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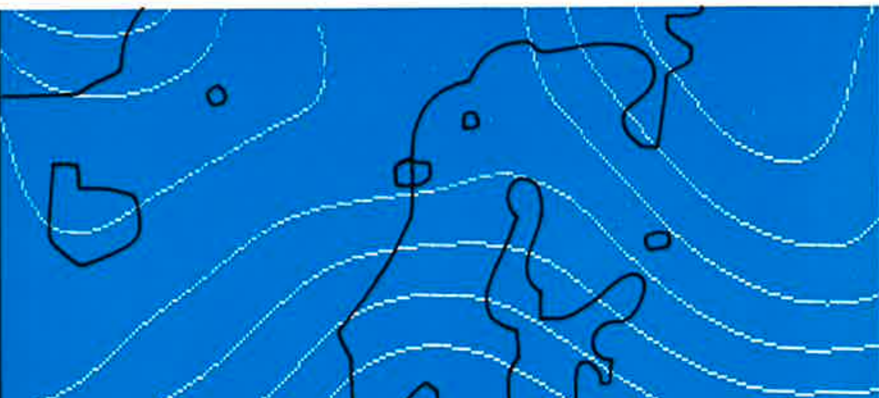
ND NEWS

SPECIAL ISSUE ON METEOROLOGY



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DECEMBER 1972 - No. 6

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ND-NEWS is a quarterly magazine published by A/S Norsk Data-Elektronikk, a Norwegian manufacturer of computers. The purpose of ND-NEWS is to promote new ideas in computer applications and to be a forum where specialists from any field can present their problems and achievements.

In February this year A/S Norsk Data-Elektronikk delivered a multicomputer installation to the Norwegian Meteorological Institute. This edition of ND-NEWS wants to focus on the activities going on in the meteorology sector today and is solely devoted to meteorology and meteorological data processing.

Some of the articles are addressed to the meteorologists, e.g. "Atmospheric Predictability" by Professor Wiin-Nielsen. The subject, however, concerns all of us, and the results, as well as the prediction methods introduced, are worthwhile to be studied by the non-meteorologist.

In the article, "NORDIC — The Multicomputer Installation at the Norwegian Meteorological Institute" the NORD Integrated Computer System is explained. Three identical computers and a special fast compute module share the working load at the meteorological centre. The idea is to have several possibilities for backup of important routines while each of the four computers is devoted to special tasks in a normal situation.

"Meteorological Telecommunication" questions some of the ideas in the Global Telecommunication System now to be realized around the world. The article also gives examples of how the telecommunication problem is being solved at the national centre in Norway.

"On the Use of a Medium-Sized Computer for Numerical Weather Prediction" the numerical weather analysis for a national centre is outlined.

And finally, an article which really needs no introduction is the interview with Dr. Ph. Ragnar Fjörtoft about his works and life: "A Look at Modern Meteorology". Read it!

ND-NEWS est une revue trimestrielle publiée par A/S Norsk Data-Elektronikk, constructeur norvegien d'ordinateurs. La redaction de la revue favorise la presentation de systèmes et d'applications d'ordinateurs. La facon la plus fructueuse d'echange d'idées se fait au cours de reunion entre specialistes de differentes milieux techniques et philisophiques: c'est une experience souvent demontrée. La redaction de ND-NEWS s'efforce d'offrir de telles possibilitees à ses lecteurs.

En fevrier, cette année, A/S Norsk Data-Elektronikk a delivré un système multi-ordinateurs à L'institut de Météorologie Norvegienne. Nous desirons par la mème occasion attirer l'attention de nos lecteurs sur les activitées du secteur météorologique. Ce numero est entièrement dédié à la météorologie, et à l'emploi d'ordinateurs et de l'informatique dans ce domaine.

Certains de ces articles sont adressés aux meteorologistes, par exemple "Atmospheric Predictability" du Prof. Wiin-Nielsen. Mais le sujet traité nous conserne tous. L'article donne une vue sur les differentes methodes employées dans la météorologie; il presente les limites theoriques et practiques sur le nombre de jours par lesquels il est possible de predire le temps.

Dans l'article "NORDIC — The Multicomputer Installation at the Norwegian Meteorological Institute", nous presentons le principe des systèmes multi-ordinateurs. NORDIC est consisté de trois ordinateurs identiques, et d'un ordinateur très rapide. Ces quatre ordinateurs se partagent le travail. L'idée est, entre autre, de donner des possibilitées de securité et de reserve (normalement chaque ordinateur a ses programmes spéciales et bien définis. En cas d'arrêt impreuve de l'un d'eux, un autre ordinateur peut prendre le travail important de celui-ci).

"Meteorological Telecommunication" pose differentes questions sur certain principes dans lesquels est etablié le "Global Telecommunication System" (GTS). GTS est un système international de communication et echange d'information météorologique. L'article donne aussi une vue sur la façon dont a été resolue le probleme de telecommunication météorologique au centre national de Norvège.

"On the Use of a Medium Sized Computer for Numerical Weather Prediction" montre comment un petit pays se sert de l'ordinateur pour des analyses et des prognostics, en employant des methodes dynamiques ainsi que statiques.

Le premier article de ce numero special, n'a probablement pas besoin d'introduction. C'est un interview de Dr. Ph. Ragnar Fjörtoft: sa vie, ses traveux scientifiques: "A Look at Modern Meteorology" est recommendé!

Журнал *Новости техники счетно-электронных машин*, издаваемый *А/О Норвежская счетно-электронная аппаратура*, выходит одни раз в квартал. Названное выще акционерное общество является одновременно и производителем счетно-электронного оборудования в Норвегии. Основную свою задачу журнал видит в ознакомлении потребителей с системами и применением счетно-электронной аппаратуры. Практика покаэывает, что наиболее плодотворной формой обмена идеями является личное общение между специалистами, представляющими различные взгляды и общественные формации. Журнал *Новости техники счетно-электринных машин* как раз и стремится стать своего рода посредником в обмене идеями в области счетно-электронной техники.

В феврале 1972 г. *А/О Норвежская счетно-электронная аппаратура* поставило Норвежскому Институту Прогнозов комплексное электронно-вычислительное оборудованне. В связи с этим мы хотели бы обратить ваше внимание на активность, проявляемую в области метеорологических исследований. Учитывая эту возросшую активность, мы и выпускаем специальный номер журнала, целиком посвященный метеорологии и обработке метеорологических данных с помощью счетно-электронных машин.

Отдельные статьи журнала непосредственно обращаются к метеорологам. В качестве примера можно назвать статью профессора Вин-Нильсена *Атмосферные прогнозы*. Однако вопросы, затрагиваемые в этой статье, имеют значение не только для узкого круга специалистов. Профессор Вин-Нильсен дает точное описание некоторых методов обработки данных и проводит границу теоретических и практических возможностей предсказывания погоды на более длительный срок.

В статье *Нордик-комплексная счетно-электронная установка Норвежского Метеорологического Института* излагаются принципы работы сложных электронно-вычислительных устройств. Комплексное оборудование состоит из трех одинаковых машин и одного скоростного вычислительного устройства. Запрограммированная работа равномерно распределяется между этими четырьмя машинами. Движущим принципом системы является обеспечение запасных возможностей при выполнении основного программирования. Этим достигается устранение непредвиденных случайностей при выполнении каждой отдельной машиной специально запрограммированного задания.

В статье *Метеорологическая телесвязь* анализируются принципы, на основании которых создана Международная Система телесвязи (МСТ). МСТ обеспечивает бесперебойный обмен метеорологическими данными, поступающими со всех концов земного шара. В статье указывается также, каким образом проблемы телесвязи решены в Норвегии.

В статье *Об использовании компьютера средней мощности для обработки данных по прогнозам погоды* отмечается, каким образом в условиях малой страны можно применять электронно-вычислительную аппаратуру при анализе и прогнозах димаництескими и статистическими методами обработки данных.

В заключение укажем, что статья, которой открывается этот номер журнала, не нуждается в специальном вступлении. В ней просто приводится интервью с доктором философии Рагнаром Фьертофтом, который рассказывает о своей жизни и научных трудах. Статья озаглавлена *Взгляд на современную метеорологию*. Мы рекомендуем ее вашему вниманию.

*

ND-NEWS es una publicación trimestral edita por A/S Norsk Data-Elektronikk, un producente noruego de calculadores digitales (ordenadores). El objeto principal de la publicación es presentar sistemas y aplicaciones de los calculadores. La práctica ha demostrado que el camino hacia un desarollo más fructuoso es la comunicación e intercambio de ideas entre especialistas de diferentes ambientes y con distinto fondo en diálogo cuando se reunen. ND-NEWS se propone ser un tal foro para cambio de ideas.

En Febrero del corriente año A/S Norsk Data-Elektronikk entregó a Det Norske Meteorologiske Institutt (Instituto Meteorológico Noruego) un multi-sistema de ordenadores. En tal ocasión deseamos dirigir la atención hacia la actividad que hoy día se está ejerciendo en el sector de meteorología, y presentar una publicación especial consagrada en su totalidad a la meteorología y la utilización de ordenadores con relación a datos meteorológicos.

Parte de los artículos son dirigidos a los meteorólogos. Por ejemplo "Atmospheric Predictability" (Probabilidad de pronóstico atmosférico) por el profesor Wiin-Nielsen. No entanto, el tema que se trata nos atañe a todos. Se hace una exposición clara sobre el límite, tanto teórico como el práctico, de cuantos días en adelante es posible pronosticar el tiempo.

En el artículo, "NORDIC — The Multicomputer Installation at the Norwegian Meteorological Institute", (NORDIC — la Instalación Multicalculadora en el Instituto Meteorológico Noruego), se explica el principio sobre compatibilidad de ordenadores. NORDIC se compone de un equipo compuesto por 3 ordenadores idénticos y de una unidad calculadora rapidísima. Estas cuatro unidades reparten el trabajo entre sí. La ides es tener varias posibilidades en reserva para rutinas de importancia caso apareciera algún problema inesperado, en cuanto cada unidad estuviera acupada en su rutina especializada.

"Meteorological Telecommunication" (Telecomunicación Meteorológica) plantea unas cuestiones sobre algunos de los principios según los cuales se basa "The Global Telecommunication System (GTS)" (El Sistéma Global de Telecomunicación, "GTS"). GTS es una red mundial de datos para intercambio de informaciones meteorológicas. El artículo, además, da ejemplos de cómo el problema de telecomunicación, en el centro nacional de Noruega, ha sido solucionado.

El artículo "On the Use of a Medium Sized Computer for Numerical Weather Prediction" (Acerca de la utilización de un calculador (ordenador) de tipo medio para pronóstico numérico del tiempo) demuestra cómo un pequeño país utiliza el sistema calculador digital para análisis y pronósticos por métodos tanto dinámicos así como estadísticos.

Y por fin, el artículo que encabeza la publicación, en realidad, huelga darle introducción alguna. Es una entrevista con el Dr. Phil. Ragnar Fjörtoft sobre su vida y trabajos al servicio de la ciencia: "A Look at Modern Meteorology", (Un vistazo a la meteorología moderna). Lo recomendamos sin reserva.

A look at modern meteorology

AN INTERVIEW WITH DR. PHILOS. RAGNAR FJØRTOFT

Dr. Ragnar Fjørtoft, Director of the Norwegian Meteorological Services and Professor at the University of Oslo, was born in Oslo in 1913. He completed his Masters Degree in 1940, and was by that time already engaged as a forecaster at the Meteorological Office in Bergen where he worked until 1946. From 1946 to 1949, he was a forecaster at the Meteorological Institute in Oslo. From 1949 to 1951, on leave from the Meteorological Institute, he worked as a research associate at the Institute for Advanced Study, Princeton. In 1951 he was created Doctor of Philosophy at the University and in 1952 he became professor in meteorology at the University of Copenhagen. In 1955 he became Director of the Norwegian Meteorological Services, a position he still holds, he is also professor in the Meteorology Department at the University of Oslo.

When ND-NEWS asked for an interview with Dr. Fjørtoft, the answer was, "Come anytime!" We met him in his office at the Meteorological Institute in Oslo. The Institute is situated near the campus of the University of Oslo, in a pleasant park with quiet surroundings.

As director of an institution with 500 employees, three main divisons, Oslo, Bergen and Tromsø, some 15 airport offices, two weather ships and 134 telegraphing observation stations. Dr. Fjøtoft is a man who reaches over everything and who has time for all. He is a careful listener and takes his time with every question. We understand why he is praised as a teacher, researcher and director!

ND-NEWS: Dr. Fjørtoft, without exaggeration we may say that your life has been dedicated to meteorology. First as a forecaster, then research worker, professor, and now director for the Meteorological Services in Norway.

The intention of this interview is to get first-hand information on some of the events in modern meteorology and particularly the branch in which you have participated. May I start this interview by asking you about your life as a student in Oslo? When did you decide that meteorology would become your field?

Dr. Fjørtoft: I decided for meteorology after having studied zoology and mathematics for two years. I came in contact with Vilhelm Bjerknes and his assistant Einar Høiland. Bjerknes, Høiland, and Halvor Solberg, who was the professor in Meteorology and who gave lectures in hydrodynamics and meteorology at the Astrophysical Institute. I had also a friend who was in that group, Professor Eliassen, and we became very interested in hydrodynamics and meteorology.

ND-NEWS: Vilhelm Bjerknes, what professorship did he have?

Dr. Fjørtoft: He did not have any professorship at the University, but funds from the Carnegie Foundation which allowed him to work on his textbooks in theoretical physics. One volume has appeared, and the plan was to continue this work with the help of his assistant, now Professor Høiland. However, only the lectur notes became available. The way Vilhelm Bjerknes looked upon hydrodynamic phenomena in the atmosphere was very instructive. He liked to understand the phenomena in simple terms.

ND-NEWS: When was this?

Dr. Fjørtoft: This was in 1935.

ND-NEWS: With teachers as Solberg, Høiland, and Bjerknes, your studies must have been very interesting. Can you say who inspired you most?

Dr. Fjørtoft: Professor Høiland, and the rest of the group around Vilhelm Bjerknes. It consisted of some students who were very concerned with these topics, and dedicated to meteorology. Then there was Professor Halvor Solberg who was a very instructive lecturer, in his way.

ND-NEWS: Was Professor Høiland recognized outside Norway at that time?

Dr. Fjørtoft: At that time he was too young, but his scientific papers made him well known quite rapidly.

ND-NEWS: What was your first publication?

Dr. Fjørtoft: That was my Master Thesis which was published in "Meteorologiske Annaler" (1). This was a work on stability problems. My next publication was also on stability problems in the atmosphere (2), and then it was, I guess, my Doctoral Thesis (3) in 1950.

ND-NEWS: You finished your studies in 1940?

Dr. Fjørtoft: Yes, at that time I was already employed in the meteorological service. Those who had attended the practical course led by Professor Sverre Pettersen, were appointed before the final graduation. There was a great need for meteorologists because of the increased importance of forecasting for aviation.

ND-NEWS: Professor Sverre Pettersen, was he in Oslo also?

Dr. Fjørtoft: No, he was Chief of the Weather Forecasting Bureau in Bergen. From 1938 to 1939, however, Professor Sverre Pettersen gave a course in practical meteorology in Oslo. These lectures were later to become his first book. Professor Eliassen, the late Professor Bjørgum, and several other well known meteorologists from all over the world took part in this course. But then came the war.

ND-NEWS: How were the conditions for the meteorological service during the war?

Dr. Fjørtoft: There was no forecasting made by Norwegian meteorologists, it was taken over by the occupation forces, but the climatological work continued, and the work in the field stations. We had a lot of time for scientific work.

ND-NEWS: Professor Godske told about field work that the institute did in meteorology. Did you participate in any of these programs?

Dr. Fjørtoft: Yes, I came to Bergen in the spring of 1939, Godske was professor in meteorology at the Institute of Geophysics. This was before it became the University of Bergen. He was very interested in local meteorology and organized systematic investigations in Bergen and the surroundings. I remember my route was to start at Solheimsviken about 4 o'clock just before sunrise and walk along a path to Laksevågmountain, and then back to Bergen again, and then up again to the top of the Løvstakken mountain. I measured the temperature at the ground and two meters above the ground along the route in order to find the influence of the night cooling. On the way to the mountain top. I measured an inversion of 10° C which I found very sensational at that early time of my career as a meteorologist. This was very early in the morning and there were very few people walking in the mountain at that time of the day. Only some German soldiers were watching when I came with this Assmann Psycrometer, you know it makes quite a noise!

ND-NEWS: I guess the guards were very suspicious.

Dr. Fjørtoft: Yes, they were. I was afraid, because at that distance they might have the opinion that I had some kind of weapon.

Well, these were useful investigations.

ND-NEWS: From 1946 you were back in Oslo, and at the same time Dr. Charney came to Norway with a scholarship. On what occasion did he come to Norway?

Dr. Fjørtoft: I cannot recall it exactly. You know, he had studied with Professor Holmboe and Jack Bjerknes at the University of California, and had written his Doctoral Thesis on stability of baroclinic waves. I guess Professor Holmboe and Jack Bjerknes with their ties to Norway and with their connection with Høiland and Eliassen and, to some extent, myself may have encouraged Professor Charney to go to Oslo and continue his work there.

ND-NEWS: Was it difficult to be a forecaster and at the same time a scientist?

Dr. Fjørtoft: I liked very much to work as a forecaster. I found it particularly inspiring as a forecaster to watch the developments in the atmosphere on the weather maps, in light of the theory.

ND-NEWS: Your work, published in 1950 about the baroclinic disturbances (3), was this a thing had occupied you for a long time?

Dr. Fjørtoft: Oh yes, I started already in Bergen, and during the war there I got most of the ideas for my Doctoral Thesis.

ND-NEWS: The work of Charney, Eady and yourself supplement each other to some degree. Did you have any connection with the other two?

Dr. Fjørtoft: No, I did not know of the work of Eady and Charney at that time. My Doctoral Thesis represented, first of all, a systematic application of a certain method to different wave and stability problems. With this method I was able to give some new results and some accurate proofs of stability.

ND-NEWS: In 1949 you became a research associate at the Institute for Advanced Studies. Can you tell something about the Institute and the time you spent there?

Dr. Fjørtoft: I was with a group there led by Professor von Neumann, with Dr. Charney as the leading meteorologist.

ND-NEWS: This was at Princeton?

Dr. Fjørtoft: Yes, and it was a certain government project with the use of the Princeton electronic computer, which was really the first efficient computer after the ENIAC.

ND-NEWS: We know they worked on this Princeton-IAS-computer for a long time, but was the computer ever completed?

Dr. Fjørtoft: Well, it took quite a lot of time to finish it, too long as I understand it, I mean, year after year. They had the goal of finishing it at a certain time, and then they set a new goal, and so on. We got a saying about "von Neumann's Constant". This is the period of time the designer specifies that it takes to complete a computer whenever you ask him. So we went to Aberdeen in Maryland where they had the ENIAC and made the first forecast on an electronic computer, based on the so-called barotropic model. It took 24 hours to finish a 24 hour forecast. Today it takes half a minute on the best computers. We had to shuffle cards and you could see the accumulators in the computer in the dark room. You had to have it dark so that the operator could follow the lights to see whether the machine worked correctly or not. It was rather amazing.

ND-NEWS: Did it strike anyone as a sensation when the group made this numerical prognosis?

Dr. Fjørtoft: It was rather well known to the meteorological community in the United States that this group was there to carry out the experiment. When the results were published (4), the big surprise to many scientists was that the results of the integration, which was based upon real data, verified so well. It took 24 hours but, of course, we realized that after a few years this would be reduced very much.

ND-NEWS: How was the Institute for Advanced Studies concerned with meteorology?

Dr. Fjøtoft: The Institute for Advanced Study is a free scientific institution for leading mathematicians, physicists, philosophers, economists, and political scientists. A decision had then been made as a government project, to build an electronic computer and to use this for meteorology. The project was located at the Institute for Advanced Study, but it had nothing to do with the institute itself. Of course, some people there, as for instance the leader of the Institute, Professor Oppenheimer, got very interested. Dr. Charney gave lectures at the Institute and informed them about what we were doing. Von Neumann was a member of the Institute; he was one of the first members and very well known. The fact that this very well known mathematician and physicist took an interest in meteorology had tremendous implications for raising the prestige of meteorology in the United States and elsewhere. He played a role similar in some respects to the one that V. Bjerknes played many years earlier in Norway. As you may know, meteorology was not considered as an exact science in many countries.

ND-NEWS: Von Neumann is today referred to as one of the fathers, perhaps the father, of the programmable electronic computer. Did he also have any knowledge of meteorology?

Dr. Fjørtoft: With his fabulous brain and with his background as a physicist and of course, he knew very much of hydrodynamics, it was not so difficult for him to be acquainted with the major problems we had to deal with in order to integrate the equations. For instance, he was the one in the group who formulated the boundary equation which is necessary for making a unique solution for a limited area.

ND-NEWS: In 1951 you became a Doctor of Philosophy at the University of Oslo, and in 1952 professor in meteorology at the University of Copenhagen. Was it here that the "Fjørtoft-method" (6, 8) originated?

Dr. Fjørtoft: At least the paper on this method was written in Copenhagen.

ND-NEWS: This graphical method introduced by you, can it be elaborated any further?

Dr. Fjørtoft: It can but it is of no use. I mean, nobody would think of doing this now.

ND-NEWS: But some institutes use it even today.

Dr. Fjørtoft: Oh yes, but they do not have an electronic computer. The importance of this method was in the first place to pull a number of meteorologists into the field of numerical weather forecasting. They saw they could do some of these integrations in a simple way, and they became devoted to the field.

ND-NEWS: Your work on two-dimensional flow published in "Tellus" in 1953 (7) has new currency these days. Can you explain the essential point of this work?

Dr. Fjørtoft: This is a paper on how you would expect changes in the spectral distribution of energy to take place in a non-divergent, two-dimensional flow. This assumption in the first approximation then makes it applicable to the horizontal flow in the atmosphere, particularly about the 500 millibar surface. It is a rather short paper, but this principle there of energy flowing in both directions of the spectrum is rather interesting. This as in contrast to the three-dimensional spectral change of energy.

ND-NEWS: Your institute introduced the electronic computer in meteorological routines very early. When did you get your first computer?

Dr. Fjørtoft: We got it eleven years ago; this is the computer which has now been replaced.

ND-NEWS: In which area has the computer become most useful?

Dr. Fjørtoft: The first years it was in forecasting routines. Later these forecasts became available also from other sources. Therefore, special forecasts, forecasting of waves in the North Sea, temperature, etc., became relatively more important; and of course, all our work with application of past weather data.

ND-NEWS: If you think back to the first attempt to solve the equations governing the atmosphere, has the development gone slowly or rapidly since that time?

Dr. Fjørtoft: For some I think it has gone more slowly than expected; because they might have been too optimistic. It depends upon to whom you put this question.

ND-NEWS: Well, we are asking you, since you have participated from the beginning and, have watched the development carefully.

Dr. Fjørtoft: I did not belong to those who were too optimistic, so I consider the development as quite astonishing, particularly the forecasts based on the more advanced physical models and computers. What they noticed in the United States when they went over to a new model with more levels and primitive equations and a smaller distance between the grid-points was a sudden improvement in the goodness of the forecast. Further development will depend on a greather understanding of some of the physical processes, as for instance, the exchange between the atmosphere and the underlying surface. It also depends very much upon the data coverage. There is no doubt that when the forecasts go badly wrong, this is due to a combination of lack of knowledge of the state of the atmosphere and proper data.

ND-NEWS: You think that observations and the understanding of the atmosphere is the most important for getting better forecasts?

Dr. Fjørtoft: I have no opinion of what is the most important, but I will tell you that this is one of the major tasks for the groups that prepare GARP (Global Atmosphere Research Program). They are trying to find out what are the main reasons why we do not proceed and improve the forecasts significantly. Is it mainly because of the models which are not physically so sound as they should be, or is it mainly because of lack of knowledge of the atmosphere, or is it both? Why does the forecast go wrong after 4—5 days; this we really do not know, and there are many problems to be solved.

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NORDIC - The Multicomputer Installation at the Norwegian Meteorological Institute

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Cand. mag. mathematics, physics, and geophysics. University of Bergen 1963.
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Systems Analyst A/S Norsk Data-Elektronikk 1971 — present.
Published several papers on subjects radar-radio-meteorology and on-line data processing.

In February of this year, A/S Norsk Data-Elektronikk delivered the second phase of the NORDIC (Nord Integrated Computer System) to the Norwegian Meteorological Institute in Oslo. Phase 1, which has been successfully running for a year, was a single NORD-1 computer with a mass storage and telecommunication equipment. This computer is connected to the national teleprinter net and will be connected to the Global Telecommunication System when the lines are ready. The first NORD-1 is now directly integrated to three other computers which comprise a total NORDIC system. This system will cover all the Meteorological Institute's operational needs for telecommunication, high reliability back-up, data processing and large file storage and very high speed computing.

In this article, reference will be made to each of the four computers which constitute the NORDIC installation. The software system will be described and examples given of how jobs are run on the multicomputer installation. Lastly, the different tasks for the new computer will be elucidated.

THE NORDIC SYSTEM

The computer installation is shown schematically in *figure 1*. Three of the processors are identical NORD-1 computers connected to the very fast compute module NORD-5. NORD-5 has 64 32 bit general registers that can be arranged as 64 fixed point or 32 floating point registers with 64 bits. Floating Point multiply takes 950 ns and floating point divide 4 μs. One of the three NORD-1's is dedicated for telecommunication work. The two other NORD-1 computers share the work load generated by the operating system, program testing, computation etc. All computational jobs are routed to the system work horse, the NORD-5. Any NORD-1 can be immediately console switched to take over any of the other duties, thus giving a high system availability for time-critical observations.

The guiding principle in the NORDIC system is that there should always be a back-up method for running important programs, without having duplicate units standing idle. Parts of the system can be phased out for maintainance or repair, while the rest of the system still takes care of important jobs.

The telecommunication processor

Figure 2 shows schematically the complete NORDIC system delivered to the Meteorological Institute in Oslo. To the left, is shown the telecommunication processor. It consists of a 16K 16 bit core memory, a 256K Drum, connected to the national teleprinter net and Modem to be connected to medium speed lines to Bracknell in England and to Copenhagen in Denmark respectively. The teleprocessor will:

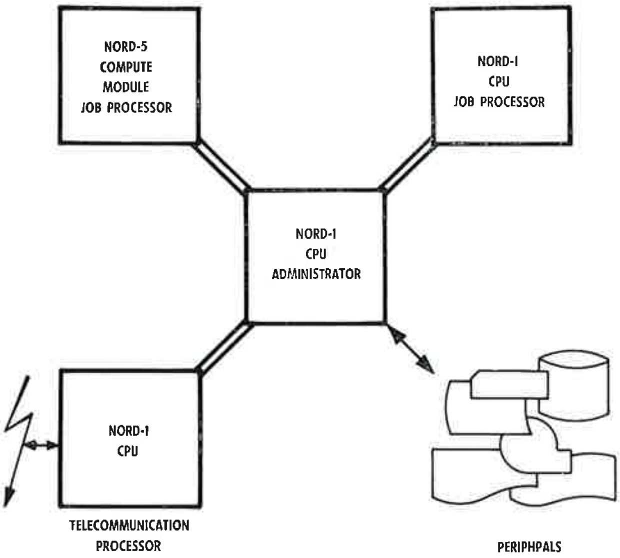
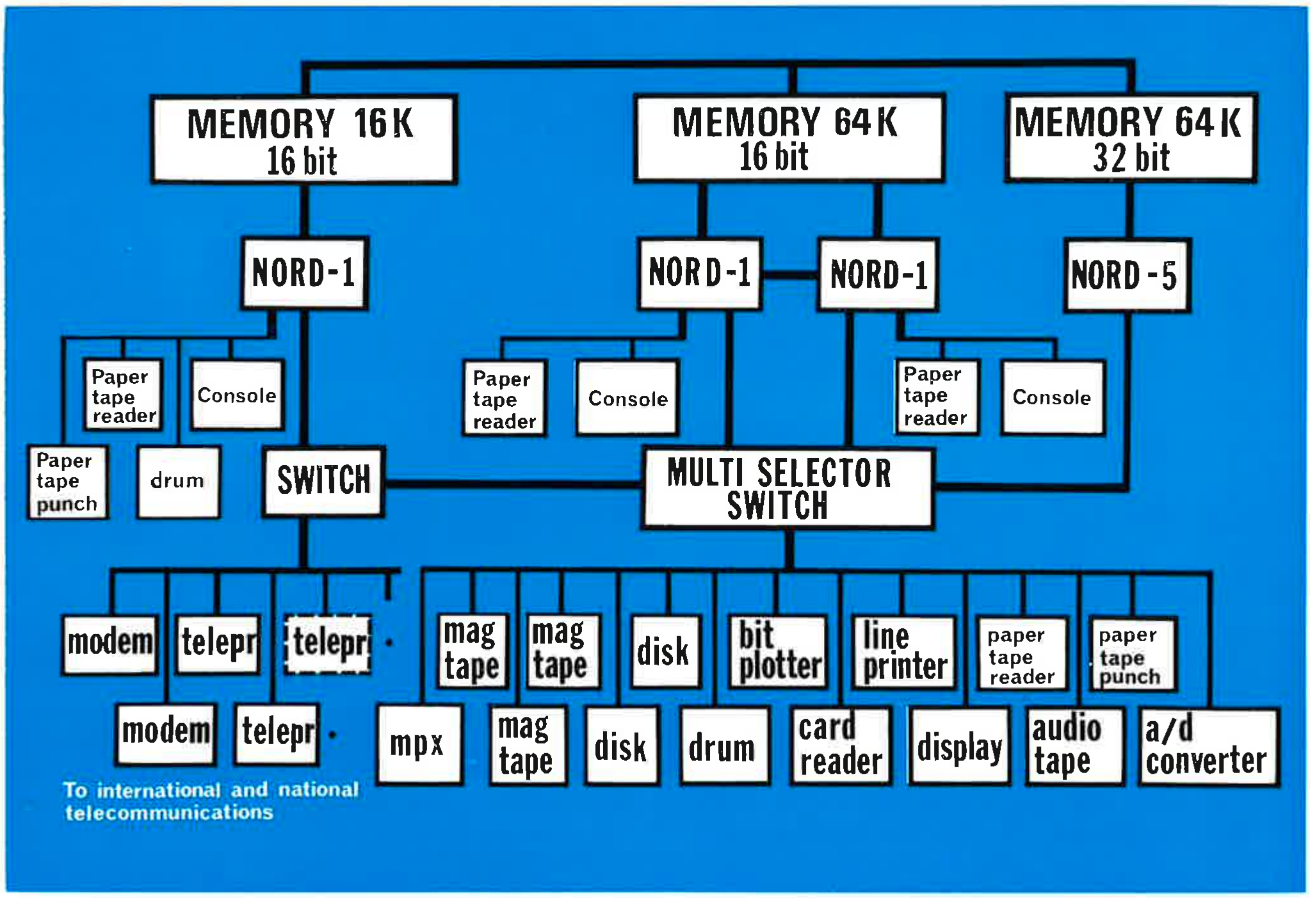


Figure 1: The Multiprocessor configuration of NORDIC.

Figure 2: The NORDIC system at the Norwegian Meteorological Institute, Oslo.



- act as a node in the Global Telecommunication system receiving and transmitting data on medium speed lines in accordance with the recommendation given by WMO
- select, sort and store meteorological messages wanted by the user
- take care of speed conversion, receiving data on medium speed and transmitting on low speed lines and vice versa. This includes interstorage, formatting and error checking of the observation.

The observations from the medium speed lines are double buffered. A sorting routine sorts the data on different lists and stores the data on the drum. When sufficient data have been received, the teleprocessor sends a message to the administrator in the NORDIC system which decides what action should be taken next. The data are transferred from the mass storage through the Inter Core Channel to the Memory of one of the two job processors, NORD-1 or NORD-5, or to mass storage for later processing.

The administrator and the job processors

In the middle of *figure 2,* the dual NORD-1 configuration is shown. The two CPU's share between them a common 64K Memory pool. Each memory control's and handles four possible data streams simultaneously. Thus the two CPU's can run programs in one part of the memory, while mass storage from two different groups can have access to another part of the memory. Both computers can address all 64K of core.

The peripheral units are divided into two groups. One group contains all the telecommunication equipment, the other group contains mass storage and different input/output units. The telecommunication group can be connected to any of the three NORD-1's by switches. By means of a multi-selector switch, any of the peripheral units in the big group can be connected to one of the two NORD-1's in the dual configuration. The switch can be operated manually, or program controlled.

The peripheral units are divided into four groups, each having its own I/O-Channel. The two Discs in the system are connected to different I/O-Channels, the same with Magtapes and other duplicate units. In this way one can assure high reliability. The peripheral units consist of

- two NCR Dual Disc units with capacity of 8 million 16 bit word, average access time 45 ms
- one Vermont Drum, capacity 256K 16 bit words, access time 10 ms average
- three Magtape units, 9 track IBM compatible
- Card Reader, 300 cards per minute
- Line Printer 1500 lines per minute
- Paper Tape Reader 333 characters per second
- Paper Tape Reader 2000 characters per second
- Paper Tape Punch 60 characters per second
- One Matrix plotter

NORD-5

NORD-5 is a special-purpose high speed compute module designed to be attached to a general purpose NORD computer system, or to computers from other manufacturers, in order to handle heavy compute-bound tasks. The idea behind the NORD-5 is that tasks which require large amounts of computations are sent out from the main system for processing while the main computer continues with other tasks. The operating system is contained in the NORD-1 computer.

NORD-5 has its own core and executes one program at a time. Assembly and compilation are done by the main system which produces object code for NORD-5. An installation with many heavy compute-bound jobs can be equipped with several NORD-5's that may share a common core pool, where all processors can address all core.

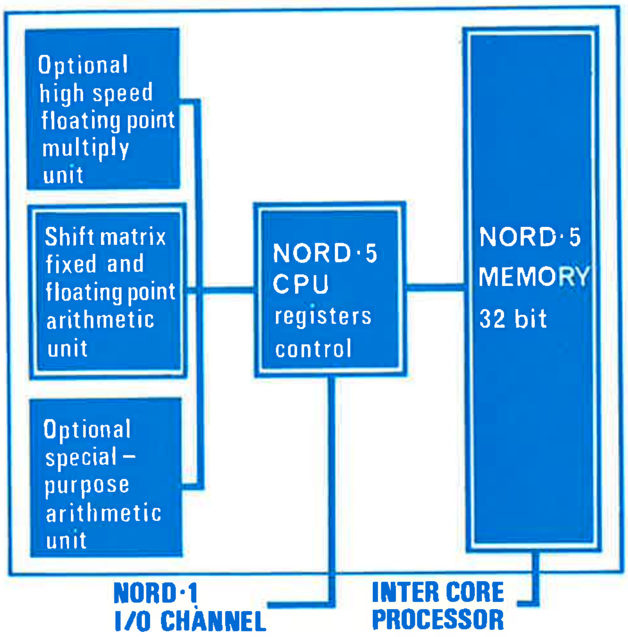


Figure 3: NORD-5 architecture.

A standard NORD-5 is equipped with a shift matrix and floating point unit with a speed of 950 ns for floating point add and subtract, and also 950 ns for all kind of shifts and bit manipulations (regardless of shift count). Floating point multiply and divide require 4 μs for 64 bit numbers. Optionally, a high speed multiply unit may be installed, giving a speed of 950 ns for floating point multiply (64 bits). Other special-purpose arithmetic units may be included in the NORD-5 as indicated in *figure 3.*

The arithmetic units in the NORD-5 are asynchronously connected to the NORD-5 CPU, allowing a range of performances. To achieve the high computational speed, the floating and shift module and the high speed multiply module are built as a logical array and in the multiply and divide module Schottky TTL circuits are used. The whole installation is shown on the photo on *figure 4.*

Figure 4: Panorama of the NORDIC installation.

SYSTEM SOFTWARE

NORD-OPS operating system for NORDIC

The operating system for the NORDIC consists of the Real-Time operating system SINTRAN II and a file oriented batch operating system NORD-OPS. The design philosophy of NORDIC has been to develop a system which is truly modular and which may be expanded at any time. The same philosophy form the basis of the operating system. One may note that the user has access to a real-time operating system and can write programs in a special version of FORTRAN called Real-Time FORTRAN. These real-time programs can run along with the batch jobs.

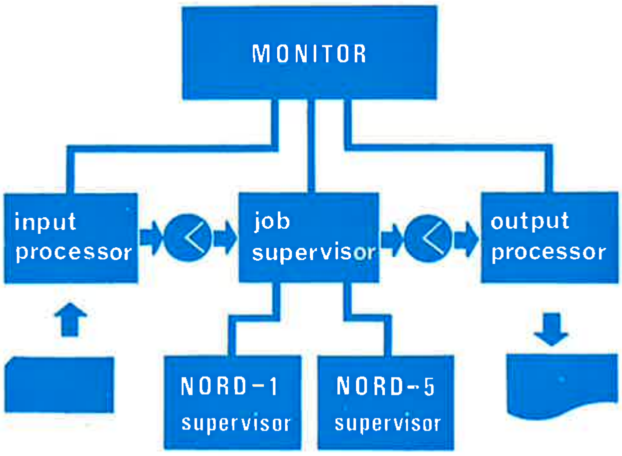


Figure 5: The NORD-OPS operating system.

NORD-OPS for a multicomputer installation

In the NORDIC system the processing of jobs is divided among several central processing units. These CPU's are either NORD-1 or NORD-5 computers. The operating system is always running in a NORD-1 computer and the I/O units are connected to this CPU. NORD-OPS for a multi computer installation is shown in *figure 5.* The supervisors for the NORD-1 and NORD-5 will take care of all functions in the CPU's. It is easy to see how NORD-OPS may be extended to take care of new processors and new functions by adding new supervisor routines.

Jobs and tasks

The input data are organized in jobs, one for each user. Each job is again divided into tasks. A task may be the compiling of a program, loading, execution, etc. The tasks may be of three types: a) NORD-1 tasks, b) NORD-5 tasks, and c) System tasks, depending on which CPU would be used to run them.

Each job is executed sequentially task by task. However, since the system may handle several jobs simultaneously, each CPU may have tasks from different jobs running in the system multiprogrammed. By adding more CPU's the overall effectiveness of the system can be increased and the resources can be organized in the most effective way as the job structure changes.

Figure 6: Minister of Industry Mr. Finn Lied and Director Ragnar Fjørtoft discuss the numerical weather analysis.

Processing of jobs

The Job Supervisor will distribute the tasks among the different CPU's. Depending on which type it is, the whole job with the tasks is transferred to a queue for the correct CPU. These queues are administered by the NORD-1 Supervisor or the NORD-5 Supervisor. The system has four queues:

- one queue for jobs processed by the input processor that are waiting to be processed by the Job Supervisor
- one queue of jobs with the NORD-1 tasks that the NORD-1 Supervisor will handle
- one queue with NORD-5 tasks that the NORD-5 Supervisor will handle
- one queue with processed jobs waiting to be printed. These are taken care of by the Output Processor.

In the queues the jobs are stacked by priority and they are usually executed consecutively. However, special jobs may interrupt the execution and be handled immediately. Usually the jobs are read from cards. Other jobs may be on files and transferred to Job Supervisor on a special command from a real-time program. This makes it possible to start a batch-job at a predefined point in time. Programs may be started by any of the following events: an external interrupt, the end of a time interval, a time-of-day is reached, an I/O-transfer completion an interrupt from another program, and operator activities.

Interconnections to other CPU's

A CPU does not have to be connected to the NORDIC system as a task CPU. Other computers may run their own operating systems and still have to access to the files of NORD-OPS. This is made possible by introducing new real-time programs.
For example NORD Time-Sharing System includes a general file system, linking facilities between one or many terminals, and an accounting system. NORD TSS can run FORTRAN IV, BASIC, Assembler, QED editor concurrently for many users.
The Time-Sharing is not included in the NORDIC system delivired to the Meteorological Institute in Oslo.

CONVENTIONAL AND UNCONVENTIONAL TASKS FOR THE NORDIC COMPUTER

The different tasks for the new computer installation can be divided into four categories: real-time jobs; computational jobs; data processing and statistics; and research and program development. *Figure 7* indicates the information flow.

Category A, real-time jobs:

In this category one finds the telecommunication routines. weather monitoring and some particular computational routines. The meteorological telecommunication routines are described elsewhere in this number and will not be mentioned here.

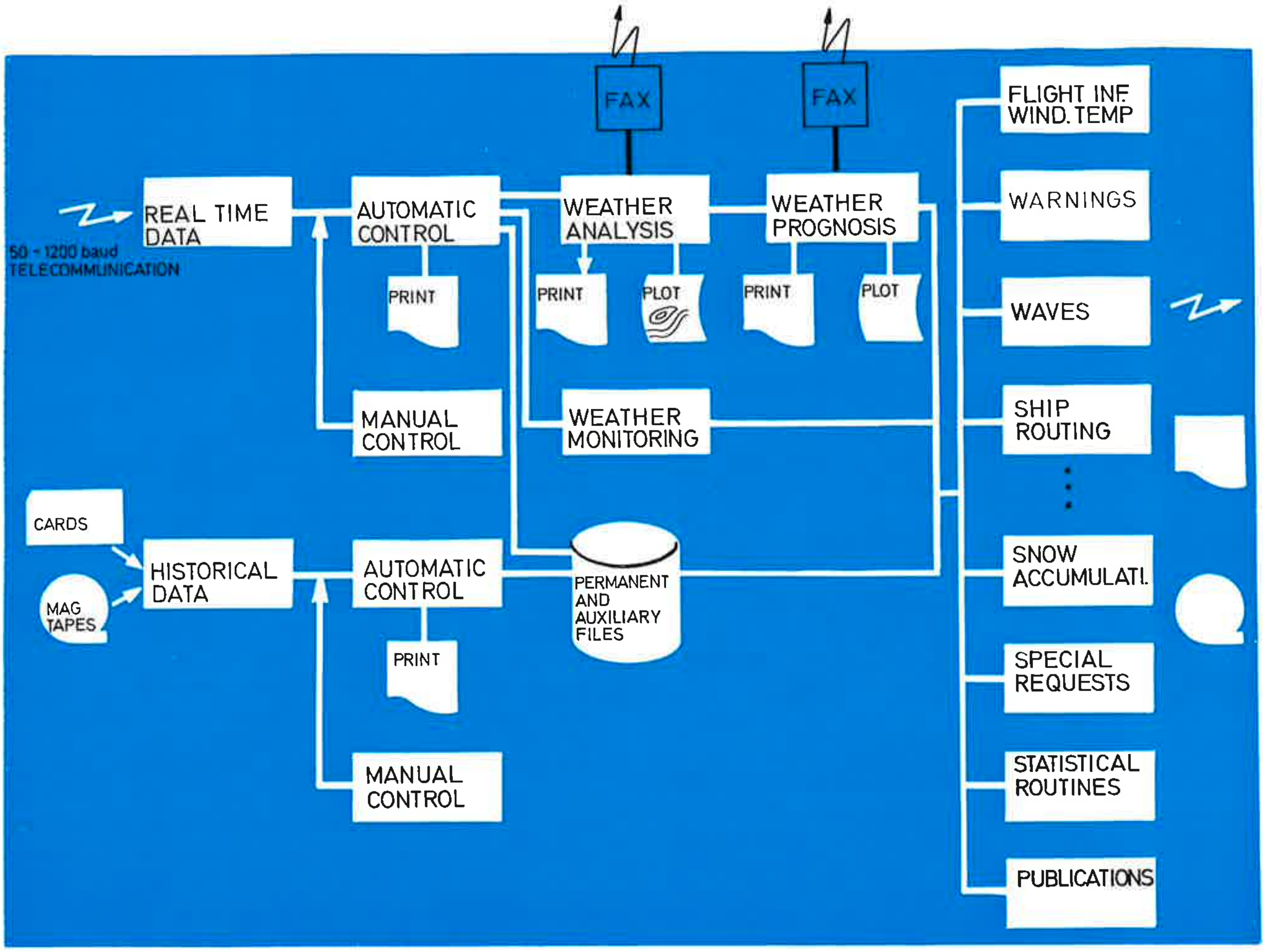


Figure 7: The information flow at the Norwegian Meteorological Institute.

Weather monitoring is an interesting field in which one foresees much activity in the years to come. A part of this activity will be a continuous check of incoming data from Norway and adjacent areas. If these observations exceed some critical values, or a certain combination of observations shows a particular trend, short computational routines will be activated which will explain more fully the consequences of these alarm observations and give warning to the forecaster. This can, for example, be a rapid increase in wind force, development of fog, icing and the like. The goal is to have the first of these warnings from the observation monitoring not later than ten minutes after the observation time. Another part of the monitoring will be following-up of the prognosis. If the observations show signs that the weather does not develop as predicted, an updating may be necessary and a new forecast can be given. Some computational jobs may also be categorized as real-time or at least quasi real-time.

This may be the type of job which must be initiated in order to be completed before a certain point in time so that the results are ready for transmitting according to the scheduled telecommunication plan. Some of these jobs are described next.

Category B, computational jobs:
The main computational job is the numerical forecasts, i.e. the weather analysis and prognosis. The analysis consists of calculating a three dimensional picture of pressure, wind and temperature from the synoptic observations taken at the earth's surface and in the free atmosphere. The results form the basis of the prognosis. The prognosis are made from the equations indicating the variations in the atmospheric process. The results give variations in the pressure, wind and temperature for a time interval in advance.

The calculations involved with the prognosis are so complicated and timeconsuming so that even with the most advanced computer existing today, it is not possible to run a full global scale model in real-time. The method is therefore either to compute a complex model for limited area, or reduce the complexity of the model. The proceedings here are explained more thoroughly in the article: "On the Use of a Medium-Sized Computer for Numerical Weather Prediction" in this magazine.

The prognosis gives input for several standard routines. Among these can be mentioned:

- Wind forecasts for aeroplanes
- Forecasting of seawaves and swell
- Routing of ships
- Quantitative rain forecasts
- Tracing of air particles with reference to air pollution
- Agriculture forecasts, for instance: minimum — maximum temperature,
- potatoe disease, conditions favourable for noxious insects.

Category C, data processing and statistics
An important part of the data processing is control of the observations. This control is partly of the observations that are received in real-time and used in the prognosis, and partly a more thorough control of the Norwegian observations that will form the basis for the climatological statistics.

On a routine basis climatological and precipitaion statistics of different kinds are computed and results are published in the institute's own publications and distributed to many different kinds of users. In addition to conventional statistical work, special statistical calculations for the Meteorological Institute's own use and for several external projects are done on request. This can be climatological appraisal of a new industrial area, a study of the effects of water-way regulations and the like.

A file is created, consisting of Norwegian observations, some selected foreign observations and part results from the prognosis. This file is easily accessable to the researcher in house and to people in other institutes who are interested in weather information.

Category D, research and program development
The capacity of the new computer will give the possibility to improve substantially the methods used in addition to select new tasks. This means that a good deal of problem oriented research can be done at the Institute. Such research has been intensified in the past and will continue at full speed in the years to come.

The NORDIC installation will also be used for external projects where meteorological data constitute part of the problem.

Summing up, one may say that the NORDIC computer installation can do simultaneously real-time jobs (e.g., Telecommunication and weather monitoring jobs), big computational jobs (e.g., numerical weather analysis and prognosis), routine jobs (e.g. data processing and compiling and testing of programs), and input and output of data and programs.

The modular structure of the installation gives safety and possibilities for continous operation, and the computational speed as well as the storage capacity makes it possible to use better methods for the conventional computational jobs as well as to select and solve new problems.

ACKNOWLEDGEMENTS
The author wishes to thank Mr. Odd Haug, Head of the computer division at the Norwegian Meteorological Institute, and Mr. Lars Håland from the same Institute for furnishing the material regarding the different tasks for the computer, and for all help while preparing this manuscript.

Meteorological telecommunication

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History

A precise description of the state of the atmosphere is the very first condition for any type of weather forecast. Observations of the weather parameters from a dense network both in time and space, are essential to the meteorological services. A modern weather service will require observation from all over the hemisphere, at least four times a day and from a somewhat limited area, every third hour. Even in the present state of affairs, quite formidable amounts of data are exchanged. As an example: the Norwegian Meteorological Service receives and transmits some 4 million characters per day.

The present lack of reliable observation from the oceans and from sparsely populated areas, seriously hampers the development of better weather forecasting. The great costs involved if conventional observation techniques are applied have prevented the establishment of a denser network in these areas. By the new observation techniques, of which satellite observations seems to be the most important, this deficiency may be overcome, provided that the efficiency of the telecommunication system is increased accordingly.

It is obvious that the data collection and exchange system can be established by international cooperation, and the organization of the worldwide meteorological net of observation and telecommunication has been one of the most important tasks for the World Meteorological Organization, WMO.

The first organized effort was transmission of observations in Morse code from a net of broadcasting stations. Functionally, this system was exellent. Each user could select the data of particular interest to him and not be bothered with duplicate transmission of all the superfluous data of today. The total costs, however, were large since broadcasting requires expensive equipment and many operators were needed at each forecasting office.

After the Second World War it became clear that this system should be replaced by a more economical integrated system. The first integrated telecommunication system was the teleprinternet that is still in operation today.

The system is a Torn Tape switching system based on bulletins consisting of individual messages varying from 50 to 2000 characters in size. The switching is done according to fixed programs agreed by the users. The system has gradually become very complicated and duplicate transmissions occur to a considerable degree. A simplification is desirable and at the same time the new observation techniques demand faster and more efficient data exchange methods. Even with a high degree of data reduction at the centers before data is fed into the system a teleprinternet is insufficient. Therefore, all the organizations which constitute WMO have decided to convert to an automatic data-transmission system on medium-speed lines, i.e., 1200 to 4800 baud.

Automated Communication

The fundamental feature of the system will be a ring, the Main Trunk Circuit, which will pass through Washington, London, Paris, Offenbach, Prague, Sofia, Moscow, Cairo, New Dehli, Melbourne, Tokyo, and Washington. Through these, and a group of supplementary centers in connection with Main Trunk, the remaining countries will come into contact with each other. A drawing of Main Trunk, showing the World and Regional Centers is presented in figure 1.

The deciding factor for the wider development of a system of this nature will be the determination through negotiation of the common denominator of the different national systems. The most important factors which limit the proposed system are:

— A group of countries wants a hardware-switched system

— A group of countries asks for the transmission of facsimile signals on the lines as a supplement to the digital traffic

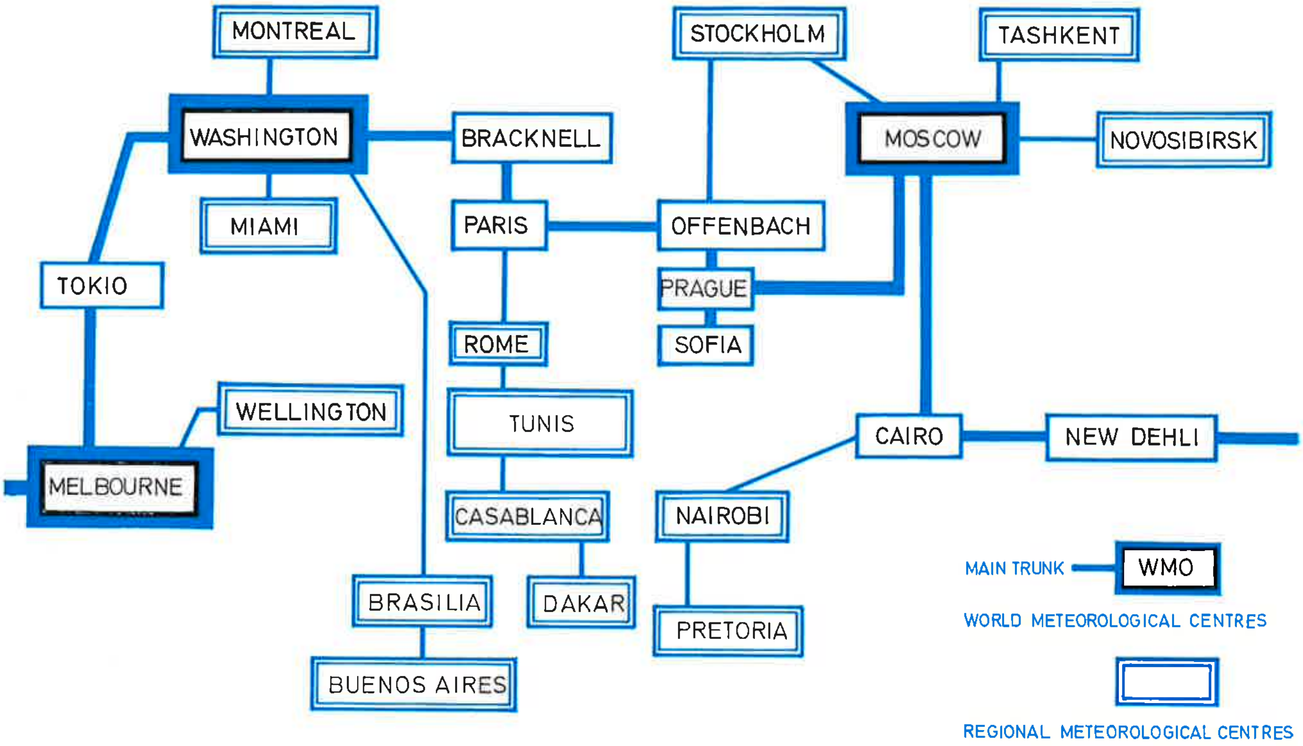

Fig. 1. Main Trunk Circuit and Main Regional Circuits.

— Too large a number of countries wishes to operate centers on the Main Trunk Circuit itself.

As individual parts of the ring are of unlike types, it will scarcely be possible to bypass a center in the event of its failure. This means that the operating security at each center must be high. Dual operation of two similar computers is necessary to guarantee the operation of the center and large mass-storage capacity must be present in order to guarantee correct restart after a break-down of the lines. Since a large part of the available resources is used for these security precautions, other important data-handling tasks (e.g. data format control) will suffer. Therefore, the individual countries which receive service from a center must count on having to do much of this work themselves.

The operation mode of Main Trunk Circuit is the so-called "store and forward". This means that the data are received, stored in the mass-storage device, edited together with the data the center has collected itself, and the entire data stream is then sent on to the next center on the ring. Therefore. the opening of each new center will cause a delay in the transmission of the data. Since so many countries wished to open centers on Main Trunk Circuit, its structure became relatively complicated and unnecessary ramifications were occasionally brought in. The delays which will occur because of this expansion will be noticeable, but if only the transmission of digital data were concerned they would not be especially serious. It is quite another case when analouge facsimile data are also sent on the ring. Because of the type of equipment used, these transmissions cannot be broken off. Since one transmission can take as long as 20 minutes, it is easy to see that a chain of centers could result in quite serious delays, not only of the facsimile transmissions, but also of the high-priority digital data. Therefore, location desiring to link to Main Trunk Circuit ought to appraise carefully the priorities for the different types of data and the degree to which delays are acceptable.

Principal Solution for the Meteorological Institute in Oslo

In order not to risk being cut off from important types of data in the future, a data-link of the same transmission speed as Main Trunk Circuit (1200 to 4800 baud) is desirable. Because of this and in order to obtain flexible data selection and reduction, the editing of the data for the national communication program and of the international data needed by the Meteorological Institute will be undertaken by the Institute itself. It is not thought necessary from the security point of view to spend the money to run a dual computer. Instead, the center will depend on the large mass-storage devices which already exist at the Main Trunk Circuit centers. However, there will be a reserve computer exactly like the one normally used for telecommunications If the telecommunication computer breaks down all the data stored in mass-storage in this machine will of course be lost and have to be retransmitted by the Main Trunk Circuit Center. The system is, however, adjusted in such a way that it is never necessary to retransmit more data than those which give information about the last 3-hour time period.

The present amount of digital data will hardly be sufficient to fill a medium speed line in 24 hours operation. It may then seem very tempting to use also the network for transmission of facsimile charts, and the proposed mode on the Main Trunk Circuit is a mixed analogue/digital one. On the line to Oslo, such a mixed mode is not regarded as desirable due to the technical and operational complications involved. Experience indicates that the difficulties of the mixed operation mode may have been underestimated. The recent development of digital facsimile transmission on part of the WMO has been worthy of note. The system at the Norwegian Meteorological Institute can, of course, handle the latter type of facsimile transmission.

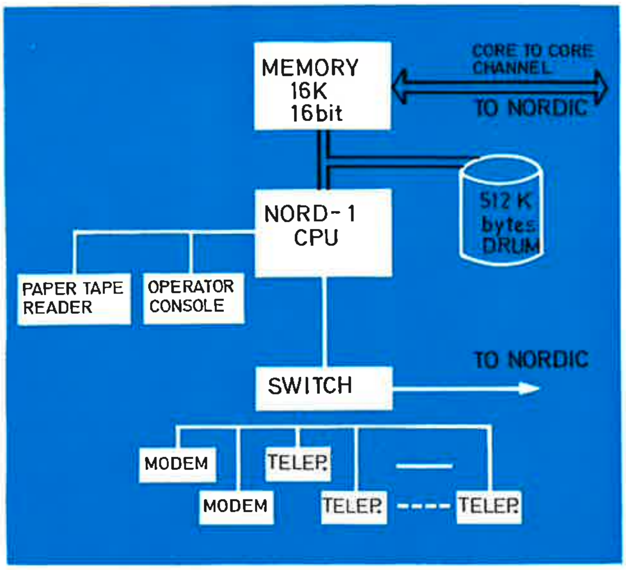

Fig. 2. Computer Configuration.

Bracknell, England, was chosen as the linkage point. This was done, firstly, because the weather data from the west are of high priority since the majority of weather systems tend to move from the west toward the east, and secondly, because it is desirable to have the closest connection with the largest data installation in the U.K. and the U.S.A.

The Practical Solution

The computer configuration chosen is shown in figure 2. It consists of one NORD-1 with 16K core memory and a drum of 512K bytes. The modems will serve a duplex connection to Bracknell and a simplex connection to Copenhagen at 1200 baud, and lastly, there are 7 half-duplex and 5 full-duplex connections at speeds of 50 — 200 baud present.

There is a direct connection between the core memory at the telecommunication computer and the core memory at the main installation. One of the two NORD-1 computers which forms a part of the main plant can be unhooked from this installation together with the main installation's drum and with

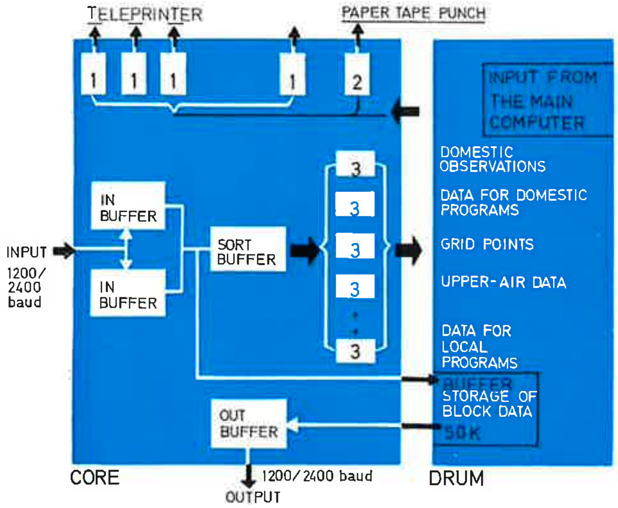

Fig. 3. Outline of the main dataflow 1 = output buffer, 2 = output if overflow at drum, 3 = link buffer for data to drum.

16K from core memory. The telecommunication lines can be hooked up to this computer; thus, there is a complete reserve computer in case the normal telecommunication computer breaks down. Otherwise, this will certainly prove to be a useful configuration for the testing of the new telecommunication programs. The consequence for the main installation will be that all data processing will go more slowly when the remaining NORD-1 computer has to be used for operational system functions as well as for straight data processing. None of these back-up functions are automatic. If a new configuration proves desirable, all computers will be stopped, the new configuration will be switched on manually, and the correct set of operating systems will be taken from the magnetic tape. The whole procedure will only take a few minutes, and no serious operational problems are involved in this procedure.

In the first step of the development, the telecommunication computer will receive data on a 1200 — 4800 baud line from Bracknell and retransmit these data to Copenhagen. The operation will have error control procedures set up according to WMO's specifications. The computer will edit two national telecommunication programs that are transmitted on lines with a speed of 50 baud. The data will be roughly sorted into 5 main categories for transmission to the main installation. The Norwegian observations will also be fed into a computer which will take care of formatting and send the data to Stockholm and Bracknell. The dataflow of this step is outlined in figure 3.

The next step of development, will most likely be the inclusion of the aeronautical telecomminication system, MOTNE, in the computer, reducing the manual work at the telecommunication center to a minimum.

A full quality-control of Norwegian synoptic data may also be included in the system.

The telecommunication computer does not by itself have this capability but the close connection to the main installation makes such a development possible.

On the use of a medium-sized computer for numerical weather prediction

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INTRODUCTION

In most contexts numerical weather prediction means forecasting one or more weather elements (wind, temperature, etc.) directly by means of the equations governing the state and motion of the atmosphere. The term "dynamical weather prediction" is also used for this method of forecasting, since the theoretical basis is closely tied to the special branch of the atmospheric science called dynamical meteorology. A well known procedure for making such forecasts is the graphical method invented by Dr. Fjørtoft, which shows that computers are not really essential for this dynamical approach, although widely in use, because of their efficiency. For our purpose, however, it is convenient to give the therm "numerical weather prediction" a somewhat wider definition, including also quantitative forecasts made by statistical methods, either alone or in combination with the dynamical methods just mentionned. The actual computation of these statistical forecasts does not necessarly take much computer time, and may in some cases be made by hand. However, the deduction of the formulae to be used, involves a considerable amount of computation.

Data handling, including numerical analysis, is the natural base for this type of quantitative forecasting. In addition it may serve as a useful tool to the meteorolo gist, simply by organizing the vast amount of data which constantly is calling upon his attention. Furthermore, very simple methods based for instance on extrapolation, may be fitted into the scheme of preliminary data processing in order to get short-term forecasts quickly.

In the following I shall try to give a broad outline of how these forecasting techniques may be applied in a national weather service of a small country with limited resources, and it is convenient to start with the dynamical approach.

DYNAMICAL PREDICTION

It is probably dangerous in an article like this to try to give a short description of the method. It will be superfluous for those who already have some knowledge in this field. For others it may not be sufficiently comprehensive. Furthermore, some readers who do not like mathematics, may put away the article at the first mention of an equation. However, it is tempting to give at least some indication of the basic concepts and in order to do so, I find it impossible to avoid the use of a few equations, which, at least formally, are rather simple:

$$\frac{\partial u}{\partial t} = F_1 \quad \frac{\partial v}{\partial t} = F_2 \quad \frac{\partial T}{\partial t} = F_3 \quad \frac{\partial m}{\partial t} = F_4 \quad \frac{\partial P}{\partial t} = F_5$$

Here, u, v, T, m and P are horizontal wind components, temperature, mixing ratio of water vapour to dry air, and the surface pressure. These are the basic variables, which are functions of location (x and y), height (z) and time (t). The F's are functions of these basic variables, and the functional relationship is known, at least in principle. The notations on the left hand side represent the rate of change per time unit (second) of the variables.

The equations are derived from well known physical laws. Indeed, the first two of them come from Newton's second law of mechanics, the third is the first law of thermodynamics, the fourth expresses the balance in the content of water vapour, and the fifth comes from the so-called continuity equation which governs the change of density. There are other necessary equations which we have neglected for the sake of simplicity, for instance the hydrostatic equation, which gives the connection between temperature and pressure in a vertical column of air.

The dynamical method of weather prediction is brought out by the following argument. Suppose that at a given time, t, we know the value of all the variables: This makes it possible to compute the value of the right hand side of the equations. Thus we know the rate of change per time unit of the variables u, v. T, m, and P, and can make a short extrapolation of their values to the time t + dt.

We then go back and recompute the functions and are ready to make a new extrapolation to the time t + 2 dt, and so on.

This is basically the way the dynamical weather forecasting was outlined by V. Bjerknes in 1904. However, he was most certainly not aware of all the difficulties involved. Some of them were encountered by L. F. Richardson in 1922 when he tried to perform an actual forecast in this way (he did not succeed). It would lead too far to explain how the difficulties arise, but I shall at least list some of them. Going back to the description of the procedure, we realize that we could go on for ever doing our extrapolations provided the computations were accurate enough, the state of the atmosphere was sufficiently well known from observations at starting time, and the computer was big enough. None of these conditions are fulfilled, but let us linger for a while over the last one, since this point may seem least obvious to most readers.

The weather conditions in one place influence the conditions in the neighbourhood after a certain time. As time goes on this influence spreads to larger and larger areas. which means that we must take into consideration a large part of the earth's atmosphere if we want to make forecasts which are useful for an extended period of time. I shall return to this point later. Also, the equations we have referred to express physical laws which in principle are known to the necessary degree of accuracy. However, the numerical procedure becomes so tedious that we would need a computer powerful beyond our comprehension.

What do we do then? The only way is to make simplifications in the equations, and also in the numerical procedure, guided by our knowledge of the atmospheric physics and the mathematical theory of differential equations. In this way we get a hierarchy of simplified models of the atmosphere, with names like ''primitive equation models'', ''filtered'' models, and ''barotropic'' models.

The barotropic model is the most simplified one. It is based on the assumtion that the vertically averaged wind fields are approximately non-divergent. Experience has shown that this rather crude assumption is valid to a surprisingly high degree. It is quite natural that the first numerical forecast performed by Charney, Fjørtoft and von Neuman on the ''ENIAC'' computer was based on this model, since it does not need so much computing power. As bigger computers were developed, more complicated models came into use: first, in the ''fifties, the filtered models, and later, in the 'sixties, the primitive equation models. In the 'seventies, we shall probably see the development of huge global models for forecasting up to one or two weeks.

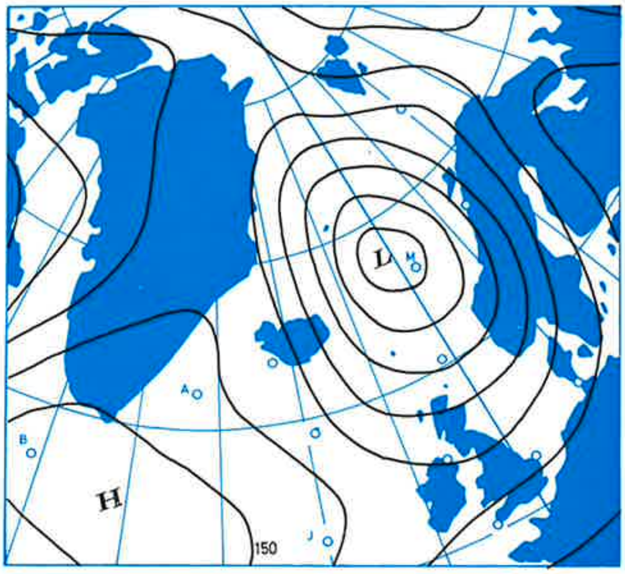

Fig. 1. Objective 850 mb analysis for Sept. 8th 1972 00 GMT.

Such ''medium range'' forecasting will need a vast computing power. Besides, since the model operates on a global basis it would obviously be reasonable not to make such forecasts in every country. What then, will be the natural use of a comparatively small computer installation in a national weather service? Let us first consider the prognoses which will be result of the global models, and try the find out what we can expect of them. They will be good for the larger synoptic scales, but lack small-scale details, since even the largest computers are unable to handle global models with a horizontal resolution less than a few hundred kilometers. They will be late, since it will take time to collect and analyze all the data necassary for such forecasts.

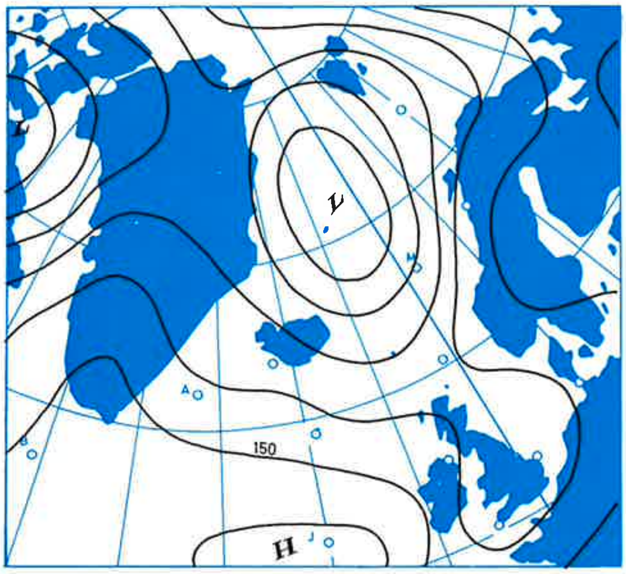

Fig. 2. Dynamical 36 hrs prognosis for the 850 mb level, verifying Sept. 9th 1972 12 GMT.

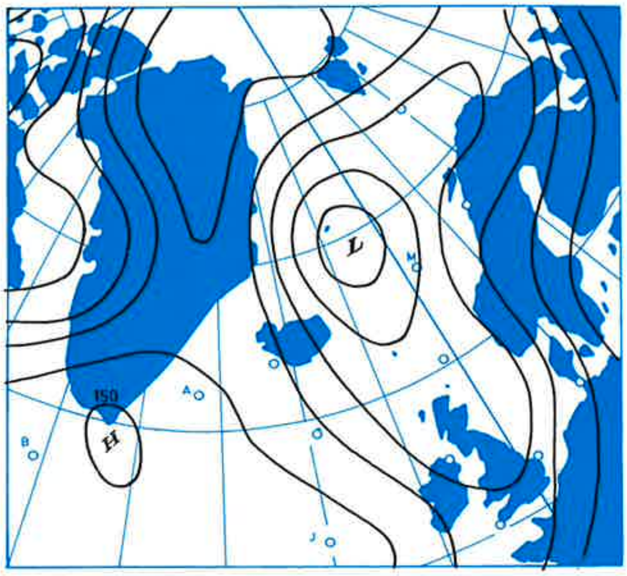

Fig. 3. Objective 850 mb analysis for Sept. 9th 1972 12 GMT.

If we restrict the horizontal area covered by the model to give, say, 5 x 10^7 km, which is one tenth of the surface of the globe, we cannot expect the model to give useful prognoses for a time longer than one or two days. The reason, of course, is that the values of the variables at the lateral boundary are not determind exclusively by what takes place inside these boundaries. If we map the errors, we may observe how the prognoses gradually deterioate from the boundary inward, with a speed equal to the characteristic horizontal wind velocity. On the other hand, the forecast may be computed comparatively fast, even with a finer horizontal resolution. Furthermore, the computation can be started earlier, since we do not have to wait for observations coming in from remote areas. If we also can make a more detailed analysis, the prognosis may benefit from this also. Besides, even if we cannot make an accurate detailed analysis, the topography, which is believed to have an important influence on all scales, is known to any degree of accuracy, and could be taken into account better. Finally, there will be a general improvement in the forecasts when a finer lattice is used, simply because numerical errors are reduced.

Instead of keeping the values at the boundary fixed or determined only by the conditions inside, we can prescribe boundary values as functions of time, derived from a model with a coarser grid covering a larger horizontal area. These boundary values may be obtained from other services with a larger computer installation. Also, if they are derived from a numerical prognosis based on data collected 12 hours earlier, they can be made available in time to start the fine-mesh model as soon as sufficient observations are at hand. Such a procedure would reduce large-scale errors, but we could still have errors originating from the small-scale phenomena which may move in from the surrounding coarse-mesh area where they are not properly defined. However, small-scale features do not usually move so fast as the larger ones, and in most cases also have a shorter life-span. This means that we may narrow the horizontal area still more, and use the computational capecity we save to increase the resolution.

As an example, I demonstrate a successful forecast made by a rather simple filtered model, intended to produce short-term forecasts for the 850, 700, 500 and 300 mb. pressure levels. Figure 1 shows the initial 850 mb. analysis, produced numerically by the computer, Figure 2 is the 36 hrs. prognosis and Figure 3 is the verification map. As may be seen, the model developed a low in a fairly accurate position over England and the North Sea, and this low had a great influence on the weather in Southern Norway. It so happened that none of the other numerical prognoses we had access to in the Norwegian Weather Service had developed this low with comparable accuracy, although some of these prognoses were made by more sophisticated models and bigger computers. There can be little doubt that the success was caused more by an accurate initial analysis than by any special virtue of the model itself. This shows how a system of numerical analysis and forecasting carefully tuned to a special requirement can produce short-term forecasting of extreme importance for the local weather service.

STATISTICAL PREDICTION

The dynamical models may be expected to forecast such elements as wind and temperature in the free atmosphere, sea level pressure and, to a certain degree, precipitation and general cloudiness. They cannot give details such as local surface wind, temperature and precipitation, which to a large degree depend on topographical details too small to be taken care of in a dynamical model. For instance, in Norway the daily amount of precipitation in the winter season has proved to be determined by the speed and direction of the geostrophic wind to a remarkably high degree (see example below). The dependence, expressed as a regression equation, depends on the location, and it must in general be determined separately for each observing station. The relation may be improved by taking into account elements other than the geostrophic wind, such as humidity and temperature. Furthermore, the synoptic-scale vertical velocity, which can be derived from dynamical models of the filtered type, may be useful. One may also utilize predicted values of the determining variables.

Similar forecasts may be computed for temperature, wind, etc. In many cases these forecasts are good enough to be given directly to the public; in other cases they may serve as a useful guidance for the meteorologist.

As an example, the regression equation for the 12 hrs. precipitation, R (18), valid at 18 hrs. GMT for the observing station "Byglandsfjord" in Southern Norway (1) is given here:

$$\begin{aligned} R\,(18) = {} & 0.6685\,(SE(06) + 2\,SE\,(12) + SE\,(18)) \\ & + 0.19\,SE\,(06)\,SW_2\,(18) \\ & - 0.3278\,(SW_1\,(06) + SW_1\,(18)) + 0.3 \end{aligned}$$

The symbols on the right hand side represent pressure differences between observing stations in Southern Norway and in Denmark. The optimal stations to be used are selected by the regression analysis program itself, but the specific choice of symbols is meant to indicate the direction of the geostrophic wind component determined by the respective differences.

Time of observation follows each symbol in brackets. For instance, SE (06) means a pressure difference determined by the observations at 06 GMT on two specific stations, and these two stations determine a geostrophic wind component coming approximately from the southeast. Of couse, if the formula is to be used in daily weather forecasting, the observed pressure must be replaced by prognostic values.

The following two tables of verification will show the usefulness of the above formula. Table 1 applies to the prediction of measurable precipitation ($R \geq 0.1$ mm), and contains 455 cases. It shows that out of 208 cases where measurable precipitation was observed, 171 were predicted by the formula, while 37 were unpredicted. Similarly, in the 247 cases where measurable precipitation was not observed, the formula falsely predicted precipitation in 75 cases, while the remaining 172 cases were correct.

A similar verification of precipitation equal to or greater than 5.0 mm is found in Table 2. Obviously, the ratio of the number of the successful cases to the number of the unsuccessful ones is still more favourable than in the previous table.

Table 1: *Verification of predicted measurable precipitation ($R > 0.1$ mm).*

	Predicted	Not predicted	
Observed	171	37	208
Not observed	75	172	247
	246	209	455

Table 2: *Verification of predicted precipitation equal to or greater than 5 mm ($R > 5.0$).*

	Predicted	Not predicted	
Observed	59	26	85
Not observed	20	350	370
	79	376	455

DATA ORGANIZATION

The vast amount of data that continously flows into a modern forecasting office, is difficult to handle and utilize, even for a whole team of meteorologists and assistants, using traditional methods. Even to sort out the significant data from the not so significant is a formidable task. Much of this data handling is just the type of work that the computer is excellently suited to take over. The computer can sort the different types of messages as they are coming in through the telecommunication lines, and store them in its own mass storage units, either for a limited time, or more permanently. It can check and correct the data for most of the more obvious errors, and many of the not-so-obvious ones. It can analyze the data in different ways, for instance in the form of a traditional surface analysis. Finally, the computer can present the data to the meteorologist in the most convenient form, either in accordance with a fixed schedule, or at the request of the meteorologist. It can even warn him if something "unexpected" is observed, which calls for his special attention, like a strong pressure fall, thunderstorm, strong winds, etc. Of course, what is "unexpected", will have to be defined in advance, in relation to the time of day or year, or the weather situation. It may be useful to let the computer make quick and detailed forecasts for a short time period, say 12 to 24 hours, using very simple, but quick methods, like extrapolation of the observed changes, or displacement in a wind field derived from the products of a dynamical model. In this way we may, for instance, get very accurate predictions for the time of a frontal passage. The initial location of the front may be derived from a sea level or upper air analysis, or simply fed into the computer upon special instructions by the meteorologist taking the location from his hand analysis.

CONCLUDING REMARKS

In this short paper I have tried to outline some ideas we have in the Norwegian Weather Service about the use of a medium-sized computer, Hopefully, it has become clear to the reader that the motivation for our effort has been to produce useful products that we cannot expect to get from other places, for instance from the world or regional WWW centres (World Weather Watch organized by the World Meteorological Organisation). Of course, new developments in computers, observation technique, and telecommunication may change today's picture. For instance, one may visualize a mammoth computer tied directly to a network of automatic observing stations through a sophisticated telecommunication system, and the output from the the computer coming into the national weather services in vast amounts. However, in the national centres expert meteorologists will be needed to explain the implications of these results to the public. To train such experts in sufficient numbers may prove to be a formidable task. A country which has a staff of meteorologists already trained through the use of a computer of their own will have a great advantage.

Jack Nordø: "Scale Analysis of Precipitation, and its Statistical — Dynamical Prediction". Lecture held at the International Symposium on Probability and Statistics in the Atmospheric Sciences, 1971, Hawai.

Atmospheric predictability

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INTRODUCTION

The question of atmospheric predictability, which has received considerable attention during the last few yers, is concerned with the maximum time for which it is possible to make predictions of the state of the atmosphere. We are all used to the daily forecasts of the weather for tomorrow, and we also have forecasts for periods of 4 to 5 days or occasionally a week. In addition, some very general predictions are made for a month or even a season, but in this paper we will not be concerned with such long range forecasts which do not attempt to predict the weather in reasonable detail. Weather predictions become more and more difficult with increasing prediction time, and a practical upper limit to the prediction period is reached when the meteorological forecasts no longer are of value to the user. One purpose of this paper is to discuss the practical predictability of the atmosphere.

Formulation of the problem

The requirements for making good forecasts are to have an accurate description of the existing state of the atmosphere, to know the formulation of the physical laws which determine development, and to have the proper means to solve the mathematical aspects of prediction. This formulation of the weather prediction problem is applicable to many types of predictions which appear in other branches of the physical and natural sciences, e.g. astronomy where the relative positions of the sun, the planets and the moon can be precalculated for very long periods. While prediction, in a general sense, is a purpose of all sciences, it is probably only in meteorology that predictions, in the more narrow sence of "foretelling the future", have played such a prominent role that to admit that you are a meteorologist is almost identical to invite a request for the forecast for the next day.

Weather analysis and prognosis have only been developed in the last century from a meagre beginning in the middle of the 19th century. Several meteorological services across the world can celebrate centennials, but only during the last 20–25 years has it been possible to produce weather predictions firmly based on a physical and mathematical framework. The necessary developments were the establishment of a worldwide network of the meteorological stations and the invention of electronic computers. The revolution in the meteorological practices which took place in the fifties and sixties has drastically changed working conditions for the practising meteorologist. The process of producing a weather forecast is now a more objective procedure, while in the past the dominant role was played by the empirical rules which, although of great practical value, provided little insight in to the physical processes at work in the atmosphere. Parallel to the development of numerical methods for objective weather analysis and prognosis, meteorologists have gained additional understanding of atmospheric dynamics, leading to a fruitful cooperation between theorist and practitioner, dynamical and physical meteorologists micro- and macro-meteorologists, and the communities of applied mathematics and atmospheric sciences. It has generally been believed that better observations at more places combined with steadily more powerful computers will result in more accurate forecasts over longer and longer periods. This point of view has, by and large, been true because extensive statistical tests of long series of forecasts have shown a marked increase in the accuracy of the 1 or 2 day predictions since the fifties.

Laplace: "The whole physical universe is predictable"

The basic foundation for the meteorological prediction problem is Newtonian mechanics. Many problems in mechanics and dynamics were solved in the centuries following Newton, and the power of the Newtonian formulation of the physical laws was so strong the Laplace expressed that the whole physical universe was predictable, at least in principle, and since what was possible in principle could be only more or less difficult in practice it was generally believed that most physical problems could be solved if they were attacked with sufficient eagerness.

The first formulation of the meteorological prediction problem as an initial-boundary value problem based on the equations of motion, the gas equation, the continuity euation and the thermodynamic energy equation was given by V. Bjerknes at the beginning of this century. It was formulated as a deterministic problem within Newtonian mechanics, saying essentially that if we know the state of the atmosphere at one instant, it will be possible—in principle—to calculate its future state at any time from the basic equation describing its development. It is essentially this point of view which has governed the modern development of prediction methods.

Know the state of the atmosphere

The key to the understanding of the predictability problem lies in the words "to know the state of the atmosphere". It must be realized that it is impossible to observe the behavior of every single little eddy, let alone to describe its birth, development and decay. The observational network available today has an average distance of a couple of hundred kilometers between observation stations. Many phenomena on a small scale can "disappear between stations", since we can only hope to describe systems above a certain scale, determined by the grid size of the network. Thus, if all stations were arranged in a regular square grid we might decide that we need at least 8 gridpoints to determine the shape of an atmospheric wave, and the minimum resolvable scale would be 8 times the grid size.

It becomes clear that there will always exist an uncertainty in the initial state of the atmosphere because the observations are far apart and because there always are errors in observations. This uncertainty in the initial state is unavoidable and has been considered as one source which limits the predictability of the atmosphere. We shall consider this aspect in greater detail later. At this moment, we note that the situation need not necessarily be serious because we could hope that all answers of interest to the prediction were determined entirely from the large scale flow which is well described by the observing network. This assumption must to a very large extent be made in practical forecasts by neglecting exchange of energy and other physical quantities between small and large scale atmospheric flow. Although no sharp distinction exists between various scales, by large scale flow, we mean here the components which are well described by the network, while the small scale flow consists of all components which fall between stations.

Atmospheric Scales

The concept of scale becomes very important in the discussion of atmospheric predictability. While the scales in the atmosphere range from tiny millimeter size eddies up to sizes equal to the circumference of the eart in a continuous spectrum, it is nevertheless useful to divide the spectrum in a few parts related to the network. It is customary to make the following division:

1. Micro-meteorological systems (individual elements of a cloud, the individual eddies in a turbulent flow, to give some examples).
2. Meso-meteorological systems (squall lines, thunderstorms and other systems, important for the prediction, but too small to be observed in detail by the observing network).
3. Transient synoptic systems (the travelling waves in the upper atmosphere, cyclones and anticycylones, tropical storms).
4. Quasi-stationary synoptic systems (The semi-permanent lows and hights, some very long waves in the upper atmosphere).
5. The wole atmosphere.

The division above is only schematic, and the limits between the various categories is far from sharp. The last three categories can be resolved with the existing observational network, while the first two subdivisions of the spectrum contain phenomena which cannot be analysed but only inferred from the large scale flow in an average sense. In the forecast preparation the interaction between the first two and the last three categories can either be neglected or incorporated in a statistical sense expressed in terms of the large scale parameters.
In the following sections, we shall report on various attempts to determine the theoretical limit of predictability and then discuss the present practical limit set by the network and the accuracy of our present models.

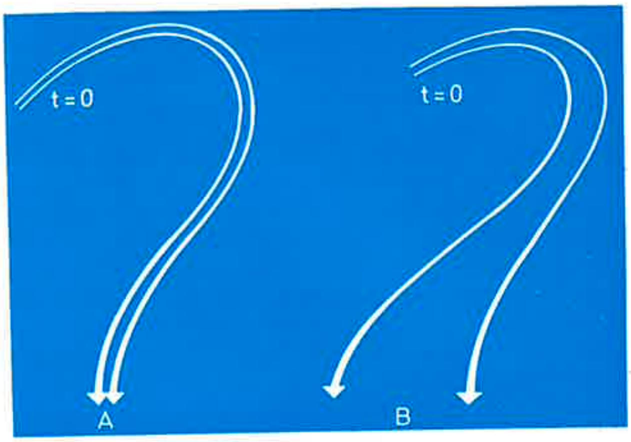

Figure 1: Symbolic representation of the developments of two predictions starting from slightly different initial states: (a) the case where the two predictions stay close to each other during the whole forecast. (b) the case where the deviation between the forecasts become larger and larger as time increases.

THEORETICAL LIMIT FOR PREDICTABILITY

Let us—somewhat unrealistically—assume that we have a model of the whole atmosphere.

a) which describes all physical processes in the atmosphere
b) for which we can specify the initial state on all scales
c) for which we (by numerical methods) can calculate the future state of the atmosphere without committing significant numerical errors.

If such a model were in existence, we could use it to determine the theoretical limit of predictability defined as the time, measured from the initial time, when two solutions, starting from almost (but not quite) identical initial states, will start to deviate significantly from another (see figure 1). The reason why the two solutions in general will deviate from eachother after a sufficiently long time is not only the uncertainty in the initial state, but rather the fact that the laws governing the atmosphere are such that significant non-linear interactions may take place between the various parts of the atmospheric flow, i.e. between the motion on the small scale and the motion on the large scale. These interaction processes, sometimes called cascade processes, may transfer energy from the large to the small scales or vice versa. This means that as long as we have some energy on the scales below the gridsize it is possible that a part of this energy—(regardless of how good the observations and the network are)—will show up as energy on the large scale due to the non-linear cascade processes. One may think that this situation could be avoided by selecting the gridsize so small that it was of the same order of magnitude as the smallest eddy permitted by the dissipation. However, if this was done the gridsize would be so small that it could not be used in practice.

The arguments presented above show that it is impossible to predict for an infinitely long time, and that a theoretical limit of predictability exists. It is also clear that it is not an easy task to determine what the limit is, because the conditions a) to c) are not fulfilled at the present time. We are therefore not in a position to give a final determination of the theoretical limit of predictability. Nevertheless, attempts have been made to estimate the order of magnitude of this limit, and in the following we shall describe some of the procedures used.

The Dynamical Method for Estimation of Predictability

In one series of attempts it was argued that in spite of the fact that we do not have models satisfying the conditions a) to c) we do have models which describe the behavior of the atmosphere reasonably well in an averaged sense because these models can reproduce with a fair degree of accuracy the present climatic conditions as observed. These models are known as general circulation models, and they have mainly been used to make long term integrations starting from idealized initial conditions. The models can reproduce flow patterns which have all the characteristics of the observed atmospheric flow, including the formation, development and decay of atmospheric waves and the maintenance of the very long quasi-stationary waves created by large scale topographic effects and contrasts between continents and oceans. Therefore, it appears that model designers have been successful in incorporating the most significant physical processes which determine the character of atmospheric fields of temperature, pressure and wind. Thus, it is not unreasonable to use the models to estimate the theoretical predictability time by starting from two slightly different initial fields and make two separate integrations as described earlier.

Several experiments of this kind have been carried out by various model designers. They take as initial condition the state at an arbitrary time during a certain long term integration. The only condition is that the flow pattern at the selected time should look like a weather map. The time-integration from this point in time is now called the control experiment. The initial conditions are next changed by the introduction of an "error" which can be a sinusoidal wave of a certain scale, a point error, or a superposed random field. If we restrict ourselves to the case of a sinusoidal disturbance we find a different behavior in various models. In one model (figure 2) the rms (root-mean-square) temperature error decreased from an initial value of 0.5°K to a very small value and then increased again until it finally settled at an almost constant value of 0.12°K. If this model was a true representation of the atmosphere we would have a very long predictability time because the model has a most efficient diffusion mechanism which removes the energy of the disturbance which was introduced. There is now general agreement that the real atmosphere is not equally effective in removing the energy on the same scale. Figure 3 shows the result of the same experiment with another model. In this case we find also an initial decrease of the error, but afterwards there is an exponential growth of the difference between the two fields and one finds a doubling time of the error of approximately 5 days. If we consider the prediction useless when the rms-difference is larger than, say 2°K we would from this experiment get a theoretical predictability of slightly more than two weeks. The result of still another experiment is shown in figure 4 in which the number N means the number of gridpoints between pole and equator on the earth. Thus, if N = 20 we have a gridsize of approximately 526 km. The lower curves in figure 4 show the growth of the rms temperature error as a function of time starting from a value of 0.5°K at t = 0. The upper curves, marked persistence, show the rms error which one would have if the initial values of the

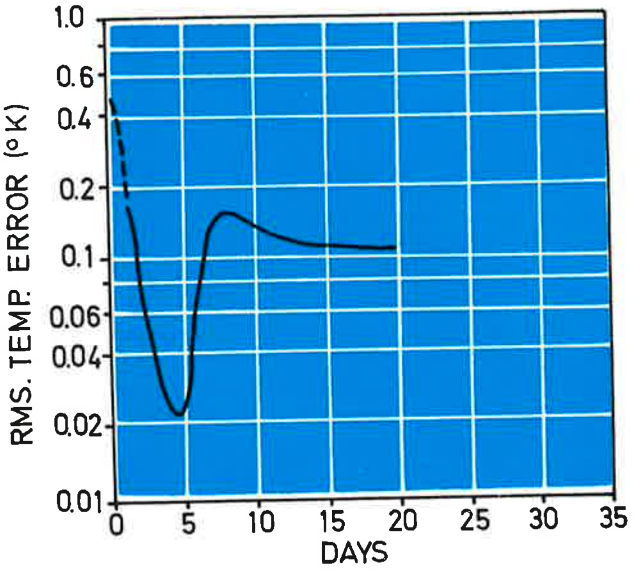

Figure 2: The development of an initial disturbance with an rms-difference of 0.5° Kelvin from the "true" state as a function of time in a model with a very large dissipation at the grid point scale (from reference 1).

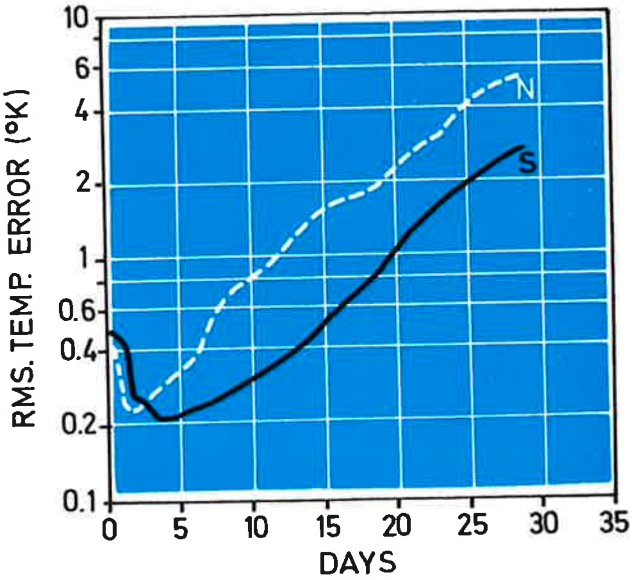

Figure 3: The development of an initial disturbance with an rms-difference of 0.5° Kelvin from the "true" state as a function of time in a model with small dissipation. The N-curve refers to the Northern hemisphere and the S-curve to the Southern hemisphere. Note that the ordinate is on a logaritmic scale, and that the error doubles in about 5 days. (From reference 1.)

temperature were used as the prediction. We may say that the forecast becomes useless when the curve for the forecast crosses the curve for persistence. We note that no intersection of the curves take place within the 21 days covered in figure 4. A comparison of figure 3 and figure 4 shows that the temperature error doubles in a much shorter time on figur 4 than on the previous figure. The reason for this is probably that the gridsize in figure 3 was so large that the most important atmospheric waves, the baroclinic waves in the upper atmosphere, did not have a possibility to develope in a proper manner.

In addition to temperature one may naturally also consider the rms-error of other meteorological parameters. An investigation of the error in the height field shows that this error also stays below persistence for the 21 day period, but that the error growth is somewhat closer to persistence close to the ground as compared with the upper atmosphere.

The same is true for the temperature. Based on the experiment shown in figure 4 and a much closer investigation of many other aspects of the whole calculation one arrives at the conclusion that the theoretical predictability time for the large scale flow of the atmosphere is at least 3 weeks.

It is thus seen that an order of magnitude estimate of the atmospheric predictability has been attempted with various models. It would be erroneous to state that there is complete agreement in the meteorological community regarding the interpretations of these experiments. As can be seen from figure 2, 3 and 4 there is undoubtedly a dependence on the particular model which is used in the experiment. It is also true that the predictability to some degree will depend on the nature of the disturbance which is introduced at $t = 0$. It seems that the spectral distribution of the initial disturbance is important, and that the growth of the rms-values as a function of time also to some degree depend on the variables

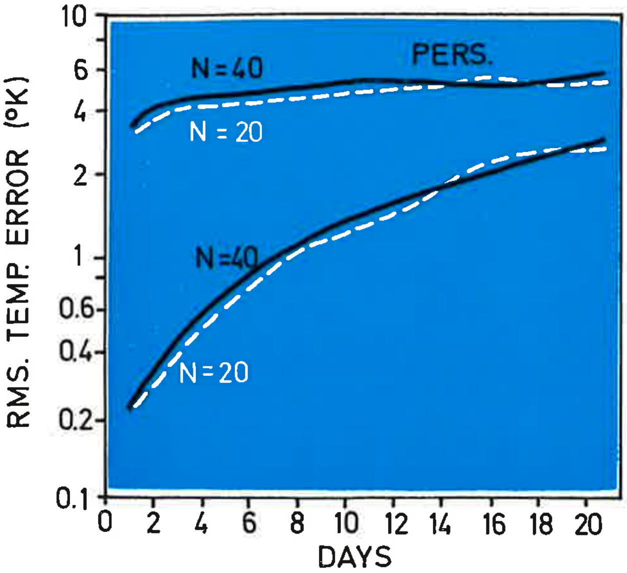

Figure 4: The same arrangement as in the two preceeding figures, but with still another model. The upper curves correspond to a persistence forecast while the lower curves show the performance of the model. Note that the doubling time here is considerably shorter than in fig. 3. The meaning of N is explained in the text. (From reference 8.)

in which the initial error is introduced. Some critics of these experiments will even go as far as saying that the predictability is typical of the model, but not of the atmosphere. In any case, we have here seen examples of the so-called dynamical approach to estimating the atmospheric predictability, which at best can give the predictability of the large scale flow of the atmosphere.

The Spectral Approach to Estimating Predictability

The main critisism of the dynamical method is that it treats only the large scale motion in an explicit way. The small scales, i.e. the scales which are too small to be well defined in the grid, are only included through the net statistical influence of the small scale motion on the large scale, and in addition, the statistical influence is necessarily expressed in terms of the parameter available for the description of the large scale flow. It goes without saying that such a description never can be fully correct. It is thus desirable to obtain methods for the estimates of the predictability which will be able to treat all scales of motion in the atmosphere. So far we have not obtained fully general results, but we may illustrate the approach by using a relatively simple model of the flow.

Let us assume that we have a system governed by the equation:

$$(1) \qquad \frac{\partial \xi}{\partial t} = J(\xi, \psi), \quad \xi = \nabla^2 \psi$$

in which ξ is the vertical component of the vorticity, while ψ is the stream function. The equation describes the conservation of vorticity in a two-dimensional flow, and it is seen that the equation has only the dependent variable ψ. The Jacobian J(a, b) is defined as

$$(2) \qquad J(a, b) = \frac{\partial a}{\partial x}\frac{\partial b}{\partial y} - \frac{\partial a}{\partial y}\frac{\partial b}{\partial x}$$

We assume now that ψ is the stream function for the control experiment while $\psi + \varepsilon$ is the stream function for the predictability experiment. The deviation ε between the two stream functions is a measure of how much the two forecasts deviate from each other. We may find an equation for the development of ε by noting that $\psi + \varepsilon$ also satisfies eq. (1). We get in this way:

$$(3) \qquad \frac{\partial \nabla^2 \epsilon}{\partial t} = J(\nabla^2 \epsilon, \psi) + J(\nabla^2 \psi, \epsilon) + J(\nabla^2 \epsilon, \epsilon)$$

which is the equation describing the development of the error field. As long as the errors are small we may safely assume that the last term in (3) is small, and we may simplify eq. (3) to

$$(4) \qquad \frac{\partial \nabla^2 \epsilon}{\partial t} = J(\nabla^2 \epsilon, \psi) + J(\nabla^2 \psi, \epsilon)$$

which is simpler to handle mathematically than (3). As a measure of the average error we shall take the error kinetic energy:

$$(5) \qquad G = \frac{1}{2}\, \overline{\nabla \epsilon \cdot \nabla \epsilon}$$

where the bar denotes an area average. It is now possible to develop an equation for G. In addition, since we are interested in the development of the errors on various scales, it is of interest to develop equations describing the time-development of the spectral components for G. We define:

(6) $$G = \int_{-\infty}^{+\infty} Z(k)\, d(\log k)$$

in which k is the wave number while Z(k) is the spectral component. It is the time-development of Z(k) which is of interest, and it turns out that equations for the rate of change of Z(k) may be obtained, but only under rather restrictive assumptions. We should next point out that the forecast will have lost all value when the error kinetic energy becomes sufficiently large. One may for example consider the forecast useless if the error kinetic energy on a given scale is as large as the kinetic energy itself on that scale. If we denote the total kinetic energy by E, and its spectral decomposition by the equation

(7) $$E = \int_{-\infty}^{\infty} x(k)\, d(\log k)$$

where X(k) is the spectral component of E, we may say that we look for the time t(k) at which the value of Z(k) is as large as the value of X(k). Using this definition t(k) becomes the predictability.

The equations for Z(k) are integrated until the time t(k) is found, and the result is shown in figure 5 in which the heavy curve is the basic atmospheric energy spectrum as a function of scale while the dashed lines are isolines for equal predictability. The diagram shows that the predictability times are very short when the scale is small, but that the predictability increases rapidly as a function of scale and becomes about 5 days for a horizontal wavelength of a few thousand kilometers. The predictability results obtained from experiments of this kind depend rather strongly on the shape of the heavy curve in figure 5, i.e. the kinetic energy in the atmosphere as a function of the horizontal scale. The limitations of the spectral approach to estimating predictability are mainly that the basic equation (1) is too simplified, that the assumption made in going from (3) to (4) breaks down as soon as the errors increase, and that the results are sensitive to the shape of the basic energy spectrum.

The Stochastic-Dynamic Method

As a final approach to the determination of the theoretical limit of predictability we shall briefly describe the so-called stochastic-dynamic method.

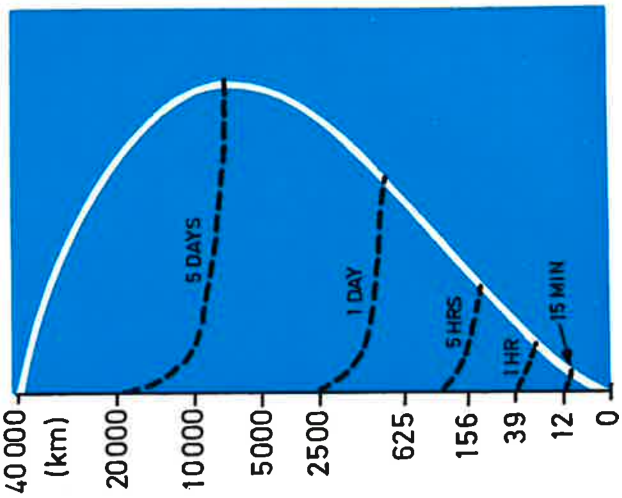

Figure 5: The horizontal scale is horizontal wave length measured in kilometers. The limiting curve is a basic atmospheric energy spectrum in arbitrary units. The regions to the right of the curves marked 15 min., 1 hr, etc. and upward bounded by the energy spectrum are the scales predictable within the time given on the curve. As an example, the scales shorter than approximately 10 000 km are predictable up to 5 days. (From reference 6.)

In order to introduce this approach we shall first consider an arbitrary state of the atmosphere. We may describe such a state by giving the value of the atmospheric parameters (pressure, temperature, humidity, the wind components) in a three-dimensional grid covering the whole atmosphere. Each state of the atmosphere may therefore be characterized by a (very long) string of numbers, say N numbers. We may therefore consider a single state of the atmosphere as a point in an N-dimensional space which has the values of all the atmospheric parameters along the N axes. If we change the value of, say, the temperature in a single grid-point in the three-dimensional grid covering the whole atmosphere, we will move to a new point in the N-dimensional so-called parameter space. If we were able to observe the atmosphere in full detail, say, every 10 minutes we would be able to plot the development of the atmosphere as a trajectory in the N-dimensional parameter space. We may also say that a prediction obtained from a given mathematical model of the atmosphere is a good one if the trajectory in the parameter space stays close to the trajectory for the observed state of the atmosphere. These considerations may be expressed in mathematical form in the following way.

A given state of the atmosphere is characterized by a position vector in the N-dimensional parameter space as follows:

$$\vec{x} = (x_1, x_2, x_3, \ldots\ldots, x_N) \tag{8}$$

The physical laws governing the atmosphere may now in a very abstract way be expressed in the form:

$$\frac{dx_i}{dt} = F_i(x_1, x_2, x_3, \ldots\ldots, x_N) \tag{9}$$

which just says that the time-development of the parameter X(i) is a function of the values of all the other parameters and itself. To be more specific it may be mentioned that it is possible to write all the equations governing the atmosphere in the form:

$$\frac{dx_i}{dt} = \sum_{p,q} a_{pqi} x_p x_q - \sum_p b_{pi} x_p + C_i \tag{10}$$

in which the values of the coefficients a(pqi), b(pi) and c(i) are given constants.

The Stochastic Description of State

Let us now imagine that we have performed an analysis of the state of the atmosphere from the available observations at some time, say t = 0, i.e. we have by some method determined the values of all the meteorological parameters in all the grid points of the three-dimensional grid in the physical space. Equivalent to this we may say that we have selected a point in the N-dimensional parameter space, representing the state of the atmosphere. As we have realized earlier, we cannot be sure that the atmosphere should be represented by just that point because of all the uncertainties in the observations and, above all, the sparseness of the observations. It is therefore likely that the atmosphere also could be represented by another point in parameter space, or, to be more precise, to each point in parameter space we may assign a probability that the state of the atmosphere is represented by that point. Mathematically, we may state this fact in the form that to each point in parameter space, X, and to each point in time, t, there exists a probability $\varphi = \varphi(\mathbf{X},t)$ such that the state of the atmosphere is characterized by the point **X** at the time t. The function $\varphi = \varphi(\mathbf{X},t)$ is called the probability density function, and it has positive values only, i.e. $\varphi \geqq 0$. We shall in addition assume that the probability density function has been normalized in such a way that the integral of the function over the total parameter space is unity, i.e.

$$\iiint \ldots \int \phi \, dx_1, dx_2, dx_3 \ldots\ldots dx_N = 1 \tag{11}$$

It is possible to formulate an equation governing the rate of change of the probability density function. Such an equation is derived in the same way as the mass continuity equation in fluid dynamics by saying that there can be no creation nor any destruction of probability in parameter space. One finds that

$$\frac{\partial \phi}{\partial t} + \nabla_N \cdot (\phi \dot{\vec{x}}) = 0 \tag{12}$$

where

$$\nabla_N \cdot = \frac{\partial}{\partial x_1} + \frac{\partial}{\partial x_2} + \ldots\ldots + \frac{\partial}{\partial x_N} \tag{13}$$

and $\bar{x}$ means the rate of change of the position vector in parameter space, or, in other words, the velocity along the trajectory in this space. We note that (12) kan be used to predict the future values of the probability density function but that we must know the values of the rate of change which in turn are obtained from the N equations (10). The total set of equations is therefore N + 1, i.e. (10) and (12). To perform an integration of all the coupled equations (10) is quite a task on any electronic computer because N is indeed a very large number. An order of magnitude estimate is of some interest. If we used a horizontal grid size of 5 degrees in longitude and latitude we will cover the globe with 2520 points. The most advanced models of the atmosphere use presently about 10 levels to cover the vertical extent of the atmosphere, giving 25200 points. In each of these points, however, we must carry the values of 7 parameters, and we therefore get 176400 parameter values. It is true that some savings may be made in various ingenious ways by not carrying every value in all the grid points, but the number above is of the correct order of magnitude. With these values of N we can manage to integrate the equations (10), although the integration requires the best and the fastest of available computers.

Imagine for a moment, however, that we wanted to include (12) in our integrations. We would then have to cover the whole parameter space with grid points. This space has N dimensions. If we decide to use L grid points in each direction, we will need N^L points. Even if N and L were only 10, we would have 10^{10} points which clearly is too many for any present computer, and N and L are much larger as we have seen. It follows that it is utterly impossible to include the prediction of the probability density function in our scheme.

However, we can in most cases be satisfied with considerably less than a knowledge of the function in all gridpoints and at all times in parameter space. It is this fact which leads to the stochastic-dynamic methods which we shall now attempt to sketch.

The Stochastic Measures of Change

Let us first consider an arbitrary function f(**X**). The so-called expected value of f(**X**) is defined as

$$(14) \qquad E\,[f(\vec{x})] = \int f(\vec{x})\,\phi(\vec{x},t)\,d\vec{x}$$

where the integral covers the whole parameter space. If we have the function f(**X**)of the form

$$(15) \qquad f(\vec{x}) = x_1^a\,x_2^b\,x_3^c\,.....$$

we have defined the moments of the probabality density function. For example the mean value (the first moment) is:

$$(16) \qquad \mu_i(t) = \int x_i\,\phi(\vec{x}_1 t)\,d\vec{x}$$

While the second moment is

$$(17) \qquad \rho_{ij}(t) = \int x_i\,x_j\,\phi(\vec{x},t)\,d\vec{x}$$

In general, we do not work with the second moment, but rather with the variance

$$(18) \qquad \sigma_{ij}(t) = \rho_{ij} - \mu_i\,\mu_j$$

when $i = j$, or the covariance when $i \neq j$. We note that we may show that the covariance is the second moment of the deviations from the mean values, i.e.

$$(19) \qquad \sigma_{ij} = E\,[(x_i - \mu_i)(x_j - \mu_j)]$$

In a similar way we write

$$(20) \qquad \tau_{ijk} = E\,[(x_i - \mu_i)(x_j - \mu_j)(x_k - \mu_k)]$$

for the third central moment around the mean values.

The main point is now that it is possible to derive equations for the rate of change of the first, second, third, . . . moments starting from (10). The derivations become quite involved, but after considerable labour one arrives at the following equations for the rate of change of the first and second moments, i.e. the mean values and the variances and covariances:

$$(21) \quad \frac{d\mu_i}{dt} = \sum_{p,q} a_{pqi}\,(\mu_p\mu_q + \sigma_{pq}) - \sum_p b_{pi}\,\mu_p + C_i$$

$$(22) \quad \frac{d\sigma_{ij}}{dt} = \sum_{p,q} [a_{pqi}\,(\mu_p\,\sigma_{jq} + \mu_q\,\sigma_{jp} + \tau_{pqj}) + a_{pqj}\,(\mu_p\,\sigma_{iq} + \mu_q\,\sigma_{ip} + \tau_{pqi})] - \sum_p [b_{pi}\,\sigma_{pj} + b_{pj}\,\sigma_{pi}]$$

We note that (21) contains not only the respective mean values, but also the various co-variances. It reduces to the original equation (10) if the co-variances are all zero, but this is of course not the case, generally. Similarly, the equation for the rate of change of the co-variance contains in turn the third moments.

The Closure Problem

The equation for the third moment's rate of change contains the fourth moments which in turn depend on the fifth moments, and an infinite number of equations are required if we want to describe the rate of change of all the moments. It goes without saying that we must replace the infinite system with a finite system in practical applications. However, how should we do this? It is by no means obvious in which way we should obtain a set of equations with as many variables as we have equations. This problem is called *the closure problem* because we get a closed set of equations. By far the most simple way to close the equations is to *assume* that all the moments from a certain order are zero. For example, if we assume that the third moment is identically zero we get a closed system from (21) and (22). In any case, it follows that a closure assumption always is necessary, and the various stochastic-dynamic predictions differ mainly in the closure approximation, in addition to the physical model used in the predictability experiments.

The Stochastic Definition of Predictability

Just as before one defines the limit of predictability when the variances are in some sense large compared with the mean values. One way of doing this is to calculate the energies of the states characterized by the mean values, called the "certain" energy because it is connected with the "deterministic" part of the state, and the energies connected with the variances, the "uncertain" energy. Expressed this way we may regard the limit of predictability reached when the uncertain energy becomes of comparable mangitude to the certain energy. For the atmospheric general case we get then an energy diagram as shown in figure 6. In the atmosphere we deal normally with two forms of energy. The first form is the available potential energy which may be defined as that portion of the total potential and internal energy which can be transformed into kinetic energy by the atmospheric processes. The second form of energy is the kinetic energy. It is also customary to divide all the atmospheric fields into the averages taken along the latitude circles, called the zonal average, and the deviations from these averages, called the eddies. In agreement with this convention, we may identify four forms of energy: A(z), the zonal available potential energy, A(e), the eddy available potential energy, K(z), the zonal kinetic energy and, finally, K(e), the eddy kinetic energy. For each of these forms of energy we have certain and uncertain energy, and we end up with altogether 8 energy reservoirs, as shown in figure 6.

The lines between boxes in figure 6 signify the physical processes of generation, conversion and dissipation of the various forms of energy, as they appear in a rather general atmospheric model. We note in particular that there are energy conversions between the certain and the uncertain energy energy reservoirs, implying that the uncertain energy may increase or decrease depending on the direction of the energy conversion. It is not given a priori that the uncertain energy always must increase.

Examples

Let us first consider a comparatively simple example. If we restrict the model atmosphere to contain only horizontal motion with no divergence we get the so-called barotropic model which has been of great use to the meterologist in spite of its simplicty, since vertical motion in general is two orders of magnitude smaller than horizontal motion. In such a model we can describe everything in terms of the kinetic energy, and the general energy diagram reduces to the diagram in fig. 7 which shows the four reservoirs connected with the kinetic energy. Table 1, lists the results of an experiment in which the initial values of K(z) and K(e) were 1040 kj m^{-2} and 1120 kj m^{-2}, respectively, while the corresponding values of the uncertain parts were 10 and 172 kj m^{-2}. The integration was carried out for a period of 3 weeks. It is seen that the uncertain kinetic energy in the eddies, i.e. UK(e), grows rather rapidly and is a considerable fraction of K(e) after one week, while it is more than twice as large after two weeks. Again we find a predictability time between one and two weeks.

Table 1
Barotropic Energyconversions

Time (days)	K(z)	K(e)	UK(z)	UK(e)	Total
0	1040	1120	10	172	2342
7	728	832	270	512	2342
14	767	404	168	1003	2342
21	822	471	220	829	2342

We consider next the results of an experiment with the full energy diagram as shown in fig. 6. Of the many interesting features which can be deduced from such an experiment, we shall look at the importance of knowing the heat sources with various degrees of accuracy. In the first experiment it was assumed that the heat sources were known perfectly. The predictability time, determined by all other processes and their uncertainties, came out to be 20.5 days for the horizontal scale of wave number 6 (corresponding to 6 waves around the globe measured along a latitude circle), while the predictability time was 10.2 days for the smaller horizontal scale corresponding to wave number 12.

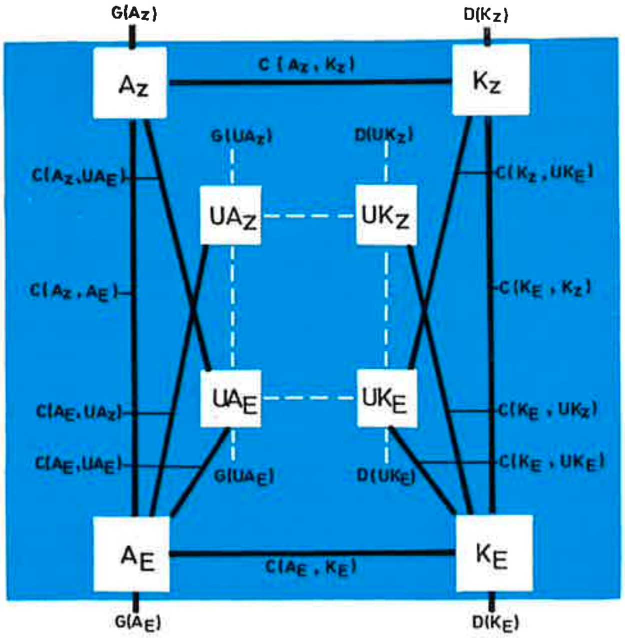

Figure 6: The basic energy diagram describing the generation, conversions and dissipations for the "certain" and "uncertain" energies. Each box represents an energy reservoir and the lines between the boxes represent energy conversions. (From reference 4.)

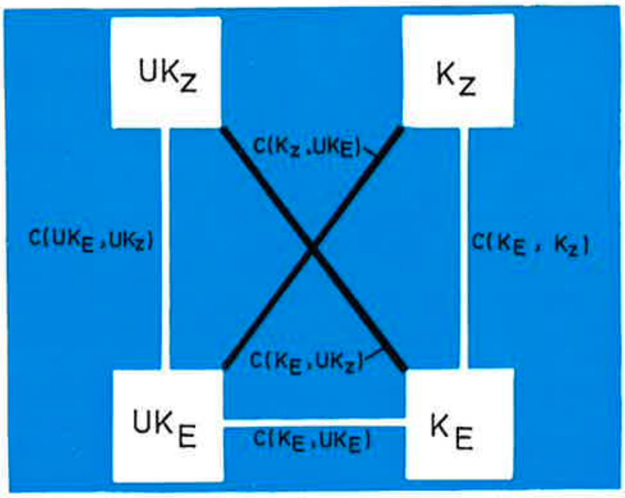

Figure 7: The energy diagram for a stochastic dynamic prediction of barotropic flow. Interpretation as in fig. 6. (From reference 4.)

We may further point out that the generations and dissipations depend on the physical processes going on in the atmosphere. The most significant process entering the generations is the heating of the atmosphere through radiation, heat exchange with the underlying surface, and the heat of evaporation and condensation, while the various frictional processes in the atmosphere, especially in the boundary layer close to the ground, are responsible for the dissipation.

New experiments with increasing uncertainty in the determination of the heat sources were then performed, and the predictability time measured in days was determined for each experiment. The very last experiment was made with no heat sources at all. The results, given in Table 2, show the predictability decreasing rather rapidly for both of the two scales (wave numbers 6 and 12*) as the uncertainty in the heat sources increases. However, the smallest predictability time is found in the case where there is no heating at all. Thus, a rather accurate determination of the driving mechanisms in the atmosphere seems necessary in order to increase the predictability times, as one indeed would have guessed in advance. The real value of the experiments is that they tell us what increases may be expected in the predictability as uncertainties in the heat sources are deminished.

Table 2
Predictability time (in days) for various uncertainties in the knowledge of the heat sources in the atmosphere

Wave number	0 %	2.5 %	5 %	10 %	No heating
6	20.5	14.0	12.2	7.0	4.2
12	10.2	7.0	4.2	3.2	2.2

All experiments described in this section, have been aimed at an estimate of the theoretical predictability for the earth's atmosphere. The different approaches which have been described are in no way perfect, and we must admit that we do not know the predictability with any great accuracy, although it appears to be of the order of 2 weeks for the large scale flow in the atmosphere. This number can easily be in error, upwards or downwards, by a factor of two. We have also learned that there is not a unique

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* Wave number 6 corresponds to a wave length of approximately 5000 km in middle latitudes, while the wavelength is 2500 km for the wave with wave number 12.

answer to the question of the predictability time for the atmosphere, because the predictability is very dependent on the scale of the motion. Moreover, it appears possible to increase the practical predictability in the future, because there is still a considerable gap between the one to two day forecast which we are used to and the theoretical limit of predictability of a couple of weeks. The question of the present practical predictability will be considered in the following section.

PRESENT PRACTICAL LIMIT FOR PREDICTABILITY

Knowledge of the practical predictability at any point in time is valuable since it would allow evaluation of the possible gain from an increase in the number of stations, a new observing technique or other factors which influence the uncertainty in the initial state for the predictions. Since we have frequent changes in the observations, especially during the World Weather Watch (WWW) and during various phases of the Global Atmospheric Research Program (GARP) in the future, we may expect changes in the predictability from time to time. However, at any given moment we may find the practical predictability by numerical experimentation. The results depend not only on the observations, but also on the particular atmospheric model selected for the study. It is important to know how various physical processes are included in the model, and also what numerical technique is used to perform the time integration since accuracies differ between various numerical techniques. Only during the last few years have meteorologists started to perform such experiments although any forecast center probably had a general idea of how far into the future they could use their model under general circumstances. This is also the reason why we get rather detailed forecasts for the first day or two, but rather general statements for the next 3 to 5 days.

In the following we shall give some results from a predictability experiment performed by Miyakoda et al. (7). The experiment was made with a series of 12 forecasts, all from initial states in the month of January. The starting days were selected with two dates from each of the years 1964–1969. Almost all forecasts were made for a two week period with the most advanced model available in the late 1960's. The model had nine vertical levels and was very advanced with respect to the physical processes included in the model. (But it will go too far to try to describe it in detail here.) The grid covered only the northern hemisphere because sufficient data are not available to allow a good initial analysis over the entire southern hemisphere. The model was well tested in advance because it has been used in general circulation studies of the earth's atmosphere.

In each case, the forecasts were compared to the observed state of the atmosphere for each one of the days within the two weeks forecasts. We shall in the following look at some of these verifications.

A number of statistical measures can be used for the goodness of a given forecast. As one measure of the accuracy of the predictions we shall use the standard deviation between the height fields of the two maps, i.e. the predicted map Z(p) and the observed map Z(o). The standard deviation is naturally zero for a perfect forecast where $Z(p) = Z(o)$ in all points, and gets larger and larger the greater the differences are between the two fields. We shall measure the goodness of the predictions against the standard deviation obtained using the initial map as a forecast, and denoting this "persistence" in the figures to follow. We shall say that a forecast is without value if the standard deviation between the predicted and the observed fields exceeds "persistence", i.e. the standard deviation between the initial field and the observed field at verification time.

Another statistical measure, much used in the field of short range predicetion, is the correlation coefficient between predicted and observed changes, both measured as changes from the initial maps. This goodness measure is naturally such that a perfect forecast will give a correlation coefficient of 1, while progressively worse forecasts will have smaller and smaller correlation coefficients with the absolutely lowest value being −1. It is debatable which value of the correlation coefficient we want to select as the minimum value below which the forecast is of no practical use. Many authors argue that a value of 0.5 is a reasonable limit and we shall use this value in our figures.

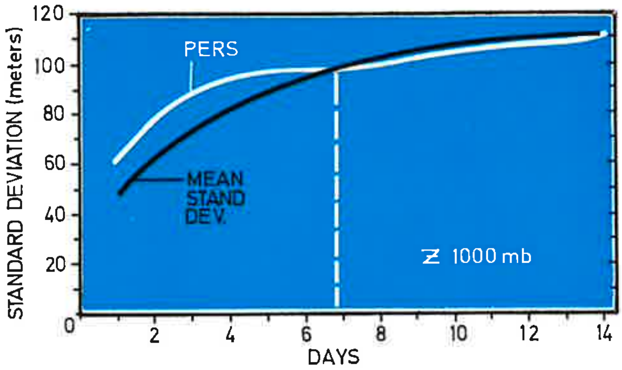

Figure 8: The growth of the standard deviation between predicted and observed 1000 mb fields, averaged over 12 experimental 14 days forecasts, as a function of time. The solid curve is for the forecasts while the dashed curve is for a "persistence" forecast. The limit of predictability is about 7 days measured by the point where the solid and dashed curves intersect. (From reference 7.)

Figure 8 shows the mean standard deviation for all 12 forecasts for the 1000 mb height field (measuring conditions close to the surface of the earth). Included in the figure is also the curve showing "persistance" as defined above. We note that the 1000 mb standard deviation stays below persistence up to about seven days, and after which there is little difference between the mean standard deviation and the persistence curve. Figure 9 shows conditions at 500 mb (about 5 km above the earth). Here, the mean standard deviation stays below the persistence curve during the entire two week period, although this did not hold for some of the individual predictions in the sample of 12 cases. In some of these forecasts the standard deviation curve crossed the persistence curve at 9 to 10 days. At any event, a comparison of figure 8 and figure 9 shows that the predictability time is somewhat larger at 500 mb than at 1000 mb, a probable reflection of the very complicated physical process taking place in the atmosphere boundary layer.

Essentially the same result is obtained when we use the correlation coefficient between computed and observed changes of the heigth field as our measure of forecast accuracy. Figure 10 and figure 11 show this measure as a function of time for the 1000 mb and the 500 mb surfaces. In all we conclude from

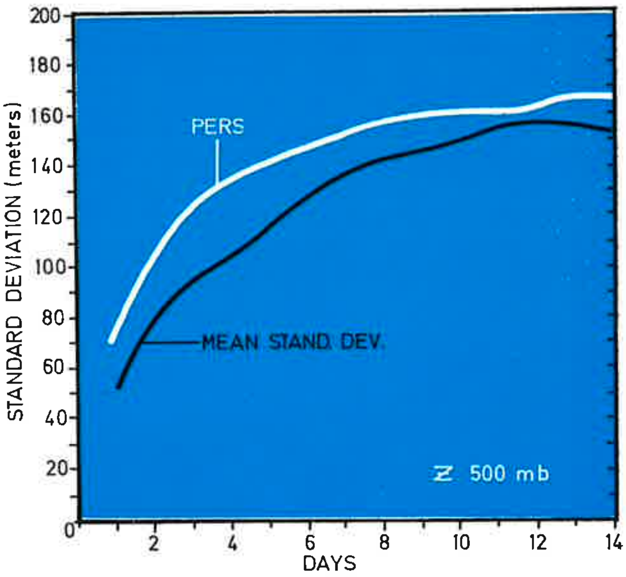

Figure 9: Same arrangement as in fig. 8, but for the 500 mb surface.

figures 9–11 that the practical limit of predictability at the present time is about 1 week for conditions close to the ground, and a few days longer for conditions above the atmospheric boundary layer.

Naturally, many other aspects of these experimental long range forecasts may be examined. We have considered the accuracy of the height field only, but other meteorological variable are also being investigated. For example, it is interesting to find out where the greatest errors occur in the forecasts because this will help identifying the physical processes which are poorly modeled.

Concluding remarks

The investigations described in the preceeding sections show a sufficient gap between the theoretical and practical limit of predictability for the earth's atmosphere to warrant work on forecast improvement. It is clear that additional meteorological stations or new ways to observe the physical and kinematical state of the atmosphere are needed in order to obtain a better definition of the initial state,

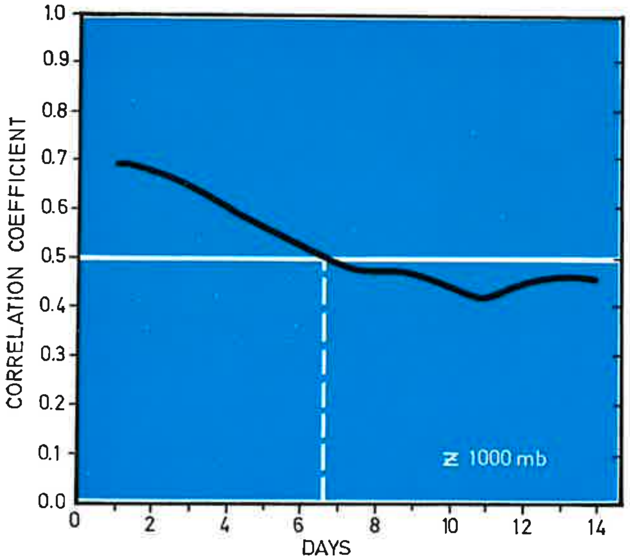

Figure 10: The averaged correlation coefficient, for the 12 experimental 14 days forecasts, between observed and predicted changes of the 1000 mb height field as a function of time. (From reference 7.)

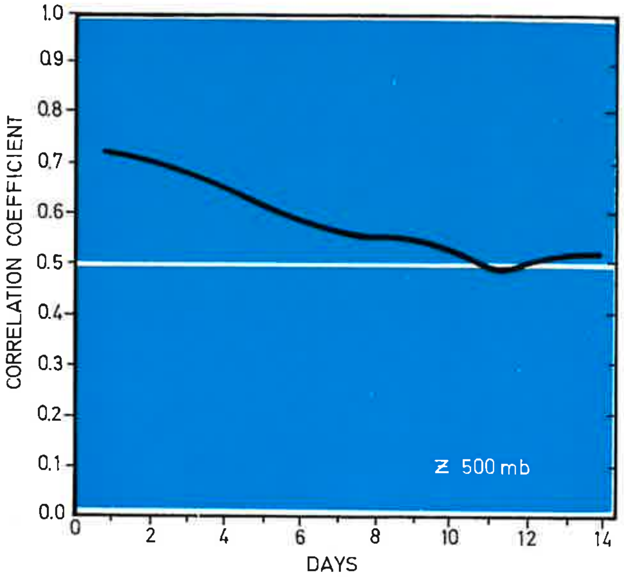

Fig. 11: Same arrangement as in fig. 10, but for the 500 mb surface.

which in turn will help to close the gap between the practical and theoretical limits of predictability.

The major new development is that the meteorologists begin to realize not only that an upper limit exists for the prediction time, but also what this time is. At the moment we can only obtain rather crude estimates of the theoretical limits of predictability, but the results will undoubtedly be improved in the future. With respect to the practical limit of predictability, we have at least the means to determine the limit for the present network of observations and a given dynamical model of the large scale atmospheric conditions. Any major modification of the network or the model will result in a change in the practical limit of predictability—hopefully toward improvement of predictions.

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The paper is based on a lecture given at the Nordic Meteorologists Meeting (NMM 8) held in Copenhagen in June 1972. The author has drawn freely on the material covered in the papers given in the references below.

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