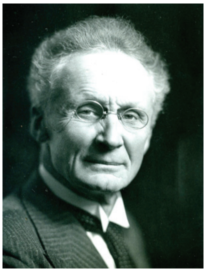
1. Advent of Numerical Weather Prediction

The dawn of numerical weather prediction corresponds with the proposition of the "laws of motion" by Newton (1642-1727), of which the relevant law states that "The rate of change of momentum of a body is equal to the sum of the forces acting on the body". This law is the basis of weather prediction. The scientific achievements in fluid dynamics have been applied to atmosphere such as of Euler's (1707-1783) equations for fluid motion in incompressible, non-viscous flows to represent the changes at specified locations in space and of Claude-Louis Navier (1785-1836) and George Gabriel Stokes (1819-1903) who described the motion in viscous fluid with the addition of a diffusive viscous force term. Cleveland Abbe (1838-1916) was the first to recognise the application of hydrodynamics and thermodynamics to the atmosphere, and to propose a mathematical approach to weather forecasting.



Vilhelm Bjerknes
(1862–1951)

Vilhelm Bjerknes (1862–1951), Norwegian scientist, was the first to postulate the possibilities of weather prediction and identify the need for detailed observations in 3-dimensional space and application of appropriate physical laws. Bjerknes recognised pressure, temperature, density, humidity and three components of velocity as the seven basic variables and the seven independent equations as the three equations of motion, the continuity equation, the equation of state and the equations for the two laws of thermodynamics. Bjerknes, being aware of the unattainable analytical integration, perceived a procedure based on graphical charts representing the initial state and estimating their future evolution.

Exner (1908) came up with a different methodology to calculate the pressure changes resulting from advective process, using mean zonal wind derived from observed temperatures and with the constrained assumptions of geostrophic balance and constant thermal forcing. His calculations of pressure changes were realistic and were recognised as a first attempt at systematic weather forecasting.

Lewis Fry Richardson (1881-1953) was the first to attempt numerical weather forecasting through a direct solution of the equations of motion using finite difference method. Richardson, who had been working on graphical methods and the development of finite difference method for a different application in 1910, considered its application of these methods for weather forecasting in 1911. But he got interested in weather prediction problem only in 1913, when he joined the Meteorological Office in the Southern Uplands of Scotland. He learnt of the weather forecasting problem enunciated by Bjerknes and realising the possibilities of applying finite difference methods for solving the differential equations came up with a precise computational scheme for the Bjerknes prognostic component. Richardson was aware of the complexities and enormity of the numerical computation and impracticality of its immediate application but could foresee its real time weather predictability with future developments in algorithms and computational speed. His dream had come true in 1954 with the first real time NWP experiment at Princeton, USA. Although Richardson started his work on weather prediction in 1913 and initiated his computations to generate pressure changes, the progress was constrained due to his work as an ambulance driver for about 2 years in France during the world war period of 1916-1918.

Richardson used the seven differential equations formulated for atmospheric processes to represent the state of the atmosphere through seven variables: pressure, temperature, density, water content and velocity components eastward, northward and upward as of Bjerknes. Richardson divided the 3-dimensional atmosphere into 60000 cube elements with a resolution of 3^0 in east-west, 200 km in north-south and 5 cells in the vertical covering the globe. The variables were defined at the centre of each cell, the differential equations were approximated in finite difference form, and the rates of change of the variables were then calculated. Richardson calculated the pressure changes in 6-hours over central Europe. Perhaps Richardson might have spent about 1000 hours in about 2 years to produce this forecast. Unfortunately his forecast was registered as a catastrophic failure as his calculations yielded a pressure change of 145 hPa in 6-hours.

Richardson (1922) published a book “Weather Prediction by Numerical Process”, in which he narrated the details of his research. This book was acclaimed by many, and Sir Napier Shaw regarded it as ‘a magnum opus on weather prediction’.
Richardson identified the reasons for the failure of his calculations as related to large, spurious convergence values that resulted from errors in the wind observations, large grid distance, and the interpolation process.

F. J. W. Whipple, perhaps was the first to understand and suggest the reasons for Richardson’s unrealistic forecast as due to the presence of gravity and sound waves, which move faster than meteorological phenomena as solutions of the numerical equations that were used. This argument was later realised to be true and not the reasons related to sparsity of observations. Richardson’s supposition of the large distances between observations as the cause of spurious convergence estimates is not true as the error results from the compensating terms in the convergence equation.

The calculations of Richardson show large disparity in the magnitudes of the pressure gradient and Coriolis force terms, which should have been of equal magnitude and opposite sign. Sir Napier Shaw was fully aware of the atmosphere tending to restore a balance of pressure gradient and wind velocity and the transition takes place in infinitesimal stages implying the changes in the balance also to be infinitesimal which is now known to be geostrophic adjustment. Richardson provided more emphasis on controlling the spurious divergence and neglected the role of ageostrophic wind component.

Max Margules (1904) examined the predictability of pressure changes using the conservation of mass principle and identified that synoptic-scale pressure changes cannot be estimated due to the possibilities of errors srising from compensating terms in the equation of continuity.

Rossby (1898-1957) had made profound influencing contributions to both applied and theoretical meteorology and oceanography. His theoretical results have shown that the large scale and synoptic scale changes in the atmospheric circulation could be predicted by considering readjustments of the horizontal velocity field neglecting the changes in the vertical structure of the atmosphere. His theoretical results have segregated the high-frequency gravity-inertia waves with phase speeds of up to hundreds of metres per second and large divergence and the low frequency motions with phase speeds of the order of ten metres per second and characteristic periods of a few days which are of meteorological significance. Rossby's theoretical work on atmospheric waves had been the basis of the development of atmospheric models for weather prediction. The geostrophic theory enunciates the dominance of rotational mode containing the bulk of energy over divergence in large scale atmospheric flow and the weak interaction between the fast speed and slow moving waves. Rossby and his collaborators carried out the first numerical prediction experiment in 1940s using a "single-layer barotropic atmosphere" which had set the initiative for the development of forecasting theory and techniques through comparisons of calculated and observed atmospheric states.

During 1940s, four significant advancements had helped the formulation of models for weather prediction. These are (i) the pioneering works of Jack Bjerknes, Sutcliffe on the dynamics of development of middle latitude systems; Rossby's description of atmospheric waves; Kuo's work on barotropic instability and Charney's work on baroclinic instability which improved the understanding of the dynamics of pressure systems and waves, (ii) radiosonde observations that improved the initial state, (iii) Courant's work on the stability properties of finite difference schemes and the inference of the Courant, Friedrichs and Lewy stability criterion, and (iv) the development of automatic electronic computing machines that could enhance the computational speed.

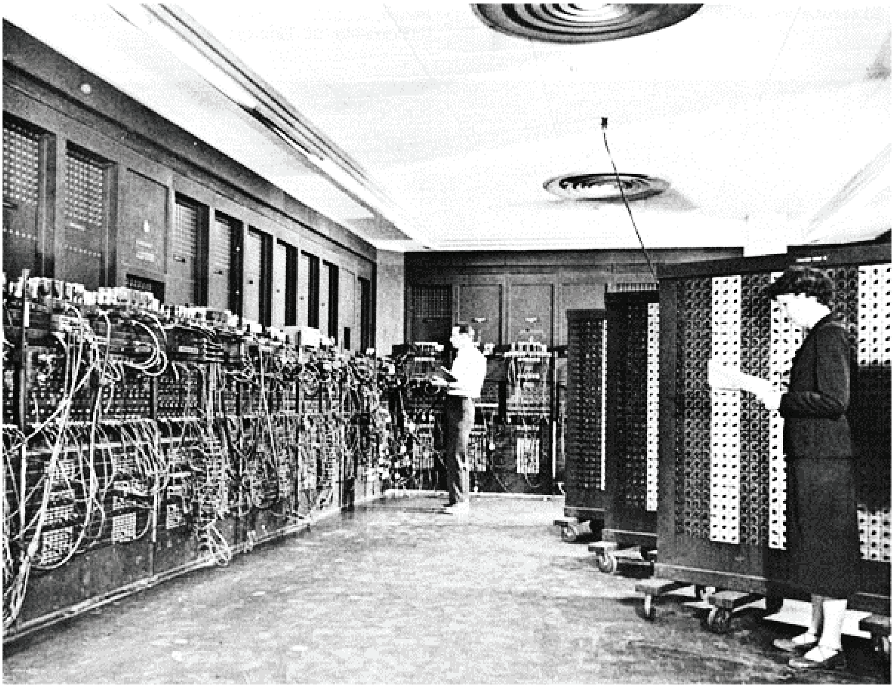
The contributions of Charney towards NWP were phenomenal. Charney postulated the physical basis for numerical prediction of large-scale atmospheric motions, and the filtering of the high frequency waves that would allow numerical prediction up to 2-days. This filtering of meteorologically unimportant sound and gravity waves helped with the choice of larger time step satisfying the CFL stability criterion and had been the basis of a hierarchy of filtered models that were used for NWP in 1950s and 1960s.

Charney (1947) postulated the importance of quasi-geostrophic balance which indicates the forcing mechanisms and dominant modes of hydrodynamic instability and of the manner in which energy is dispersed and dissipated in the atmosphere. Observations show that the bulk of the energy in the troposphere is in rotational modes with advective time scales, and the forcing of gravity waves is weak due to the longer time scale of the external solar forcing than the inertial time scale, implying that the coupling between the rotational and gravity wave components is also weak. This quasi-geostrophic theory has been the basis for success of numerical weather prediction in 1950s.

Charney (1948) published his analysis on the scale of atmospheric motions which lead to the mathematical elimination of gravity waves through geostrophic assumption which lead to postulation of the quasi-geostrophic system. Charney (1949) advocated the use of barotropic vorticity equation with the assumption of constant static stability following Rossby (1939) as the simplest of the hierarchy of the filtered quasi-geostrophic models that would help further development of baroclinic models as needed for the prediction of developing pressure systems (such as cyclones).

Independently, Arnt Eliassen (1949) also developed semi-geostrophic equations with the use of geostrophic assumption in the acceleration equations and was the first to transform the equations of motion to isobaric coordinate system, which had become important in subsequent applications in the numerical modelling of the atmosphere.

Charney, Fjørtoft and von Neumann (1950) made their first numerical forecast using the non-divergent barotropic vorticity equation. This forecast was obtained using the first ever electronic digital computer ENIAC built in 1945 at Maryland, USA. It was a huge machine with 18,000 thermionic valves, massive banks of switches and large plug boards with tangled skeins of connecting wires, filling a large room and consuming some 140 kW (kilo Watt) of power. Program commands were specified by setting the positions of a multitude of 10-pole rotary switches on large arrays called function tables, and input and output was by means of punch-cards. Charney et al used the barotropic vorticity equation transformed to polar stereographic projection, discretised to a grid of 19 × 16 points which corresponded to 8 degrees longitude at 45oN (736 km at the North Pole and 494 km at 20oN), adopted centered spatial finite difference and leapfrog time differencing schemes.



Electronic Digital computer ENIAC

This was the first successful experiment which led to the development and use of different quasi-geostrophic models for weather forecasting in middle latitudes. Since the filtering concept is based on the hydrostatic and geostrophic approximations, the forecasts were constrained as the approximations may not hold good all over the globe, especially that the geostrophic approximation holds good where Coriolis force term had enough magnitude equal to the pressure gradient force.

Prof. Charney (1917-1981)

Model initial conditions were at 500 hPa level and the model integrations were performed for 24-hours keeping the values at the lateral boundaries constant.

Fjørtoft, returned to Norway in 1951 after being a part of the first successful NWP and not having a computer to continue his work on NWP, developed a graphical method (1952) to integrate the barotropic vorticity equation. The computations of vorticity advection and the solution of Helmholtz equation were performed graphically completing a 24-hour forecast within 3-hours. A repetition of the Princeton experiment using ENIAC has shown that the graphical method produced results comparable with those using the ENIAC. Fjørtoft's method had been used by several Air Force weather forecast centres in 1952 and 1953. Although this manual method was in use for a brief period, it is historically important as this was the first effort to use Lagrangian advection method and also as the first successful effort to establish the graphical methods proposed by Vilhelm Bjerknes.

The first computer based 72-hour predictions using real time observations suitable for operational use were made at the International Meteorological Institute at Stockholm University, Sweden in November, 1954 using a Swedish computer "BESK" (Persson, 2005). As the results of trials were encouraging, regular operations have been started in 1956. The Swedish work of operational objective forecasting using barotropic vorticity equation was useful for almost a decade.

The occurrence of a severe storm in November, 1950 over the east coast of the United States, and the incapability of the barotropic model to predict it have brought out the need for development and application of models with barioclinic dynamics. Subsequently several baroclinic models were developed all based on quasi-geostrophic system. The numerical prediction group at Princeton reported good simulation of the November-1950 severe storm using 2- and 3-level models. Thus, the operational use of baroclinic models in operational forecasting had started.

The successes of weather prediction with the baroclinic models lead to the formation of a Joint Numerical Weather Prediction Unit in USA in July, 1954 combining the units of Air Weather

Service, the Naval Weather Service and the Weather Bureau. The unit had George Cressman as Director, Joseph Smagorinsky as head of the operational section, Philip Thompson as head of the development section and Art Bedient as head of the computer section which had started operations in 1955. Here it had transpired that some of the earlier successes with the quasi-geostrophic baroclinic model was only a chance and that the multi-level model consistently fared worse than the barotropic version (Shuman, 1989). Due to this reason, operational forecasting reverted to the use of single-level model from 1958.

Phillips (1990) had presented an interesting analysis that the numerical prediction of Charney et al in 1954 was successful because of the choice of a large geographical area although the grid resolution had to be coarse to satisfy the CFL stability criterion. He commented that had the experiment was confined to a smaller area with finer resolution, it would have been a failure attributing the scientific reason to the spread of errors across the lateral boundaries. In this context, use of multi-level models meant smaller forecast domain that will have increased forecast errors propagating through the lateral boundaries due to the retention of the initial values at the boundaries.

At those contemporary times, the limitations of using multi-level quasi-geostrophic models were noted in Britain and Germany. Phillips (2000) contented that the use of "stream function" in the place of "geopotential" could have improved the predictions, which may have been true to some extent but the limitations on the applicability of geostrophic approximation in the tropics returned the entire procedure back to the use of the original governing equations of the atmosphere as employed by Richardson.

Research with the primitive equations began at NMC (now NCEP) in 1959. Charney, realising the problems with quasi-geostrophic models, initiated use of a linear barotropic primitive equation model containing the CFL stability criterion. Initial work of Charney had shown that the predicted motion field consisted of both the Rossby and gravity wave motion which had helped to explore the feasibility of integrating the primitive equations. The use of a six-level primitive equation model was initiated in June, 1966, running on a CDC-6600 (Shuman and

Hovermale, 1968) which had shown considerable improvement in the forecast skill. Platzman (1967) compared the NMC primitive equation model with that of Richardson and reported more similarities than differences although the NMC model had been independently developed using Eliassen's (1949) formulation of equations in isobaric coordinates.

Karl-Heinz Hinkelmann of Germany had advocated the use of primitive equations citing that the atmospheric dynamics and energetics would be simulated more realistically than the filtered equations. He made the first systematic attempt to generate suitable initial conditions through control of high frequency oscillations by taking up appropriate initialization and argued that the larger computational time due to smaller time step would be offset by simpler algorithms free of the solution of elliptic equations in the quasi-geostrophic models. Hinkelmann's first prediction experiments with the primitive equations had yielded a very good simulation of the evolution of extra-tropical frontal system. This success was the prelude to the initiation of operational numerical forecasting in the Deutscher Wetterdienst in 1966 (Reiser 2000), and this was the first ever use of the primitive equations in an operational environment.

At the beginning, the primitive equation models (Smagorinsky, 1958; Hinkelmann, 1959) were adiabatic, with dry physics. Later an equation for moisture has been introduced into the primitive equation system and its introduction had caused numerical problems with the rapid development of small scale convective systems arising from grid scale conditional instability. To overcome this problem, the concept of "moist convective adjustment" had been imposed that would supress gravitational instabilities. Subsequently this had been the starting point for developing parameterization theories for cumulus scale convection.

In Britain, the concept of using single-level models for weather forecasting was not accepted. Only in 1972, a ten-level primitive equation model (Bushby and Timpson, 1967) incorporating parameterisation of physical processes of heat, moisture and momentum through the bottom boundary, topographic forcing, sub-grid scale convection and lateral diffusion had been started which yielded credible forecasts of precipitation. Although

Britain was initially hesitant, the UK Met Office held a leading position in the development of numerical weather prediction.

Initialization: At the time when the application of atmospheric models had been shifted to the use of primitive equation models, more attention was drawn towards the problem of initialization. When primitive equations are used for numerical prediction, any imbalance between the mass and velocity fields in the initial state would reflect as anomalously large gravity-inertia waves that may persist for a long time yielding to spurious forecasts. It was the presence of such imbalance in the initial fields that gave rise to the totally unrealistic pressure tendency of 145 hPa/6h obtained in Richardson experiment.

Balance in the initial data is achieved by a process noted as initialization, in which the initial fields are presented in such a way that the amplitude of the gravity inertia waves remains small throughout the forecast. If the fields are not initialized the spurious oscillations will occur leading to forecast errors.

The atmospheric balance is subtle, in the sense that minor perturbations may disrupt it but robust that local imbalances tend to be removed through dispersion by gravity-inertia waves leading towards natural adjustment between the mass and wind fields.

Numerical forecast experiments with and without initialization have shown contrasting differences with the absence of spurious oscillations and realistic tendencies in the initialised prediction process. The initialization was achieved through static and dynamic strategies.

Hinkelmann (1959) derived the initial winds using the geostrophic relation, and integrated the primitive equations using a very short time step. Although Hinkelmann's experimental forecasts with the primitive equations and initialization were noted to be far superior to the quasi-geostrophic model integrations, Charney (1955) proposed that the use of nonlinear balance equation may produce a better estimate of the initial wind field, as this equation includes the curvature of the streamlines implying the wind as non-divergent. The difficulty with the solution of the balance equation using the geopotential and stream function fields was the constraint that the data satisfy an ellipticity relation. To overcome this problem, Phillips (1960) suggested that an improvement of balance would result if the vertical velocity field is derived using quasi-geostrophic ω–equation and the equation of continuity. Each of these methods had rendered improvements but the noise problem persisted.

Sasaki (1958) formulated an initialization method based on variational calculus. In this method, both the wind and mass fields were constrained to fit a balance condition while remaining close to the original analysis by a suitable choice of weighting functions, with more weightage for the wind in low latitudes (tropics) and more weightage for the height in high extra-tropical latitudes. Although this variational method of initialization was not widely used, this method is now the basis of modern data assimilation techniques. All the above methods are the static initialization methods.

In the approach of dynamic initialization, a forecast model itself was used to define the initial fields (Miyakoda and Moyer, 1968; Nitta and Hovermale, 1969). The supposition is that the dissipative processes damp out high frequency noise as the forecast evolves. In this process, numerical integration schemes having selective damping of high frequency components can be utilised. In one of the approaches, the model is integrated forward one time-step and then backward to the initial time with the dissipation action completing one cycle and the cycle is repeated enough times till the high frequency components were damped out. The forecast starting from this initialization is noise-free, but had the problem of damping the meteorologically significant motions as well as the gravity waves.

In another approach, the initial fields are segregated into normal mode components, the gravity-inertia waves are filtered retaining the slow moving rotational waves (Dickinson and Williamson, 1972). Although this process of 'linear normal mode initialization' would assure a noise-free forecast, it was noted that the noise reappeared due to nonlinear interaction of the slow waves leading to appearance of gravity waves. So the problem of noise essentially remained. Machenhauer (1977) presented the method of "'nonlinear normal mode initialization" to control the growth of gravity waves, in which the initial rate-of-change of the gravity waves were set to zero and this method remarkably helped, as the model forecasts initialised this way were very smooth and without the appearance of the spurious gravity wave oscillations. Baer (1977) developed a similar method based on more rigorous mathematical reasoning but it was more difficult to use and so the Machenhauer's method was the most popularly used.

However, there were problems to use the normal mode initialization method in the case of limited area models; wherein the normal modes at the lateral boundaries cannot be derived. Daley (1991) provided detailed discussion on the various methods of initialization such as the bounded derivative method, the implicit normal mode method and the Laplace transform method.

A new approach, the method of digital filter initialization (DFI) was introduced by Lynch and Huang (1992). This method uses an optimal filter. The method is similar to that applied in signal processing, in which low-pass, high-pass and bandpass filters are generated and applied. Essentially for the initialization problem in weather prediction, a filter is applied to preserve the low-frequency oscillations from contamination by the high-frequency oscillations. This method is now being used for application in limited area models such as WRF etc.

The development of NWP in different countries was mainly dependent on the availability of computational resources and the knowledge of the atmospheric model developments. For example, the weather changes are linked to large-scale quasi-geostrophic regimes in the middle latitudes, sub-synoptic scale features related to topography and convection dominate the weather in the tropical regions. Thus, the simple models such as barotropic models and quasi-geostrophic models which could be run on the computer systems of 1960s had helped development of NWP in middle latitude regions, where the use of primitive equation models suitable for prediction over tropics requiring computer systems of 1980s was needed and hindered the application of NWP over tropical regions.

While the above methods are related to dynamic initialization, Krishnamurti (1991) proposed a novel method of physical initialization, in which the vertical atmospheric structure is adjusted to the observed rainfall rates through the convection parameterization scheme and the method was found to significantly improve numerical weather prediction in tropics. While there is no doubt that the development of NWP was confined to USA in the first two decades of 1960s and 1970s, other countries soon started application of NWP and contributed to the development of their regions.

Japan: Japanese scientists have made many important contributions to the development of NWP. Prof. Shigekata Syono, a Professor of Meteorology at Tokyo University during 1945-1969, was not only responsible for the progress of NWP but also for mentoring many researchers who have made invaluable contributions in Japan and USA. Syono and his group published their first research on one-dimensional barotropic forecasting in 1950 in the *Journal of the Meteorological Society of Japan* which indicated similarity of their ideas with those of Charney's group in USA. Kanzaburo Gambo, one of Syono's students, worked at the Institute for Advanced Study in Princeton (IAS) with Charney's group for two years during 1952-1954 and got updated with the progress of NWP in USA. Between 1954 and 1960, the Japanese meteorologists performed their numerical calculations using Fjørtoft's graphical methods, desk calculators and a small relay-switching computer (FACOM 100) to produce predictions of precipitation, tropical cyclone movement.

The Japan Meteorological Agency (JMA) started their NWP activities in March 1959, with the acquisition of IBM-704 computer and soon after started giving 48-hour predictions using a hemispheric barotropic model operationally.

The organisation of an international symposium on NWP at Tokyo in 1969 (7-11 November) helped the scientists of USA and Japan with the exchange of ideas and this was the meeting where the need for development of primitive equation models had been recognised and Ed Lorenz presented his results on the divergence of nonlinear computations due to round-off errors.

Some of the students of Syono, due to limited opportunities in Japan at that time, migrated to USA in 1960s and made significant contributions to atmospheric modeling and NWP. To mention a few of them are: Akio Arakawa, Syukuru Manabe, Kiku Miyakoda, Michio Yanai, Yoshi Sasaki, Akira Kasahara, Yoshio Kurihara whose contributions are now well known to meteorologists all over the world.

Germany: Like Japan, Germany also lacked the resources to be at the forefront of European meteorology. The Deutscher Wetterdienst (DWD) (German meteorological service) was in the US-Zone after World War II, where Hermann Flohn was the head of the research division. Karl-Heinz Hinkelmann, of the meteorological service, visited the Swedish Meteorological Institute in 1951 where he worked on barotropic model calculations under the guidance of C G Rossby. Hinkelmann started working on baroclinic models soon after his return. In 1952 DWD was created by West Germany and Hinkelman had started model integrations using graphical methods. By 1954, access to computers had helped produce barotropic model forecasts up to 72-hours using first the Swedish computer BESK, and later an IBM 704 in Paris. Although Hinkelmann viewed the application of hydrostatic primitive equation models for NWP, the same could not be realised till a CDC3400 computer was acquired in November 1965. At DWD, operational barotropic forecasts for 72-hours started in October 1966, and baroclinic forecasts started in 1967 with the arrival of a computer CD 3800. In the former German Democratic Republic, the acquisition of a Soviet computer BESM-6 helped initiate routine NWP in January 1971. Later the GDR meteorological service ran a 4-level with 300 km resolution, to generate numerical forecasts up to 72 hours.

France: France was one of the first few countries whose national meteorological organisation evinced interest in NWP as early as 1952. In 1954, Guy Dady was sent to Stockholm for a few months to work with Rossby's group. After his return, Dady was permitted a few hours access to one of the three computers (available in France at that time), which he used to generate predictions up to 72 hours with a simple barotropic model at a grid resolution of 400 km. Although the Met´eorologie´ Nationale (now Meteo France) acquired its own computer KL901 in November 1960, the progress of NWP in France was slow due to the political turmoil till 1964. Daniel Rousseau, a junior scientist to Dady, was sent to MIT, USA in 1965 where he completed his Master's program and thesis on general circulation model under Prof. Charney's guidance. On 1

December 1967 the Met´eorologie´ Nationale acquired a new computer, CDC 6400, and operational NWP with a single filtered barotropic model was started in 1968. Subsequently in 1970, experiments with balanced and multi-level primitive equation models had been initiated along with operational predictions with a filtered model. Robert Sadourny and Olivier Talagrand, had received training at UCLA in 1965 and started working on data assimilation and global models. The purchase of the CDC6400 in 1970 helped the French scientists to develop primitive equation models. The NWP division, led by Guy Dady and Rousseau developed a 10-level primitive equation model with 36-km grid resolution suitable for small-scale studies, and since 1972 a research version with 180-km grid resolution was run on daily basis to supplement the operational NWP with a filtered model.

Algeria: The Algerian Meteorological Service, with the support from WMO, had acquired a small computer and started NWP activity. Dr. Coiffier with help of Dr. Jean Lepas, France had started a numerical model set up which included Cressman objective analysis and a filtered model.

Belgium: The group of Jacques van Miegham, J. van Isacker and Defriese started work on a barotropic model in 1955 using a computer at Antwerp. Operational NWP forecasts for Western Europe have started in 1962 using a barotropic model at 500-km grid resolution covering the hemisphere. Later a 2-parameter model was used. Belgium was one of the countries that supported the establishment of the ECMWF.

Italy: The Italian Meteorological Service started NWP in 1955, and the first daily forecasts were produced in 1959-60. Sabino Palmieri, who received training in NWP for two years at the Joint Numerical Weather Prediction Unit, Maryland, USA, was the first to introduce and develop a barotropic model in 1960, for the Italian Meteorological Service with the available limited computer time of about 1 hour/day. The model integration area covered half of the hemisphere and required 1-hour computer time for 2-day integration. A Numerical Forecast Centre was established in 1967, and as the Italian Meteorological Service acquired an IBM 360/30 in 1968, a two-level quasi-geostrophic model replaced the barotropic model.

Later the model was upgraded to 4-level quasi-geostrophic model in 1970 as the computer was upgraded to IBM360/40.

Canada: Canada had contributed to the development of atmospheric models. NWP was first initiated in the mid-1950s at the University of Toronto. Dr. Michael Kwizak, of the Canadian Meteorological Service, was the one who initiated NWP in Canada. Andre´ J. Robert joined Dr. Kwizak in 1959 and the two of them developed NWP. Their efforts resulted in starting operational NWP using a non-divergent barotropic model on 1 September 1963. This group had developed a four-level baroclinic model on the 28 × 32 grid, and later enhanced the same to a 51 × 55 grid which was used for NWP. Dr. Robert was responsible for the development of global spectral model in Canada which had been the basis of present day global spectral models.

Australia: Australian meteorologists started NWP as early as 1950s. The meteorology groups at the Melbourne University initiated NWP education and later advancements followed at the Bureau of Meteorology. Dr. Ross Maine of the Melbourne University reported their work on Charney- Eliassen one-dimensional model as early as 1957. Teaching and research in NWP was started at the Department of Meteorology in 1958, and Mr. Jensen made a Master thesis "Numerical forecasting with the barotropic model", in which 24-hour predictions on a 21 x 17 grid with 300-km resolution were reported. Later Jensen and Radok produced their first barotropic predictions in 1960 using the UTECOM computer facility at the University of New South Wales.

The Bureau of Meteorology took up NWP actively since 1963, started their operational forecasts in 1969 using a barotropic model with a 24x36 grid with a resolution of 254 km, and hemispheric forecasts in 1973.

New Zealand: The NWP experiments covering the Southern Hemisphere had been carried out in New Zealand first using the Fjørtoft graphical method, and later using a barotropic model run on an IBM 650. The predictions were of stream function using quasi-geostrophic barotropic model on a 12x18 longitude-latitude grid.

Israel: NWP was started in 1962, giving 72-hour forecasts of 500 hPa using a geostrophic barotropic model run on a Philco 2000.

USSR: USSR started NWP following the Bergen school of thought and reported to have come up with numerical model calculations by Kibel and Blinova in 1960s. The development of NWP was not well followed due to political situation in erstwhile USSR and also that, much of the scientific material was in Russian language. Reports indicate that solution of quasi-geostrophic model using graphical methods was started in 1954, and the operational forecasts using a barotropic model started in 1959. The Hydrometeorological Service of the USSR, in 1962, reported the use of a 3-level quasi-geostrophic model with 26x22 grid points and a resolution of 300 km for 48-hour forecasts, and a primitive equation model on experimental basis twice a week. In Leningrad a 2-level quasi-geostrophic model, and in Novosibirsk a 5-level quasi-geostrophic model were used for NWP.

Czechoslovakia: A small group of scientists under the leadership of S. Brandejs started their research in NWP at the Meteorological Institute of Charles University in Prague as early as 1952. By 1963, the Meteorological Institute of Charles University (headed by S. Brandejs), the research department of the Central Hydrometeorological Institute (headed J. J´ılek), and the department of atmospheric circulation at the Meteorological Laboratory of the Czechoslovak Academy of Sciences (headed by V. V´ıtek) had initiated NWP research work at their laboratories. Initial NWP research on barotropic models was carried out using a Soviet computer, Ural 1. Routine operational forecasts with a barotropic model (domain of 24x20 and 315-km resolution) started in 1966 using a British-made computer LEO 360. In 1966 Michal Bat'ka worked with Professor Brandejs on a model using the omega equation. The scientists struggled through the times of cold war and Soviet occupation periods to move forward in NWP finally establishing them to have a consolidated NWP department in Central Hydrometeorological Institute where the ALADIN model is being run now on a small NEC-SX6 machine.

People's Republic of China: According to the information available, NWP had started in 1954 with the use of a 2-layer model being solved using graphical methods. Barotropic model forecasts for 48-hours period using a computer were initiated in 1960. During early 1960s, research on quasi-gestrophic baroclinic models and later on primitive equation models had been reported.

Finland: NWP had its roots in the Department of Meteorology, University of Helsinki. Dr L. A. Vuorela, was the first to take up NWP in the early 1950s as a visiting scientist in Sweden and the USA. The first NWP effort was put up by Daniel Soderman and Juhani Rinne using a barotropic model (18x20 grid points) on an IBM 1620. Operational NWP forecasts with a 3-level filtered model were started in 1970 at the Finnish Meteorological Institute under the leadership of Dr Eero Holopainen, acting Chief of the Weather Forecasting Section.

Denmark: The progress of NWP in Denmark was in three phases, first in mid-1950s, second during 1960-70 and the third in mid-1980s. During 1950s, Ragnar Fjørtoft at the University of Copenhagen developed the graphical method for solving the barotropic vorticity equation, which was used till the computers became available. Aksel Wiin-Nielsen, Hans S. Buch and Harry van Loon, who worked with Fjørtoft on this project joined other institutions and contributed to NWP. Ole Lang Rasmussen, at the Danish Meteorological Institute, started NWP producing 48-hour forecasts (32x40 grid points at 300-km resolution) with a barotropic model. In 1973, forecasts with a baroclinic model (25x23 grid points, 254 km resolution) were started. The Nordic countries (Denmark, Finland, Iceland, Norway and Sweden) had initiated a coordinated project on NWP in 1984, under the leadership of Bennert Machenhauer, to develop a High Resolution Limited Area Model (HIRLAM). The HIRLAM had largely contributed to the progress of NWP in the NORDIC countries.

Netherlands: NWP started in mid 1960s at the Royal Meteorological Institute of the Netherlands (KNMI) under the leadership of F. H. Schmidt. Operational numerical weather forecasts were issued using a 3-level baroclinic model at a resolution of 375 km.

Norway: The Norwegian Meteorological Institute (DNMI) started their operational NWP forecasts in 1962, releasing two sets of

48-hour predictions, one using a barotropic model applied at the 500 hPa level and the other by a baroclinic model to derive 300-700 hPa thickness. Norway did not join the ECMWF initially but joined later with minimal participation. Three Norwegians, Einar Hoiland Ragnar Fjørtoft and Arnt Eliassen were famous for their significant research contributions but they could not promote progress of NWP in Norway for different reasons. Hoiland dedicated to theoretical hydrodynamics, Fjørtoft restricted to his graphical methodology, and Eliassen despite his association with the first NWP experiment at Princeton confined himself to research (famous contributions of Eliassen–Palm flux and Sawyer–Eliassen theories) at his university leaving NWP to the meteorological organisation.

Spain: Spain evinced interest in NWP around 1960 but could not progress due to paucity of computational resources. In 1965, a NWP group was formed as a part of the National Meteorological Service (NMS) whose collaboration with the Swedish Meteorological and Hydrological Institute helped their progress with NWP. The meteorological service acquired its first computer, IBM 360/340 in 1966-67 and started producing NWP forecasts using a hemispheric barotropic model. The National Meteorological Institute (formerly NMS) developed the Swedish limited area model based on the ECMWF global model in 1984 due to the upgradation with a Fujitsu computer.

Yugoslavia: Operational NWP with a barotropic model was started in 1970 using IBM 360/44, generating 96-hour predictions of 500 hPa geopotential (330 km resolution) covering the areas of Europe, Atlantic and North America. Two research groups at the Federal Meteorological Institute contributed to NWP, one used a two-parameter model and the other a primitive equation model. Mesinger and Janjic had developed the first successful primitive equation model in 1976, which later became popular as the Hydrometeorological Institute and Belgrade University HIBU) model.

Ireland: The Irish Meteorological Service first used the Swedish quasi-geostrophic model running it on an outside computer, but with the acquisition of a DEC20/50 computer in 1979 switched to the Yugoslav five-level primitive equation model.

Indian Scenario: Meteorology in India had started with the setting up of the first observatory at Madras (now Chennai) in 1802 by the East India Company. Meteorological observations were started at different locations gradually over the next decades. The establishment of the India Meteorological Department (IMD) in 1875 was the dawn of meteorology in India. The work at IMD was mostly confined to the establishment of weather observatories till about 1945 (i.e.) the end of World War II, as all efforts were devoted to aviation services. Numerical weather prediction in India was initiated by Dr. P.K. Das. The first ever numerical forecasting experiment was carried by Dr. Das in 1958, wherein he attempted to predict a monsoon depression using a geostrophic barotropic model and solving the Laplacian equation by relaxation method manually as electronic computers were not available at that time in India.

IMD could not keep pace with the scientific developments in atmospheric dynamics and scientific computing outside due to dedication of all IMD services to aviation sector during the two world war periods. Atmospheric research in universities and academic institutions was yet to start in India. Prof. P. K. Das, who had joined the IMD in early 1950s, took the initiative and leadership of NWP in India. The establishment of "Institute for Tropical Meteorology (presently the Indian Institute of Tropical Meteorology) in November 1962, exclusively to promote meteorological research, had helped initiation of research relevant to Indian region which included numerical weather prediction. Prof. P.R. Pisharoty, the founding Director of ITM and also a student of the renowned American Professor J. Bjerkenes, acquired the first electronic computer IBM 1620 for meteorological research. This had helped many of the Indian meteorologists to step into NWP.

Dr. Prasad Kumar Das (1926-2005)

The first research efforts at ITM were on the barotropic and baroclinic instabilities of Indian summer monsoon using quasi-geostrophic models by Dr. S. Daggupaty and Dr. VBRao. Dr. G. C. Asnani, a student of Prof. Pisharoty, started working with quasi-geostrophic barotropic models for weather prediction in 1967. Three of the ITM scientists visited the National Meteorological Centre (NMC) in USA during 1967, who received training in objective analysis, satellite meteorology and NWP. During this period, they had the opportunity to attend special lectures in NWP by Dr. Takahashi Nitta of Japan, who was then a visiting scientist at the NMC, which generated their interest in the NWP. As a part of the visiting program, Sikka was introduced to satellite data inputs to numerical analysis and prediction (SINAP). Dr. Shukla visited Japan Meteo-rological Agency, Tokyo for two months on his return from US where he worked with a two-level primitive equation model under the guidance of Prof. K. Gambo and Dr. T. Nitta, and the results of his study were later presented at the NWP symposium in Tokyo in 1968.

Due to encouragement given to young scientists by Dr. Saha, the then Head of the Forecasting Division since 1967, significant research efforts were made by Asnani on the barotropical model with geopotential as input; Mr. Shukla on the non-divergent barotropic model with stream function as the predicted variable; Mr. Ramanathan on the objective analysis methods and Mr. Dixit on the derivation of geopotential field from winds using the reverse balance equation.

As work on NWP at ITM progressed, the institute's IBM 1620 computer was found inadequate for NWP, ITM scientists were permitted to use the CDC 3600 computer at Tata Institute for Fundamental Research (TIFR) for their NWP work. In 1970, Mr. Shukla and Mr. Sikka reported the first successful integration of the non-divergent barotropic model with winds, the results of which were appreciated by Prof. P. Koteswaram, the then Director General of IMD. Subsequently Dr. Ramanathan started work on the primitive equation (PE) barotropic model and Mr. Sikka on a five-layer quasi-geostrophic model with geopotential derived from winds. By 1974, Dr. Ramanathan was successful in using limited area primitive equation barotropic model for NWP over India, and Mr. H. S. Bedi, a meteorologist at IMD, successfully integrated a global barotropic model. After Shukla's departure for USA in 1971, Mr. S. S. Singh took his place and started working on a multi-level PE model. Mr. Singh was sent to Japan for training in NWP models, and he published results of his joint study with Dr. M. Sugi on the prediction of monsoon depressions in 1980. During the period 1966-1986, several researchers (a few of them: Mr.

S. Rajamani, Dr. S. K. Mishra, Dr. G. C. Asnani, Dr. R. N. Keshvamurthy, Mr. S. T. Awade) made diagnostic and prognostic studies using quasi-geostrophic models and balanced models. Most importantly, all the computer codes were prepared by the concerned researchers themselves which helped the learning and application of numerical modeling for weather prediction.

India Meteorological Department: Dr. P. K. Das's affiliation with the IMD in 1950 marks the beginning of NWP era in India. Ever since, he had contributed enormously for the growth of NWP not only at IMD but also at IITM, IIT-Delhi, Andhra University and various national organisations and academic institutes. Dr. Das, with education and training in meteorology at Imperial College, London and due to his keen interest in atmospheric dynamics, initiated NWP at IMD. His earliest contribution was in 1957 on the numerical prediction of a monsoon depression using a barotropic model. He had to use graphical methods for the solution of the model equations as computers were not available. There was not much progress for a decade due to lack of computer facility. The IMD group headed by Dr. Das started using the available computers in New Delhi at that time, an IBM 1620 computer at the Planning Commission, the ICL 1901 computer at Delhi University and a computer at IIT-Delhi. Using these facilities, the small NWP group of R.K.Datta, B.M. Chabra and B.V.Singh successfully produced numerical predictions with a quasi-geostrophic barotropic model and a multi-level quasi-geostrophic model and made them operational in 1970 and 1975 respectively. IMD acquired their first computer, IBM360/44 in 1973 and the NWP progressed rapidly thereafter. The IMD group streamlined NWP by incorporating suitable methodologies for data acquisition, quality control, objective analysis and model integration. The shift of Dr. Y.Ramanathan and Dr. H.S. Bedi from IITM to IMD and the joining of Dr. M.C. Sinha by 1975 consolidated the NWP group. Simultaneously, improvements on the operational multi-level quasi-geostrophic model, development of a multi-level primitive equation model and generating model diagnostics had consolidated the NWP applications. IMD had provided excellent operational weather prediction support, using multi-level quasi-geostrophic limited area model, during MONEX (Monsoon Experiment) in 1979. Dr. P.K.Das had designed a model and simulated the storm surge associated with a severe tropical cyclone that struck Bangladesh in 1971 which had been the beginning of the modeling of cyclone-induced-storm surges at IIT-Delhi in India.

The NWP efforts at IMD were stimulated due to the Indo-US Science & Technology Initiative (STI) launched in 1985, under which Dr. Bohra visited Florida State University (FSU) to learn about the regional primitive equation model and Dr. Basu had been exposed to NMC's R40L18 global spectral model at the National Meteorological Centre (now NCEP) in USA. Later the FSU regional model was implemented at IMD in 1987. Under the same program, Dr. M.B.Mathur and Mr. Bansal visited NMC in 1987 to work on quasi-Lagrangian model for tropical cyclone prediction and optimum interpolation method for objective analysis respectively.

The European Centre for Medium Range Weather Forecasting (ECMWF), established in 1974 for the development and application of medium-range weather forecasting models in Europe, facilitated participation of researchers from several countries to collaborate in their development efforts. As a part of this, Dr. R. K. Datta worked on "the prediction of monsoon flow over the Indian sub-continent by the ECMWF model" during a visit to the ECMWF in 1985, the results of which were published as a Technical Memorandum (No.113) of ECMWF in 1986. Subsequently Dr. A. Hollingsworth of ECMWF visited IMD in 1986 and collaborated with Dr. Datta and his group at IMD to evaluate the ECMWF model's performance for predicting characteristic weather situations over India. This has provided the IMD scientists an exposure to the global atmospheric models for weather prediction applications.

The India Meteorological Department had made rapid strides in the development of weather predictions on different time and spatial scales to meet national requirements. A High Performance Computing System (HPCS) with peak speed of 14.2 Tera Flops was commissioned in January 2010 to run different models. The HPCS receives all data from manual and automatic devices across the globe, processes it and generates global and regional forecasts. The Global Data Assimilation (GDAS) cycle is used for assimilation of all available observations and run 4 times a day (00, 06, 12 and 18 UTC). IMD had adopted the Global Forecast System (NCEP, USA) at

T382L64 resolution and now runs it in real-time mode for generating 7-day predictions. IMD currently runs several models operationally, the Limited Area Model (LAM), MM5, WRF and Quasi-Lagrangian Model (QLM) models for short range prediction. The MM5 model is run at the horizontal resolution of 45 km; WRF model is run at 9 km resolution both models using boundary conditions from NCMRWF T-254 Global Forecast System (GFS). The QLM model is specifically used for cyclone track prediction over North Indian Ocean. IMD is also making nowcasting, on experimental basis, using "Warning Decision Support System Integrated Information (WDSS-II)", software developed by National Severe Storms Laboratory, USA. With the ingesting of Indian DWR observations, the application software is capable of detecting storm cells and removing anomalous propagation echoes. IMD is currently producing weather parameters for generating agro-meteorological advisories at district level, using model outputs from five different global models – (i) NCMRWF- T254, (ii) ECMWF-T799, (iii) JMA-T859, (iv) UKMO and (v) NCEP GFS T-382 considering them as ensemble members. IMD in cooperation with IITM is predicting the monsoon weather on extended time scales of 7 to 30 days using four variants of CFSv2 coupled model, which are (i) CFSv2 at T382 (~38 km) (ii) CFSv2 at T126 (~100 km) (iii) GFSbc (bias corrected SST from CFSv2) at T382 and (iv) GFSbc at T126. The Multi-model ensemble (MME) out of the above 4 suite of models are run operationally for 32 days once a week (with Wednesday initial conditions) with 4 ensemble members (one control and 3 perturbed) each for CFSv2T382, CFSv2T126, GFSbcT382 and GFSbcT126 and average ensemble forecast anomalies that are computed using the 4 sets of model runs of 4 members will constitute the ensemble prediction.

National Centre for Medium Range Weather Forecasting: In January 1988, Government of India approved the establishment of National Centre for Medium Range Weather Forecasting (NCMRWF) on similar lines of ECMWF due to its success in Europe, with the main objective of providing medium-range (~7 days) weather predictions for preparing agriculture advisories to 127 agro-meteorological field units of India. With this mission, NCMRWF has grown to be a "Centre of Excellence", continuously striving to improve NWP systems through research, development and applications.

Government of India acquired the first super computer, Cray XMP-14 (One processor and four million words memory) vector machine for use by NCMRWF for weather prediction in India, which was formally inaugurated by Mr. Rajiv Gandhi, the then Honorable Prime Minister on March 25, 1989.

Due to the mandate of providing medium range weather predictions, need for use of global atmospheric models had become imminent. Initial rapid development of NCMRWF operations were due to the strong support from Centre for Ocean Land and Atmosphere Interactions (COLA) and National Centers for Environmental Prediction (NCEP). Due to the support from Prof. Shukla and his COLA team, their R40 model had been adopted for experimental forecasting at NCMRWF during 1990-1994. Prof. Kanamitsu, NCEP helped with the installation and use of their T80 model which became operational at NCMRWF in 1993. NCEP's support has been continuous providing access to their advanced analysis assimilation system, ocean wave forecast system, mesoscale ETA Model System and in 2006, NCEP provided their T254L64 model which is used for operational NWP since June 2007.

Support also came from the Australian Bureau of Meteorology, the Japan Meteorological Agency (JMA) and the U.K. Met Office for the medium range forecasting efforts at NCMRWF. Thus, effective support from various organisations and individual scientists helped NCMRWF to rapidly advance from the application of simple limited area models to sophisticated global models at the operational level. Concurrently NCMRWF achieved success in the other important components of starting Agricultural Meteorology Field Units (AMFU), streamlining communications, downscaling the variable information to the desired AMFU level, and preparing advisories involving agricultural scientists.

Due to the importance for data in NWP, procedures have been developed for data quality control and data assimilation towards improvement of initial conditions. At NCMRWF, during the initial periods, it was realised that the mass and momentum fields were not well balanced in the tropics which prompted the development of assimilation strategies such as the use of empirical orthogonal functions (EOFs) and variational methods.

The computing resources at the Centre had also been upgraded at regular intervals, replacing the first Cray XMP-14 with Cray XMP-216, acquiring PARAM-1000 computer from CDAC, Pune and the Cray SVI system. At present, NCMRWF produces 7-day predictions using a global T254L64 model; 8-member ensemble 5-day predictions with a global T80L18 model; and 3-day predictions with limited area models (i.e.) the ARPS, MM5, WRF, ETA models at different horizontal resolutions for high impact weather forecasting. Global and regional data assimilations are made using 3-D Variational (3DVAR) assimilation method.

IIT-Delhi: Efforts on development of atmospheric models and numerical weather prediction were initiated at IIT-Delhi in 1979 through the establishment of the Centre for Atmospheric Science (CAS) with the support of IMD and the Ministry of Education. The Centre used Indo-French and Indo-UK Programs to enhance their atmospheric modeling efforts. The first big effort was the import of French global atmospheric model through collaboration with Prof. Sadourny's group at the Laboratoire de Météorologie Dynamique (LMD), France. Similarly, a storm surge model from collaboration with Prof. B. Johns of the University of Reading, UK and a regional weather prediction model of the US Naval Research Laboratory (NRL) were acquired for research. In later years, mesoscale models such as MM5, ARPS and WRF were extensively used for simulation and prediction of mesoscale atmospheric phenomena over India. Along with, a global T21 model from ECMWF was imported and used for long-range forecasting of Indian monsoon. With several of the research programs related to atmospheric modeling, the CAS of IIT-Delhi had become one of the major research Centres by 1985 and contributed to the progress of NWP in India.

Andhra University: The Department of Meteorology and Oceanography is the first in Asia to have initiated teaching and research in meteorology as early as 1949. Teaching and research in NWP was started in 1977 at this department by Bhaskar Rao. At first, a simple barotropic model was developed for which the computer programs were written locally and run on IBM1130 computer. Many students received education and training in NWP continuously as they contributed to the research through their Master theses. As University Grants Commission (UGC), Government of India started M.Tech.

program in Atmospheric Sciences at Andhra University in 1988 as part of national human resource development which helped extension of NWP education to M.Tech. students. Since 1949, many students received education in NWP at Andhra University, who later joined various national institutions and contributed to NWP in India. Bhaskar Rao received exposure and to atmospheric modeling and NWP, especially related to tropical cyclones, through two visits under INSA-JSPS program. Bhaskar Rao was responsible for developing tropical cyclone models for the North Indian Ocean region. Advancements in NWP continued along with the availability of computer resources. The legacy of education in atmospheric modeling and NWP is continuing and Andhra University is identified as a leading contributor for NWP at the national level.