The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

SMR/1849-28

Conference and School on Predictability of Natural Disasters for our Planet in Danger. A System View; Theory, Models, Data Analysis

25 June - 6 July, 2007

Predictability of Tropical Weather - II

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Predictability of Tropical Weather

K. Puri

(Thanks to many colleagues)

Lecture 2
Outline

The emphasis is on some current modelling systems being used operationally for tropical applications:

- **Operational NWP systems being used at the Australian Bureau of Meteorology**
- **Use of Ensemble Prediction Systems for TC track prediction, monsoon onset and precipitation forecasts**

Tropical NWP at the Australian Bureau of Meteorology

K. Puri, N. Davidson and R. Bowen

Bureau of Meteorology Research Centre

Melbourne, Australia

Modelling issues for tropics

- Diabatic processes play an important role in determining the circulation in the tropics
- Current NWP models have problems in adequately handling these processes –
  - Sparcity of data
  - Deficiences in parametrisation of physical processes
  - Inability of analysis schemes to include information on diabatic heating
  - Inability to provide initial fields that are dynamically consistent and sensitive to regions of heating and cooling

Modelling issues for tropics

- One of the reasons for the poor representation of tropical diabatic forcing is sparcity of moisture data
- Geostationary satellites provide useful **proxy** sources of moisture data

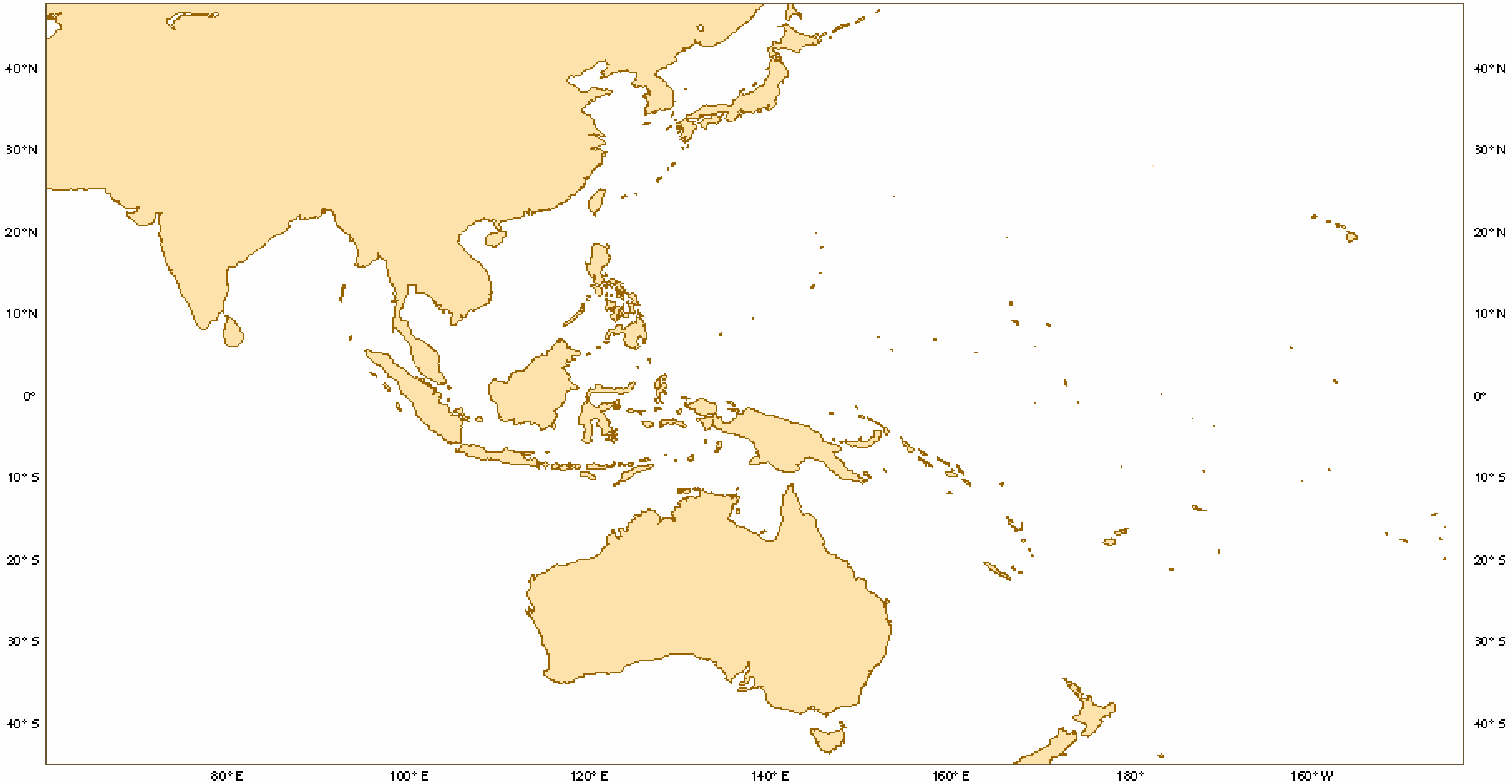
TLAPS

The Bureau of Meteorology operationally runs a Tropical Limited Area Prediction System, TLAPS

Main features

- High order numerics
- Detailed parameterisation of physical processes
- Generalised statistical interpolation analysis
- Options for data assimilation and dynamical nudging
- Flexibility to run at different resolutions and domains

TLAPS Domain

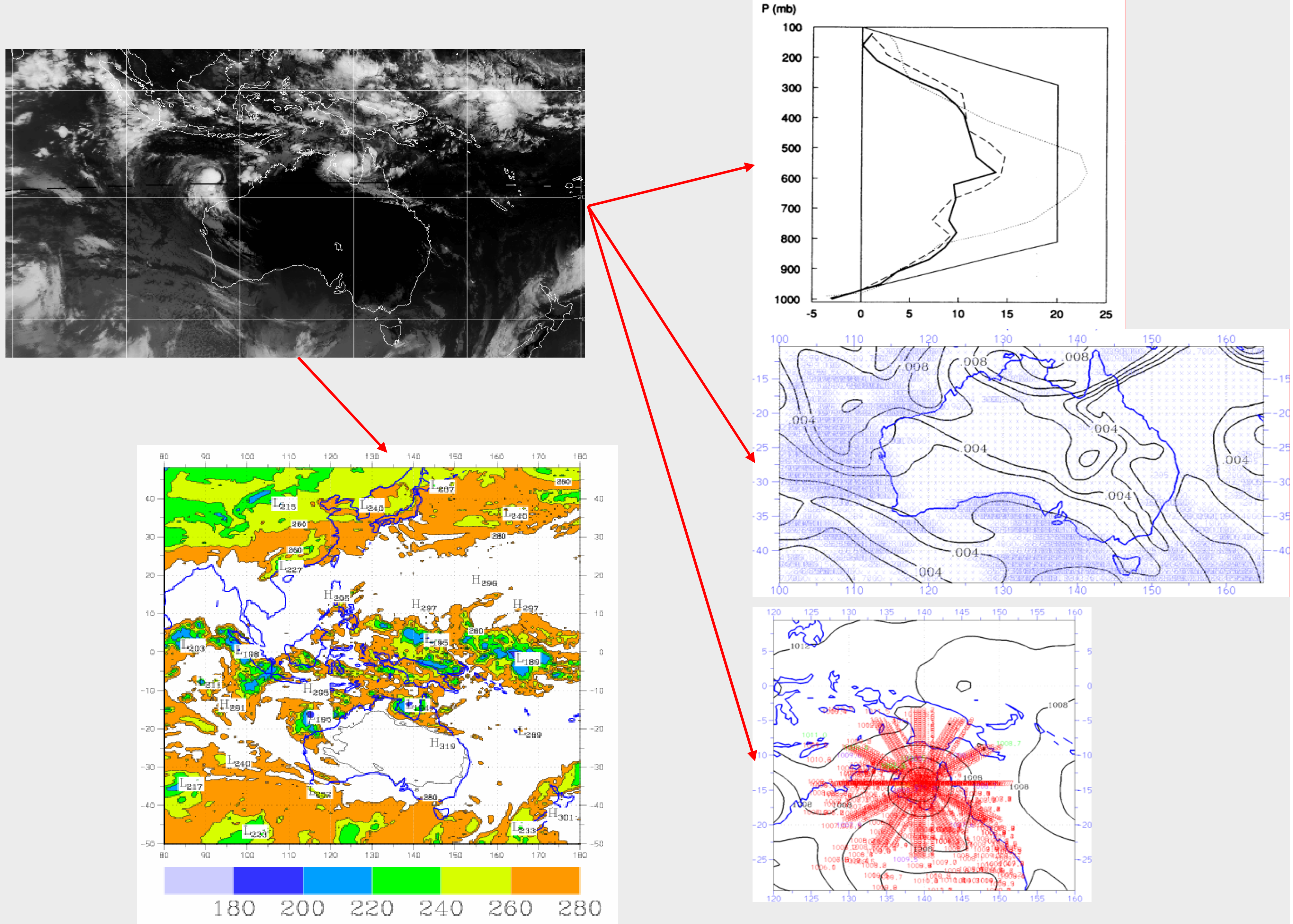


Resolution: 0.375°x0.375°, 51 Levels

TLAPS

TLAPS includes features that are specifically designed for the tropics

- **Use of diabatic heating information inferred from GMS imagery**
- **Use of proxy moisture data inferred from GMS imagery**
- **Use of tropical cyclone bogus data**



P (mb)
100
200
300
400
500
600
700
800
900
1000
-5
0
5
10
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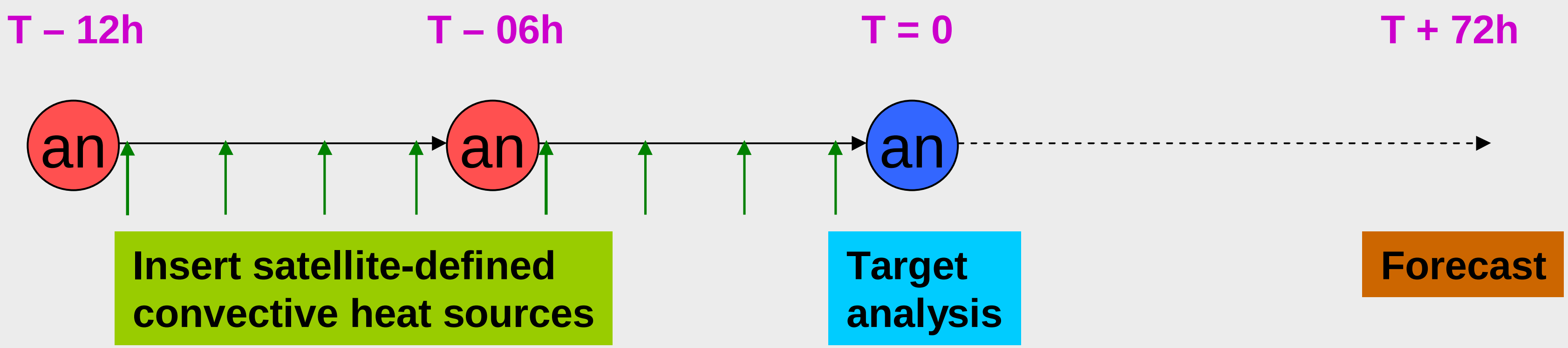
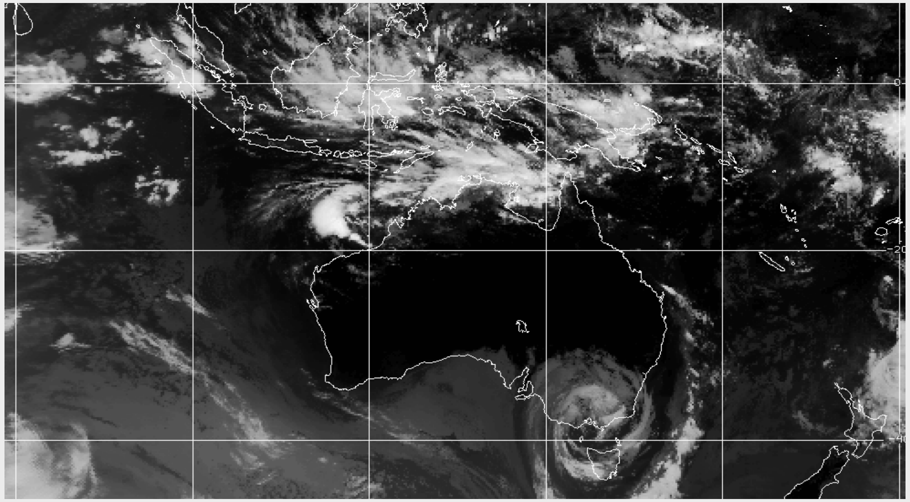
20
25
.008
.004
180
200
220
240
260
280

Dynamic nudging scheme used in TLAPS



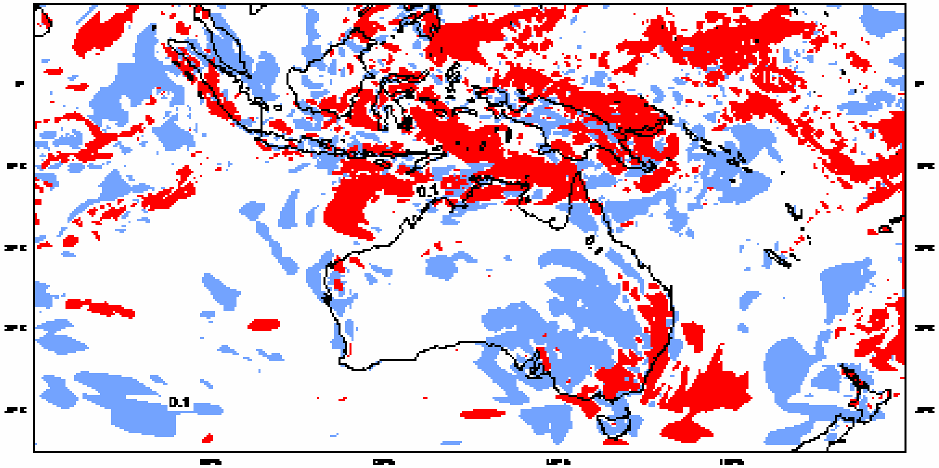
- Target analysis: reanalysis of all data + TC bogus + satellite data
- Nudge to preserve observationally reliable rotational wind component in the target analysis
- Replace model heating with satellite defined heat sources updated every 6 hours – forces divergent wind component

20050204 00Z

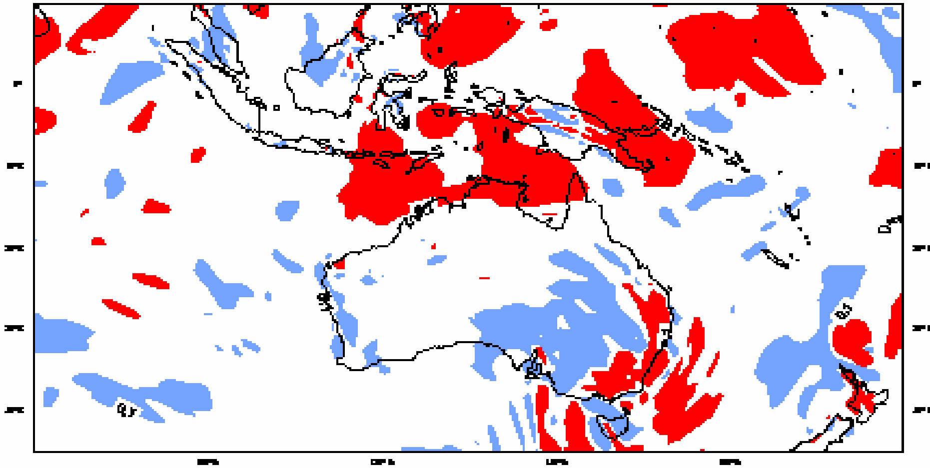


Omega analyses, 500hPa

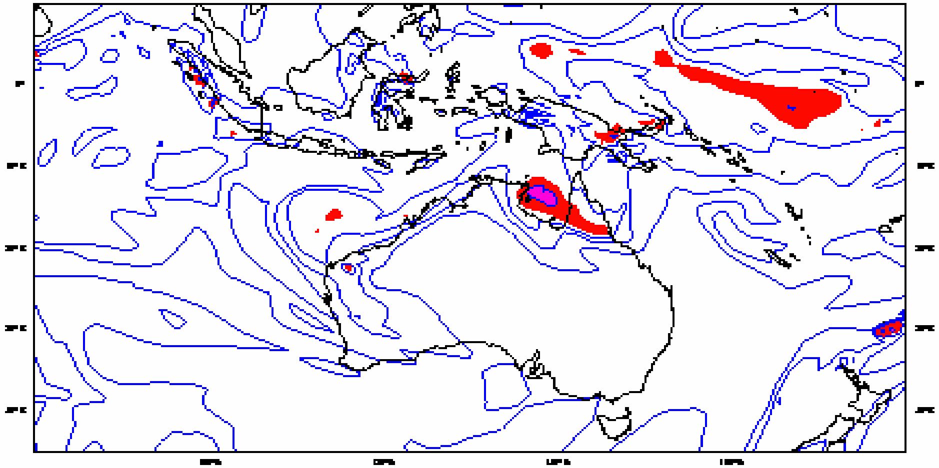
With gms



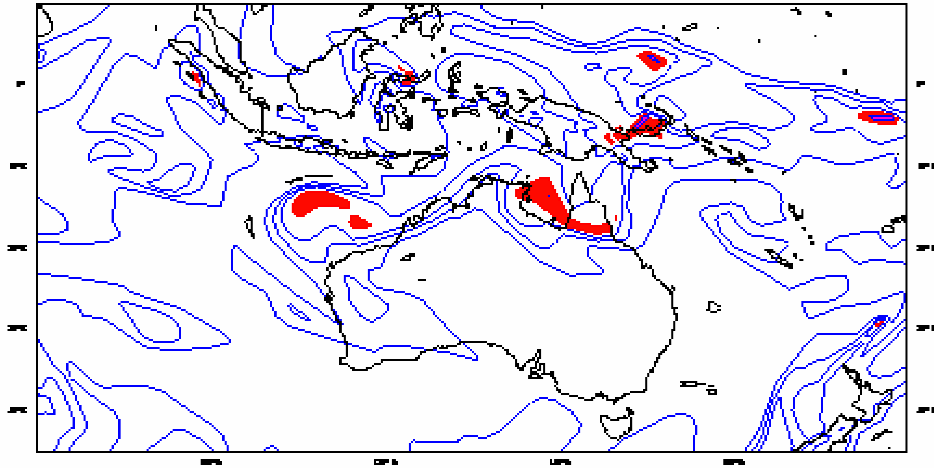
No gms



With gms 20050206 00Z

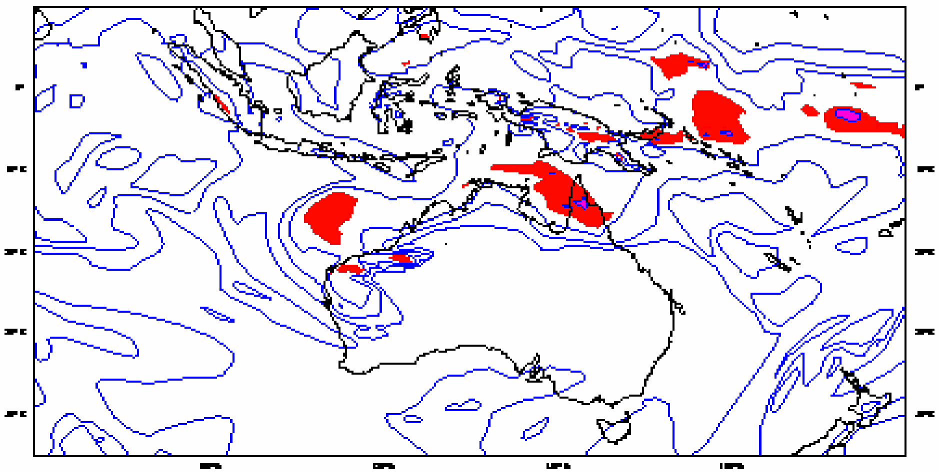


No gms 20050206 00Z

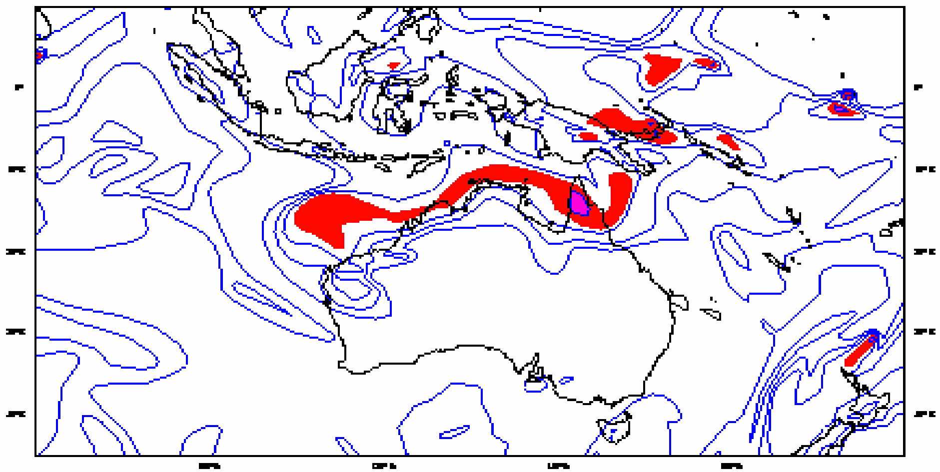


Mixing ratio analyses, 500hPa

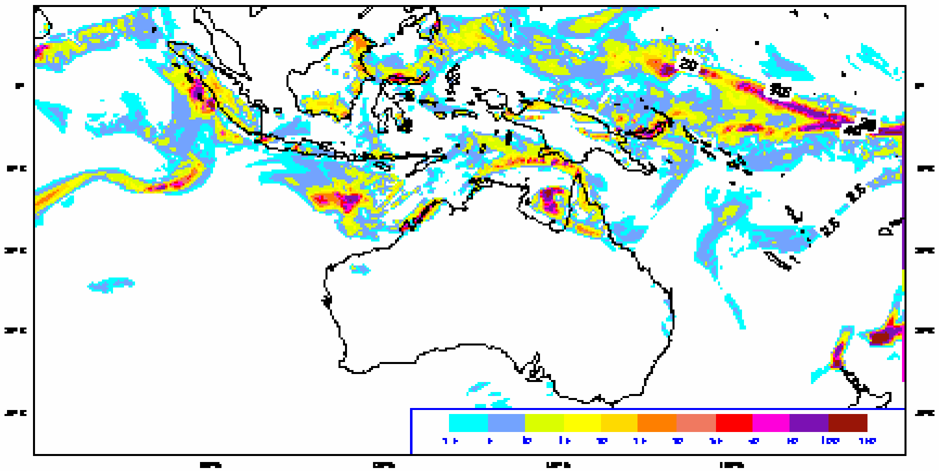
With gms 20050205 12Z



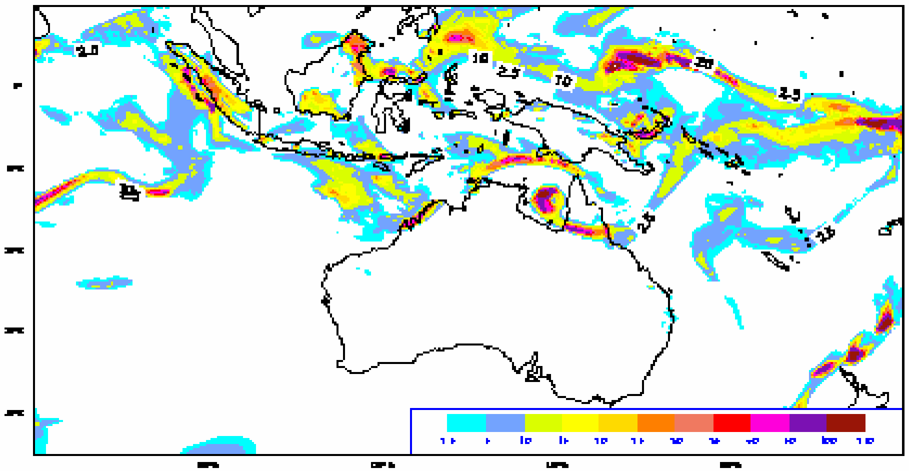
No gms 20050205 12Z



With gms **20050206 00Z**

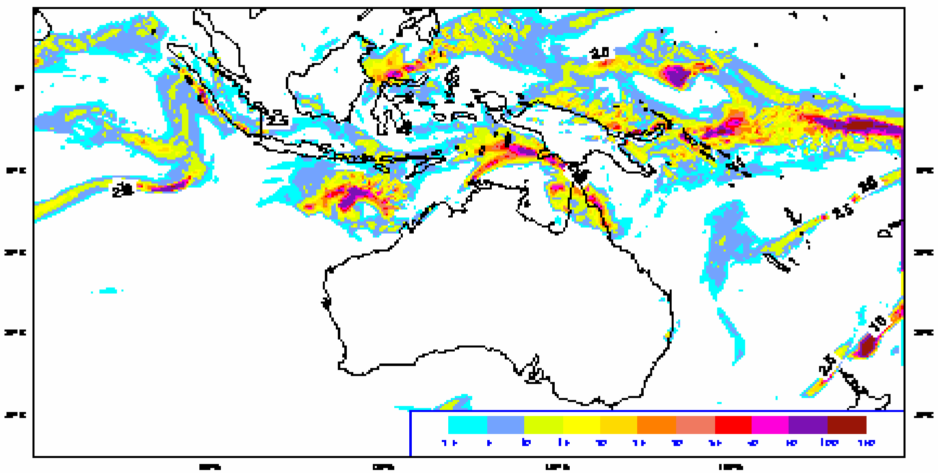


No gms **20050206 00Z**

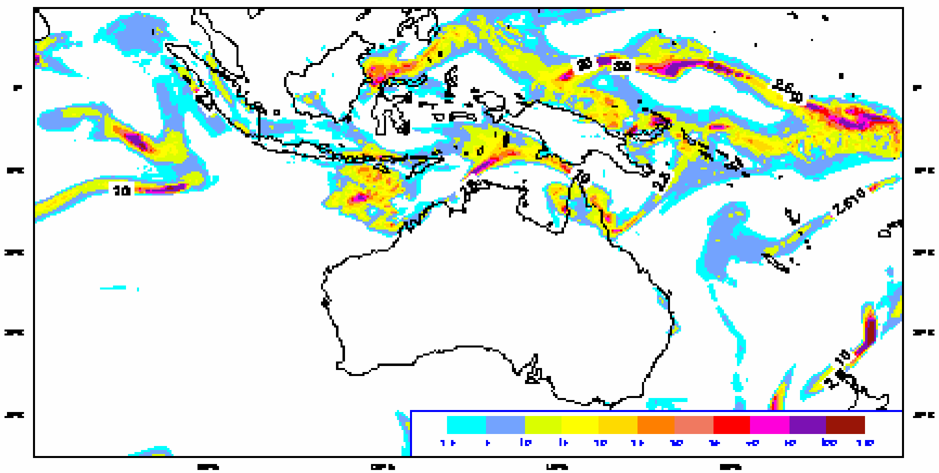


12 hour precipitation forecasts

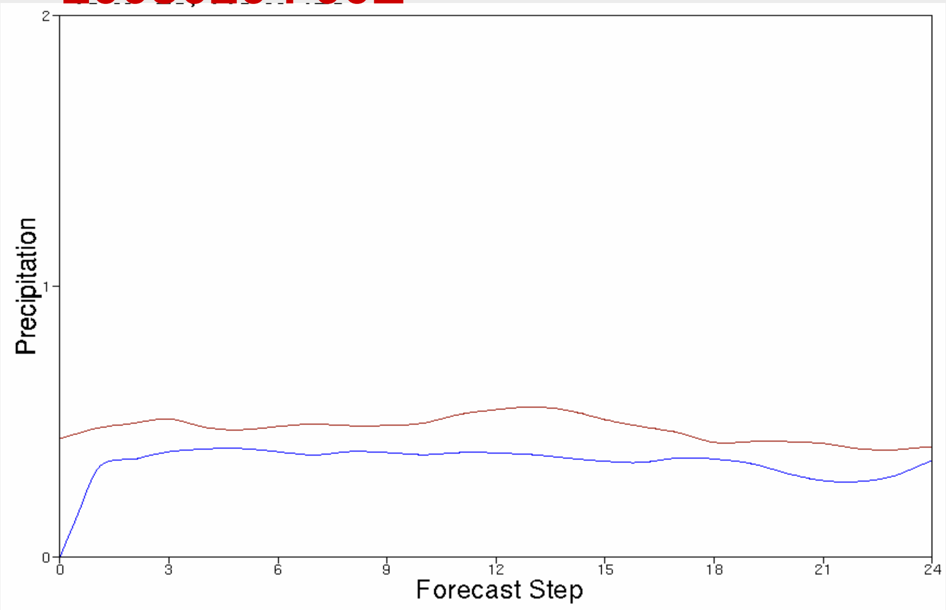
With gms **20050205 12Z**



No gms **20050205 12Z**



20050204 00Z

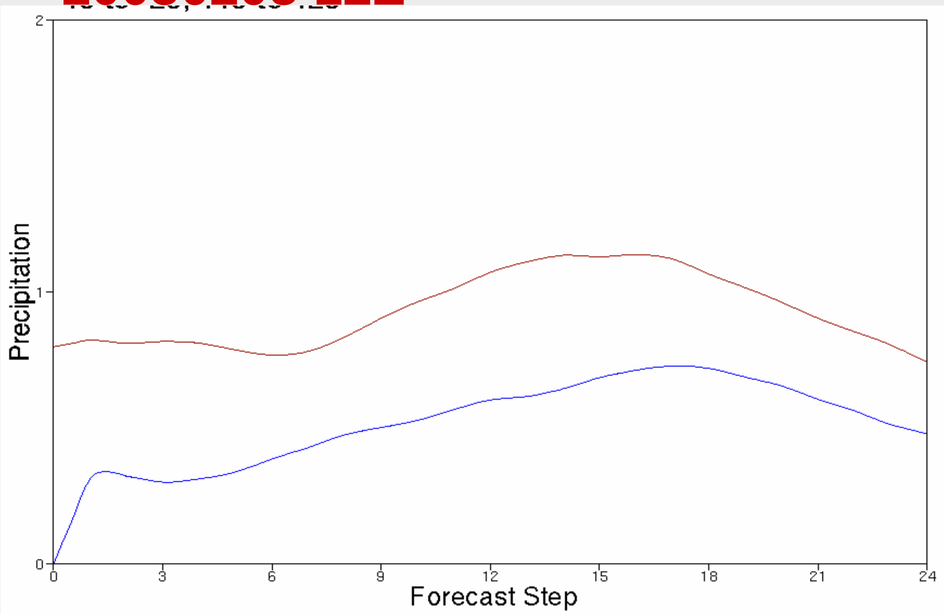


Area average 10S-20S; 110E-120E

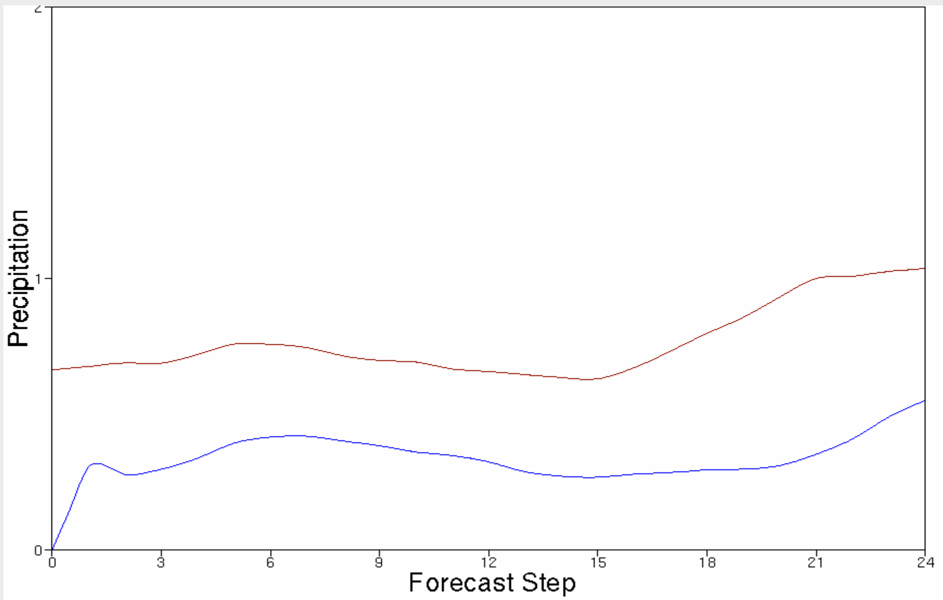
With gms

No gms

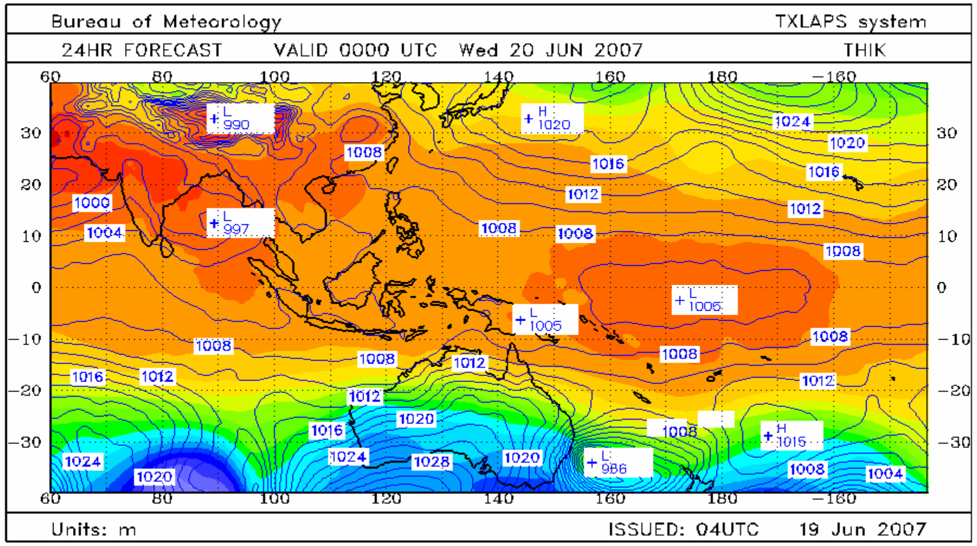
20050205 12Z

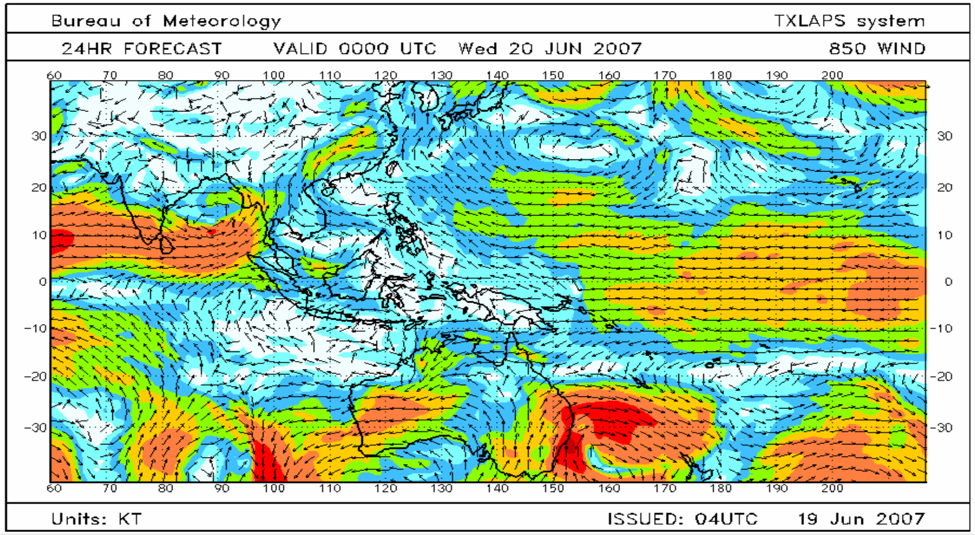


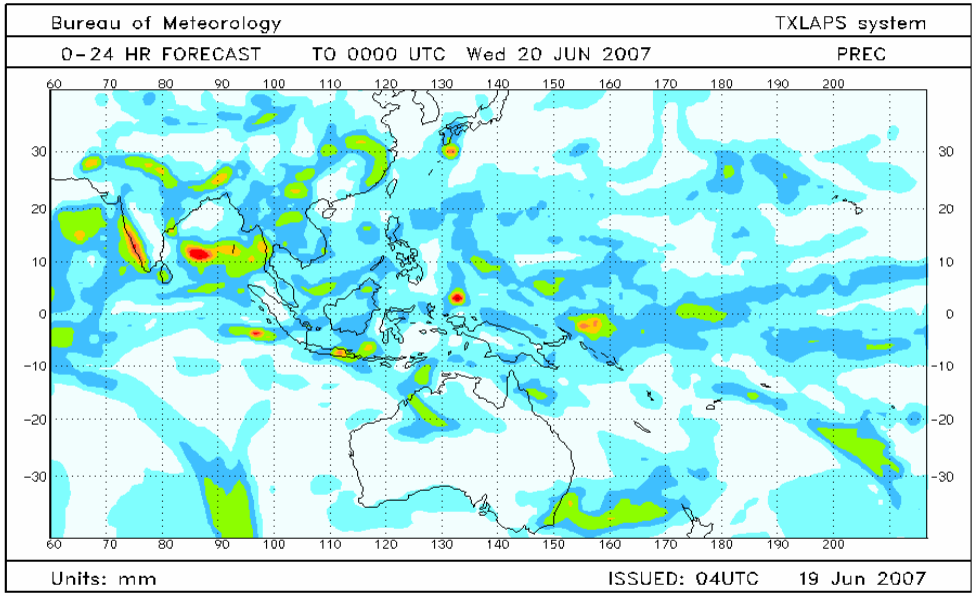
20050206 00Z

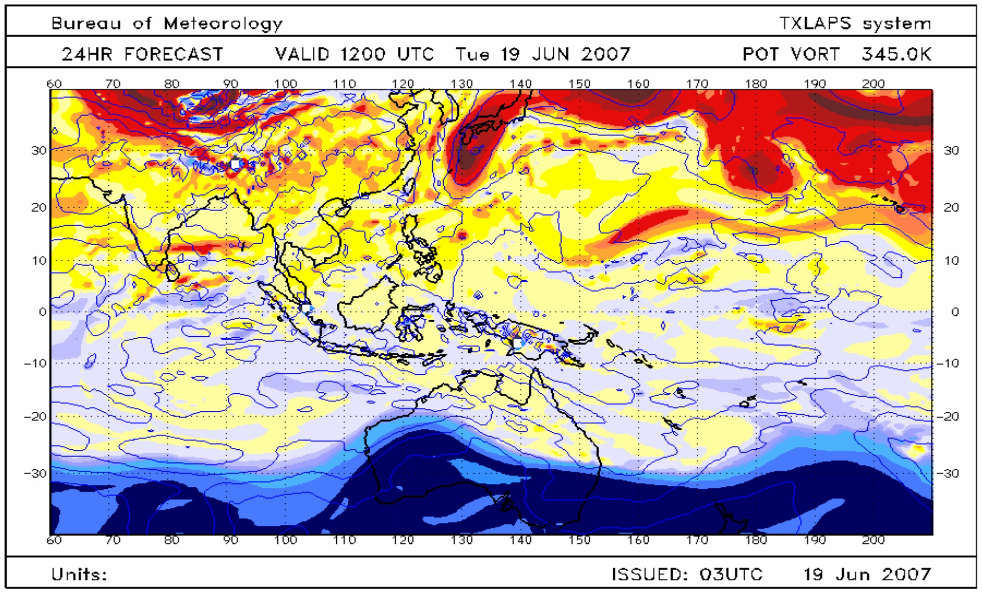


Operational products

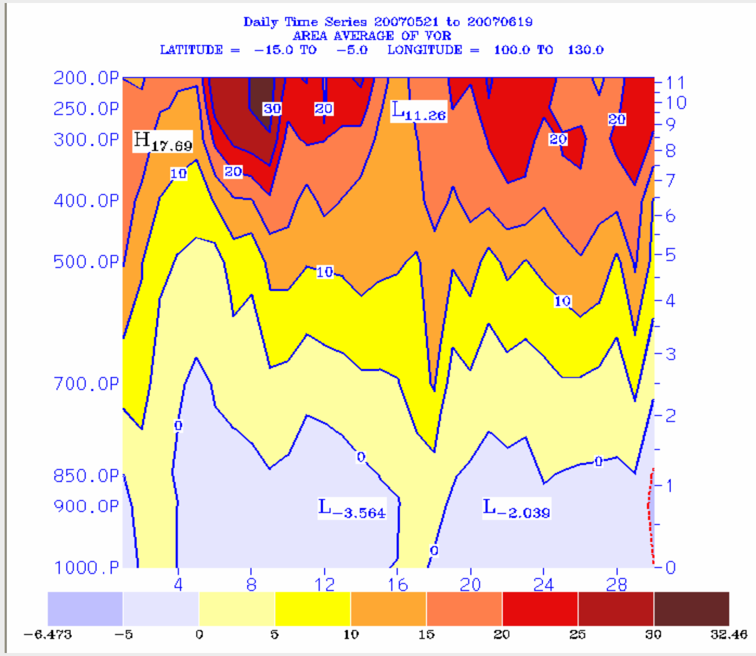




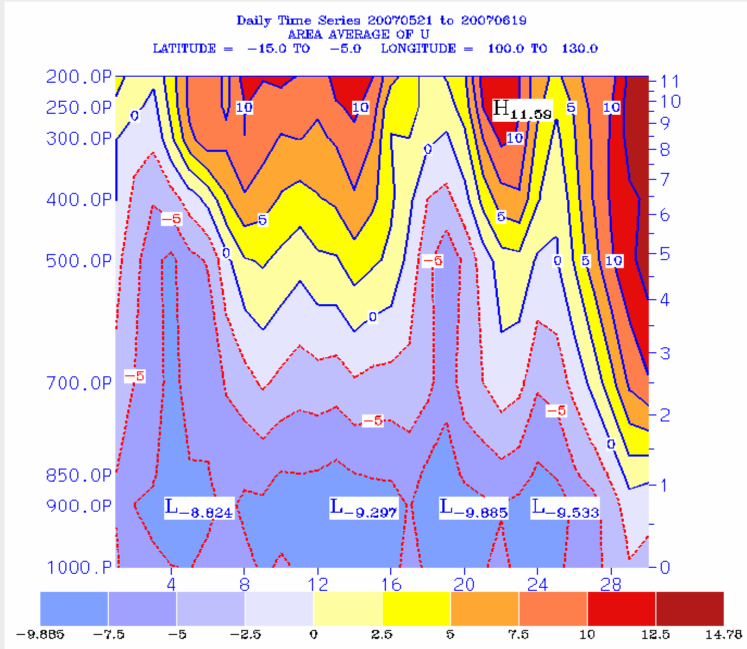




Operational products



VOR



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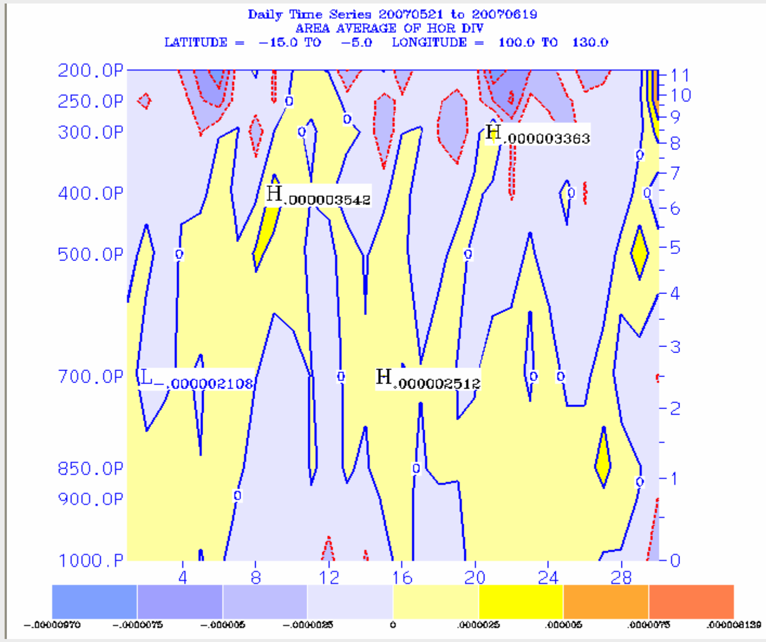

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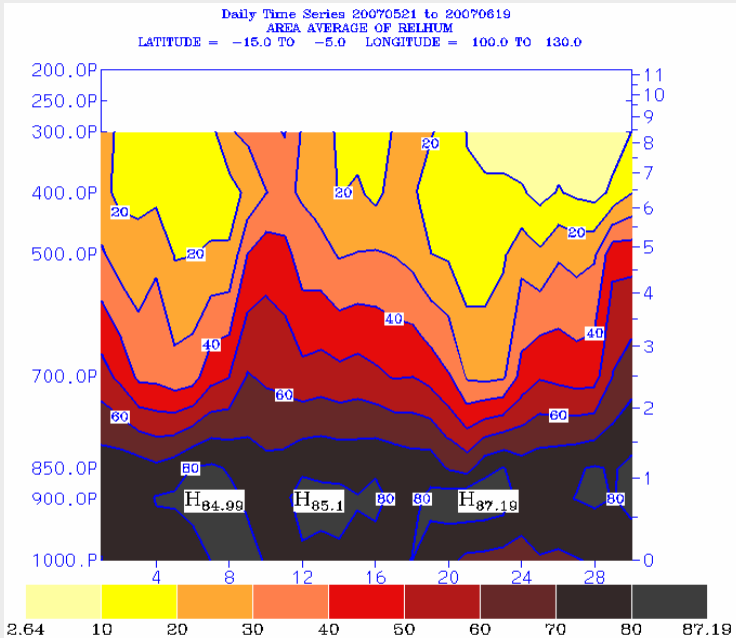


RH

TLAPS – *key issues*

- Inferring heating rates from GMS clearly has large errors in intensity
- Moisture estimates also have errors
- Current development is to assimilate information (rain rates and water vapour) from SSM-I; this will be discussed in the next lecture

TCLAPS

Tropical cyclone prediction

- Tropical cyclones represent major natural meteorological disasters affecting the tropical regions
- An average of ~10 TCs form in the Australian region during the TC season (December to March)
- They can have major impact on the mining and tourism industries
- TC prediction is therefore is an important component of the Bureau of Meteorology’s activities

Tropical Cyclone Track and Intensity Prediction

Noel Davidson, Harry Weber[1] , Kamal Puri, Peter Steinle, Lawrie Rikus, Kevin Tory, Richard Dare, Chris Tingwell, ChiMai Nguyen[2,3], Michael Reeder[3] and Joe Courtney[4]

BMRC, Melbourne, Australia

[1]Meteorological Institute, University of Munich

[2]National HydroMeteorological Service, Hanoi, VietNam

[3]School of Mathematical Sciences, Monash University, Victoria

[4]Tropical Cyclone Warning Centre, Western Australia Regional Office

** US Office of Naval Research

TC-LAPS - Operational from 1999
Davidson and Weber, 2000, MWR

TCLAPS has five major components – all are critical

1. Data assimilation to establish the storm's large scale environment (LSE) and outer structure (0.375º 51L) – from TLAPS
2. Vortex specification to construct the inner core circulation and asymmetries consistent with the estimated size, intensity and past motion, and then to relocate the circulation to the observed position

TCLAPS

3. **High resolution (HR) analysis with appropriate observation errors, length scales and quality control tolerances to merge vortex into the LSE (0.15^{o} 29L)**
4. **Initialisation with diabatic, dynamical nudging to balance the vortex using the model's dynamics, and to redefine the vertical motion to be consistent with the satellite imagery**
5. **High resolution prediction (0.15^{o} 29L)**

Vortex Specification

Construction of Symmetric Vortex

- INPUT: size (ROCI), intensity (Pc), past motion (0, -6, -12 hour locations; and LSE (Large Scale Environment) from DA
- Surface Pressure Distribution: Analytical form (Fujita, Holland, Chan and Williams), merge with LSE using SIZE ROCI.
- Assume thermal structure at storm centre is

  a moist adiabat from surface (Tc)
- Pc, Tc => Zc (geopotential height at centre of storm)
- Interpolate between Zc and Zlse using an empirical structure function and Storm Size to obtain Z
- Compute winds from Z using Gradient Wind Equation

=> Symmetric Vortex **(NO SECONDARY CIRCULATION; LACKS BALANCE BETWEEN the MASS and WIND FIELDS<<<<<)**

Nudging Initialization

```
t=-24            t=-18              t=-12             t=-6              t=0
                HRGenSI            HRGenSI           HRGenSI           HRGenSI
|-------------------|-------------------|-------------------|--------------------|---→48 hours..
```

|LAPS Forc with NI towards HR GenSI anals…………………| -→ Forecast

|…...^ GMS ^……....^ GMS ^.……......^ GMS ^.….....^ GMS ^….|

|Deep Convection only:

Rationale:

DA builds analysed rotational flows to construct LSE and outer structure of storm.

VS constructs Synthetic Vortex and merges it with LSE and outer structure from A

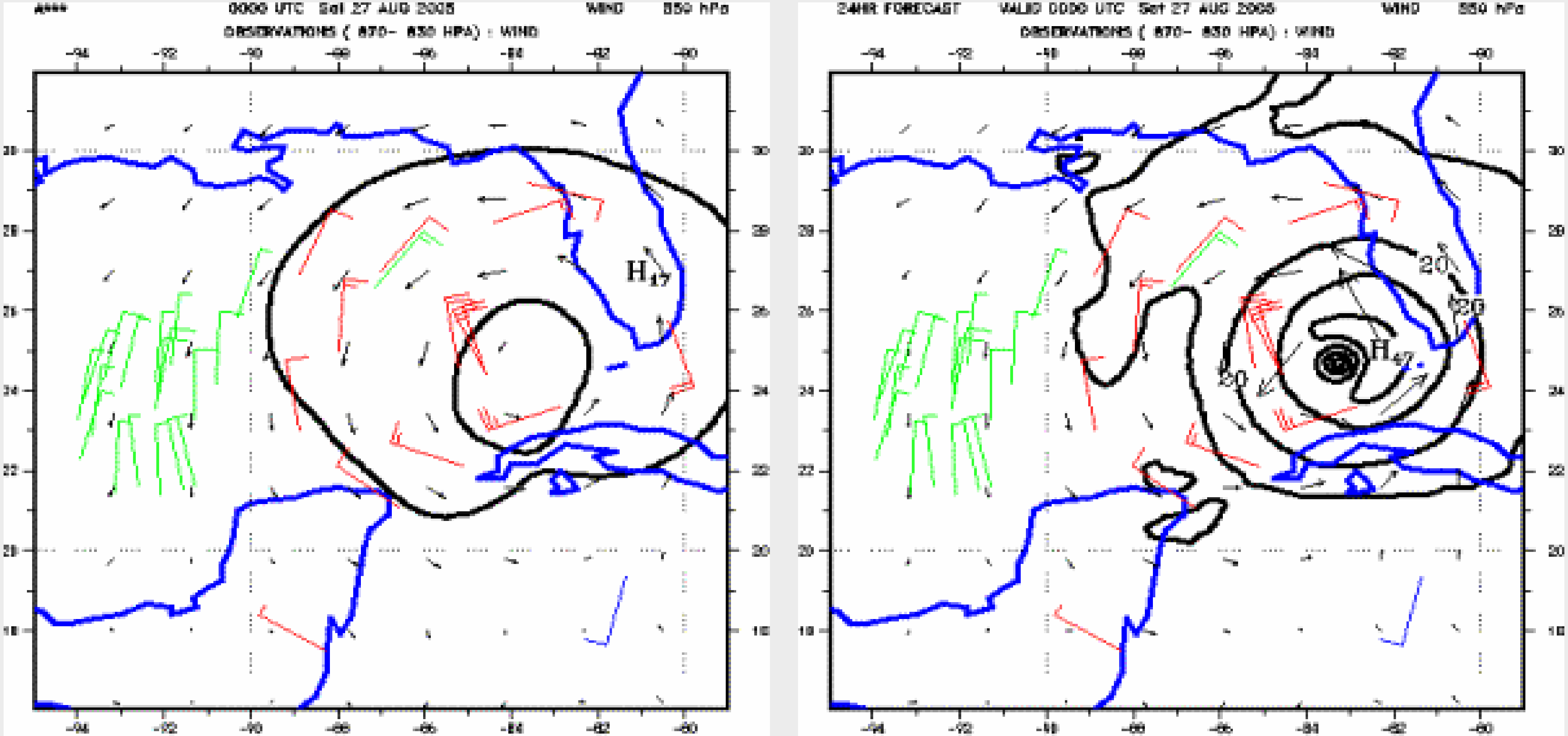
NI creates 'mesoscale balance' and local, "estimated" divergent flows, consistent with cloud imagery, while preserving rotational flows. (Insert empirical convective heating profiles in regions of satellite-observed deep convection. Model tries to remove inserted heat sources with adiabatic cooling by ascent => ascent develops where deep convective clouds are observed)

After initialization, ***if all goes to plan***, the initial condition contains a vortex with :

- An accurate analysis of the large-scale environment
- Model-balanced primary and secondary circulations,
- A primary circulation which is consistent with estimated characteristics of TC (location, size, past motion, intensity, vertical structure, RMW, …),
- A vertical motion field consistent with satellite

Unfortunately, everything does not always go to plan.

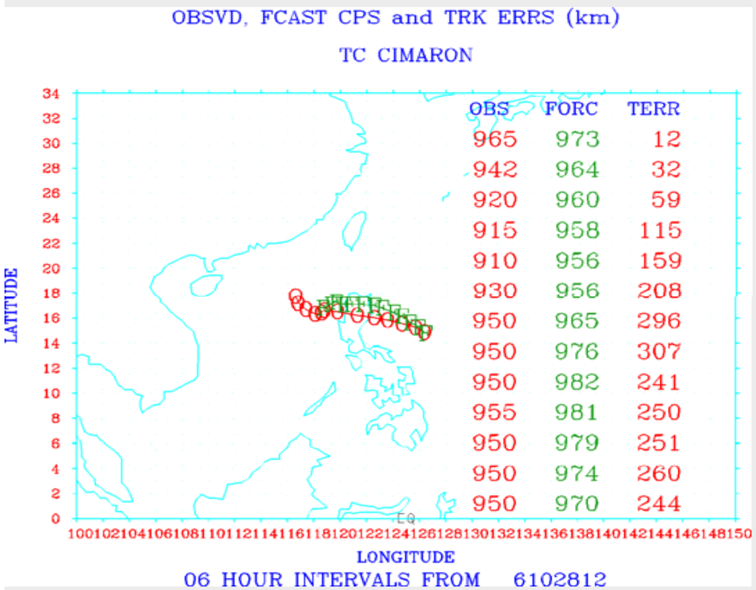
Additionally, the circulation may not fit all conventional obs!!

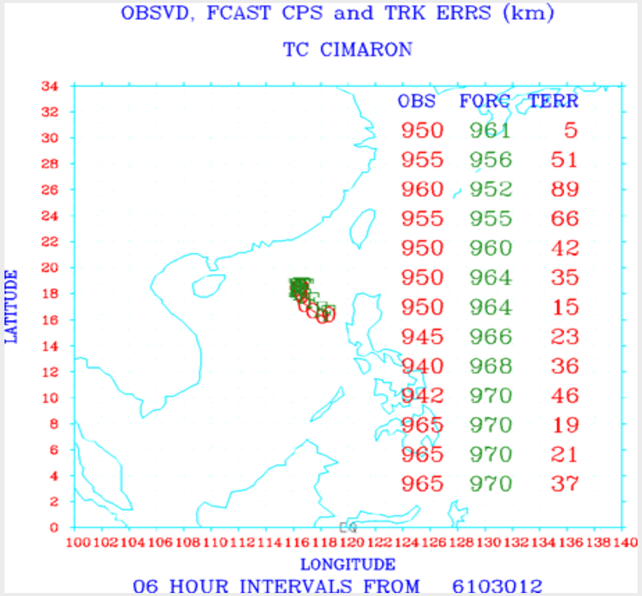


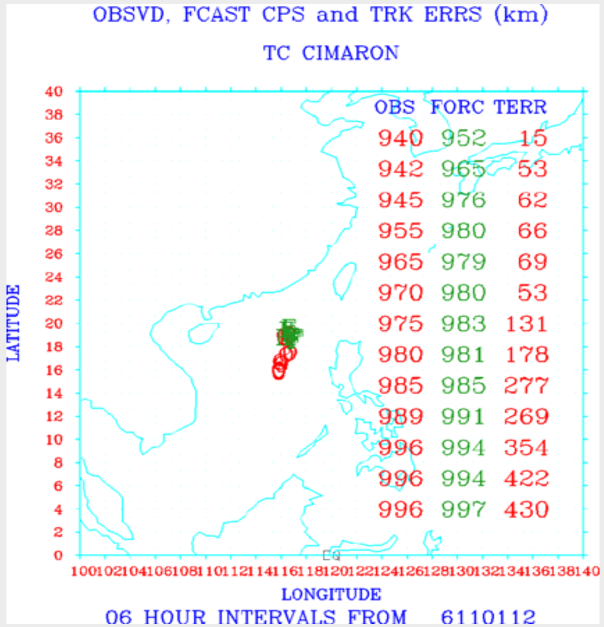
<u>Challenge</u>: Construct an intense (here, ~938 hPa) circulation,

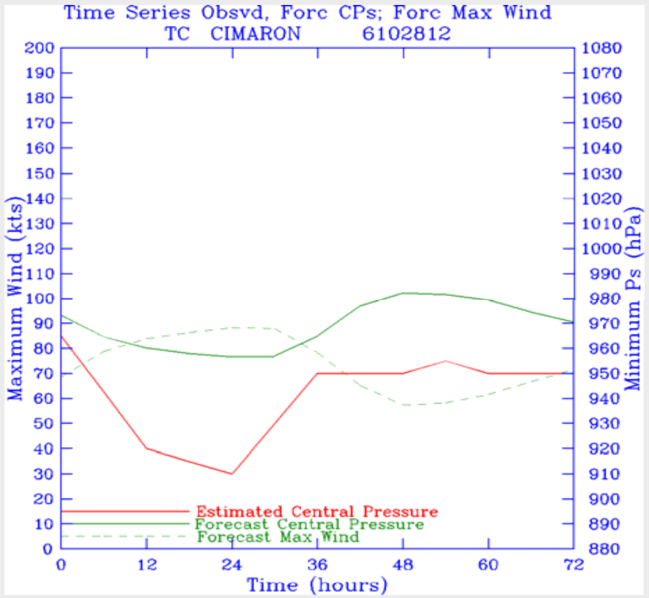
with balanced primary and secondary circulations,

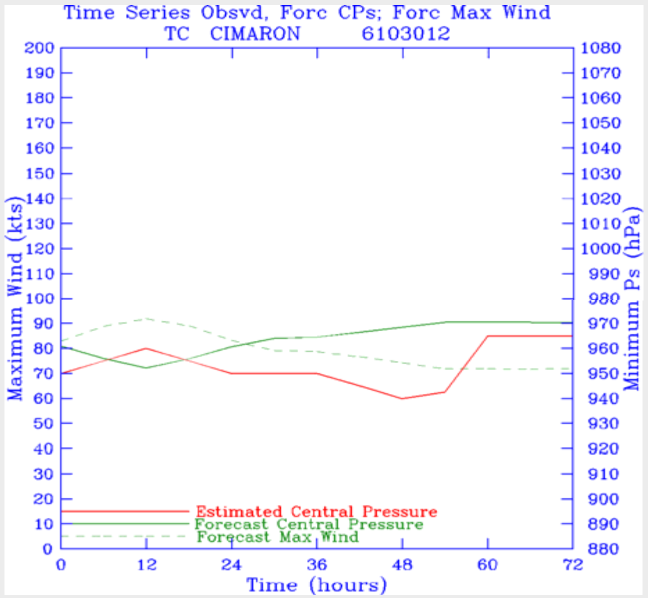
which fits the observations!!

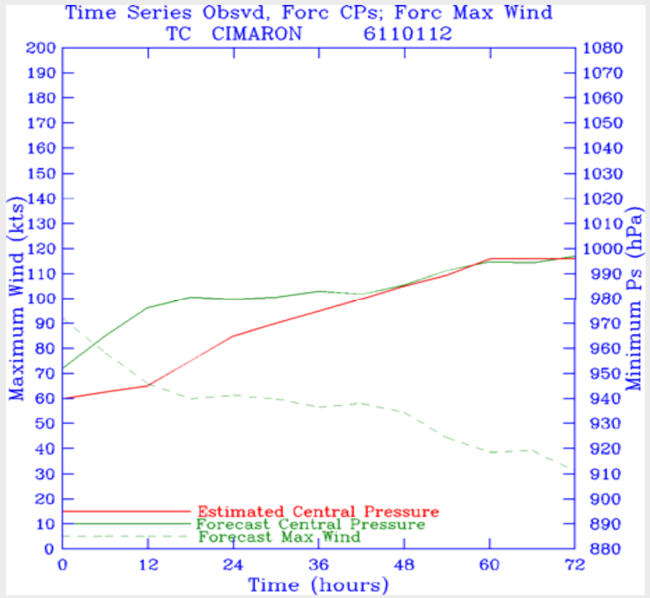

OBSVD, FCAST CPS and TRK ERRS (km)
TC CIMARON
OBS FORC TERR
965 973 12
942 964 32
920 960 59
915 958 115
910 956 159
930 956 208
950 965 296
950 976 307
950 982 241
955 981 250
950 979 251
950 974 260
950 970 244
LATITUDE
LONGITUDE
06 HOUR INTERVALS FROM 6102812


OBSVD, FCAST CPS and TRK ERRS (km)
TC CIMARON
OBS FORC TERR
950 961 5
955 956 51
960 952 89
955 955 66
950 960 42
950 964 35
950 964 15
945 966 23
940 968 36
942 970 46
965 970 19
965 970 21
965 970 37
LATITUDE
LONGITUDE
06 HOUR INTERVALS FROM 6103012

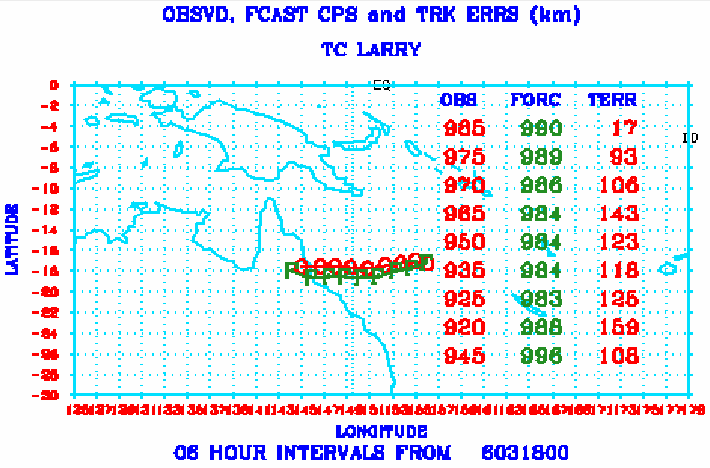

OBSVD, FCAST CPS and TRK ERRS (km)
TC CIMARON
OBS FORC TERR
940 952 15
942 965 53
945 976 62
955 980 66
965 979 69
970 980 53
975 983 131
980 981 178
985 985 277
989 991 269
996 994 354
996 994 422
996 997 430
LATITUDE
LONGITUDE
06 HOUR INTERVALS FROM 6110112

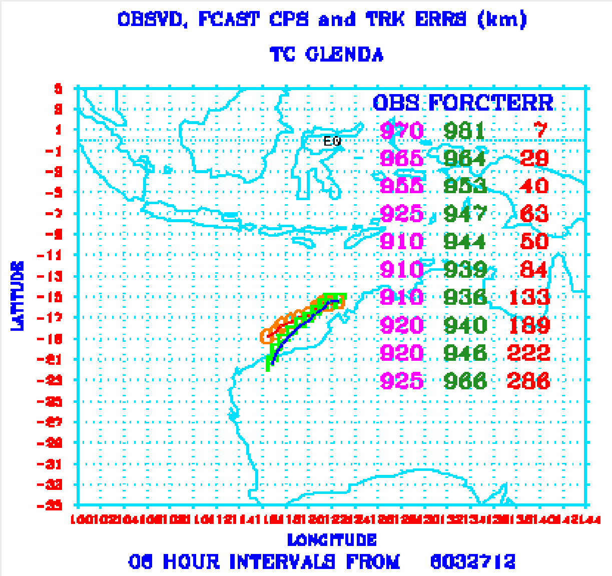

Time Series Obsvd, Forc CPs; Forc Max Wind
TC CIMARON 6102812
Maximum Wind (kts)
Minimum Ps (hPa)
Estimated Central Pressure
Forecast Central Pressure
Forecast Max Wind
Time (hours)

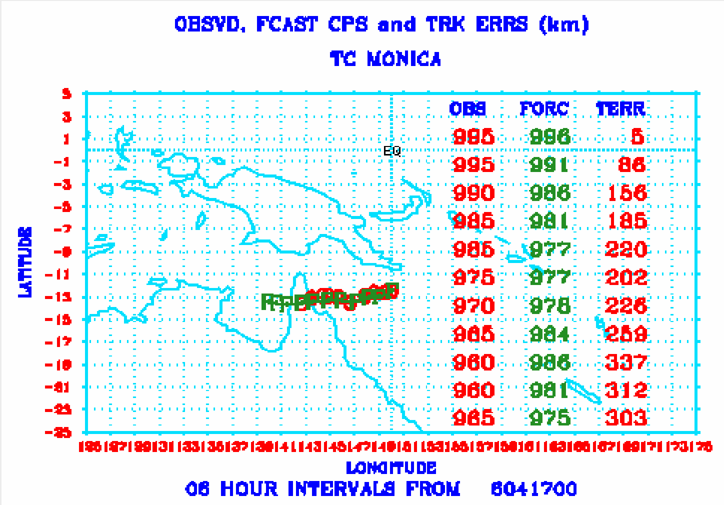

Time Series Obsvd, Forc CPs; Forc Max Wind
TC CIMARON 6103012
Maximum Wind (kts)
Minimum Ps (hPa)
Estimated Central Pressure
Forecast Central Pressure
Forecast Max Wind
Time (hours)

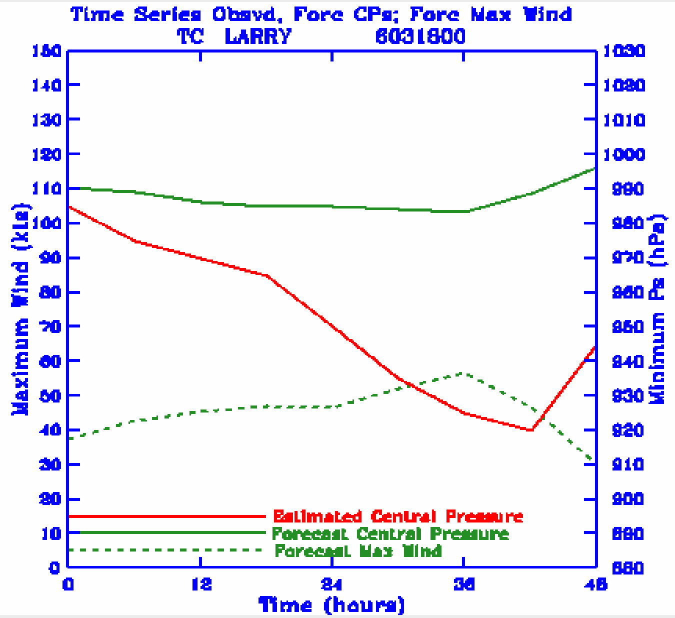

Time Series Obsvd, Forc CPs; Forc Max Wind
TC CIMARON 6110112
Maximum Wind (kts)
Minimum Ps (hPa)
Estimated Central Pressure
Forecast Central Pressure
Forecast Max Wind
Time (hours)

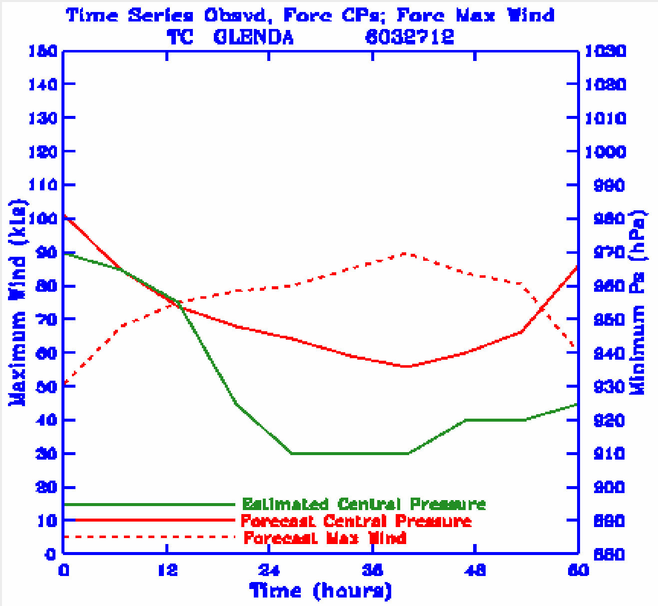
Operational TC-LAPS Forecasts for Larry, Glenda and Monica

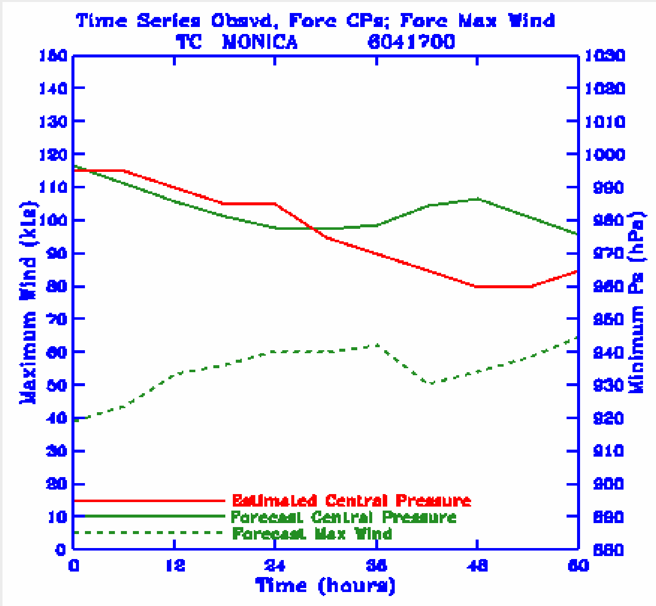












VERIFICATION OF TC-LAPS : Australian Region 2004-2005

- **Forecast model initialized and verified against AR Operational Track Data**

	t = 00 hrs	t = 24 hrs	t = 48 hrs	t = 72 hrs
Mean Direct Position Error (kms)	14.7	148.9	245.1	361.6
Mean Abs Central Pressure Error (hPa)	6.1	13.0	17.6	21.6
Number of forecasts	62	56	43	31

	0-100	100-200	200-300	300-400	400-500	500-600	600-700
No of 48 hour errors in 100km bins	7	9	13	11	2	0	1

- **Quite competitive for track and intensity.**
- **Major Errors : At 48 hours , ~ 1 BUSTS (> 500km).**
  Related to (a) Initial Vortex Structure, and/or (b) Analysis and Forecasts of the Large Scale Environment (DA).
- **Systematic Errors : Westward and Poleward Bias . Underestimation of Intensity (Central Pressure). Unusual Behaviour around Coast.**

TC STRUCTURE

NW Pacific Storms : Podul, Fengshen, Fung-Wong, Rammasun, Utor

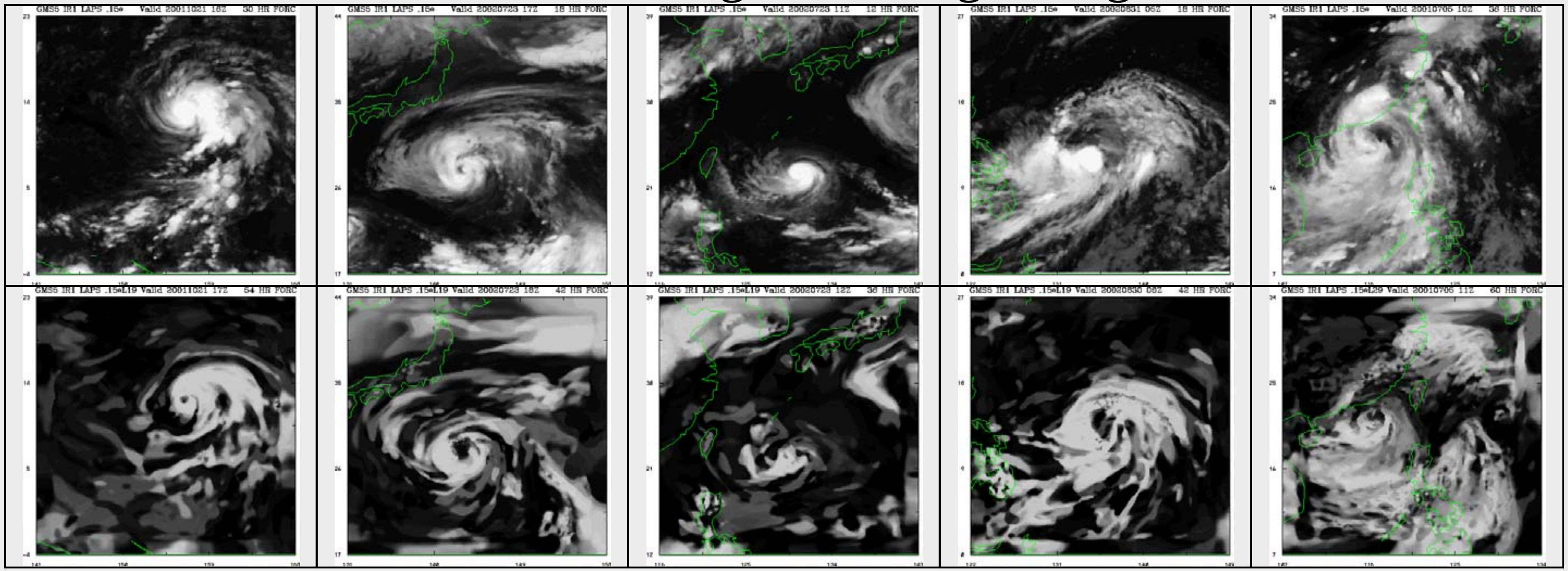
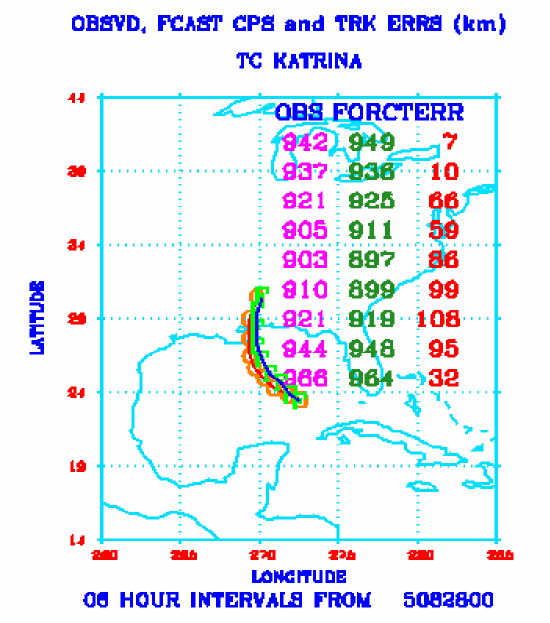
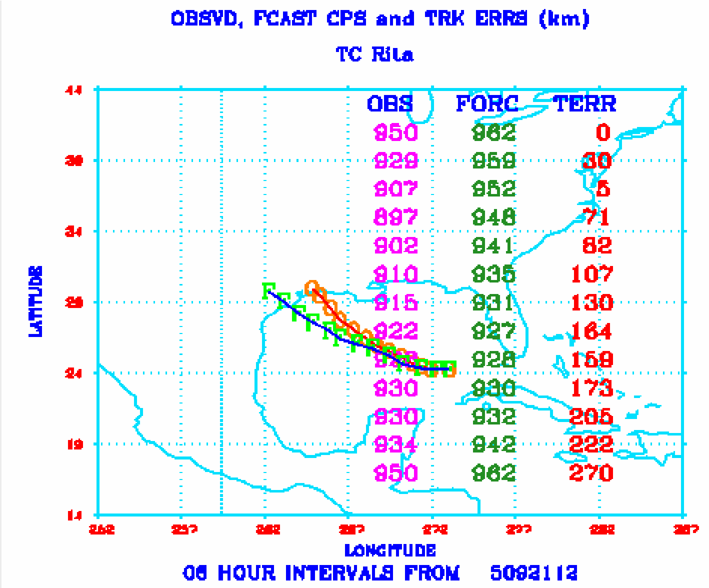
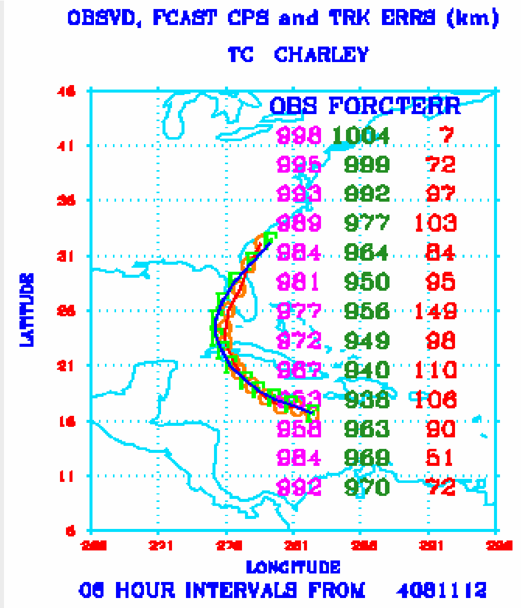
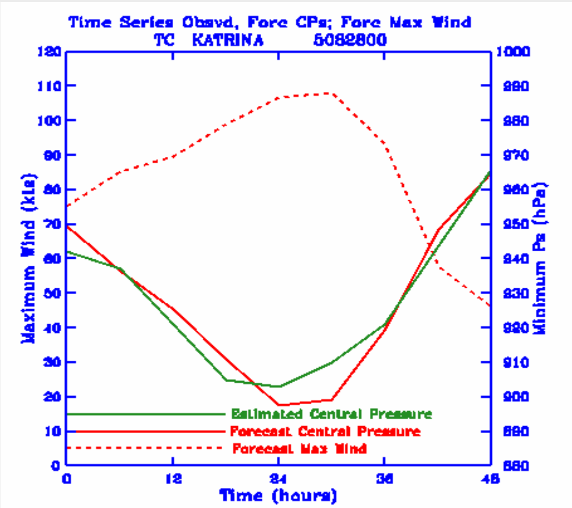


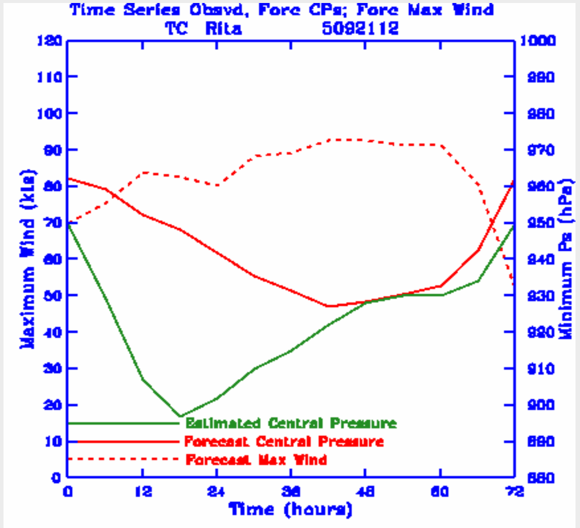
Figure 1 : Actual satellite cloud imagery from GMS (top panels), and (lower panels) corresponding synthetic cloud imagery **(Rikus and Sun, 2004)** from operational TC-LAPS for TCs Podul (30 hour forecast), Fengshen (18 hour), Fung-Wong (12 hour), Rammasun (18 hour), Utor (36 hour)

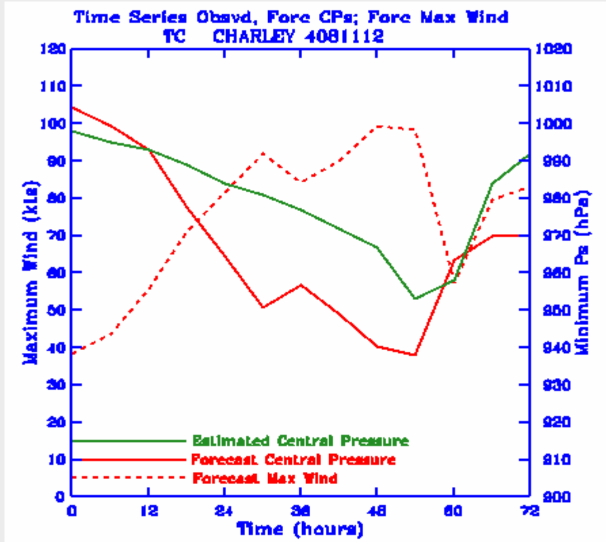












****Good OBS NETWORK + sophisticated High-Resolution Modelling System = well-defined LS Environment + consistent, well-defined Vortex Structure**

=> Some skill in Intensity Forecasts!!

Forecast Duration (hrs)	0	24	48	72
#Forecasts	39	39	34	27
MDPE (nm)	5	54	104	169
MAIE (knots)	0	12	16	20

Table 1. Verification statistics for forecast sample. MDPE is Mean Direct Position Error in nm. MAIE is Mean Absolute Intensity Error in knots (corrected by initial intensity error).

(Wilma, Rita, Katrina, Ivan, Charley, Jeanne, Dennis)

Ensemble prediction

Application to TC track prediction

Ensemble Prediction

- Ensemble prediction has become an established part of operational global weather (and seasonal) prediction at a number of Centres such as CMA, CMC, ECMWF, JMA, NCEP)
- A global EPS is used operationally at the Australian Bureau of Meteorology
- A limited area EPS is being run experimentally at the Australian Bureau of Meteorology
- Multi-model multi-analysis “Poor Man’s” ensembles are being studied at a number of Centres such as BMRC (Ebert), UKMO

Source of uncertainties

The following factors lead to uncertainties in analyses and forecasts -

- **Errors in observations**
- **Errors in analyses**
- **Model errors - dynamics and physical parameterisations**
- **Additionally, in limited area systems, errors in lateral boundary systems**

Since the aim of ensemble prediction is to provide an indication of magnitude of these errors (*spread in forecasts*), it needs to take account of these factors

Applications of EPS

- As a measure of predictability
- As an indicator of possible alternative developments

  Clustering, Tubing
- To produce local probabilistic forecasts of weather parameters
- Economic value of EPS

  Using a simple cost/loss ratio (C/L) decision model, one can compute the expense associated with different decision-making strategies

Applications of EPS

- Meteograms
- Ensemble data assimilation - New J_B
- Ensembles using multiple models/analyses
- Hessian SVs - Reduced-rank Kalman filter
- Tropical cyclone track prediction

TC track prediction

Inspite of the impressive progress made in TC track prediction, a number of problems remain

- There can be considerable variability in performance of models
- For a particular TC there can be a large variation of tracks from one day to the next
- Thus a major problem facing a forecaster is lack of information on reliability and error bars for a particular track forecast

Ensemble prediction provides one possible means of addressing track uncertainty

Ensemble Prediction

- Most EPS have been designed for application to the extra-tropics
- Some systems do not even include perturbations in the tropics and as such are not of much use in the tropics
- We will now present examples of ensemble systems designed for applications to the tropics

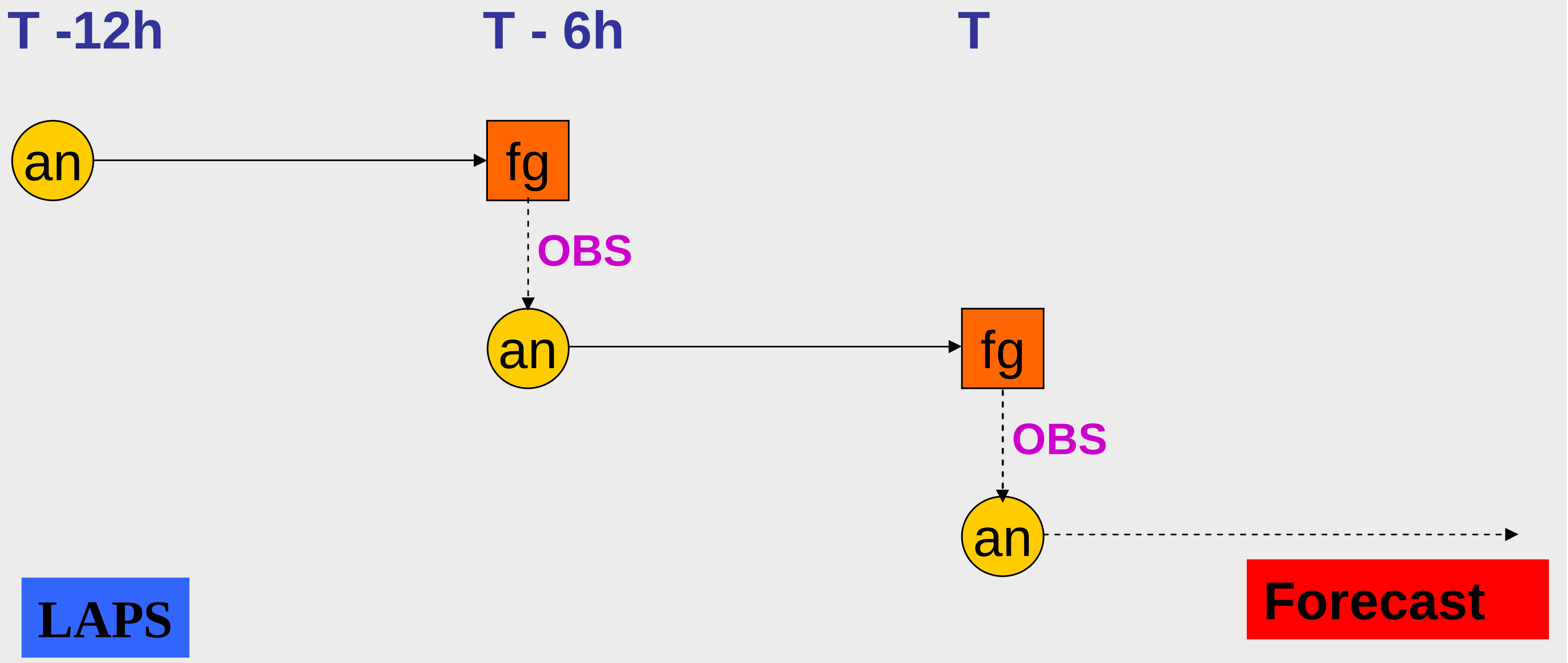
TC EPS

There are inevitable uncertainties in TC track prediction resulting from:

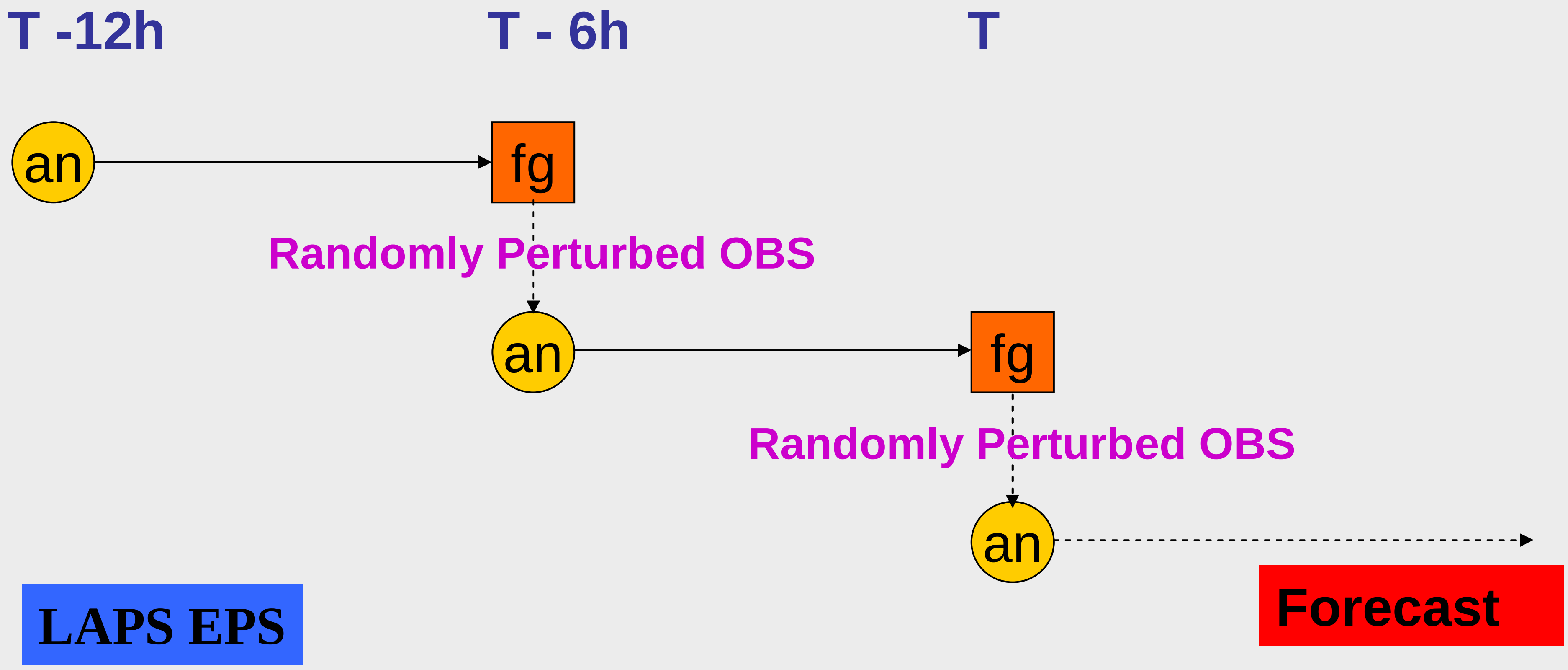
- Insufficient observations
- Observation errors
- Model errors

The Bureau’s LAPS EPS attempts to provide an indication of the uncertainty in track prediction

Bureau’s operational LAM



Bureau's LAM EPS

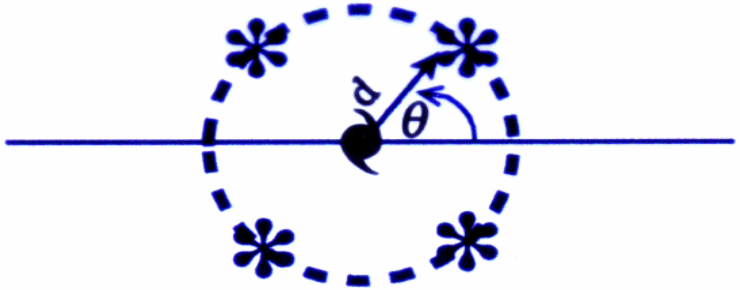


Perturbations to TC Structure for Ensemble Prediction

Location Change

d ~ 50km

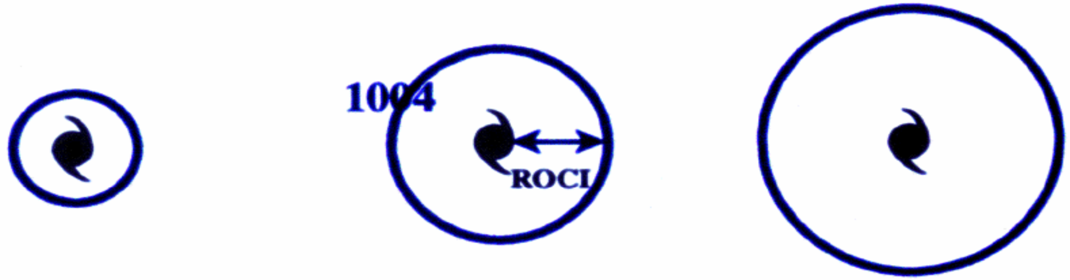
θ ~ N x 45^0



Size Change

Radius of Outer Closed Isobar

ΔROCI ~ 80km



Drift Speed change

% of estimated

ΔV ~ 50%

Drift Direction Change

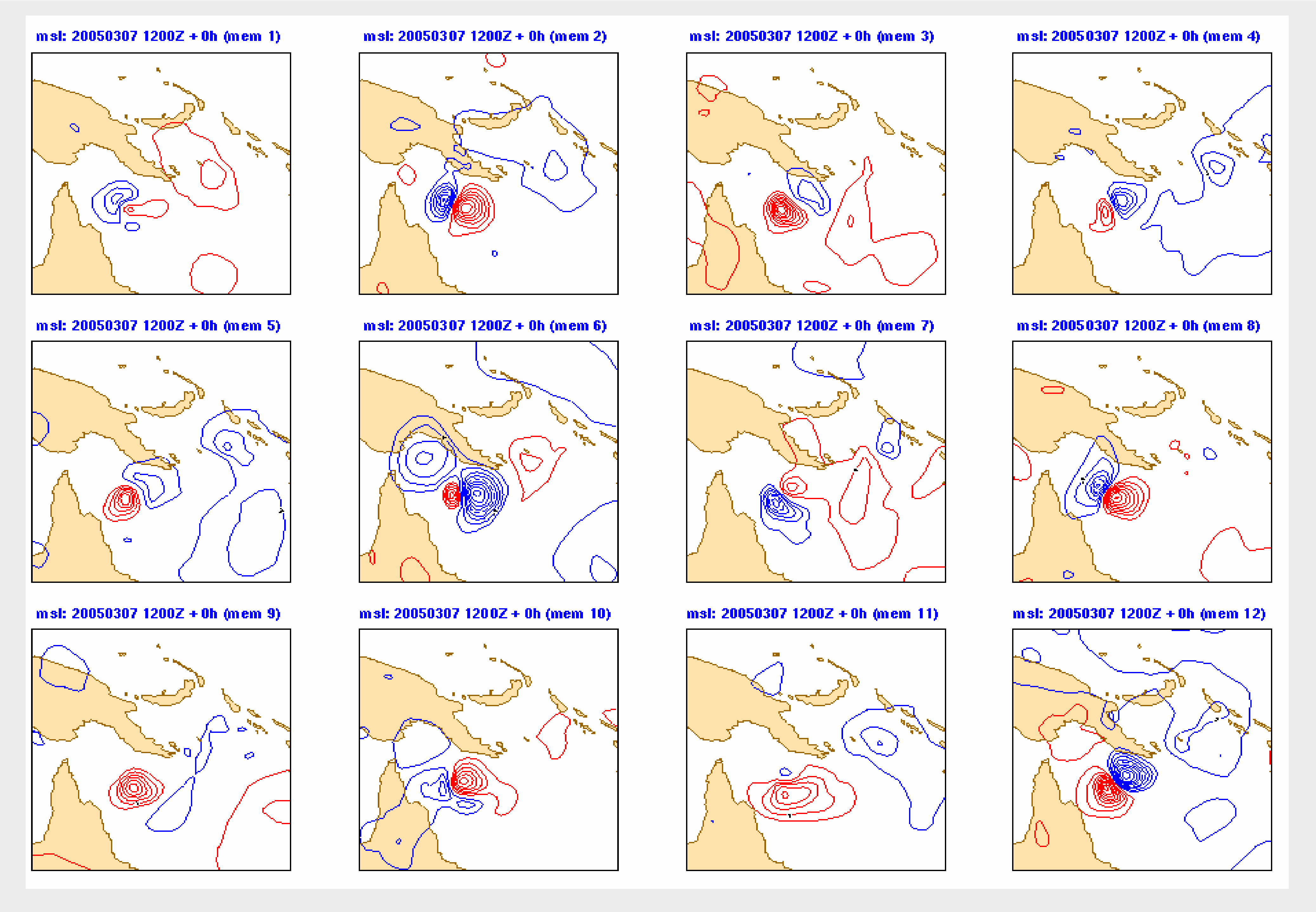
Deviation relative to estimated

$\Delta\theta$ ~ 45^0

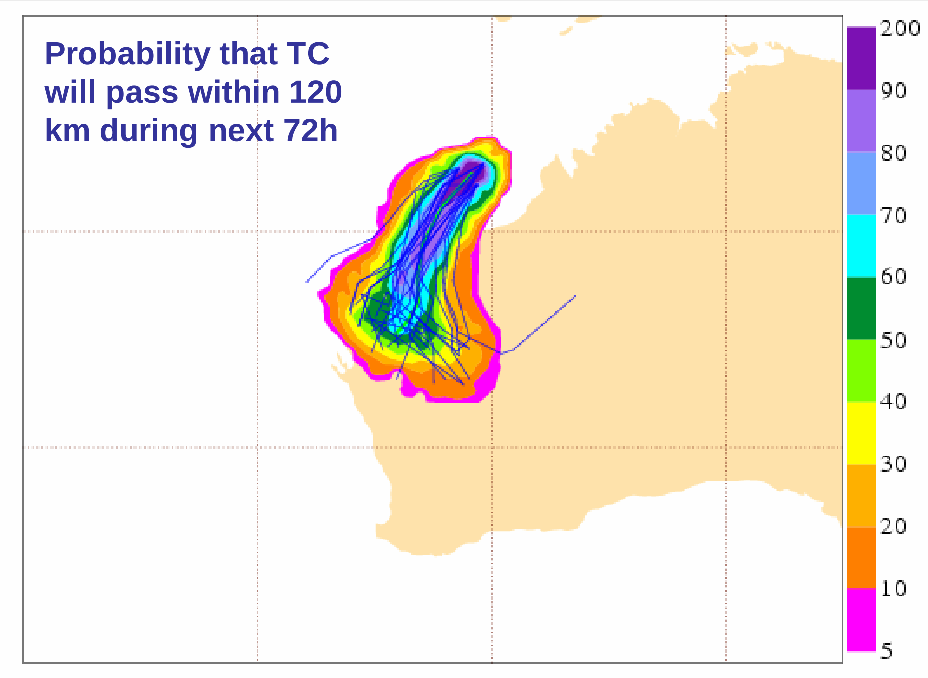
Bureau LAM EPS

The LAM EPS is run in the following configuration:

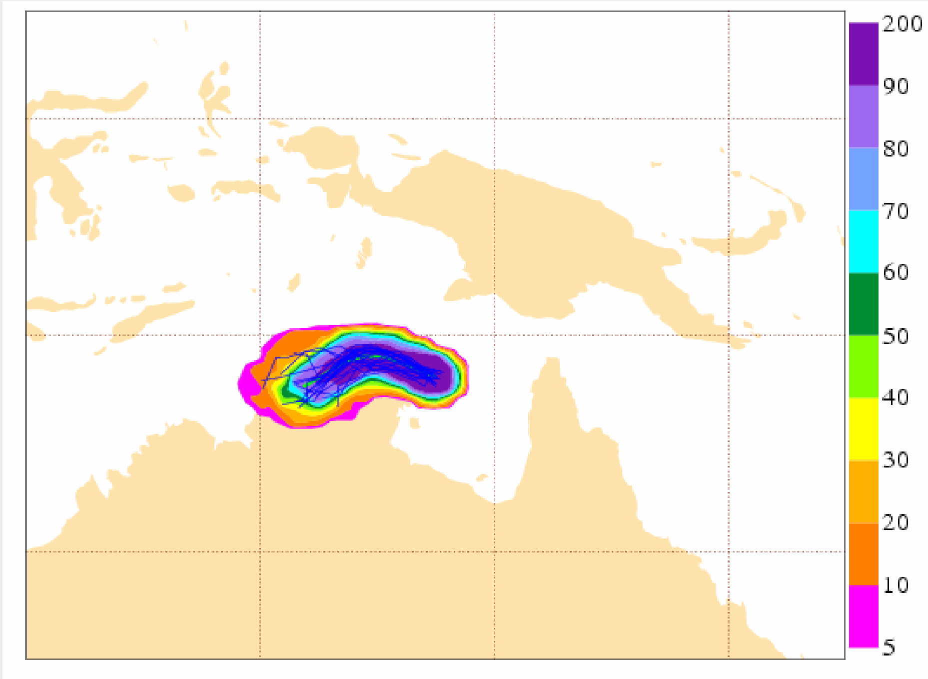
- $0.5^o x 0.5^o$ with 29 levels
- 24 members
- Random perturbation of observations to generate initial perturbations
- Stochastic physics following ECMWF approach
- EPS forecasts run to 72 hours once per day (12UTC)

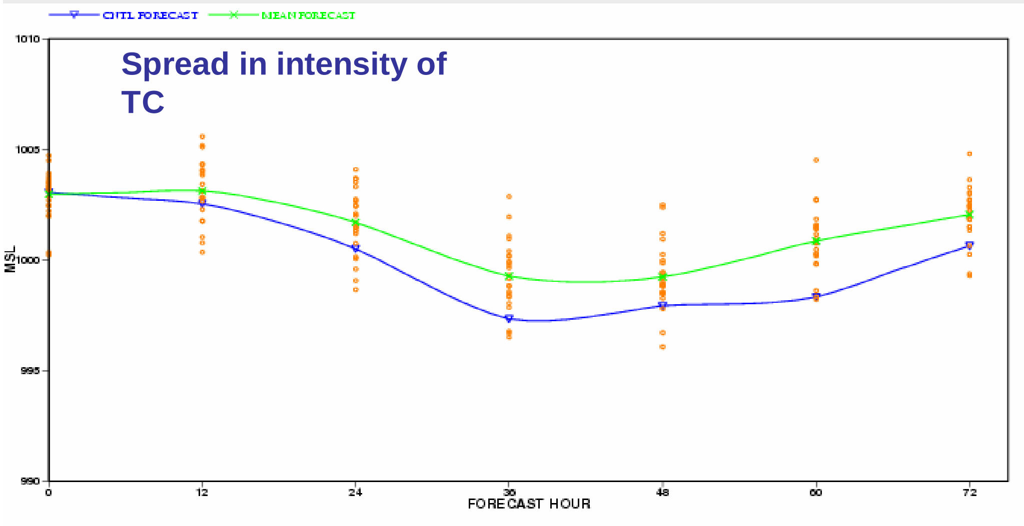

msl: 20050307 1200Z + 0h (mem 1)
msl: 20050307 1200Z + 0h (mem 2)
msl: 20050307 1200Z + 0h (mem 3)
msl: 20050307 1200Z + 0h (mem 4)
msl: 20050307 1200Z + 0h (mem 5)
msl: 20050307 1200Z + 0h (mem 6)
msl: 20050307 1200Z + 0h (mem 7)
msl: 20050307 1200Z + 0h (mem 8)
msl: 20050307 1200Z + 0h (mem 9)
msl: 20050307 1200Z + 0h (mem 10)
msl: 20050307 1200Z + 0h (mem 11)
msl: 20050307 1200Z + 0h (mem 12)

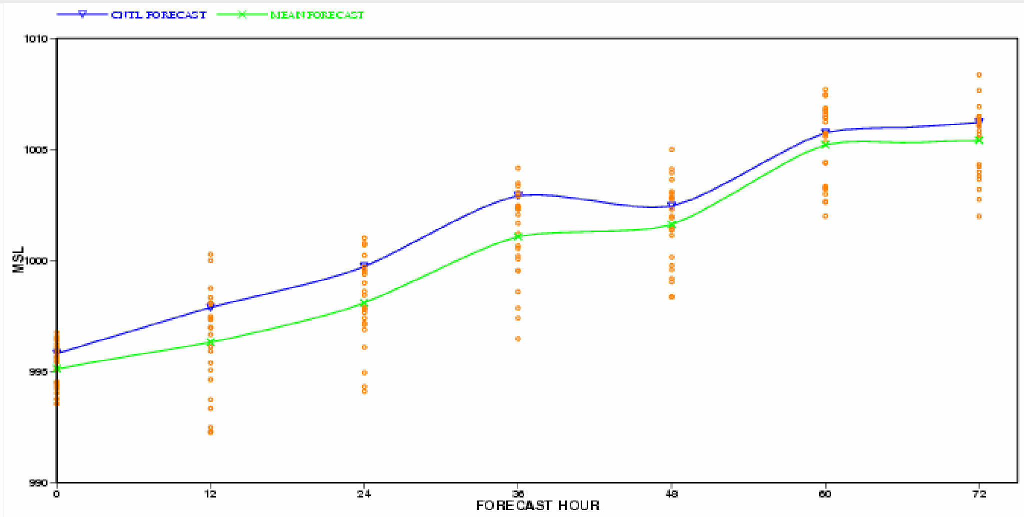
TC Clare



TC Ingrid





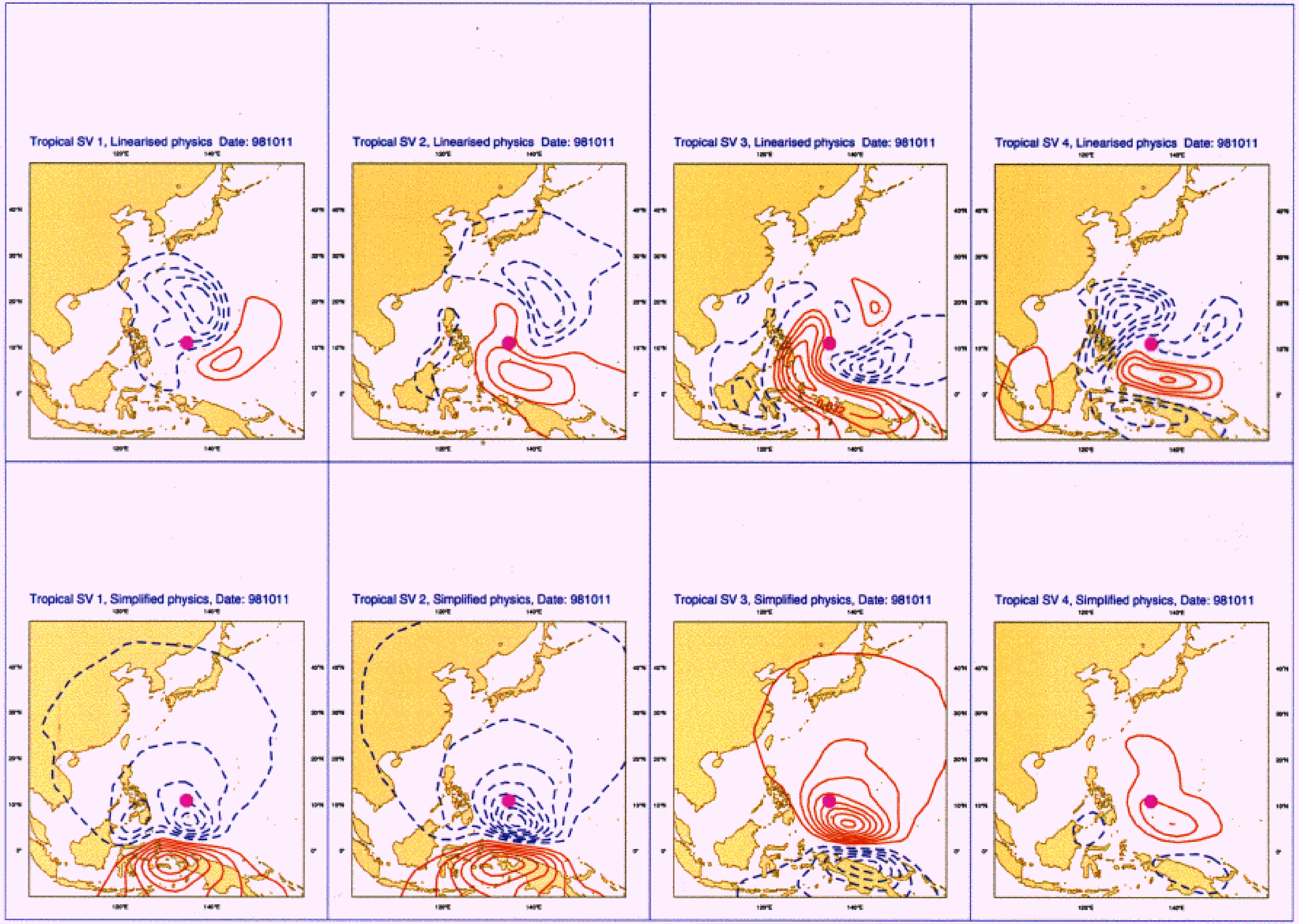


ECMWF EPS for TC applications

The ECMWF includes the following specific features for TCs

- Use of **diabatic SVs** computed using a **linearised full physics** when a TC is present

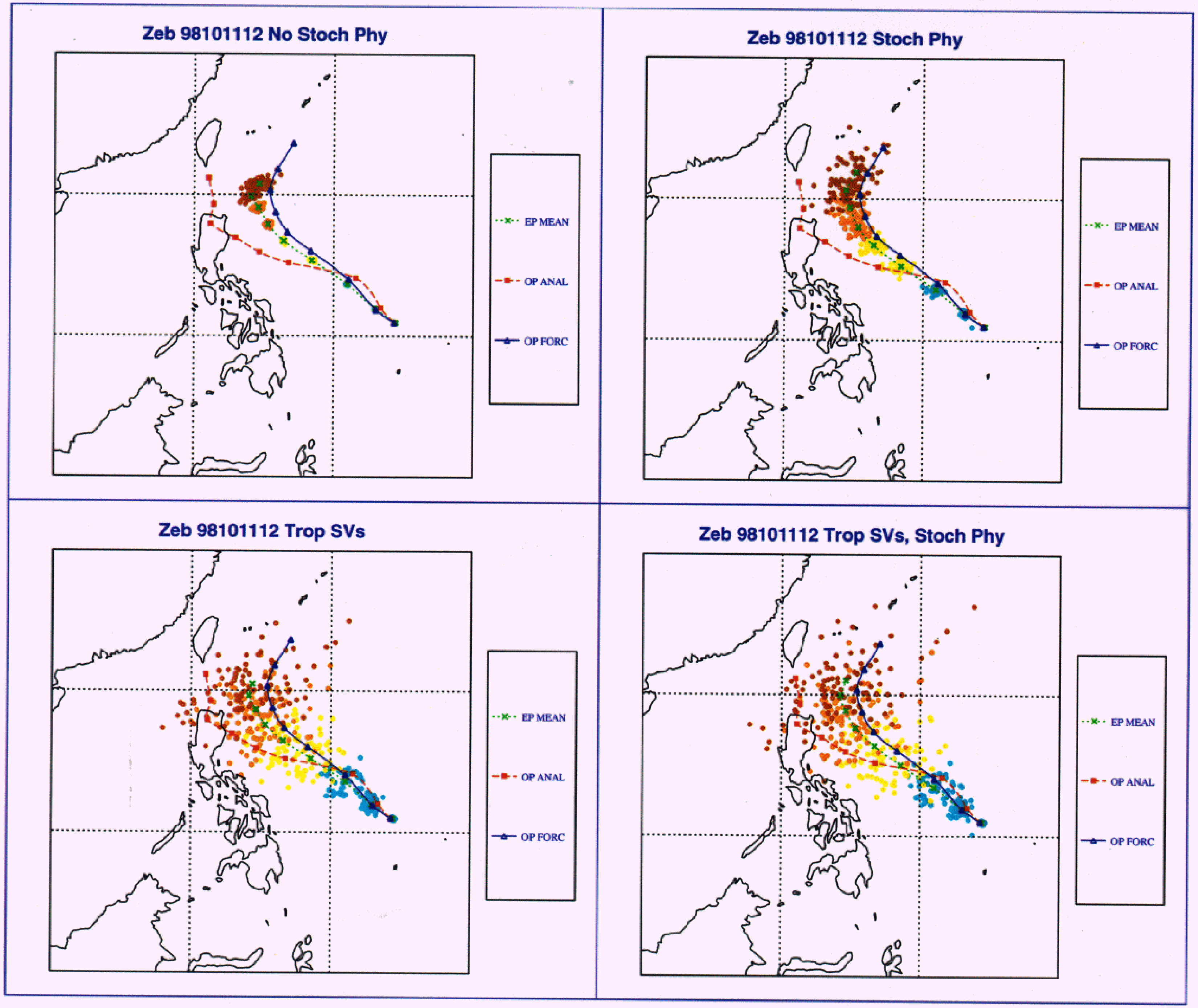
  The linearised full physics includes *vertical diffusion, gravity wave drag, large-scale condensation, deep cumulus convection and long wave radiation*
- SVs are **targetted** in a region surrounding the TC
- Stochastic physics (which is not TC-specific) leads to larger spread in the central pressures



Linearised full physics

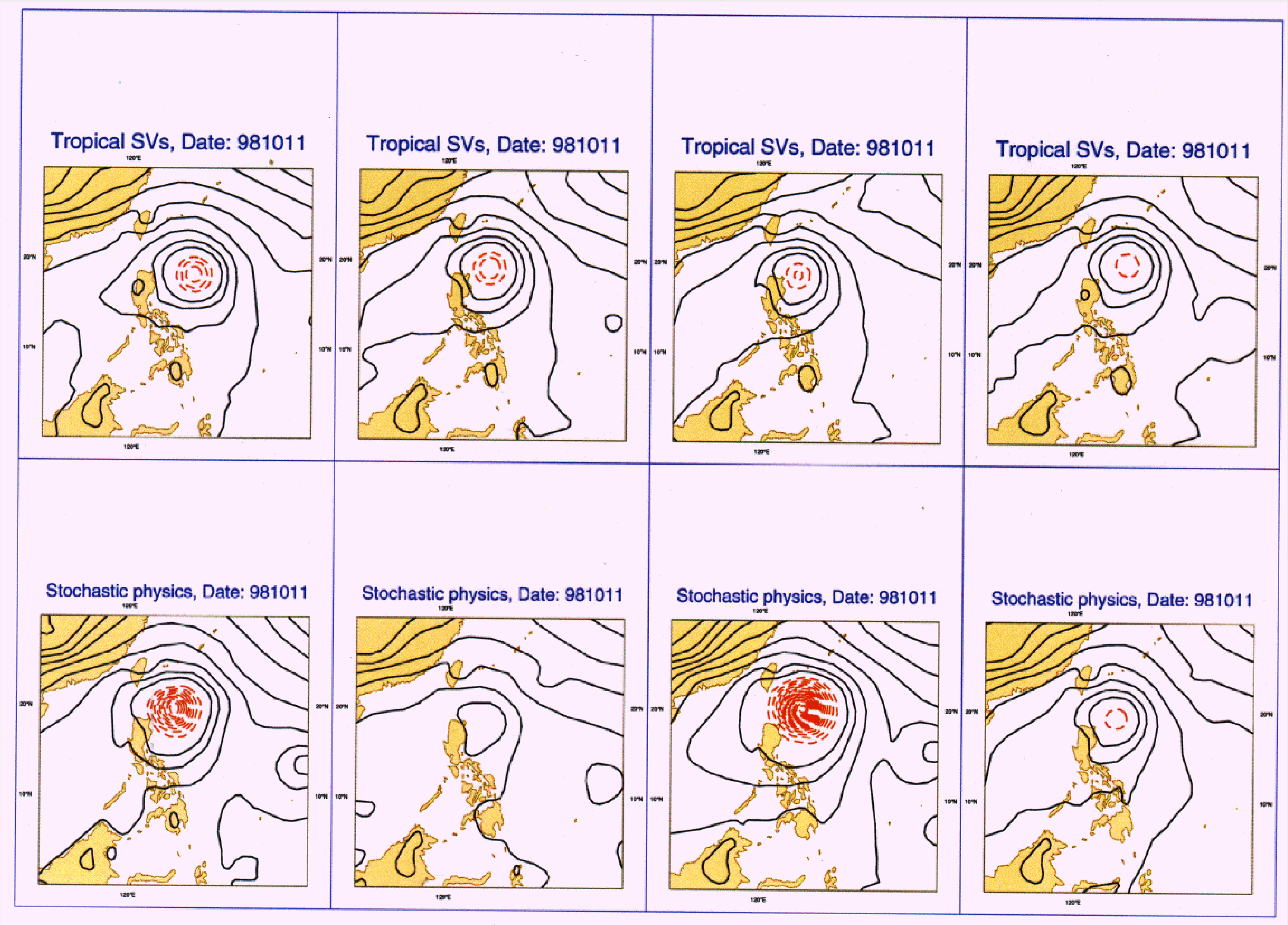
Linearised full physics

ECMWF EPS Perturbations using targeted diabatic SVs


Zeb 98101112 No Stoch Phy
EP MEAN
OP ANAL
OP FORC
Zeb 98101112 Stoch Phy
EP MEAN
OP ANAL
OP FORC
Zeb 98101112 Trop SVs
EP MEAN
OP ANAL
OP FORC
Zeb 98101112 Trop SVs, Stoch Phy
EP MEAN
OP ANAL
OP FORC

ECMWF
EPS

Impact of stochastic physics in ECMWF EPS

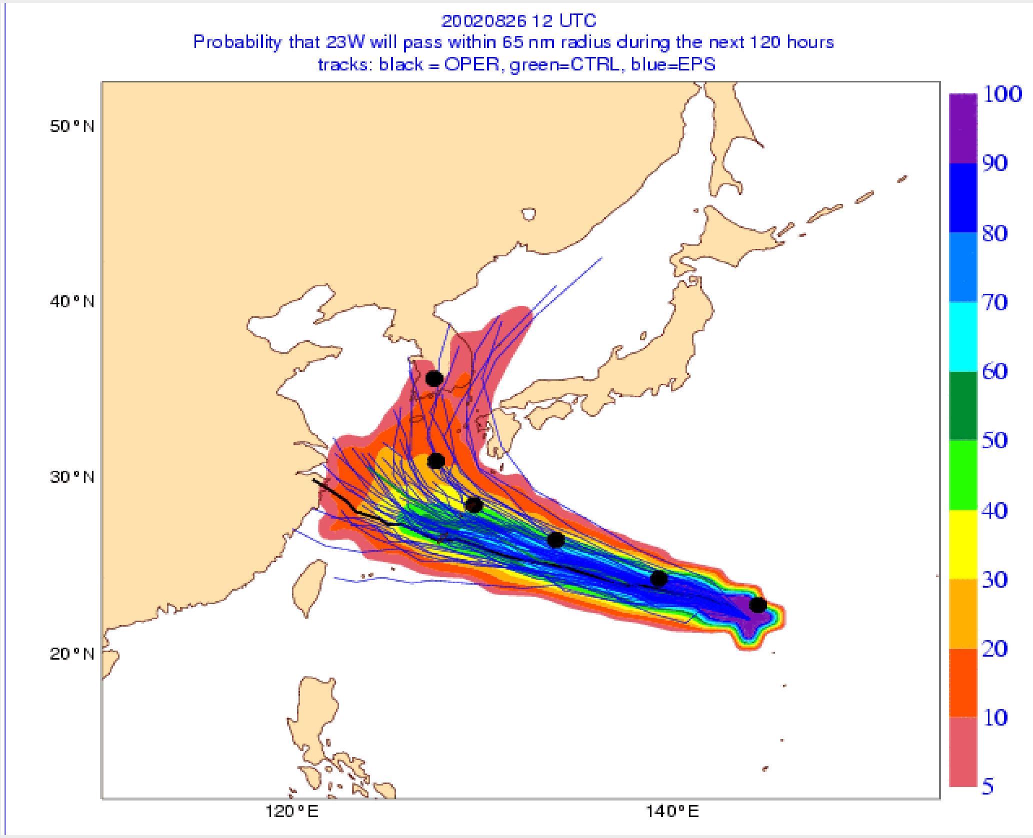


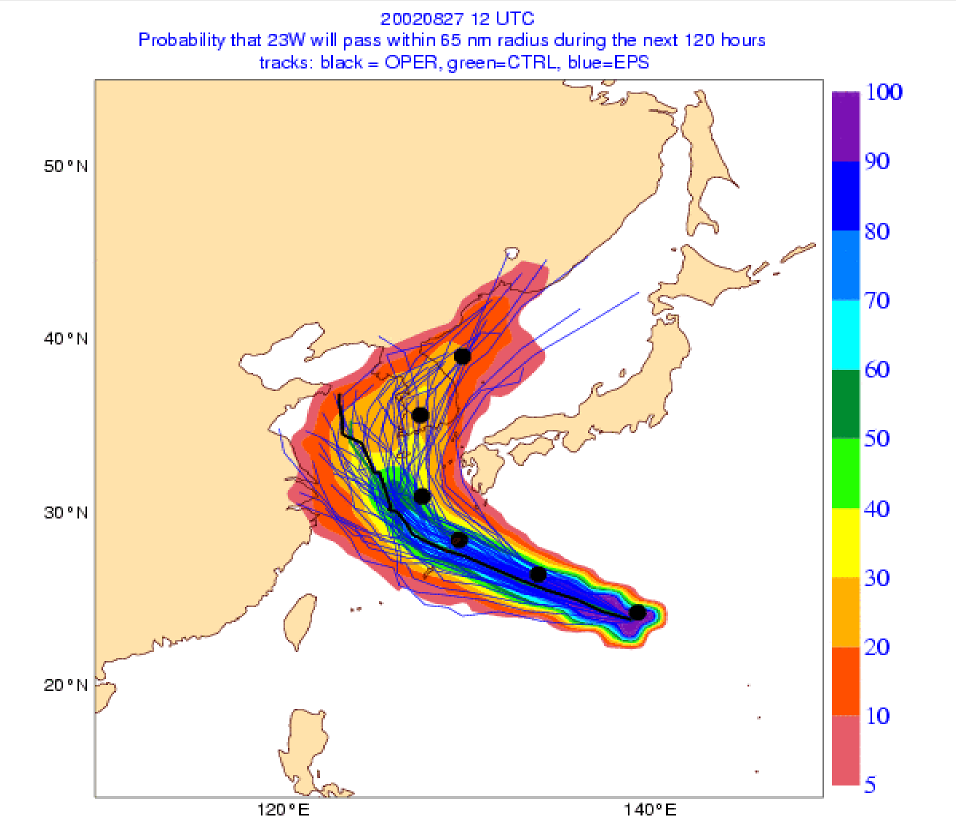
No SP

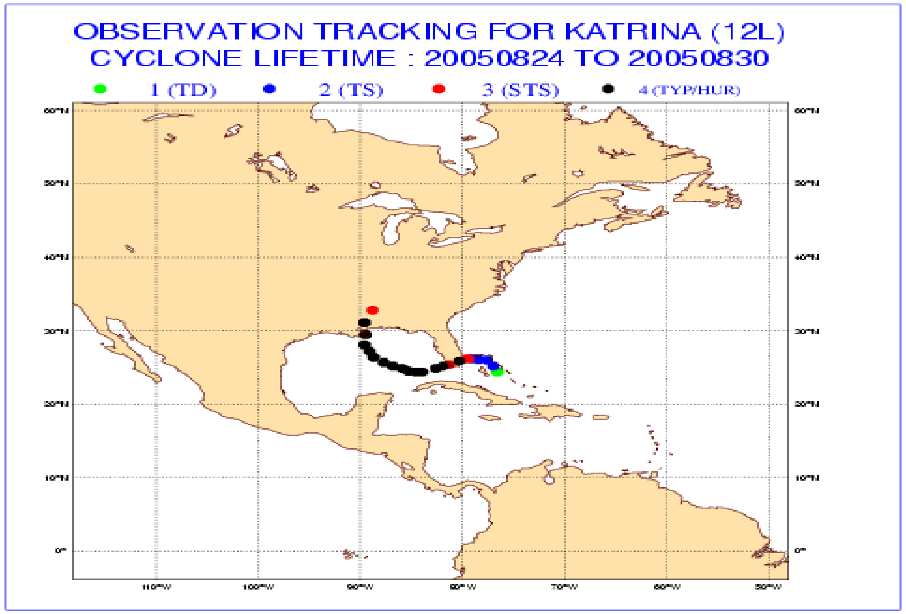
With SP

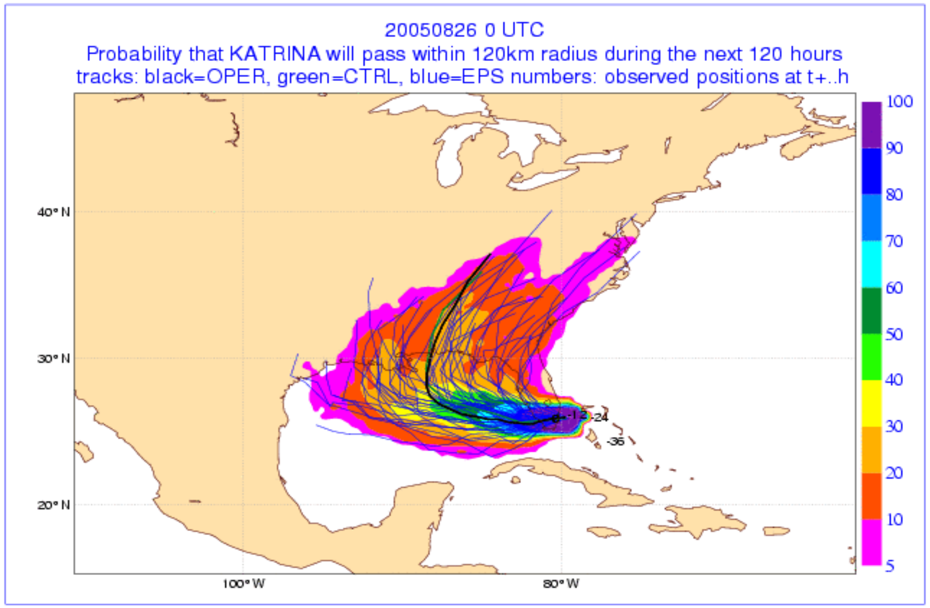
Typhoon Rusa

Strike probability for next 120 hours starting 26 and 27 Aug 2002 12 UTC

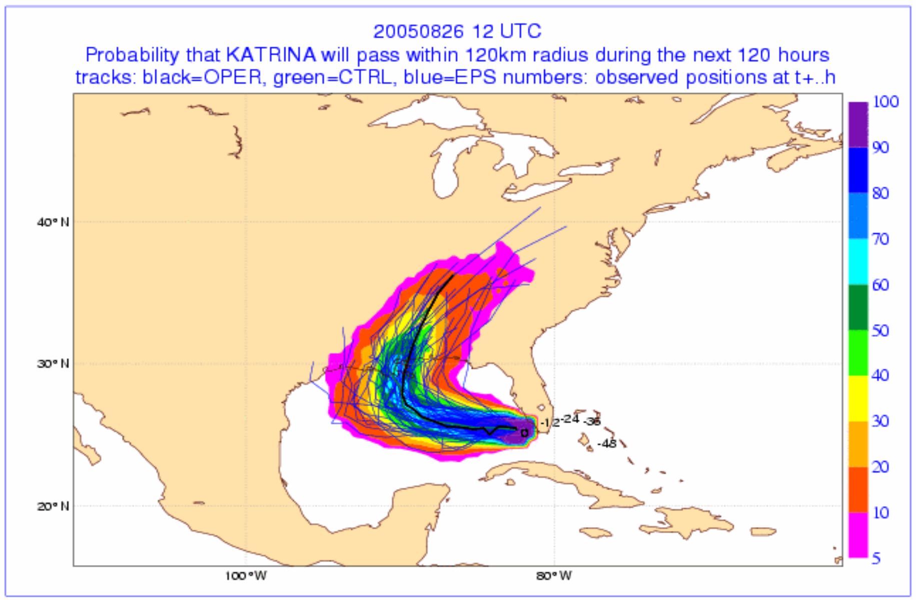




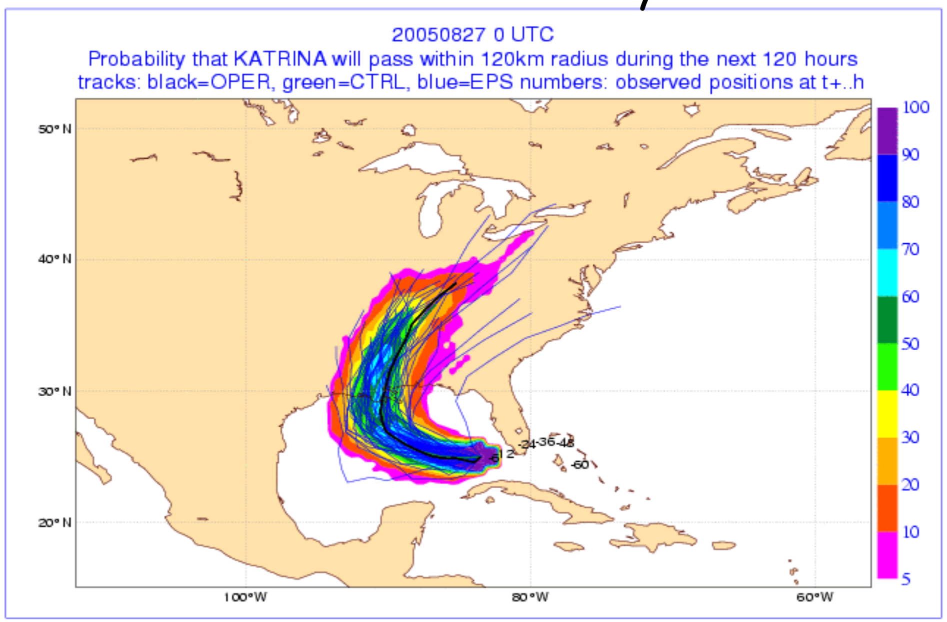




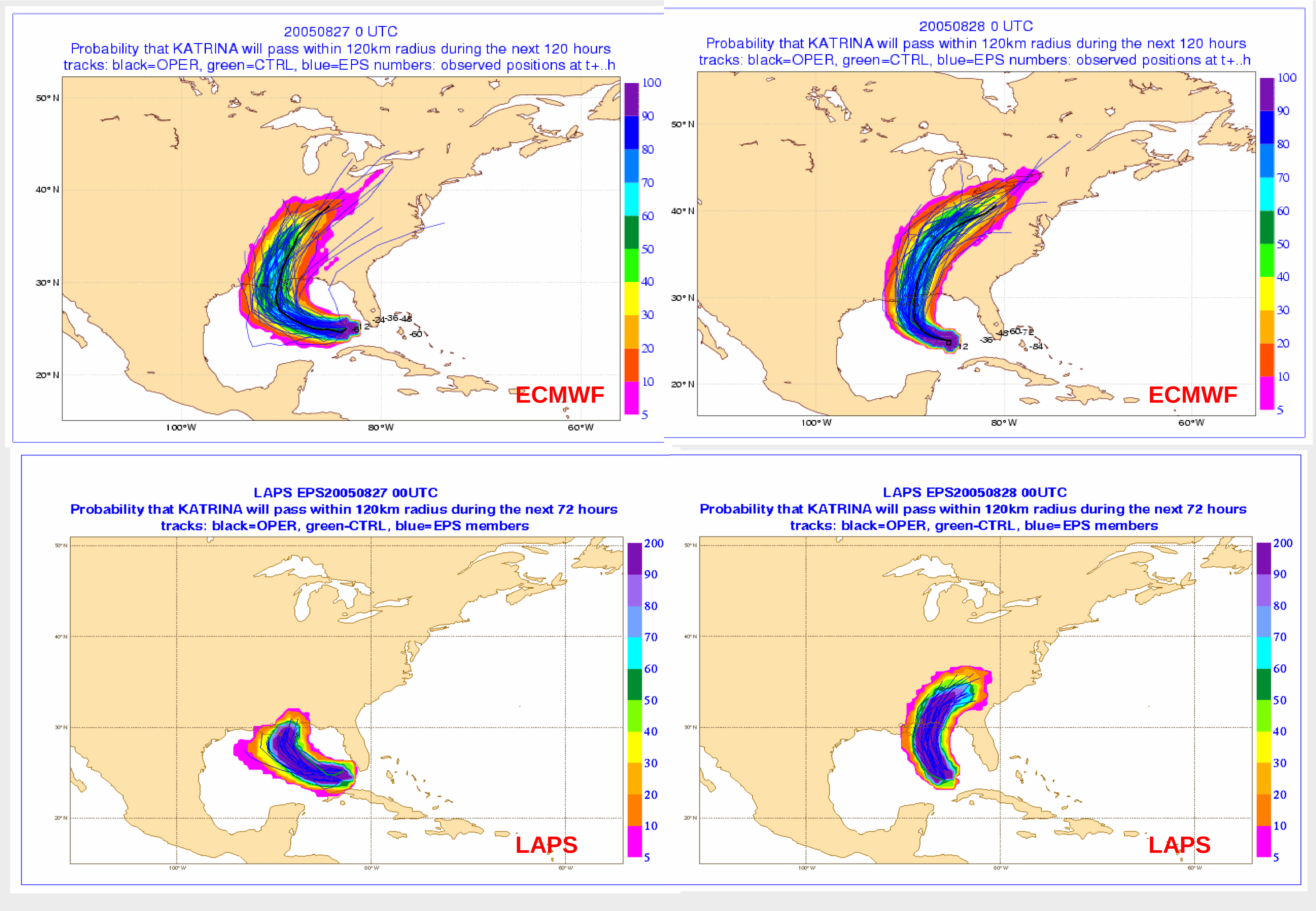
26th 00UTC 3.5 days



26th 12UTC

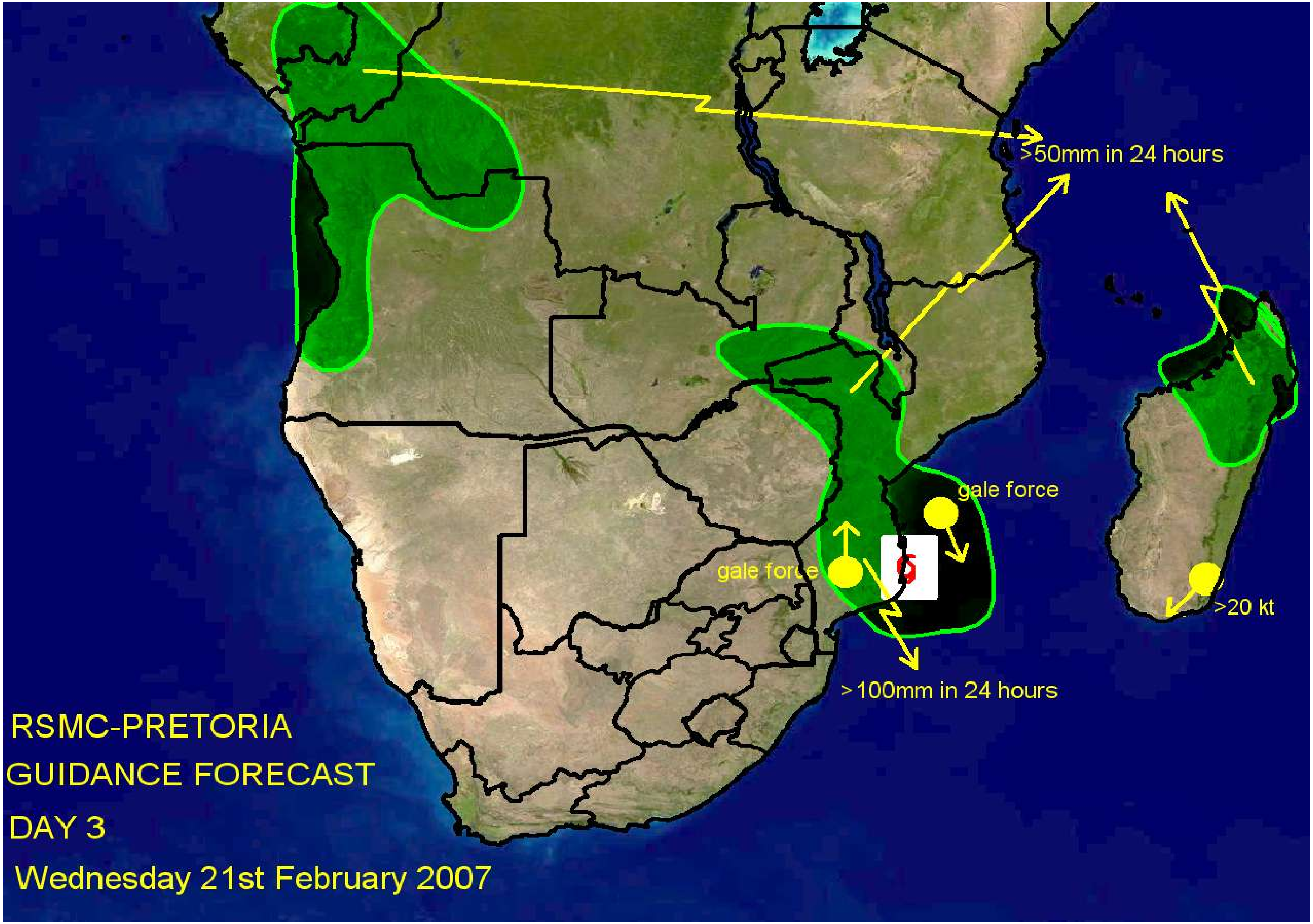


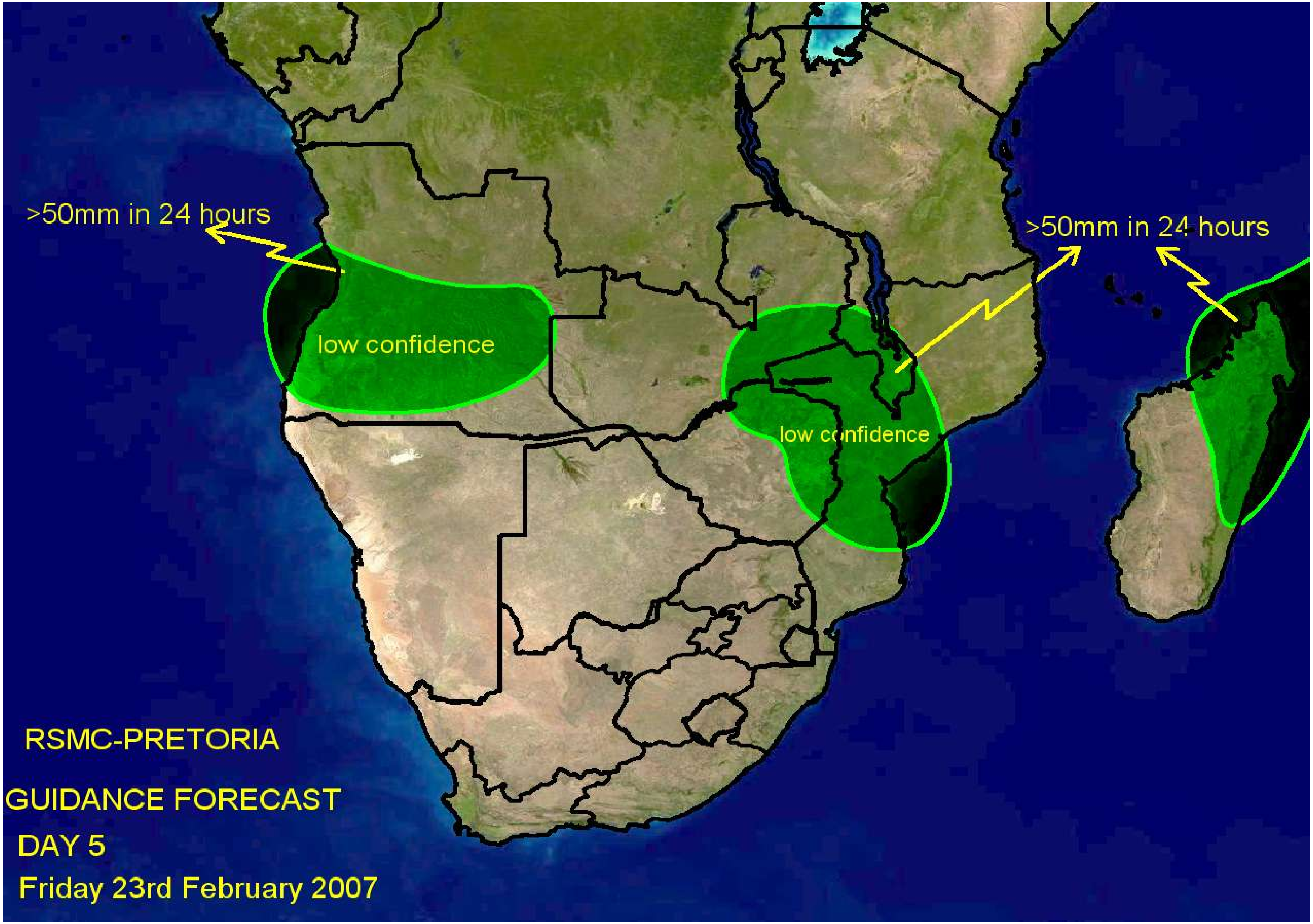
27th 00UTC 2.5 days


20050827 0 UTC
Probability that KATRINA will pass within 120km radius during the next 120 hours
tracks: black=OPER, green=CTRL, blue=EPS numbers: observed positions at t+..h
ECMWF
20050828 0 UTC
Probability that KATRINA will pass within 120km radius during the next 120 hours
tracks: black=OPER, green=CTRL, blue=EPS numbers: observed positions at t+..h
ECMWF
LAPS EPS20050827 00UTC
Probability that KATRINA will pass within 120km radius during the next 72 hours
tracks: black=OPER, green-CTRL, blue=EPS members
LAPS
LAPS EPS20050828 00UTC
Probability that KATRINA will pass within 120km radius during the next 72 hours
tracks: black=OPER, green-CTRL, blue=EPS members
LAPS

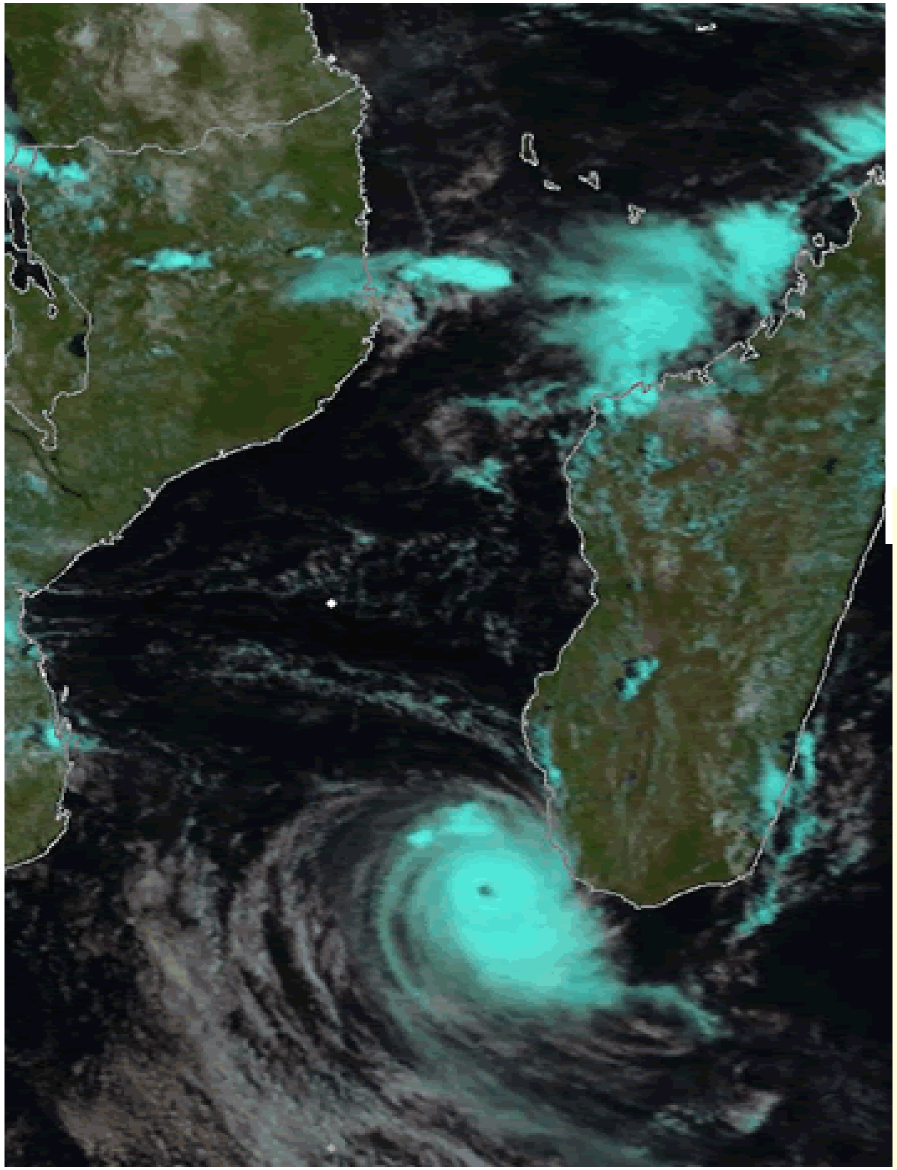
Recent application by the South African Weather Service

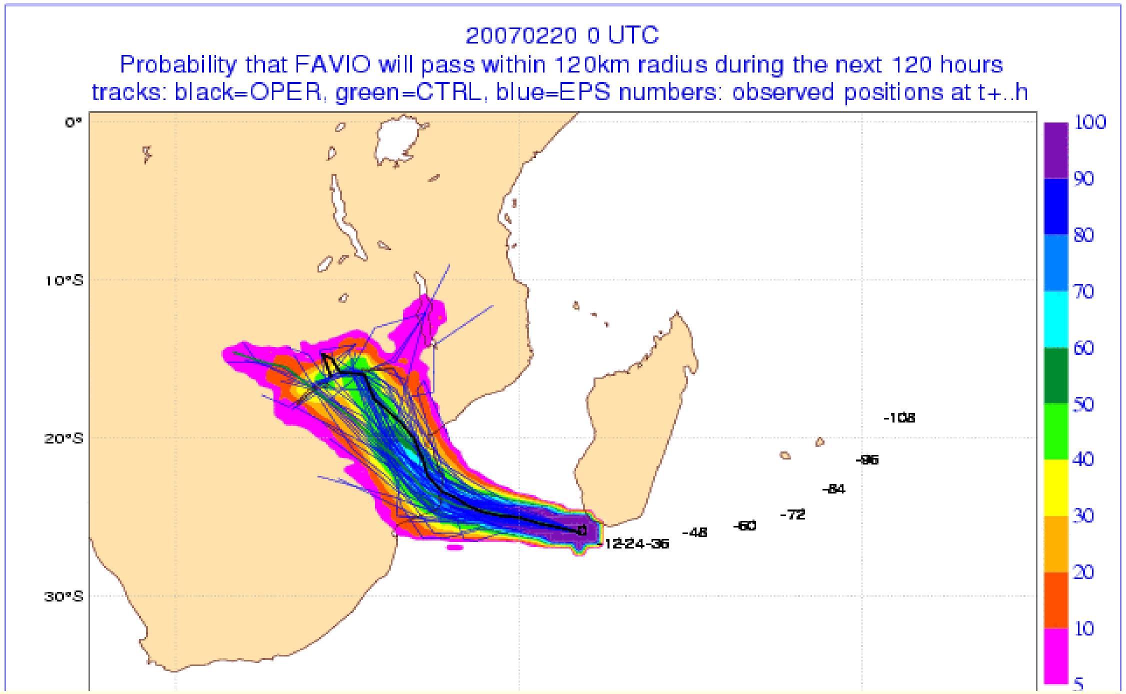
- **Tropical cyclone FAVIO in SW Indian Ocean**
  - Developed off east coast of Madagascar around 15 February 2007
  - Travelled in a W-NW track and made landfall south of Beira, Mozambique
  - Not much widespread damage from wind but heavy rain on already saturated soil necessitated disaster management action
  - First TC “eye” observed on southern Africa Radar
  - Weather system well tracked and forecast as part of the WMO-CBS SWFDP in southern Africa

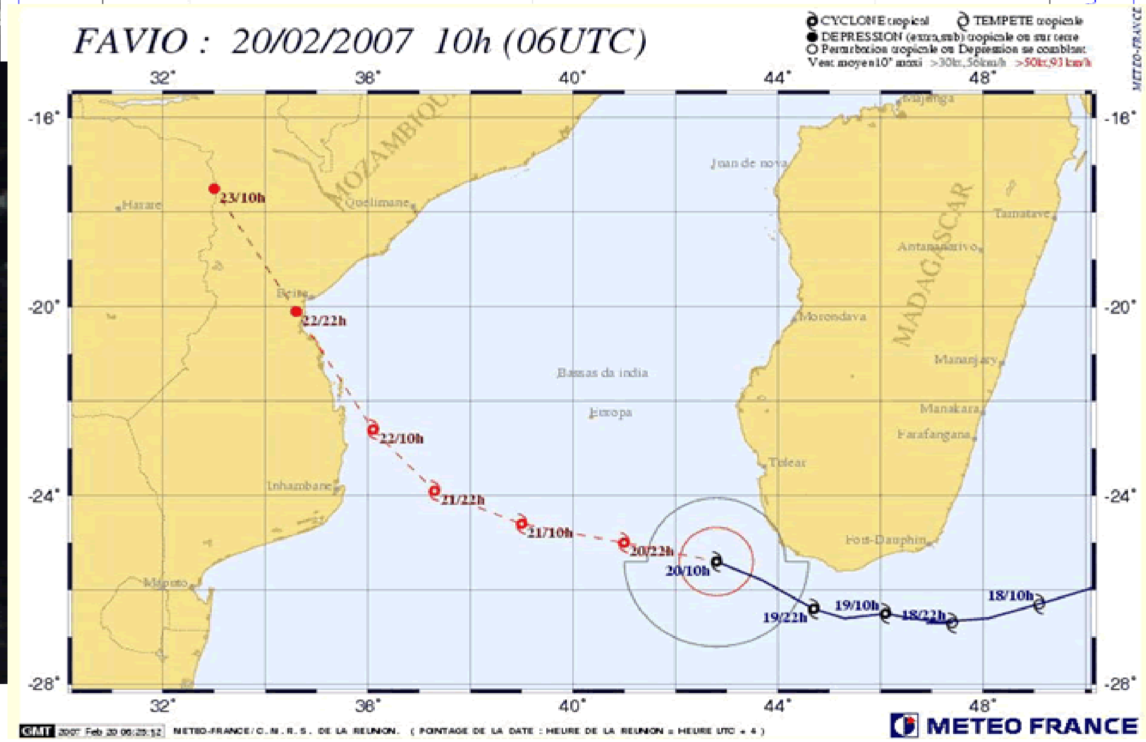

>50mm in 24 hours
gale force
gale force
>20 kt
>100mm in 24 hours
RSMC-PRETORIA
GUIDANCE FORECAST
DAY 3
Wednesday 21st February 2007

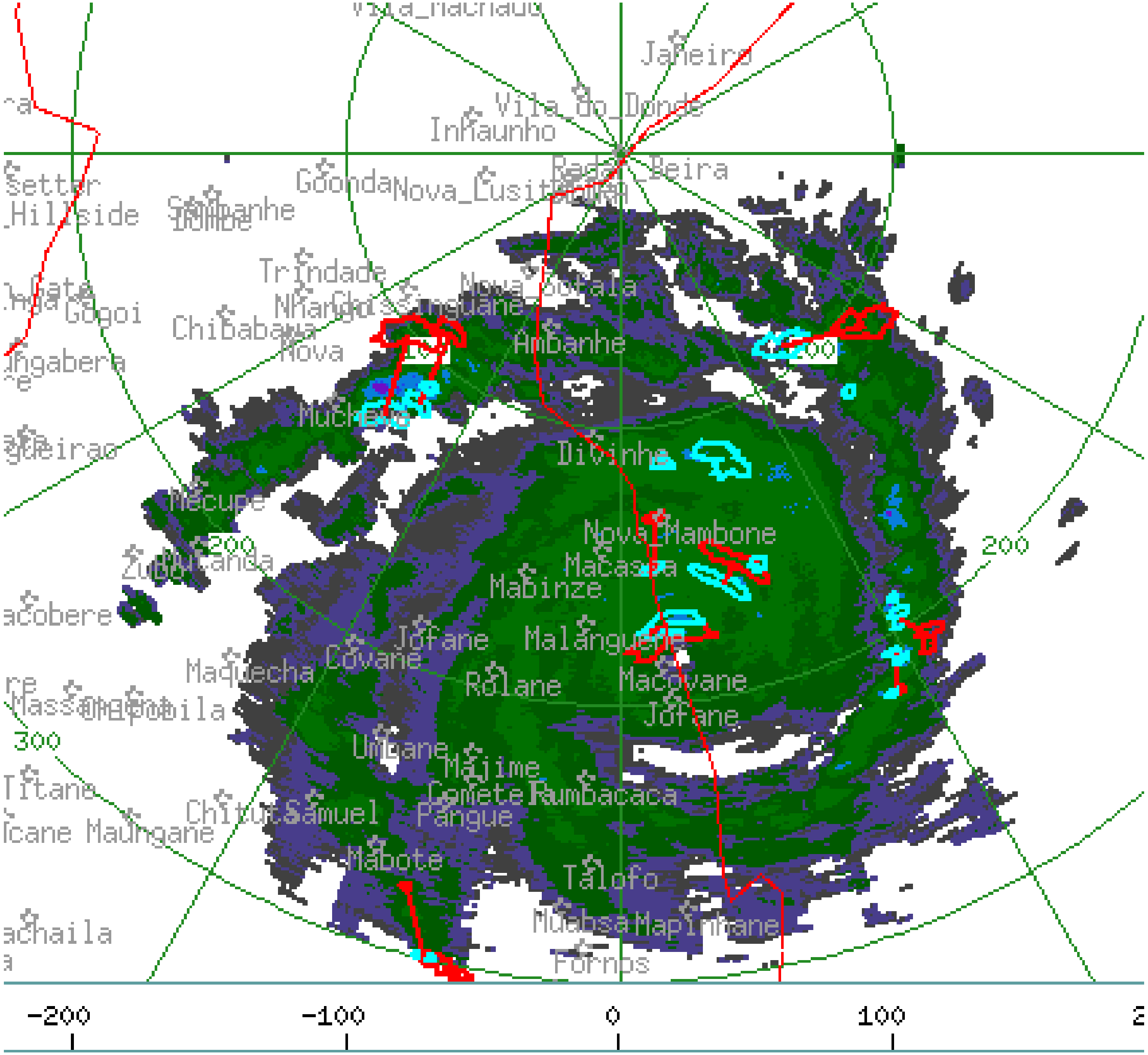

>50mm in 24 hours
low confidence
>50mm in 24 hours
low confidence
RSMC-PRETORIA
GUIDANCE FORECAST
DAY 5
Friday 23rd February 2007

Favio forecasts





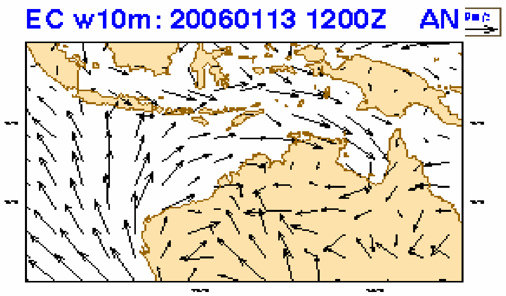




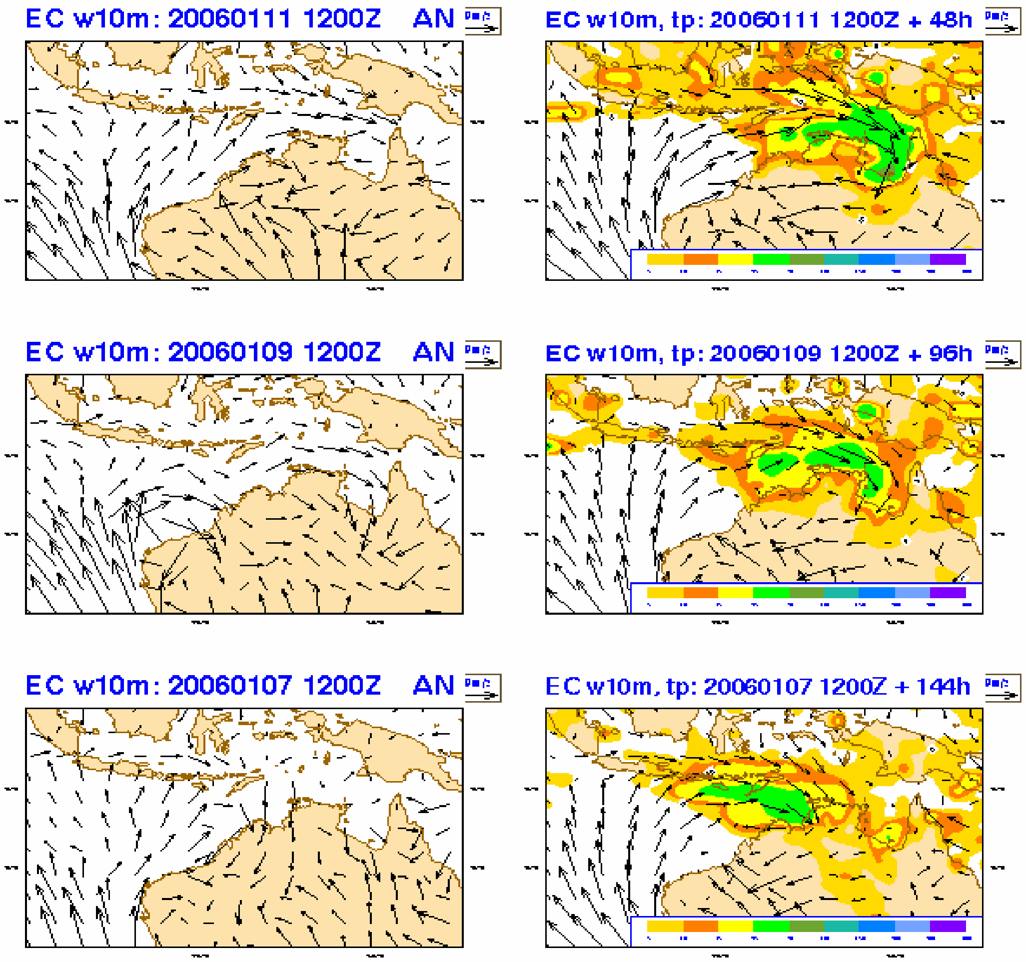
Beira
Goonda
Trindade
Chibabava
Nova
Divinhe
Nova_Mambone
Mabinze
Jofane
Covane
Maquecha
Rolane
Macovane
Umbane
Majime
Pangue
Mabote
Talofo
Fornos
200
300
-200
-100
0
100

Applications of Australian Monsoon

- Probability of winds being westerly as an indication of monsoon onset
- Example shown is for the 2005-2006 season when the monsoon onset occurred on 13 January 2006

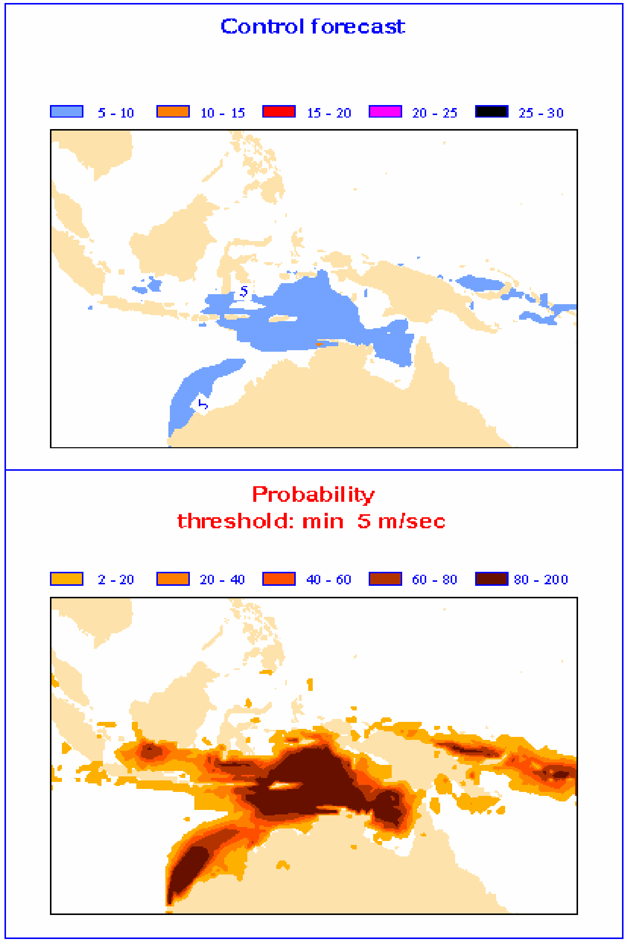


Deterministic forecast – ECMWF model

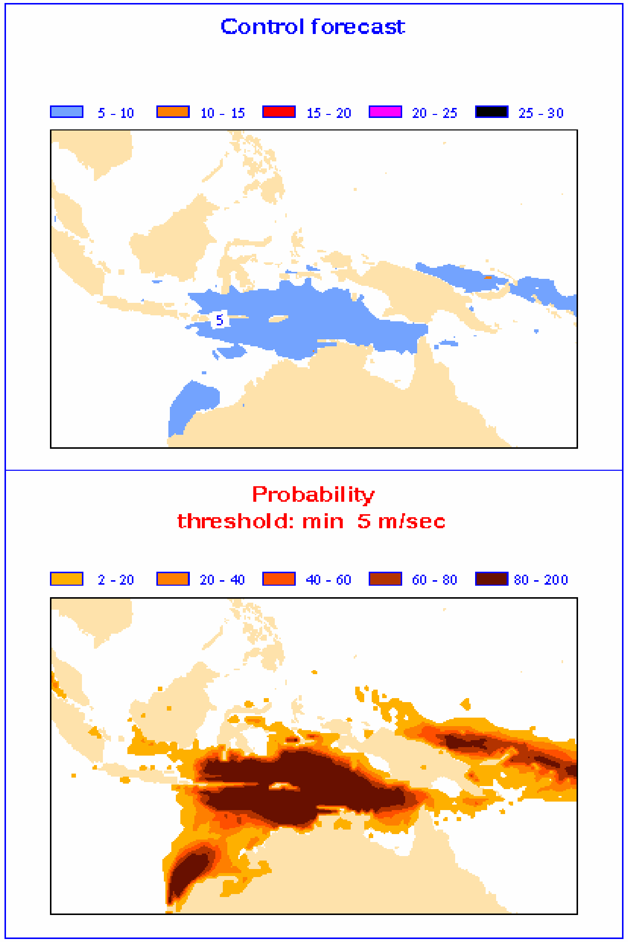


Probability of winds being westerly

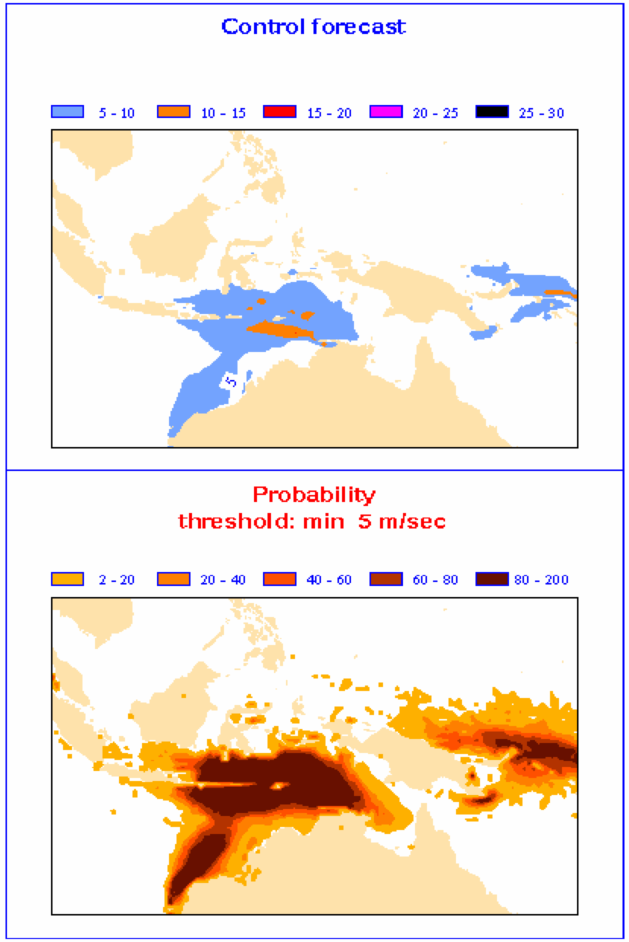
Forecasts valid for 12Z on 13 January 2006



24h



48h



72h

LAPS EPS

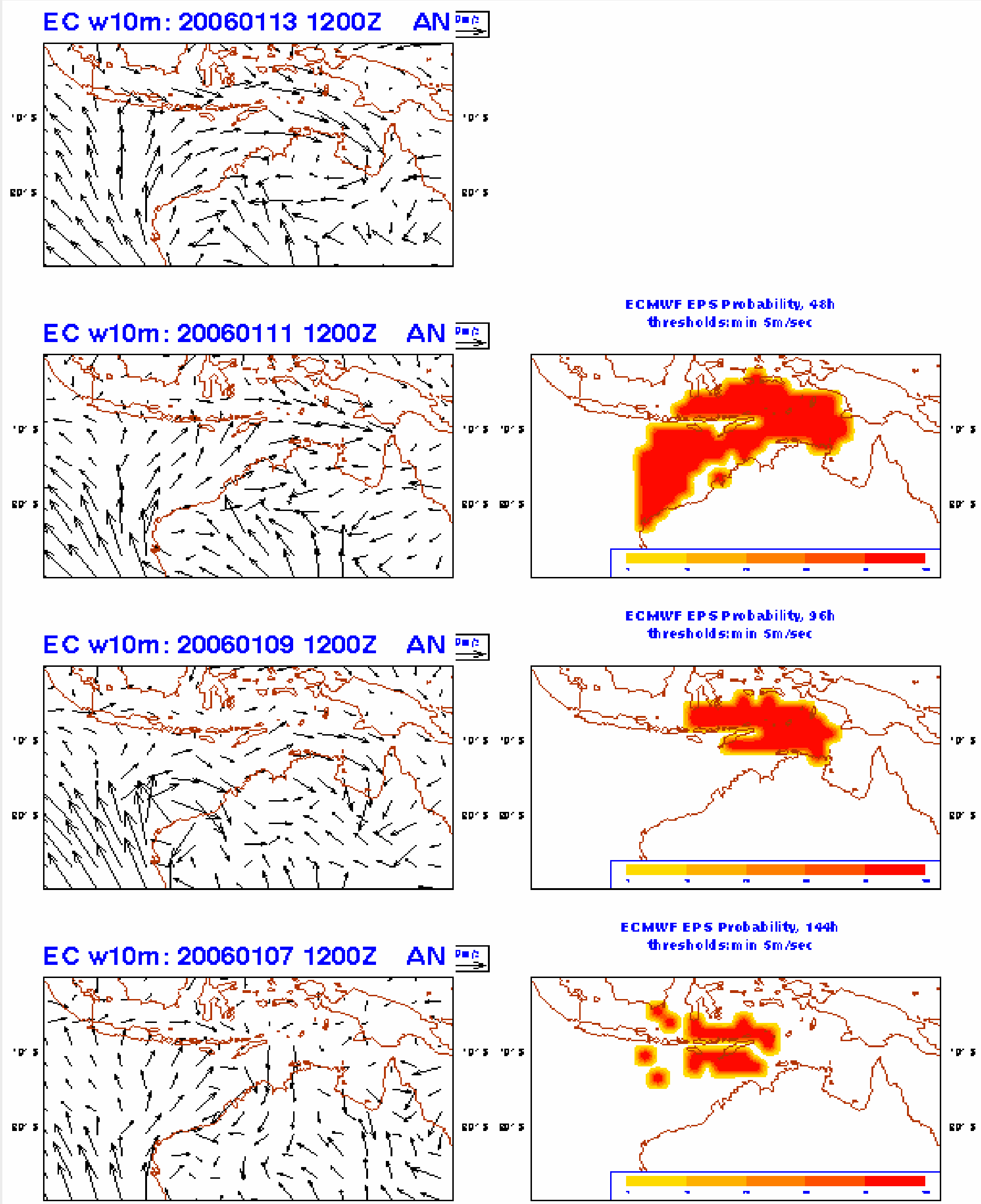
Probability of winds being westerly

Forecasts valid for 12Z on 13 January 2006

Verifying analysis

Starting analyses

↓



Forecasts

48h

96h

144h

ECMWF EPS

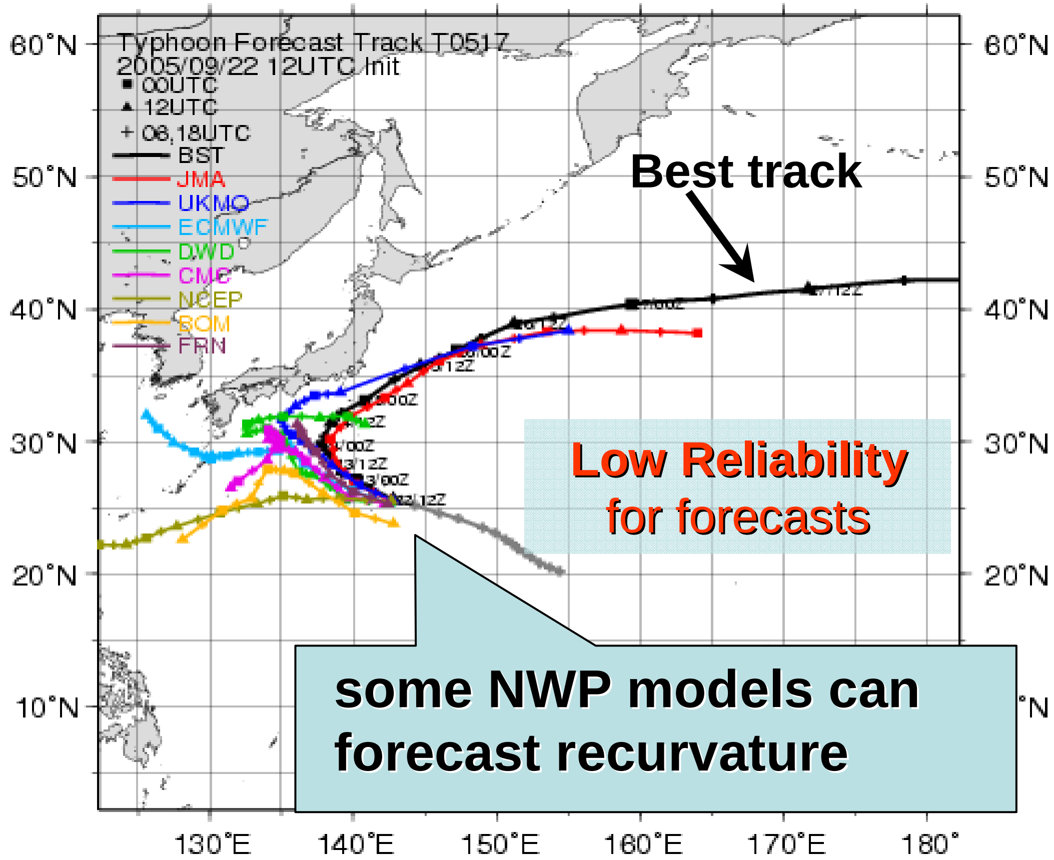
‘Poor Man’s ensemble’

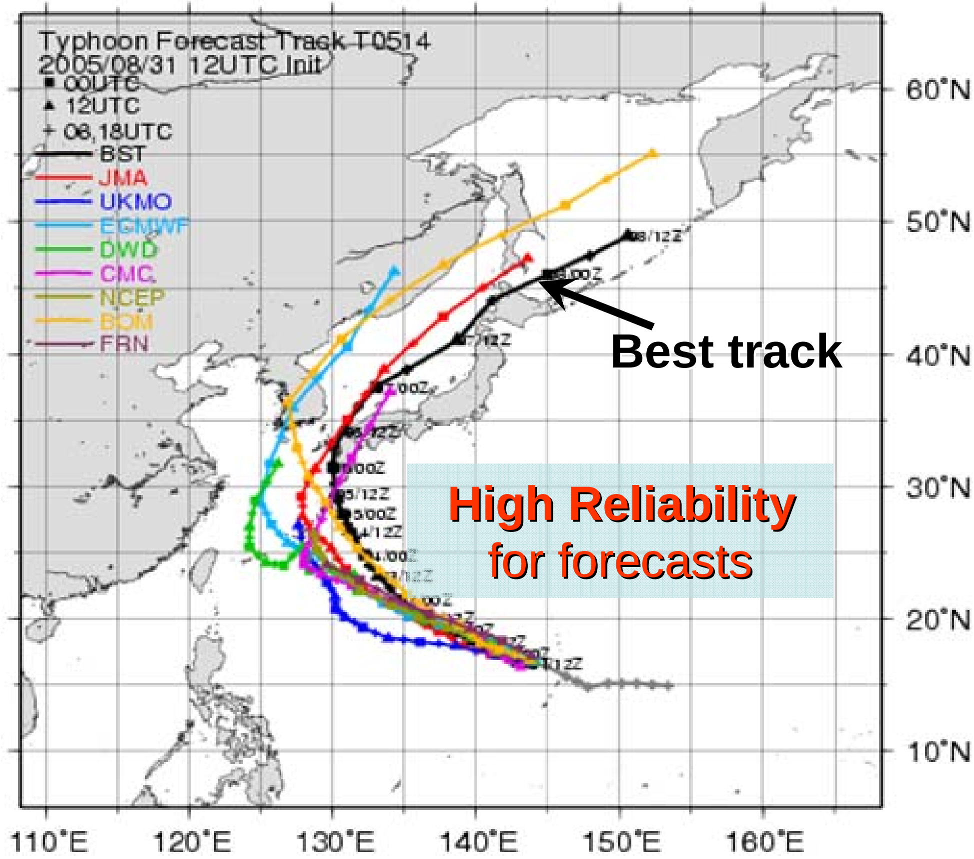
‘Poor Man’s ensemble’

- Simple (or probability matched) averaging of operational forecasts received via GTS or through direct links
- Has the following advantages:
  – Members of the ensemble are the high resolution deterministic forecasts
  – Sample larger analysis space
  – Sample large model error space (greater variety of physical parametrisations
- Major disadvantage is small sample size

SAOLA(T0517) & ***NABI***(T0514)

- western North Pacific area -

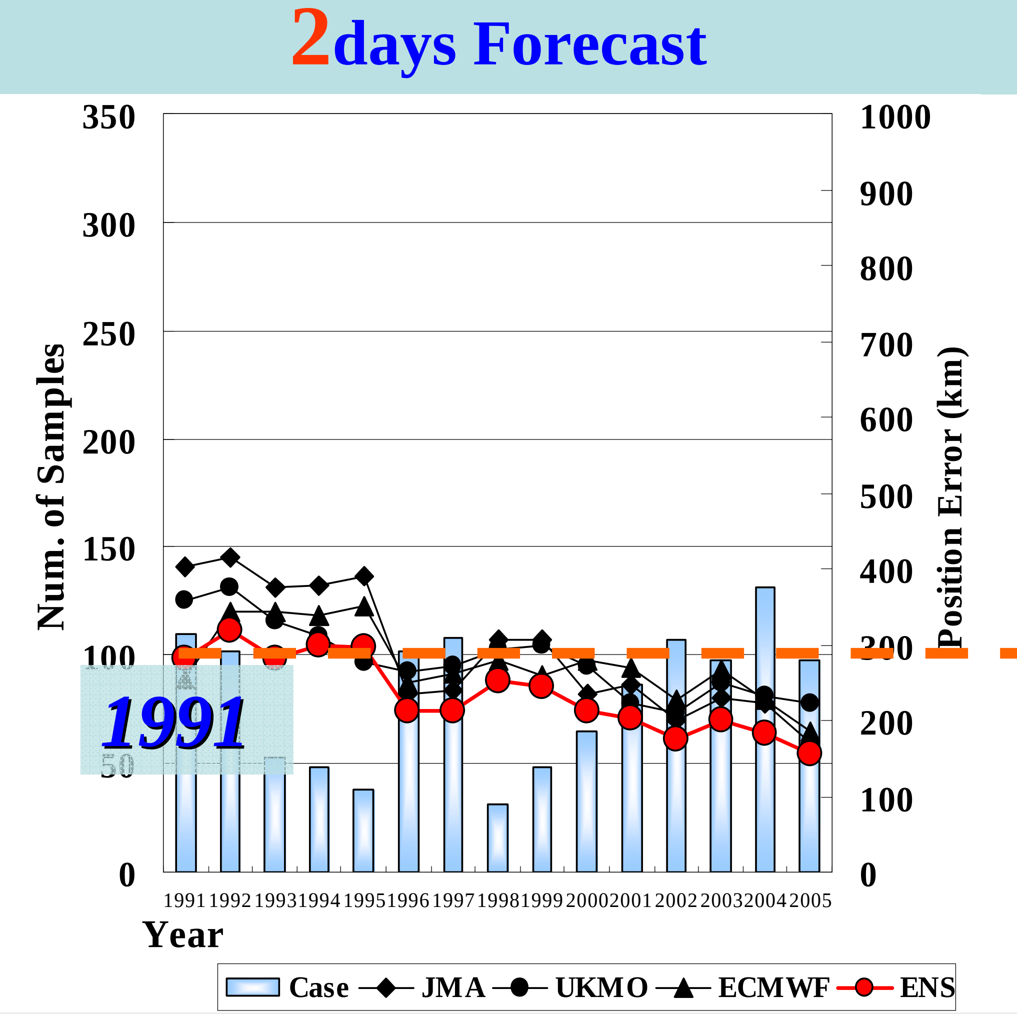


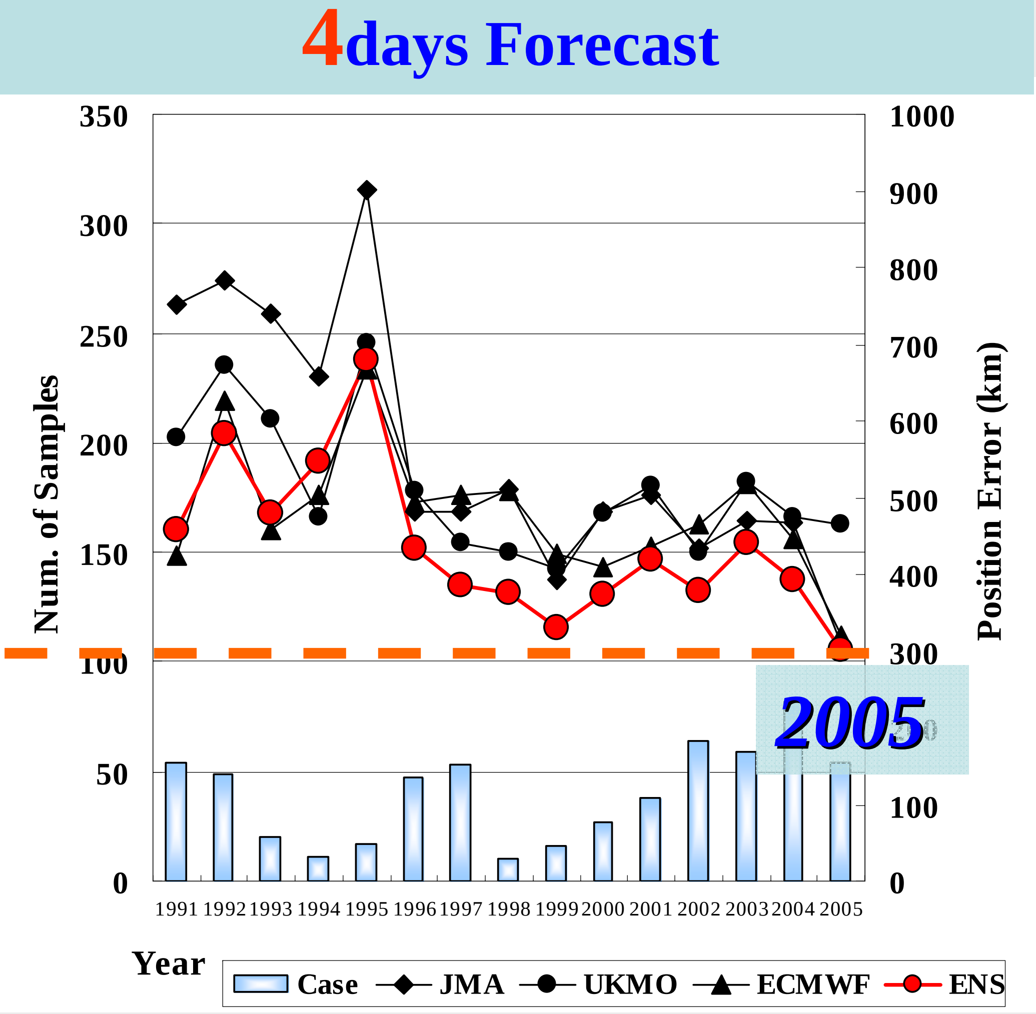


International ensemble forecasts can deliver a probabilistic forecast with reliability.

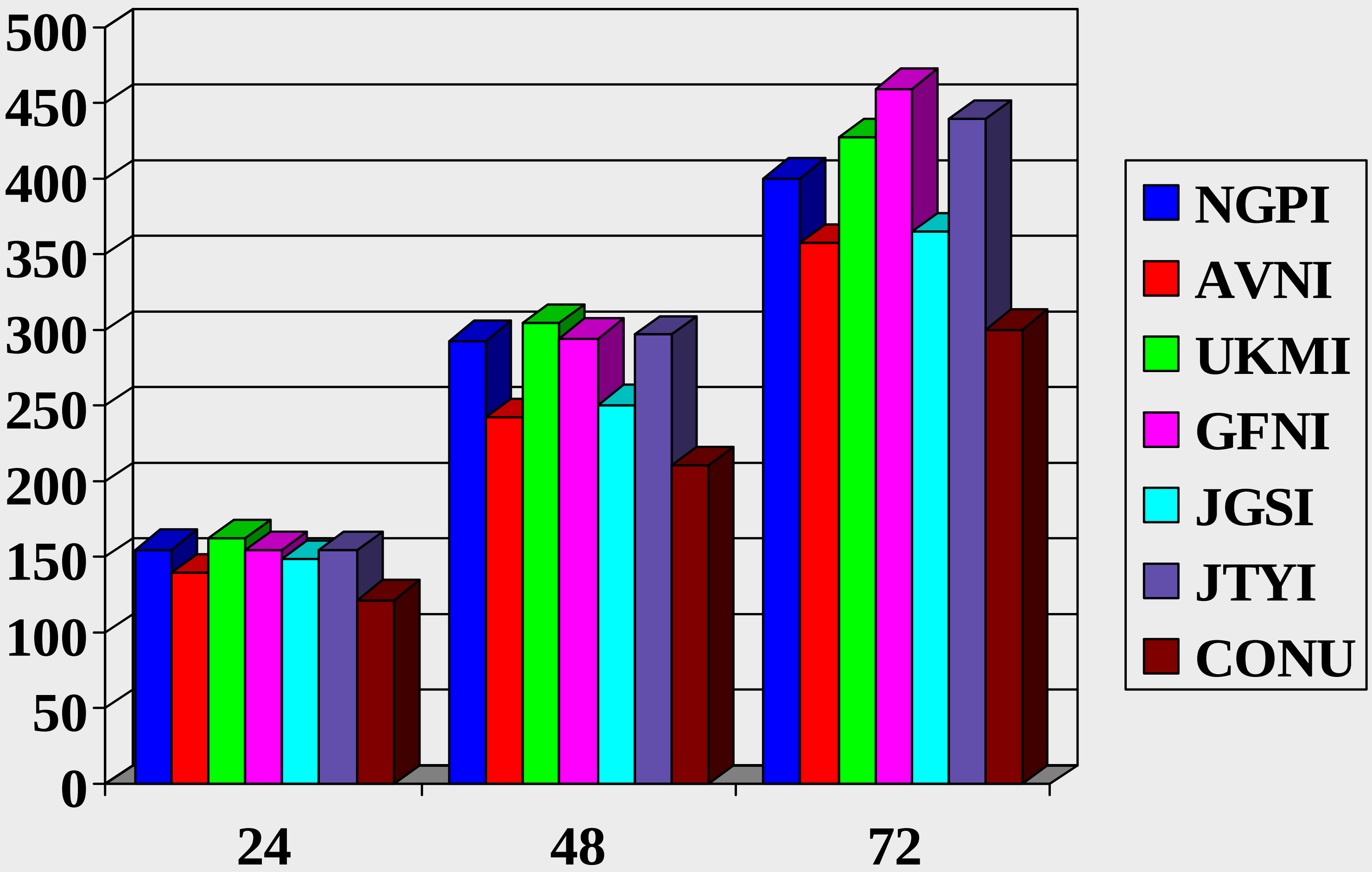
3 NWP Multi-Model Ensemble (JMA, ECMWF, UKMO)

- western North Pacific area -





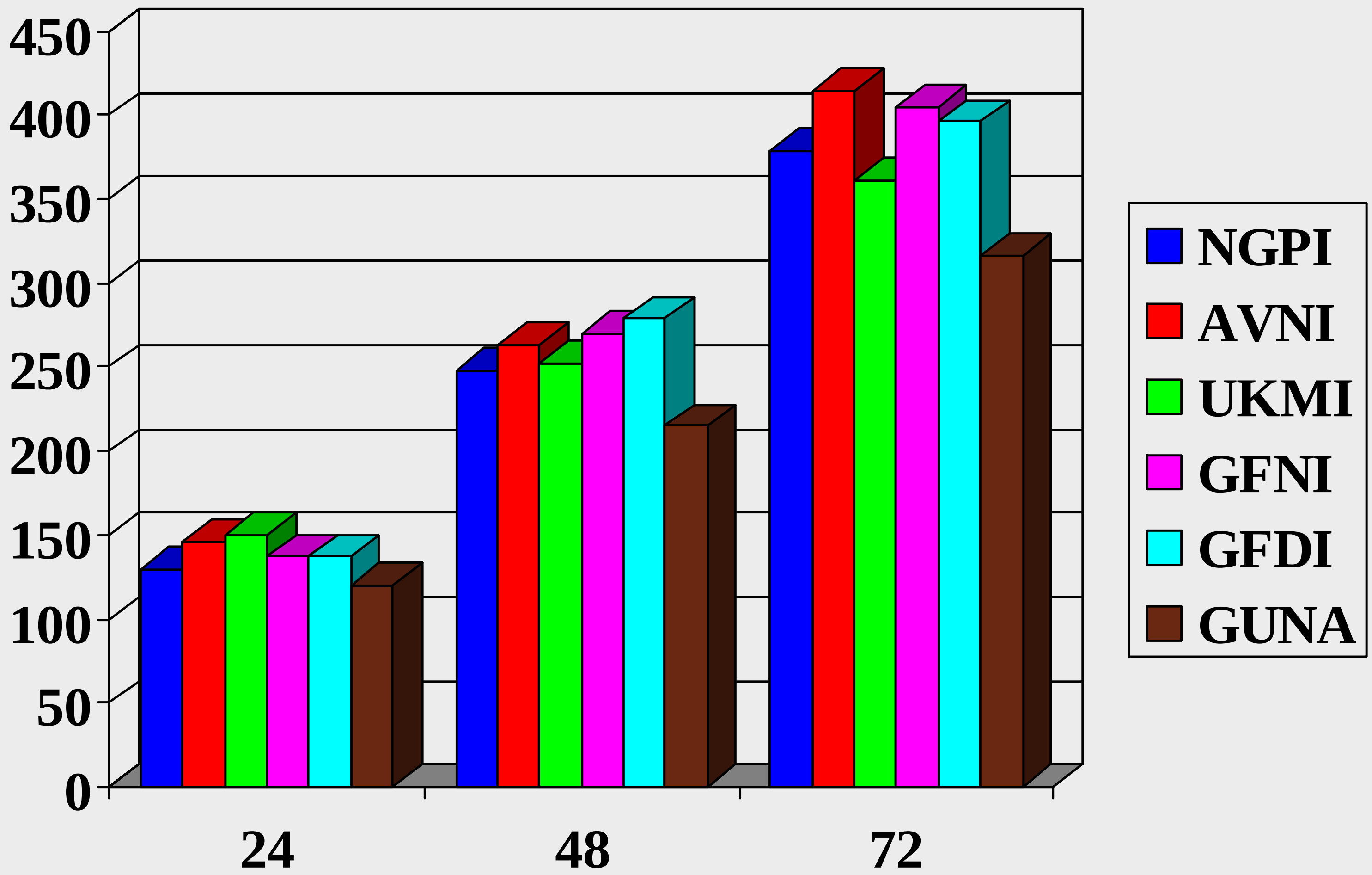
2002 Western North Pacific
TC Forecast Error (km)



J. Goerss

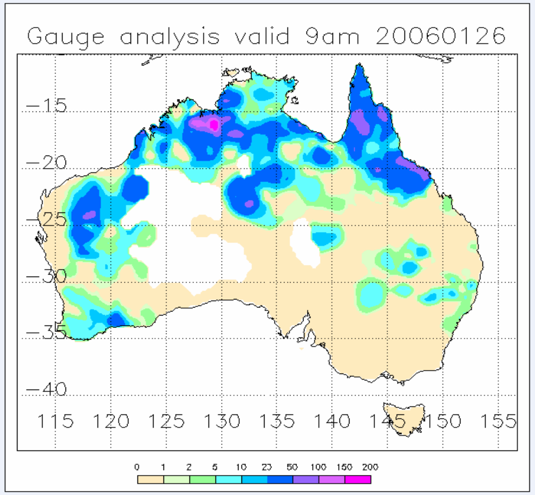
584 479 383 Number of Forecasts

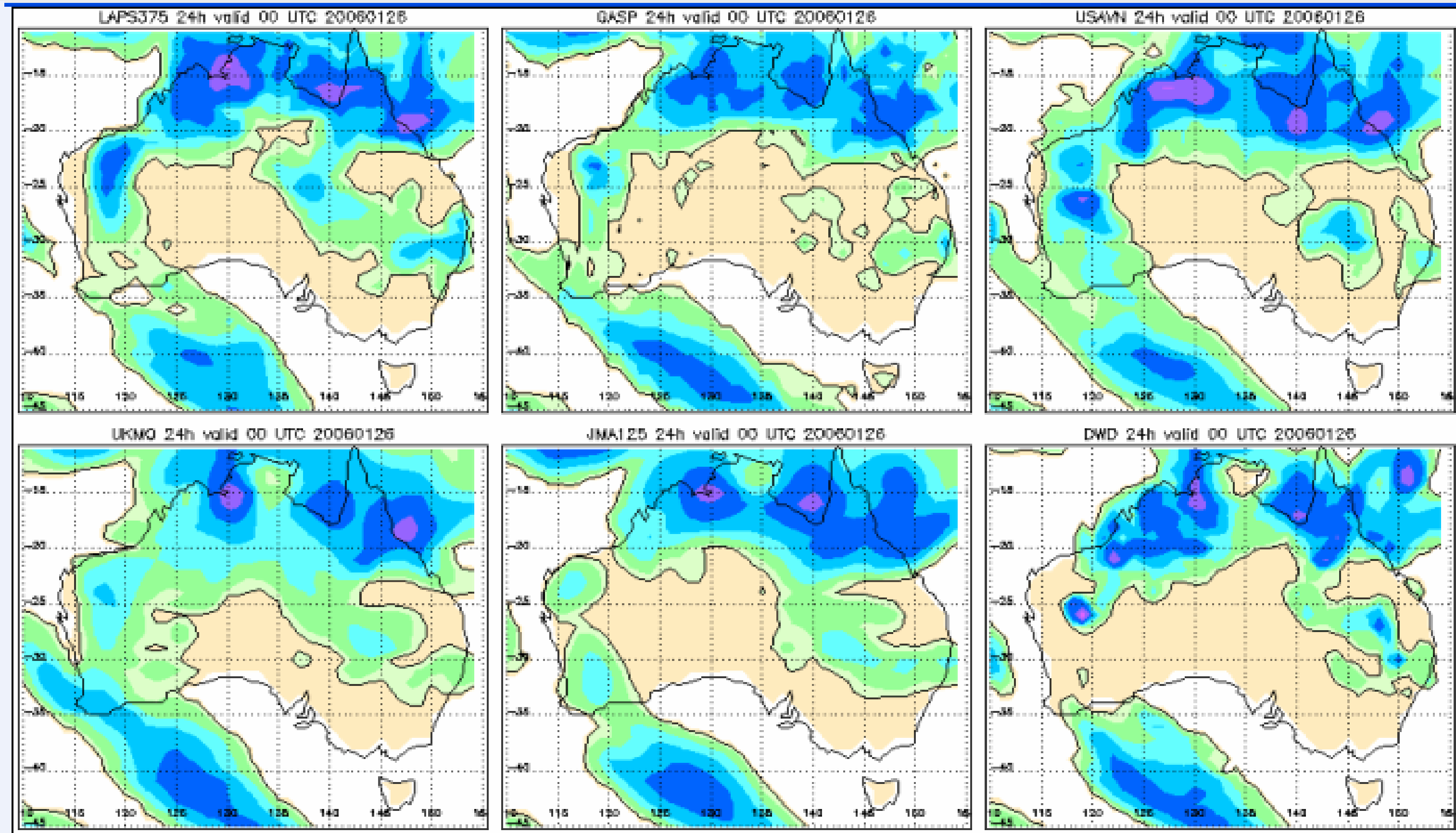
2002 Atlantic
TC Forecast Error (km)

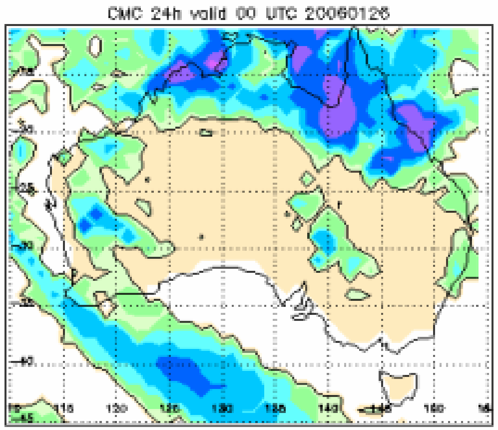


J. Goerss

192 142 102 Number of Forecasts

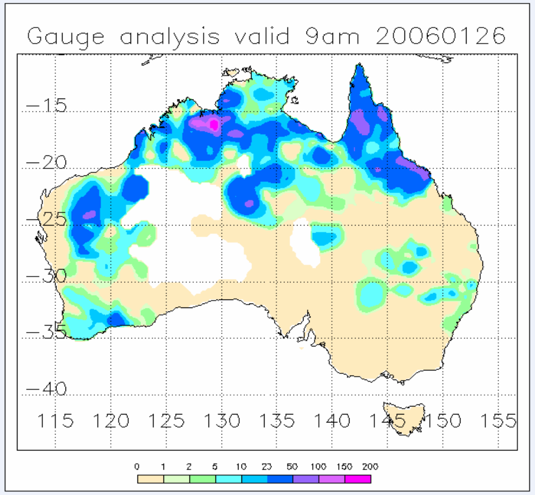




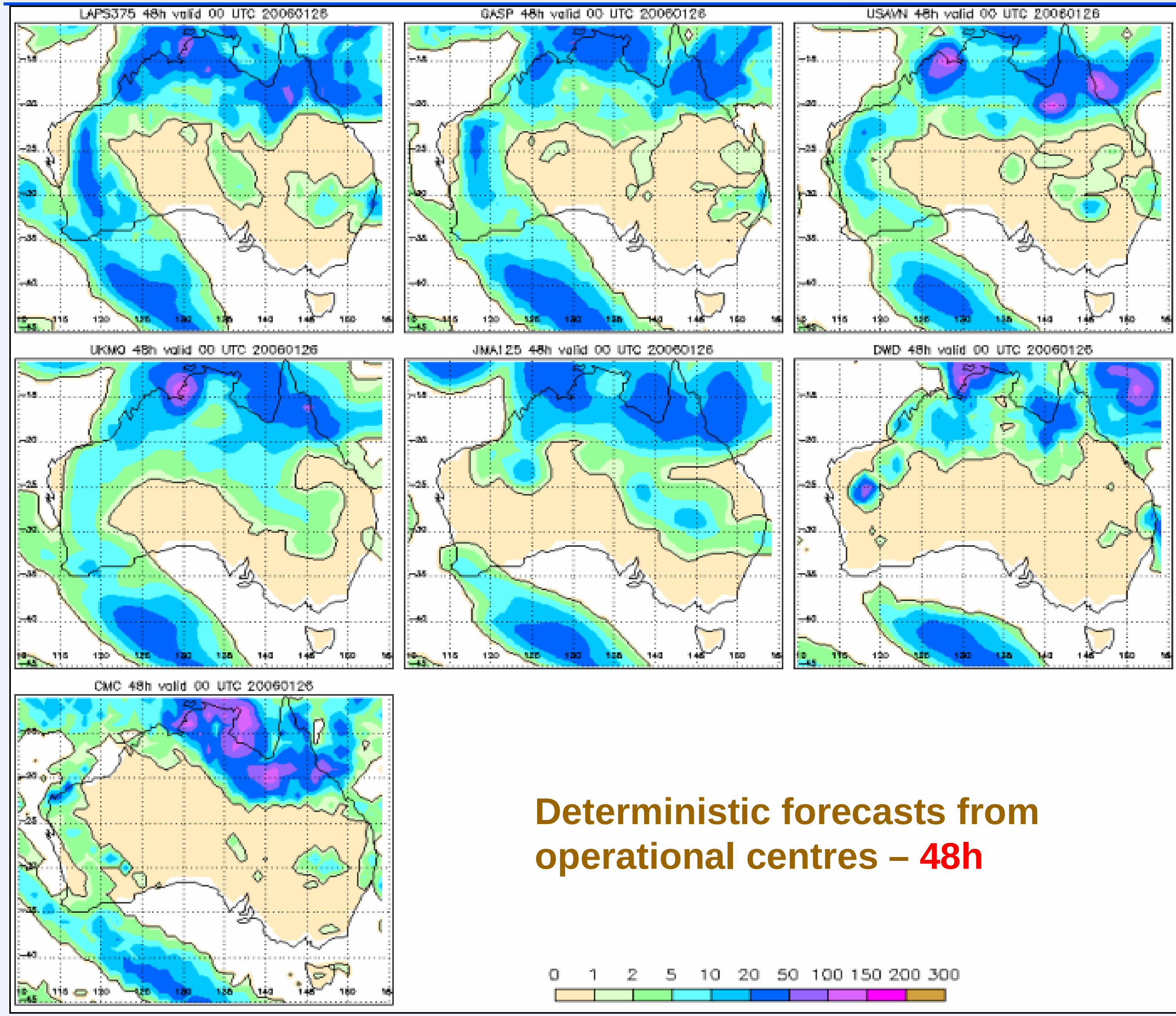


Deterministic forecasts from operational centres – 24h

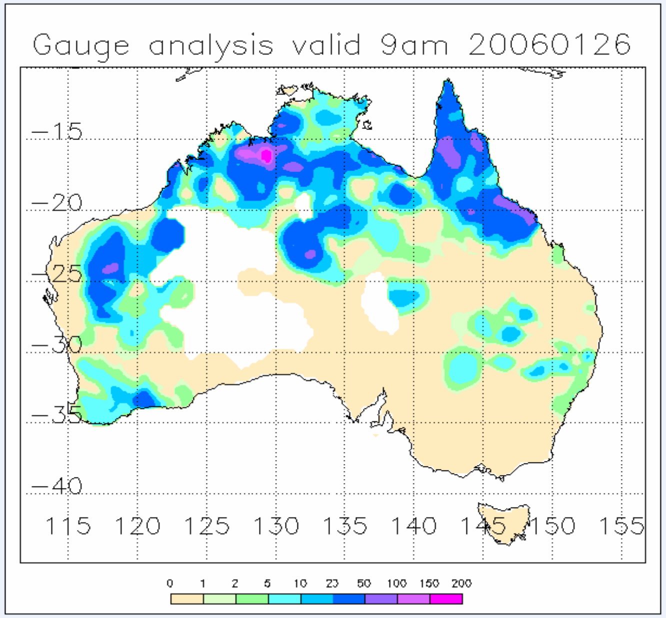
E. Ebert

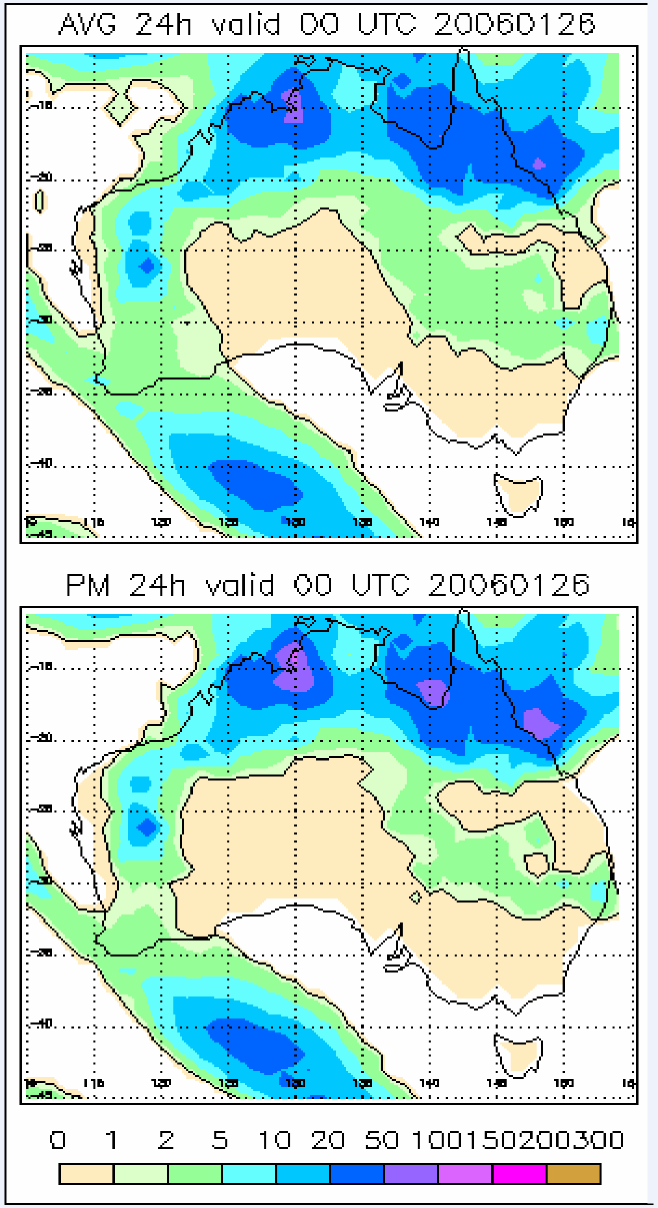


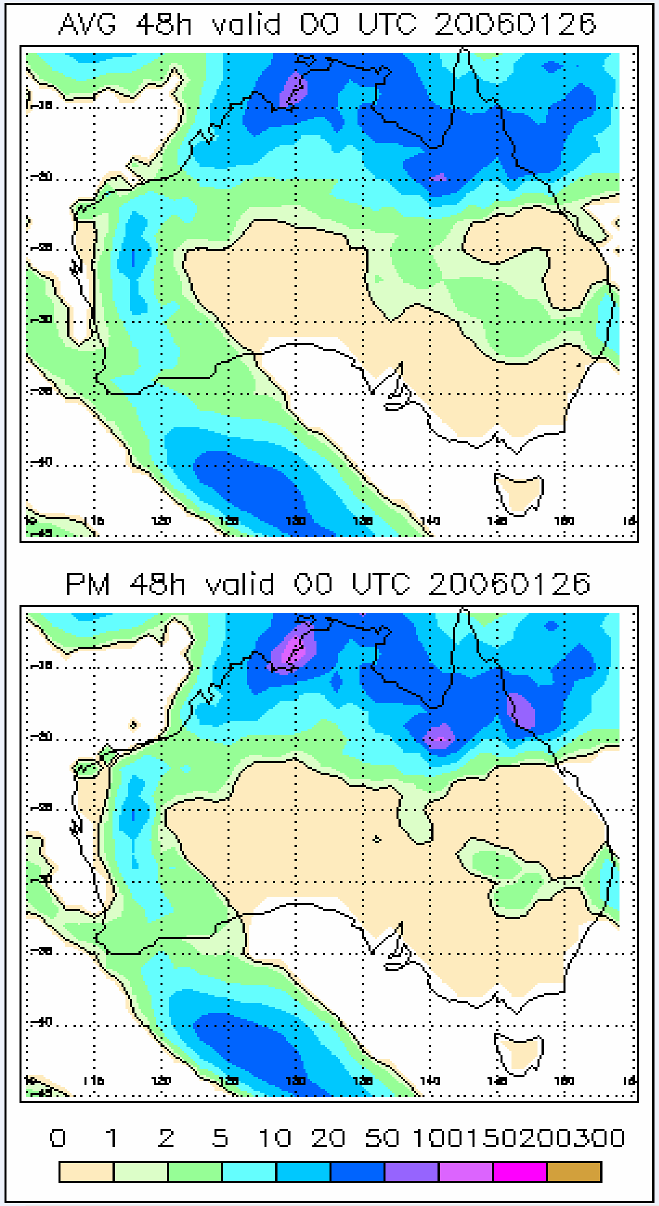
Deterministic forecasts from operational centres – 48h



E. Ebert



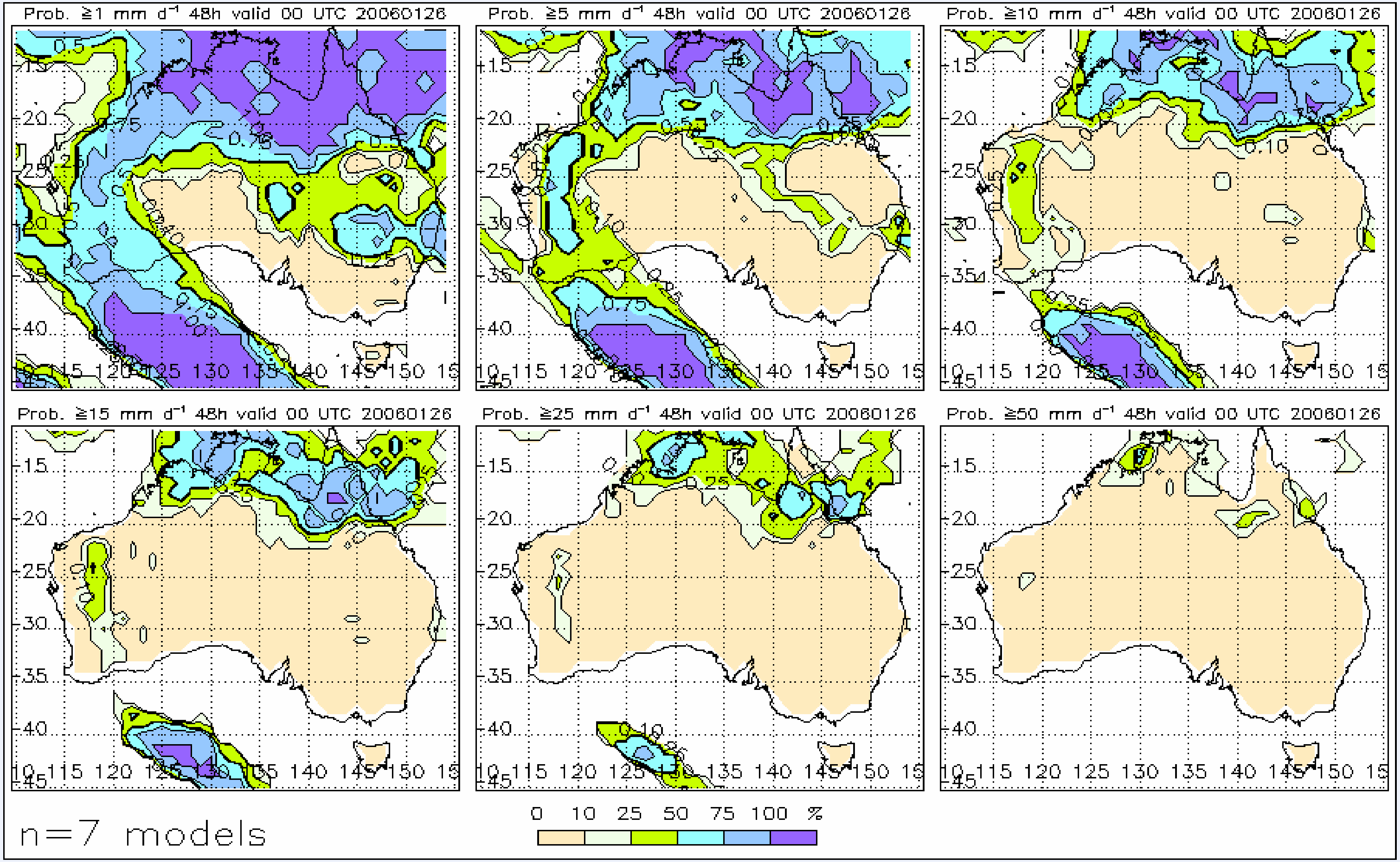




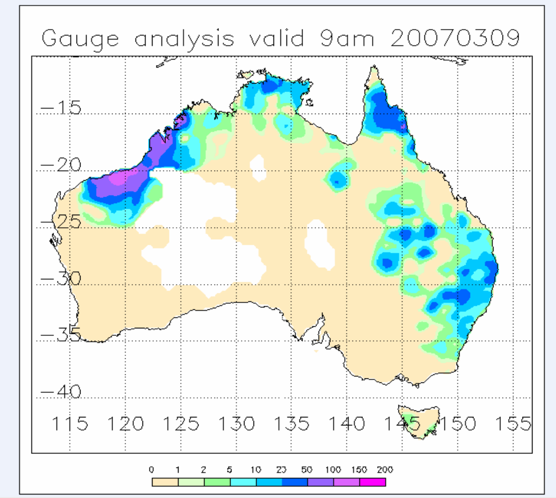
Mean of all models

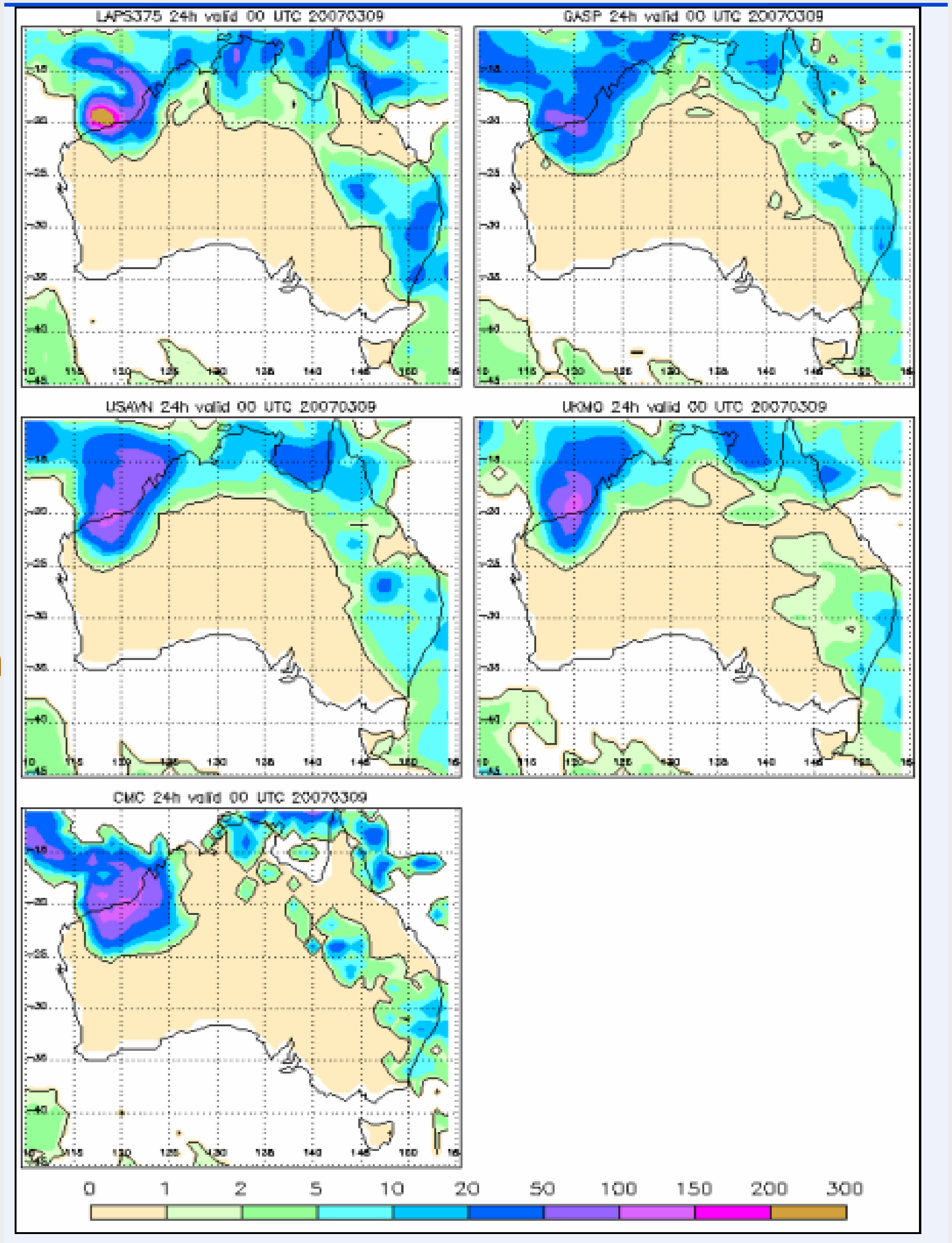
E. Ebert

Probability of rainfall exceeding thresholds



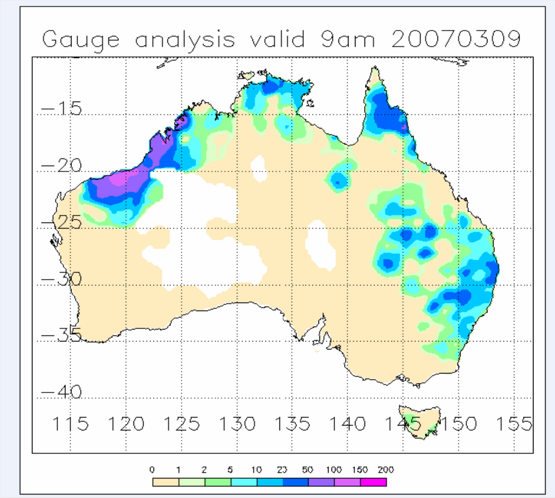
E. Ebert



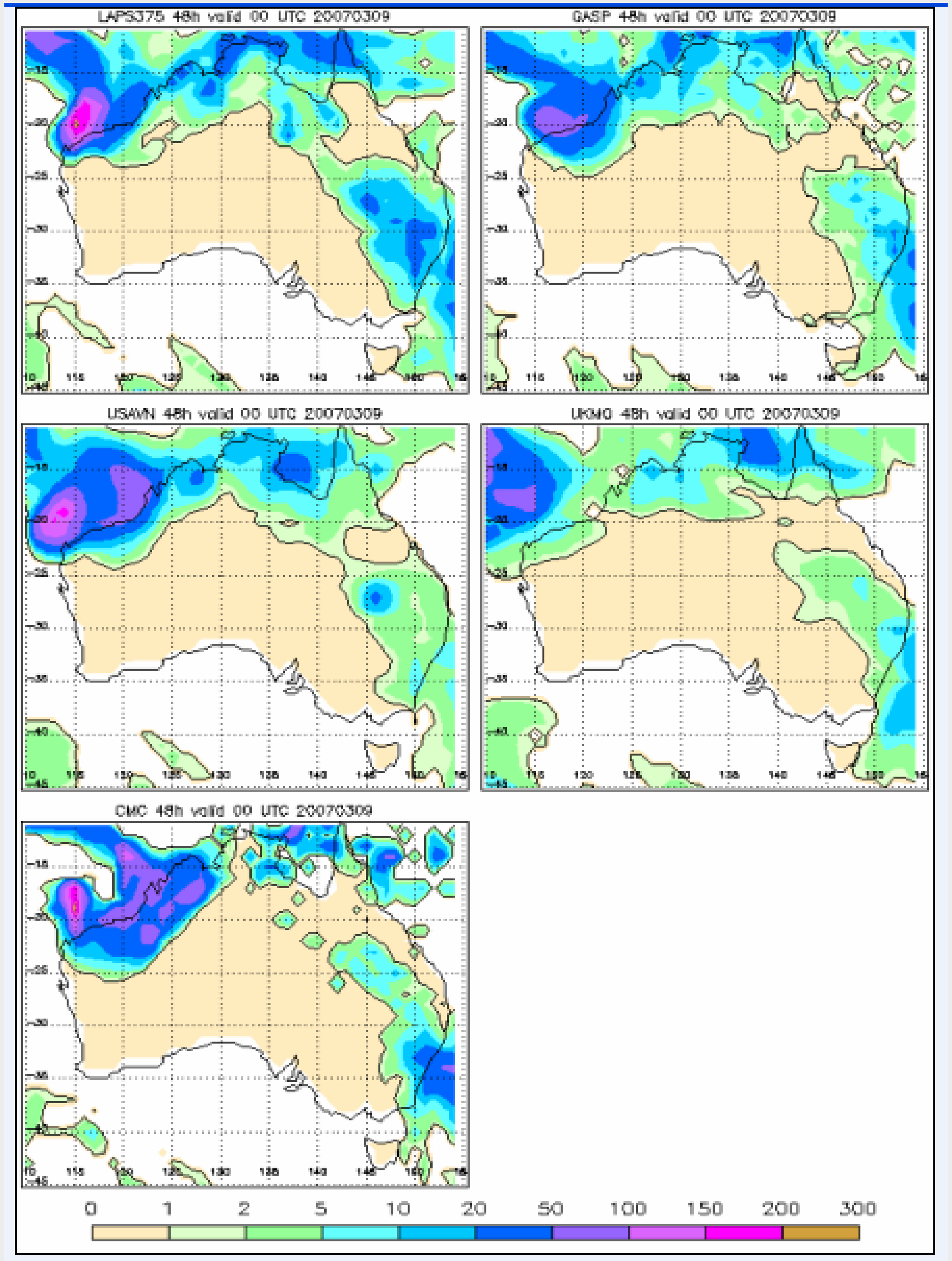


Deterministic forecasts from operational centres – 24h

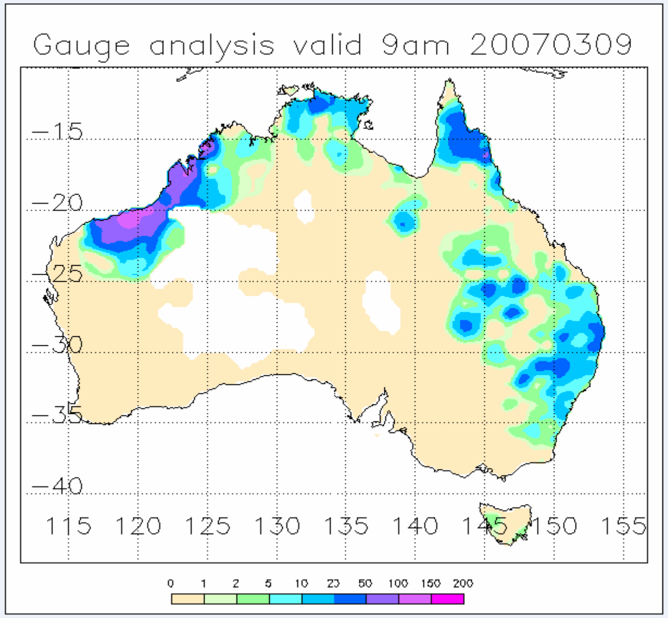
E. Ebert

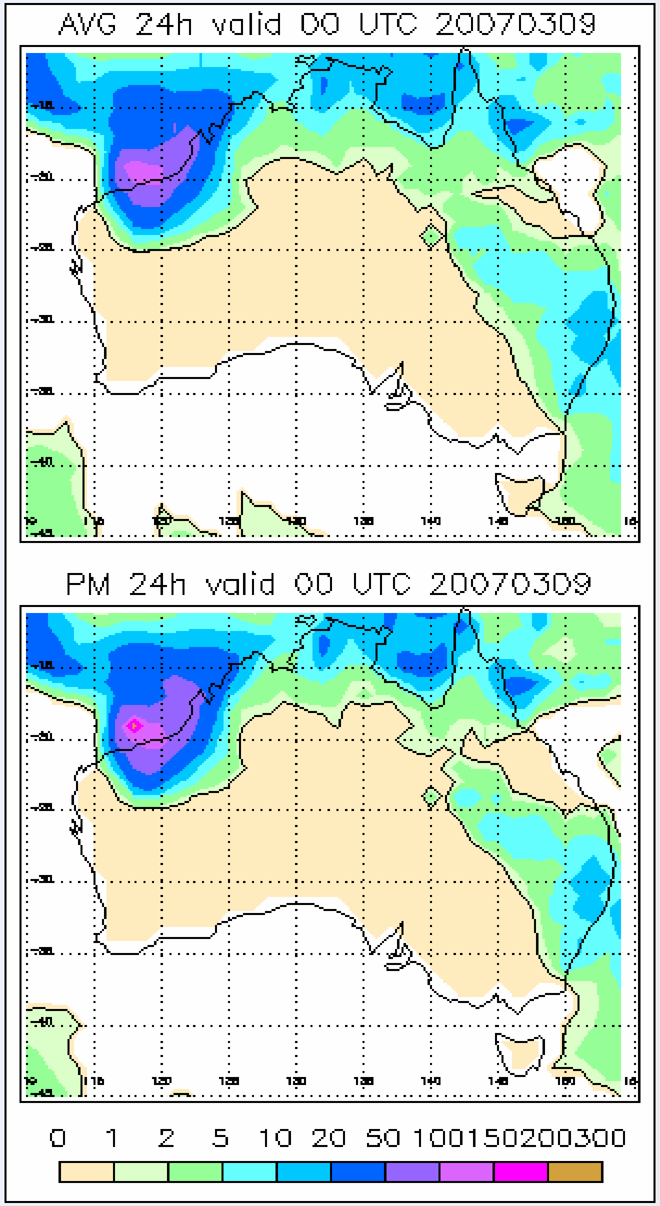


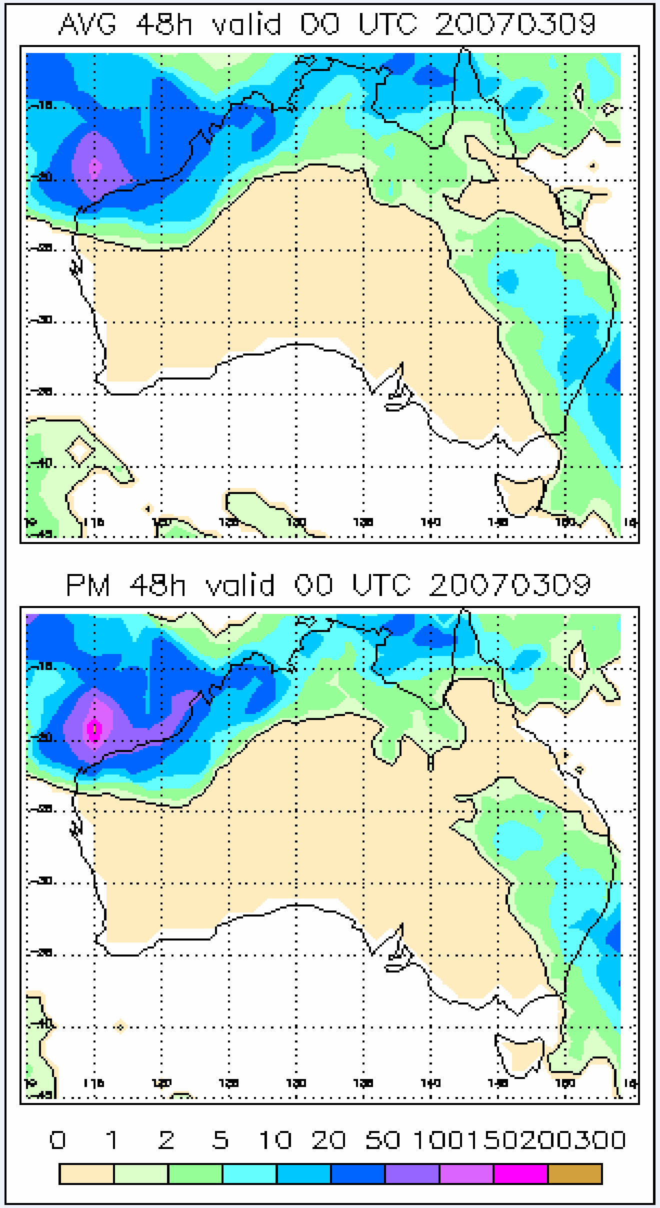
Deterministic forecasts from operational centres – 48h



E. Ebert



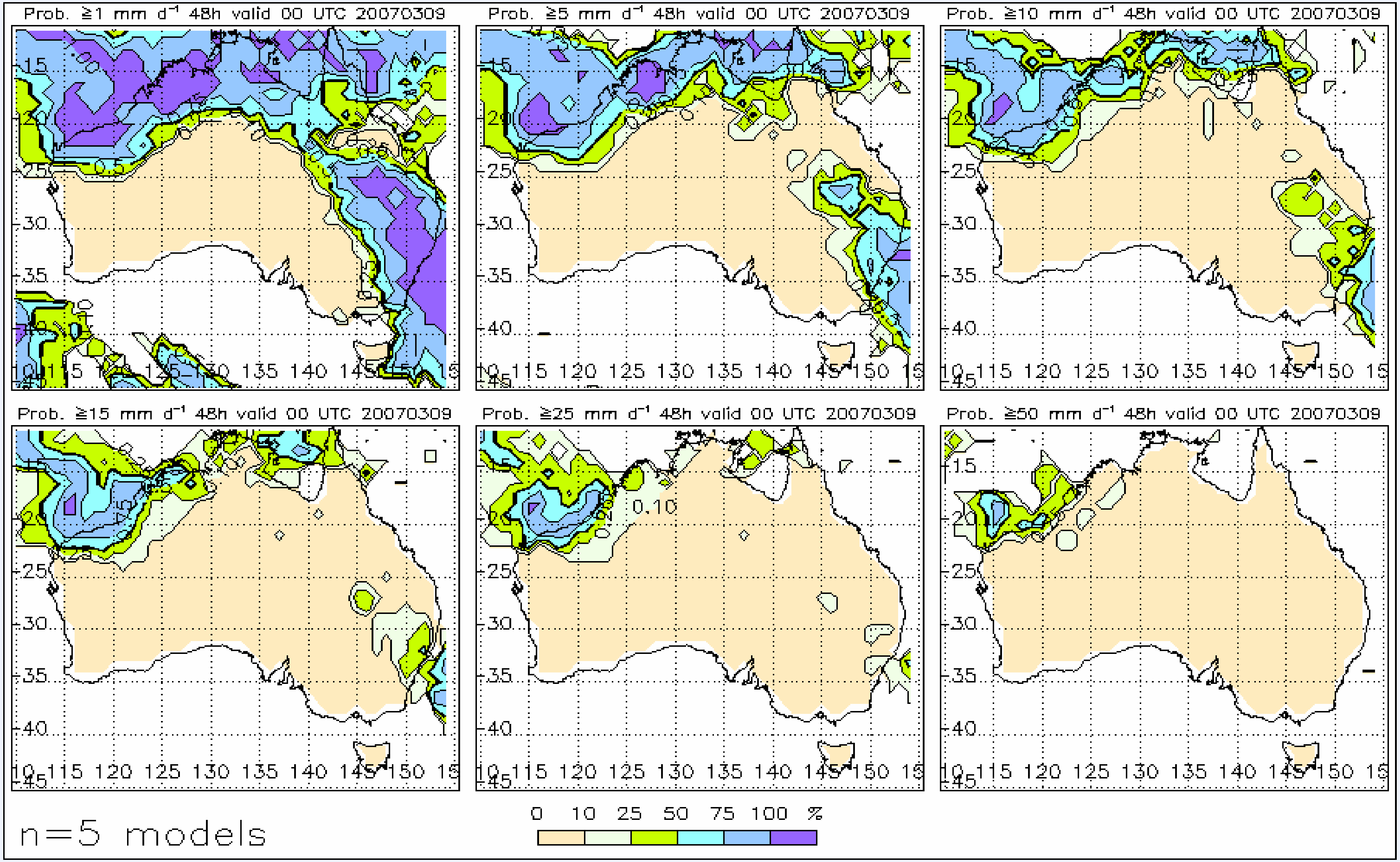




Mean of all models

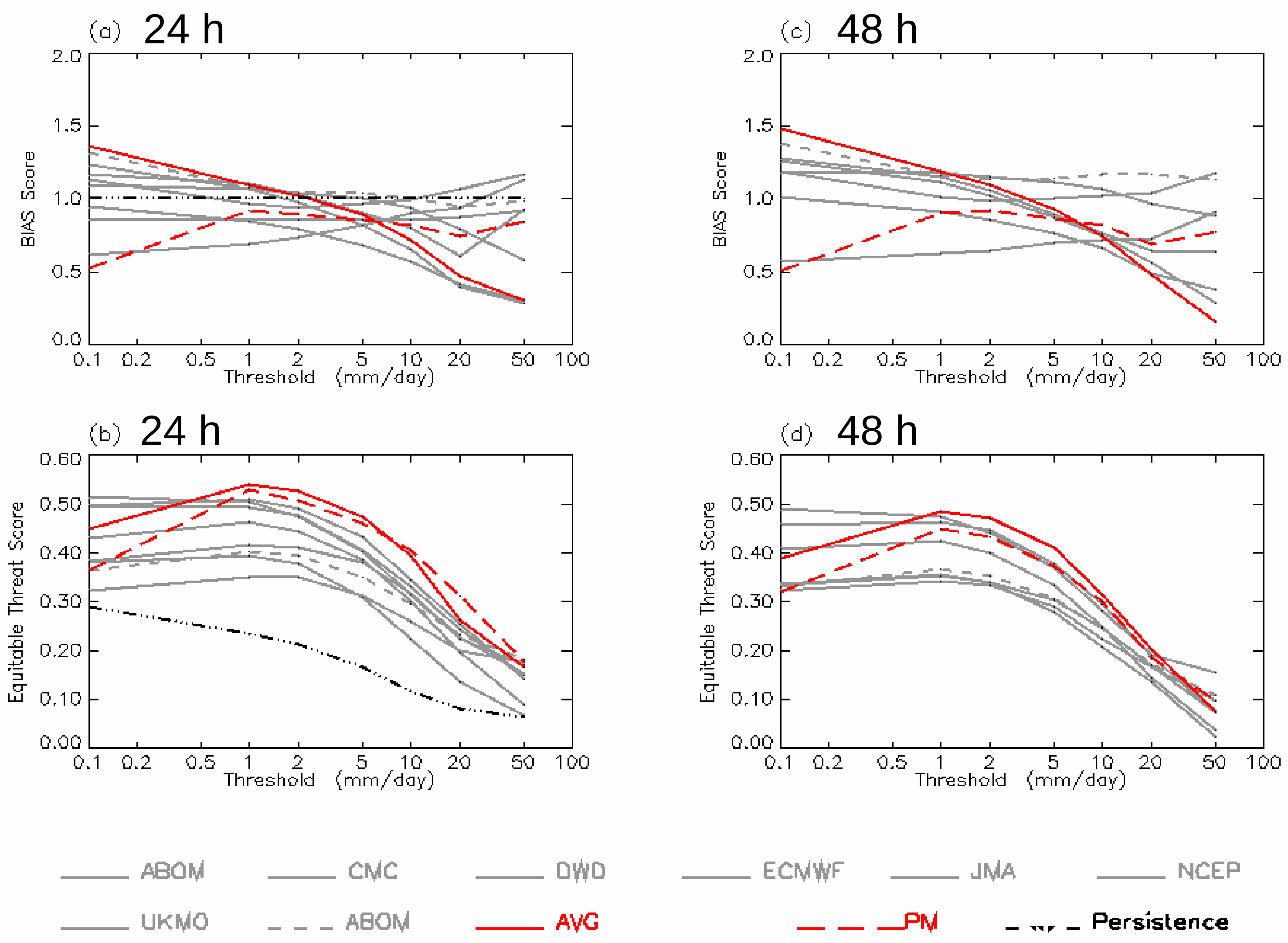
E. Ebert

Probability of rainfall exceeding thresholds



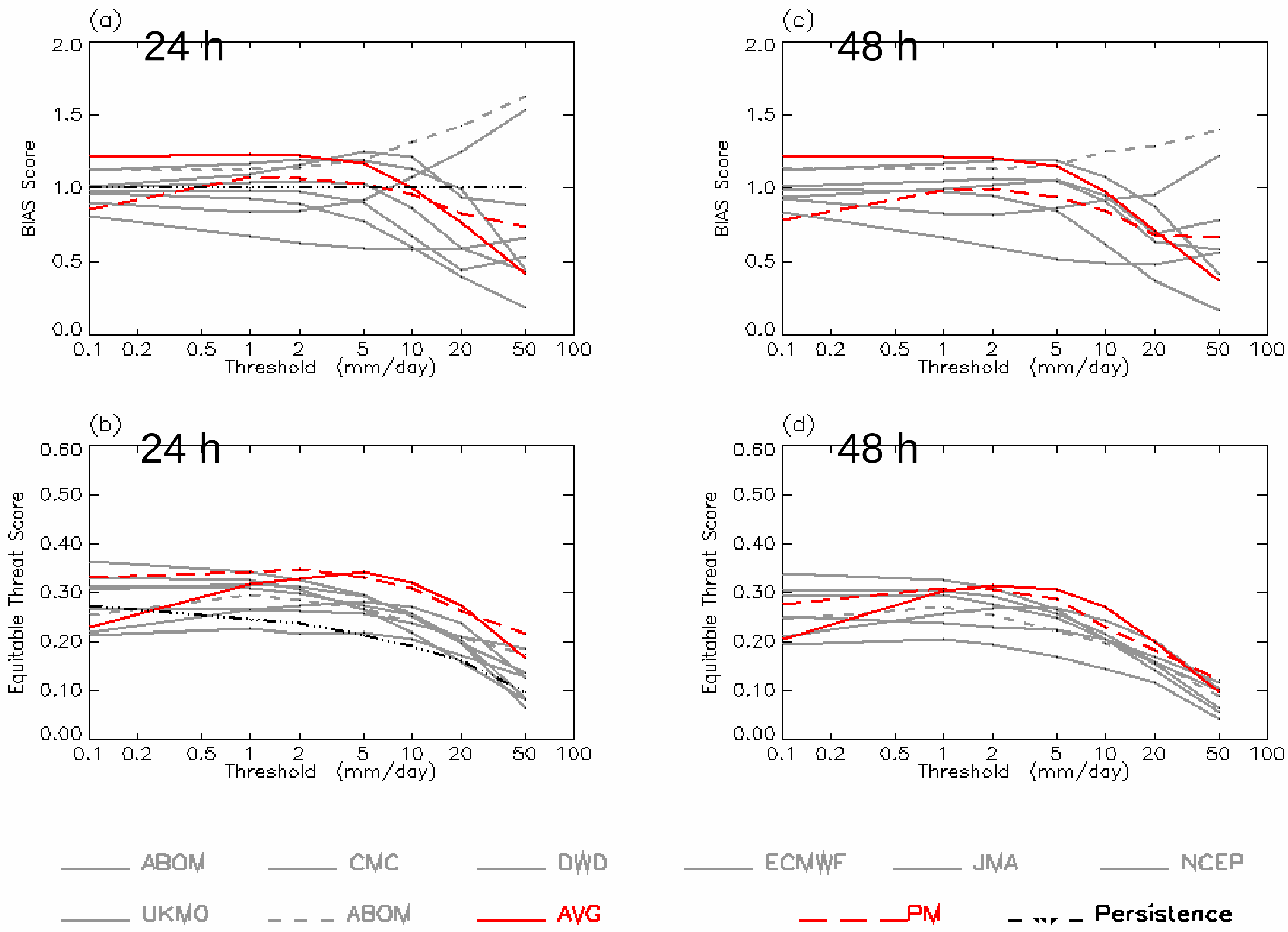
E. Ebert

Results for mid-latitude Australia
September 2000 - August 2002



E. Ebert

Results for tropical Australia
Summer 2000-2002



E. Ebert

Lecture 2
Summary

Examples were provided for:

- **Operational NWP systems being used at the Australian Bureau of Meteorology**
- **Use of Ensemble Prediction Systems for TC track prediction and precipitation forecasts**

These examples were shown to indicate modelling applications specifically designed for tropical weather prediction

- **The next lecture will discuss future directions in tropical NWP**

Conclusions

- Limited area models designed for tropics are used operationally at some operational centres
- Significant progress has been made in TC track prediction.

  Ensemble prediction has enhanced this progress
- Ensemble prediction systems show encouraging potential for application to monsoon prediction, rainfall prediction

Conclusions

- Till recently analysis of moisture has not been taken seriously – simple methods have been used to initiate diabatic processes
- Current satellite sensors and future missions will provide reliable and good coverage of moisture and precipitation
- Operational Centres have or will soon start **assimilating rainfall data** - this has potential to provide significant improvements in tropical NWP, and in particular **rainfall prediction**