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Verification of medium range forecasts produced by a global spectral model

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सार – 15 दिसम्बर 1986 के 12 ग्री. मा. स. के आरंभिक क्षेत्रों से आरम्भ होने वाली 23 दिवसीय अवधि के लिए गोलीय निर्देशांकों में डायबेटिक पूर्वग समीकरणों पर आधारित एक 40 तरंग 12 सतही भूमण्डलीय स्पेक्ट्रल मॉडल समाकलित किया गया है। इस अध्ययन में विश्व मौसम संगठन द्वारा निर्धारित प्रक्रिया का अनुसरण करते हुए मॉडल निर्गमों के सत्यापन के परिणाम प्रस्तुत किए गये हैं। भूमण्डलीय सम्पूर्ण क्षेत्र तथा भारतीय गवाक्ष (45° पू.-120° पू., 15° द.-55° उ.) के लिए निर्देश सत्यापन सांख्यिकी का परिकलन किया गया है। यह पाया गया है कि भूमण्डलीय क्षेत्र (डोमेन) और भारतीय गवाक्ष दोनों के लिए 5 दिनों की अवधि तक के लिए अनारंभिक विश्लेषण और पूर्वानुमान का आपस में अच्छा संबंध है।

ABSTRACT. A 40 wave 12 layer global spectral model based on diabatic primitive equations in spherical coordinates has been integrated for a 23-day period starting with the initial fields of 12 GMT of 15 December 1986. Results of verification of model outputs, following the procedure laid down by WMO, are presented in this study. Model verification statistics have been computed for the global regime as well as the Indian window (45° E- 120° E, 15° S-55° N). It is found that uninitialised analysis and forecast are well correlated for a period up to 5 days for both the global domain and the Indian window.

1. Introduction

For medium range (3 to 10 days) forecast of weather it is desirable to work with a spatial domain encompassing the whole of the globe. A global domain has further advantage as artificial boundaries and associated problem of assigning correct fluxes across such boundaries are eliminated.

At present, global forecast models are of two distinct types : (a) the grid point models in which a field variable is represented by its value at a set of discrete points and (b) the spectral models in which a field variable is represented by the coefficients of an expansion in orthogonal functions. In the grid point method both space and time derivatives are approximated by truncated Taylor series expansions which lead to significant error when accumulated over large number of time steps. In the spectral method derivatives can be obtained by analytically differentiating the series approximation of the field variables and thus eliminating all errors inherent to the finite difference approximation except, those related to truncation of waves. In addition, analytical differentiation used in spectral method is free from the problems of linear and non-linear instability, misrepresentation of amplitude, phase and speed of waves, dispersion of waves etc associated with the finite difference method.

In present day spectral models integrations in time and vertical dimension are still done by finite difference methods while the horizontal variation of meteorological variables is expressed in terms of a finite series in orthogonal functions. The spherical harmonics provide a convenient set of such functions as they are orthogonal over the domain of the surface of a sphere. At present no suitable set of functions could be found which is orthogonal over a domain limited to a part of the surface of the globe. Hence, spectral formulation of the limited area models are still in preliminary stage of development.

The formulation of spectral method for treating physical processes are also not available at present and effects of such processes are still evaluated in the spatial domain. Transformations from spectral domain to spatial domain and back are done by Fast Fourier Transform (FFT) in the east-west and by Gaussian quadrature in the north-south. The relationship between the spectral (wavenumber) domain and the spatial domain is global in the sense that the whole of the wavenumber spectrum is taken into consideration for constructing the value of a variable at any space point. Conversely, values of a variable at all space points are taken into account to construct each coefficient in the spectral expansion. Thus in spectral method, any error generated locally is immediately transmitted throughout the globe while in the grid point method such errors move slowly through adjoining grid points and contaminate values at far off locations only after large number of time steps. On the other hand, in spectral method, amplitudes of local errors are reduced to a large extent as they are distributed over the whole globe.

TABLE 1

Sigma values of model layers

Parameter	Layers 1	2	3	4	5	6	7	8	9	10	11	12
Sigma thickness	.075	.125	.150	.150	.125	.075	.050	.050	.050	.050	.050	.050

As per the model definition of sigma, surface of earth is at sigma = 0.0 and top of the atmosphere at sigma = 1.0.

2. Spectral method

In the spectral method, spatial and temporal dependence of field variables are separated out and each field variable is expressed as a series in products of two functions—one of which depends exclusively on time and the other on space. This method is a special case of the Galerkin procedure which requires that the error introduced in approximating a field variable by a finite series of functions of space be orthogonal to the set of functions themselves. In the spectral method the basis functions are the spherical harmonics which are the solutions of Laplace's equation in spherical coordinates. Because of the approximate spherical shape of the earth, these functions are natural choice for the orthonormal basis functions.

In most of the spectral models in use at present complete spectral expansion is not attempted. Instead the atmosphere is sliced into a finite number of layers in the vertical and each prediction equation is reduced to a set of 2-dimensional equations, one for each layer.

3. Equations of motion

The spectral form of the equations governing the flow of a diabatic baroclinic atmosphere (Eliasen *et al.* 1970; Bourke 1972, 1974; Sela 1982) are used in the model. In the present model vertical coordinate chosen is $\sigma = 1 - (p/p_s)$ and the distribution of model variables are as follows :

(*i*) wind and temperature are at the centre of layers and

(*ii*) geopotential and vertical velocity at the interfaces of layers.

Finite differencing in the vertical is done by the quadratic conserving scheme of Arakawa and Mintz (1974).

It was shown by Robert (1965) that the components u and v of the wind field constitute pseudo-scalar fields over the globe and hence are not suitable for scalar spectral expansion. He suggested that horizontal wind components weighted by cosines of latitude should be used for spectral expansion. Since these pseudo-winds are identically zero at poles, problems of solving prediction equations at poles are also eliminated by their use. However, presence of the weight factor (cosine of latitude) in the pseudo-wind components implies that the truncation of their spectral expansion series must be suitably adjusted (Eliasen *et al.* 1970) to make them compatible with the truncation of other variables. Such adjustments in the truncation of the spectral series are not required if the model equations are formulated in terms of the scalar quantities, vorticity and divergence, as prescribed by Bourke (1972).

4. Model description

The model adopted by India Meteorological Department and used for experimental runs at Delhi is a 40-wave rhomboidal truncation model based on the aviation forecast model used at NMC, Washington and has at present, 12 layers in the vertical. Sigma values of the model layers and interfaces are given in Table 1.

Inputs for the model are spectral coefficients of horizontal wind components and geopotential heights at twelve standard millibaric levels up to 50 mb, relative humidity at six standard millibaric leve's up to 300 mb, surface topography, monthly mean sea surface temperatures and surface drag coefficient.

The forecast module has a nonlinear normal mode initialization (Machenhauer 1977) package which is invoked only once before the time integration is started. It was determined from numerical experimentation that two iteration using four vertical modes are sufficient to produce smooth predicted surface pressure profiles.

The time integration is done by using the semi-implicit (centred) formulation of Robert (1969) with a moderate time filter.

5. Model physics

The following physical processes are included in the model :

(a) orography

(b) surface friction

(c) horizontal diffusion

(d) large scale precipitation

(e) deep convection based on the Kuo (1965) scheme and

(f) latent and sensible heat transport from underlying sea surface.

Most of the physics packages are applied at a point on the surface of earth as spectral formulation of physical processes are yet to be developed. A convenient grid for application of physics packages consists of equally spaced 128 points along a latitude circle and unequally spaced 102 Gaussian latitudes in the N-S direction. Conversion from spectral coefficients to grid values is through the Legendre and the fast Fourier transforms.

In the present model the effect of orography is treated spectrally. The spectral coefficients for orography are obtained by first smoothing the gridded field of mountains and then expanding it in the truncated series of spherical harmonics. Smoothing is done by passing the gridded field through a nine-point filter twice.

TABLE 2

Computer (NEC, S-1000/20-D) resources required for a 5-day forecast

Job step activity	EPU time h m s	Input/output time h m s
	Pressure to sigma	
Compilation	00 : 00: 05.760	00 : 01 : 33.198
Link	00 : 00 : 00.537	00 : 00 : 17.103
Execution	00 : 02 : 26.458	00 : 00 : 21.444
	Forecast 5 days	
Compilation	00 : 00 : 05.661	00 : 01 : 43.194
Link	00 : 00 : 00.531	00 : 00 : 18.422
Execution	23 : 36 : 19.497	00 : 05 : 58.599
	Sigma to pressure	
Compilation	00 : 00 : 05.721	00 : 01 : 34.875
Link	00 : 00 : 00.549	00 : 00 : 16.900
Execution	00 : 02 : 41.900	00 : 00 : 19.655

Time mentioned in the above table is in hour: minute : second accurate up to one-thousandth of a second'

The surface friction is simulated in the model by a bulk formula using a geographically variable drag coefficient suggested by Cressman (1960). The value of drag coefficient resembles the orography and increases from .00129 over sea to .00850 (in MTS units) over the Rocky and the Himalayas.

Horizontal diffusion, representing subgrid scale dissipation, is parameterised by a fourth power of del operator formulation. From numerical experiments it was found that a value of diffusion coefficient equal to 6.0×10^{15} produces sufficiently smooth predicted fields. No horizontal diffusion is applied to the surface pressure field. No vertical diffusion is included in the model.

The forecast of moisture variable and the treatment of precipitation are done in several steps. Initially a forecast of the mixing ratio (moisture variable in the model) is done along with other prognostic variables. These preliminary values of moisture and temperature are passed through the Kuo (1965) scheme of deep convection and large scale precipitation algorithm to allow for convective and stable rainfall processes.

The Kuo-type convection is an adaptation of Phillips (1979) formulation of moist convective processes in his nested grid model. This formulation checks the following conditions as a pre-requisite for convection to occur.

(*i*) moisture convergence in the first four layers (sigma $= 0.0$ to sigma $= 0.5$) exceeds the threshold value of 10^{-4} Pascal/sec,

(*ii*) change in specific humidity of the layer closest to surface in the last time step is positive,

(*iii*) temperature of the layer closest to the surface (sigma thickness $= 0.075$) exceeds 5 degrees Celcius,

(*iv*) relative humidity of the layer closest to surface is greater than 65 per cent and

(*v*) no inversion of temperature exists between the layer closet to the surface and the layer immediately above it.

To save computer time a constant lifting condensation level, located at the middle of the layer closest to the surface, is assumed instead of computing the same for each grid point. The moist adiabatic temperatures and saturated vapour pressure are interpolated from pre-computed tables.

The large scale precipitation formulation compares the forecast value of specific humidity with the saturation specific humidity at the forecast values of pressure and temperature and allows for condensation at relative humidity less than 100 per cent. The reduction factor depends on the layer's elevation. The reduction factor begins with a value equal to 1.0 for the layer at closest to ground and reduces to a value 0.8 for the topmost moisture bearing layer. For the second and third layer (from bottom) this factor is a function of the bottom layer temperature as follows:

$$\text{Reduction factor} = 0.8 \qquad T < -12.5$$

$$= 0.8 - 0.005(0.015T - 0.734T^2 - 11.6) \qquad -12.5 < T < 18.5$$

$$= 0.9 \qquad T > 18.5$$

Re-evaporation of falling rain in the lower unsaturated layers is permitted if the relative humidity in the layer is less than 80 per cent (90 per cent for the topmost moisture bearing layer). At each time step, only a fraction of difference between the actual and the saturation specific humidities is allowed to be met by the evaporation of falling rain. This factor varies from 0.04 for the topmost moisture bearing layers to 0.25 for the layer closest to the surface.

The modified temperature field is now checked for superadiabatic lapse rate. If such a lapse rate is encountered between any two adjoining layers, the temperature field is adjusted by a dry convective adjustment process and the moisture content is re-distributed (Sela 1982) to conform with the re-adjusted temperatures. The prognostication of temperature and moisture fields is complete only after all these ajdustment processes have been taken care of.

In the present version of the model sensible heat transfer is allowed only over water surfaces. The rate of heating of the lowest model layer is parameterised as:

$$dT(l)/dt = (G_D + .00007\ V)\ V\ [\theta s - \theta(l)]/h$$

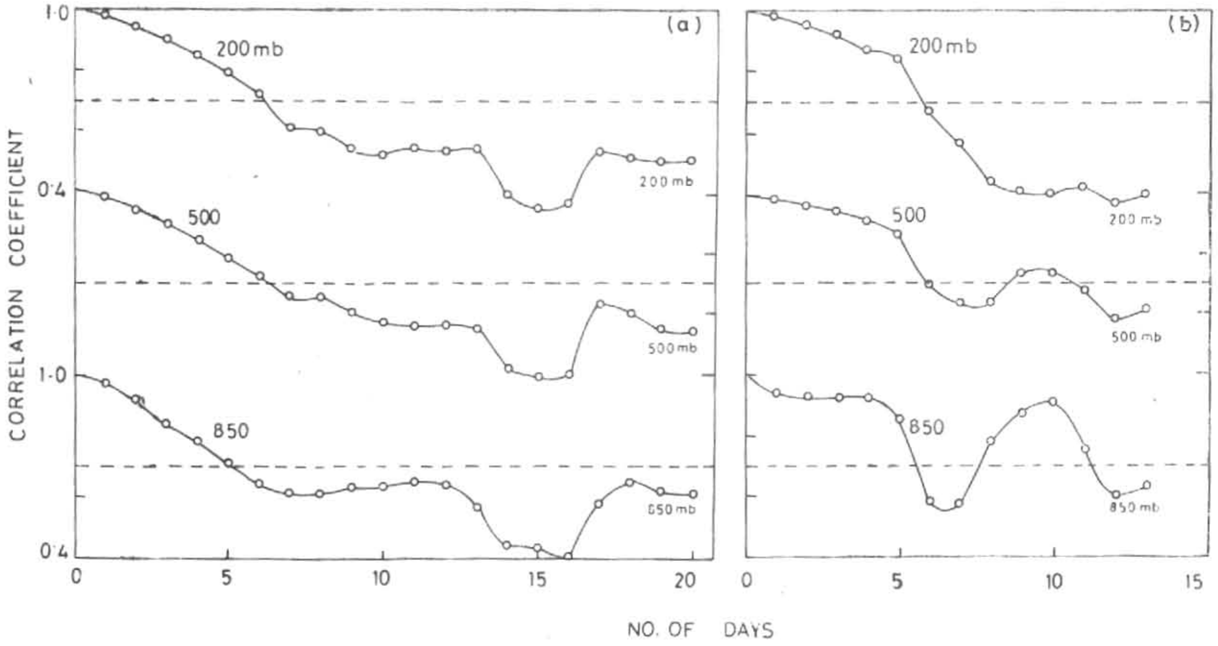

Fig. 1. Correlation coefficient of forecast and analysed geopotential heights for different lengths of forecast

where, $T(l)$ = temperature of the lowest layer
G_D = drag coefficient
V = wind speed in the lowest layer
θs = potential temperature at the surface
$\theta(l)$ = potential temperature of the lowest layer
h = thickness of the lowest layer.

This formulation of sensible heat transfer permits enhanced (by a factor of 2 or more) exchange between air and sea under high wind conditions. The transport of latent heat also follows the above equation except that potential temperatures are now replaced by mixing ratios. The potential temperature and mixing ratio at surface are computed from the mean monthly sea surface temperatures provided to the model as a input.

6. Computer resources

The present version of the model is run at present at the S-1000/20-D (NEC) computer system available at New Delhi. In its present resolution (40 wave rhomboidal, 12 sigma layers and limited physics) the model takes about 1 hour 40 minutes to complete global forecast for a 24-hour period. This estimate of time is much less than the time taken to run the same model earlier (Basu 1987). The reduction in run time has been obtained by reorganising the code so as to make extensive use of the array processor available with the S-1000 system. It may be noted here that the array processor has a restriction on the size (memory requirement) of a subroutine. Detail break up of computer memory and time requirement for different modules are given in Table 2.

7. Data

In the present study data used for verification are the 30-wave coefficients obtained as the output from the Global Data Assimilation System (GDAS) operational at NMC, Washington. This system uses the 6-hourly forecast (after normal mode initialisation) produced by a 40-wave, 18-layer global spectral model, with radiation and elaborate surface physics parameterisation, as the first guess input for optimum interpolation method of data analysis. In data sparse regions the analysis is essentially the same as the first guess. Statistics for data reception at NMC for the month of October 1986 show that on the average upper air data from 16 to 17 Indian stations reach the centre within a period of 12 hours of observation time. Since, the cut-off time for final analysis at NMC is 6 hrs for 00 GMT and 8.5 hrs for 12 GMT, it may be presumed that upper air data from 10 to 14 Indian stations are used for analysis. Out of these, data from some of the stations are rejected as they do not satisfy the quality control checks. Thus, the analysis over India and adjoining sea areas reflect mostly the 18 layer model climate.

Results of verification presented here should be viewed with the following considerations in mind :

(*i*) A 12-layer, 40-wave model of limited physics has been run using the 30-wave coefficients produced by a data assimilation system tuned to produce input for a 18-layer model with detailed physics. This affects the verification results to a significant extent for the first day or two of integration.

(*ii*) The Indian window has, within its domain, the largest plateau and the tallest mountain in the world. For the purpose of verification, forecast values of all variables available at model sigma layers are extrapolated to standard millibaric levels through the topography. Small differences close to the surface are usually amplified by the extrapolation procedure. Since, the 12-layer model has much coarser resolution close to the surface than the 18-layer model used to produce the data set, large difference between forecast and analysis is expected at lower tropospheric levels.

(*iii*) In tropics, persistence is a much better estimate of realised fields than in extratropics.

(*iv*) The analysed fields used for verification are uninitialised. Initialisation leads to large changes in the wind field.

8. Results

An experimental forecast run of the model for a period of 23 days starting with the initial data of 12 GMT of the 15 December 1986 has been completed. The initial fields are 30-wave spectral coefficients of wind and geopotential analysis of NMC (Washington) for 12 GMT of 15 December 1986 which is one of the dates representative of the persistent blocking high over Europe. To run the 40-wave model, remaining coefficients are made zero in the beginning.

Verification of the model forecast against the NMC analysis has been done for the full 23-day period (December 1986 case) following the procedure prescribed by WMO (Manual on GDPS, attachment II.14, pp. 22-23). Results of verification of the surface pressure, geopotential heights and winds at standard millibaric levels, for the global as well as Indian window (45°E-120°E, 15°S-55° N), are presented in Tables 3-6. Correlation coefficients between forecast and analysed height fields are presented in Fig. 1.

In the winter case it is seen that the root mean square error (RMSE) of forecasts for surface pressure is significantly better than that of persistence for a forecast period up to 13 days for the global domain and up to 14 days for the Indian window. The forecasted values of geopotential over the global domain are better than persistence for forecast periods of 12 to 13 days in the lower troposphere, 6 to 8 days in the middle troposphere and 5 days at 100 mb. For the Indian window corresponding values of forecast lengths are less by a day in the middle troposphere and by two days in the upper troposphere.

The RMSE of forecast wind field in winter is better than that of persistence for about 6 days (except at lower troposphere over Indian window) for both the global domain and the Indian window. The difference between forecast and persistence is more significant at upper tropospheric levels than at lower and middle troposphere. At 100 mb, the small value of persistence may be due to lack of observation at that level.

A scrutiny of the correlation coefficients for the global domain as well as the Indian window shows that even for a 5-day forecast these are better than 0.70 which is the accepted value of the lowest limit of correlation coefficient of a forecast with some skill. However, for the Indian window, correlation coefficients fall off sharply theeafter.

The rainfall forecasts produced by the model could not be evaluated by comparison with actual rainfall values as there was practically no rainfall over mainland India during the period of integration.

9. Conclusions

In view of the incompatible data sets used for starting the model integration and for verification, it is not possible to evaluate the model's performance level especially in its present vertical resolution. However, the following conclusions can still be arrived at :

(*i*) During winter RMSE of surface pressure and geopotential of both forecast and persistence are, in general, much smaller for the Indian window than for the globe. RMSE of wind field do not exhibit significant difference between global domain and Indian window. Noting the analysis in Indian area may be reflection of forecast, as the data is sparse, this is expected.

(*ii*) A study of correlation coefficients shows that, for the global domain, forecast geopotential fields are well correlated with the uninitialised analysis up to a forecast period of 5 days in winter. For the Indian window also forecast geopotentials are well correlated with analysis for a period up to 5 days in winter.

(*iii*) The model in its present resolution and in absence of proper physical parameterisation packages may not be suitable for forecasting of rainfall. The model, however, has some skill in prediction of geopotential height and wind specially in the middle and upper troposphere and may be of use for aviation purposes.

For medium range forecasting, it is essential to include radiative processes in the model. For radiative transfer computations, prognostication of surface temperature is also required. The latter, in turn, requires estimates of heat and moisture fluxes from surface and the heat flux from sub-surface layers.

In addition, it is also desirable to include a shallow convection scheme in the model to account for momentum transport in the vertical, especially in the tropics.

The model has already been modified to higher vertical resolution of 18 layers. In one of these 18-layer versions more number of layers have been introduced in the upper troposphere and the stratosphere while the other version has more resolution in the lower and middle tropospheres. At present both these versions are being evaluated *vis-a-vis* the performance of the 12-layer model. A set of

TABLE 3

Result of model verification for 15 December 1986 (pressure and height)

Root mean square error (r. m. s. e.) for surface pressure and geopotential heights at standard millibaric levels. Quantities in bracket are corresponding values for persistence. All values refer to global domain

Pressure (mb)	24 hr	48 hr	72 hr	96 hr	120 hr	144 hr	168 hr	192 hr	216 hr	240 hr
Height (gpm)										
Surface	3.47 (13.5)	5.12 (12.7)	7.00 (12.8)	8.64 (13.2)	9.96 (13.0)	10.76 (12.9)	10.84 (13.0)	11.18 (13.8)	11.07 (14.5)	10.56 (14.4)
1000 mb	28.4 (108.1)	41.9 (101.7)	57.4 (102.5)	70.5 (105.7)	80.5 (104.4)	87.1 (103.3)	87.3 (104.2)	89.8 (109.6)	88.7 (114.8)	85.1 (114.4)
850 mb	24.0 (97.1)	37.6 (93.6)	52.0 (93.3)	62.2 (95.4)	72.1 (95.5)	80.7 (96.0)	85.1 (97.4)	88.4 (102.3)	86.9 (103.4)	85.2 (101.0)
700 mb	23.2 (104.1)	39.7 (104.5)	55.5 (105.5)	66.6 (106.9)	78.3 (108.5)	89.0 (110.7)	97.8 (112.8)	100.7 (115.8)	100.8 (112.9)	100.8 (107.7)
500 mb	27.8 (135.7)	51.3 (139.0)	72.6 (142.7)	89.4 (146.3)	106.2 (149.9)	124.3 (154.0)	141.1 (157.8)	143.4 (158.1)	145.4 (147.6)	150.1 (141.6)
300 mb	38.5 (181.9)	73.1 (186.4)	102.8 (192.5)	128.9 (200.4)	154.8 (206.6)	183.8 (211.3)	209.5 (215.7)	214.1 (212.9)	219.4 (198.6)	225.7 (190.4)
250 mb	39.8 (183.6)	74.2 (188.2)	105.3 (195.3)	131.8 (202.2)	157.9 (208.2)	188.4 (213.2)	217.6 (218.3)	223.5 (214.6)	229.9 (201.0)	235.7 (191.3)
200 mb	40.7 (176.0)	72.5 (179.8)	102.0 (186.9)	126.5 (191.0)	153.4 (196.4)	184.2 (201.8)	215.3 (207.1)	223.3 (203.3)	229.7 (193.4)	233.7 (185.6)
100 mb	53.2 (157.6)	76.1 (160.2)	95.2 (161.0)	115.5 (162.5)	141.5 (166.9)	173.5 (172.9)	202.9 (176.0)	211.9 (172.6)	217.7 (170.6)	219.3 (166.6)

TABLE 3 *(contd)*

pressure (mb)	264 hr	288 hr	312 hr	336 hr	360 hr	384 hr	408 hr	432 hr	456 hr	480 hr
Height (gpm)										
Surface	9.81 (14.0)	10.01 (14.0)	11.78 (14.3)	12.64 (11.2)	11.69 (10.1)	12.51 (10.2)	12.39 (14.5)	11.09 (14.1)	10.68 (13.6)	10.47 (12.8)
1000 mb	78.9 (111.1)	80.8 (111.1)	94.6 (113.6)	100.4 (87.9)	93.82 (80.9)	99.4 (81.2)	98.8 (115.3)	88.3 (111.9)	85.5 (108.4)	83.6 (101.7)
850 mb	78.5 (96.3)	79.8 (95.4)	90.9 (97.7)	91.4 (79.4)	88.7 (76.3)	90.1 (75.0)	88.5 (100.5)	81.5 (99.7)	85.9 (97.1)	88.6 (92.3)
700 mb	97.5 (102.4)	98.8 (100.3)	108.3 (103.9)	106.8 (81.1)	108.5 (82.7)	107.3 (80.5)	103.0 (108.2)	100.7 (108.5)	109.5 (108.8)	114.2 (105.1)
500 mb	149.7 (135.7)	151.7 (133.2)	161.9 (138.9)	163.4 (107.6)	169.0 (112.2)	166.8 (110.6)	162.4 (147.7)	165.1 (147.0)	175.1 (150.1)	180.8 (145.7)
300 mb	227.4 (184.8)	233.7 (181.8)	247.9 (192.0)	253.5 (150.8)	261.0 (157.9)	259.3 (154.9)	257.1 (201.7)	263.9 (199.7)	273.7 (206.5)	280.3 (200.1)
250 mb	238.5 (188.3)	245.5 (185.1)	259.7 (195.1)	265.7 (152.2)	274.1 (160.2)	272.5 (155.3)	272.7 (202.3)	279.9 (201.6)	287.8 (208.7)	293.5 (201.3)
200 mb	237.6 (182.0)	247.5 (179.2)	261.5 (186.5)	267.9 (144.3)	279.0 (153.4)	276.3 (146.2)	279.1 (192.3)	285.3 (190.5)	292.7 (198.6)	297.0 (190.5)
100 mb	223.9 (167.9)	239.0 (166.7)	254.6 (170.7)	259.4 (111.1)	275.3 (119.4)	273.6 (115.4)	277.1 (173.9)	275.6 (169.8)	285.2 (175.6)	294.4 (170.6)

TABLE 4

Model verification for 15 December 1986 (wind)

Vector root mean square error (r. m. s. e.) for winds at standard millibaric levels. Quantities in bracket are corresponding values for persistence. Both values are in metres per second

	24 hr	48 hr	72 hr	96 hr	120 hr	144 hr	168 hr	192 hr	216 hr	240 hr
					Wind (m/s)					
1000 mb	7.11	8.01	9.03	9.46	9.22	9.71	8.42	10.86	10.22	10.73
	(9.11)	(9.75)	(10.53)	(10.47)	(10.61)	(10.88)	(5.78)	(10.54)	(10.17)	(11.68)
850 mb	6.79	7.95	10.51	9.72	9.84	10.42	8.98	11.70	11.49	12.22
	(9.74)	(10.54)	(13.43)	(12.41)	(12.82)	(12.96)	(6.94)	(12.69)	(12.56)	(13.84)
700 mb	7.31	8.38	11.07	10.88	10.39	11.33	9.63	11.69	12.78	14.14
	(10.56)	(11.84)	(14.35)	(13.35)	(13.33)	(14.16)	(8.01)	(13.69)	(14.47)	(15.43)
500 mb	7.75	11.65	12.34	13.33	13.75	15.19	12.59	15.75	16.60	17.60
	(13.84)	(17.09)	(18.31)	(17.19)	(17.80)	(17.65)	(11.30)	(18.53)	(19.02)	(18.59)
300 mb	12.16	17.49	18.59	18.81	19.43	22.01	17.48	21.74	23.74	24.92
	(21.22)	(25.05)	(27.29)	(25.55)	(25.42)	(27.02)	(18.96)	(26.43)	(25.77)	(25.58)
250 mb	11.75	16.16	17.55	18.37	19.12	22.22	17.80	21.86	24.20	25.04
	(19.44)	(23.66)	(25.75)	(24.37)	(25.27)	(27.30)	(19.15)	(25.81)	(24.63)	(25.63)
200 mb	10.30	13.57	14.77	16.73	17.67	19.61	17.18	20.81	22.78	22.47
	(16.60)	(20.81)	(21.97)	(22.26)	(22.26)	(24.74)	(16.57)	(23.79)	(23.83)	(22.15)
100 mb	7.43	10.15	10.79	11.74	13.76	14.57	11.78	16.91	16.69	17.28
	(10.19)	(13.53)	(13.50)	(13.88)	(14.70)	(15.74)	(10.71)	(16.11)	(14.86)	(14.72)

TABLE 4 (*contd*)

	264 hr	288 hr	312 hr	336 hr	360 hr	384 hr	408 hr	432 hr	456 hr	480 hr
					Wind (m/s)					
1000 mb	10.47	10.38	10.73	10.87	10.40	10.36	10.07	10.97	10.54	10.77
	(10.58)	(10.76)	(10.70)	(11.98)	(11.40)	(11.59)	(10.65)	(11.58)	(10.49)	(10.71)
850 mb	11.28	12.08	11.79	11.73	12.03	11.80	11.24	11.83	12.06	12.15
	(12.45)	(13.41)	(13.08)	(13.85)	(13.39)	(13.55)	(12.51)	(12.79)	(12.47)	(11.92)
700 mb	12.34	12.07	12.45	12.44	12.47	13.04	12.05	12.41	13.34	13.43
	(14.01)	(14.43)	(13.98)	(14.46)	(14.00)	(14.43)	(14.14)	(14.26)	(13.66)	(12.36)
500 mb	16.74	15.98	16.77	16.22	15.89	17.20	17.17	15.96	16.56	17.42
	(18.07)	(19.25)	(19.61)	(19.40)	(18.40)	(19.50)	(19.83)	(18.25)	(18.27)	(16.59)
300 mb	24.07	23.78	23.16	23.48	22.58	24.17	23.40	23.87	22.81	24.06
	(24.86)	(27.75)	(28.42)	(26.91)	(27.24)	(28.00)	(26.75)	(26.58)	(25.34)	(25.26)
250 mb	24.75	24.20	23.18	23.41	22.52	24.12	23.02	23.68	22.69	23.72
	(24.77)	(26.68)	(26.91)	(26.44)	(27.26)	(28.04)	(25.16)	(26.54)	(24.55)	(25.04)
200 mb	23.62	22.72	21.93	21.80	21.62	21.89	22.50	21.57	21.40	22.36
	(22.97)	(23.61)	(23.85)	(23.85)	(24.59)	(24.75)	(23.15)	(23.78)	(22.24)	(22.54)
100 mb	17.02	17.15	16.56	16.85	16.82	16.89	16.58	16.39	15.88	15.40
	(15.95)	(15.90)	(16.65)	(17.01)	(16.65)	(15.86)	(16.08)	(16.57)	(15.53)	(14.57)

TABLE 5

Result of model verification for 15 December 1986 (pressure and height)

Root mean square error (r, m.s.e.) for surface pressure and geopotential heights at standard millibaric levels. Quantities in bracket are corresponding values for persistence. Both values refer to Indian window region

Pressure (mb)	24 hr	48 hr	72 hr	96 hr	120 hr	144 hr	168 hr	192 hr	216 hr	240 hr
Height (gpm)										
Surface	3.81 (9.9)	4.27 (11.0)	5.37 (12.0)	4.53 (10.8)	5.58 (9.9)	5.91 (7.8)	6.40 (8.2)	6.72 (10.2)	6.67 (10.8)	5.71 (11.2)
1000 mb	30.2 (76.8)	33.0 (84.5)	40.8 (92.6)	35.9 (83.6)	44.6 (77.6)	47.7 (62.5)	50.2 (64.5)	49.9 (77.7)	48.8 (81.7)	41.7 (84.7)
850 mb	20.7 (59.5)	22.3 (63.0)	25.2 (66.4)	32.1 (63.3)	38.0 (59.9)	47.8 (50.3)	50.5 (54.5)	43.3 (59.6)	32.3 (58.6)	31.5 (58.2)
700 mb	16.9 (59.2)	17.5 (59.0)	25.1 (63.5)	38.6 (62.8)	43.1 (62.5)	54.7 (56.3)	60.9 (63.7)	56.5 (62.4)	45.2 (59.0)	48.9 (57.2)
500 mb	18.9 (89.5)	22.9 (83.6)	36.4 (87.9)	55.1 (91.0)	65.7 (98.2)	75.9 (85.7)	90.9 (94.9)	101.1 (95.6)	89.9 (94.3)	86.5 (87.5)
300 mb	25.0 (137.6)	42.2 (128.9)	66.1 (129.4)	94.0 (131.6)	112.3 (147.3)	124.1 (127.9)	151.4 (141.2)	176.5 (142.5)	175.5 (145.8)	166.9 (142.2)
250 mb	27.7 (147.4)	47.5 (137.4)	74.0 (135.4)	104.0 (134.9)	123.2 (151.5)	138.5 (133.1)	169.7 (146.9)	197.2 (146.3)	202.5 (153.5)	193.2 (152.5)
200 mb	30.3 (150.4)	50.3 (139.7)	77.1 (134.7)	105.9 (129.4)	127.4 (143.1)	149.2 (132.1)	183.7 (143.6)	213.8 (143.3)	222.6 (152.3)	217.3 (154.3)
100 mb	33.9 (112.3)	43.6 (104.8)	66.2 (93.4)	101.8 (83.3)	126.2 (89.4)	153.1 (93.9)	181.8 (95.5)	214.6 (99.9)	224.9 (106.7)	228.9 (117.8)

TABLE 5 (*contd*)

Pressure (mb)	264 hr	288 hr	312 hr	336 hr	360 hr	384 hr	408 hr	432 hr	456 hr	480 hr
Height (gpm)										
Surface	5.84 (10.5)	6.17 (9.6)	4.37 (8.0)	4.73 (7.1)	6.14 (6.3)	7.14 (6.8)	6.90 (8.1)	6.33 (8.4)	5.72 (8.4)	5.22 (7.2)
1000 mb	45.3 (80.8)	49.7 (75.1)	35.6 (63.3)	38.3 (55.4)	49.2 (50.2)	57.2 (53.3)	54.1 (63.0)	50.0 (66.7)	44.6 (66.1)	40.4 (57.2)
850 mb	47.5 (57.1)	60.9 (54.4)	55.7 (50.3)	51.3 (49.8)	52.3 (45.2)	64.9 (49.8)	58.1 (53.3)	51.7 (54.9)	42.2 (51.6)	35.4 (46.5)
700 mb	62.0 (53.5)	78.5 54.5)	74.2 (58.0)	67.9 (42.0)	69.0 (42.9)	85.5 (51.3)	86.8 (64.0)	83.7 (64.3)	68.4 (60.7)	53.8 (57.2)
500 mb	96.4 (85.3)	112.6 (86.9)	109.9 (88.5)	104.5 (45.8)	116.6 (55.0)	137.5 (59.3)	150.6 (104.3)	151.5 (106.5)	128.1 (97.9)	107.9 (96.2)
300 mb	171.6 (144.4)	186.0 (141.5)	181.1 (133.4)	175.7 (65.3)	196.3 (78.7)	230.9 (78.9)	250.5 (159.5)	257.3 (166.5)	229.4 (155.4)	208.1 (152.7)
250 mb	195.2 (154.7)	207.3 (151.4)	203.0 (143.2)	194.9 (67.7)	216.1 (80.3)	252.5 (79.5)	272.1 (168.4)	279.3 (176.3)	252.7 (165.7)	231.6 (159.9)
200 mb	220.8 (156.0)	228.9 (154.5)	221.7 (148.9)	208.4 (63.8)	225.1 (74.9)	256.2 (74.6)	272.4 (163.7)	283.0 (174.3)	260.6 (165.0)	242.0 (156.2)
100 mb	252.4 (133.2)	252.4 (123.7)	228.2 (115.1)	207.2 (60.0)	201.8 (53.8)	203.2 (49.0)	210.8 (110.7)	222.8 (123.4)	207.1 (117.8)	203.5 (110.7)

TABLE 6

Model verification for 15 December 1986 (wind) — Indian Window

Vector root mean square error (r. m. s. e.) for winds at standard milli baric levels are presented. Quantities in bracket are corresponding values for persistence. Both values are in metres per second

	24 hr	48 hr	72 hr	96 hr	120 hr	144 hr	168 hr	192 hr	216 hr	240 hr
Wind (m/s)										
1000 mb	5.99 (5.22)	6.61 (6.82)	7.29 (5.58)	7.13 (5.21)	7.44 (6.10)	8.00 (5.99)	8.42 (5.78)	8.11 (6.11)	7.78 (6.11)	7.45 (5.69)
850 mb	5.97 (5.93)	6.34 (6.82)	6.77 (7.35)	7.24 (6.38)	7.73 (7.17)	8.60 (8.00)	8.98 (6.96)	8.98 (7.61)	8.38 (7.94)	7.94 (6.90)
700 mb	5.32 (6.57)	5.88 (7.89)	6.23 (7.99)	7.16 (7.58)	8.11 (8.60)	9.03 (9.15)	9.63 (8.01)	9.26 (8.70)	8.26 (8.82)	8.93 (8.68)
500 mb	6.03 (9.87)	7.02 (11.02)	7.51 (11.55)	9.29 (12.30)	11.17 (14.57)	12.66 (13.13)	12.59 (11.30)	12.19 (13.31)	9.86 (14.01)	10.08 (13.61)
300 mb	7.98 (15.41)	10.46 (16.66)	10.67 (16.81)	12.12 (18.16)	15.10 (23.76)	17.52 (21.16)	17.48 (18.96)	17.28 (22.17)	15.30 (21.18)	15.46 (21.22)
250 mb	8.84 (15.39)	11.66 (16.61)	12.21 (17.34)	12.16 (18.52)	14.71 (23.94)	17.43 (19.63)	17.80 (19.15)	18.74 (22.26)	16.86 (21.12)	16.12 (20.80)
200 mb	9.11 (12.83)	12.30 (13.79)	12.71 (15.48)	11.95 (16.97)	13.23 (20.46)	16.31 (18.98)	17.18 (16.57)	18.61 (18.67)	16.81 (18.11)	16.41 (18.18)
100 mb	8.08 (7.68)	10.00 (10.12)	8.70 (11.07)	10.02 (10.87)	9.89 (10.91)	10.40 (10.22)	11.78 (10.71)	13.72 (10.98)	13.24 (10.65)	13.69 (13.37)

TABLE 6 (*contd*)

	264 hr	288 hr	312 hr	336 hr	360 hr	384 hr	408 hr	432 hr	456 hr	480 hr
Wind (m/s)										
1000 mb	7.07 (6.26)	7.79 (6.79)	7.48 (6.70)	7.28 (6.30)	7.25 (5.99)	7.84 (5.75)	7.45 (5.25)	7.07 (5.33)	7.14 (5.57)	7.01 (6.14)
850 mb	8.09 (7.42)	8.34 (8.42)	8.31 (8.25)	7.72 (7.92)	7.92 (7.82)	8.62 (7.04)	8.36 (6.32)	6.99 (6.36)	7.18 (6.26)	7.17 (7.49)
700 mb	8.62 (8.57)	8.91 (9.67)	8.76 (9.28)	8.78 (9.42)	8.51 (9.09)	9.50 (8.69)	9.89 (8.21)	7.83 (7.84)	7.46 (7.64)	7.20 (8.49)
500 mb	10.60 (13.51)	11.45 (13.73)	12.13 (13.14)	12.53 (12.78)	13.27 (14.34)	13.86 (13.74)	13.85 (12.46)	11.58 (12.26)	10.82 (11.19)	10.05 (12.26)
300 mb	17.61 (22.38)	19.76 (21.68)	18.50 (20.47)	19.02 (21.80)	21.10 (23.81)	21.30 (22.06)	20.82 (21.20)	17.16 (19.05)	16.25 (17.52)	15.51 (19.10)
250 mb	19.92 (23.24)	22.20 (23.16)	19.38 (20.61)	19.79 (22.31)	22.03 (24.17)	22.28 (22.30)	21.92 (21.07)	17.81 (18.56)	17.03 (18.02)	16.37 (18.55)
200 mb	20.08 (20.38)	22.07 (20.60)	18.98 (18.63)	19.32 (19.25)	20.55 (21.12)	21.57 (20.18)	21.06 (18.00)	17.20 (15.40)	16.81 (15.98)	16.47 (15.03)
100 mb	14.24 (13.58)	14.43 (12.93)	12.03 (11.01)	13.67 (11.60)	13.98 (11.48)	13.54 (10.49)	13.61 (10.68)	12.41 (11.57)	12.84 (12.93)	13.03 (13.03)

packages for computation of surface and sub-surface fluxes, surface temperature and radiative transfer is available at I.M.D. for use with the 18-layer model with finer resolution close to surface. A shallow convection scheme is also available for the same resolution. The next step in the development of the model will be to introduce these physics packages and study their impact on foreacast outputs.

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