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Early operational Numerical Weather Prediction outside the USA: an historical introduction: Part II: Twenty countries around the world

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1. Introduction

When computers became available in the 1950s meteorologists were among the first to display a keen interest in their use. They also placed the highest demands on their capacity. The earliest NWP initiatives came both from the universities and from the meteorological institutes, especially when the development of computers allowed operational runs.

The reason why some countries developed useful NWP systems quite early while other countries came on the scene much later is not simply a question of resources and meteorological traditions. In some climatological regions (for example western and northern Europe), a large part of the meteorological variability is linked to large-scale quasi-geostrophic regimes, whereas in other regions (for example, the southern and eastern parts of Europe) the geostrophic coupling is weaker and the importance of sub-synoptic features (mountain effects and organised convection) plays a larger role. Whereas barotropic and quasi-geostrophic models could be successfully run on the computers of the 1960s it needed the computers of the 1980s to apply high-resolution, primitive equation models to the weather that was of interest for these regions.

The historical accounts of early NWP given below are based on a multitude of sources: the incomplete record of contemporary 'NWP Progress Reports' in the SMHI library, NWP conferences in Germany (Deutscher Wetterdienst 1957), Japan (Tokyo 1962, 1969) and in the USSR (Leningrad 1965), some WMO Technical Notes (Bolin et al. 1962; Döös et al. 1965), Hessan Taba's interviews in the *WMO Bulletin* with leading meteorologists, my own correspondence with some participants and passing remarks in scientific papers, and a questionnaire that George W. Platzman distributed to all meteorological centres in 1955 (George Platzman, personal communication 2003).

Before we go to the description of the development in 20 countries, we need to agree on what is meant by 'NWP. Between the conventional weather forecasting practices and the computer based forecasts, there were several semi-objective graphical forecast methods, some of which could be, and often were, converted into computer code. The most popular and widespread was Ragnar Fjørtoft's quasi-Lagrangian graphical method of integrating the barotropic vorticity equation.[1] The method was presented at the NWP symposium in Stockholm in 1952 (Fjørtoft 1952) and was widely used in the 1950s and 1960s by many minor meteorological services, which did not yet have access to computers. When a computer became available, experience with Fjørtoft's method often encouraged development of a proper NWP model. It also paved the way for Lagrangian or quasi-Lagrangian numerical techniques. However, I have chosen not to include those institutes, which, up to 1970, *only* used Fjørtoft's method. The reason is mainly that it deserves its own scientific and historical presentation.

The three articles that make up this historical assessment of NWP outside the USA have benefited from contributions from and discussions with Ray Bates, Radmila Brožkova, Jean Coiffier, Lilian Frappez, Kanzaburo Gambo, Petar Gburčik, Jean-François Geleyn, Sigbiørn Grönås, Eero Holopainen, Zavis Janjić, Jean-Pierre Javelle, Anne-Mette Jørgenssen, Graham Kelly, Per Kållberg, Sir John Mason, Fedor Mesinger, Robert Mureau, Jean Pailleux, Sabino Palmieri, Manuel Palomares, Lars Prahm, Jussi Rinne, Ernesto Rodriguez, Daniel Rousseau, Kazuo Saito, John S. Sawyer, Andrew Staniforth, Daniel Söderman and Aksel Wiin-Nielsen. A warm thanks to the kind and helpful staff at the libraries of several national meteorological institutes.

2. Japan

The history of Japanese NWP is not only about difficulties in a war-torn country, but also about a constant 'brain drain' to foreign institutions, most notably in the USA. The contributions that the Japanese

[1] Fjørtoft (1952) followed an old suggestion by Vilhelm Bjerknes to solve a non-linear equation by graphical methods.

have made to NWP are therefore as much part of the NWP development in the USA as in their own country.

The story starts in 1949 with the (late) arrival at the Geophysical Institute in Tokyo of Jule Charney's 1947 paper on baroclinic disturbances in the westerlies. As Akira Kasahara told John Lewis (1993), Professor Syono rushed into the classroom one day in 1949 with a copy of Charney's article in his hand and excitedly proclaimed: 'Look! This paper has modernised the science of meteorology!' Shigekata Syono had been appointed professor of the meteorological department at Tokyo University in 1945 (a post he held until 1969). The students obviously had to read the Charney paper carefully from beginning to end. Kasahara had the feeling that Syono himself had been thinking of developing a similar theory and now was excited that his long-term wish had been granted. Syono had always emphasised to his students that the research atmosphere in dynamical meteorology in Japan was inferior compared with other countries and so he strongly encouraged his students to make contact with their international colleagues.

2.1. The first NWP group

A NWP group was formed around Syono which included young staff members, scientists, and researchers from the Japanese Meteorological Agency (JMA). The group studied other papers from overseas, among them Charney & Eliassen (1949) on one-dimensional barotropic forecasting. In 1950 Syono and some members in his group published the first in a series of three papers on 'numerical weather prediction' in the *Journal of the Meteorological Society of Japan*. The first was a comparison between Syono's ideas and Charney & Eliassen's, which were rather similar.

In the meantime one of Syono's students, Kanzaburo Gambo, had entered into correspondence with Jule Charney. Gambo had graduated from the University of Tokyo in 1945. In 1947 he was employed as a research associate. The times were hard; researchers were poorly paid and had to find part-time work as teachers in high schools to make ends meet. One of his first papers (Gambo 1951) was a study of downstream development, much inspired by Rossby's Chicago group, in particular by the work of the Chinese student T.-C. Yeh (1949). In 1952 Syono and Gambo published two more papers on NWP in the *Journal of the Meteorological Society of Japan*. Now, they felt they were following much more closely in the steps of Charney and Rossby.

They were indeed; Gambo was invited to spend two years at the Institute for Advanced Study in Princeton (IAS) with Charney's group. He also had contacts with George Platzman at the Chicago University. During the stay he sent letters home to report on the progress of NWP.

2.2. NWP research

When Gambo came back to Japan in 1954 he established a NWP research group in Tokyo. Together with Syono he coordinated a monthly set of lectures that included about 25 researchers who were either graduates or JMA employees. The lectures, which were held in the outskirts of Tokyo, covered a broad spectrum of subjects including dynamical meteorology and numerical weather prediction. From the mid-1950s there were a number of seminal contributions from the members of the NWP group, for example the first paper on barotropic typhoon track forecasting by Sasaki and Miyakoda (see also Staff Members 1955a, 1955b and 1960).

The ability of Japanese meteorologists to make important contributions to NWP at this stage is the more remarkable since they had limited financial support from the federal government (except for the stipend to Gambo). As a matter of fact, their greatest sponsor was one of the largest newspaper companies in Japan, the Asahi Press. In May 1954 it provided a lump sum gift of US$ 2,800, which significantly enhanced the group's activities.

Between 1954 and 1960 the Japanese meteorologists performed their numerical calculations using Fjørtoft's graphical methods, desk calculators and the FACOM 100, an electromechanical relay-switching computer that was built by the Fuji Tsu Shin Ki Company (what we today know as Fujitsu). They carried out prediction experiments of a wide range of problems, including predictions of precipitation, motion of tropical cyclones as well as extended forecasts.

2.3. JMA joins the NWP work

It was not because of lack of interest that the JMA had not been actively involved in NWP. In 1950 its Director General, Kiyoo Wadati, had visited Canada and the USA. He had been much impressed by what he saw: weather radar, automated observations and NWP. In the mid-1950s the time was ripe for Wadati to start to put in requests for money to install their own electronic computer.

But it was not until April 1959 that the JMA succeeded in obtaining an IBM704 (memory 8KW).[2] With this the time was right to create a formal NWP section at JMA within the Electronic Computation Centre (ECC). Gambo and others joined from the University of Tokyo.

[2] According to what Wadati told Taba (1985a) NWP was introduced in Japan in March 1959. According to Staff Members (1960) the IBM computer was acquired in April 1959 and regular barotropic forecasts started in June (Bushby 1986) or July 1959 (Bolin et al. 1962). Bushby presented his information, which he had got from Japanese colleagues, during a conference in Tokyo and published it in the *Journal of the Meteorological Society of Japan*.

The plan was to make NWP operational and by the summer of 1959 they had a hemispheric barotropic model running forecasts to +48 hours. The model was very similar to the one used by NMC with a grid length of 381 km. The reception by the forecasters was mixed: 'At that time, some forecasters understood our efforts well, while others did not accept our efforts'(K. Gambo, personal communication 1995).

As with their US colleagues their model experienced serious problems with rapid retrogressive motion of the planetary waves. It was solved by introducing the so-called 'Cressman term.[3]

2.4. The lateral boundary conditions

In my correspondence with Professor Gambo I asked specifically about problems with constant boundary conditions. He assured me emphatically that there had been few problems:

> In case of NWP over Japan, the westerlies are not at their maximum over Japan due to the Himalayas. As is well known, the maximum speed of the jet stream is found over the middle of the Pacific Ocean, not over Japan, which is situated on the western side of the Pacific Ocean. In this sense, the problem of the western boundary in relation to the energy dispersion was not serious for short-range forecasts (2–3 days).

There were actually more problems with non-adiabatic effects due to sensible heat fluxes from the warm water in the Pacific Ocean. Experiences from the eastern side of an ocean (e.g. Europe) are not necessarily applicable to regions on the western side of an ocean (e.g. Japan and China).

2.5. The 1960 Tokyo NWP Symposium

Professor Syono, worked passionately to organise a large international NWP symposium to be held in Tokyo 7–11 November 1960 in order to show the world what was being accomplished in Japan and to benefit from work in other countries. It was a great success and became a milestone for the advancement of numerical weather prediction. It was here that the development of primitive equation (PE) models was definitely put on the agenda, it was also here that Edward Lorenz presented his first experiences of diverging non-linear computations due to small round-off errors. 'Looking back, it is fair to say that the meeting was one of the epoch-making events in the history of NWP' (A. Kasahara in Lewis 1993). The 1960 symposium (Tokyo 1962) was followed in autumn 1968 by a second symposium on NWP (Tokyo 1969).

In 1961 the ECC team had developed a baroclinic model, first with three, later with four levels. It was, according to Gambo (1995, personal communication), run 'informally' and not operationally. In January 1965 the JMA acquired a new computer (HITAC 502F/5020) which became operational in February 1967 after which the baroclinic models became operational in 1970 (Bushby 1986).

3. Germany

Like Japan, meteorologists in war-torn Germany lacked the resources to bring the country back to the position it had traditionally held at the forefront of European meteorology. But, like the Japanese, what they lacked in finanacial and technical resources, they compensated for by their enthusiasm and the use of their human resources in heroic efforts (see Reiser 2001 for a detailed account of early German NWP).

In 1949 the main German meteorological service was in the US-Zone in Bad Kissingen. The research department was lead by Hermann Flohn (Taba 1983). One of his co-workers was a young, gifted meteorologist, Karl-Heinz Hinkelmann (Taba 1985c; Flohn 1973). He had become interested in the problem of 'noise' in the equations of motion. At a symposium in Germany in 1951 he met Rossby, who invited him to Stockholm. There he took part in the tendency calculations for the barotropic model. When Hinkelmann returned from Stockholm he wanted to proceed to make baroclinic models.

In 1952 Deutscher Wetterdienst (DWD) was created by a merger of all the weather services in West Germany. The fact that there was no computer available did not deter Hinkelmann. If it was possible to manually integrate the barotropic model in one time step of 12 hours, perhaps the same could be done with a baroclinic model.

3.1. The manual calculations

The baroclinic model which Hinkelmann first defined had levels at 850, 500 and 225 hPa with 34 × 25 (737) grid points 300 km apart. To perform the calculations he set up a group of two meteorological students and two female clerks. They were all crammed into a narrow room in an old hotel full of cigarette smoke and dust.

The forecast office at DWD manually prepared the initial analyses. The group then spent several days evaluating the vorticity and the Jacobians by graphical methods. The grid point values then had to be

[3] This term is often called 'artificial', but has a solid physical-hydrodynamical basis. By allowing the upper surface to become an *internal* surface it could increase its motion so that some of the energy that previously went into moving the ultra-long waves westward was now deflected upwards (Cressman 1958). George Cressman focused on making all the terms in the models relate to something happening physcially. His colleague Paul Wolff is said to have been the 'if it works, use it' school of NWP modeling: 'Hey, if you add 1.0 and it works, then go for it!' (K. Harper, personal communication 2004).

interpolated, read out and written very small on a huge sheet of paper covering the blackboard. The main step of the work was the solution of the three-dimensional elliptic equations for the tendency by relaxation. One female clerk read out the figures of the difference operator to the other, who sat at a very heavy noisy, slow mechanical calculator. She called the results back to her colleague.

So it went on from grid point to grid point, from row to row. After some hours, the women changed places. After a couple of days they had done one iteration for the whole field, and after several weeks they got figures which they assumed to be the solution to the elliptic equation. The tendency was converted back to a map and graphically added to the initial field, giving them a 12-hour forecast. The entire procedure was then repeated to give a 24-h prediction. The result of some months of work did not look "totally unreasonable" (Taba, 1985c p. 277).

By now (around 1954) access to computers was becoming more feasible. According to DWD's answer to Platzman's 1955 questionnaire they ran barotropic forecasts up to +72 h on and a limited number of baroclinic forecasts with 850, 700, 500 and 300 hPa on the Swedish computer BESK. Later they seem to have used an IBM704 in Paris.

3.2. A new direction for NWP?

The period 1956–60 was, according to several accounts, the critical years of NWP world-wide. The baroclinic quasi-geostrophic models did not perform as well as expected, the barotropic models had large scale errors due to retrogression of the planetary waves and, finally, there were alternative propositions that numerical weather forecasting could be run rather along statistical than dynamical lines.[4]

It was now that Hinkelmann pointed out a new direction, namely to develop hydrostatic primitive equation models. At first his idea flew in the face of the opinions of many experts, even that of Rossby (Wippermann 1988). Flohn later remembered (Taba, 1983, p. 194) a late-night discussion with Rossby in 1956 in a railway station, where Rossby was finally won over.[5] Meanwhile the rapid progress in computer technology made the integration of more ambitious prognostic systems technically and economically feasible (Wippermann 1958).

The years 1957–60 were frustrating because the DWD refused to buy a computer. They regarded Hinkelmann as an unrealistic romantic, something that made him rather bitter and he decided to leave DWD as soon as an opportunity offered itself (Flohn 1973).

3.3. Operational NWP

However, in the 1960s the tide slowly began to turn. In 1965 Hinkelmann became Head of Research at DWD. Its president, George Bell, was becoming less hesitant about purchasing a computer. It seems to have been the persuasive powers of Erich Süssenberger and Ernest Lingelbach (meteorologists at the Ministry of Transport) which brought about this change. In November 1965 a CDC3400 was delivered to the DWD and in October 1966, operational NWP started with +72 h barotropic forecasts and three-dimensional atmospheric analyses at a resolution of 381 km. In the summer of 1967 a new CD 3800 arrived and in October baroclinic forecasts started over an octagonal area with 1940 grid points, which were increased to 2080.

The following year, 1968, the opportunity Karl-Heinz Hinkelmann had been awaiting offered itself and he accepted a professorship at the University of Mainz.

3.4. Developments in the former German Democratic Republic (GDR)

According to Wolfgang Böhme (Taba 1998), in the late 1950s the group of younger scientists to which Böhme belonged wished to introduce new objective procedures on the basis of theoretical meteorology and the use of computers.

At that time they had no computer, only some manual or electrically powered table calculators and machines for punch tapes. The first computer, of medium efficiency, was developed and produced by the Carl Zeiss Enterprise in Jena. As of 1961 they could, in principle, use this machine but there were too many demands by other customers who had priority. It was only available at night or over weekends. Two years later, they were able to use machines of a similar nature at other sites, such as the astronomical observatory in Babelsberg.

Finally, in 1969, with strong support from the Russian scientist Academician E.K. Fedorov, the authorities gave them the Soviet machine BESM-6. A new building for the computer was constructed and staff training followed. As a preparation for the new developments a three-day seminar was held at the Baltic Sea resort

[4] The American mathematician Norbert Wiener suggested that statistical schemes were able to replicate non-linear time evolutions. It was with the purpose to look into this that Edward Lorenz in 1958–9 was running his rather abstract non-linear mathematical models to see if their variations could be reproduced by statistical methods. It was during such a calculation that the famous coffee break occurred after which he discovered 'chaos'.

[5] Rossby, as many others, were sceptical about the primitive equation approach because, as they felt, there was nothing to be taught about the real atmosphere. As Edward Lorenz would later phrase it: it is through *non-perfect models* that we learn how the real atmosphere works.

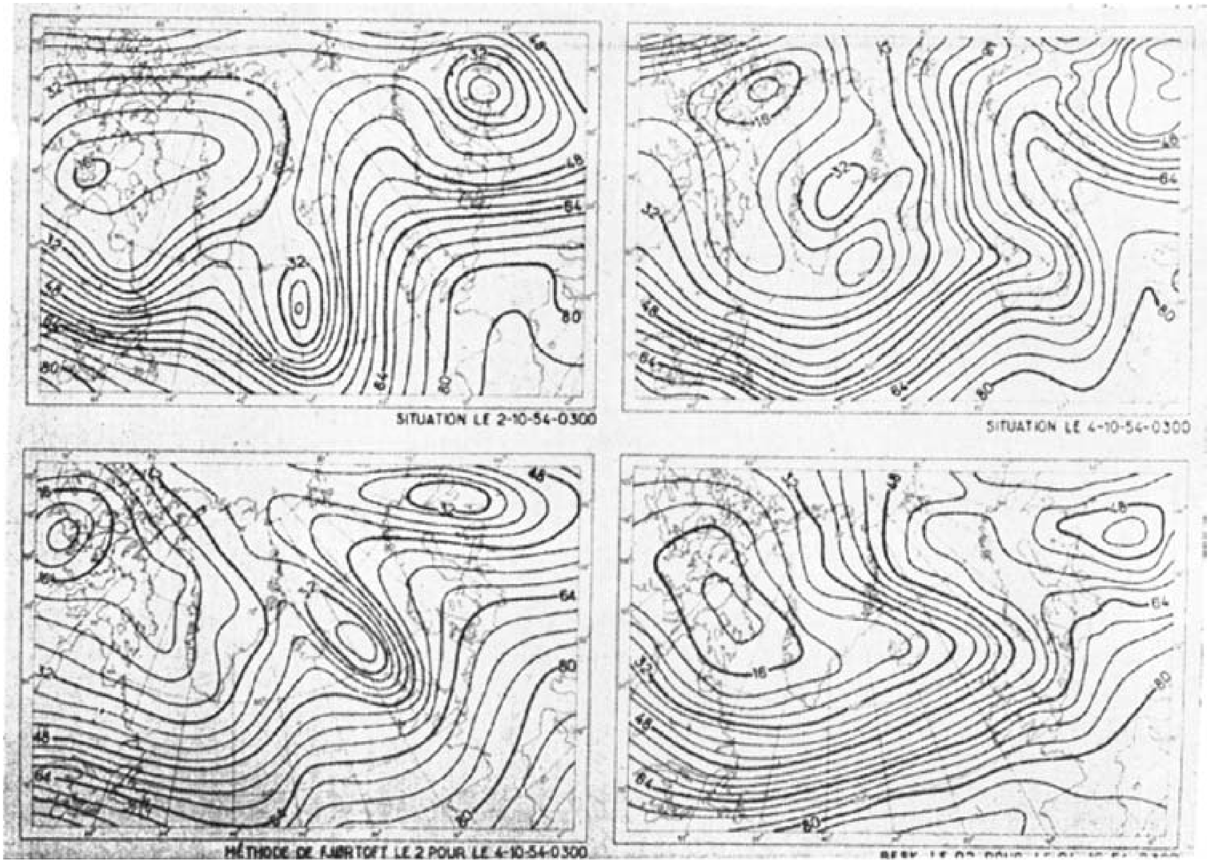

Figure 1. *A contemporary comparison between two +24-hour barotropic forecasts, one made according to Fjørtoft's graphical method (lower left), another according to a BESK integration of the barotropic vorticity equation (lower right). The initial analysis, 2 October 1954 03 UTC, is on the upper left, the verifying analysis, 3 October 1954, is on the upper right. Until 1957 the radio soundings were launched at 03 and 15 UTC (Dady 1955).*

of Kühlungsborn, 2–4 October 1969.[6] Most of the participants were from the Communist states, with the exception of Helmut Flohn from Bonn University, Bo Döös from MISU and Olof Lönnqvist from SMHI.

BESM-6 was a relatively fast computer and routine NWP started in January 1971. Three years later the DDR meteorological service ran a model (outlined by Hinkelmann a few years earlier) using an analysis scheme presented by Gandin at the same time (see Leningrad 1969 for these contributions). The model consisted of four levels (850, 700, 500 and 300 hPa) with 300 km resolution. The model was run twice a day up to 72 hours. The output was used for a very elaborate statistical interpretation scheme providing extreme temperatures, precipitation, the duration of sunshine and surface winds up to 45 hours (WMO Progress Report for 1974).

4. France

One of the first national meteorological institutes to show an active interest in NWP was Météorologie Nationale (Météo France). But it was not until the early 1970s that it started to make itself known in the field. The history behind the 'Big Bang' in French dynamic meteorology is worth telling in some detail (see Comptes Rendus 1954–72 for annual reports).

4.1. The pioneers

At the beginning of the 1950s Jean Bessemoulin, head of the Forecasting Division at Météorologie Nationale, discussed NWP with his deputy, Robert Pône. Pône was keen to start such activity and in October 1952 he attended the NWP conference in Stockholm, where he remained until Christmas.

In autumn 1954 Météorologie National sent their leading theoretician, Guy Dady, to Stockholm for a few months. This was the time of the first operational NWP and the Dady (1955) article in 'La Météorologie' is one of the few 'eye witness accounts' with unique illustrations. Later Dady (1991) remembered:

> At the end of 1954, during one season, I had the privilege almost daily, to have lunch with Rossby, and at those occasions to talk with him.[7] He was improving his

[6] See the 1971 edition of Zeitschrift für Meteorologie, Band 22, Heft 1–5 for the presentations.

[7] At this time the dominating news from the US was that the Senate voted to condemn Joseph McCarthy and his anti-Communist

> French and being the only person of this nationality at the institute, I was quite happy to give him this favour. Rossby was a man of great simplicity, which also manifested itself both in his behaviour and his scientific logic. He thought that the problems [in meteorology] only appeared complicated to us, just because we had not tackled them in the right way.

Concerning the problem of synoptic or planetary forecasting Rossby said that we should not be scared by the apparent complexity of the atmosphere as seen by us humans on the Earth, but adopt a "Sirius perspective".

For Rossby the atmosphere was two-dimensional and the 500 hPa level could be used to represent it. With this approximation the forecast problem was simply one of 'advection and integration of Poisson's equation'. But Dady realised that Rossby saw deeper: 'But this prediction prototype is poorly understood ... it is generally interpreted as a forecast of the 500 hPa, which it is not.' Dady also remembered Rossby's irritation when he learned that the British meteorologist Reginald C. Sutcliffe tried to treat the atmosphere as a two-layer model.

4.2. First computer calculations

Before Dady went to Stockholm he had experimented with a kinematic numerical prediction method designed in 1929 by A. Giao based on extrapolation of isobaric and isallobaric fields.

In 1954, there were only three computers in France. The following year Dady was allowed 'some hours per week' (during lunchtime!) to use one of them, at the Direction des Études et Fabrications d'Armement. According to Dady the resistance towards NWP at that time did not come from the forecasters, as one might surmise, but from Dady's colleagues at the research department EERM (l'Établissement d'Études et de Recherche Météorologiques). Dady therefore joined forces with Robert Pône on the operational side at SMMA (Service Prévisions de la Météorologie Nationale).

In 1955 Guy Dady, Robert Pône and Jean Andreoletti got access to a French machine CAB2022 (Calculatrice Binaire Arithmétique), built in 1954.[8] It had innumerable bugs and breakdowns, but allowed them to im plement a simple barotropic model +24, +48 and +72 hours ahead. The area contained 1024 (32 × 32) grid points with a grid length 400 km.

At this time Dady (1957) argued strongly that the Météorologie Nationale should acquire its own computer: 'France is about two years behind the USA, UK, Sweden and USSR.' In fact, Météorologie Nationale had already made a decision to acquire a computer in 1956. The necessary money had been granted in October 1957. Still, it was not until October 1960 that the KL901 computer was installed and inaugurated on 18 November 1960. Societé Nouvelle d'Electronique Radio Industrie (SNERI) (Dady and Pône 1958; Pône 1993) built the machine especially for Météorologie Nationale.

4.3. 'A brain within a brain'

A year before this happy event the French Meteorological Society in November 1959 organised a full-day symposium in conjunction with the French Society of Hydrotechnique. The theme was 'The mechanics of fluids and meteorology'. Among the speakers were Guy Dady and Robert Pône. Dady spoke about the 'Special character of the mechanics of meteorological fluids' and Pône about 'Perspectives of numerical prediction of precipitation'. The chairman, Joannès Thomas, acting for the Director André Viaut, who was away, presented Dady as 'the meteorologist who is most envied by his colleagues' because of the imminent arrival of a computer:

> Indeed, if one is committed to play with the characterisation, I would say that Monsieur Dady is in fact 'a brain within a brain', because we await, this year, at the Meteorological Service, the installation of an electronic machine, that will be used to forecast the weather.

The talks by Dady and Pône seemed to have been well received and were followed by long discussions. One participant asked Dady if the same equations were used abroad, and Pône fielded questions about the possibilities of forecasting rain.

Since the KL901 was a prototype computer the work in NWP was mainly experimental. The computer was used, apart from running the barotropic model, for automatic plotting, chart drawing, and analysis.[9] At that time Fjørtoft's method seems to have offered operational possibilities with tendency correlations of 80% for +24 h, 74% for +48 h forecasts (Lepas 1963). The forecasts were run with 1024 grid points and 400 km grid lengths.

4.4. The NWP development stagnates

In the decade 1952–62 France experienced ten years of great difficulties: a painful retreat from Indochina,

campaign. Dady got the impression from Rossby that by returning to Sweden he had also wanted to escape the US political environment.

[8] The first French computer CUBA (Calculatrice Universelle Binaire Arithmetique) from 1952 did not function operationally.

[9] The annual report to the French National Committee on Geodesy and Geophysics in 1959 suggests that Météorologie Nationale was trying to run the barotropic model hemispherically. If this were true, Dady and Pône would have encountered the common problem of retrogression of ultra-long planetary waves.

a change from the 4th Republic with its constant governmental crises to the 5th Republic under de Gaulle, with right-wing terrorism and insurrection after the traumatic war in Algeria. The development of NWP at this point seemed to grind to a halt – but Dady kept the flame alive. He was teaching dynamic meteorology at the École Nationale Météorologique (ENM) for the coming generation. At a conference organised by the French Meteorological Society in November 1962 Dady made a strong case for the use of dynamic meteorology in daily meteorological forecasting, although it contained 'certain weaknesses' in its 'logical comprehension and experimental verification'. He presented to the audience his ideas on filtering the equations, models, influence functions and spectral techniques (Dady 1962). At this time he worked on an approach where the atmosphere was represented by spectral functions in the horizontal and empirical orthogonal functions (EOF) in the vertical. He had on this topic relation with Van Isacker in Belgium (see 6. below).

In 1964 the political turmoil was left behind and one might have expected the development of NWP to take a more optimistic turn. But at a WMO meeting in 1964 Director Viaut said that with respect to NWP 'progress was deliberately slow' in France. To find the cause of this caution we must go even further back in history – in fact the cause of the stagnation in the early 1960s actually dates back to the period at the end of the Second World War!

In the aftermath of the liberation in 1944–5 the staff of Météorologie Nationale was made up of completely new personnel. A number of young scientists joined in the period from 1945 to 1951, but in those days, they had to spend their first years doing national service in Africa. So they knew more about tropical meteorology than NWP. After 1952 there were no retirements, and consequently no recruitment!

Only in the mid-1960s did civil servants again begin to retire and make room for young scientists. The first one to enter was a man who was to become the leader of the modern generation of French dynamical meteorologists: Daniel Rousseau.

4.5. The father of modern French NWP

When Daniel Rousseau joined Météorologie Nationale in 1963 he was in fact the first young scientist to join after a very long period. No wonder he was warmly welcomed by Dady, Lepas, Pône and others. Rousseau says he was very fortunate to have Guy Dady as his teacher in 'Météorologie Dynamique et Prévision Numérique' at the 'Ecole Nationale de la Météorologie' (ENM). It was thanks to Dady's support that Rousseau would spend a year abroad.

At this time Météorologie Nationale had taken a strategic decision of decisive importance. Instead of challenging the Anglo-Saxon dominance in meteorology by (for example) rallying French meteorology around *La Météorologie* as a French-speaking alternative to *Quarterly Journal* or the *Journal of Meteorology*, it was wisely decided to send out staff in all directions in the world, in particular to the United States.

In 1965 Rousseau was sent to spend a year at the Massachusetts Institute of Technology (MIT). Although the theoretical teaching in dynamical meteorology was very good in France (works by Rossby, Charney, Kibel, Gandin, Lorenz were very familiar), numerical analysis was largely neglected. He therefore learned more at MIT in the mathematics department (Prof. Gilbert Strang) and in the NWP lectures in the meteorology department (Roger T. Williams who replaced Norman A. Philips in 1965–6) than in France. He attended Jule Charney's course on 'Planetary fluid dynamics'. Charney was his adviser for a Master's thesis, a work on the interpretation of the first days of Mintz' general circulation model.

4.6. Operational upgradings

In the same year, 1965, Jean Lepas and Jean Labrousse went to the USA to study at the Weather Bureau there, mainly in relation to NWP, and to get information on computer manufacturers. On their initiative a special section, CETI (Centre de Traitement de l'Information) was created within Météorologie Nationale, which was dedicated to the development of automatic data processing. CETI was in the operational department but served as a support both for operations and research. Operational forecasts were produced in real time, using a barotropic model with quite good results. But, according to Jean Bessemoulin, the French forecasters were not accustomed to interpreting 500 hPa patterns and did not know what to infer from them (Taba 1982).

The research at Météorologie Nationale was mainly operational, while the university research was analytical and theoretical (Paul Queney). Paradoxically the initiative for a NWP computer came from the operations department. Later in 1965 the acquisition of a commercial computer came with strong support from the research institutions (which gave scholarships to send people abroad and helped to finance the computer).

On 1 December 1967 the Météorologie Nationale acquired a new computer, a CDC 6400 (Rousseau 1976), the decision for this being taken in late 1966 or early 1967 (Rousseau et al. 1995).

The surge that French dynamic meteorology was to undergo probably owed a lot of its success to Guy Dady. His vision and teaching had intellectually paved the way for the technological advance. The interest that French meteorologists displayed in spectral methods can to some degree be credited to him. At a conference organised by the French Meteorological Society in February 1968 Dady's entire talk was devoted to spectral methods. He was keen, both at the conference and in a subsequent article (Dady 1968) to argue on a non-technical level, avoiding 'minute description of the techniques used'. An echo of this work can be heard in a discussion about objective analysis with L. S. Gandin at the 1968 NWP Symposium (Tokyo 1969, p. VI-53).[10]

1968 was the year of the 'May Events' in France. Related or unrelated to this upheaval, there were profound changes at the Météorologie Nationale. It was the start of operational NWP with a single filtered barotropic model and an analysis system. In 1970 an acclimated version of the 'Shuman model' was run operationally. This first primitive equation model was not very successful in France and the routines were halted in 1972. Until 1979 the main operational model continued to be the filtered model.

Parallel to the primitive barotropic model, there were balanced models with several levels, and experiments were under way using multi-level primitive equation models.

4.7. French meteorologists go abroad

As mentioned above, in 1965–70 the Météorologie Nationale adopted a policy of sending French meteorologists abroad to study. The aim was to develop meteorological research and the possibility of further training abroad was an element to attract young scientists. More than a dozen scientists benefited from this policy from 1965 to 1975:

Daniel Rousseau 1965 USA (MIT)
François Cayla 1967 USA
Claude Pastre 1969 USA (NOAA)
Frederic Delsol 1969 USA (GFDL)
Jean-Pierre Labarthe 1968 USSR (Akademgorodosk)
Giles Sommeria around 1970 USA (NCAR)
Claude Sinolecka 1970 USSR (Moscow)
Michel Rochas 1971 USSR (Akademgorodosk)
Jean-Paul Goutorbe 1970 USA (NCAR)
Jean-Claude André 1971 USA (NCAR)
Jean-François Geleyn 1973 Germany (Mainz)
Marc Gilet 1974 USA (Miami)
Jean-Pierre Chalon 1974 USA (NCAR)

Many of these were involved with NWP or modelling (Rousseau, Cayla, Delsol, Labarthe, Sinolecka, Rochas, André, Geleyn).

Other scientists from CNRS who benefited from the same program were Robert Sadourny who spent 1965 at UCLA and Olivier Talagrand. The latter had been working in a group headed by Pierre Morel since autumn 1966 on a project of the general circulation of the Southern Hemisphere using constant level drifting balloons. In 1969 Morel arranged his visit to GFDL from January 1969 to July 1970 through Smagorinsky.

4.8. France regains the lead in dynamic meteorology

The purchase of the CDC6400 allowed the scientists to develop their first elementary primitive equation models.[11] Now France, for the first time since the days of Léon Teisserenc de Bort, moved to the forefront of meteorological developments. A landmark was the 1970 summer school in Lannion in Brittany where Norman A. Phillips, Jule Charney, Verner Suomi and other leading meteorologists lectured for a French-dominated but international team of young scientists. It was important because it established new links between meteorologists from the Météorologie Nationale and other scientists in the meteorological field or in the space community (Dady 1980; Rousseau et al. 1995).

The research division contained a NWP section (led by Guy Dady until Rousseau succeeded him in 1969). They developed a primitive equation model for small-scale studies (barotropic, then 10 level model, mesh 36 km). From 1972 to 1979 a version of this research model (mesh 180 km) ran daily and was available to the forecasters in Paris, as a complement to the operational filtered model and the NWP from NMC, UKMO and DWD.[12]

5. Algeria

In the summer of 1968 the Algerian Meteorological Service had, with the help of the WMO, implemented a small computer. They were now looking for someone able to build an atmospheric model. The

[10] Strangely Dady was reluctant to give too much importance to numerical methods. In the introduction to his 1968 textbook on dynamic meteorology, in which he asked Rousseau to write the chapter on numerical methods, Dady wrote: 'The apparent simplicity with which the physical problems of the atmosphere let themselves be treated by multiplying the memories, by speeding up the calculations, deprives meteorology of reflections. It tends only to transform it into bad numerics, which only seeks 'fixes'. In our opinion it is a serious danger.'

[11] Rousseau developed the primitive equation model by elaborating a regional numerical model. First the coupling was studied between two primitive equation barotropic models, one large-scale model and a second fine mesh model. The experiment was successful (published in 1968) and demonstrated the feasibility of the approach. A two-dimension vertical model was done to study the vertical aspect before constructing the three-dimensional primitive equation model (1969). It was available in three versions: a hemispherical 360-km mesh (A), an European-Atlantic 180 km mesh (B) and a French for dynamical adaptation 36 km mesh (C). The B version was run daily from 1972 to 1979 coupled with the operational hemispherical filtered model except from 1974 to 1976 when the A version was also run.

[12] From 1975 the efforts were concentrated on the development of the AMETHYSTE forecasting system in cooperation with the forecast division. It entered into operation in 1979 and was used until 1985 to be replaced by Emeraude and Péridot models (when Jean-François Geleyn succeeded Daniel Rousseau).

Director of IBM in Algiers introduced to the Algieran meteorologists a young French engineer who was looking for a job in scientific calculation.

Jean Coiffier had a background in electronics and did not at this time know anything about meteorology. Opportunities in professional training and military service had oriented him towards computer sciences and numerical calculation rather than weather forecasting.

But the challenge was very attractive. Coiffier accepted and began to read various books on meteorology. His first practical job was the decoding of the TEMP contained on punched strips. Then he tackled the problem of the objective analysis by using IBM software based on geometrical interpolation. Finally he arrived at the numerical model and spent a lot of time seeking an efficient method to solve large linear systems.

As pointed out by Coiffier (1995) it was very important in 1968 for a meteorological service of a developing country to recognise the importance of NWP, to be able to mobilise resources in order to implement a small (but efficient) computer and to create a training school where this emerging science could be taught.

Two names stand out: Kamel Mostefa-Kara who was at the ENM at the same time as Daniel Rousseau, and Mahi Tabel-Aoul who was at the ENM in 1967. Coiffier does not exactly remember the exact position of both of them inside the Algerain administrative structure. K. Mostefa-Kara was probably responsible for the meteorology at the Algerian Transportation Mininstry while M. Tabet-Aoul, was in charge of meteorology inside the Civil Aviation Security. They had taken the initiative to launch, with the support of WMO, a project for automating the meteorological applications (including of course NWP) and the creation of a training school (for all the former WMO levels of competence, i.e. up to the Class I).

At this time Coiffier met Jean Lepas who had been designated as WMO adviser for the Algerian Met. Service. Lepas was quick to make Coiffier understand that the problem was simpler than he had imagined. Thanks to Lepas' good knowledge of NWP and enthusiastic support they were able to implement rapidly a complete numerical suite including TEMP decoding, Cressmann objective analysis and a filtered barotropic model providing charts on the printer. They had the opportunity to make a demonstration for the former WMO Secretary General Sir Arthur Davies when he visited the computer at the NMS Algiers.

Then, following the advice of Jean Lepas, Coiffier decided to join the Research Department of the Météorologie Nationale in Paris where he worked with Daniel Rousseau on the implementation of primitive equation models.

Two years later (probably in 1972) Jean Lepas was working for the WMO as the head of the Institute Hydrométéorologique de Formation et de Recherches (IHFR) in Oran. One day he asked Coiffier to come for a month to transfer the small NWP operational suit they had implemented. As the memory of the IBM 1130 computer was larger, they also increased the horizontal size of the covered area. Thanks to the help of Guy Der Megreditchian (trained in USSR but recruited to the Météorologie Nationale in 1971) they completed this suit by implementing a statistical interpretation of the model outputs.

Coiffier is keen to stress that the early development of NWP techniques in Algeria is mainly the work of Jean Lepas who had the luck to find a zealous worker! Jean Lepas also encouraged and personally helped many young students of the IHFR to carry out studies related to dynamic meteorology and numerical weather prediction.

6. Belgium

According to Platzman's 1955 questionnaire, Jacques van Miegham, with J. van Isacker and Defriese as collaborators, at this time worked on a barotropic model. The area was Western Europe with constant boundary conditions. The computer was stationed at the Institute de la Réchèrche Scientifique in Antwerp. Later they used the IBM704 in Paris. Operational forecasts seem to have started in 1962 when a larger computer became available. The model was barotropic with a 500-km hemispheric grid. It took two hours to run a 48-h forecast. It was replaced by a 2-parameter model in the mid-1960s with 300–700 hPa as the relative topography.

Van Isacker did not publish much of his work, which was rather theoretical dealing with the problem of reducing the multilevel isobaric data information from radio soundings by empirical orthogonal functions (EOF). In 1964 the Royal Belgian Meteorological Service moved from an IBM7070 to IBM7040.

Belgium would soon be one of the countries that most enthusiastically supported the establishment of the ECMWF.

7. Italy

In 1955 the Italian Meteorological Service (IMS) began to study the numerical methods of dynamic meteorology and five years later the first daily forecasts were run. The key figure in this development was Sabino Palmieri, who in 1958–9 spent two years at JNWPU in Suitland (Maryland) as a young visiting scientist. His task was to follow the progress in numerical forecasting and to develop an early model for the IMS to be run on the extremely limited computing facilities that were expected to be available shortly in Italy. At that time the head of the JNWPU was George Cressman, while senior experts in atmospheric modeling were F. Schuman, L. Vanderman and Aksel Wiin Nielsen.

Palmieri produced and tested a simple barotropic model, partially linearised by using a space mean advecting field constant for 12 hours. After the implementation of the vorticity advection in a sequence of hourly time steps, the height field was recovered from the predicted vorticity field at the end of the 12-hour run by means of a Liebman sequential relaxation process. The procedure could be then iterated to extend the forecast in time. The integration area was half of the Northern Hemisphere. The 500-hPa geopotential heights at points 300 km apart were manually extracted from maps as input data. The time required for a 12-hour forecast was 12–14 minutes, for a full two-day forecast it was around an hour.

When Palmieri came back to Italy in 1960 the IBM 1401 was installed at the Defence Ministry as a multipurpose computing facility and the IMS succeeded in reserving sufficient computing time (about 1 hour) for a daily run of the barotropic model. The model was used, with minor refinements to account for the effect of major topographic features, until 1963. At that time the introduction of new energy conserving advecting schemes and higher resolution suggested a thorough redesign of operational models.

In 1967 a Numerical Forecast Centre was established. By then the IMS had acquired an IBM 360/30 and in 1968 its core memory was enlarged to 64 KB. An automatic data analysis system prepared by Francesco Mosco became operational and a two-level quasi-geostrophic model by Lodovico La Valle replaced the barotropic model. This model used Lagrangian advection, forward time integration and influence functions. In 1970 the Centre was equipped with an IBM 360/40 computer with memory of 129 KB. During the same year the number of levels incorporated in the quasi-geostrophic model was increased to four. Up to the early 1970s this work involved scientists Francesco Mosco, Ludovico La Valle and Carlo Finizio (Sabino Palmieri, personal communication 2004 and WMO Progress Report 1974).

8. Canada

In the mid-1950s NWP was already on the agenda at the University of Toronto with plans to start a barotropic mode for a numerical weather prediction program using its computer. What came out of this has not been possible to establish.[13] Instead, the next initiative seems to have come from the French speaking province of Quebec, which since then has given Canadian NWP a certain Gallic flavour.

8.1. Kwizak and Robert

André J. Robert (1929–93) was a forecaster when, in 1953, he became interested in NWP from American and European journals. Since the forecast office was in the same building as the local meteorological bureau he used to attend and hold seminars about NWP.

In 1959 Robert was transferred to the newly created Dynamic Prediction Research Division, led by Michael Kwizak. As André Robert told Andrew Staniforth (1997):

> It was Kwizak who initiated NWP in Canada. He was at the bottom of everything. He had to fight the Director of the Canadian Meteorological Centre who really did not believe in NWP.

Kwizak wrote to the headquarters of the Canadian Meteorological Service in Toronto to ask for funds to buy time on the computer owned by Canadair. Not only did they get money right away, they got three times more than they had asked for. Two new members joined the group: Robert Strachan and Amos Eddy. Strachan wrote programs to decode data and Eddy created an objective analysis system using the Cressman scheme. In September 1962 they had got their own computer, Bendix G-60.

8.2. Operational NWP starts

After a year's work of applied research and development, programming, and reprogramming, routine NWP with a non-divergent barotropic model was introduced on 1 September 1963. It had 28 × 32 grid points with grid lengths of 381 km with topographic effects and stabilising of the retrogressive planetary waves. Two runs were made daily (at 00 AND 12 UTC). The 00 UTC run went up to +36 h and was available at 06 UTC, the second to +72 h and available at 18 UTC. Problems at the boundaries were suppressed by smoothing.

During the second half of 1963 the research and development program in NWP was completely taken up with changing over from the 700-point rectangular grid used in earlier work to the 1709-point octagonal grid used at the Central Analysis Office.

8.3. Towards baroclinic models

In 1960 the Operational Development and Evaluation Unit of the Central Analysis Office at Montreal Airport began a systematic study of baroclinic models. This

[13] In the membership journal of the Canadian branch of the Royal Meteorological Society there is in 1954 (vol. 5, no. 3) an enthusiastic article by Warren Godson on NWP: 'These charts will add a new dimension to the tools available to the weather forecaster.' He envisaged the day when raw data from the teletype circuits would be fed directly into an electronic computer which would proceed to grind out prognostics contour height and vertical motion data for various levels and time intervals (Godson, 1954; Taba, 1993).

was done to increase the Unit's knowledge of, and experience with, more comprehensive mathematical prediction models. The choice of a particular baroclinic model was limited by two factors. The model had to possess operational potential and development flexibility. Secondly, its study had to be feasible on the IBM 650 installation at McGill University, which was sometimes restrictive for this scale of study. In particular the model had to be capable of predicting hourly vertical motions and similar dynamical effects. By 1962 the group had also developed a four-level baroclinic model on the 28 × 32 grid. It was intended to be implemented in the winter of 1964, but it was not until 1969, after an upgrading of the computer in 1967, that an enlargement of the computational area to a 51 × 55 grid was possible (Lin et al. 1997; Ritchie & Robert 1997; Staniforth 1997 and early 'Progress Reports' from the 1960s in the SMHI library).

9. Australia

Like their overseas colleagues, Australian meteorologists followed with great interest the development of numerical forecasting during the 1950s. When W. C. Swinbank (1955) came back from a IUGG meeting in Rome he reported on the progress of NWP in the United States and Europe: 'Australia would do well to notice the progress of these techniques.' Those who took the lead were the universities (mainly the University of Melbourne), but in the 1960s the responsibility gradually passed to the Bureau of Meteorology.

9.1. Early work at the university

In 1955–6 Ross Maine (1957) worked on Charney-Eliassen's one-dimensional model. In March 1957 Uwe Radok held a seminar on NWP at the University of Melbourne. In summer 1957, W. J. ('Bill') Gibbs (Gibbs 1982; Taba 1985b,), responsible for research, attended a meeting in Moscow where NWP was discussed. Radok held a new seminar in October 1958 and showed a barotropic forecast run on the University's CSIRAC digital computer (Maine 1957; Priestley 1982; Leslie & Dietachmayer 1992; 'Progress Reports' in the SMHI library).

Numerical forecasting started as part of the course provided by the Meteorology Department in the university. The first full barotropic forecasting program was written in 1958 by M. J. D. ('Dick') Jenssen, a physicist working for a MSc degree. He obtained it in 1959 with a thesis entitled 'On numerical forecasting with the barotropic model'. Jenssen used data and analysed charts provided by the Bureau of Meteorology and the University's CSIRAC computer, an old machine which at that time had only small direct-access storage (512 words of 20 binary digits each) with a slow backing store of 1024 words. Owing to these limitations the first 24-hour forecast for a 21 × 17 grid with 300-km grid interval required 4½ hours of real time. Many of them came to grief over machine errors, difficult to evade in such protracted calculations.

Jenssen surveyed the larger computers available in Australia at the time (1959) and selected the DEUCE type computer UTECOM of the University of New South Wales for future work on numerical analysis and NWP.

The first barotropic forecasts with the UTECOM program was made in 1960 by Jenssen and Radok and presented at the Bureau of Meteorology's Symposium on rain. They found that relatively minor changes in the initial 500 hPa pattern drastically altered the forecast.

This work, nevertheless, was immensely useful, and enabled Jenssen, apart from becoming familiar with NWP in other countries, to develop a 'quasi-stream function' which avoided the common problem of spurious anti-cyclogensis.

9.2. The Bureau of Meteorology takes over

It seems that the Australian Bureau of Meteorology became actively involved from about 1963 (Jenssen 1966; Clark 1967; Jenssen 1967; Maine 1967; Maine & Seamann 1967) when they started to develop an automatic analysis system in cooperation with the university. The first computer was installed in 1968 and the first operational NWP ran in 1969. The domain was 24 × 36 with a grid of 254 km and the model was probably barotropic. Australia occupied a third of the longitudinal area (40° out of 120°). This area, where the effect of the south-western quadrant was felt, was retained up until 1990. The first hemispheric forecast was run in 1973.[14]

10. New Zealand

The first numerical forecasting experiments in the Southern Hemisphere had been carried out in New Zealand using the Fjørtoft (1952) technique. According to early 'Progress reports' from 1960 a barotropic model was run on an IBM 650 computer owned by the Treasury. Since 28 May 1963, analyses and 24-hour forecasts of the 500 hPa height were computed on a routine basis of six to eight times per month. The forecasts were barotropic and quasi-geostrophic using a stream function. Forecasts based on the 00 UTC data were available in the forecast room at about 05 UTC. A longitude-latitude grid was used which varied between 322 and 547 km in a 12 × 18 grid point area.

[14] The continuation of the story of NWP in Australia can be found in a rare publication: 'CMRC/ANMRC Valedictory Report 1969–84' published by Australian Numerical Meteorology Research Cantre in 1984.

11. Israel

Routine forecasting started in November 1962. The model was barotropic geostrophic and run once a day based on 00 UTC data, producing forecasts up to +72 hours of the 500 hPa field. The machine was a Philco 2000. The time taken to run a forecast was $1\frac{1}{2}$–2 minutes. The 24-hour forecasts were comparable to conventional forecasts. The +48-hour forecasts often gave good indications but the +72-hour forecasts were never used. The forecast area was 60°N–10°W, 60°N–40°E, 30°N–40°E, 30°N–10°W. The resolution was defined in a peculiar variable latitude-longitude grid with gridpoints along every 5th meridian and a resolution which changed with latitude to make the distances between grid points equal to the distances between the above meridians.

12. USSR

The former Soviet Union (USSR) was not only the first country to wholeheartedly welcome and actively promote the Bergen School of ideas in the early 1930s (Tor Bergeron, personal communication 1968–74), but it was also actively exploring NWP by the early 1940s when I. A. Kibel and E. N. Blinova were conducting numerical calculations of the atmospheric flow pattern (see Phillips et al. 1960 for a detailed and comprehensive description of Soviet NWP up to 1960). The reason why not more of this is known to the outside world is, apart from the political situation, that most of the material was published in Russian. What follows in this overview is a regrettably short summary of the main developments up to 1970. The full history of Soviet NWP has still to be published, at least in a non-Russian text.

Work on an operational system seems to have started in January–October 1954 when graphical methods were used to integrate a quasi-geostrophic model on 48 cases, each with a range of +24 hours. The forecasts were, however, regarded as inferior to subjective ones.

The first operational NWP was in 1959, according to a report by Bugaev to WMO in 1964 (Döös et al. 1965). The model was barotropic.

In 1962 the Hydrometeorological Service of the USSR reported that they continued to use their three-level (850, 500, 300 mb) quasi-geostrophic model. The analysis was based on optimum interpolation and covered an area of 26 × 22 points with a grid distance of 300 km. Forecasts were run up to +36 and +48 hours. The forecasts were available 5–6 hours after the observation time. Twice a day a 24-hour forecast was run which contained the levels 850, 700, 500 and 300 hPa. This was similar to a model used in Leningrad (see below).

In 1965 the Department for Short-Range Weather Forecasting and Meso-meteorology in Moscow ran an operational three-level quasi-geostrophic model 26 × 22 with 300 km resolution and 37 × 37 grid, at the 850, 500 and 300 hPa levels. From 1964 they were also running, experimentally, a primitive equation model of 26 × 22 grid points with 300 km resolution. It was run at first twice weekly, then five days a week.

The Leningrad operational NWP operational model was a two-parameter model with EOF implementation. According to the limited computer resources the model parameters were two main modes (eigenfunctions or 'normal modes') of quasi-geostrophic atmospheric dynamic equations. As output the model predicted six levels of geopotential heights (1000, 850, 700, 500, 300, 200 hPa) up to 36 hours for limited area (Bushkova et al. 1975).

In Novosibirsk a 5-level quasi-geostrophic model was run with 26 × 22 grid points and five levels at 1000, 850, 700, 500 and 300 hPa. In Leningrad a two-level quasi-geostrophic model was run for 850 and 500 hPa (Rukhovets 1964; Belousov 1965; Leningrad 1965).

13. Czechoslovakia

In 1952 a small group of scientific workers and students at the Meteorological Institute of Charles University in Prague, on the initiative of S. Brandejs, began to explore methods of numerical weather prediction and related problems of dynamical meteorology. During the following ten years about 80 papers were published in Czechoslovakia on NWP. According to early Progress Reports, in 1963 three departments were dealing with NWP:

1. The Meteorological Institute of Charles University (headed by S. Brandejs),
2. The research department of the Central Hydrometeorological Institute (headed J. Jílek), and
3. The newly established department of atmospheric circulation at the Meteorological Laboratory of the Czechoslovak Academy of Sciences (headed by V. Vítek).

Although the small volume and limited means of Czechoslovak meteorology did not permit complex research, research into numerical forecasting methods had a positive influence on the development of Czechoslovak meteorology since it oriented it along physical-dynamical lines against the then prevailing statistical approach.

13.1. Preparation for NWP

After introductory studies of Kibel's method and Sutcliffe's development equation the research moved to developing a barotropic model. Czechoslovak meteorology at that time had no high-speed computer at its disposal. A successful but isolated attempt at numerical integration of the barotropic vorticity equation was made by means of a Fourier transformation on a calculating punch machine made by Aritma, a national enterprise. A few years later the barotropic vorticity equation was solved on a Soviet high-speed computer, Ural 1, at the Computer Laboratory of Transport.

The computer Ural 1 (and later Ural 2) had a very atypical input via perforated film bands and thus telex machines could not be used: the input data were therefore brought in by car (a distance of 15 km) and perforated onto the film band on the spot, then verified once more. Results were brought back again by car to be manually analysed. Although the 24 h forecast at the 500-hPa level took 15 minutes on the machine, most manual data pre-processing took more than 4 hours and manual post-processing needed another 30 minutes. The experiment on the Ural 1 computer encouraged further experiments since it showed a barotropic model was possible of a large region even on a relatively small standard computer. The time handicap was the main reason why daily computations had to wait till 1966.

13.2. Operational forecasts in 1966

The routine operations started in 1966 on a British-made computer LEO 360 also at the Computer Laboratory of Transport. The model was barotropic at the 500 hPa level. Already the Czechs had developed a system for objective analysis (based on the optimum interpolation method but with climate values as first guess). Calculations were made in a grid of 24×20 points for a grid length of 315 km using uncentred differences in the time integration. A barotropic forecast for 24 hours took about 4 hours. This promising activity was brought to a halt in August 1968 with the invasion of Czechoslovakia by the Warsaw Pact military forces.

13.3. Some personalities

But the Czech meteorologists did not give up in the face of these crises. Today's young Czech meteorologists, when they look back in history, point to the influence of particular individuals. One key researcher was Miroslav Škoda. It was he who really pushed to build a new team, to find a better computer, practically up to the beginning of the 1990s.

One of the most important outcomes of Miroslav's efforts was the training of a new generation of meteorologists and maintaining a minimum level of NWP expertise. Other researchers who made important contribution to training and education in NWP include Michal Bat'ka, a mathematician specialising in numerical methods, who wrote the program for the first model together with Jaroslav Vocetka (they both worked at the Computational Laboratory of Transport where they were recruited by Škoda). In 1966 Michal Bat'ka went to the Faculty of Mathematics and Physics where he worked with Professor Brandejs on a model using the omega equation and later taught students numerical methods in meteorology. In the second half of the 1980s Martin Janoušek and Radmila Broškova were his students and they worked out a HPE SI-SL model, operationally running on a technologically obsolete computer EC1057 made in ex RDA, but at least located in CHMI.

The pioneering NWP trials, struggling for survival at the time of the Cold War and Soviet occupation, helped build Czech meteorology into the position it is today. They regard themselves as a small but consolidated NWP department in CHMI where they today operate the ALADIN model on a small NEC-SX6 machine. But that is another story ...

14. People's Republic of China

The main source for information on China and NWP is the article in the *Bulletin of American Meteorology Society* by Blumen & Washington (1973). According to this, work on NWP seems to have started in 1954. Until 1958 operational activity was confined to graphical integrations of a two-layer model. Barotropic forecasts up to +48 hours were run, probably on a computer, starting in 1960.[15] The computational area seems to have been large, because they experienced problems with the retrogression of the longest planetary waves. In the first half of the 1960s, before the political turmoil of the Cultural Revolution, baroclinic models were run on a research basis and there were experiments with primitive equation models. During the same time the operational +48 hour forecasts were improved by the introduction of a divergence term which made them superior to manual 500 hPa forecasts.

15. Finland

Numerical weather prediction (NWP) in Finland has its roots in the Department of Meteorology at the University of Helsinki. Dr L. A. Vuorela, later Professor of Meteorology there, first became involved with NWP in the early 1950s as a visiting scientist in Sweden and the USA. He gave the first lectures on NWP in Finland.

In the summer of 1961 Daniel Söderman worked as an assistant to Professor Erik Palmén, who was investigating moisture convergence over the Sahara. Palmén was employed by the Finnish Academy of Science and had access to the computer ELLIOT803 at the Technical University. Palmén became impressed with the computer's capabilities, so in autumn 1962 he sent Söderman over to Stockholm to join Bo

[15] At a seminar at SMHI in the late 50's or early 60's a leading Chinese meteorologist, Dr Koo, is said to have shown a hand calculated hemispheric +24 hour 500 hPa forecast.

Döös and Lennart Bengtsson's aerological division at SMHI. Söderman worked part-time work at SMHI from December 1962 until 1967. There he participated in the building up of the operational forecasting system on the SAAB D21 computer.

15.1. First NWP experiments at the university

The first modelling experiment was performed in April 1964 at the Department of Meteorology, University of Helsinki, with the financial support of The Finnish Society of Sciences and Letters. The young enthusiasts in the area were Daniel Söderman and Juhani Rinne with a barotropic model on an IBM 1620, with one time-step requiring 8 minutes of computations for an area with 360 (18 × 20) grid points. The forecast run was terminated by printing out text which read *'Olen tehnyt historiaa'* (I have made history), which proved to be an unexpectedly factual statement as the forecast had progressed backwards in time owing to a sign error in the code.

This initial test run was followed by sporadic experimentation on the Technical University Elliot 803/503 system, and by an annual training course on numerical weather prediction at the University of Helsinki.

Barotropic forecasts were then carried out once a month primarily for educational and training purposes. Owing to the relatively low internal speed of the available electronic computer, the computing time for a 48-hour forecasts on a area of 360 grid points was about 8 hours.

15.2. Operational runs in 1970

For a long time at the Finnish Meteorological Institute (FMI) there was little hope of acquiring a computer. In the 1950s its Director, Matti Franssila, hoped at most to be able to influence the purchase of a computer at the University. When Söderman and Rinne started their experiments they were given administrative support and encouragement by Franssila and Dr Eero Holopainen, the acting Chief of the Weather Forecasting Section of FMI.

In September 1967 a computer group was formed at the FMI with Eero Holopainen as leader. At a Nordic Directors Meeting in Helsinki in September 1968 it was reported that, since March, barotropic forecasts were run up to +96 hours on a copy of the Swedish model. At the end of 1968 the first experiments with 1–2 day forecasts started with the Elliott 503 at Helsinki Technical University.

The year 1969 saw revolutionary changes at FMI. In April 1969 a computer division was set up at FMI with Daniel Söderman as leader. A decision was made to purchase a Datasaab D21 for FMI with the full SMHI software package included in the deal.

Operational NWP started in February 1970 when Holopainen had just returned from a fact-finding mission to Sweden and the USA. The forecasts were based on the three-level filtered model developed by Lennart Bengtsson and Lars Moen and run daily at 00 and 12 GMT in a 300 km grid to +36 hours and thereafter barotropically at 500 hPa until +96 hours. In addition, 150-km forecasts were run to +36 hours at 12 and 18 GMT during summer. Later the Swedish model was run four times a day at 300-km resolution, with boundaries transferred to an inner 150-grid version.

Two years earlier FMI had moved to a new location in Helsinki. The Head of the Weather Department, Sulo Nestori Venho, who was in charge of the new building, told Söderman that the building had been planned on the assumption that it would never house any computers. When Söderman left ten years later (for ECMWF) there were around thirty and a staff of 42 in the division.

16. Denmark

Denmark's involvement in NWP can be divided into three periods: one rather premature start in the mid-1950s, a second period of half-measures in the 1960s and 1970s, and a third period from the mid-1980s which brought Denmark to the forefront of NWP in Scandinavia.

16.1. The premature years

During his time as professor at the University of Copenhagen (1951–5), Ragnar Fjørtoft gathered around him three enthusiastic students: Aksel Wiin-Nielsen, Hans S. Buch and Harry van Loon. The project was not to explore NWP but to develop Fjørtoft's own graphical method. Wiin-Nielsen (1990, 1997, 2001) has given vivid descriptions of this work. The group dispersed when Fjørtoft went back to Oslo in 1955. Wiin-Nielsen moved to Rossby's institution in Stockholm, Buch went into other fields in meteorology and van Loon emigrated to the United States.

16.2. The period of unfulfilled attempts

In 1956–7 another Danish meteorologist from the Danish Meteorological Institute (DMI) Ole Lang Rasmussen, visited Rossby's institution to learn about NWP. On his return he created a barotropic model which was run irregularly, producing +48 h forecasts over an area of 32 × 40 gridpoints of 300-km intervals. The calculations were made on DASK, a Danish copy of BESK, at the Danish Computer Centre. When Rasmussen left DMI in 1961, the work was taken over by J. Walter Larsen (later head of the Computer

Division). Barotropic forecasts were run irregularly after 1963 on a 25 × 23 grid of 254 km. In 1969 the DMI started to develop an objective analysis scheme. Only in 1971 did the DMI acquire a computer, a RC4000, and in 1973 a baroclinic model was started on the 25 × 23 (254 km) grid.

The first WMO 'NWP Progress Report' for 1974 contains a brief description of this three-parameter baroclinic model by Bjarne Byrnak and Gorm Raabo-Larsen. In the following three years there are no entries from Denmark at all. One reason might be that Raabo-Larsen was then working in England to help set up ECMWF. In 1978 there is again a short report from Raabo-Larsen, and his co-workers Anne Mette Jørgenssen and Niels Woertmann-Nielsen. Their report mentions plans to develop and implement a short-range, fine mesh numerical NWP model for Danish forecast areas, including Greenland and the Faeroe Islands, improve the data assimilation system and study the ECMWF medium-range NWP system.

16.3. Denmark moves to the forefront

According to the WMO Progress Report for 1986 fundamental changes were under way. In 1985 the Nordic countries fulfilled a long-time ambition, first aired in the mid-1950s *to co-ordinate their NWP work*. A project had been initiated in 1984, with the Danish meteorologist Bennert Machenhauer as leader to create a High Resolution Limited Area (HIRLAM) model. The staff, located in Copenhagen, consisted of two members from each participating country.[16] The location at the Meteorological Institute in Copenhagen was made possible thanks to the installation of the first supercomputer, a Sperry 118, at the institute with a fast attach processor, creating the fastest computer system for scientific calculations in northern Euorpe (Lars Prahm, personal communication 2004).

The role HIRLAM played in the development of NWP in these smaller countries deserves its own history. The profound changes in Danish meteorology were simultaneous with Aksel Wiin-Nielsen's appointment as Director of DMI in 1983. But the practical initiative from the Danish side was taken by the Head of the Computer Division, Lars P. Prahm, who from 1987 was the Director of the DMI and in August 2004 was appointed as Director General for EUMETSAT.

17. Netherlands

Operational NWP seems to have started in the late 1960s at the Royal Meteorological Institute of the Netherlands (KNMI). It had been prepared by early research using the computer at the University of Utrecht.

There was some resistance to NWP – there is anecdotical evidence from the early 1960s that the director (Warners) was heavily against computers and tried to keep them out as long as possible.

Numerical modelling at KNMI started late with J. van Galen in the mid-1960s. Other people involved were D. Bouman, W. J. A. Kuipers[17] and H. Timmerman, under the Head of Research F. H. Schmidt. They used a Phillips computer EL-X8 with 16K core memory. The language was ALGOL 60.

There was an operational limited area model BK3 (Baroclinic 3 levels) as early as 1968–70 after Lodewijk Heijboer had joined KNMI. There was, as one of my sources said, a 'decent activity', although it was always a bit subdued and overshadowed by what they assumed was happening in Britain and America. The activity is reflected in a (Dutch-language) KNMI Scientific Report WR 69–3 'Speciale Projectgroep Numerieke Voorspelmethoden' from 1969. It describes, extensively, the code to be implemented on the computer. The chapters are:

1 Introduction; 2 Automated data extraction; 3 Data correction; 4 Objective (Cressman) analysis; 5 Barotropic model; 6 Three-parameter baroclinic model; 7 Numerical calculations of the water levels along the Dutch coasts.

The introduction mentions that the machine is in place and that the group soon will be working with a model with a resolution of 375 km. No authors are mentioned but the various chapters in the report were written by Kuipers, Galen, Timmerman and edited by Bouman.

18. Norway

The development of NWP in Norway is, at least for an outside historian, shrouded in some mystery. The facts are the following: In 1961 DNMI, (the Norwegian Meteorological Institute) as one of the first meteorological services, acquired a computer, a FACIT EDB. From 1962 to 1971 two types of operational NWP models were run, one barotropic for the 500 hPa surface, another baroclinic 2-parameter model using the 300–700 hPa thickness.[18] Forecasts were run up to +48 hours in a 600 km grid (probably reduced to 300 km at some stage). There was no explicit forecast for 1000 hPa, the tendencies for that level were calculated from the tendencies at 700, 500 and 300 hPa (Økland 1963a). In 1971, when DNMI got a new computer, the

[16] A special agreement was made with the Dutch meteorological service, which contributed two scientists. Ireland and Spain joined the HIRLAM group later.

[17] One of the creators of the Hanssen-Kuipers verification score.

[18] Until Spring 2004, before I alerted my colleagues at the Norwegian Meteorological Institute, their www.met.no website stated incorrectly that the Norwegian operational NWP model up to 1972 was only barotropic.

2-parameter model from 1962 was replaced with a four-level baroclinic, balanced model borrowed from a 1965 Japanese version (Grönaas & Lystad 1975).

This is not bad in comparison with other small European nations at that time. But meteorologically Norway was not a 'small' country. Indeed, Norway belonged to the meteorological 'super powers'. It had a long history of outstanding geophysical research with an impressive list of scientists, among them Henrik Mohn, Gustav Adolf Guldberg, Vilhelm and Jack Bjerknes, Carl Ludvig Godske, Jörgen Holmboe, Sverre Petterssen, Einar Höiland, Ragnar Fjørtoft, Arnt Eliassen, Enoch Palm.

But there are more things that are difficult to explain. At about this time, in the early 1970s, when other small European nations came together and planned who would join the ECMWF, Norway practically decided to stay outside. It signed the convention, but did not take an active part until 1988. Since then only a few Norwegian meteorologists have worked there, and only for short periods.

When one tries to understand what lies behind this one encounters some frustration in the development within the Norwegian meteorological community. On one hand there is a bitterness of lost opportunities and a feeling that Norway took the wrong track. There is also a certain reluctance to discuss the matter, since it would unavoidably focus on three Norwegian meteorologists of great fame and stature: Einar Höiland, Ragnar Fjørtoft and Arnt Eliassen.

Einar Höiland (1907–74) was a student of Vilhelm Bjerknes and the leading meteorological theoretician in post-war Norway. He was regarded as over-theoretical and his work was characterised by a high degree of formalism. He was plainly interested in hydrodynamics and wrote hydrodynamical papers, very mathematical, which had nothing to do with weather and climate. Höiland had a strong will and nobody dared to argue against him.

Ragnar Fjørtoft (1913–98) is well known for his participation in the first ENIAC run in 1950 (Taba 1988) But during his period as professor in Copenhagen (1952–5) he concentrated on refining his graphical method of integration of the barotropic model (Wiin-Nielsen 2001). When he returned to Oslo and became Director for the Meteorological Service his aim was still to develop and promote his graphical method rather than to develop domestic NWP.

He tried to develop his method by using an optical analogue method where the calculations could be evaluated by passing light through two film sheets whose transmittance represented two space functions. However, in spite of heroic efforts involving the calibrations of thousands of small pieces of film with various degrees of blackening, the results were discouraging and the idea was abandoned.

It is true that the Fjørtoft (1952) method was accessible and that it helped many poorly equipped meteorological services to get a taste of NWP. It is also true that this quasi-Lagrangian method helped to inspire the use of semi-Lagrangian numerical techniques (Haug 1957; Pedersen 1960; Økland 1962, 1963b).[19] But it should have been clear to Fjørtoft that his graphical technique would have been extremely useful only if computers (and Rossby's barotropic concept) had been born a few decades earlier. In the long run his method would not be able to compete with the computer-based NWP.

Finally there is Arnt Eliassen (1915–2000) who is made up of two personalities. There is the 'International Eliassen', who worked with Charney, Rossby and others on NWP from 1948 to 65. This Eliassen is a towering figure in the history of NWP. And then there is the 'Norwegian Eliassen' who produced fundamental research on important aspects of dynamic meteorology with concepts such as the 'Eliassen–Palm flux' and 'Sawyer–Eliassen theory' on cross-frontal circulation (Taba 1997). But he seemed to have stayed outside active involvement in domestic NWP. It is true that Eliassen was based at the university and that NWP was mainly a duty of the meteorological institute. But as we have seen in other countries, it was quite common for NWP to be developed as a cooperative project. It would have been particularly favourable in Norway because it is just a few minutes walking distance between the two institutions! Eliassen and Fjørtoft are prominent figures in the history of NWP – except in their own country!

To understand why Norway stayed outside ECMWF we need to focus on another meteorologist. The DNMI is governed by the Church and Educational Department, and one of its key civil servants was Olaf Devik (1886–1987), one of Vilhelm Bjerknes' first students. Devik seems to have maintained his influence even after his retirement in 1951. The policy of the Church and Educational Department was to follow the advice of Ragnar Fjørtoft and Arnt Eliassen – also after *their* retirement. Fjørtoft and Eliassen recommended to the ministry that Norway should not join the ECMWF: the USA was already preparing medium range forecasts globally, so why set up another centre?

It is true that there was also scepticism in Norway that the ECMWF was politically rather than scientifically motivated. At that time (1971–4) the United Kingdom had not yet been admitted to the EEC. The Convention establishing the ECMWF came into force on 1 November 1975, having been ratified by a dozen

[19] Platzman (1963) noted in his report from the successful international symposium on NWP in Oslo 11–16 March 1963 that Lagrangian or quasi-Lagrangian methods were 'gaining ascendancy in some circles, in particular in Norway'. He was also impressed by Kaare Pedersen's precipitation forecasts from a quasi-geostrophic model and by Ragnar Fjörtoft's 'remarkable discovery' of balanced equations of a 'mixed type'.

Member States – six months after the British in a referendum voted to join the EEC.

19. Spain

International co-operation often results in geographically distant countries being brought closer together. The reason why Spain chose to join the Dutch-Irish-Scandinavian HIRLAM group in 1993 can be traced back to the 1960s.

Spanish meteorologists showed interest in the future development of NWP well before 1960, although they had no resources or opportunities to get involved themselves. In 1955 a Spanish 'Introduction to NWP' was published by the National Meteorological Service (NMS). It was followed by translations of papers on Fjørtoft's 'vorticity technique' and on numerical prediction of the 500 hPa topography.

In February 1958 Dr Jose M. Jansa from the NMS published a long article in the official magazine of the Air Ministry (to which the NMS belonged) titled 'Numerical Prediction' and described the mathematical background of NWP and its future perspectives.[20]

In 1965 a group for NWP was created at NMS under the meteorologist Rafael Azcárraga. Lacking computer resources the intention was limted to study recent developments and attend relevant meetings abroad. In 1966 Azcárraga gave a lecture at the NMS on 'NWP, objective analysis, data selection and applications to Spain'. The second part of the lecture mainly referred to his contacts with experts from the Nordic countries, Bo Döös and others. He translated a paper in *Tellus* on the experiences of Sweden with the computers Besk and SAAB D 21. This was probably the origin of collaboration with the SMHI which would be continued during the later years by the Spanish Service (Manuel Palomares, personal communication).

In 1966–7 the NMS acquired its first computer, an IBM 360/340, and Rafael Azcarraga implemented a barotropic model developed by van Isacker at the Belgian Met. Service. The model domain was hemispheric and the forecasts were presented as 'zebra' maps.

The barotropic model was run almost without interruption from the late 1960s until the early 1980s. The acquisition in 1984 of the Fujitsu machine allowed the National Meteorological Institute (INM, as NMS was now called) to make a further qualitative jump. A new suite was implemented consisting of the LAM version of the ECMWF global model, an adaptation of the Swedish limited area model and the analysis codes from SMHI.

With regard to universities probably almost nothing was done before 1970. There were only three departments of Atmospheric Physics at the universities of Barcelona, Madrid and Salamanca. Their first computers did not arrive until the late 1960s.

20. Yugoslavia

The Yugoslav contributions to NWP have been profound but, as was the case with Norway, these have benefited the world more than they have benefited the country itself.

20.1. Introduction

To understand the development of NWP in Yugoslavia over the last fifty years one must not only bear in mind the lack of resources, but also a particular feature – its great emphasis on schemes to suppress devastating hailstorms. Even today the schemes absorb a huge part of the Met. Service budget. Meso-scale storms, enhanced by the orography, are indeed difficult to forecast and forecasting the daily weather has often had to come second. In Yugoslavia gifted meteorologists interested in NWP therefore had to compete for limited resources and political support.

20.2. A new generation of meteorologists

The first information about NWP that the meteorologists in Belgrade obtained was in 1954 from Dr Marjan Cadez, who taught Dynamical Meteorology at the university and Dr Wippermann who gave a lecture about NWP in Belgrade.

About 100 students studied for their diploma in Belgrade during the period 1953–1960, and this was the new (post-revolution) generation that constituted the meteorological staff and chiefs of the following decades. In 1960 'three musketeers' of this generation – Dusan Djuric,[21] Fedor Mesinger and Petar Gburčik – defended their theses and in 1961 became assistant professors.

In 1963 Djuric came back from Germany and brought Edelmann's model (for the Europe–Atlantic area) to implement as NWP. After about a year they realised that the model did not work technically.

However, the management of the Federal Hydrometeorological Institute[22] wanted to include Yugoslavia in the World Weather Watch and turned to Petar Gburčik

[20] With respects to limited area modelling it was noted that 'the only way for reducing the influence of errors from boundary is to extend the boundaries to pay attention to what happens in places at long distance from the forecast area with as much detail as possible'.

[21] Dusan Djuric (1930–2005) spent 1955–57 with Rossby's group and left Yugoslavia in 1965 to start an academic career in the USA.

[22] 'Federal' applies to the whole Yugoslav State, 'Republic' to separate states within the federation.

in the hope that he would implement a working NWP system. He was offered the post as the Head of the Federal Weather Forecast department in October 1968.

Gburčik had already some experience of dynamic meteorology and NWP. His doctoral thesis was on the 'The Cyclogenesis in the Gulf of Genoa', which he tried to explain by analysing the 'twisting terms' of the vorticity equation. In 1957 he implemented at the Met Service, on the suggestion of Dusan Djuric, Fjørtoft's graphical method of vorticity barotropic forecast.

20.3. NWP without a computer

Gburčik appreciated the work of the federal institute and its staff. They had an orientation that was reminiscent of the 'pre-war' generation: they strictly followed WMO recommendations and looked at 'how the Germans do it'. In his new position Gburčik had the possibility of organising the fax emissions to the services in the republics and had a staff of experienced forecasters, telecommunication experts and one programmer (Stevan Grujic). There was no in-house computer and connections had to be made to computers in different parts of the city. So Gburčik decided that the only realistic solution was to construct a simple model which gave as much as possible with the least investment. But even a simple model was hard to organise without a computer of their own.

The first operational run of the barotropic model using the balance equation and the filtered two-parameter model in Belgrade was in May 1970. Most of the computations were performed on a mid-1960's vintage IBM 360/44, located 20 km from the Met. Service, at the Mathematical Institute of the Serbian Academy of Sciences and Arts. It was considered specialised for scientific computations and had 64 Kbytes of memory and was almost as fast as a Macintosh of the mid-1980s.

The area of the analysis covered Europe, the Atlantic and a small part of North America. The mesh width was 330 km. The analysis was performed on geopotential heights, by a correction method with a 12-h preliminary field. In areas where data were scarce, in particular over the Atlantic, use was made of the subjective analysis and data for a few gridpoints were introduced manually. The prognostic equation was the vorticity equation. The main output products of the model were the 500 hPa height, the relative topography 500–1000, surface chart and vertical velocities (see figure 2 for an example of a NWP chart).

Integrations were performed twice daily up to 96 hours. These products were transmitted by fax from the Federal Hydrometeorological Service to all six meteorological services in Yugoslavia. The values in grid points were plotted and the isobars were drawn by hand. At that time they already had the 'zebra plots', but for data exchange they had only teletypes at their disposal. The prognostic chart with isobars drawn by hand was transmitted by fax to the republic's Met. Services.

20.4. A computer at last

Since his appointment Gburčik had asked for funds from the Computing Centre at the Yugoslav Met. Service, not only for the model but also for automatic data control and processing. At last in 1971 the institute obtained the money. But it was not until 1974 that an IBM 370 with the internal memory of 256 Kb was actually installed. 'This was the second birth of my model' (Gburčik, personal communication 2004).

The initial model was continually improved, at first by including the influence of orography and later through introduction of 'error fields' (Gburčik 1971, 1975, 1976). This method for improvement of the prognostic charts was introduced in 1976, and was designed for man-machine mix applications. The error fields were computed and used to improve later forecast charts. Investigations were oriented to translate prognostic rules into mathematical tools. In this way the equation system of the prognostic model was expanded to include the forecast of the error-field (Gburčik 1976).

At this time there were two groups working with NWP at the Federal Meteorological Institute. One was working with the two-parameter model and the correction method analysis led by P. Gbučik, S. Grujić, Z. Buljevac and T. Stojiljković, which tried under difficult conditions to build a practically working NWP system within the existing technical framework, with possibilities for man-mix-machine applications. The other was the primitive equation (PE) analysis and forecasting model group of Z. Janjić, F. Mesinger, I. Slavić and M. Jovašević which tried, under equally difficult conditions, to build a NWP system which was scientifically ambitious but which almost exhausted the technical resources.

Mesinger and Janjić's first PE-model, developed in 1973, was not successful and was not implemented. The first successful PE-model was developed in the summer of 1976 and was designed the HIBU model. It became operational on 1 January 1978. But the full story of this famous model is a story in its own right and lies beyond the time range of this overview, which is concerned with early operational NWP.

21. Ireland

In 1976 Ray Bates worked in Cairo for the UN Development Programme, invited there by the head of the Egyptian NWP group, Mahmoud El-Sawy, to implement the Yugoslav primitive equation model at the Egyptian Meteorological Service. The experiences were positive and in August 1976 Bates asked the

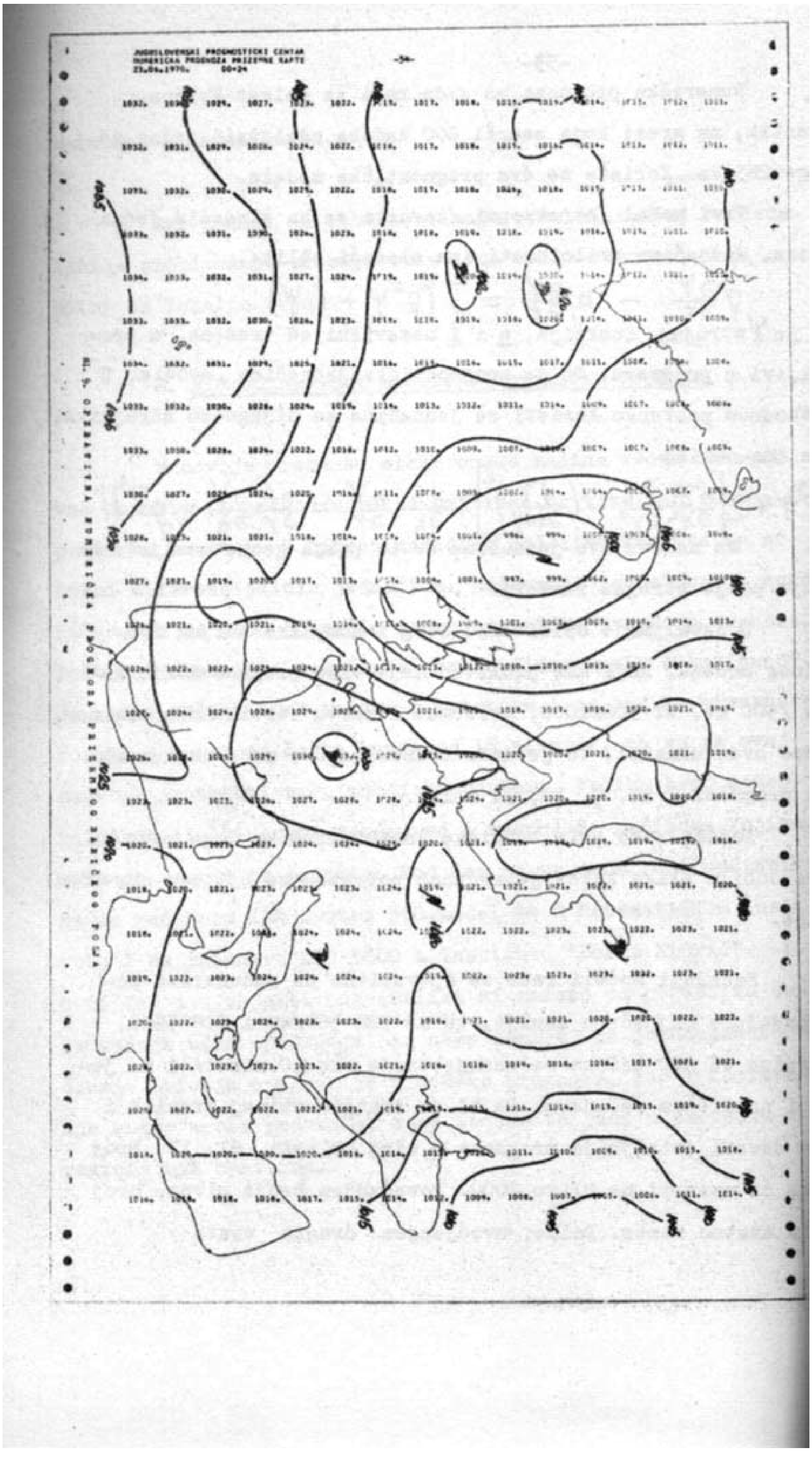

Figure 2. *An example of a sea-level prognostic chart from 25 April 1976 (courtesy Petar Gburčik).*

Yugoslavs if it was possible to use the model at the Irish Meteorological Service. At that time they were running the Swedish quasi-geostrophic model on an outside computer, and were trying to convince the government to buy them their own computer. The analysis was the optimal interpolation scheme developed at SMHI by Nils Gustafsson. When in 1979 a DEC20/50 computer (memory 256 K 36-bit words, speed 1 MIPS) was acquired, the Yugoslav five-level primitive equation model with [sigma]-coordinates was implemented.

* * * * * * *

After surveying NWP in twenty countries the reader might think that "it's all over".

-*Well, it isn't!*

The greatest story is still to be told.

The reason why British NWP is given a special section is not only because of the story itself, but, like an old Shakespearean drama, brings up issues, which are still relevant today.

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