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The Trafalgar storm 22–29 October 1805

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Summary

The Battle of Trafalgar is one of the best-known events in British history. Yet in that heyday of the sailing ship weather often had a critical role to play in the outcome of naval engagements. This observation is no less true of Trafalgar, and this paper takes as its subject the storm that followed the battle and examines its character and possible origins. Its historical importance is matched by its unusual ferocity and duration, making it in every sense a notable occurrence.

1. Introduction

The author (Wheeler 1985) has recently offered some tentative suggestions concerning the weather of the Trafalgar campaign, which can be thought of as embracing the Royal Navy's blockade of Cadiz, the battle itself and the week-long storm that followed the engagement. All these events fell into the single month of October 1805. Of particular interest, to both historians and meteorologists, is the storm; an event of unusual ferocity visited upon an already weary fleet whose very survival is a signal testimony to the qualitities of its leadership and manning.

Here an attempt is made to draw comparisons between what is known of the weather of that tempestuous week and present-day examples of what may be similar synoptic conditions, and to analyse the nature of the storm. Such an undertaking is fraught with inevitable hazards and the interpretations offered here can never be wholly proven on the basis of the relatively scant evidence currently available. They are, nevertheless, offered with a reasonable degree of confidence.

2. Data sources

Recent analogous events may be sought in the published daily charts of the Meteorological Office (covering the period before 1981) or the Deutscher Wetterdienst. Information for the events of October 1805 is inevitably more sketchy, geographically inconsistent and, however accurate the data may be, subject to a variety of interpretations. But, setting aside these reservations, there exists a surprising fund of information on the Trafalgar storm. Data exist for a number of sites in Britain. The Goodwood House Observatory, Sussex, was active in recording wind direction, air pressure, temperature, and weather features thrice daily. In Newcastle upon Tyne, James Losh maintained a valuable sequence of observations covering those same aspects, again thrice daily, as did Samuel Robertson at Ednam in the

Tweed valley between Kelso and Coldstream. Information from further north is found in the diary of James Ramsey, who lived not far from Perth. He maintained a daily record of wind and weather for a number of years about this time. Data from mainland Europe in these troubled times are less forthcoming. The forces of revolution had swept away the potentially fruitful sources of the Société Royale de Médecine of France (Kington 1970) and no Iberian material is available.

The most valuable sources have been the logs of ships engaged at Trafalgar or blockading the French Atlantic ports further north. Oliver and Kington (1970) have examined the utility of such documents as meteorological source material and confirmed their value. In addition to general observations on the running and progress of the vessel, the logs pay close attention to the prevailing weather during the day's watches. The essential meteorological data consist of wind-speed estimates that are all but identical to the descriptions used in the Beaufort scale. Thus, for example, terms such as 'fresh' or 'strong' breezes are commonplace and can be confidently interpreted as force 5 and 6 respectively. Associated wind direction is recorded using a 32-point compass, and further useful information appears in the form of comments made on the incidence of thunder, lightning, squalls, rain, fog, etc., which despite their qualitative presentation help to create an impression of conditions at the time. Such descriptive observations were, to a greater or lesser degree, discretionary and not all ship's masters, for it was their responsibility to maintain the logs, were as assiduous as others and the quality and usefulness of account varies from vessel to vessel. Unfortunately no shipboard barometric data exist for this period. The simultaneous existence of the captain's or junior officer's logs gives a misleading impression of a wealth of data. In reality the latter were only a copy, often abridged, of the master's log which should always be the preferred reference. To this brief account of the sources little need be added other than to confirm the author's faith in their general reliability. Indeed an event such as the blockade of Cadiz gathered many ships together in the same waters and allows their logs to act as mutual checks on consistency and accuracy; in the present case no serious discrepancies were encountered in the 12 closely studied logs. But, although such clusterings have their uses, the general geographical spread of data is poor, with gaps between the areas of principal naval activity. Furthermore, the observations are inevitably limited to those aspects important to mariners; rainfall amounts and temperature are notable absences.

Supplementary information can also be drawn from the private letters and reports, both English and Franco-Spanish, written after the battle. But these lack the close attention to meteorological detail found in the official logs and are best used in a supporting role.

3. The Trafalgar storm 22–29 October 1805

The storm which seized upon friend and foe alike after the battle of Trafalgar figures prominently in the private and official correspondence. Of its severity there can be little doubt. The logs record almost continuous 'hard gales' reaching a peak on the 26th. Frederick Ruckert, master of the fleet's senior frigate *Euryalus*, noted on the morning of the 23rd '...strong gales and rain with heavy squalls. The topmast staysail split and blown away by a heavy squall from the westward.' The small cutter *Entrepenante* was even less fortunate. Her log records '...hard gales with heavy seas. Split the mainsail...shipped several heavy seas. Made several signals of distress.' Whether these signals were answered is not recorded; the larger vessels were fully occupied with their own survival. But survive the *Entrepenante* did, to reach Gibraltar on the 26th. Thomas Watson, master of the *Achille*, wrote in his entry for the 23rd '...strong gales with showers of rain, at 9 the hawser broke from the Spanish prize which we had in tow. At 11 strong gales and heavy squalls, with rain. Split the main staysail.' And so it goes on around the fleet, varying only in detailed timing and estimate of intensity, all vessels relating the same story of battle against this unrelenting and tireless foe.

The letters from the seamen are no less eloquent. The seasoned Captain Henry Blackwood, again of the *Euryalus*, wrote to his wife on the 23rd '...it has blown like a hurricane.' Henry Walker, midshipman on the *Bellerophon*, wrote to his mother on 22 November; his letter contains the following description of the battle and its aftermath '...but in the ensuing night (of 21st) a storm came on, such as I have never witnessed, and for the four following days we had a much severer struggle against the elements than the enemy.' The day of the battle had, however, been tranquil. The two fleets, some 10 miles distant at dawn, were not able to engage at close quarters until after midday. The English fleet was in two columns vaguely line-ahead, with a following wind, such as it was, and even with full spreads of canvas made little more than 2 knots as it bore down on the enemy line. But even as the events of the day unfolded the growing westerly swell forced Nelson to turn his thoughts to the hours after battle and even in his dying moments, aware of the impending storm portended in the sea conditions, urged Captain Hardy to anchor the fleet at close of action to prevent the weary crews from being driven onto the rocky lee shore of Cape Trafalgar.

The ominous westerly swell (Fig. 1) was also noted as early as the evening of 20 October by Captain Jean Jacques Lucas of the French ship *Redoutable* (from whose tops Nelson was shot). Most English logs make their first entry of the swell a little later. Such disagreements on precise timing are not uncommon and make it difficult, for example, to be confident concerning the arrival time of the storm, but a most probable point would be about midday on the 22nd. The storm then raged, albeit with fluctuations, until 29 October. Throughout this time the winds were largely from between west and south-south-west. Again, however, precise uniformity should not be expected as the log of the *Royal Sovereign*, for example, notes a west-north-west wind. Meanwhile the squadron then blockading the port of Brest was battling against east to south-east gales; an important observation as this suggests that the storm's circulation embraced also these northern latitudes. A storm centre somewhere approximately midway between the two may be postulated, perhaps off the Spanish Cape Finisterre. Shipboard barometers were in use at that time and Nelson was known to have used one, but the records, if any were kept, appear not to have survived and their absence is to be regretted.

Photograph by courtesy of the National Maritime Museum, London

Figure 1. 'Evening at Trafalgar'. This oil on canvas painting by William Huggins (1781–1845) depicts the scene at dusk on 21 October 1805. Although Huggins was not present at the battle he may well have drawn upon contemporary sources for his picture and the impression he creates of vessels wallowing in a heavy swell certainly echoes the evidence of the contemporary documents. This heavy westerly swell was the herald of the storm that was to break the following day.

4. Interpretation and hypothesis

Certain points concerning the Trafalgar storm, even on the basis of the meagre evidence to hand, can be agreed upon; its cyclonic nature, its duration, its seeming lack of mobility over the final week and, most notably, its intensity and geographical extent. Is it possible from these conclusions to hypothesize its nature? The brief answer is yes.

One may first be tempted to be persuaded by Captain Blackwood's vivid account and view it as a hurricane, but there are good grounds for declining this opinion. Firstly, Blackwood's use of the term 'hurricane' was indiscriminate, the word did not enjoy the currency it possesses today and was applied to any severe storm, tropical or otherwise. Indeed, one of the Trafalgar logs demonstrates just such an inconsistent application, but with respect to the term 'gale'. Captain Henry Digby of the *Africa* prepared a log in which the term 'gale' appears on days when no other log records anything above strong breezes. But Digby may not have been consistently miscalculating the strength of the wind, merely following the old convention of describing any stiffish breeze as a gale. A second reason for rejecting the hurricane hypothesis is found in the study by Neumann *et al.* (1981) of hurricane tracks of the North Atlantic between 1871 and 1980 which fails to yield a single example of such a feature even entering the Trafalgar sea area (as currently defined), let alone lingering actively for 7 days. The majority of hurricanes recurving across the Atlantic do so along routes followed by mid-latitude systems, leaving Iberia undisturbed to their south. There is a tendency, though no more, for late-season storms to follow slightly more southerly routes, but not to the degree required here.

There is, interestingly, evidence for at least one 'hurricane' in the North Atlantic during that historic month. The New England cleric James Bentley describes a storm to strike the coast of Maine on 3 October '...in the morning it began to rain at north east, wind increasing till noon and then blew violently. Houses, barns, trees and fences were in devastation...it is called a tornado, hurricane and storm. It appears to have been a violent north-east rain storm.' The confused terminology is significant, warning against unquestioning reliance on qualitative description. However, this storm can hardly have been that which struck the English fleet 19 days later off Cadiz. In fact the nearest-ever mapped approach by a designated hurricane to the region came as recently as November 1966 when hurricane Louis, though at that stage moribund, reached a point about 500 miles west of Cape Finisterre, where it finally dispersed on the 14th. The position is best summarized thus '...very few depressions enter the region (Azores to Britain) as well-developed hurricanes.' (Meteorological Office 1978).

Yet storms and gales were a well-known hazard in these waters. The archives at Lloyds of London contain an interesting memorandum in an unknown hand concerning navigation in a storm off Cape Trafalgar. It begins 'People who are ignorant of the navigation of the coast between Cape Trafalgar and Cape St. Maries (*sic*) are much alarmed with the idea of a south-west gale, and for want of a proper knowledge how these gales come on frequently get into difficulties. The gale is always far southerly on its outset for six or eight hours, but at the same time the sea will make from the westward.' The document goes on to describe how winds will veer to the south-west as the storm rises. Indeed, so distinguishable are these south-westerly gales that they enjoy the distinction of the local name *los vendavales*. But, more importantly, the pattern here described in such general terms bears a strong resemblance to the sequence of events already related. On leaving Cadiz, the combined French and Spanish fleets were prevented from making a rapid passage to the Strait of Gibraltar by a southerly wind, while the subsequent westerly swell and veering winds are well documented.

These waters are too far south to be influenced by normal mid-latitude cyclones but fall well within the latitude of those features generally described as cut-off lows. Here lies the most likely explanation of the Trafalgar storm and the most fruitful source of comparison with more recent and well-studied events.

With regard to these cut-off features the Meteorological Office (1978) has amply demonstrated that October and November are the very months when they occur most frequently. In a study period of

10 years, 75 were recorded of which 20 arrived during those 2 months. Most persisted for only a few days but, significantly, almost 20% lasted for a week or more.

Capel Molina (1980) has shown that the development of meridional upper-air streams leads to cut-off lows and pools of cold air at the latitude of Iberia. Of the routes the consequent lows follow, 36% track south-eastwards to approach the Gulf of Cadiz but only half of those fail to pass through the Strait of Gibraltar, and founder against the abrupt relief of the Iberian massif. In this position they bring some of southern Spain's heaviest rainfalls and strongest winds. Another route, but followed by only 11% of cut-off lows and generally in the summer months, is to approach Iberia from the west. Such depressions bring occasional heavy showers to interior Spain but have generally dissipated their energies before reaching the east coast.

The general characteristics of the Trafalgar storm, its timing, location and behaviour, conform to those of a cut-off low. Such an interpretation gains further support from the contemporary British conditions. Pressure data for three sites, Goodwood House, Newcastle upon Tyne and Ednam, all indicate a rise of pressure on the 18th, the anticyclonic conditions lasting until the 24th. Correction to appropriate sea-level figures is a hazardous process but there is a clear impression of a northward increase in pressure which at Newcastle was above 1030 mb, approximately 5 mb higher than at Goodwood House. In addition Newcastle recorded air frosts on the 20th and 21st and Ednam on the 19th, 20th and 21st. Both locations variously described the weather as fine, dry and calm. Further north, James Ramsey's diary records calms from the 19th to 22nd with frost every night, snow having already fallen on the nearby hills. Winds were variable and light in the north throughout this period. This evidence of anticylconic conditions supports, though obviously cannot prove, the cut-off hypothesis.

Southern England appears to have been peripheral to both the storm and the anticyclone. The Goodwood House records reveal 'brisk' easterlies and north-easterlies with temperatures possibly 9 °F above those in Newcastle. *Foudroyant*'s log makes reference to south-easterly gales on the 22nd, 23rd and 24th, at which time this former command of Nelson's was weathering the conditions some 70 km off Ushant. Fig. 2 depicts the general pressure patterns as they may have appeared on 22 October 1805 and is based on the contemporary evidence discussed in the foregoing paragraphs.

The most probable date for the birth of the storm is 19 October. The arrival of a cold pool of air over Iberian waters at this season would have found the seas at their warmest, between 17 and 20 °C, giving ample scope for instability and intensified activity. Indeed such southward eruptions of cold air are a feature of the Spanish climate, often bringing the summer to an abrupt close. The following quotation is of more than passing interest 'In terms of pressure patterns the most striking feature is the autumn break which shows up prominently about 20 October on all pressure curves from Perpignan and Gibraltar to Malta...' (Meteorological Office 1962).

However, the duration of the anticyclone does not match that of the storm. The anticyclone dispersed, or retreated, on 24 October to be replaced in all areas by much milder, wetter conditions. The winds became moderate to fresh north-east and east until the 28th over the whole of Britain. The weather was occasionally sunny, but with rain showers in the north developing into more persistent and frequent rain in the south. Numerical data from the records of the Reverend James Cowe at Sunbury (Middlesex) show 0.86 inches of rainfall on the 24th, nil on the 25th, 0.48 on the 26th and 0.1 on the 27th. Such a pattern of wet easterlies argues in favour of a depression passing to the south of England and, in view of *Foudroyant*'s records, possibly along the English Channel; 'variable with rain' appears as an entry on the 25th.

This disruption to the anticylcone may have invigorated the storm to the south. There is a suggestion from the logs that by the 25th it was on the decline, many vessels noting strong breezes to replace gales. All this changed on the 26th which, if the logs are to be believed, must have had the most serious day's weather of the week, most ships recording gales which were frequently strong in nature and severe enough to cause Admiral Cuthbert Collingwood to order his fleet to cast off and scuttle the few valuable prize ships left at this stage. This important resurgence of activity may have been brought about by the further introduction of cold northerly air following in the wake of the northerly located depression. But, whatever the cause, the storm was vigorous enough to sustain itself until 29 October when it finally yielded to more settled conditions.

5. Analogues

The behaviour of cut-off systems is sufficiently consistent to have enabled Boyden (1963) to identify some useful criteria for their prediction. Nevertheless, a search of the past 25 years of weather charts has failed to produce a sequence of events to match those of that fateful October week in 1805. Given the inherent variability of weather systems this failure is not unexpected and need not refute the arguments offered above. It may also be added that Colman's (1986) research has shown the first two decades of the nineteenth century to be the northern hemisphere's coldest for over 200 years, suggesting that the general conditions then and now may not be perfectly comparable. Nevertheless, some situations were found that echoed, in part, those of 1805 in general character though not in degree or persistence.

Tolerably close analogues for the first phase of the storm between 20 and 24 October are not hard to find and of the several encountered that of January 1963 came as close as any. The situation was again one of severe weather, but with respect to the anticyclone and not the cut-off depression itself, for January 1963; indeed the whole of that winter was a time of exceptionally cold weather. This aspect may not be without further importance, for Birkeland's (1949) study of the Norwegian temperature records from 1761 showed October 1805 to have been a month of unusually low temperatures, departing from

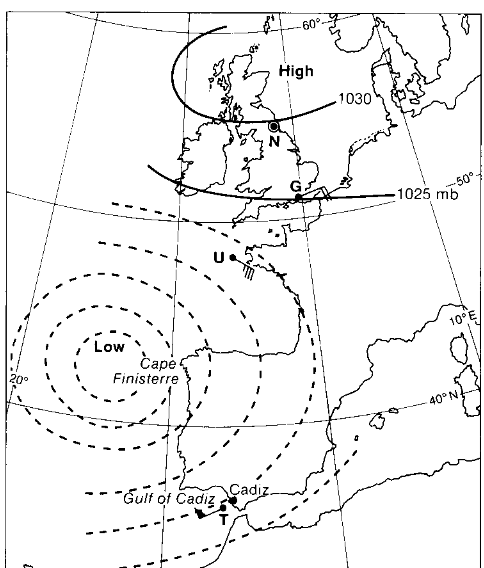

Figure 2. Reconstructed synoptic situation for 22 October 1805. It was on this day that the storm struck the vessels which survived the battle. It seems probable that the strong south-easterlies recorded off Ushant (U) would have been part of the same circulation that generated the gales at Trafalgar (T). Contemporary data for the British Isles indicate east-north-east winds at Goodwood House (G) and calms over much of northern Britain, as for example at Newcastle upon Tyne (N). The barometric data for the latter two locations allow an approximate quantification of the local isobars, but elsewhere on the map such evidence is lacking and the isobars are used merely to indicate the interpreted general trend of pressure over the Atlantic seaboard.

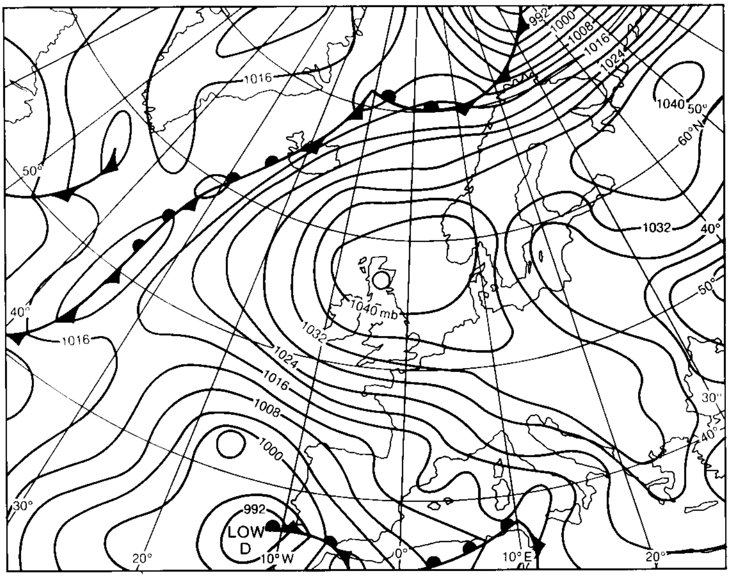

Figure 3. Surface analysis at 1200 GMT on 17 January 1963. In terms of at least the disposition of pressure systems the situation resembles that of 22 October 1805. Only the strength of the south-west winds over the Gulf of Cadiz fall short of the requirements. The generally easterly air flow over southern England and the English Channel, together with a calmer atmosphere in the north corresponds well with what is known of weather over Britain around the time of the battle.

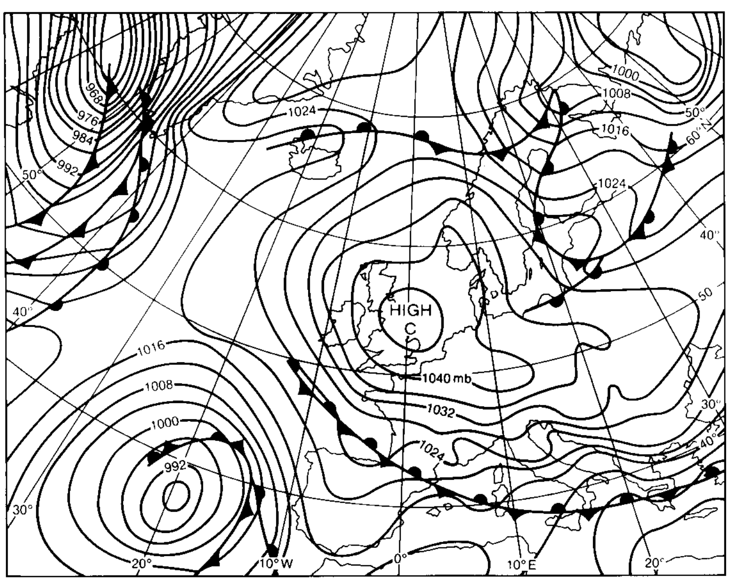

Figure 4. Surface analysis at 1200 GMT on 22 January 1963. The large and well-developed cut-off low, then approaching Iberia, had formed on the 19th and travelled east-south-east to its location. The situation, with the advancing depression and light winds over the Gulf of Cadiz (and a probable westerly swell), echoes that of the day of battle (21 October 1805). The high pressure over Britain conforms to the impression given by contemporary observations, with easterlies in southern districts but calmer, more anticyclonic, conditions to the north.

the mean by as much as 2.9 °C. Indeed the 1762–1946 records used by Birkeland show only six colder Octobers. Manley's (1974) central England temperature record also shows the month to have been cool, nearly 2 °C below average. January 1963 was the coldest month on record at many sites; the England and Wales deficit was 5.3 °C while at Kew it was the coldest month since January 1838.

Against this significant background the events of 17–29 January 1963 may be reviewed. In fact this 2-week period produced two cut-off situations off Iberia, both with possible similarities to the first phase of the Trafalgar storm. On 17 January (Fig. 3) the well-established anticyclone over Britain, together with the depression centred west of the Gulf of Cadiz, represented a situation not unlike that of 22 October 1805. The 'high' is seemingly more intense and the 'low' less well developed but the wind directions conform perfectly with the evidence already reviewed: south-west off Cadiz, east to south-east over the English Channel and southern Britain and calm over northern Britain. However, low 'D' then pursued an unusual northerly track along the Iberian coast before filling on 20 January off Cape Finisterre. The system was, then, neither so long-lived nor stationary as its 1805 predecessor. In addition the anticyclone remained active for much longer and was associated with the second analogous event of 21 January.

High 'C' (Fig. 4) was born out of the merging of the northward-moving anticyclone discussed above with another system over Greenland on the 19th. This new feature drifted south-south-east then south to lie off the coast of north-east England on the 22nd. The large and active 'low' nearing the Gulf of Cadiz formed at 43° N, 38° W on the 19th and then moved east-south-east. The situation depicted in Fig. 4 is similar to that on the day of battle (21 October) when light winds prevailed over the Gulf of Cadiz but were about to give way before the advancing depression. Although the 1963 system remained identifiable until the 29th, and thus matched the original in its duration, it failed to continue its progress and remained too far to the west to influence inshore waters. The anticyclone over Britain persisted unabated throughout this time to deny any further southward movement of cold air at this longitude.

6. Conclusion

It is the nature of weather events that no two will ever be perfectly alike. But patterns and similarities in cause and consequence do exist. This paper has attempted to reconstruct the synoptic situation for a momentous historical event in which weather exercised a major influence. The storm threatened to destroy the English fleet but had it arrived only 48 hours sooner would have saved the Franco-Spanish vessels, for it would have dispersed Nelson's fleet and enabled the enemy to slip through the Strait of Gibraltar and make good their flight into the Mediterranean, and the battle of Trafalgar might never have been fought.

The study has called upon instrumental and qualitative information, both of which have yielded an encouragingly consistent view of conditions. The analogue of January 1963, the closest to be found for recent times, was interesting in that it was also a month of exceptionally cold conditions in northern latitudes although this feature is more likely to be a consequence than a cause of the synoptic situation. But more informative is the failure to find a close analogue in terms of the combined intensity and duration of the Trafalgar storm; a fact that emphasizes its exceptional meteorological character.

Acknowledgements

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The MORECS climatological data set — a history of water-balance variables over Great Britain since 1961

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Summary

Hydrometeorological and water-balance variables are calculated weekly from meteorological observations over Great Britain by the Advisory Services Branch of the Meteorological Office using the Meteorological Office Rainfall and Evaporation Calculation System (MORECS). To allow current values to be placed in perspective, meteorological data from 1961 onwards have been used retrospectively in MORECS to produce a climatological data set of these variables.

1. Introduction

Although the hydrological cycle is well known for its contrasting properties of being conceptually simple yet difficult to quantify, calculations of the values of its constituent parameters are increasingly required for cost-effective and efficient water management over areas ranging from fields to river catchments. For example, a reliable assessment of irrigation requirements benefits farmers, whereas the evaluation of catchment water balance and river flow assists water authorities in managing water supplies and handling flood situations.

The relevant variables are precipitation amount, evaporation, and soil moisture deficit (SMD). All are capable of being measured, and the first is sampled extensively, but the other two are hardly measured at all, their values being derived from pertinent meteorological information. Rainfall values have been measured and collected in an organized and consistent manner since the formation of the British Rainfall Organization in 1860. However, the absolute accuracy of surface point rainfall measurements has not increased appreciably since that time, mainly due to the cost and logistics of improving the simple rain-gauge. Although there are inaccuracies in point rainfall totals and, more importantly, inaccuracies in areal rainfall totals derived for use in water-balance calculations, there is considerably more uncertainty associated with measurements of evaporation and SMD.

Evaporation has been measured using tanks of water placed in the ground and noting the difference in the levels of water over a period of time with allowance being made for any precipitation during that period. This technique was established on a regular basis more than 100 years ago when it was discussed, together with other evaporimeters, in the 1869 edition of *British Rainfall.* Tanks of a similar design were still in use recently and the results from these should indicate potential evapotranspiration (PE), i.e. the quantity of water vapour added to the atmosphere from a surface covered by green vegetation with no lack of available water; however, there is evidence that the exposure of these tanks was less than ideal. Data from a few lysimeters are available, but these instruments need careful maintenance and are, therefore, usually sited only at research establishments. They consist of pans on a weighing mechanism within a cavity created by removing a section of land, that section being placed in the pan with as little alteration to its structure as possible. The lysimeters are capable of measuring PE or actual evaporation (AE) depending upon whether or not they are irrigated.

The SMD can be determined using a device called a neutron probe. Fast neutrons, emitted by a portable source inserted in the ground, lose energy at a rate dependent upon the soil moisture. The slow neutrons can be detected and an estimate derived of ground moisture. This is a comparatively recent invention and again, very few measurements are available, and none routinely to the Meteorological Office.

United Kingdom observations of evaporation and SMD are thus insufficient in quantity or quality for any operational or climatological purpose. However, estimates of these parameters can be derived from meteorological observations. The near real-time requirement for water balance information is satisfied by the Advisory Services Branch of the Meteorological Office using the operational system called MORECS (Meteorological Office Rainfall and Evaporation Calculation System) which uses observations provided by the synoptic meteorological observing stations (Thompson *et al.* 1981)*. MORECS is the successor to the ESMD (Estimated Soil Moisture Deficit) bulletins and, as such, uses a more sophisticated theoretical model together with realistic information on vegetative cover and land use. MORECS has been used to produce historical values of water-balance variables, using carefully monitored data going back to 1961, to give a 26-year climatological data set over Great Britain†. Although the detection of climatic change in water-balance variables would need observations over many years, a useful description of their variation from year to year can be obtained over such a period.

2. MORECS

The input data to MORECS are rainfall, sunshine duration, temperature, vapour pressure and wind speed. Because of the need for a timely dissemination of MORECS products, data can be used only from those stations reporting daily in near real time, approximately 200 for rainfall and sunshine and 50 for vapour pressure, temperature and wind speed. Rainfall and sunshine are reported as daily totals, the

* Thompson, N., Barrie, I.A. and Ayles, M.; *The Meteorological Office Rainfall and Evaporation Calculation System MORECS (July 1981).* Meteorological Office, 1981.

† Further information about the climatological data set may be obtained from the Advisory Services Branch, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ.

remaining variables are usually sampled more than once per day and a daily-mean value calculated. The data are then normalized as follows:

(a) Rainfall is expressed as a percentage of the annual station average.
(b) Sunshine is converted to a percentage of the average daily duration for the month.
(c) Temperature and vapour pressure are corrected to mean sea level using standard factors.
(d) The 10-metre wind speed is converted to a value appropriate to a standard site using an empirical factor related to the general terrain roughness around the station.

The weekly values for these normalized data at a network of irregularly spaced stations are then used in an interpolation procedure to produce estimates for an array of 190 grid points with a 40 × 40 km spacing covering Great Britain. In general, the interpolation is more realistic if the field upon which it is operating has only a small range, and this is a justification for normalizing the raw data prior to using the procedure. The grid-square (areal) values are then obtained from the grid-point values; for example, for rainfall, the product of interpolated grid-point percentage and average annual rainfall (1941–70) for the square yields the grid-square rainfall.

The daily PE is computed for each grid square for a range of surface vegetation by using the appropriate grid-square values as input to the Penman–Monteith equation. This equation takes into account aerodynamic mass transfer and energy-budget considerations together with the inclusion of physiological factors via atmosphere–plant–soil resistance terms. Estimates of AE are then formed for soils with high, medium and low available water capacity. The daily water balance is calculated for various types of cropped surfaces and also for the average land use for each square. The final step is the construction of computer-drawn maps for grass and real land use, showing the grid-square weekly averages of temperature, vapour pressure and wind speed, the weekly totals of rainfall and sunshine, together with weekly totals of PE, AE and hydrologically effective rainfall (the rainfall remaining after SMD and evaporation loss is removed) and end of week SMD. An example of the type of map produced by MORECS is given in Fig. 1.

Each week, the MORECS suite of programs is run operationally using data from the previous seven days and the output is disseminated to customers by post, telex, facsimile or Prestel. The MORECS climatological data set exists in machinable form and can be browsed, or used as input to statistical routines to provide, for example, 26-year averages of the hydrometeorological and water-balance variables, their standard deviations and maxima and minima for one or more squares. The climatological data set is continually updated from the operational MORECS products.

3. Some results from the MORECS climatological data set

The 25-year monthly averages of SMD, AE, PE and rainfall for two contrasting MORECS squares are shown in Fig. 2, and Table I lists the corresponding variability and ranges for rainfall. Fig. 2(a) contains information for square 83 which covers the Lake District, the major land use being permanent grass and rough grazing, whilst Fig. 2(b) refers to square 141 which covers Suffolk (and includes the much drier and flatter countryside around Bury St. Edmunds) where the land use is mainly permanent grass, cereals and main-crop potatoes. The location of these squares is shown in Fig. 1.

The most noticeable features about the soil moisture budget of the Lake District are:

(a) the very large rainfall totals (100 mm or more, on average, every month),
(b) the comparatively small SMDs, and
(c) the similarity between AE and PE.

As the ground, on average, is not far from being at field capacity (i.e. the ground is nearly saturated), it would be expected that evaporation occurs at very nearly the potential rate and, indeed, the two curves are almost coincident.

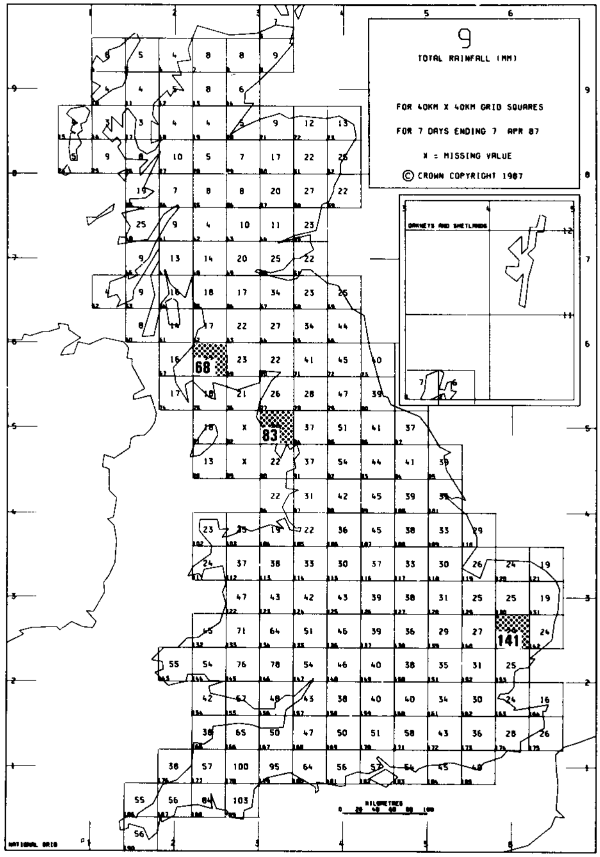

Figure 1. A computer-drawn map showing rainfall values produced by MORECS. The shaded squares are those referred to in the text.

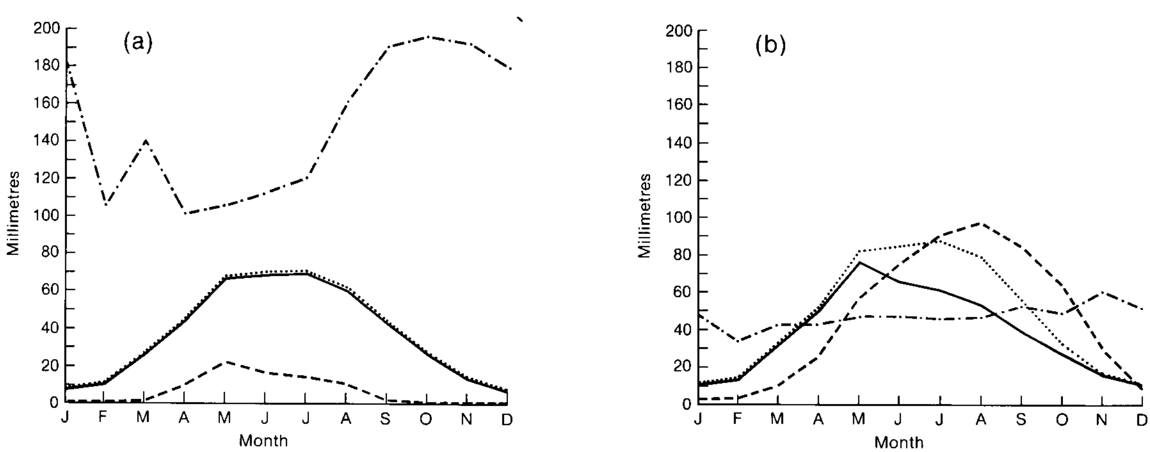

Figure 2. Mean monthly soil moisture budget for (a) MORECS square 83 (Lake District) and (b) MORECS square 141 (Suffolk), showing soil moisture deficit (dashed line), actual evaporation (solid line), potential evapotranspiration (dotted line) and rainfall (dot-dash line).

Table I. *Variability of rainfall and its range, for two MORECS squares (25-year monthly averages)*

Square number	Month	Coefficient of variation	Maximum rainfall (mm)	Minimum rainfall (mm)
83 (Lake District)	Jan.	0.42	414.0	34.9
	Feb.	0.54	231.3	16.4
	Mar.	0.45	284.2	58.0
	Apr.	0.51	184.2	7.0
	May	0.52	244.8	21.1
	June	0.36	187.4	51.1
	July	0.41	248.7	48.6
	Aug.	0.46	334.6	14.4
	Sept.	0.35	306.5	28.4
	Oct.	0.48	427.0	78.0
	Nov.	0.33	322.2	90.8
	Dec.	0.42	294.4	56.3
	Mean	0.44		
141 (Suffolk)	Jan.	0.40	88.2	14.6
	Feb.	0.49	68.2	9.9
	Mar.	0.51	96.4	7.3
	Apr.	0.51	92.3	8.7
	May	0.43	78.6	9.8
	June	0.58	117.6	5.6
	July	0.51	94.5	5.9
	Aug.	0.54	110.7	12.9
	Sept.	0.66	124.1	1.3
	Oct.	0.70	121.9	2.8
	Nov.	0.46	154.2	19.8
	Dec.	0.42	101.4	15.4
	Mean	0.52		

By contrast, the data for Suffolk show that:

(a) the average monthly rainfall totals are more variable and much less than those in the Lake District,

(b) the maximum SMD is approximately five times greater than the maximum in the Lake District, and

(c) the difference between PE and AE is now significant because of the dryness of the ground, and this is an indication that irrigation of some crops may prove beneficial.

In Table I it can be seen that the variability of monthly rainfall totals over Suffolk is larger than that in the Lake District, and substantially so in summer; a consequence of the increased susceptibility of the former to showery activity.

Fig. 3 shows the end of July SMD over grass for both squares varying from year to year. Notable features include the rainfall deficiency of 1976, shown by the relatively high SMD. In addition to graphical output, tabular output is available detailing monthly values of a wide range of variables for the 25-year period.

4. Some uses of the climatological data set

An important application for such a data set will be to place specific, especially notable, meteorological events in perspective. The rainfall deficiency of 1984 which affected mainly northern and western districts of the United Kingdom between February and the end of August provides a comparatively recent example. Several places experienced a 5-month (April to August) rainfall total of

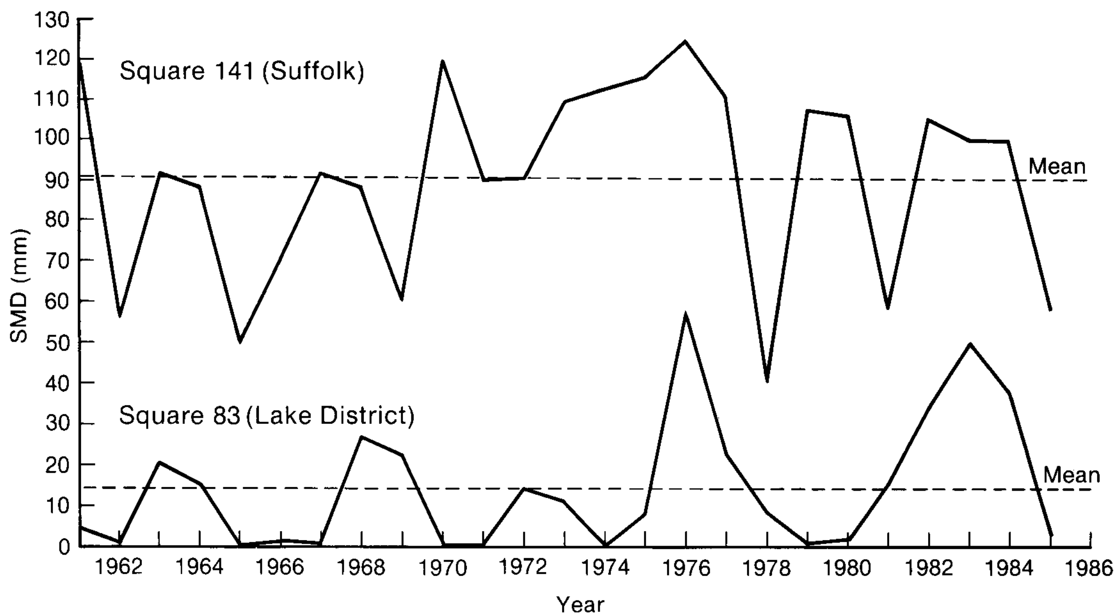

Figure 3. End of July soil moisture deficits (grass) for MORECS squares 141 and 83 for the period 1961–85.

less than 30% of the 1941–70 average, whilst over the area administered by the Welsh Water Authority only 44% of the long-term average rainfall was recorded for these same months, an event with an estimated return period of at least 200 years. The values of SMD and rainfall for February–September 1984 for square 68 (Dumfries and Galloway, Scotland) are listed in Table II, together with values for the same months of 1976. Although well remembered as a period of below-average rainfall, 1976 is seen to have been less severe than the event of 1984. Similar results have been obtained for other squares in Scotland.

Table II. *Values of rainfall (R) and soil moisture deficit (SMD) for the period February–September in 1976 and 1984 for MORECS square 68 (Dumfries and Galloway, Scotland). Values in millimetres*

	Feb.		Mar.		Apr.		May		June		July		Aug.		Sept.	
	R	SMD	R	SMD	R	SMD	R	SMD	R	SMD	R	SMD	R	SMD	R	SMD
1976	133.7	0.0	130.8	0.0	69.5	25.3	192.2	0.0	70.6	26.3	53.3	57.4	35.5	81.9	171.5	0.0
1984	138.1	0.2	56.4	2.1	40.3	26.5	21.8	74.9	76.0	69.6	42.7	85.0	75.9	77.4	180.4	0.0

Another obvious use of the climatological data set will be to allow current (operational) MORECS values to be categorized, thereby enabling customers to make informed commercial decisions in the light of their own previous experiences. The agricultural community would be potential users, for example in irrigation planning, although such information could be of considerable value to commodity brokers in assessing the probabilities of bumper or meagre harvests.

5. Conclusions

A consistent and comprehensive climatological data set of the main hydrometeorological and water-balance variables has been produced for the period 1961–85. It is intended that the operational

MORECS values will be added to the climatological data set, thereby improving the usefulness of the results.

The network of stations contributing data to the model has remained fairly static over the past 25 years, but the implementation of automatic weather stations should result in an increase in the number of stations reporting in near real time, particularly rainfall stations. This is important because the current 200 or so are insufficient to represent reliably the spatial characteristics of this very variable meteorological parameter. It is possible that radar measurements of rainfall can also be used to supplement the rain-gauge observations. If the climatology is to be of benefit in the years to come, then the effects of an increasing amount of input data on the computed water balance must be investigated to enable relevant comparisons to be made.

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Meteorological Office catches FIRE!

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Summary

During June and July 1987, a field experiment designed to study in detail the processes active in extensive low-level cloud sheets is being held off the coast of California. This is one part of a larger programme called FIRE which aims to investigate the properties of those cloud fields which play an important role in determining the earth's climate through cloud–radiation feedback mechanisms. This article briefly describes the major objectives of the programme and the observations which will be made during the field experiment.

1. Introduction

Although it has long been recognized that clouds are one of the most important factors influencing the global climate, the representation of large-scale cloud systems in numerical climate models remains one of their weakest points. Since it has been estimated that a change in the global cloud cover of only a few per cent could offset the anticipated global warming due to a doubling in carbon dioxide levels, this clearly constitutes a major source of uncertainty in such forecasts. One of the main factors contributing to this uncertainty is undoubtedly the limited understanding of the processes which control the formation and dispersal of various cloud types, and therefore the cloud amount. It is also not clear how this balance varies in different areas of the world or how radiation and cloud fields interact. A better understanding of these issues is a prerequisite for better representations of clouds in numerical models. Indeed, the World Climate Research Programme has placed the highest priority for climate research on two areas: ocean–atmosphere interaction and cloud–radiation feedbacks, and clouds are a central element in both problems.

Of course, it is not only through their effect on climate that clouds exert an important influence, since virtually all areas of meteorological interest are either closely associated with cloudy processes or are affected by their presence. Weather forecasters and the public are, therefore, likely to be eventual beneficiaries from increased understanding in this area.

Until quite recently there have been very few comprehensive, quantitative measurements of clouds, largely because of the observational difficulties, and most of the measurements have been taken during specialized research projects of limited duration. Routine operational data have traditionally relied on reports from ground-based observers with little benefit from quantitative instrumentation. Cloud climatologies have, therefore, been based on limited information and are essentially local, not global, in scope. In an attempt to improve this situation, the International Satellite Cloud Climatology Project (ISCCP) is currently gathering satellite observations to provide better information about the distribution of cloudiness around the globe (Schiffer and Rossow 1983). Furthermore, analyses of geostationary satellite data have already revealed features in cloud fields which were hitherto undetected. One example is the coherent diurnal and seasonal variation of subtropical stratus cloud which is clearly important and which requires explanation (e.g. Minnis and Harrison 1984). At the same time, the treatment of clouds in numerical models has also been quite rudimentary, partly reflecting the lack of observational data. It is therefore highly desirable to improve cloud models and methods of parametrizing their effects to include representations of the important physical processes and to compare the predictions of these models with the new observations.

With all these points in mind, a broadly based research programme, called the First ISCCP Regional Experiment (FIRE), was set up in the United States to carry out a comprehensive study into some of these issues, within the context of the ISCCP.

FIRE consists of a set of self-contained experiments, designed to address specific parts of the cloud–radiation feedback problem, containing both observational and modelling programmes.

Two types of cloud system have been identified for special attention:

(a) marine stratocumulus which occupies extensive areas especially over the eastern ocean-basins where it is associated with the regions of highest-average global cloud cover, and

(b) cirrus whose global distribution is still very uncertain.

Marine stratocumulus exerts a strong influence on the energy transfers between the atmosphere and the ocean and on the structure of the boundary layer, while cirrus has a major effect on the flux of infra-red radiation lost to space.

Because an independent Meteorological Office research programme with many similar aims was already under way (Nicholls 1984, Nicholls and Leighton 1986, Turton and Nicholls 1987, Nicholls 1987), the Office was invited to participate in FIRE. As a result, three Meteorological Office research groups from the Cloud Physics Branch, Boundary Layer Research Branch and the Meteorological Research Flight (MRF) will make a sizeable contribution to the FIRE marine stratocumulus investigation.

The objectives and experimental strategy discussed in the next two sections refer to the situation as it existed in May 1987.

2. The objectives of the FIRE marine stratocumulus investigation

The goal of the FIRE marine stratocumulus studies is to seek a better understanding of the interaction of the physical processes which determine the evolution of these cloud systems, especially their radiative properties. Observations will be made on a wide variety of time and spatial scales to enable current ideas and models to be tested and refined (Randall *et al.* 1984). It is hoped that this will ultimately lead to better representations in global climate studies and provide a data base suitable for testing a wide variety of models, including detailed radiative transfer and microphysical calculations, and different types of boundary layer model.

This broad strategy may be further broken down into a number of more specific aims. Although not a complete list, attempts will be made to:

(a) investigate the relationship between the cloud structure, its microphysical properties and its radiative properties by making simultaneous measurements at different levels,

(b) study the droplet distributions within the clouds, the processes influencing them and the growth of precipitation,

(c) measure and investigate the factors controlling the entrainment rate at cloud top,

(d) determine how radiation affects mixing within the boundary layer, especially the response of the clouds to the diurnal cycle,
(e) characterize the structure of cloud fields on various time and spatial scales using satellite observations,
(f) test satellite cloud retrieval algorithms, e.g. for cloud amount and cloud-top height,
(g) determine the factors that affect fractional cloud cover and cloud morphology,
(h) study the formation and break-up of cloud sheets and provide data to enable models of these processes to be constructed and tested, and
(i) assess the role of mesoscale processes and their effects on these cloud fields.

3. Implementation — experimental strategy

Achieving the aims of the investigation requires a diverse set of observational and modelling techniques — this demands a collaborative approach. The logistics are being co-ordinated through a FIRE project office set up by the National Aeronautics and Space Administration (NASA), while the scientific aspects are managed by the 40-strong FIRE science team which comprises most of the principal investigators. The FIRE participants have agreed to pool their data in a common format for use by any of the others.

The area chosen for the marine stratocumulus experiment lies off the coast of California (see Fig. 1). Stratocumulus covers extensive areas of the eastern Pacific, including this region, for much of the summer. The cloud lies beneath a strong temperature inversion associated with the subtropical anticyclone and over a relatively cool ocean surface. Similar conditions exist in other eastern ocean-basins at similar latitudes. Climatological records show that offshore cloud cover at San Nicolas Island (see Fig. 1) exceeds 6 oktas for 40% of the time during June and July.

There are basically two types of observational strategy:

(a) Extended Time Observations (ETO) based largely on routine satellite products with a minimum of local ground-based measurements, and
(b) Intensive Field Observations (IFO) where an intensive local measurement campaign is organized for a relatively short period.

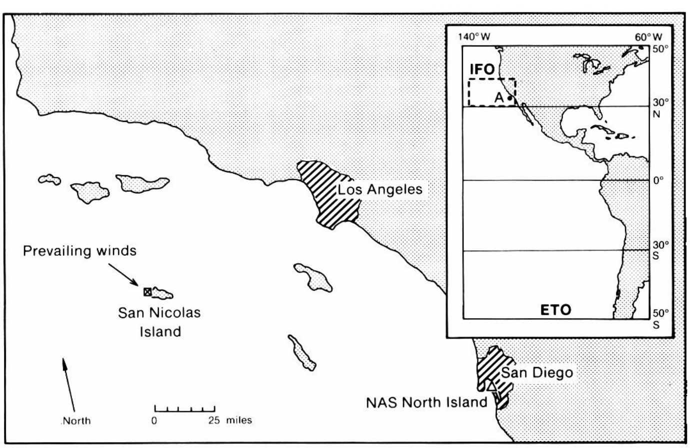

Figure 1. The location of the experimental areas for the FIRE marine stratocumulus Extended Time Observations (ETO) and the Intensive Field Observations (IFO). The more detailed map shows the locations of the aircraft base and IFO Operations Center at Naval Air Station North Island and the offshore San Nicolas Island site.

The two are designed to be complementary. The ETO provide data on large spatial and long time-scales, while the IFO provide the high-resolution, detailed, small-scale data with the ETO as a background.

The ETO began in April 1986. The first IFO will take place during a three-week period in June and July 1987, with a second follow-up IFO period in the same area planned for summer 1989. There will be three groups of measurements during the IFO: high-resolution satellite observations, and aircraft data and surface-based data, as listed in Table I. The instrumentation will comprise the largest, most diverse set ever assembled to investigate these conditions.

The MRF C-130 Hercules will be based, with most of the other aircraft and the IFO Operations Center, at the Naval Air Station, North Island, San Diego. It will fly in conjunction with the other aircraft making *in situ* measurements of turbulence, cloud and aerosol microphysics, and radiation (both broad-band irradiance and narrow-band multi-angle measurements). These multi-aircraft combinations will be a particularly exciting part of FIRE since they offer an opportunity to overcome many of the restrictions imposed by the limited resources available to individual groups, which limit the scope of the investigations that can be undertaken by single investigators. Thus, extended-trajectory

Table I. *Summary of the main FIRE marine stratocumulus observing systems*

Satellite observations	
GOES	VISSR data — 1 km resolution visible, 8 km resolution infra-red, every 30 minutes VAS sounder data
NOAA polar orbiters	AVHRR HRPT data — 1 km resolution, 5 spectral bands TOVS radiance data — 20 spectral bands
LANDSAT	Thematic mapper data — 30 m and 120 m resolution, 7 spectral bands
ERBS	All available archived ERBE and relevant SAGE II data
DMSP	1 km resolution visible and infra-red data
SPOT	10 m or 20 m resolution, visible and near infra-red data
Aircraft observations	
NASA ER-2	Downward-looking lidar mapping cloud top, multi-channel scanning radiometer, thematic mapper simulator, other radiometers
NCAR Electra	Turbulence, cloud microphysics, broad-band radiometers, downward-looking lidar, atmospheric chemistry, constant-level balloon tracker
UW C-131	Cloud microphysics, aerosols, cloud-absorption radiometer
MRF C-130	Turbulence, cloud microphysics, aerosols, multi-channel scanning radiometer, broad-band radiometers
NOSC Navajo	Cloud microphysics, aerosols
All aircraft	Standard meteorological data: winds, temperatures, etc.
Surface observations on San Nicolas Island	
19 m tower	Turbulence, standard meteorological data, aerosols
Surface instruments	Broad- and narrow-band radiometers, cloud-base recorder
NASA tethered balloon	MRU Cardington multiple turbulence probes, single CSU radiation and cloud microphysics package
NRL/NOSC tethered balloon	Single package with standard meteorological data, liquid water
Rawinsonde	2 to 8 soundings per day
UHF profiler	404 MHz Doppler wind-profiling radar
Acoustic sounders	Doppler trimonostatic — wind and turbulence profiles Doppler bistatic — inversion interface structure
Microwave radiometer	Dual 21 and 32 GHz channels giving column-integrated liquid and water vapour
Other surface-based observations	
Ship Point Sur	Radiation, aerosols, microphysics, standard meteorological data, release of constant-level balloons
Coastal rawinsondes	Standard network with extra stations

flights, day–night flights, co-ordinated flights with simultaneous sampling above and within the cloud layer and multi-aircraft runs in broken-cloud conditions will be feasible, all of which are needed to achieve the aims outlined in section 2. Flights will be carried out over the open ocean, away from possible continental influence, and in conjunction with the surface-based instrumentation around San Nicolas Island. Flights will be planned to coincide with satellite passes (especially LANDSAT) and will also be co-ordinated with high-flying aircraft carrying satellite-derived instrumentation to view the clouds at many different scales, angles and frequencies.

Instruments from the Meteorological Research Unit (MRU), Cardington will be flown by the NASA tethered-balloon facility which will be located with the other surface-based equipment on San Nicolas Island. Several of the new turbulence probes designed and built at the MRU will be deployed at intervals along the balloon's tether cable to make simultaneous, multi-level measurements with fine height-resolution. The balloon itself is expected to fly at heights which comfortably exceed the cloud top (which is typically near 1 km). Another instrument package primarily measuring cloud microphysics and radiation data is being developed at Colorado State University (CSU) and this will also be flown from the balloon. The other instrumentation which is expected to be deployed is listed briefly in Table I, and represents a very wide range of observations.

4. Concluding remarks

The marine stratocumulus component of FIRE will probably be the most comprehensive study of these clouds undertaken during the next decade. It offers new opportunities to improve our understanding of the processes controlling layer clouds, especially their interaction with radiation, and will stimulate and focus future research effort in this area. The collaborative nature of the project is an exciting and efficient use of the diverse resources committed to it. Moreover, the wide range of observational methods should result in a number of simultaneous, independent interpretations of the same situation, although each will have a slightly different perspective. It is hoped that this combination will increase our understanding of these types of cloud sufficiently to enable improved representations to be developed in numerical models.

Acknowledgements

Much of the information on which this article is based has been drawn from the FIRE research, implementation and operations plans produced by various members of the FIRE science team.

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Verification of global model forecasts of tropical cyclones during 1986

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Summary

Forecasts of tropical cyclones from the Meteorological Office operational global model have been verified. Two examples of model forecasts are shown and verification statistics are given for mean and median errors of the forecast position of all major tropical cyclones in the North Atlantic and North Pacific during 1986.

1. Introduction

Since the introduction of the Meteorological Office operational global model in 1982, its accuracy in middle and high latitudes has been closely monitored. Numerical products covering much of the globe are now distributed to a great many users world-wide and there has been increasing interest in the quality of tropical forecasts, in particular the accuracy of forecasts of tropical cyclones. During 1986, forecasts of all major cyclones in the North Atlantic and North Pacific have been verified and the results are presented below.

The movement of tropical cyclones is difficult to predict by subjective forecasting methods; persistence and climatology offer useful guidance on occasions, but sudden variations in direction and speed of movement are common, especially when systems interact with troughs in the middle-latitude flow. A great many statistical methods have been developed for the prediction of cyclone tracks. Most use multiple regression techniques based on past movement, present fields, and, perhaps also, on forecast fields from a coarse-resolution numerical model. Verification of these methods shows that useful accuracy can be achieved (e.g. Ramage 1980, Allen 1984). Models have also been developed which represent cyclone structure at relatively high resolution (40–60 km perhaps) within a limited area. Boundary conditions to these models are supplied by a coarser-resolution global or hemispheric model so that they can be used for operational forecasting (Harrison and Fiorino 1984, Marks 1985).

The successful forecasting of tropical cyclone movement almost certainly requires not only an accurate representation of the physical processes close to the cyclone centre but also an accurate representation of the large-scale dynamics of the tropics and of the troughs in the middle-latitude flow which frequently extend towards the equatorial regions. These last two large-scale aspects are handled relatively well by global models and, in spite of their low resolution, it is reasonable to expect them to offer some help in the problem of tropical cyclone forecasting. The Meteorological Office global model, having a resolution of around 200 km near the equator, is unable to resolve any of the small-scale structure occurring in tropical cyclones, and indeed the resolution of the model is too coarse to define some of the smaller tropical systems. However, mature typhoons and hurricanes may have horizontal dimensions of 1000–1500 km, and it is these that the model should be able to represent quite well.

2. Verification method

Model forecasts have been verified against reports received regularly on the global telecommunication system from the major tropical forecasting centres. The reports give position and intensity at least every six hours and are based on satellite imagery and observational data, some of which may not be widely available (e.g. from reconnaissance flights). Since reports of cyclones in the Indian Ocean and southern hemisphere are received irregularly at the Meteorological Office, only the North Atlantic and North Pacific areas have been considered in this study.

The forecasts verified have been restricted to those for which the reported maximum wind speed of the cyclone was in excess of 50 kn at the time of verification. No attempt has been made to verify forecasts of weaker systems which are often beyond the model resolution. The verification of the cyclone positions has been performed manually and is presented as the distance between the lowest pressure on the forecast mean-sea-level pressure chart and the reported position. Only forecasts valid for T+24, T+48 and T+72 hours from 00 GMT analyses have been evaluated.

3. Results

There were 169 occasions when the reported maximum wind of cyclones in the North Atlantic and North Pacific was in excess of 50 kn at 00 GMT. Many of the cyclones were large systems having a horizontal scale of, typically, 1000 km; an example of a model analysis and 72-hour forecast for one of them (typhoon Ben) is shown in Figs 1(a) and 1(b). The forecast in this case was particularly good and demonstrates what can be achieved by a numerical model having a resolution of just 200 km. The observed and forecast tracks of this typhoon are shown in Fig. 2. Between 20 and 24 September the typhoon moved fairly steadily north-west becoming gradually more intense, and by 0600 GMT on the 25th maximum winds of 100 kn were estimated. For the next two days it became almost stationary before accelerating north-east on the 28th as it engaged the flow on the forward side of an amplifying upper trough over Japan. In general, both the slowing down and the final accelerating phase of the typhoon movement were well forecast by the model even at T+72 hours. This was a large tropical system, which the model was well able to resolve, and clearly in the final stages the accurate handling of the middle-latitude upper trough was crucial for successful forecasts.

A second example of forecast tracks is given in Fig. 3 for hurricane Charley which passed close to the east coast of North America. The hurricane was almost stationary during 16 and 17 August, and maximum winds of 65 kn were reported. By the 18th it was accelerating north-east and on the 20th it became extra-tropical and moved east in the middle-latitude flow across the Atlantic. As in the first case the accelerating phase of the hurricane movement was handled well by the model, though the forecast from 00 GMT on the 18th failed to predict the subsequent north-easterly track.

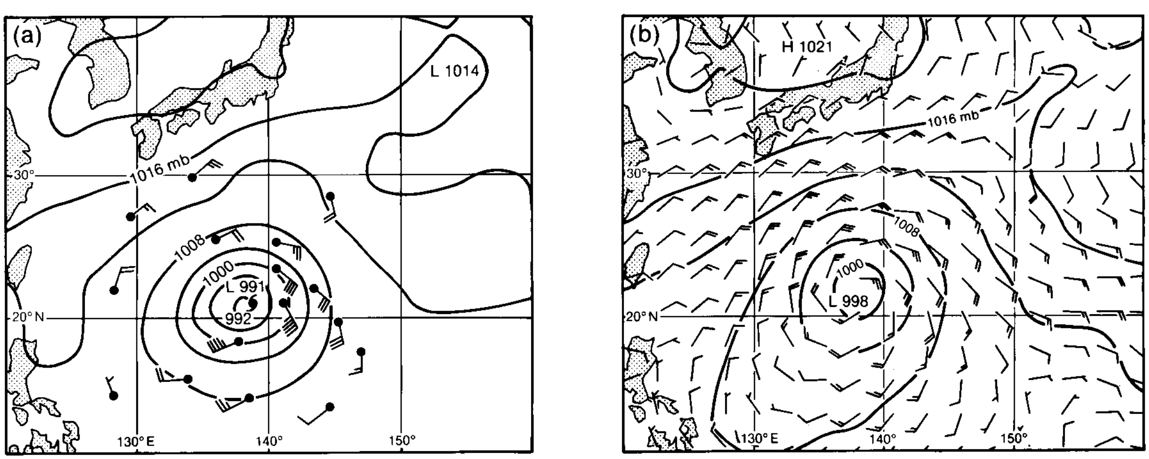

Figure 1. (a) Model mean-sea-level pressure analysis and observed surface winds for 00 GMT on 26 September 1986; the hurricane symbol (☉) marks the reported centre of typhoon Ben. (b) The T+72 hours forecast mean-sea-level pressure and surface winds for 00 GMT on 26 September 1986.

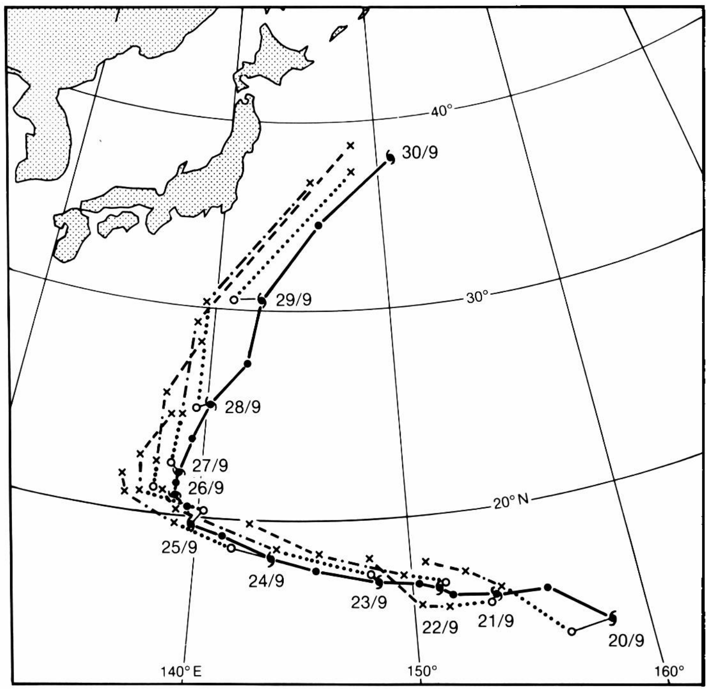

Figure 2. Observed and forecast tracks of typhoon Ben, 20–30 September 1986. The observed track is shown by a solid line with the hurricane symbol marking the 00 GMT positions used for verification, with the date shown alongside. The position of the cyclone centre analysed by the model is shown by an open circle connected by a thin line to the corresponding observed position. The forecast positions at 24-hour intervals are shown by crosses connected by a dotted line for the T+0 to T+24 hours forecast, a dot-dash line for the T+24 to T+48 hours forecast and a dashed line for the T+48 to T+72 hours forecast.

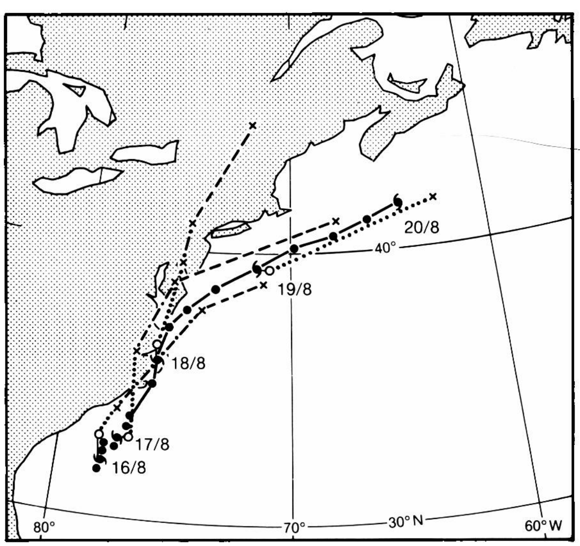

Figure 3. Observed and forecast tracks of hurricane Charley, 16–20 August 1986; legend as Fig. 2.

The tracks of all the cyclones in 1986 have been verified and the mean and median forecast errors are given in Table I. The number of cases where no low centre corresponding to the cyclone was identifiable on the analyses and in the forecasts are also given. Care must be taken when comparing these forecast errors with other published figures since their magnitude is very dependent on which cyclones are chosen for verification. Some tropical systems are poorly defined by the model analyses and have a weak circulation or are totally missing in the forecasts. The criteria used to define which cyclones are identifiable, and therefore used for verification, can have a large impact on the magnitude of the forecast errors obtained.

In general, there seems to be useful skill in the forecasts of cyclone position, especially at T+48 and T+72 hours when persistence and climatology can lead to large errors. The tracks of some of the systems were particularly irregular and model guidance in these cases often has a great deal to offer. On several occasions it seems likely that poor analyses led to poor forecasts. Data are sparse over much of the tropical oceans and there are large areas with no radiosonde observations. Cloud-track winds are an aid to the analysis of the tropical wind field and occasionally they are available within the circulation of a cyclone. Ship reports provide a relatively good coverage in parts of the west Pacific, but over much of the tropical Atlantic and especially in the east Pacific they are received very infrequently.

Global model analyses are regularly monitored in the Meteorological Office and there is a facility to introduce data generated by the human analyst (bogus data) when the model analyses are believed to be in error. On several occasions in 1986 bogus data were used to adjust the analysed cyclone position to the reported position. Due to time constraints this was seldom achieved before the operational forecast run. However, this action affected the update analysis and consequently the first-guess fields for the next analysis cycle were improved.

Table I. *Verification of the analysed/forecast positions of tropical cyclones by the Meteorological Office global operational model in 1986; 00 GMT runs only. Reported maximum winds ⩾ 50 kn.*

		T+0 hours			T+24 hours			T+48 hours			T+72 hours		
Area	N	NA	MNE	MDE	NF	MNE	MDE	NF	MNE	MDE	NF	MNE	MDE
Atlantic	14	1	84	90	2	135	85	3	202	130	5	241	220
East Pacific	34	7	111	118	15	180	140	10	198	165	14	249	220
West Pacific	121	1	80	68	13	143	120	17	214	175	31	270	215
All	169	9	86	77	30	148	122	30	210	164	50	264	217

N = number of cases
NA = number of cases where cyclone not analysed by model
NF = number of cases where cyclone not forecast by model
MNE = mean error in the analysed/forecast position of the cyclone in n miles
MDE = median error in the analysed/forecast position of the cyclone in n miles

4. Conclusions

The Meteorological Office operational global model has shown considerable skill in predicting the movement of tropical cyclones during 1986, especially when they engage upper troughs in the middle-latitude flow. On some occasions there was a poor representation of the cyclone position in the model's initial state, largely as a result of the poor data coverage over the tropical oceans. Clearly there is a role for the human analyst to improve the model analysis in such cases. Further investigations need to be made into the most effective methods of using bogus data, and the impact they have on the forecasts has yet to be fully assessed.

Acknowledgements

Thanks are due to Captains Phillips, Hall and Borthwick of the Ship Routeing Section of the Meteorological Office, Bracknell for doing much of the manual plotting of cyclone positions and forecasts.

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The historical background to the collection of meteorological observations from South Georgia

S.D. Merrick*

Meteorological Office, Royal Air Force, Mount Pleasant

Summary

A brief history of meteorological observations from South Georgia is given; this is based on evidence from original letters which describes these observations.

South Georgia is a barren, rocky and mountainous island (Fig. 1) situated about 1400 km to the east-south-east of the Falkland Islands (Fig. 2). Much of the island is covered in snow and ice throughout the year, but despite its unfavourable climate it has several good deep harbours on the northern side of the island, and it was there that settlements developed. Whaling was the major industry in the period up to about 1930, but after that time a long period of decline set in.

The early meteorological observations at South Georgia were made by the naturalist Johan Reinhold Forster who in 1775 accompanied Captain James Cook in the ship HMS *Resolution* on his second epic voyage of exploration. One of the objects of this voyage was to investigate the little known 'Southern Continent' of Antarctica. Cook landed at Possession Bay in South Georgia, and Forster must have found much to delight a naturalist. Whilst there Forster noted temperatures daily and recorded an average of 2.4 °C on deck and 5.5 °C in his cabin!

The next important meteorological event was the arrival in 1882 of the German International Polar Year expedition. One of their primary tasks was to observe the transit of Venus on 6 December 1882, but hourly meteorological observations were also made. The expedition left the island in September 1883.

* Now at Royal Air Force, Brize Norton.

Photograph by courtesy of J. Elliott

Figure 1. Grytviken and the surrounding mountains.

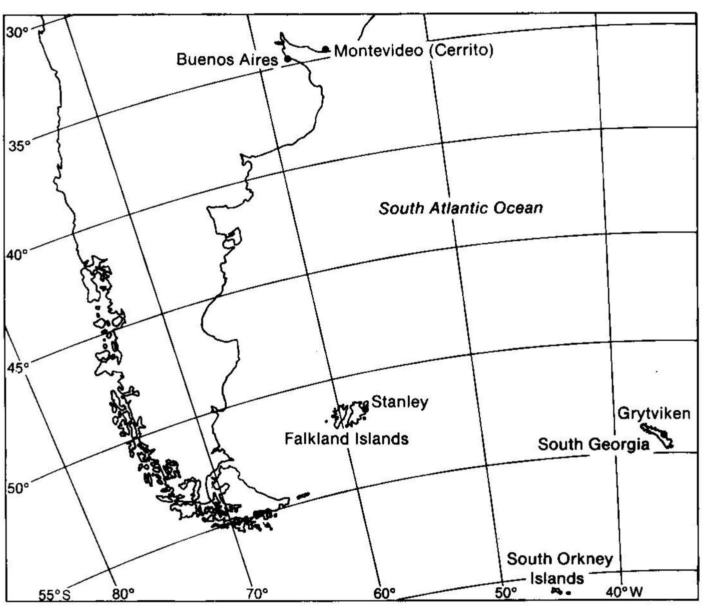


Figure 2. Positions of places mentioned in the text.

The growth of the whaling industry by the early 1890s led to the establishment of the 'Compania Argentina de Pesca', a Buenos Aires based whaling company led by a colourful Norwegian whaling captain named Carl Anton Larsen. Under the terms of its lease, the company was obliged to make regular meteorological observations. These were initiated at Grytviken on 17 January 1905 and use was made of instruments provided by Walter Davis, formerly of the Ben Nevis Observatory in Scotland, who had become the head of the newly established Argentine Meteorological Office in Buenos Aires*. At about the same time the Argentinians had taken over the running of the meteorological station at Laurie Island (in the South Orkney Islands) from the Scottish National Antarctic Expedition.

This was the state of affairs up to the year 1923 when, at the Meteorological Conference held in Utrecht in September of that year, Resolution 34 proposed that increased attention should be paid to the collection of observations from the South Atlantic.

Subsequently a letter dated 17 November 1925 from the Brazilian Embassy in London to the Right Honourable Austen Chamberlain MP, His Majesty's Secretary of State for Foreign Affairs, proposed that:

> Every effort should be made by the meteorological services interested with a view to prepare daily synoptical charts for the South Atlantic Ocean.

The same letter also stated that:

> The main obstacle for the realisation of a complete service is the equipment and maintenance of radiotelegraphic posts in all these islands, and the Brazilian Department of Meteorology suggest, as the only means of a satisfactory solution, that the Governments interested in the matter should divide the expenses thereby incurred.

The matter was duly considered and, in a letter dated 18 March 1926 from the Air Ministry to the Under Secretary of State at the Colonial Office, the Air Council instructed that the Brazilian Ambassador be informed that it was in favour of the proposal and that:

> The Council consider that every encouragement should be given to Colonies and Dominions concerned to take their part in the proposed organisation.
>
> The ever increasing practical applications of meteorology depend upon the rapid collection of data from as large an area as possible. This has largely been achieved in the Northern Hemisphere by the various governments concerned collecting observations within their own territories and transmitting them broadcast from high power telegraph stations. It frequently happens that most important observations are required from distant islands or sparsely inhabited regions and the duty of the government concerned to provide such information is generally recognised.

The letter continued:

> If this system is to be extended to the Southern Hemisphere, it will be necessary for the British Empire to take a large part, for the outlying islands from which observations of great importance are required, are generally British territory.
>
> South Africa and Australia are also very much interested in this question and the Council understand that the meteorological services of Brazil, South Africa and Australia are in communication with the object of organising the exchange of information necessary to the preparation of daily meteorological charts for the whole of the Southern Hemisphere. Thus any help given in response to the request from Brazil will help a scheme in which the British Empire has a preponderating interest.

Finally, the letter suggested what action should be taken:

> The Air Council consider that the Government of the Falkland Islands should be asked to co-operate with the meteorological services of South America and South Africa, and to undertake the issue from the wireless stations the meteorological information required.
>
> With regard to the reply which should be given to the Brazilian Ambassador, the Air Council suggest that the above information might be given to him with a promise to use our good offices with the British Administrations concerned to obtain the meteorological information required. The Council do not consider that at this stage the particulars to be included in the daily transmissions need be considered. These details should be left to be arranged by the meteorological services concerned who would no doubt draw up a suitable scheme in collaboration.

---

* Headland, R.K.; *The island of South Georgia*, Cambridge University Press, 1984.

The problem was then referred to the Governor of the Falkland Islands, Sir John Middleton, KBE, CMG, for action. This resulted in a letter dated 20 September 1926 from the Governor's Office to the Magistrate in South Georgia which requested that:

> You will furnish your observations on the proposal that the meteorological station at Grytviken should co-operate in the arrangement.

The reply from the Magistrate on 21 October 1926 indicated that there were no difficulties foreseen and asked what particulars should be included in the message. A further letter from the Colonial Secretary dated 15 February 1928 said:

> With reference to the proposed arrangements for radio telegraphic transmission of meteorological observations taken at Grytviken in accordance with the scheme outlined by the Brazilian Government for the development of synoptic meteorology in the Southern Hemisphere, I am directed by the Governor to inform you that it has now been decided that daily midday Greenwich observations should be telegraphed to Cerrito from which station they will be broadcast.
>
> I am accordingly to request that you will arrange with the observer at Grytviken that messages in the form and code set out in the accompanying pamphlet should be telegraphed daily to Stanley for retransmission to Cerrito.

The outcome was indicated in a letter dated 21 September 1928. This letter originated in the Ministry of Foreign Affairs in Rio de Janeiro and was addressed to His Excellency Sir Beilby Alston, KCMG, BE, His Brittanic Majesty's Ambassador to Brazil, stating:

> The telegrams sent daily from Cumberland Bay, South Georgia through the intermediary of the radiotelegraphic station at Cerrito, Montevideo, have been amply sufficient for the requirements of our weather service.

These arrangements continued until 1950 when the Falkland Islands Dependencies Meteorological Service assumed responsibility for the meteorological station at Grytviken. In 1950 responsibility was transferred to the British Antarctic Survey, and there was no further change until April 1982. This long tradition of meteorological observations continues to the present day with the army detachment at Grytviken making six-hourly observations. The South Georgia observations continue to be invaluable to modern day meteorologists based at the newly constructed airport at Mount Pleasant, Falkland Islands, and presumably are of equal value to the Brazilian meteorologists, at whose instigation the observations were first broadcast.

The letters on which this article is based are dated from around 1926 and were recently discovered when the Meteorological Office at RAF Stanley, Falkland Islands moved to the new site at Mount Pleasant Airport. They are the property of the Falkland Islands Government, and the originals have now been returned to the Attorney-General's Office in Stanley.

Reviews

Wind as a geological process on Earth, Mars, Venus and Titan, by R. Greeley and J.D. Iversen. 155 mm × 235 mm, pp. xii + 333, *illus.* Cambridge University Press, 1985. Price £35.00, US $59.50.

It is crucial to an appreciation of the author's aims, and indeed in the prospective reader's interest, that proper regard be paid to the planetary references in the full title of this book. The stated intention is that the book be used 'as reference and text for . . . graduate courses in comparative planetology', a discipline which, apparently, 'has as its goal the definition of the fundamental processes that have shaped and modified the planets, satellites and other "solid surface" bodies in the solar system'. Indeed, it is claimed to be the first book to deal with aeolian (i.e. wind-related) processes in a truly planetary context. The preface rightly opens with due reference to the universally acknowledged classic, *The physics of blown sand and desert dunes*, by R.A. Bagnold (published in 1941 by Methuen, London), while the authors are at pains to emphasize that it is not their intent to 'replace' Bagnold's book or the research it represents. Rather, they claim to have built upon its solid foundation and, as is manifest from their title, to have extrapolated some of Bagnold's results to other planetary environments.

Those who do not adhere to the 'because-it-is-there' school of justification for any study may be more persuaded by the authors' claim that some processes which are difficult to assess on the Earth are easier to understand on the other planets. The argument being that although the Earth is the primary data base for interpreting aeolian processes, its surface processes are much more complicated than those of other planets mainly because of the presence of liquid water and vegetation. The specific list of Earth, Mars, Venus and Titan (the last named being the largest of the Saturnian satellites) in the title has been compiled by surveying the solar system and acknowledging that any body with a dynamic atmosphere and a solid surface might be subject to surface-based aeolian processes. In spite of a clear exposition of the authors' purpose, this intriguingly selective, yet comprehensive, title still seems somewhat contrived to this reviewer who, admittedly, lays no claim to being well versed in comparative planetology.

Aeolian processes have shaped, and continue to shape, the character of the Earth's surface and are known to be active also on Mars. Varying degrees of faith and/or speculation are needed, however, in order to stretch the list to include Venus and Titan. Venus is completely enveloped in a perpetual shroud of cloud that hides the surface from view and is the least understood of the terrestrial planets. However, Russia has landed several spacecraft which have survived long enough to return pictures and sufficient wind and surface-composition data to encourage some 'experts' to infer, somewhat speculatively, the likelihood of past and present aeolian activity. In contrast, so little is known about Titan's atmosphere and surface that the authors are reduced to statements such as 'Dunes composed of methane ice particles and ice grains being blown in the dense, extremely cold nitrogen atmosphere border on the realm of science fiction but remain a possibility'. The specific inclusion of Titan in the title is thus based effectively on pure speculation about the existence and importance of aeolian processes at its surface. In the same vein, one might be tempted to recommend (tongue-in-cheek) the science fiction classic, '*The Sirens of Titan*' by Kurt Vonnegut — but I digress. If the authors genuinely seek data bases other than the Earth for the study of surface aeolian processes, it would seem that the only conceivably practical alternative at present is Mars. Hence my contention that the title is somewhat contrived.

It is mooted that 'perhaps more than in any other field, planetology requires a multi-disciplinary approach'. This, it is acknowledged, leads in turn to the severe difficulty of communication among the various disciplines involved. Greeley and Iversen bring their combined talents as geologist and engineer, respectively, to their discourse which deals mainly with the geological aspects of windblown material. They do not claim (nor do they display) any particular meteorological expertise. Likewise, this reviewer is neither geologist nor engineer. The risk of being too critical of the sections where the authors may be least familiar with the underlying basic meteorology is compounded by my inability to provide adequate critical appraisal of the areas in which the authors have been presumed expert. However, any inadvertent bias resulting from this dichotomy may not prove too amiss in a review written for practising meteorologists.

The structure and scope of the seven main chapters are displayed clearly and in detail in the contents. Chapter 1, *Wind as a geological process*, introduces the reader to aeolian processes and provides a general overview of such activity on other planets. It also serves to remind us of the significance of aeolian processes on Earth, from the effects of local-scale dust storms to the global-scale problem of desertification with its consequent implications for climate change. The recent, seemingly continuous, exposure of the problems of Africa goes only part way to preparing us for an appreciation of the full enormity of the extent of desertification. 'Although more than one third of the Earth's land is arid or semi-arid, somewhat less than half of this area is so dry that it cannot support human life. Over 600 million people live in dry areas, and about 80 million of these live in lands that are nearly useless because of soil erosion and encroachment of sand dunes or other effects of desertification. Desertification of arid lands . . . is evident on all inhabited continents of Earth'.

Chapter 2, *The aeolian environment*, is the most meteorological section of the book; however, considering the stated goal of comparative planetology and the emphasis on a knowledge of atmospheres, it is particularly disappointing. In spite of the authors' earlier claims of the need for a multi-disciplinary approach, this chapter does not appear to lay a foundation of basic meteorological theory, whose understanding is invoked in later sections of the book. On the contrary, it seems more a token acknowledgement that some basic meteorology needs to be included for appearance's sake. Section 2.4, which deals with the atmospheric boundary layer, was the easiest for this reviewer to examine critically. Even allowing that meteorology may not be the authors' strong point, it would be remiss of me not to comment on the several significant errors that occur in the basic equations and figures. Some of the 'explanations' of the most fundamental concepts I found, at best, confusing. The whole tenor of this section cast a cloud over my enjoyment of the book which I found difficult to dispel when viewing it in its entirety. I doubt whether the students for whom it is intended will find this particular section informative or easy to comprehend fully. I was left with perhaps the rather jaundiced opinion that the authors are clearly more confident when speculating about aeolian features on the unseen surface of Titan than they are when trying to explain the rudiments of the Earth's atmospheric boundary layer. Fortunately, but perhaps sadly, a proper understanding of the fundamentals of this chapter does not appear to be crucial to an appreciation of the rest of the book.

Chapter 3, *Physics of particle motion*, is the most mathematical and quantitative of the chapters. I only hope that its 41 'engineering' equations are more free of errors than those of the preceding chapter — I did not check. It is tempting to suggest that chapters 2 and 3 could be glossed over by the general reader who does not need, nor wish, to know the mathematical detail. Chapter 4, *Aeolian abrasion and erosion*, returns to a more descriptive and qualitative style and introduces ventifacts (wind-modified objects) and yardangs (aerodynamically shaped, elongated hills oriented parallel to the wind). There are several intriguing and striking pictures, in particular those depicting such surface features on Mars. Chapter 5, *Aeolian sand deposits and bedforms*, is the largest single chapter and is devoted effectively to sand dunes. Dune classification is bewildering on first acquaintance and, in that sense, is very reminiscent of cloud classification. One can contend readily with the three primary types, viz. longitudinal, transverse and parabolic, and that they may be simple, compound or complex; but then comes falling, climbing, echo, reversing, dome, star, and a host of other terms. Examples of many of the special dune structures discussed are illustrated in a most dramatic series of pictures. Chapter 6 considers the interaction of wind and topography and finally chapter 7, *Windblown dust*, discusses problems concerning fine-grained material carried aloft in suspension.

The book itself is very stylishly produced as one expects from an issue in the Cambridge Planetary Science Series (editors: W.I. Axford, G.E. Hunt, R. Greeley). Its clear, comprehensive appendices include very helpful nomenclature, glossary and reference sections. The nature and considerable number of the errors in the meteorological sections rather dulled my appetite for the book and prevent me from recommending it unreservedly. I would be interested to see a review written by someone more knowledgeable than me in the planetary and geological aspects of the book. Arguably, the book's most striking, instructive and successful feature is its remarkable and generous gallery of pictures.

D.J. Carson

Atmospheric chemistry and physics of air pollution, by J.H. Seinfeld. 155 mm × 230 mm, pp. xxiii + 738, *illus*. New York, Chichester, Brisbane, Toronto, Singapore, John Wiley and Sons Ltd, 1986. Price £61.35.

In his introduction Professor Seinfeld gives an all-embracing definition of air pollution as 'any atmospheric condition in which substances are present at concentrations high enough above their normal ambient levels to produce a measurable effect on man, animals, vegetation, or materials'. It is clear that no book could hope to address all the topics implicit in such a catch-all definition, and indeed the author only makes brief excursions into areas that might not normally be considered mainstream air-pollution chemistry and physics, e.g. radiative effects of carbon dioxide and the influence of halocarbons in the stratosphere. However, within the areas where Seinfeld concentrates, he does for the most part produce a good effort.

The book's 18 chapters are divided into 6 parts. Chapters 1, 2 and 3 which form Part 1 deal with *Air pollutants, their sources and effects*. Setting the scene for the book, they indicate what sort of substances air pollutants are, the concentrations they can be expected at, the effects that they can induce and where such pollutants originate. This part of the book, which could stand alone, is full of data from a wide variety of sources, which one might not normally come across. Did you know, for instance, that nasal breathing removes almost all particles with diameters greater than 10 μm while oral breathing only removes particles with diameters greater than 15 μm? Well now you do! There is also quite an interesting description and analysis of the internal combustion process and the effects of 'lean burn' on carbon monoxide and nitrogren oxide output. This sets the trend in the rest of the book for quite detailed and specific mathematical analysis of the processes involved.

Part 2 deals with *Air pollution chemistry*. This covers gas-phase reaction, aqueous-phase reactions, and chemical aspects of the transfer of chemical species from atmosphere to droplet. Chapter 4 on gas-phase chemistry is, for me, one of the highlights of the book. It contains a great deal of information on many important chemical species and sets out in a very clear way the complex pathways by which hydrocarbons are oxidized to carbon dioxide, producing several ozone molecules on the way. The introduction of complexity in a hierarchical fashion, when it is required to bring out a new feature of such chemical systems, works very well. As with elsewhere in the book, the important processes are put on a quantitative footing with the working of a few examples. There is also a small section on the destructive effects of nitrogen oxides and halocarbons on stratospheric ozone. The next two chapters on solution chemistry and transfer processes (which describes how different species get into water droplets) could have usefully been reversed, so that one has an idea of the physical processes which control how gas molecules enter the droplet, before discussing the chemical equilibria which control the uptake within the droplet. However, within the chapters the various processes are handled in a consistent and logical manner.

Part 3 deals with *Aerosols*, in four chapters starting with size distributions, processes relevant to single aerosols, nucleation processes, i.e. how individual aerosol particles form, and finishing with the processes which govern how aerosol populations evolve. Much of this could be considered as a generalization of cloud microphysics. Some interesting facts come out of these chapters, for instance, sulphuric acid vapour can promote rapid nucleation of water droplets at 50% relative humidity with only a few parts per billion of sulphuric acid, suggesting why pollution episodes produce a very hazy atmosphere as various photochemical processes convert sulphur dioxide molecules into sulphuric acid molecules. Incidentally, sulphuric acid is 10^9 times more effective in these processes than another common atmospheric acid, nitric acid.

Part 4 entitled *Air pollution meteorology* is really about meteorology relevant to air pollution problems, since both chapters in this section make almost no mention of air pollution. Seinfeld begins with a brief look at radiation, parcel theory and air motions, continuing in chapter 12 with micrometeorology which relies heavily (but not completely) on *The structure of atmospheric turbulence* by Lumley and Panofsky (1964) (also published by Wiley) for much of its mathematical development, but has nevertheless been well presented. Seinfeld redeems himself in Part 5, *Atmospheric diffusion*, by weaving into material from Lumley and Panofsky an extension to include chemical species, which exacerbate the closure problem and is a specific instance of a general problem in atmospheric chemistry, i.e. that of describing rate equations containing products such as $[A]\cdot[B]$ since if, as is usual, we represent the concentration of a species A, $[A]$ as a mean term $\overline{[A]}$ and a fluctuating term $[A]'$, we have no real basis to speculate on the magnitude and sign of the terms $\overline{[A]'\cdot[B]'}$.

Finally, Part 6 on *Special topics* discusses air pollution statistics, i.e. probability of exceeding threshold values, and goes into some detail on the atmospheric aspects of acid rain.

Each chapter of the book has a few pages of questions, many of a numerical nature, which if worked through (I did not) would give the student a feel for the size of numbers he is dealing with, and a fairly comprehensive list of references. The quality of the printing is good, as is the quality of the diagrams. There are few errors (I found only five or six minor typographical errors) and most of the mathematics is clear. However, there are two or three points which I would make. In chapter 4 on gas-phase chemistry, the symbols $[A^*]$ are used to denote the concentration of species A in an activated state; an asterisk is also used to reference a footnote, thus $[A]^*$. While this combination of symbols has no specific meaning it could very well cause confusion to the uninitiated. In chapter 11, Fig. 11.4 has been copied inaccurately from the original source. It has the absorptivity of ozone in the 9.6 μm band in excess of one, and other spectral features in the wrong place. Lastly, throughout the book, Seinfeld takes us through the derivation of most of the important equations. However, there can be too much of a good thing, and multiple derivations are one of them; for example, I do not really need three derivations of equation 13.60 for the slender plume approximation, especially when there is little new physical insight in subsequent derivations.

At £61.35 I would not recommend that students buy a copy, but should persuade their library to obtain one, as the book contains many clear expositions. The book has a reasonable index and is a handy reference text as I have discovered through usage.

D.S. McKenna

Books received

The listing of books under this heading does not preclude a review in the Meteorological Magazine at a later date.

Arctic air pollution, edited by B. Stonehouse (Cambridge University Press, 1987. £30.00, US $49.50) presents an up-to-date review of this increasingly important subject for both scientists and administrators concerned with world-wide, as well as polar, pollution problems. It consists of an edited collection of papers first presented at a conference held at the Scott Polar Research Institute in Cambridge in 1985.

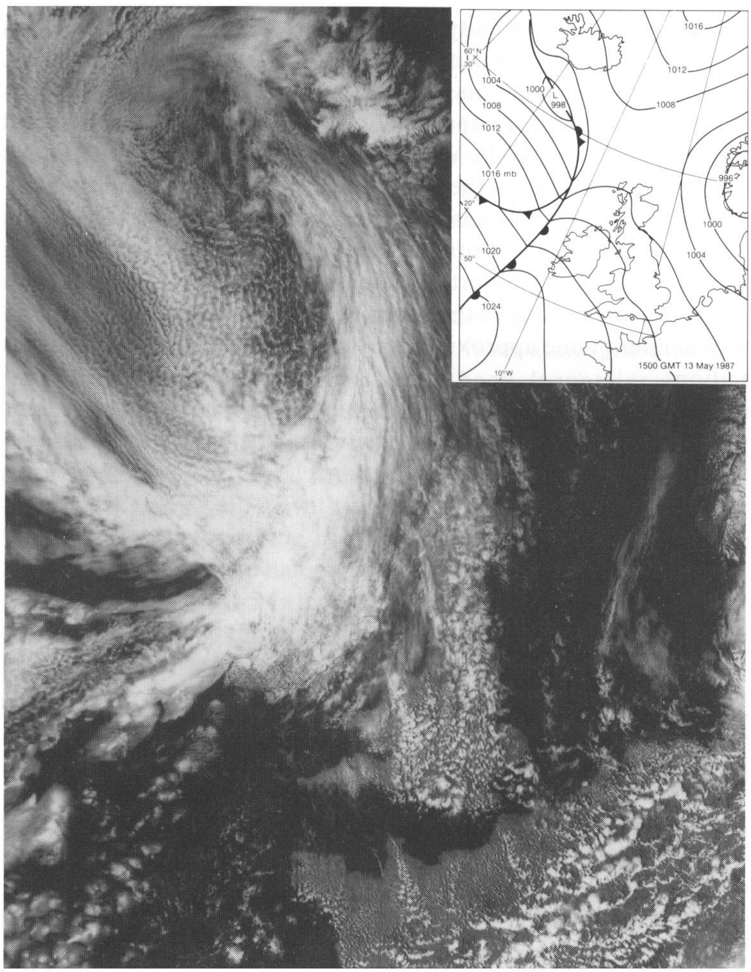
The Irish Meteorological Service: the first 50 years, 1936–86, edited by L. Shields (Dublin, The Stationery Office, 1987. Ir. £6.00) contains an historical perspective followed by a group of articles about the meteorological services available today. The second half contains many more articles on various facets of Irish meteorology. The book is fully illustrated, many in colour.

Satellite photograph — 13 May 1987 at 1410 GMT; visible image

The pattern of convection covering much of Britain and the near Continent typifies that which occurs in cool north-westerly airstreams during spring and summer, daytime convection being restricted to inland areas, well away from onshore coasts. The exception to this can be seen over narrow peninsulas, in particular, north-west Wales and the Cherbourg peninsula, where convection and resulting shower activity is concentrated into bands parallel to the flow.

Thicker cloud is approaching north-west Britain. It is associated with a frontal system (see inset) which is 'forward sloping', with the cold front lying along the rear (western) edge of the cloud mass. Behind the front, extensive shallow convection cells can be seen.

Peninsular convection and forward-sloping cold fronts are common over the British Isles, and are discussed in more detail in Browning *et al.* 1987*.



Photograph by courtesy of University of Dundee

* Browning, K.A., Bader, M.J., Waters, A.J., Young, M.V., and Monk, G.A.; Application of satellite imagery in nowcasting and very short range forecasting, *Meteorol Mag*, **116**, 1987, 161–179.

Meteorological Magazine

GUIDE TO AUTHORS

Content

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Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary*.

References should be made using the Harvard system (author, date) and full details should be given at the end of the text. If a document referred to is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to.

Tables should be numbered using roman numerals and provided with headings. We consider vertical and horizontal rules to be unnecessary in a well-designed table; spaces should be used instead.

Mathematical notation should be written with extreme care. Particular care should be taken to differentiate between Greek letters and Roman letters for which they could be mistaken. Double subscripts and superscripts should be avoided, as they are difficult to typeset and difficult to read. Keep notation as simple as possible; this makes typesetting quicker and therefore cheaper, and reduces the possibility of error. Further guidance is given in BS1991: Part 1: 1976 and *Quantities, Units and Symbols* published by the Royal Society.

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