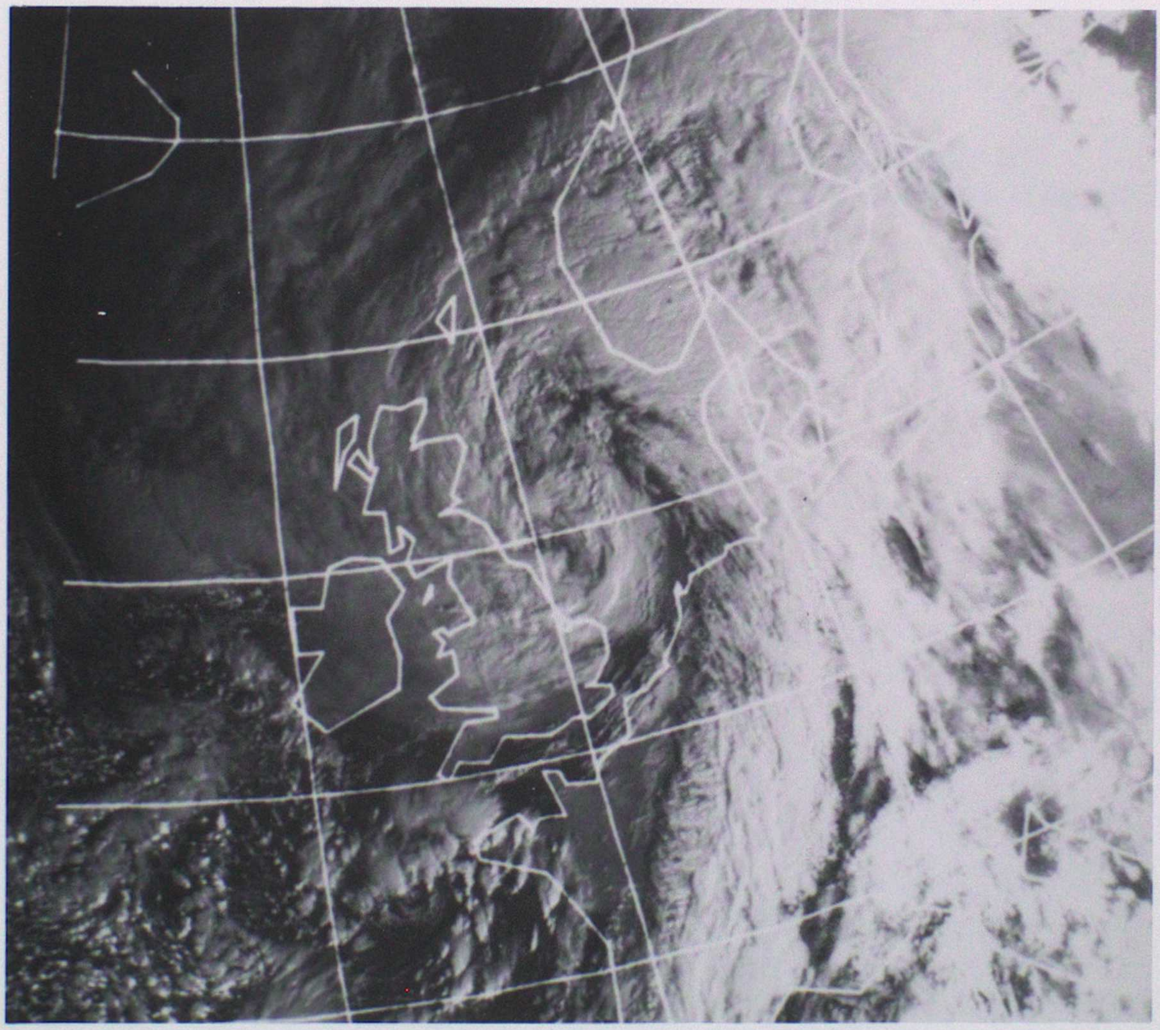
THE STORM OF 15/16 OCTOBER 1987



REPORT FOR THE SECRETARY OF STATE FOR DEFENCE
BY SIR PETER SWINNERTON-DYER AND PROFESSOR ROBERT P PEARCE

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"Cover photograph:

A photograph of the storm taken from the NOAA 10 orbiting satellite at 0819 GMT on 16 October 1987 when the storm centre had just moved into the North Sea. At this time the sun had just risen over the British Isles and with the sun at this altitude the cloud features are particularly well defined. The winds over SE England had passed their maximum speed but severe gales were still affecting the area and the adjacent North Sea.

(Photograph reproduced by kind permission of the University of Dundee Satellite Station)."

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REPORT OF THE SECRETARY OF STATE FOR DEFENCE'S ENQUIRY INTO THE STORM OF 16 OCTOBER 1987

1. Introduction

1.1 Our brief, described in the Secretary of State for Defence's press release of 20 October (see Annex 1), was to consider the findings of the Meteorological Office (MO) internal enquiry into the forecasts of the storm which struck South-East England in the early hours of Friday 16 October and report our conclusions to him. During the period when the internal report was being prepared we had consultations with the Director-General of the Meteorological Office and his senior staff including the chief forecaster, and visited the London Weather Centre, which issues forecasts for south-east England, the European Centre for Medium Range Weather Forecasts and the French Meteorological Service (see Annex 2). Subsequently we interviewed the senior forecasters at the Meteorological Office who were on duty on 14 and 15 October.

1.2 Before examining the MO report, we formed our own general assessment based on interviews and examination of actual and forecast weather charts for the storm period. We then drew on this assessment in our consideration of the MO report. Our conclusions are contained below in Section 7. Section 2 contains a brief account of the process of weather forecasting. Section 3 contains a survey of the present state-of-the-art in predicting severe storms, and describes the reasons why they are often difficult to predict, drawing attention to the need for forecasters to allow for the limitations of computer models when using their products as forecasting guides. Section 4 contains an account of the information available to the forecasters on 14 and 15 October, the days preceding the storm, and the problems they had to resolve. The approaches adopted by the MO forecasters and by those in the French Meteorological Service are described. In Section 5 comments are made on the role played by the media and weather presenters in disseminating the forecasts. Section 6 comments explicitly on the MO report and its recommendations.

1.3 We have tried to make our report largely self-contained and intelligible to the non-expert, though there are a few places where to save duplication we refer the reader to the MO report. In the interests of intelligibility we have been forced into a certain looseness of language in some places.

2. The process of weather forecasting

2.1 Weather forecasting is not an exact science. Weather is generated by a large and complicated system, whose main components are the atmosphere including water vapour, clouds and rain, the surface of the ocean and the surface of the land. Their interaction is the subject matter of meteorological physics. In a highly idealized form, the process of weather forecasting can therefore be described as follows:

(i) Determine, and express in mathematical form, the laws of nature which govern the development of the weather system over time.

(ii) Find by observations the exact state of the weather system at the instant from which calculation is to start.

(iii) Solve numerically the equations which describe the development of the weather system from the initial state obtained in step (ii), for as far forward in time as may be needed.

(iv) From the resulting description of the weather system, obtain forecasts for the weather itself.

In practice, each of these steps involves major complications.

2.2 Although the basic laws of nature which govern the development of the weather system are recognized, their precise application is still only imperfectly known. There is a continuing programme of research, both in the MO and in universities, to improve the state of knowledge. The pay-off from that research will be better forecasts in the future, though there is an unavoidable time lag between discovering new knowledge and incorporating it into the forecasting process. For instance, much of the research has to be done by detailed observations and measurement from a properly instrumented and dedicated aeroplane - the Meteorological Research Flight; this is inevitably expensive.

2.3 To describe the exact state of the weather system at a given moment requires an infinite amount of information; that cannot be collected and could not be handled if it were collected. What one seeks to do is to collect enough information to provide a reasonably accurate picture, at an affordable cost. The value of additional information for improving forecasts has to be set against the cost of obtaining it. The sources of information are diverse. Satellite photographs show the cloud pattern, among other things; commercial aircraft automatically measure upper atmosphere winds; ground-level observations are regularly made from a large number of observing stations on land, from the three remaining weather ships in the Atlantic and from some North Sea oil rigs - as well as more irregularly from commercial ships; instrumented balloons are sent up regularly, and make measurements of the atmosphere at all heights above certain places. All this information is gathered and exchanged internationally. But systematic gathering of information over the sea is much more expensive and difficult than over the land; it is therefore unfortunate that so much of Britain's weather comes from the Atlantic.

2.4 The equations which describe the development of the weather system are far too complicated to be solved exactly; they therefore have to be simulated on a computer and the simulated equations solved numerically. An exact description of the weather system would involve calculating such variables as temperature, pressure, wind velocity and water vapour density at every point in the atmosphere. The crucial step in the simulation is to restrict calculations to the values of these variables at the points of a grid. How fine the grid can be depends on the speed of the computer which is being used, and more particularly on the size of its memory. It is desirable to use as fine a grid as possible, partly to reduce the error in simulating a continuous system by a discrete one but primarily because the computer calculation cannot take adequate account of weather features whose scale is smaller than the grid interval.

2.5 The computer calculations therefore present a picture of what the weather system will look like in the future, but it is not a totally accurate picture. The three main sources of error have already been described: the initial information is imperfect, our understanding of the laws of meteorological physics is incomplete, and replacing a continuous calculation by a discrete one introduces further errors. The errors arising from the second and third sources build up with time; this is why one expects long-range weather forecasts normally to be less accurate than short-term ones. Moreover, there is more information inside the computer than the human forecaster can cope with; what is provided to him is only a selection of what is inside the computer, and that selection process may be a further source of error.

2.6 The task of the human forecaster is to make the best forecast he can on the basis of the information available to him. The most important source of information is the computer, and the more reliable the computer model has proved in the past, the more reluctant the human forecaster will be to amend or override what it says. [The MO forecaster in fact has access to the output of several different computer models, whose predictions will not always wholly agree with one another; but the custom of the Office, based on experience, is to give preference to their own fine mesh model.] But the final judgement lies with the human forecaster; he should have, by experience and education, abilities which we do not yet know how to incorporate into the computer program. In particular, he has to judge whether there are phenomena in the initial data which are on too small a scale for the computer to take adequate account of, but which are likely to have a significant effect on the development of the weather system.

2.7 For what follows, there is one other important group of ideas - those which relate to sensitivity. As with most complex physical systems, there are some states of the weather system in which a relatively small change in the situation now will rapidly build up and lead to very substantial changes in the way the system develops. (For an analogy, consider a pin standing on its point; it will certainly fall over, but very small changes in its initial position may totally alter the direction in which it falls.) Research has reached the point of being able to recognize some but not all such sensitive states of the weather system. Much the same is true of computer simulations of the weather system; there too, small changes in the initial conditions can in some circumstances lead to substantial changes in the way the computer model develops. Such phenomena are not common, but subsequent MO calculations (described in Chapter 3 of their report) make it clear that the computer simulation of the events of 15/16 October was highly sensitive to the initial conditions. The same may well have been true of the actual weather system, but of that we have no way of being sure.

2.8 Akin to these, but much easier to recognize, are situations in which what would appear to be small changes in the output of the computer would lead to substantial changes in the weather forecast. This is something that the human forecaster must always be alert for.

3. The structures of rapidly deepening depressions and their prediction

3.1 Before considering the quality of the forecasts of the storm of 16 October, it is appropriate to comment on the state-of-the-art in predicting extreme events of this kind. Present-day computer models of the atmosphere are basically capable of simulating these intense storms, provided the computers are of sufficient speed and capacity to describe their full structural detail at each stage of development. But it is not clear that they can yet routinely do so, since computer models of such storms may be very sensitive to initial data. Furthermore, a recent American study of a somewhat similar extreme event to which the public was not alerted, the President's Day storm (see below), concluded that more research was needed on how fine a vertical grid resolution was required to enable computer models adequately to simulate this kind of storm. We are not aware of anywhere in in the world where this research has yet been carried out.

3.2 Some idea of the complexity of the structure of the storm, typical of such systems, is provided by the satellite cloud pictures in the MO report (pp 1.20 - 1.25, 1.30 - 1.36) and by the vertical cross-section of winds at various levels across S. England shown in Fig. 1. The latter also shows schematically the concentrated regions of ascent and descent through the depth of the atmosphere which are perhaps the most significant and characteristic features of these systems. The areas of cloud in satellite pictures, with accompanying heavy rain, are associated with the strong ascent and the cloud-free areas with descent. The sharpness of the cloud edges, often indicating fronts, demonstrates how pronounced are these contrasts between ascent and descent, and indicate the demands made on computer models if they are to represent them sufficiently accurately to generate good forecasts. The regions of ascent and descent are often linked with belts of strong upper and low-level winds, the latter referred to as a low-level jet;

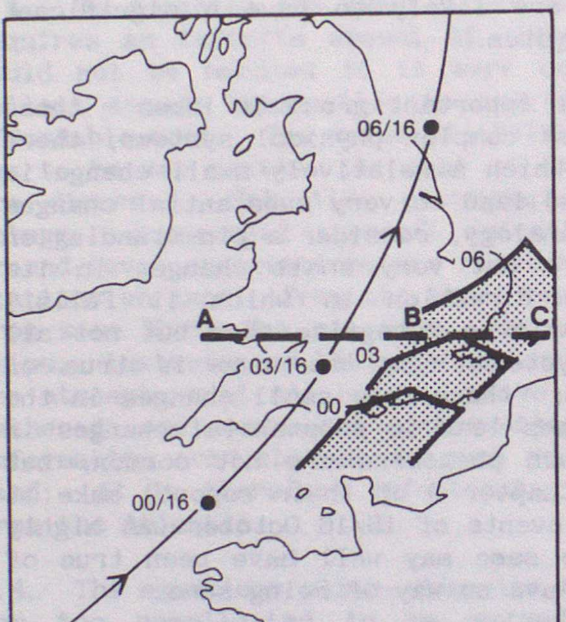

Figure 1(a) The progression of the storm centre and region of gale force winds across England on 16 October. The full line shows the track of the main depression centre with times indicated, e.g. 03/16 means 0300 on 16 October. The regions bounded by broad arrows show the progression of the northern edge of the gales.

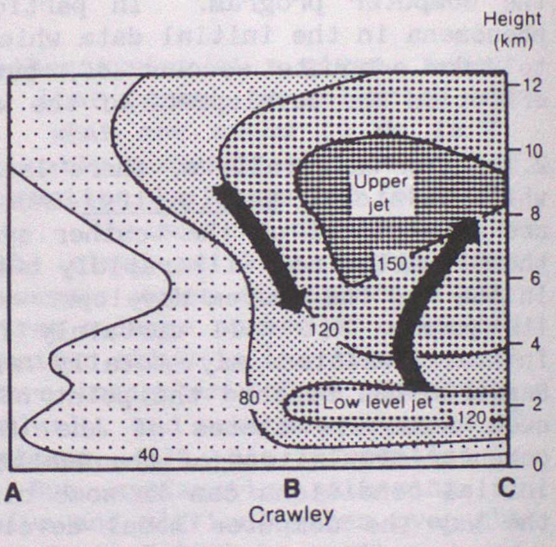

Figure 1(b) A vertical section of the wind structure at 0600 on 16 October along the line A B C, based on winds measured at Aberporth, Larkhill, Crawley and De Bilt (Netherlands). The wind strength is indicated in m.p.h. by shading, the heavier the shading the stronger the wind. The maximum strength of the lower jet is about 120 m.p.h. and of the upper jet 150 m.p.h. The arrows indicate schematically the vertical motion usually associated with the jets.

this feature was clearly present over SE England during the height of the 16 October storm, with a maximum speed of at least 120 m.p.h. at a height of about 1 km (see Crawley ascent on p.3.15 of the MO report). Turbulent eddies in the lower layers, bringing down air from near the low-level jet, were responsible for the 100 m.p.h. gusts at the surface. The upper-level wind maximum, or 'jet streak', approaching 150 m.p.h. at a height of about 10 km, was a feature which could be traced back across the Atlantic over the previous two days and probably originated from hurricane Floyd in the Caribbean. Its arrival off the Bay of Biscay during 15 October was a major contribution towards the rapid development there, including the production of regions of strong ascent and descent and the low-level jet which had such disastrous consequences.

3.3 Similar features were all present in the major cyclonic snow-storm which developed along the middle Atlantic coast of the United States on 18-19 February 1979. This produced a heavy snowfall from North Carolina to New York and has been studied in considerable detail by U.S. meteorologists, motivated by the need to restore their credibility after not having forecast the heavy snowfall on what happened to be a public holiday - President's Day. The cyclone is now referred to as the 'President's Day storm'. As a result of this and other similar studies, the factors associated with these rapid developments are now quite well understood. This means that general mathematical theories have been proposed which explain why, under certain combinations of upper and lower level atmospheric conditions, rapid development of storm systems will occur. These conditions may be quite subtle, so that whether a computer model successfully simulates the development of this kind of storm depends crucially on the adequacy of the observations from which its initial conditions are derived. It follows, therefore, that since the observation network is poor to the south-west of the British Isles where such storms affecting southern England originate, computer forecasts of these storms for southern England stand a fair chance of being inaccurate. The forecaster must bear this in mind and often has to exercise his professional judgement concerning the likely intensity of a developing storm and its track. To reach his conclusions he will use his experience, both of previous similar instances and of the behaviour of models under these circumstances. But for his success to be maximised, experience must be combined with a sound knowledge of modern theory and an ability to interpret his computer outputs in such a way as to determine whether the subtle conditions favouring rapid development are present. Many forecasters still base their assessment primarily on mean-sea-level pressure charts, which have always been the most favoured and convenient representation of weather patterns. These though, taken alone, are quite inadequate for identifying the critical conditions favouring rapid development. Satellite images also help considerably, but for their full exploitation for forecast purposes require a detailed analysis of the dynamics of the flow through most of the depth of the atmosphere and over a region of continental dimensions. Modern computers are capable of providing such analyses in sufficient time for their use in preparing even short term (6-12 hour) forecasts. These so-called 'diagnostic packages' are continually being developed by meteorological services, but the level of their sophistication and their efficient use requires forecasters to have a much higher level training, particularly in atmospheric science as distinct from forecasting techniques, than was necessary even ten years ago.

3.4 In summary, then, rapidly deepening depressions have a complex structure. Our present-day computer models <u>can</u> successfully simulate them, but in an operational forecasting situation may well not do so, primarily because of the inadequacy of the observational network; equally, they may simulate developments which do not in fact occur. The forecaster thus needs to exercise judgement in interpreting computer forecasts, and even then he will sometimes have to admit that he cannot be confident whether a storm will develop or not. To maximise his success he must rely not only on his previous experience, but also on his knowledge of theory, much of which is at a scientifically advanced level and is continually being developed.

4. Computer predictions of the October 15/16 storm and their use by the forecasters

4.1 Chapter 2 of the MO report is devoted to a presentation of the computer forecasts available to the duty forecasters on October 15/16. One crucial problem which the forecasters had to resolve was what would be the track of the low. It was clear that it would run north-eastwards across England, and that there would be severe winds to the south-east of its track - though how severe the winds would be would depend on the depth of the low. (Severe winds are associated not with a low as such, but with a strong pressure gradient, which is indicated by the isobars being close together. Virtually all of the charts from Figures 2.5 to 2.12 inclusive of the MO report indicated that the severe winds would be to the south and south-east of the low.)

4.2 The variability of the predicted location of the low for midnight on 15/16 October made by the MO, ECMWF and US global models, starting at different times during the previous few days, is well illustrated in Figs. 2.1, 2.2 and 2.3 of the MO report. Movement of the storm during the night across England into the North Sea, when the extensive wind-damage occurred, was well predicted 24 hours ahead by the UK global model but not, surprisingly, by the 24 hour forecast of the fine-mesh model which predicted a track further south with SE England missing the gales; the 12-hour fine mesh forecast moved the centre too rapidly north-eastwards, but did predict strong (although not exceptional) winds over S.E. England.

4.3 This diversity well illustrates the dilemma posed for the forecasters. At about 1500 on the afternoon of 15 October, the senior MO forecaster had in front of him the mid-day analysis showing a depression with a centre of 970mb just to the north of Cape Finisterre (MO report, Fig. 1.3(b)), having deepened by about 6mb since 0600; surface observations at 1300 and 1400 would confirm this. He would also have the Meteosat images from the previous midnight (see Figs. 1.2 (a) to (c) of the MO report) and the Meteosat water-vapour channel images, which are particularly useful in identifying regions of strong ascent and descent - these reinforcing the indicators of these regions in the Meteosat cloud images. In addition he would have crude versions of the NOAA-10 orbiting satellite images received up to that time - not like the highly detailed versions reproduced in Fig. 1.4 of the MO report, which are post-processed at the University of Dundee. Together with these observations he had the most recent prediction sequences from the MO global and fine mesh models (Figs. 2.9, 2.10, 2.11 and 2.12 of the MO report and the 36-hour forecast from the ECMWF model (Fig.2.6(c)), indicating only light winds over S. England. He would be aware that the most reliable guidance usually comes from the MO fine-mesh model. The synoptic review issued at 1545 (see MO report Annex 2.3) based on this evidence followed the fine mesh prediction in most respects, emphasising the rain sequence but not the strong winds; but a correction issued at 1640 spoke of "severe gale force at times in exposed coastal districts...especially...over the extreme southeast". It was not until the 2235 GMT (2335 BST) synoptic review that land gales were mentioned and, subsequently, warnings issued to subscribers.

4.4 The forecasters of the French Meteorological Service were faced with a similar situation, although predictions, particularly of wind strengths, over France were on this occasion somewhat more straightforward than for England. This was because the likelihood of gales over N.W. France did not depend much on the precise track of the cyclone; the occurrence of gales could therefore be predicted with high confidence - though not their extreme severity.

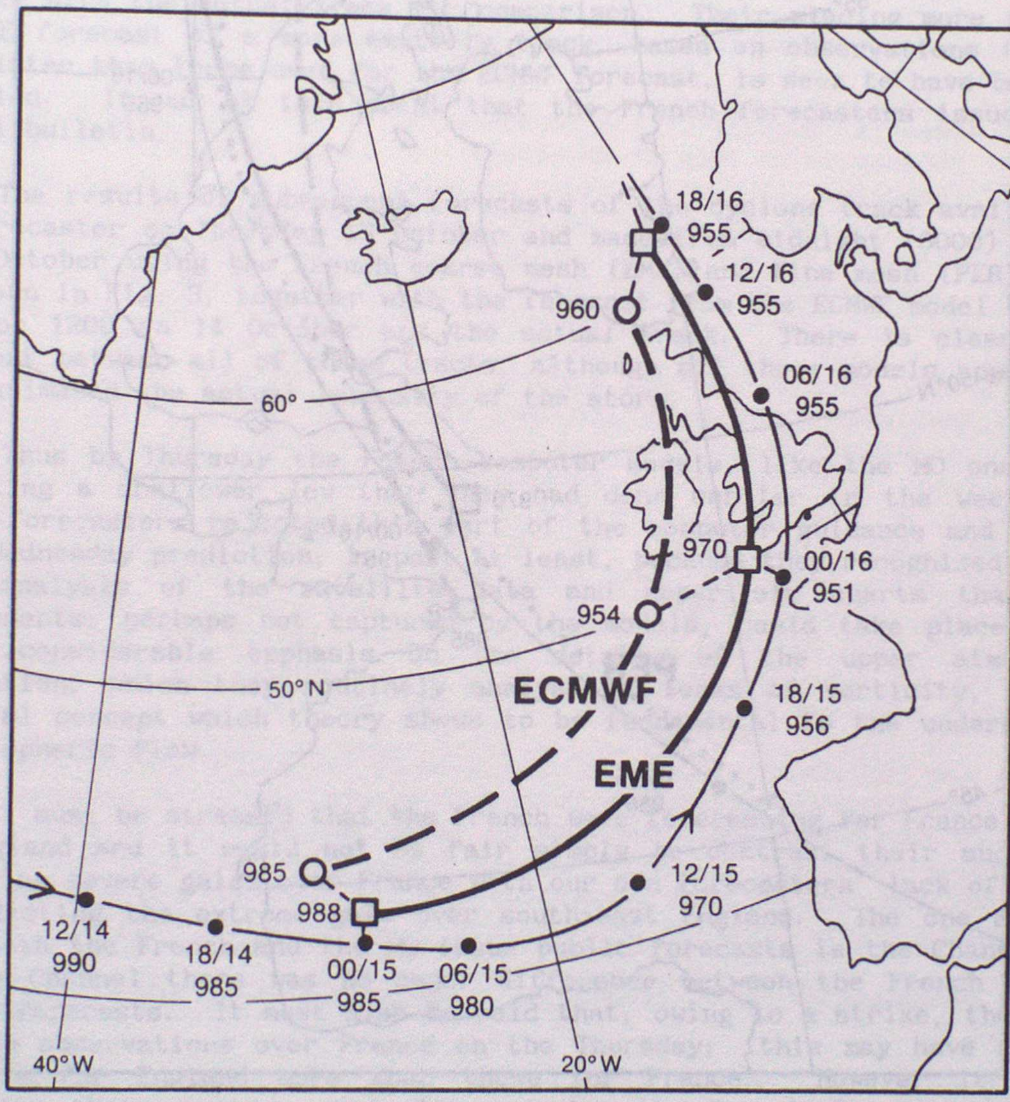

Figure 2 Forecast tracks and central pressures of the storm centre used by the French forecasters as a basis for issuing a special storm bulletin on Wednesday 14 October. The ECMWF forecast using initial data for 1200 GMT 13 October is shown by dashed lines, and that from the French operational model (EME) using initial data for 0000 GMT 14 October by a full line. These tracks are compared with the actual track shown by a thin full line. The positions and depths at various times are also shown in coded form; thus 12/15 indicates the centre's position at 1200 GMT on 15 October and 970 the central pressure as 970 mb. The thin dashed lines link the forecast centre positions with the actual positions and the numbers on the forecast track indicate the forecast central pressures.

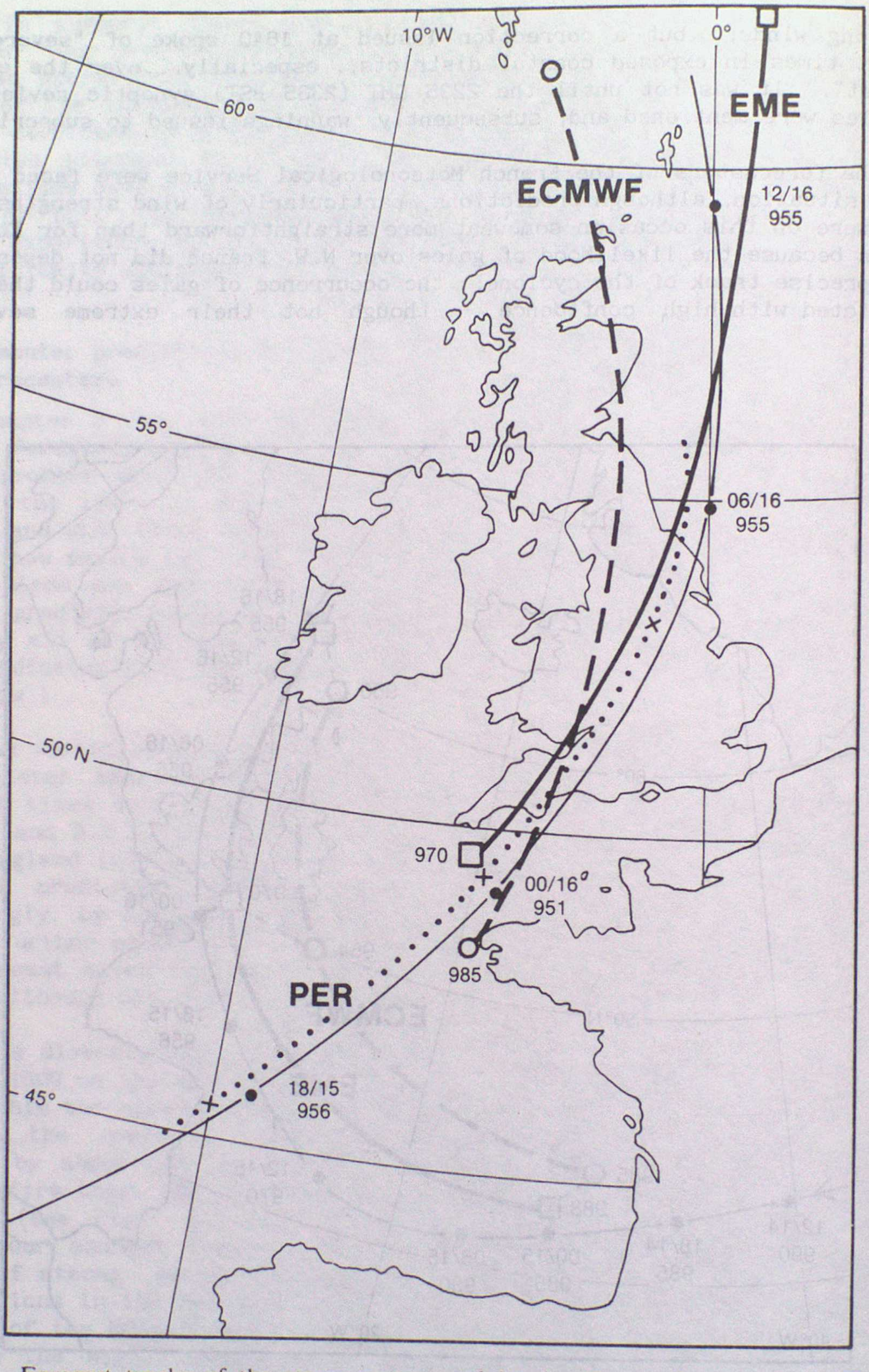

Figure 3 Forecast tracks of the storm centre used by the French forecasters on Thursday 15 October. The latest ECMWF forecast track (dashed line and circles) used initial data for 1200 GMT 14 October and the French EME (full line and squares) and fine-mesh (PER — dotted line and crosses) forecasts used initial data for 0000 15 October. The actual track is shown by a thin full line with times and pressures indicated as in Fig. 2. The forecast central pressures at 0000 GMT on 16 October when this had reached its lowest value (951 mb) are also shown; note that these are appreciably higher than the actual value.

Earlier in the week both the French and the MO computer models had forecast severe conditions, probably worse in France than in England. These, for England, were indeed announced by the Meteorological Office in their five-day forecasts (see MO Report Annex 4.5). On Wednesday 14 October the French issued a special meteorological bulletin - a thing which they do about half-a-dozen times a year (see MO report Annex 4.19). This referred explicitly to gusts exceeding 100 km per hour (60 m.p.h.) inland over Brittany, north-east and north France, and over 90 m.p.h. in coastal regions; this was consistent with the 60-hour prediction of the ECMWF global model which, as it happens, gave the deepest low of all the computer models, taken along with that of their own operational model (EME). The forecast storm tracks available from these models on 14 October are shown in Fig. 2, together with the actual track for comparison. Their placing more faith in the EME forecast of a more easterly track, based on observations taken 12 hours later than those used for the ECMWF forecast, is seen to have been well justified. It was at this point that the French forecasters issued their special bulletin.

4.5 The results of subsequent forecasts of the cyclone track available to the forecaster on Thursday 15 October and made from midnight (0000) data on 14/15 October using the French coarse mesh (EME) and fine mesh (PER) models are shown in Fig. 3, together with the forecast from the ECMWF model based on data for 1200 on 14 October and the actual track. There is clearly good agreement between all of these tracks, although all three models appreciably underestimated the actual intensity of the storm.

4.6 Thus by Thursday the French computer models, like the MO ones, were predicting a shallower low than they had done earlier in the week. The French forecasters rejected this part of the computer guidance and kept to their Wednesday prediction, in part at least, because they recognised through their analysis of the satellite data and upper air charts that rapid developments, perhaps not captured by the models, could take place. They placed considerable emphasis on the details of the upper atmospheric circulation, which they routinely analyse in terms of vorticity, a fluid dynamical concept which theory shows to be fundamental to the understanding of atmospheric flow.

4.7 It must be stressed that the French were forecasting for France and not for England and it would not be fair simply to contrast their success in predicting severe gales over France with our own forecasters' lack of success in predicting the extreme gale over south-east England. The one area for which both the French and the MO issue public forecasts is the Channel, and for the Channel there was no major difference between the French and the English forecasts. It must also be said that, owing to a strike, there were very few observations over France on the Thursday; this may have affected forecasts for England more than those for France. However it is our impression that on this particular occasion the French forecasters showed the better appreciation of the nature of the phenomenon they were dealing with. This enabled them to interpret the forecasts of the computer model with deeper insight, making much more allowance than did our own forecasters for model limitations.

4.8 In our judgement, there were two major reasons why the MO central forecasters failed to predict the severity of the storm:

(i) The fine-mesh computer model predicted that the low would be less severe than it actually was, and the forecasters largely accepted the prediction of the model.

(ii) The forecasters were either not aware of, or underestimated the importance of, the low-level jet and some other features of the structure of this particular depression.

These were independent causes of error, but each of them worked to make the impending storm appear less severe than it actually was.

5. Presentation of forecasts of the storm to the public

5.1 The essential <u>content</u> of the forecast is the ultimate responsibility of the senior forecaster on duty at Bracknell. It is he who tells the presenter of the BBC forecasts, whether on radio or television, what aspects need to be emphasised. This was reflected in the forecasts presented on 15 October where the main emphasis was on the rainfall to be expected during the evening and night. The presenters, particularly those on television, are expected to put over their material as interestingly as possible and are generally successful in this respect - some outstandingly so. The television presenters also have to perform without a script, because they do not know until the last moment how much time they will be allowed. This is liable to lead to some degradation in the quality of the forecast, and may account for the old wives' tale that radio forecasts are better than television ones. Incidentally, we were told by the French that sailors rely on radio forecasts rather than television ones. The television presenters, unlike those on radio, did play down the wind even more than the central forecasters' guidance did. But in view of the briefing they received from the senior forecaster on this occasion they cannot be blamed in any way for the failure to forecast the severity of the storm. The subsequent hostile reaction to them in some sections of the press was grossly unfair.

5.2 We are fortunate in that in this country the media authorities accept that weather forecasts should be presented to the public by meteorologists; furthermore that they should exercise no undue pressure on the presenters to dilute their material in order to make their broadcasts more entertaining. This is not the case in many countries, and our TV and radio weathermen are generally highly regarded both nationally and internationally.

5.3 Our recommendations in respect of media presentation are at (5) and (6) of Section 7.

6. The report of the MO internal enquiry and its recommendations

6.1 Our own independent comments on the prediction of storms and on the particular problems facing the MO forecasters on the 15 October are reflected to a large extent in the MO report in Chapters 1 to 3. The main difference is that we place considerable emphasis on the judgement required of forecasters in interpreting computer predictions.

6.2 As a result of our examination of the observations and computer forecasts available to the forecasters and interviews with the individuals concerned, we are satisfied that Chapters 1 and 2 of the MO report give a comprehensive and accurate account of these factors.

6.3 The scientific assessment contained in Chapter 3, produced by the research branch, reports the results of tests carried out on the fine-mesh model which performed unusually poorly on 15 October. An important conclusion is that the situation over the east Atlantic when the storm developed was one in which the model forecasts were particularly sensitive to the initial observed upper winds; had aircraft reports been included in the initial data, the model's forecasts would have been better. Also, some technical adjustments to the model, still under test, would have resulted in further improvements.

6.4 We were pleased to read that the research section is developing more sophisticated outputs from the model (para. 3.4) to help forecasters understand the reasons for rapid developments. Such diagnostic outputs are essential if forecasters are to make the best judgements concerning the reliability of model forecasts, but their production needs considerable software development.

6.5 Chapters 4 and 5 of the report concerning the public forecasts and warnings of the storm and subsequent media reaction are factual and need no comment. Chapter 6 contains the recommendations arising from the internal inquiry. We entirely endorse three of these, those concerning improvements in the observational network over the Atlantic to the south and west of the U.K. (para. 6.3.4), model improvements (para. 6.3.5.) and additional model forecasts (para. 6.3.6.). We would particularly emphasize the benefit that will come when satellite-borne microwave sounders come into service in 1992. These should more than make up for the phasing out of weather ships - a process which we regret but recognize as inevitable. We also endorse the recommended new instructions to Senior Forecasters concerning critical situations (para. 6.2.6.) but would wish to include this within a much wider review of the functional role of forecasters within the Meteorological Office (see Section 7 below). The recommendations on Public Forecasts and Warnings, and on relations with the media, seem to us sensible; but our experience and background does not entitle us to make an authoritative judgement on them.

6.6 Our own further recommendations can be found in Section 7.

7. Summary and conclusions

7.1 The lack of adequate public warning of the storm of 16 October arose from two direct causes, both related to the production of the forecast for that day at the Central Forecasting Office:-

(a) The computer forecasts available to the Meteorological Office on 15 October were not in agreement, and all, including that from what is usually the most reliable model, underestimated the winds over S.E. England.

(b) The duty forecasters followed the guidance of their model too closely and did not recognize a situation in which the model was likely to underestimate the strength of the winds.

7.2 The presenters and the media cannot be held responsible for failing to issue warnings with which they were not supplied. But it must be said that on this occasion the television forecasts played down the winds over land even more than the forecasters' guidance did.

7.3 The main underlying factors responsible for (a) were as follows:-

(1) The usually more reliable high-resolution model is particularly sensitive to error under conditions of rapid storm development where sufficient observations are lacking.

(2) There were, as usual, rather few observations over the sea, particularly to the west of Spain where the storm developed on Thursday 15 October. Because the coarse-mesh model is run later than the fine-mesh model it was able to take account of more observations; this seems to be the reason why the coarse-mesh model, which should in principle be inferior, performed better on this occasion. Subsequent analysis has shown that wind observations in this area from transatlantic aircraft would have been particularly crucial; more surface ship reports received in good time would also have helped.

7.4 These aspects of model failure are recognized in the MO report, and the recommendations made there (para. 6.3.5.) provide sound guidance for attacking these problems. The computer forecasts available at the French Meteorological Service were somewhat more consistent than ours, mainly because they have access to a more powerful computer, but they equally underestimated the storm's intensification.

7.5 The MO fine-mesh model has a well-deserved reputation; indeed, when we visited the French Meteorological Service, they went out of their way to praise it. We believe both the mathematical formulation and the computer simulation to be as good as any in the world - though we trust that both of them will continue to be improved by incorporating the results of continuing research. But the model does suffer from one unnecessary handicap. The computer on which it runs (a Cyber 205) is significantly less powerful than the Crays available both to the ECMWF and to the French Meteorological Service, and in particular it has a smaller memory. One consequence is that the French fine-mesh model uses a mesh twice as fine as that of the MO; the advantages this confers have been explained in Section 2.

7.6 In this context we would stress the importance of ensuring that the Meteorological Office always has at its disposal the most powerful computer available. Underprovision of computing power would indeed be a false economy, because it would undermine the campaign to increase the MO's commercial income - and this campaign is essential to the MO's future funding strategy. We are relieved to hear that the MO will be provided with an ETA 10 supercomputer in the Spring, even though the cost has had to be found by internal economies. We are not in a position to comment on the damage done by these economies beyond saying that it will have to be endured because the new computer is essential.

7.7 The computer models, and their enhancements, are among the major products of the Research Division of the MO. That Division provides good value for money, and without it the MO would rapidly fall behind its competitors in other countries. There is a continuing need for research, both in the MO and in universities. The division between the two is about right, research and development in the MO being closely motivated by operational needs and research in universities being more fundamental -

though that too will eventually be reflected in better forecasts. In atmospheric science, the MO's links with university departments have recently been strengthened. We regret, however, that it has not been possible to interest academic numerical analysts in the (probably very difficult) problems related to weather forecasting, including the fundamental problems of atmospheric predictability. This is particularly true of the 'spin-up' problem - the problem of transforming initial observations to initial conditions on the grid on which the computer calculations are done. If the MO were to fund one or two CASE studentships in this area, that might create useful links at inconsiderable cost.

7.8 So far as (b) is concerned, no individual should be seriously blamed for the failure to forecast the severity of the storm. There are two main reasons for this. One is that the demands on the forecasters on this occasion were unusually heavy. Whoever happened to be on duty on 15 October was going to face what was likely to be the severest test of his career. The interpretation of computer forecasts is largely a subjective process and the model's guidance was, on this occasion, unusually confusing. Although most forecasters would have stressed the possibility of severe land gales, as indeed did the French, it seems to us possible to defend the failure of the senior forecaster actually on duty to do so.

7.9 The other reason relates to the senior forecaster's work schedule. His first task on taking up his duty is to assess the meteorological situation. He then prepares his 'synoptic review' describing his assessment and this is subsequently used, with periodic updating, as guidance for the detailed forecasts issued to the public and subscribers (Annexes 2.1 to 2.5 of the MO report contain the synoptic reviews issued during 15/16 October). The senior forecaster taking up duty at 0800 is expected to issue his review by about 1000. Under normal conditions this gives him reasonable time in which to study the charts and computer forecasts and to identify and deal with any tricky aspects of the situation. Under exceptional weather conditions, however, his assessment needs more information than is at present readily available, and more time. Consultation with senior colleagues could also help. This was an occasion when none of these conditions could be met.

7.10 The question then arises "*What steps need to be taken to enable our forecasters to cope more effectively with exceptional conditions?*" The general public understandably expects forecasters nowadays, with computers and weather satellites at their disposal, to be able to predict the weather more accurately than in the past and, in particular, give due warning of exceptionally severe events. The experience of this storm shows that, if forecasters are to meet these expectations, they need improved computer models. But, equally important, they also need sufficient background knowledge and experience to not only interpret computer forecasts but also assess their reliability. We are therefore led to recommend a re-examination of certain aspects of training and organization within the MO. The ones that particularly concern us are as follows:-

(1) The training which our forecasters receive needs to be improved and lengthened. Compared with the French forecasters, the training which ours receive is shorter (and therefore cheaper) and lays less emphasis on meteorological theory. French forecasters complete two years of a first degree course, usually in mathematics or physics, followed by a three-year course at the meteorological college at Toulouse. In effect, when they start work they already have a Master's degree in Meteorology. Our forecasters are recruited on the basis of a first degree, again usually in mathematics or physics. During their career they will take a number of short courses at the

Meteorological Office College, but their training relies extensively on on-the-job training - in effect an apprenticeship system. This does not give them the background of theory which they need if they are to take the fullest advantage of the strengths and weaknesses of the computer models at their disposal. It also puts them at a disadvantage when they are faced with exercising judgement in a situation that has no precedent within the collective memory of the Office. We recommend that the training of our forecasters be reviewed, and that the review should include a more detailed comparison with what happens in other countries than we have had time to carry out.

(2) The duty senior forecasters carry on their shoulders the full responsibility for forecasts and warnings issued by the Meteorological Office. Their rank of PSO is below that of senior research scientists (and senior administrators), who however have no responsibility for issuing forecasts. These disparities reflect the relatively lower status of the senior forecasters within the hierarchy which, in view of their ultimate responsibility for the successful performance of the organisation, is inappropriate. At least the best of them should have the opportunity of being promoted to SPSO on merit, without thereby being forced to move to other jobs within the Office.

(3) It is our impression that, as a result of the economies imposed on the MO in recent years, the staff on duty in the Central Forecasting Office has been cut to the minimum needed to do the work in normal circumstances. Any increased staffing would be in a sense a diseconomy; but the effect of the cuts is that when exceptional problems occur there is no spare effort that can be devoted to thinking them through. An alternative, and probably better, way to remedy this would be to provide better display facilities and more interactive computing; this would need considerable extra programming effort.

(4) There seems to be no formal arrangement within the MO under which, when there is a situation of unusual uncertainty with a possibility of particularly severe conditions, the senior forecaster on duty can consult more widely than usual. That this was such a situation should have been obvious very early on 15 October when it became clear that different computer models were giving diverse guidance; also fewer than usual midnight observations were being received from France. Wider consultation on 15 October would have enabled decisions, possibly different ones, to have been made at a high level as to whether the threat of an exceptional storm was sufficient to warrant alerting the public and, if so, at what stage.

(5) Similarly, when there are conditions of unusual uncertainty that uncertainty should be allowed to come through to the general public. The senior forecaster's synoptic reviews issued during 15 October reflect some uncertainty - though less than he probably felt at the time - but little if any of this came through in the radio and television forecasts. Part of the senior forecaster's responsibility should be to assess the degree of uncertainty that should be presented to the general public.

(6) There are times, particularly when the weather situation is complex, when the time allocated to the presenter is inadequate if the public is to be provided with sufficient detail, particularly of weather hazards. The media should be prepared to introduce sufficient flexibility into their programme scheduling to allow, at short notice, more time to the weatherman on such occasions.

7.11 Our first three conclusions are not reflected in the MO report. The report does, however, contain a recommendation concerning instructions to Senior Forecasters in dealing with critical situations, i.e. to provide more information to the public on alternative possibilities. This recommendation, which we support, relates to our fourth and fifth conclusions but we perceive the need for a more radical initiative.

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Peter Swinnerton-Dyer

8 January 1987 Robert P. Pearce

ANNEX 1

SECRETARY OF STATE FOR DEFENCE'S PRESS RELEASE OF 20 OCTOBER 1987

METEOROLOGICAL OFFICE

The Director General of the Meteorological Office, Professor John T. Houghton, FRS, has already instituted an internal enquiry into the weather forecast that the Met Office made in the period preceding the storms of Thursday 15/Friday 16 October over southern England. The S of S for Defence has today invited Sir Peter Swinnerton-Dyer, FRS, the Chairman of the University Grants Committee, and Professor Robert Pearce, Head of the Dept of Meteorology at Reading University, to consider the findings of the internal enquiry when they are available and to report their conclusions to him. Their report to Mr Younger will be published.

ANNEX 2

INDIVIDUALS CONSULTED IN CONNECTION WITH THE PREPARATION OF THIS REPORT

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Dr. D.N. Axford (Director of Services)

Mr. A. Gilchrist (Director of Research)

Mr. R.M. Morris (Chief Forecaster)

Mr. R. Hunt (Officer in charge, London Weather Centre)

Mr. D. Johnson (Deputy Director Forecasting Services)

and duty senior forecasters on 14 and 15 October 1987.

FRENCH METEOROLOGICAL SERVICE

M. A. Lebeau (Le Directer de la Météorologie Nationale)

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