Recent Development of NCEP GFS for High Performance Computing

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Introduction

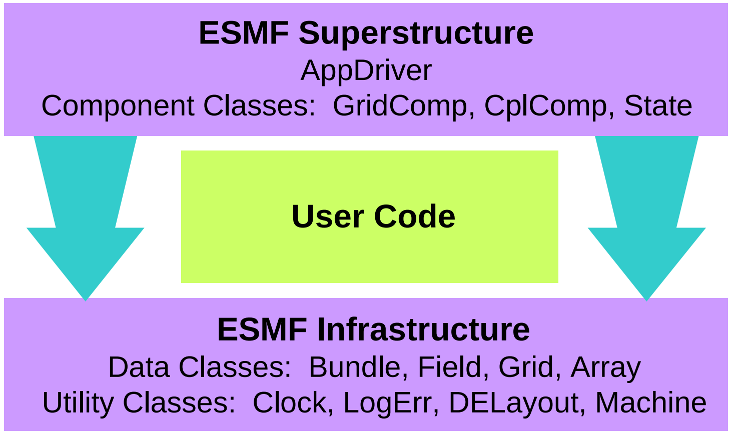
- NCEP GFS is an NCEP operational global forecast system, mainly refers to a global spectral model.
- GFS comprises model dynamics and physics in hydrostatic system with reduced Gaussian grid, for weather and seasonal forecasts.
- Report on recent developed and developing systems for requiring HPC

High performance computing needs

- Concurrent Ensemble forecast
- Coupled atmospheric-ocean-land
  - High horizontal resolution
- Couple with space environmental model
  - More layers, hybrid coordinates
  - Deep-atmosphere approach
- Adopt ESMF for concurrency & coupling

What is ESMF?

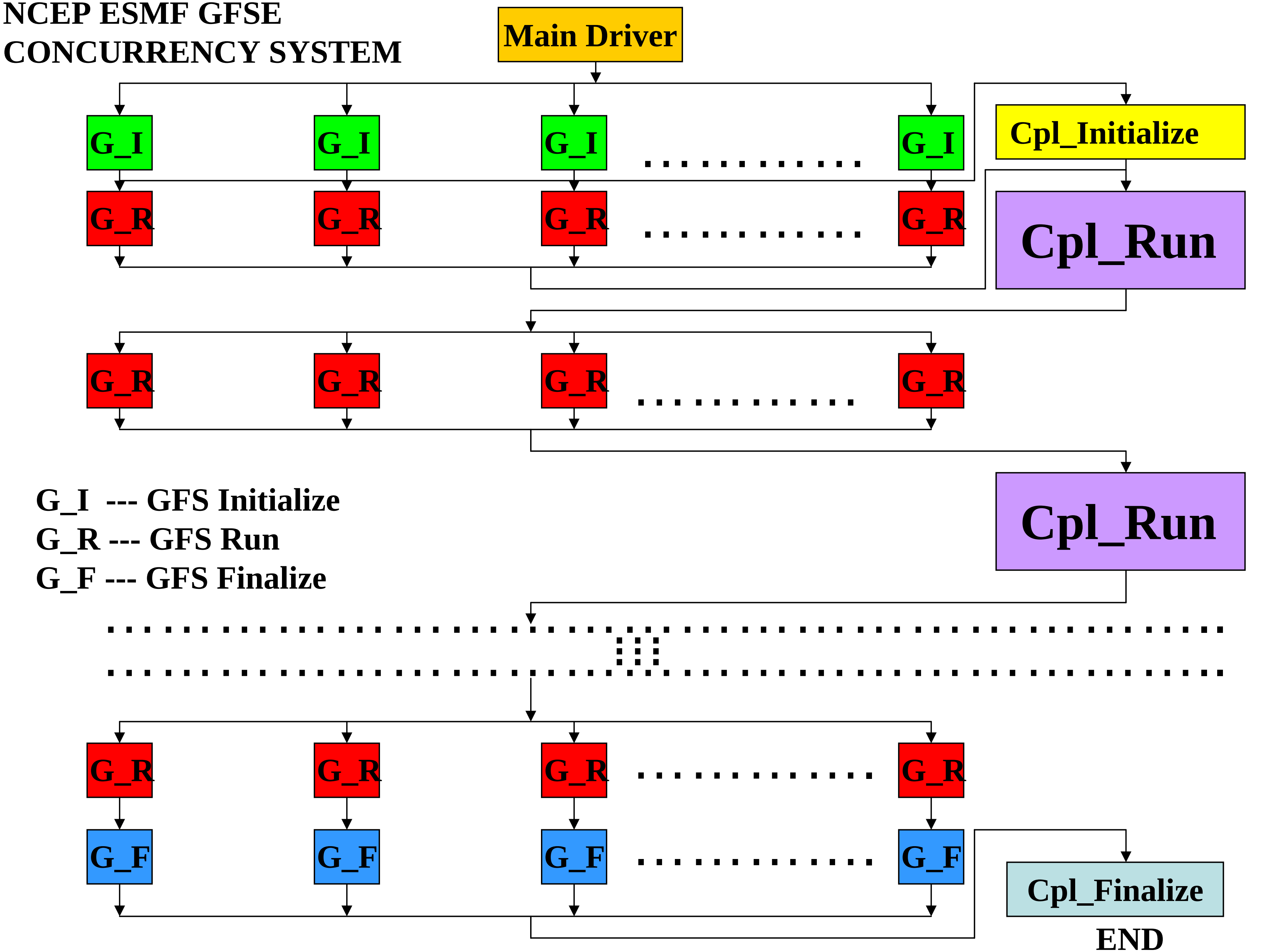
- ESMF provides tools for turning model codes into components with standard interfaces and standard drivers.
- ESMF provides data structures and common utilities that components use for routine services such as data communications, regridding, time management and message logging.



ESMF GOALS

1. Increase scientific productivity by making model components much easier to build, combine, and exchange, and by enabling modelers to take full advantage of high-end computers.
2. Promote new scientific opportunities and services through community building and increased interoperability of codes (impacts in collaboration, code validation and tuning, teaching, migration from research to operations)

NCEP ESMF GFSE CONCURRENCY SYSTEM



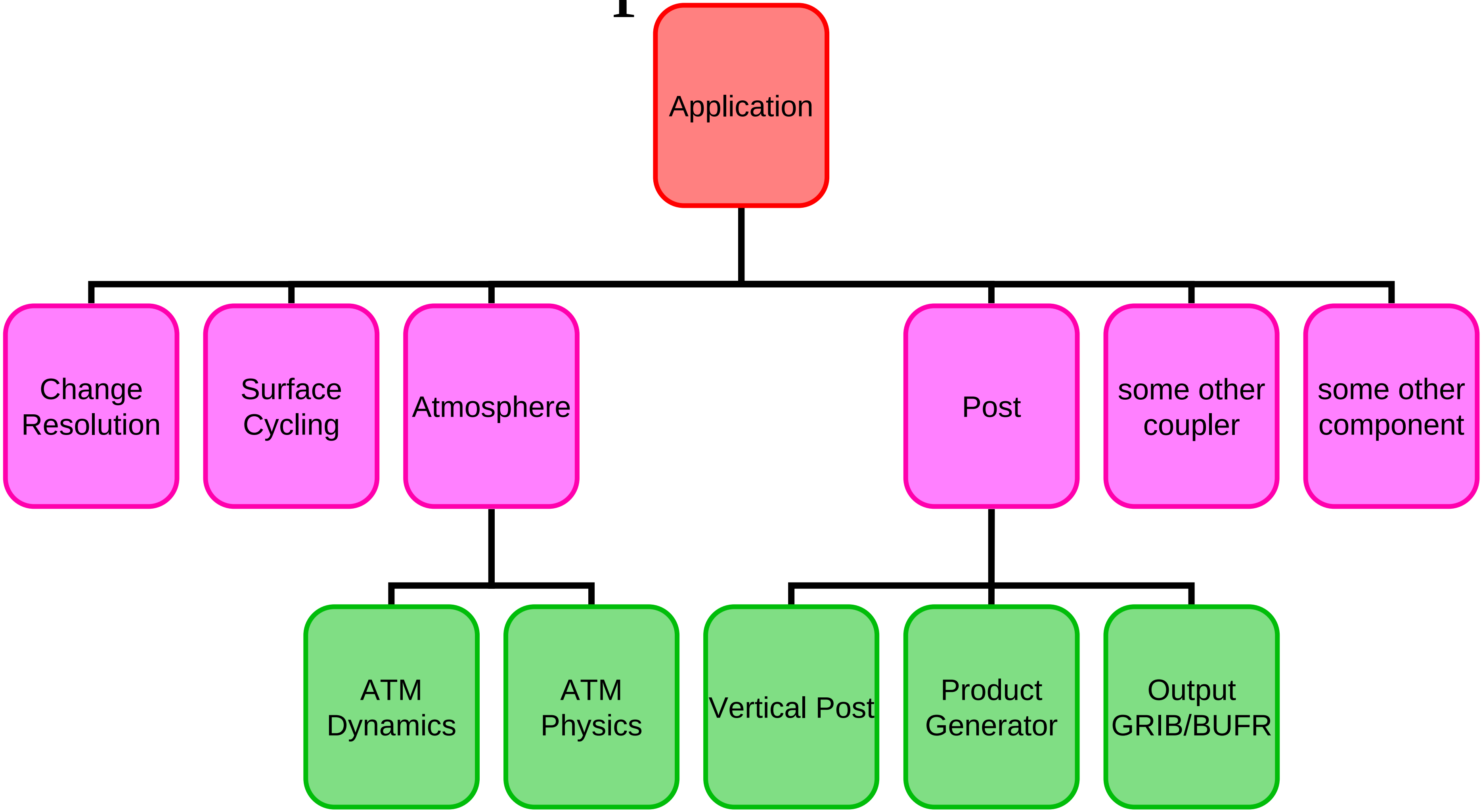
Timing for 11 members

T126L64 48 h fcst	#	cpu	Event Wall time(s)	Total Wall time(s)
Concurrent ESMF	11	55	2082	2082
parallel	1	5	2086	2086
sequential	1	65	214	2354

Concurrent EFS with ESMF

- Concurrently run all ensemble GFS forecast members.
- No extra resource cost with concurrent ESMF as compared to other runs
- The ensemble run members can exchange their information at any time you need.
- One coupler couples all ensemble members and creates the new initial conditions for them to run the next ensemble run.

ESMF Component Framework



Improve vertical coordinates

Generalized hybrid

For specific hybrid coordinate

$$\hat{p}_k = \hat{A}_k + \hat{B}_k p_s + \hat{C}_k \left(\frac{T_{vk-1} + T_{vk}}{T_{0k-1} + T_{0k}} \right)^{C_p / R_d}$$

where variables with ^ are at model interfaces,
p, T and ps are function of 3-D space and time
A, B, and C are layer constants, only function of k

Sigma-p | Sigma-theta

A=0 | C=0

$$\hat{p}_k = \hat{A}_k$$

B=0

$$\hat{p}_k = \hat{C}_k \left(\hat{T}_{vk} / \hat{T}_{0k} \right)^{C_p / R_d}$$

B=0

$$\hat{p}_k = \hat{A}_k + \hat{B}_k p_s$$

$$\hat{p}_k = \hat{B}_k p_s + \hat{C}_k \left(\hat{T}_{vk} / \hat{T}_{0k} \right)^{C_p / R_d}$$

A=0 | C=0

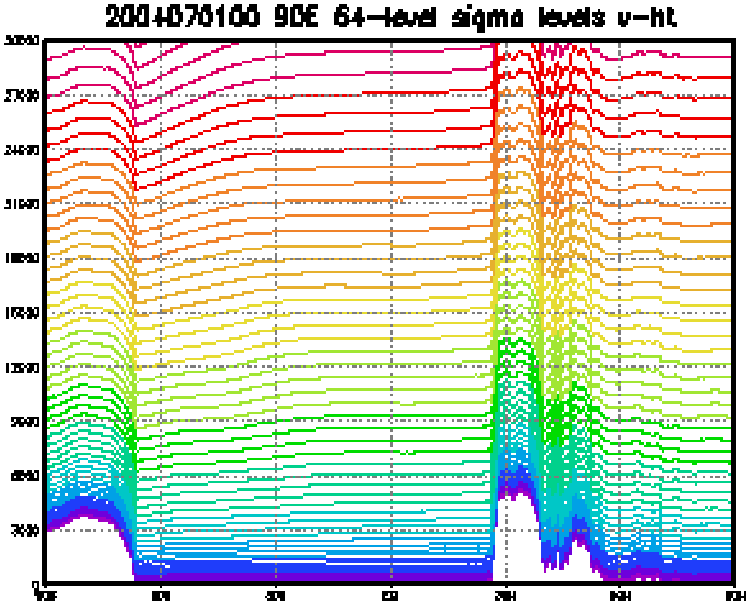
A=0

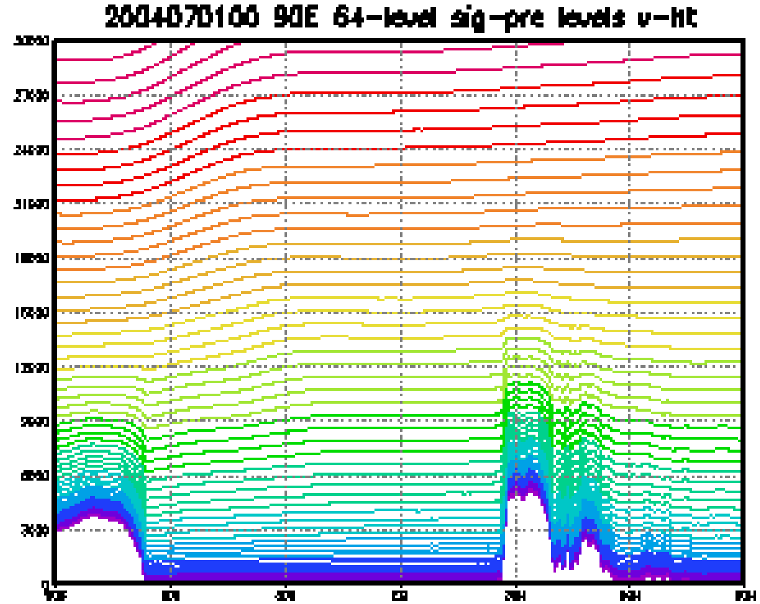
$$\hat{p}_k = \hat{B}_k p_s$$

$$\hat{p}_k = \hat{B}_k p_s$$

C=0

B=1


2004070100 90E 64-level sigma levels v-ht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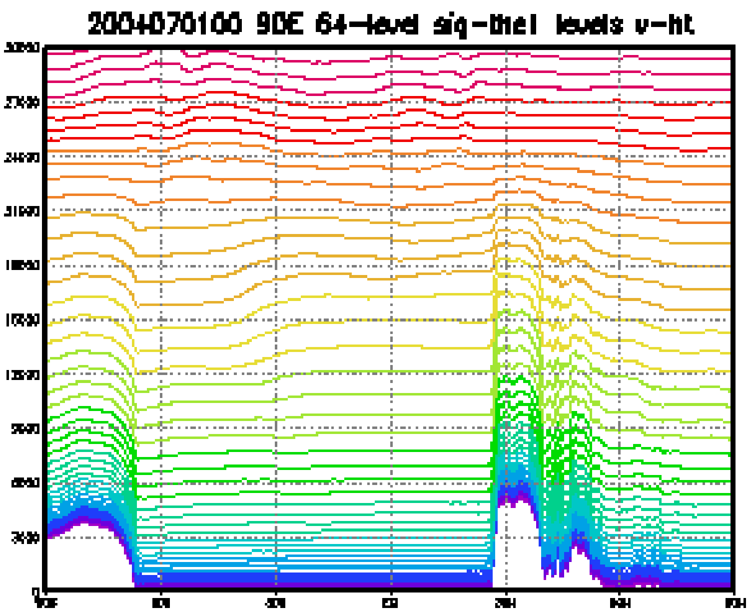
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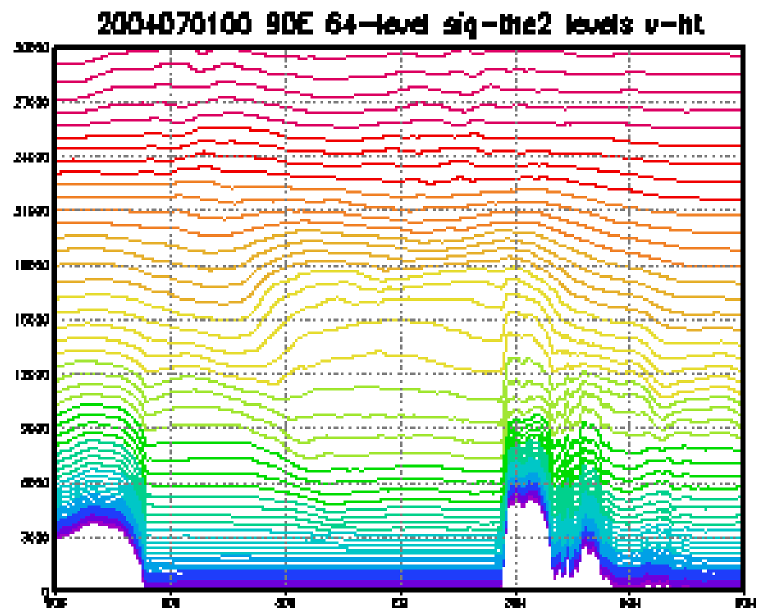
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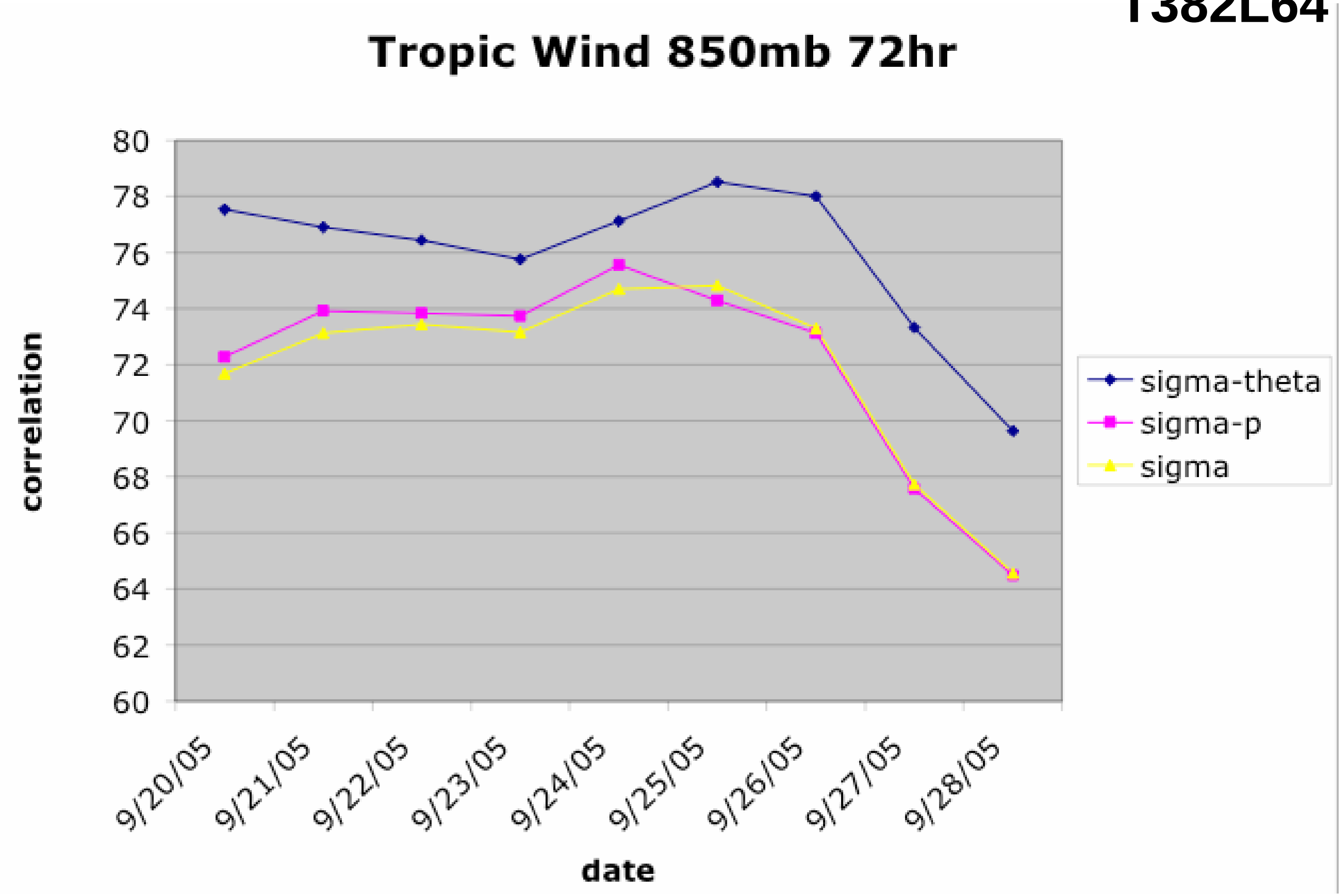
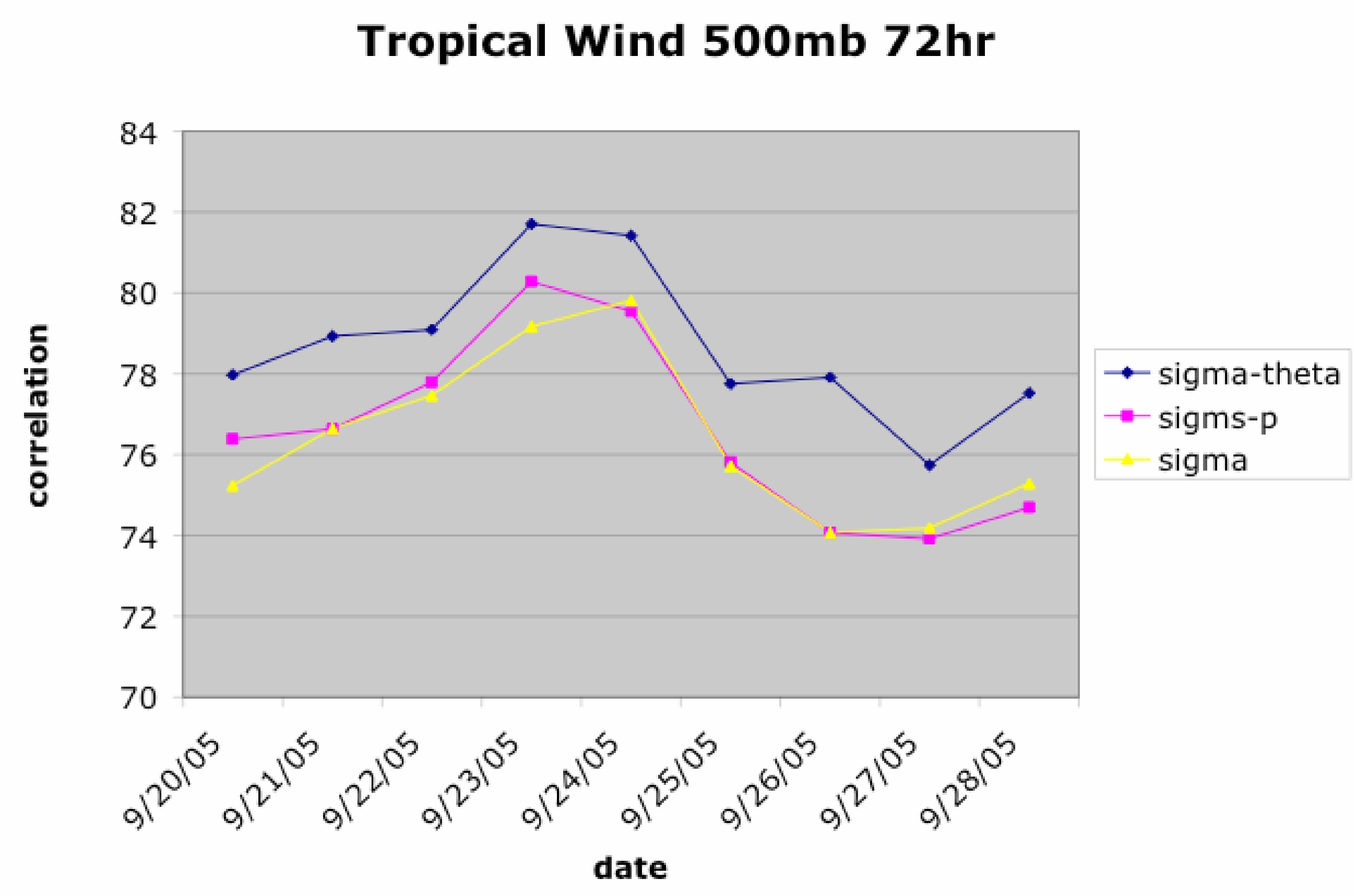
T382L64

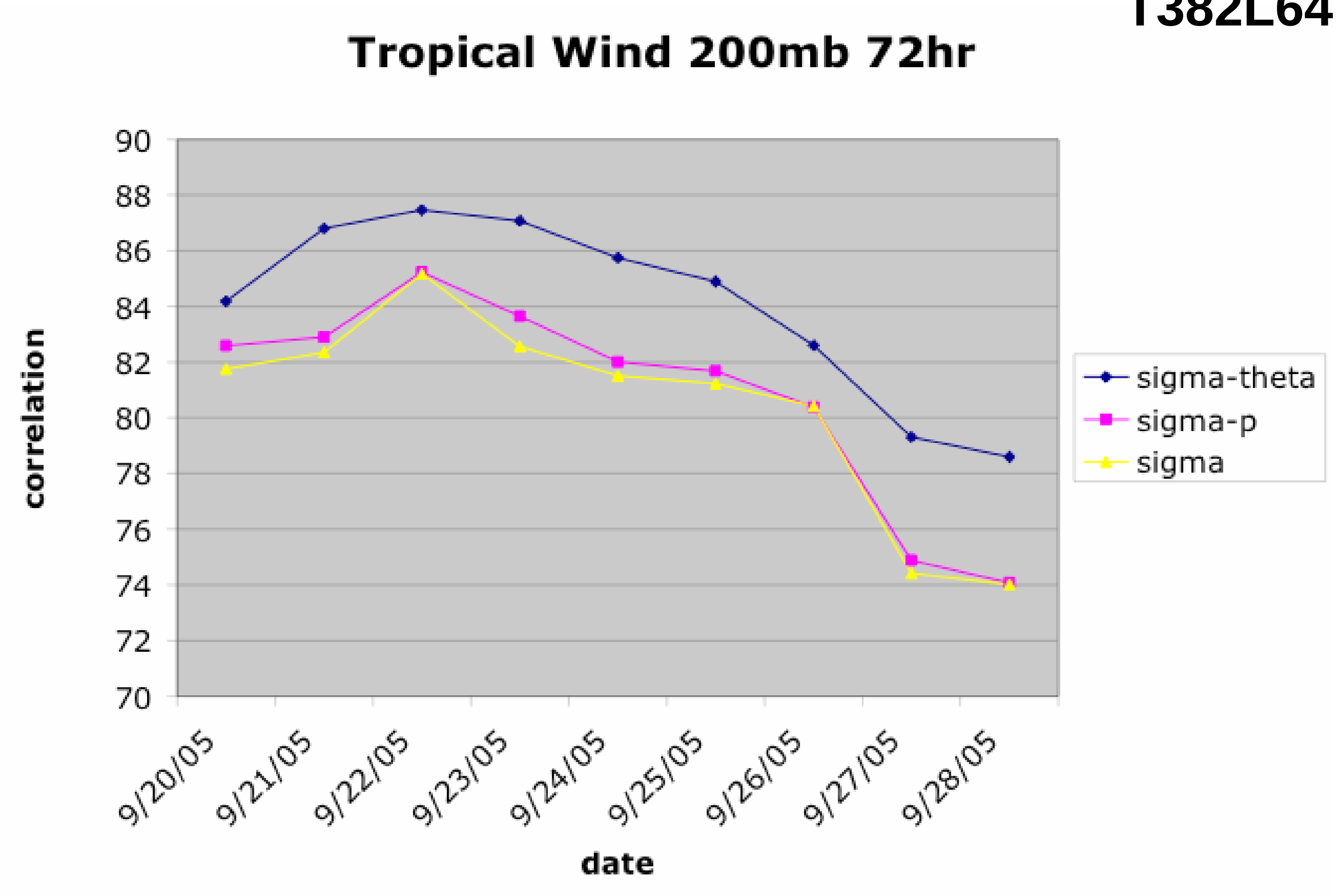

Tropic Wind 850mb 72hr
correlation
80
78
76
74
72
70
68
66
64
62
60
9/20/05
9/21/05
9/22/05
9/23/05
9/24/05
9/25/05
9/26/05
9/27/05
9/28/05
date
sigma-theta
sigma-p
sigma

T382L64



Tropical Wind 500mb 72hr
correlation
84
82
80
78
76
74
72
70
9/20/05
9/21/05
9/22/05
9/23/05
9/24/05
9/25/05
9/26/05
9/27/05
9/28/05
date
sigma-theta
sigms-p
sigma

T382L64



Tropical Wind 200mb 72hr
90
88
86
84
82
80
78
76
74
72
70
correlation
9/20/05
9/21/05
9/22/05
9/23/05
9/24/05
9/25/05
9/26/05
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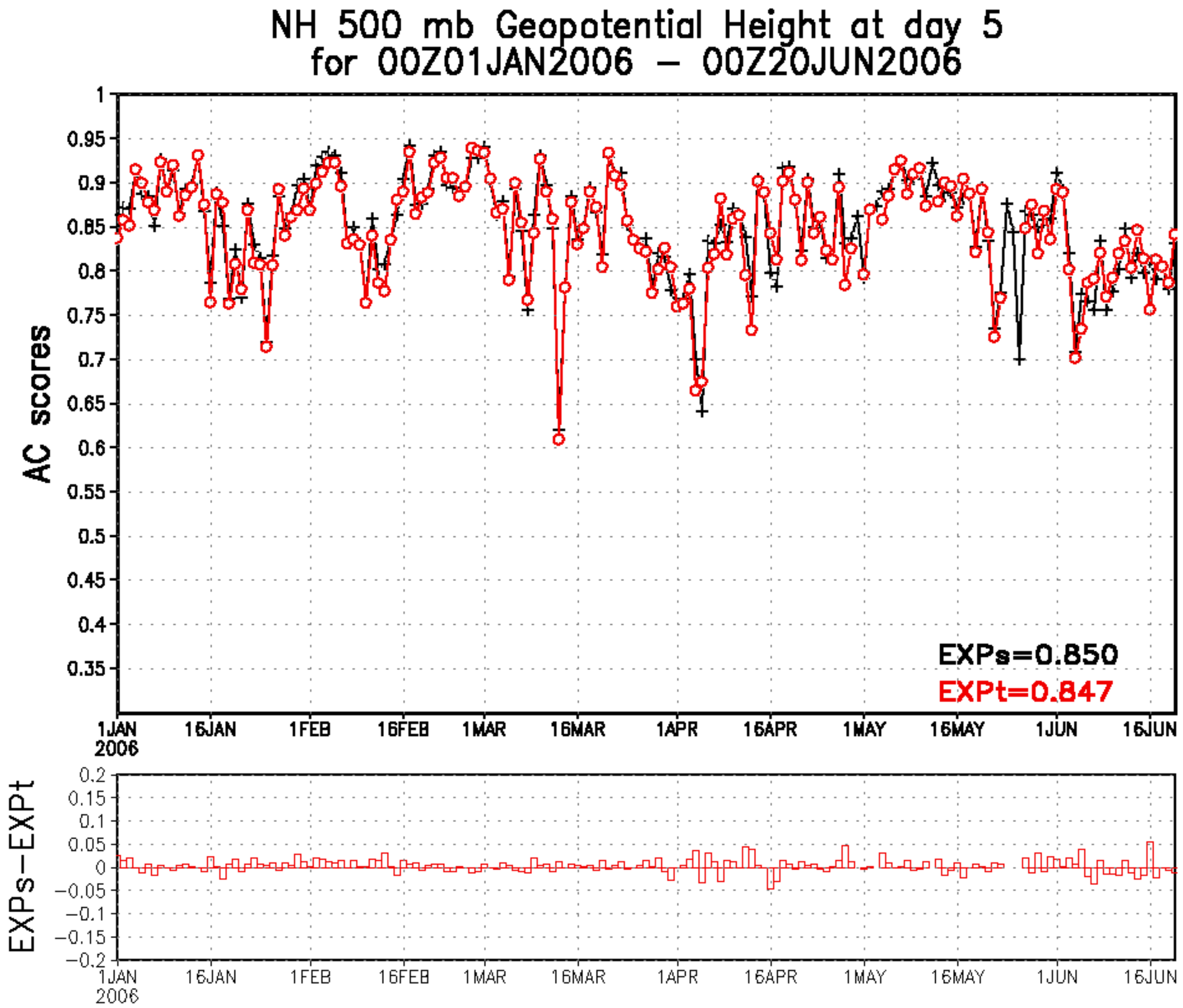
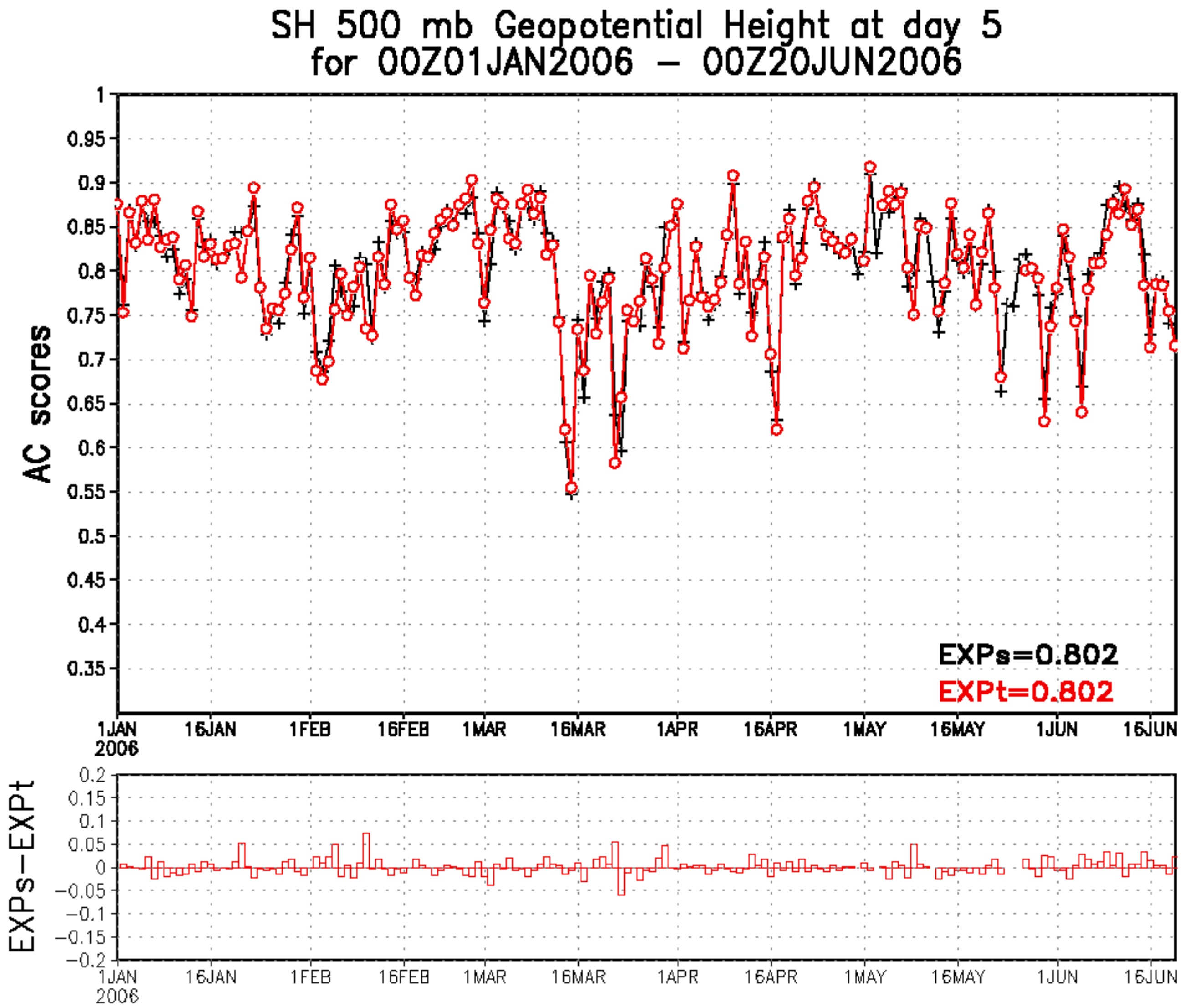
9/28/05
date
sigma-theta
sigma-p
sigma



Black s: operational GFS Red t: sigma-theta GFS



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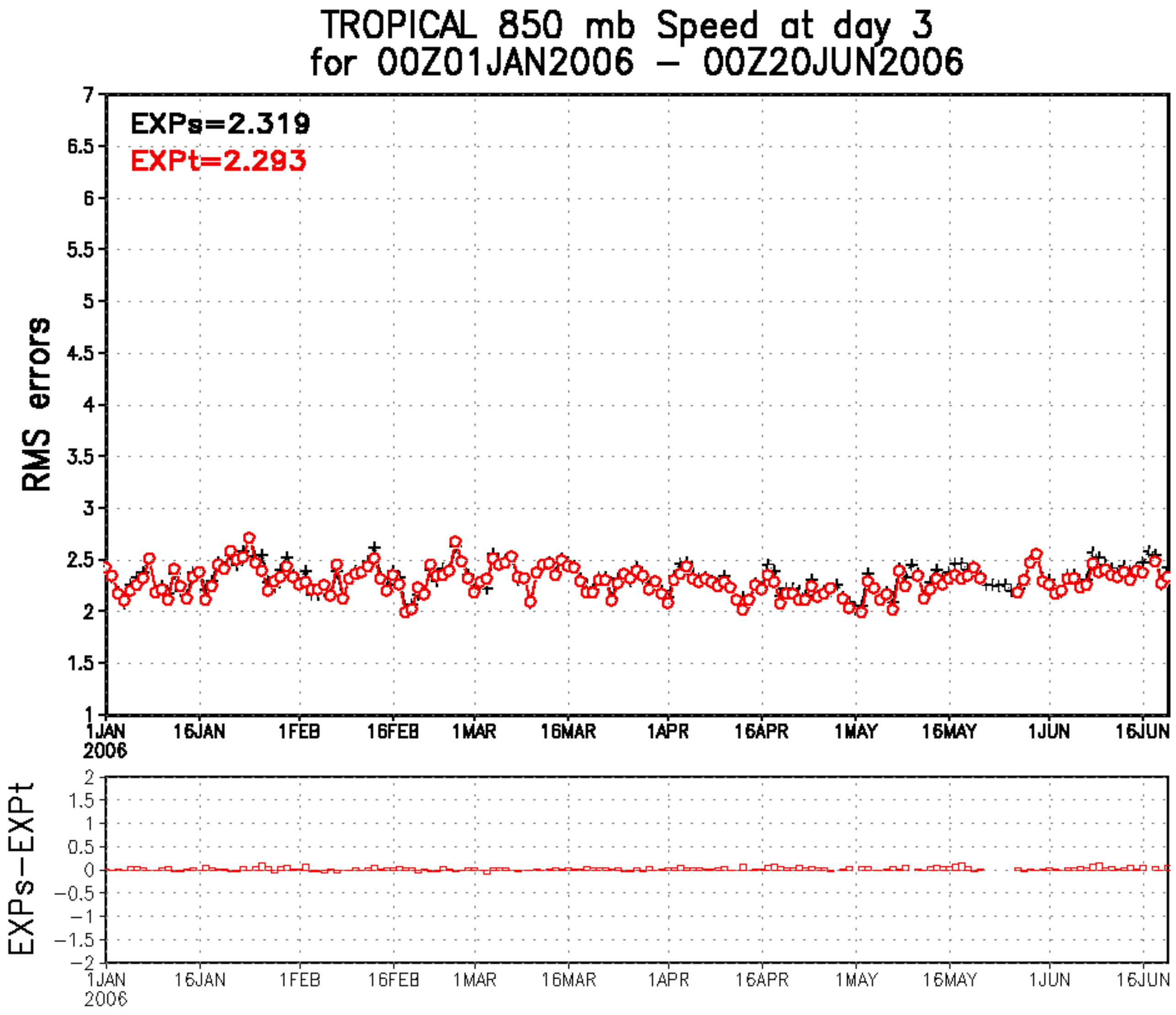

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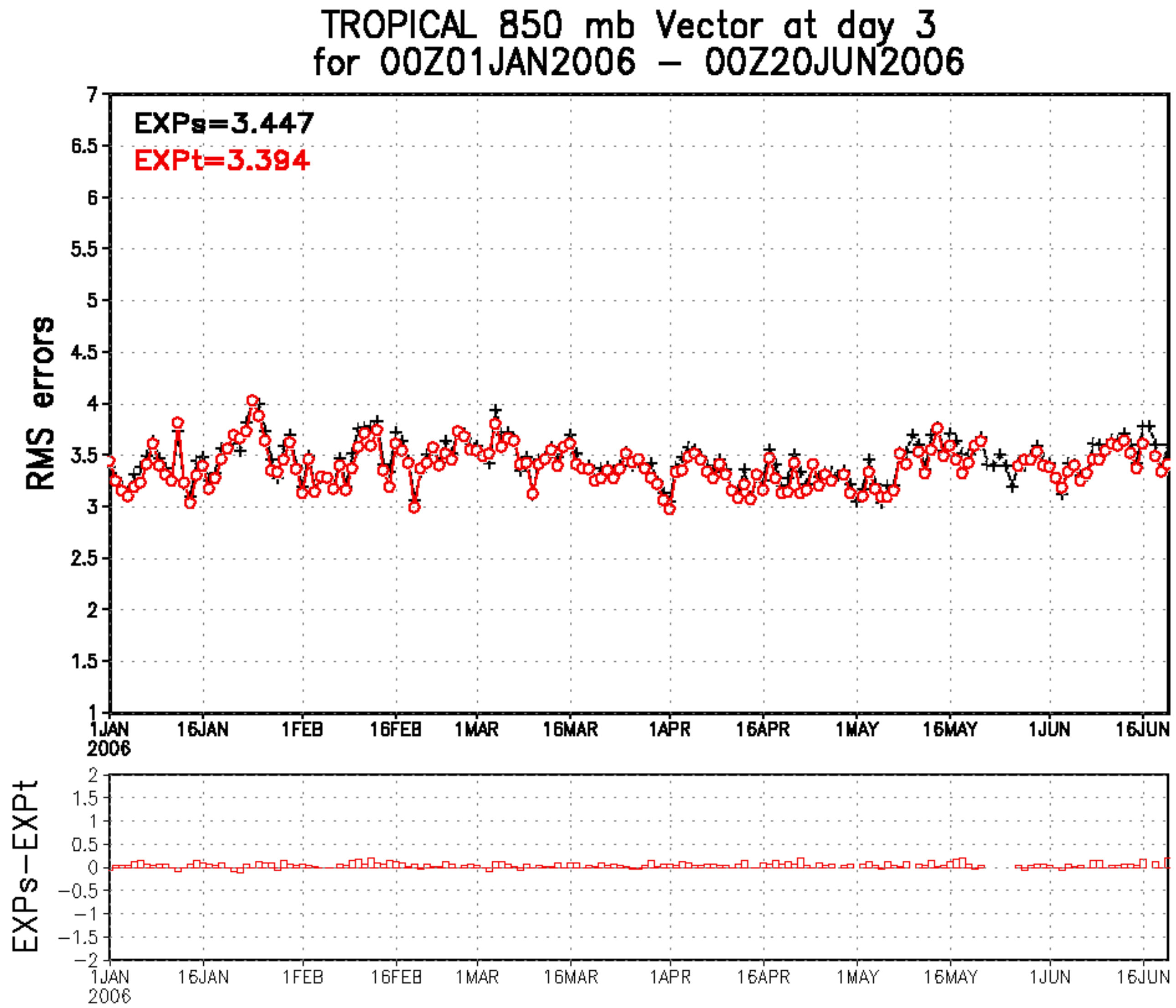
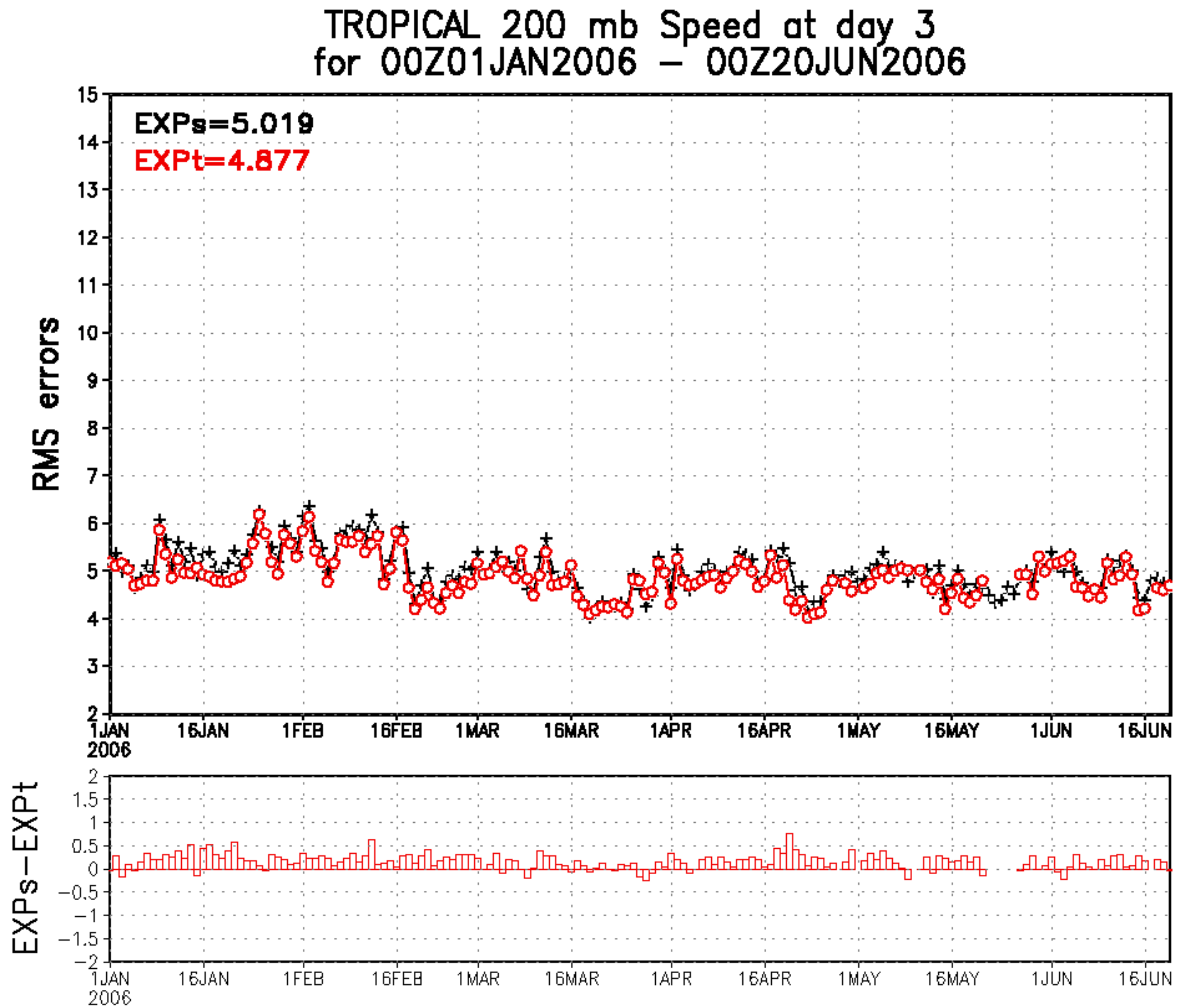
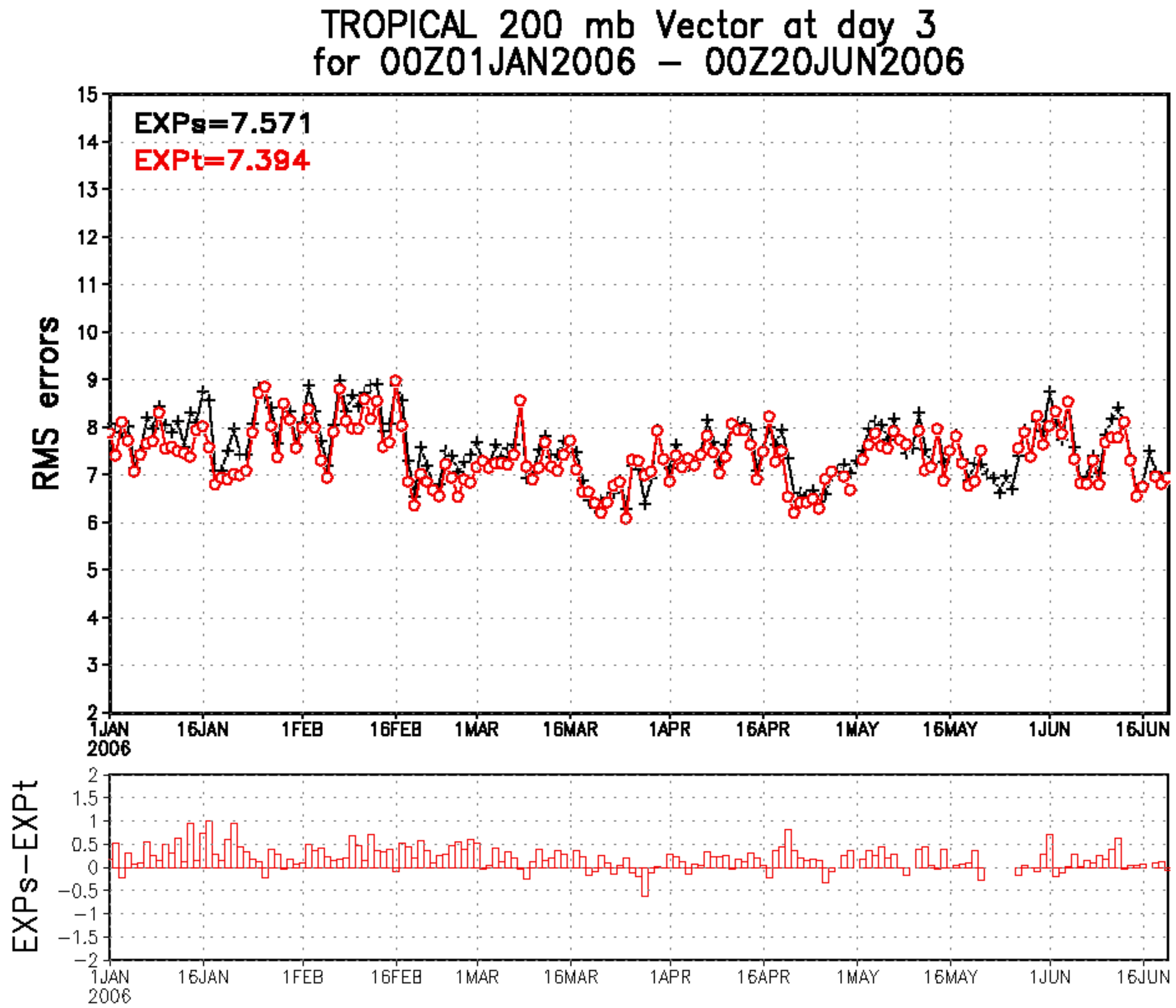


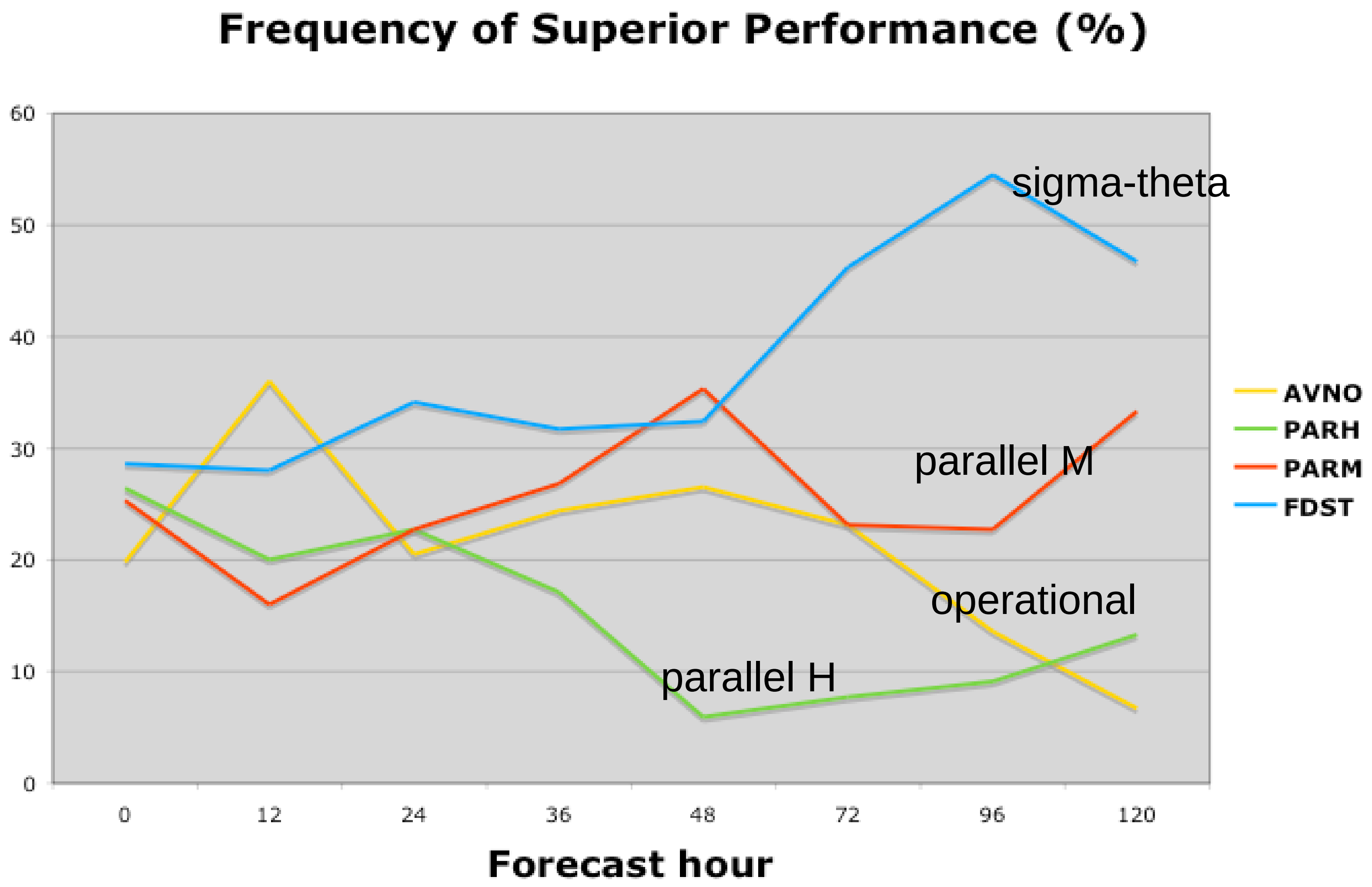
Black s: operational GFS   Red t: sigma-theta GFS



Black s: operational GFS Red t: sigma-theta GFS



Black s: operational GFS   Red t: sigma-theta GFS



2005 hurricane season

Increase vertical layer number

Consider deep atmosphere

Deep Atmosphere

Z(km)	T(K)	Cp(J/kg/K)	g(m/s2)
1	289	1008.5	9.80
10	230	1008.5	9.77
50	261	1008.5	9.66
100	190	1019.3	9.50
200	950	1134.5	9.20
300	1059	1220.8	8.92
400	1068	1265.2	8.70

Consider three dimensional R and Cp by tracers

$$R = \sum_{i=0}^{Ntracers} R_i q_i = (1 - \sum_{i=1}^{Ntracers} q_i) R_d + \sum_{i=1}^{Ntracers} R_i q_i$$

$$C_P = \sum_{i=0}^{Ntracers} C_{P\,i} q_i = (1 - \sum_{i=1}^{Ntracers} q_i) C_{P\,d} + \sum_{i=1}^{Ntracers} C_{P\,i} q_i$$

We need the values of all R and Cp

Our current tracers are
specific humidity, ozone and cloud water, thus Ntracers=3

From internal energy equation
We have

$$\rho \frac{dC_P T}{dt} - \frac{dp}{dt} = \rho Q$$

from ideal-gas law, and let $h = C_P T$ as enthalpy

the above energy equation can be re-written as

$$\frac{dh}{dt} - \frac{\kappa h}{p}\frac{dp}{dt} = Q$$

This can be as thermodynamic equation with h as prognostic variable, and same form as T.

$$\frac{dT}{dt} - \frac{\kappa T}{p}\frac{dp}{dt} = Q_T$$

From horizontal pressure gradient

We have

$$-\frac{1}{\rho}(\nabla p)_z = -\frac{RT}{p}(\nabla p)_z = -\frac{\kappa h}{p}(\nabla p)_z$$

from generalized coordinate transform, above can be written

$$-\frac{\kappa h}{p}(\nabla p)_z = -\frac{\kappa h}{p}\left[(\nabla p)_\zeta - \frac{\partial p}{\partial \Phi}(\nabla \Phi)_\zeta\right]$$

from hydrostatic $\frac{\partial p}{\partial z} = -\rho g(z)$ and $\frac{\partial \Phi}{\partial z} = g(z)$ or $\Phi = \int_o^z g(z)dz$

the pressure gradient force and hydrostatic can be written as

$$-\frac{\kappa h}{p}(\nabla p)_z = -\frac{\kappa h}{p}(\nabla p)_\Phi = -\frac{\kappa h}{p}(\nabla p)_\zeta - (\nabla \Phi)_\zeta$$

$$\frac{\partial \Phi}{\partial \zeta} = -\frac{\kappa h}{p}\frac{\partial p}{\partial \zeta}$$

Put previous into generalized coordinate system

$$\frac{\partial u^*}{\partial t} = -m^2 u^* \frac{\partial u^*}{a\partial\lambda} - m^2 v^* \frac{\partial u^*}{a\partial\varphi} - \dot{\zeta}\frac{\partial u^*}{\partial\zeta} - \frac{\kappa h}{p}\frac{\partial p}{a\partial\lambda} - \frac{\partial\Phi}{a\partial\lambda} + f_s v^*$$

$$\frac{\partial v^*}{\partial t} = -m^2 u^* \frac{\partial v^*}{a\partial\lambda} - m^2 v^* \frac{\partial v^*}{a\partial\varphi} - \dot{\zeta}\frac{\partial v^*}{\partial\zeta} - \frac{\kappa h}{p}\frac{\partial p}{a\partial\varphi} - \frac{\partial\Phi}{a\partial\varphi} - f_s u^* - m^2 \frac{s^{*2}}{a}\sin\phi$$

$$\frac{\partial h}{\partial t} = -m^2 u^* \frac{\partial h}{a\partial\lambda} - m^2 v^* \frac{\partial h}{a\partial\varphi} - \dot{\zeta}\frac{\partial h}{\partial\zeta} + \frac{\kappa h}{p}\frac{dp}{dt}$$

$$\frac{\partial(\partial p/\partial\zeta)}{\partial t} = -m^2\left(\frac{\partial u^*(\partial p/\partial\zeta)}{a\partial\lambda} + \frac{\partial v^*(\partial p/\partial\zeta)}{a\partial\varphi}\right) - \frac{\partial\dot{\zeta}(\partial p/\partial\zeta)}{\partial\zeta}$$

$$\frac{\partial q_i}{\partial t} = -m^2 u^* \frac{\partial q_i}{a\partial\lambda} - m^2 v^* \frac{\partial q_i}{a\partial\varphi} - \dot{\zeta}\frac{\partial q_i}{\partial\zeta}$$

Developing Status

- 130 layers with more than 60 layers above is running with coupled space environmental model (SEM) physics
- Enthalpy is implemented into GFS
- Adopt SEM's physics into GFS
- Change a to be r=a+z in deep atmospheric system with full Coriolis force and vertical momentum equation

Increase horizontal resolution

Test T1278

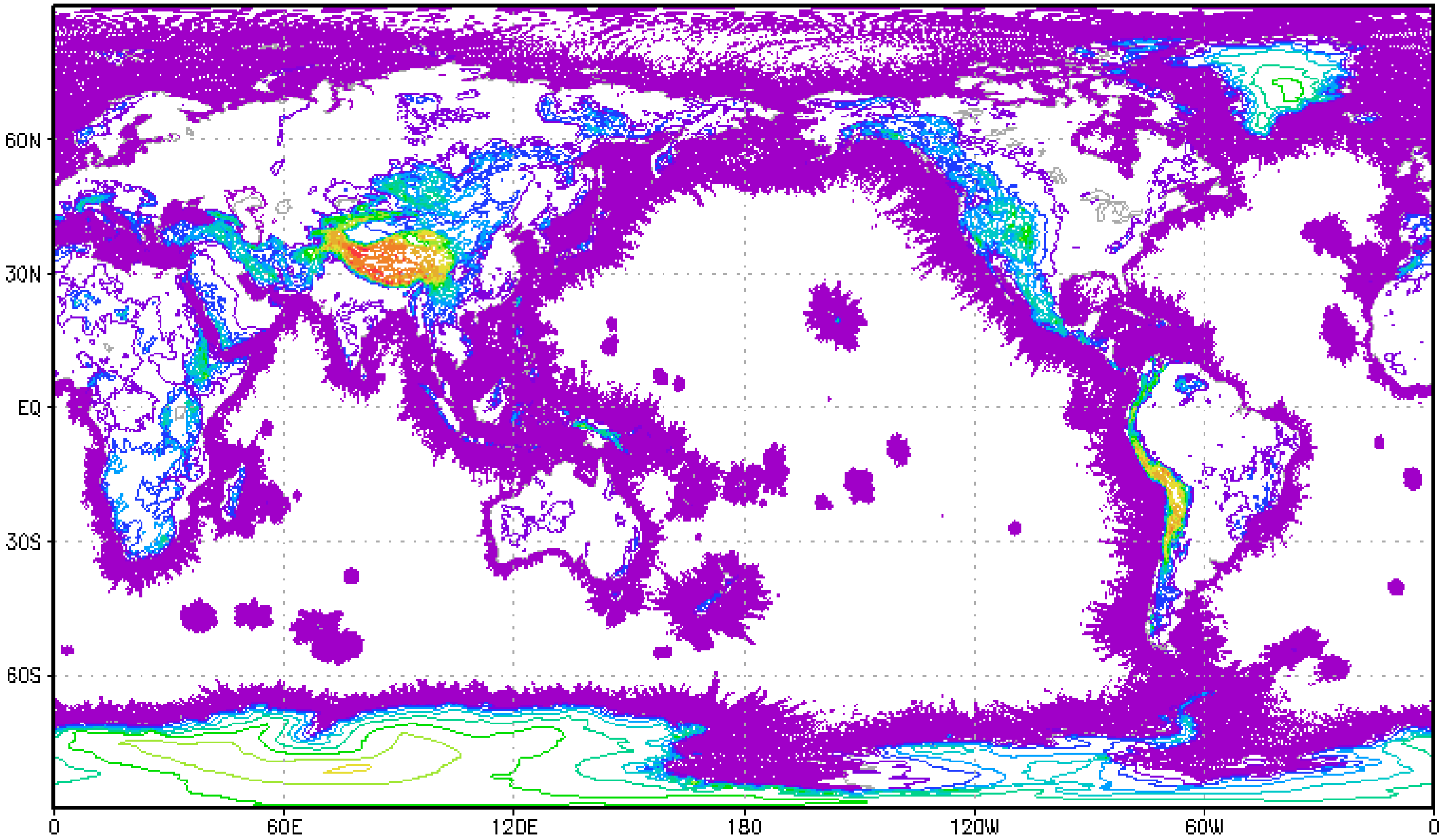
Compared to T382

	T382	T1278
# of longitude	1152	3840
# of latitude	576	1920
Time step(sec)	180	40
# of step/1h	20	90
Relative # of opr/1h	1	50

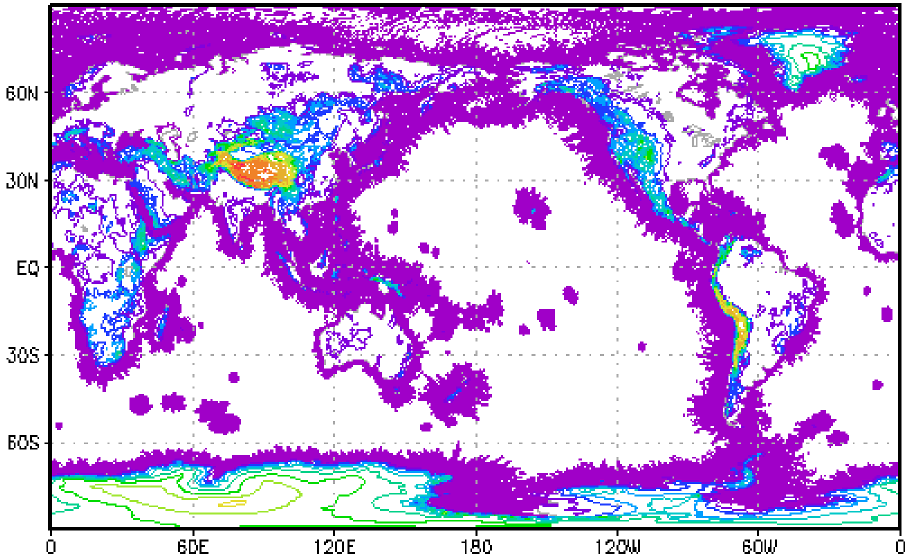
Estimation

- T382L64: 1 hour forecast with 31 cpu costs 4 min.
- T1278L64: 1 hour forecast with 375 cpu cost 25 min.
- factor of T1278 (3840*1920*90) to T382 (1152*576*20) is 50.
- 4min*31cpu*50/375=17min, but 25min, it implies a 47% performance reduction.

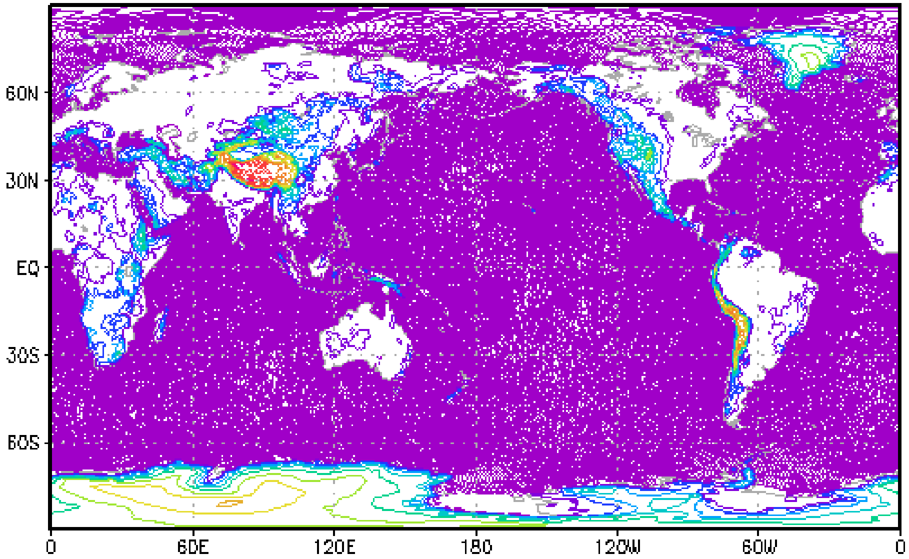
Model terrain (m) T1278

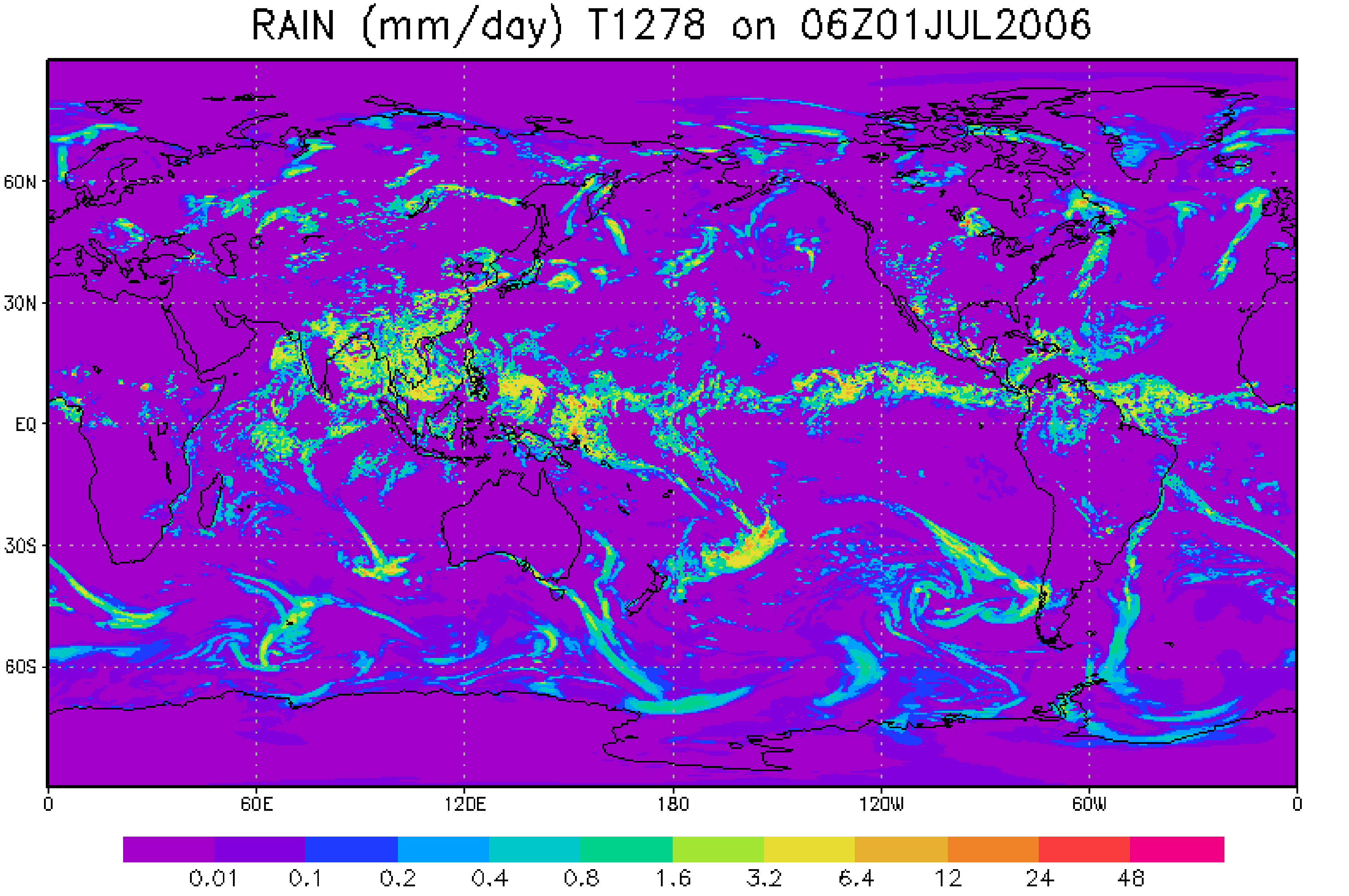


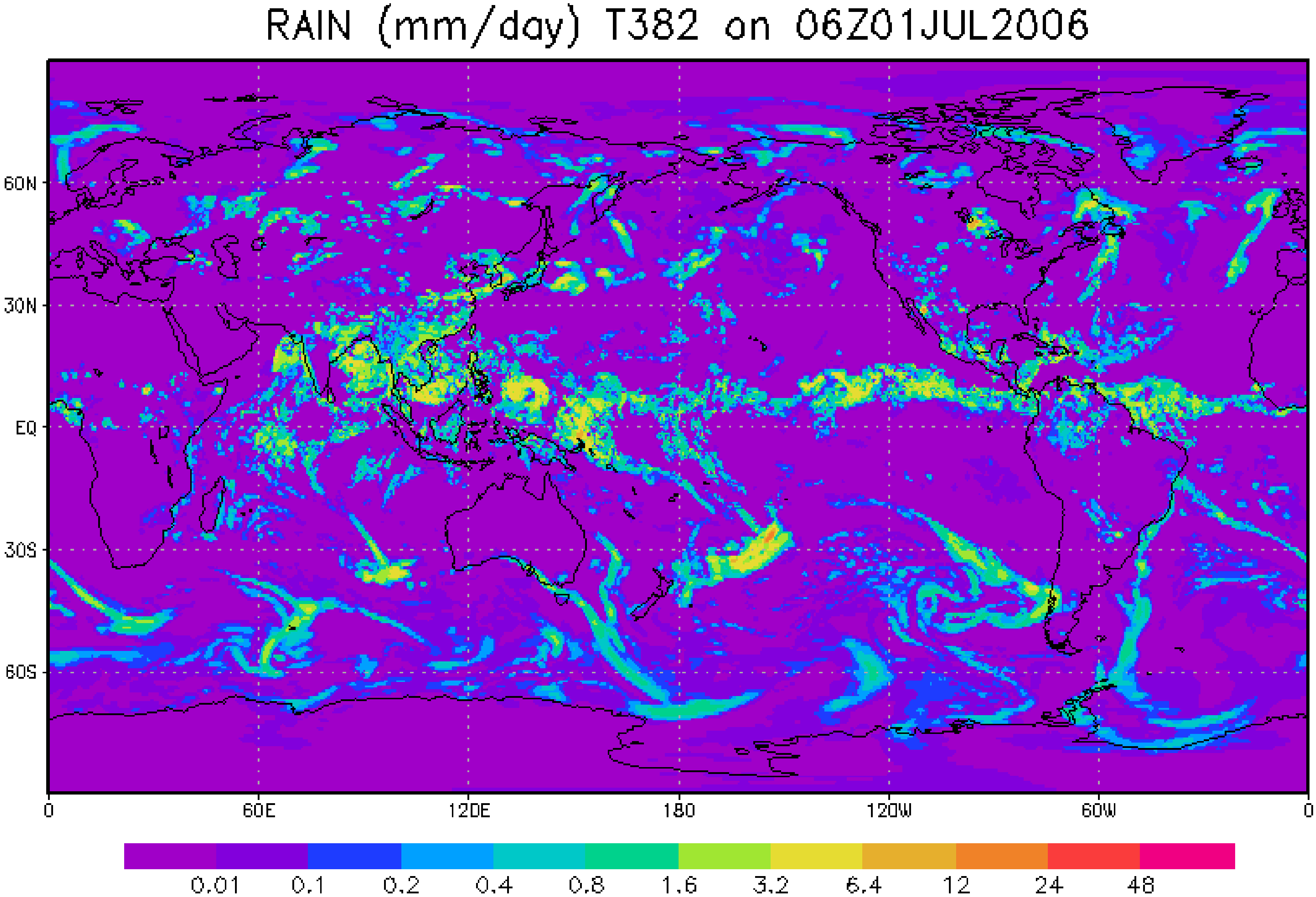
Model terrain (m) T1278

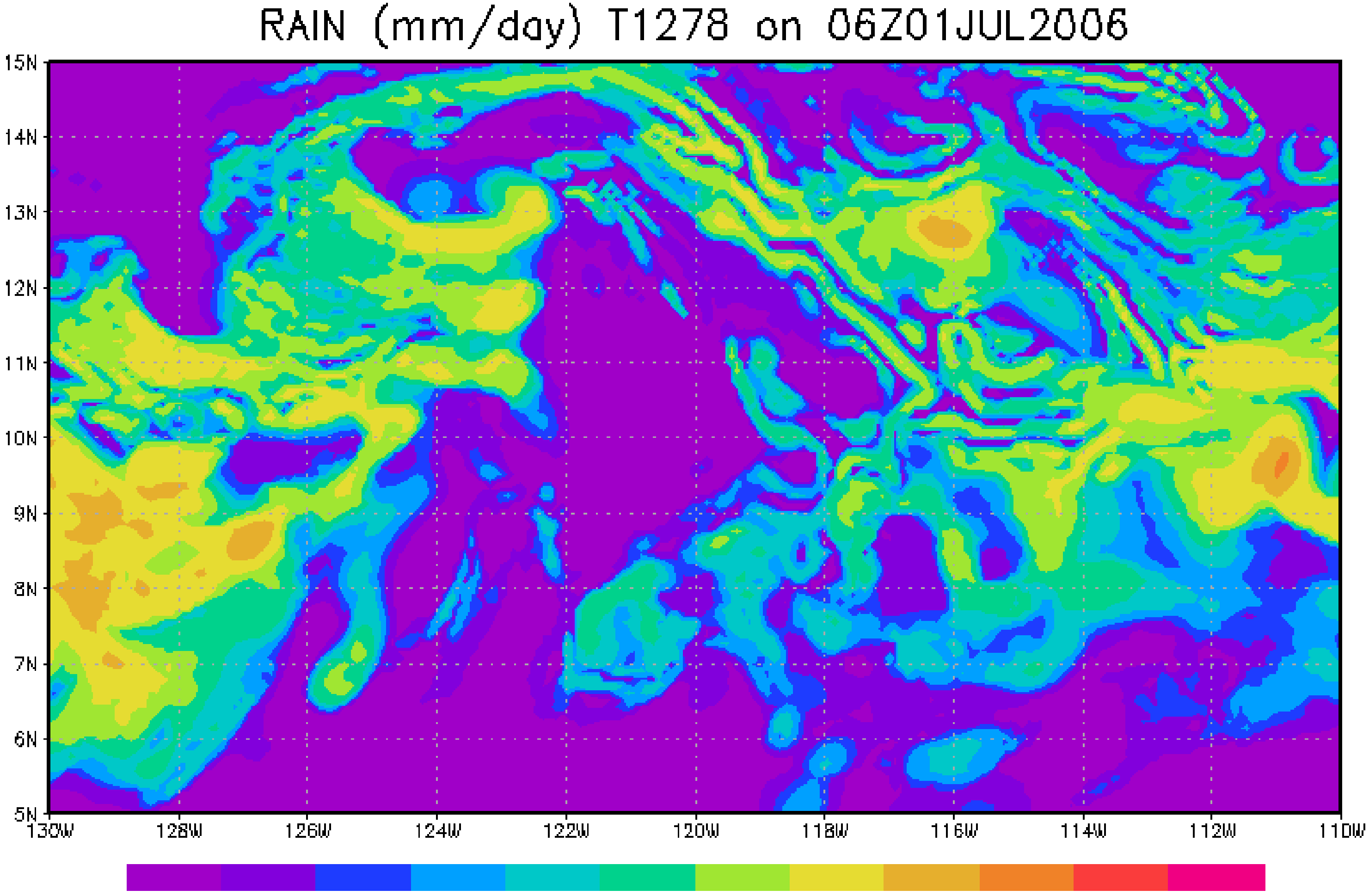


Model terrain (m) T382

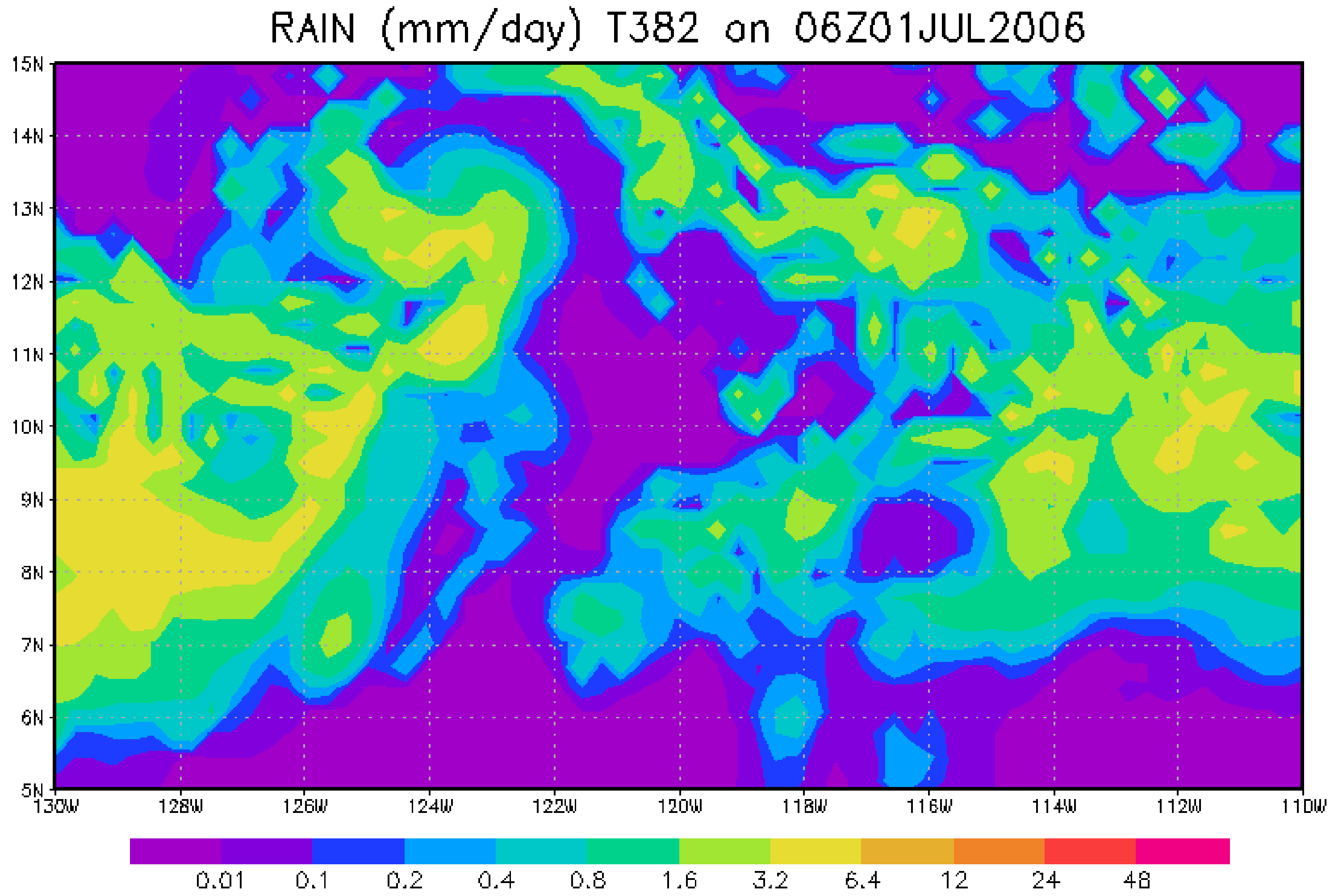


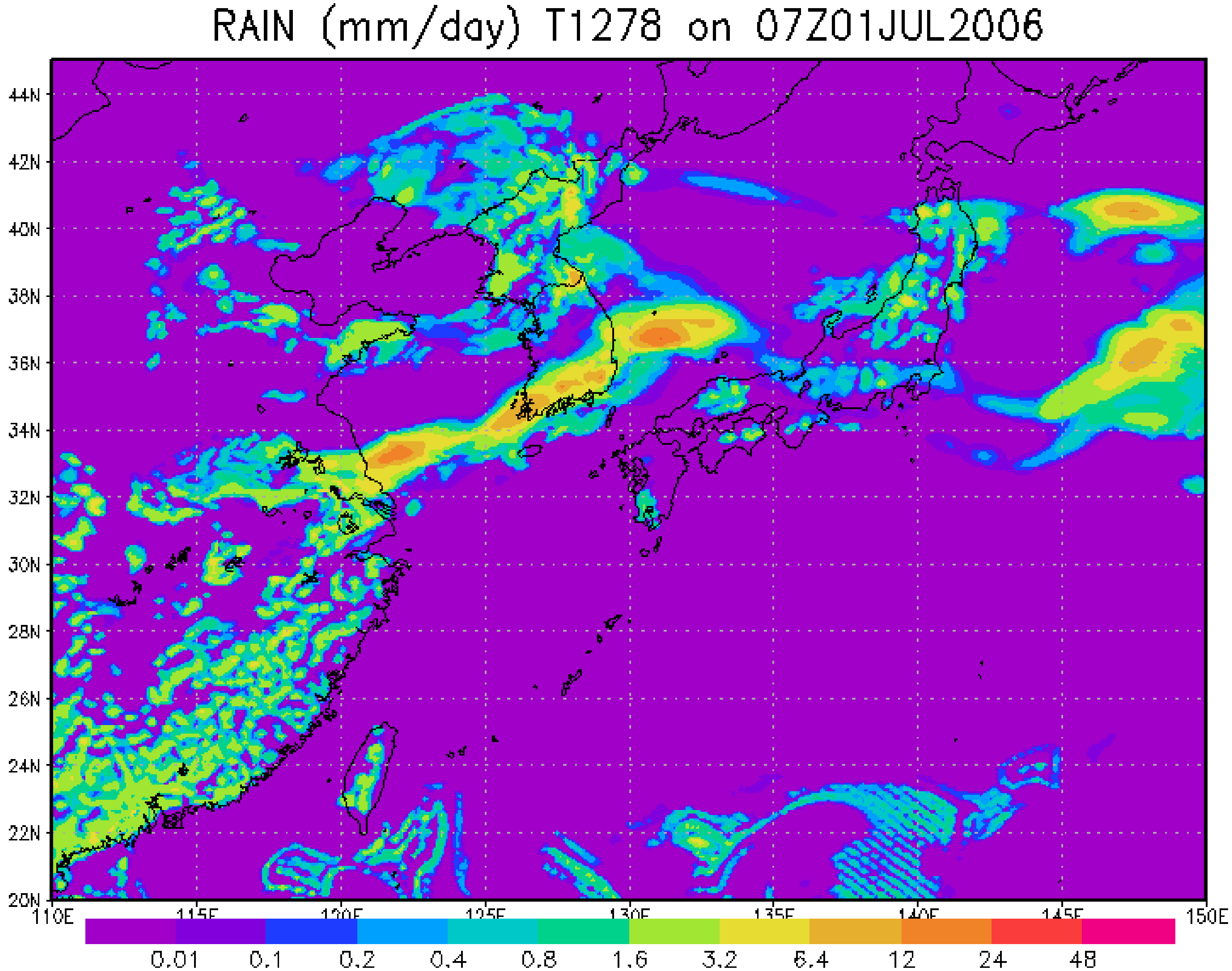

RAIN (mm/day) T1278 on 06Z01JUL2006
60N
30N
EQ
30S
60S
0
60E
120E
180
120W
60W
0
0.01
0.1
0.2
0.4
0.8
1.6
3.2
6.4
12
24
48

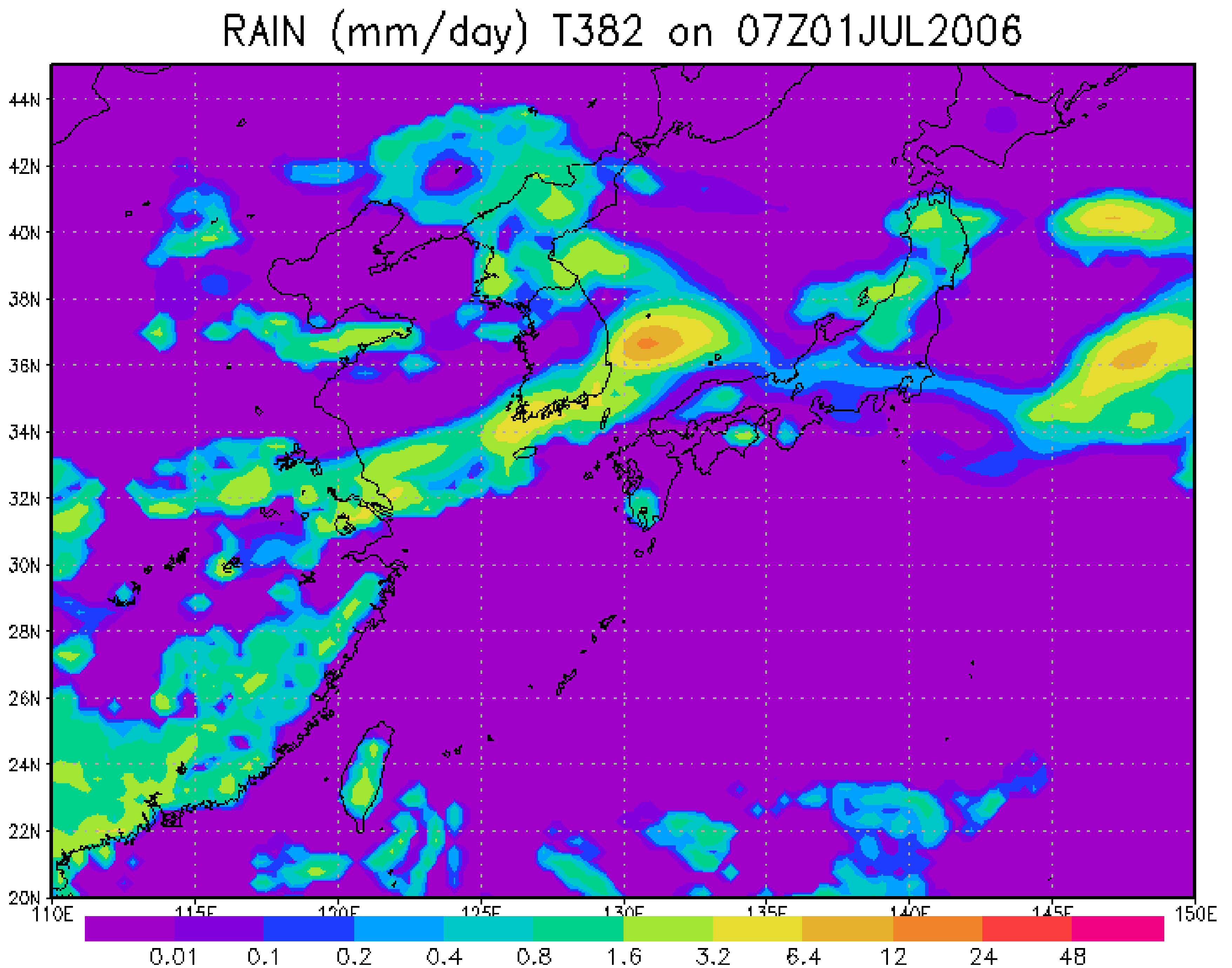

RAIN (mm/day) T382 on 06Z01JUL2006
60N
30N
EQ
30S
60S
0
60E
120E
180
120W
60W
0
0.01
0.1
0.2
0.4
0.8
1.6
3.2
6.4
12
24
48



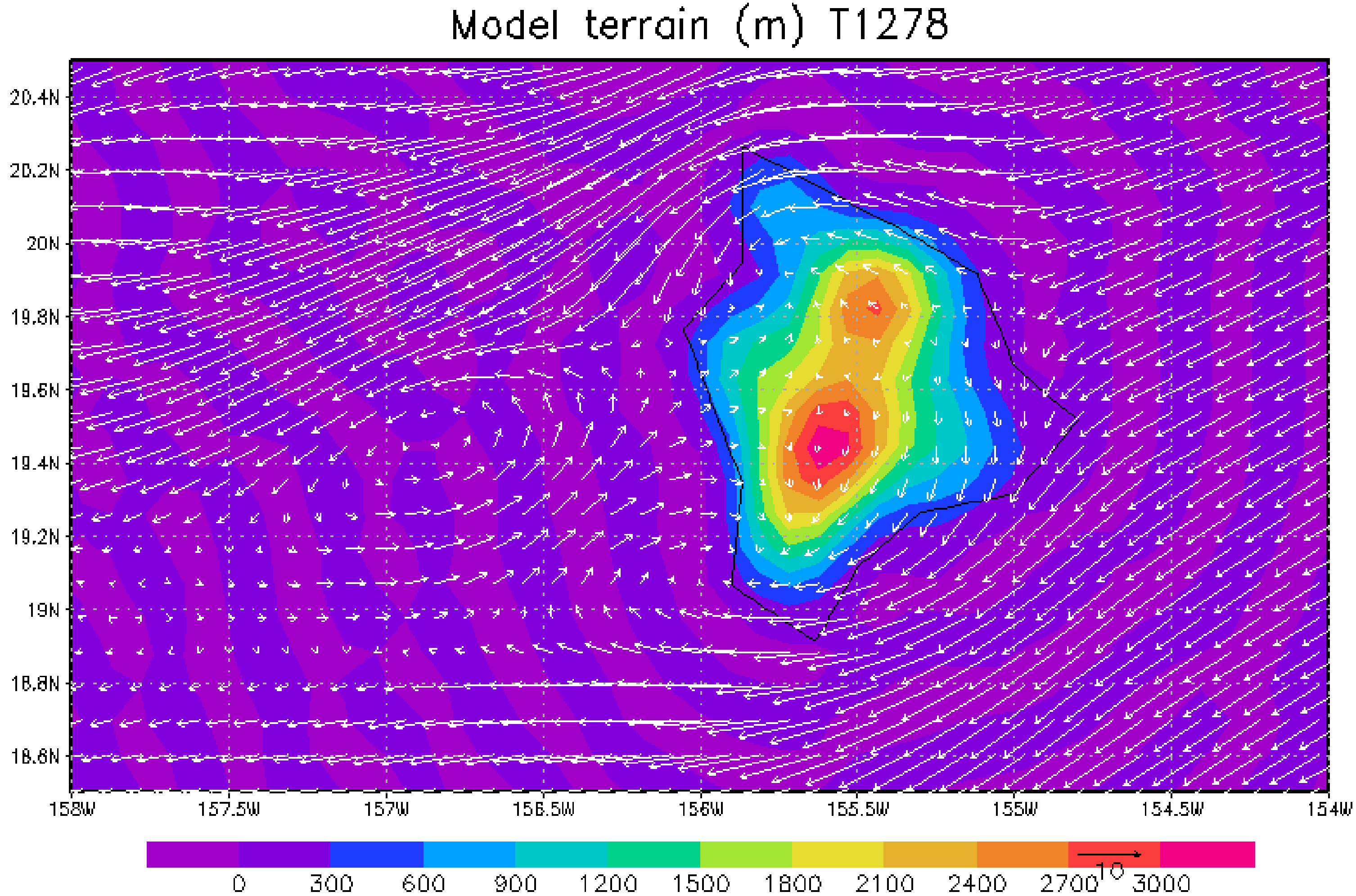
RAIN (mm/day) T1278 on 06Z01JUL2006
15N
14N
13N
12N
11N
10N
9N
8N
7N
6N
5N
130W
128W
126W
124W
122W
120W
118W
116W
114W
112W
110W
0.01
0.1
0.2
0.4
0.8
1.6
3.2
6.4
12
24
48


RAIN (mm/day) T382 on 06Z01JUL2006
15N
14N
13N
12N
11N
10N
9N
8N
7N
6N
5N
130W
128W
126W
124W
122W
120W
118W
116W
114W
112W
110W
0.01
0.1
0.2
0.4
0.8
1.6
3.2
6.4
12
24
48

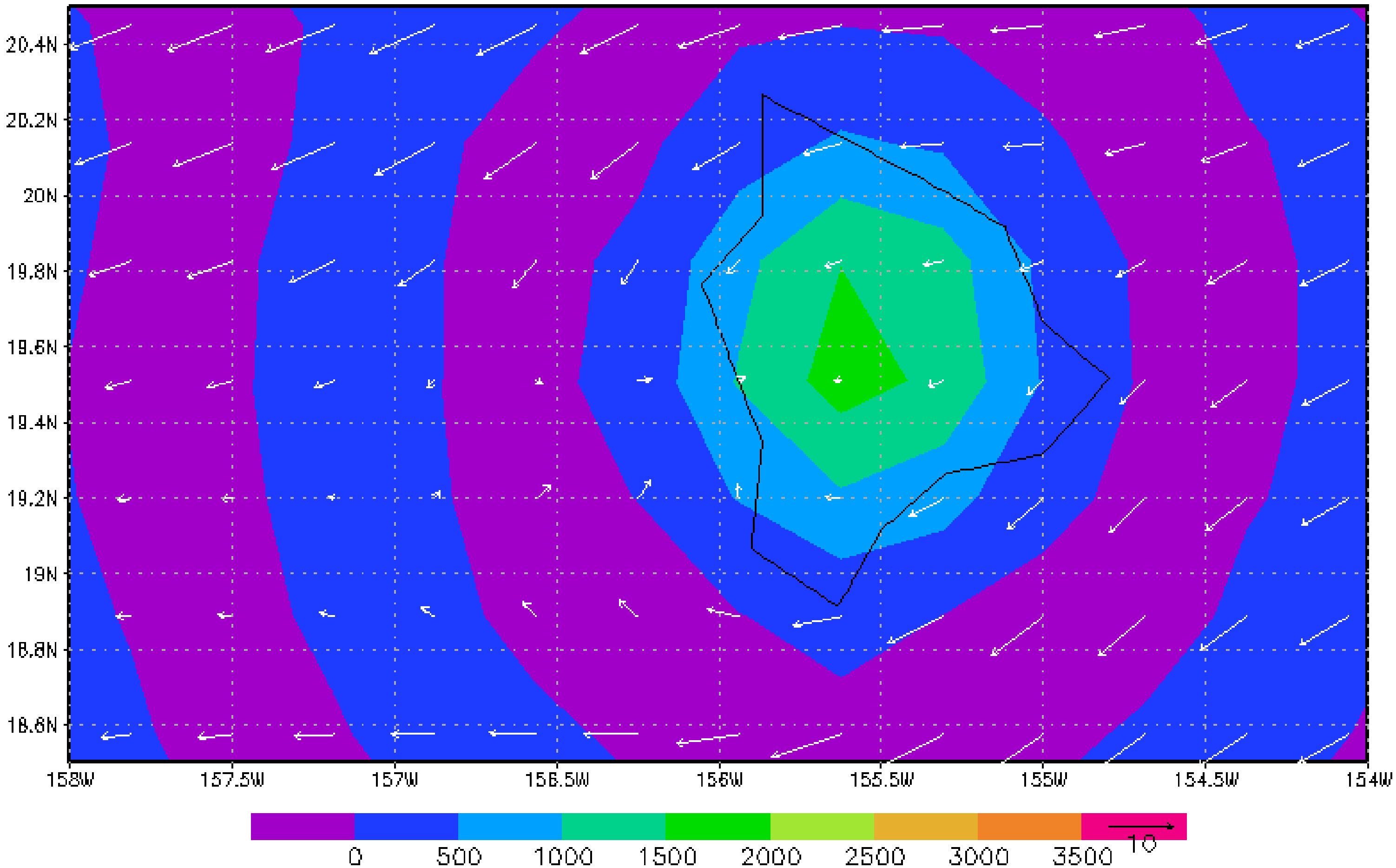

RAIN (mm/day) T1278 on 07Z01JUL2006
44N
42N
40N
38N
36N
34N
32N
30N
28N
26N
24N
22N
20N
110E
115E
120E
125E
130E
135E
140E
145E
150E
0.01
0.1
0.2
0.4
0.8
1.6
3.2
6.4
12
24
48



RAIN (mm/day) T382 on 07Z01JUL2006
44N
42N
40N
38N
36N
34N
32N
30N
28N
26N
24N
22N
20N
110E
115E
120E
125E
130E
135E
140E
145E
150E
0.01
0.1
0.2
0.4
0.8
1.6
3.2
6.4
12
24
48


Model terrain (m) T1278
20.4N
20.2N
20N
19.8N
19.6N
19.4N
19.2N
19N
18.8N
18.6N
158W
157.5W
157W
156.5W
156W
155.5W
155W
154.5W
154W
0
300
600
900
1200
1500
1800
2100
2400
2700
3000
10

Model terrain (m) T382



Developing Status

- Preliminary results show T1278 provides mesoscale features well.
- Very cost, 47% reduction in performance.
- Reduce amount of spectral transform is important, such as reduced spherical transform and/or Lagrangian advection.
- Speedup Legendre transform is another essential act.
- These should be benefit to current resolution of GFS, though T1278 is not in the near future.

Summary

- Recent developments of NCEP GFS
  - Concurrent ensemble
  - Extended vertical resolution
  - Increasing horizontal resolution

  require high performance computing (HPC)
- Further studies to have better modeling
  - Improved spherical transform
  - Less assumption forecast equations

  make NCEP GFS use HPC effectively & efficiently