

Met.O.801

METEOROLOGICAL OFFICE

***the
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METEOROLOGICAL OFFICE

27 MAR 1968

N.A.A.S. BRISTOL

MARCH 1968 No 1148 Vol 97

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By P. G. F. CATON, M.A., Ph.D.

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THE METEOROLOGICAL MAGAZINE

Vol. 97 No. 1148, March 1968

551.463:551.465.4

AN INVESTIGATION OF SOME PHYSICAL PROCESSES ASSOCIATED WITH THE VERTICAL FLOW OF HEAT THROUGH THE UPPER OCEAN

By J. D. WOODS, Ph.D.

Summary. Investigations by skin divers, who film the flow patterns of small quantities of fluorescein dye, have established the main processes responsible for the downward flow of heat through the summer thermocline. It is now known that the thermocline is divided into a series of relatively uniform *layers* separated by thin interfacial regions or *sheets* which contain a laminar-flow régime. Preliminary calculations show that the 'molecular' leakage through these laminar-flow sheets makes virtually no contribution to the heat flux through the thermocline, but that almost all the heat passes through relatively small, short-lived apertures formed by wave-induced Kelvin-Helmholtz instability. Heat is transported through the *layers* by very weak turbulence, whose properties have been explored with dye tracers.

Introduction. In studying the transfer of heat between the ocean and atmosphere the most valuable (and almost the only) oceanographic data come from ocean weather ships, which make twice-daily bathythermograph soundings to a depth of 450 feet. Recently, teams from the Meteorology and Oceanographic Services (Navy) have supplemented these routine observations with a limited series of more frequent bathythermograph soundings, designed to provide statistical information on rapid fluctuations in the depth of the thermocline.

In analysing weather ship bathythermograph soundings, the investigator's first consideration is to compute the net quantity of heat flowing into or out of the ocean during the period under consideration. Summaries of the methods used in such heat budget calculations will be found in the standard textbooks (for example Defant¹). Having calculated the gain or loss of heat at the surface, the next step is to estimate the rates at which heat is transported vertically through the various layers of the upper ocean and, in particular, how the thermocline affects this flow. Finally, it is necessary to assess the extent to which the differences between the calculated temperature profiles and the measured profiles may be explained by the presence of (i) internal waves and (ii) the advection of persistent large-scale oceanographic thermal structures past the fixed station.

Each of these four stages in the analysis (and thence the prediction) of the temperature structure of the upper ocean requires an estimate of the part played by the atmosphere, firstly in controlling the flux of heat across the interface, secondly in determining the transport rate through the upper

ocean, thirdly in generating and modifying internal waves and fourthly in initiating relatively persistent fluctuations in the large-scale oceanic systems. The meteorological incentive to study the distribution of heat in the upper ocean rests largely on the effect this has on the sea surface temperature, which plays a major role in determining the transport characteristics of the marine atmosphere (see, for example, Roll²).

This paper is concerned with the second part of the computation, namely determination of the heat transport rate through the top 50–100 m of the ocean. In particular, the evidence of three years' investigation of the summer thermocline around Malta will be used to offer an insight into some of the processes acting in this region.

Experimental techniques.

(i) *Soundings*. Temperature and salinity profiles were constructed from spot measurements made every metre from the sea surface to a maximum depth of 50 m using a portable temperature-salinity bridge (Cox³). Temperature gradient profiles were obtained by plotting on a pen chart recorder the difference in temperature between two thermistors set 10, 25 or 50 cm apart along a vertical frame lowered at approximately 5 cm/s by hand. The depth of this probe was detected by a strain gauge transducer and was recorded on a second channel of the pen chart recorder. A typical temperature, temperature-gradient profile is shown in Figure 1.

(ii) *Shear*. The difference in velocity between any two layers was measured from time-lapse photographs of the dye streak left in the wake of a tiny pellet of congealed fluorescein powder dropping freely through the sea. Plate I shows that such a streak consists of a series of eddies shed in the pellet's wake; a reproducible pattern was obtained by carefully controlling the size and shape of the pellets. The individual eddies act as neutrally buoyant markers whose relative positions are plotted in successive photographs.

In the more turbulent layers of the thermocline the dye streaks were filmed to provide a record of the water motions for use in estimating the local vertical eddy diffusivity.

(iii) *Wave motions*. Selected levels of the thermocline were coloured with fluorescein dye emitted from an array of porous dye-packets tied to a horizontal line suspended between two moored, submerged floats (Plate II).

Summary of the thermocline structure. The results of the investigation in no way conflict with the description of seasonal stratification given by Tully and Giovando,⁴ but we can now extend their model by adding the fine structure that controls the stratification's development. The thermocline is divided into *layers* a few metres thick and characterized by weak temperature gradients ($\sim 10^{-3}$ degC/cm), shear ($\sim 10^{-2}$ cm/s per cm) and turbulence (mean velocity ~ 1 mm/s); these *layers* are separated by *sheets*, which are a few centimetres thick* and are characterized by strong temperature gradients up to 5×10^{-2} degC/cm and shear (~ 0.1 cm/s per cm) and little or no turbulence. Mature sheets contain a thin laminar-flow zone at their centres.

Neighbouring sheets often have different turbidities and salinities, showing that they have followed independent trajectories for a considerable time, with only very slow exchange across the intervening sheet. This is consistent with

* Sometimes sheets up to a metre thick are detected, but these appear to be aggregates of the '10 cm' thick sheets.

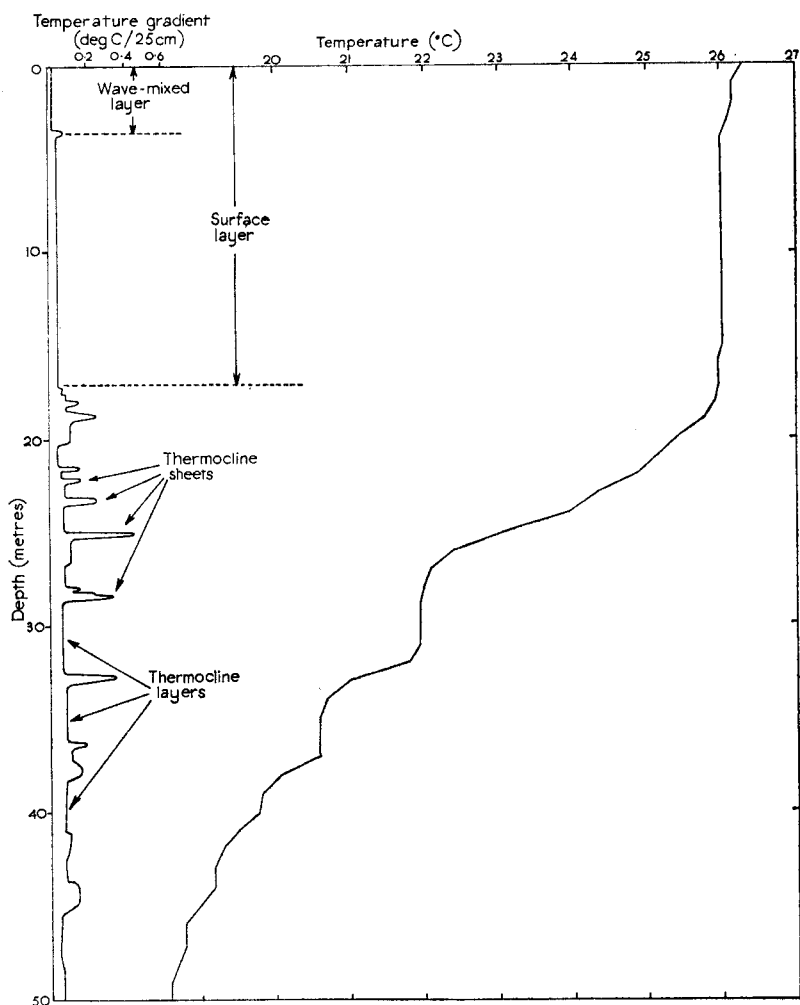


FIGURE 1—TEMPERATURE AND TEMPERATURE-GRADIENT SOUNDINGS FOR MALTESE WATERS, 14 SEPTEMBER 1967
Temperature 0918–0929 local time, (i.e. GMT + 1).
Temperature gradient 1132–1145 local time.

the observations of Isaacs and Folsom,⁵ who found that radioactive debris from an instantaneous release in the thermocline was carried for many days within discrete layers about 7 m thick. (The boundaries of these layers were blurred because the γ -rays being sampled had a penetration of about 1m.)

The horizontal extent of the thermocline lamination is as yet uncertain, although individual layers have been followed for up to 40 miles in soundings made simultaneously from two high-speed launches and layers are identified on successive soundings made at a fixed site over a period of many hours. Stommel and Fedorov⁶ have reported a similar lamination in the Timor Sea, with a horizontal extent of at least 12 miles.

Figure 2 illustrates the relationship between the lamination as detected by the temperature gradient meter and the temperature profiles in selected idealized situations.

Internal waves and breakers. When dye is injected into a thermocline sheet (by the method described in the paragraph on wave motions) it is found that there is a central laminar-flow region only a centimetre or so thick (Plate IV). Dye trapped in this laminar-flow zone is spread rapidly across the steady current direction by internal waves to form a broad carpet of colour. This follows the contours of the laminar-flow sheet allowing the observer to examine and photograph the internal waves traversing it.

The maximum scale of internal wave detected in this way is, of course, limited by the visual range of the diver, but off Malta this frequently exceeds 30 m. Within this range, most of the wave energy appears to be concentrated into a narrow band of wavelengths between 5 and 10 m; such waves generally are found in long coherent trains, each apparently associated with a single sheet. The waves are remarkably steep, often having wave heights as great as 1 m; their periods and phase speeds are about 5 minutes and $2\frac{1}{2}$ cm/s respectively. (Plate V).

The orbital water motions associated with these waves produce fluctuating shears across their sheet which are comparable with the intense shears due to the relative drift* of the layers directly above and below. This leads to the striking meandering of the dye released from a fixed point source (Plate VI).

The existence of a laminar-flow core in the sheet indicates that it is stable to the shear across it and, following Miles and Howard,⁷ we conclude that the sheet's Richardson number is larger than $\frac{1}{4}$. This is confirmed by measurements of temperature gradient and shear obtained by the methods described in the section on experimental techniques. However, occasionally and over a limited area, the shear from the internal waves, which is strongest at their crests and troughs, combines with the drift shear to produce a local instability in the form of wavelets (Plate VII) which grow to breakers (Plate VIII) with the familiar Kelvin-Helmholtz form. The prediction of Miles and Howard that these wavelets should have a wave-length 7.5 times the sheet thickness has been confirmed by the underwater measurements (Woods⁸). The breakers rapidly degenerate into a patch of turbulence (Plate IX) which entrains water from the layers above and below the sheet until, after a few minutes, the turbulent patch on the sheet has thickened sufficiently for the turbulence no longer to be able to extract sufficient energy from the mean shear to meet the losses due to viscosity and work done against gravity. The turbulence then dies, leaving a 'scar' on the sheet (Plate X) which slowly 'heals over' to re-form the laminar-flow sheet.

Vertical heat flow through the thermocline. During the period of maximum heating the thermocline with its series of laminar-flow sheets extends right to the sea surface as shown in Figure 2A. So the heat which is to be stored in the top 100 m of the ocean must be carried down through a greater or lesser part of the thermocline from near the surface where it is first absorbed. In the layers this downward heat flux is effected by weak

* The concentration of 'drift' shear at the sheet results from the very low (molecular) viscosity found there compared with the far higher (eddy) viscosity found in the adjacent layers.

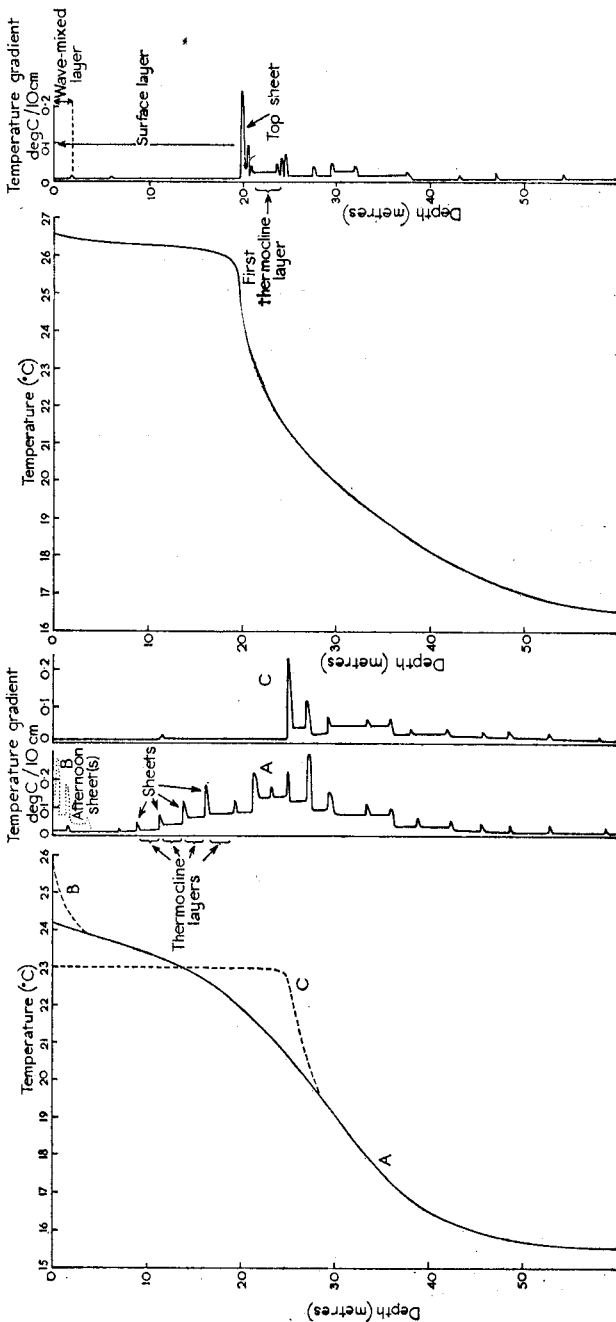


FIGURE 2—IDEALIZED TEMPERATURE AND TEMPERATURE-GRADIENT PROFILES
FOR MALTESE WATERS IN EARLY JULY AND LATE AUGUST

- EARLY JULY
A Calm weather (morning).
B 'Afternoon effect' (surface warming without wave-mixing).
C Mixed surface-layer following an extended period of rough seas.
- LATE AUGUST
Moderate seas.

turbulent motions. The direct investigation of these motions by means of dye tracers has shown that they have typical length- and time-scales of about 25 cm and 300 s respectively and that the fluctuating water-speeds associated with them are about 1 mm/s. From these values we deduce an effective turbulent transport coefficient of the order of 2 cm²/s (i.e. unlikely to depart from this value by more than a factor of 10). In the laminar-flow sheets, however, the downward flux must be carried by molecular processes, with a thermal conductivity of 1.4×10^{-3} g cal/cm²s per degC/cm. So the ratio of the vertical transport coefficients in the layers and in the sheets is of the order of 1000:1.

Soundings with the temperature gradient probe have shown that, typically, the peak temperature gradient in a sheet seldom exceeds that in the adjacent layer by a factor of more than 10. We conclude that the vertical flux of heat through the layers is therefore of the order of 100 times greater than that which leaks through the sheets. A re-examination of the observations fails to reveal any uncertainty that is sufficiently large to account for so large a discrepancy in the heat fluxes, so clearly there must be some other mechanism responsible for carrying heat through the sheets. It is proposed that the process of wave-induced shear instability described in the previous section provides a sufficient mechanism.

The temporary apertures afforded by short-lived patches of breakers and turbulence permit the passage of heat through the thermocline sheets with a transport coefficient of the order of 10 cm²/s (based on consideration of the breaker height ≈ 20 cm and the associated water speeds $\approx \frac{1}{2}$ cm/s.) The breaker height is about twice the sheet thickness, so the effective temperature gradient through the aperture is about half that of the sheet. Thus the vertical heat flux through the aperture will be of the order of 50 times that through the layers and 5000 times that through the laminar-flow regions of the sheets.

Observations have shown that aperture creation, which depends upon the presence of steep internal waves, is rather irregular and that individual apertures last for only about five minutes. On average, apertures are seen to occupy only a small fraction of the surface area of any sheet. The mean fractional coverage (f) that would lead to a balance between the heat fluxes through sheets and layers is given by equation (1).

$$(1-f) K_{\text{mol}} \left(\frac{\partial T}{\partial z} \right)_{\text{sheet}} + f K_{\text{aperture}} \left(\frac{\partial T}{\partial z} \right)_{\text{aperture}} = K_{\text{layer}} \left(\frac{\partial T}{\partial z} \right)_{\text{layer}} \quad \dots (1)$$

where K_{mol} , K_{aperture} and K_{layer} are the vertical conductivities for the laminar-flow sheet, the apertures and the layer, and $(\partial T/\partial z)_{\text{sheet}}$, $(\partial T/\partial z)_{\text{aperture}}$ and $(\partial T/\partial z)_{\text{layer}}$ are the temperature gradients in the laminar-flow sheet, the apertures and the layer.

In the example given above the balance would be struck for an aperture coverage of the order of one part in fifty ($f = 0.02$). Observation has shown that the typical aperture area is about 20 m², so we can expect to find on average one aperture every 1000 m² of the sheet surface. This is approximately equal to the area covered by the visual range of a diver in the clear Mediterranean Sea off Malta and underwater observation is consistent with the above prediction, although it must be emphasized that there is considerable variability. The temporal variation in the penetration of heat through the

thermocline sheets is largely taken up by the thermal inertia of the layers on each side (their thermal relaxation time is given by $\tau \sim H^2/8K$ where the typical thickness $H \sim 4$ m and the eddy conductivity $K \sim 2$ g cal/cm²s per degC/cm give $\tau \sim 2\frac{1}{2}$ hours), while the spatial variability is largely smoothed out by the weak shear within the layers. (The velocity difference of the order of 3 cm/s across a typical layer gives a horizontal displacement roughly equal to the mean aperture spacing in about 10 hours.)

Vertical transport through the surface layer. The aperture conduction process described above operates within the thermocline, where it probably controls the vertical flux of heat through the series of laminar-flow sheets and hence through the thermocline as a whole. However, it has been shown that by mid-September a permanent surface layer develops between the surface and the uppermost sheet.

This surface layer is generally found to be weakly stable, with temperature gradients in the range 10^{-2} to 10^{-1} degC/m. Three principal sources have been proposed for the supply of energy to the turbulent motions that carry heat vertically through this surface layer: (i) surface waves, caused by strong winds, (ii) convection due to surface cooling at night and (iii) convection during the day due to the absorption at depth of the incoming solar radiation which results in an upward flux of heat to supply the heat lost by cooling at the surface.

The dye experiments failed to detect any convective overturning in the surface layer, either at dawn, when the layer should be at its least stable following the overnight cooling, or during the day, when the radiation effect should be most active. This observation implies that mechanically generated turbulent motions appear to dominate (or, rather, inhibit) those due to thermal instability.

The wave-mixed layer is made clearly visible by the dye, but in moderate sea conditions (up to force 5) this does not extend right through the well-developed surface layer of late summer, but terminates at some fairly well-defined level (Plate III). Occasionally, but not always, it was possible to associate this level with a change in the temperature gradient detected by means of the temperature-gradient probe — presumably on the remaining occasions the change was below the sensitivity of the instrument (10^{-2} degC/25 cm). Below the wave-mixed layer (but still in the surface layer) the energy of the turbulent motions, as detected by dye, is greatly reduced. The generation of this weak turbulence is surely mechanical (because the layer is always statically stable at these depths), but whether the energy source is shear motion associated with either internal waves or wind-driven surface currents is not clear and remains the subject for further study, together with the mechanism which generates the turbulent motions.

Conclusion. During the summer, the top 100 m of the Mediterranean Sea around Malta is statically stable and heat is carried down from the surface by mechanically generated turbulence. The wave-mixed layer never penetrates further than the first of a series of thin thermocline sheets. In the layers between these sheets there is a weak turbulence, whose energy comes from either internal waves or wind-driven currents and counter currents; the precise mechanism for this process is not clear. Heat transfer through the sheets is effected by short-lived turbulent apertures, which must cover about

2 per cent of a sheet's surface in order to pass the heat which is flowing through the adjacent layers. A negligible amount of heat penetrates the remaining 98 per cent of the sheet's surface by molecular conduction through a thin laminar-flow zone. The generation of apertures through the sheets is not an inevitable consequence of the vertical heat flow, but depends upon the passage, over the sheet's surface, of steep internal waves from a distant source. The mechanism by which these short, steep, internal waves are generated is at present unknown.

Acknowledgements. The field work in Malta during the summers of 1965-67 was supported jointly by the Meteorological Office and the Meteorology and Oceanographic Services (Navy). The temperature-gradient meter was designed and made at the Admiralty Research Laboratory, Teddington, and other instruments were kindly loaned by the National Institute of Oceanography, Wormley. The author wishes to acknowledge the assistance afforded by officers and men of the Mediterranean Fleet Clearance Diving Team and the Royal Air Force Marine Craft Unit, Marsaxlokk.

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551.5:551.507.362.2:061.3

THE PACIFIC SATELLITE METEOROLOGY SEMINAR, 1967

By P. G. RACKLIFF*

A satellite meteorology seminar was held during the three-day period 12-14 September 1967, in the auditorium of the Institute of Geophysics, University of Hawaii, Honolulu, who jointly sponsored the meeting with the Environmental Science Services Administration (ESSA) Weather Bureau, Pacific Region. The seminar was attended by 90 meteorologists, mostly United States Weather Bureau, Air Force and Navy staff (including a number of senior pilots) drawn from the North Pacific region. Mr E. M. Carlstead, Regional Meteorologist, Honolulu, welcomed participants and introduced the two lecturers, Mr V. J. Oliver, National Environmental Satellite Centre, Washington D.C., and Mr James C. Sadler, University of Hawaii, Honolulu.

Mr V. J. Oliver commenced the series of lectures and discussions with a brief survey of the weather satellite programme, and explained the essential differences between TIROS, NIMBUS and ESSA vehicles. The early TIROS satellites were space-stabilized and gave no complete coverage of earth. Photographs took the form of discrete strips and coverage was limited and sporadic. The

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first NIMBUS satellite was earth-stabilized to point straight down towards the earth's centre and flew the advanced vidicon camera system (AVCS) with the automatic picture transmission facility (APT). NIMBUS satellites are intended primarily for research, both instrumental and environmental, and provide for space-testing of new and modified apparatus. The more recent ESSA series are operational satellites, and with the advent of ESSA 1 early in 1966, complete coverage on a daily basis began operationally.

A problem had arisen with some of the earlier satellites in the form of a signal shift, resulting in poor quality pictures after some lapse of time. This has been rectified by designing an electronic 'black-box' which is connected to the APT receiver. This apparatus corrects for the shift of signal, and it has thus been possible to re-utilize transmissions from previously abandoned NIMBUS satellites. The latest applications technology satellite, ATS-1, provides pictures every 23 minutes and, because it is earth synchronized, it is possible to compile movie-type films of the Pacific area, from a daily series of photographs. The WEFAX experiment also centres on ATS-1 and its use as a communications satellite; data from satellites with no APT circuit are received and gridded at remote command and data-acquisition stations, and then retransmitted throughout the Pacific via ATS-1. Mr Oliver stressed the fact that ATS-1 gave good resolution because of the direct transmission; no vidicon-tube scanning was involved.

The morning session continued with a study and discussion of slides depicting a large variety of cloud systems. The pictures demonstrated the importance of identification and interpretation of shadows, and the cellular nature of most clouds, including stratocumulus. The greater range of grey tones, available with photo-prints produced by some of the latest facsimile equipment, was a useful aid in cloud interpretation. Satellite pictures of large vortices and associated frontal systems also drew attention to the need for recognition of secondary positive (cyclonic) vorticity maxima to the rear of the parent systems. Many pictures clearly delineated the cloud-free zone, separating 'comma' shaped clouds associated with an area of maximum positive vorticity advection (PVA_{max}), from the preceding cold-frontal system. At this stage of development, the satellite pictures could help the analyst in oceanic regions of sparse data, and he would not be tempted to draw a pronounced frontal wave, linking the two separate cloud systems. The lecturer pointed out that the region of secondary vorticity maximum occurs close to the axis of the upper-level trough, and that the intersection of this trough with the main cold front is indicated by a distinct change in cloud character. The high resolution infra-red radiometer (HRIR) of NIMBUS, measuring cloud-top temperature, showed a distinct change from white clouds to much darker clouds with lower and warmer tops west of the upper trough. All these features, and many others, have been ably described and illustrated in a technical note by Anderson, Ferguson and Oliver.¹

During the afternoon, participants watched a movie-type film depicting one day (excluding the night period) over the Pacific area, compiled from photographs taken by the ATS satellite. The film was produced by Dr Fujita and colleagues of the University of Chicago. The dynamic nature of cloud systems was clearly shown, especially the relatively rapid movement of cirrus clouds and the diurnal variation of cumulonimbus, with anvil streaming. A discussion on jet-stream clouds followed. Jet cirrus invariably exhibited

a sharp edge on the poleward side of the jet axis, and often cast a shadow on underlying cloud layers. Occasional transverse banding and turbulence was another noteworthy feature of some jet systems. Mr Oliver confirmed that the cirrus edge is aligned along the jet axis at the level of maximum wind and is not necessarily parallel with the contours at any one level.

An interesting exercise wound up the first day's proceedings. All participants were handed a folder containing four transparencies and a cloud picture. Two transparencies consisted of North Pacific charts with plotted data for the surface and 300-mb levels, respectively, and two displayed the final analyses best fitted to all available data including the composite cloud picture, an ESSA 5 digital product for the period 20–21 June 1967. The aim was to analyse both charts by referring to the plotted data only, and then to adjust the analyses with the aid of the satellite picture. Finally, the modified analyses could be compared with the surface and 300-mb solutions, given in the folder. In this way, a logical interpretation of the satellite picture proved to be a very valuable aid in achieving a coherent and accurate analysis.

The morning of the second day opened with a discussion on orographic effects and phenomena, including wave and banner clouds, plumes, cloud streets, forked lines, and their interpretation. The phenomenon of sun-glint was also studied, including the relationship between a real extent of the reflection and state of sea. Slide illustrations covered fair-weather cumulus formations, and associated cloud-free areas over rivers and lakes. Mr Oliver warned that things were not always what they seemed; because of the current limitations of resolution a satellite picture could show an apparent grey overcast actually composed of fair-weather cumulus. Further discussion centred on cloud structure, texture and reflectivity. Estimates of high-level winds had been made with the aid of photographs showing the orientation and configuration of cirrus bands and plumes. Reflectivity was an important aid in cloud identification, with tones ranging from the brightness of cirrus shields associated with large cumulonimbus, to the dark greys of strato-cumulus or small cumulus.

During the afternoon, Mr J. C. Sadler lectured on the subject of tropical vortices developing in shearing zones over the North Pacific Ocean, and the role of the upper tropospheric trough was studied. This trough is commonly referred to as the mid-Pacific trough (MPT) after Ramage.²

Recent research, described in a comprehensive report by Sadler,³ supported the theory that a number of tropical storms developed through the downward penetration of cyclonic cells within the MPT. Some broad general features had been observed by satellite, including the occurrence of major cloud systems south of the trough line, and the association of cyclonic cells with the more intense convective cloud systems. These cells normally slope towards the south-east with decreasing height.

Because of this slope, the low-level convergence and cloud systems occurred beneath the divergent region of the upper circulation, in agreement with the circulation model for sustained vertical motion. Mr Sadler showed a number of slides, including charts of the surface and 250-mb analyses, mean position of the upper tropospheric and surface troughs, and mean sea surface temperatures, during the month of August. A study of these charts, and the mean typhoon tracks for the latter half of August, seemed to indicate that a large proportion of August typhoons originated close to the western extremity of the

MPT, and within the area bounded by the 29° C isotherm of sea temperature.

It had been possible to assess the intensity and movement of many North Pacific storms close to the time of satellite pictures, through the agency of Navy and Air Force reconnaissance flights. The crews provided valuable data, which were the key to an accurate interpretation of storm photographs.

On the morning of the final day, another movie-type film was shown; this time the subject was the tropical Atlantic region. This film represented a five-month period, telescoped into a very short projection period by using a picture frequency of one frame per day. Once again, the dynamic nature of the cloud systems was emphasized, and their interaction with deep cold outbreaks from the north was a notable feature. The tail-ends of cold fronts, 'racing' out of the north-west, appeared to lash the northern boundary of the tropical systems like huge and powerful whips, cutting out masses of material which were carried quickly away to the north-east. Mr Oliver also ran a film-loop, in which cloud pattern and movement gave a clear illustration of cross-equatorial flow. The morning session closed with the study of a selection of astronauts' photographs. The clarity was excellent and these pictures have been of considerable use to geologists and oceanographers, as well as to meteorologists.

After lunch, discussion revolved around the new satellite climatology, which is built on a foundation of cloud pictures and derived nephanalyses. It was now possible to tabulate and map mean cloud amounts over oceanic and sparsely populated land areas, and the gradual accumulation of data would provide for the calculation of new statistical averages.

As a final topic, Mr Oliver spoke of future plans. The launching of another ATS satellite, to be positioned in earth-synchronous orbit over the equatorial Atlantic, is imminent. It is planned to fly another NIMBUS in February 1968, and experimental equipment on board will include spectroscopic instruments designed to measure temperature through various layers of the atmosphere, by scanning at discrete wavelengths. More constant-density balloon flights are planned, and balloon transmissions will be monitored by satellite. The recent GHOST series of flights from Christchurch, however, seemed to indicate that balloons of this type will be useful only at levels above the weather systems; at lower altitudes they are liable to be 'rained-out' by precipitation and icing encountered in storms. A new series of satellites has been designed to fly direct read-out infra-red radiometers (DRIR) and humidity sensors, and there are plans for high-level sondes, utilizing a parent satellite which will eject a family train of sounding vehicles, whilst in orbit.

Acknowledgements. The author wishes to thank Qantas Empire Airways Ltd, and the Director, New Zealand Meteorological Service, for their co-operation and assistance in providing familiarization flight facilities and he is also most grateful to the Regional Director, ESSA Weather Bureau, Honolulu, and the Institute of Geophysics, University of Hawaii, for their kind invitation to attend this Seminar, and for their permission to publish this note.

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551.524.2(425):551.542(4):551.589.1

RELATIONS BETWEEN SUMMER AND SEPTEMBER TEMPERATURE ANOMALIES IN CENTRAL ENGLAND

By R. F. M. HAY, M.A.

Summary. Systematic differences found between monthly pressure patterns over north-western Europe during the period from June to September (1874–1963) have been related to typical sequences of temperature anomalies in central England in summers and their subsequent Septembers.

Warm summers appear likely to be followed by warm Septembers whenever a ridge from the Azores anticyclone extends across the British Isles to include most of Scandinavia during June to August; whereas when this ridge extends to the British Isles, but no further eastwards, a cold September is likely in central England. Also, when a monthly low centre is found over Scandinavia as the summer progresses, the probability of a cold September becomes still higher.

Cold summers of a type having monthly low centres lying near the west or north-west of the British Isles are usually followed by cold Septembers, and this sequence is even more likely when a monthly low centre occurs over Scandinavia during June to August. In the few cases when warm Septembers followed cold summers, low centres were seldom found in summer near to west or north-west of the British Isles and lows over Scandinavia were less common than during seasons in which the cold persisted in central England from summer to September.

Factual and statistical support for these results was obtained from an analysis of monthly pressure differences at Edinburgh and Trondheim for the 146-year period 1818–1963, and a brief though plausible explanation of them is offered by means of synoptic arguments.

Statistical associations: central England, 1874–1963. A matter of importance to farmers, holiday-makers and others is whether September brings a prolongation, or otherwise, of the weather which has characterized the previous summer. Summer is taken here to include the three calendar months June, July and August in accordance with the accepted definition of the season.

Table I shows contingency tables formed between summer temperatures and the temperatures of the Septembers after each summer. The temperatures have been classified into their appropriate terciles to show which summers and which Septembers were warm, average and cold respectively. Data for central England for the period 1874–1963 were available from a long series derived in the manner described by Manley¹ from the average of Radcliffe (Oxford) and Lancashire monthly mean temperatures. (The series available in the Meteorological Office consists of the data published in Manley's paper, with an extension to recent years and backwards in time to the 17th century.²) It was considered advisable to take some account of changes in circulation which have occurred over the past 90 years, from a rather meridional 'blocked' type of circulation early and late in the period, to a more zonal 'westerly' type of circulation in the middle years of the period. This has been done by splitting the period into two equal intervals in which the years from 1874–95 and from 1941–63 were assigned to the blocked type of circulation, while the period 1896–1940 has been taken as coinciding with the period of westerly circulation. While this division may appear to be somewhat arbitrary, at least it makes some allowance for the existence of large-scale modifications in the general circulation patterns which most authorities³ consider to have been real, although there is not the same measure of agreement regarding the precise dates when the changes between the types took place.

From the two contingency tables in Table I a positive association between summer temperature and subsequent September temperature is apparent in both blocked and westerly periods. Chi-square tests (comparing the actual contingency tables with tables showing no relationship) indicate that the

TABLE I—SUMMER AND SEPTEMBER TEMPERATURES IN CENTRAL ENGLAND
(i) Blocked periods (1874–95, 1941–63)

	Cold		Summer Average		Warm		Total	
September								
Warm	1890		1875	1961	1884	1949		
	1891		1880		1941	1955		
	1956		1895		1945	1959		
			1958		1947			
Average	1883	3	1874	1948	1878		7	15
	1946		1886	1951	1893			
	1963		1889	1953	1943			
			1942	1960	1950			
Cold	1879	1892	1877		1876		4	15
	1881	1894	1957		1887			
	1882	1954			1944			
	1885	1962			1952			
	1888							
Total		9		2			4	15
		15		15			15	45

Chi-square = 9.60

(ii) Westerly period (1896–1940)

	Cold		Summer Average		Warm		Total	
September								
Warm	1913		1898	1938	1901	1926		
			1917	1939	1906	1933		
			1929		1911	1934		
			1936		1921	1935		
Average	1903	1920	1896		1899	1940	8	15
	1907	1924	1908		1900			
	1915		1914		1932			
	1916		1930		1937			
Cold	1902	1919	1904	1928	1897		5	15
	1909	1922	1905		1925			
	1910	1927	1918					
	1912	1931	1923					
Total		8		5			2	15
		15		15			15	45

Chi-square = 9.20

relationship between summer temperatures and September temperatures is significant at a level which is marginally better than the 5 per cent level for the blocked periods, and marginally worse than the 5 per cent level during the westerly periods. Since the general circulation in the nineteen sixties is considered still to be showing the features of the 'blocked' régime, it is the first of the two contingency tables which probably has the greater relevance at the present time. Out of 15 cold summers during the blocked period, only 3 were followed by warm Septembers and 9 were followed by cold Septembers. It is of interest that for the extreme summers and Septembers in the 'westerly' period of circulation, this positive association showed up even more strongly. Only 1 summer out of 15 cold summers was followed by a warm September in central England, and only 2 out of 15 warm summers were followed by cold Septembers.

Synoptic associations: monthly mean pressure patterns, 1874–1963. Some plausible synoptic associations between the weather of the summer and that of the September following have been found by examining and classifying monthly mean pressure patterns for the summer months and

September for the period 1874–1963. Tables derived from these data (but too lengthy for inclusion here) showed several points of interest, for instance: in the majority of warm summers which were followed by warm Septembers (see Table I), it was found that a ridge of high pressure extending across the British Isles from the Azores anticyclone was present on a very high proportion of the monthly mean pressure charts for summer. In addition, this ridge extended far enough to the north-east to cover Scandinavia in a substantial proportion of the summer months and sometimes included a separate anticyclonic centre over Scandinavia or the southern Norwegian Sea. During summers of this type monthly mean low centres lay typically to the west or north-west of Iceland, or to the west of southern Greenland in all three summer months, and no low centres were found in the vicinity of Scandinavia.

Examples of typical patterns.

Warm summer, warm September. The summer of 1959 afforded a recent example of a warm summer followed by a warm September and the monthly mean pressure patterns over much of the northern hemisphere during August and September 1959 are shown in Figures 1 and 2. The associated thickness patterns (1000–500 mb) are also shown in these and the following examples and are relevant to the synoptic situations discussed in the last portion of this paper. Except in 1945, the Septembers after these fine summers were also associated with a persistence of the ridge across Britain to Scandinavia, or with a separate anticyclone centre over Scandinavia.

Warm summer, cold September. The contingency table at Table I includes four years in the blocked period when warm summers were followed by cold Septembers. When the monthly mean pressure charts for these years were examined, some notable differences were found between their synoptic patterns and those typified by Figures 1 and 2. These differences occurred mainly in the vicinity of Scandinavia and usually began to show quite early in the season. Whereas in 10 out of 12 of these summer months preceding cold Septembers, a ridge from the Azores anticyclone extended far enough eastwards to cover the British Isles, there was only one of these months (June 1876) when this ridge also extended across to Scandinavia and showed a

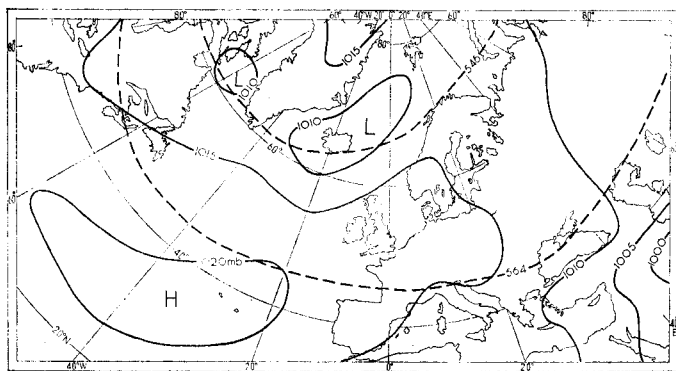


FIGURE 1—MEAN PRESSURE PATTERN, AUGUST 1959—WARM SUMMER, WARM SEPTEMBER

———— Monthly mean MSL pressure in mb.
 - - - - - Monthly mean 1000–500 mb thickness in decametres.

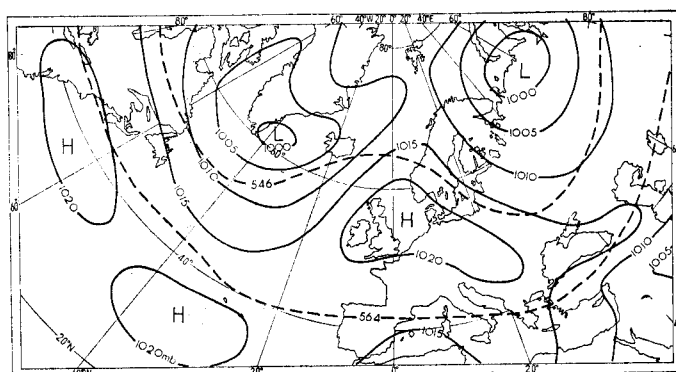


FIGURE 2—MEAN PRESSURE PATTERN, SEPTEMBER 1959—WARM SUMMER, WARM SEPTEMBER

— Monthly mean MSL pressure in mb.
 - - - Monthly mean 1000-500 mb thickness in decametres.

separate centre there. In fact a monthly mean low centre commonly became established over Scandinavia quite early in these summers, and this low centre over Scandinavia also became a feature of the September mean pressure chart in three of these four years. The summer of 1952 is an example of this type. A reference to Figures 3 and 4 makes it evident there was a striking difference between the pressure charts for August and September 1952 and those for the same months in 1959.

Cold summer, cold September. In the blocked period 9 cold summers were followed by cold Septembers and 3 were followed by warm Septembers. Figure 5 is the mean pressure chart for July 1954 and shows low centres near the west or north-west of the British Isles and simultaneously over Scandinavia. This pattern is typical of a cold summer followed by a cold September (see Figure 6).

Cold summer, warm September. During cold summers followed by a warm September, low centres near the British Isles are missing in June and July, while Scandinavian low centres are slightly less common than when cold persists from summer to September. Figures 7 and 8 for July and September 1956 are examples of this type. There is also some evidence to suggest that the presence of a broad zonal ridge over the north-west and middle part of the North Atlantic in July and August during a cold summer in England and Wales is associated with a warm September to follow, as shown in Figures 9 and 10 giving pressure patterns for July and September 1890.

Some relationships of pressure patterns with temperature sequences. Table II shows, for the blocked and westerly periods, how summer and September temperature are associated for each of four pressure types. Extensions of high pressure across the British Isles to Scandinavia (type 1) are strongly associated with persistence of warmth into September. This is true both for blocked and for westerly periods. The table also shows how seldom a cold September follows a warm summer of type 1.

Extensions of the Azores high pressure to the British Isles may fail to reach Scandinavia (type 2). In quite a high proportion of the warm summers of this type the following Septembers are cold during the blocked periods but not during the westerly periods.

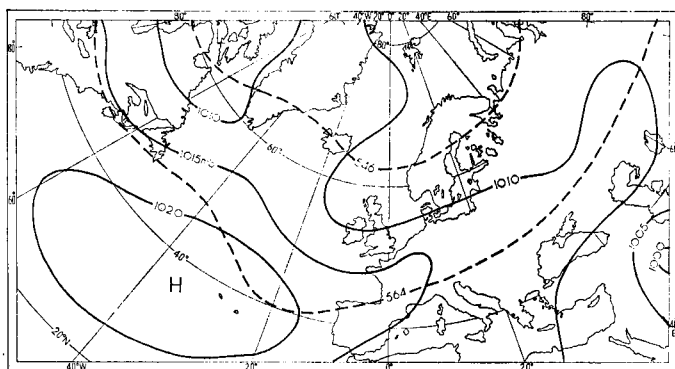


FIGURE 3—MEAN PRESSURE PATTERN, AUGUST 1952—WARM SUMMER, COLD SEPTEMBER

— Monthly mean MSL pressure in mb.
- - - Monthly mean 1000–500 mb thickness in decametres.

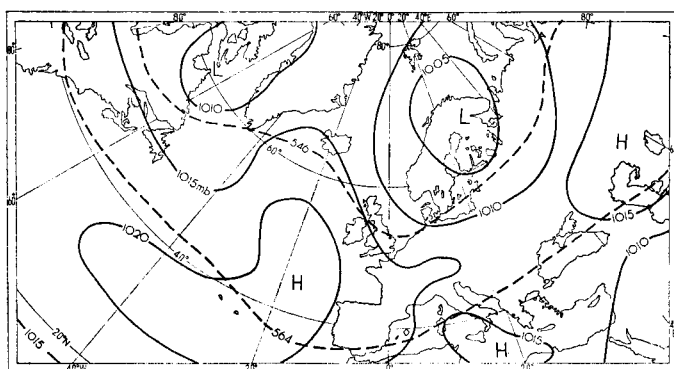


FIGURE 4—MEAN PRESSURE PATTERN, SEPTEMBER 1952—WARM SUMMER, COLD SEPTEMBER

— — — — Monthly mean MSL pressure in mb.
- - - - Monthly mean 1000–500 mb thickness in decameters.

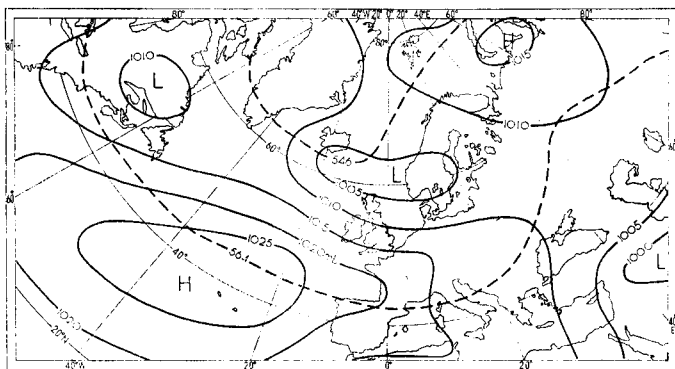


FIGURE 5—MEAN PRESSURE PATTERN, JULY 1954—COLD SUMMER, COLD SEPTEMBER

— Monthly mean MSL pressure in mb.
- - - Monthly mean 1000-500 mb thickness in decametres.

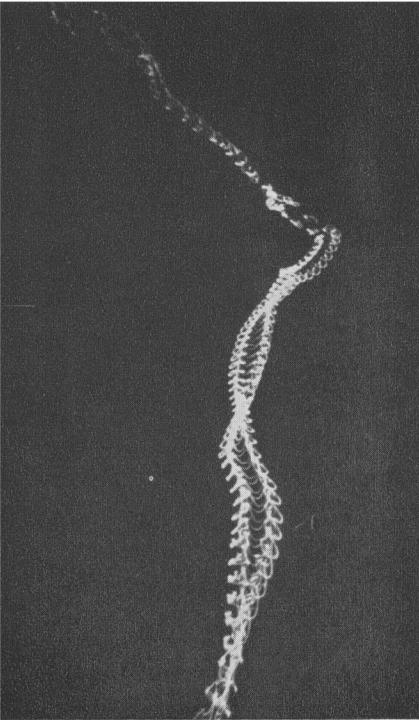


PLATE I—THE TRAIL OF EDDIES LEFT
BEHIND A FALLING PELLET OF CON-
GEOLED FLUORESCIN POWDER

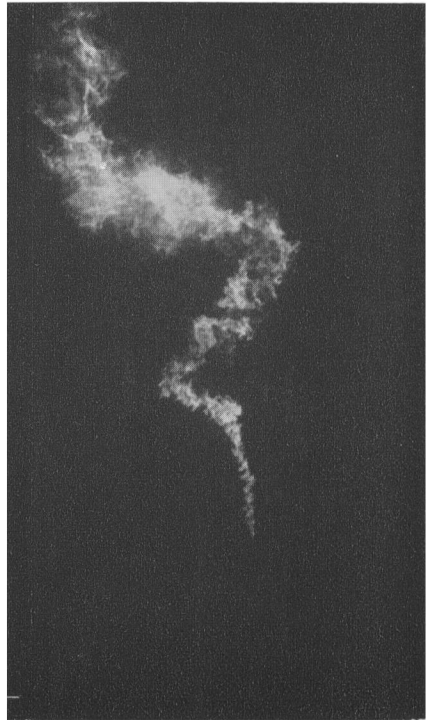


PLATE III—THE WAVE-MIXED LAYER
TERMINATING ABOUT 4 M BELOW THE
SURFACE



PLATE II—A HORIZONTAL ARRAY OF FLUORESCIN PACKETS INJECTS DYE INTO A
THERMOCLINE SHEET, SHOWING THE LAMINAR FLOW
Note the internal wave visible at the top of the picture.

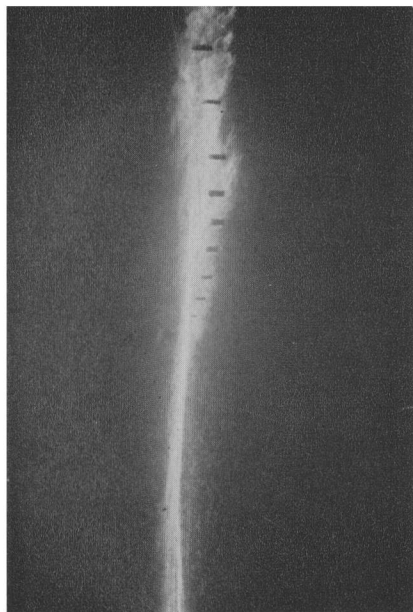


PLATE IV (*above*)—AN EDGE-ON VIEW OF THE DYE IN A LAMINAR-
FLOW SHEET

The dye layer is about one centimetre thick.



PLATE V (*upper right*)—A STEEP INTERNAL WAVE ON A LAMINAR-
FLOW SHEET

Wavelength ≈ 10 m, wave height ≈ 75 cm.

PLATE VI (*lower right*)—DYE, FROM THREE PACKETS $2\frac{1}{2}$ FT
APART ON A VERTICAL LINE, MEANDERS DUE TO THE COMBINED
SHEARS OF WAVE AND DRIFT

Note the patch of instability near the top of the picture (arrowed).

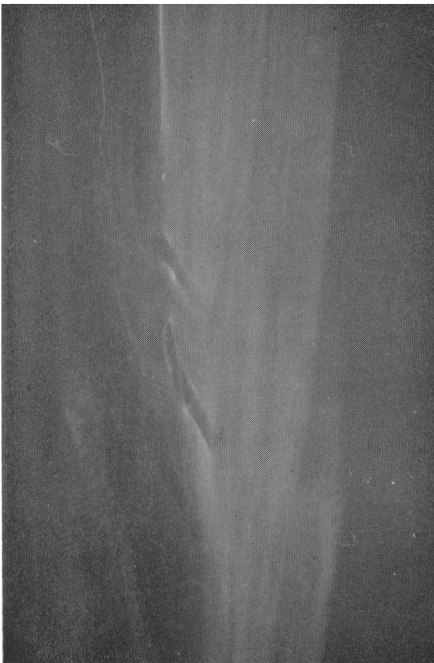
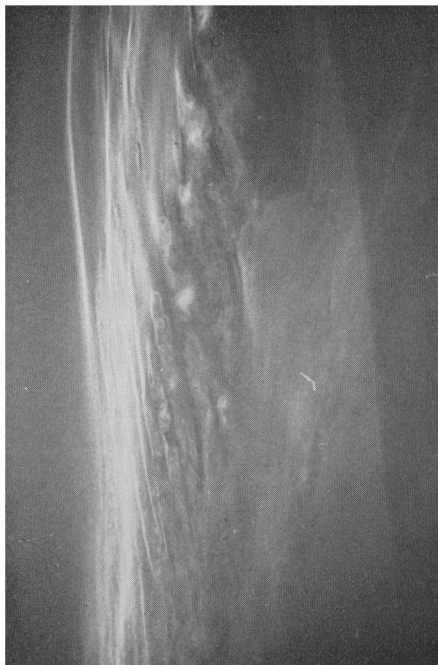


PLATE VII (*above*)—DYE REDISTRIBUTION, TO FORM BANDS
PARALLEL TO THE CRESTS OF A GROWING TRAIN OF WAVELETS,
PROVIDES THE FIRST INDICATION OF INSTABILITY

PLATE VIII—*see overleaf*.

PLATE IX (*upper right*)—A PATCH OF BREAKERS GENERATED BY
THE INTERNAL WAVES SEEN ON THE HORIZON

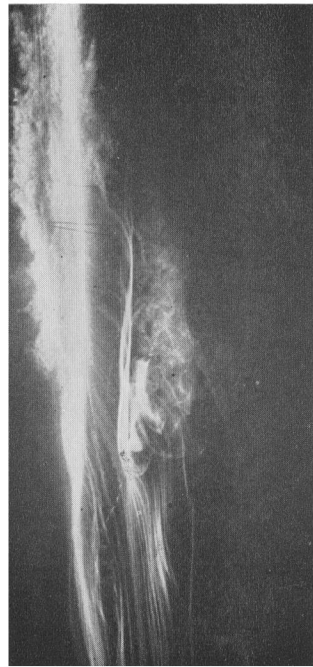
PLATE X (*lower right*)—A 'SCAR' LEFT ON THE THERMOCLINE
SHEET BY A PATCH OF BREAKERS



(b) The completed breaker.



(d) Top view showing the neighbouring breakers.



(a) The initial steep wave.



(c) End view of the breaker roll, with a secondary breaker.

PLATE VIII—THE DEVELOPMENT OF ONE OF FOUR BREAKERS

Wavelength = 75 cm, wave height = 20 cm.

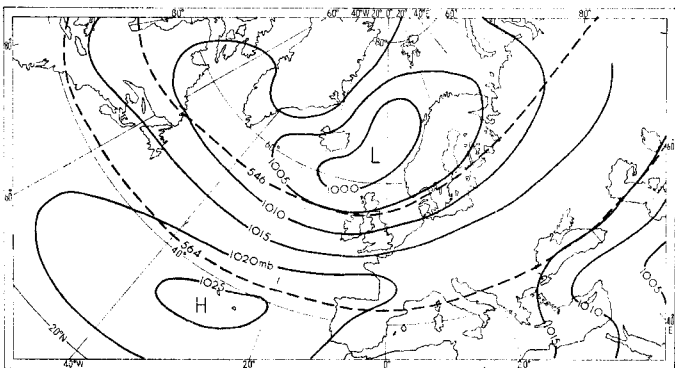


FIGURE 6—MEAN PRESSURE PATTERN, SEPTEMBER 1954—COLD SUMMER, COLD SEPTEMBER

— Monthly mean MSL pressure in mb.
- - - Monthly mean 1000-500 mb thickness in decametres.

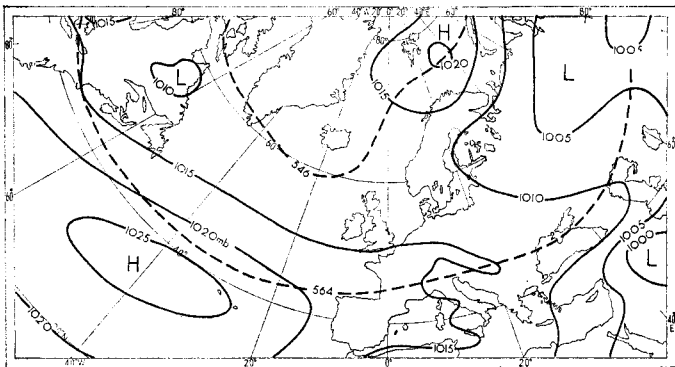


FIGURE 7—MEAN PRESSURE PATTERN, JULY 1956—COLD SUMMER, WARM SEPTEMBER

— Monthly mean MSL pressure in mb.
- - - Monthly mean 1000-500 mb thickness in decametres.

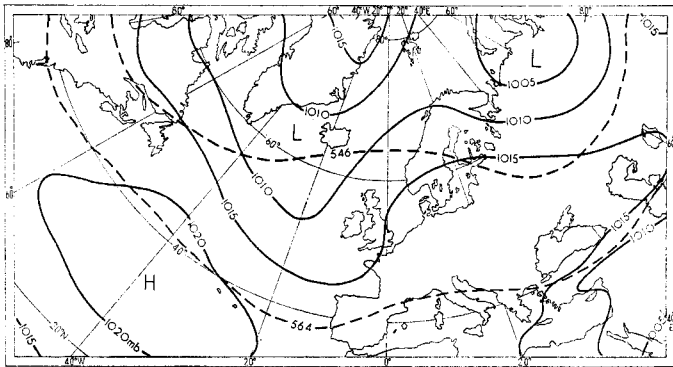


FIGURE 8—MEAN PRESSURE PATTERN, SEPTEMBER 1956—COLD SUMMER, WARM SEPTEMBER

— Monthly mean MSL pressure in mb.
- - - Monthly mean 1000-500 mb thickness in decametres.

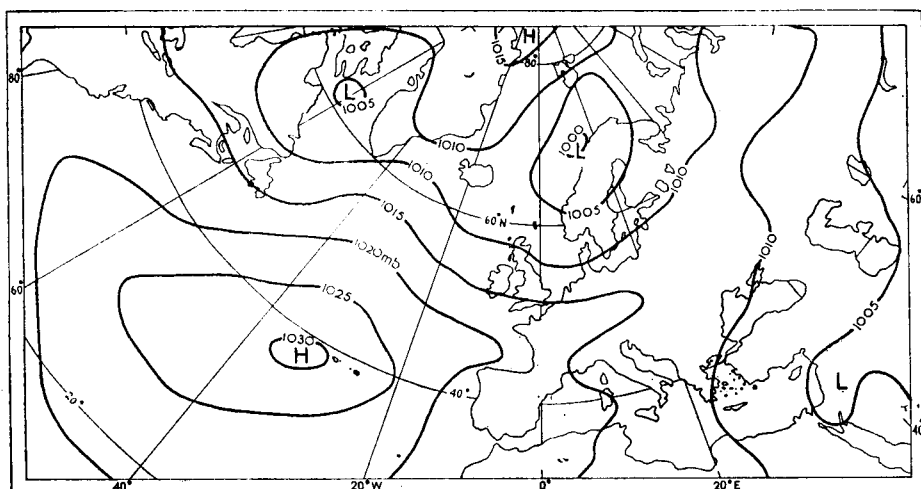


FIGURE 9—MONTHLY MEAN MSL PRESSURE IN MILLIBARS FOR JULY 1890—COLD SUMMER, WARM SEPTEMBER

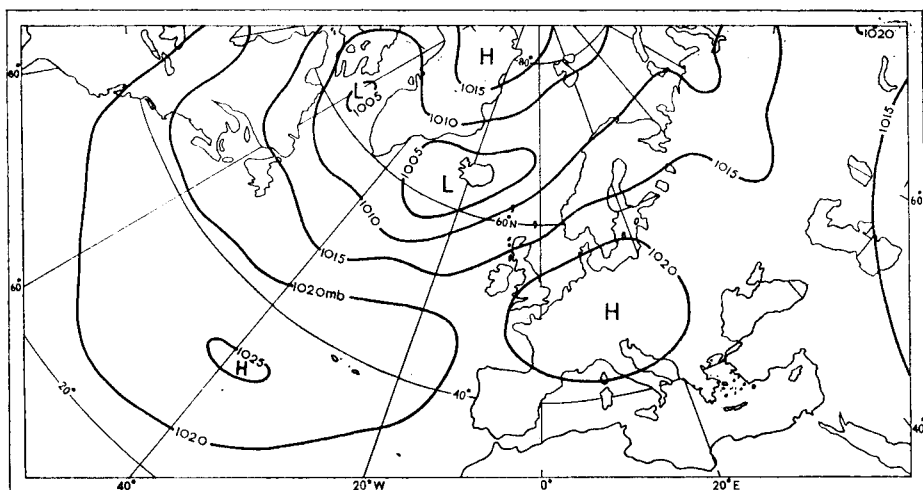


FIGURE 10—MONTHLY MEAN MSL PRESSURE IN MILLIBARS FOR SEPTEMBER 1890—COLD SUMMER, WARM SEPTEMBER

In the blocked and in the westerly periods Table II also shows that type 3 (lows near the west or north-west of British Isles) and type 4 (lows over Scandinavia) were more frequent in cold and average summers before a cold or average September than they were before a warm September.

Analysis for 1818–1963: monthly mean pressures at Edinburgh and Trondheim. Monthly mean synoptic charts are not available before 1873, so monthly mean pressures for Edinburgh (*E*) and for Trondheim (*T*) were used instead as an indicator of the pressure distribution over Britain and Scandinavia. Reliable records for both of these stations are available back

TABLE II—RELATIVE FREQUENCIES OF SUMMER MONTHS FOR EACH OF FOUR SPECIFIED TYPES OF SYNOPTIC PATTERNS RELATED TO TEMPERATURE ANOMALIES FOR CENTRAL ENGLAND IN SUMMER AND IN THE SEPTEMBER FOLLOWING

		Blocked period (1874-95, 1941-63) Summer temperature			Westerly period (1896-1940) Summer temperature		
		Cold	Average	Warm	Cold	Average	Warm
Type 1							
Ridge from Azores anticyclone across British Isles (and northern France) to Scandinavia							
September following	Warm	0(18)	5(30)	28(42)	2(6)	2(36)	9(48)
	Average	0(18)	5(48)	2(24)	0(36)	5(24)	9(30)
	Cold	2(54)	0(12)	3(24)	0(48)	0(30)	0(12)
Type 2							
Ridge from Azores anticyclone across British Isles (and northern France) not extending to Scandinavia*							
September following	Warm	0(18)	7(30)	1(42)	4(6)	14(36)	34(48)
	Average	3(18)	18(48)	6(24)	15(36)	7(24)	14(30)
	Cold	5(54)	6(12)	24(24)	19(48)	23(30)	6(12)
Type 3							
Low centre near to the west or north-west of the British Isles							
September following	Warm	6(18)	6(30)	2(42)	0(6)	6(36)	5(48)
	Average	5(18)	11(48)	7(24)	10(36)	6(24)	3(30)
	Cold	18(54)	2(12)	2(24)	16(48)	9(30)	4(12)
Type 4							
Low centre over Scandinavia or the adjacent Norwegian Sea (sometimes associated with type 3)							
September following	Warm	9(18)	9(30)	3(42)	0(6)	5(36)	0(48)
	Average	8(18)	17(48)	4(24)	5(36)	3(24)	0(30)
	Cold	34(54)	4(12)	2(24)	9(48)	3(30)	1(12)

* In a number of the cases in type 2, a low centre is situated over Scandinavia or the Norwegian Sea.

Notes. Synoptic classifications of individual months (June, July, August and September, 1874-1963) were made initially by using an extension of the types 1 to 4 shown in this table. A distinction was made between months when a type was well developed and close to the pertinent area, and other months when a type was weaker and/or somewhat displaced from the area in question.

Frequencies shown in this table were then derived by giving a score of 1 to each month in which the type under consideration was well developed and a score of $\frac{1}{2}$ to each month when the type was weaker (as described above), and then by summing the scores for all months in each cell of the tables.

Both sets of figures in each cell were multiplied by two, to get rid of fractions. The figures in brackets refer to twice the actual number of summer months included in each cell (they can also be derived by multiplying the number of years in each cell in Table I by a factor of six). In each case, these bracketed figures also represent the highest possible value for the frequency shown in the same cell, supposing that the same classification to which the cells refer had occurred — fully developed, not associated with another classification and close to the area described — in every summer month included in the same cell.

to at least 1818. As a first step monthly values of pressure for Edinburgh, and of pressure differences, Edinburgh minus Trondheim ($E-T$), for the months from June to September inclusive, were ranked and classified in terciles for the 146 years from 1818 to 1963. Tercile limits for each month and data for the extremes are given in Table III. The long-period averages for the monthly mean pressures are higher at Edinburgh than at Trondheim from June to September and hence there is an appreciable north-westerly component of monthly mean geostrophic wind flow between the two places.

TABLE III—TERCILE LIMITS AND EXTREMES OF MONTHLY MEAN PRESSURE AT EDINBURGH (E) AND OF THE DIFFERENCES BETWEEN MONTHLY MEAN PRESSURES AT EDINBURGH AND TRONDHEIM ($E-T$) DURING SUMMER MONTHS (1818–1963)

	Edinburgh pressure (E)				Pressure difference Edinburgh–Trondheim ($E-T$)			
	June	July	Aug.	Sept.	June	July	Aug.	Sept.
	<i>millibars</i>				<i>millibars</i>			
Limits: T_3 above	1016.2	1015.0	1013.9	1015.3	2.8	2.7	2.8	3.8
T_1 below	1013.5	1011.7	1010.5	1011.9	0.5	0.8	0.6	0.4
Highest monthly mean (mb)	1025.6	1022.1	1022.4	1024.6	11.5	9.1	9.0	8.4
Year	1826	1825	1947	1894	1923	1928	1940	1852 1931
Lowest monthly mean (mb)	1004.8	1003.7	1002.4	1000.8	-6.6	-4.6	-5.0	-7.0
Year	1860	1861	1860	1839	1933	1854	1950	1830

Thus, a classification of monthly values of $E-T$, by the use of terciles, affords a ready method of identifying months when this north-westerly geostrophic wind component between Edinburgh and Trondheim was much larger ($E-T$ value in tercile 3) or much smaller ($E-T$ value in tercile 1) than usual. Mean temperatures for summer (June to August) and for September, for central England, were also ranked and classified in quintiles for the same period, and a contingency table was made between temperatures of the summers and temperatures of the Septembers following. Quintile limits for summer and September and data for the extremes are given in Table IV.

TABLE IV—QUINTILE LIMITS AND EXTREMES OF SUMMER AND SEPTEMBER TEMPERATURES FOR CENTRAL ENGLAND (1818–1963)

		Summer	September
		<i>degrees Celsius</i>	
Limits:	Q_5	above 15.8	above 14.2
	Q_4	above 15.4	above 13.3
	Q_3	above 15.0	above 12.8
	Q_2	above 14.5	above 12.3
Highest monthly mean ($^{\circ}\text{C}$)		17.6	16.3
Year		1826	1865, 1949
Lowest monthly mean ($^{\circ}\text{C}$)		13.5	11.7
Year		1860	1836

One of the main intentions of this investigation was to find out whether any typical differences exist between the monthly synoptic patterns that are characteristic of persistence or of antipersistence between the weather of summer and that of September. With this end in view, two tables were produced but they are too detailed for publication here. The first included (a) years when the June pressure at Edinburgh was in tercile 3 (T_3 high pressure) while the July pressure was in tercile 3 or 2, together with (b) years with June pressure in tercile 2 and July pressure in tercile 3. Thus, this sample effectively includes all summers when June and/or July were more anticyclonic than usual at Edinburgh. The second table included (a) years when the June pressure at Edinburgh was in tercile 1 (T_1 low pressure) while the July pressure was in tercile 1 or 2, together with (b) years with June pressure in tercile 2 and July pressure in tercile 1, and thus it related to all summers which were more cyclonic in type than is usual in June and/or July at Edinburgh. The two tables also included the temperature categories of the chosen summers and associated Septembers, to allow comparisons to be made

with the changes of temperature from summer to September. These tables were used for deriving the frequencies of occurrence of E and $E-T$, classified into their appropriate terciles as shown in Table V, which separates the years into four contrasting categories as follows:

- (i) Warm summers in central England together with high pressure at Edinburgh in June and July, followed by Septembers as warm as, or warmer than, the previous summer.
- (ii) Summers as in (i) but followed by appreciably colder Septembers, (at least two quintiles different).
- (iii) Cold summers in central England together with low pressure at Edinburgh in June and July, followed by Septembers as cold as, or colder than, the previous summer.
- (iv) Summers as in (iii) but followed by appreciably warmer Septembers (at least two quintiles different).

This table allows a rough assessment of the pressure distribution in the vicinity of southern Scandinavia and Scotland to be made by inspection. In considering the chief points of interest in the changes of $E-T$ and of E , inferred from Table V and described below, it needs to be remembered that the values of $E-T$ are dependent upon the selection of high and low E values in June and July, and that the table is subdivided according to temperature relationships of summer and Septembers.

(i) *Warm summers (central England) with high pressure (June, July) at Edinburgh, followed by equally warm or warmer Septembers.* As described, selection from cases of higher Edinburgh pressures (T_3 or T_2) in June affects the bias towards large pressure differences of $E-T$ (10 out of 18 cases in T_3). But

TABLE V—MONTHLY FREQUENCIES OF OCCURRENCE OF EACH TERCILE OF EDINBURGH PRESSURE (E) AND OF PRESSURE DIFFERENCES BETWEEN EDINBURGH AND TRONDHEIM ($E-T$) (FOR FOUR SPECIFIED TEMPERATURE RELATIONSHIPS)

(i) Warm summers followed by warmer (or equally warm) Septembers in central England. (Persistence)

Tercile of Edinburgh pressure (E)	Frequencies (No. of months in each tercile)				Tercile of pressure difference ($E-T$)	Frequencies (No. of months in each tercile)			
	June	July	Aug.	Sept.		June	July	Aug.	Sept.
T_3	13	8	7	6	T_3	10	5	4	3
T_2	5	10	5	6	T_2	5	7	6	7
T_1	0	0	6	6	T_1	3	6	8	8
Totals	18	18	18	18		18	18	18	18

(ii) Warm summers followed by cold Septembers in central England. (Antipersistence)

T_3	7	10	6	1	T_3	5	11	4	9
T_2	6	3	4	6	T_2	5	1	5	2
T_1	0	0	3	6	T_1	3	1	4	2
Totals	13	13	13	13		13	13	13	13

(iii) Cold summers followed by cold Septembers in central England. (Persistence)

T_3	0	0	3	10	T_3	4	4	8	10
T_2	8	6	10	6	T_2	9	6	9	5
T_1	15	17	10	7	T_1	10	13	6	8
Totals	23	23	23	23		23	23	23	23

(iv) Cold summers followed by warmer Septembers in central England. (Antipersistence)

T_3	0	0	3	5	T_3	1	3	2	3
T_2	4	4	2	2	T_2	5	4	2	4
T_1	7	7	6	4	T_1	5	4	7	4
Totals	11	11	11	11		11	11	11	11

already in July a small bias in $E-T$ shows in the other direction (13 out of 18 cases in T_2 and T_1) and this bias strengthens in the months following (14 out of 18 cases in August and 15 out of 18 cases in September in T_2 and T_1). Since monthly pressures at Edinburgh are evenly distributed in frequency between T_3 , T_2 and T_1 in August and in September (also shown in Table V), this result implies that the frequency of large pressure differences between Edinburgh and Trondheim decreases through successive summer months, i.e. monthly mean pressures remain relatively high at Trondheim in these cases. This result is consistent with the synoptic and statistical data.

(ii) *Warm summers (central England) as for (i) above, followed by colder Septembers.* A slight bias towards large pressure differences ($E-T$) in June (10 out of 13 cases in T_3 and T_2) is again to be expected because the sample has been selected from the cases of higher Edinburgh pressure (T_3 or T_2). The important feature is the strong bias to large $E-T$ which follows in July (11 out of 13 cases in T_3), implying that a marked fall of pressure occurs at Trondheim in July in these summers, because July pressure remains high (T_3 or T_2) at Edinburgh. Again, this deduction is consistent with the synoptic and statistical data.

No bias to large $E-T$ shows in August (4 out of 13 cases in T_3). However, a strong bias reappears in September (9 out of 13 cases of $E-T$ in T_3), implying again a fall of pressure at Trondheim.

This last result is no doubt related to the fact that cold Septembers in central England are often associated with synoptic types which favour enhanced north-westerly airflow between Edinburgh and Trondheim.

(iii) *Cold summers (central England) with low pressure (June, July) at Edinburgh, followed by equally cold or colder Septembers.* The bias to small values of $E-T$ in June and July (partly due to sampling as mentioned earlier) shifts towards large values of $E-T$ in August and September (17 out of 23 and 15 out of 23 cases in T_3 and T_4). Reference to Table V shows that higher monthly pressure at Edinburgh occurs with greater frequency from July to August and from August to September (0 out of 23, 3 out of 23 and 10 out of 23 cases respectively in T_3). These results together suggest that while pressure often rises at Edinburgh throughout these summers, it remains mostly low at Trondheim, thus enhancing a north-westerly airflow in this locality as the summer progresses. This result is also consistent with an earlier conclusion in this paper.

Frequencies of monthly mean pressure at Edinburgh, shown in Table V (iii) and (iv), also yield slight evidence for distinguishing between persistence and antipersistence of temperature in Septembers following cold summers.

When persistence exists, only 3 out of 23 cases in T_3 occur in August, whereas, when antipersistence exists, pressure in August already shows some rise at Edinburgh as compared with the previous months (3 out of 11 cases in T_3).

(iv) *Cold summers (central England) as for (iii) above, followed by warmer Septembers.* The bias to small values of $E-T$ persists through June, July and August (10 out of 11, 8 out of 11, 9 out of 11 cases in T_1 and T_2) on these occasions, implying that monthly pressures remain low at both Edinburgh and Trondheim and that north-westerly airflow in this locality is reduced below its average value.

Additional tests. Table V shows the marked changes, in the bias of frequencies of terciles of $E-T$ between certain summer months, found in connexion with the more extreme cases of persistence and antipersistence of temperature between summers and Septembers. Student's t -test was applied to the actual values of $E-T$ for the individual years included in the four groups of years listed in Table V, to determine whether the means of the two values of $E-T$ in each set were significantly different from each other. When this test was made, it was found that the mean pressure differences for the two sets of cases (Table V (i) and (ii)) were significantly different at the 5 per cent level. On the other hand the difference between $(E-T)_{\text{mean}}$ for cases (iii) and (iv) of Table V falls slightly short of being significant at the 5 per cent level. These results are shown in Table VI.

Possible synoptic interpretations. The facts needing explanation can be summarized as follows. During both warm and cold summers in England and Wales the pressure distribution over Scandinavia bears an important relation to the temperature of the September to follow. In a warm summer a ridge from the Azores high normally extends as far as the British Isles. When this ridge also extends across to Scandinavia, and when a separate monthly high centre shows over Scandinavia, conditions are favourable for a warm September to follow in England and Wales. As a warm summer

TABLE VI—MONTHLY MEAN PRESSURE DIFFERENCES BETWEEN EDINBURGH AND TRONDHEIM ($E-T$) IN GROUPS OF YEARS SELECTED FOR TEMPERATURE PERSISTENCE AND ANTIPERSISTENCE FROM SUMMER TO SEPTEMBER

Warm summer with warmer (or equally warm) September. (Persistence)						Warm summer with cold September. (Antipersistence)					
Year	Tercile of E		Temperature quintile Sum-Sept.*	$E-T$ July		Year	Tercile of E		Temperature quintile Sum-Sept.†	$E-T$ July	
	June	July		+	-		June	July		+	-
			mer	mb					mer	mb	
1857	3	2	5	5	4.9	1870	3	3	5	3	2.8
1858	3	2	4	5	2.0	1887	3	2	5	1	3.5
1865	3	2	4	5	3.1	1893	3	2	5	3	1.1
1868	3	3	5	5		1897	3	3	5	1	3.7
1869	3	3	3	5	1.7	1899	3	3	5	3	3.5
1874	3	2	3	4	1.5	1905	3	3	4	2	4.6
1884	3	2	4	5	1.0	1925	3	2	4	1	0.2
1906	3	2	4	4	1.8						
1934	3	2	5	5	1.9	1818	2	3	5	3	5.8
1941	3	2	4	5	1.3	1847	2	3	4	1	2.8
1942	3	2	4	4	2.5	1859	2	3	5	3	3.4
1949	3	3	5	5	1.9	1876	2	3	5	2	6.3
1959	3	2	5	5	0.3	1878	2	3	5	3	5.9
						1952	2	3	4	1	4.8
1825	2	3	4	5	5.4	No. of years		13			
1898	2	3	3	5	8.0	$(E-T)_{\text{mean}}$		3.72 mb			
1901	2	3	4	4	0.3	Standard deviation		1.80 mb			
1917	2	3	4	4	0.7	Value of t		2.17			
1951	2	3	3	4	3.8	(For significance at		2% level, $t=2.46$			
No. of years			18					5% level, $t=2.04$			
$(E-T)_{\text{mean}}$			2.05 mb					10% level, $t=1.70$			
Standard deviation			2.31 mb					for 29 degrees of freedom)			

* Summer in Q_3 , Q_4 or Q_5 ; the following September is in the same quintile, or 1 or 2 quintiles warmer

† Summer in Q_3 or Q_4 ; the following September is 2 or 3 quintiles colder

TABLE VI—(contd.)

Cold summer with cold September (Persistence)						Cold summer with warmer September (Antipersistence)					
Year	Tercile of E		Tempera- ture quintile		E-T August	Year	Tercile of E		Tempera- ture quintile		E-T August
	June	July	Sum- mer	Sept.*	+ - mb		June	July	Sum- mer	Sept.†	+ - mb
1830	1	1	1	1	2.6	1843	1	2	1	5	0.8
1836	1	1	3	1	8.0	1854	1	2	2	5	0.7
1838	1	2	3	2	2.3	1862	1	1	1	3	1.2
1840	1	1	2	1		1890	1	1	1	5	2.5
1845	1	2	1	1	0.8	1946	1	2	2	4	1.1
1848	1	1	2	2	1.4	1948	1	2	2	4	0.2
1851	1	1	2	2	2.4	1958	1	1	3	5	2.3
1853	1	1	2	1	1.3						
1881	1	2	2	2	5.8	1841	2	1	1	4	3.1
1882	1	1	2	2	4.8	1880	2	1	3	5	1.1
1910	1	1	2	2		1924	2	1	1	3	1.1
1912	1	2	1	1	0.0	1936	2	1	3	5	4.7
1922	1	1	1	1	2.1	No. of years			11		
1927	1	2	2	2		(E-T) mean			0.40 mb		
1928	1	2	2	2	0.4	Standard deviation			2.18 mb		
1839	2	1	2	2	2.7	Value of <i>t</i>			1.83		
1861	2	1	3	3	4.5	(For significance at			5% level, <i>t</i> = 2.04		
1873	2	1	3	1	4.3				10% level, <i>t</i> = 1.70		
1877	2	1	3	1					for 32 degrees of freedom)		
1888	2	1	1	1	1.7	† Summer in Q ₁ , Q ₂ or Q ₃ ; the following					
1894	2	1	1	1	5.5	September is 2, 3 or 4 quintiles					
1918	2	1	2	1	2.9	warmer.					
1931	2	1	2	1	3.5						
No. of years			23								
(E-T) mean				2.13 mb							
Standard deviation				2.75 mb							

* Summer in Q₁, Q₂ or Q₃; the following September is in the same quintile, or 1 or 2 quintiles colder.

progresses, if the ridge over Britain does not extend to Scandinavia, a cold September should be expected in central England. This expectation is further increased whenever separate monthly low centres are found over Scandinavia. Two other factors which can evidently be linked with the broad-scale synoptic patterns in which they occur are: an apparent association between strong northerly or north-easterly pressure gradients over northern Scandinavia in cold summers prior to a cold September, and the presence of a broad zonal ridge over the north-west of the North Atlantic in cold summers prior to a warm September. Reference to the appropriate monthly mean pressure charts shows that, in the first case, the flow of air from the Siberian Arctic regions to much of Europe and the north-east of the North Atlantic is greatly increased. (In some instances the cold air penetrates additionally to middle latitudes in the north-west of the North Atlantic.) In contrast, whenever a broad zonal ridge is present over the north-west of the North Atlantic and there is no north-easterly pressure gradient over Scandinavia (as in 1890 and 1891), the direct export of Arctic air masses to Scandinavia, western Europe and much of the North Atlantic is greatly reduced.

These facts can be broadly confirmed and interpreted by appeal to synoptic experience. When there is a recurrence of synoptic situations which allow anomalous heating of the air masses over western and northern Europe to continue into the late summer, the associated thickness patterns tend to steer

the major disturbances away from Europe, that is, from the north-east Atlantic toward the Norwegian Sea. Alternatively, repeated developments of low pressure over Scandinavia, as the summer proceeds, are usually associated with a thickness trough over Europe which tends to divert Atlantic depressions eastwards into Europe, and these depressions in their turn assist in regenerating this trough. This pattern evidently shows considerable persistence and therefore prevents, or modifies, the seasonal tendency for the main depression track to shift northwards near the end of August, resulting in a cool September to follow. In the synoptic patterns of 1890 and 1891, when pressure was relatively high over the North Atlantic to the west of the British Isles and also over Scandinavia, it can be plausibly argued that, although these summers were cold in central England, the seasonal shift of depression tracks to the northward at the end of the summer was able to occur together with a re-establishment of high pressure over western and central Europe, resulting in Septembers which were warm in central England in both years.

Conclusions.

(1) A chi-square test shows that a positive association at a level which is marginally better than 5 per cent, is evident between central England temperature in summer and that in the September following, during the years included in the blocked periods (taken as 1874-95 and 1941-63).

(2) A chi-square test similarly undertaken for the years included in the westerly period (taken as 1896-1940), showed a positive association (at a level marginally worse than 5 per cent) between central England temperature in summer and that in the September following. However, in the case of extreme summers and Septembers (those in T_1 and T_3), this positive association appeared to be stronger during the westerly period than during the blocked period.

(3) Analysis of monthly mean pressure charts of the months from June to September inclusive, for all years in the blocked periods and the westerly period (as defined above), has shown that differences in pressure patterns over north-western Europe can be related to the different types of temperature anomaly relationships in central England between summer and September, as follows :

- (i) *Warm summers followed by warm Septembers.* In a majority of months of the summers in this category a ridge from the Azores anticyclone extended across the British Isles to Scandinavia and in many cases a separate anticyclonic centre was also found over Scandinavia or the southern Norwegian Sea.
- (ii) *Warm summers followed by cold Septembers.* A ridge extended across the British Isles from the Azores high but rarely extended farther to Scandinavia. Quite early in several of these summers, a monthly mean low centre became evident over Scandinavia, although pressure remained mostly high over Britain (blocked period only).
- (iii) *Cold summers followed by cold Septembers.* Monthly mean low centres are found near to the west or north-west of the British Isles and/or over or near Scandinavia.
- (iv) *Cold summers followed by warm Septembers.* Monthly mean low centres are seldom found near to the west or north-west of the British Isles

in summer in the few cases available for study, while lows over or near Scandinavia are less common than for summers followed by cold Septembers.

(4) Monthly mean pressures at Edinburgh (E) and Trondheim (T) for the period from June to September were analysed for the 146-year period 1818–1963. The pressure difference Edinburgh minus Trondheim ($E-T$) was used as a broad indicator of the synoptic pattern between Scotland and western Scandinavia, because monthly mean pressure charts are not available prior to 1873. The analysis of this long period fully supports the conclusions in paragraph (3) above.

(5) Analysis of the pressure difference ($E-T$) showed two additional facts of interest. When warm summers are followed by appreciably colder Septembers it appears that the fall of pressure over Scandinavia, mentioned under the conclusion at paragraph (3) (ii) above, shows up most strongly in the month of July, if the longer (146-year) period is considered.

(6) When summers are cold, it appears, from analysis of $E-T$, that August is the month which shows the largest dissimilarity in $E-T$ as between cases of subsequent warmth, or of coldness, in September.

(7) By means of t -tests upon values of $E-T$ in the individual years, it was found that the difference between the two sets of values of $E-T$ for July, in having cold or warm Septembers respectively following warm summers, was significant at slightly above the 5 per cent level; whereas in the case of the difference between the two sets of values of $E-T$ for August, in years having warm or cold Septembers respectively following cold summers, the level of significance was slightly below 5 per cent.

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NOTES AND NEWS

Interaction between the oceans and the atmosphere

At the invitation of the Director-General of the Meteorological Office, a lecture was given at Bracknell on 25 October 1967 by Professor M. J. Lighthill, F.R.S., the distinguished fluid-dynamicist, who chose for his topic air-sea interaction. In a brief introduction, Dr Mason pointed out the importance of knowing more about energy exchanges across the boundary between air and ocean. Meteorologists were aware of lack of data in this field, but international plans promised soon a great deal of extra effort in the investigation of exchange processes across the surface of the oceans.

Professor Lighthill suggested that until recently air-sea interaction tended to be neglected because of the difficulty of getting meteorological and oceanographical organizations working together on the problem. As a result, the exchange processes at or near the sea surface had been less closely studied than, say, atmospheric circulations or the general ocean structure. Now,

however, oceanographers recognize the importance of the mechanism of momentum input from the atmosphere to the sea, and there is an increasing amount of theoretical and practical work being done on this subject. The importance, too, of sea surface temperature variations and the transfer of heat and moisture from the sea to the atmosphere had been highlighted by the growth of numerical forecasting and thus the interest of meteorologists, in air-sea interaction is being further stimulated.

The bulk of Professor Lighthill's lecture was a description of the way in which the atmospheric circulations interact with the oceans to produce ocean currents, and the factors that control these currents, with the North Atlantic used as an example. Until the development of the swallow float, which was designed to follow currents along surfaces of constant density, much of the information on ocean currents was of a somewhat indirect nature, obtained by tracking water masses using salinity and density as tracers, and from temperature measurements at various depths. The picture has emerged of an ocean with a barotropic bottom layer, and a generally baroclinic upper layer much influenced by interaction with the winds. The basically westerly wind régime in middle and high latitudes and the easterlies nearer the equator tend to generate anticyclonic vorticity in the ocean. The major balance to this vorticity comes from the 'Rossby' term due to the variation of the Coriolis parameter with latitude (the 'Sverdrup' effect). Other factors, such as horizontal mixing, bottom topography and advection of relative vorticity, tend to be much less important. The effect of the Rossby term is to introduce a southward return flow connecting the Gulf Stream to the westward-flowing North Equatorial Current.

A feature of the Gulf Stream which is reflected by similar currents in other oceans is that on the western side of the ocean it occurs as a very narrow northward flow. Professor Lighthill described a number of different processes which had a bearing on this and the subsequent motion of the Gulf Stream across the Atlantic. Thus, horizontal mixing and advection of relative vorticity 'feed in' cyclonic vorticity which keeps the jet running along the western boundary. Bottom topography has an influence in that shallowing reduces the cyclonic vorticity and this prevents the current flowing over the Continental Shelf. Evidence to support this is found in the way the Gulf Stream hugs the Continental Shelf as it travels eastwards after leaving the North American coast. However, the effect weakens as more and more of the energy of the flow is drawn off southward because of the Sverdrup effect. Of particular interest to meteorologists is that water-flow changes often mirror atmospheric changes with a time lag of about a month. The changes can be considered as Rossby waves whose group velocity or direction of energy transfer tends often to be westward, and this is borne out by measurements of root-mean-square velocities in currents, which give magnitudes two or three times larger in the west than in the east of the North Atlantic. Similarly, flow disturbances tend to be reflected from the eastern boundary, but those reaching the west converge until the area of interaction shrinks to the width typical of the Gulf Stream in that region, the time scale being about a month.

After a brief reference to the general importance of ocean currents and their fluctuations to, for example, marine biologists and fishermen, Professor Lighthill concluded by answering a number of questions from the audience.

I, and probably many others as well, left the hall with the impression that the success of long-range weather forecasts in particular may well depend on taking adequate account of the general circulation of the oceans and their degree of interaction with the atmosphere.

N. THOMPSON

REVIEWS

Water, weather and prehistory, by R. Raikes. 8 $\frac{3}{4}$ in \times 5 $\frac{1}{2}$ in, pp. xvi+208, *illus.*, John Baker Publishers Ltd, 5 Royal Opera Arcade, Pall Mall, London, SW1. Price: 45s.

This book, by a water engineer with long experience in the Mediterranean and the arid and semi-arid lands of the Near and Middle East, is aimed at demonstrating the importance of scientific hydrology to an understanding of prehistory. So far, so good; and one must give the fullest support to the author's plea for an interdisciplinary approach (the title of his last chapter) to the problems of archaeology and, for that matter, to those of ancient climates. Unfortunately, the author's own approach is almost the exact opposite of that and amounts to a one-sided attempt to explain everything (or as much as possible) in solely hydrological terms without sufficient understanding of the evidence from other disciplines. Archaeologists, we are told have neglected hydrology and they have been too much in the habit of publishing their conclusions in specialist journals where they escape criticism. Botanists and others are alleged to have been too prone to interpret their findings as evidence of climatic changes, and they have used ugly nordic-sounding (*sic*) words like Boreal and Atlantic to name the supposed different climatic epochs since the ice-age. Their evidence is made to look chaotic by a presentation here that takes no account of tolerance limits or error margins. It can all be explained much better in terms of the carelessness of Man in his use of water, or in overgrazing and so on, with the climate playing only its well-known mischievous role of purely local and erratic vagaries and surprises.

This is a tract rather than a scientific treatise. Written as a narrative in the first person, its argumentative style makes somewhat tiresome and difficult reading. It is to be doubted whether it will do much to advance the recognition that hydrology should (but also largely does) have.

There is little meteorology in it. The most extensive passage of meteorological writing quoted — the speculations, about the probable and (possibly) not so probable physical causes of climatic change, of a man who, however eminent, has never worked on the problems of climatic history or climatic change — is apparently mistaken as a verdict against the occurrence of any world-wide climatic changes in post-glacial time. Elsewhere, a minor allusion by another meteorologist to the interpretation of archaeological finds, such as camel remains in Alaska, is so distorted by partial quotation as to give a false impression of the interpretation suggested.

The author modestly enough proclaims that he is not qualified to question the deductions from much of the evidence in specialized fields regarding post-glacial climatic change. And the book is full of misrepresentations of this

evidence. For example, it is surely no more than an accident that the short-lived and rather minor warm epoch around 9000 BC, known as the Allerød, occurred about the climax of one of Milankovitch's 20 000-year-plus oscillations of the summer radiation budget in high northern latitudes and quite wrong to suggest that the two are equated. Nor does the sea level respond so rapidly to large-scale warm and cold epochs that anyone expects the fluctuations of sea level and climate to be simultaneous.

The book is enlivened at the outset by a foreword from Sir Mortimer Wheeler, who, despite the forthright language in which he accepts and enjoins on other archaeologists the challenge to re-examine and re-think old conclusions and old classifications of data, is led by this book into somewhat belittling the contributions of his own and earlier generations.

Knowledge of the facts of human prehistory and of the archaeology of the environment, including climate, can be built up only gradually, each generation building on and refining, occasionally correcting, the results of its predecessors. Probably the big events, which have left marks of their big effects, as with the climates of the ice ages and interglacials and the post-glacial 'optimum' (warmest epoch), which were the easiest and therefore first discoveries made, will remain the most securely established. Later work will doubtless go on adding detail, some of which may be found intelligible and stand the test of time, though at some point the finer details will elude us because of the margins of error to which our dating and diagnostic techniques are liable. The closer the co-operation between all the relevant disciplines, the farther we shall get along this road and the better the ultimate diagnosis will explain the interrelationship of all the known facts.

There is a special danger which subtly threatens the analytical mind in approaching any problem which requires contributions from several disciplines for its solution. The theoretician and the experimental physicist both like to isolate and consider the effects of each variable influence separately. Similarly the scholar in humane studies may like to consider the effects of Man (and his improvidence) in an environment which otherwise remains constant. Perhaps, that is also why the author of this book likes to believe the climate has been constant for 9000 years and his meteorological mentor likes to exclude sun-spots and sea temperature from any climatic variations that did occur. Unfortunately, nature is not so obliging and most problems of the development and history of our environment are essentially multivariate problems. That suggests we need to know the facts of many cases for their solution, and in the systematic establishment of the facts of the past there is still a fascinating future for co-operative endeavour in natural history and human archaeology, using every relevant new technique that comes along. It is a pity that this book goes so obliquely about it.

H. H. LAMB

Weather and agriculture, edited by J. A. Taylor. 9½ in × 6½ in, pp. ix + 225, illus., Pergamon Press Ltd, Headington Hill Hall, Oxford, 1967. Price: 80s.

The Agricultural Advisory Council in their second progress report to the Minister of Agriculture, Fisheries and Food stated that 'agricultural meteorology can help farmers and horticulturists: (i) in the shorter term, by giving

guidance on when to take action against pests or diseases or on frost protection, etc.; (ii) in the middle term, by giving guidance on irrigation, crops and livestock shelter, buildings, weather conditions affecting plant and animal diseases, etc., and by aiding farm investment decisions; (iii) in the long term, by seasonal and climate forecasting, which could be of considerable benefit in deciding on the best use of land for siting agricultural systems.' The Council then recommended the strengthening of the agricultural meteorology branch of the Meteorological Office. It emphasized the importance of co-operation between agricultural research workers and meteorologists in relating crop, soil and animal resources to climate, and in the use of climatic trends and weather probabilities for decisions on husbandry management and capital investment (e.g. in irrigation or livestock shelter). It also stressed the need for accurate weather forecasting.

The present book makes useful contributions on most of the subjects stressed by the Advisory Council. It is a selection from the papers given at the first eight (1958-65) of the annual symposia organised at the Department of Geography, University College of Wales, Aberystwyth, by its enthusiastic editor, J. A. Taylor, who contributes a thoughtful introduction. He groups the papers under three headings. The first group 'Environment' includes contributions on the thermal growing season, soil climate and wind in hill climates, but not, surprisingly, anything on radiation receipts or on energy/moisture balances which are increasingly used, e.g. in irrigation. The second section, on 'the Hazards', admirably demonstrates the range of usefulness of meteorological data to the farmer and the agricultural administrator in crop and animal disease control (including specifically plant virus diseases, potato blight and liver fluke) and in milk production. The final section headed 'Productivity' is rather mixed. After useful papers on, firstly, the relation between variability in energy/moisture balances on the one hand and national and regional milk production on the other, and secondly, the probabilities of suitable weather for the several techniques of hay-making, there are two historical contributions on the agroclimatology of Wales and one on the effect of marling on soil temperatures. There is, unfortunately, neither an author index nor a subject index in this book.

To sum up, this book is a useful but understandably mixed contribution to a subject which grows in importance as farming becomes more important and more capital is invested. It is, perhaps inevitably, limited in outlook to the United Kingdom, with many examples drawn from Wales. Its limitations underline the needs both for a well-planned authoritative scientific and practical textbook on agrometeorology, and for the continuance of the Aberystwyth annual symposia which, *inter alia*, help to create the corpus of knowledge on which such a textbook must be based and at the same time bring agriculturists, geographers and meteorologists together. Perhaps, out of these meetings, an Agricultural Meteorology Society will emerge. Its U.S. counterpart has shown the value of such an inter-disciplinary group.

A. N. DUCKHAM

OBITUARY

It is with regret that we have to announce the death of Mr C. D. Barrow (S.X.O.) on 21 December 1967.

OFFICIAL PUBLICATION

New rainfall map for the twentieth century

A vivid impression of some of the basic climatic variations between different parts of Great Britain is conveyed by a new rainfall map published by the Ordnance Survey for the Meteorological Office, the Ministry of Housing and Local Government, and the Scottish Development Department.*

Many of the published rainfall maps in current use are based on data collected over 50 years ago. Their revision is long overdue. This new map, with its accompanying explanatory text, provides the kind of detailed and up-to-date information which will enable such revision to be carried out.

Based on meteorological records from over 6000 stations, the map shows the average annual rainfall for 1916 to 1950, the latest period for which fully analysed and detailed data are available. It is the latest addition to the national planning series of 1/625 000 (10 miles to one inch) maps of Great Britain, and replaces the earlier one which covers the period 1881 to 1915. The map is in two sheets, north and south respectively of a line lying just north of Kendal and Scarborough, and covers the whole of England, Wales, Scotland and the Isle of Man.

The overall distribution of rainfall is immediately apparent, the wetter and drier extremes being shown in distinctive blue and buff shades respectively. The general wetness of hilly districts is obvious, but the map also reveals much finer distinctions such as the relative dryness of some quite high areas like the Cotswolds and the Grampians, or of lower-lying areas near but in the lee of mountainous areas, such as the Hereford and Perth districts.

Additional information is shown in the form of an inset map showing the proportion of rain falling in the summer, of vital importance in agricultural and water conservation matters. Graphs for selected places show the actual rainfall totals for each month during the period 1916–1950 and therefore act as a guide to rainfall variability and the extremes which may be expected.

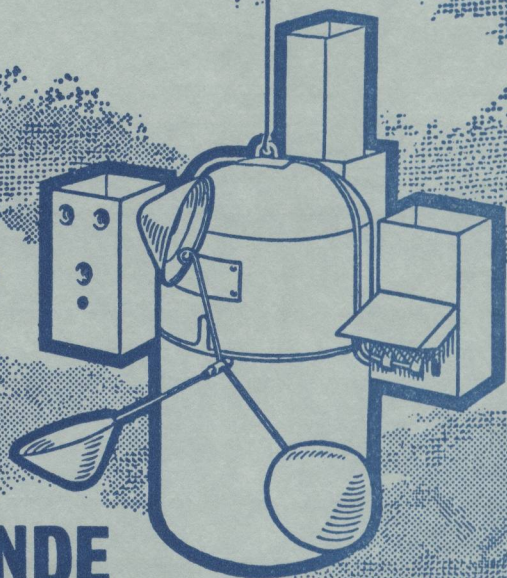
The accompanying text adds further to what may be learned from this map. It is a comprehensive tract ranging from the historical background of rainfall work, through a description of the present map and the method of compilation, to guidance on the validity and usefulness of the information, and a discussion on the degree of stability of annual rainfall averages. This brings in a brief but interesting reference to climatic change, which is illustrated by two tables enabling a comparison of the two periods 1881–1915 and 1916–1950 to be made. On the whole the later period was wetter by 5 per cent or 6 per cent, but this generalization masks more complex geographical variations ranging from increases of up to 14 per cent in parts of Scotland to decreases of up to 4 per cent in parts of eastern England. The text is rounded off with maps which enable the reader to reconstruct the average monthly rainfall throughout the year for any locality in Great Britain.

Apart from its rainfall information, the map is of interest in that it was produced by means of the trichromatic process, in which the cartographer's colour drawing was photographed through magenta, cyan (blue), and yellow filters to produce three printing plates which enabled the original range of thirteen shades to be reproduced with only three inks.

This handsome new map does credit to its compilers and publishers, and will be an important and interesting source of information to people and organizations interested in, for example, meteorology, geography, planning, agriculture, and hydrology, especially water supply and conservation.

* London, Ordnance Survey. Rainfall: Annual average 1916-1950. London, 1967. (Obtainable from Edward Stanford Ltd., 12-14 Long Acre, W.C.2, and from other Ordnance Survey agents, price 12s. 6d. per sheet and 2s. 6d. for the text, plus packing and posting charges of 2s. 9d. for the two maps and 9d. for the text).

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Printed in England by The Bourne Press, Bournemouth, Hants.

and published by

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Dd. 133110 K16 2/68

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