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Introduction

The production of weather forecasts for use by the general public, governments, the military, news media and a wide range of industrial and commercial activities is a major international activity. It involves tens of thousands of people and many billions of pounds worth of high-tech equipment, such as computing and telecommunications networks, satellites and land-based observing systems. Most nations across the world have a national meteorological agency which generates forecasts for both government and commercial customers, although the size and scope of these agencies varies widely from country to country. There are also many private companies producing weather forecasts. These companies often specialise in forecasts for particular niche markets – news media, commercial shipping, offshore oil and gas exploration and production, the agricultural sector and so on. In some cases, weather forecasts can have very large financial benefits to particular customers. Power generation companies can make many thousands of pounds on the basis of a single weather forecast of a cold spell, as this allows them to buy gas at a low price prior to the increased demand during cold weather pushing the price up. Offshore gas and oil exploration companies can avoid multimillion dollar damage to drilling platforms by shutting down operations prior to the onset of a severe storm. Major supermarket chains use weather forecasts to plan their stock control in the knowledge that a spell of cold weather will result in increased sales of foods like soup whereas a spell of warm weather will increase demand for ice cream and barbecues.

The production of weather forecasts is based on a sound scientific understanding of how the atmosphere works, coupled with a vast amount of technical investment in observing, computing and communication facilities. The current state-of-the-art forecasting facilities at the world's major meteorological centres have evolved over a period of many years and are the result of scientific research and technical development. At the heart of any major weather forecasting centre is a numerical weather prediction (NWP)

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model – a computerised model of the atmosphere which, given an initial state for the atmosphere, derived from observations, can generate forecasts of how the weather will evolve into the future. Prior to the advent of NWP, forecasts were produced manually, usually by forecasters drawing maps of the current state of the atmosphere and then, using their knowledge of typical weather patterns together with a set of empirical rules, attempting to predict how that state would evolve. These days the computer model has taken over the task of predicting the evolution of the atmospheric state but there is still a big role for the human forecaster in the system.

This book is not a guide to the detailed formulation and coding of an NWP model. Nor is this book a manual on how to be a weather forecaster. Individual meteorological services produce training manuals for their forecasters which go into the specifics of forecast production within their organisations. Rather, this book will describe the end-to-end process of weather forecast production, with a focus on the NWP tools available to forecasters in major meteorological centres. The nature of the weather forecasting problem is discussed in Chapter 2. Chapter 3 focuses on the observations of the weather that allow forecasting centres to set the initial conditions for their forecasts. These same observations also form an important part of the forecast production process in the sense that human forecasters will continually check the observations against the NWP forecasts and modify the forecasts as and when necessary. Chapters 4 and 5 look at the basic ingredients of NWP models and how these ingredients are applied in order to produce operational forecasting systems for specific tasks. In Chapter 6 the role of the human forecaster within the NWP forecast production process is examined. Chapter 7 concentrates on the specific challenge of forecasting for periods of several weeks to several months ahead and, finally, Chapter 8 looks at how NWP forecasts are verified and measured, and how this process then feeds into the process of continuing development and improvement.

1.1 A brief history of operational weather forecasting

Many different human activities have always been sensitive to prevailing weather conditions and so people have been trying to predict the weather, both on a day-to-day basis and for the coming few months, since ancient times. As far back as the earliest civilizations, the weather during the growing season has affected crop production and so farmers have always taken note of the weather and climate. The ancient Egyptians, for instance, kept detailed records of the flooding of the Nile – an annual event that had a big impact on soil fertility and which was strongly affected by the intensity of the rainy season around the headwaters of the Nile.

Any kind of weather prediction prior to the scientific advances of the nineteenth century was largely based on folklore and perceived relationships between events in nature and the weather. Certainly there was no scientific basis to most of these forecasting methods but farmers and people who spent most of their days in the open air were certainly well attuned to the prevailing conditions and by observing changes in clouds and wind could make reasonably good predictions of the forthcoming weather for the next few hours or even a day or two. However, there was no systematic attempt to predict the weather in any kind of organised way.

The first organised meteorological agency was set up by the British government in the mid-nineteenth century as a response to loss of shipping on the trade routes that sustained the British Empire. In 1854 the British Board of Trade appointed Admiral Robert FitzRoy as its 'meteorological statist'. FitzRoy was an oceanographic surveyor with a reputation for producing detailed and accurate hydrological charts of coastal waters around the world. The Board of Trade hoped that he would also be able to produce an equivalent *meteorological* atlas charting weather conditions around the world which would serve to inform shipping lines and crews of the risks of storms, allowing them to make choices about when to sail and what routes to take.

FitzRoy began this task but he was also interested in the possibility of being able to issue more specific predictions of the weather conditions in coastal waters around Britain on a day-to-day basis. Since the invention of the barometer by Toricelli in the seventeenth century, people had started to realise that atmospheric pressure was correlated with weather conditions, with falling pressure often presaging unsettled or even stormy conditions, and rising or steady pressure indicating settled conditions. FitzRoy made use of this concept by designing a barometer specifically for use in ports, with information on what weather conditions to expect given an observed trend in the pressure. A version of this barometer was set up in all the major harbours around the United Kingdom, so that captains could consult the barometer prior to setting sail. Interestingly, as well as advice on the expected weather conditions associated with rising and falling pressure, there was also advice on how to interpret the colour of the sky at dawn and dusk in terms of forthcoming weather conditions. The recent advent of the electric telegraph allowed FitzRoy to take the use of these barometers one stage further. Regular readings from the barometers around the country, together with information about other weather variables, such as wind and cloud, could be telegraphed back to FitzRoy's office in London and the readings could be plotted onto a chart that summarized the atmospheric pressure distribution around the country. A sequence of these charts could then be used to predict the winds and prevailing weather around the country in the coming hours and even a day or so ahead. Furthermore, by building up an archive of these charts – today we'd probably call it a database – it

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might be possible to compare the current pressure distribution with similar pressure patterns from the past and use the knowledge of what happened to the weather in the earlier cases to predict what might happen this time. Predictions could then be telegraphed back to the port authorities. In this way FitzRoy invented the concept of operational weather forecasting, and probably also coined the term 'weather forecast'.

Of course, the infinitely variable nature of the weather meant that many of FitzRoy's forecasts went wrong and, particularly after making his forecasts more widely available to the public through the daily newspapers, FitzRoy received a lot of criticism from the public and the scientific community. This criticism was one of the several factors that led to FitzRoy's suicide in 1865. The work of the Meteorological Office of the Board of Trade continued though, with the forecasting methods being refined and new ones being developed. Napier Shaw took over the directorship of the Meteorological Office in 1905 and was instrumental in introducing more scientifically based forecasting methods.

The French government set up its first national weather service in 1855, once again as a response to the loss of shipping – this time due to a storm in the Black Sea during the Crimean War. In 1870 the US government, under President Ulysses S. Grant, also set up a meteorological service, this time under the auspices of the US War Office. Grant's recent experience as a general in the American Civil War had made him well aware of the impact of the weather on military operations, and the military forts around the United States provided the ideal locations for a weather observing network. The US National Weather Service became a civilian agency in 1890 when it was moved into the Department of Agriculture. The Australian Bureau of Meteorology was set up in 1906, although prior to this date each state had its own meteorological service.

Throughout the twentieth century, further scientific advances in weather prediction continued to be made. The British meteorologist Lewis Fry Richardson developed, single-handed, a method of forecasting the evolution of the state of the atmosphere using the set of physical equations that govern atmospheric motion. During World War I, in which he served as an ambulance driver, Richardson developed a way of solving these equations numerically and even performed a six-hour forecast of the pressure in central Europe, using data from 20 May 1910. This was a Herculean task involving many thousands of calculations that needed to be performed and double checked without the aid of any kind of electronic calculation device. The result was completely wrong but in his 1922 book, *Weather Prediction by Numerical Process*, Richardson set down his methods; these have formed the basis of numerical weather prediction ever since.

During World War II, the massive use of military aviation and shipping to conduct the fighting over wide areas demanded advances in weather forecasting. Aircraft on long range bombing missions relied on favourable weather

conditions in order to be able to see the ground on arrival over their targets and naval vessels, particularly those involved in the Pacific campaign in the part of the world most prone to tropical cyclones, needed to be able to avoid damaging storm conditions. Weather observing and forecasting practices improved rapidly through this period, with forecasters for the first time starting to pay attention to the development of the middle and upper troposphere in order to determine what might happen to the weather. The use of weather balloons carrying instrumented packages to observe the upper troposphere became more widespread as a result. Probably the most famous single weather forecast of all time was made during WWII, with forecasters led by Captain James Stagg advising the Allied Command to delay the D-Day Normandy landings in June 1944 by 24 hours.

Following the war, research into forecasting methods followed two main strands. In the United Kingdom meteorologists developed techniques based on looking at maps of the state of the middle and upper troposphere in order to predict where significant weather system developments would occur. In the United States researchers at a number of different institutions were working on developing and refining the numerical methods proposed by Richardson to produce forecasts. The availability of numerical computing devices, such as the ENIAC machine, greatly aided this strand of development. The results of the first computerised atmospheric forecast were published in 1950 by a research group at Princeton University, which included the mathematician John von Neumann and the meteorologist Jule Charney. The numerical model used had been developed over the preceding few years and was actually somewhat simpler than that used by Richardson. However, it produced a reasonably good 24-hour prediction of the evolution of the mid-tropospheric flow over the continental United States and this encouraging result led to further refinements of the numerical methods. At this stage, the method was in no way ready for operational use – the computing time alone was about 24 hours for a 24-hour forecast and this didn't include the time spent preparing the initial conditions for the forecast and inputting them into the computer.

The first *operational* numerical weather forecasts were made by the Swedish Military Weather Service in 1954. The development of the methods used in these forecasts was led by Carl-Gustav Rossby, a native Swedish meteorologist who had worked in the USA, principally at Chicago University, during the 1930s and 1940s. On returning to Sweden in 1947 he founded the Swedish Institute of Meteorology and continued to develop numerical forecasting methods.

The UK Met Office came to numerical weather prediction (NWP) rather late. During the 1950s and early 1960s the UK Met Office had to do its research into NWP on borrowed computers and it wasn't until the mid-1960s that it actually had its own computing facility. In 1965 the UK Met Office started

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to routinely produce numerical weather forecasts and in 1967 it had the distinction of producing the first numerical prediction of precipitation. Prior to this, numerical forecasts had only predicted the evolution of pressure, geopotential height and vorticity patterns and it was left to experienced forecasters to interpret these patterns in terms of the actual weather that would occur in association with them.

By the 1970s most of the major meteorological agencies around the world were well established and starting to use NWP methods as the basis of their operational forecasts. One major development in the 1970s was the setting up of the European Centre for Medium-range Weather Forecasts (ECMWF), in Reading, UK, in 1975. The aim of the centre was to develop operational NWP forecasts for the medium range (out to about 15 days) using funding from all the main European meteorological services, which would not have been able to develop such facilities with their own resources. The forecasts would then be made available to the National Weather Services of all the member states. ECMWF pioneered the operational use of *ensemble forecasting* techniques (more details are given in Chapter 5) and has since developed numerical methods and models for prediction on the monthly to seasonal timescale. Such techniques require vast amounts of computing power and it is only through the collaborative funding of all the member states that such facilities can be maintained and upgraded. The supercomputing facilities at ECMWF regularly top the league table of computing power in the United Kingdom and the NWP forecasts produced using these facilities are widely regarded as being the best in the world. The US National Center for Environmental Prediction (NCEP) started to produce ensemble forecasts in the early 1990s. More recently many forecasting centres have introduced ensemble methods as computing facilities have developed. The UK Met Office and the Australian, Chinese, Japanese, Korean, French, Brazilian and Canadian National Meteorological Services all now routinely run ensemble forecasts in some form.

Since the 1970's NWP methods have become more accurate and the models used have become faster. Communication networks have improved massively over this period too. As recently as the early 1980's an outstation weather forecaster working at a military airfield for instance, would have had very little access to the output from numerical models, and what few products were disseminated often arrived too late to be of any use in making forecasts for the aircrews. This lack of up-to-date model output made many forecasters somewhat wary of using NWP products to guide their forecasts. Similarly outstation forecasters saw very few satellite images. It wasn't until the advent of high bandwidth communication networks in the 1990's that forecasters working at locations remote from the main meteorological service headquarters got to see a wide range of guidance from numerical models together with

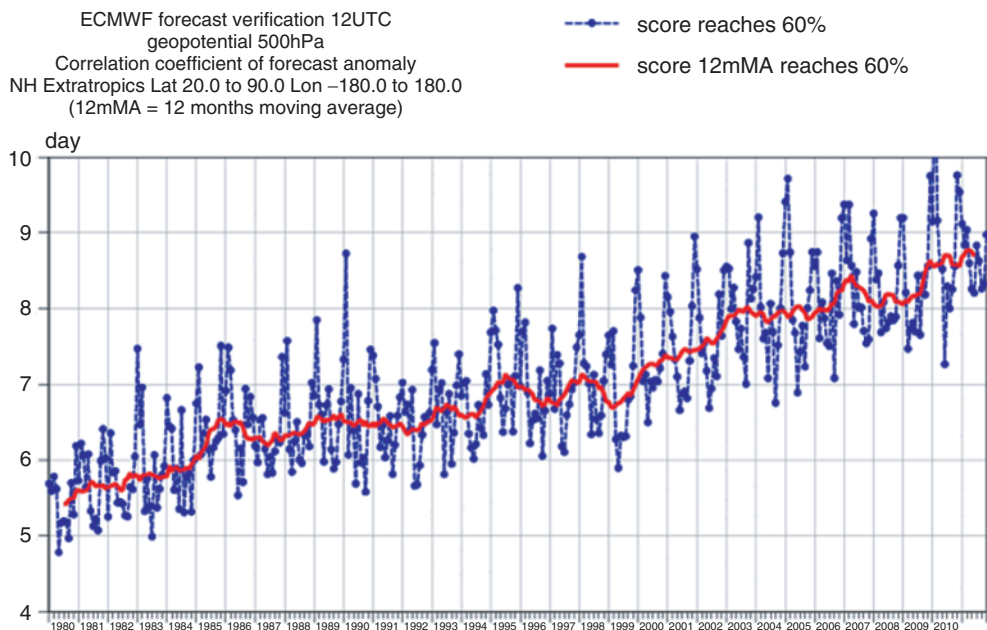


Figure 1.1 A time series of the anomaly correlation between the forecast and observed 500 hPa geopotential height anomaly in the northern hemisphere extra-tropics from the ECMWF forecast model. The vertical scale shows the point of the forecast in days at which this correlation falls below 60%. The blue dashed line shows this value for every month and the red solid line shows the 12-month running mean. (Reproduced by permission of ECMWF.)

regular, detailed satellite imagery. So going right back to FitzRoy who was able to make use of the newly invented electric telegraph system, it is clear that communication networks play a vital part in operational meteorology.

Improvements in forecast accuracy since the 1980s are illustrated in Figure 1.1. It shows, for the ECMWF model, the point in the forecast at which the correlation between the forecast and observed 500 hPa geopotential height anomaly in the Northern hemisphere extra-tropics falls below 60%. This value is considered to be a measure of the usefulness of the forecast, with values above 60% representing skilful forecasts. The blue dashed line shows the value for each month since January 1980, and the red solid line shows the 12-month running mean of the monthly values. In 1980 the correlation fell below 60% at about 5.5 days into the forecast. By 2010 this had risen to about 8.5 days into the forecast. Effectively this means that in 2010 ECMWF was producing forecasts which were skilful for an average of three days longer than in 1980. Other forecast centres show similar improvements in skill. Of course, to most users of weather forecasts the anomaly correlation of the Northern hemisphere 500 hPa geopotential height is a pretty meaningless

measure of the quality of a weather forecast and there are many ways of measuring forecast skill that are more focused on the interests of specific customers. These are discussed in detail in Chapter 8.

Recent developments in operational forecasting have been many and varied, all helped along by regular increases in the availability of computing power to meteorological agencies. More forecasting centres are now running ensemble forecasting systems and a wider range of numerical models, some with global coverage and others with very fine scale resolution over limited areas. So-called 'storm resolving models', which can explicitly represent organised convective storms, have started to come into operational use over the past few years and new ways of incorporating observations, such as rainfall rates from meteorological radar, into models are improving the way that these highly detailed forecasts are initialised. At the other end of the time and space scales, more forecasting centres are now running monthly and seasonal forecast models. Some of these developments are described in more detail in the relevant chapters of this book.

Despite the advances in technology which are driving improvements in forecast accuracy, there is still a fundamental place in the weather forecasting process for human experts. Even the most sophisticated numerical models of the atmosphere may produce forecasts which diverge significantly from reality even at quite short time ranges. In these circumstances a team of expert forecasters can spot the problems at an early stage and consider how best to amend the forecast. Models also have known systematic errors and biases, particularly when producing forecasts of local detail, and an experienced forecaster will be able to take account of these issues when producing forecasts for specific customers. Many customers of weather forecasts also require a human forecaster to act as an interface between them and the numerical weather forecast, such as military aircrew receiving a face-to-face briefing from a forecaster prior to flying weather sensitive missions or local government agencies needing briefing and hour-by-hour advice on potential disruption due to snow and ice or flooding. Often the most visible weather forecasters to the general public are those presenting weather forecasts on television but it must be remembered that these people are just the visible face of a large team of experts running, monitoring and analysing the numerical forecasts and deciding what the key weather issues for each day's forecast will be.