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TROPICAL CYCLONE-RELATED NWP PRODUCTS AND THEIR GUIDANCE

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TROPICAL CYCLONE-RELATED NWP PRODUCTS AND THEIR GUIDANCE

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INTRODUCTION

The twelfth WMO Congress (May/June 1995) endorsed the implementation of a project entitled "**Tropical Cyclone-related NWP Products and their Guidance"** under the Tropical Cyclone Programme (TCP Sub-Project No. 18) within the framework of the Fourth WMO Long-term Plan (4LTP) (1996-2005). The objectives of the project were to determine the type of NWP products required to support the operations of tropical cyclone forecast offices, to serve as an essential reference for all operational tropical cyclone forecasters on the availability and use of NWP products and provide a link with other organizations which have an interest in various aspects of NWP.

The project was first proposed by the first TC RSMC Technical Coordination Meeting (Tokyo, December 1992) and was then elaborated at a TCP expert meeting in Mexico in December 1993.

In August 1995, the Secretary-General of WMO invited all Permanent Representatives of countries running NWP models for tropical cyclone forecasting to participate in the project through the provision of appropriate material.

This publication is the first update of the guide which was published in 1999 with Mr Alan Radford (UK) as Chief Editor and with contributions from six other highly qualified NWP specialists from six countries (Australia, France, India, Japan, UK and USA). This edition of the guide incorporates the contributions from three more WMO Members namely China; Hong Kong, China and Republic of Korea. It is hoped that other Members will also contribute to future updates.

The electronic version of this guide is also available at:

http://www.wmo.ch/web/www/TCP/TDs/TD9662002ed.doc

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CHAPTER 1

General summary of NWP models used to provide tropical cyclone guidance

1.1 Introduction

The rapid increase in computer power in recent years has enabled numerical models to attain resolutions where small-scale systems such as tropical cyclones are resolved. These models are displaying real skill with motion prediction, and have the potential to handle formation. However, only a limited number of models (Kurihara et al., 1995, for example), have attained resolutions where cyclone structure (including intensity) can be addressed.

Current research models and research programs indicate that numerical model forecasts of tropical cyclones will continue to improve. Improvements will also come from the ability to resolve fine-scale structure as computing power and memory continue to increase and become less expensive.

In order to understand how to use tropical cyclone-related NWP products it is important that forecasters have an appreciation of the manner in which numerical models are constructed, their basic physics, and the constraints under which they operate. This chapter therefore gives a brief overview of numerical models and their features, including methods of bogussing tropical cyclones.

Numerical models use a subset of the full fluid dynamics and thermodynamics equations describing the atmosphere. Subsets that are used for tropical cyclone track prediction include barotropic, non-divergent, shallow-water equations, truncated baroclinic and full primitive-equation models. The essential elements of these systems are:

- a grid of points at which atmospheric parameters are held (grid-point model), or a series of polynomials or spectral functions that approximate the atmospheric fields (spectral models);
- one or more distinct layers or levels in the vertical;
- an analysis/assimilation cycle to obtain the initial fields;
- a method for integrating the model equations forward in time;

- some form of physical parameterization to incorporate the effects of systems smaller than can be resolved by the grid or spectral wave numbers being used;
- a means of handling forcing from the model boundaries.

In addition, most systems now include a means of bogussing observations to provide additional information in data-sparse regions.

Full details of these processes are beyond the scope of this publication and may be found in standard texts, such as Haltimer and Williams (1979). Here we provide some of the essentials and requirements for such processes.

1.2 Model Grids

All operational models, including spectral models, start with atmospheric fields on a regular grid array, on which the required atmospheric parameters are held. Model grids can have any shape; they do not need to be regular, or square. The grid may be distorted to provide higher resolution in a specified region or near a system of interest (e.g. ARPEGE, section 2.3.1). Alternatively, higher resolution grids may be successively nested within each other to provide a telescope effect with a high-resolution focus on the region of interest (e.g. GFDL, section 2.7.3). The grid also may be regular, with all data held at common grid-points, or it may be staggered, with data split between two overlapping grids.

1.3 Model Vertical Structure

The vertical layers, or layers, are defined by using some form of vertical co-ordinate. In the early days of modelling, the simple pressure co-ordinate was widely used. This then tended to give way to the ‘sigma’ co-ordinate, which has the advantage of adjusting the variable orography into a ‘flat’ surface with a value equal to zero. Nowadays, many NWP centres use a hybrid combination of the pressure and sigma co-ordinate systems, providing the benefits of a terrain-following system in the lower atmosphere with a pure pressure co-ordinate higher up.

It is normal to vary the vertical resolution considerably, especially to provide high resolution in the atmospheric boundary layer and in the upper-level outflow region, where sharp vertical gradients occur.

1.4 Analysis, Assimilation and Bogus Observations

Analysis and assimilation consists of taking all available data and converting them to a form suitable for model integration. The data are obtained from a variety of sources and instruments, including direct temperature, moisture and wind from radiosondes, remotely sensed temperature derived from satellite sounding instruments, winds from satellite cloud drift calculations, direct radiances, etc. Observations with high consistency and low error characteristics need to be given priority over concomitant observations of lower quality. Typically, all of these observations are then combined together with a ‘background’ or ‘first-guess’ field into an initial analysis.

In regions of poor data coverage, it is often useful to include ‘bogus’ observations derived from human interpretation or empirical relationships to provide an indication of major weather patterns that would otherwise go unobserved. Of particular interest here is the process of tropical cyclone vortex bogussing.

Since most tropical cyclones have very few observations in the vicinity, they often go undetected by standard analyses or are analyzed very poorly, with centres ill-defined and in the wrong location. Such initial errors obviously have a major impact on the forecast of cyclone tracks and many attempts have been made to provide bogus vortices to approximate the cyclone. These attempts are helped by observations and theory (Elsberry, 1987) that the motion of tropical cyclones is not overly sensitive to details of the inner structure. Care must be taken, however, with the cyclone size and outer structure and with careful specification of the near environmental flow.

Most operational centres use some form of tropical cyclone bogus. These all utilize estimated location and intensity of cyclones from a variety of sources, together with current structural knowledge of tropical cyclones and any other available observations to generate mass and wind data representative of the system to be bogussed. Chapter 2 describes the methods in use at the various NWP centres.

Inserting the chosen bogus cyclone into the analysis is a difficult task. Typically , two less than optimal methods are used. In the first, the cyclone is smoothly added to the original analysis. In the second, the bogus cyclone circulation is used to generate a set of observations that are inserted into the analysis cycle.

Both methods have shortcomings. The bogus vortex addition can introduce significant shocks to the system in the early model integration, which can degrade the subsequent model forecast. In the second method, the bogus data (and any conventional data around the storm) can be rejected by the objective analysis scheme. The rejection occurs because of unacceptable differences from the first guess used by the analysis. This can be somewhat alleviated by use of more appropriate structure functions and error limits in the cyclone vicinity.

1.5 Physical Parameterization

All numerical models operate on a finite grid, or with a finite number of waves to describe the spectral signature. As a result, they cannot adequately resolve small-scale features, such as cumulus convection, or the interchange of energy between the surface and the ocean. Those “sub-grid-scale” processes that have an important impact on the forecasts are included by parameterising their effects on the larger scale.

As an example, let us consider cumulus convection. This is known to be related to the large-scale convergence in the lower troposphere and the degree of convective instability. One type of scheme, called convective adjustment, “adjusts” the atmosphere back to a defined lapse rate whenever convective instability of a prescribed amount develops. Alternative schemes depend on both a conditionally unstable atmosphere and local convergence. Once such conditions are satisfied, convection is assumed to occur and a parameterisation scheme is invoked. Such schemes can be relatively simple and based on a defined vertical heating profile with magnitude specified by the degree of moisture convergence (e.g. Kuo, 1974). Or they can be very complex and based on equilibrium conditions between a population of cloud types (Arakawa and Schubert, 1974). In all cases, the aim is to proved the model with an indication of changes required as a result of the unresolved convective activity.

The choice of convective parameterization scheme can greatly affect the quality of tropical cyclone forecasts.

1.6 Boundary Conditions

A very important consideration for limited area numerical forecasts is the quality of the boundary conditions (e.g. Errico and Baumhefner, 1987). This is because atmospheric waves and disturbances generated at the boundary can rapidly propagate throughout the domain and swamp the model forecast cycle. Two types of boundary therefore need to be carefully handled: the real boundaries at the earth's surface and top of the atmosphere; and the pseudo horizontal boundaries required because of capacity limitations with computers used for operational forecasting. At the earth's surface, models often have many layers close together to help provide the best simulation of such surface effects as local orography and sea-surface temperature. For a region of several thousand kilometers per side, the model solution will tend to be swamped by the horizontal boundary conditions after 2-3 days. For this reason, regional forecast models are always nested into global forecast systems.

CHAPTER 2

Details of operational NWP models used to provide tropical cyclone guidance and products

2.1 Introduction

The purpose of this chapter is to provide details of the characteristics of those operational NWP models currently used to provide tropical cyclone (TC) guidance and products. Each sub-section contains details of those models run by a particular Meteorological Service. In some cases more than one model is in operational use.

For each model, the following sub-sections are included:

a) Data Assimilation

Details of the data assimilation and analysis systems used for the model.

b) Initialization of TC's

Details of how tropical cyclones are initialized in the model including any bogus methods.

c) Forecast Model

Details of the forecast model, e.g. resolution, dynamics.

d) Physical Parameterisations

Details of the physical parameterization schemes used in the model.

e) Operational Schedule

The frequency at which the model is run operationally and the forecast range.

f) Forecasts of TC Track, Structure & Intensity

Specific forecasts produced by the model relating to the track, structure and intensity of tropical cyclones. These may only be available to internal users of the model.

g) TC Guidance Products

Tropical cyclone guidance products generally available to outside users.

A summary of all models is given in Table 1.

Table 1 – Summary of NWP models used for Tropical Cyclone Prediction

NWP Centre	Valid	Assimilation	TC Bogus	Model Type	Model Resolution	Model Schedule	Model TC Products
Australia	Dec 98	Diabatic, dynamical nudging scheme	Yes	Limited area grid-point – 2 nested grids, inner grid is relocatable (180 x 180 points)	Outer grid – 0.75^{o} latitude 0.75^{o} longitude 19 levels Inner grid –	(Experimental only)	(Experimental only)

					0.15^o latitude 0.15^o longitude 19 levels		
China	Apr 97	multivariate optimum interpolation	Yes	Limited area grid-point	0.9375^o 15 levels	four times a day	track forecasts
France ARPEGE-TROPIQUE	Jan 2002	4-dimensional variational assimilation	Yes	Global spectral	TL299 41 levels	Once a day from 00 UTC out to 72 hours (00 UTC)	None
France ALADIN-Réunion	Oct 2001	Interpolation from ARPEGE-TROPIQUE	No	Spectral LAM	~ 30 km over Indian Ocean	Once a day from 00 UTC out to 72 hours (00 UTC)	
France ARPEGE	Jan 2002	4-dimensional variational assimilation	No	Global spectral	TL298C3.5 41 levels	Twice a day from 00 UTC and 12 UTC out to 96 hours (00 UTC) and 72 hours (12 UTC)	
Hong Kong, China		3-dimensional multivariate optimum interpolation	Yes	Limited area grid-point	outer grid – 60km inner grid – 20km 15 levels	6 hourly runs of 60-km ORSM	TC track forecasts
India	Apr 98	3-dimensional multivariate optimum interpolation	Yes	Limited area grid-point	1^o 12 levels	Twice a day from 00 UTC and 12 UTC out to 48 hours	Track forecasts based on 850 vorticity maxima-experimental, used as guidance in RSMC New Delhi
Japan – GSM	Mar 01	3-dimensional multivariate optimum interpolation	Yes	Global Spectral	T213 (~55 km) 40 levels	Twice a day from 00 UTC and 12 UTC out to 90 hrs (00 UTC) and 216 hrs (12 UTC)	6-hourly forecasts of central position, central pressure, max sustained wind, radii of 30 kt winds, radii of 50 kt winds
Japan – TYM	Mar 01	3-dimensional multivariate optimum	Yes	Limited area spectral-for each target TC	C106 (~40 km) 25 levels	Twice a day from 00, 06, 12 and 18 UTC out to 84 hrs only	6-hourly forecasts of central position, central pressure,

		interpolation				when TC(s) exist in the responsibility area: 0oN-60oN, 100oE-180oE	max sustained wind, radii of 30 kt winds, radii of 50 kt winds
ROK (GFDK)	1997	GDAPS analysis & prognosis	Yes	Limited area grid-point	18 levels	Twice a day at 06UTC and 18UTC	central position and pressure, max winds every 6 hrs up to 72 hrs
ROK (BATS)	1997	GDAPS analysis & prognosis	Yes	Limited area grid-point	0.6^o	4 times a day	central position every 6 hrs up to 60 hrs
UK	Feb 99	Analysis Correction scheme	Yes	Global grid-point	0.56^o latitude, 0.83^o longitude, 30 levels	Four times a day out to 144 hours (00 UTC, 12 UTC) out to 48 hours (06 UTC, 18 UTC)	12-hourly track forecasts based on 850 hPa vorticity maxima
USA-AVN	Jun 99	3-dimensional variational assimilation	Yes	Global spectral	T170 42 levels	Four times a day from 00, 06, 12 and 18 UTC	Track forecasts out to 72 hours based on combination of 6 parameters
USA-NOGAPS	Feb 99	Multivariate OI (volume method)	Yes	Global spectral	T159 24 levels	Twice a day from 00 UTC and 12 UTC	Track forecasts out to 144 hours based on 1000 hPa wind circulation.
USA-GFDL	Feb 99	Adjustments to AVN analysis near tropical cyclone	Yes	Limited area grid-point	3 nested grids (inner grid 0.17^o) 18 levels	Four times a day	Track and intensity forecasts out to 72 hours
USA-LIBAR	Feb 99	Adjustments to AVN analysis near tropical cyclone	Yes	Limited area spectral (barotropic)	75 km transform grid spacing, single vertical layer	Four times a day	Track forecasts out to 72 hours
ECMWF	Apr 99	4-dimensional variational assimilation	None	Global spectral	T_L319 50 levels	Once a day from 12 UTC out to 10 days	None

2.2 Australia

2.2.1 Tropical Cyclone Limited Area Prediction System: TC-LAPS

Details of the TC limited area assimilation and prediction system (TC-LAPS) are described in Davidson and Weber (2000). The system became operational for the 1999-2000 Australian tropical cyclone season.

TC-LAPS has five basic components:

a) Data assimilation to establish the storm's large scale environment (LSE) and outer structure.
b) Vortex specification to construct the inner core circulation and asymmetries consistent with the estimated size, intensity and past motion.
c) High-resolution (HR) analysis, with appropriate observational errors, length scales and quality control tolerances, to merge the intense vortex into the LSE.
d) Initialisation with diabatic, dynamical nudging, to balance the vortex and insert satellite-defined cloud asymmetries.
e) High-resolution prediction with the TC-LAPS forecast model, which contains high order numerics and sophisticated physical parameterisations.

a) Data Assimilation and Coarse Resolution Configuration

Domain - Large Scale Environment (LSE):	55.0°S–56.75°N, 70.0°E-164.75°W
Assimilation cycle:	6 hour cycle
Horizontal resolution:	0.75° (150x170 lat-lon grid)
Vertical resolution:	19 sigma levels from 0.991 to 0.05
Analysis Method:	Multi-variate Statistical Interpolation
Analysed Variables:	Geopotential and wind fields
Initialisation:	Digital Filter

Nesting – LSE:	Lateral boundary at 6-hour intervals from operational global model
Soil Moisture Analysis:	Daily 0.25^ox 0.25^o over Australia. Fortnightly 0.8^ox 0.8^o climatology elsewhere
Sea Surface Temperature Analysis:	Weekly 1.0^ox1.0^o
GMS Bogus Moisture data:	6 hourly 0.5^ox0.5^o
GMS Cloud Top Temperature data:	Hourly 0.5^ox0.5^o

b) Initialisation of TC's

Construction of the TC vortex is based on a TC advisory issued by RSMC Darwin on the past motion and structure of the storm. A symmetric vortex is constructed using an empirical surface pressure profile, assuming a moist adiabat at the TC centre, and empirical relations to define the mass field between the centre and the LSE. The wind field is obtained by gradient wind balance. A wave number one asymmetry is constructed such that the observed drift speed equals the sum of the environmental flow and the flow induced by the artificial asymmetry at the observed vortex centre. The synthetic vortex (sum of symmetric and asymmetric components) is implanted into the global analysis after filtering to remove any previously existing, weak and misplaced circulation. Synthetic observations are produced at high horizontal resolution to define the inner core structure. These are used in the HR objective analysis.

24 hours of diabatic, dynamical nudging is used to balance the vortex and re-define the vertical motion field to be consistent with the satellite cloud imagery. The model is "nudged" toward objective analyses that include the synthetic vortex. Analysed values of vorticity and surface pressure are preserved. During nudging, heating from the moist processes is switched off and vertical heating profiles defined from the cloud imagery are inserted. This procedure initialises the vortex and generates ascent in those areas where cold cloud tops exist.

c) High Resolution Forecast Model

The TC-LAPS system is double-nested, with the large-scale environment (LSE) nested within the global forecast, and the high-resolution (HR) relocatable domain, centred on the TC, nested within the LSE forecast.

Domain – High Resolution (HR):	Variable 27^ox27^o, TC centred
Horizontal resolution:	0.15^o (180x180 lat-lon grid)
Analysis Method:	Univariate Statistical Interpolation
Vertical resolution:	19 sigma levels from 0.991 to 0.05
Initialisation:	24 hours diabatic, dynamical nudging
Nesting:	Boundary conditions at 3-hour intervals derived from +0 to +72 hour LSE forecasts.

d) Physical Parameterisations and Surface Grid Fields

Convection:	**ECMWF's Mass-flux**
Large scale rain:	Supersaturation Scheme
Boundary Layer:	ECMWF's VB Scheme
Short Wave Radiation:	3-hourly, Lacis and Hansen
Long Wave Radiation:	3-hourly, Fels and Schwarzkopf
Topography:	Derived from 0.1^o resolution data
Soil Moisture Analysis:	Daily 0.25^ox 0.25^o over Australia. Fortnightly 0.8^ox 0.8^o climatology elsewhere

Sea Surface Temperature Analysis:	Weekly 1.0^ox1.0^o
Albedo:	Climatology

e) Operational Schedule

TC-LAPS runs over a high-resolution TC centred domain, twice a day to T+72h, based on data valid at 00 and 12 UTC. It can be run twice, centred on two separate systems for both time periods

f) Forecasts of TC Track, Structure & Intensity

Track forecasts are produced within the high-resolution domain out to 72 hours using an automated vortex tracking routine that locates the centre from the MSLP and low-level wind fields. This produces centre location, central pressure and the maximum wind below 850 hPa.

g) TC Guidance Products

Guidance products for 6-hourly periods out to 72-hours from TC-LAPS are made available through registered user access to the Darwin RSMC web page at:

http://www.bom.gov.au/weather/nt/rsmc/

These products include:

- MSLP;
- Winds at 950, 850, 700, 500, 250, 200 hPa;
- 24-hour precipitation;
- Forecast and observed track.

Additionally the forecast track data is e-mailed to regional TC warning centres.

Davidson, N.E. and H. C. Weber, 2000: The BMRC High-Resolution Tropical Cyclone Prediction System: TC-LAPS. *Mon. Wea. Rev.,* ***128***, 1245–1265.

2.3 China

2.3.1 Model for Typhoon Track Prediction (MTTP)

a) Data Assimilation, objective analysis and initialization

Data assimilation	None
Method of analysis	Multi-variable Optimum Interpolation (O/I)
Analysed variables	u, v, T, RH
First guess	12h forecasts by T63L16
Coverage	O^{o}N-50.625^{o}N, 84.375^{o}E-161.25^{o}E
Horizontal Resolution	0.9375^{o}
Vertical Resolution	12 (p levels)
Initialization	Adiabatic non-linear NMI

b) Initialization of TC's

The twice typhoon bogus technique was used in the operational MTTP since 15 April 1997. The typhoon bogus is blended first time before the objective analysis, second time after the objective analysis. Of course, the first typhoon bogus is associated with the first guess data, and the second typhoon bogus is linked with the objective analyzed data.

c) Forecast Model

Basic equations	Primitive equations in Lat.-Lon.
Independent variables	u, v, ps, T, q, Ts, qs
Dependent variables	$\varnothing$, σ
Numerical Techniques	in horizontal - Lat.-Lon. finite difference in vertical - irregular discretization in time - leap - frog

Integration domain	6.5625^oN – 42.890625^oN, 101.25^oE – 150.46875^oE ps – 0hPa
horizontal resolution	0.46875^o
vertical resolution	15 (σ)
time step	30s
Orography	smoothed
Gravity Wave drag	none
Horizontal Diffusion	second order non-linear
Vertical Diffusion	Louis (1979)
Planetary Boundary Layer	Simple
Treatment of sea surface, earth surface and soil	yes
Radiation	Lacteal (1974)
Convection	
• deep convection	Kuo-74 scheme
• shallow convection	Tiedte (1987)
Atmospheric moisture	modification of moisture
Lateral Boundaries	Davies scheme

In 1998, the operational MTTP system was modified by a “movable interior area” of the model. It means that the interior area center of the model is not fixed, but movable inside of the exterior area at initial time of each run, and its movement depends on the position coordinates of observed typhoon (or tropical cyclone). However, when more than one typhoon (or tropical cyclone) are observed at initial time of the run the interior area center of the model is not moved. At present, MTTP has a grid size of 0.9375 Lat.- Lon., degree and grid numbers of 83*55 for the exterior area of the model.

2.3 France

2.3.1 ARPEGE-TROPIQUE Model

a) Data Assimilation

The assimilation runs with a 6-hour cycle, with a 3 hours short cut-off to run the forecast model, and a 9 hours cut-off for 00 UTC and more than 12 hours cut-off for 06 UTC, 12 UTC and 18 UTC. The objective analysis is performed with a (T107) 4D variational scheme, and works on wind, temperature and relative humidity fields in 3D, and geopotential at the altitude of the model surface in 2D.

Assimilated data:	TEMP and TEMPSHIP (part A, B, C and D), PILOT (part A, B, C and D), AIREP, AMDAR, ACARS, SATOB, TOVS 120, with observation time in [H-3h, H+3h] for the analysis at H, SYNOP, SHIP, BUOY, BATHY with observation time in [H-30m, H+30m], BUFR message from RSMC La Réunion (cf. b above)
Assimilation cycle:	6 hour cycle.
Analysis method:	Four dimensional variational analysis
Analysed variables:	Wind, geopotential and relative humidity fields on model levels.
First guess:	A 6-hour forecast of ARPEGE-TROPIQUE. By default a 12, 18 or 24-hour forecast. Climatological fields when forecasts are unavailable.
Cover:	Global cover
Horizontal resolution:	Observation are assimilated on a T107 resolution (124.6 km), but with short waves coming from ARPEGE-TROPIQUE forecast model (see Forecast model).
Vertical resolution:	41 levels (hybrid vertical co-ordinate) from screen up to 1 hPa.
Initialisation:	Digital filter initialisation.

b) Initialisation of TC's

By introducing a bogus observation of minimum of pressure at the centre of the tropical cyclone as seen by RSMC La Réunion forecasters through Dvorak Analysis. The error observation is fitted not to have too deep pressure at the centre.

c) Forecast Model

ARPEGE-IFS is a common development between Météo-France and ECMWF. ARPEGE (Action de Recherche Petite Echelle Grande Echelle) is the French name while IFS (Integrated Forecast System) is the name used by ECMWF.

Basis equations:	Primitive equation system.
Independent variables:	Both components of the horizontal wind, temperature, specific humidity and surface pressure.
Dependent variables:	Vertical velocity and density
Numerical technique:	Spectral 2 time-level semi-lagrangian model. Temporal discretisation using leapfrog semi-implicit scheme.
Integration domain:	Global.
Resolution, time step:	Triangular truncation TL299 (44,6 km). It has 41 vertical levels from screen level up to 1hPa, using the hybrid co-ordinate from Simmons and Burridge (1981). The time step is 1350 seconds.

d) Physical Parameterisations

Orography, Gravity wave drag:	The orography of this model is computed on the Gauss grid from US NAVY 10' x 10' data using a variational technique that strongly reduces the noise associated to Gibbs waves (see Bouteloup, 1993). The gravity wave drag takes in account some anisotropy, blocking and mid-tropospheric effects.
Horizontal diffusion:	Implicit in spectral space and incorporating an orography dependent correction for temperature
Vertical diffusion:	Scheme linked to PBL (see next point)
Planetary boundary layer:	ECMWF method (Louis *et al.,* 1981)
Earth surface:	Fixed analysed sea surface temperature and amount of sea -ice; very simplified model for evolution of surface temperature and moisture.
Radiation:	Hyper-simplified scheme at every time step (Geleyn and Hollingsworth, 1979)

Convection:	Mass flux scheme (Bougeault, 1985) modified.
Humidity:	Specific humidity is the variable: no storage of condensate; evaporation of falling rain; treatment of the ice-phase.

e) Operational Schedule

00 UTC data: 3h00 cut-off, ARPEGE analysis and forecast up to 72 hours.

f) Forecasts of TC Track, Structure & Intensity

From sea level pressure.

g) TC Guidance Products

None at present.

2.3.2 ALADIN-REUNION Model

a) Data Assimilation

No assimilation is performed. The initial fields are initialised by interpolation from ARPEGE-TROPIQUE fields.

b) Initialisation of TC's

None at present.

c) Forecast Model

ALADIN-REUNION is a spectral limited area model, developed in ALADIN project team from many countries over Europe (http://www.cnrm.meteo.fr/aladin/).

Basis equations:	As ARPEGE-TROPIQUE
Independent variables:	As ARPEGE-TROPIQUE
Dependent variables:	As ARPEGE-TROPIQUE
Numerical technique:	As ARPEGE-TROPIQUE
Integration domain:	From 1.2 S to 36 S, and 29.3 E to 100.7 E
Resolution, time step:	Spectral E124x63 L41 gives us a 31.5 km mesh over Indian ocean. It has 41 vertical levels from screen level up to 1 hPa, using the hybrid co-ordinate from Simmons and Burridge (1981). The time step is 1350 seconds.

d) Physical Parameterisations

As ARPEGE-TROPIQUE

e) Operational Schedule

00 UTC after ARPEGE-TROPIQUE analysis and forecast are completed, and forecast up to 72 hours.

f) Forecasts of TC Track, Structure & Intensity

None at present

g) TC Guidance Products

None at present.

2.3.3 ARPEGE Model

a) Data Assimilation

The assimilation runs with a 6-hour cycle, with 10 hours 45 minutes (10h45m) cut-off for 00 UTC and 12 UTC, and 5h30m cut-off for 06 UTC and 18 UTC. The objective analysis is performed with an incremental (T107/T161) variational scheme, and works on wind, temperature and relative humidity fields in 3D, and geopotential at the altitude of the model surface in 2D.

Assimilated data:	As ARPEGE-TROPIQUE except BUFR message from RSMC La Réunion
Assimilation cycle:	As ARPEGE-TROPIQUE
Analysis method:	As ARPEGE-TROPIQUE
Analysed variables:	As ARPEGE-TROPIQUE
First guess:	A 6-hour forecast of ARPEGE. By default a 12, 18 or 24-hour forecast. Climatological fields when forecasts are unavailable.
Cover:	As ARPEGE-TROPIQUE
Horizontal resolution:	Observation are assimilated on a T161 resolution (82.8 km), but with short waves coming from ARPEGE model (see Forecast model)
Vertical resolution:	As ARPEGE-TROPIQUE
Initialisation:	As ARPEGE-TROPIQUE

b) Initialisation of TC's

None at present.

c) Forecast Model

As ARPEGE-TROPIQUE, but ARPEGE uses Schmidt's transformation leading to variable mesh configurations, having a pole of maximum resolution and a resolution varying continuously from that pole to the antipode. T being the nominal truncation and C the "stretching factor", the local resolution of the model is T x C over the pole, and T / C at the antipode.

Basis equations:	As ARPEGE-TROPIQUE
Independent variables:	As ARPEGE-TROPIQUE
Dependent variables:	As ARPEGE-TROPIQUE
Numerical technique:	As ARPEGE-TROPIQUE
Integration domain:	As ARPEGE-TROPIQUE
Resolution, time step:	Triangular truncation T298 with a stretching factor C3.5. The resolution varies from T 1043 over France (12.8 km equivalent mesh for a finite difference model) to T85 over New Zealand (156 km equivalent mesh). It has 41 vertical levels from screen level up to 1 hPa, using the hybrid co-ordinate from Simmons and Burridge (1981). The time step is 830 seconds.

d) Physical Parameterisations

As ARPEGE-TROPIQUE

e) Operational Schedule

00 UTC data: 1h50 cut-off, ARPEGE analysis and forecast up to 96 hours.

12 UTC data: 1h50 cut-off, ARPEGE analysis and forecast up to 72 hours.

f) Forecasts of TC Track, Structure & Intensity

None at present

g) TC Guidance Products

None at present.

2.5 Hong Kong, China

2.5.1 ORSM

a) Data Assimilation, objective analysis and initialization

Assimilated data:	From GTS: SYNOP, SHIP (surface data and ship data) TEMP, PILOT (radiosonde and pilot data) AIREP, AMDAR (aircraft data) SATEM (satellite thickness data) TOVS, ATOVS (virtual temperature profile) SATOB (satellite wind data) From RSMC Data Serving System (DSS) of JMA: GMS digital data – total cloud amount, mean cloud top temperature and its standard deviation for moisture bogus GMS cloud motion vectors during tropical cyclone situations From NCEP data server Daily sea surface temperature analysis at 1-degree resolution Locally generated data Tropical cyclone bogus data during tropical cyclone situations
Initialization	Non-linear normal mode initialization

Three-dimensional multivariate optimal interpolation is performed four times a day based on 00, 06, 12 and 18 UTC for the 60-km outer domain. Data cut-off time is about three hours after the observation time. For the inner domain, the same objective analysis scheme is performed 8 times a day based on 00, 03, 06, 09, 12, 15, 18 and 21 UTC. Data cut-off time is about 2 hours. All analyses are applied to 36 vertical levels.

The horizontal domains of both inner and outer models compose of 151 x 145 model grids in Mercator projection. The first guess fields of the model analyses are provided by their respective latest forecasts.

Hourly rainfall information derived from real-time calibration of radar reflectivity with rain gauge data as well as from the GMS digital cloud data, are incorporated into the model through a physical initialization process. In this process, the moisture of the initial field (between the lifting condensation level and the cloud top inferred from the cloud top temperature) at the point where rain is observed is adjusted to allow precipitation process to be switched on. The heating rate of the precipitation process is also adjusted to correspond to the rainfall amount observed. The rainfall information in the hour preceding analysis time is used in the outer model. For the inner model, pre-runs for 3 hours preceding analysis time are performed to incorporate the rainfall information.

b) Initialization of TCs

Tropical cyclone bogus data is created during tropical cyclone situations.

c) Forecast Model

Basic equations	Primitive hydrostatic equations
Vertical	Sigma-P hybrid coordinate, model top at 10 hPa
Forecast Parameters	Ln (surface pressure), horizontal wind components, virtual temperature, specific humidity
Numerical Methods	
• Horizontal	Double Fourier
• Vertical	Finite Difference
• Time	Euler semi-implicit time integration
Initialization	Non-linear normal mode initialization

d) Physical Parameterisations

Physical Processes	
• Radiation scheme	Sugi *et al.* (1990)
• Short Wave	calculated every hour
• Long Wave	calculated every hour
Moisture Processes	
• Cumulus Convection	Arakawa-Schubert (1974)
• Mid-level Convection	Moist convective adjustment proposed by Benwell and Bushby (1970) and Gadd and Keers (1970)
• Large-scale Condensation	Included
• Grid-scale evaporation and Condensation	Included
Planetary Boundary Layer	Scheme proposed by Troen and Mahrt (1986) in which non-local specification of turbulent diffusion and counter-gradient transport in unstable boundary layer are considered.
Surface	4-layer soil model daily sea surface temperature analysis (fixed in forecast) Climatological snow and sea ice distribution Climatological evaporation rate, roughness length and albedo

Topography	Envelope topography, derived from 30-second latitude/ longitude resolution grid point topography data
Boundary conditions:	For the outer model, 6-hourly boundary data including mean sea level pressure, wind components, temperature and dew point depression at 15 pressure levels (1000, 925, 850, 700, 500, 400, 300, 250, 200, 100, 70, 50, 30, 20, 10 hPa) and the surface, are provided by the Global Spectral Model of JMA. For the inner model, hourly boundary data are provided by the outer 60 km model.
Horizontal diffusion	Linear, second-order Laplacian

e) Operational Schedule

The outer 60-km ORSM is run four times a day with a cut-off time of 3 hours to produce 48-hour forecasts for the area 9^oS – 59^oN, 65^o-152^oE based on 00, 06, 12 and 18 UTC analysis data. The inner 20-km ORSM is run 8 times a day for 24-hour forecasts for the area 10^o-35^oN, 100^o-128^oE based on 00, 03, 06, 09, 12, 15, 18 and 21 UTC analyses.

f) Forecasts of Tropical Cyclone (TC) Track

TC track forecasts from consecutive 6-hourly runs of 60-km ORSM are generated to facilitate forecaster's interpretation of model forecasts. Ensemble forecast of TC track derived from global model outputs is also complied. Forecasters can modify the weightings for different members and generate the ensemble forecast interactively.

2.6 India

2.6.1 Limited Area Analysis Forecast System (LAFS)

a) Data Assimilation

The grid point for running the forecast model are prepared from the conventional and unconventional data received through the GTS. The input data used for analysis consist of :

- Surface – SYNOP/SHIP
- Upper air – TEMP/PILOT, SATEM, SATOB,
- Aircraft reports – AIREP, AMDAR, CODAR

Which are extracted and decoded from the raw GTS data sets. All the data are quality controlled and packed into a special format for objective analysis. Provision exists for inclusion of cyclone bogus data in the input data file whenever required.

The objective analysis is carried out by a three dimensional multivariate optimum interpolation procedure. The variables analyzed are the geopotential, u and v components of wind and specific humidity. The temperature field is derived hydrostatically from the geopotential field. Analysis is carried out on 12 sigma surfaces in the vertical and on a 1° x 1° latitude-longitude grid for a 'regional' or 'limited area' horizontal domain (91x51 grid points). The sigma fields are post-processed to pressure surfaces for display and archival.

The background fields required for objective analysis are obtained from the global model forecasts of the National Centre for Medium Range Weather Forecasting, New Delhi.

b) Initialization of TC's

The scheme used for initialization of tropical cyclones generates synthetic observations based on an empirical structure of cyclones. First, the surface pressure field is constructed on a dense grid. Surface winds are obtained from the surface pressure by use of the gradient wind relationship. Upper winds are obtained from the surface winds with the aid of composite vertical wind shear factors. Appropriate inflow and outflow angles are added to the compound winds to ensure proper convergence in the lower levels and divergence in the upper levels. The humidity field is prescribed as near saturation value within the field of the vortex. These steps have been introduced to ensure a proper spin up of the vortex during the course of integration of the forecast model. Details of the scheme are provided in the following paragraphs.

(i) Construction of surface pressure field

We make use of the empirical model developed by Holland to prescribe the surface pressure field. The relationship is given by:

$$P_r = P_c + (P_e – P_c) \exp(-a/r^b)$$

where

P_r : is the pressure at radius r,
P_e : is the environmental pressure,
P_c : central pressure, and

a and b are empirical constants.

The constants a and b are related to the radius of maximum wind (RMW) in a cyclone by the following equation.

$$RMW = (a)^{1/b}$$

The constants a and b have to be determined empirically and may differ from regions to region and even from cyclone to cyclone. It has been found that the value of 'b' varies from 1.0 to 2.5 for cyclones in the Indian seas and that each has a unique value. Application of the above model for deriving the surface pressure distribution is dependant upon the availability of the following parameters.

- Central pressure
- Radius of maximum wind
- Value of constant 'b'

The central pressure is estimated with the help of the pressure drop corresponding to the satellite T-Number classification of the storm and the pressure of the outermost closed isobar. The radius of maximum wind may be estimated from the radius of the eye as available from the radar report, if already in the range of a coastal cyclone detection radar station, or the satellite imagery if the storm is out at sea. For the present the value of RMW is taken as 30 km in all case. As mentioned earlier, the value of constant 'b' needs to be determined for the region and the particular cyclone empirically. In the present case, however it was taken as 1.5, which is tentatively found to be appropriate for the Indian region. Pressure data are generated up to 400 km radius, on a grid of 50 km spacing.

(ii) Surface Winds

After the surface pressure distribution is defined, the surface winds are derived using the gradient wind relation. A correction for storm motion is applied. In the absence of friction and expression for wind speed, V, inside the cyclone field is obtained in the form.

$$V= -\alpha + (\alpha^2 + r/\rho.\partial p/\partial r)^{1/2}$$

Where
$2\alpha=fr-V_c \sin\theta$
f= Coriolis parameter
r= radial distance
V_c= storm speed
θ= Azimuthal angle measured clockwise from direction of motion (taken as 0^0)

The above expression is obtained from the gradient wind equation expressing balance of forces in the absence of friction.

$$1/r.\partial p/\partial r – fV - V^2/r + VV_c \sin\theta/r = 0$$

(iii) Upper Winds

The upper winds are derived from the surface winds by assuming an *ad hoc* vertical wind shear, which decreases the strength of the vortex with increasing height. Values of composite vertical wind shear factors are taken from the following table:

Surface	850 hPa	700 hPa	500 hPa	400 hPa	300 hPa
1.0	0.9	0.8	0.7	0.65	0.35

The composites indicate a wind speed varying very slowly with height up to 400 hPa with rapid decrease above. The factors would vary from case to case and depend upon thermal stability and stage of development of the system.

In order to ensure a proper low level convergence and an upper level divergence in the vortex field and inflow angle is added in the lower levels varying from 30° at the surface becoming zero at 500 hPa. The circulation at the upper levels 250 and 200 hPa is made anticyclone and an outflow angle of 20° is added.

c) <u>Forecast Model</u>

The forecast model is a semi-implicit semi-Lagrangian multilayer primitive equation model. It uses the sigma vertical co-ordinate system and has staggered Arakawa C-grid in the horizontal. The present version of the model has a horizontal resolution of 75 km and 16 sigma levels (1.0 to 0.05) in the vertical. The forecast model is constructed from the equations of motion, the thermodynamic energy equation, the mass continuity equation, the moisture continuity equation, the hydrostatic equation and the equation of state.

The lateral boundary data for running the forecast model are obtained from the global model forecasts of the National Centre for Medium Weather Forecasting, New Delhi.

d) <u>Physical Parameterisations</u>

The following physical processes are included.

- Large scale condensation
- Shallow moist convection
- Deep cumulus convection
- Surface fluxes
- Vertical diffusion
- Short-wave radiation
- Long-wave radiation
- Surface energy balance
- Orograhy

e) Operational Schedule

LAFS runs in operational mode on the CYBER 2000U computer system in IMD, twice a day out to T+48 based on 00 UTC and 12 UTC data. LAFS is also implemented on Origin-200 computer system

f) Forecasts of TC Track, Structure & Intensity

The track forecast up to 48 hours is prepared by taking the centre of the 850 hPa vorticity maxima from the predicted fields. The forecasts are currently experimental and are used as guidance products within the IMD.

The following chart products are also:

- Analysed and forecast grid point fields of basic flow variables:

  - sea level pressure
  - geopotential
  - wind
  - temperature
  - humidity

- Derived fields:

  - vorticity
  - divergence
  - vertical motion
  - integrated moisture flux divergence
  - precipitated water
  - vertical wind shear
  - equivalent potential temperature and its lapse rate

g) TC Guidance Products

There are no tropical cyclone guidance products from LAFS generally available to users outside of IMD.

2.6.2 Quasi-Lagrangian Limited Area Model

A Quasi-Lagrangian Model (QLM) for cyclone track prediction has been implemented at RSMC New Delhi in 2000.

a) Data Assimilation

A new version of the IMD's operational optimum interpolation scheme for objective analysis (used for generating initial fields for IMD LAM) has been developed to suit the QLM grid structure, which is quite different from the grid structure of LAM in horizontal and vertical both. The symmetric vortex as described in the preceding subsection, and the analysis are then merged using appropriate weighting functions (see below). The symmetric vortex fields are first projected on the QLM grid and then merged with the analysed fields. . The initial analysis and lateral boundary conditions are generated from operational analysis and forecasts produced by the global spectral model of National Centre for Medium Range Weather Forecasting (NCMRWF), New Delhi. The initial fields for QLM are obtained as follows. First, the analysis valid at the map time is carried out by updating the NCMRWF GCM forecast, 12H (for 12 UTC run) or 24H (for 00 UTC run) with current observations by optimum interpolation (OI) scheme.

The NCMRWF forecast fields are a set of spectral coefficients being the outputs of a T80 GCM on 18 sigma levels. The spectral coefficients are transformed to QLM grid and vertical interpolation carried out to get QLM sigma fields from GCM sigma levels. OI analysis is carried out directly on the QLM sigma levels.

b) Initialization of TC

The prescription of idealised vortex is based on the storm's central pressure p_c, the pressure of the outer most closed isobar p_b and its distance R (size) from the centre. These parameters (p_c, p_b and R) together with the location of the storm centre are derived from synoptic analysis and satellite imagery information like T Number estimate.

The surface pressure p_{sfc} (r) at a radius r in the idealised symmetric vortex is obtained from:

$$p_{sfc}(r) = p_{max} - [\Delta p \exp(-x^2)] / (1+ax^2)^{1/2} \quad r < R$$

$$p_{sfc}(r) = p_b \quad r \geq R \tag{1}$$

here x = r/R, a is a specified constant and the other two constants, p_{max} and Δp are evaluated from the conditions $p_{sfc}(0) = p_c$, and $p_{sfc}(R) = p_b$.

The large pressure gradients observed in intense cyclones cannot be prescribed well with the use of a coarse grid (40 km in the QLM). Therefore a lower limit has to be set to the central pressure, which is 970 hPa whenever a lower value occurs.

This has been arrived at based on past cases of model runs. In the rare cases when the reported storm size R is less than 170 km, R is reset to 170 km, because at least four grid points in the radial direction are required to capture a storm's basic structure.

The winds at pressure levels are specified as follows:

First, the wind $v_g(r)$ at 1000 hPa is obtained from the quadrant wind flow:

$$v_g^2 / r + f_c v_g - \partial\phi / \partial r = 0 \tag{2}$$

Where f_c is the Coriolis parameter at the latitude of the storm centre, g is the acceleration due to gravity and geopotential ϕ at 1000 hPa is obtained from the approximate relation $\phi=8[p_{sfc}(r) - 1000]$ (with p_{sfc} in hPa).

A set of horizontal and vertical functions is used to derive the winds at higher levels.

$$v(r,p) = [F(p) - G(p)H(r)]\, v_g(r) \qquad (3)$$

Where $F(p) = 0.5\,[1 + \tanh(\pi (p - Pa)/\Delta P_a)]$

$G(p) = \text{sech}[(p - P_a)/\Delta P_a]$
$H(R) = \text{sech}[(r - R_a)/\Delta R_a]$

The location of maximum cyclonic winds is controlled by the parameter a in Eq. (1); the rate of decrease of cyclonic winds in the vertical by Pa and ΔP_a; and the strength and location of anticyclonic winds in the higher atmosphere by R_a and ΔR_a.

Fixed values of a=100, P_a=150 hPa, ΔP_a=200 hPa, R_a=280 km and ΔR_a=200 km are used in the QLM. With the above specifications and the values of p_c, p_b and R corresponding to a mature cyclonic storm, the structure of the winds obtained from (3) consists of cyclonic winds everywhere in the lower levels with the maximum winds located at 2 to 3 grid intervals from the centre, cyclonic winds extending into the middle troposphere with a slight decrease in their strength, the cyclonic winds decreasing rapidly above the middle troposphere, and anticyclonic winds appearing in the upper troposphere.

The geo-potentials at interior grid points are obtained from the wind field with the use of gradient wind relation using the geo-potential at radius R as the boundary value, which in turn is evaluated as the mean geo-potential value at R from the initial analysis. Temperatures are derived hydro-statically from the geo-potential.

The vertical column at the vortex centre is specified to be nearly saturated. Somewhat lower values of RH are specified at R. The RH at intermediate grid points is interpolated linearly from the values at the centre and R. The rate of convective precipitation depends on RH distribution.

Since this rate is expected to be smaller in weaker storms, the RH values are reduced by a factor B= 0.85 + 0.015 ($p_b - p_c$) for an initial disturbance with $p_b - p_c < 10$ hPa. Prescription of near saturation values of RH is necessary to induce proper convection in the storm field, which has a significant contribution in its development and movement process.

The following relation is used for the merging process:

$$X = w X_v + (1-w) X_a$$

Where X is one of the variables u, v, θ, q and p_{sfc} and the subscripts v and a denote a field in the vortex and analysis respectively. The weight w is given by:

$w = \cos(\pi/2.\ r/R) \quad r < R;$

$w = 0$ otherwise.

Prescription of a steering current:

A steering current, which is specified based on the current storm speed and direction is superimposed on the analyzed fields. The steering current is computed by constructing a dipole circulation.The dipole winds and geopotential height fields (incremental heights calculated from dipole winds geostrophically) are added to the vortex fields at all levels.

Thus the two special attributes of the QLM are: (i) merging of an idealized vortex into the initial analysis to represent a storm in the QLM initial state; and (ii) imposition of a steering current over the vortex area with the use of a dipole. Full details of model can be seen in Mathur (1991).

c) <u>Forecast Model</u>

The QLM is a multilevel primitive equation fine-mesh model cast in the sigma coordinate system ($\sigma = p/p_s$; pressure divided by surface pressure). The model has a limited area domain using a cartesian grid. The horizontal grid spacing is 40 km, 16 layers in the vertical and the integration domain consists of 111x111 grid points in a 4400x4400 km^2 domain that is centred on the initial position of the cyclone.

d) <u>Physical Parameterisation</u>

The model incorporates physical processes which include surface frictional effects, sea-air exchange of sensible and latent heat, convective release of latent heat, divergence damping, horizontal diffusion, and isobaric condensation of water vapour. Radiation and turbulent processes, which have only marginal impact in the development, are currently excluded to minimize computational time. The numerical integration of the model is carried out by using the so-called quasi-Lagrangian method.

e) <u>Operational Schedule</u>

The model forecast are produced for 00 and 12 UTC when the system attains the TC intensity. The model provides track forecasts out to 36 hours at present.

f) <u>Forecasts of TC Track</u>

A quantitative assessment of the performance of forecast model was made by computation of track prediction errors. Two types of prediction errors have been attempted. Direct position errors (DPE) have been calculated by taking the geographical distance between the predicted position in each case of forecast and the corresponding observed position. The second type of error is the angular deviation between the observed and predicted track vectors starting from a given initial position of the storm. While the former gives a measure of the absolute error of prediction, later provides an indication of the closeness of the predicted direction of movement and the observed direction.

The mean position errors for 24H forecast ranges between less than 100 km and a maximum of about 115 km. The 36 H forecast have these errors varying between around 119 km to as much as 237 km.

The angular deviations vary between about 5° to 25°. The overall average position errors for all the cases taken together (shown at the bottom of the Table) workout to 100 km (24H), and 173 km (36H) and angular deviation less than 20 degrees for both hours.

g) TC guidance Products

Forecast track positions are provided at 12 hourly interval.

2.7 Japan

2.7.1 Global Spectral Model (GSM 0103)

a) Data Assimilation

- 3-D multivariate optimum interpolation with its own 6-hour prediction used as first guess field.
- Data cut-off at 2.5 hours from synoptic time for the forecast model and at 7.5~13.0 hours from synoptic time for the assimilation cycle.
- ~0.5625^{o} x 0.5625^{o} Gaussian grid (320 x 640 points).
- 40 hybrid vertical levels + surface

b) Initialisation of TC's

Tropical cyclones are bogussed using a combination of:

- axisymmetric structure based on Frank's (1977) empirical formula with parameters prescribed on forecasters' analysis mainly applying the Dvorak method to GMS imagery, and
- asymmetric structure derived from the first guess filed (6-hour prediction by GSM).

c) Forecast Model

- Hydrostatic, primitive, Eulerian-form equations.
- Semi-implicit time integration.
- T213 (~55km grid) spectral discretization in the horizontal.
- Finite differencing on 40 hybrid levels in the vertical.

- Initialization: non-linear normal-mode initialization with full physics by Machenhauer (1977), modified with a complex under-relaxation factor, for the lowest five vertical modes whose eigen periods are shorter than 48 hours.
- Boundary conditions:
  SST – 1.0o x 1.0o daily analysis with climatic seasonal trend;
  Surface properties – 1.0^{o} x 1.0^{o} daily analysis.

d) Physical Parameterisations

- Horizontal diffusion by linear second-order Laplacian ($K \nabla^4$).
- Arakawa-Schuber (1974) cumulus parameterisation with modifications by Moorthi and Suarez (1992), Randall and Pan (1993), and Pan and Randall (1998).
- Grid-scale condensation with threshold at 100% RH with evaporation of falling rain.
- Tiedtke (1985) shallow convection by enhanced diffusion.
- Prognostic cloud water scheme
- Bulk formulae for surface fluxes with similarity functions by Louis (1982).
- Vertical diffusion with the level-2 closure model by Mellor and Yamada (1974).
- Long- and short-wave radiation schemes.
- Gravity wave drag by Palmer *et al.* (1986) and Iwasaki *et al.* (1989).
- Simple Biospheric Model (SiB) by Sellers *et al.* (1986) and Sato *et al.* (1989a, b).

e) Operational Schedule

00 UTC data: analysis and forecast up to 90 hours.
12 UTC data: analysis and forecast up to 216 hours.

f) Forecasts of TC Track, Structure & Intensity

6-hourly prediction of:

- central position
- intensity (central pressure)
- sustained maximum wind
- radii of 30 kt winds in four quadrants
- radii of 50 kt winds in four quadrants

g) TC Guidance Products

JMA operates the RSMC Data Serving System (RSMC DSS) to provide the WMO Members, especially those of the ESCAP/WMO Typhoon Committee, with the JMA NWP products in the FM92 GRIB Code through the Internet or ISDN under mutual agreements. As the RSMC DSS is basically a file server system based on password-protected ftp (file transfer protocol), the registered Members are able to obtain the necessary files by using standard ftp commands.

Products include:

- Limited area (20^{o}S-60^{o}N, 60^{o}E-160^{o}W) at 1.25 resolution
  - surface, all standard pressure levels from 1000 hPa to 10 hPa
  - sea-level pressure, geopotential, vorticity, wind, stream function, velocity potential, total precipitation, temperature, dew point depression, vertical velocity (depending on level)
  - T+0 to T+72 every 6 hours (00, 12 UTC)
  - T+0 to T+192 every 6 hours (12 UTC) surface data only

- Global area at 2.5^o resolution
  - surface, all standard pressure levels from 850 hPa to 100 hPa
  - sea-level pressure, geopotential, wind, total precipitation, temperature, dew point depression (depending on level)
  - T+24 to T+72 every 24 hours (00 UTC)
  - T+0 to T+120 every 24 hours (12 UTC)

- Global area at 2.5^o resolution (00 UTC only)
  - surface, all standard pressure levels from 1000 hPa to 10 hPa
  - sea-level pressure, geopotential, wind, temperature, dew point depression (depending on level)
  - T+0 (00 UTC)

Specific tropical cyclone forecast guidance bulletins are issued within 5~5.5 hours from the initial time (0000, 1200 UTC) and disseminated on the GTS with headers FXPQ20-25 RJTD. They include T+6, 12, 18, ---, 78, 84 predictions of:

- central position
- central pressure (change from initial time)
- maximum wind speed (change from initial time)

Prognostic charts of streamlines covering the area 20^{o}S-60^{o}N and 80^{o}E-160^{o}W are also issued twice a day (0000, 1200 UTC) via JMH. They have the headers:

- FUXT852 (850 hPa T+24)
- FUXT854 (850 hPa T+48)
- FUXT202 (850 hPa T+24)
- FUXT204 (850 hPa T+48)

2.7.2 Typhoon Model (TYM 0103)

a) Data Assimilation

- 3-D multivariate optimum interpolation with GSM 6-hour prediction used as first guess field
- Data cut-off at 1.5~2.5 hours from synoptic time.
- ~0.5625^o x 0.5625^o Gaussian grid (320 x 640 points). Note: Forecast model is higher resolution
- 40 hybrid levels + surface. Note: Forecast model is lower resolution.

b) Initialization of TCs

Tropical cyclones are bogussed using a combination of:

- axisymmetric structure based on Frank's (1977) empirical formula with parameters prescribed on forecasters' analysis mainly applying the Dvorak method to GMS imagery, and
- axisymmetric structure derived from latest 12-hour prediction of TYM and tuned so that the initial translation velocity better fits latest analysed track.

Tropical cyclones are implanted in the model using:

- axisymmetric sea-level pressure field based on the Fujita formula,
- axisymmetric ideal mass fields of warm core with hydrostatic balance,
- axisymmetric ideal wind fields with gradient-wind balance,
- Ekman-spiral inflow in planetary boundary layer and compensating outflow at upper levels,
- modification of RH near TC centre,
- blending with initial fields using a linear weighting function in an annulus zone while asymmetric components preserved.

c) Forecast Model

- ~6480 km x 6480 km square domain, located for each target tropical cyclone (TC) and fixed during integration.
- Mercator (Lambert) map projection when the target TC is initially located between 20^{o}N and 0^{o}N (north of 20^{o}N).
- Hydrostatic, primitive, Eulerian-form equations.
- Semi-implicit time integration.
- C179 double-Fourier (~24 km grid) spectral discretization in the horizontal.
- Finite differencing on 25 hybrid levels in the vertical.
- Non-linear normal-mode initialisation, diabatic by Takano *et al.* (1989) using Machenhauer's (1977) method, for the lowest five vertical modes whose eigen periods are shorter than 6 hours.
- Boundary conditions:
  SST – 1.0^{o} x 1.0^{o} daily analysis.

d) Physical Parameterisations

- Horizontal diffusion by linear second-order Laplacian ($K \nabla^4$).
- Arakawa-Schuber (1974) cumulus parameterisation with modifications by Moorthi and Suarez (1992), Randall and Pan (1993), and Pan and Randall (1998).
- Grid-scale condensation with threshold at 100% RH with evaporation of falling rain.
- Bulk formulae for surface fluxes with similarity functions by Louis (1982).
- Vertical diffusion with the level-2 closure model by Mellor and Yamada (1974)
- Long- and short-wave radiation schemes.
- Gravity wave drag by Iwasaki *et al.* (1989).

- 4-layer soil model.

e) Operational Schedule

00, 06, 12 and 18 UTC data: analysis and forecast up to 84 hours.

TYM is only triggered if at least one of the following conditions is satisfied:

- one or more tropical cyclones of TS/STS/TY intensity are present in the area of responsibility ($0^oN – 60^oN, 100^oE – 180^oE$),
- one or more tropical cyclones are expected to reach TS intensity within 24 hours in the area of responsibility,
- one or more torpical cyclones of TS/STS/TY intensity are expected to move into the area of responsibility within 24 hours.

A maximum of 2 tropical cyclones (i.e. 2 separate model runs) can be targeted at each synoptic time (00, 06, 12, 18 UTC).

f) Forecasts of Track, Structure and Intensity

3-hourly prediction of:

- central position
- intensity (central pressure)
- sustained maximum wind
- radii of 30 kt winds in four quadrants
- radii of 50 kt winds in four quadrants

g) TC Guidance Products

Forecast guidance bulletins are issued within 2 hours from the initial time (0000, 0600, 1200, 1800 UTC) and disseminated on the GTS with headers FXPQ20-25 RJTD. They include T+6, 12, 18, ---, 78 predictions of:

- central position
- central pressure (change from initial time)
- maximum wind speed (change from initial time)

2.8 Republic of Korea

2.8.1 GFDK Typhoon Model

The GFDL's hurricane model in Korea (GFDK) is the KMA version of hurricane model developed by NOAA's Geophysical Fluid Dynamics Laboratory. It runs at 06 UTC and 18UTC and has been used for the prediction of typhoon track and intensity since 1997. The GFDK has a triple nested, movable mesh with the innermost grid spacing of 1/6, and with the sophisticated vortex initialization procedure.

Input Data	Global Data Assimilation and Prediction System (GDAPS) analysis and prognosis
Vortex Bogusing and	Vortex specification by filtering procedure to remove the

Initialization	original vortex from the GDAPS analysis field Axisymmetric component of specified vortex generated by time integration of the axisymmetric typhoon model
Vortex Bogusing and Initialization (II)	Asymmetric components generated by time integration of a simplified barotropic vorticity equation with beta effect Specified vortex (symmetric + asymmetric) + environmental field Consistency of moisture field with the wind field
Dynamics	
Basic equation	Primitive equations on latitude-longitude coordinate
Vertical resolution	Sigma coordinate with 18 levels
Grid system	Triple-nested movable mesh (1, 1/3, 1/6^o)
Domain	Width of 75^o in both meridional and longitudinal directions
Physics	
Surface flux	Monin-Obukhov framework, NOAA's weekly mean SST
Bondary Layer	Mellor and Yamada level-two turbulence closure scheme
Cumulus convection	Moist convective adjustment scheme
Radiation	Short wave and long wave scheme with diurnal cycle and cloud variation considered
Products	Central position (lat./long.) and pressure, and maximum tangential winds every 6 hours up to 72 hours in advance.

2.8.2 BATS Model

The Barotropic Adaptive grid Typhoon System (BATS) is based on the continuous dynamic grid adaptation technique with the innermost grid spacing of 0.3. This model is specially designed to run with high resolution grids with little computational load. It runs four times a day since 1997.

Input Data	GDAPS analysis and prognosis
Vortex Bogusing and Initialization	Specified vortex generated by empirical formulas Global objective analysis field with the symmetric typhoon vortex
Dynamics	
Basic equation	Shallow water equations on the latitude-longitude coordinate
Horizontal representation	Grid distance of 0.6^o with the innermost grid distance of 0.3^o on the continuous dynamic grid adaptation
Domain	101 grid points both in zonal and meridional directions over the domain of 60^o.60^o
Products	Central position (lat./long.) every 6 hours up to 60 hours in advance.

2.9 UK

2.9.1 Unified Model (Global)

a) Data Assimilation

Analysed variables:	ıction, unbalanced pressure and relative humidity. Global sea-surface temperature analysed once a day. Sea ice: analysis using NCEP SSM/I; partial cover 0.5 to 1, thickness = 2 m, Arctic, 1 m Antarctic.
Horizontal grid:	See forecast model.
Vertical grid:	See forecast model.
Interpolation method:	Based on successive correction scheme.
Assimilation method:	3D variational analysis of increments (Lorenc *et al*. 2000). Data grouped into 6-hour time windows centred on analysis hour for quality control.
Assimilation cycle:	Data assimilation starts from previous global analysis 6 hours earlier.

b) Initialisation of TC's

Initialisation of TC's is achieved by the creation of bogus data, which are fed into the numerical forecast model. TC advisory bulletins received on the GTS from NHC Miami, JTWC Hawaii and RSMC's are used to provide the input data to this process. The creation of TC bogus data is totally automated, but forecasters in the National Meteorological Centre (NMC) at the Met Office have the facility to override the automatic system and create their own bogus data if required.

Computer programs extract information such as position, maximum wind speed, radius of gale force winds from the TC advisory bulletin and bogus wind observations at the surface, 850hPa, 700hPa and 500hPa are created. A profile of surface wind speed is constructed by using information contained in the advisory bulletin (e.g. radius of 35, 50, 100 knot winds) in conjunction with real observations of surface or low-level winds in the area. A simple exponential curve-fitting routine is used to produce a best-fit curve through the observations and advisory information.

Tangential bogus winds are then derived from this curve at the appropriate distance from the centre. Bogus data are created on rings of radius 1.25°, 2.5° and 4°. If the storm has a maximum sustained wind of greater than 30 knots, bogus data are also produced at 6° radius, and 8° if the strength is greater than 40 knots. There are 4, 4, 6, 8 and 10 points on each ring respectively. Low-level convergence is created by imposing an inflow angle of 12° at all surface bogus points.

Winds at 850 hPa are the same strength as those at the surface, but 700 hPa winds are reduced by 5%, and 500 hPa winds are reduced by 15%.

Finally, an indication of the steering flow is included. The present or past 6-hour movement, specified in the TC advisory bulletin, is imposed on each of the tangential wind values already derived by a simple vector addition.

Full details of the bogus technique may be found in Heming *et al.* (1995).

c) Forecast Model

Basic equations	Hydrostatic primitive equations with approximations accurate on planetary scales (White & Bromley, 1995). Fourth order accurate advection.
Independent variables	Latitude, longitude, eta, time.
Dependent variables	Horizontal wind components, potential temperature, specific humidity, specific cloud water (liquid and frozen), surface pressure, soil temperature, soil moisture content, canopy water content, snow depth, sea-ice temperature, boundary-layer depth, sea-surface roughness.
Diagnostic variables	Geopotential, vertical velocity, convective-cloud base, top, amount and layer-cloud amounts.
Integration domain	Global.
Horizontal grid	Spherical latitude-longitude with poles at 90ºN and 90ºS. Resolution: 0.56º latitude, and 0.83º longitude. Variables staggered on Arakawa B-grid.
Vertical grid	30 levels, hybrid co-ordinates ($0 = A/p_o + B$);
Integration scheme	Split-explicit finite difference. Adjustment uses forward-backward scheme, second-order accurate in space and time. Advection uses a two-step Heun scheme with fourth-order accuracy. Adjustment time-step = 133.3 s; advection time-step = 400 s; physics time-step = 1200 s.
Filtering	Fourier damping of mass-weighted winds and mass-weighted increments to potential temperature and humidity. Adapts to strength of wind at each latitude.
Horizontal diffusion	Linear fourth order with co-efficient $K = 2.0 \times 10^7$ (but linear, second order on top level with $K = 7.0 \times 10^5$) for winds, liquid potential temperature and total water content. No diffusion where co-ordinate surfaces are too steep (near orography).
Vertical diffusion	Second-order diffusion of winds only between 500 & 150 hPa in Tropics (equatorwards of 30º).
Divergence damping	Nil.

Orography	Grid-box mean, standard deviation and sub-grid-scale gradients (for gravity wave surface stress) derived from US Navy 10' dataset. Orographic roughness parameters linearly derived from standard deviation, and from 1 km data (N.America) and 100m data (Europe).
Surface classification	Sea: global SST analysis performed daily. Sea ice: analysis using NCEP SSM/I; partial cover 0.5 to 1, thickness = 2 m, Arctic, 1 m Antarctic. Land: geographical specification of vegetation and soil types that determine surface roughness, albedo, heat capacity, and surface hydrology; snow amount from modified monthly climatology of Willmott et al. (1985).

d) <u>Physical Parameterisations</u>

Surface and soil:

Met Office Surface Exchange Scheme (MOSES 1; Cox *et al.* 1999), which includes:

- A Penman-Monteith surface flux formulation with a 'skin' surface temperature;
- A 4-layer coupled soil hydrology and thermodynamics model;
- An interactive canopy resistance model;
- Sea-surface roughness dependent on wind speed (Charnock constant = 0.12). Surface fluxes of heat, moisture and momentum dependent on surface roughness and local stability.

Boundary layer:

Turbulent fluxes in lowest 5 layers depend on moist local stability and low-cloud cover (Smith, 1990). Implicit integration scheme. Non-local mixing of heat and moisture in unstable conditions. Form drag effects modelled via an effective roughness length calculated from the silhouette area of unresolved orography and standard deviation of orography height within the grid box.

Cloud/precipitation:

Liquid and ice content included. Large-scale precipitation takes into account accretion and coalescence for rain. Frozen cloud starts precipitating as soon as it forms (Smith, 1990). Evaporation of precipitation depends on phase, temperature and rate.

Radiation:

Fully interactive using 6 bands in the long-wave and 4 in solar calculations. Long-wave gaseous transmission adapted from Morcrette *et al.* (1986). Fractional cloud in all moist layers and convective tower. Cloud emissivity and optical properties depend on phase and water content

	(Slingo, 1989).
Convection:	Penetrative mass-flux scheme based on a simple cloud model (Gregory and Rowntree 1990). Initial mass flux depends on buoyancy. Downdraught representation included. Convective momentum transports included. CAPE closure dependence with adjustment time scale of 1 hour.
Gravity-wave drag:	Surface stress estimated from sub-grid variance of orography and the orography gradient vector; high drag states, flow blocking, and drag due to trapped lee waves are represented. Vertical stress profile for hydrostatic waves determined by critical saturation stress law similar to Palmer et al., (1986).
Horizontal diffusion	Linear fourth order with co-efficient K = 2.0 x 10^7 (but linear, second order on top level with K = 7.0 x 10^5) for winds, liquid potential temperature and total water content. No diffusion where co-ordinate surfaces are too steep (near orography).
Vertical diffusion	Second-order diffusion of winds only between 500 & 150 hPa in Tropics (equatorwards of 30º).

e) Operational Schedule

The model runs twice a day to T+144 (from 00 and 12 UTC data with a cut-off of 180 minutes) and twice a day to T+48 (from 06 and 18 UTC data with a cut-off of 110 (06 UTC) /115 (18 UTC) minutes).

f) Forecasts of TC Track, Structure & Intensity

Preliminary forecasts of TC tracks are derived automatically. A computer program examines model output fields for maxima in the 850 hPa relative vorticity. These maxima are tracked from one forecast period to the next, using a search algorithm, and the values are presented to the forecaster as a 'first-guess'. No attempt is made to predict the structure of the TC, but rough estimates of intensity, and intensity change, are indicated based on the maximum value of 850 hPa relative vorticity.

g) TC Guidance Products

TC guidance messages are issued from the NMC with the specific purpose of defining the forecast tracks of TC centres. They are disseminated twice a day, after each forecast run of the global model, in a plain language format. The forecaster has the opportunity to change the automatic 'first guess' guidance (see previous section) before issuing the product if the storm centre in the model forecast appears to have been incorrectly tracked. In general the 850 hPa vorticity maximum will be close to the surface pressure minimum. However, in cases when the vortex is highly asymmetric, or when the TC is undergoing extra-tropical transition, the two positions can be different.

Advisory messages are made available on the GTS with the following bulletin headers:

Eastern North Pacific and North Atlantic Oceans	WTNT80 EGRR
Western North Pacific Ocean	FXXT03 EGRR
North Indian Ocean	FXIO40 EGRR
Western South Indian Ocean	FXXT02 EGRR
Eastern South Indian & South Pacific Oceans	FXXT01 EGRR

They are transmitted twice a day at around 0600 UTC and 1800 UTC during the appropriate season. Outside the season, guidance messages will only be transmitted if a TC is forecast to develop or is active and a warning message has been received at Bracknell. These messages are also available in real-time on the Met Office web site http://www.metoffice.com.

A set of standard global model forecast products, e.g. sea-level pressure and 10m wind components, are distributed on the GTS in grid-point format. The horizontal resolution of these products is necessarily much coarser than that of the numerical model and may not be sufficient to define small-scale circulations. The binary format code is FM92 GRIB with resolution 2.5º x 2.5º in GRIB IX. Fields available include geopotential height, temperature, wind and relative humidity on standard levels, and mean sea level pressure. Fields of analysed data (T+0) are available as well as forecasts at 6 or 12 hour intervals out to T+120.

2.10 USA

2.10.1 GFS Model

a) Data Assimilation

The GFS (previously known as AVN) uses a three-dimensional variation assimilation method.

b) Initialisation of TCs

The GFS does not routinely use “bogussing” of a tropical cyclone. A new technique, vortex relocation is now employed. This gives much improved TC track forecasts. The relocation involves a re-positioning of the TC (to the position reported by RMSC Miami) in the first guess field of the global analysis. Details may be found at:
http://www.nws.noaa.gov/om/tpb/472.htm

iThere is a specialized technique for initializing tropical cyclone circulations where synthetic wind observations are added to the global data assimilation system. The synthetic observations are constructed from the sum of a steering flow and a symmetric vortex. The steering flow is determined from the spectral truncation, which produces a vertically averaged wind that is closest to the current motion of the storm. The symmetric vortex at low-levels is constructed from operational estimates of central pressure, radius and pressure of the outermost closed isobar, the radius and value of the maximum low-level winds and the 34 kt wind radii in the four quadrants (NE, SE, SW, NW). Synthetic winds are included at about 50 locations within about 200 nautical miles of the storm centre at each mandatory level from the surface to the maximum level of the storm circulation (typically 300 hPa). Empirical functions are used to extrapolate the low-level vortex to the upper levels.

c) Forecast Model

The Global Forecast System (GFS) is the official National Centers for Environmental Prediction (NCEP) model. The resolution of the GFS has increased to 64 levels in the vertical and to T254 in the horizontal for the first 84 hours of the forecast. This is roughly equivalent to increasing the horizontal resolution to 55 km. A corresponding increase in the associated physics grid has also been implemented over the the first 84 hours. Forecasts beyond 84 hours remain at T170 truncation and 42 vertical levels. The data assimilation system, which uses the 6-hour forecast as a first guess for the next model analysis, has been recalibrated to reflect the new error characteristics of the higher resolution model. Additional information can be found at: www.emc.ncep.noaa.gov/forecasts/

d) Physical Parameterisations

The model includes parameterisations of convective, radiative and boundary layer processes.

e) Operational Schedule

As of 24 April 2002, the Environmental Modeling Center/Global Modeling Branch moved from once-daily 384-hour forecasts (the so-called MRF run at 00Z) and four 126-hour AVN forecasts to four daily GFS 384-hour forecasts.

f) Forecasts of TC Track, Structure & Intensity

An automated tracking algorithm, which combines several parameters associated with the cyclone at the storm centre. These parameters are: surface pressure, relative vorticity, geopotential height and minimum in the wind speed at 850 and 700 mb levels, respectively. Further details are included in Marchok, 2002.

g) TC Guidance Products

Track positions and maximum surface winds are provided at 12-hour intervals using an automated searching procedure.

2.10.2 NOGAPS Model

a) Data Assimilation

Multivariate optimum interpolation (volume method).

b) Initialisation of TCs

Generally speaking, the NOGAPS bogussing scheme consists of adding synthetic observations that represent the storm circulation to the data assimilation system. The current scheme utilizes synthetic observations at 13 points around the storm. These observations are created from the sum of an environmental flow and a symmetric vortex.

c) Forecast Model

NOGAPS is the U.S. Navy's global spectral forecast model with 30 sigma levels, a triangular truncation of 239 waves, parameterisations of physical processes and a tropical cyclone bogussing scheme.

d) Physical Parameterisations

The model includes parameterisations of convective, radiative and boundary layer processes.

e) Operational Schedule

NOGAPS runs every six hours, forecasting to six days at high resolution. In addition, a lower resolution bred-mode ensemble runs once a day, forecasting out to 10 days.

f) Forecasts of TC Track, Structure & Intensity

NOGAPS track forecasts are routinely produced out to 144 hours using a tracker that locates the maximum of 850 hPa vorticity.

g) TC Guidance Products

Storm centre positions and minimum sea-level pressure values are provided at 6-hour intervals out to 144 hours using an automated tracking algorithm.

For more details on the NOGAPS model, please see:
http://www.fnmoc.navy.mil/PUBLIC/MODEL_REPORTS/MODEL_SPEC/nogaps4.0.html

2.10.3 GFDL Model

a) Data Assimilation

None. The initial and boundary conditions are obtained from the GFS model.

b) Initialisation of TCs

The GFDL model has a specialized method for initializing the storm circulation. The representation of the storm circulation in the global analysis, obtained from the GFS model, is replaced with the sum of an environmental flow and a vortex generated by nudging the fields in a separate run of the model to an idealized vortex. This idealized vortex is based upon a few parameters of the observed storm, including the maximum wind, radius of maximum wind and outer wind radii. The environmental flow is the global analysis modified by a filtering technique, which removes the hurricane circulation.

c) Forecast Model

GFDL (Geophysical Fluid Dynamics Laboratory) is a limited area baroclinic model developed specifically for hurricane prediction. It includes 18 sigma levels and uses a horizontal finite-difference method with two nested grids. The inner grid moves to follow the storm, and the resolution of the inner domain is 1/6 degree. A more detailed description of the GFDL model is given by Kurihara *et al.* (1995).

The model was upgraded for the 2001 hurricane season to include a coupled ocean- atmosphere model for the Atlantic Basin. The ocean model used for the GFDL coupled system is a modified version of the Princeton Ocean Model developed at the University of Rhode Island. Initial conditions are obtained from the current GFS run. Input parameters for each storm are provided by the Tropical Prediction Center and include the latitude and longitude of the storm center, current storm motion, the central pressure, and radii of 17 m/s and 25 m/s winds. Output from the model consists primarily of forecast horizontal fields on pressure surfaces such as wind and sea-level pressure, and some graphics products such as a swath of maximum wind speeds and total precipitation throughout 126 hours.

d) Physical Parameterisations

The GFDL model includes convective, radiative and boundary layer parameterizations.

e) Operational Schedule

The GFDL model run 4 times per day to 126 hours, starting with analyses valid at 00, 06, 12 and 18 UTC.

f) Forecasts of TC Track, Structure & Intensity

GFDL is considered a ‘late’ model because it is not available to the forecasters until after the advisories are sent out. Therefore, they typically use the GFDL prediction from the previous synoptic time in preparing their forecasts. To overcome this problem, an interpolation technique has been developed to transpose the previous GFDL forecast to the current storm position. This is also applied to intensity forecasts. The forecasts from the interpolated GFDL forecasts are designed by 'GFDI'. Further details on this interpolation technique are described by Horsfall *et al.* (1997).

g) TC Guidance Products

Track positions and maximum surface winds are provided at 12-hour intervals using an automated searching procedure.

2.11 ECMWF

a) Data Assimilation

A four-dimensional incremental variational analysis (4D-Var) with implicit flow-dependent background errors, is used operationally. On 12 September 2000, the data assimilation procedure moved from 6-hour to 12-hour cycling. 4D-Var now processes the observations in 12-hour sets, spanning 03-15 UTC for the 12UTC analysis, and 15-03 UTC for the 00 analysis. Surface analyses still run every six hours. Analysis fields are archived every six hours. The 4D-Var incremental formulation had also been changed in that the low-resolution increment is added to the high-resolution trajectory at analysis time (00 and 12 UTC), instead of at the start of the 4D-Var window. The minimisation (inner loop) is run at T_L159 (previous it was T63) using new semi-Lagrangian tangent linear and adjoint codes.

The radiation code during the data assimilation is called hourly rather than three-hourly, since June 2001.

The data used are:

- global satellite data (AMV, ATOVS, SSM/I, QuikSCAT)
- global free-atmosphere data (AIREP, ACARS, AMDAR, TEMP, PILOT, PROFILER, DROPSONDE(when available)
- oceanic data (SYNOP/SHIP, PILOT/SHIP, TEMP/SHIP, DRIBU)
- land data (SYNOP)

b) Initialisation of TC's

No specific initialisation of tropical cyclones takes place. However, initial perturbations for the Ensemble Prediction System in the tropics are included since January 2002. The perturbations are generated for a maximum of four target areas by Gaussian sampling of the five leading singular vectors for each area. The Caribbean (0-25^o N and 100-60^o W) is always a target area, as is every tropical storm category larger than 1 between 25^{o}N and 25^{o}S. If these criteria produce more than four target areas, the closest areas are merged.

c) Forecast Models

1) Deterministic

Since 21 November 2000, the deterministic model runs with T_L511 resolution (triangular truncation, resolving 511 waves along the great circle on the globe). This is roughly equivalent to 40 km grid length in the mid-latitudes. There are 60 levels in the vertical. A new finite-element vertical discretization was included in January 2002.

At each Gaussian grid-point and for each time-step wind, temperature, humidity, liquid and ice water content, cloud fraction and pressure (at surface grid-points only) are computed.

The T_L511 is coupled with a wave model that runs at approximately 55 km horizontal resolution and it has spectral information given by 24 directions and 30 frequencies.

The SST (derived from NCEP 0.5x0.5) is kept constant from the analysis.

2) Ensemble Prediction System (EPS)
The EPS has 50 members plus the control run and it runs (since November 2000) with T_L255 resolution, which corresponds roughly to 80 km grid-length (in the mid-latitudes). There are 40 levels in the vertical. The initial perturbations are computed with initial and evolved singular vector at T42 resolution in the Northern and Southern Hemisphere (outside the Tropics). Tropical single vectors are calculated in the Tropics (see point b). A representation of model errors is introduced through the stochastic physics.

d) Physical Parameterisation

The model includes:

- orography (derived from GTOPO30, 30''x30'')
- one surface and four sub-surface layers (allowing for vegetation cover, gravitational drainage, capillarity exchange, surface and sub-surface run-off, deep-layers soil temperature and moisture),
- stratiform and convective precipitation
- carbon dioxide(345 ppmv fixed), aerosol, ozone, solar angle
- diffusion
- ground and sea roughness
- sea surface temperature and sea ice concentration
- snow-fall, snow cover and snow melt
- radiation(incoming and outgoing long-wave).
- friction (at surface and in the free atmosphere)
- orographic drag
- evaporation
- sensible and latent heat flux
- tiled skin surface temperature, with up to six different tiles per land grid box and two per ocean grid box.

e) Operational Schedule

The deterministic forecast model is run once a day from 12 UTC out to ten days. The Ensemble Prediciton System (EPS), with 50 members and TL255L40, also runs once a day.

f) Forecasts of TC Tracks, structure and intensity

No specific products.

g) TC Guidance Products

A variety of forecast fields in both FM92 GRIB ($2.5^o x 2.5^o$) and FM47 GRID ($5^o x 5^o$) are available on the GTS. In the tropical belt , these are:

- u,v components at 850 and 200 hPa
- divergence at 700hPa
- vorticity at 700hPa

A complete list may be found at http://www.ecmwf.int

CHAPTER 3

Verification of TC track and intensity forecasts

3.1 Introduction

The purpose of this chapter is to give an indication of the recent performance of the various models described in Chapter 2. In the first edition of this publication it has not been possible to include verification statistics from every model. Nor are the statistics generally compatible between the models. However, it is to be hoped that in the future a common verification scheme can be specified for use by all NWP centres.

Most of the verification statistics relate to the forecast tracks of tropical cyclones. However, the statistics for the GSM and TYM models (Japan) and the GFDL mode (USA) also include the verification of intensity forecasts. As the resolution of other NWP models increases we can expect to see more intensity forecasts generally available.

There is no commentary on the statistics included. Readers are left to make up their own minds as to the relative merits of the models.

As in Chapter 2, each sub-section contain details of those models run by a particular Meteorological Service.

3.2 Australia

3.2.1 Tropical Cyclone Limited Area Prediction System: TC-LAPS

The following statistics are for the 2001 North West Pacific season.

When multiple storms were present, the principal storm at the base time of the forecast was verified (until recently only one forecast to 48 hours was made per base time).

Total number of TCs verified = 16

Chebi Durian Utor Trami Kong-Re Toraji Man-Yi Pabuk Danas Nari Vipa Francis Lekima Krosa Haiyan Podul

(i) Track errors

Forecast Interval	No. Cases	Error (km)
T+0	117	20.8
T+24	110	138.7
T+48	89	236.9

Distribution of errors in 100 km bins for the 48-hour forecasts

0-100	100-200	200-300	300-400	400-500	500-600	600-700	>700
14	25	27	10	8	4	1	0

(ii) Central pressure errors (hPa)

Forecast Interval	No. Cases	**RMS Error**		Mean Error		Abs Error	
		TCL	**PRS**	TCL	PRS	TCL	PRS
T+0	117	**6.5**	**0.0**	-5.0	0.0	5.4	0.0
T+24	110	**11.0**	**13.7**	-5.6	-3.6	8.7	11.0
T+48	89	**16.6**	**21.8**	-10.0	-8.2	13.2	18.0

(TCL = TC-LAPS; PRS = Persistence)

3.3 China

No tropical cyclone verification statistics are available.

3.4 France

No tropical cyclone verification statistics are available.

3.5 Hong Kong, China

No tropical cyclone verification statistics are available.

3.6 India

3.6.1 Quasi-Lagrangian Limited Area Model

TRACK PREDICTION ERRORS

YEAR	*PERIOD*	*24 HRS*		*36 HRS*	
		MEAN POSITION ERROR (KM)	*ANGULAR DEVIATION BETWEEN OBSERVED AND PREDICTED TRACK VECTORS (RMSE) (DEG.)*	*MEAN POSITION ERROR (KM)*	*ANGULAR DEVIATION BETWEEN OBSERVED AND PREDICTED TRACK VECTORS (RMSE) (DEG.)*
1998	20-22 NOV.	146.2	17.4	242.6	12.7
	6-10 JUN	140.1	32.4	205.2	27.9
1999	16-20 MAY	97.4	12.1	133.0	12.2
	15-18 OCT	151.4	13.7	426.5	20.7
	26-30 OCT	107.7	19.2	185.7	23.0
2000	15-19 OCT	105.0	25.8	237.1	23.8
	27-30 NOV	114.8	05.7	161.5	15.5
2001	21-28 MAY	90.0	15.2	160.0	20.1
	24-27 SEP	110.0	10.1	180.0	15.1
	14-17 OCT	120.0	12.3	210.0	22.0
	MEAN	**118.3**	**16.4**	**214.1**	**19.3**

Observed track vector : Initial (at T0) to observed (at T0+24H or T0+36H) positions
Predicted track vector : Initial (at T0) to predicted (at T0+24H or T0+36H) positions

3.7 Japan

3.7.1 Global Spectral Model (GSM 9603)

All the statistics shown below are made for tropical cyclones in the western north Pacific during the years of 1996-1998 and are calculated against the TC RSMC Tokyo-Typhoon Center Best Track data.

(i) GSM – Mean position error and skill compared with persistence (PER)

TIME	MODEL	RECURVATURE BEFORE	RECURVATURE DURING	RECURVATURE AFTER	ALL
T+12	GSM	101.0	102.1	112.1	104.6
	PER	96.5	107.2	123.0	106.7
	Skill	-4.6%	4.7%	8.9%	2.9%
(num. of cases)		(397)	(160)	(245)	(802)
T+24	GSM	156.0	155.1	175.3	162.0
	PER	184.3	203.2	273.3	216.5
	Skill	15.4%	23.7%	35.9%	25.2%
(num. of cases)		(352)	(143)	(234)	(729)
T+36	GSM	201.3	202.8	236.5	213.4
	PER	281.0	321.7	447.7	344.8
	Skill	28.4%	36.9%	47.2%	38.1%
(num. of cases)		(308)	(128)	(220)	(656)
T+48	GSM	239.2	249.4	310.9	266.9
	PER	402.1	432.7	636.1	491.9
	Skill	40.5%	42.3%	51.1%	45.7%
(num. of cases)		(264)	(113)	(211)	(588)
T+60	GSM	287.1	287.9	408.9	334.2
	PER	507.3	572.9	826.3	642.8
	Skill	44.3%	49.7%	50.5%	48.0%
(num. of cases)		(222)	(102)	(203)	(527)
T+72	GSM	332.6	344.6	490.8	398.3
	PER	613.3	730.2	1001.5	791.4
	Skill	45.8%	52.8%	51.0%	49.7%
(num. of cases)		(187)	(88)	(184)	(459)
T+84	GSM	371.3	404.9	585.1	469.8
	PER	726.7	798.1	1234.4	959.0
	Skill	48.9%	49.3%	52.6%	51.0%
(num. of cases)		(155)	(74)	(174)	(403)

Table 3.7.1.1: Mean error (km) of GSM central positions, stratified according to stage of motion with respect to recurvature, and skill (%) compared with persistence. 'Before', 'During', and 'After' mean TC's moving to directions in 180-320 deg, 320-10deg, and 10-180 deg, respectively. 'Skill' is defined as 100 x (PER-GSM)/PER.

(ii) GSM – Distribution of central position errors

Error (km)	Number of predictions		
	T+24	T+48	T+72
> 1000	0	1	16
950 – 1000	0	0	2
900 – 950	0	0	1
850 – 900	1	4	4
800 – 850	0	1	8
750 – 800	0	2	12
700 – 750	0	3	11
650 – 700	0	5	14

600 – 650	0	3	11
550 – 600	1	16	26
500 – 550	3	18	25
450 – 500	6	36	22
400 – 450	10	23	43
350 – 400	25	40	34
300 – 350	33	63	36
250 – 300	56	66	47
200 – 250	71	68	42
150 – 200	135	89	36
100 – 150	159	58	32
50 – 100	143	62	31
0 – 50	86	30	6

Table 3.7.1.2: Distribution of GSM central position errors (km), stratified in ranges of 50 km.

(iii) GSM – Distribution of central pressure errors

Error (hPa)	Number of predictions		
	T+24	T+48	T+72
>42.5	99	126	115
37.5 - 42.5	37	24	35
32.5 - 37.5	32	41	26
27.5 - 32.5	47	35	39
22.5 - 27.5	58	54	39
17.5 - 22.5	73	58	39
12.5 - 17.5	100	64	34
7.5 - 12.5	129	76	38
2.5 - 7.5	100	55	43
-2.5 - 2.5	48	42	30
-7.5 - -2.5	5	8	19
-12.5 - -7.5	1	5	1
-17.5 - -12.5	0	0	0
-22.5 - -17.5	0	0	1
-27.5 - -22.5	0	0	0
-32.5 - -27.5	0	0	0
-37.5 - -32.5	0	0	0
-42.5 - -37.5	0	0	0
< -42.5	0	0	0

Table 3.7.1.3: Distribution of GSM central pressure errors (hPa), stratified in ranges of 5 hPa.

(iv) GSM – Distribution of maximum sustained wind errors

Error (ms^{-1})	Number of predictions		
	T+24	T+48	T+72
> 18.75	6	6	4
16.25 - 18.75	1	1	3
13.75 - 16.25	6	4	3
11.25 - 13.75	12	4	3
8.75 - 11.25	5	3	4
6.25 - 8.75	2	0	0
3.75 - 6.25	0	0	0
1.25 - 3.75	0	0	0
-1.25 - 1.25	2	1	4
-3.75 - -1.25	13	13	12
-6.25 - -3.75	61	39	23
-8.75 - -6.25	101	53	40
-11.25 - -8.75	100	61	39
-13.75 - -11.25	77	67	29
-16.25 - -13.75	106	64	44
-18.75 - -16.25	121	123	101
< - 18.75 - -18.75	116	149	150

Table 3.7.1.4: Distribution of GSM maximum sustained wind errors (ms^{-1}), stratified in ranges of 2.5 ms^{-1}.

3.7.2 <u>Typhoon Model (TYM 9603)</u>

All the statistics shown below are made for tropical cyclones in the western north Pacific during the three years of 1996 – 1998 and are calculated against the TC RSMC Tokyo – Typhoon Center Best Track data.

(ii) TYM – Mean position error and skill compared with persistence (PER)

TIME	MODEL	RECURVATURE			ALL
		BEFORE	DURING	AFTER	
T+12	TYM	101.7	99.6	105.6	102.5
	PER	102.3	107.3	126.8	110.9
	Skill	0.6%	7.2%	16.8%	7.6%
(num. of cases)		(379)	(153)	(239)	(771)
T+24	TYM	157.8	156.4	167.8	160.8
	PER	188.9	209.0	273.6	220.6
	Skill	16.5%	25.2%	38.7%	27.1%
(num. of cases)		(335)	(134)	(230)	(699)
T+36	TYM	203.7	198.3	246.9	217.6
	PER	285.9	332.5	452.3	352.3
	Skill	28.7%	40.3%	45.4%	38.2%
(num. of cases)		(292)	(121)	(218)	(631)

T+48	TYM	251.3	249.7	328.5	279.4
	PER	399.5	418.2	657.1	498.0
	Skill	37.1%	40.3%	50.0%	43.9%
(num. of cases)		(254)	(107)	(211)	(572)
T+60	TYM	310.1	302.7	428.6	354.9
	PER	511.0	555.2	862.0	656.4
	Skill	39.3%	49.3%	50.3%	45.9%
(num. of cases)		(213)	(98)	(199)	(510)
T+72	TYM	359.7	369.1	532.7	432.6
	PER	591.2	724.5	1058.6	808.3
	Skill	39.2%	49.0%	49.7%	46.5%
(num. of cases)		(182)	(84)	(186)	(452)
T+84	TYM	386.3	363.3	575.3	462.6
	PER	665.5	716.9	1181.0	893.4
	Skill	41.9%	49.3%	51.3%	48.2%
(num. of cases)		(171)	(74)	(181)	(426)

Table 3.7.1.1: Mean error (km) of TYM central positions, stratified according to stage of motion with respect to recurvature, and skill (%) compared with persistence. ‘Before’, ‘During’, and ‘After’ mean TC’s moving to directions in 180-320 deg, 320-10deg, and 10-180 deg, respectively. ‘Skill’ is defined as 100 x (PER-TYM)/PER.

(ii) TYM – Distribution of central position errors

Error (km)	Number of predictions		
	T+24	T+48	T+72
> 1000	0	2	23
950 – 1000	0	1	2
900 – 950	0	3	7
850 – 900	1	1	4
800 – 850	0	4	9
750 – 800	1	2	11
700 – 750	0	4	10
650 – 700	0	7	13
600 – 650	0	8	17
550 – 600	2	6	23
500 – 550	3	16	23
450 – 500	4	29	22
400 – 450	12	31	36
350 – 400	19	55	35
300 – 350	28	48	39
250 – 300	46	66	35
200 – 250	77	64	53
150 – 200	120	93	40
100 – 150	184	63	23
50 – 100	144	47	21
0 – 50	59	22	6

Table 3.7.2.2: Distribution of TYM central position errors (km), stratified in ranges of 50 km.

(iii) TYM – Distribution of central pressure errors

Error (hPa)	Number of predictions		
	T+24	T+48	T+72
>42.5	35	43	45
37.5 - 42.5	13	17	24
32.5 - 37.5	14	29	15
27.5 - 32.5	34	26	21
22.5 - 27.5	42	31	34
17.5 - 22.5	51	35	31
12.5 - 17.5	70	53	31
7.5 - 12.5	95	70	47
2.5 - 7.5	116	93	55
-2.5 - 2.5	120	69	49
-7.5 - -2.5	70	51	36
-12.5 - -7.5	22	29	34
-17.5 - -12.5	14	20	14
-22.5 - -17.5	1	3	12
-27.5 - -22.5	2	2	4
-32.5 - -27.5	0	0	0
-37.5 - -32.5	0	1	0
-42.5 - -37.5	0	0	0
< -42.5	0	0	0

Table 3.7.2.3: Distribution of TYM central pressure errors (hPa), stratified in ranges of 5 hPa.

(iv) TYM – Distribution of maximum sustained wind errors

Error (ms^{-1})	Number of predictions		
	T+24	T+48	T+72
> 18.75	0	0	0
16.25 - 18.75	0	3	4
13.75 - 16.25	3	3	4
11.25 - 13.75	10	12	9
8.75 - 11.25	25	20	11
6.25 - 8.75	40	30	30
3.75 - 6.25	79	55	33
1.25 - 3.75	85	72	51
-1.25 - 1.25	118	76	61
-3.75 - -1.25	103	79	55
-6.25 - -3.75	72	66	30
-8.75 - -6.25	66	43	40
-11.25 - -8.75	33	30	39
-13.75 - -11.25	30	27	28
-16.25 - -13.75	6	12	24
-18.75 - -16.25	4	20	17
< - 18.75 - -18.75	1	3	4

Table 3.7.2.4: Distribution of TYM maximum sustained wind errors (ms^{-1}), stratified in ranges of 2.5 ms^{-1}.

3.8 Republic of Korea

No tropical cyclone verification statistics are available.

3.9 UK

3.9.1 Unified Model (Global)

All verification statistics presented here relate to the track of the tropical cyclone (TC) as objectively determined from the model forecast, as described in section 2.6.1(f), but with some manual quality control included. The final product issued by the forecaster (as described in section 2.6.1(g)) is also verified, and the errors are not significantly different.

Tables of statistics are given for individual ocean basins as well as on a hemispheric basis. The direct positional error (DPE) is calculated by calculating the great-circle distance between the observed and predicted positions. It is always positive. The key to individual statistical parameters is as follows:

Poss Ver - no. of forecasts that could possibly be verified at this time (fulfilling conditions 1, 2, & 4 below *).

Det Rate - detection rate: the percentage of possibly verified forecasts that also fulfil condition 3 below.

Mean DX - mean of all forecast positional errors in the east-west direction (positive if forecast position lies eastwards).

Mean DY - mean of all forecast positional errors in the north-south direction (positive if forecast position lies polewards).

Mean AT - mean of all forecast positional errors in the along-track direction of the TC (positive if forecast position lies ahead).

Mean CT - mean of all forecast positional errors in the cross-track direction of the TC (positive if forecast position lies right of the track in the NH and left in the SH)

Mean DPE - mean of the direct positional errors.

Skill - percentage improvement of mean model forecasts over CLIPER forecasts (positive value indicates the model was better)

* Conditions for verification:

1. Observed maximum sustained wind at least 31 knots at the verifying time.
2. Forecast TC centre equatorwards of 45°.
3. Forecast TC centre relative vorticity above critical limit for verification.
4. Observation within 6 hours of verifying time.

Notes:

- Detection percentage gives an indication of how frequently the TC has been dissipated too early by the model.
- All errors are measured in kilometres.
- CLIPER software was provided by NCEP, Washington and FNMOC, Monterey.
- All forecasts from 00 UTC and 12 UTC are included in the verification.
- Southern Hemisphere verification is for all TC's occurring during the 2000-1 season and is with respect to best-track data, provided by RSMC La Réunion, BoM Melbourne and RSMC Nadi, Fiji. Northern Hemisphere verification is for all TC's occurring during the 2001 season and is with respect to real-time data received from RSMC Miami and JTWC Hawaii. Verification for the Northern Hemisphere 2001 with respect to best-track data will be available in due course, but experience indicates that the results will not be significantly different.
- Up-to-date verification statistics may be found at the Met Office (MetO) web site - http://www.metoffice.com.

(i) Southwest Indian Ocean (west of 90°E) - 2000-1 season

Number of tropical cyclones: 9

	T+00	T+24	T+48	T+72	T+96	T+120
Poss Ver	62	50	40	29	20	14
Det Rate (%)	100	100	100	100	100	100
Mean DX	12	-29	-135	-268	-350	-405
Mean DY	14	90	177	191	289	459
Mean AT	2	34	160	251	381	522
Mean CT	20	29	42	-38	-39	34
Mean DPE	**44**	**161**	**291**	**380**	**545**	**703**
Skill (%)	**-**	**5**	**11**	**-1**	**-**	**-**

Table 3.9.1.1: Mean errors (km) and skill (%) of the MetO model for all tropical cyclones in the Southwest Indian Ocean during the 2000-1 season.

(ii) Southeast Indian (east of 90°E) and South Pacific Oceans - 2000-1 season

Number of tropical cyclones: 13

	T+00	T+24	T+48	T+72	T+96	T+120
Poss Ver	87	64	44	28	14	6
Det Rate (%)	100	100	100	100	100	100

Mean DX	0	-51	-158	-295	-369	-436
Mean DY	2	29	-12	-42	-4	-52
Mean AT	-30	-56	-121	-125	-86	-325
Mean CT	-3	-73	-151	-290	-409	-475
Mean DPE	**64**	**185**	**315**	**447**	**543**	**722**
Skill (%)	**-**	**9**	**14**	**17**	**-**	**-**

Table 3.9.1.2: Mean errors (km) and skill (%) of the MetO model for all tropical cyclones in the Southeast Indian and South Pacific Oceans during the 2000-1 season.

(iii) Southern Hemisphere (Total) - 2000-1 season

Number of tropical cyclones: 22

	T+00	T+24	T+48	T+72	T+96	T+120
Poss Ver	149	114	84	57	34	20
Det Rate (%)	100	100	100	100	100	100
Mean DX	5	-42	-147	-281	-358	-414
Mean DY	7	56	78	77	169	306
Mean AT	-16	-17	13	66	189	268
Mean CT	7	-28	-59	-162	-191	-119
Mean DPE	**56**	**174**	**304**	**413**	**544**	**709**
Skill (%)	**-**	**7**	**13**	**6**	**-**	**-**

Table 3.9.1.3: Mean errors (km) and skill (%) of the MetO model for all tropical cyclones in the Southern Hemisphere during the 2000-1 season.

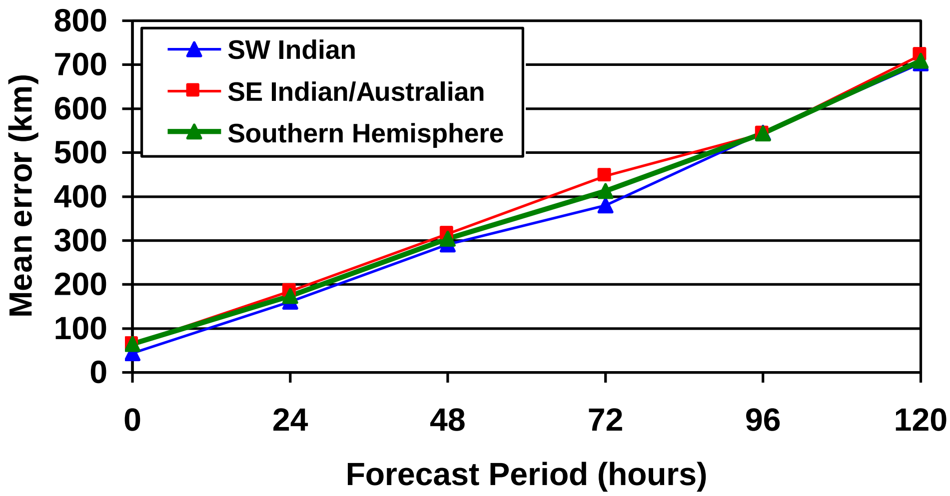

Figure 3.9.1.3: Mean errors (km) of the MetO model for tropical cyclones in the Southern Hemisphere during the 2000-1 season.

(iv) North Atlantic Ocean - 2001

Number of tropical cyclones: 15

	T+00	T+24	T+48	T+72	T+96	T+120
Poss Ver	132	99	71	48	36	26
Det Rate (%)	100	100	99	94	86	88
Mean DX	-3	-20	-32	-82	-61	-39
Mean DY	4	42	83	75	77	178
Mean AT	-14	-43	-57	-40	8	-94
Mean CT	-4	1	-5	-56	-34	-43
Mean DPE	**35**	**134**	**256**	**351**	**366**	**474**
Skill (%)	**-**	**42**	**48**	**62**	**-**	**-**

Table 3.9.1.4: Mean errors (km) and skill (%) of the MetO model for all tropical cyclones in the North Atlantic Ocean during 2001.

(v) Eastern North Pacific Ocean - 2001

Number of tropical cyclones: 15

	T+00	T+24	T+48	T+72	T+96	T+120
Poss Ver	118	87	60	40	28	17

Det Rate (%)	100	100	98	88	75	71
Mean DX	9	-1	2	54	167	246
Mean DY	-4	3	-44	-111	-154	-115
Mean AT	-12	-30	-85	-158	-260	-249
Mean CT	4	-1	-48	-60	-10	72
Mean DPE	**31**	**110**	**199**	**297**	**389**	**361**
Skill (%)	**-**	**25**	**32**	**24**	**-**	**-**

Table 3.9.1.5: Mean errors (km) and skill (%) of the MetO model for all tropical cyclones in the Eastern North Pacific Ocean during 2001.

(vi) Western North Pacific Ocean - 2001

Number of tropical cyclones: 28

	T+00	T+24	T+48	T+72	T+96	T+120
Poss Ver	287	230	183	141	106	74
Det Rate (%)	100	100	100	95	92	80
Mean DX	-6	-22	-83	-162	-239	-400
Mean DY	1	22	32	3	-29	-135
Mean AT	-5	-11	-23	-54	-116	-207
Mean CT	-2	-13	-64	-136	-194	-240
Mean DPE	**37**	**132**	**253**	**359**	**528**	**768**
Skill (%)	**-**	**27**	**33**	**39**	**-**	**-**

Table 3.9.1.6: Mean errors (km) and skill (%) of the MetO model for all tropical cyclones in the Western North Pacific Ocean during 2001.

(vii) Bay of Bengal and Arabian Sea - 2001

Number of tropical cyclones: 5

	T+00	T+24	T+48	T+72	T+96	T+120
Poss Ver	24	14	10	8	6	4
Det Rate (%)	100	100	100	75	83	75
Mean DX	7	29	-23	-89	-169	-166
Mean DY	-6	40	127	152	140	-7
Mean AT	-13	-30	-24	49	23	-61

Mean CT	9	-13	-29	-93	-196	-162
Mean DPE	**30**	**144**	**270**	**343**	**358**	**259**
Skill (%)	**-**	**-15**	**-41**	**-36**	**-**	**-**

Table 3.9.1.7: Mean errors (km) and skill (%) of the MetO model for all tropical cyclones in the Bay of Bengal and Arabian Sea during 2001.

(viii) Northern Hemisphere (Total) - 2001

Number of tropical cyclones: 63

	T+00	T+24	T+48	T+72	T+96	T+120
Poss Ver	561	430	324	237	176	121
Det Rate (%)	100	100	99	93	88	80
Mean DX	-2	-15	-54	-109	-146	-227
Mean DY	0	23	32	4	-19	-54
Mean AT	-9	-23	-42	-65	-106	-181
Mean CT	-1	-7	-47	-106	-137	-153
Mean DPE	**35**	**128**	**244**	**347**	**471**	**632**
Skill (%)	**-**	**30**	**36**	**44**	**-**	**-**

Table 3.9.1.8: Mean errors (km) and skill (%) of the MetO model for all tropical cyclones in the Northern Hemisphere during 2001.

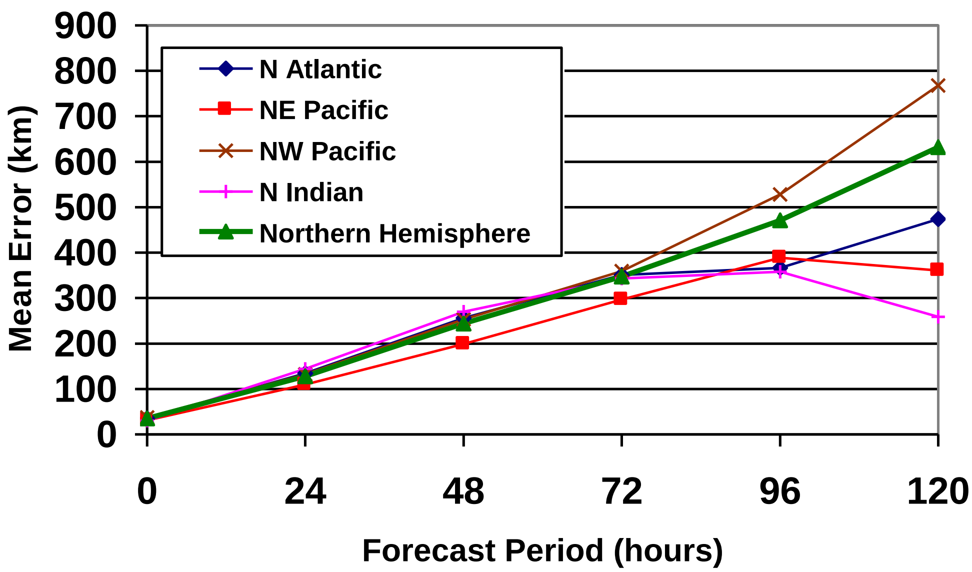

Figure 3.9.1.8: Mean errors (km) of the MetO model for tropical cyclones in the Northern Hemisphere during 2001.

3.10 USA

Homogeneous verification results for the 2002 hurricane seasons are presented. The model forecasts are evaluated by comparison with the best track positions. The track error is calculated as the great circle distance from the forecast to the observed storm position. A comparison with the mean CLIPER error is also provided. Only those cases where the storm is of tropical storm strength (maximum winds >34 kt) or greater are included in the verification sample.

Table 1. Track errors - North Atlantic (2002)

Model	Forecast Period (h)				
	12	24	36	48	72
CLIPER	52 (92)	102 (80)	162 (68)	231 (54)	357 (43)
GFDL	42 (92)	66 (80)	93 (68)	117 (54)	188 (43)
AVNO	42 (92)	68 (80)	102 (68)	117 (54)	194 (43)
NGPS	39 (92)	59 (80)	84 (68)	101 (54)	159 (43)

Table 2. Track errors - Eastern North Pacific (2002)

Model	Forecast Period (h)				
	12	24	36	48	72
CLIPER	42 (77)	85 (67)	130 (57)	171 (49)	223 (32)
GFDL	34 (77)	53 (67)	77 (57)	100 (49)	142 (32)
AVNO	38 (77)	54 (67)	70 (57)	83 (49)	118 (32)
NGPS	100(77)	125(67)	145(57)	154(49)	201 (32)

3.11 ECMWF

3.11.1 T_L319L31 Model

(i) T213L31 track errors – western north Pacific (1992-1997)

Verification statistics specific to tropical cyclones are not routinely produced by ECMWF. However, the Hong Kong Observatory has produced some statistics on the performance of the previous model version (T213L31) for the western north Pacific for the years 1992 – 1997. These relate only to TC's entering the area 10^{o}N – 30^{o}N, 100^{o}E – 125^{o}E (Hong Kong Observatory's shipping warning area). The centre of the forecast TC was defined using the mean sea level pressure field at 2.5^o resolution. ECMWF short-range forecasts (T+24, T+48 and T+72 valid at 12 UTC) were verified against the Hong Kong best tracks.

Year	T+24		T+48		T+72	
	e	n	e	n	e	n
1992	189	28	302	20	465	11
1993	274	32	450	22	515	10
1994	189	20	252	15	261	10
1995	194	35	393	25	422	13
1996	190	22	279	17	316	9
1997	144	16	246	13	315	9

Table 3.11.1.1: ECMWF forecast errors in tropical cyclone positions (e = mean error In km, n + number of forecasts) in the area 10^{o}N – 30^{o}N, 100^{o}E – 125^{o}E, from 1992 – 1997.

Figure 3.11.1.1: ECMWF forecast errors in tropical cyclone positions in the area 10^{o}N – 30^{o}N, 100^{o}E – 125^{o}E, from 1992 – 1997. *(available in hardcopy only)*

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