Some recent results on numerical weather prediction over the tropics

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A review of some recent results on numerical weather prediction over the tropics is presented here. The emphasis of this review is on the prediction of hurricane formation and motion from global models. Also presented is a brief summary of results from regional single and multilevel models.

The major new results on the global models are that with increasing resolution in the horizontal and in the vertical (especially in the boundary layer) major improvements have been possible. The model is quite sensitive to data sets, the performance being considerably better with the final FGGE data sets as against the operational data sets. Improvements in short to medium-range prediction are contributed by refinements in the parameterisation of physical processes. High resolution global models show major improvement in storm tracks; the hurricane formation is very well handled with these modelling refinements although the inner storm area (radius less than 150 km) is not resolved by the high resolution global models. Thus the maximum speeds and minimum pressure of storms are not well handled in the present state of the art.

Introduction

Various centres in Europe, Australia, United States, Japan and Asia have contributed to the recent development of numerical weather prediction models (NWP) over the low latitudes. The range of these models includes single level vorticity and potential vorticity conserving models, regional high resolution primitive equation models and high resolution global spectral models. Operational efforts at ECMWF, UK Meteorological Office, Japan Meteorological Agency, The US National Meteorological Center and the Australian Bureau of Meteorology Research Centre have placed a major emphasis on the evaluation of NWP over the tropics. (A list of acronyms is given in Table 1.) The skill scores based on the performance of the global model at the ECMWF demonstrate a useful skill of roughly 2½ days for the tropical belt 30°S to 30°N. This skill is based on the root mean square error of the vector wind and is measured against the persistence error. The statistics of the prediction error cover an extended period of time, i.e. one year of global forecasts. Overall, the tropical wind errors in global models have been reduced somewhat in recent years. This improvement has come largely from model improvement. We shall be addressing some of these areas in the following section.

Several improvements in the modelling efforts relevant to the tropical numerical weather prediction have occurred in recent years. Much effort has gone into evaluating model performance in

<table>
<thead>
<tr>
<th>acronyms</th>
<th>symbols</th>
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<tr>
<td>ECMWF</td>
<td>European Center for Medium Range Weather Forecasts</td>
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<td>FGGE</td>
<td>First GARP Global Experiment</td>
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<td>FGGE IIb</td>
<td>Analysed gridded final FGGE data sets</td>
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<td>NMC</td>
<td>National Meteorological Center</td>
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<tr>
<td>4D</td>
<td>Four dimensional data assimilation</td>
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<td>Florida State University</td>
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<td>Optimal interpolation</td>
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<td>Universal time</td>
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<td>Sanders Barotropic Model</td>
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<td>NHC YR</td>
<td>National Hurricane Center's Statistical Model for different years</td>
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<tr>
<td>T21,T31,...,T106</td>
<td>Various resolutions of Spectral Model, Triangular truncation</td>
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<td>WWW</td>
<td>World Weather Watch</td>
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<tr>
<td>( \zeta )</td>
<td>Vorticity</td>
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<tr>
<td>D</td>
<td>Divergence</td>
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<tr>
<td>S</td>
<td>Dew-point depression</td>
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<tr>
<td>( \ln p_0 )</td>
<td>log of surface pressure</td>
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<tr>
<td>( \sigma )</td>
<td>Vertical coordinate</td>
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<tr>
<td>k</td>
<td>diffusion coefficient</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>Time filtering coefficient</td>
</tr>
<tr>
<td>q</td>
<td>Specific humidity</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>Vertical velocity in sigma coordinate</td>
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the areas of analysis and short-range prediction. Kanamitsu (1985) examined the performance of 2 to 3-day forecasts of the ECMWF model over the tropics and noted that although the skill scores of prediction in the tropics were quite low, the model predicted the phase speed and amplitude of African waves reasonably well. Reed et al. (1986, 1987) presented an impressive account of the ECMWF analysis system for the African region. They have shown that the 4D analysis provides a realistic structure of the African waves initially and the model forecasts onto the time frame of 3 to 4 days are very realistic.

Puri and Bourke (1982), Puri (1983, 1987) have addressed the inclusion of diabatic heating in the normal mode initialisation. Their work is particularly noteworthy in reference to the description of the tropical Hadley cell.

In a first such study, Bengstson et al. (1982) describe ‘intense hurricane-type vortices’ which developed in many ECMWF operational grid-point model forecasts of 1980 around the fourth day of their forecasts. Although in some cases the model storms appeared similar to actual storms, there were several cases where spurious cyclogenesis occurred. The model exhibited a definite bias for the number of northwest Pacific storms. The authors felt this was attributable to relatively high sea-surface temperatures used in the model. That was required to enhance the transport of moisture upward from the boundary layer. Since 1980 major improvements have been incorporated in the formulation of the surface layer physics at the ECMWF.

Dell’Osso and Bengtsson (1985), in a later study, discuss the relative merits of two models by carrying out three-day forecasts of typhoon Tip of 1979. Tip was a major super typhoon of that year. The two models were the ECMWF operational global grid-point model and a limited-area version (ELAM) of this same model. The global model output was used to provide boundary conditions for ELAM. ELAM’s grid resolution was around 57 km, as compared to roughly 208 km for the global model. The most striking aspect of the ELAM was its ability to provide a reasonable track forecast. The track of the typhoon in the global model run was somewhat worse. It appeared from this study that model resolution had a significant impact on the accuracy of track forecasts. Such an increase in skill may in part be due to the simulation of the mesoscale typhoon structure on the finer grid. The typhoon’s cross-sectional structure was much more realistic in the ELAM forecasts. The ELAM storm exhibited realistic tangential velocity, a smaller radius of maximum wind, a stronger warm core, and a steeper surface pressure gradient compared to the global model. Another remarkably realistic aspect of the ELAM forecast was the prediction of very realistic-looking spiral precipitation bands, the location of these bands corresponded closely with those seen on satellite photographs. In this study, the authors demonstrate that, beginning with large-scale data, a sufficiently high-resolution model can, with reasonable accuracy, simulate the development, structure and motion of a tropical cyclone; although the model’s need for time to develop the mesoscale structure from the large-scale data contributes substantially to errors in the track forecast.

Heckley et al. (1987) described two forecasts of Hurricane Elena starting from 31 August 1985. These were made with a global spectral model at a resolution of T106 waves (Triangular Truncation). The passage of this storm along the northern Gulf of Mexico was of interest here. One of these was an operational forecast while the other used an experimental version of the operational global spectral model. The only difference in these two experiments was in the parametrisation of cumulus convection. The operational model utilised a version of Kuo’s parametrisation scheme (Kuo 1974) for deep convection and a diffusive scheme (following Tiedke 1986) for shallow convection. The experimental model uses a lagged adjustment scheme (Betts 1986; Betts and Miller 1986) for its parametrisation of deep and shallow convection. The operational forecast was somewhat poor; it carried the storm roughly 200 km to the south of the Louisiana coast, whereas the experimental forecast showed a landfall very close to the reported location on the Louisiana coast.

Tuleya (1987) described the genesis of three tropical storms and the non-development of a tropical wave during the FGGE year 1979. For his study he utilised a regional model at a resolution of 28 km. For each case he carried out two experiments, the execution of which differed only in the boundary conditions. In one experiment real data at the boundaries from the ECMWF FGGE IIIb data were used, while in the other series of runs the boundary conditions from an R30 version of a global spectral model run were used. In each case the forecasts began with an incipient disturbance, moreover, development or non-development was reasonably predicted. The results did not seem to be particularly sensitive to these boundary conditions.

Tropical data sets

The operational data sets are received via the global telecommunication system. The operational prediction suffers from problems such as poor communication of data, poor quality of observations, missing observations and the short
cut-off time for the receipt of observations. As a consequence, less than 40 per cent of the data from the total observation taken over the global tropical belt are utilised in the global analysis. Only in special efforts, requiring delayed mode collections, has the input been drastically improved. That was demonstrated in the collections for the GATE and FGGE periods. (These data inventories are available at the World Data Center, Asheville, NC, USA.) In the present review we shall mostly be addressing results based on FGGE data sets. The FGGE IIb data sets prepared by the European Centre are described in Bengtsson et al. (1982). The European Centre’s final IIb analysis includes a multi-variate optimal interpolation and a 4-dimensional data assimilation. This data set is made available to the users at a resolution of 1.875° latitude/longitude mesh.

The tropical data coverage of the final FGGE IIb is much superior to the operational NMC IIa data sets. The analyses, based on these, are used in intercomparison experiments reviewed here. Differences in these two data sets arise from the shorter cut-off time on the GTS for the data receipt at NMC as compared to the ECMWF and also from the larger covariance matrix of the multivariate 01 of the ECMWF IIIb. There are also major differences in the 4 D assimilation methodology. We shall next present an outline of the FSU global model which is used for some of the studies reported here.

**An outline of the FSU global spectral model**

Domain: global;
Dependent Variables: $\zeta$, D, T, S, $l_n P_S$; (A list of symbols is given in Table 1);
Vertical Coordinate: $\sigma$ (12 layers);
Computational Methods: (see below)
Horizontal: spectral representation $T_{21}$, $T_{31}$, $T_{42}$, $T_{63}$, $T_{106}$;
Vertical: finite difference representation;
Transform Method: alias-free nonlinear advection;
Time Differencing: semi-implicit, Asselin time filter $\gamma = 0.5$; Asselin (1972)
Horizontal Diffusion: linear (fourth order), Kanamitsu et al. (1983).

$$K = 2 \times 10^{15} \text{ m}^2 \text{s}^{-1} (\zeta, T, S)$$

$$K = 2 \times 10^{16} \text{ m}^2 \text{s}^{-1} (D)$$

Envelope-orography: $\eta + 2\sigma$ follows Wallace et al. (1983)
Basic data based on NAVY’s 10-minute resolution tabulation over the global area used.
Vertical Boundary Conditions: kinematic, $\sigma = 0$
top and bottom;

**Data:** ECMWF FGGE IIIb;

**Initialisation:** non-linear normal mode with physics,
5 vertical modes; Kitade (1983).

**Physical processes**
Large-scale Condensation: disposition of supersaturation $T$, $q$;
Dry Convective Adjustment: Kanamitsu (1975);
Shallow Convection: Tiedke–Slingo (1985);
Deep Moist Convection: Krishnamurti et al. (1983);
Planetary Boundary Layer: surface fluxes: similarity theory;
vertical distribution: Richardson number dependent;
Radiative Processes: long-wave radiation—Band model, Harshvardhan and Corsetti (1984);
short-wave radiation—Lacis and Hansen (1974);
cloud feedback is based on threshold relative humidity;
diurnal change invoked via a variable zenith angle;
surface temperature is based on a 10-day mean fixed SST over oceans;
ground temperature is calculated from a surface energy balance over land which is coupled to surface similarity fluxes and surface hydrology.

In the following two sections we present a brief summary of the important physical processes.

**Cumulus parametrisation**
Four of the well known methods in current use include (a) the soft convective adjustment, (b) modified version of the so called Kuo’s scheme, (c) the Arakawa–Schubert cumulus parametrisation and (d) the Betts–Miller adjustment scheme. Versions of the soft convective adjustment scheme have been used by Kurihara and Tuleya (1981), Bender and Kurihara (1986). These are successful studies on the formation of tropical storms under a variety of initial conditions and different configurations of horizontal and vertical wind shear. Realistic warm core storms form in these simulations. Cumulus convection is shown to be important for the generations of the warm core. The Arakawa and Schubert (1974) scheme has been used in various
global modelling efforts. It is based on a quasi-equilibrium hypothesis. The performance of this scheme and that of a modified Kuo's scheme (Kuo 1974; Krishnamurti et al. 1983) are comparable in describing the heating and moistening rates over the tropics.

The Betts and Miller scheme (1984) is a soft convective adjustment scheme which has been refined considerably from the classical adjustment schemes. This method has shown much promise in recent integrations of the global model at the ECMWF.

Here we shall present an example illustrating the sensitivity of tropical prediction to cumulus parametrisation. Figures 1(a), (b) and (c) illustrate the results of a six-day global prediction from the use of a T42 version of the global model. The three respective panels show: (a) the observed 850 mb flow field for 12 UTC 17 June 1979; (b) the six-day prediction of the 850 mb flow field for 12 UTC 17 June 1979 from a use of a Modified Kuo's scheme, Krishnamurti et al. (1983, 1984); and (c) a six-day prediction of the 850 mb flow field for 12 UTC June 1979 from the use of Classical Kuo's scheme, Kuo (1974).

The differences in the forecasts from the two versions of the Kuo's scheme are quite large. The formation of a tropical storm (called the onset vortex) over the northern Arabian Sea is reasonably predicted by the modified Kuo's scheme that provides larger heating rates. This large sensitivity of tropical prediction to the cumulus parametrisation is an area that deserves much further work.

Planetary boundary layer

This is another area of the physical parametrisation to which the tropical predictions exhibit a large sensitivity. In this paper the surface layer fluxes of momentum, heat and moisture are calculated via the surface similarity theory following Chang (1978). The vertical distribution of fluxes utilises a Richardson number dependent mixing length concept. The large sensitivity is evident when one compares a poorly resolved with an explicitly resolved planetary boundary layer.

Hurricanes and typhoons

The operational prediction of hurricanes relies largely on extrapolation, analog and statistical methods. For very short range prediction of the order of 6 to 12 hours, the positions of the most recent storm centres are generally based on coastal or airborne radar fixes. They provide the most reliable extrapolative predictions. Analog methods such as HURRAN (probability) and various versions of the NHC-YR (multiple regression) have been used extensively by the National Hurricane Center in the US and several other countries. Anthes (1982) provides an excellent review of these methods. The overall prediction skill of these methods are of the order of 100 km (for the position of the storm centre) for 24-hour prediction and of the order of 250 to 300 km (for the 48-hour positions). The statistical methods appear to be slightly superior to the analog methods.

The operational dynamical methods include the vertically integrated equivalent barotropic model (SANDBAR) (Sanders and Burpee 1968) that is in much use and has a skill comparable to the aforementioned methods for the 24 to 48-hours prediction. For longer periods, i.e. of the order of 72 hours, the best guidance is provided by multilevel primitive equation grid-point
models, (MNGM, the Movable Nested Grid point Model of NMC), Hovermale and Livezy (1977). However, the position errors in this time frame are still quite large = 300 to 500 km. Table 2 outlines the mean forecast errors based on the statistics for the period 1975-1984, Fiorino (1985).

Here we shall be reviewing some recent results on the formation and motion of these storms from high resolution global models.

Table 2.

<table>
<thead>
<tr>
<th>Model</th>
<th>24 HR</th>
<th>48 HR</th>
<th>72 HR</th>
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<tr>
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<td>207</td>
<td>337</td>
<td>424</td>
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<tr>
<td>HNC</td>
<td>181</td>
<td>390</td>
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<tr>
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<td>468</td>
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<tr>
<td>SANDBAR</td>
<td>192</td>
<td>472</td>
<td>625</td>
</tr>
<tr>
<td>NMC73</td>
<td>189</td>
<td>385</td>
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</tr>
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</table>

Formation of hurricanes with very high resolution global models

With the use of the FGGE IIIb data sets and a detailed version of the global model, considerable success has been demonstrated in the formation of several hurricanes and typhoons. It should be stated that in these experiments we have started with an incipient wave or a weak depression which is resolved by the FGGE data sets. The incipient disturbances considered here have speeds less than 10 m s\(^{-1}\) initially. In many ways this appears to be one of the most promising areas of research. After carrying out a series of some 12 experiments at a resolution of T42 and eleven vertical layers we recognised that this resolution was inadequate to address the hurricane formation problem. This T42 version of the model had a vertical resolution of roughly 50 mb below the \(\sigma = 0.8\) surface. The failure was diagnosed to the vertical resolution near the earth's surface. The vertical discretisation for the 11-level model is presented in Fig. 2(a).

A T42 version of the model with 12 vertical levels with an explicit constant flux layer near the earth's surface (located at \(\sigma = 0.99\)) was able to predict the formation of several hurricanes (and typhoons). This vertical discretisation is presented in Fig. 2(b). This was tested for 4 different storms of 1979. At the resolution T42 the size of the storms and the location of maximum wind from the storm centre was too large. Storms also formed at the resolution of T31, T63 and T106 when the same vertical discretisation was used. The model failed to predict storms at a resolution of T21. The best results in terms of the track and strength of winds were obtained at a resolution of
T106. It was also apparent that the results gradually improved as the resolution was increased to T106. When the horizontal resolution was increased for this 12-layer model, the air-sea flux of water vapour dramatically increased. This appeared to be one of the important factors in the development of these storms.

An advantage of this type of experimentation is that at the same time one can examine the results of the high resolution global forecasts over all of the tropics (as well as over the globe). It is possible to compare the tropical prediction of monsoons, trades, tropical jets, equatorial waves and any other phenomena of interest that are covered by the initial state. Studies on model output diagnostics over the tropics (based on ECMWF model) have been very effectively demonstrated by Reed et al. (1986, 1987).

Dynamics at a lower resolution and physics at a higher resolution

The results of three prediction experiments are presented here:

1. A 12-layer global model forecast with T42, Fig. 3(a),
2. A 12-layer global model forecast with T106, Fig. 3(b), and
3. A 12-layer global model forecast using T42 dynamics and physics calculated over the T106 transform grid, Fig. 3(c).

This was a first such study on mixed resolution experiment that was completed recently. Figures 3(a), (b) and (c) show the 72-hour wind field at 850 mb from these respective experiments. Here we present the results on the formation of hurricane Frederic of 1979. The forecast of the storm from an incipient easterly wave and its westward motion are reasonably handled at the resolution T106. The predicted maximum wind at hour 72 was around 28 m s⁻¹. It should be noted that even at the best resolution considered here, i.e. T106, the maximum winds are underestimated by almost a factor of two. The inner rain area, radius < 150 km, is not resolved by these resolutions. At the resolution for T42 the development was very weak and the speed reached about 16 m s⁻¹; the phase speed was very low. The third experiment was very similar in behaviour to the T42 experiment. In this mixed resolution experiment a storm did form with maximum winds of the order of 18 m s⁻¹. However, its westward motion was still too slow. It appears that a lower resolution dynamics is not able to handle the phase speed as accurately although the higher resolution physics appeared to resolve the heating and rainfall rates comparable to the second experiment which was a straight run with a T106. We propose to carry out a reverse resolution experiment utilising dynamics at T106 and physics at a lower resol-

From the computational point of view this would be economical since the dynamics is fully vectorised in the code. We expect that this experiment would provide a reasonable phase speed and possibly also reasonable amplitudes.

The results on the formation of hurricane Frederic appear quite reasonable at the resolution of T106. Observationally all of the waves considered in this study became hurricanes between hours 48 to 60 from the initial time. The storm slowly organises into a closed circulation with a strong wind speed area to the north. The storm formed around hour 48 of the prediction as it moved westward. The phase speed of the predicted storm was still somewhat slower than the best track positions. The inner storm area (radius r < 150 km) is hardly resolved at the resolution of T106. The predicted maximum speeds are underestimated by almost a factor of 2 at this resolution.

Strong horizontal shear flows evolve as a function of time in the very high resolution experiments. That was clearly evident for the T106 resolution. Such strong shear force flows did not show up in the experiment with lower

Fig. 3(a) Hurricane Frederic: Predicted winds at 850 mb, hours 24, 48, 72 (T42). Streamline and isolachs (m s⁻¹).
Fig. 3(b) Hurricane Frederic. Predicted winds at 850 mb hours 12, 24, 36, 48, 60, 72 (T106). Streamline and isotachs (m s⁻¹).
Fig. 3(c) Hurricane Frederic. Predicted winds at 850 mb hours 12, 24, 36, 48, 60, 72. Mixed resolution experiment. T42 dynamics with T106 physics. Streamline and isotachs (m s⁻¹).
resolution i.e. T42 and T63. Figures 4 (a),(b) and (c) and 5 (a),(b) and (c) show respectively, the zonal wind charts over the storm region for days 1 and 3 at the resolution (a) T42, (b) T63 and (c) T106. It is apparent that the higher resolution model appears to create stronger horizontal shear flows; the eventual formation of the hurricane in these regions of strong horizontal shear is accompanied by strong convection. The high resolution rainfall forecast for days 1 and 3 displays organised convection over the region of strong horizontal shear. This is a major contributor to the formation of the hurricane. In the prediction experiments this region, however, was characterised by weak vertical shears at all resolutions.

When one performs a zonal harmonic analysis of detailed large-scale data sets in the tropics and the middle latitudes, one usually finds that most of the variance, almost 95 per cent, is usually accounted for by the first 15 zonal harmonics. It would thus appear that there is not much information content beyond zonal wave number 15. However, when one examines the history of evolution of forecasting errors, as the resolution of the models were increased from T21 to T42, and on to T106 waves, the skill of forecasting indeed improves. The skill scores, based on experiments at different resolutions from the operational ECMWF model, show this increase of skill with resolutions. This was also noted by the

Fig. 4 Predicted wind speed (m s⁻¹) at 850 mb at resolutions (a) T42, top panel. (b) T63, middle panel. (c) T106, bottom panel: at the end of one day forecast.

Fig. 5 Predicted wind speed (m s⁻¹) at 850 mb at resolutions (a) T42, top panel. (b) T63, middle panel. (c) T106, bottom panel: at the end of three-day forecast.
limited amount of numerical experimentation that was completed at FSU from R30 to T42, T63 and T106 waves. These studies strongly suggest that useful 4-dimensional information in fact exists in the initial state and is tapped to some extent by the high resolution global model during the course of the prediction. We cannot say that useful information at higher resolutions will always be created by a model during the course of prediction. However, understanding of this cascade of information is a major scientific problem. We believe that the totality of WWW data sets including high resolution cloud drift winds, satellite soundings, commercial aircraft data and the marine data carry important implicit information on scales somewhat beyond what is seen from the variance spectra of the zonal harmonics. Coarse resolution models are not able to bring out some of that implicit information to higher scales.

Hurricane David (1979)
This storm formed over the tropical Atlantic and moved westward along 10°N. The initial maximum speed at 850 mb was around 6 m s⁻¹, the initial pressure around 1012 mb and the initial relative vorticity was around 0.1 x 10⁻⁴ s⁻¹. This storm formed into a closed circulation by hour 48 (Fig. 6) and intensified by hours 60 and 72. The predicted maximum speed at hours 60 and 72 reached about 17 m s⁻¹. The position error of the predicted storm was very small at 72 hours. The observed and predicted tracks are discussed below. A closer look at this storm formation appears to suggest that a region of intense convergence first appeared over northern Brazil by hour 36 as the easterly wave approached to the north. The storm forms rapidly thereafter over the Atlantic Ocean as these two systems merge. The phase error at the end of 3 days was around 100 km.

Formation and landfall of typhoon Hope (1979)
An extensive study was made on the formation and landfall of typhoon Hope. We have examined the formation problem by carrying out 5-day integrations at all of the horizontal resolutions from T21 to T106. At the final resolution the integrations were extended out to 10 days in order to investigate the landfall. Typhoon Hope was a major super typhoon of 1979. It first became a typhoon on 29 July near 135°E and 16°N. It followed a west-northwestward track towards Hong Kong. It attained a maximum intensity soon after 31 July when the surface pressure attained a value of 898 mb while the surface winds attained a maximum value of around 65 m s⁻¹. Typhoon Hope made a landfall just 20 km north of Hong Kong on 2 August 1979. Subsequently it weakened into a depression and moved westwards across central Indochina and Burma towards northern India.

The forecasts were made, starting at 12 UTC 27 July 1979, with the 12 vertical layer version of the global model. As before, ECMWF IIIb data were subjected to a nonlinear normal mode initialisation with physics at five different resolutions. Selected initial fields are shown in Figs 7(a), (b) and (c). The motion field at 850 mb at the initial time shows a depression located near 140°E and 15°N. The maximum winds were roughly 15.5 m s⁻¹, Fig. 7(a). The initial maximum relative vorticity, Fig. 7(b), was around 0.7 x 10⁻⁴ s⁻¹, while the central pressure was around 1008 mb, Fig. 7(c). Another tropical depression was located to the west, near 122°E and 20°N. The global model was extremely successful in predicting the track of typhoon Hope to 6 days with the T106 version. The predicted storm moved somewhat north of the observed position and the phase speed was slightly slower. The prediction error at the end of day 6 was around 200 km. The observed positions are based on the best track positions from the Guam summaries, while the predicted positions were based on the location of the maximum relative vorticity at 850 mb. Figure 8 illustrates the tracks.

The observed motion field at 850 mb for the 6 days after the initial time are shown in Fig. 9. These are based on the ECMWF's FGGE IIIb analysis. According to this analysis the storm acquired a speed of 22 m s⁻¹ by day 3 (i.e. 27 July) when the super typhoon formed. The speed increases to roughly 26 m s⁻¹ by day 5 and it weakened somewhat by day 6 as landfall occurred. The IIIb analysis at a resolution of 1.875° (latitude/longitude) does not describe the mesoscale structure and intensity of the typhoon. The gross features of the storm circulation and path were reasonably described by the analysis, although the speeds were underestimated.

The T106 forecasts, of the 850 mb flow fields, are shown in Fig. 10. This exhibits a reasonable motion of the storm at 850 mb. The predicted storm acquires an intensity of 28 m s⁻¹ by day 3. It makes landfall by day 6 of the prediction and westerly winds weaken to roughly 20 m s⁻¹.

The predicted motion field at 850 mb at the different resolutions at the end of days 1, 3 and 5 of the forecast showed the following features:

At the resolution T21: The storm moved slowly from roughly 170°E (day 1) to about 118°E (day 5). During this period the maximum speed in typhoon Hope increased from about 6 m s⁻¹ (day 1) to about 15.3 m s⁻¹ (day 5).

At the resolution T31: The storm moved from roughly 140°E (day 1) to about 120°E (day 5). During this period the maximum
Fig. 6  Three-day forecast showing the formation of Hurricane David. Maps are at intervals of 12 hours starting at hour 12. The maps show 850 mb streamlines and isotachs (m s⁻¹).
Fig. 7 Initial state for typhoon Hope 1979. (a) Top panel, 850 mb streamlines and isotachs (m s\(^{-1}\)). (b) Middle panel, 850 mb relative vorticity \(10^{-4} \text{ s}^{-1}\). (c) Bottom panel, sea level pressure, mb.

Fig. 8 Observed and predicted track, Typhoon Hope. T106.

Speed increased from 12.5 m s\(^{-1}\) (day 1) to 36 m s\(^{-1}\) (day 5).

At the resolution T42: The storm moved from roughly 140°E (day 1) to 117°E (day 5). During this period the maximum wind speed increased from roughly 17 m s\(^{-1}\) (day 1) to 43 m s\(^{-1}\) (day 3) and weakened somewhat to 34 m s\(^{-1}\) by day 5 as it approached the coast of China.

At the resolution T63: The storm moved from roughly 140°E (day 1) to roughly 115°E (day 5). During this period the maximum wind speed increased from roughly 22 m s\(^{-1}\) (day 1) to 23 m s\(^{-1}\) (day 3) and weakened somewhat to roughly 20 m s\(^{-1}\) (day 5).

At the resolution T106: The storm moved from roughly 140°E (day 1) to roughly 113°E (day 5). During this period the maximum wind speed increased from roughly 20 m s\(^{-1}\) (day 1) to 36 m s\(^{-1}\) (day 4). The storm weakened by day 6 as it moved inland north of Hong Kong.

As the resolution is increased the phase speed of the storm improves considerably. The formation of the typhoon was reasonably represented by all except T21 by 29 July 1979. At T21 the formation was slower although it did organise into a large depression by 1 August. At this time the separation of the region of maximum wind from the storm centre was nearly 900 km at this resolution. The higher resolution models show a gradual improvement in the location of the maximum wind with respect to the storm centre. The size of the storm improves with resolution. The maximum speed does not linearly increase with the resolution from T21 to T106 as one might have anticipated. The transform grid at T106 (100 km) does not resolve the inner core of strong winds that are usually found some 30 km from the storm centre. We have also run all of the cases at these resolutions. In all of these cases the predicted maximum wind in the storms at T106 were always stronger compared to T42.
The T106 forecasts clearly indicated the formation of banded vertical velocity and rainfall patterns as the hurricanes (and typhoons) formed in our experiments. Figures 11(a), (b) and (c) illustrate the predicted rainfall rates. In each of these panels we show the evolution of these fields at hours 24, 48 and 72. The fields clearly portray the evolution of banded heavy precipitation around the storm centre. It appears when we proceed to still higher resolution it should be possible to discern the detailed features of the rainbands and the eye wall. The maximum predicted rainfall rate in typhoon Hope at hours 48 and 72 at the resolution T106 reached values of 232 and 168 mm/day.

Motion of typhoon Abby

This storm formed east of Guam on 7 August 1983. This was a major super typhoon of the year 1983. Figure 12 shows its observed track based on Guam summaries. Around 11 August it recurved north-northeastward. The recurvature of this storm has been studied in much detail by several investigators. This storm attained a maximum surface wind of 145 knots on the 10th and had a minimum surface pressure of 888 mb. Chan
Fig. 10 6-day prediction of streamlines and isotachs (m s$^{-1}$) of Typhoon *Hope* 1979. T106 experiment. 850 mb.

*SIX DAY FORECAST WINDS FOR TYphoon HOPE (1979)*
(1986) reported on the results of several forecasts that were carried out with a multilevel regional model. A striking feature of the forecasts was a pronounced westward drift while the storm was in fact recurving and moving towards Japan. *Abby* weakened as it moved over central Japan on 17 August. Heavy rains caused severe flooding and landslides in Japan. Several people were killed as this storm traversed across central Japan. The systematic westward drift in the early numerical weather prediction experiments, Fig. 13, reported by Chan (1986), were attributed to a spurious intensification of the subtropical high in the models.

In our studies we carried out a 48-hour forecast of typhoon *Abby* starting on 8 August 1983. We used the 12-layer version of the model at a resolution of Triangular 106 waves. Our interest in these forecasts was to examine the nature of the track forecasts at very high resolution in the global spectral model. We have used the operational data from the European Centre to initialise our model with the nonlinear normal mode initialisation with physics.

Figure 14 illustrates the motion field based on the ECMWF analysis. Here we show the streamlines and isotachs at 850 mb from 12 UTC 8 August to 12 UTC 10 August 1983 at intervals of every 12 hours. The analysis shows a maximum intensity of 28 m s⁻¹ on 8 August when the storm had in fact reached super typhoon intensity. The ECMWF analysis utilises a transform grid of T63 for the 4-dimensional data assimilation. The transform grid around 15°N has a grid resolution of roughly 160 km. At this resolution the model is incapable of identifying features in the inner storm area. Another factor is, of course, the distribution of data sets around the storm. The operational data include cloud winds tracked from the Japanese geostationary satellite, commercial aircraft wind reports and the conventional observations from the World Weather Watch.

The predicted motion fields at intervals of 12 hours are shown in Fig. 15(a). These are at 850 mb. The corresponding predicted sea level pressure fields are shown in Fig. 15(b). The predicted motion of typhoon *Abby* corresponds very closely to the best track position; the 24 and 48-hour
position errors are around 1° latitude. These forecasts do not exhibit a westward drift in this single short-term integration. The sea level pressure drops from an initial value of 1006 mb to a value of 996 mb by hour 48. The observed minimum pressure attained by the storm, on hour 48, was around 990 mb. At the resolution of T106 the maximum winds in the storm reached 25 m s⁻¹ while the observed maximum wind was roughly 60 m s⁻¹. The differences are largely attributable to resolution; the inner rain area is not resolved by T106. The evolution of the predicted wind at 850 mb in typhoon Abby shows a pronounced asymmetry with respect to the storm centre. The prediction appears quite impressive at this resolution. It is difficult to interpret the reasons for the lack of a spurious westward drift. The prediction of subtropical highs are very sensitive to the radiative forcing. Our use of a sophisticated radiative parametrisation has contributed to an improved prediction of the subtropical high and the Hadley cell. We feel that the lack of westward drift of the storm in the prediction may be related to an overall improvement of the tropical prediction.

Formation of a composite super typhoon

Table 3 illustrates the dates and position of the initial formation of a number of super typhoons that formed close to 135°E and 12°N in recent years. This is a general location where a substantial number of these storms have been known to form. For some time we have been preparing a composited 4-dimensional structure of the life cycle of a super typhoon over a 25° latitude/longitude square; we have composited the observations of these super typhoons for days −8 to +3 with respect to a moving frame of reference. Here day 0 refers to the date when a super typhoon first

<table>
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<th>Year</th>
<th>Mon</th>
<th>Day</th>
<th>Hour</th>
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<th>Wind (knots)</th>
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formed. In the present study we have merged the day –3 global analysed data set (of ECMWF) with the aforementioned inner composited data. By this process the inner 25° latitude/longitude region contains the typhoon data, while the far field beyond that is simply a globally averaged data for super typhoon cases for day –3. The merging \( Q_{\text{final}} \) allows a slow transition from the inner \( Q_{\text{inner}} \) to the outer \( Q_{\text{outer}} \) data on 3 lines using an averaging procedure where,

\[
Q_{\text{final}} = \alpha Q_{\text{outer}} + \beta Q_{\text{inner}}
\]

and \( \alpha + \beta = 1 \).

\( \alpha \) changes from 1.0 to 0.66, then to 0.33, and finally to 0.00 in this transition region. The global data at all vertical levels for all variables were initialised, as before, and a 3-day global forecast (from day –3 to day 0) was carried out with the high resolution model.

The initial fields of wind at 850 mb, relative
Fig. 15(a) T106 forecast at 850 mb of Typhoon Abbey 1983. Hours 0 through 48. Streamlines and isotachs (m s⁻¹).

FORECAST WINDS FOR TYPHOON ABBY (1983)

- 0 hours
- 12 hours
- 24 hours
- 36 hours
- 48 hours
Fig. 15(b) T106 forecast of sea level pressure mb. Hours 0 through 48, Typhoon Abbey.
vorticity and sea level pressure over the Pacific Ocean (for day -3 of the composited field), are shown in Figs 16(a), (b) and (c). At 850 mb a strong initial vortex with a maximum speed of around 8 m s\(^{-1}\) is located near 135°E and 12°N. At the upper level this region is characterised by anti-cyclonic circulation. The initial sea level pressure is around 1009 mb while the initial relative vorticity was around 0.5 x 10\(^{-2}\) s\(^{-1}\). The predicted motion field for the first three days at 850 mb are shown in Fig. 17. A marked increase of wind speed from x1 to x2 to x3 m s\(^{-1}\) occurs during days 1, 2 and 3 of forecast. Although super typhoon scale winds are not resolved by T106. A strong typhoon does form in this integration. Its track also resembles closely the composited super typhoon track. The observed and the predicted storm positions are shown in Fig. 18. Here we show the tracks for hurricanes *Frederic* and *David*, and typhoons *Hope* and the composite.

The four examples of hurricanes (and typhoons) illustrated in this section are suggestive of the potential of the high resolution global model, although it is obvious that more critical research is needed prior to any generalisation of such results.

**Prediction of monsoon at different resolutions: (T21, T31, T42, T63 and T106)**

A series of global prediction experiments starting at 12 UTC 27 July 1979 was carried out to study the initiation of an active spell of monsoon rain. This was a period just after a break in the Indian monsoon, the break lasted from roughly 12 to 27 July 1979. A monsoon depression formed over the Bay of Bengal around 28 July and was followed by a revival of the monsoon rains over the land areas. The model was run at five different resolutions from T21 to T106. Nonlinear normal mode initialisation with physics (Kitade 1983) was encoded at all these resolutions. Five vertical modes were retained in these experiments. This required the calculation of eigenfunctions of the vertical modes at the different resolutions. We have examined in detail the results of the initialisation at the different resolutions. Precipitation rates at the initial time for one series of experiments are shown in Fig. 19. As to be expected initial rainfall rates increase with resolution. Global tropical grids of 'observed' 24-hourly rainfall totals were prepared from a mix of satellite and raingauge observations (this follows the procedure outlined in Krishnamurti *et al* 1983).

It is interesting to compare the predicted rainfall intensity and distribution at T21 with those based on satellite and raingauge. The
Fig. 17 Predicted mb wind field for hours 12 through 72, T106 experiment. Streamlines and isotachs (m s\(^{-1}\)).
Fig. 18 Observed and predicted tracks of four storms. T106 experiments.

![Observed and predicted tracks of four storms. T106 experiments.](image)

location of major precipitation areas over the West Coast of India, Bangladesh and over the western Pacific Ocean along 20°N are reasonably initialised at T21, however the rainfall amounts at T21 are underestimated. The rainfall rates increase from roughly 10 mm/day to 40 mm/day as the resolution is increased from T21 to T106. A further marked increase in the rainfall rates occur during a one day spin up in T106 as the rainfall rates increase to as much as 60 mm/day. During this time typhoon Hope was forming over the western Pacific Ocean where the rainfall rates increased to almost 250 mm/day as that storm formed.

In these experiments the forecasts for wavenumber 0 (zonal mean) for the zonal wind, temperature and specific humidity appear nearly identical through 5 days of integration for all of these resolutions (i.e. T21, T31, T42, T63 and T106).

The Hadley Cell is strongly resolution dependent. The forecasts of the Hadley Cell at the end of 3 days are shown in Fig. 20. They show a much narrower axis of ascent which is almost an order of magnitude stronger at T106 compared to that at T21. This also implies narrower geographical axis of stronger rainfall rates along the ITCZ at T106.

At T21 a strong depression forms over southern India and is associated with heavy rain, however the observations show a depression forming over the northern Bay of Bengal. The forecasts at T106 show a more realistic formative position for this depression. Figure 21 illustrates the forecasts of the 850 mb motion field at the different resolutions. A diagnosis shows that the orography and cumulus convection at T106 were important factors for these improved results. Other factors include stronger low-level flow regimes with stronger horizontal shear at T106 compared to that of T21. We found that the results improved as the resolution was increased.

A three-day mean predicted rain over the monsoon region at the different resolutions is compared with the observational estimates (Fig. 22). The forecasts at T21 showed the heavy rainfall over southern India, that was related to the large error in the location of the storm. The coastal rainfall off the west coast of India and the rainfall associated Bay of Bengal system are reasonably handled at the higher resolution forecasts.

The circulation forecasts improved considerably with the increase in the resolution. Besides the Somali jet at 850 mb, the tropical easterly jet at 200 mb over the Arabian Sea exhibited a narrower axis with sharper gradients. The available observations are not able to resolve such features. The wind forecasts are consistent with the divergent circulation that evolved with the cyclogenesis over the Bay of Bengal.

**Planetary scale divergent circulations**

The most striking results from the variation of resolution emerged in the location of the centre of the monsoonal divergent outflows at 200 mb, Fig. 23(a), (b), (c), (d), (e) and (f). The erroneous placings of the storm over southern India at T21 produces an enhanced convection over that region. A pronounced centre of divergent outflow at 200 mb is located over southern India for the T21; that centre shifts gradually towards northern Bay of Bengal as the resolution is increased. A depression had already formed by day 3 (i.e. 30 July 1979) over the northern Bay of Bengal. The 3-day prediction at T63 shows the location of the divergent outflow centre somewhat to the west.
Fig. 19 Initialised precipitation for 27 July 1979, 12T for different resolutions T21, 31, 42, 63, and 106. The bottom right panel shows observed estimates based on satellite and raingauge. Units mm/day.

INITIAL PRECIPITATION
The best results at day 3 were obtained at T106.

Glancing at the results of the tropics we note the following changes in the divergent circulations as the resolution is increased from T21 to T106. A prominent centre of divergent inflow at 200 mb is usually located over the general region of South Africa, Krishnamurti (1985). At T21 we find its location over the southern tip of the Mozambique Channel. As the resolution is increased this centre shifts gradually northwards and is located over the Kalahari desert of South Africa at T106. The strength of the divergent wind between the centre of the divergent outflows and inflows increases slightly over the Arabian Sea — from 4.5 m s\(^{-1}\) at T21 to 7.3 m s\(^{-1}\) at T106. A spurious convective cluster forms near 170°E and the equator at T21 which is quite strong and exhibits a strong divergent outflow. As the resolution is increased to T106 this system weakens considerably. The Walker Circulation is most pronounced at T106 near 120°W, exhibiting a strong dipole structure to the east and west of the region. The monsoonal east west circulation is more pronounced along 135°W over a broad belt of the Pacific Ocean. The strongest local Hadley type vertical overturning is evident in the Indian Ocean and is most pronounced at the highest resolution, i.e. T106.

**Global tropical disturbances**

In order to find out whether the global model produces spurious storms during the course of integration all of the tropical waves and depressions of the initial state were tagged and monitored. Here we shall show an example of the global tropical streamline-isotach charts at 850 mb and the corresponding hour 72 prediction, Figs 24(a) and (b). The salient tropical disturbances (waves, depressions and storms) around the global tropical belt are illustrated on these diagrams. In these charts, other than the named storm Hope, no other disturbances reached typhoon intensity during these periods. The T106 forecasts also did not exhibit any unusual development for any of the many tropical disturbances during these periods.

**On the sensitivity of the results to data sets**

Within the ECMWF FGGE IIb analysis the FGGE IIb data sets were subjected to a multivariate optimal interpolation, and a four dimensional data assimilation. The FGGE IIb data sets include delayed data from the global experiment and include data from all of the surface and space-based platforms. A detailed data sensitivity study is not completed at this time. We shall discuss the comparisons from a
Fig. 21 Predicted motion field at 850 mb for the different resolutions at the end of day 3 of forecasts. Streamlines and isotachs (m s⁻¹).

T106 experiment where the global NMC IIIa data sets were utilised. These are part of the operational global data sets produced by NMC during 1979. Because of the 6-hour cut-off time for the acceptance of observations from the global telecommunication systems this data set is quite inferior to the FGGE IIIb especially over the tropics. Conspicuously lacking are the high resolution cloud winds, the special FGGE IIb collection of commercial aircraft data, data from special oceanic buoys, the delayed WWW and many ship observations from the FGGE/
MONEX research ships. An inspection of the NMC's FGGE IIA data sets over the Atlantic Ocean revealed that the tropical northern Atlantic Ocean near 10°N to 15°N was essentially a data sparse region. In the FGGE IIb this region does include a large number of high resolution cloud winds (processed by the University of Wisconsin) and a sizeable collection of commercial aircraft wind reports. Furthermore around the region of the initial disturbance (Frederic), many observations over West Africa and coastal South America were not included in the FGGE IIA collection of the 12Z data sets. Thus it was not surprising that the initial state of the operational NMC analysis did not describe the incipient disturbance adequately. The 72-hour forecast at the highest resolution (T106) based on these data sets is shown in Fig. 25. This forecast failed to identify or form hurricane Frederic.

It is perhaps somewhat premature to conclude that the operational NMC data during 1979 were inferior to the ECMWF FGGE IIb for such high resolution prediction experiments. Further evaluation is certainly necessary since a purpose of these high resolution experiments is to assess the full capabilities of operational data sets. Such studies require very careful diagnosis of the analysis procedures and data sets.
Fig. 23 Predicted Velocity Potential $\chi$ at 200 mb at the 5 different resolutions for day 3 of forecasts.

Fig. 24 (a) Observed (top) and (b) predicted (bottom); global tropical motion field at 850 mb for day 3. Streamlines and isotachs (m s$^{-1}$).

Fig. 25 NMC analysis (left panel) and T106 prediction (right panel) starting from NMC analysis. 72-hour forecast. Streamlines and isotachs (m s^{-1}) at 850 mb.
Single level regional models

An extensive review of results from some 980 experiments with simple vorticity and potential vorticity conserving models were presented by Krishnamurti et al. (1987). These experiments utilised a mesh size of the order of 100 km. Roughly 980 experiments were carried out over tropical regional domains with the two models. The main findings of these experiments at 700 mb were as follows.

Both models seem to perform reasonably well over west Africa and the tropical eastern Atlantic Ocean. Over this region the shallow water equations (mean free surface height 2 km and bottom topography with maximum height of 1 km) performs better than persistence (for wind forecasts) to almost 3 days. The barotropic model has a useful skill for wind forecast to about 1 day.

Over the Monsoon regions (summer and winter monsoon) these models do not show much skill.

Over most other regions these models exhibit rather low skill, i.e. of the order of one day.

The model performance can be enhanced by optimising the two parameters, i.e. the mean free surface height and the maximum height. This was demonstrated from a series of experiments over China where the wind prediction skill increased for roughly 12 hours to 72 hours for selected periods.

The model is quite sensitive to boundary conditions. The real data time-varying boundary conditions provide unrealistically high skill. Fixed time-invariant boundary conditions provide a low skill. The use of boundary conditions from a global model provide a skill that is lower than those from the use of real data.

Multilevel regional model

Two recent reviews by Krishnamurti (1985) and Krishnamurti et al. (1987) describe the performance of multilevel regional models over the tropics. These models describe the prediction of rainfall and other large-scale parameters such as winds, temperature, pressure and humidity. The models are fairly comprehensive in their global parametrisation. The models have been tested against GATE and MONEX observations. Cyclic conditions in the zonal and real data along the meridional boundaries are used in these studies. Dynamic initialisation provides a pressure-wind balance for the initial state.

The major results of these studies show that the regional model successfully predicts the westward passage of African waves and monsoon depressions. The model also successfully simulates the formation of tropical depressions. This success on the 2 to 3-day time frame has only been possible over regions with adequate synoptic scale data coverage. This is, however, not possible over many parts of the tropical belt. The pressure of lateral boundaries limit the range of prediction beyond 3 days.

Concluding remarks

The high resolution global models seem to hold much promise for the prediction of a variety of tropical disturbances including the formation of hurricanes. The present studies utilise a resolution of T106 waves. With the presently available supercomputing capabilities it should be possible to extend this resolution further to somewhere around T170. That resolution, we feel, may be necessary for handling the storm pressures and wind speeds. With a transformation of coordinates it should be possible to extend the tropical resolution for global models. The mixed resolution experiments described previously can be extended much further. Since the dynamics are fully vectorised (on supercomputers), the use of very high resolutions for the dynamics can improve the phase speed of disturbances including tropical storms. The computation of physical processes at a somewhat lower resolution might perhaps be adequate for determining reasonable amplitudes of rainfall and heating rates. Further work in these areas of research seems to be quite important.

The regional models will be developing to very high resolutions. With the use of boundary conditions from high resolution global models we can expect much further improvement in the performance of regional models. Physical initialisation entailing Newtonian Nudging of the physical processes is expected to initialise the rainfall and diabatic processes very realistically (see Krishnamurti et al. 1988). Much promising work has already been done in these areas. The mix of semi-implicit-semi-ergangrannian advective schemes, boundary conditions from very high resolution global models and detailed initialisation procedures are expected to improve the quality of prediction immensely. The data problem needs to be addressed from the use of newer satellite technology in order to provide adequate coverage for such very high resolution models.

Acknowledgments

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