SMHI

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$$\frac{\partial}{\partial t}\nabla^2\phi = J(\zeta + f, \phi)$$

$\phi =$ geopotential height $\qquad m =$ mapfactor

$$\zeta^{\tau+1} = \zeta^{\tau-1} + 2\,\Delta t\,J(m^2\zeta^{\tau} + f, \phi^{\tau})$$

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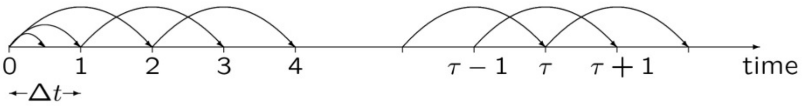

Front:
Model equations and time-stepping scheme of the first SMHI NWP model on BESK and initially on Datasaab D21

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Abstract

Sweden was a pioneering country in the development of Numerical Weather Prediction (NWP). The worlds first operational numerical forecast was produced already in 1954 by the International Meteorological Institute in Stockholm. SMHI started a bit later, but in 1961 a long term program for development of NWP was initiated. The activities grew gradually during the 1960's and resulted in a core component for the SMHI forecast services. An early challenge was to overcome the limited computational resources with slow computational speed, small memory size and primitive software support. It was necessary to compensate for these limitations with dedicated work and creativity. A core component in this work was the software system MAC (Meteorological Auto Code) that was developed by the NWP group at SMHI. The MAC system is described in detail in this report and it included all computational software needed for the weather service, for example numerical models, objective analysis techniques, automatic data extraction, quality control of observations as well as forecast products in graphical or digital form.

We hope that this report will provide the younger generation with some insight into the conditions for development of NWP during the 1960's.

Sammanfattning

Sverige var ett föregångsland inom numeriska väderprognoser och den allra första operativa väder-prognosen gjordes redan 1954 på det Internationella Meteorologiska Institutet i Stockholm. SMHI kom igång senare, men 1961 startade man ett långsiktigt program för NWP (numerical weather prediction). Projektet växte gradvis under 1960-talet och blev så småningom en central komponent i SMHIs prognostjänst. En utmaning under de tidiga åren var de begränsade dataresurserna med primitiv programvara, och med dagens mått begränsat minnesutrymme och låg beräkningshastighet. För att kompensera dessa brister krävdes både beslutsamhet och ett stort mått av kreativitet. Som en central komponent i arbetet utvecklade NWP-gruppen datorsystemet MAC (Meteorological Auto Code) som här beskrivs i detalj samt också alla de beräkningsprogram som krävdes för prognostjänsten. Detta inkluderade olika prognosmodeller, analys samt program för databehandling och observationskontroll samt produktion av prognosresultaten i grafisk eller digital form.

Det är vår förhoppning att föreliggande artikel skall ge den yngre generationen en inblick i hur det var att syssla med NWP under 1960-talet.

Contents

1 Introduction

Numerical weather prediction started very early in Sweden under the auspices of the International Meteorological Institute (IMI) supported by the Swedish Military Weather Service. IMI was established in 1951 under the leadership of Carl-Gustav Rossby and reported directly to the Ministry of Education but from 1955 to Stockholm University. The worlds first operational numerical forecast ever was carried out in 1954 using the Swedish-built computer BESK.

SMHI started later but in 1961 a small research and development group for NWP was set up. This was initiated and initially led by Bo Döös. Döös had considerable experience as he had been one of the leading scientists at IMI that developed a comprehensive NWP-system used for a real-time prediction in 1955 by the Swedish Air Force.

SAAB (Svenska Aeroplan AB) was during the period in the process to develop a more advanced computer, D21, than the computer used by the Rossby group. It was faster than BESK and had a larger memory. It was also technically more advanced and used more modern hardware components than BESK, but it still used the same primitive systems for input and output.

Compared to the computer systems of today, more than half a century later, the D21 was also utterly primitive, in particular with regard to software. There was no operating system and no compilers available when SMHI started to use D21. There was no hardware available for floating point calculations, hence all programming had to be done with fixed point numbers and in machine language. Special users oriented compilers and operating systems had to be developed by the group at SMHI.

The D21 at SMHI initially had a memory of only 12288 24 bit words or 36 kilobytes. The computer had some 40 different operations. There were special codes for indirect addressing and for double word length operations. The time for a typical operation like addition was 9.6 microseconds (μs), some 3-4 orders of magnitude slower than today's portable computers and mobile telephones. The requirements on the programmers were substantial and a major objective was to write efficient codes that used a minimum of memory space.

The main objective of this paper is to explain the structure of the code and the system that was developed from scratch. We will refer to this system as the Meteorological Auto Code (MAC) system. The MAC system was used at SMHI until the late 1970's when it was replaced with a modern Fortran based system. It was also implemented in a few other countries such as Finland and Czechoslovakia.

The structure of the code was based on an octal number system using the numbers 0-7 for instructions, data and meteorological parameters but including 8 to represent relative addressing and 9 to indicate individual programs. As will be shown in this article this was found to be very useful.

The individual programs were arranged in four separate groups; data handling including decoding and error control of individual observations, programs for analysing the data into grid point fields, numerical modelling codes and programs for presenting the result in different ways.

In the following sections these systems will be described and examples will be provided. A short history will also be given on the state of computing in Sweden in the 1950's. Appendix A includes a MAC subroutine for the barotropic model and Appendix B provides some remarks on people and social life.

2 A brief history of early Swedish computers

The urgent need for computers ('matematikmaskiner') for Swedish research and for the Swedish defense, was recognized early in the 1940's. The Swedish Board for Computing Machinery (Matematikmaskinsnämnden, MMN) was established through a decision by the Government on the 26th of November 1948. Included among the members of the MMN were representatives from universities, academia and the Swedish defence. MMN was given the task to follow the international development in computing and to investigate possibilities to provide computers for the Swedish needs. Initially, the possibilities for importing computers from the U.S. were explored. Several experts were sent to study ongoing computer projects at U.S. universities and several commercial providers of computers in the U.S. were contacted. From the contacts with U.S. Governmental authorities it was realized, however, that the chances of getting a license for export of computers to Sweden were very small. The logical and brave recommendation by MMN in January 1949 was to initiate construction of computers in Sweden. This recommendation was very important for Swedish activities in computing science, computer industry and numerical weather prediction for decades to come!

The MMN initiated a strategy for the construction of Swedish computers along two different time scales, one fast line of development (months) based on standard telephone relays and a more long term (2-3 years) project for development of electronic computers based on vacuum tubes.

One early computer BARK (Binär Aritmetisk Relä Kalkulator) was based on standard telephone relays and it was completed already in January 1950. It had a memory with 100 changeable registers and 200 fixed registers, a computing accuracy corresponding to 7 decimal digits (a 24 bits mantissa and a 6 bits exponent) and the computing speed was approximately 100 ms for addition and 250 ms for multiplication. BARK was utilized by various users on a commercial basis from June 1950. Among the application areas were development of numerical techniques, aerodynamics, ballistic calculations for the defense and sediment age estimations.

The first Swedish electronic computer based on vacuum tubes developed by MMN was BESK (Binär Elektronisk Sekvens Kalkulator) that was completed in 1953 and was used until 1966. BESK was a very modern and innovative construction, it was even for a short period the fastest computer in the world and it had an outstanding influence on many computing oriented activities in Sweden, not the least for numerical weather prediction. The potential of BESK was realized early by Carl-Gustav Rossby, one sign of this is that the first course in coding for BESK, mainly intended for meteorologists, was arranged already during the autumn of 1952 at the University of Stockholm.

BESK was a 40-bit machine with an instruction length of 20 bits. The electrostatic memory could store 512 words, addition took 56 μs and multiplication took 350 μs. At the start BESK had a British Williams tube memory that later was replaced with a ferrite core memory. The BESK computer was coded in machine language with input of instructions in hexadecimal form. The BESK computer was successfully used for a wide range of calculations. It was for example used by the SAAB aircraft company for simulating the wings of the defense aircraft under construction, by the Swedish National Defense Radio Establishment for cracking encrypted code messages and by the International Meteorological Institute in Stockholm in collaboration with the Swedish Air Force to carry out numerical weather prediction. The worlds first weather forecasts based on operational numerical weather prediction, calculated on the BESK computer, were issued by the Swedish Air Force in 1955. The Swedish Meteorological and Hydrological Institute started operational numerical weather prediction on BESK a few years later, in 1961.

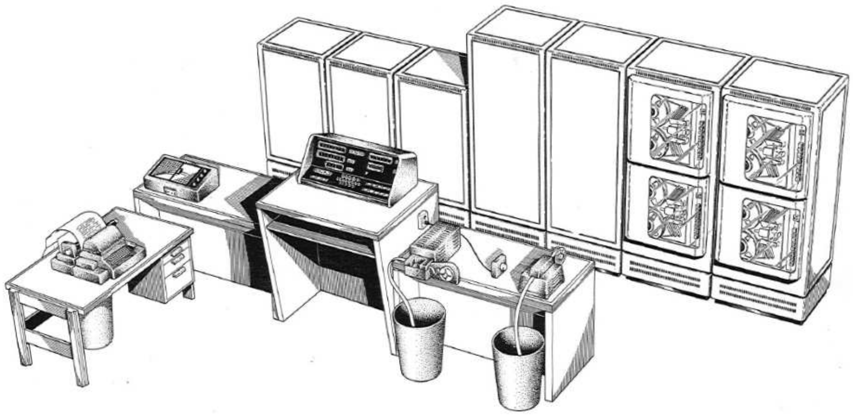

Figure 1: The DATASAAB D21 computer with memory and processor cabinets, magnetic tape stations, paper tape reader, paper tape printer, display consoles and type-writer

Several of the BESK developers were hired by the Facit company and 9 copies of the BESK computer were constructed. Four of these were sold commercially and one of these, the Facit EDB 3, was used by the Norwegian Meteorological Institute for numerical weather prediction purposes.

A clone of BESK named SARA was also built by SAAB in 1954. SAAB had realized that increased computing power was needed for aircraft navigational purposes and for aerodynamic simulations. SAAB started their own computer design and development, in the beginning mainly for military aircraft purposes. The first civil and commercially available computer was DATASAAB D21 (See Figure 1) that was completed in 1960. D21 was fully transistorized and it had a memory of up to 32768 24 bit words. An addition on D21 took 9.6 μs and a multiplication approximately 35 μs. D21 used paper tape and magnetic tapes for input and output. D21 was followed by faster and larger memory versions D22, D220 and D23, which were available until the SAAB civilian computing activities were incorporated into the Sperry Univac company by the end of the 1970's. The DATASAAB D20 series of computers were commercially successful, regularly beating competing companies like IBM in selling large computing systems, for technical as well as administrative purposes. A contributing factor was very modern software, for example the ALGOLGENIUS language, an extension of ALGOL with possibilities for description of structured data records.

The Swedish Meteorological and Hydrological Institute began using D21 computers for numerical weather prediction in 1962 and the first D21 was installed 1964 at the SMHI premises in Stockholm. More details on the use of D21 for NWP will be given below.

3 The challenge of numerical weather prediction in the early 1960's

The first numerical weather prediction model was formulated by Charney, Fjörtoft och von Neumann and published in 1950 (Charney et al., 1950). It was a barotropic model based on the principle of conservation of absolute vorticity and applicable on the 500 hPa level. Most operational weather models around 1960 were based on the filtered or quasi-geostrophic equations at low horizontal and vertical resolution but research work had started with models based on the primitive equations. Germany was in fact running an operational primitive equation model (Hinkelmann, 1959). Major problems were related to the limited storage space and the poor speed of available computers but also to observational limitations over the oceans and for the tropics and the Southern Hemisphere.

A particular problem was the initialization of the primitive equations as there was no effective way to separate the Rossby waves from gravity waves. The technique was to use a heavily damping integration scheme that unfortunately had the disadvantage to damp the high frequency Rossby waves (Matsuno, 1966). This was highly negative since such Rossby waves often were associated with intense weather systems important to predict as accurately as possible. It was not until the end of the 1970's that these problems were overcome (Machenhauer, 1977, Baer and Tribbia, 1977).

Planning had started to significantly enhance the global observing systems under the international GARP program (Bolin, 1971). The first satellites had indicated enormous potential for observations from space including radiation measurements by means of remote sensing but all this was at least a decade into the future.

In the field of programming, major efforts were under way to develop higher order programming languages in order to make programming easier and to involve more scientists in the work. Different languages were under way such as Fortran but it would take some time before they were to replace simpler assembler languages and machine coding as the required storage capacity was not available or was prohibitively too expensive.

4 Modelling and data assimilation

4.1 Introduction

The modelling development at SMHI that used the MAC system was based on the filtered equations. This was because the area of interest was in the extra-tropics where quasi-geostrophic models are good approximations. It was also due to the fact that at the time primitive equations for predictions a few days ahead were only barely more accurate and required significantly more computer time. However, during the period 1961-1977 the operational models underwent a large number of developments including improved vertical and horizontal resolution and the integration domains were extended as more memory space became available. Energy- and enstrophy conserving numerical schemes were used and iterative methods were employed to consider higher order divergence terms in the equations (Moen, 1974). Fast physical processes such as convection and latent heat release were also included. High resolution limited area models using boundary conditions from the coarse resolution integrations were developed and successfully used to predict intense weather and for aeronautical services (Bengtsson and Moen, 1971). SMHI was one of the very first meteorological services that used this method op-

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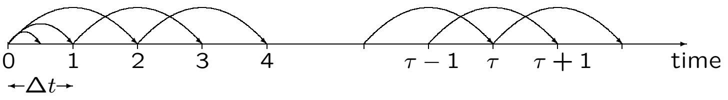

Figure 2: Model equations and the leapfrog time integration scheme of the barotropic vorticity advection model on BESK and in the first version on D21

erationally. The initial data for the prediction was based on the method of successive corrections described below.

4.2 The model development

The barotropic model is based on the conservation of absolute vorticity. To develop a model for a limited area requires that there is no net divergence flux through the boundary. This was a demanding task to program in the MAC system. It was carried out in two steps. Firstly the net divergence flux was calculated by integrating stepwise around the boundary. In a second step the corresponding residual was then distributed evenly around the boundary by integrating around the boundary in the reverse direction. The numerical integration on BESK and in a first version on D21 is indicated in Figure 2. The calculations require 3 fields and there are three basic calculations for each time step. Using first order accuracy a set of 3 by 3 grid points is sufficient to calculate both the geostrophic vorticity and the Jacobian. The change in geopotential given by a Poisson equation was calculated by Liebmann overrelaxation, which with the use of a linear first guess normally only required ca 10 iterations to provide a reasonable accuracy. As can be seen from Fig 2 after an initial forward time step a central time step with good accuracy was used and the method was generally applied also for the baroclinic models.

A computationally faster version of the vorticity advection model on D21 is described in Appendix A.

The first major baroclinic model used three vertical levels, the surface, 500 hPa and 300 hPa. This was found to provide a reasonable representation of developing cyclones and meant a significant improvement in the numerical predictions leading to better acceptance by the meteorological forecasters as it provided significantly better guidance in cases with severe weather. The 3-parameter model was used for more than a decade and was also used at some other meteorological services. An investigation by Bodin (1974) to optimize the three level model by means of vertical empirical orthogonal functions, confirmed the good choice of the levels at the surface, 500 hPa and 300 hPa. Further improvements were achieved later when the number of vertical levels was increased to six.

From a programming perspective the development of forecasting models within the MAC system was in several ways as easy as with a high level language such as Fortran. Special efforts were devoted to develop a generalized set of subroutines that could easily be used in different applications as well as having a special section in the memory with general physical parameters. Two different kinds of geometry were used either a polar stereographic projection or a hypothetical channel version with cyclic boundary conditions. The later version was very helpful for debugging purposes and in comparing with analytic solutions.

4.3 Objective analysis of meteorological fields

The basic algorithm for objective analysis in the SMHI NWP system until 1977 was the successive correction scheme of Bergthorsson and Döös (1955), first developed for the barotropic model on BESK. It was a data assimilation scheme where a short range forecast model state (the background field) was corrected based on deviations between observations and the background field (the innovations) in the vicinity of each grid point:

$$A_g = BG_g + \sum_{i=1}^{nobs} \alpha(r_{ig}, \rho_i)(OBS_i - BG_i) \tag{1}$$

A_g is the analysis in the grid point, BG_g is the background forecast in the grid point, OBS_i are the influencing observations, BG_i are background values interpolated to the observation positions and $nobs$ is the number of influencing observations. The empirical weighting factors $\alpha(r_{ig}, \rho_i)$ were explicitly calculated and were depending on distances r_{ig} between the observation stations and the grid points and also on the local spatial density ρ_i of observation in the vicinity of each observation station. The analysis formula was applied in iterations, or in successive analysis scans, taking the analysis from the previous iteration as the background for the current iteration, and reducing the horizontal scale of the weighting factors for each analysis scan. This approach was developed by the group at SMHI.

The successive correction method is quite empirical. It is interesting to note that Bratseth (1986) managed to mathematically prove that a successive correction scheme, similar to the one with a station density factor described above, gave a solution that converged to the more elaborate and computationally expensive optimum interpolation solution (Eliassen, 1954, Gandin, 1965).

A spatial quality control (a ’neighbour check’) was also applied to try to eliminate gross observation errors that had managed to escape the internal QC algorithms mentioned above. Based on the observed deviations from the background forecast field, a ’voting’ among neighbouring stations was set up to find any observed values that were likely to be erroneous. With the manual observation and reporting practices in the 1960’s, gross observation errors were common and failures of QC algorithms occurred from time to time. Fortunately, most mistakes by the QC algorithms were related to surface pressure observations from SHIP reports. Numerous case studies showed that the numerical forecast was less sensitive to the details in the surface pressure analysis, but significantly more sensitive to the dynamics of the upper air flow (vertical wind shear, for example).

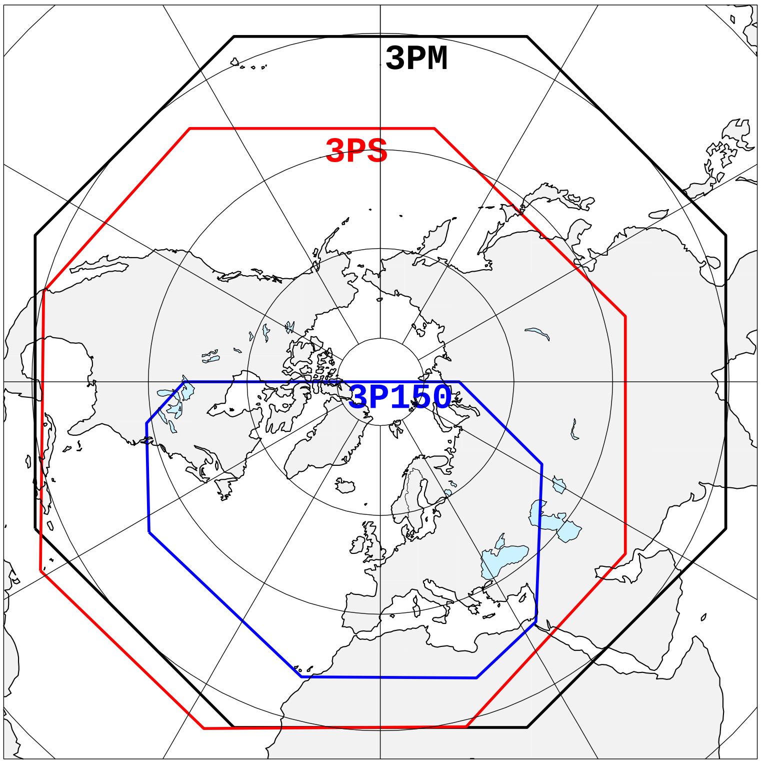

Figure 3: Model domains 3PS, 3PM and the limited area model domein 3P150 (see text)

5 Building a computer based forecasting system

The model domains for the SMHI forecasting system on the Datasaab computers in its first version during the early 1960's (the 3PS system), in its final form during the 1970's (the 3PM system) and in its high resolution limited area form (the 3P150 system) are shown in Figure 3. The 3PM area is a large domain including the whole Northern Hemisphere down to $20°N$, and the forecast model was applied at a 300 km horizontal resolution over this domain. The number of horizontal grid points was 1856. The concept of Limited Area Models (LAM) with variable lateral boundary conditions was developed by the group in the late 1960's (Bengtsson and Moen, 1971), but initially lateral boundaries had to be fixed during the forecast model integration. In order for these crude lateral boundary conditions not to contaminate the forecast quality over the 2-4 days of extended forecast range that was applied, the lateral boundaries had to be placed in remote areas with less interaction with the development of extra-tropical atmospheric waves and disturbances.

An overview of the computer based forecasting system of SMHI in the 1960's is provided in Figure 4. Most components that form modern forecasting systems of today were present already 50 years ago, although in a more primitive form, in particular with regard to input/output and telecommunication.

5.1 Decoding and quality control of observational data

The observation data available for the NWP system were radiosonde and wind profile data from land stations and ships, surface data from land and ship stations and manual aircraft data. These data were collected and distributed via the WMO WWW Global Telecommunication Sys-

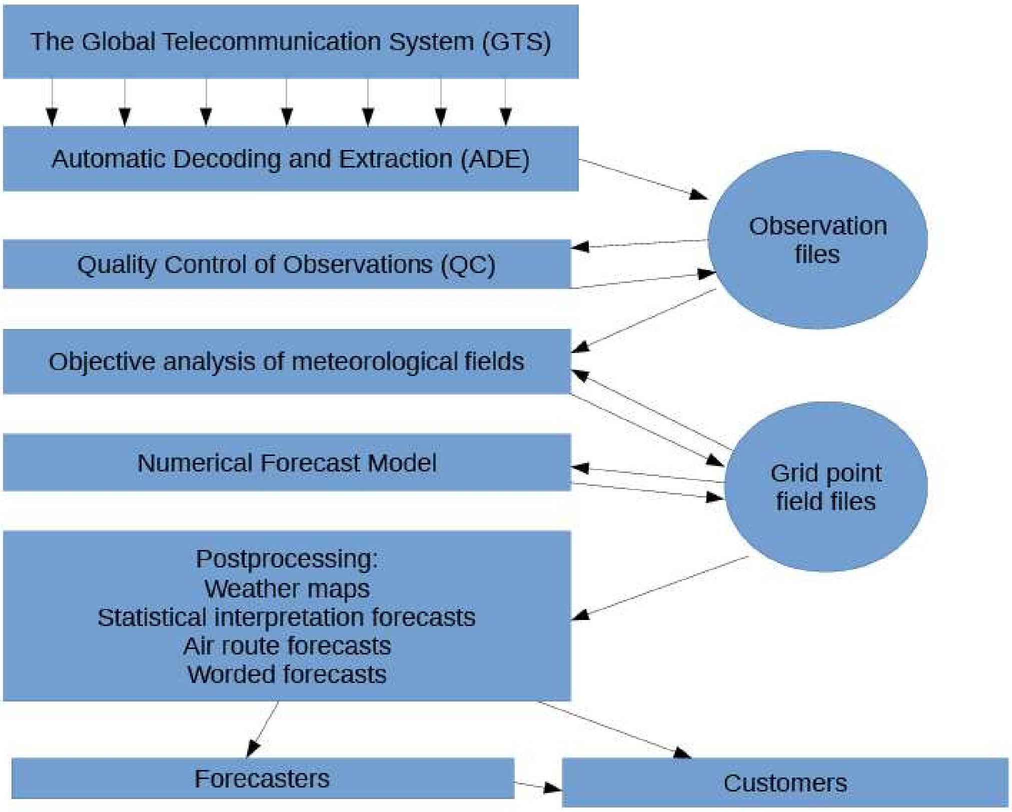

Figure 4: Components of the SMHI NWP system in the 1960's

Figure 5: Operators in action with the SMHI D21 computer, input of paper tapes with observation data

tem (GTS) in agreed upon alpha-numeric message formats (TEMP, SYNOP, SHIP and AIREP formats). The communication speed was slow, 50 baud for most of the communication lines between the weather services. All observation messages were punched on paper tapes by telex machines at the SMHI telecommunication center and then delivered manually to the computer hall (see Figure 5).

The manual handling of the paper tapes made the Automatic Decoding and Extraction (ADE) task quite challenging from a computer programming point of view. It was necessary to recover all observed data, since observations were scarce, in particular over the oceans. In order to compensate for mistakes in the manual handling of the paper tapes, the coded information coming from a piece of paper tape had to interpreted starting from the beginning of the tape, or from the end of the tape or, in both cases, as if the tape could have been read upside-down. This manual handling of observation messages and paper tapes at SMHI came to an end in 1972 with the introduction of an automatic telecommunication system, ATESTO, shared with Televerket (the Swedish authority for telecommunication), who used it for commercial telex services.

Due to the largely manual handling of measurements, visual observations, calculations, coding and typing of information at the meteorological observing stations in the 1960's, the frequency of gross errors in the transmitted messages was significantly higher than today, 50 years later, since the whole observation process to a large extent now has been automated. It was therefore necessary to design and build automatic quality control systems, that could detect and possibly also correct gross errors before the information could be utilized for numerical weather prediction. The possibilities for detection and correction of gross error depend on the degree of information redundancy in the observation messages.

A particularly powerful hydro-static quality control of radiosonde reports was, for example, made possible due to the simultaneous reporting of geopotential height and temperature data on standard pressure levels. During the 1965 WMO Conference on Numerical Weather Prediction in Moscow, Hinkelmann (1969) presented an innovative hydro-static quality control algorithm, that was coded in machine language for the Datasaab D21 computer. This QC algorithm was very successful, so the computer code was later translated (line by line) to Fortran, a coding strategy that is not recommended in general. The translated code was also used at ECMWF.

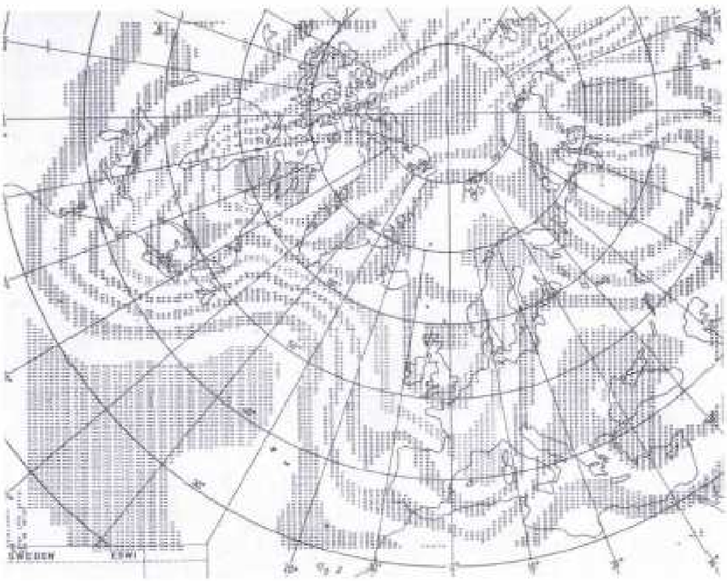

Figure 6: Example of a line-printer ’zebra’-plot

5.2 Post-processing of data

The post-processing included all further processing of data after the basic analysis and model calculations. This included graphical display of observations and grid point information on horizontal maps or on vertical diagrams, printing of information in particular formats for special users, statistical interpretation of model variables to weather parameters like precipitation and also experimental worded weather forecasts. We will mention a few such post-processing products.

Graphical display

It was not until 1970 that curve-drawing machines (plotters) for drawing of isoline maps and plotting of observations became available at SMHI. Horizontal isoline maps of the meteorological fields had to be emulated by so called ’zebra’-plots on line printer maps, see Figure 6. Special lineprinter paper with pre-printed map background was employed.

Air-route forecasts

An early direct output product for customers was tables of short range air route forecasts for the European area. These were directly formatted for the users, printed on paper tapes and distributed via telex to the airports. Since the 3-parameter model in principle only provided forecast information for 2 vertical layers up to the jet level (≈300 hPa), it was necessary to utilize additional information on vertical stability and vertical wind shear. For this reason, the objective analysis of meteorological fields was carried out for all standard pressure levels between 1000 hPa and 100 hPa.

Statistical interpretation and worded forecasts

Lönnqvist(1971) contributed with a pioneering statistical interpretation of weather parameters from the coarse resolution information provided by the 3-parameter model. His statistical interpretation method was building on a classification into weather regime classes and on the assumption that the upper air NWP forecast fields were perfect. The work of Lönnqvist also included experiments with automatically worded descriptions of the weather situations as well as worded weather forecasts. We will here give an example in Swedish with a translation to

English:

Sammanfattning och tolkning av de numeriska prognoskartorna
Väderläge den 6/5 1968 kl. 1: Inget högtryckscentrum i närheten av Skandinavien. Ett lågtryck med centrum över Norra Nordsjön utfylles. Ett annat lågtryck över södra Norrland drar i natt bort över Vita Havet. Ett nytt lågtryck bildas i natt över Kattegatt.

(Summary and interpretation of the numerical forecast fields
The weather situation 6 May 1968 13.00: No high pressure center in the vicinity of Scandinavia. A low pressure centered over the Northern Nordic Sea is filling. Another low pressure over the Southern Norrland is moving out over the White Sea. A new low pressure system is forming during the night over Kattegatt.)

6 Technical structure of the forecasting system

6.1 Constraints due to the hardware

The computer systems for numerical weather prediction at the Swedish Meteorological and Hydrological Institute (SMHI) during the 1960's and 1970's were based on DATASAAB computers D21, D22 and D23. At the start with D21 in 1963, only the hardware and a list of machine code instructions were available - no compilers for higher level programming language like Fortran existed, not even an assembler language compiler nor a linker to put different subroutines together. Everything had to be built from scratch by SMHI staff with support from DATASAAB experts.

The SMHI D21 computer from the start had a shared memory of only 12288 24-bits words for instructions and data, that later was extended to 32768 24-bits words for instructions and data. Machine code instructions were represented by 8 octal digits in the form OOIMMMMM, OO was a octal 2-digit (6 bits) operation code, I was a 1-digit octal (3 bits) indicator for indirect addressing and MMMMM the memory address. The address space $00000_8 - 77777_8$ corresponded to the maximum size of the memory of D21. Calculation instructions were only given for fixed point real numbers between -1.0 and $+1.0 - 2^{-23}$. For this reason all equations had to be scaled such that the variables obeyed the range of permitted fixed point real numbers. This scaling was efficiently taken care of by binary shifts after suitable scaling.

6.2 Programming and structuring of a complex software system

In order to make the handling of the machine code programs for the SMHI NWP manageable, it was necessary to divide the software into smaller pieces for specific tasks, similar to the use of subroutines in Fortran. Each such 'subroutine' was programmed with relative memory addressing, where the address 80000 corresponded to the first computer word of the memory space for a subroutine. Subroutines were given unique names in the form 9XXXX with XXXX being an octal 4-digit number. A machine instruction for a subroutine call was coded like 26095003. 26_8 being the octal code for jump with storing of a return address (closely corresponding to a subroutine call). 95003 was the name of a useful subroutine for handling octagonal model domains (see below).

A simple system for linking several subroutines together to create an executable machine program was developed by SMHI staff. The main tasks of this 'linker' was to search for the needed subroutines in a comprehensive subroutine library, to give each subroutine a start address and a memory space, to add this start address to the relative addresses (starting from 80000 =

relative address 0) of each subroutine and to replace the names of the subroutines (9XXXX) in the subroutine calls with their starting memory addresses.

6.3 Handling of grid point fields in model and analysis calculations

As mentioned above, the forecast model was integrated over many types of domains including irregular octagons. In order to save memory space, only grid point values inside the octagonal domain were stored in one dimensional arrays, making the calculation of finite differences in the horizontal, for example, a bit more complicated. In order to facilitate the work of the programmers, a number of efficient tools to handle grid point fields were developed.

The needed memory space for the grid point fields was statically allocated, and references to these grid point fields were simply done by a numbering 1, 2, 3, etc. Every subroutine could get access to all grid point fields ('global arrays').

Special index arrays to facilitate the calculation of finite differences over the octagonal domains were prepared by the subroutine 95003 'Ormen' (the Snake). The eight corner points of an octagonal grid point domain were defined by their the x-direction (i) and y-direction (j) indices (ic(k), jc(k), k=1,8). From this definition of the corners, the starting j-index jstart(i) and the ending j-index jend(i) for each column i of the model domain were prepared, and these index help-arrays facilitated the addressing of finite differences. One subroutine 95004 'Fältram' made it possible to carry out simple manipulations of grid point fields (similar to vector instructions in Fortran 90) and another quite complicated subroutine 95005 'Mini' helped the programmer with the memory addressing for 5-point and 9-point finite difference schemes. A very simple example of the usage of Fältram to calculate the mean value of two fields is given in subroutine 97777:

80000 00000000 ; Subroutine entry, return address is stored here
80001 26095004 ; Calling subroutine 95004 Fältram
80002 01600001 ; Fetch values from field 1 to the arithmetic register
80003 00600002 ; Add values from field 2
80004 04080007 ; Multiply by the constant 0.5
80005 06600003 ; Store in field 3
80006 22480000 ; Return jump with indirect addressing of the return address
80007 20000000 ; Fixed point number 0.5 = 2^{-1}

Note that the content of the computer words with relative addresses 80002-80005 after the call to 95004 until the return jump in 80006 should be interpreted as vector (field) instructions. Subroutine 95004 sets up the loop with these instructions over all the grid points of the field. Also note that the multiplication by a constant 0.5 could be carried out much faster with a binary shift operation (instruction 16000001 in this case).

6.4 Disposition of the small memory in model calculations, bit packing

The small memory of the D21 computer, 12288 words at the start and 32768 words a bit later, was a bottleneck for the forecast model calculations. With the 3 levels of the 3-parameter model, with the two time-levels of model fields for the leap-frog time stepping scheme, with additional fields like orography and land-sea mask and with additional work space, it was not possible to store all the required information in memory at full 24-bit accuracy. Bit-packing had to be utilized to store some fields at lower accuracy.

With the D22 and D23 computers, it was possible to utilize larger memory than originally permitted by the direct address space $00000_8 - 77777_8$ of D21. For programs written in MAC this required re-programming to utilize not only direct and indirect addressing but also index-registers for additional address information.

6.5 Connecting grid point space and observation space in the analysis - the need for efficient input/output

A system design issue in data assimilation is the organization of the selection of observations to influence each grid point value. The observations are irregularly distributed in space (and time), while the spatial distribution of model domain grid points is more regular. In early implementations of data assimilation with the successive corrections and statistical interpolation methods, influencing observations were selected locally in the vicinity of each grid point.

The local data selection for the MAC analysis had to be very fast, because the analysis was carried out through several iterative scans (successive corrections) through all the grid points, and in each scan for every model variable one needed to have access to all influencing observations in the vicinity. Two parameters were important here, the maximum influence radius R_{max} (maximum spatial distance between a grid point and the corresponding influencing observation stations) and N_{max} the maximum number of influencing observations. R_{max} = 1000 km and N_{max}=20 were typical values of these parameters in the MAC data assimilation system. In order to make the calculations fast, a list of the memory addresses and the horizontal distances to the N_{max} closest observations for each grid point was prepared in advance of the analysis calculations and was used subsequently during each analysis scan.

The list of memory addresses and distances that linked the grid point space and observation space together was too large to be stored in the small memory. To start with, it was stored sequentially on a magnetic tape that was read for every scan of the analysis calculations. With expanding number of model variables and number of analysis scans, this turned out to be very in-efficient, in particular because the magnetic tape had to be rewound to the starting point for each analysis scan. An innovative solution on D21 was to alternate between forward and backward reading of the magnetic tape and scanning through the grid points. This turned out to be very fast, and made possible only through the self-learned knowledge of the basic functions and technical possibilities of the D21 system. The availability of a disk memory on the D22 computer of course also solved this problem.

6.6 Use of the D21 loud-speaker for debugging

The control board of the D21 computer was equipped with a loud-speaker coupled to the third bit of the Multiplication Register (MR). Skillful programmers could use this loudspeaker to create wonderful music (http://www.datasaab.se/D21_D22_musik/music_eng.htm), but it could also be utilized to follow the progress of program executions. The 'sound' of the forecast model was a bit rhythmic, due to the regular switch between the right hand side calculations and the iterative solving of the Helmholz equations. In cases with a strong jet-stream, numerical instability could occur, and another sound due to switches between the iterative solver and infinite and desperate trials to smooth the fields started to occur. This was well known by the computer operators, they used to call Lennart Bengtsson, held the phone close to the D21 loudspeaker and the diagnostic remedy from Lennart to decrease the time step came quickly.

7 Back to the future

Since the NWP development at SMHI described in this report NWP has underwent an enormous development perhaps best seen by reviewing the development at ECMWF. A useful prediction (60% anomaly correlation, in fact using the 60% anomaly correlation to indicate useful forecasts was originally chosen by the forecasters at SMHI and it is still used worldwide) at ECMWF today for the Northern Hemisphere extra-tropics is ca 8.5 days in an annual average. This should be compared with similar forecasts at SMHI in the 1960's and early 1970's that was around 2.5 days. It is interesting, as has been shown by Laloyaux and Bengtsson (2015), that this was even possible to achieve for a series of 28 forecasts using observations from February/March 1965 using the ECMWF forecast model from 2015. There are indications from predictability studies that this is close to the limit of what is theoretically achievable. Similarly, prediction of extreme events such as tropical cyclones, intense rainfall and severe wind storms have also been made possible.

Equally impressive is the development in data assimilation that has contributed significantly to the huge improvement in predictive skill. This technique has also made it possible to reanalyse old weather situations in some studies going back to 1870 and might provide interesting data sets for studying the change and variation in climate on centennial time scales. Other developments in global space based observation and in computing as we can see today were not possible to foresee in the 1960's. Some of the results of this work have also influenced the development of new space based missions.

In retrospective the contribution in weather forecasting at SMHI half a century ago might seem minor but was an important step forward in the history of NWP. The intense working with the MAC system gave many of us the right sort of training and stimulation in team work and in system design that has been a source of intellectual energy. It has certainly given strength to the lead authors of this paper to continue working with enthusiasm with NWP far beyond our normal retirement age.

8 Acknowledgement

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Appendix A: Master subroutine for the barotropic vorticity advection model on D21

The barotropic vorticity advection is given by

$$\frac{D}{Dt}(\eta) = 0$$

where $\eta = \zeta + f$ is absolute vorticity, ζ is relative vorticity and f is the Coriolis parameter. Introducing the stream-function ψ, the barotropic vorticity advection may be written

$$\frac{\partial}{\partial t}\nabla^2\psi = J(\nabla^2\psi + f, \psi)$$

where J denotes the Jacobian, $J(A,B) = \frac{\partial A}{\partial x}\frac{\partial B}{\partial y} - \frac{\partial A}{\partial y}\frac{\partial B}{\partial x}$. This equation is solved by leap-frog time integration and finite difference approximations in the horizontal. After time-discretization and introduction of a polar-stereographic projection we will have

$$\nabla^2\Delta\psi^\tau = \nabla^2(\psi^{\tau+1} - \psi^{\tau-1}) = 2\Delta t J(m^2\nabla^2\psi^\tau + f, \psi^\tau)$$

where Δt denotes the length of the time-step and m the polar-stereographic map-factor. For the channel version of the model, $m = 1$ and cyclic boundary conditions are applied in the x-direction. Introducing horizontal finite differences for the Laplacian (∇^2) and the Jacobian, this equation is solved by Liebmann relaxation for each leap-frog time-step. The time-integration is started with a non-centered time-step (see Figure 2).

All calculations on DATASAAB D21 were carried out with fixed point arithmetics, such that all model variables had to be scaled to have values between -1.0 and +1.0. We will denote a scaled value of a variable ψ by $\hat{\psi}$, without going into any further details here.

The disposition of the memory during a leap-frog time-step from time $\tau - 1$ to time $\tau + 1$ is illustrated in Table 1. Note that four (4) grid-point fields are utilized for the time-integration on DATASAAB D21. This was introduced in order to speed up the computation by using an improved guess for the time-tendency in the iterative Liebmann relaxation solver. On BESK only three (3) grid-point fields were utilized due to the very small memory on that computer, but at the cost of an increased computing time (see section 4.2).

The master subroutine 90142, written in MAC, for the vorticity advection model is provided in Table 2. Note that the general field handling subroutine 95004 (Fältram), described in section 6.3 above, and also subroutines for calculation of vorticity and the right hand side as well as for Liebmann relaxation are utilized. The number of time-steps is provided as input in the Accumulator Register (AR) and the scaled input field stream-function ($\hat{\psi}$) is provided in field 4. Some constants, for example the relaxation coefficient and the relaxation residual tolerance are provided at some fixed memory adresses (corresponding to ”common” variable communication in Fortran). The subroutine also includes an option to use an empirical correction term to improve the treatment of the largest planetary scale waves resulting in a Helmholz equation instead of a Poisson equation to be solved.

A selection of D21 octal code machine language instructions are explained in Table 3.

Table 1: Disposition of the memory during time integration of the barotropic vorticity advection model

	Field 1	Field 2	Field 3	Field 4
1) Start of time-step $\tau+1$	$\hat{\psi}^{\tau-1}$		$\hat{\psi}^{\tau}$	
2) Calculate vorticity $\hat{\eta}^{\tau} = m^2\nabla^2\hat{\psi}^{\tau} + f$	$\hat{\psi}^{\tau-1}$		$\hat{\eta}^{\tau}$	$\hat{\psi}^{\tau}$
3) Calculate right hand side $\hat{RHS}^{\tau} = 2\Delta t J(\hat{\eta}^{\tau}, \hat{\psi}^{\tau})$ and tendency guess $\Delta\hat{\psi}^{\tau}$ guess = $2(\hat{\psi}^{\tau} - \hat{\psi}^{\tau-1})$ (leap-frog!)	$\hat{\psi}^{\tau-1}$	$\hat{RHS}^{\tau}$	$\Delta\hat{\psi}^{\tau}$ guess	$\hat{\psi}^{\tau}$
4) Solve Poisson equation $\nabla^2\Delta\hat{\psi}^{\tau} = \hat{RHS}^{\tau}$	$\hat{\psi}^{\tau-1}$	$\hat{RHS}^{\tau}$	$\Delta\hat{\psi}^{\tau}$	$\hat{\psi}^{\tau}$
5) Extrapolate to time-step $\tau+1$ $\hat{\psi}^{\tau+1} = \hat{\psi}^{\tau-1} + \Delta\hat{\psi}^{\tau}$	$\hat{\psi}^{\tau-1}$		$\hat{\psi}^{\tau+1}$	$\hat{\psi}^{\tau}$
6) Prepare for next time-step, move field 4 to field 1	$\hat{\psi}^{\tau}$		$\hat{\psi}^{\tau+1}$	

Table 2: Master subroutine 90142 for the vorticity advection model, MAC code and explanations

Relative adress	MAC code	Explanation
80000	00000000	Subroutine entry, the return address is stored here
80001	06080060	Save the number of timesteps (stored in AR) in work variable WORK with relative adress 80060 (see below)
80002	41080060	AR = - WORK = - number of timesteps
80003	40080061	Subtract 1 (integer representation) from AR
80004	06080057	Save AR in a loop control variable LOOP
80005	41080061	Set AR = -1
80006	46080063	Save AR in variable SIGN (to indicate first time-step)
80007	26095004	Calling subroutine 95004 Fältram
80010	01600004	AR = field 4 = ($\hat{\psi}^{\tau}$) in this time-step
80011	06600001	field 1 = AR = ($\hat{\psi}^{\tau-1}$) in the first centred time-step
80012	06600003	field 3 = AR = ($\hat{\psi}^{\tau}$) in this time-step
80013	22080014	End of parameter list for call to 95004
80014	26095004	Calling subroutine 95004 Fältram; start of new time-step
80015	01600003	AR = ($\hat{\psi}^{\tau}$)
80016	46600004	field 4 = AR = ($\hat{\psi}^{\tau}$) (save for later use)
80017	22080020	End of parameter list for call to 95004

Relative adress	MAC code	Explanation
80020	26090401	Calling subroutine 90401 for calculation of absolute vorticity ($\hat{\eta}$)
80021	00000303	Input field = 03 ($\hat{\psi}^{\tau}$); over-written by output field = 03 ($\hat{\eta}^{\tau}$)
80022	52080060	MR = 0 (to allow tests on AR only)
80023	01080063	AR = SIGN (to indicate first, second or other time-step)
80024	26090123	Call subroutine 90123 for calculation of the right hand side ($R\hat{H}S$);
		Output field 2 = $R\hat{H}S$ and output field 3 = $\Delta\hat{\psi}^{\tau}$ guess
80025	26091114	Call subroutine 91114 for Liebmann relaxtion;
		Output field 3 = $\Delta\hat{\psi}^{\tau}$ final tendency
		Input variables for 91114:
80026	00007242	First octal digit indicates type of equation
		(0 for Poisson, 1 for Helmholz) + adress of Helmholz coeff.
80027	00007240	Adress of relaxation factor
80030	00007241	Adress of residual tolerance
80031	26095004	Calling subroutine 95004 Fältram
80032	01600003	AR = $\Delta\hat{\psi}^{\tau}$
80033	16000006	AR = AR $\times 2^{-6}$, tendencies are scaled by
		2^6 for calculation accuracy reasons
80034	00600001	AR = AR + $\hat{\psi}^{\tau-1}$ = $\hat{\psi}^{\tau+1}$
80035	06600003	Store AR in field 3 = $\hat{\psi}^{\tau+1}$
80036	22080037	End of parameter list for subroutine 95004
80037	41080061	AR = -1
80040	07080063	Add AR = -1 to SIGN
80041	63080046	Jump if AR is negative
80042	26095004	Calling subroutine 95004 Fältram
80043	01600004	AR = field 4 = $\hat{\psi}^{\tau}$
80044	06600001	Field 1 = AR = $\hat{\psi}^{\tau-1}$ in next time-step
80045	22080046	End of parameters for subroutine 95004
80046	01080062	AR = 2
80047	07080063	Add AR to SIGN
80050	21080057	Add one to time step counter LOOP
80051	62080014	In case more time-steps are to be executed, jump back to 80014
80052	26095004	Calling subroutine 95004
80053	01600003	AR = field 3 = $\hat{\psi}^{\tau+1}$
80054	46600004	field 4 = AR = $\hat{\psi}^{\tau+1}$ (final result for output)
80055	22080056	End of parameters for subroutine 95004
80056	22480000	Return jump out of subroutine
80057	00000000	Loop control variable LOOP
80060	00000000	Work variable WORK
80061	00000001	Constant=1 integer representation (2^{-23})
80062	00000002	Constant=2
80063	00000000	Work variable SIGN

Table 3: A selection of Datasaab D21 octal code machine language instructions. Indicator I is used for indirect adressing, I=4 for indirect adressing and I=6 for indirect adressing with addition of 1 to the adress stored in MMMMM

Octal instruction code	Operation
00 I MMMMM	Add content of MMMMM to AR (Accumulation Register)
01 I MMMMM	Store content of MMMMM in AR
04 I MMMMM	Multiply AR with content of MMMMM and store in AR and MR (Multiplication Register)
06 I MMMMM	Store content of AR in MMMMM
07 I MMMMM	Add content of AR to content of MMMMM
15 0 NNNNN	Shift AR NNNNN steps (bits) to the left
16 0 NNNNN	Shift AR NNNNN steps (bits) to the right, the first bit of AR (the sign bit) is not changed
21 I MMMMM	Add 1 to content of MMMMM. The sign of the results is stored in the Sign indicator (1 for negative values else 0)
22 I MMMMM	Continue execution from adress MMMMM
26 I MMMMM	Continue execution from adress MMMMM+1 and store current instruction adress +1 in adress MMMMM (”subroutine call”)
40 I MMMMM	Subtract content of MMMMM from AR
41 I MMMMM	Set AR=0 and subtract content of MMMMM from AR
46 I MMMMM	Store content of AR in MMMMM and set AR = 0
52 I MMMMM	Store content of MR in MMMMM and set MR = 0
62 I MMMMM	In case the sign indicator is = 1, continue execution from adress MMMMM; The sign indicator is set by earlier instructions, for example instruction 21 used for loop control
63 I MMMMM	In case AR is negative, continue execution from adress MMMMM

Appendix B: People and social life from the perspective of a newcomer

The Numerical Weather Prediction (NWP) group at SMHI in November 1967 was a small group of meteorologists and programmers. Lennart Bengtsson was the leader and he worked with the development of the forecast model together with Lars Moen. Bo Döös, the pioneer from the BESK era, had already left for Stockholm University and Tomas Thompson had left for WMO in Geneva. Paul Jacobsson was a real programming guru, and specialized in software for Automatic Data Extraction and for graphical display of data. Gunnar Bleckert was responsible for planning of future computerized telecommunication. Ann-Beate Henriksson was one of the two females of the group, one of her specialties was trajectory calculations. Kerstin Sandberg-Fabiansen was our secretary and she took care of us all. When I arrived at SMHI, I was offered a desk close to the office of Bo Lindgren. Bo Lindgren was responsible for 'the Master' software that monitored the flow of NWP calculations and he was also handling the post-processing software. Bo was socially talented, providing the social glue that kept the group together.

The computing skill of the SMHI NWP group was widely recognized. Once Paul helped the oceanographic group to interpret information on a magnetic tape from US colleagues. With the close knowledge of the hardware, all magnetic information on the tape was interpreted. A printout turned out to include secret information on nuclear missile simulations after the information of importance for the oceanographers. An agent from the Security Police arrived and his innocent question was: 'How did you manage to read behind the End-Of-File?'

Olov Lönnqvist was a remarkable person. He was head of the meteorological division, he was President of the Commission for Basic Systems of WMO, but he seemed most happy when he developed software for statistical interpretation and worded weather forecasts behind the closed door of his office.

Daniel Söderman from from Helsinki University in Finland had contributed very much to the first version of SMHI NWP system on the D21 computers. In 1967 he was working as a consultant, mainly with the objective analysis software. One morning during my first months at SMHI he entered my office in Stockholm, coming directly from the Finland ferry and full of lively energy. He throw over a box with paper tapes containing new machine language programs for objective analysis to me and said: 'Debug this, please!'. This was a tough (but very instructive) start in data assimilation for a newcomer from the university, with knowledge mainly in mathematics and basic Fortran programming. There came a happy end. After a year or so, we could celebrate a new version of the forecasting system in my second hand flat at Lidingö, a suburb of Stockholm. Bo organized a real Swedish Thursday dinner, yellow pea-soup with 'punch' (a sweat drink) and pancakes with black currant aquavite. Late at night I could hear Daniel, with a big glass of aquavit, murmuring about the poor quality of the red wine (mild translation). The party ended after sunrise next day, but this great celebration was certainly deserved after a long and dedicated effort with the new forecasting system.

The working conditions for a newcomer in the SMHI NWP group, under the leadership of Lennart and Lars, were excellent. I followed the university education in meteorology and I was allowed to freely explore the scientific literature and to make basic experiments with new data assimilation techniques (Freedom under responsibility!). This was very useful for the design of the future generation NWP system for SMHI, a work that also Per Kållberg was involved in with a first version of a limited area model based on the primitive equations.

The work in the SMHI NWP group had strong international links. As a newcomer, I heard many stories about events during the WMO World Conference on NWP in Moscow and during an International Exhibition in Praha 1966 where Datasaab showed a D21 computer with on-line numerical weather forecasting, operated by SMHI staff. The links with Finland, now with Daniel as the head of the NWP group at FMI, continued to be close. FMI procured a Datasaab computer, and the NWP system was shared with SMHI. Before the start of operational NWP in Finland, Paul and I were invited as consultants to assist. Late one evening before the operational start, we were desperately trying to find the 'last bug'. Daniel entered, very energetic after a soccer game, and shouted: 'Hurry up dear boys, the computer is idle!!'

Collaboration between the Nordic countries has always been important in NWP. During the 1960's and 1970's this collaboration was handled by the Nordic Working Group on NWP with Lennart from SMHI, Daniel from Finland, Odd Haug from Norway, Walther Larsen from Denmark and Pall Bergthorsson from Iceland. The collaboration was also widened and several educational international workshops on NWP were arranged by SMHI. Kamel El Sawy from the weather service in Egypt was participating in one of these workshop and he was also staying for a longer period carrying out a simulation of cyclogenesis in the lee of Cyprus together with Bo Lindgren. I have very pleasant memories of a sailing tour to the Island of Lovön one summer evening with Kamel, Lennart and Bo. We had an evening meal at the Castle of Drottningholm and we were slowly sailing home along Lake Mälaren in the moonshine. Three young men jumped into the water and were swimming after the sailing boat connected with a rope. Kamel was given the responsibility for steering the sailing boat. He looked very frozen up there in the boat, possibly dreaming about Slow sailing on the River Nile.

Nils Gustafsson

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