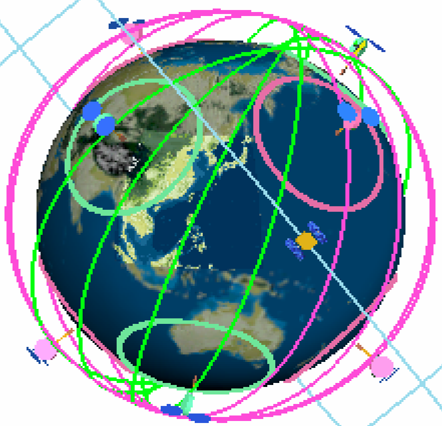
Impact of GPS Radio Occultation Measurements on Severe Weather Prediction in Asia:

What is Taiwan looking for from COSMIC



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Workshop on Applications of GPS Radio Occultation Measurements, 16-18 June 2008, ECMWF

Collaborators

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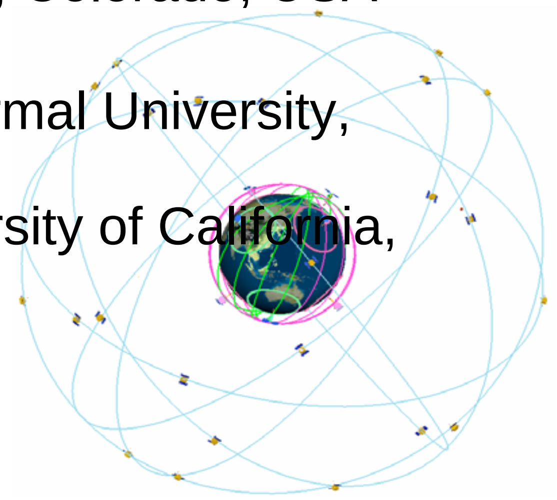
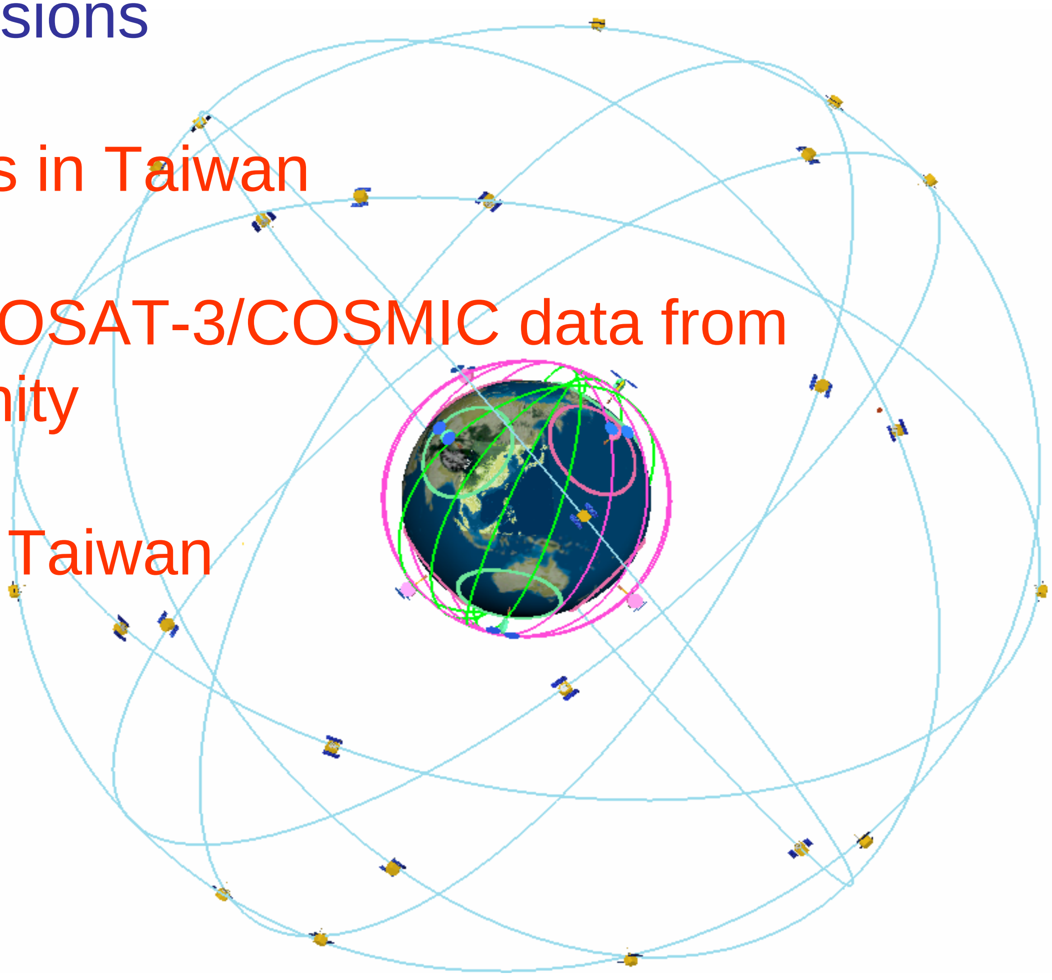


Outline

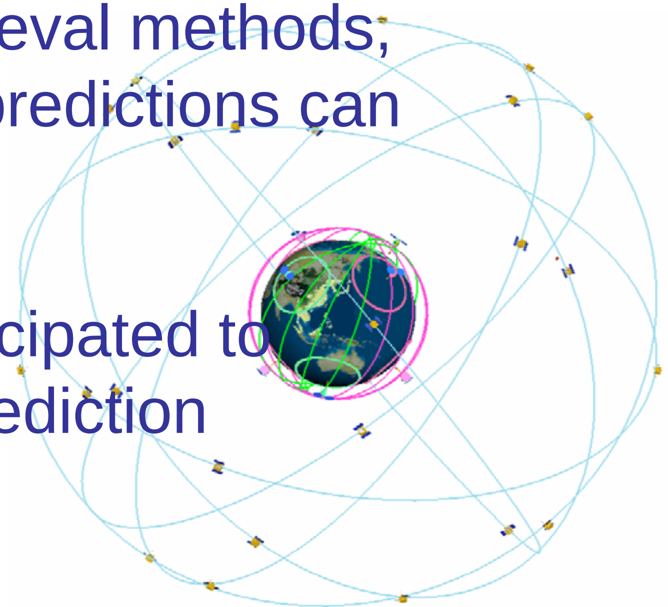
- Introduction
  - Group infrastructure
  - Focuses and missions
- Recent achievements in Taiwan
- The impact of FORMOSAT-3/COSMIC data from international community
- Prospective works in Taiwan



Taiwan's Missions of F-3/C Meteorological Research

The main goals of meteorological research in Taiwan are to develop and improve skills of data assimilation on both basic research and application, and to expose the maximum values of FORMOSAT-3/COSMIC GPS radio occultation data on global and regional weather and climate prediction. Through data assimilation of different GPS data formats and different retrieval methods, their impact on global and regional predictions can be assessed.

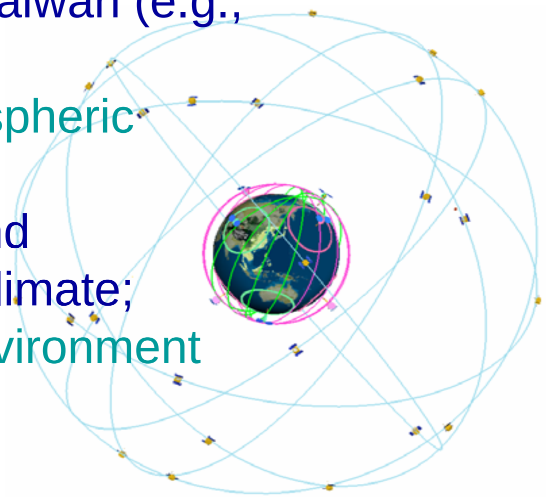
This achievement will be anticipated to improve Taiwan's weather prediction by 20%!



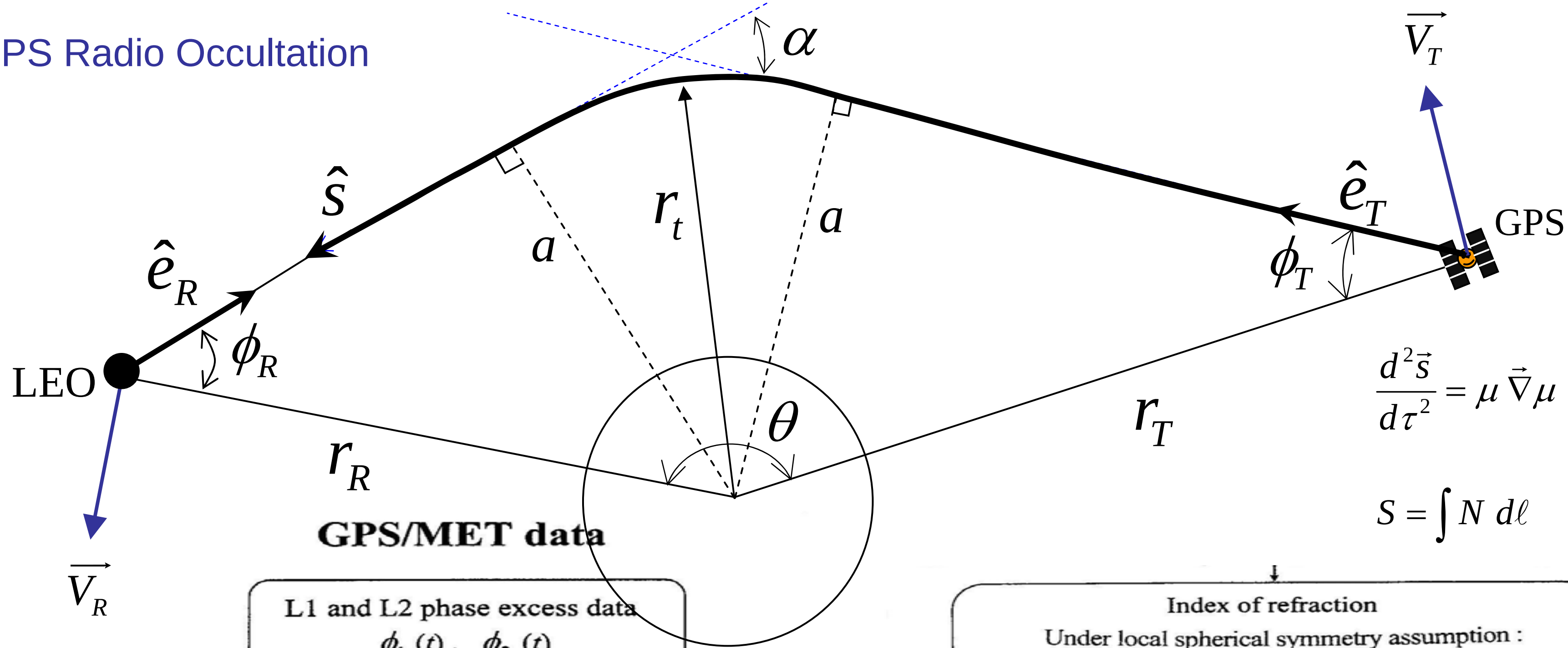
Integrated Meteorological Research in GPS Application and Research Center (GPS-ARC)

The main objectives of meteorological research in GPS-ARC are to

- establish/improve current skills of data assimilation on both basic research and application through 3DVAR and 4DVAR with GPS radio occultation and ground-based data;
- demonstrate the maximum values of FORMOSAT-3 RO and GPS ground-based data for weather and climate prediction on real-time mode and research mode;
- assess data impact on weather simulation and prediction through assimilation of different GPS data formats and different retrieval methods for severe disastrous weathers in vicinity of Taiwan (e.g., Meiyu fronts, typhoons, etc.);
- validate/improve retrieval methods/algorithms of atmospheric variables for FORMOSAT-3 data set (in collaboration);
- investigate GPS RO data impact on meteorological and hydrological analysis in application to global/regional climate;
- investigate GPS RO data impact on global/regional environment modeling (WRF-Chem and others).



GPS Radio Occultation



$$\frac{d^2\vec{s}}{d\tau^2} = \mu\,\vec{\nabla}\mu$$

$$S = \int N\, d\ell$$

GPS/MET data

L1 and L2 phase excess data

$\phi_1(t)$, $\phi_2(t)$

↓

Doppler-shifted frequencies

$$f_d = \frac{f_T}{c_0}\frac{\Delta\phi}{\Delta t}$$

↓

Bending angles and impact parameters

Satellites' geometry (GPS and LEO):

$$f_d = \frac{f_T}{c_0}\left(-u_g\cos\theta_g + u_l\cos\theta_l + v_g\sin\theta_g - v_l\sin\theta_l\right)$$

Local spherical symmetry assumption:

$$\theta_l,\ \theta_g \xrightarrow[\alpha = \theta_l - \theta_g + \psi]{a = r_l\sin\theta_l = r_g\sin\theta_g} \alpha_1,\ a_1,\ \alpha_2,\ a_2$$

ionospheric correction

$$\alpha(a) = \frac{f_{T1}^2\alpha_1(a) - f_{T2}^2\alpha_2(a)}{f_{T1}^2 - f_{T2}^2}$$

↓

Index of refraction

Under local spherical symmetry assumption :

$$\ln\mu(x) = \frac{1}{\pi}\int_x^{r_0}\frac{\alpha(a)}{(a^2 - x^2)^{1/2}}\,da, \qquad x = \mu r$$

↓

Refractivity

$$N = (\mu - 1)\times 10^6$$

↓

$$N = 77.6\frac{p}{T} + 3.73\times 10^5\frac{pq}{T^2(0.622 + 0.378q)}$$

↓

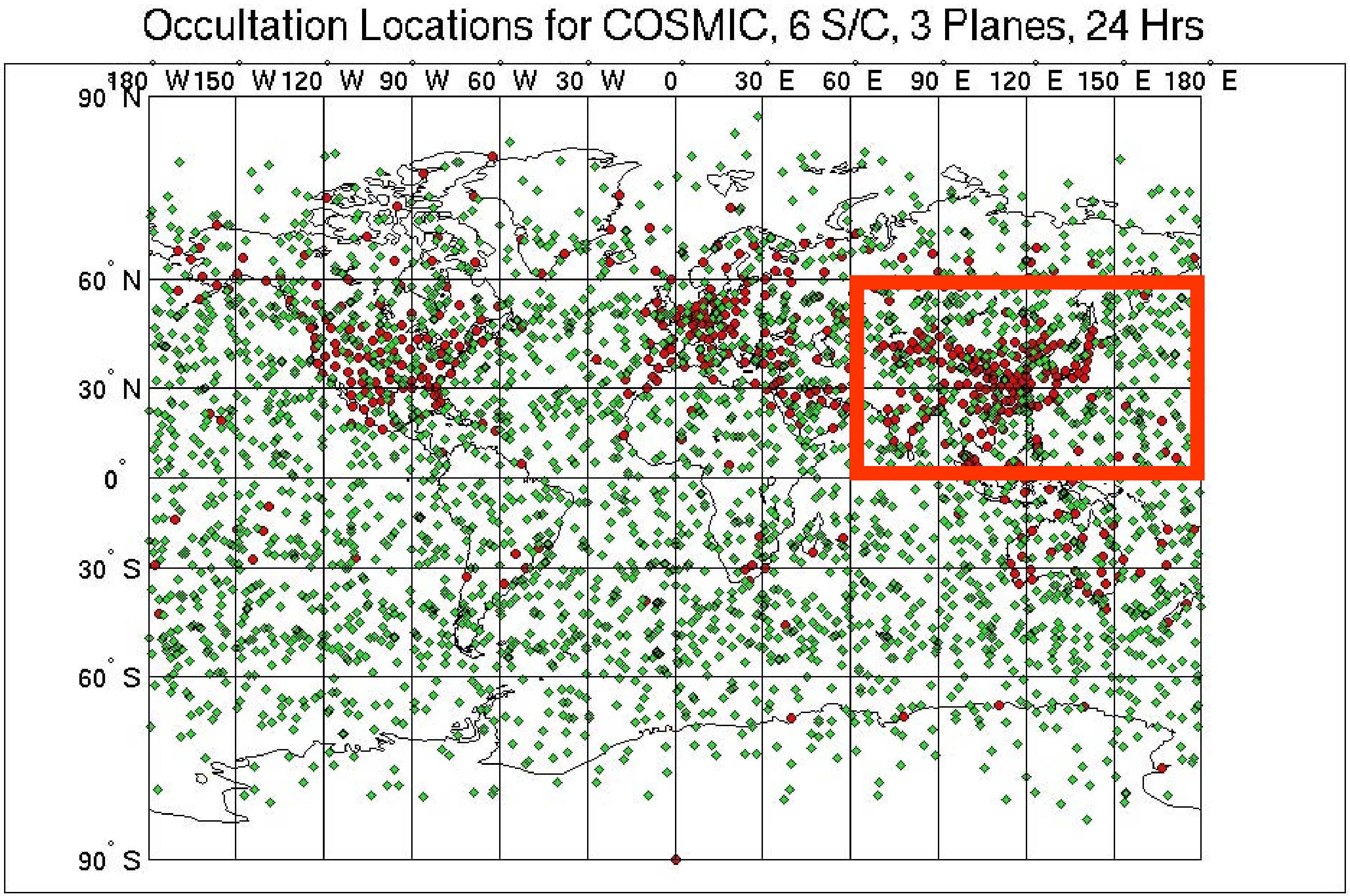
Temperature and pressure

Under dry-atmosphere assumption: $N = 77.6\dfrac{p}{T}$

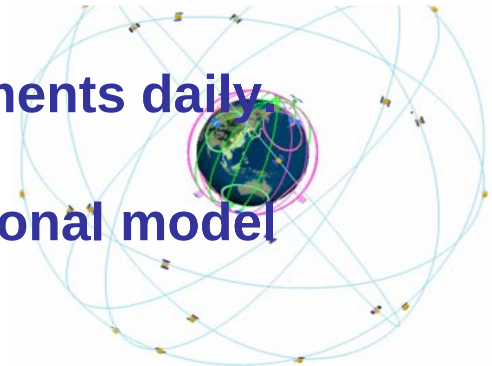
The equation of state: $\rho R = \dfrac{p}{T}$

Hydrostatic equation: $dp = -\rho g dz$

$$dp = -\frac{gN}{77.6R}dz, \qquad T = \frac{77.6p}{N}$$

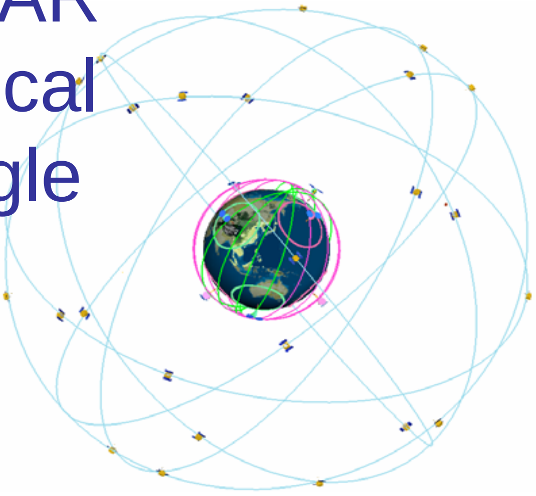


- 6 LEO satellites provide 2000~2500 measurements daily.
- It will offer up to about 50 soundings in a regional model domain for a 6-h assimilation time window.



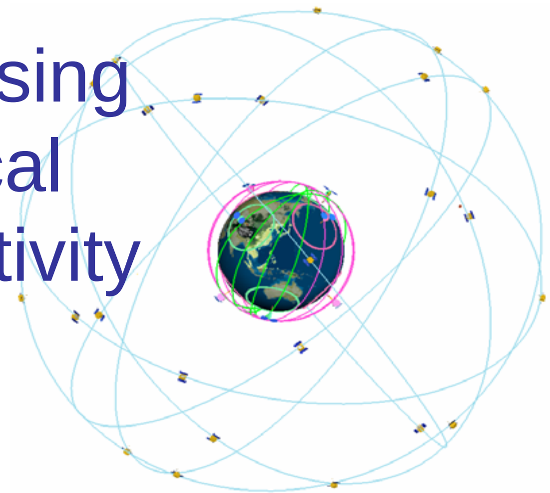
Current Assimilation Tasks in Taiwan

- Assimilation by WRF 3DVAR for local refractivity, nonlocal refractivity
- Assimilation by MM5 4DVAR for local refractivity
- Assimilation by CWB GFS 3DVAR (SSI) for local refractivity, nonlocal refractivity and 2-D bending angle



Assimilation Tasks to Be Implemented in Taiwan

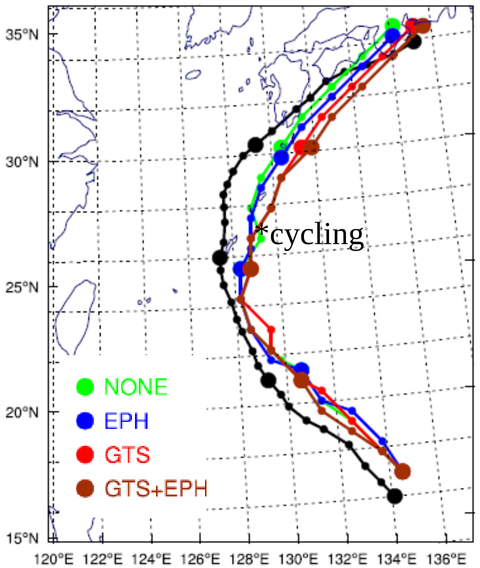
- Assimilation by WRF 3DVAR for local bending angle (2008)
- Assimilation by WRF 4DVAR for local refractivity, nonlocal refractivity
- Assimilation by WRF DART (using ensemble Kalman filter) for local refractivity and nonlocal refractivity



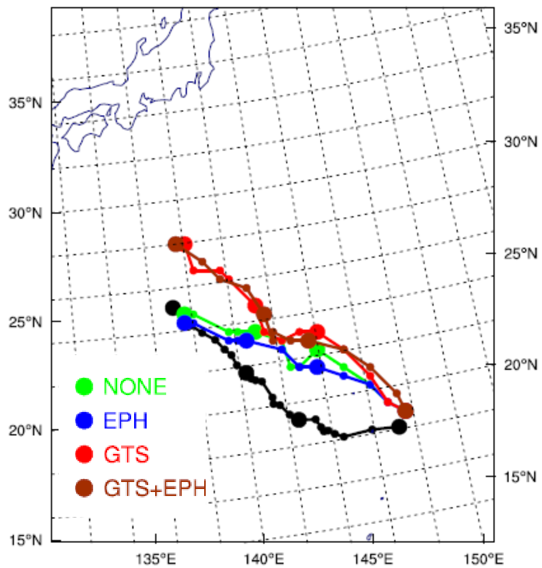
The simulated severe weather cases in 2006, 2007 and 2008 with FORMOSAT-3 RO data.

Initial Time	Event	GPS RO
2006-07-1200	Typhoon Bilis	2
2006-07-2300	Typhoon Kaemi	7
2006-09-1312	Typhoon Shanshan	27
2007-06-0212	Meiyu Front	31
2007-06-0300	Cyclone Gonu	56
2007-07-1100	Typhoon Manyi	15
2007-07-2900	Typhoon Usagi	39
2007-08-1600	Typhoon Sepat	21
2007-10-0412 (0500)*	Typhoon Krosa	31 (17)
2008-04-2900 (2906)*	Cyclone Nargis	21 (24)

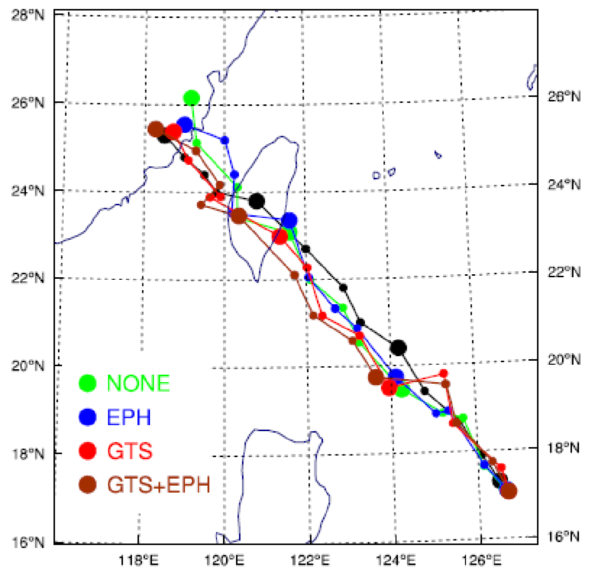
Typhoon ManYI



Typhoon Usagi

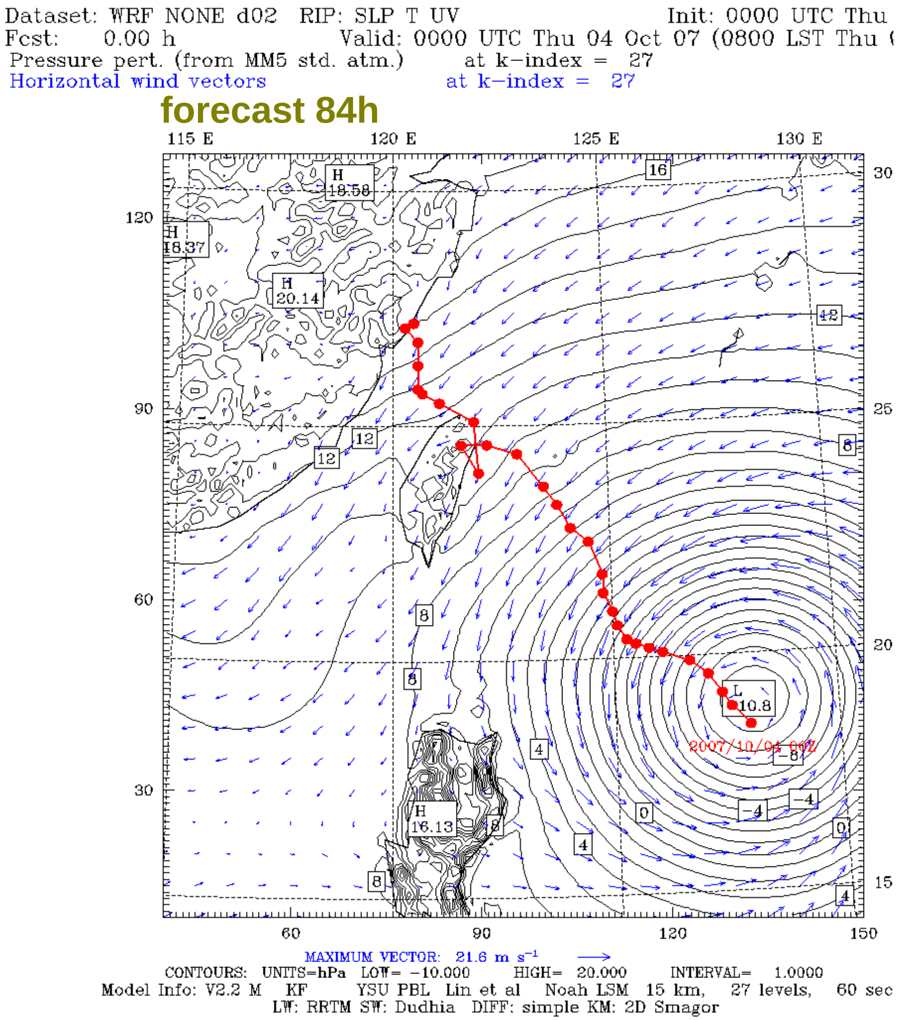


Typhoon Sepat

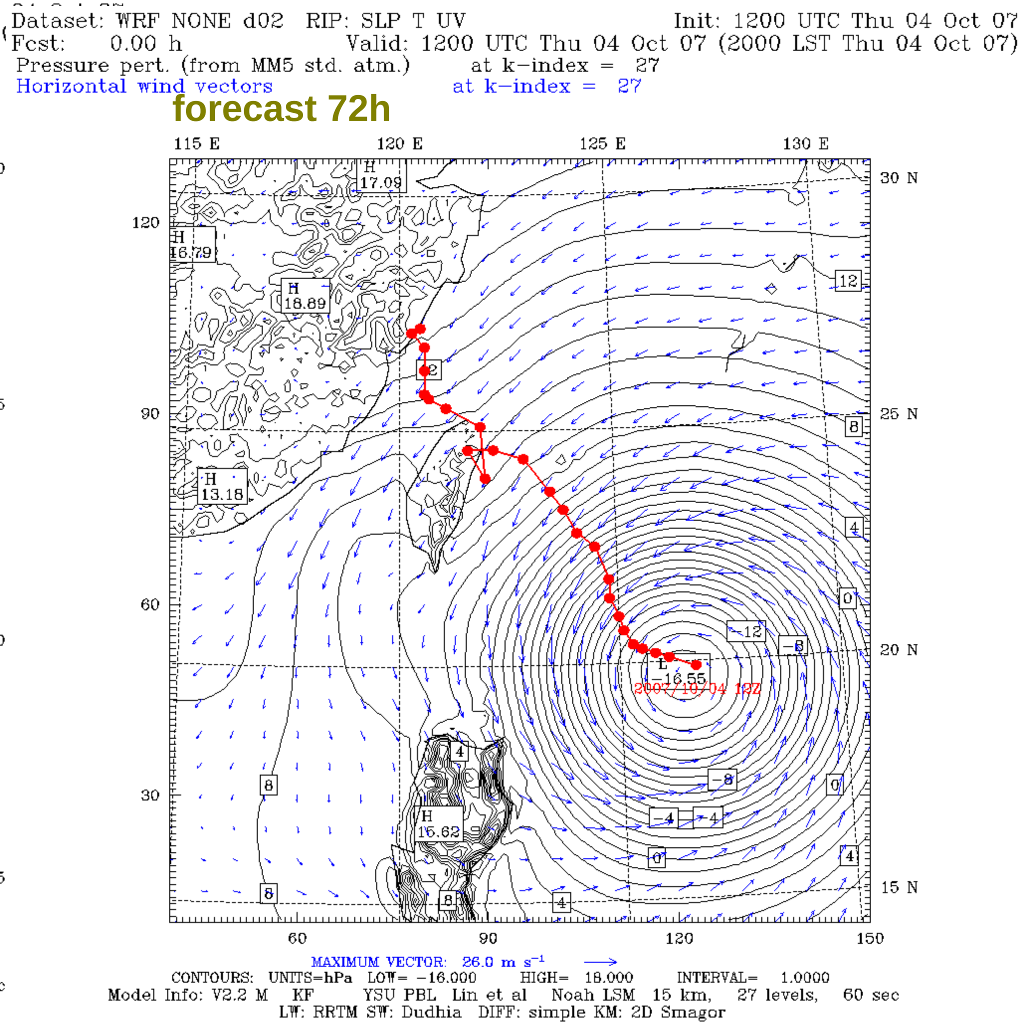


WRF (with AVN) for Typhoon Krosa

2007/10/04 0000UTC

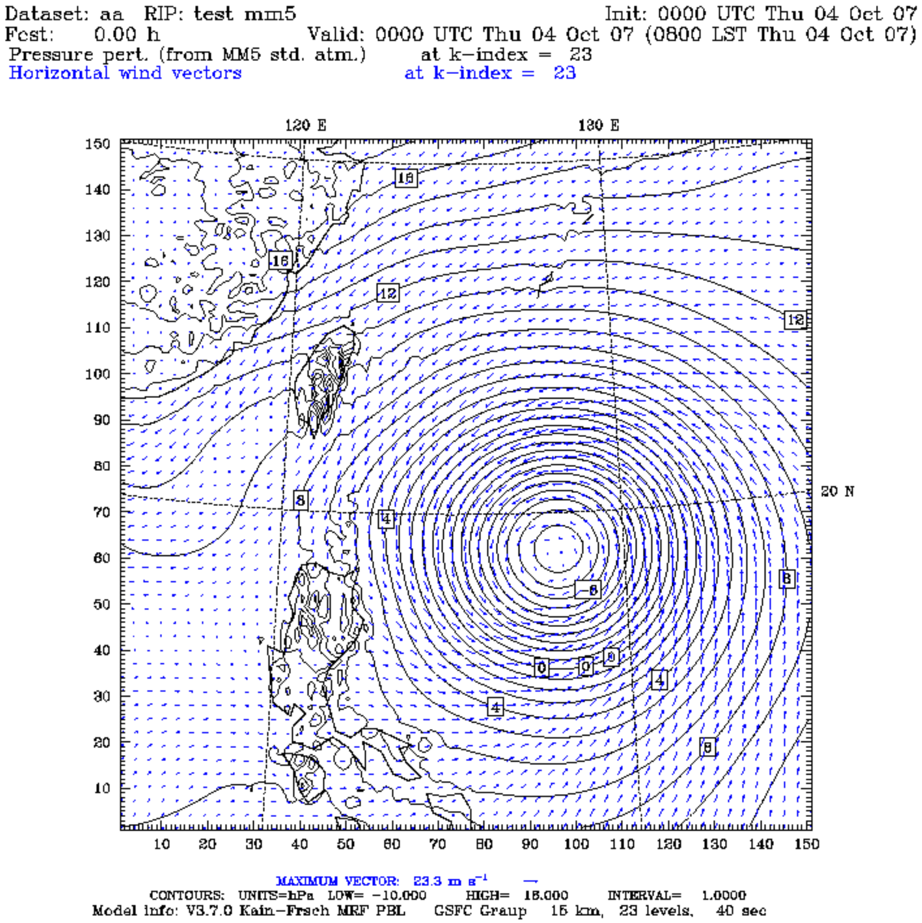


2007/10/04 1200UTC

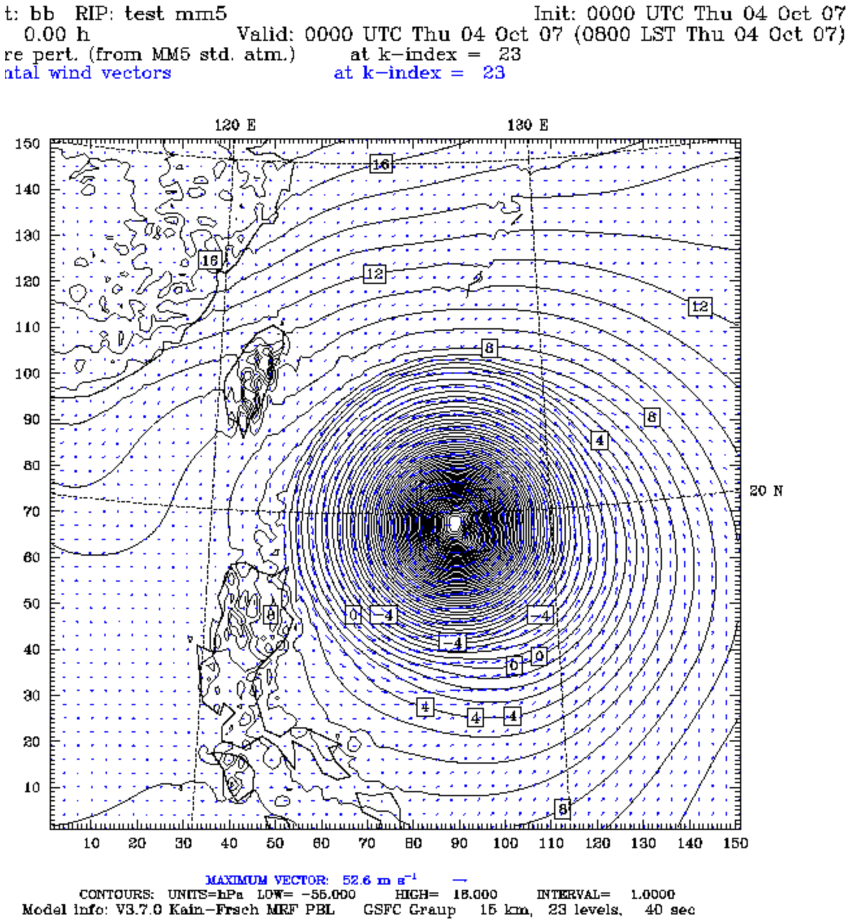


Compared with best tracks (red dotted-line) from http://agora.ex.nii.ac.jp/digital-typhoon/

(100400UTC)



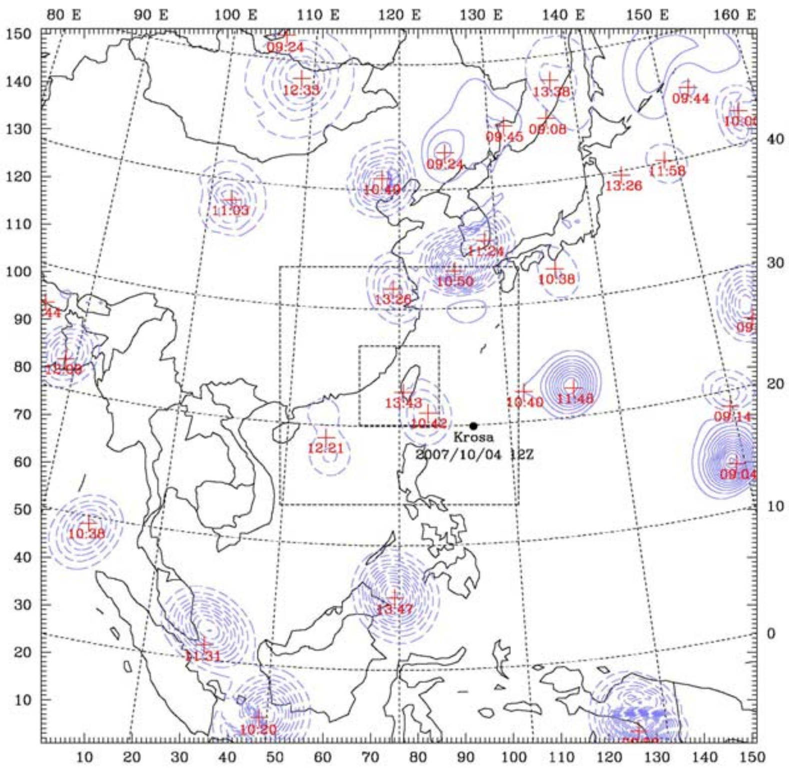
MM5 with AVN



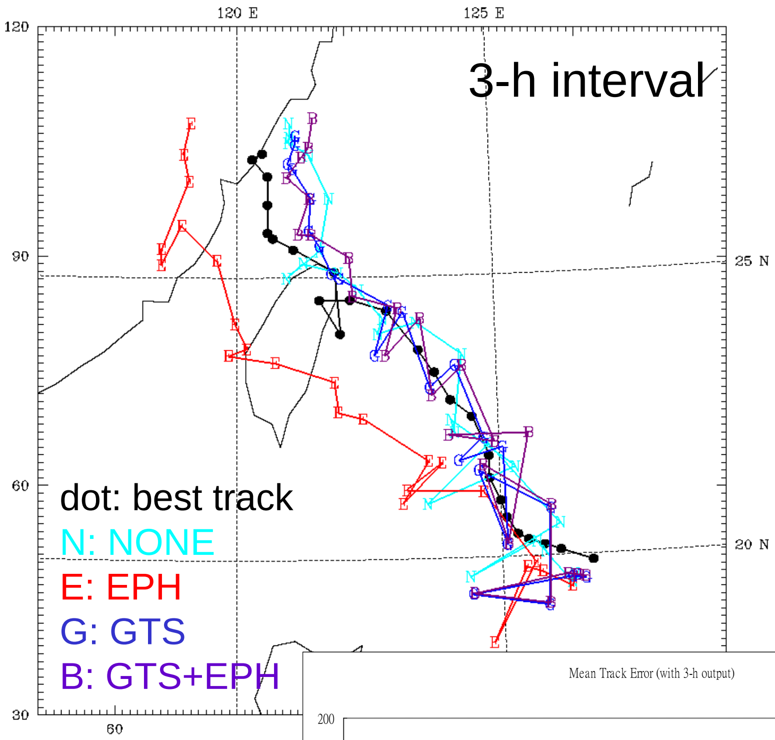
MM5 with BDA (d1)

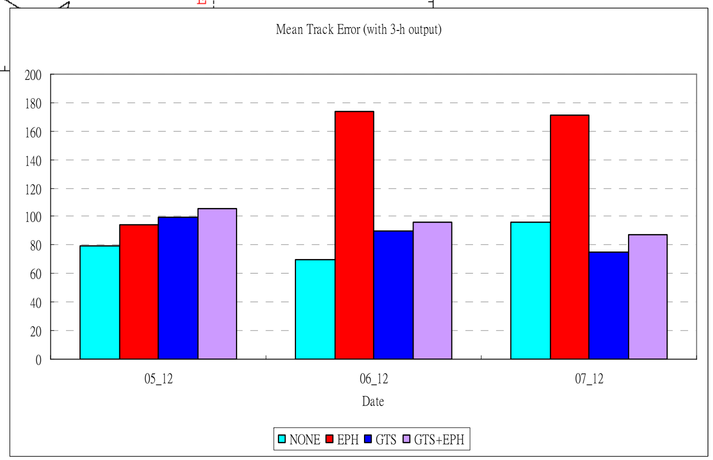
Typhoon Krosa (2007/10/04 12UTC)

Increments of N



Simulated tracks

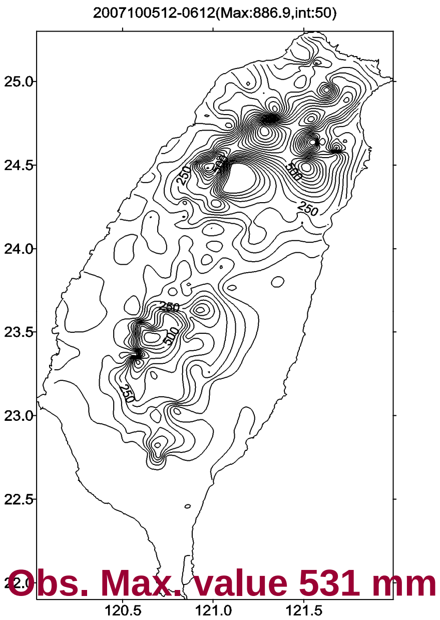




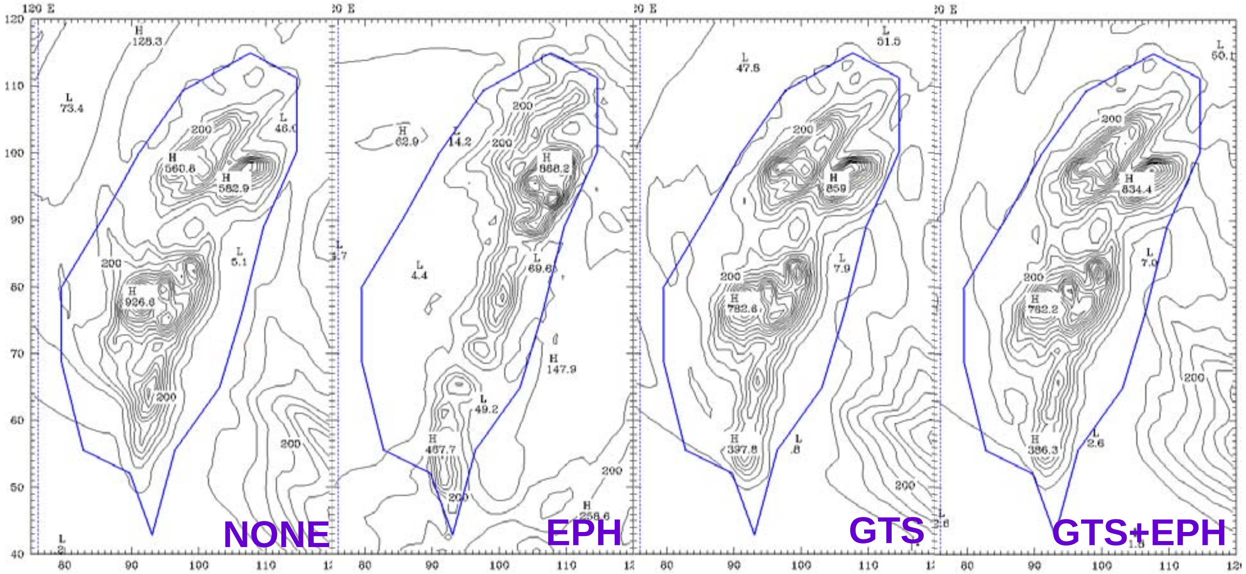
Assimilation for 3 domains

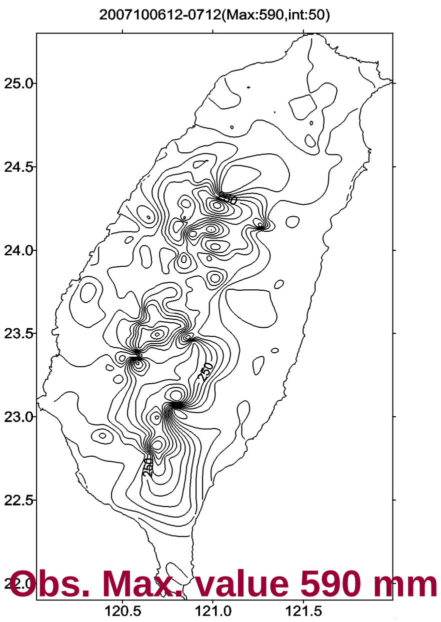
31 GPS RO Soundings

Daily Rainfall

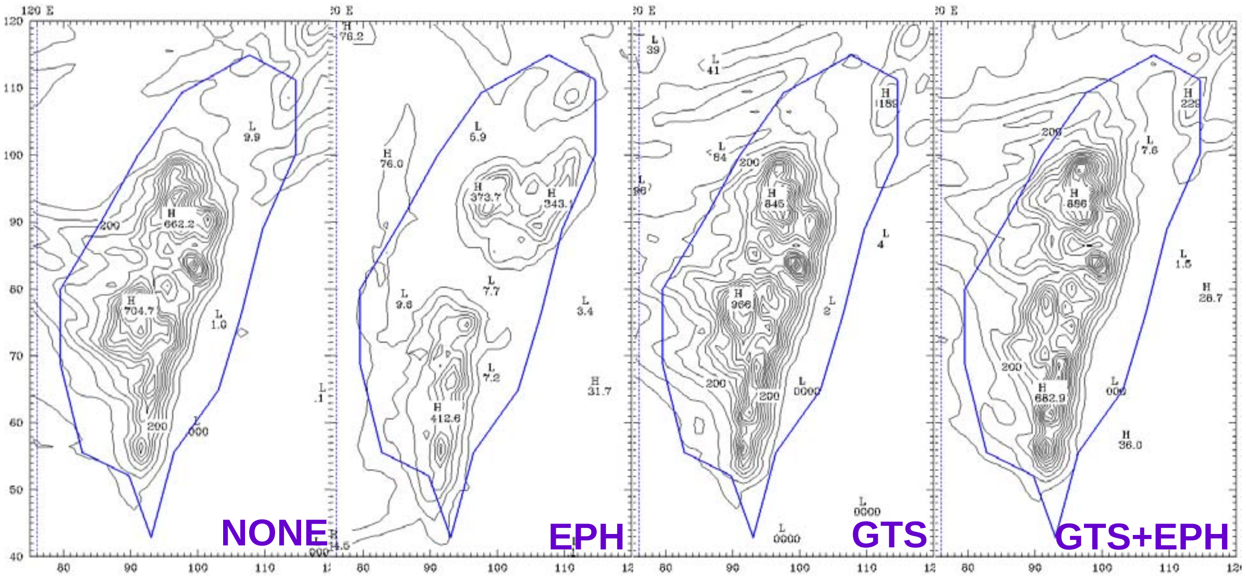


DAY 2 10/05 12:00 ~ 10/06 12:00

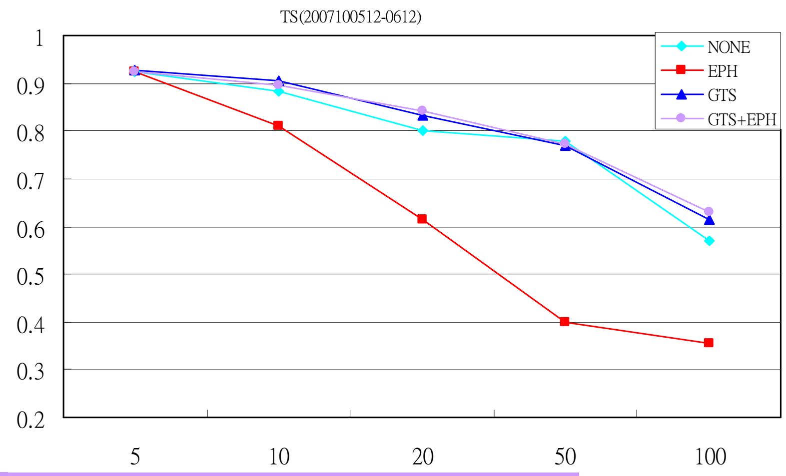


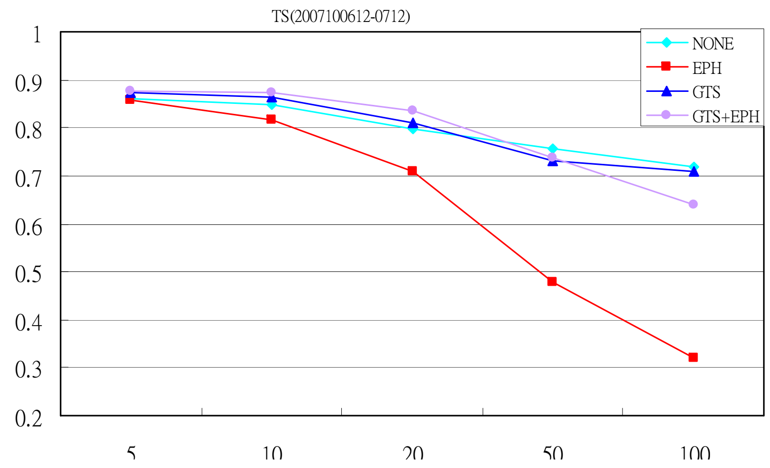


DAY 3 10/06 12:00 ~ 10/07 12:00

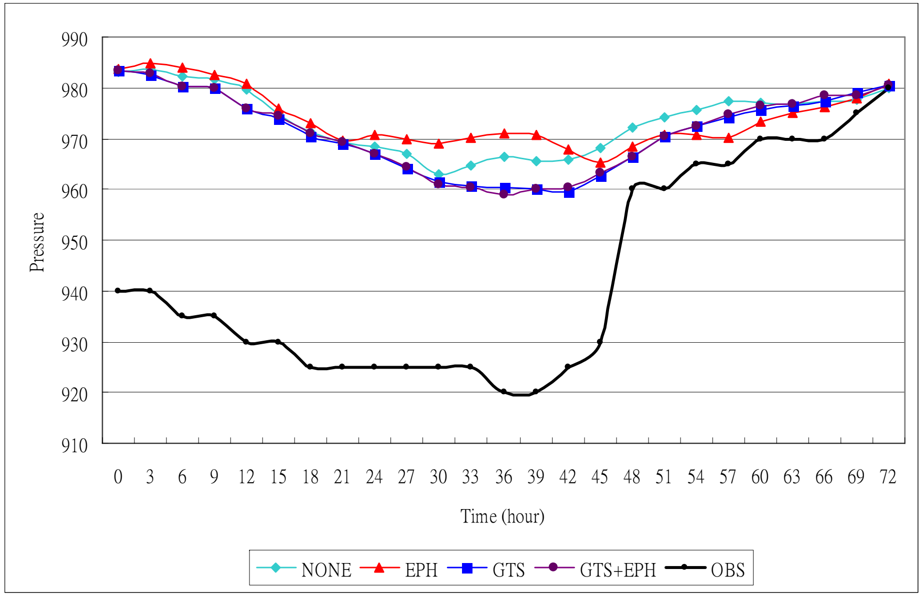


TS : Typhoon Krosa (Initial time: 2007-10-04-12:00)





Sea level pressure



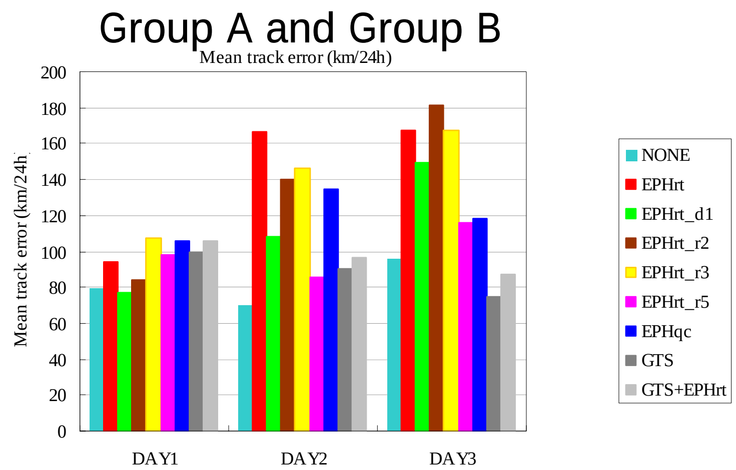
Typhoon Krosa

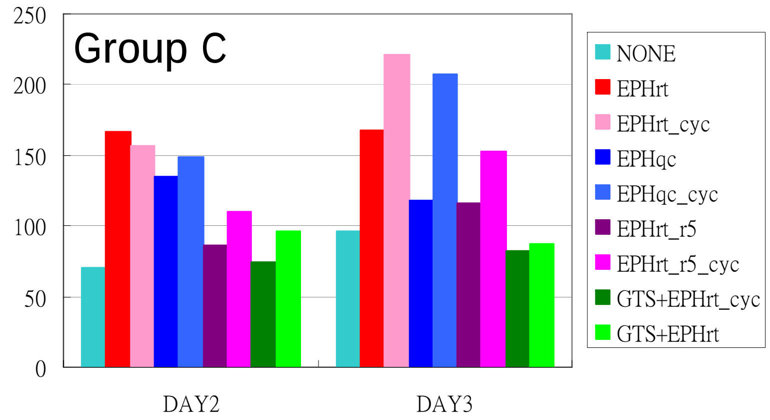
Experiments	*Assimilated data*	*Assimilated domain*
Group A: Cold start (2007-10-04:12UTC ~ 2007-10-07:12UTC)		
NONE	**None**	**None**
EPHrt	**GPS refractivity *(COSMIC real time)***	**3 domains**
GTS	**GTS data**	**3 domains**
GTS+EPHrt	**GTS data and GPS real time data**	**3 domains**
EPHqc	**GPS refractivity *(COSMIC quality check)***	**3 domains**
Group B: Sensitivity test (2007-10-04:12UTC ~ 2007-10-07:12UTC)		
EPHrt_d1	**GPS refractivity *(COSMIC real time)***	**1 domain**
EPHrt_r2	**GPS refractivity *(COSMIC real time)***	**2 domains**
EPHrt_r3	**GPS refractivity *(COSMIC real time)***	**3 domains**
EPHrt_r5	**GPS refractivity *(COSMIC real time)***	**1 domains**
Group C: Update cycle (2007-10-04:12UTC ~ 2007-10-07:12UTC)		
EPHqc_cyc	**GPS refractivity *(COSMIC quality check)***	**3 domains**
EPHrt_cyc	**GPS refractivity *(COSMIC real time)***	**3 domains**
EPHrt_r5_cyc	**GPS refractivity *(COSMIC real time)***	**3 domains**
GTS+EPHrt_cyc	**GTS data and GPS real time data**	**3 domains**

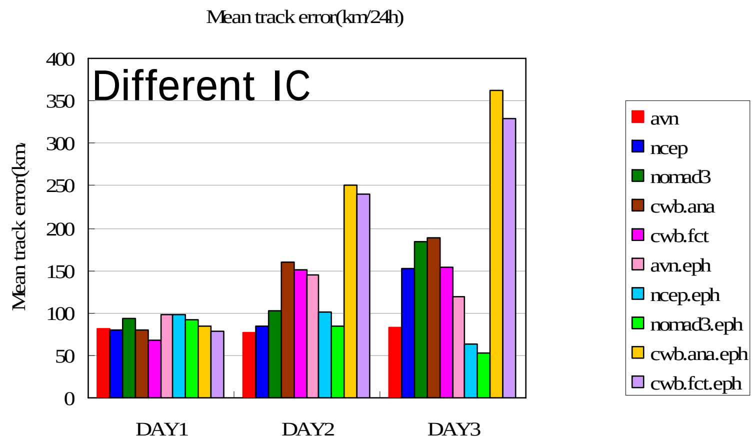
Different IC

Experiments	*Initial conditions*
AVN	**NCEP Aviation Model (AVN) global analysis (http://www.dss.ucar.edu/)**
NCEP	**NCEP / GFS forecast**
NOMAD3	**NCEP / GFS forecast (http://nomad3.ncep.noaa.gov/pub/gfs)**
CWB.analysis	**CWB / GFS analysis (Central Weather Bureau)**
CWB.forecast	**CWB / GFS forecast (Central Weather Bureau)**

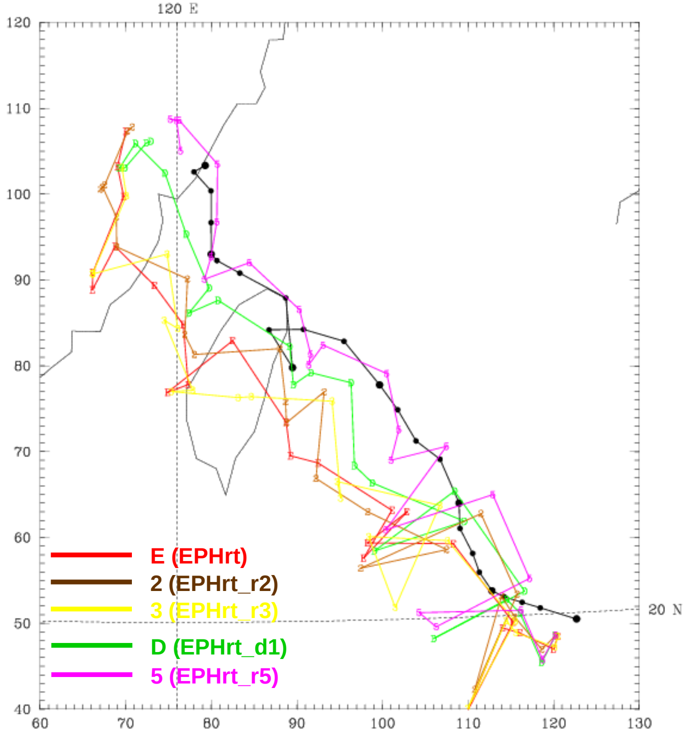
The typhoon track prediction is sensitive to many model and physical factors!

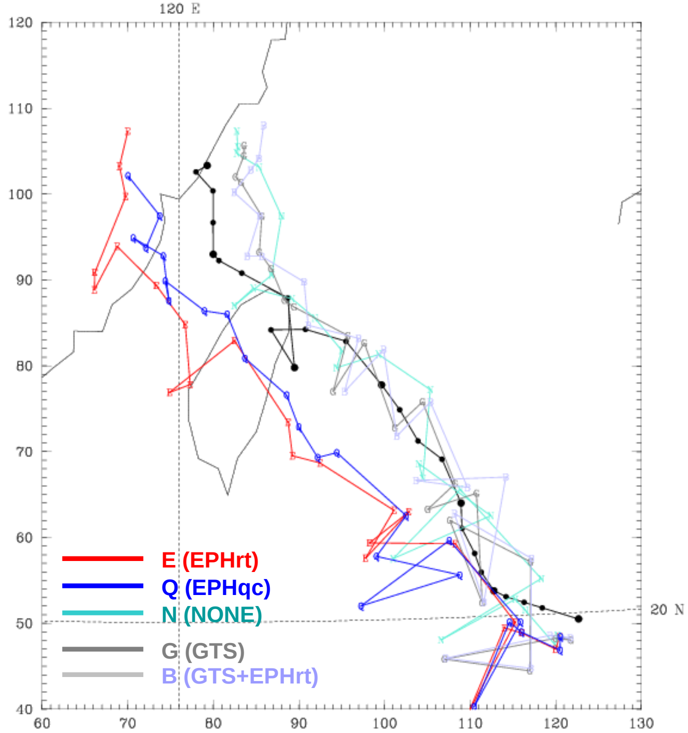


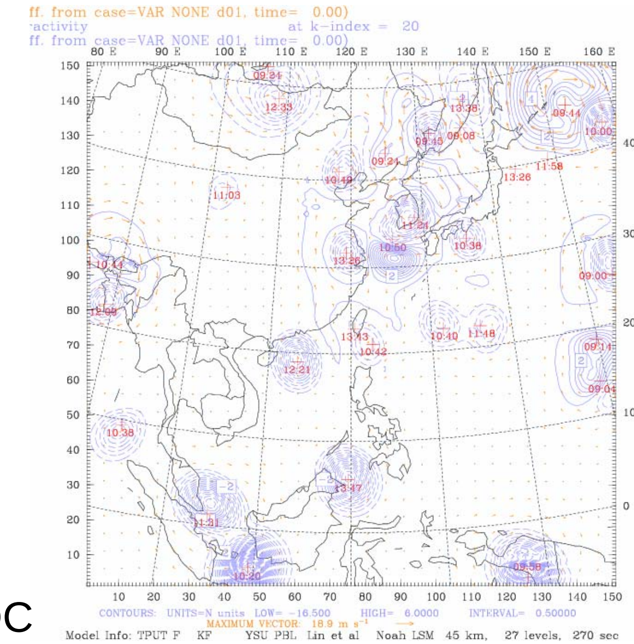




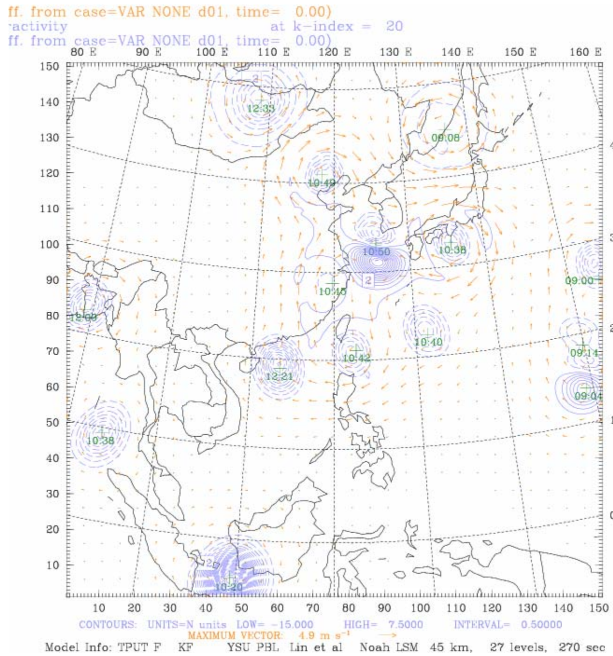
Krosa







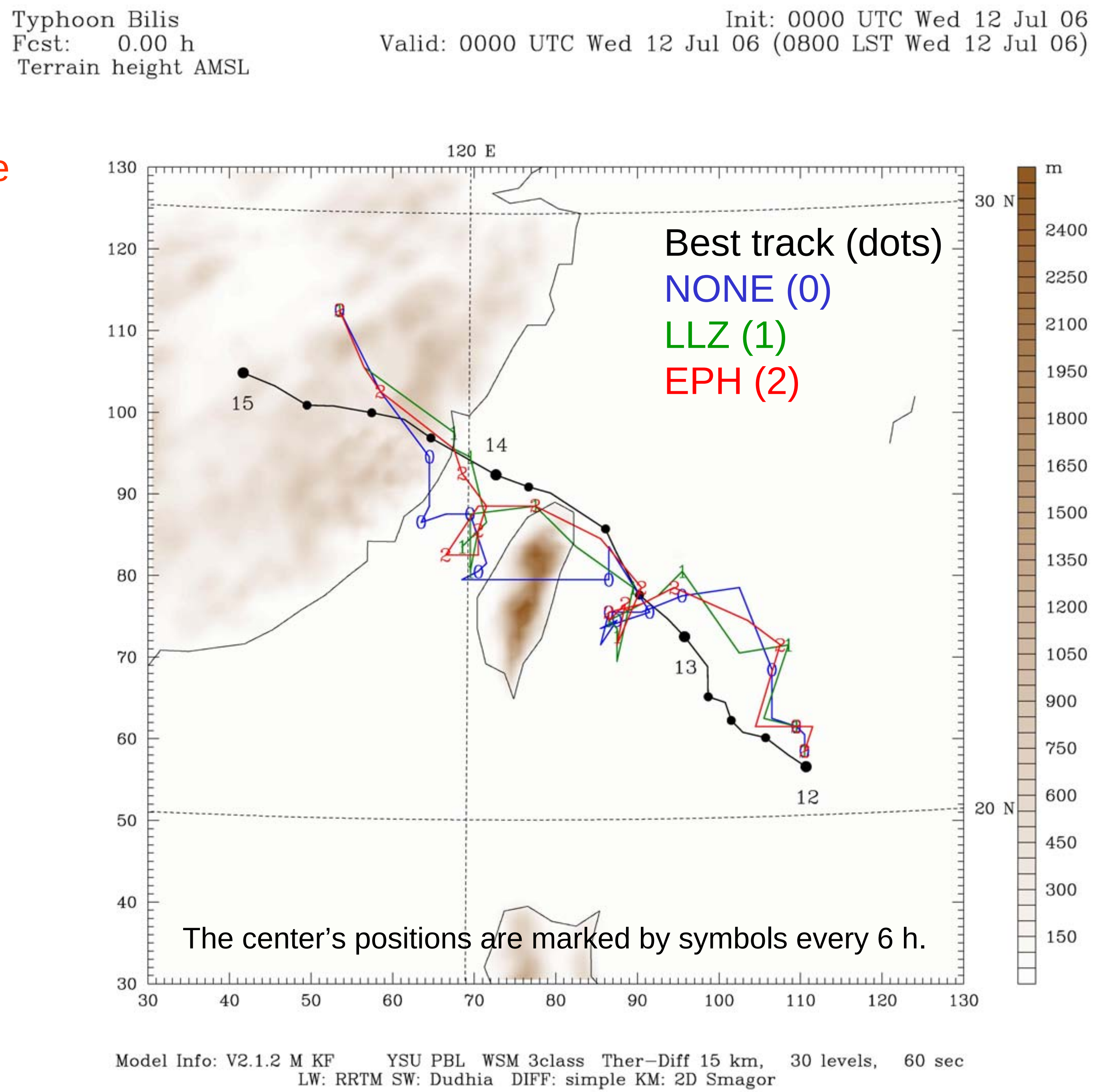
Before QC



After QC

The large impact case

Bilis (2006)

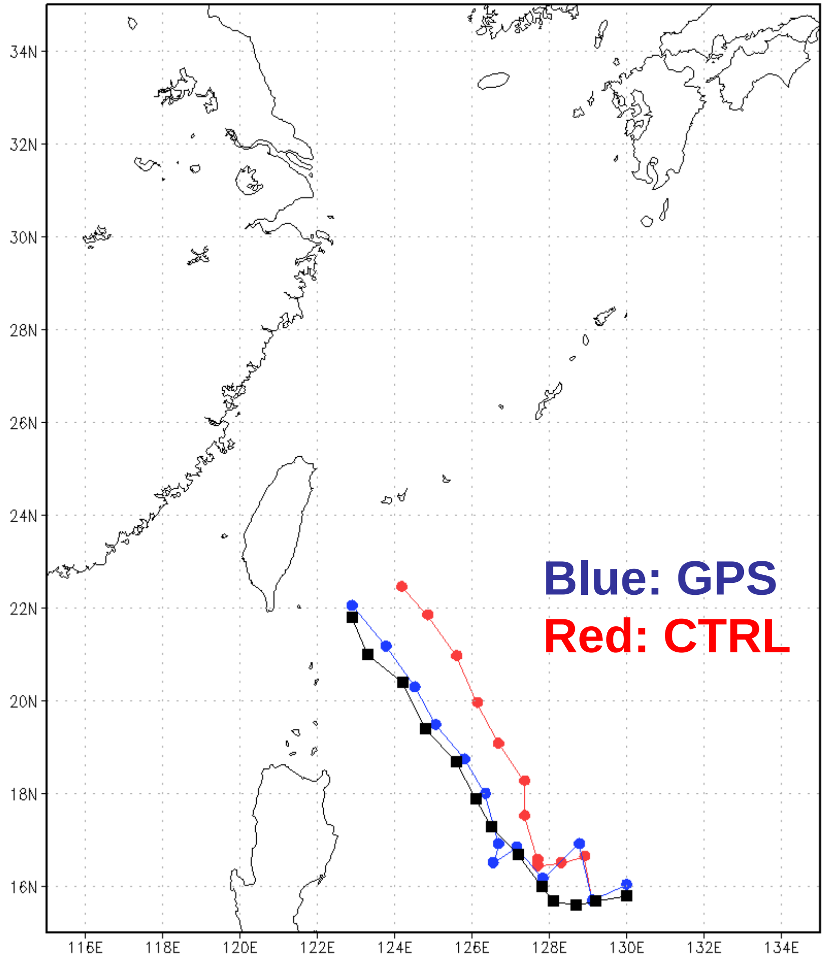


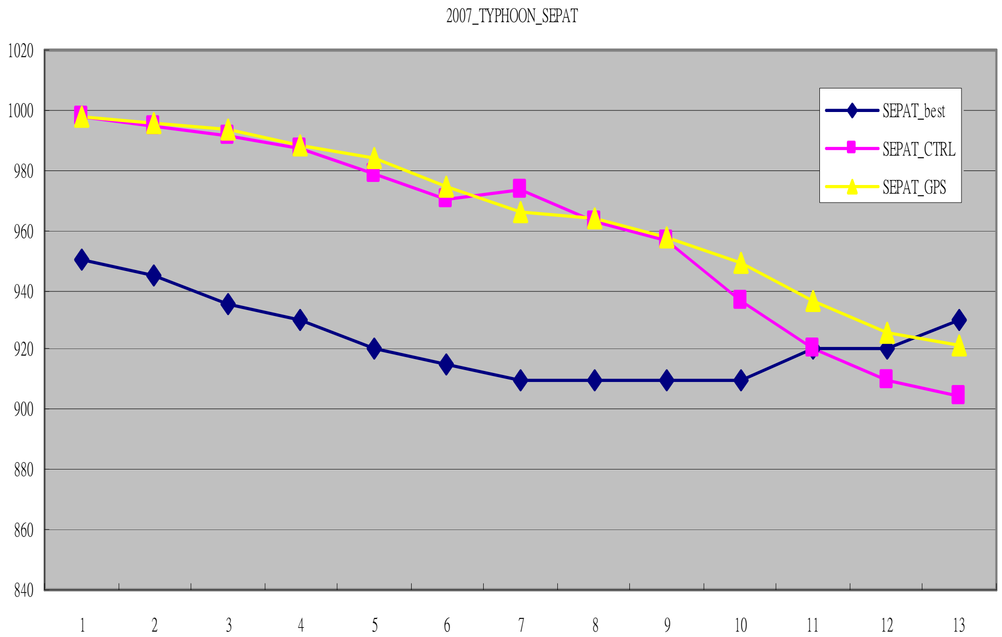
(P.-L. Lin)

The large impact case

WRF D1,D2

TYPHOON SEPAT
2007/08/14/12Z ~ 2007/08/17/12Z

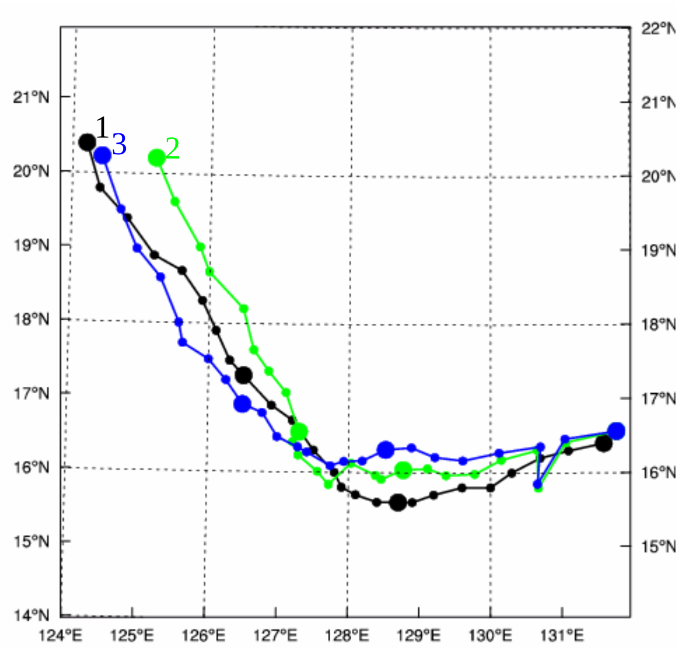




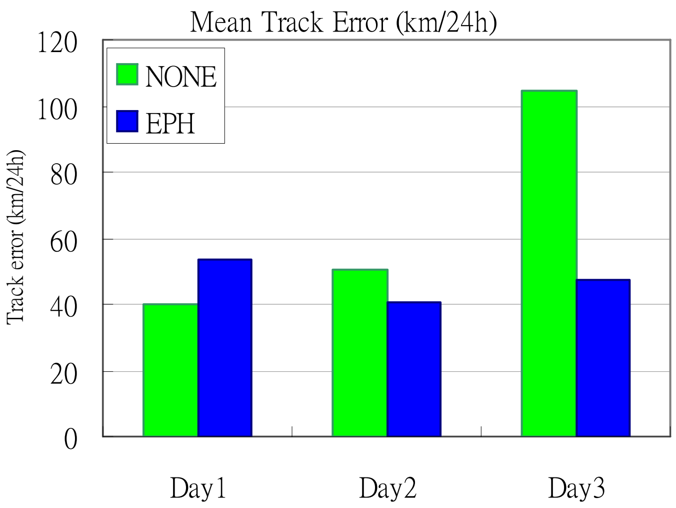
	12	24	36	48	60	72
CTRL	120	52	95	122	160	152
GPS	148	118	45	23	35	30

unit: km

Typhoon Sepat (2007)



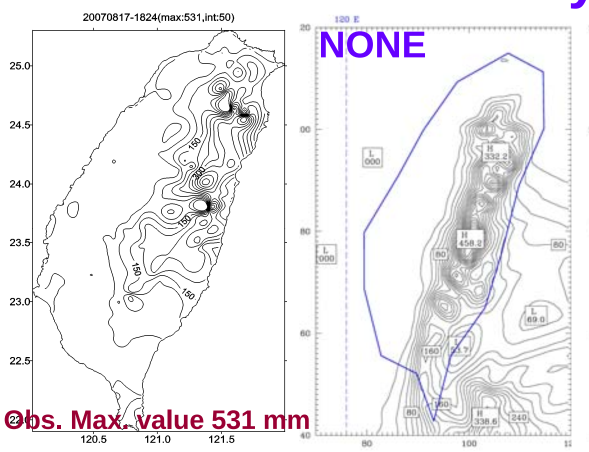
The best track (black line) and simulated tracks for experiment NONE (green line) and EPH (blue line).



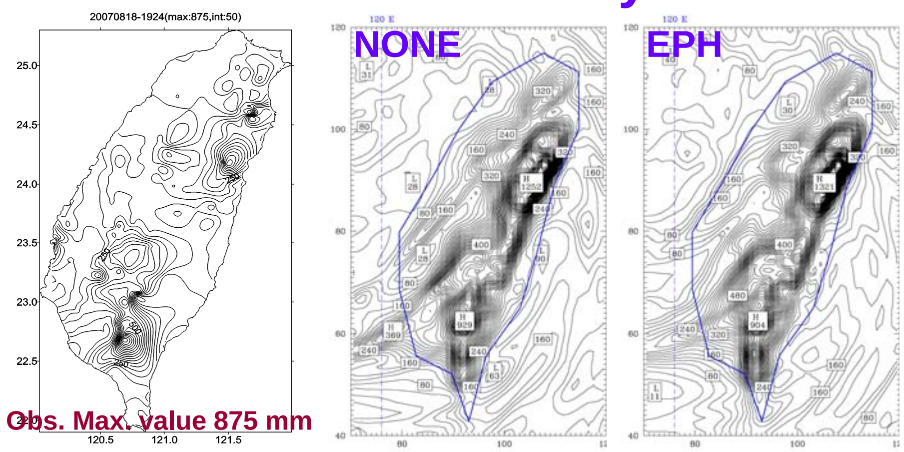
The 24-h mean track errors for experiments NONE and EPH.

24h accumulated rainfall

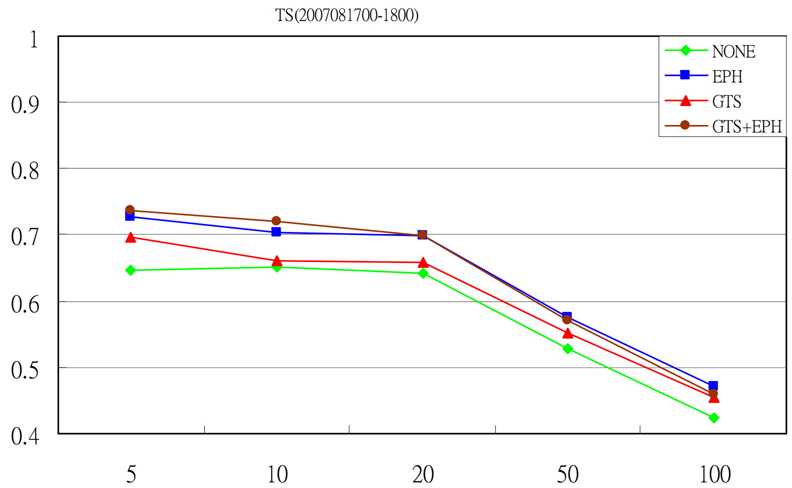
Day2

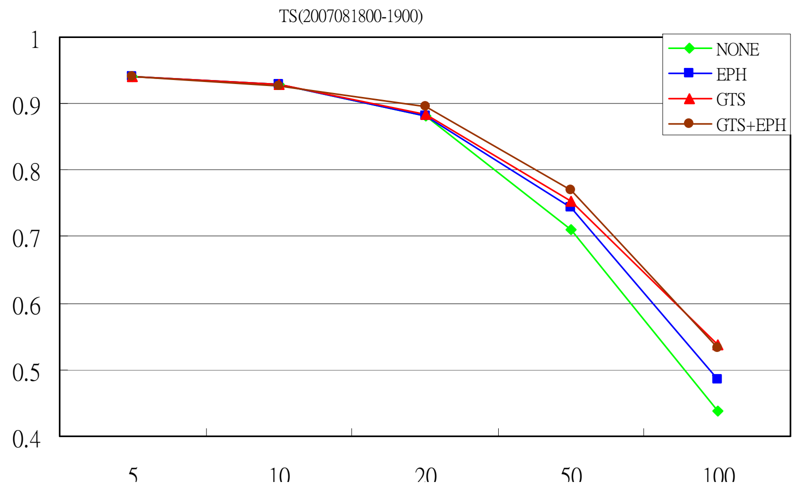


Day3



TS : Typhoon Sepat (Initial time: 2007-08-16-00:00)





Forecast track error for Typhoon Krosa (initial time : 12Z 4th Oct. 2007) using CWB WRF

2007100412	12hr	24hr	36hr	48hr	60hr	72hr
CS_NGPS / CS_NGPS	1	1	1	1	1	1
CS-WGPS / CS_NGPS	0.98	1.03	0.67	1.61	1.42	1.47
FU-NGPS / CS_NGPS	7.03	1.17	0.63	2.37	2.28	2.12
FU-WGPS / CS_NGPS	5.34	1.29	0.81	2.19	2.29	2.78
NODATA / CS_NGPS	2.34	1.41	0.97	2.36	1.51	1.92

Forecast track error for typhoon Krosa (initial time : 00Z 5th Oct. 2007)

2007100500	12hr	24hr	36hr	48hr	60hr
CS_NGPS / CS_NGPS	1	1	1	1	1
CS-WGPS / CS_NGPS	1.01	1.25	0.96	0.98	1.04
FU-NGPS / CS_NGPS	1.31	1.90	2.34	3.93	1.66
FU-WGPS / CS_NGPS	1.42	1.90	4.16	4.06	1.85
NODATA / CS_NGPS	0.84	0.57	1.02	3.61	1.36

Forecast track error for typhoon Krosa (initial time : 12Z 5th Oct. 2007)

2007100512	12hr	24hr	36hr	48hr
CS_NGPS / CS_NGPS	1	1	1	1
CS-WGPS / CS_NGPS	0.93	1.06	0.73	1.24
FU-NGPS / CS_NGPS	0.27	1.54	0.61	0.53
FU-WGPS / CS_NGPS	0.42	1.71	0.59	0.60
NODATA / CS_NGPS	2.64	0.80	0.85	0.60

Forecast track error for typhoon Krosa (initial time : 00Z 6th Oct. 2007)

2007100600	12hr	24hr	36hr
CS_NGPS / CS_NGPS	1	1	1
CS-WGPS / CS_NGPS	0.91	1.23	0.95
FU-NGPS / CS_NGPS	0.78	0.49	1.15
FU-WGPS / CS_NGPS	1.41	0.53	1.25
NODATA / CS_NGPS	1.43	0.71	0.95

- Krosa track predictions are improved with GPS RO data assimilation, for a large portion of the forecasts, in general, giving positive impact.

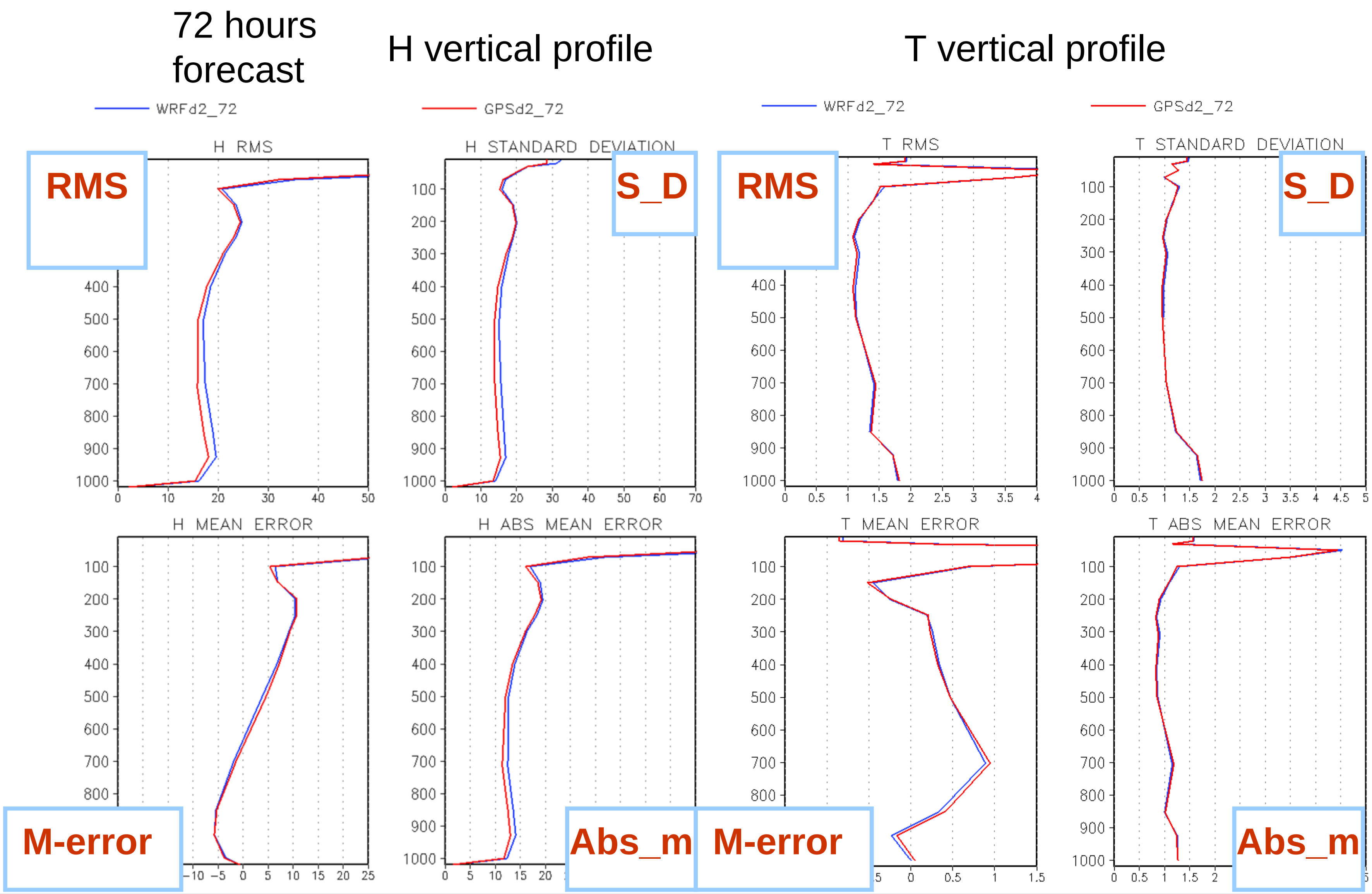
Track error ratio for Sepat during 13 to 18 August 2007 using CWB WRF

	12 H	24 H	36 H	48 H	60 H	72 H
1312	**0.88**	**1.11**	**1.67**	**1.69**	**1.92**	**2.08**
1400	**5.42**	**1.43**	**2.98**	**4.84**	**7.65**	**4.98**
1412	**0.58**	**0.20**	**0.21**	**0.04**	**0.04**	**0.27**
1500	**2.59**	**1.55**	**1.90**	**2.64**	**1.80**	**2.16**
1512	**0.29**	**0.36**	**0.36**	**0.29**	**0.31**	**0.71**
1600	**0.48**	**0.14**	**0.18**	**0.31**	**0.5**	**0.66**
1612	**0.30**	**0.70**	**0.79**	**0.90**	**1.01**	
1700	**0.90**	**1.65**	**1.09**	**0.81**		
1712	**1.57**	**1.22**	**1.46**			
1800	**0.46**	**0.16**				

The typhoon track error ratio is defined as (track error for GPS) / (track error for CONTROL). CONTROL is the experiment assimilating all the GTS observations, and GPS is the experiment assimilating GTS and FORMOSAT-3/COSMIC GPS RO data.

(P.-L. Lin) WRF D1,D2

Real-time validation (May-Sept.) in 2007



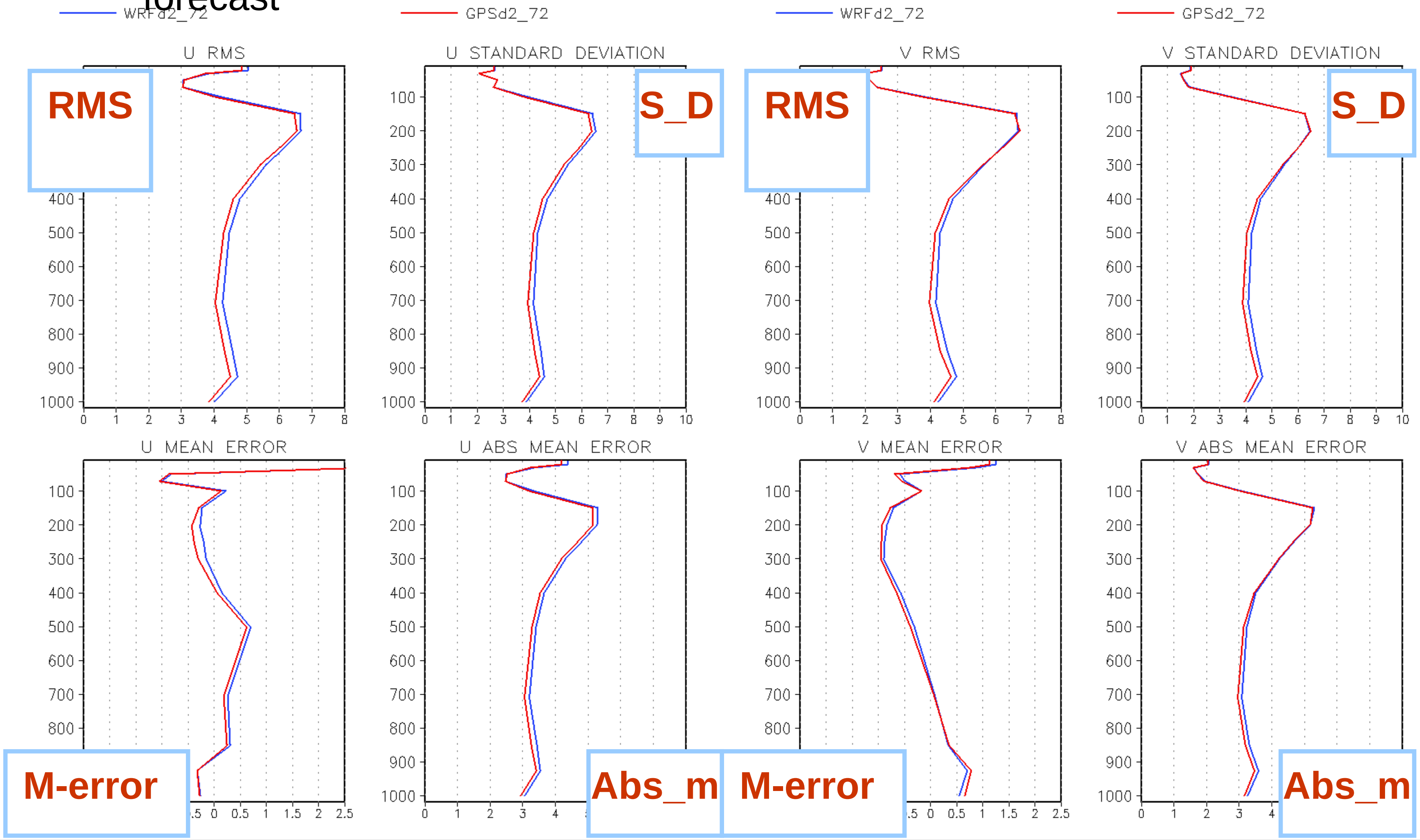
(P.-L. Lin) WRF D1,D2

Real-time validation (May-Sept.) in 2007

72 hours forecast

U vertical profile

V vertical profile

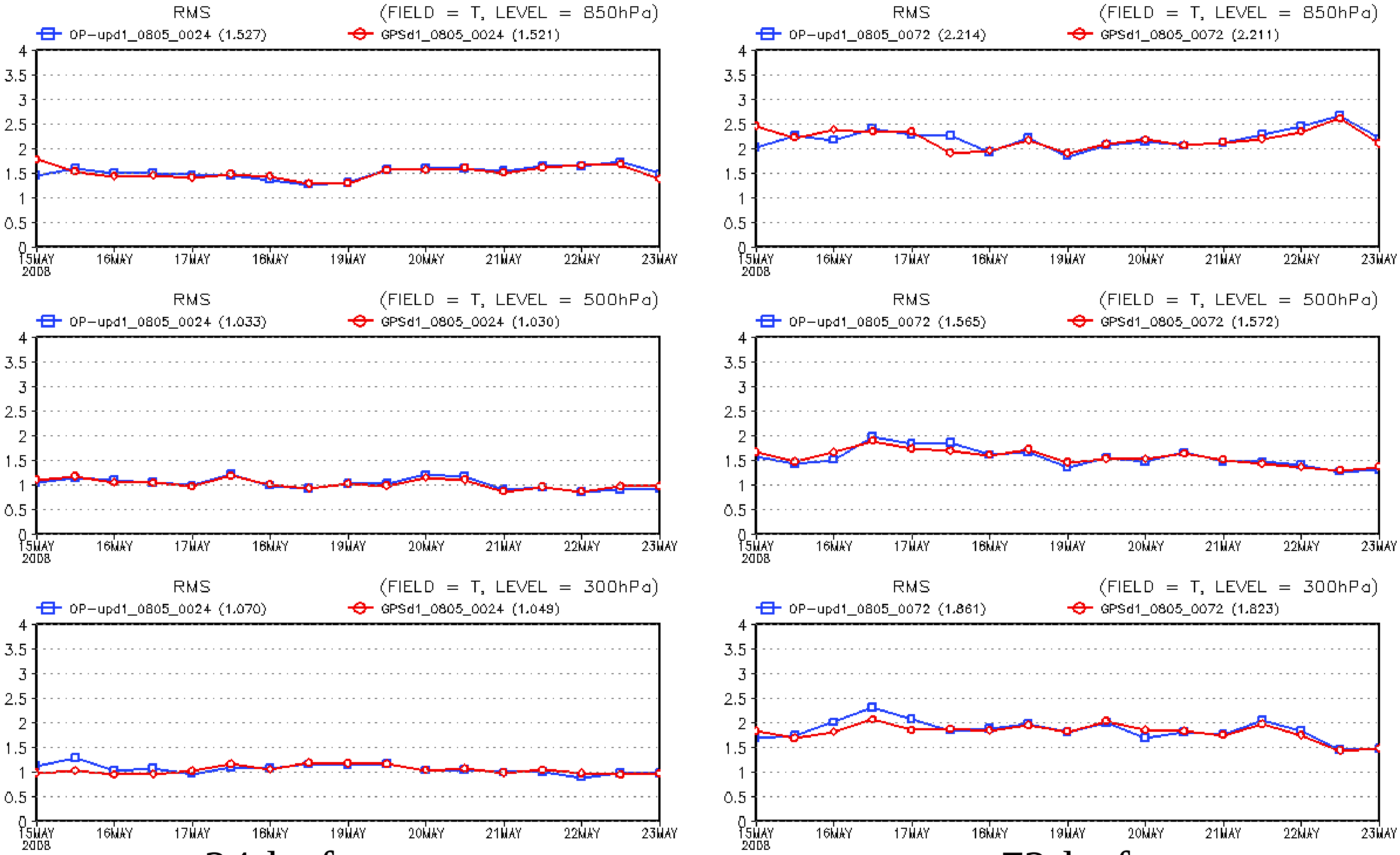


Control run -Assimilate all the GTS observations, and GPS RO

Denial run - Assimilate all the GTS observations only

2008

The forecast experiment was run 4 times a day in cold-start mode with the first guess from CWB GFS analysis.



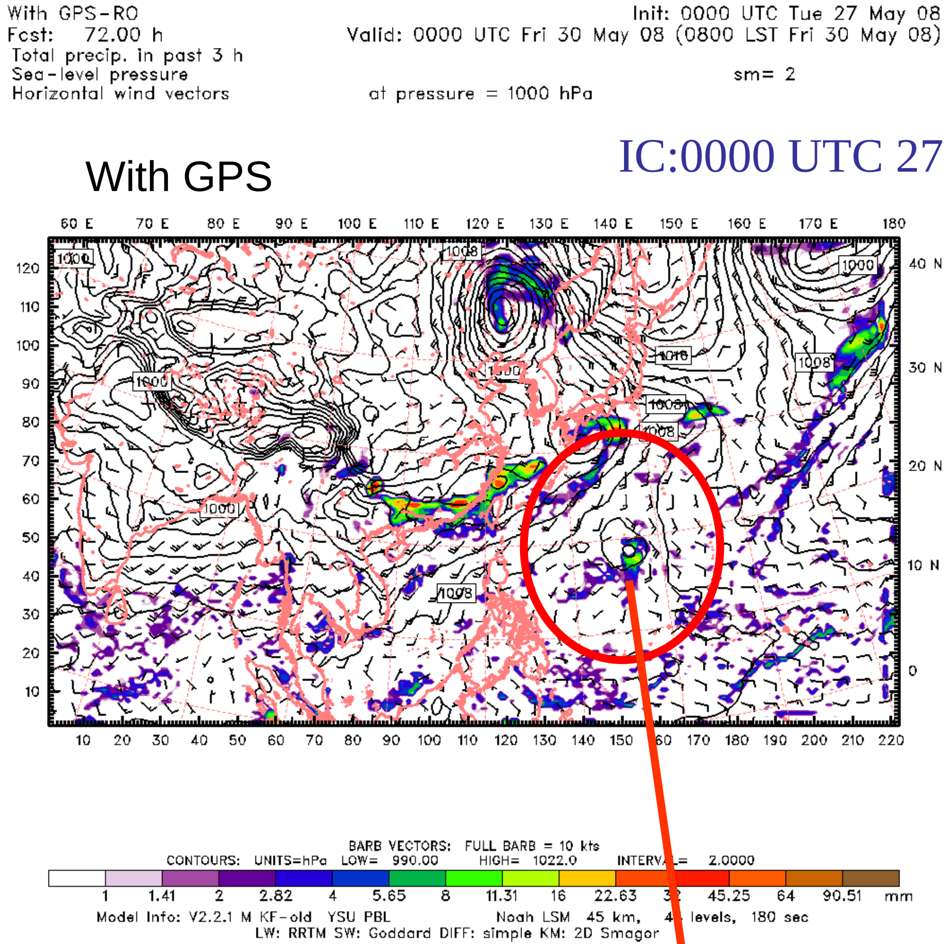
24-hr fcst

WRF D1 (45-km)

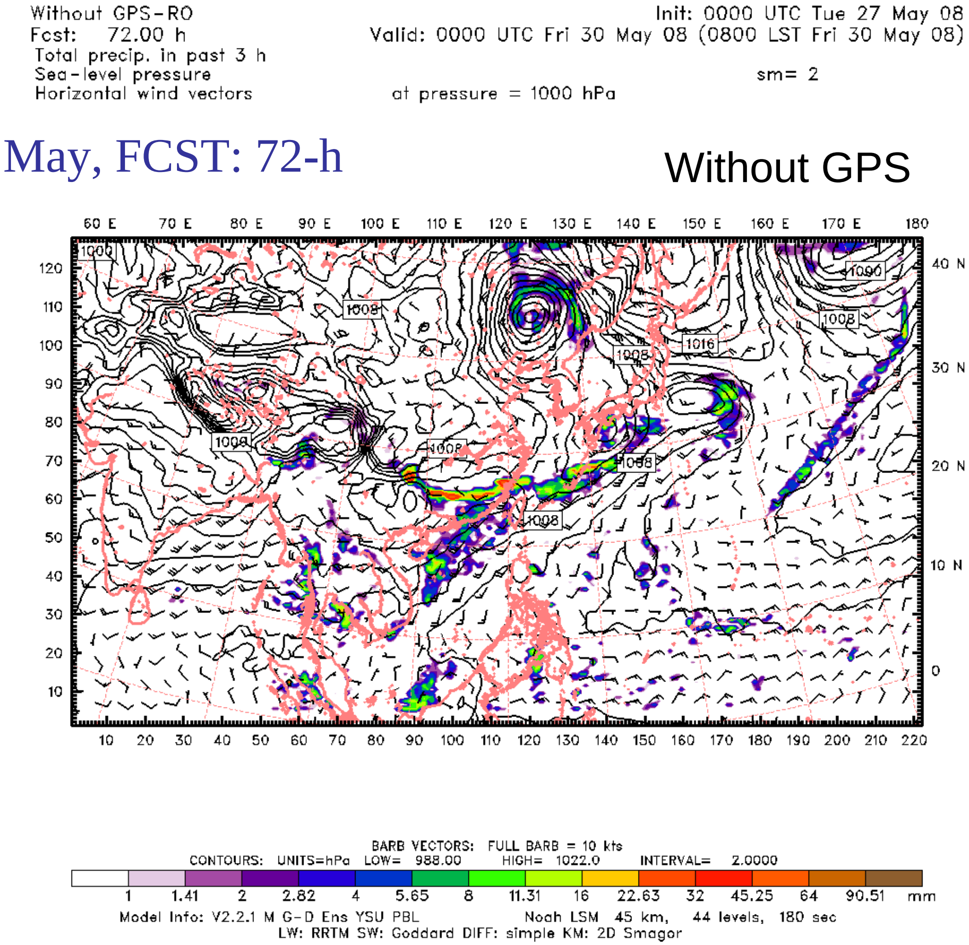
72-hr fcst

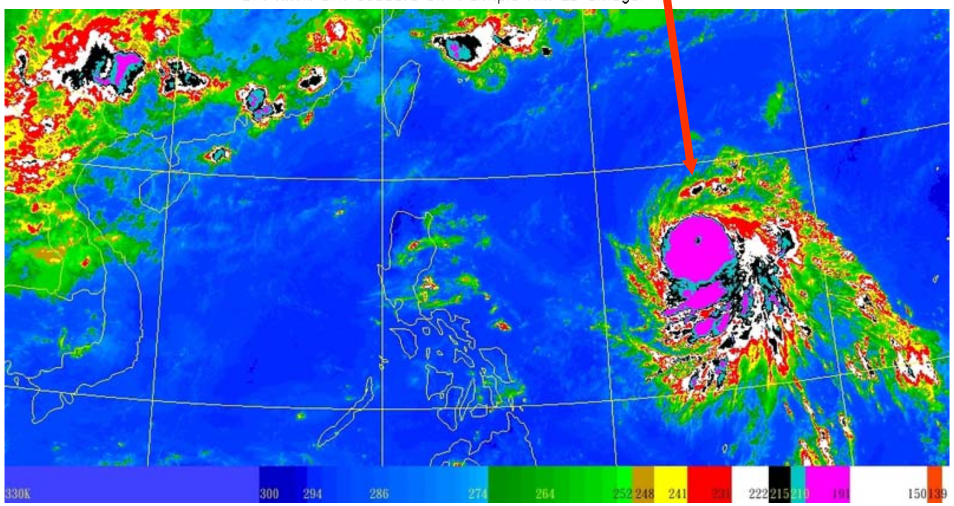
IC:0000 UTC 27 May, FCST: 72-h

With GPS



Without GPS

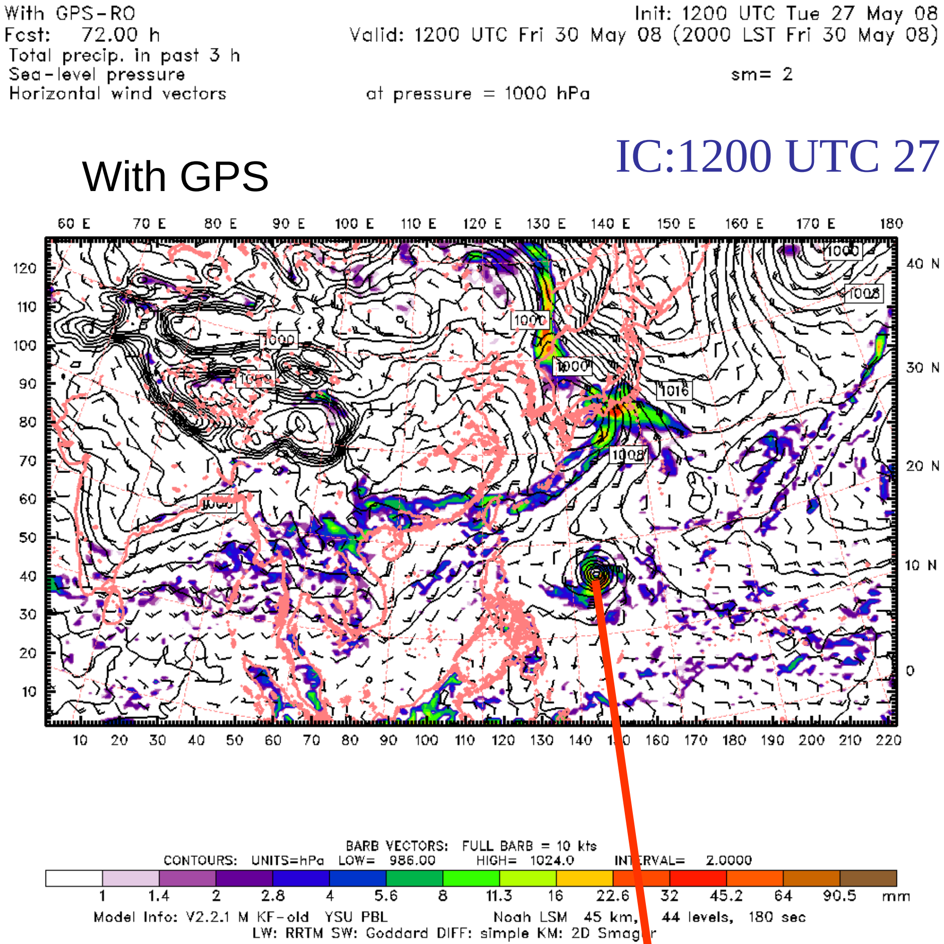




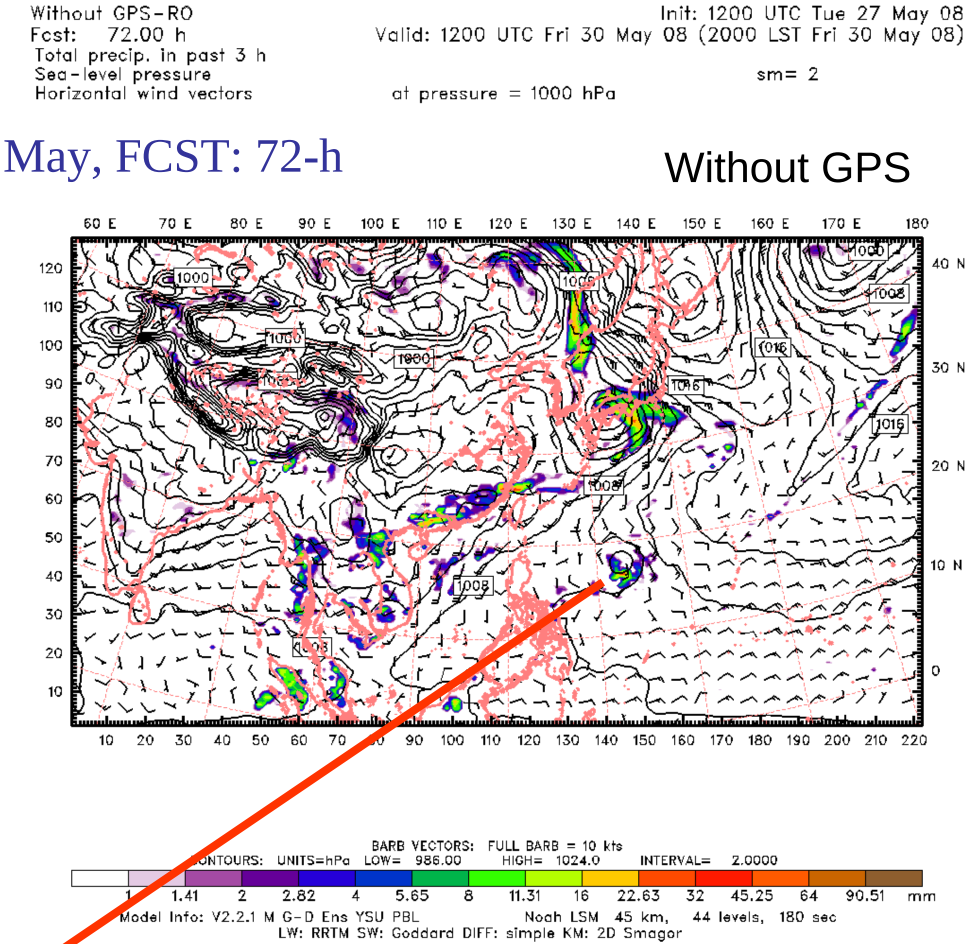
The GPS RO assimilation run shows the typhoon in 72-hr forecast, while the denial run misses the forecast.

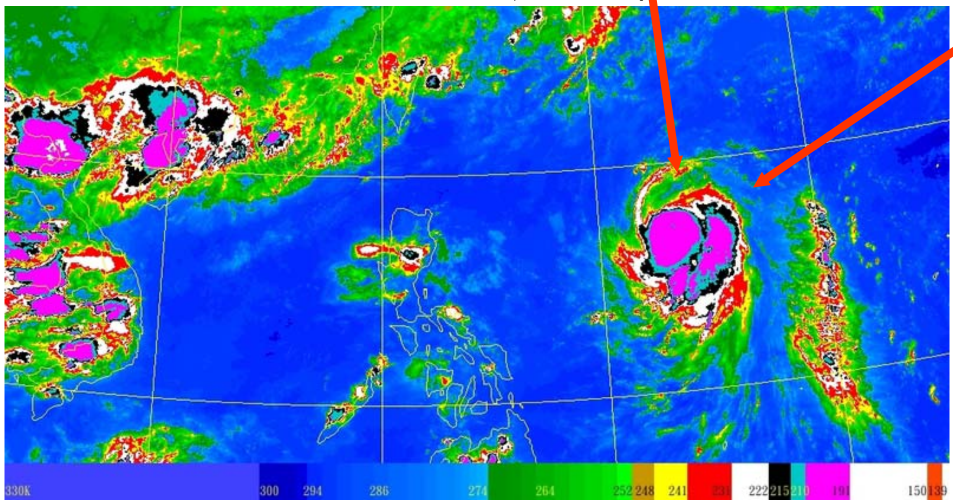
IC:1200 UTC 27 May, FCST: 72-h

With GPS



Without GPS



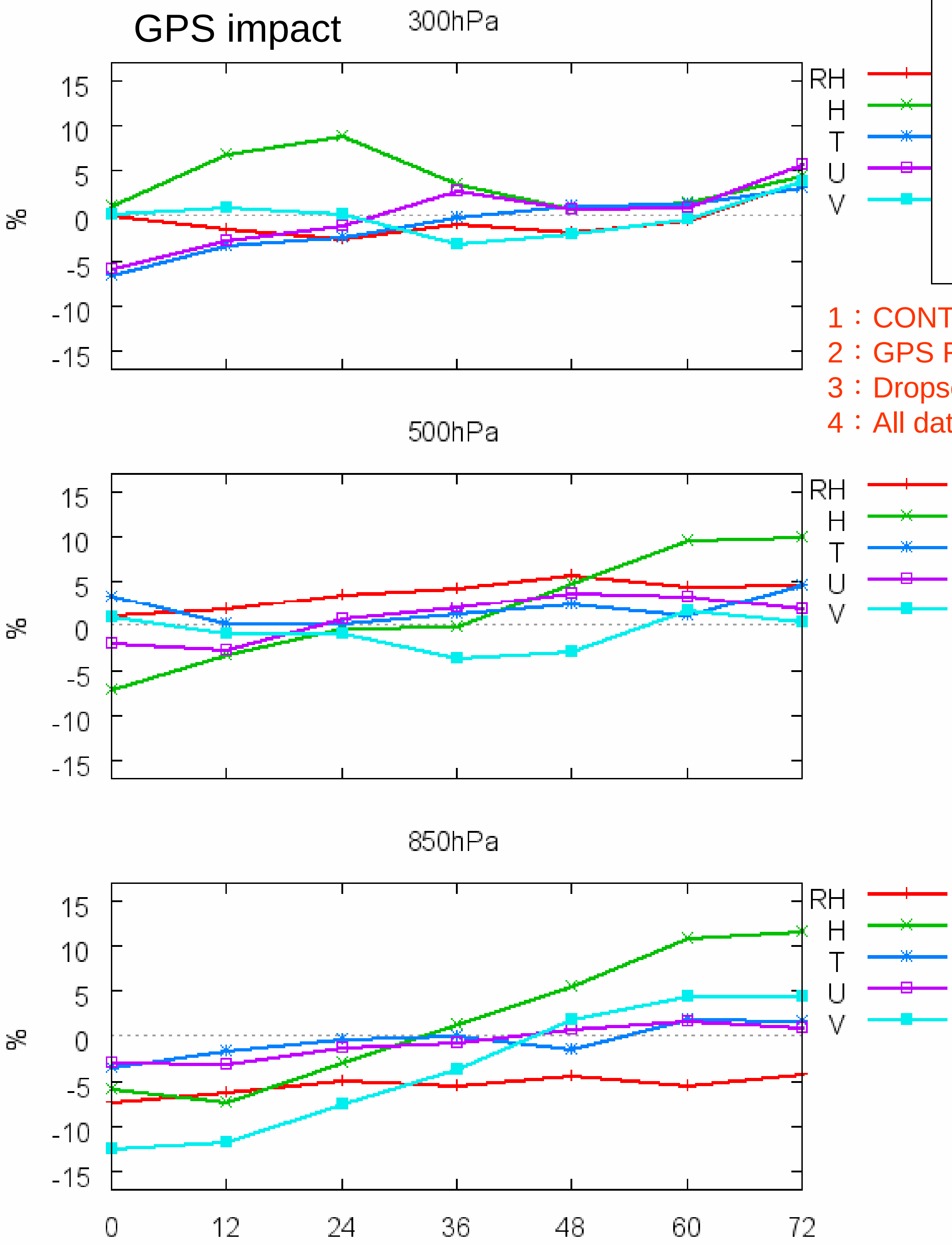


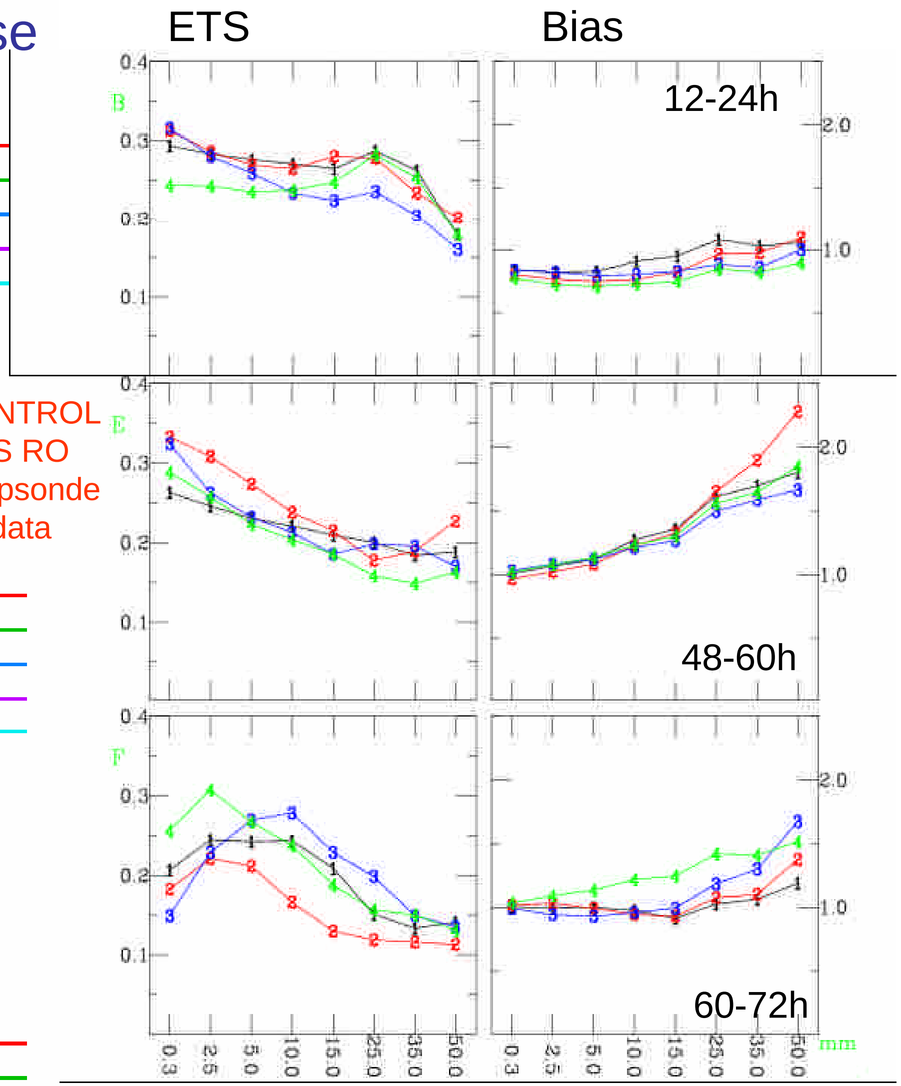
In the next initial time 12-h, the control run captures the more realistic typhoon structure at 72-h as compared with satellite image.

F.-C. Chien

Mei-yu case

GPS impact

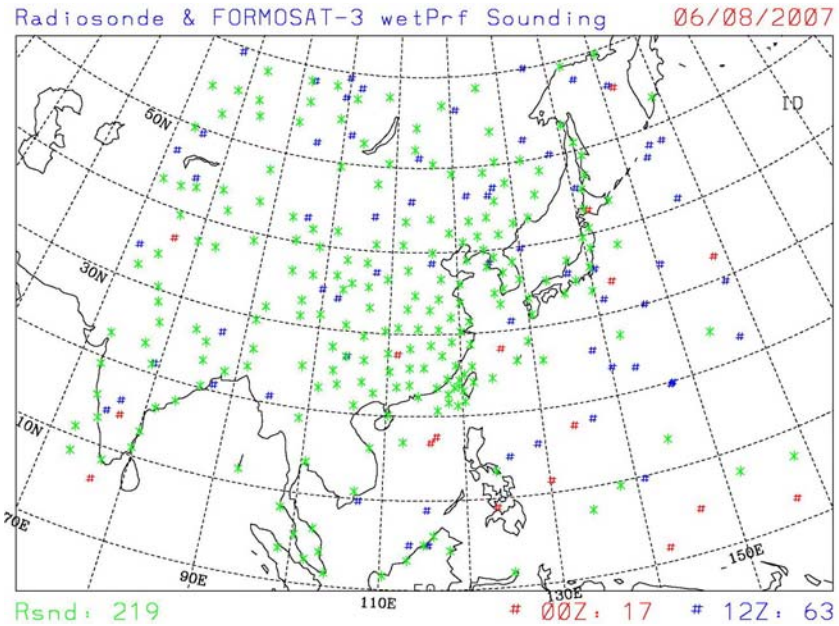




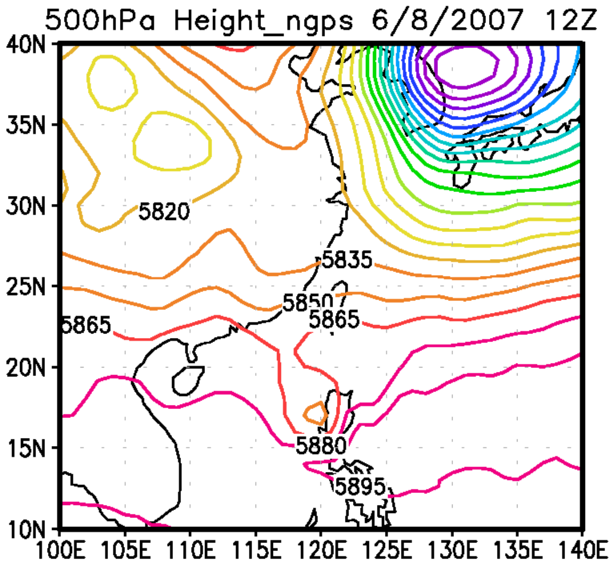
The dropsonde data were over the ocean near the southwest of Taiwan. Each experiment contains 22 runs of 72-h simulation, initialized twice daily from 0000 UTC 5 June 2007 to1200 UTC 15 June 2007 by NCEP GFS. The initial data of the other 21 runs were obtained from the 12-h update cycle of the previous WRF run.

Mei-yu case (June 2006)

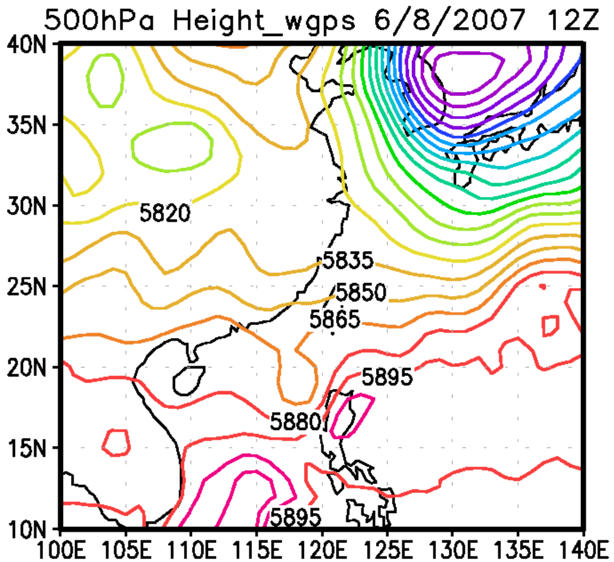
S.-C. Lin



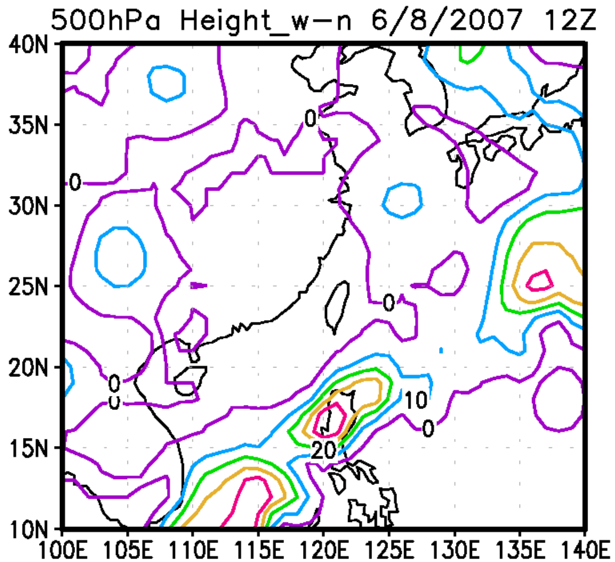
GPS RO soundings show stronger ridge extended from the western Pacific subtropical high.



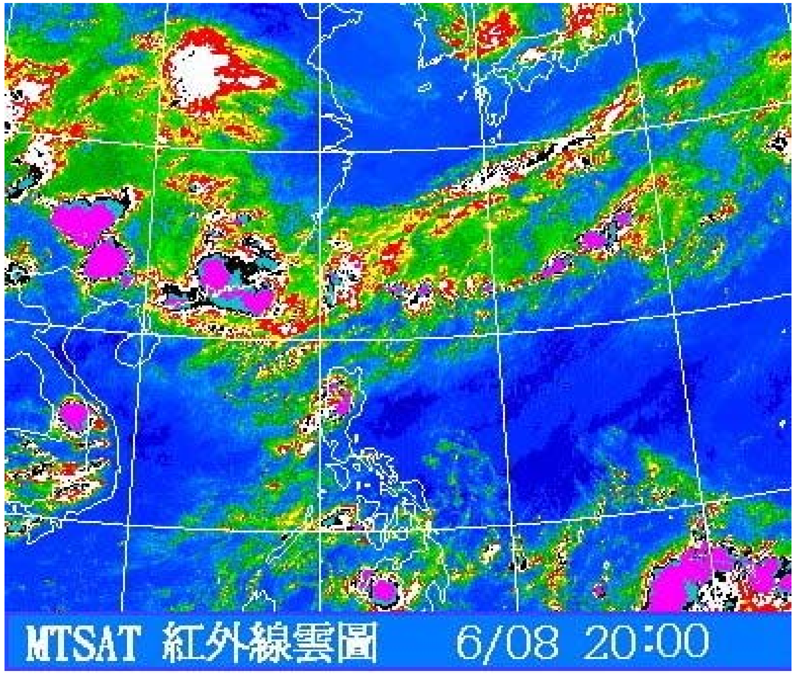
NoGPS



GPS



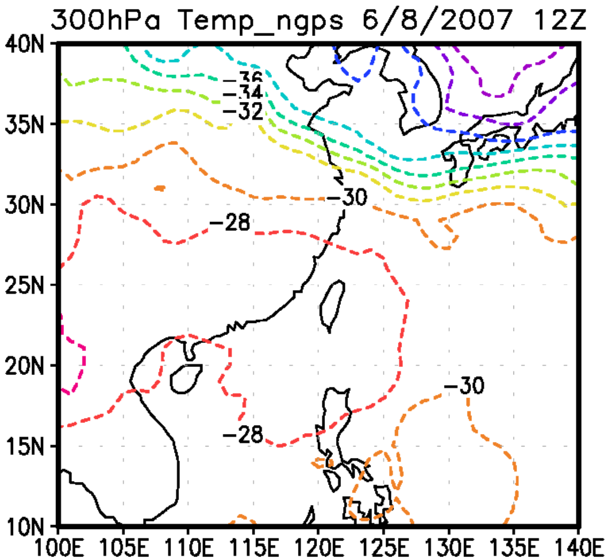
GPS-NoGPS



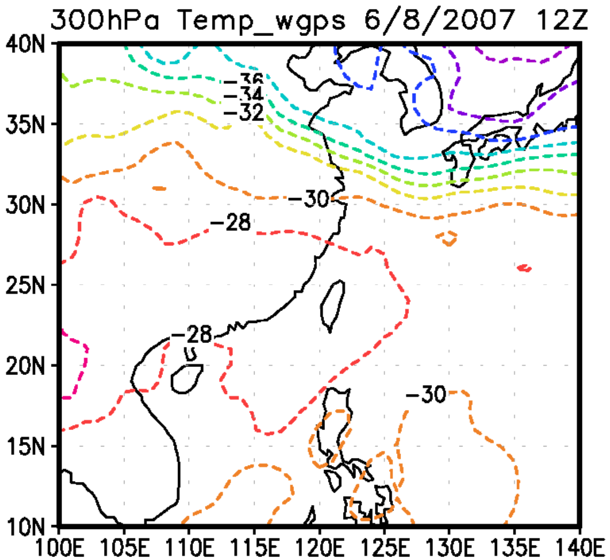
Mei-yu case (June 2006)

S.-C. Lin

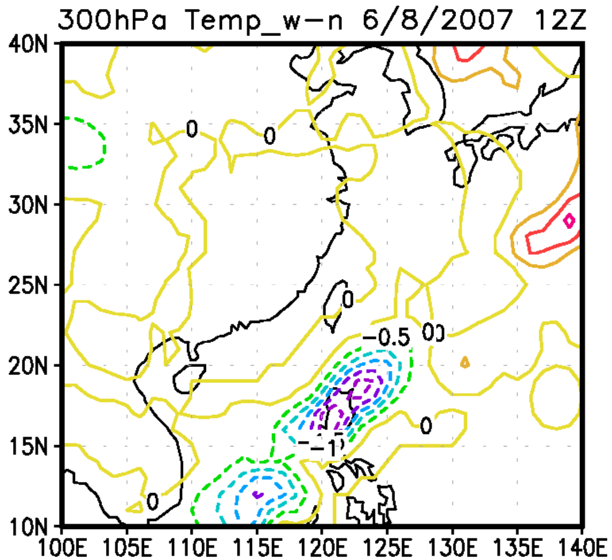
GPS RO soundings show significant cloud-top cooling over north Philippine where deep convective activities exist.



NoGPS



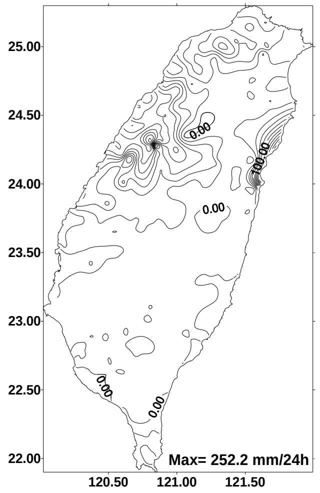
GPS

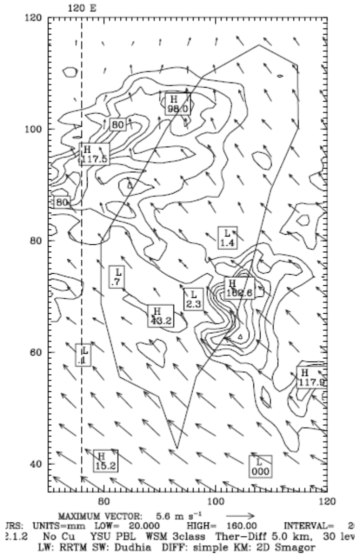


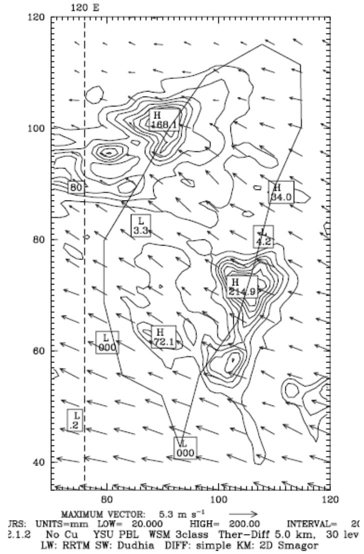
GPS-NoGPS

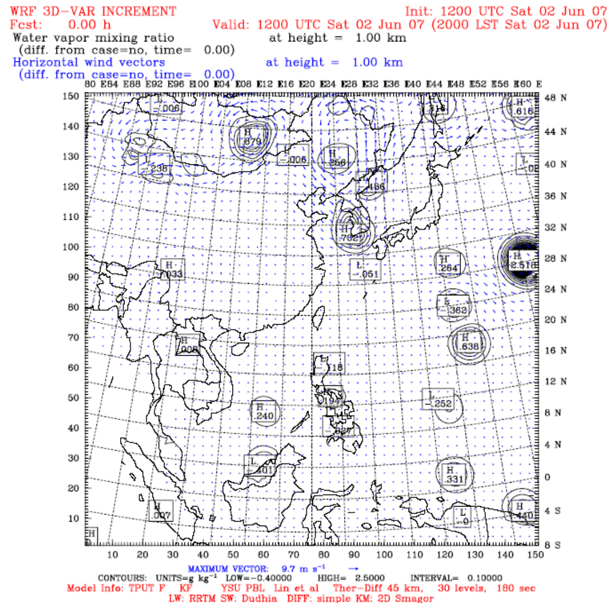
2nd OBS CTL EPH

0603:12 - 0604:12 UTC



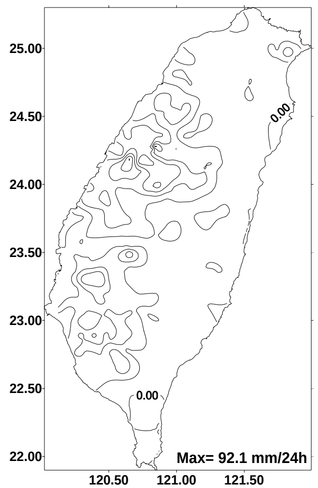


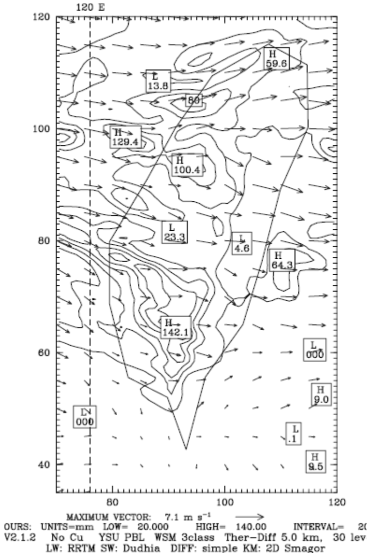


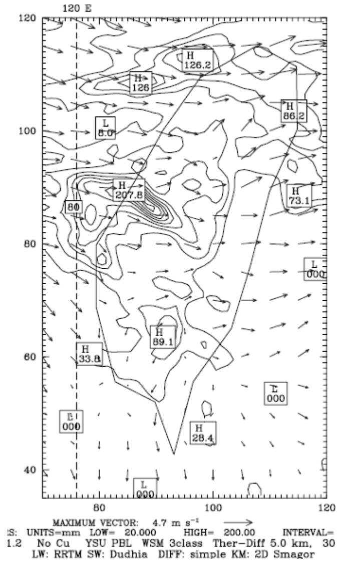


3rd

0604:12 - 0605:12 UTC



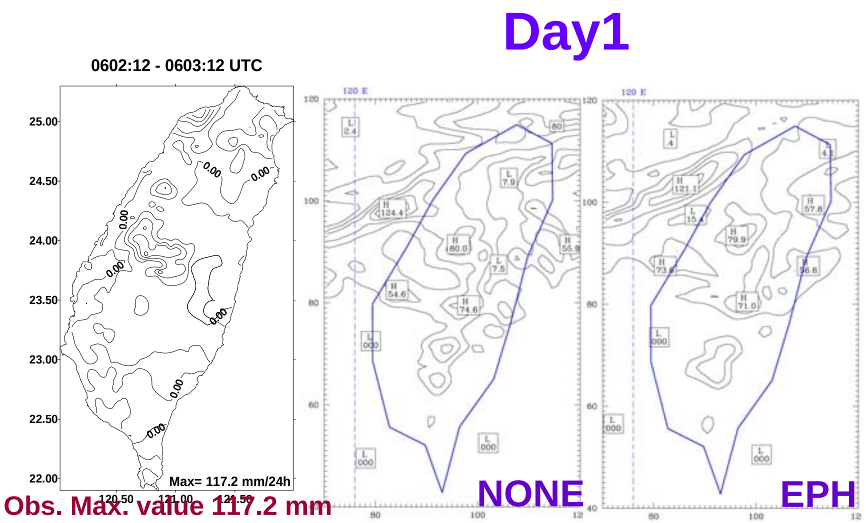


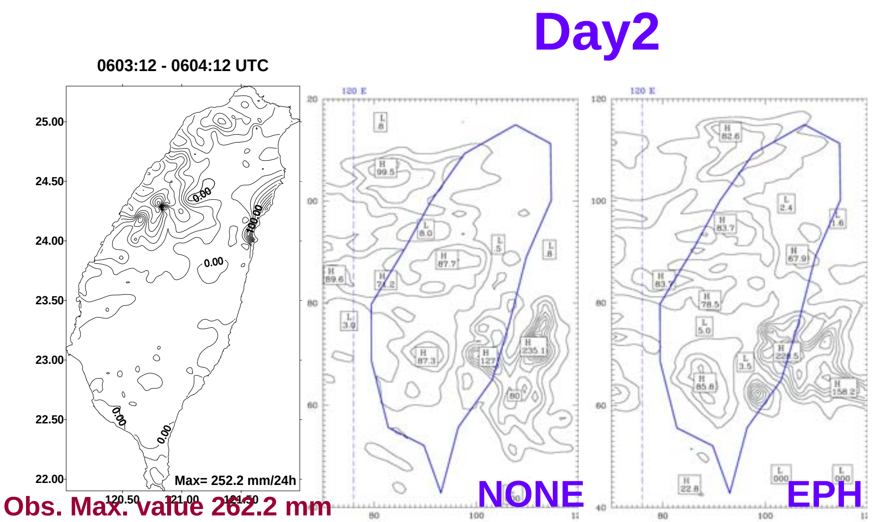


Observation of accumulated rainfall (mm) for the 2007 June 02 Mei-yu front case, the predicted rainfalls (mm) with no GPS data, and with 31 GPS RO data in the second day and the third day.

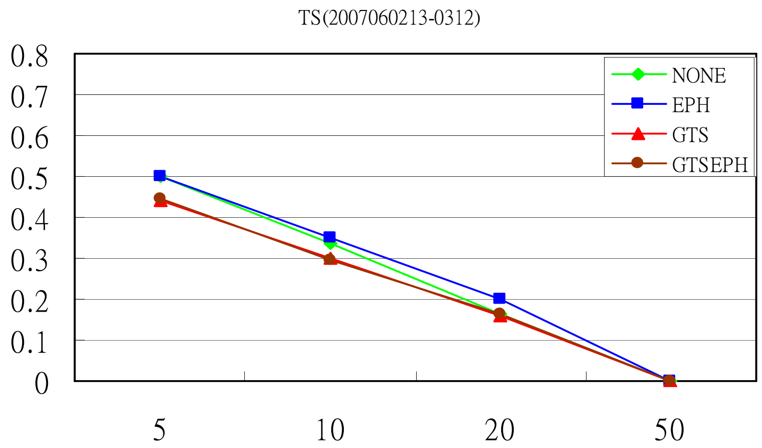
The GPS RO data give a remote impact on the Taiwan Mei-yu rainfall.

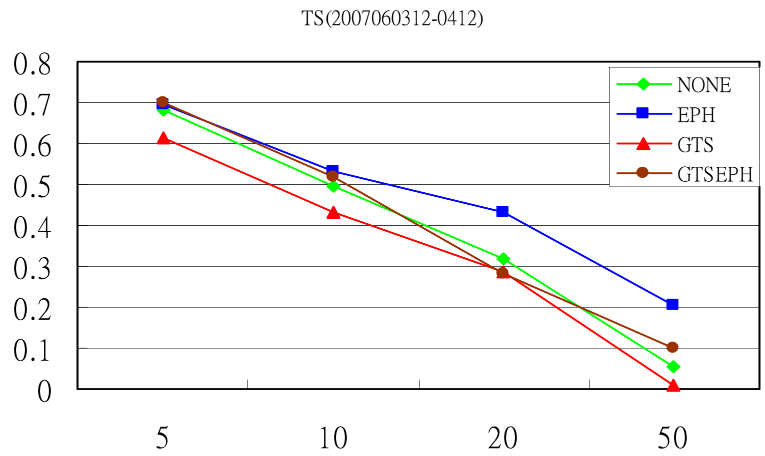
24h accumulated rainfall





Threat Score : Meiyu Front (Initial time: 2007-06-02-12:00)





Global Assimilation Methodology

- ECMWF assimilates the COSMIC GPSRO local bending angle data into the modeling system. Test result shown below is for the experiment period of 15 Dec 2006 to 28 Feb 2007.

- CWB assimilates the COSMIC GPSRO local refractivity data in the modeling system. Test result shown below is for the experiment period of 1 April to 30 April 2007.

$$\alpha(a) = -2a \int_a^{\infty} \frac{d \ln n / dx}{\left(x^2 - a^2\right)^{1/2}} dx$$

Anomaly Correlation Difference of H (GPS - NoGPS) over North Hemisphere

Healy (2008)

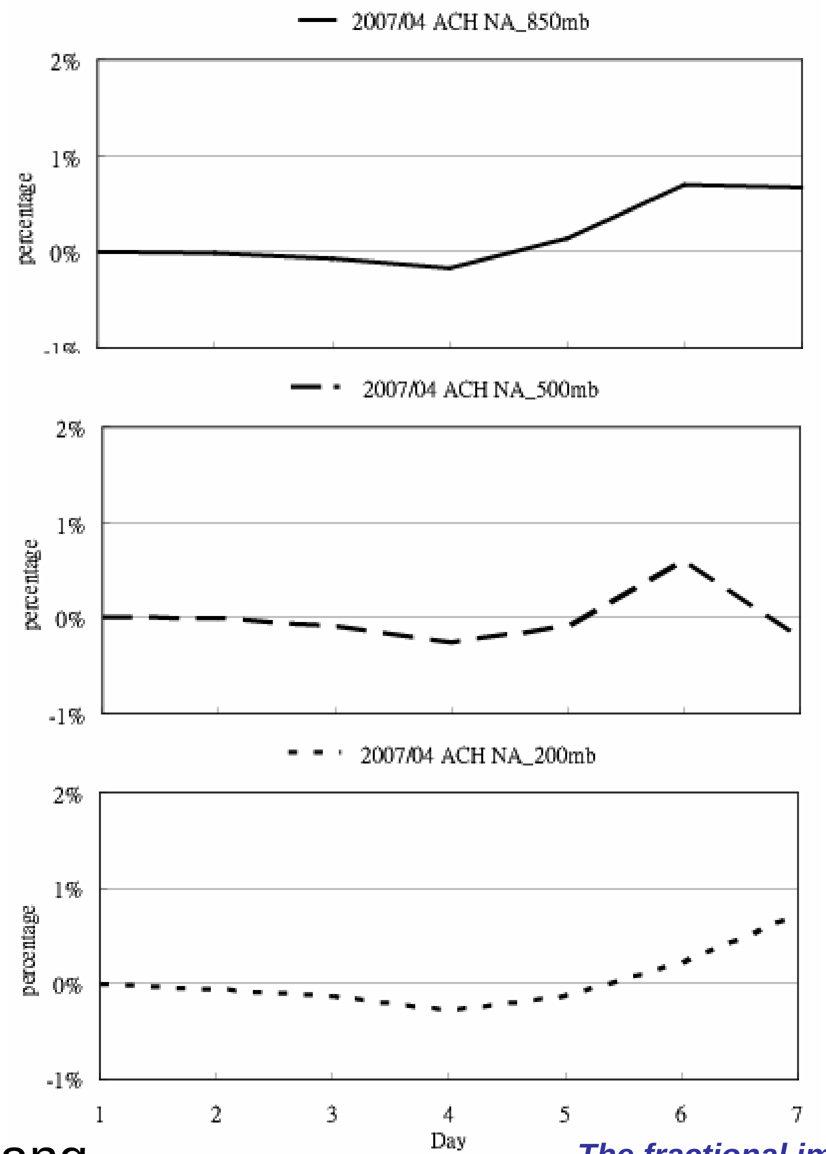
CWB result (2007/04)

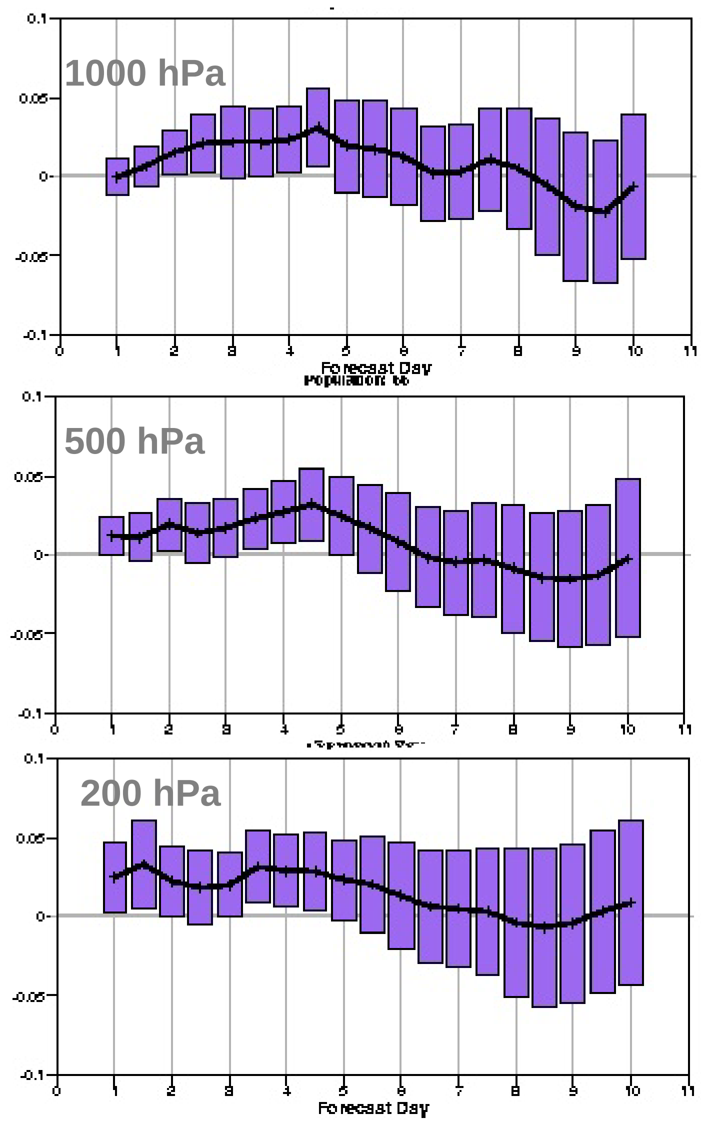
ECMWF result (2006/12~2007/02)

850 hPa

500 hPa

200 hPa





M.-J. Yang

The fractional improvement in RMS errors (RMSCTL -RMSCOS1)/RMSCTL)

Anomaly Correlation Difference of H (GPS - NoGPS) over South Hemisphere

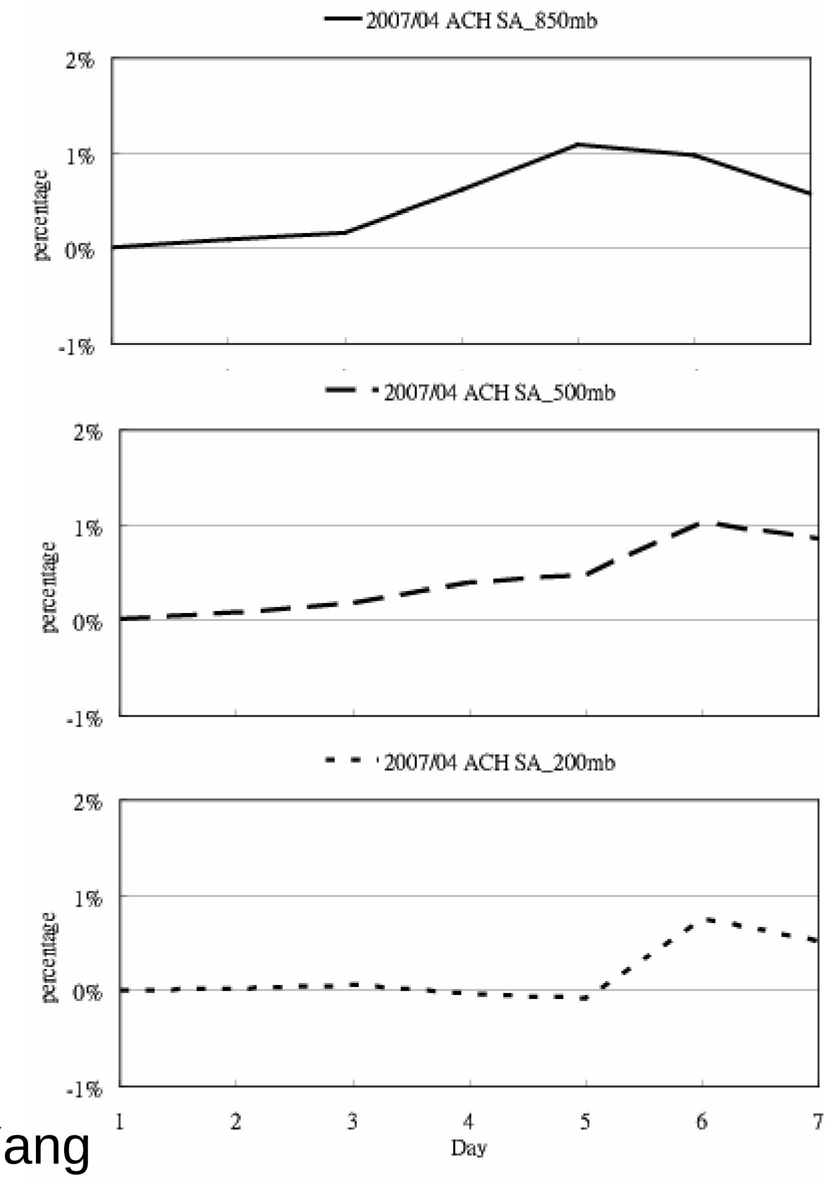
CWB result (2007/04)

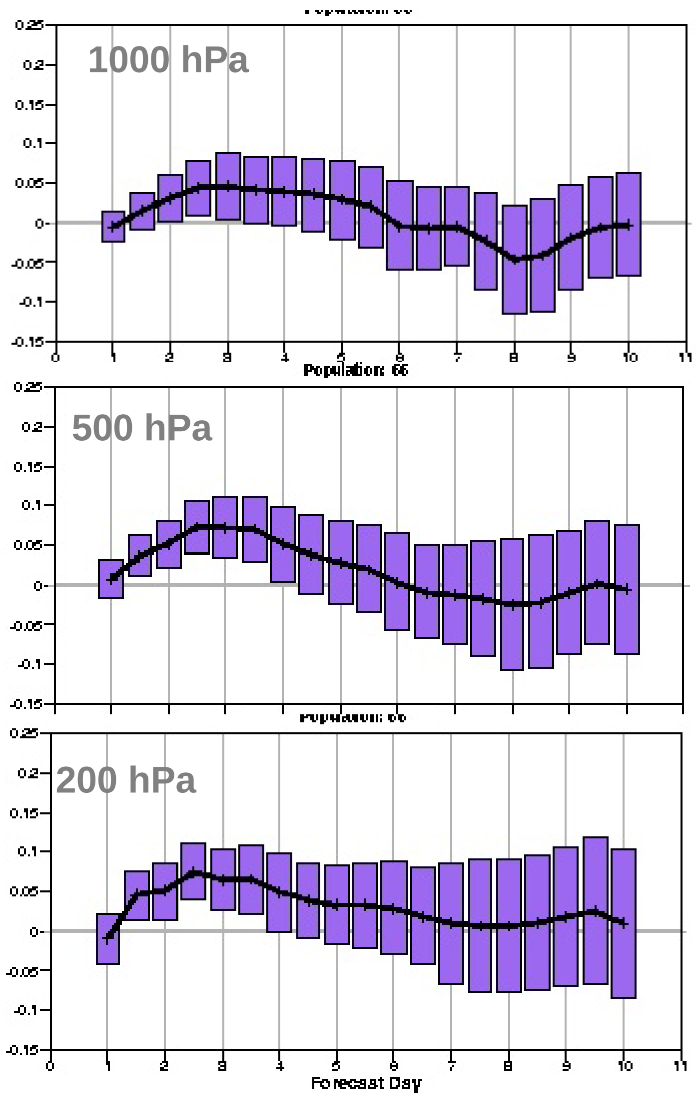
ECMWF result (2006/12~2007/02)

850 hPa

500 hPa

200 hPa



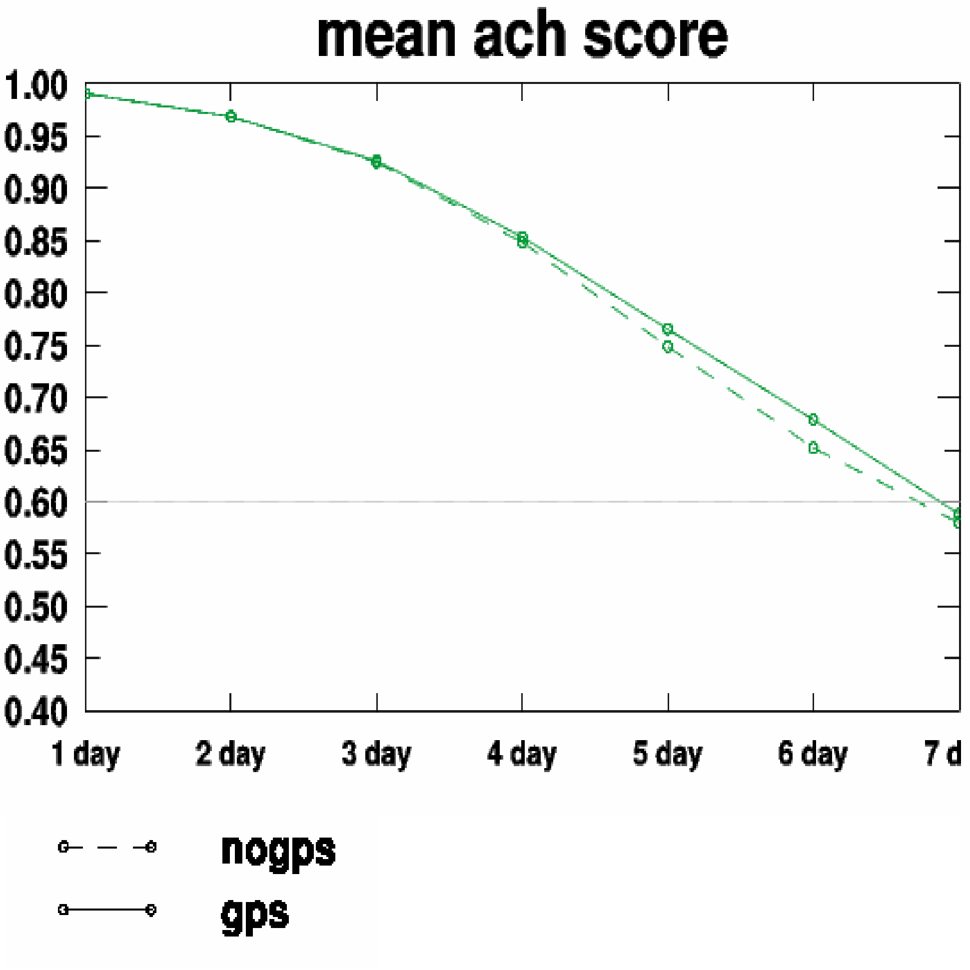


M.-J. Yang

Healy (2008)

Global assimilation of GPS/RO local refractivity

2006/10 500-hPa H over South Hemisphere



CWB (local refractivity)

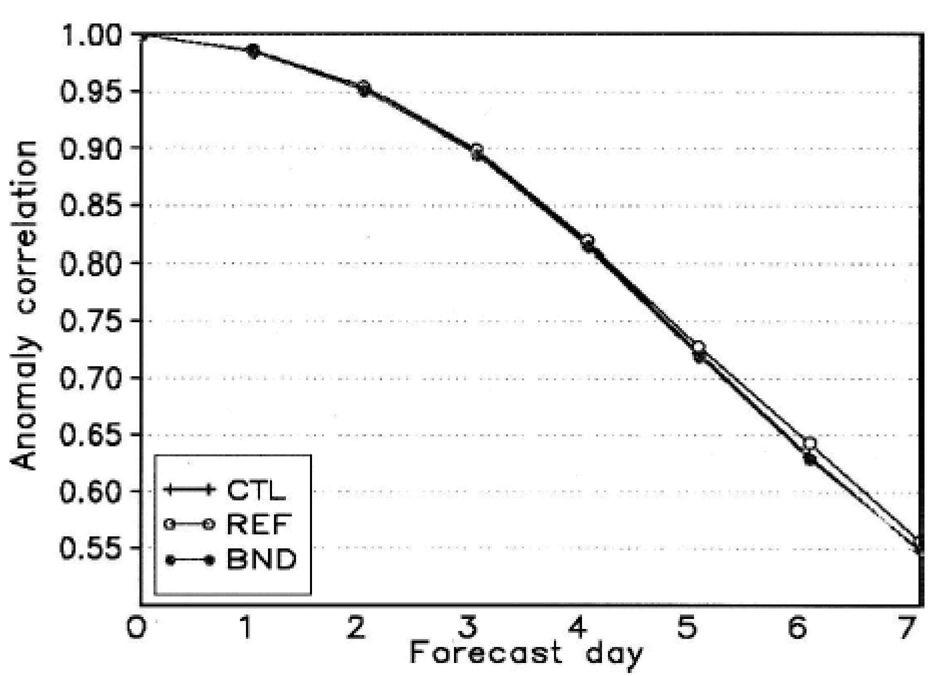
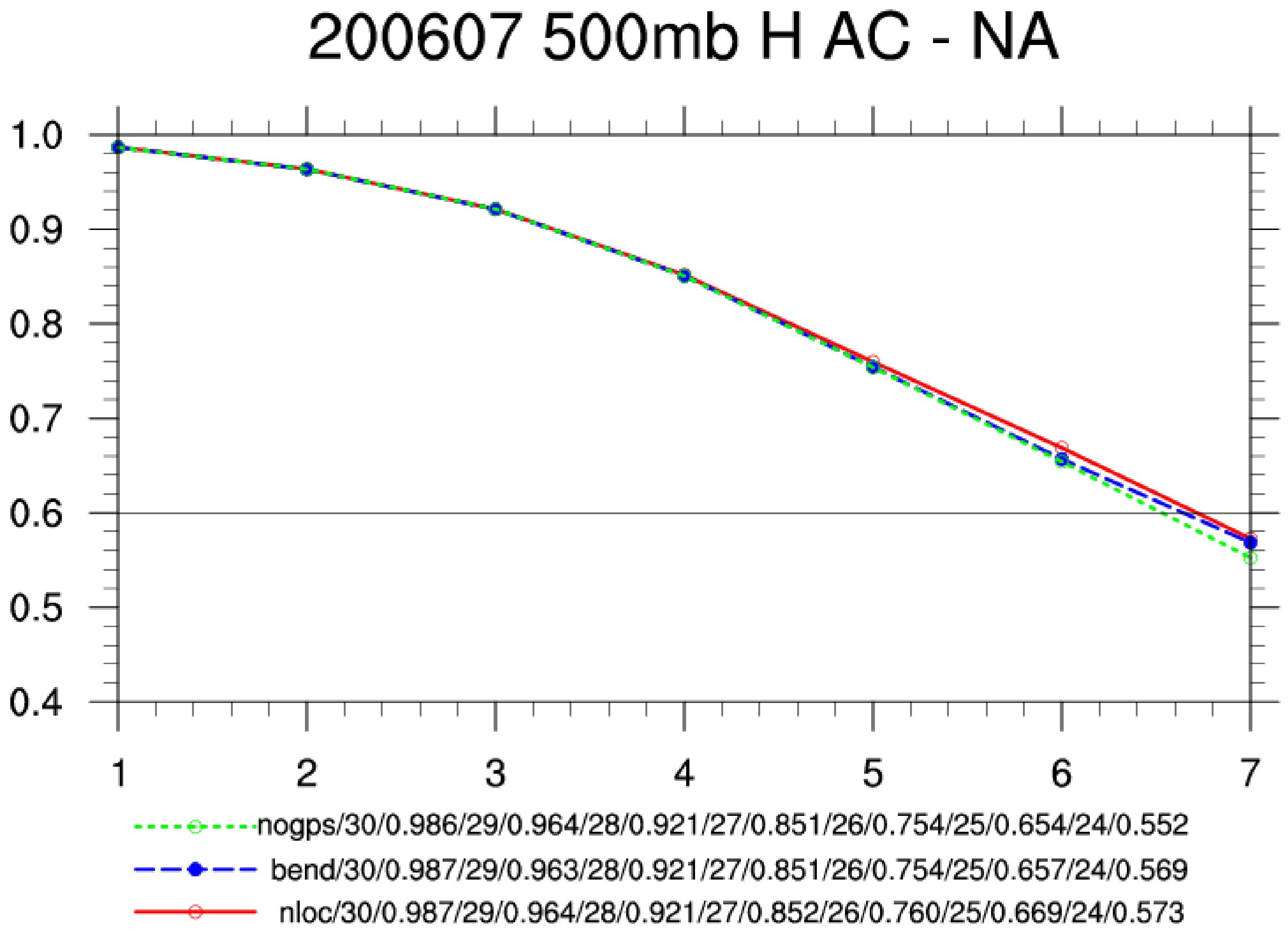


FIG. 17. Anomaly correlation scores for the 500-hPa geopotential heights in the Southern Hemisphere for CTL, REF, and BND, 0000 UTC 10 Jul–31 Aug 2005.

NCEP result
(Cucurull et al. 2007)

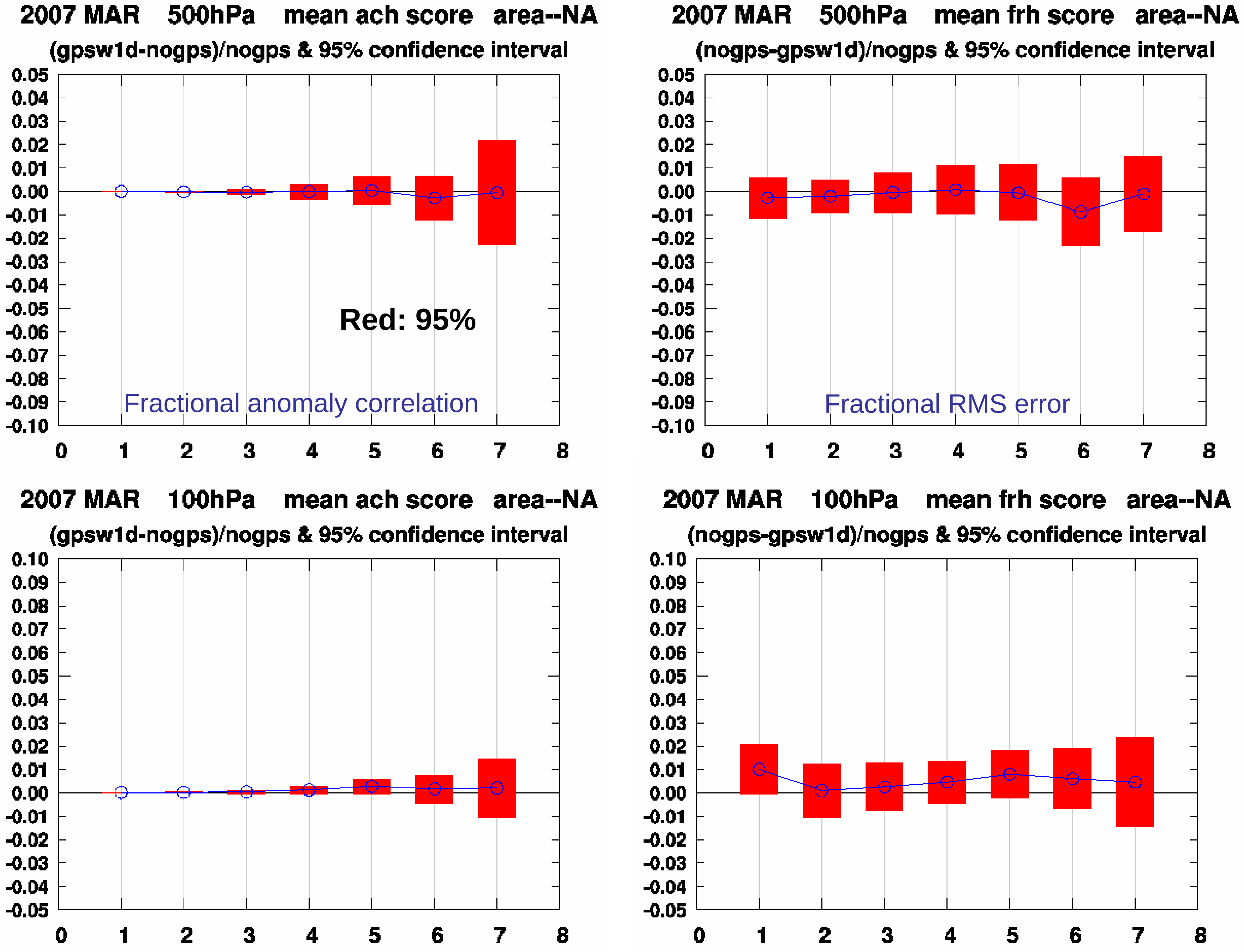
Global assimilation of GPS RO non-local refractivity

2006/07 500-hPa H over North Hemisphere

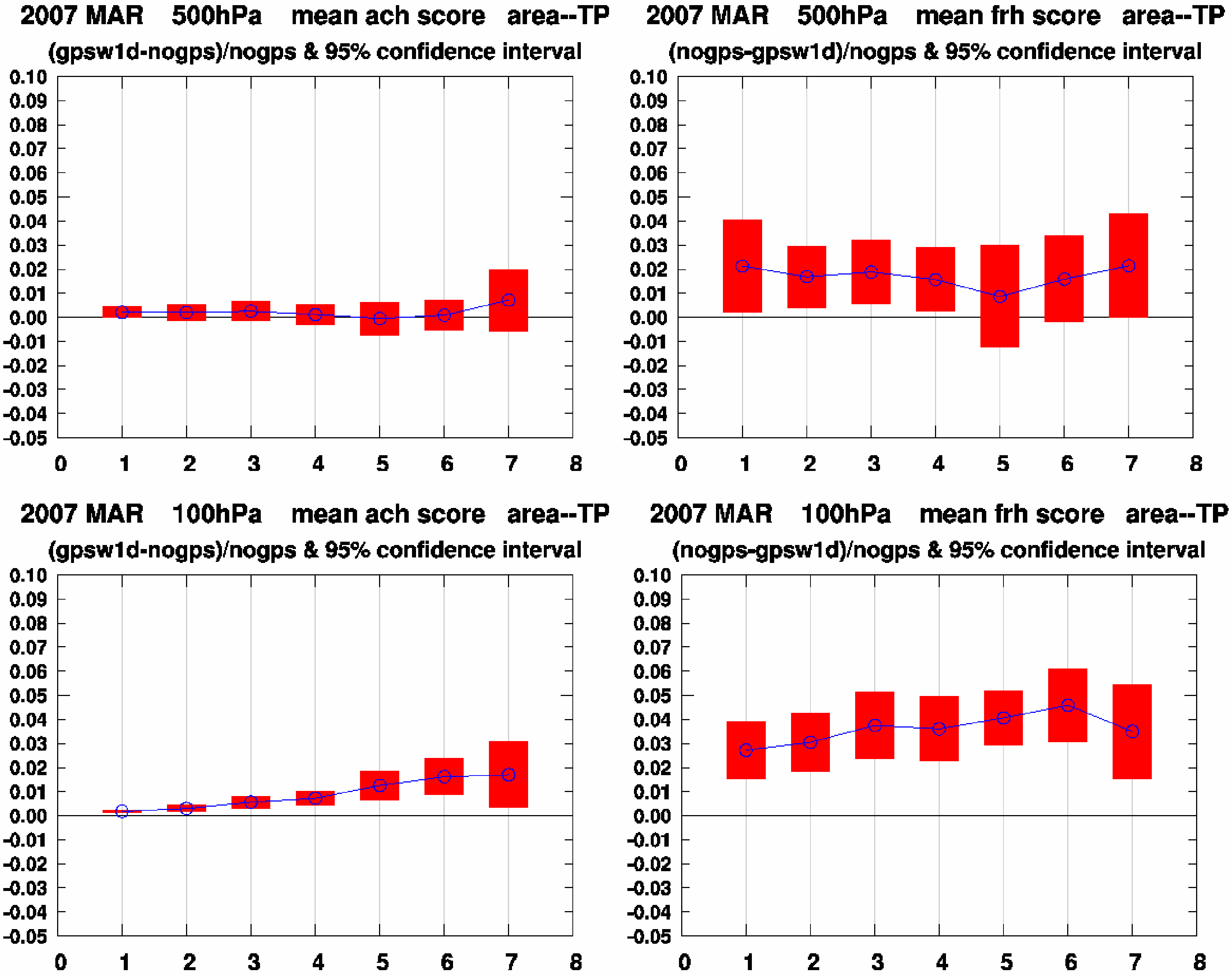


CWB (nonlocal refractivity)

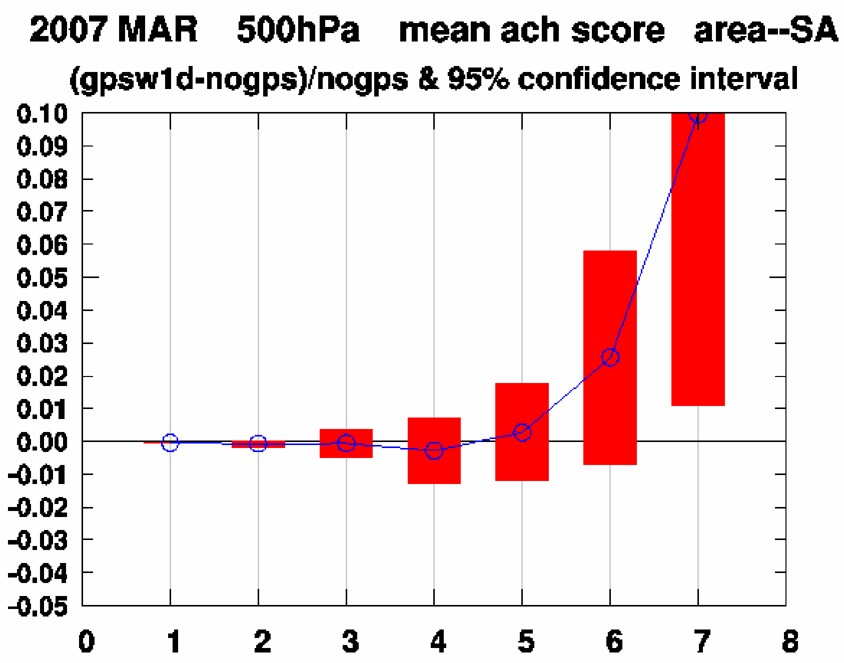
Geopotential height in N. Hemisphere (20-80N) from CWB global model



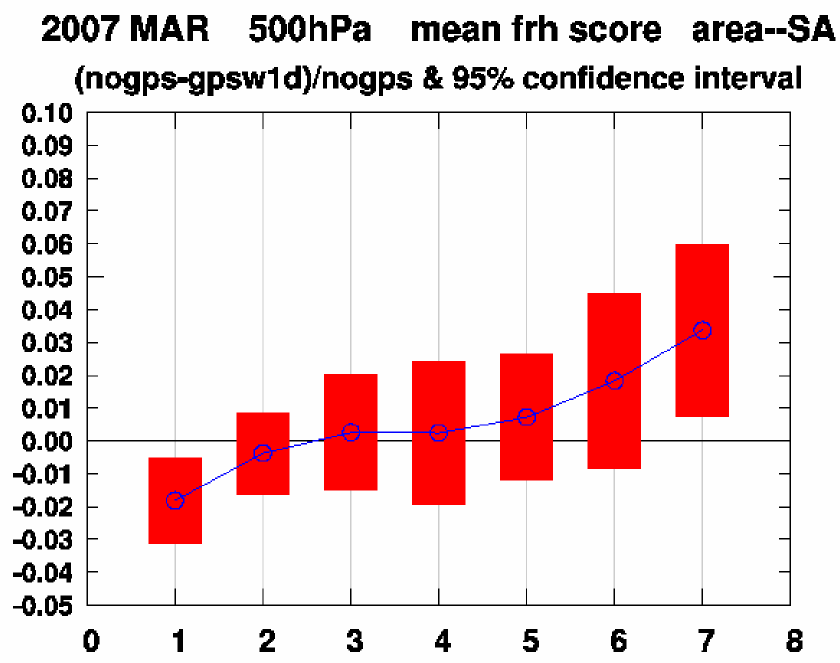
Geopotential height in the Tropics (20S-20N) from CWB global model



500 hPa height in S. Hemisphere (20-80S) from CWB global model



Fractional anomaly correlation



Fractional RMS error

100 hPa height in S. Hemisphere scores give a big jump on 7th day!

The degradation of ensuing forecasts appears to be lessoned due to continuous GPS RO data assimilation.

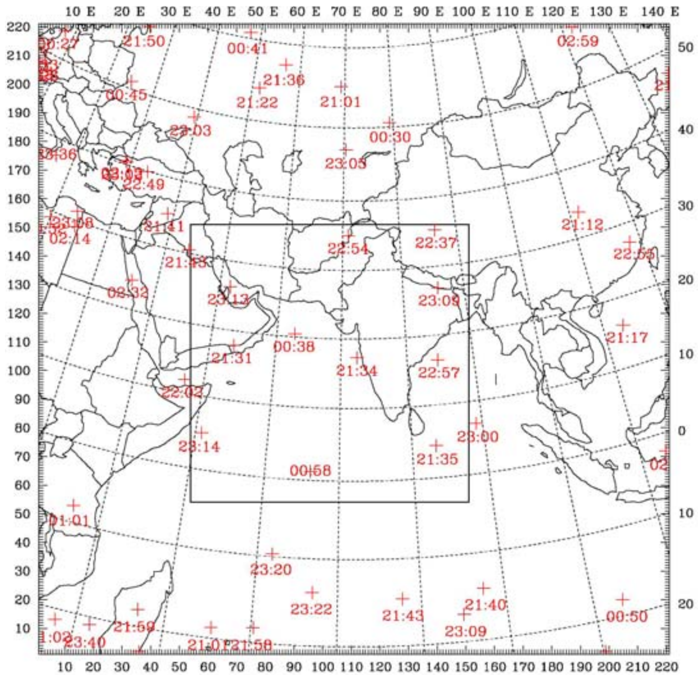
Conclusions from the Centers

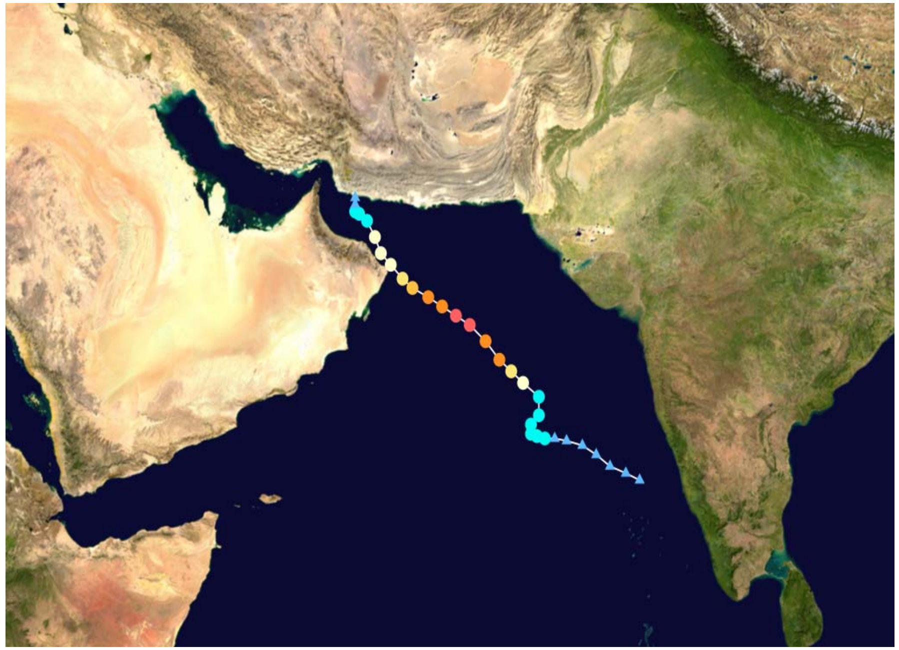
- ECMWF shows good improvement in the height scores in both the Northern and Southern Hemispheres, as well as good improvement in stratospheric temperature scores, for a longer performance time.

- CWB shows significantly better forecasting of the height field in the Southern Hemisphere, and slightly better forecasting of height field in the Northern Hemisphere for a limited time.

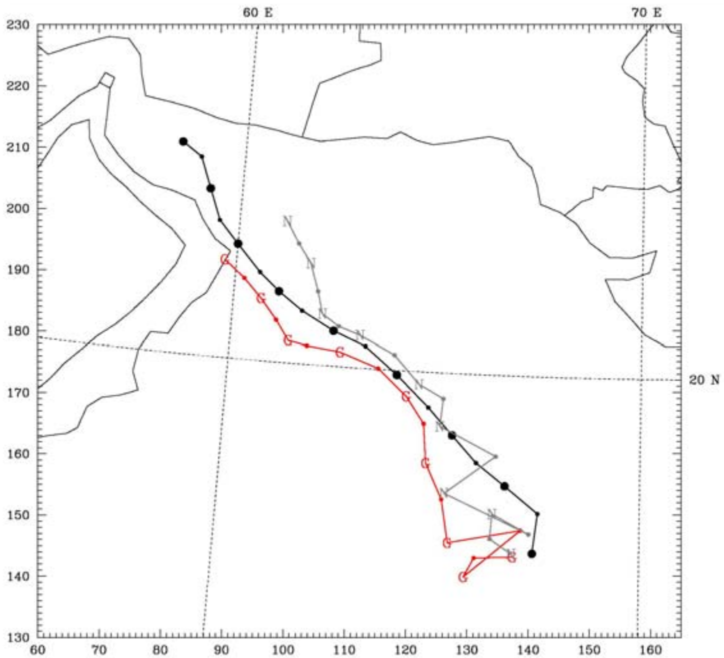
The impact of FORMOSAT-3/COSMIC data on other recent cyclone predictions

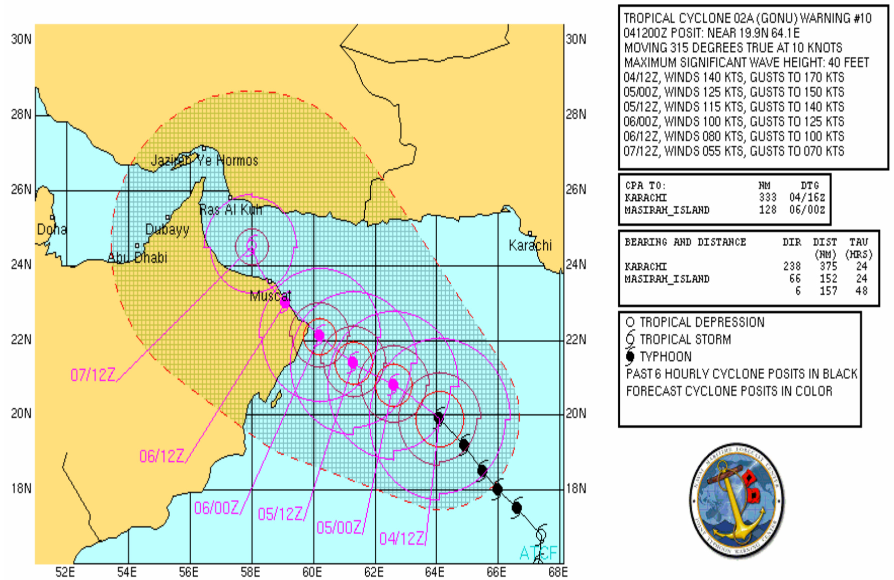
a





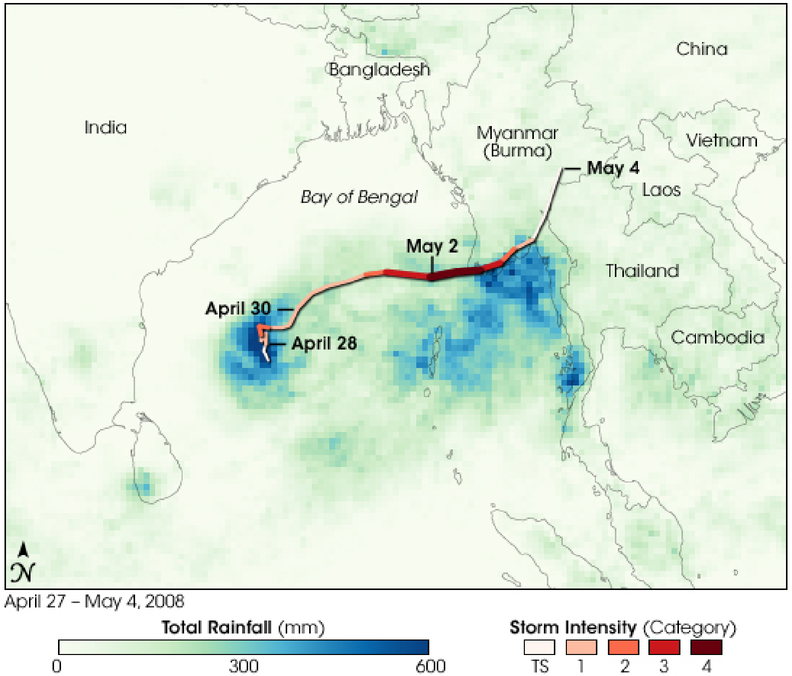
b





Gonu Cyclone: 03 June 2007. (56 GPS RO)

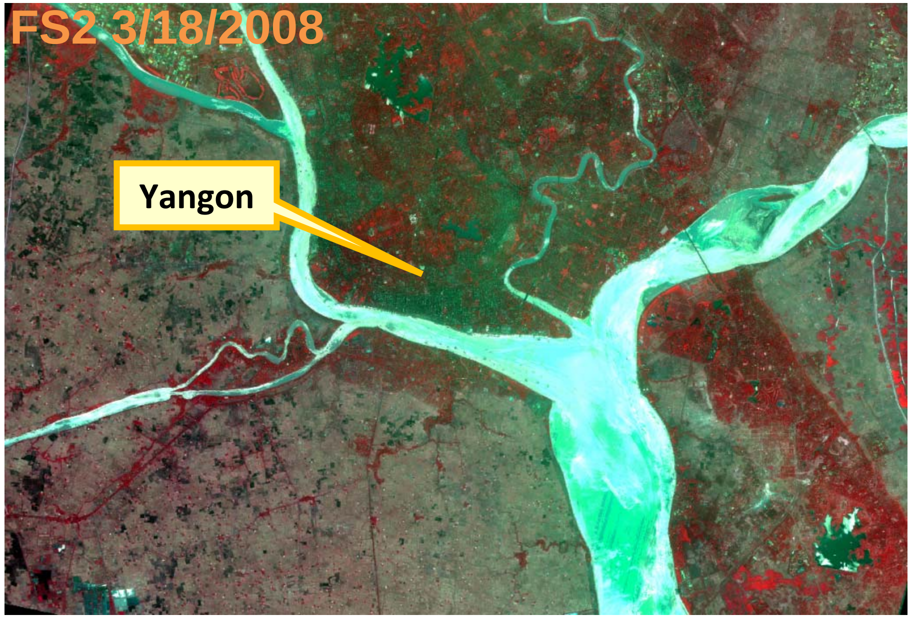
Myanmar Cyclone Nargis (2008)



Rainfall accumulations along Cyclone Nargis
by Tropical Rainfall Measuring Mission (TRMM) satellite
(http://earthobservatory.nasa.gov)

Flood area caused by Cyclone Nargis
Analyzed form MODIS data by UNOSAT
(http://services.google.com/earth/kmz/nargis_n.kmz)

A perfect cyclone!

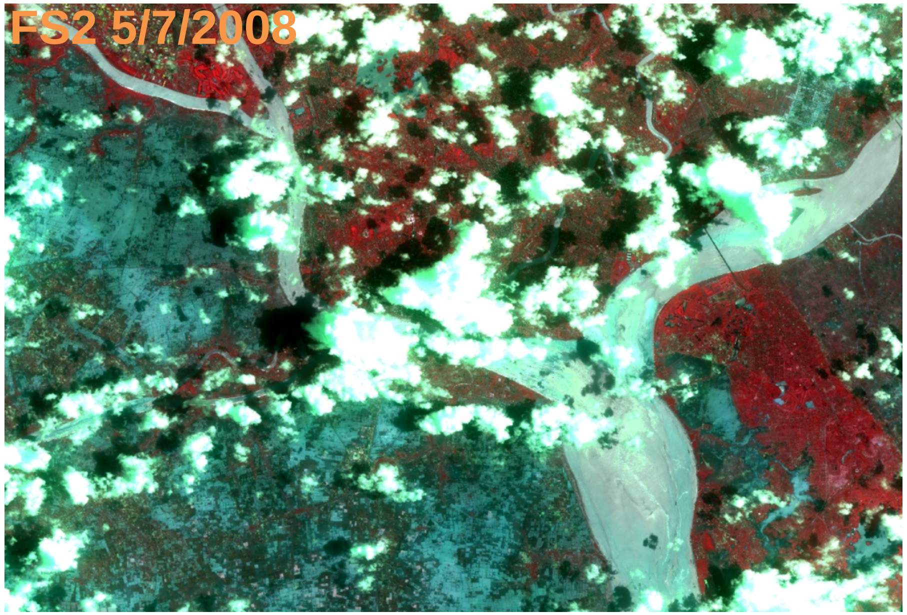


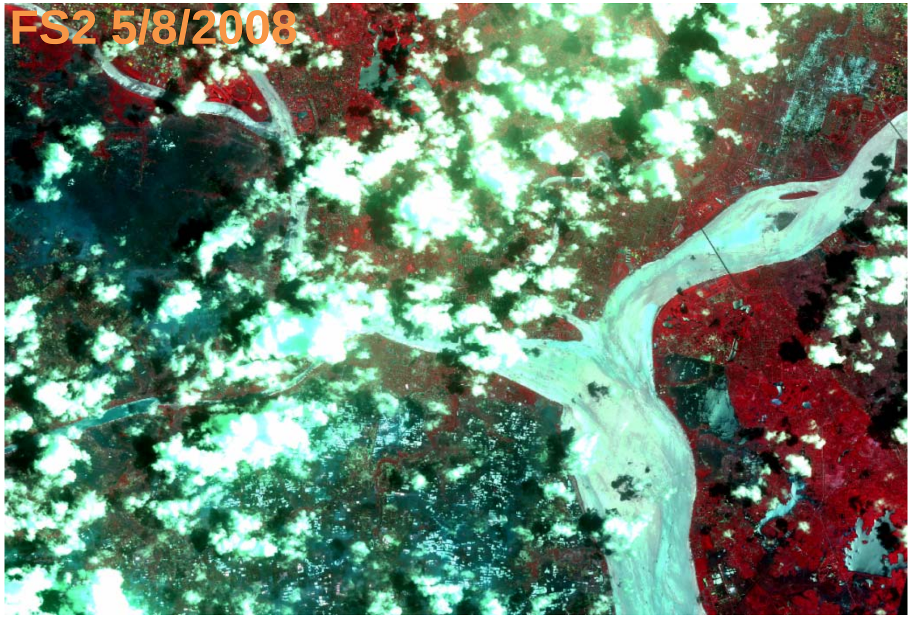
Myanmar Cyclone Nargis

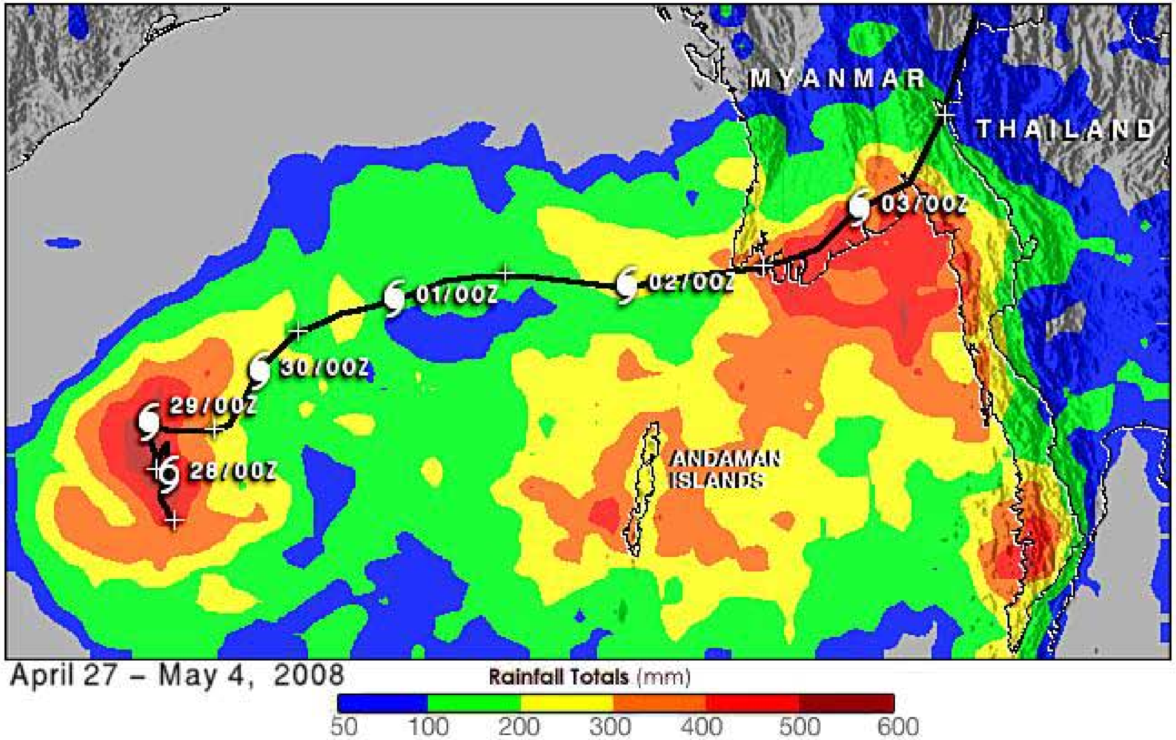
FORMOSAT-2 Image

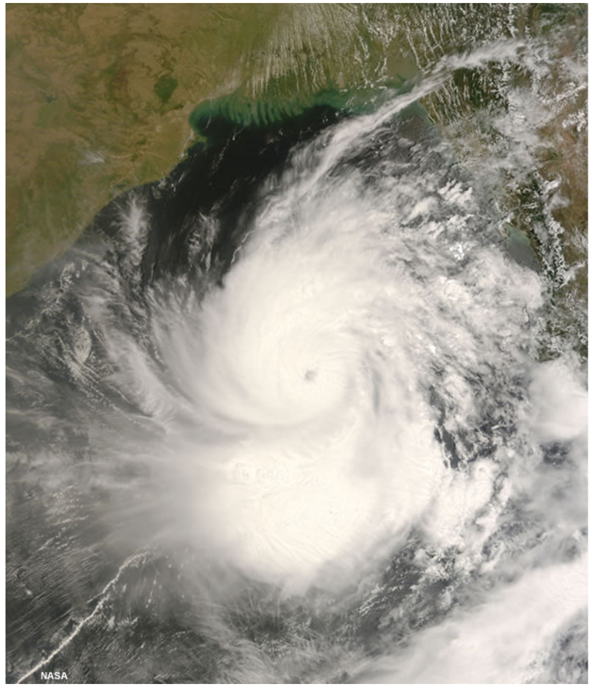
3/18/2008: Yangon farm before flood
5/7/2008: severe flood
5/8/2008 : subsiding flood

(From: CSRSR, NCU, Taiwan)

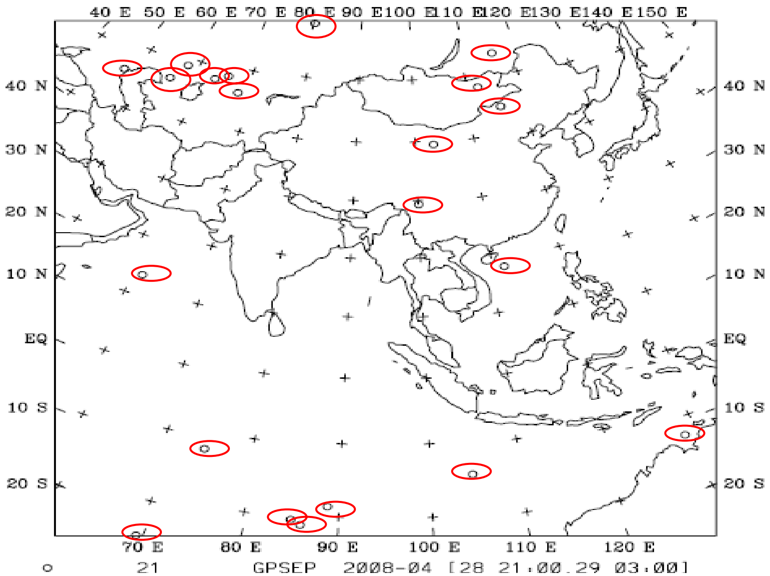






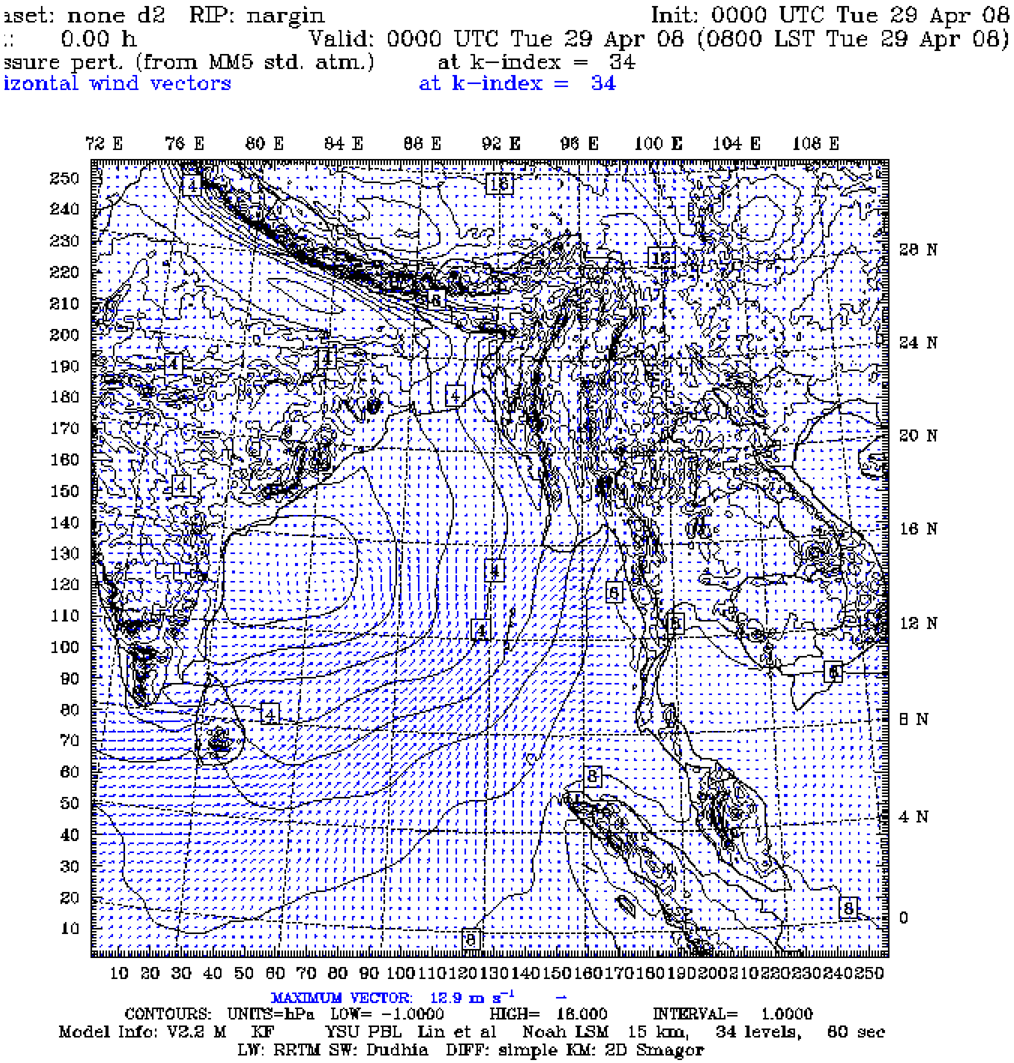


TRMM-based, near-real time Multi-satellite Precipitation Analysis (MPA) rainfall totals from April 27 to May 4, 2008. (From NOAA)

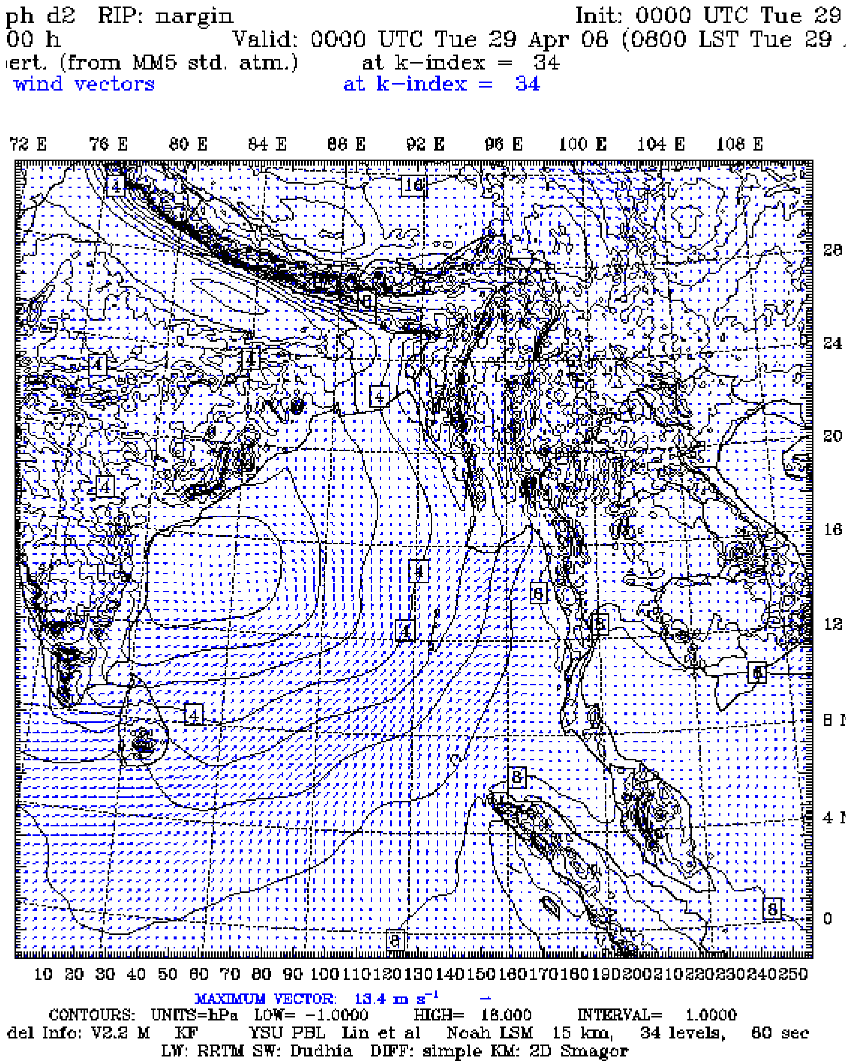


Typhoon Nargis (Initial time: 2008-04-29-00:00)

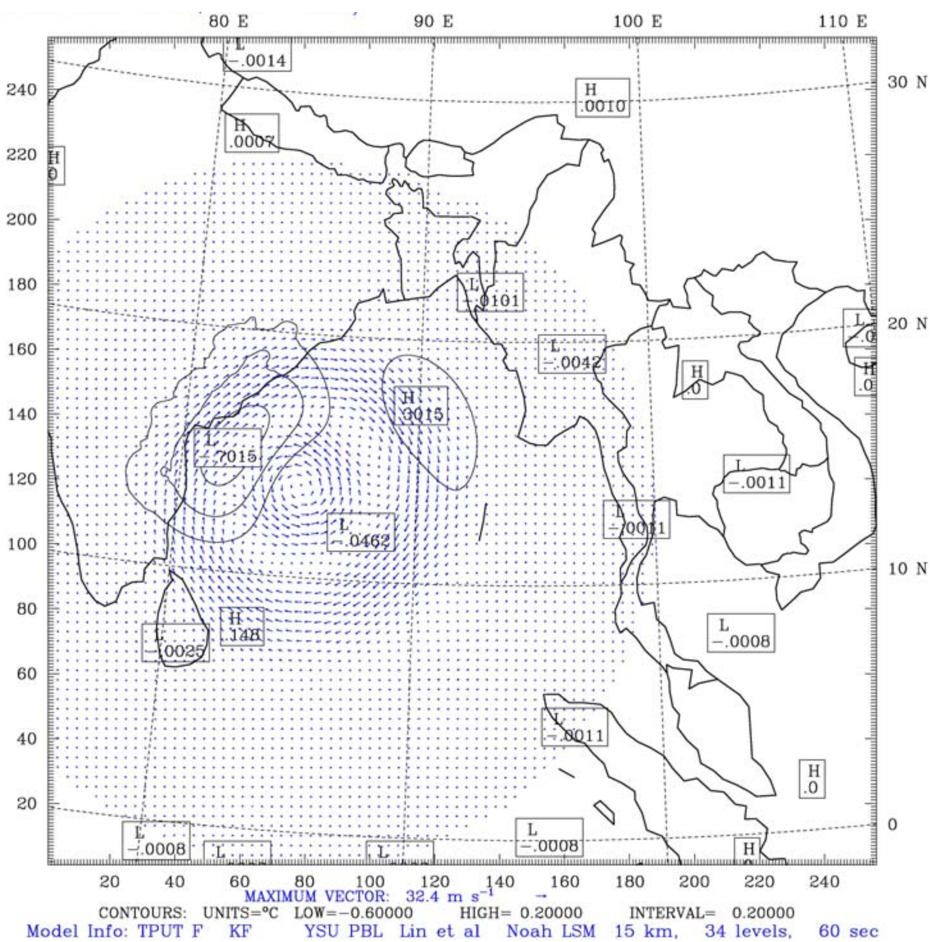
NONE (pressure perturbation and wind vector)



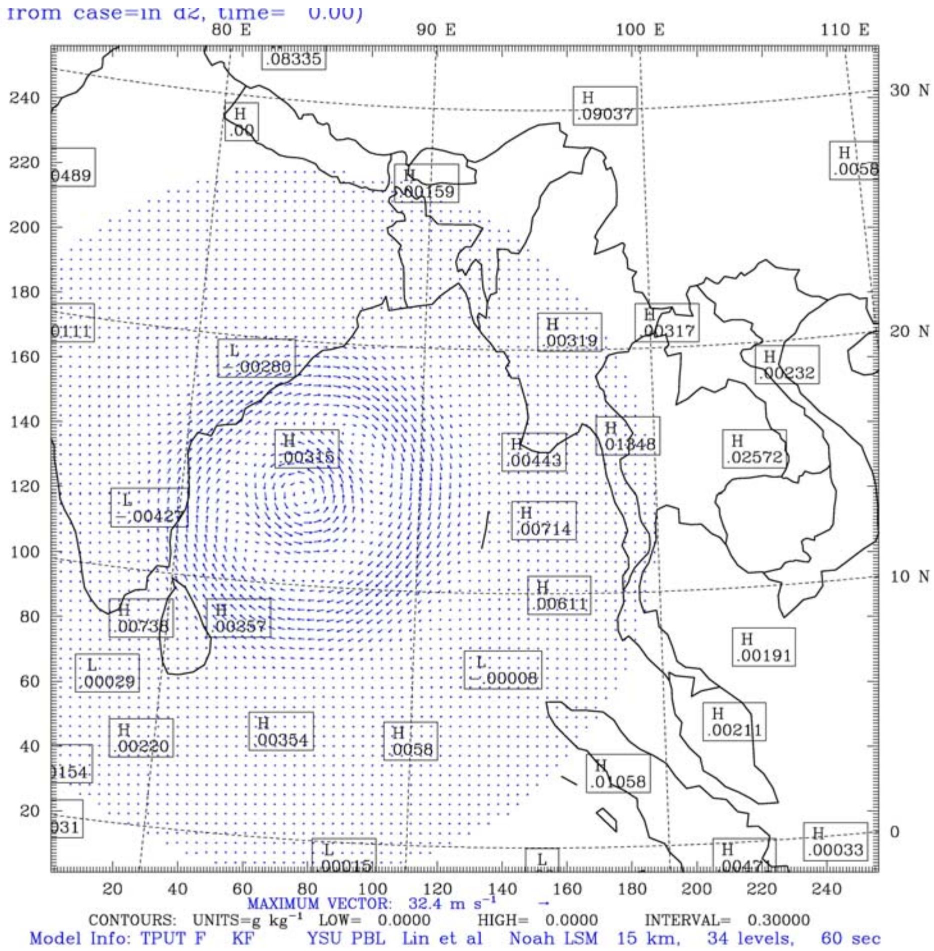
EPH (pressure perturbation and wind vector)



Initial increments of temperature and moisture and wind vector at 2km (BG)



Temperature, contour interval=0.2 ℃ 。

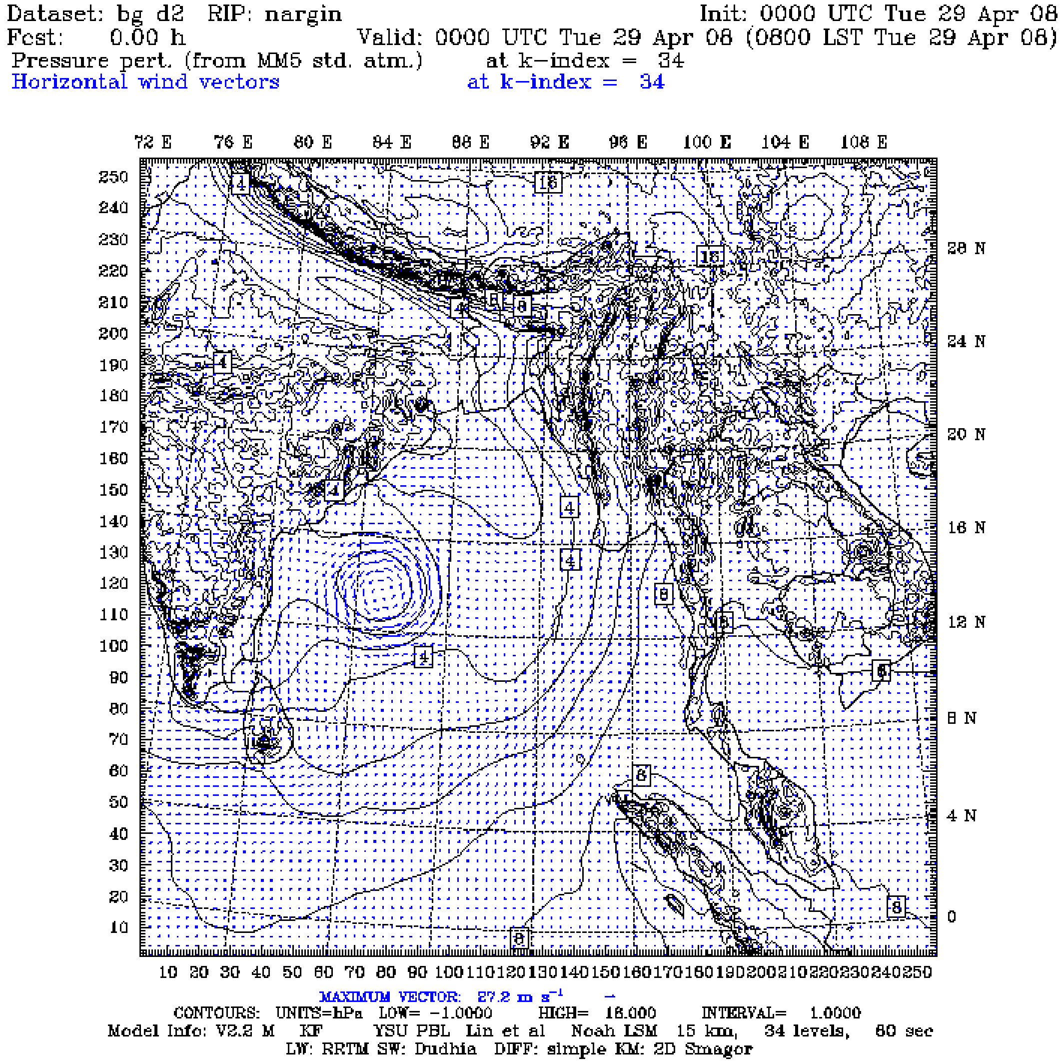


Moisture, contour interval=0.3 g kg^{-1}

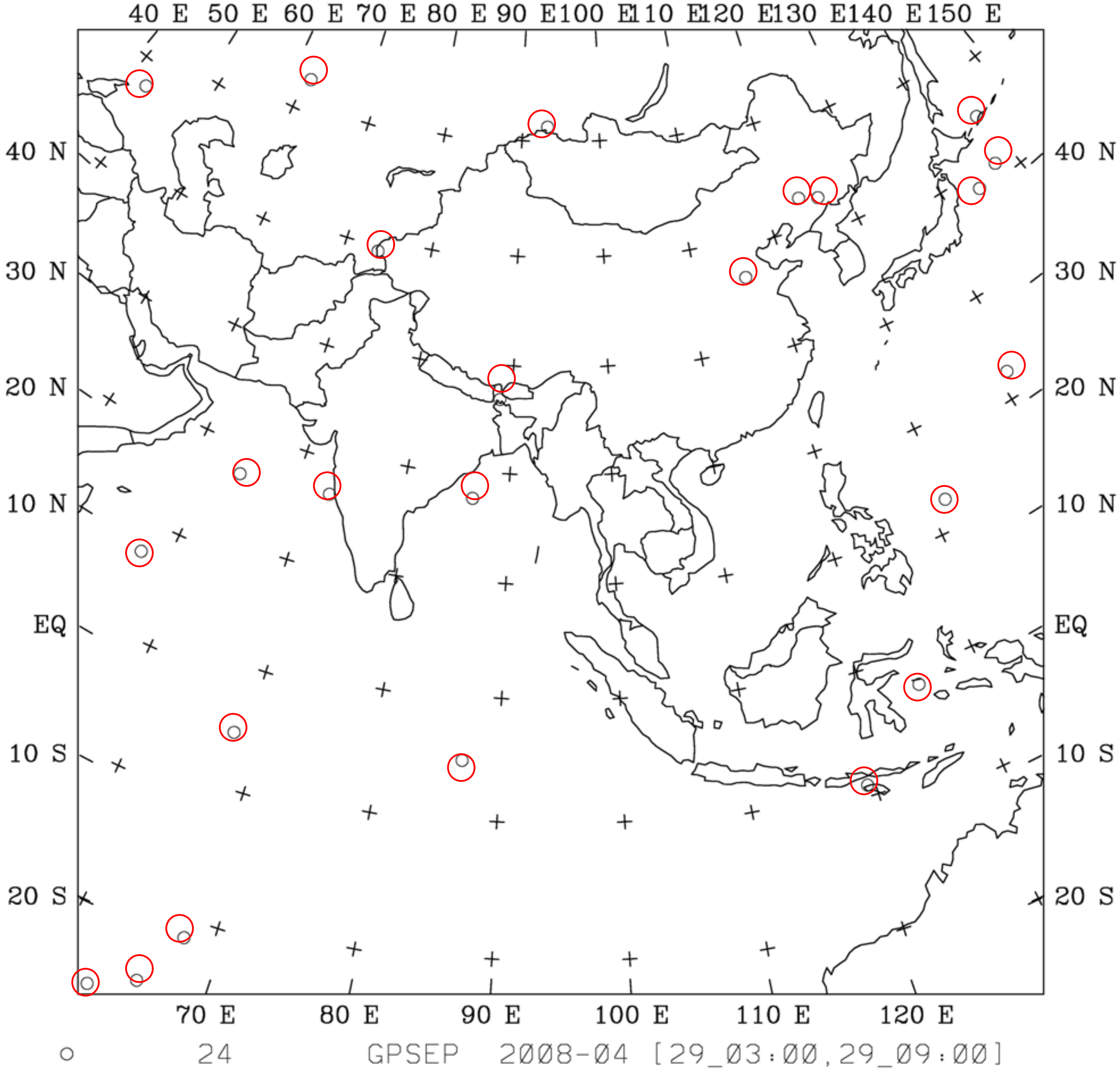
BG : assimilating a bogus Rankine vortex (P_{min}= 975 mb) at 0000 UTC 29 April 2008

Typhoon Nargis (Initial time: 2008-04-29-00:00)

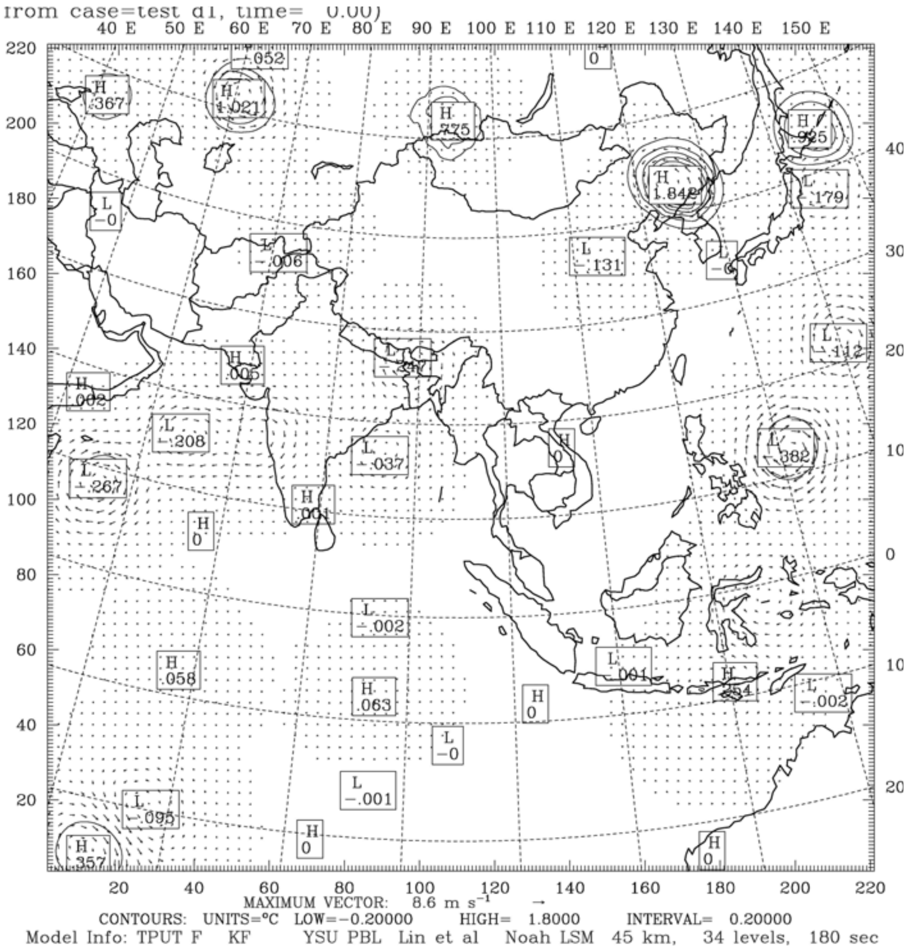
Bogus-vortex run (BG)



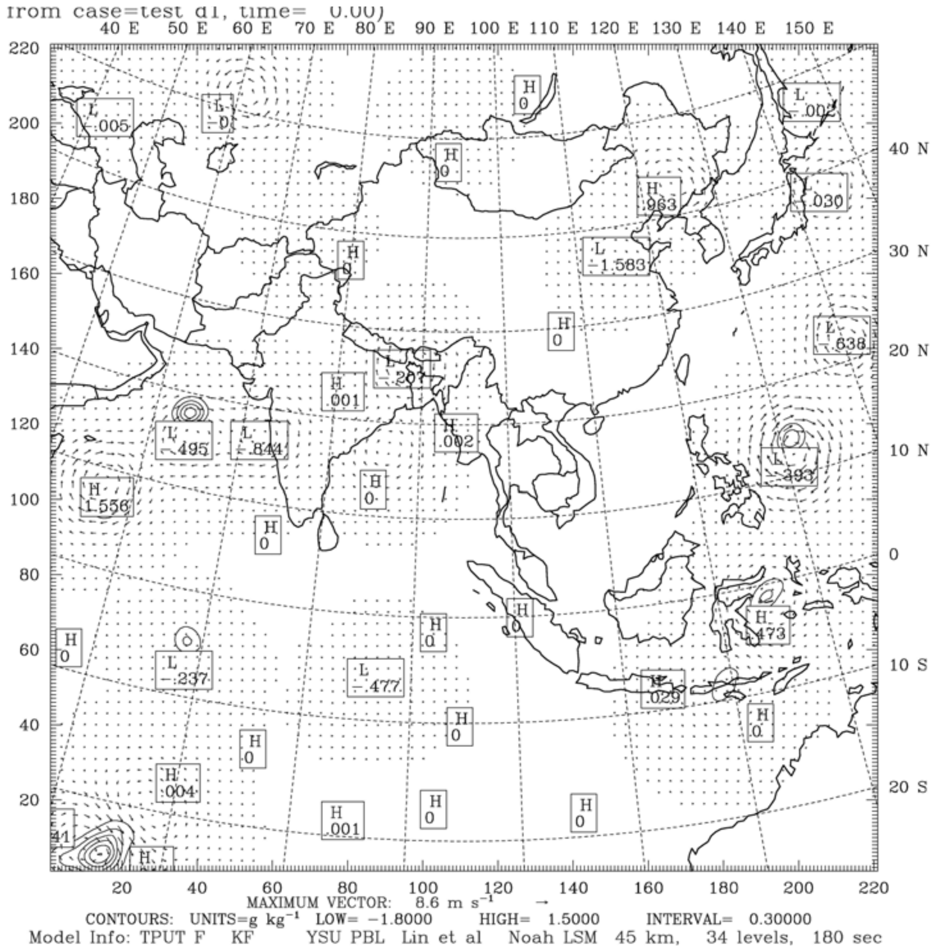
GPS RO points (Initial time: 2008-04-29-06)



Initial increments of temperature and moisture and wind vector at 2km (CYCLING)— 24 GPS RO



Temperature, contour interval=0.2 ℃ 。

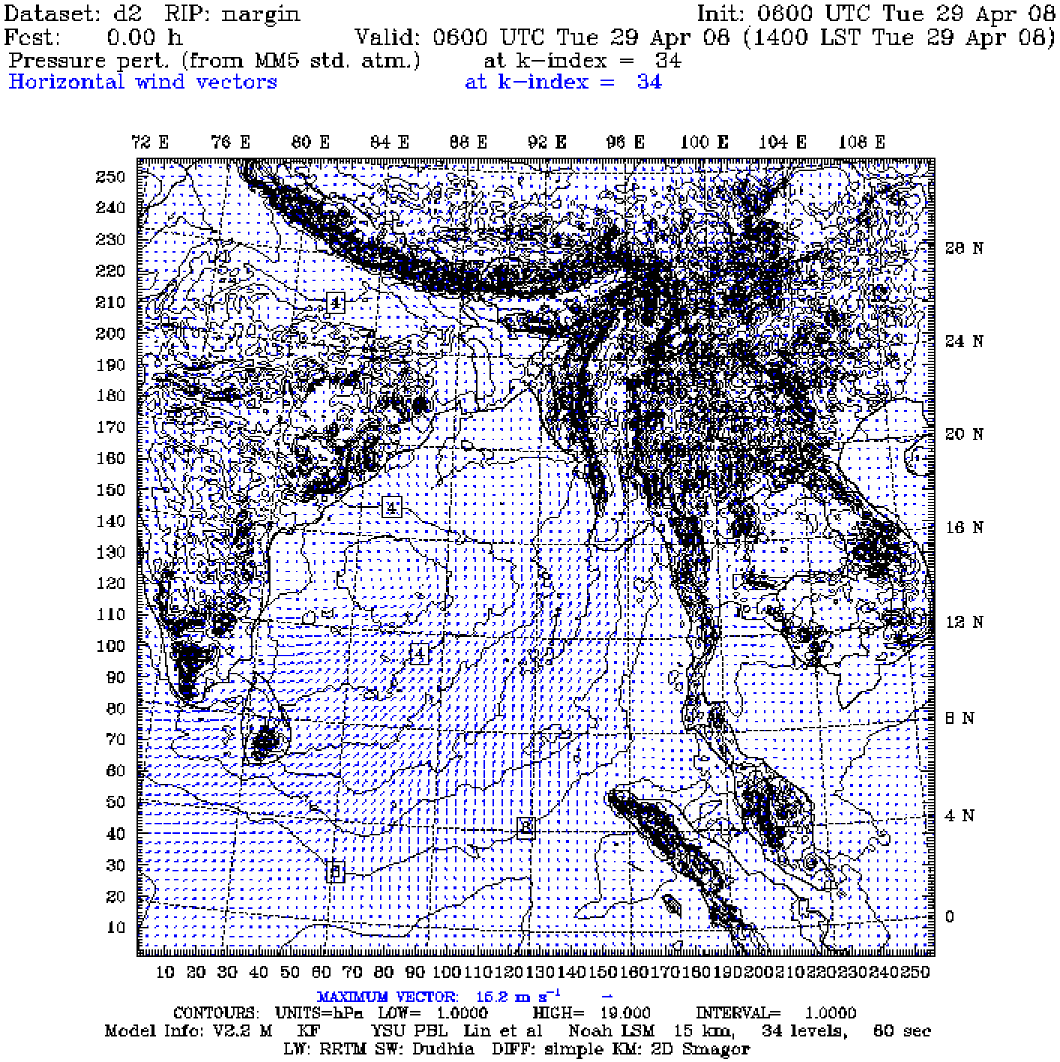


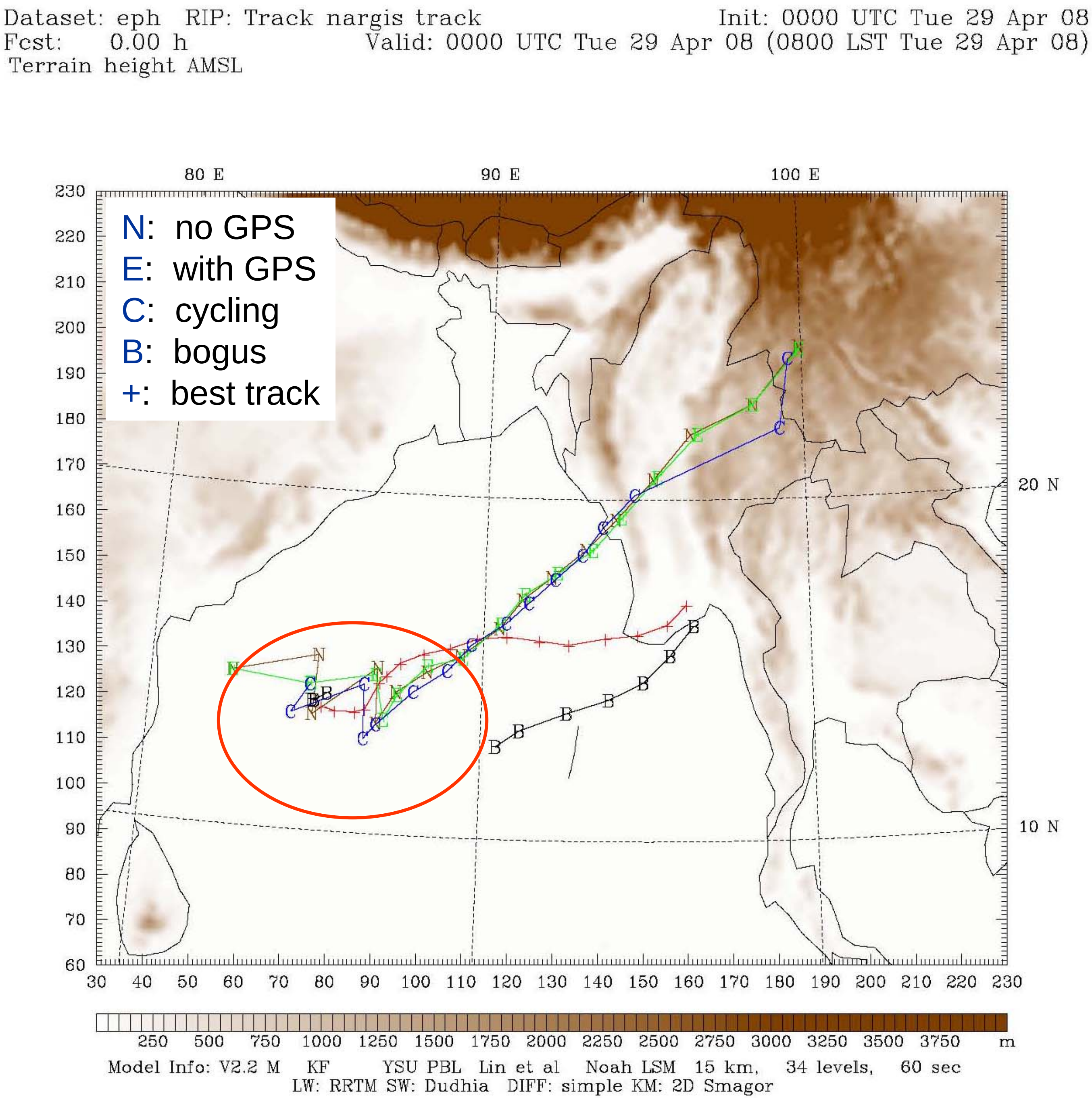
Moisture, contour interval=0.3 g kg^{-1}

- CYCLING : as EPH but with cycling GPS data at 2008/04/29/06UTC .

Typhoon Nargis (Initial time: 2008-04-29-06:00)

CYCLING (pressure perturbation and wind vector)




Dataset: eph RIP: Track nargis track
Init: 0000 UTC Tue 29 Apr 08
Fcst: 0.00 h
Valid: 0000 UTC Tue 29 Apr 08 (0800 LST Tue 29 Apr 08)
Terrain height AMSL
80 E
90 E
100 E
20 N
10 N
N: no GPS
E: with GPS
C: cycling
B: bogus
+: best track
250 500 750 1000 1250 1500 1750 2000 2250 2500 2750 3000 3250 3500 3750 m
Model Info: V2.2 M KF YSU PBL Lin et al Noah LSM 15 km, 34 levels, 60 sec
LW: RRTM SW: Dudhia DIFF: simple KM: 2D Smagor

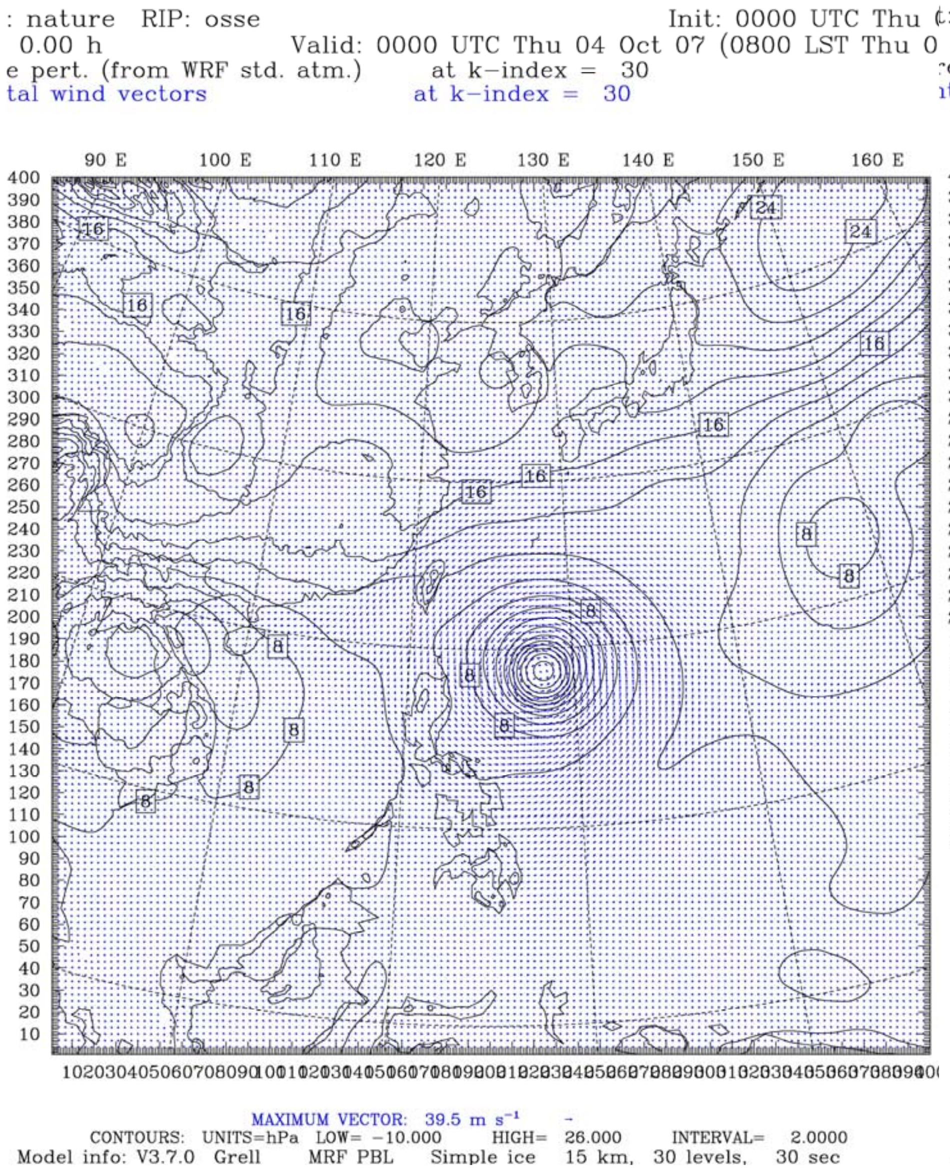
An OSSE Study for Typhoon Krosa

- Perform 96-h MM5 simulation (400x400, 15 km resolution) with an initial Rankine vortex at 0400 Oct. 2007, served as the nature run.
- Retrieve RO soundings by running a ray-tracing model with the input of the nature run to obtain bending angles (assuming uniform 45^o azimuthal angle) and the converted RO refractivity in the region of the typhoon vortex circulation at 0412 Oct. 2007.
- Perform a linear filter to smooth the nature run at 0412 Oct. 2007 to provide the control run (as the first guess at coarser resolution)
- Perform WRF 3DVAR to assimilate the RO refractivity soundings using the nonlocal operator and local operators at 041200 Oct. 2007.
- Compare the assimilation runs and non-assimilation run with the nature run.

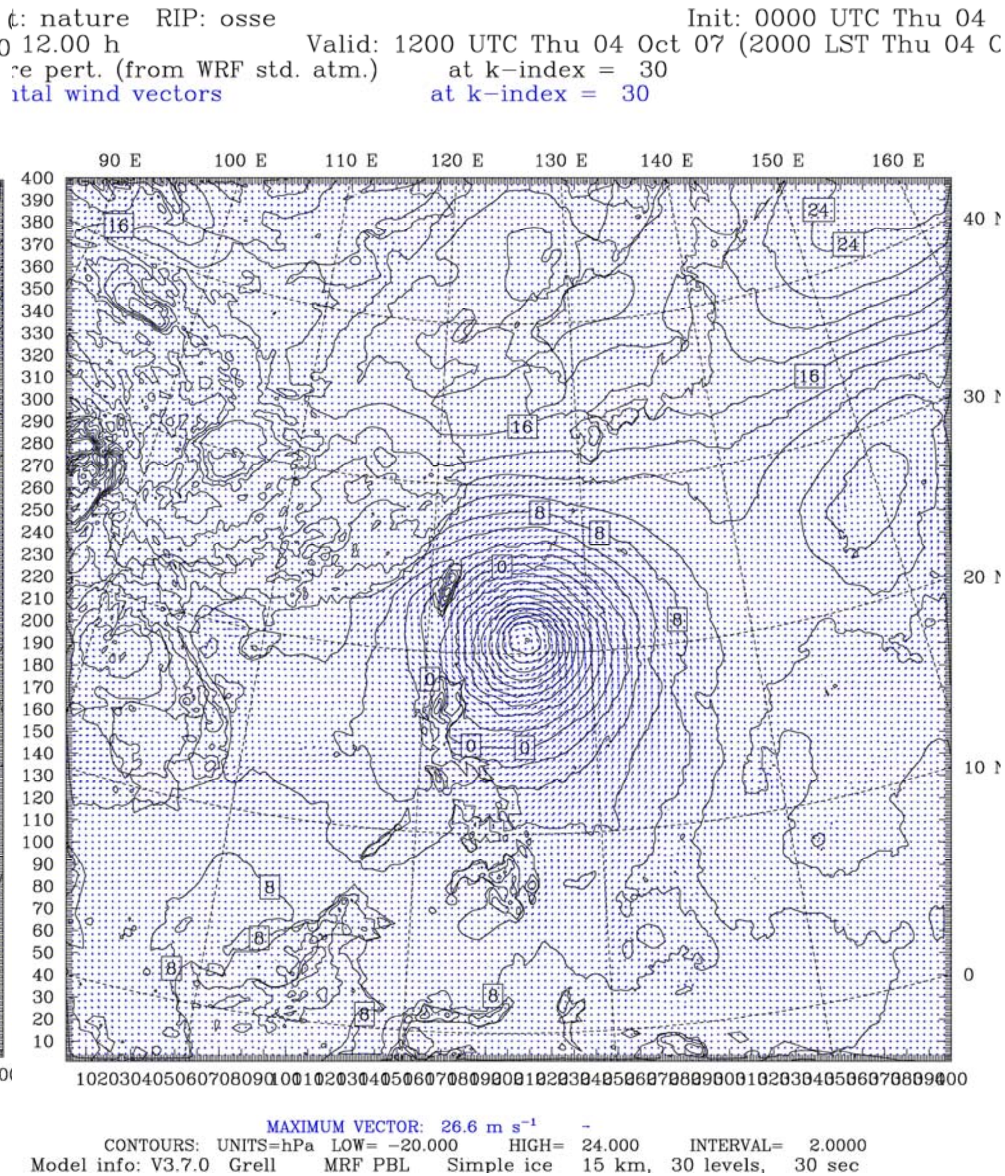
Krosa OSSE runs

Experiments	Remarks
NTL	MM5 initialization with AVN analysis at 2007100400UTC at 15-km resolution Nature with a Rankine vortex at R_{max} of 200 km and V_{max} of 46 m s^{-1}.
CTL	Degraded NTL by smoothing 100 times the model prediction at 2007100412UTC using a 1-2-1 linear filter.
REF	As CTL but assimilating nonlocal REF (as retrieved*) in the vortex (30-km resolution) using the localized nonlocal operator
EPH	As CTL but assimilating EPH (path nonlocal REF) in the typhoon vortex (30-km resolution) using the nonlocal operator
LOC	As CTL but assimilating local REF in the vortex (30-km resolution) using the localized nonlocal operator

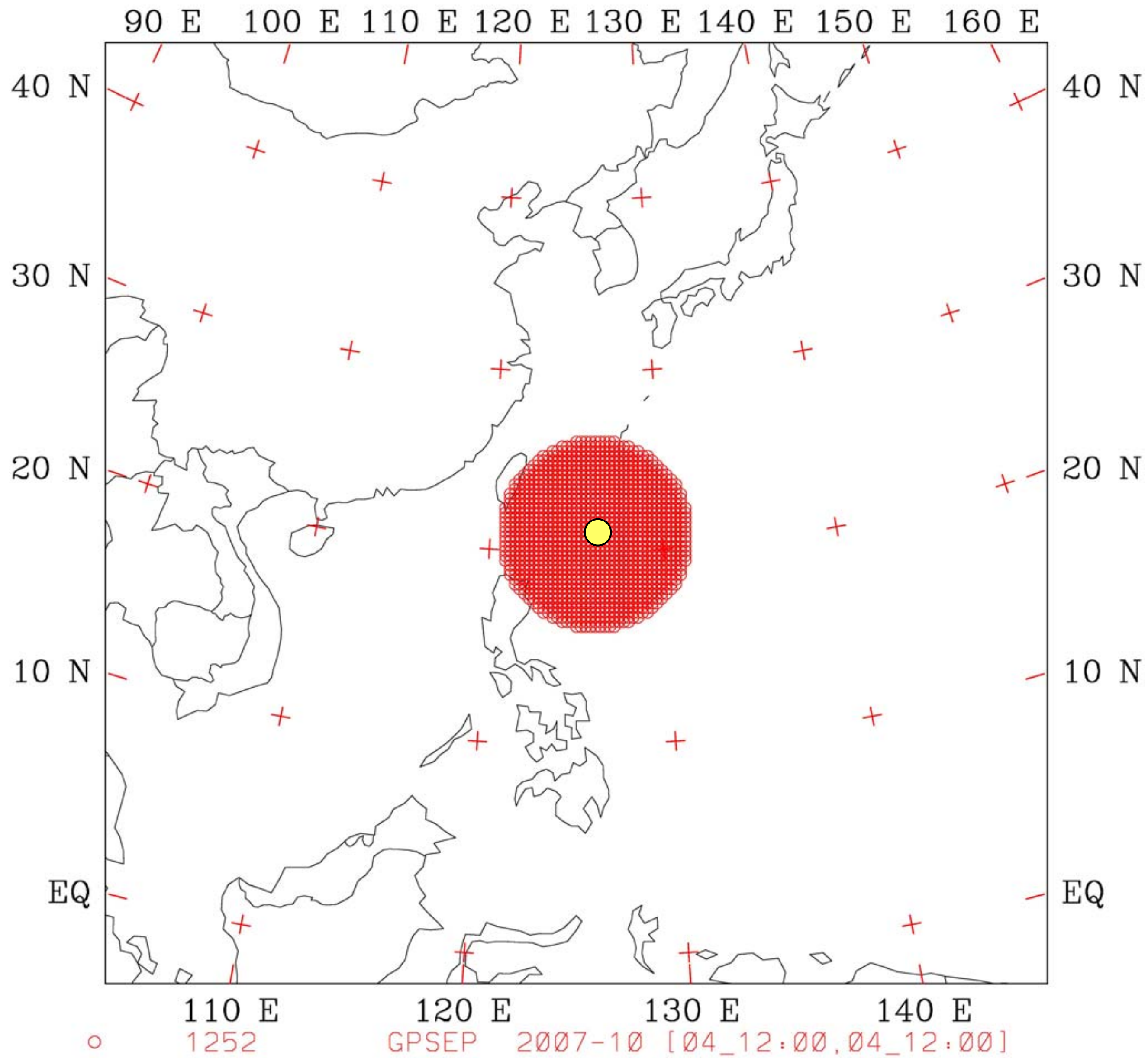
***The retrieved soundings are located within the typhoon vortex circulation at 30-km horizontal resolution, with a total of 1252 points assimilated.**



Nature run at 0400

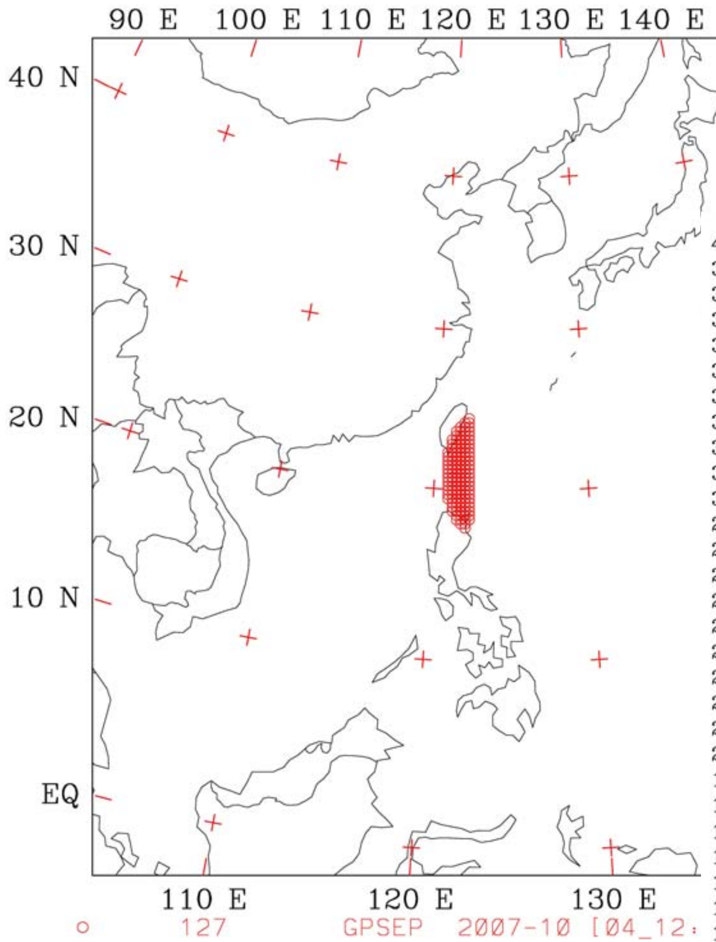


Nature run at 0412

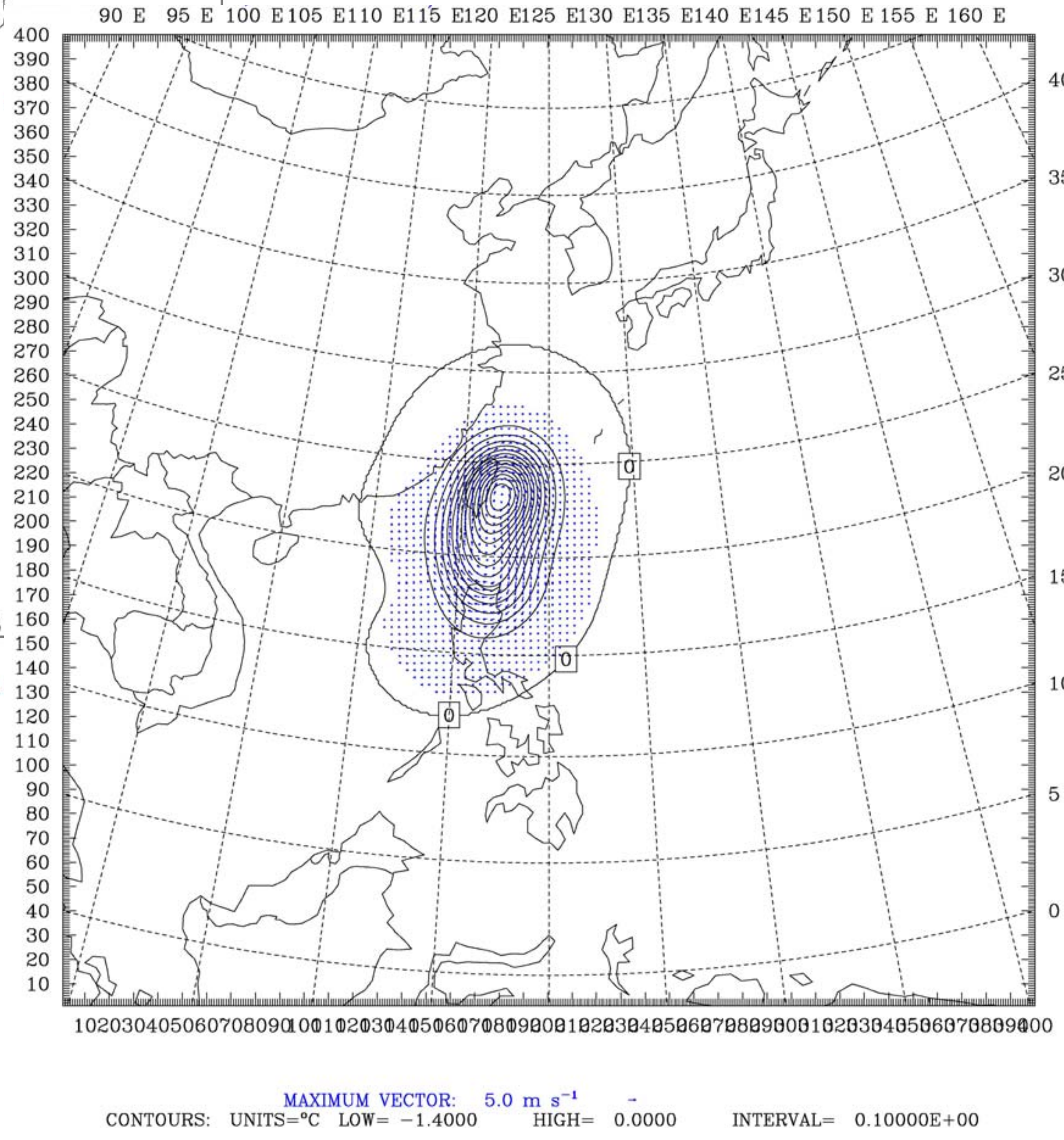


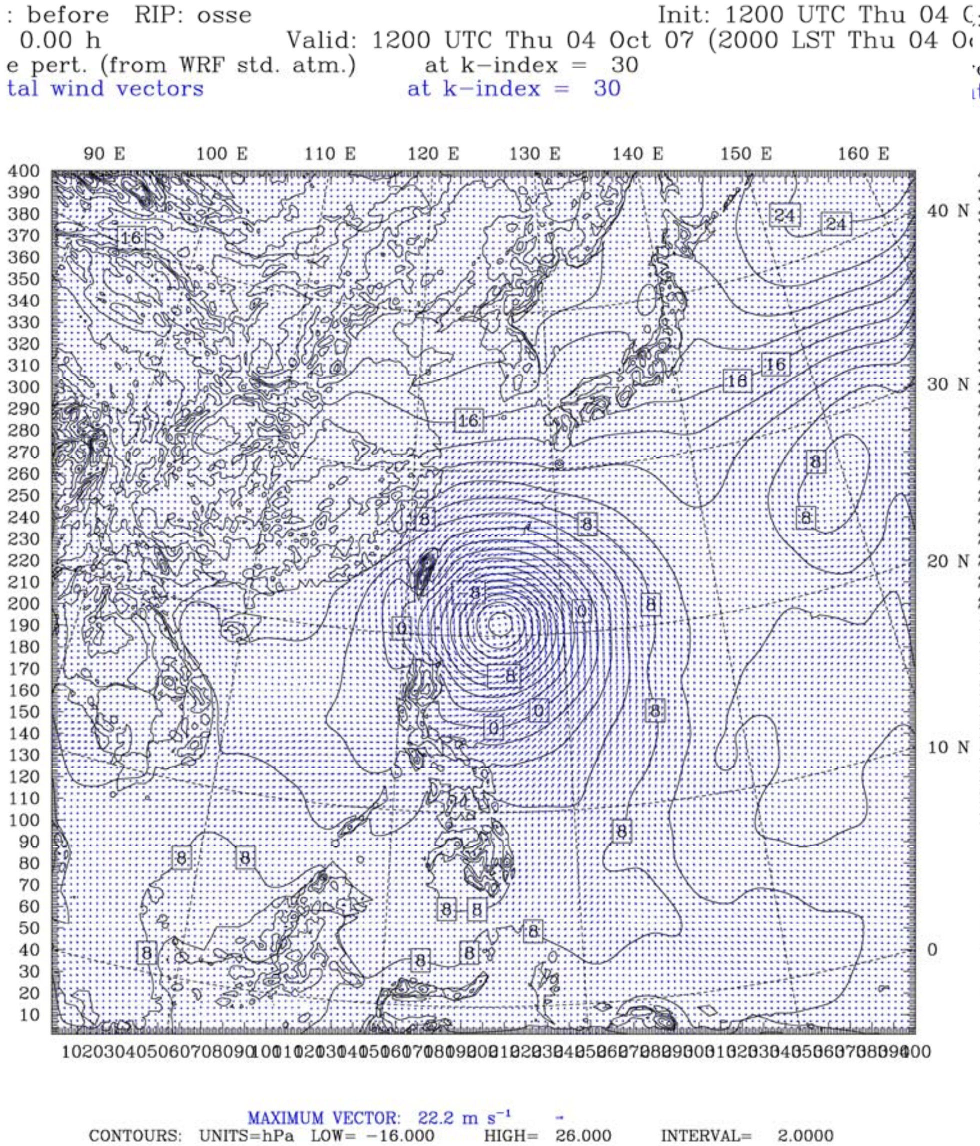
GPS RO refractivity soundings at 30-km resolution

Krosa Typhoon (2007) Temperature increment near the surface at 100412

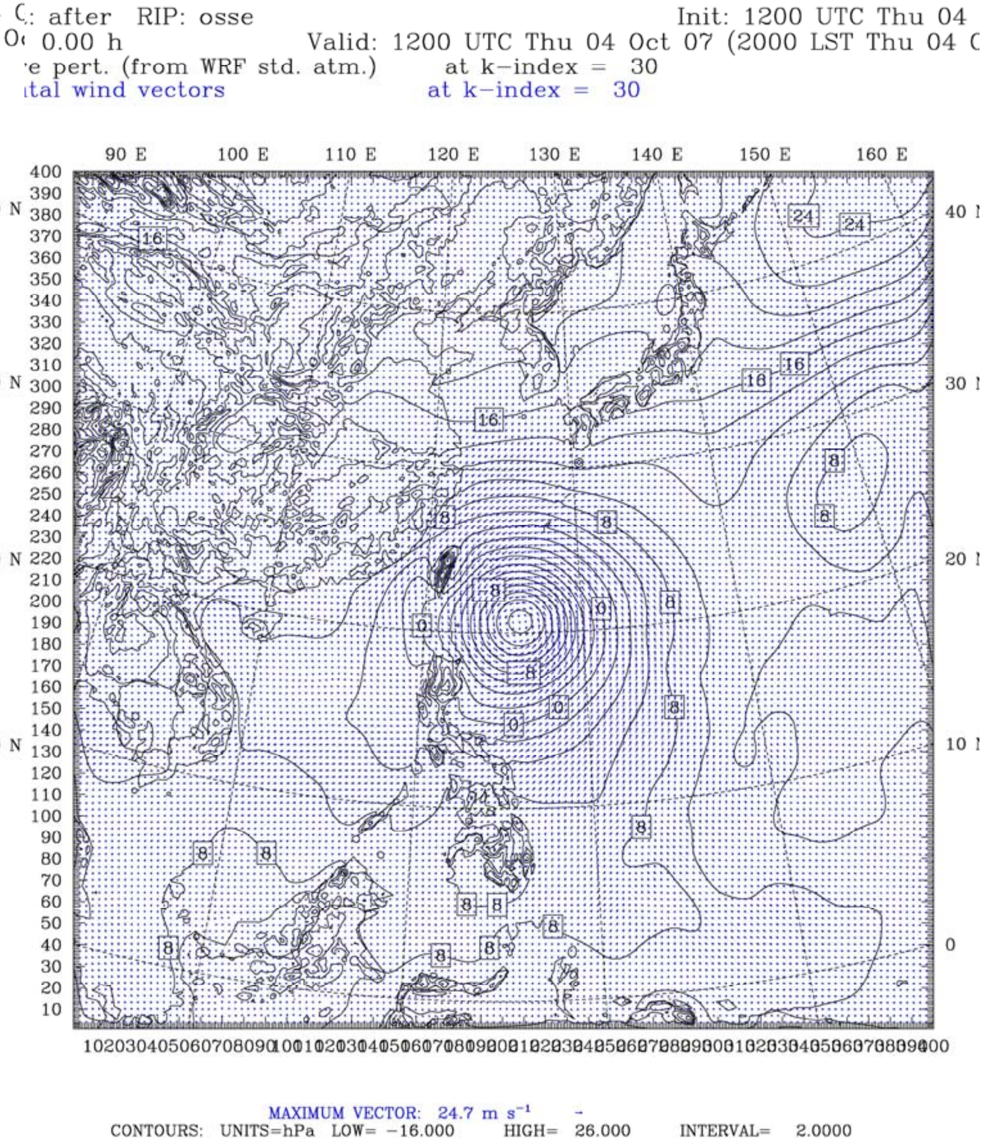


127 GPS RO soundings assimilated by nonlocal operator

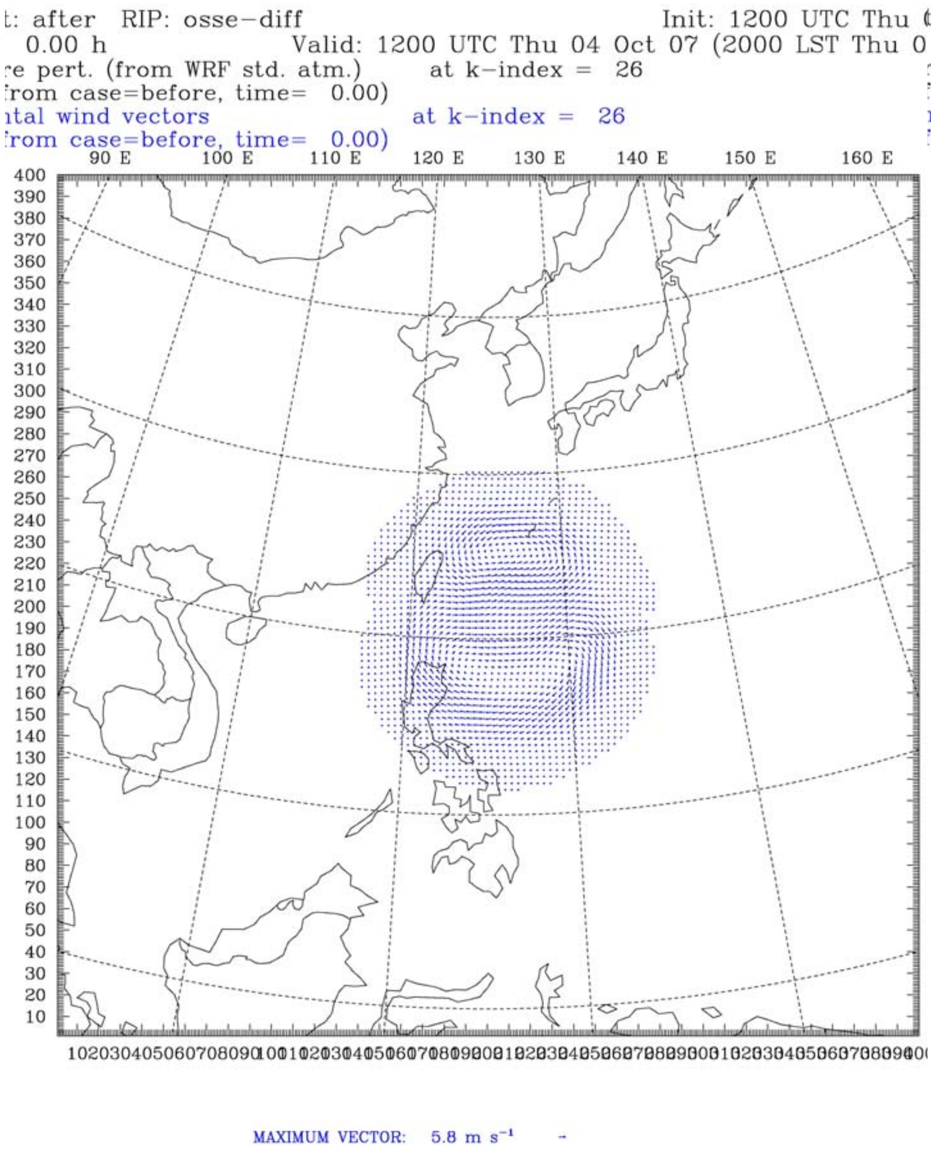




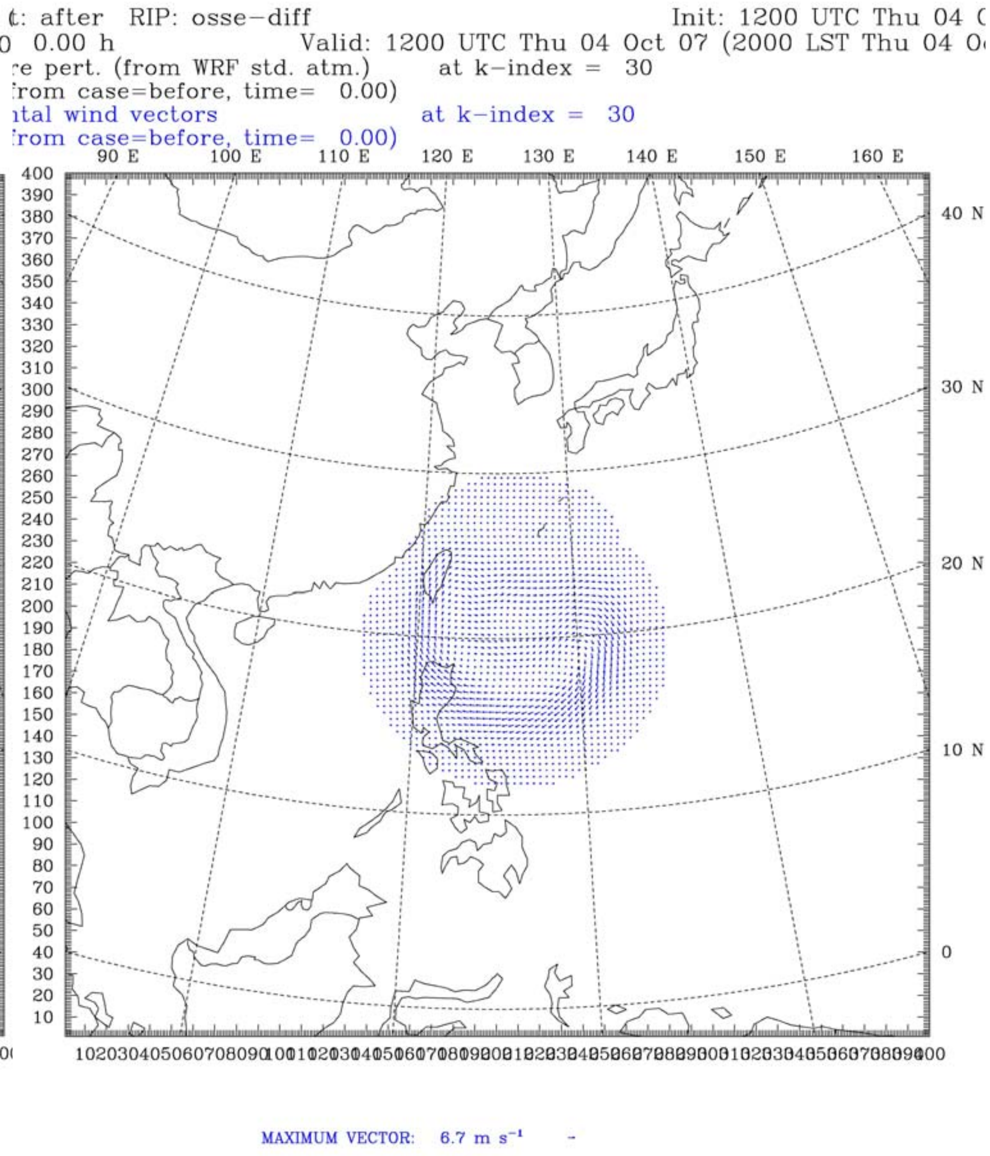
CNTL (no GPS)



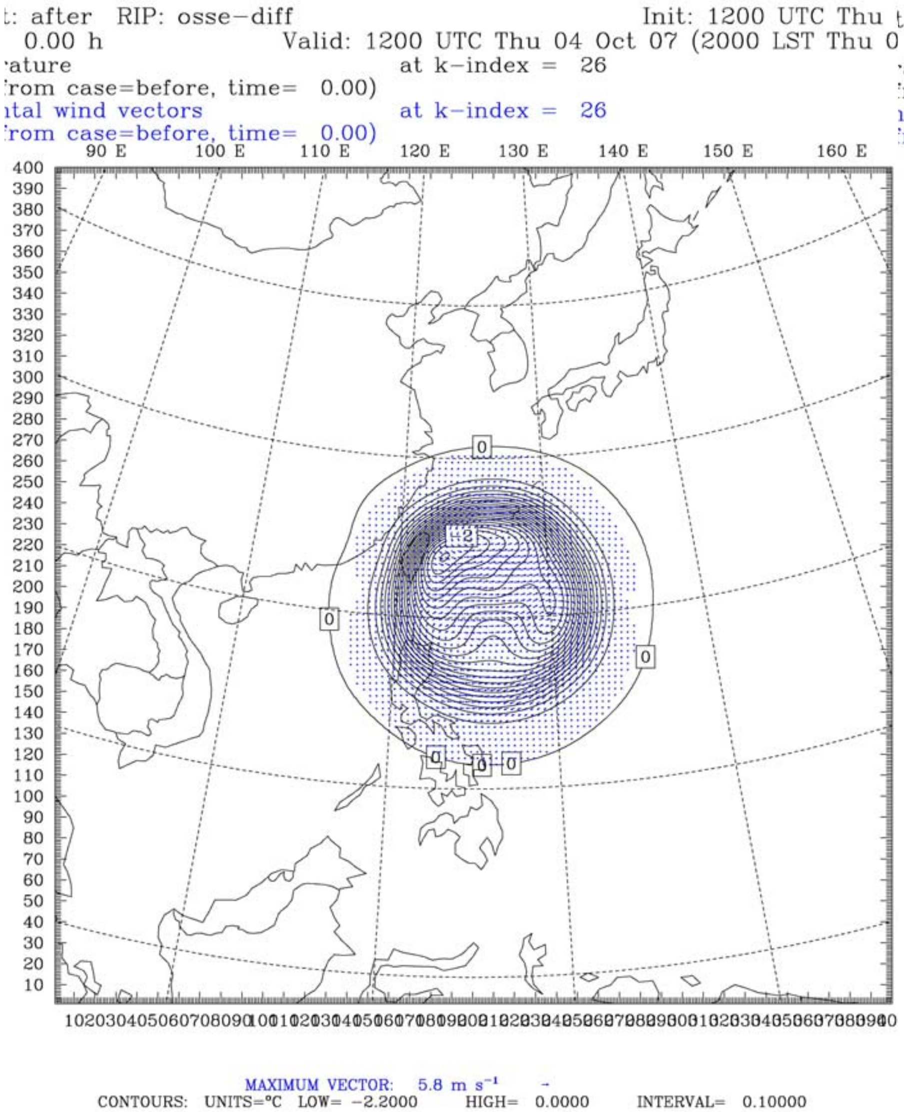
REF with 1252 GPS



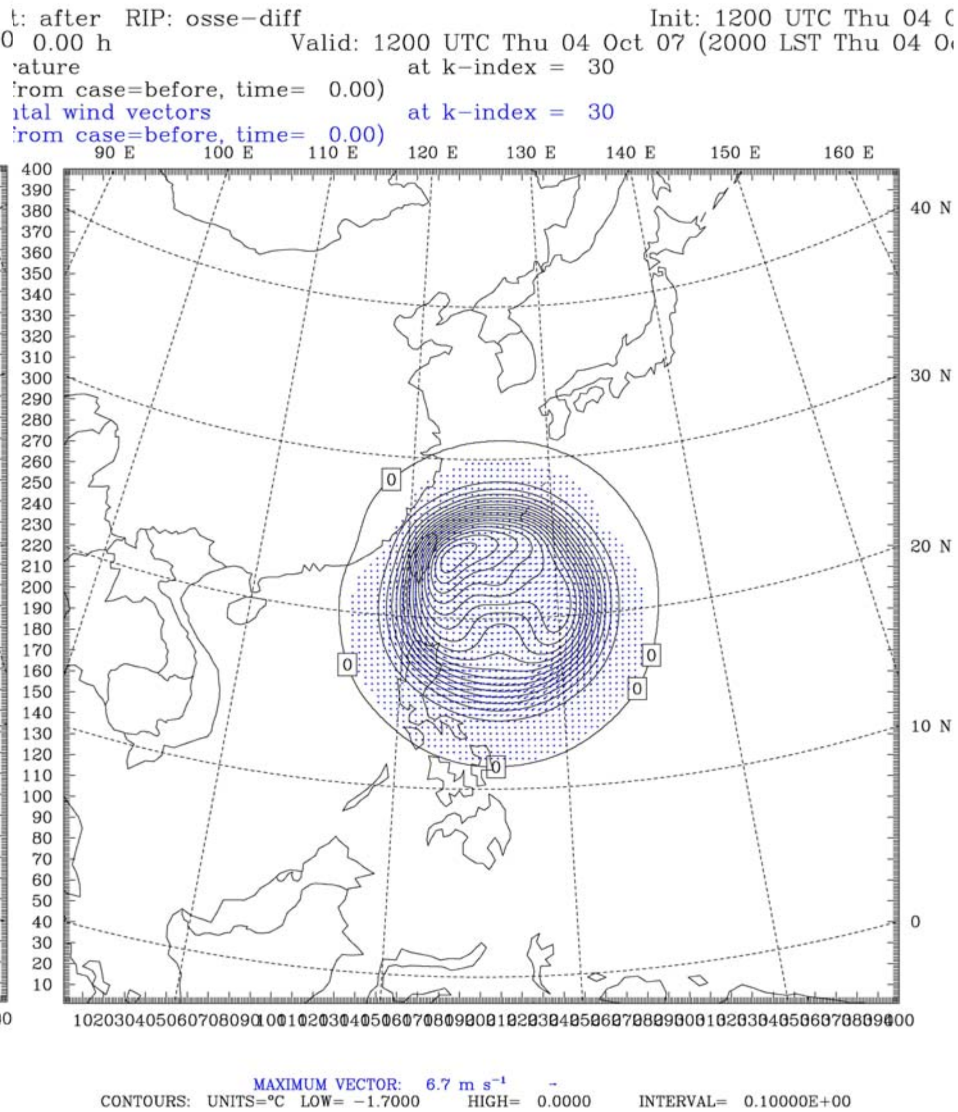
Wind difference at k= 26



Wind difference at k= 30



Temp. difference at k= 26



Temp. difference at k= 30

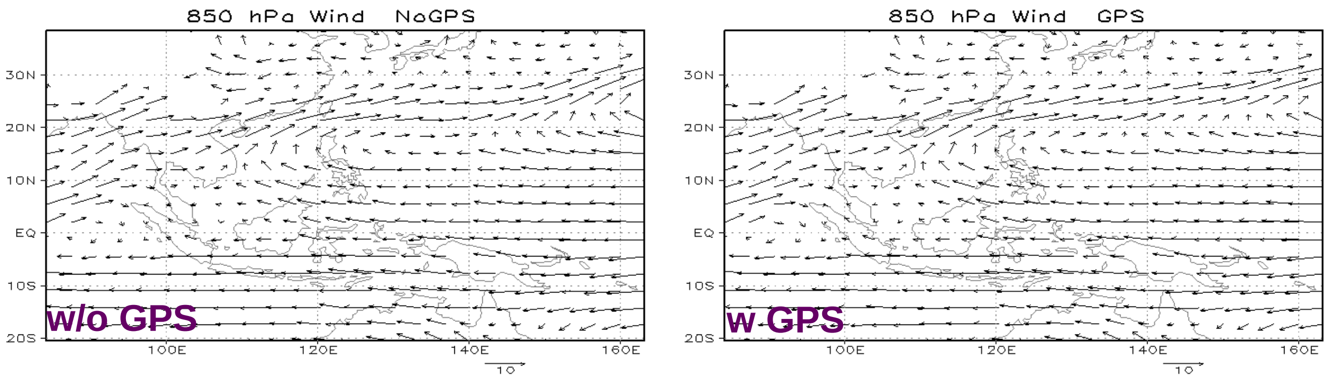
The impact of FORMOSAT-3/COSMIC data from international community

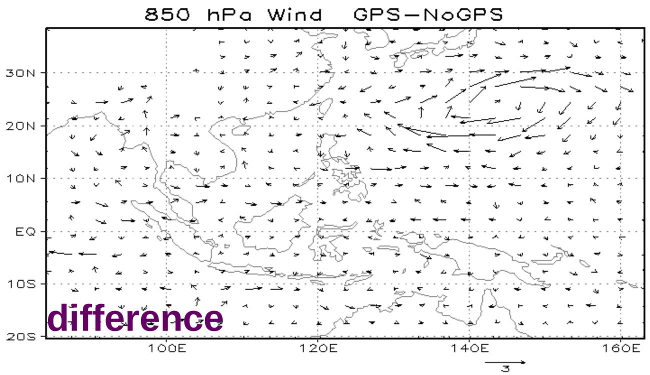
Kuo, Y.-H., H. Liu, Y.-R. Guo, C.-T. Terng, and Y.-T. Lin 2008: Impact of FORMOSAT-3/COSMIC data on typhoon and mei-yu prediction. *Submitted to NTU Department of Atmospheric Sciences 50th Anniversary Book.*

Data: FORMOSAT-3/COSMIC
Variables: local refractivity
Model: WRF 3DVAR and WRF/DART EnKF

Mei-yu case

850 mb wind fields





- The assimilation of COSMIC data significantly strengthens the Western Pacific Subtropical High, and consequently improves the prediction of Mei-yu precipitation over southern China and Taiwan.

Track forecast errors averaged over different forecast periods

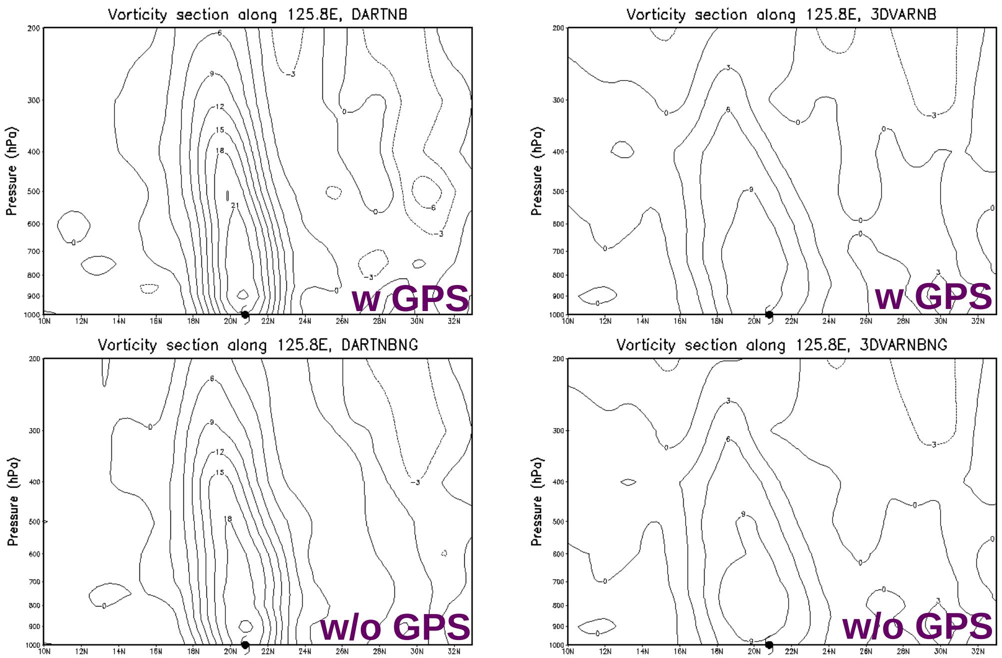
Typhoon case
(Shanshan 2006)

Experiment	3-24 h forecast	27-48 h forecast	51-72 h forecast	3-72 h forecast
NODA	276	294	248	273
COLDNBNG	197	237	264	233
COLDNB	199	233	265	232
COLDALL	111	150	160	140
CYCLNBNG	166	147	119	144
CYCLNB	117	132	82	111
CYCLALL	61	124	211	132
DARTNBNG	**75**	**57**	**94**	**75**
DARTNB	**69**	**38**	**80**	**62**

~15%

relative vorticity analysis

WRF DART **WRF 3DVAR**



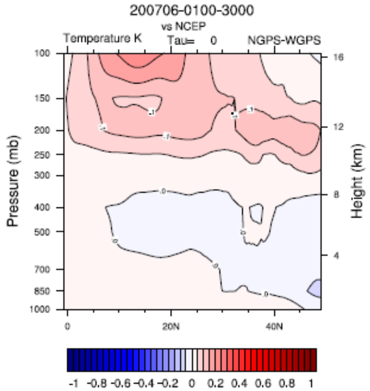
- The WRF/DART ensemble filter system can assimilate the GPSRO data more effectively than the WRF 3D-Var method.
- In particular, the WRF/DART ensemble filter system is able to produce a more coherent storm after one day of continuous assimilation, while a much weaker and less coherent storm is produced by WRF 3D-Var.

Units: 1.0 x10-5 s^{-1}

Terng, C.-T. 2007: The impact study of CWB limited area model prediction with assimilation FORMOSAT-3/ COSMIC GPS RO data. *NSPO final report in 2007.*

Data: CHAMP, and FORMOSAT-3/COSMIC (Dec. 2005 and Jun. 2006)
Variables: local refractivity
Model: WRF 3DVAR

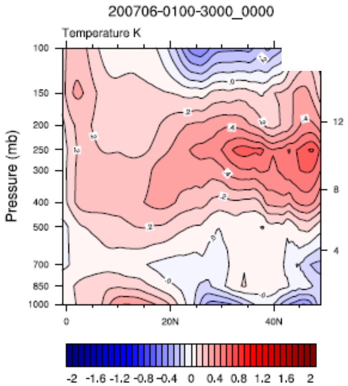
Diff. in Monthly mean increment (A-B)



Monthly mean analysis difference

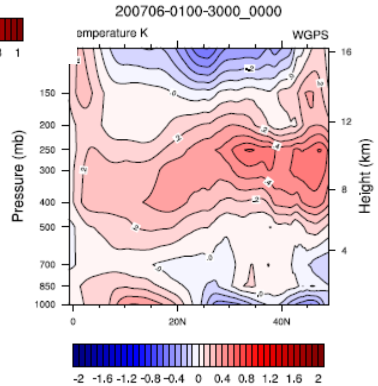
difference
Unit: 0.05 °C

Monthly mean analysis Increment



w/o GPS
Unit: 0.1 °C

Monthly mean analysis Increment



w GPS
Unit: 0.1 °C

- A significant impact on the temperaure analysis when the GPS RO data is assimilated.
- Assimilated with GPS RO data can reduce the temperature overestimeation from the global analysis in the upper model level.

Healy, S.B. and J.-N. Thépaut 2006: Assimilation experiments with CHAMP GPS radio occultation measurements. *Q. J. R. Meteorol. Soc.*, **132**, 605–623.

Data: CHAMP
Variables: 1-D bending angle
Model: ECMWF Global 4DVAR (run for 60 days)

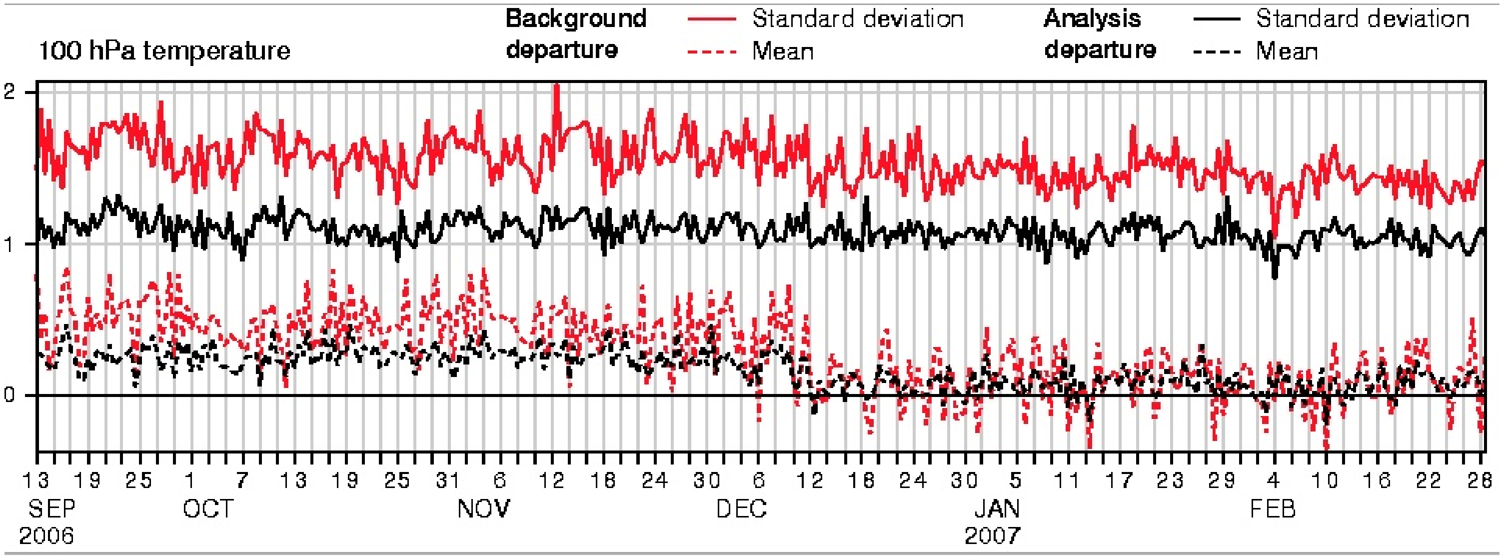
The statistical significance (%) of the chance in r.m.s. fit to radiosonde temperature values at four pressure levels (hPa) due to assimilation of GPSRO data.

	Northern hemisphere				Tropics				Southern hemisphere			
Forecast day	300	200	100	50	300	200	100	50	300	200	100	50
1	–	1.0	0.5	–	–2.0	2.0	0.1	–10.0	1.0	0.1	0.1	5.0
2	10.0	–	0.5	–	–	1.0	0.1	–	2.0	0.5	0.1	0.2
3	–	–	10.0	–	–	–	0.1	10.0	2.0	1.0	0.5	0.1
4	–	–	–	–	–	–	2.0	–	–	2.0	2.0	10.0
5	–	–	–	–	–	–	1.0	0.2	–	10.0	–	0.2

A negative value indicates that the r.m.s. fit is degraded at this level.
Only values ≤10% are considered significant. Values >10% are shown as '–'.

- Southern Hemisphere: A clear, statistically significant improvement in the r.m.s. forecast fit to radiosonde measurements over the day 1 to day 5 forecast range at 300, 200, 100 and 50 hPa.
- Tropics: An improved r.m.s. fit to radiosondes is also evident at 100 hPa

Operational implementation of GPSRO at ECMWF



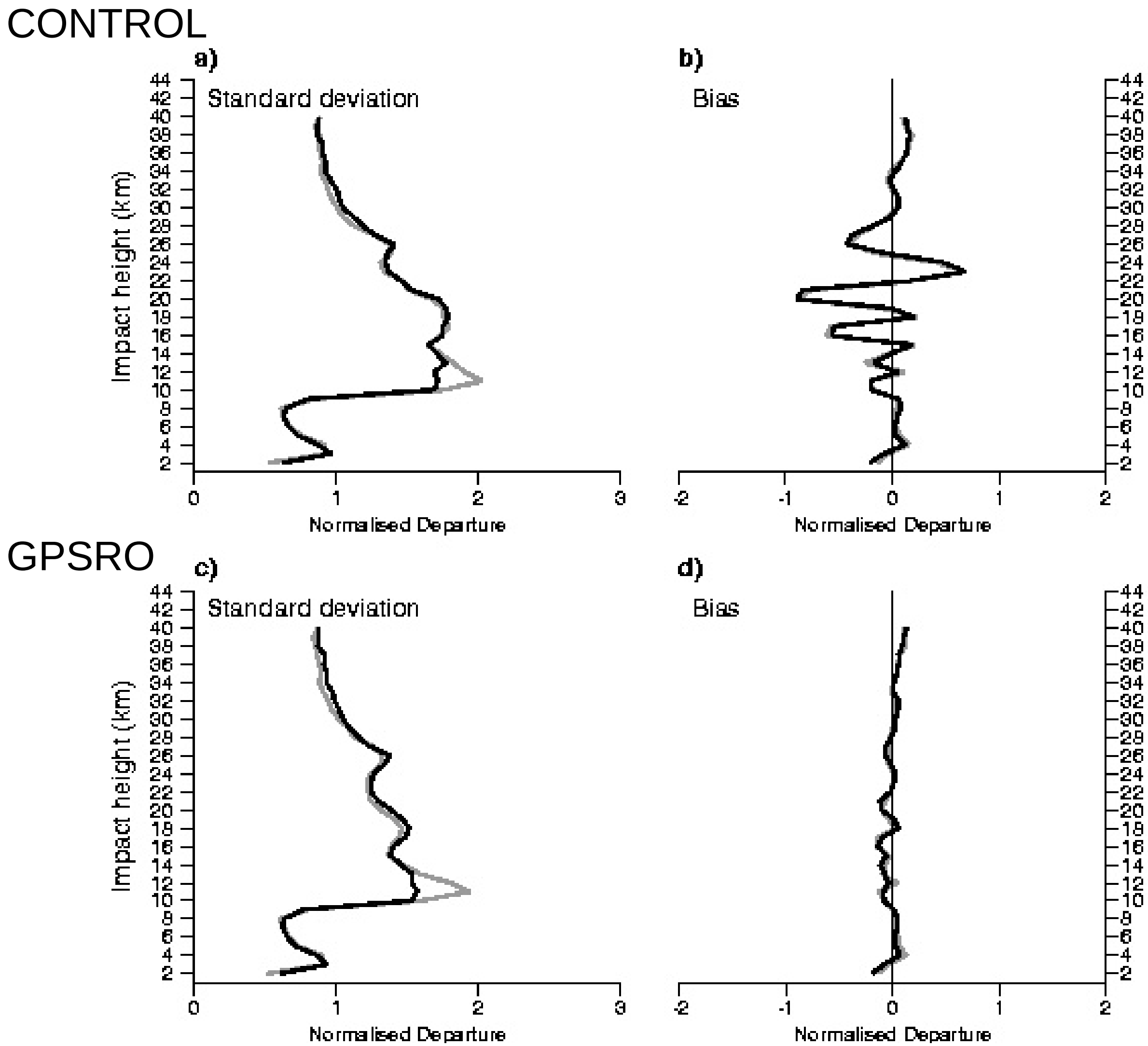
Neutral in the troposphere, but some improvement in the stratospheric temperature scores. Obvious improvement in time series for operations.

Operational implementation represented a quite conservative use of data. No data below 4 km, no rising occultations.

Next set of experiments to investigate increased use of the data.

Healy, S., 2008: Forecast impact experiment with a constellation of GPS radio occultation receivers. *Geophys. Res. Letters*

(O-B)/sigma_o bending angle statistics for rising and setting occultations (eg, SH, COSMIC-3)



BLACK = setting

GREY = rising

The only significant differences are near 10 km. This is a transition height in the processing.

Above 10 km = Phase-lock-loop.
Below 10 km = Open-loop.

Conclusions from ECMWF

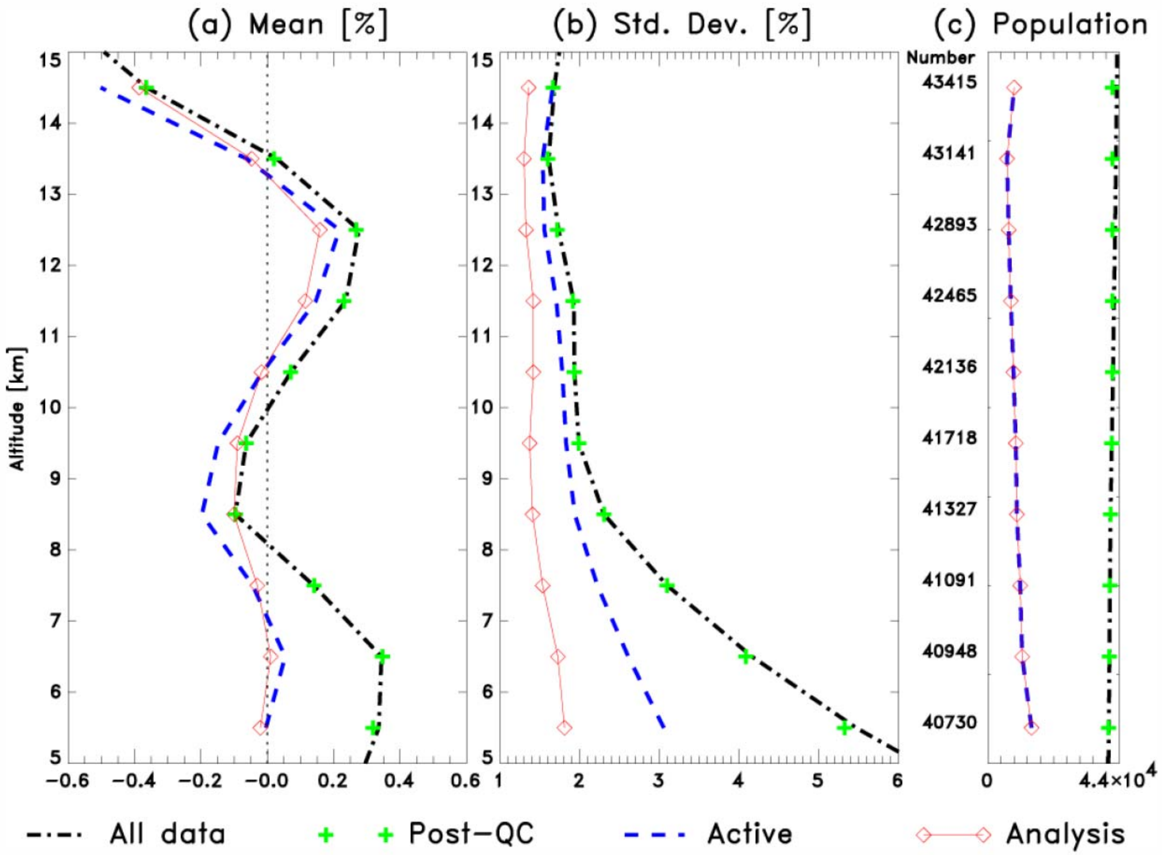
- GPSRO becomes operational from December 12, 2006. Good improvement in stratospheric temperature scores.
- Good improvement in the height scores in both Northern Hemisphere and Southern Hemisphere.
- Future missions: where does GPSRO fit into the global observing system – remember GPSRO can improve the bias correction of satellite radiances.

Poli, P., P. Moll, D. Puech, F. Rabier, and S. B. Healy 2008: Quality control, error analysis, and impact assessment of FORMOSAT-3/COSMIC in numerical weather prediction. *Terr. Atmos. Ocean*.

Data: FORMOSAT-3/COSMIC
Variables: local bending angle
Model: Météo-France 's operational global 4DVAR data assimilation system

All data
Post-QC: only those data selected by the QC
Active: only those data selected for assimilation
Analysis: in the ARPF3C experiment.
Number: the size of the total population (all data), binned to 1 km vertical resolution

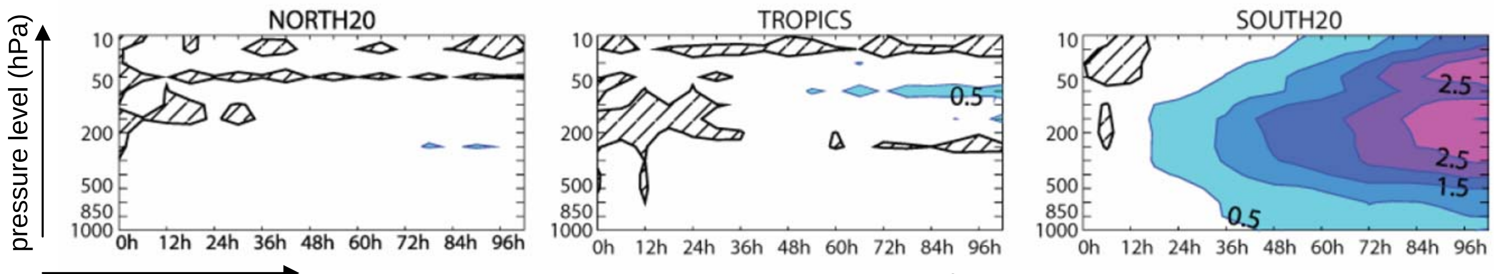
Global statistics of differences (O-B)



- After assimilation, the standard deviations of the departures are reduced between 5-15 km altitudes. The limited reduction is an effect of the conservative observation error estimate.

Forecast RMS score differences of the ARPF3C(with GPS) vs. ARPEGE(w/o GPS) system

Geopotential Height

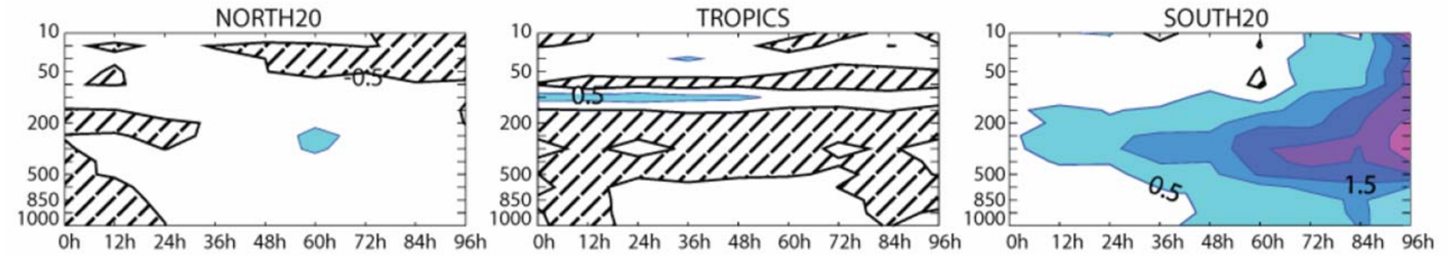


forecast lead time (hours)

clear/coloured: improvements

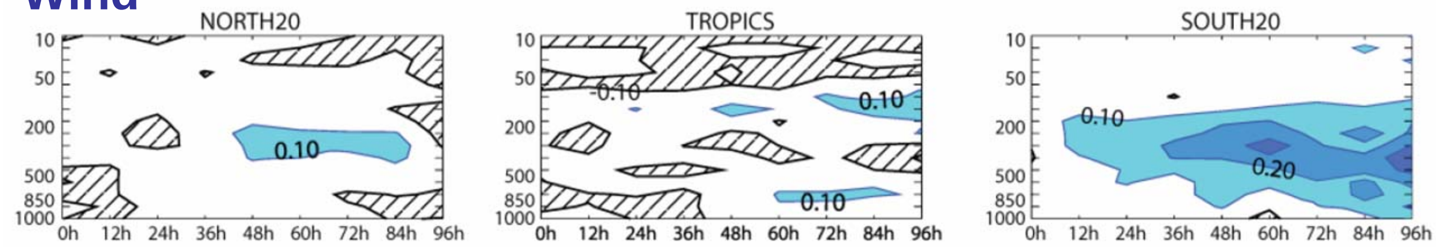
hashed: degradations

Using Analyses as verifications (contour 0.5 mgp).



Using radiosondes as verifications.

Wind



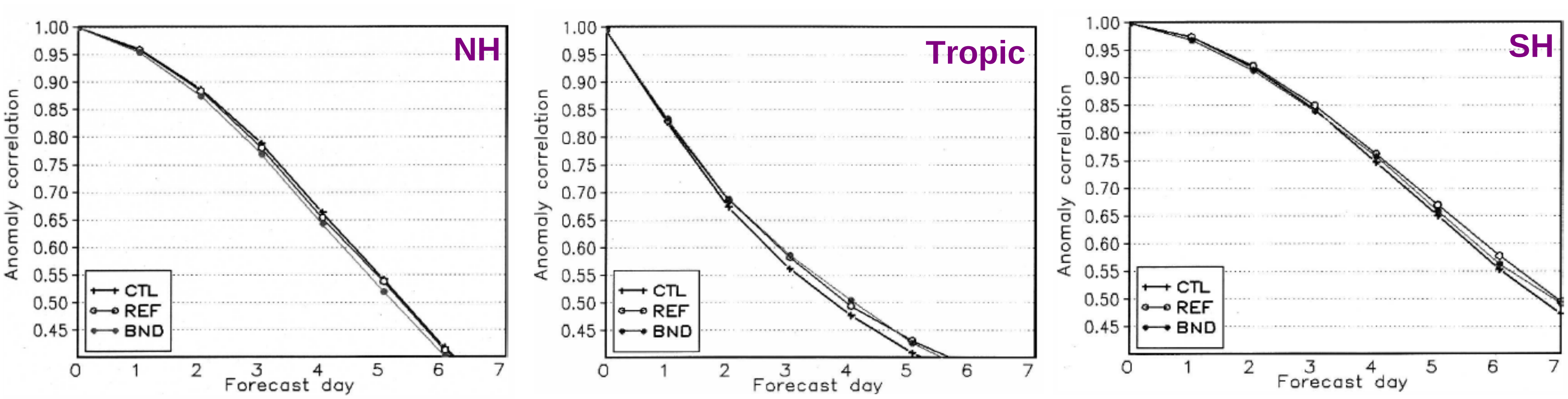
Using radiosondes as verifications (contour 0.1 m/s).

- Indicate a very clear positive impact of the assimilation of F3C bending angle data in the Southern Hemisphere for the prediction of geopotential heights and winds.
- Also observe an improvement in wind forecast skill in the Northern hemisphere, albeit smaller than in the Southern Hemisphere.

Cucurull, L., J. C. Derber, R. Treadon, and R. J. Purser 2007: Assimilation of Global Positioning System Radio Occultation Observations intoNCEP's Global Data Assimilation System. *Mon. Wea. Rev.*, **135**, 3174-3193.

Data: CHAMP
Variables: local bending angle, local refractivity
Model: Grid-point Statistical Interpolation (GSI) developed by NCEP/EMC

Anomaly correlation scores for the temperature field at 200 hPa (0000 UTC 10 Jul–31 Aug 2005)

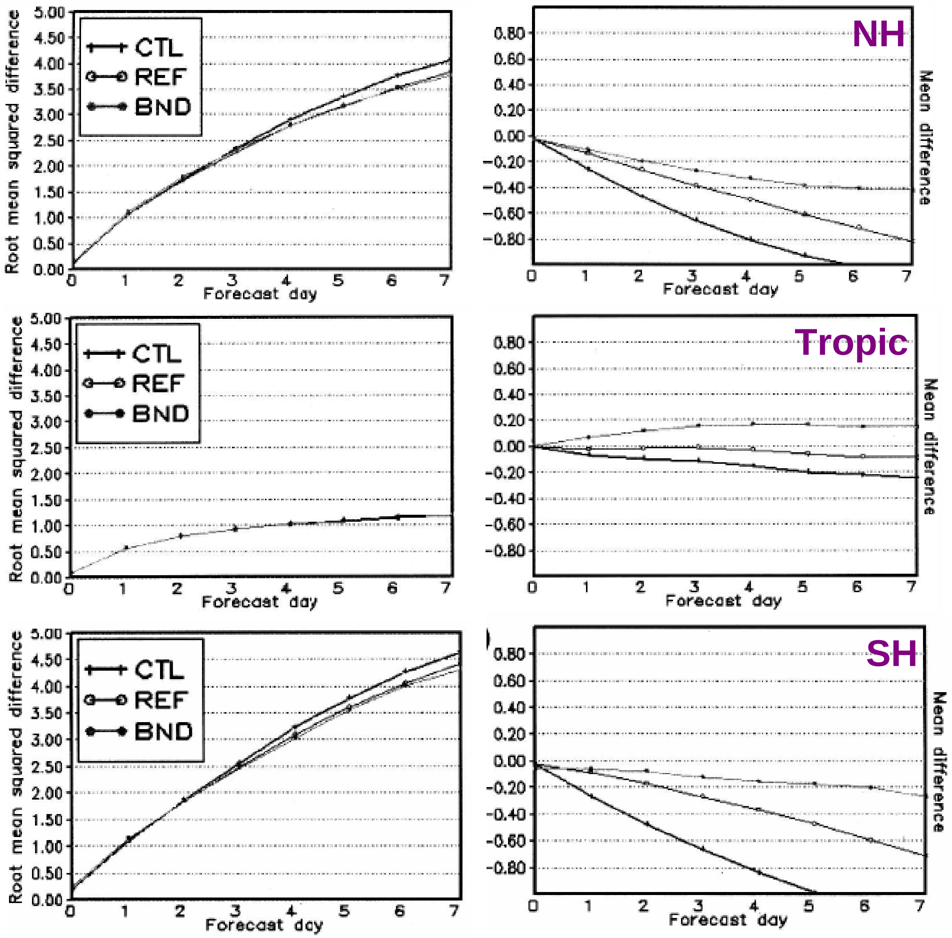


- The use of GPS RO observations slightly improves anomaly correlation scores for temperature (by 0.01–0.03) in the Southern Hemisphere and Tropics throughout the depth of the atmosphere while a slight degradation is found in the upper troposphere and stratosphere in the Northern Hemisphere.

Temperature (K) at 200 hPa

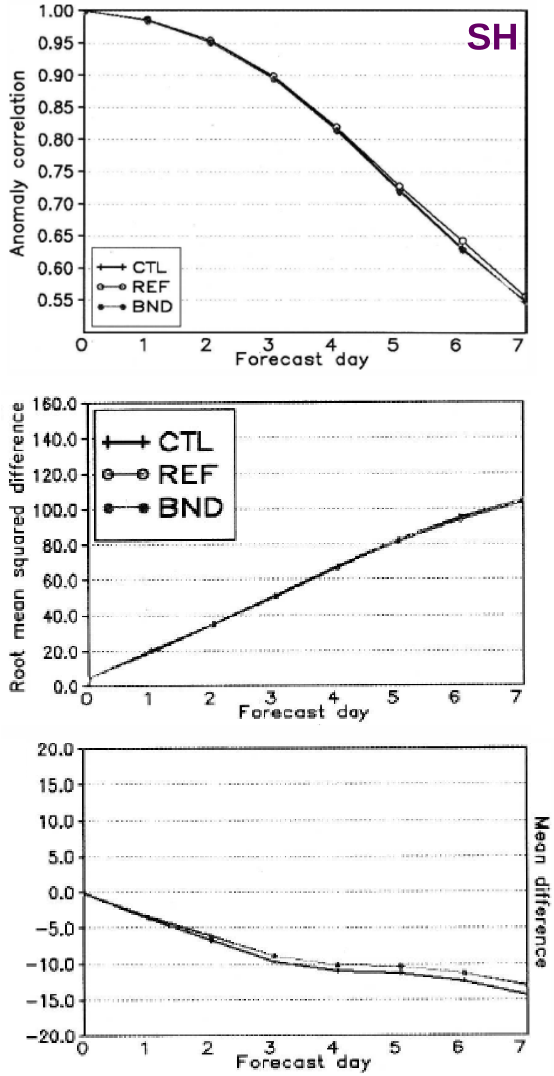
r.m.s. difference

mean difference



➢ Significant reduction of the temperature and humidity biases (not shown) is found for all latitudes.

500-hPa Geopotential height



anomaly correlation

r.m.s. difference

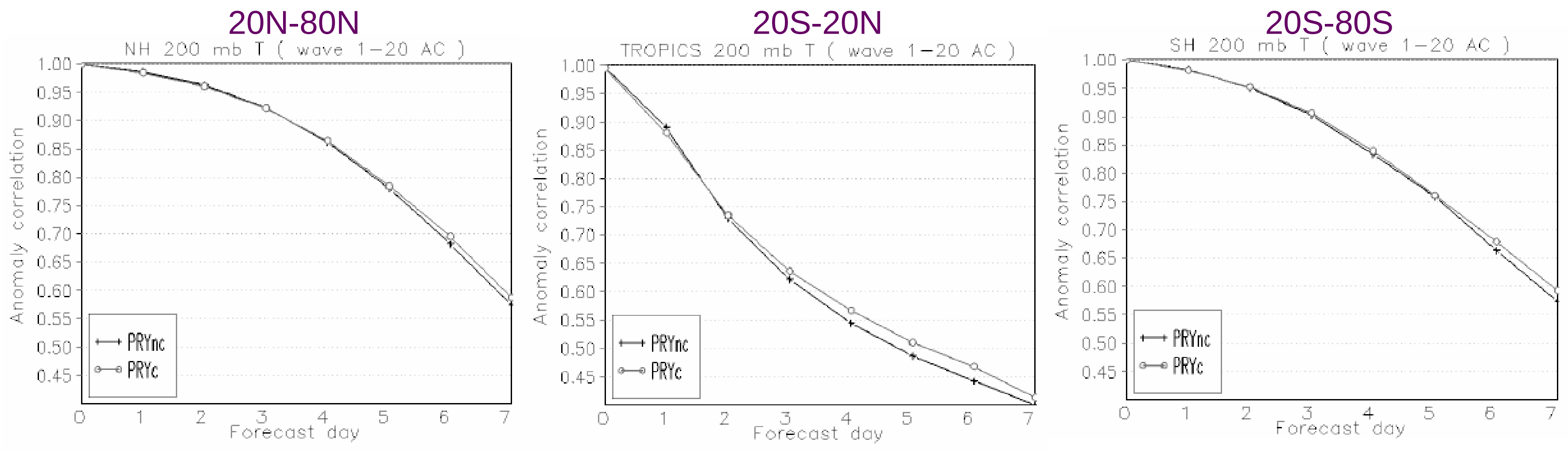
mean difference

➢ The benefits from assimilating GPS RO data also extend to other fields, such as 500-hPa geopotential heights and tropical winds (not shown).

Cucurull, L. and J. C. Derber 2008: Operational implementation of COSMIC observations into the NCEP's global data assimilation system. *Wea. Forecasting*, accepted.

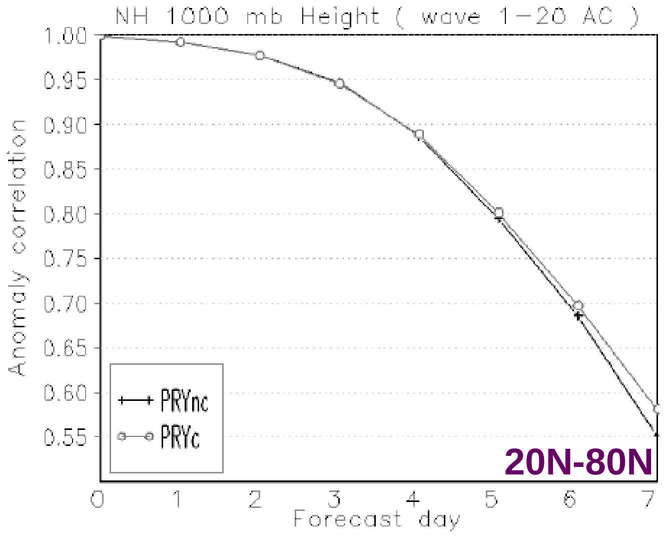
Data: FORMOSAT-3/COSMIC
Variables: local refractivity
Model: Grid-point Statistical Interpolation (GSI) developed by NCEP/EMC

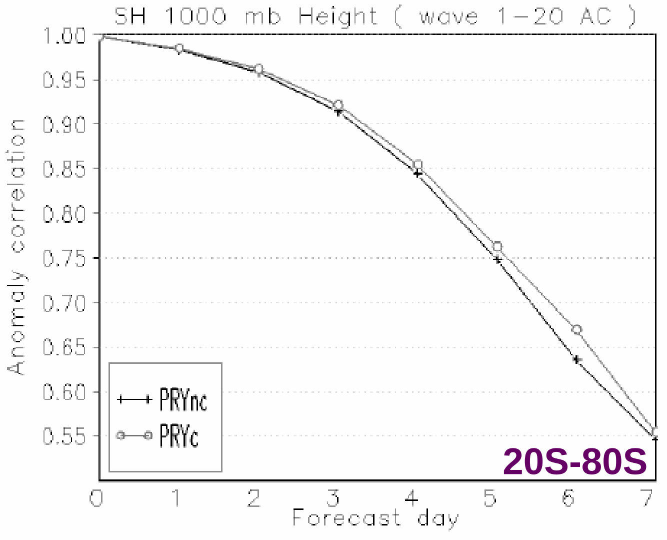
Anomaly correlation scores for the temperature field at 200 hPa

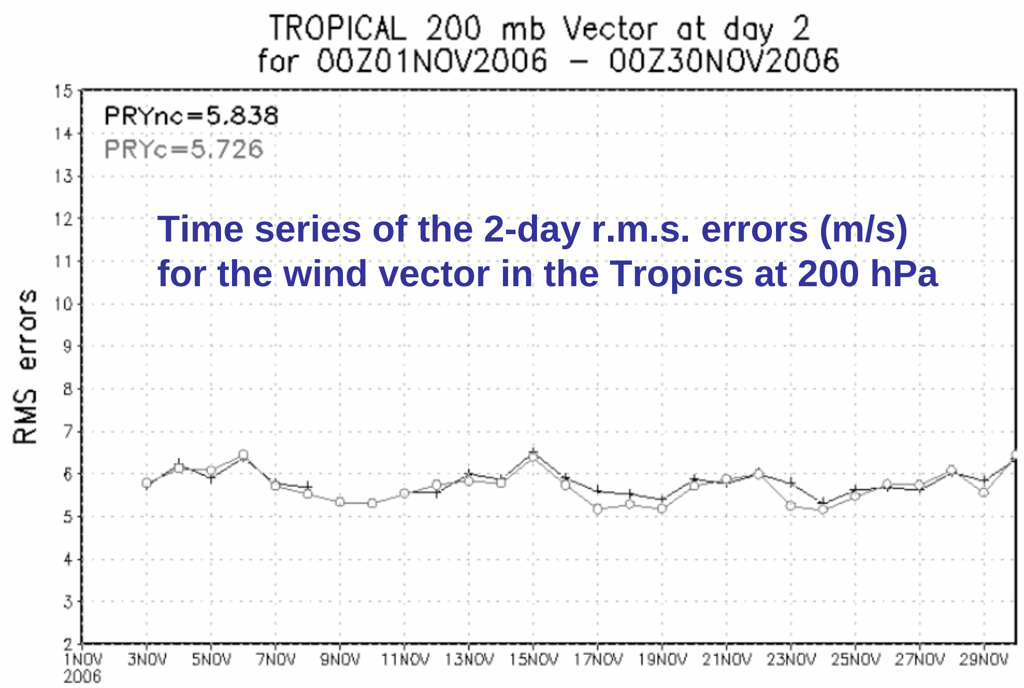


- ➢A significant improvement of the anomaly correlation skill and a global reduction of the NCEP model bias and root-mean-squared errors when COSMIC observations are assimilated into the system.
- ➢The improvement is found for the temperature, geopotential heights and moisture variables.

Anomaly correlation scores for the 1000 hPa geopotential height







Time series of the 2-day r.m.s. errors (m/s) for the wind vector in the Tropics at 200 hPa

- Larger benefits are found in the Southern Hemisphere Extratropics, although a significant positive impact is also found in the Northern Hemisphere Extratropics and Tropics.

- A slight benefit is found in the wind components.

Prospective works

- Use FORMOSAT-3/COSMIC and CHAMP data for severe weather cases, e.g. typhoon, meiyu, cold front and heavy rainfall, etc. in WRF 3DVAR, WRF 4DVAR, and WRF DART.
- Develop a local bending angle operator and insert it into WRF 3DVAR, and then compare it with the local refractivity.
- Assimilate GPS RO data by using WRF 4DVAR and/or MM5 4DVAR with local bending angle operator.
- Conduct OSSE studies to fully understand the impacts of the GPS RO data on regional weather prediction with more verifications and better quantify the performances of different GPS assimilation operators.

Prospective works (cont.)

- Help to insert the nonlocal operator into CWB WRFVAR version (operational system) and compare it with the local operator.
- Test for different data assimilation schemes in the operational system (ex. WRFVAR V3.0 and EnKF), different background errors, and investigate different data quality control.
- Quantify and clarify the impact of GPS RO data on the CWB GFS through statistically systematic yearly evaluation.
- Determine the statistical confidence level of the improvement of CWB/GFS performance introduced as assimilating the GPS RO data.