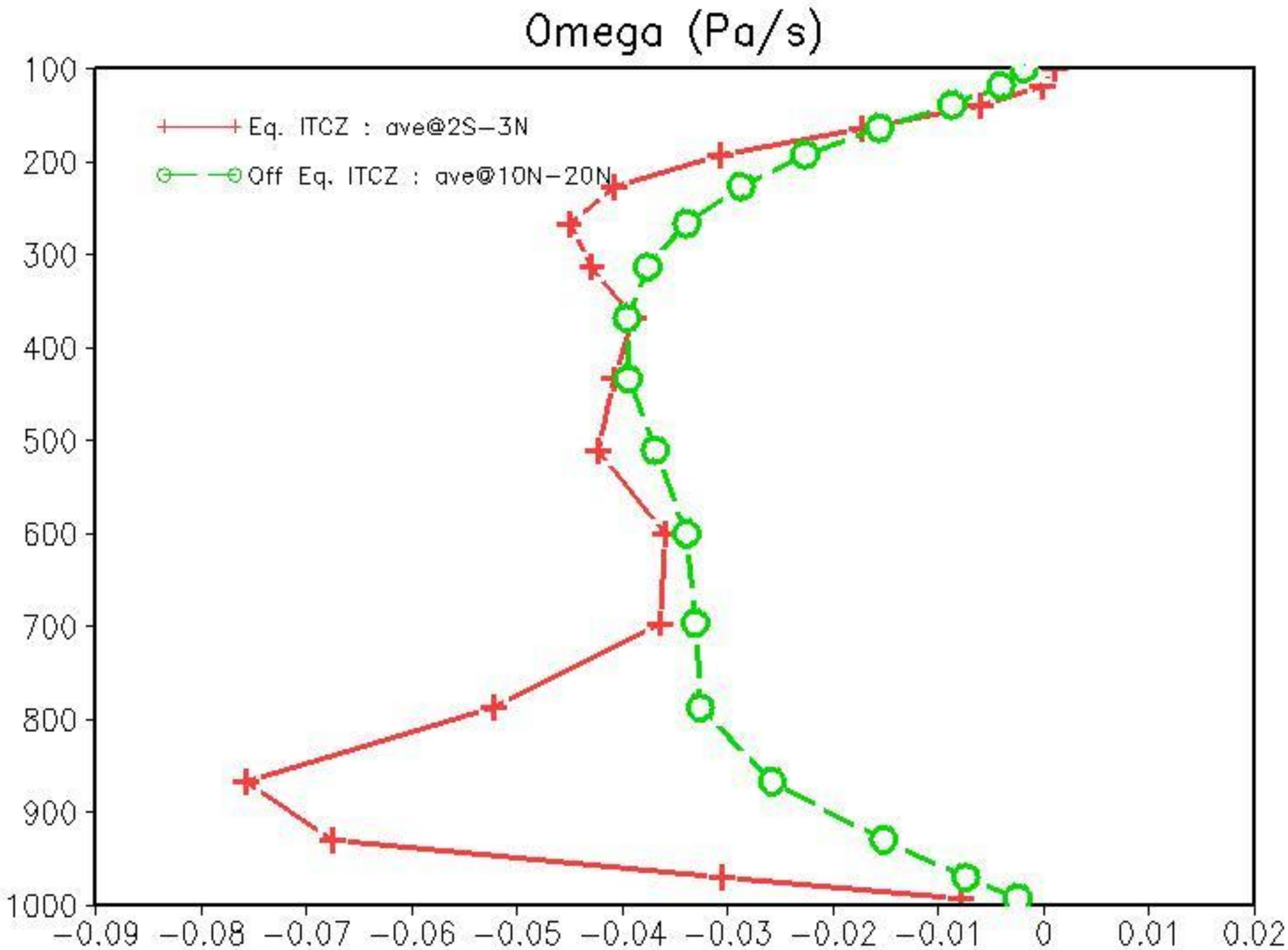

w*dm/dp BoB-Tau 1 ave@Zonal, day 1-180
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
10S
5S
EQ
5N
10N
15N
20N
25N
30N
-25
-20
-15
-10
-5
0
5
10
15
20
25
GrADS: COLA/IGES


Classical GMS (-wdmdp/wdqdp) BoB-Tau 1 ave@Zonal, day 1-180
Eq. ITCZ : 2S-3N
Off eq. ITCZ : 10N-20N
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

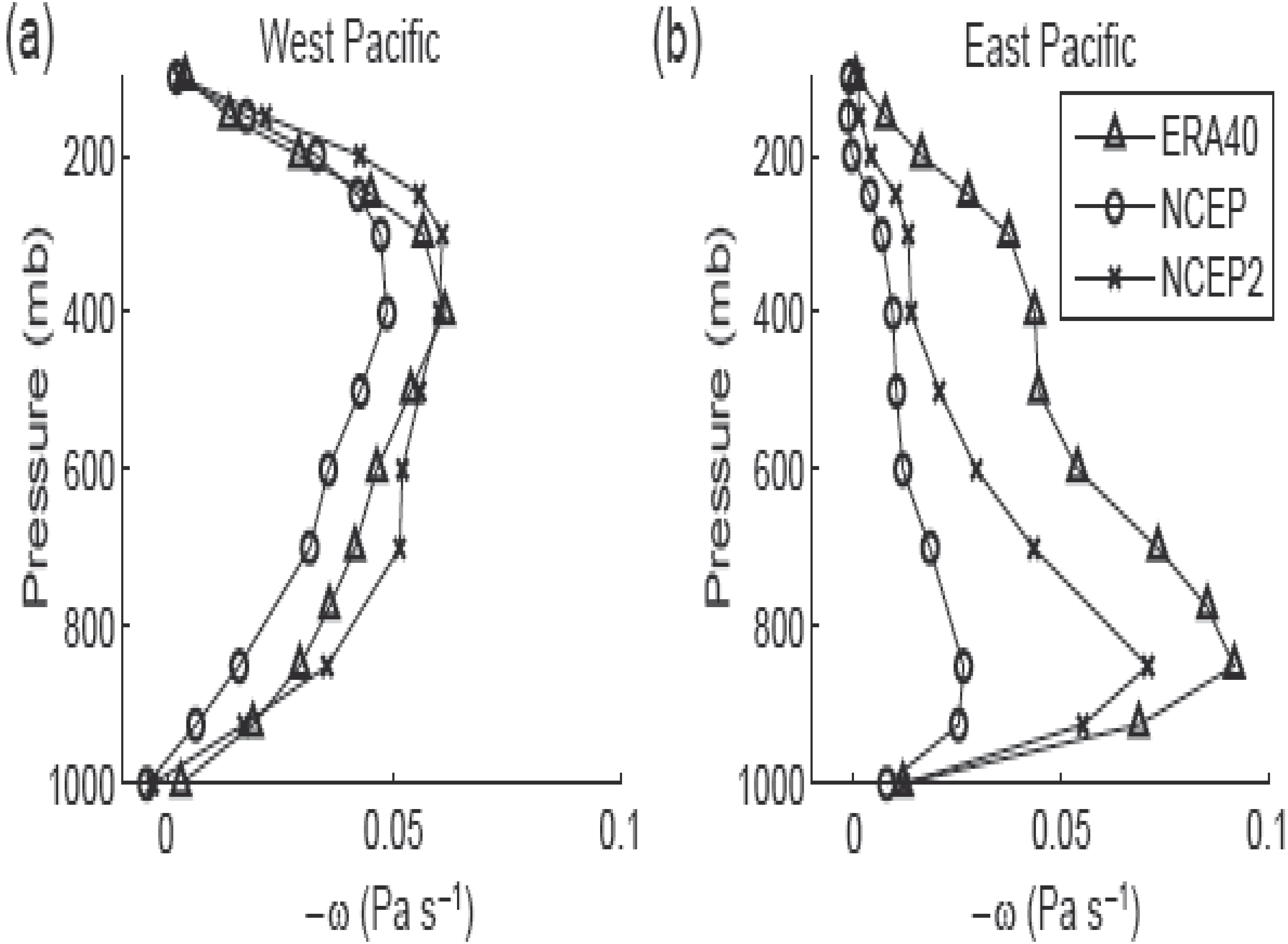

Moist static energy (MSE) BoB-Tau 1 ave@Zonal, day 1-180
Eq. ITCZ : 0 N
Off eq. ITCZ : 15 N
334
336
338
340
342
344
346
348
350
352
354



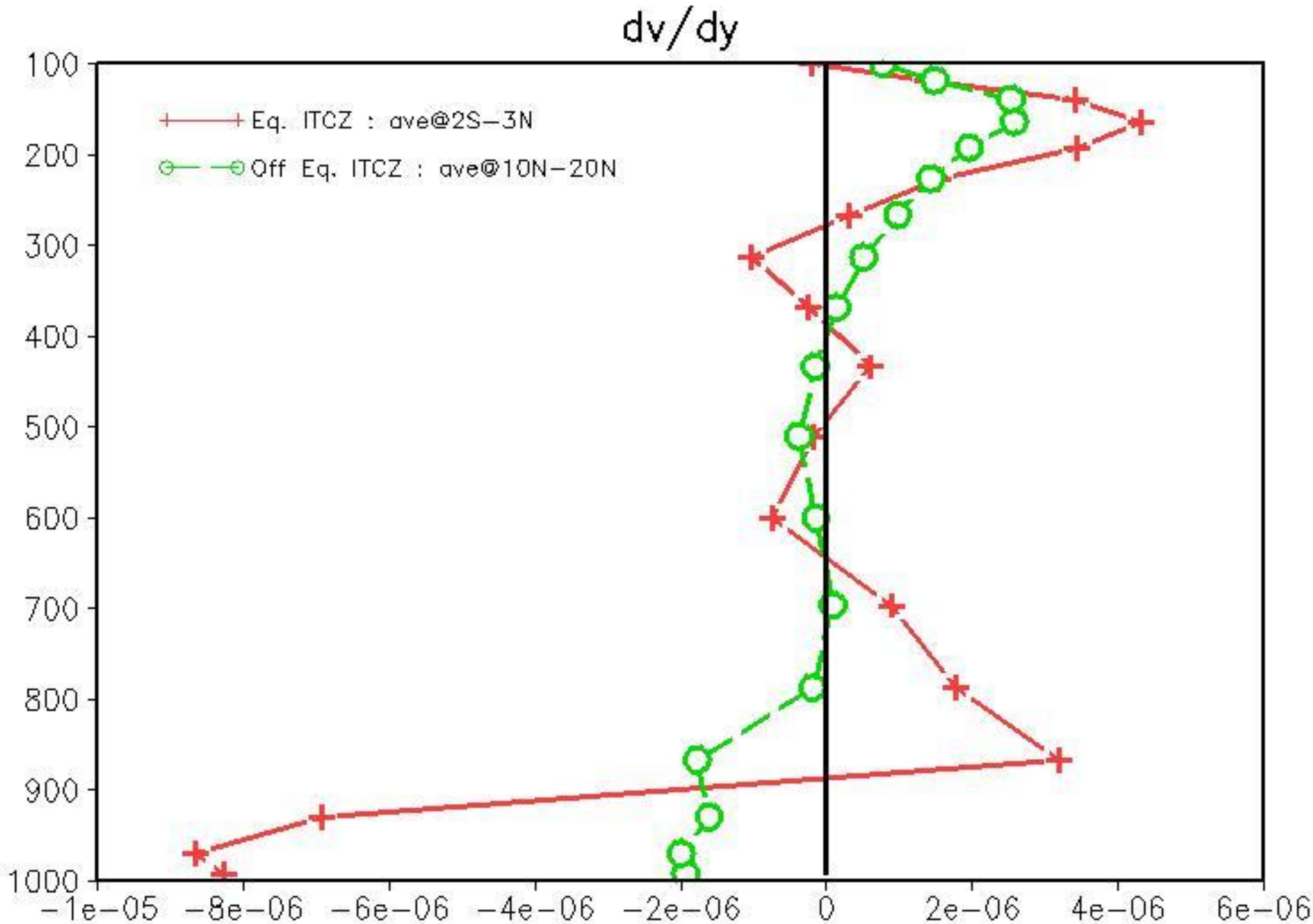
Convergence (dqv/dy*dp/g) BoB-Tau 1 ave@Zonal, day 1-180
Eq. ITCZ : 2S-3N
Off eq. ITCZ : 10N-20N
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
-200
-150
-100
-50
0
50
100
150

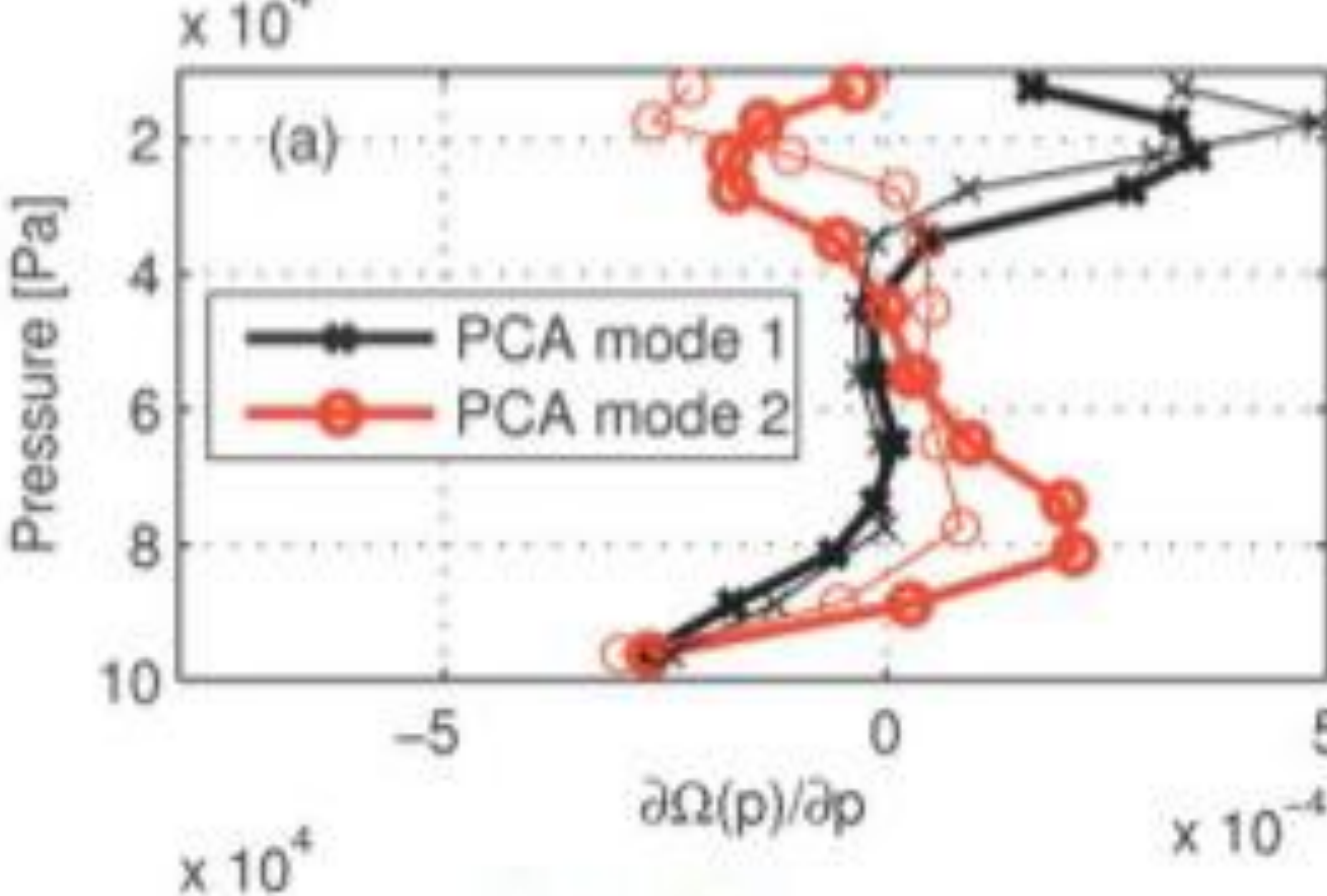


Omega (Pa/s)
Eq. ITCZ : ave@2S-3N
Off Eq. ITCZ : ave@10N-20N
100
200
300
400
500
600
700
800
900
1000
-0.09
-0.08
-0.07
-0.06
-0.05
-0.04
-0.03
-0.02
-0.01
0
0.01
0.02



(a)
West Pacific
Pressure (mb)
200
400
600
800
1000
0
0.05
0.1
−ω (Pa s⁻¹)
(b)
East Pacific
ERA40
NCEP
NCEP2
Pressure (mb)
200
400
600
800
1000
0
0.05
0.1
−ω (Pa s⁻¹)


dv/dy
Eq. ITCZ : ave@2S-3N
Off Eq. ITCZ : ave@10N-20N
100
200
300
400
500
600
700
800
900
1000
-1e-05
-8e-06
-6e-06
-4e-06
-2e-06
0
2e-06
4e-06
6e-06

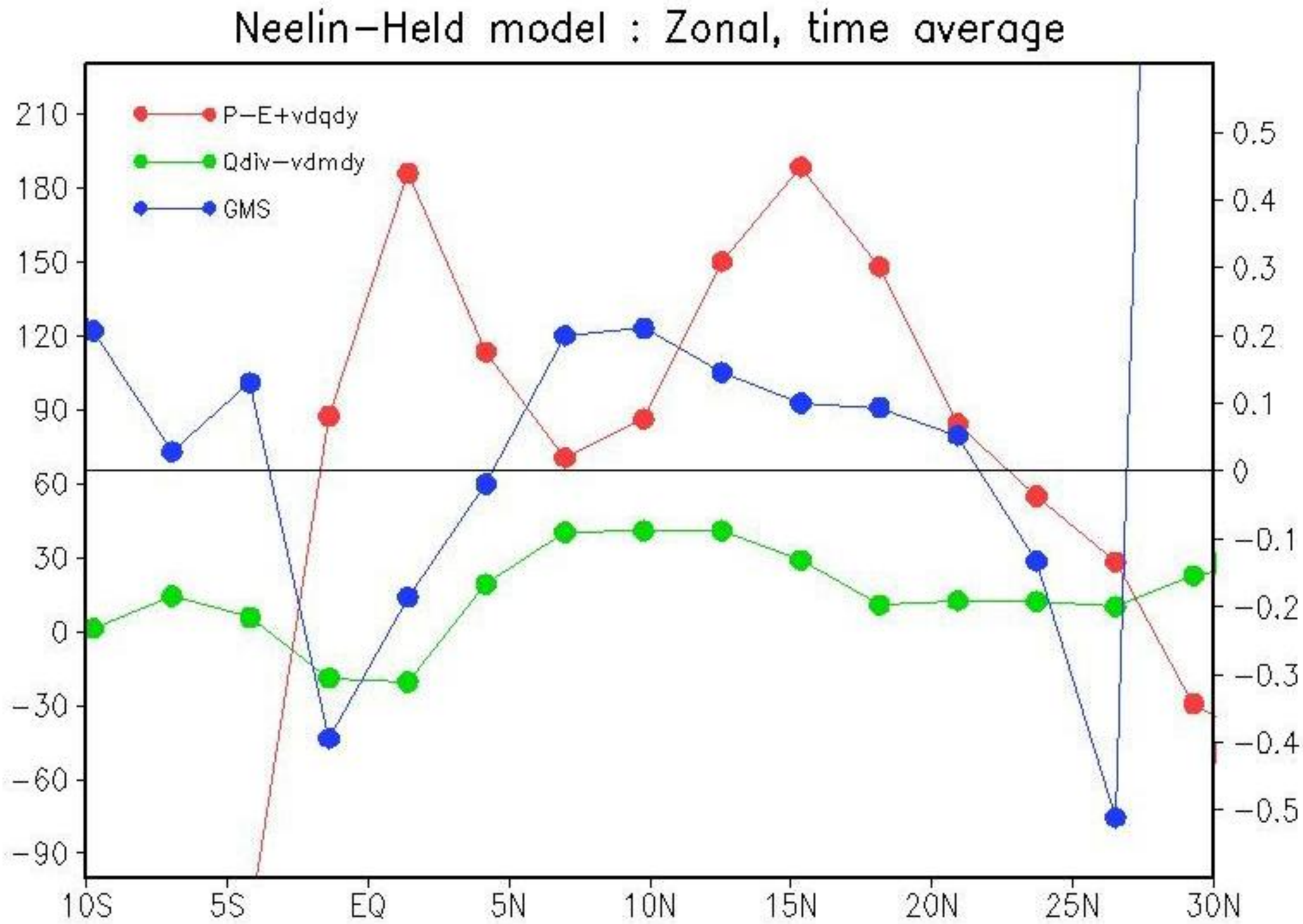


Thick :ERA   Thin:NCEP
Back and Bretherton, 2009

Assuming vertical profile of MSE is more or less constant in an ITCZ, the vertical profile of vertical velocity plays a crucial role in determination of vertically integrated export of MSE

1. Vertical velocity maxima is above MSE minima

2. Vertical velocity maxima is below MSE minima


Neelin–Held model : Zonal, time average
P–E+vdqdy
Qdiv–vdmdy
GMS
210
180
150
120
90
60
30
0
−30
−60
−90
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
−0.4
−0.5
10S
5S
EQ
5N
10N
15N
20N
25N
30N

$$P - E + \left[v \frac{dq}{dy} \right] = \frac{Qdiv - \left[v \frac{dM}{dy} \right]}{GMS}$$

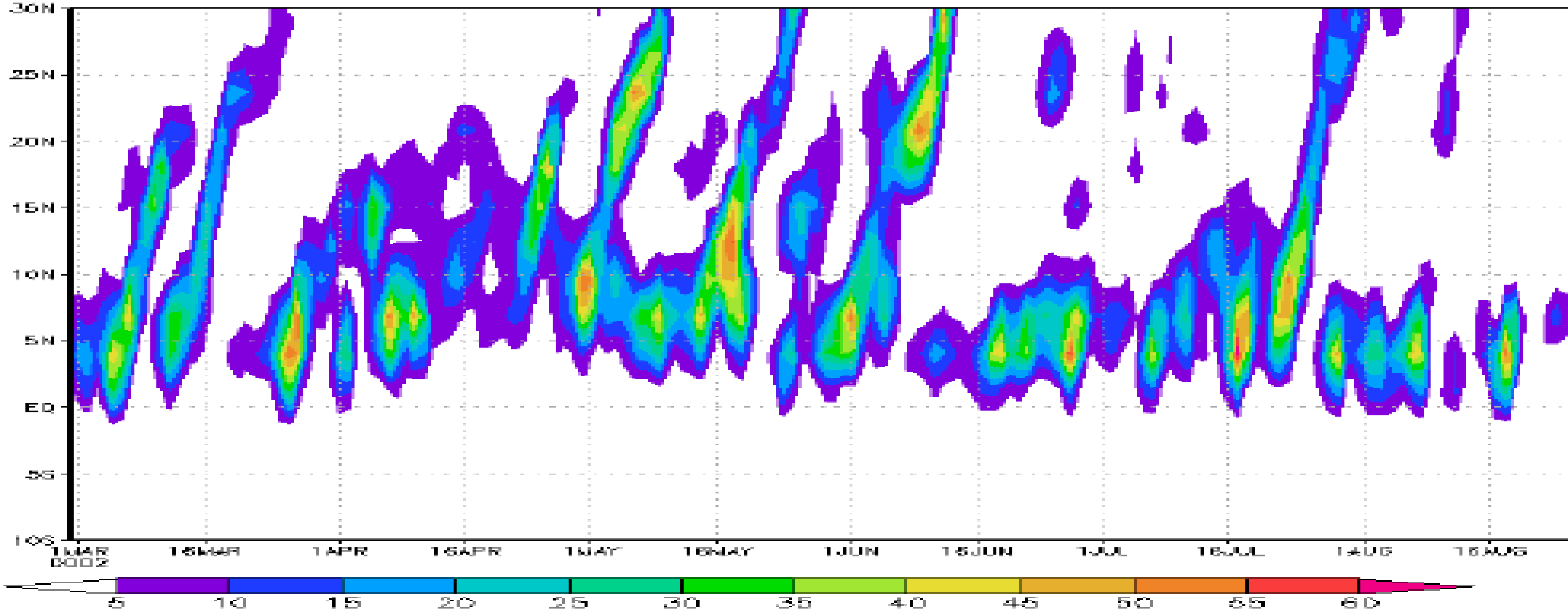
$$d(q^*v)/dy = E - P$$

$$d(m^*v)/dy = (E+S) - Q_{rad}$$

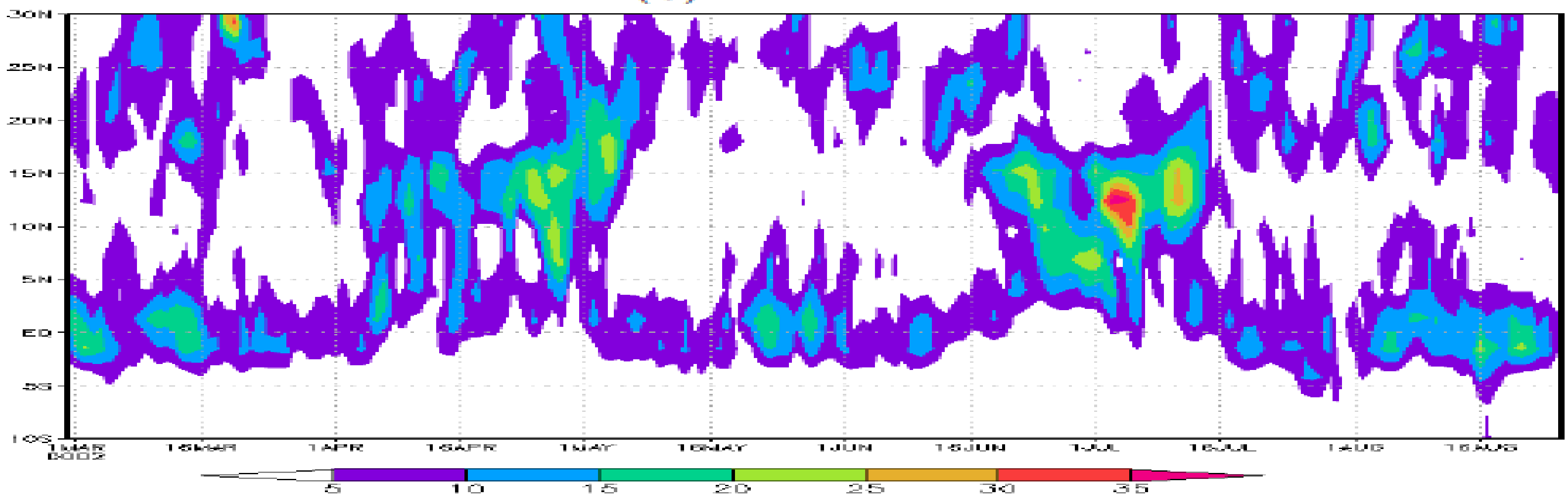
$$P - E + v^*dq/dy = Qdiv / GMS$$

$$Q_{div} = (E+S) - Q_{rad} - v^*dm/dy$$

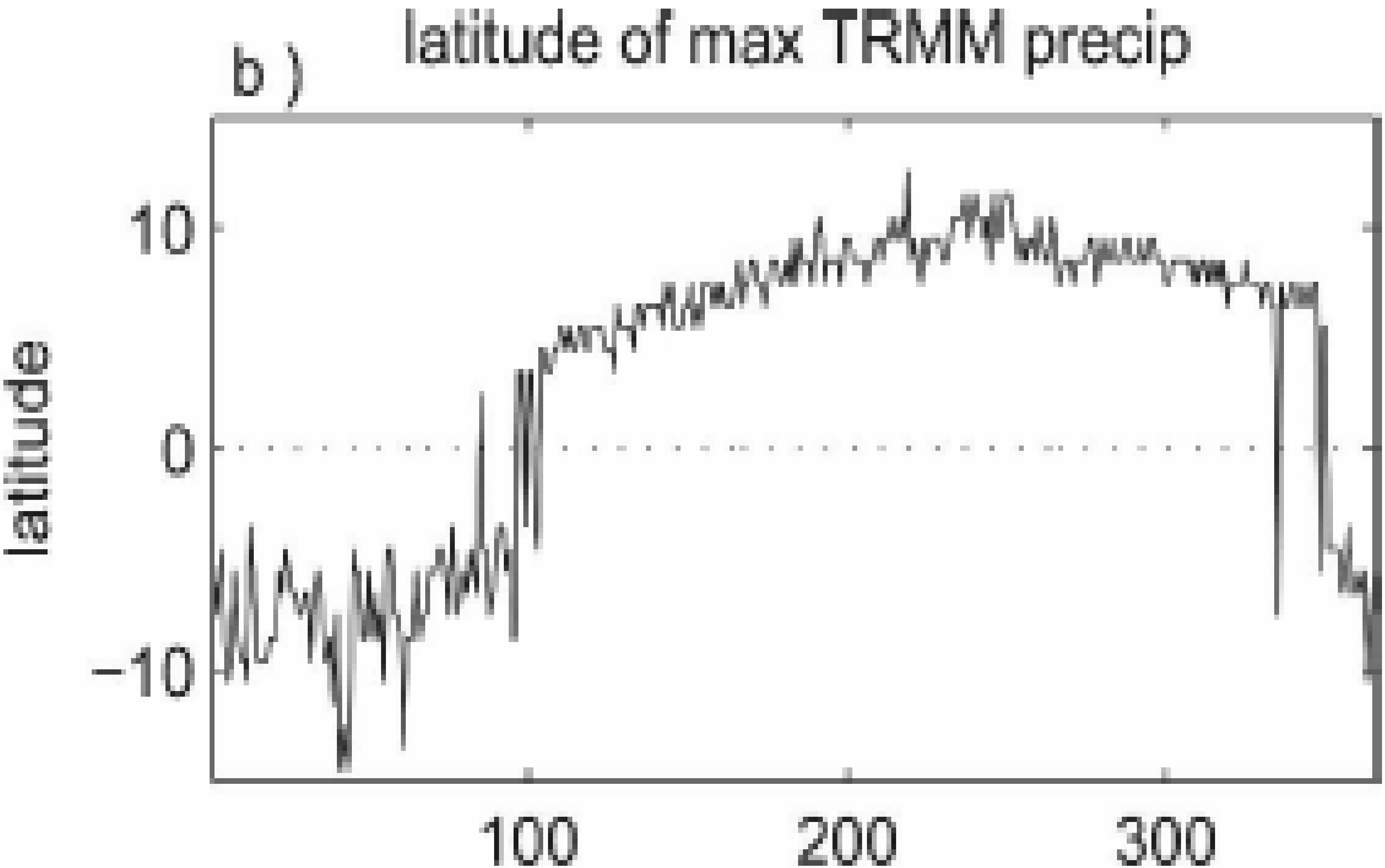
$$GMS = \frac{-\{\int \omega[\partial m/\partial p^*]\, \partial p^*\}}{\{\int \omega[\partial Lq/\partial p^*]\, \partial p^*\}}$$



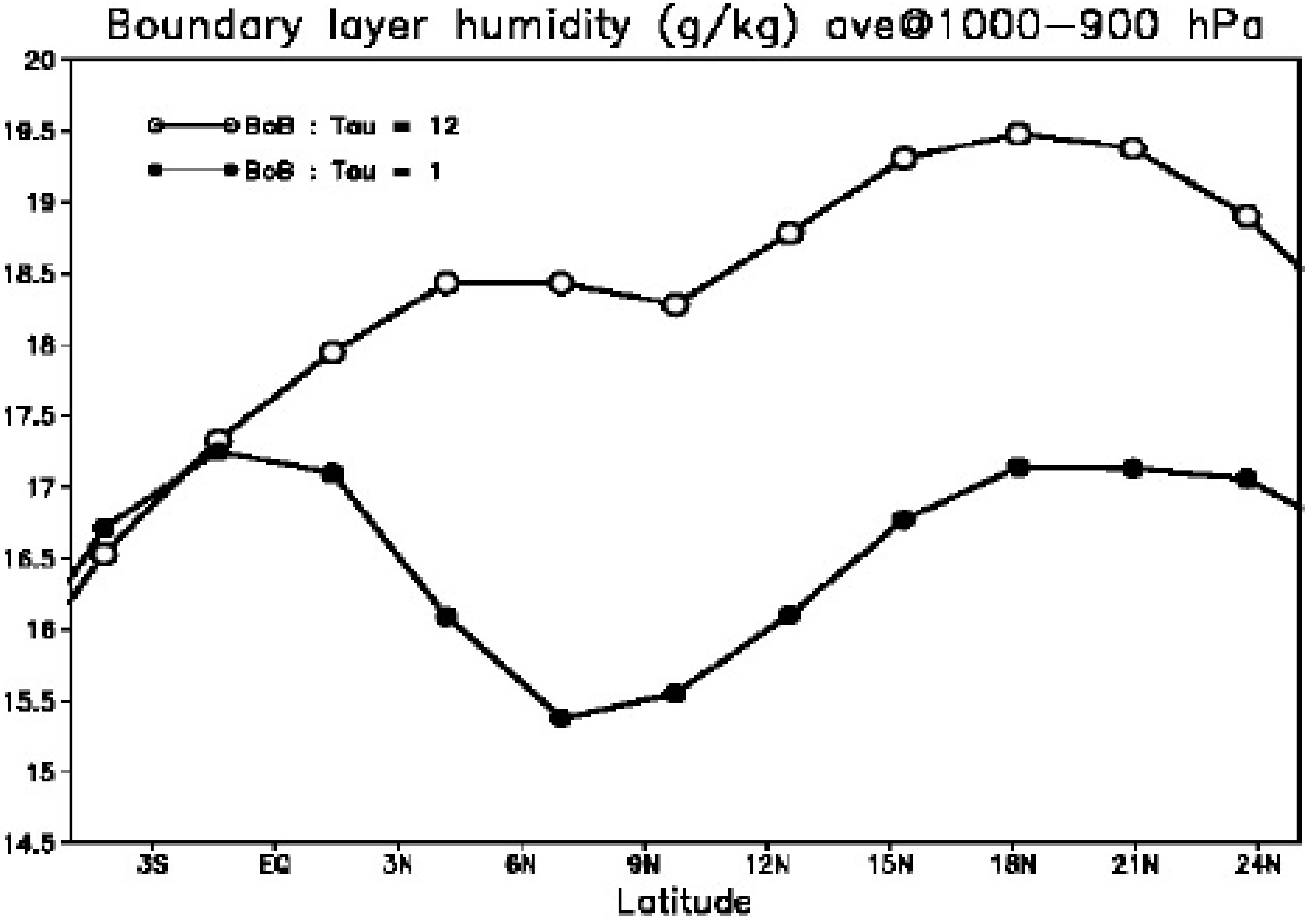
(b) τ = 12Hr



(a) τ = 1Hr

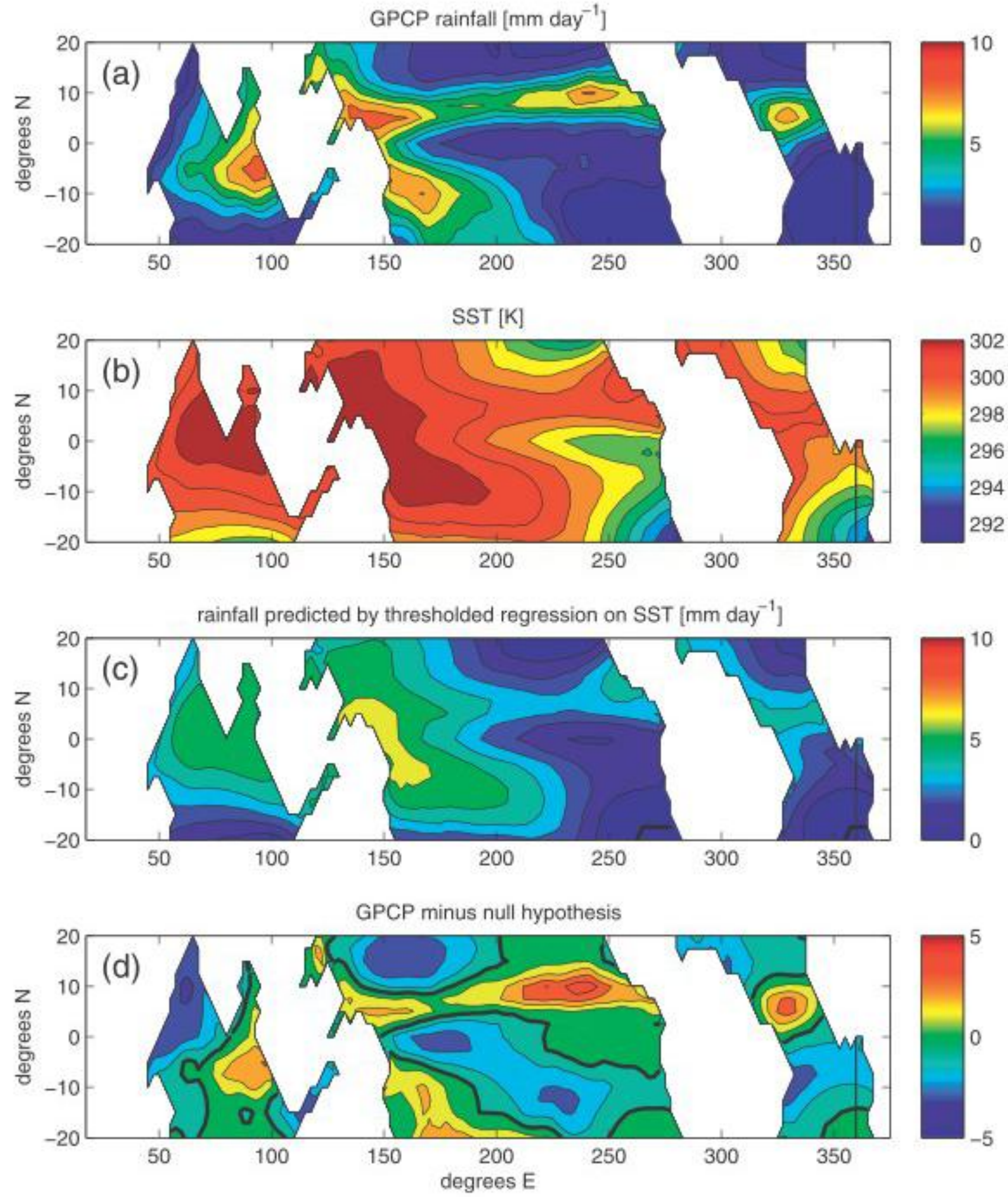


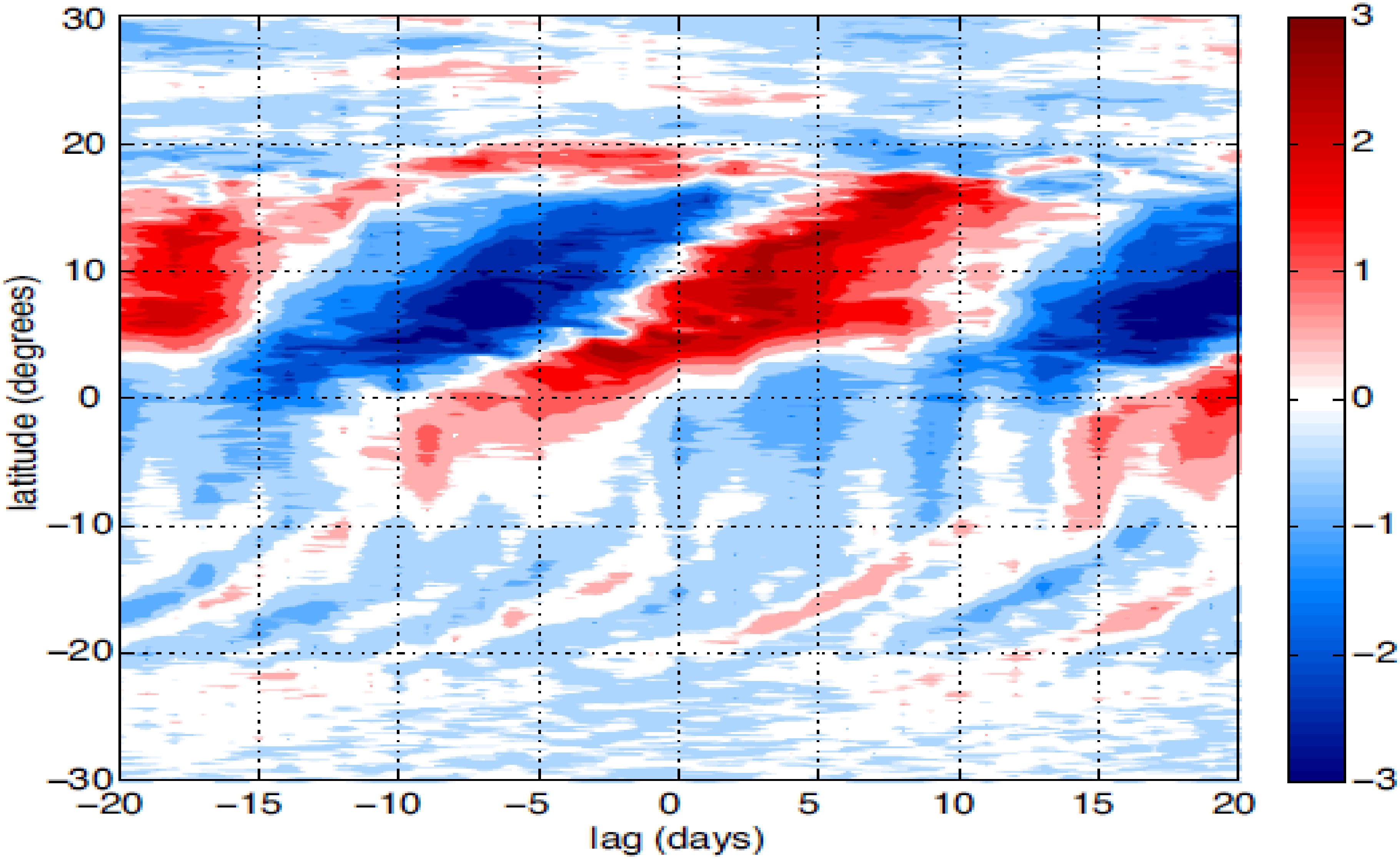
Xian and Miller, JAS, 2008


Boundary layer humidity (g/kg) ave@1000–900 hPa
20
19.5
19
18.5
18
17.5
17
16.5
16
15.5
15
14.5
BoB : Tau = 12
BoB : Tau = 1
3S
EQ
3N
6N
9N
12N
15N
18N
21N
24N
Latitude

CONCLUSIONS

- Continental ITCZ can be explained by simple Neelin & Held hypothesis
- Oceanic ITCZ can be explained by Neelin and Held model provided we include horizontal advection terms


GPCP rainfall [mm day^{-1}]
(a)
SST [K]
(b)
rainfall predicted by thresholded regression on SST [mm day^{-1}]
(c)
GPCP minus null hypothesis
(d)
degrees N
degrees E
20
10
0
−10
−20
50
100
150
200
250
300
350
0
5
10
292
294
296
298
300
302
−5



Boos and Kuang, JAS, 2010, Cloud Resolving Model