Met.O.905
METEOROLOGICAL OFFICE

# the meteorological magazine



FEBRUARY 1977 No 1255 Vol 106
Her Majesty's Stationery Office

METEOROLOGICAL OFFICE Met.O.905

# THE METEOROLOGICAL MAGAZINE

Vol. 106, No. 1255, February 1977

## RETIREMENT OF MR N. BRADBURY

Mr Neville Bradbury, Deputy Director (Forecasting), retired from the Meteorological Office on 20 January 1977 after a career of more than 39 years spent mostly on the Services side of the Office.

He graduated with high honours in both mathematics and physics from the University of London and joined the Office as a Technical Officer in 1937. Like many of his vintage he received his early training in synoptic meteorology and forecasting at Croydon. After a period of secondment to Iraq he was commissioned in the Royal Air Force in 1943 and saw service at a number of RAF headquarters, including a spell at HQ Transport Command, before demobilization with the rank of Squadron Leader in 1946. There followed a number of posts in both military and civil aviation including about four years at each of London (Heathrow) Airport and Uxbridge. In 1956 Mr Bradbury was assigned the formidable task of writing the Office's first Handbook of Weather Forecasting and it is a tribute to the excellence of his work that much of his original text remains in the revised edition at present being issued.

Another milestone in his career was his appointment in 1962 as CMetO, SHAPE with the rank of Group Captain. However, probably the greatest challenge to his versatility and tenacity came in 1965 when, with promotion to Senior Principal Scientific Officer, he was appointed Assistant Director (Data Processing) which involved the organization and management of the rapidly evolving branch concerned with large-scale computing in the Office. He rose to this challenge splendidly and when the time came to replace COMET (the English Electric KDF 9 computer) he took a major part in the acquisition and introduction into service in 1971 of the IBM 360/195 machine which is still the main work-horse for Office computing.

He was promoted to Deputy Chief Scientific Officer in 1973 and during his tenure of the post of Deputy Director (Observational Services) it fell to him to represent the UK Meteorological Office in the protracted negotiations leading up to the present Agreement for North Atlantic Ocean Stations. Even at this late stage in his career his versatility was again called on for a period as Deputy Director (Forecasting), the post from which he retired.

During his long career Mr Bradbury acquired wide experience in many different fields and became greatly respected for his sound, common-sense approach to problems and for his astute judgement. As a result, his advice was frequently sought and highly valued and he was especially a tower of strength during his later years in the Directorate. His sympathetic and wise handling of staff matters was also often in evidence and there must be many who will miss his congenial presence from our ranks.

We wish him and Mrs Bradbury a long and happy retirement in their new home in Kent.

G. A. CORBY

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## INFORMATION ON THE THERMAL STRUCTURE OF THE ATMOSPHERIC BOUNDARY LAYER FROM ACOUSTIC SOUNDING

By B. A. CREASE, S. J. CAUGHEY and D. T. TRIBBLE
(Meteorological Research Unit, RAF Cardington, Beds.)

SUMMARY

Recent results from a vertically directed monostatic acoustic sounder installation at Cardington are discussed and compared with temperature profiles of the lower atmosphere. The facsimile charts of the sounder output illustrate the presence of thermal plumes, synoptic inversions, nocturnal inversions and internal waves. An example of the echo pattern typical of that in fog conditions is also described and discussed.

### INTRODUCTION

The theory of the backscatter of sound in a turbulent medium has been developed by several authors in recent years, notably Kallistratova (1959), Tatarskiy (1961) and Monin (1962). It was shown that the strength of the scattered sound (i.e. echo) is determined by the high-frequency fluctuations of refractive index. Little (1969) pointed out that, in general, these fluctuations tend to be dominated by temperature and wind variations alone and that the echo strength is determined only by temperature fluctuations for the specific case of backscattered sound. Recently, however, Wesely (1975) has calculated that the contribution from humidity fluctuations cannot be considered negligible in certain conditions such as those present over very moist terrain and perhaps also within a synoptic inversion.

The development of acoustic sounding of the lower atmosphere proceeded rapidly following the early work of McAllister (1968). The principle of the technique is straightforward; a high intensity burst of sound (about 30 W at some 1500 Hz), in a well-collimated beam, is projected into the atmosphere using an array of loudspeakers (the inter-speaker distance being approximately equal to the half-wavelength of the transmitted sound). Alternatively a single loudspeaker and collimating dish may be used. The transmitting frequency is chosen to minimize the effects of the atmospheric absorption of sound (which increases at higher frequences) on the one hand and ambient noise (which has a greater effect at lower frequencies) on the other. The acoustic array is switched to the listening mode about 50 milliseconds (ms) after transmission when the loudspeakers have ceased ringing significantly. Any echoes received are amplified (by a factor of up to about $10^7$) and displayed, for ease of appraisal, in height–time form on a facsimile chart recorder.

The particular design of acoustic array used in this study is similar to that developed by the Department of Electronic and Electrical Engineering, University College, London (Asimakopoulos and Cole, 1977). Other sounder features including the electronic circuitry were designed and built at the Meteorological Research Unit, Cardington (see the Appendix for a summary of the operating characteristics). The sounder was sometimes operated with a pulse length of 5 ms, corresponding to a resolution of around 2 metres. This value is an order of magnitude less than that normally chosen (50–200 ms) and permits, for example, the detection of small-scale turbulent regions associated with breaking waves. The pulse repetition rate was 0·5 Hz with an operating frequency of 1732 Hz. Contamination of the echoes by environmental and wind-generated noise is reduced to a minimum by housing the array in a pit 2 metres deep and 3·6 metres in diameter. Two-inch thick polyurethane foam (which has good sound absorbing characteristics) lines the interior wall of this pit. A smooth airflow over the installation is encouraged by means of a sloping earth bank.

Acoustic sounding offers a method for remotely estimating important turbulence quantities such as the structure parameters for wind and temperature ($C_V^2$ and $C_T^2$ respectively (Tatarskiy, 1961)), at any chosen height, since the eddies producing the scattered sound are of a length scale found within the inertial subrange (Lumley and Panofsky, 1964). Detailed quantitative comparisons between sounder-derived and direct estimates have been the subject of much recent experimental work (Asimakopoulos *et alii*, 1975 and 1976; Neff, 1975). Additionally the echoes provide information on the wind structure in the boundary layer through the magnitude of the Doppler shift (Beran *et alii*, 1973). Recent comparisons have shown that the vertical velocities obtained from sounder returns compare well with direct estimates (Caughey *et alii*, 1976). The technique thereby offers an attractive method of remotely assessing the mixing quality of the lower atmosphere. Further careful comparisons between sounder-derived quantities and direct measurements (preferably at several heights simultaneously), in a wide variety of atmospheric conditions, are required to establish the accuracy limits and percentage of time that useful information can be obtained.

The object of this paper is to show that useful qualitative information can be obtained just by looking at a sounder facsimile chart. In general terms the sounder will 'see' any atmospheric structure having associated fine-scale turbulence producing significant temperature and humidity fluctuations on a length scale approximately equal to that of the transmitted sound half-wavelength (i.e. about 10 cm). Thus it will readily indicate the presence of ground-based thermal activity, synoptic and nocturnal inversions, breaking waves and the turbulent thermal structure associated with a fog. Examples of these features are given in the following section.

## DESCRIPTIVE DETAILS

Certain factors must be borne in mind when one attempts to relate the structure present on a monostatic* sounder facsimile chart to turbulent activity in the atmospheric boundary layer. Firstly, the chart illustrates only that part of the atmosphere being advected over the vertically directed transmitter–receiver system. As a consequence the sounder provides only a 'height–time' section through any structure and so any inference about the three-dimensional shape cannot be attempted nor can the Lagrangian evolution of any features of interest be usefully discussed. The correspondence between the chart-implied and the actual structure will depend closely on the applied gain and dynamic range of the system. Therefore the location of, for example, thermal plume edges may be ill-defined. Furthermore, examination of the charts reveals an apparent 'fading' of turbulent thermal activity with height. To understand this it must be remembered that the sounder 'sees' only part of the turbulent spectrum corresponding to a length scale of about the transmitted half-wavelength (in our present case 10 cm). Recent experimental work has revealed that the intensity of temperature fluctuations on this particular scale falls off rapidly with height (Kaimal *et alii*, 1976). This means, for example, that a monostatic sounder typical of those in general use will significantly underestimate the upper limit of convection in deep boundary layers.

The following factors must be recalled to mind when qualitative interpretation of facsimile charts is attempted:

(a) *Inversion-capped convective boundary layer*

The synoptic situation over the British Isles at 1800 GMT on 28 October 1975 is shown in Figure 1(a). Eastern England was under the influence of an anticyclone centred over Poland which produced a light southerly airflow. The midday Balthum (Painter, 1970) ascent at Cardington is shown in Figure 1(b) and indicates a near adiabatic boundary layer capped by a strong (10°C) inversion with a stable region aloft. The acoustic sounder was in operation with a pulse length of 50 ms and the facsimile chart for the period 1335–1445 GMT is given in Plate I. A good correspondence is apparent between the strong echo near 200 m and the inversion recorded by the Balthum. It is felt that this echo is produced by temperature and humidity fluctuations generated by breaking waves or convection-induced hummocks at the inversion base. A similar echo is not apparent at the upper boundary of the inversion near 300 m and direct measurements showed that only a small fraction (about 0·5°C) of the total inversion strength occurred across the intense echo region. Further, more comprehensive measurements of the mean and fluctuating temperature and humidity fields in the neighbourhood of inversions will be required to obtain a fuller understanding of the source of such echo layers.

A closer study of the intense echo near 200 m reveals that it is distorted by a series of perturbations of similar scale but markedly differing frequency. The larger-scale undulations (with a period of some 30 minutes) may originate from mesoscale variations of the inversion base associated with slightly deeper convection or perhaps the outcome of very low-frequency waves propagating in the stable air above. The smaller-scale irregularities, with durations of some

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* i.e. with transmitter and receiver either sharing the same antenna or placed so close to each other that their separation may be ignored.

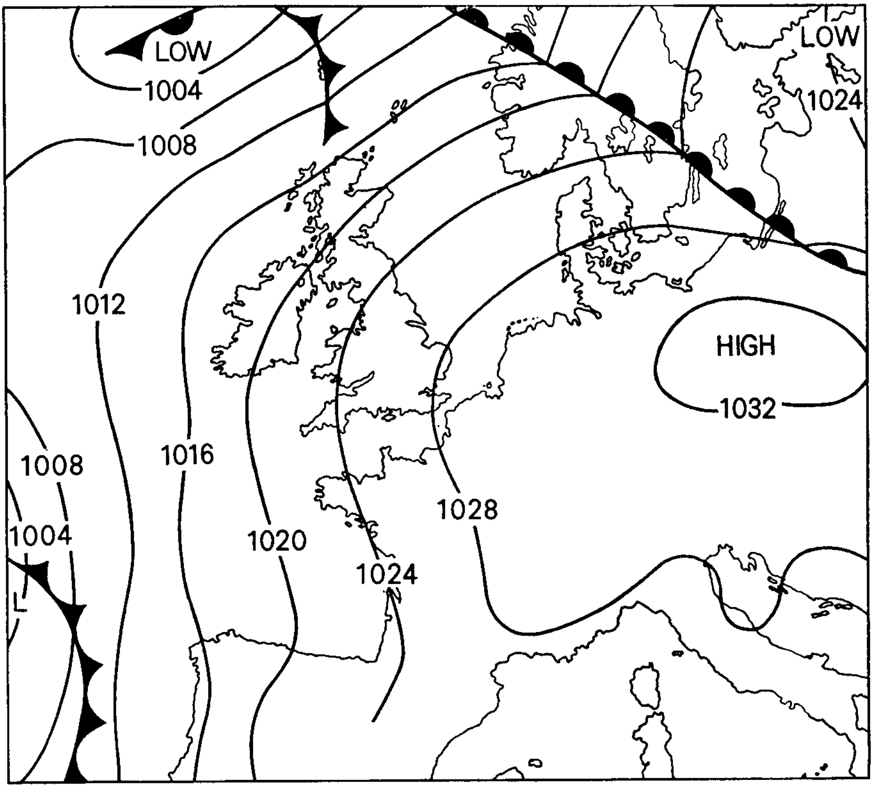


FIGURE 1(a)—SYNOPTIC SITUATION AT 1800 GMT ON 28 OCTOBER 1975

30 seconds to several minutes, have sharply defined boundaries and characteristics similar to the 'hummocks' described by Rayment and Readings (1974). These authors observed 'hummocks', some 50 m in depth and 500 m in length, propagating with approximately the mean wind speed within the mixed layer. In accordance with their findings (i.e. that these were induced by convective activity) the sounder chart indicates some correlation between thermal activity and upward movement of the echo layer. Below the inversion lower interface the 'plumes' (i.e. the column-shaped areas of more intense return on the facsimile chart) have durations comparable with these smaller-scale irregularities and those that extend towards the 200-m level can often be associated with 'hummocks' of greater vertical displacement. It is of interest to note that within the larger 'plumes', regions of enhanced return are evident and may imply a plume 'substructure' within which more intense temperature fluctuations occur (see Hall *et alii*, 1968). There is also some evidence (for example near 1426 GMT) of thermal activity extending from the inversion well down into the boundary layer. However, the energy within the mixed layer was not sufficient to effect a general lifting of the synoptic inversion on this day.

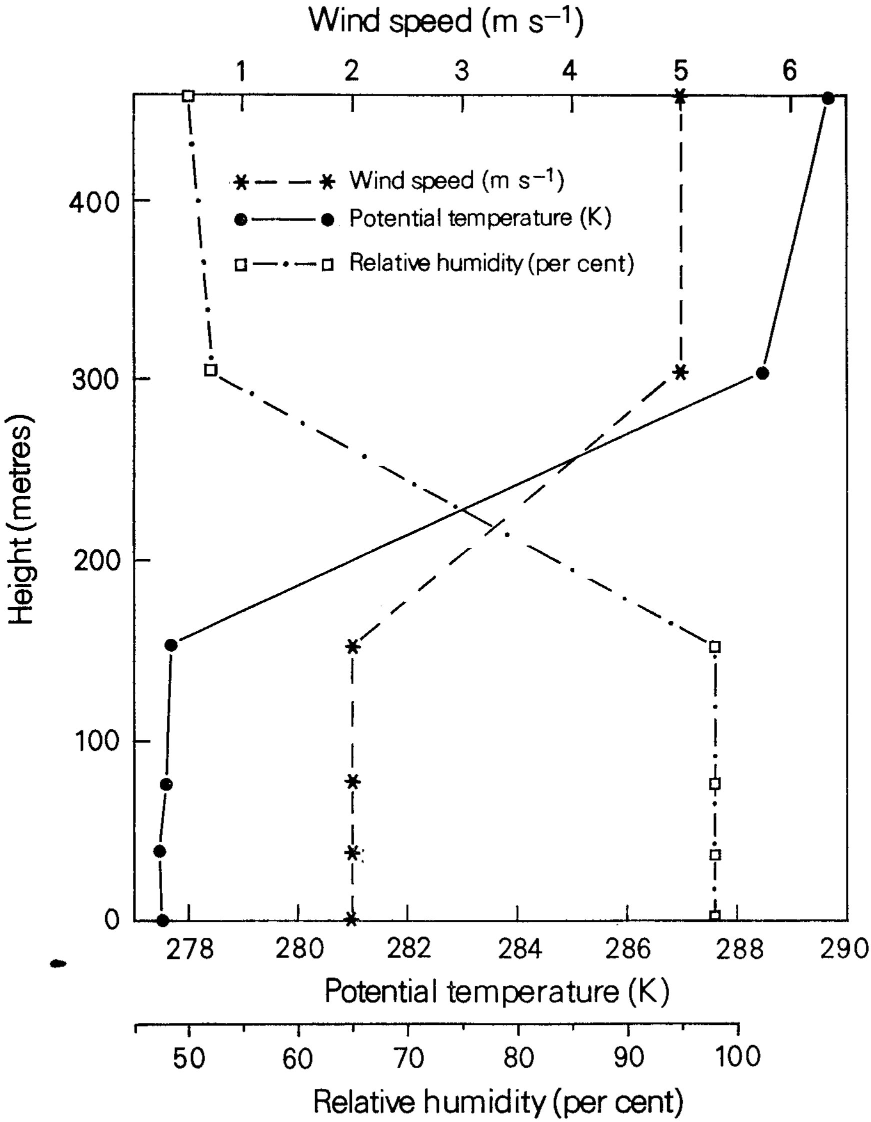


FIGURE 1(b)—CARDINGTON BALTHUM PROFILE FOR THE PERIOD 1048–1158 GMT ON 28 OCTOBER 1975

(b) *Rising inversion*

By 29 October 1975 the anticyclone present over Europe had receded eastwards and a frontal system was approaching the British Isles from the south-west. As the ridge over the North Sea declined convective activity was, on this occasion, successful in driving the inversion aloft. The acoustic sounder was used to monitor this rise (again using a 50 ms pulse duration) and a section of the facsimile chart (covering the period 1000–1100 GMT) is shown in Plate II.

Over this period the intense echo region rose about 6 mb. If it is assumed that this corresponds to an inversion-rise rate of about 6 mb per hour it is within reasonable limits of values found by other experimenters (e.g. Rayment and Readings, 1974 and Chorley *et alii*, 1975). The 'hummocks' are still clearly resolved although the intense echo is more diffuse in comparison with the previous day. (Note that the dark bands running vertically on the chart are the result of noise generated by passing aircraft.)

(c) *Fog situation*

The Cardington area was fogbound from 2000 GMT on 13 November 1975 and throughout the following day, the mean visibility being less than 100 m. On the second day the temperature only rose above 0°C during the period 1300–1600 GMT and surface winds were very light (about 1–1½ m $s^{-1}$). The sounder facsimile chart for the period 0856–0926 GMT for 14 November 1975 is shown in Plate III. This indicates an intense echo at about 100 m which correlates well with the inversion layer as recorded by the midday Balthum ascent (see Figure 2) and is probably associated with the fog top. (The humidity profile from the Balthum ascent shows much drier air above 100 m and saturated air below.) Although saturated air in no way implies the presence of fog this profile supports the notion that the layer of intense echo provides an upper limit to the depth of the fog. Within the body of the fog weak 'convective' activity is observed with features remarkably similar to thermal plumes being resolved. This agrees with the Balthum's slightly unstable profile of potential temperature extending up to near 100 m. Undulations of the echo layer, on time-scales of a few minutes, may illustrate the interaction of the weak thermals with the inversion layer present as well as the existence of waves in the stable air aloft. Regions of activity apparently extending 'downwards' from the base of the intense echo between the thermal 'plumes' could be due to the overturning of these convective elements and their interaction with tight gradients present in the inversion regions. This would strengthen the evidence for the model of downward entrainment of air through an inversion interface put forward by Readings *et alii* (1973).

During the period between Balthum ascents (i.e. 1201–1656 GMT) the fog continued to persist at the surface; however, some interesting phenomena were detected by the sounder at higher levels. Between about 1250 and 1340 GMT, when the surface visibility averaged 50 m, the echo layer (i.e. the probable vertical extent of the fog) descended substantially to be less than 50 m from the surface while the stable layer above showed the presence of a succession of waves (see Plate IV). (It was during this period that the screen temperature first rose above 0°C; having been —0·1°C at 1251, it rose to 1·4°C by 1350). The majority of waves present in the first 70 m have the same amplitude and appear to be in phase, with periods of some few minutes. Those at higher levels are of higher frequency but of similar amplitude. By 1435 GMT the oscillatory patterns have dispersed and another intense echo layer has formed but this time much closer to ground level (about 40 m). Horizontal visibility continued to decrease, being 40 m at 1450, when a surface temperature of 1·3°C was recorded. The sounder chart for the period 1435–1600 GMT is shown in Plate V and indicates that during this interval the intense echo descends by about 15 m to be at its lowest level (i.e. about 25 m) at 1555. Below the strong echo layer weak convective activity can still be just discerned. However, in the

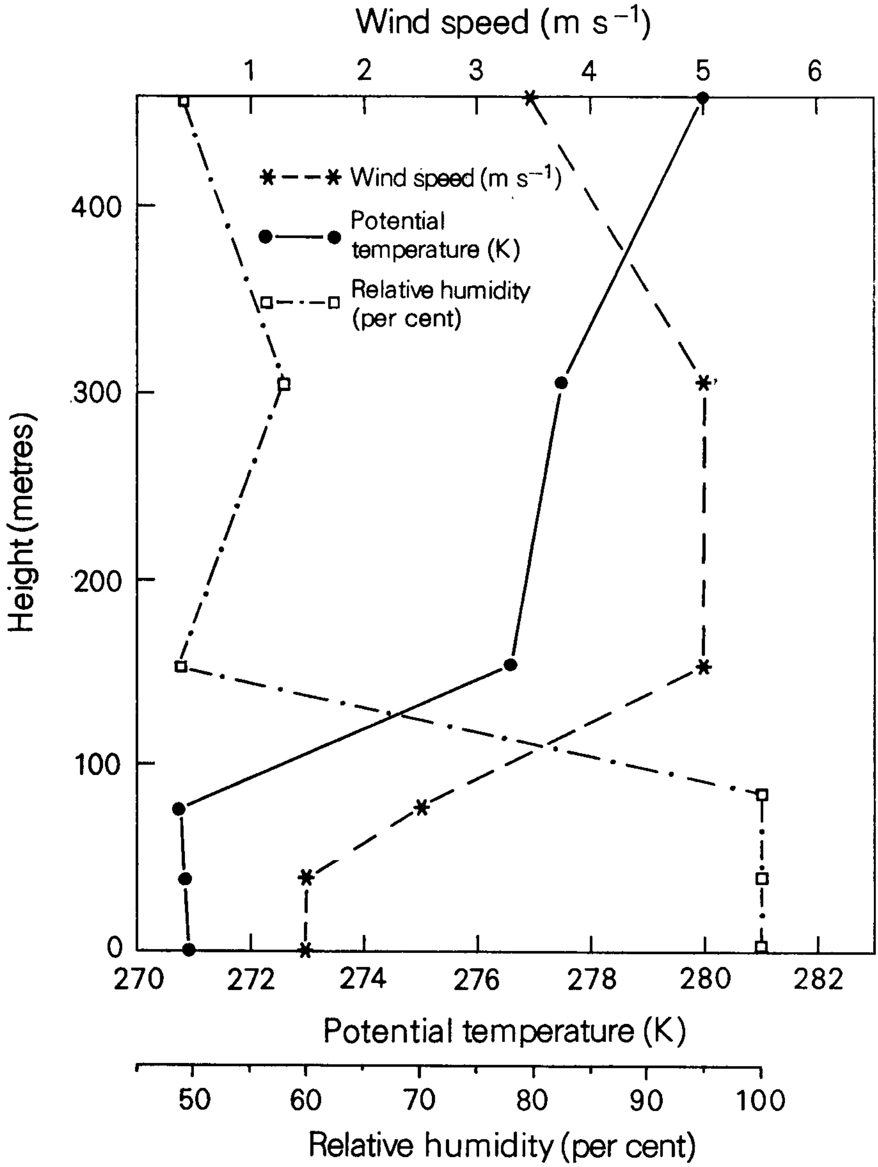


FIGURE 2—CARDINGTON BALTHUM PROFILE FOR THE PERIOD 1048–1201 GMT ON 14 NOVEMBER 1975

stable air above, the chart reveals the appearance of bursts of activity between 1455 and 1555 GMT which are probably associated with the presence of breaking gravity waves. The sounder in this instance was operating with a 5 ms pulse duration enabling structures to be resolved down to about 2 m. Therefore these oscillatory patterns must represent fluctuations occurring within a depth of only a few metres. Their structure, from the chart, resembles closely that observed by Caughey and Readings (1975) and Hooke *et alii* (1973). The temperature fell below 0°C at 1700 GMT when the lowest visibility (about 25 m) was observed and the fog persisted until 0200 GMT on 15 November when, with the approach of a warm front from the south-west and the advection of stratocumulus, it cleared within an hour. If the reasonable assumption is made that the intense echo recorded by the sounder represents the upper limit for the fog depth then it seems that the simple monostatic sounder could form a useful aid in the prediction of radiation fog clearance.

(d) *Nocturnal inversion*

The Balthum profile for the night of 6/7 November 1975 (Figure 3) shows that a strong nocturnal inversion, extending up to approximately 350 m, was present in the Cardington area. Plate VI shows the sounder facsimile chart for the period 0208–0253 GMT on this night. It reveals a 'filamentary' form of turbulence fluctuations below about 150 m, which, from the Balthum profile,

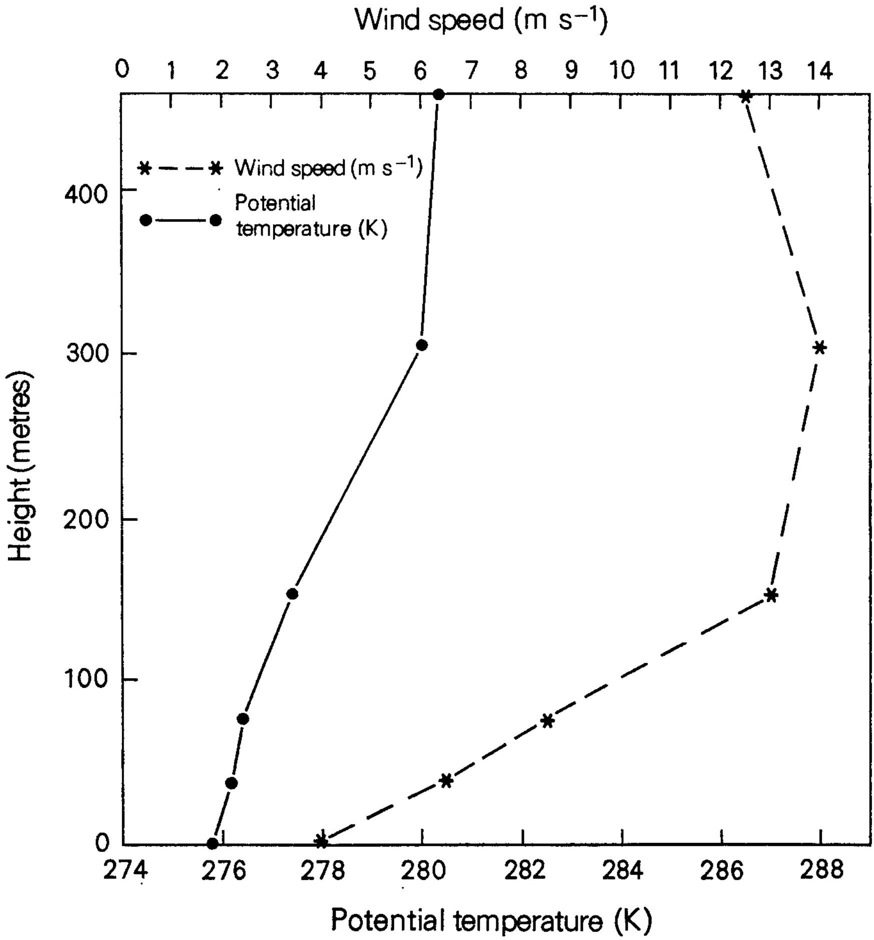


FIGURE 3—CARDINGTON BALTHUM PROFILE FOR THE PERIOD 0635–0723 GMT ON 7 NOVEMBER 1975

was a region of marked wind shear. It therefore seems plausible that the echoes on this occasion were from temperature fluctuations generated by mechanical turbulence acting on the steep temperature gradient. The 'filaments' of activity probably reflect the presence of regions of stronger mixing. In the region of small wind shear, between 150 and 300 m, no echo is evident although the temperature gradient is still quite appreciable.

## Concluding remarks

A simple vertically directed monostatic acoustic sounder has been shown to be a valuable asset in the investigation of the structure of turbulence in the planetary boundary layer. The visual display of atmospheric features provided by the sounder facsimile chart forms a very useful supplement to direct measurements of the turbulent flow. In particular it greatly aids the positioning of balloon-borne instrumental packages in regions of interest and gives a physical insight into the structures generating the average statistics. The monostatic sounder may also provide a useful aid in the prediction of radiation fog clearance and this will be investigated in field studies of fog formation and dissipation to be carried out in the near future. A bistatic sounder (i.e. recording off-axis as well as backscattered sound) should also provide useful information on the fluctuation wind field and this topic is at present under study at Cardington (Caughey *et alii*, 1976). Acoustic sounding also appears promising as a remote sensing method for quantitatively estimating important turbulence statistics and in this respect long-term evaluation studies still seem necessary.

## Acknowledgements

The authors wish to thank their colleagues at the Meteorological Research Unit, Cardington for assistance in all stages of the acoustic sounder evaluation program.

## Appendix

### Operating parameters for the Cardington acoustic sounder installation

A. *Transmitter*

1. Repetition rate: Nine settings from 0·05 to 1·0 Hz.
2. Height marks: Always in operation marking the facsimile chart every 100 m.
3. Pulse length: Continuously variable between 5 and 500 milliseconds.
4. Transmission frequency: Choice of 4 frequencies; these may be pre-set anywhere in audio-spectrum (present values 580, 820, 1300 and 1732 Hz).
5. Power output: Variable from 0 to 500 watts (r.m.s.) electrical power.

B. *Receiver*

1. Head amplifier: Has a fixed gain of $10^3$ for a frequency of 1732 Hz.
2. Ramp gain: (a) Height of ramp (where ramp is initiated by transmit pulse) is variable from $10^{-2}$ to 1.
   (b) Length of ramp is variable from 0·3 to 20 seconds (equivalent to 50–3300 m in height).
3. Band pass filter: For each of the 4 transmit frequencies a choice of bandwidth exists at $\pm 5$, $\pm 10$ and $\pm 20$ per cent of that particular transmit frequency.

4. Overall gain: Continuously variable up to maximum value of $10^7$.

C. *Outputs*

1. Data signals: Received signal converted to d.c. voltage for logging on analogue tape recorder and fast sampling by a computer-controlled analogue–digital system (voltage range 0–5·5 V); a.c. signal available for Doppler shift work.
2. Facsimile chart signals: Mufax equipment has a gain control (independent from the rest of the system) with logarithmic response as well as noise clip level. Can be varied continuously by operator to produce optimum picture quality.

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# THE ANNUAL COURSE OF SOME INDICES OF THE ZONAL AND MERIDIONAL CIRCULATION IN MIDDLE LATITUDES OF THE NORTHERN HEMISPHERE

By M. K. MILES

SUMMARY

The annual course of indices of the zonal and meridional surface circulation together with meridional thickness gradients is presented for several areas and for the whole hemisphere. It appears that if for convenience a single latitude band is desired for all areas and all seasons the 20° latitude band from 35°N to 55°N best encompasses the surface westerlies.

Some notable differences are apparent between the course of the westerlies in the Pacific and Atlantic Oceans and between the time of the winter peak of the zonal circulation and that of the meridional circulation.

## 1. INTRODUCTION

Although the climatology of the middle-latitude westerlies is well known in many respects, a study of some simple indices of the zonal circulation reveals some remarkably clear-cut differences between the rate of development of the westerlies over the Pacific and Atlantic Oceans in the late autumn. It may be important to recognize these clearly because their explanation could increase our understanding of the fluctuations of the winter westerlies which are such an important feature of our climate. These indices are presented along with appropriate mean values of the tropospheric temperature gradient, because these two features have often been linked in a kind of causal relationship, often without any quantitative study.

Some indices of the meridional circulation are also presented because of their possible relation to the meridional flux of heat and the meridional temperature gradients.

## 2. Preparation of the indices

(a) *General*

All the indices were prepared from grid-point values in the magnetic tape library of the Synoptic Climatology Branch of the Meteorological Office. These grid points are spaced 5° of latitude apart and at 10° longitude intervals up to 65°N and thereafter at 20° longitude intervals to 80°N. Most of the indices are based on means for the period 1951–70 but in a few cases values based on the period 1900–70 are shown in the diagrams.

(b) *Zonal indices—surface*

The basic units for the zonal indices are values of mean geostrophic west wind worked out from meridional surface pressure differences across 5° latitude bands. The basic time of averaging is a half month. Indices for the following longitude areas are formed by summing the values for the appropriate meridians and taking the means:

| | |
|---|---|
| Atlantic area | 60°W to 10°W (inclusive) |
| western Pacific | 140°E to 180°E (inclusive) |
| eastern Pacific | 170°W to 130°W (inclusive) |
| northern hemisphere | mean of 36 meridians. |

Values of the mean indices in metres per second are then available for six 5° latitude bands.

A band about 20° latitude wide seems to be the optimum width to represent the surface westerlies on a hemispheric basis. Values of the mean indices for half months and the seasons are shown in Table I for three 20° bands. The bands 35–55°N and 40–60°N display the westerlies about equally well, but values for 35–55°N have been used in most of the diagrams because they display the winter maximum over the oceans better, and indeed in winter the 30–50°N band is even more appropriate for the Pacific. When comparing the development of the westerlies from the autumn to the winter in the two oceans modified band widths have sometimes been used.

(c) *The meridional thickness gradient*

This has been expressed as the difference in the mean monthly thickness (1000/500 mb) between 35°N and 55°N along each meridian, each averaged over a month.

Mean values for the following longitude areas have been obtained:

| | |
|---|---|
| Atlantic area | 60°W to 10°W |
| western Pacific | 140°E to 180°E |
| eastern Pacific | 170°W to 130°W |
| Europe and Asia | 0 to 130°E |
| America | 120°W to 70°W |
| hemisphere | mean of 36 meridians. |

(d) *The meridional gradient of geopotential at 500 millibars*

This has been treated exactly like the thickness gradient.

(e) *Meridional indices—surface*

The basic unit here is the monthly mean northerly geostrophic wind determined over a 30° longitude band. These have been determined at 18 meridians

TABLE I—ANNUAL COURSE OF THE ZONAL INDEX FOR THE NORTHERN HEMISPHERE FOR VARIOUS LATITUDE BANDS—MEANS FOR PERIOD 1900–70

| *Half months* | 30–50°N | 35–55°N | 40–60°N |
|---|---|---|---|
| | | *m s*$^{-1}$ | |
| Jan. (1) | 1·5 | 2·4 | 2·5 |
| Jan. (2) | 1·2 | 1·7 | 1·7 |
| Feb. (1) | 1·1 | 1·4 | 1·2 |
| Feb. (2) | 1·3 | 1·6 | 1·2 |
| Mar. (1) | 1·1 | 1·3 | 1·0 |
| Mar. (2) | 1·1 | 1·4 | 1·2 |
| Apr. (1) | 0·9 | 1·4 | 1·3 |
| Apr. (2) | 0·9 | 1·3 | 1·0 |
| May (1) | 0·9 | 1·3 | 0·9 |
| May (2) | 0·7 | 1·1 | 0·9 |
| June (1) | 0·5 | 0·9 | 0·9 |
| June (2) | 0·5 | 1·1 | 1·3 |
| July (1) | 0·4 | 1·3 | 1·7 |
| July (2) | 0·1 | 1·2 | 1·7 |
| Aug. (1) | −0·2 | 1·1 | 1·7 |
| Aug. (2) | −0·4 | 0·9 | 1·6 |
| Sept. (1) | −0·5 | 0·9 | 1·8 |
| Sept. (2) | −0·4 | 1·3 | 2·2 |
| Oct. (1) | 0·1 | 1·9 | 2·9 |
| Oct. (2) | 0·5 | 2·2 | 3·0 |
| Nov. (1) | 1·0 | 2·5 | 2·9 |
| Nov. (2) | 1·3 | 2·6 | 2·9 |
| Dec. (1) | 1·8 | 2·9 | 2·9 |
| Dec. (2) | 2·1 | 2·9 | 2·7 |
| *Seasons* | | | |
| Winter | 1·5 | 2·2 | 1·9 |
| Spring | 0·9 | 1·3 | 1·0 |
| Summer | 0·2 | 1·1 | 1·5 |
| Autumn | 0·3 | 1·9 | 2·6 |

spaced 20° apart round the hemisphere, and are summed without regard to sign to give an index of the meridional circulation for various zones and for the whole hemisphere.

Values are available for the latitude bands 35–55°N and 55–75°N.

## 3. ANNUAL COURSE OF THE INDICES

The annual course of the surface zonal index and the meridional thickness gradient for the whole hemisphere and for the oceanic regions is shown in Figure 1. It brings out how much stronger the surface westerlies are over the oceans than over the hemisphere as a whole. In fact the land areas have a net easterly at most times of the year. The meridional thickness gradients are not, however, markedly different over the land and ocean areas. There are some interesting differences brought out in Figure 2. The rate of increase of the meridional thickness gradient from August to November is surprisingly rather greater over the oceans than over the land areas. This seems to be connected with the increase in the oceanic westerlies, especially in the Pacific, during this time. The gradient reaches its peak over the oceans in December whereas the peak over the land is not reached until February.

Figure 3 shows the zonal indices and meridional thickness gradients for the western and eastern Pacific separately. They both show peaks in November

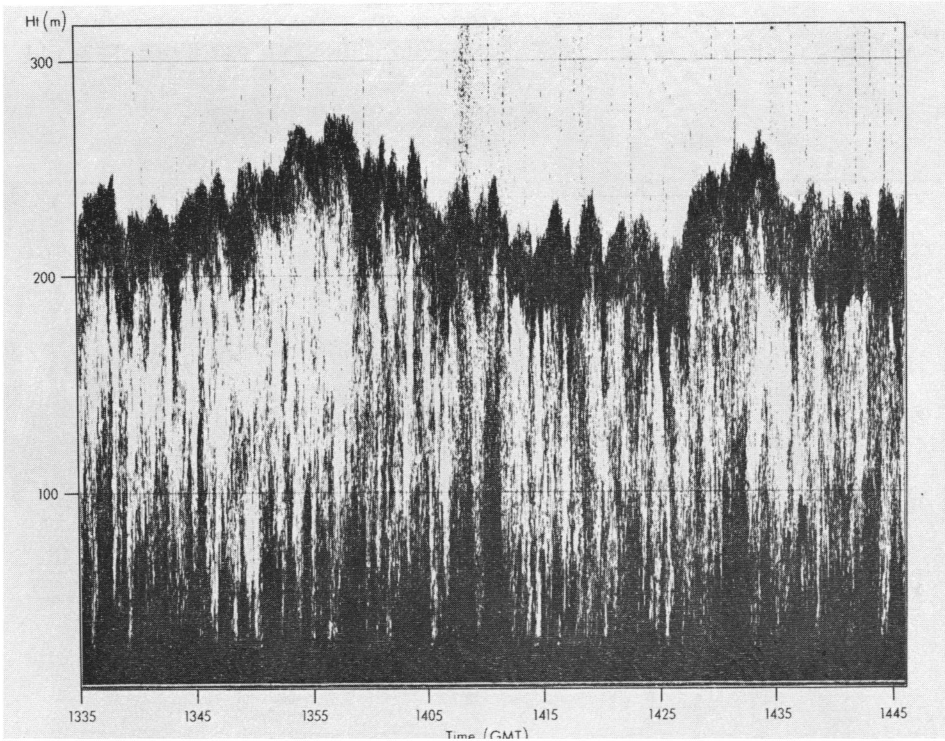


PLATE I—SOUNDER FACSIMILE CHART FOR THE PERIOD 1335–1445 GMT ON 28 OCTOBER 1975

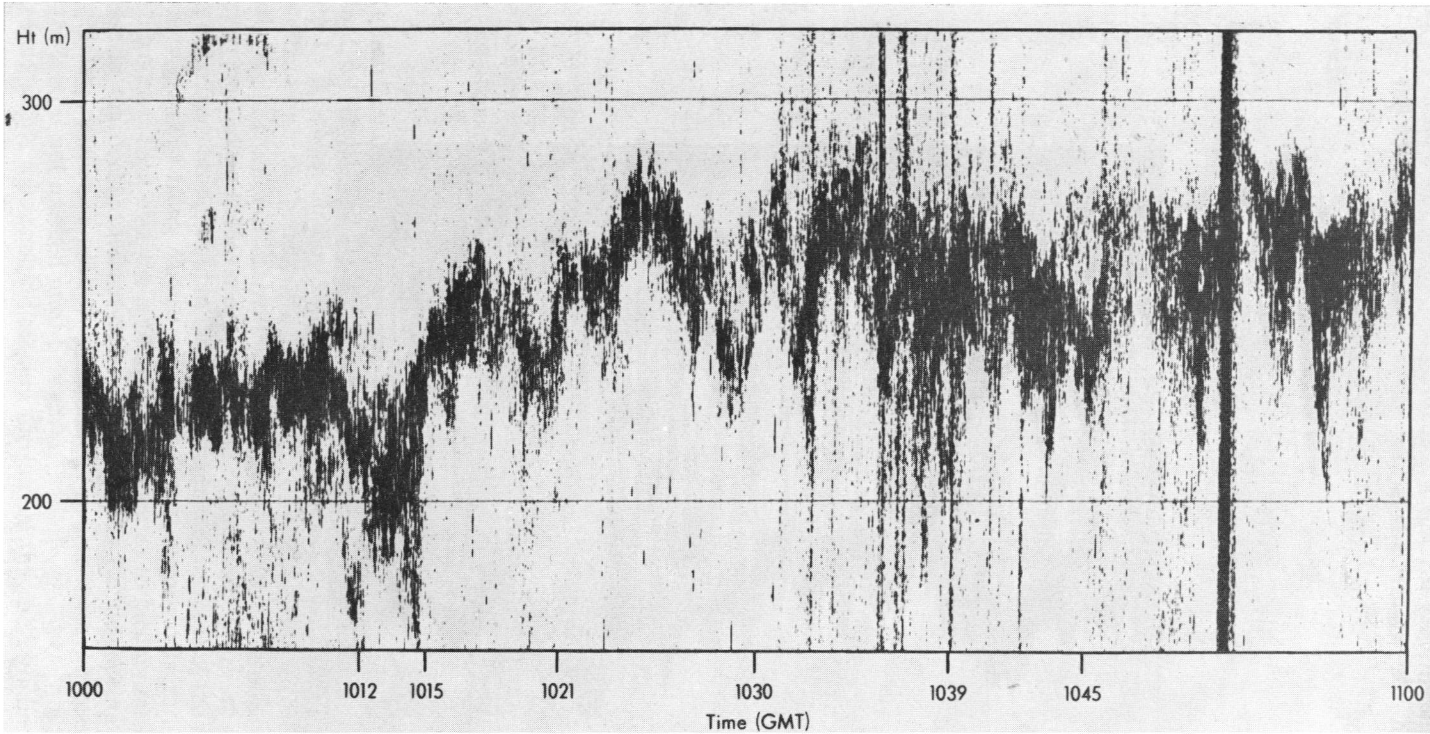


Plate II—Sounder facsimile chart for the period 1000–1100 GMT on 29 October 1975

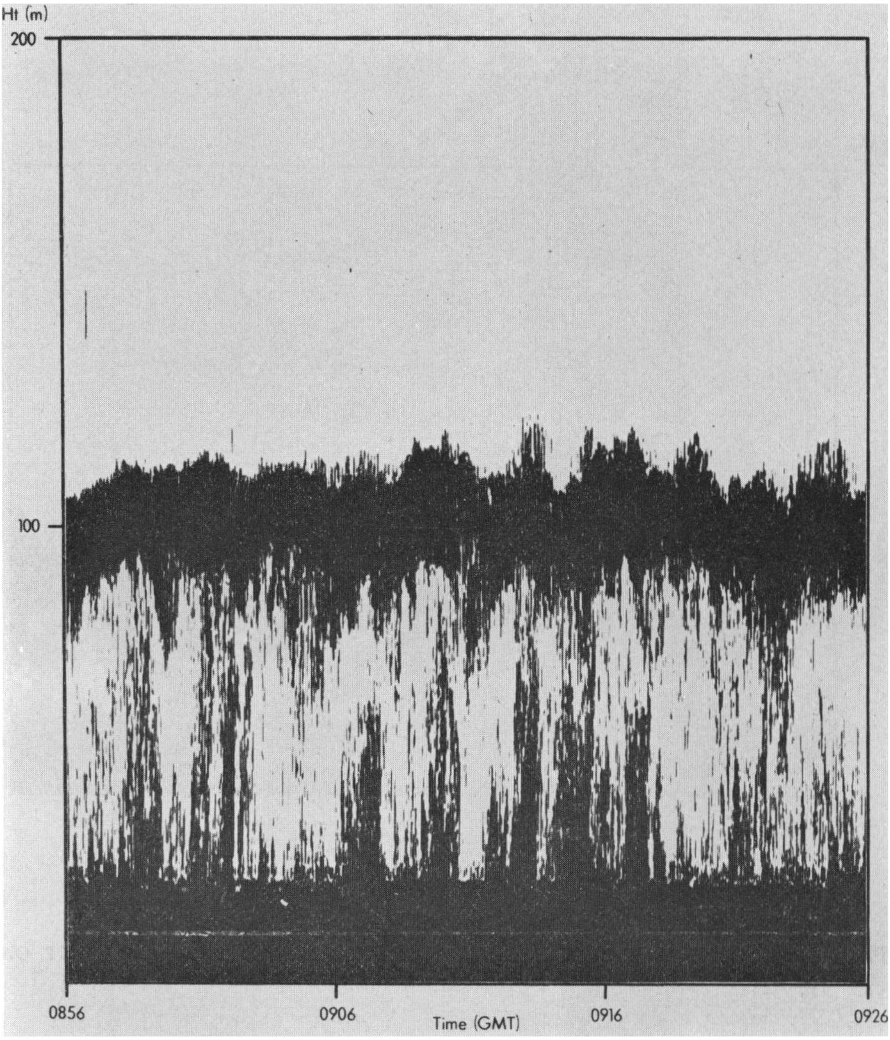


PLATE III—SOUNDER FACSIMILE CHART FOR THE PERIOD 0856–0926 GMT ON 14 NOVEMBER 1975

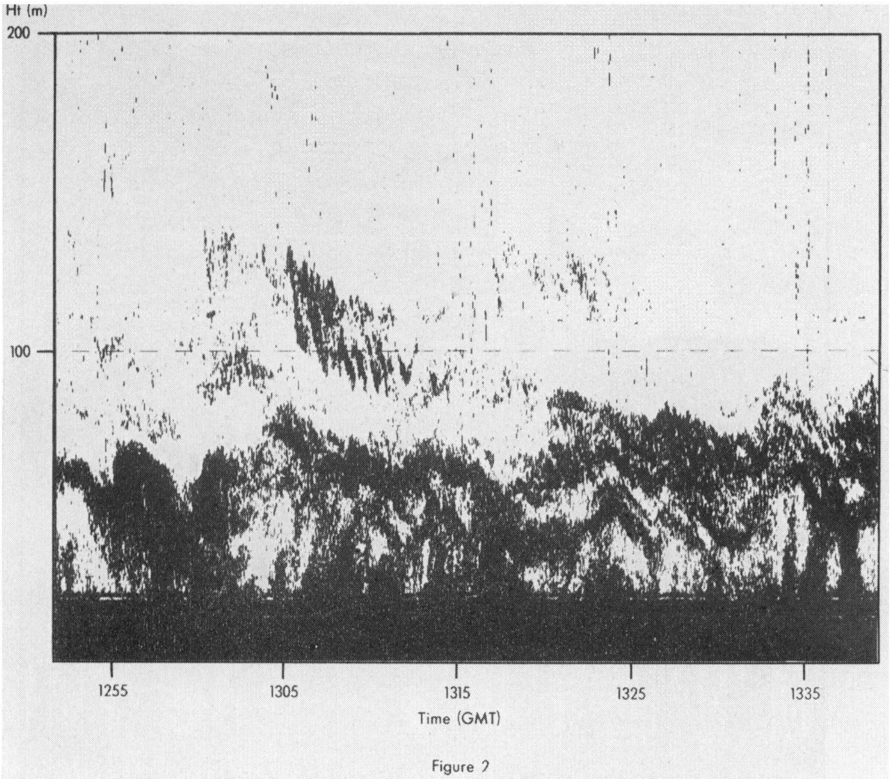


PLATE IV—SOUNDER FACSIMILE CHART FOR THE PERIOD 1250–1340 GMT ON 14 NOVEMBER 1975

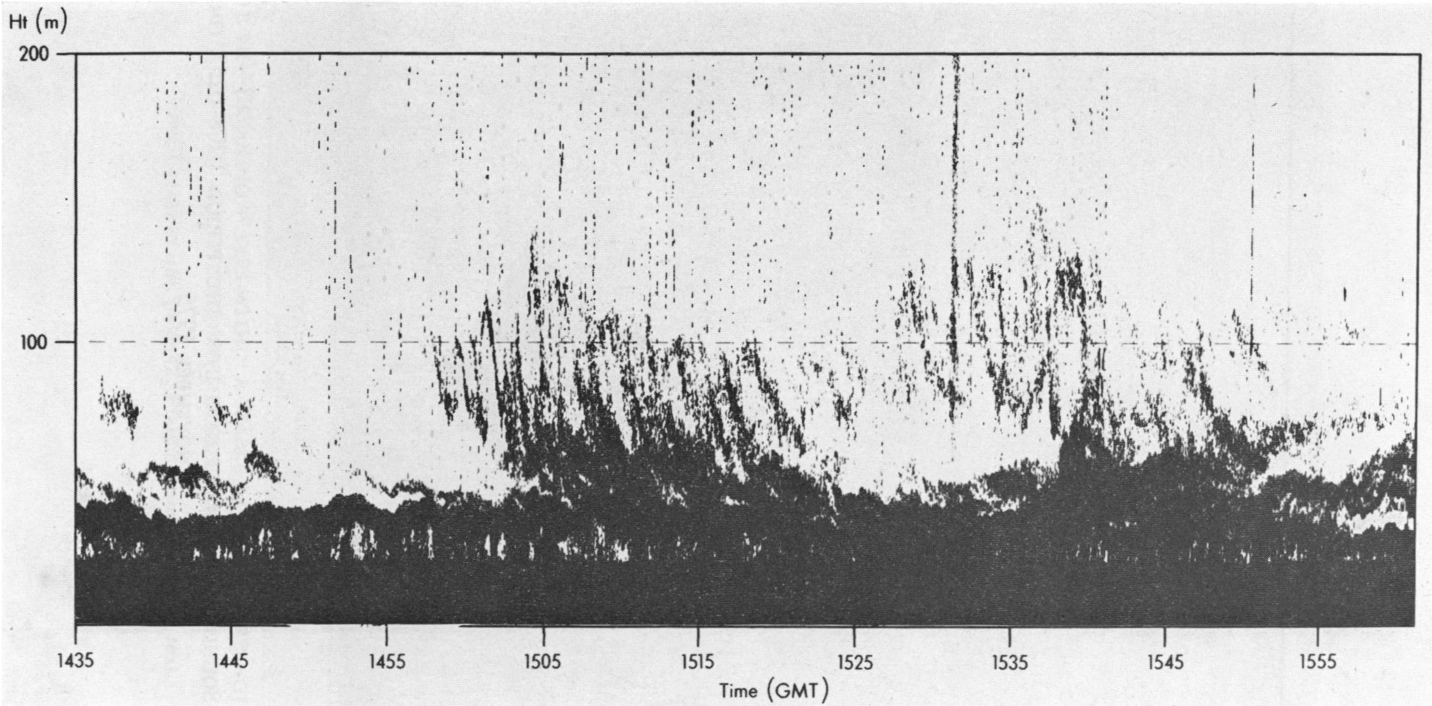


PLATE V—SOUNDER FACSIMILE CHART FOR THE PERIOD 1435–1600 GMT ON 14 NOVEMBER 1975

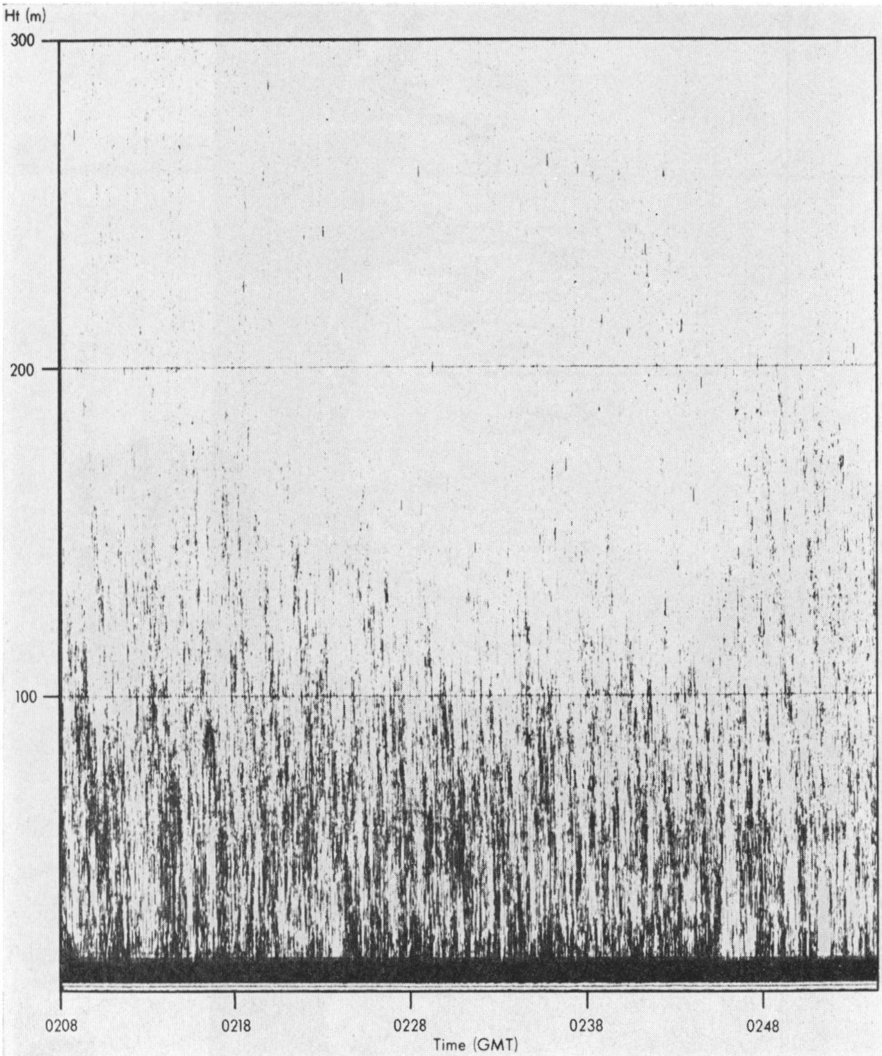


PLATE VI—SOUNDER FACSIMILE CHART FOR THE PERIOD 0208–0253 GMT ON 7 NOVEMBER 1975

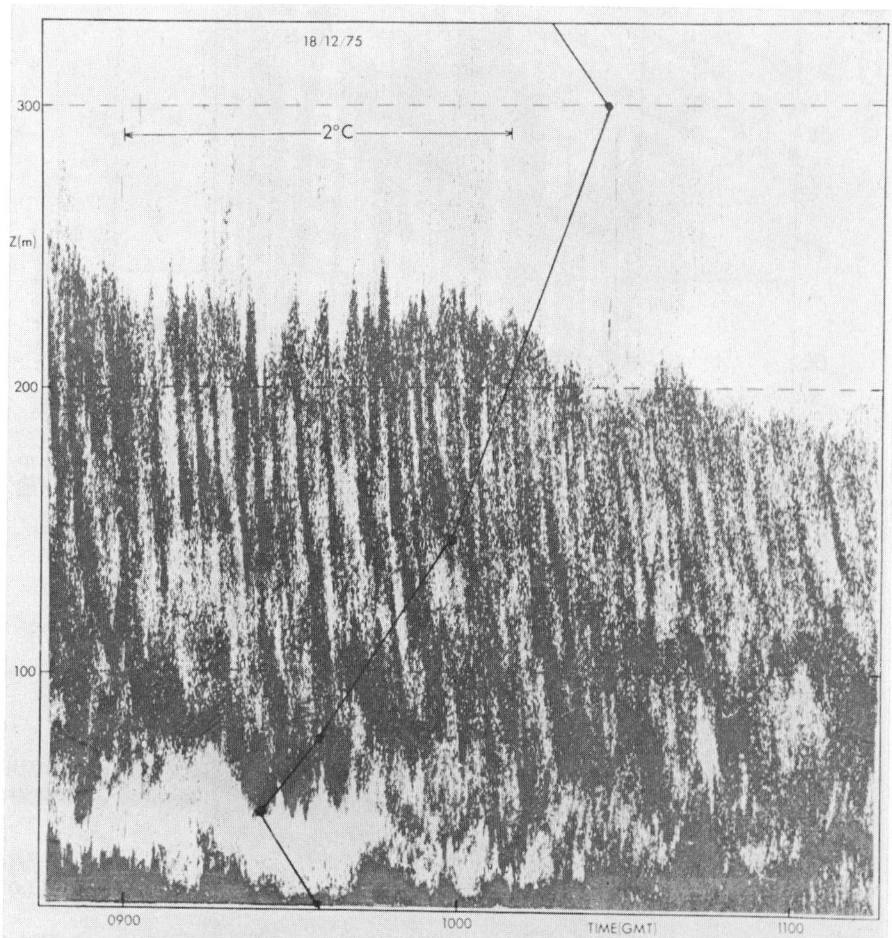


PLATE VII—BREAKING WAVES WITHIN A STABLE LAYER. A CARDINGTON BALTHUM IS SHOWN FOR REFERENCE

(See Crease *et alii*, page 42; Plate not referred to in text.)

*To face page 55*

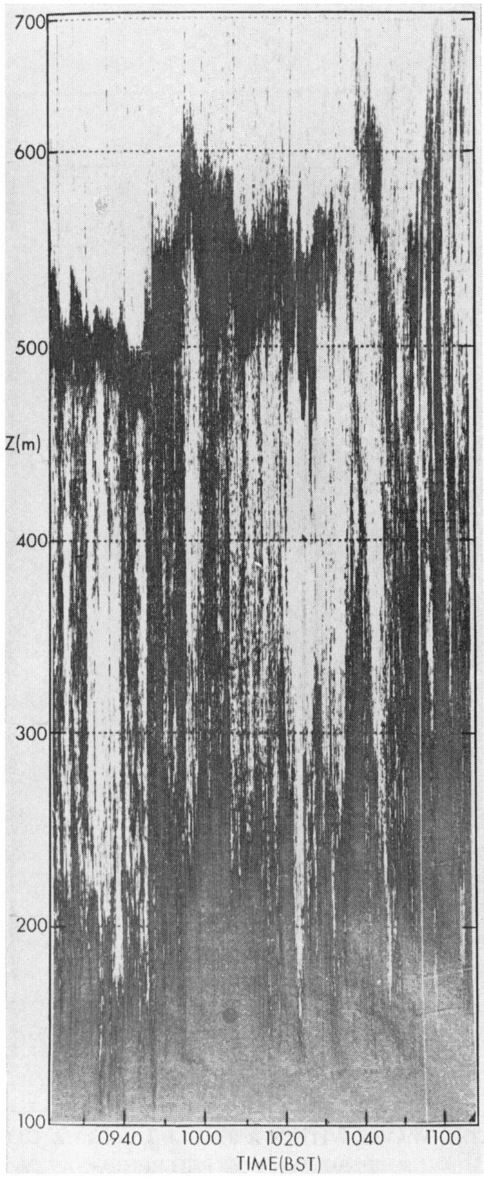


PLATE VIII—ACOUSTIC SOUNDER RECORD FROM A LAYER OF STRATUS CLOUD WHICH EXTENDED FROM NEAR THE SURFACE TO ABOUT 500 m. THE CLOUD BEGAN TO DISSIPATE (WEAKENING LAYER ECHO) AT AROUND 1030 GMT OWING TO INCREASING CONVECTION

(See Crease *et alii*, page 42; Plate not referred to in text.)

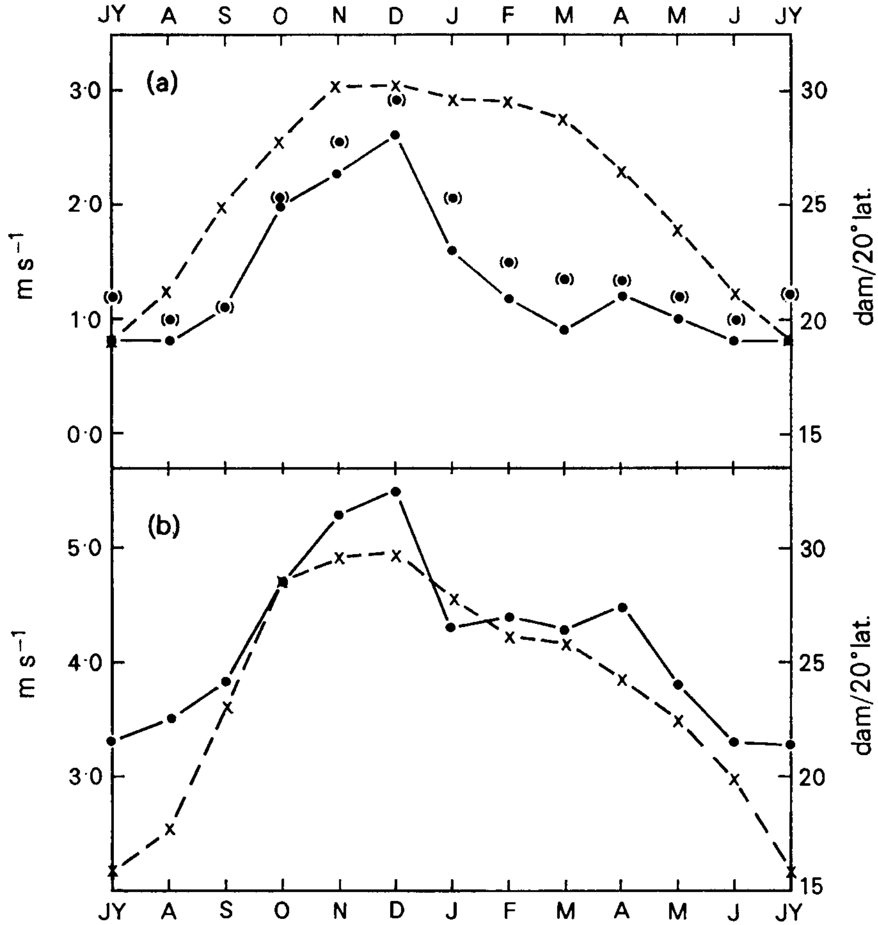


FIGURE 1—MONTHLY AVERAGES OF ZONAL INDEX (•——•) AND MERIDIONAL THICKNESS GRADIENT (1000/500 mb) (×– – –×) FOR LATITUDE BAND 35–55°N FOR PERIOD 1951–70

(Values plotted (·) are averages for 1900–70.)
(a) Hemisphere (b) Oceanic areas

but this is exaggerated because the flow moves mainly south of 50°N after November. The thickness gradient is much stronger in the western Pacific owing to the intense gradient present, just off the east Asian coast, but is not accompanied by such strong surface westerlies as in the eastern Pacific where the thickness gradient is much smaller. This is true for the 30–50° latitude band as well.

In comparing the Pacific and Atlantic it is necessary to measure the westerlies over different latitude bands, 35–55°N for the Atlantic and 30–50°N for the Pacific. The longitude band chosen for the Pacific is 150°E to 150°W which avoids the disturbing effects of the land areas on either side of the Ocean.

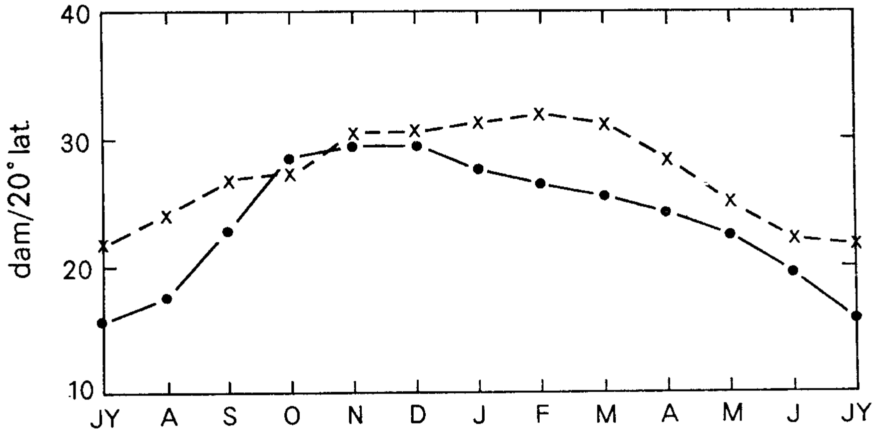


FIGURE 2—AVERAGE MONTHLY MERIDIONAL THICKNESS GRADIENT (1000/500 mb) FOR LATITUDE BAND 35–55°N FOR PERIOD 1951–70. OCEANIC AREAS (•——•) LAND AREAS (×– – –×)

Figure 4 shows the annual course of the zonal indices and meridional thickness gradients for the two oceans. The following points are worth noting:

(1) The larger seasonal range in the Pacific of both westerly wind and thickness gradient—due mainly to the intense monsoonal effect over Asia.

(2) The rapid growth in the westerlies in the Pacific between October and November in contrast to the stagnation in the Atlantic at this time.

(3) The November peak in the thickness gradient in the Pacific—one or two months earlier than in the Atlantic.

(4) The relation of the zonal index to the thickness gradient is similar in one respect: the peak of the zonal index is not accompanied by a peak of thickness gradients.

(5) Although peak values of the zonal index in the Atlantic are slightly less than in the Pacific the ratio of zonal index to thickness gradient is notably higher in the Atlantic.

Figure 5 shows that for the band 35–55°N the maximum meridional zonal gradient at 500 mb is reached over the oceans in November and December. Although the strongest flow moves southwards through the winter the 30–50° band still shows a substantial fall in gradient from December to January. Despite weaker thickness gradients in almost all months the 500 mb flow is stronger over the oceans than over the land areas—a result of the baroclinic conversion of the potential energy to zonal kinetic energy in the western parts of the oceans.

Figure 6 shows the annual course of the hemispheric meridional indices for the two latitude bands. The main features are a maximum in January in both bands, and a secondary maximum in July in the 35–55° band due largely to the monsoonal developments over Eurasia and America.

Meridional indices for the band 35–55°N chosen to represent the Pacific and Atlantic Oceans are shown in Figure 7. The maximum is reached in January or February in contrast to the earlier peaking of the zonal circulation (Figures 3 and 4). Again there is a secondary maximum in July indicating the relative accentuation of the high-pressure area over the central parts of the two oceans at this time of year.

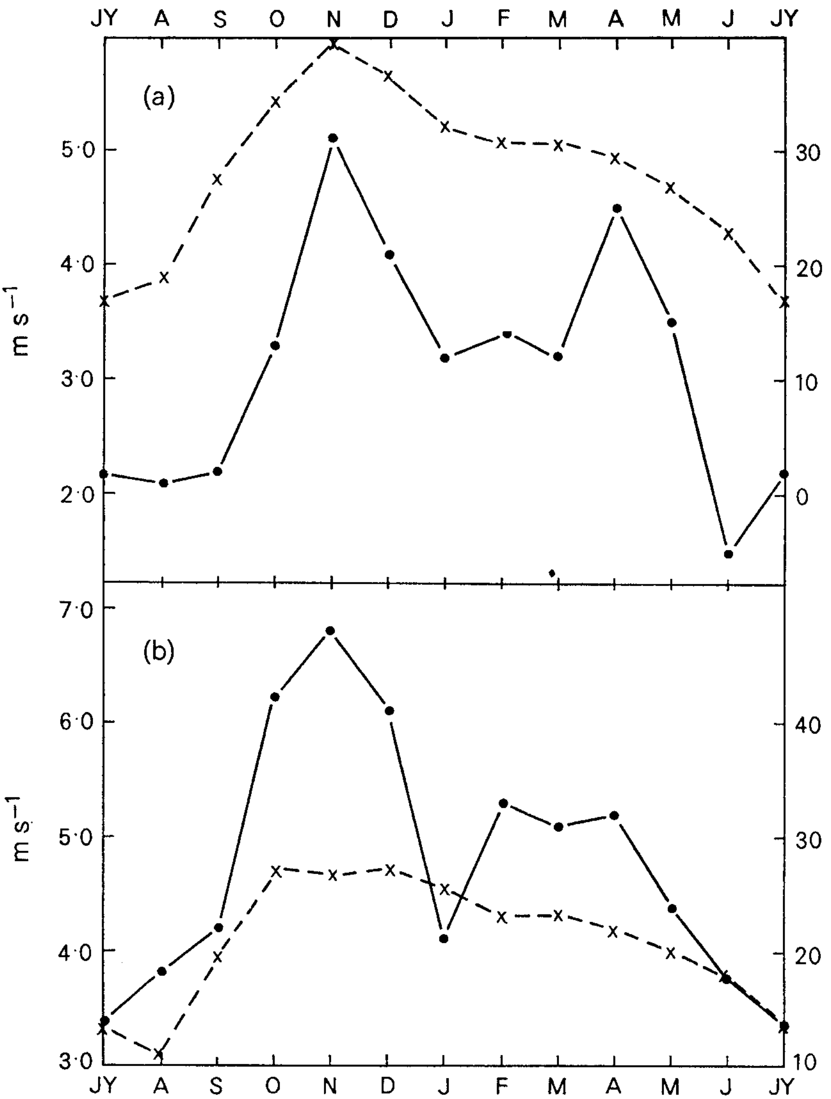


FIGURE 3—MONTHLY AVERAGES OF ZONAL INDEX (•——•) AND MERIDIONAL THICKNESS GRADIENT (1000/500 mb) (×- - -×)

(a) Western Pacific 140°E–180°E
(b) Eastern Pacific 170°W–130°W

## 4. THE VARYING RATES OF GROWTH OF THE WINTER WESTERLIES

The zonal indices show quite clearly that the autumnal increase in the westerly circulation does not occur at the same time in the three oceanic regions. It occurs earliest in the eastern Pacific Ocean where the rate of growth reaches a maximum around the end of September. Figure 8 shows the rates of growth obtained by differencing the adjacent half-month means of the zonal index.

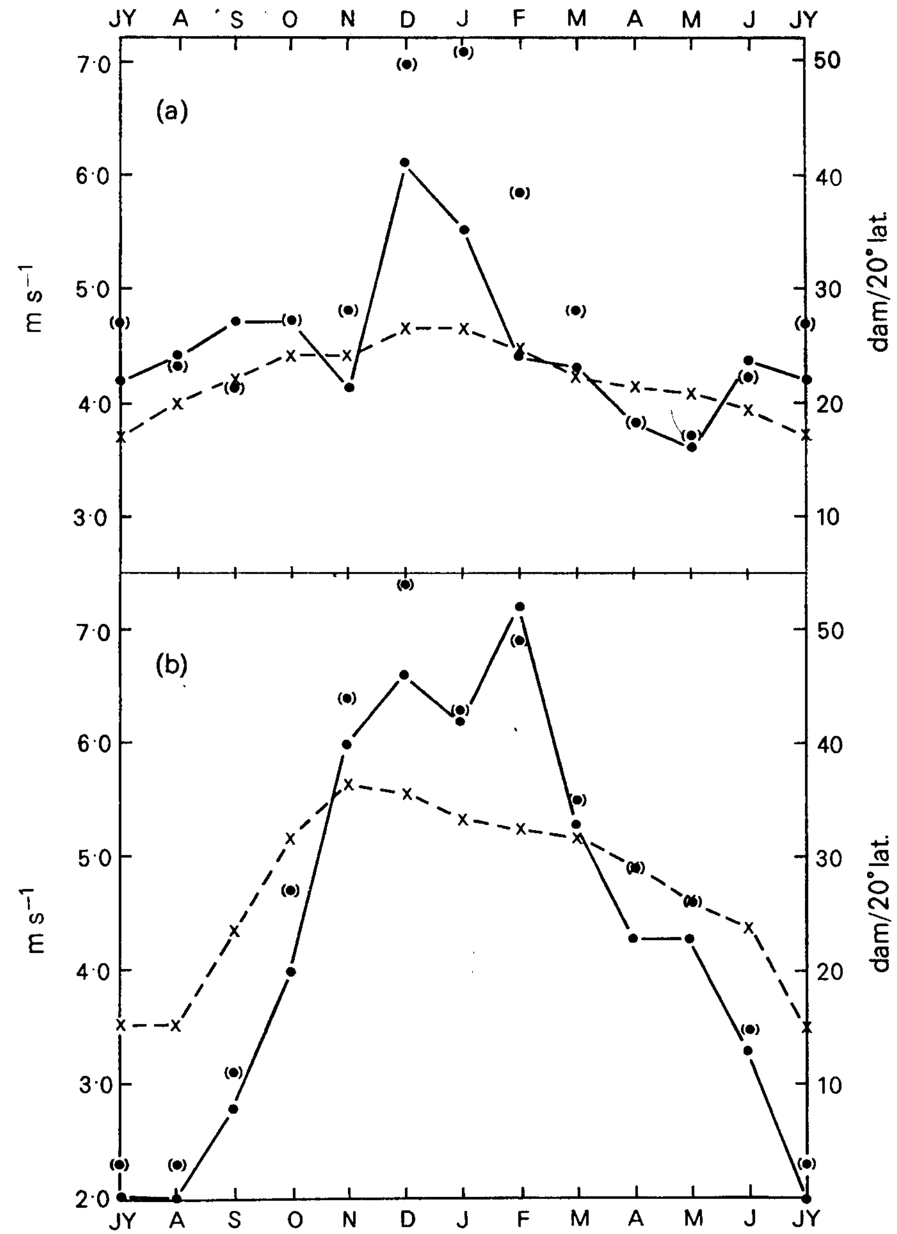


FIGURE 4—MONTHLY AVERAGES OF ZONAL INDEX (·——·) AND MERIDIONAL THICKNESS GRADIENT (1000/500 mb) (×- - - ×)

(Values plotted (·) are averages for 1900–70.)
(a) Atlantic Ocean 35–55°N
(b) Pacific Ocean 30–50°N and 150°E to 150°W

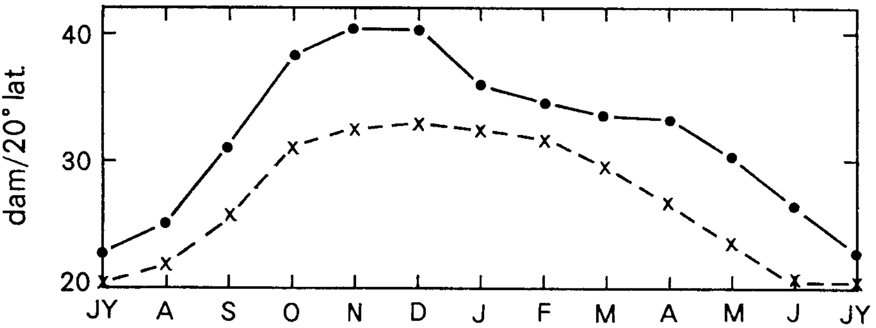


FIGURE 5—AVERAGE MONTHLY MERIDIONAL CONTOUR GRADIENT AT 500 mb FOR 35–55°N

Oceanic areas (·——·) Land areas (×- - -×)

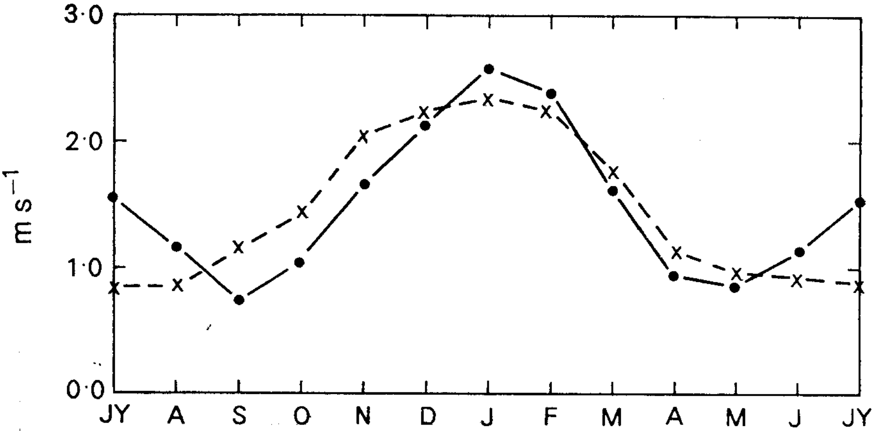


FIGURE 6—MONTHLY AVERAGES OF HEMISPHERIC MERIDIONAL INDICES FOR 35–55°N (·——·) AND 55–75°N (×- - -×) FOR PERIOD 1951–70

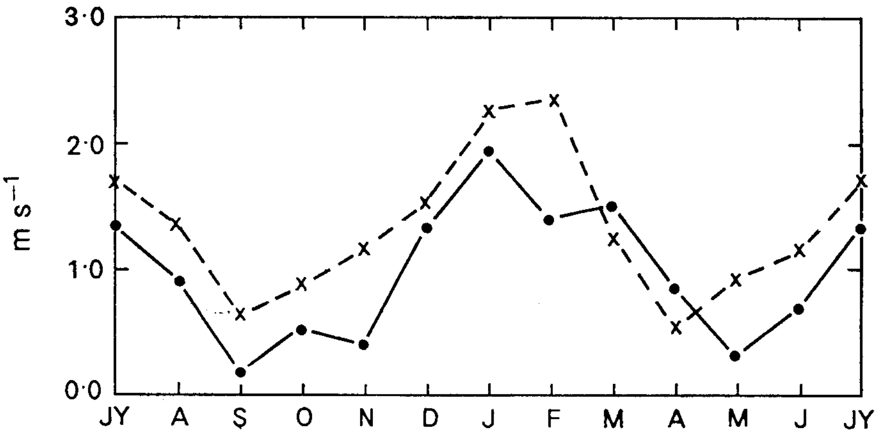


FIGURE 7—MONTHLY AVERAGES OF A MERIDIONAL INDEX FOR 35–55°N FOR THE ATLANTIC (·——·) AND THE PACIFIC (×- - -×) FOR PERIOD 1951–70

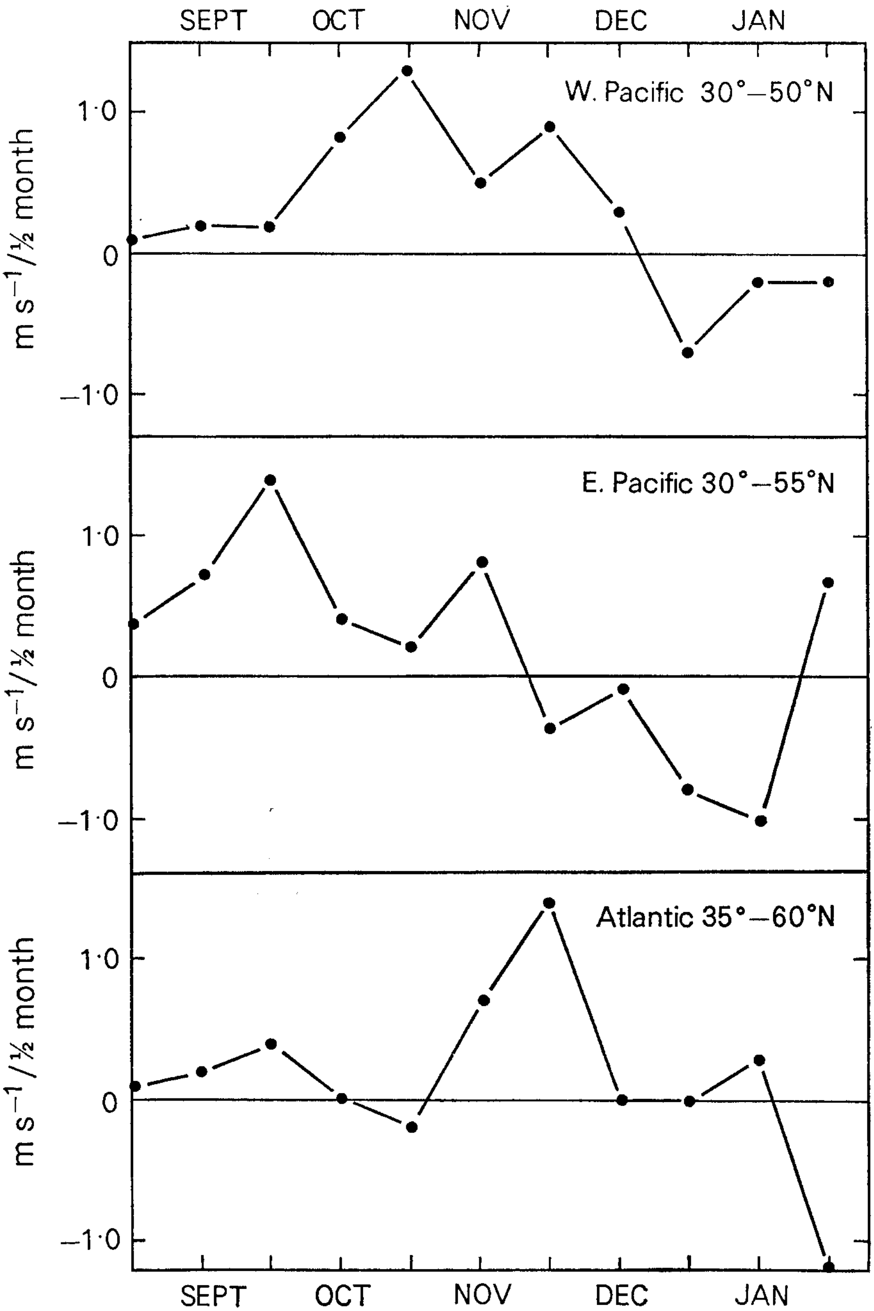


FIGURE 8—RATE OF CHANGE OF THE ZONAL INDEX FOR THREE OCEANIC AREAS IN THE WINTER HALF YEAR FROM 1900–70 AVERAGES

(The mid plot for each month is the change in the half-monthly mean index between the first and second halves of that month.)

To avoid disturbing effects arising from changes in latitude of the strongest westerlies over the period August to February, 25° latitude bands have been used—30–55°N for the eastern Pacific and 35–60°N for the Atlantic. The western Pacific westerlies show little increase until October and maximum rate of growth occurs around the end of October. The growth curve is a full month later again in the Atlantic after a minor phase of activity in October.

The same behaviour is evident in the cumulative increase from the second half of August shown in Figure 9.This flattens off after November in the eastern Pacific, after about mid December in the western Pacific and not until January in the Atlantic. This earlier and more vigorous growth of the westerlies in the Pacific compared with the Atlantic is a notable feature which deserves closer consideration. It might be said that from September to the end of October the Pacific is recovering from very low summer values and reaching the strength prevailing in the Atlantic. The growth, however, continues through November while the Atlantic index stays about the same. The thickness gradient also rises very rapidly from the very low values of July and August to an October value substantially higher than that in the Atlantic.

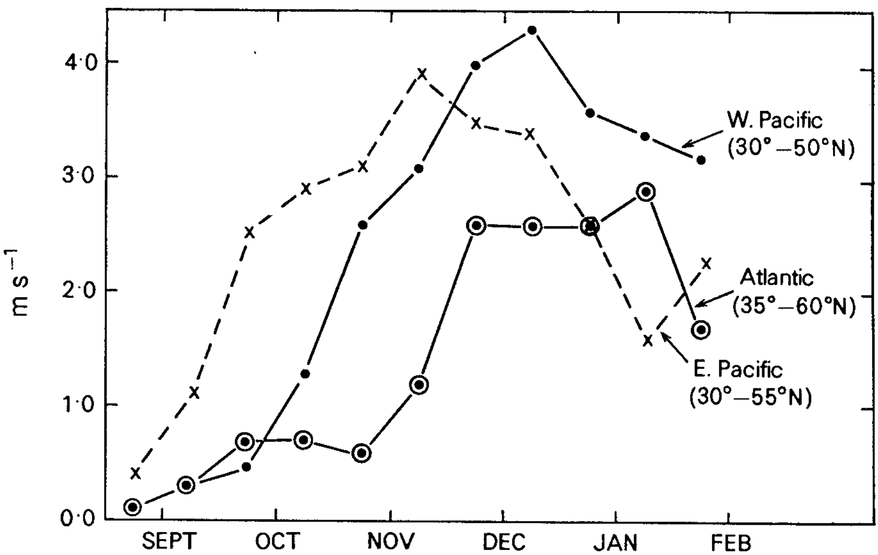


FIGURE 9—CUMULATIVE CHANGE IN THE ZONAL INDICES FOR THREE OCEANIC AREAS FROM THE SECOND HALF OF AUGUST

These differences in behaviour are reflected in the changes that occur in the zone of the upwind troughs during this period. Figures 10 and 11 show the course of the meridional thickness gradient in the regions of the American and Asian winter troughs. The values are similar in September but by November those in the Asian trough are considerably greater, paralleling the more rapid growth of the Pacific westerlies. In this association what is cause and what is effect is not easy to determine. Miles (1975) has shown that the zonal index over the Atlantic in winter has a correlation of about 0·5 with the contemporaneous thickness gradient 35–55°N in the area of the American trough. Correlations with a half-month lag and lead are lower than this and so afford no indication of which is the cause. From the data given in Table II there is little indication of a close relationship between the westerlies and the changes of thickness gradient in the upwind trough. There is a general higher ratio of zonal index to thickness gradient in the Atlantic in the autumn and early winter, with November appearing as an anomalous month in the Atlantic and February as an anomalous month in the Pacific.

TABLE II—THE RELATION BETWEEN ZONAL INDEX OVER THE OCEANS AND THE THICKNESS IN THE UPWIND THERMAL TROUGH (35–55°N FOR ATLANTIC, 30–50°N FOR PACIFIC)

| Month | Thickness gradient 60–90°W *dam/20° lat.* | Zonal index Atlantic *m s⁻¹* | Ratio zonal index/thickness gradient |
|---|---|---|---|
| Sept. | 30·1 | 4·7 | 0·16 |
| Oct. | 30·2 | 4·7 | 0·16 |
| Nov. | 34·3 | 4·1 | 0·12 |
| Dec. | 38·5 | 6·1 | 0·16 |
| Jan. | 41·4 | 5·5 | 0·13 |
| Feb. | 40·0 | 4·4 | 0·11 |
| Mar. | 35·2 | 4·3 | 0·12 |

| Month | Thickness gradient 120–150°E *dam/20° lat.* | Zonal index Pacific *m s⁻¹* | Ratio zonal index/thickness gradient |
|---|---|---|---|
| Sept. | 28·4 | 2·8 | 0·10 |
| Oct. | 35·5 | 4·0 | 0·11 |
| Nov. | 46·5 | 6·0 | 0·13 |
| Dec. | 49·2 | 6·6 | 0·13 |
| Jan. | 47·7 | 6·2 | 0·13 |
| Feb. | 46·6 | 7·2 | 0·15 |
| Mar. | 42·4 | 5·3 | 0·12 |

In Figures 10 and 11 surface temperature differences are shown as well as thickness gradients. The aim was to find some indicator of the strength of these thermal troughs which would be available before the era of radiosondes, for use in climatic change studies. The two stations chosen to represent the American trough are Moosonee (51°16′N, 80°39′W) and Cape Hatteras (35°15′N, 75°40′W) and for the east Asian trough Nikolayevsk-na-Amure (53°09′N, 140°42′E) and Tokyo (35°41′N, 139°46′E). They cover the greater part of the 20° latitude band used for the thickness gradient and lie near the longitude of the average thermal trough in the two regions. The Moosonee–Cape Hatteras surface temperature difference follows the thickness gradient throughout the year very closely but there is a considerable lack of fit for the Nikolayevsk–Tokyo difference. The greater rate of increase in the thickness gradient of the east Asia trough between October and November is however, reproduced. The decline in the thickness gradient in January is due to a substantial part moving south of 35°N. The course of thickness gradient for the band 30–50°N resembles the surface temperature difference more closely, though it has a flat maximum in December. The maximum of surface temperature difference in January is probably due to a more stable lapse rate setting in at the latitude of

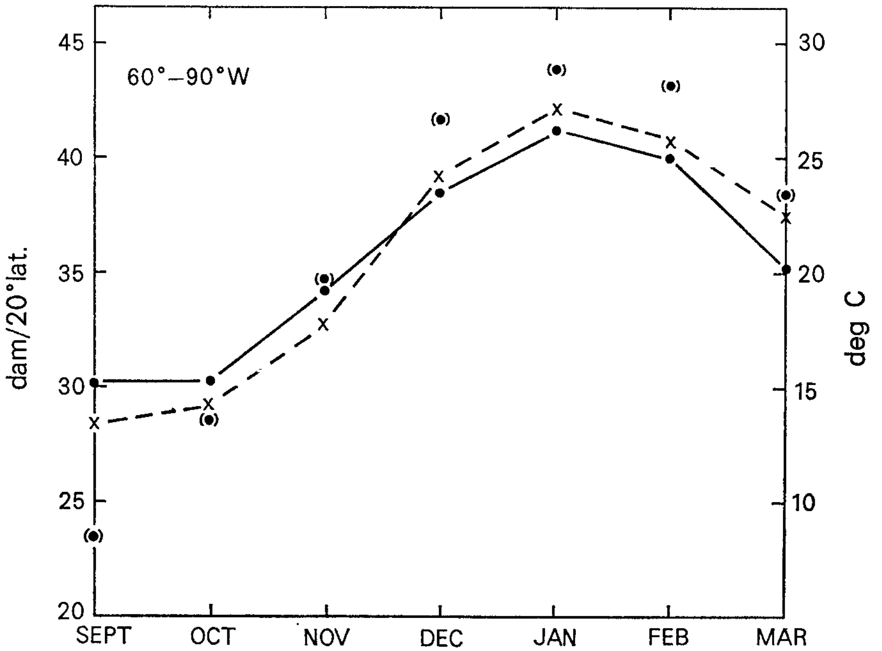


FIGURE 10—MERIDIONAL THICKNESS GRADIENT (1000/500 mb) BETWEEN 35°N AND 55°N (•——•) AND SURFACE TEMPERATURE DIFFERENCES (×– – –×) BETWEEN TWO STATIONS IN THE AREA OF THE WINTER AMERICAN TROUGH

(The scale for the temperature difference is on the right of the diagram.) Values of the thickness gradient for the band 30–50°N are plotted (•).

Nikolayevsk than at that of Tokyo. This feature come out quite clearly in Table III where zonally averaged surface temperature gradients for January are compared with 500 mb temperature gradients based on data by Oort and Rasmusson (1971).

TABLE III—TEMPERATURE GRADIENTS NEAR THE SURFACE (1000 mb) AND AT 500 mb FOR VARIOUS LATITUDE REGIONS IN JANUARY—OORT AND RASMUSSON (1971)

| Latitude region | Temperature gradients °C/20° lat. *500 mb* | *1000 mb* |
|---|---|---|
| 15–35°N | 13·6 | 13·8 |
| 35–55°N | 11·9 | 17·6 |
| 55–75°N | 6·5 | 17·8 |

The earlier and more rapid growth of thickness gradient in the east Asian trough is also associated with an earlier and stronger growth in the northerly flow in the region of the Asian trough. Figures 12 and 13 show the differences in northerly flow for two latitude bands. In particular the great increase in the northerlies 55–75°N between October and November in the Asian area is noteworthy. This mainly reflects the development of the winter north-east monsoon but in part it is due to the deepening of the Pacific low-pressure system to the east of Kamchatka, which must accompany the growth of the zonal index for the west Pacific at this time. Again cause and effect are hard to disentangle.

In the light of these various considerations it seems that the different behaviour of the westerlies in the two oceanic regions is not to be readily explained by reference to the thermal troughs over the upwind continents.

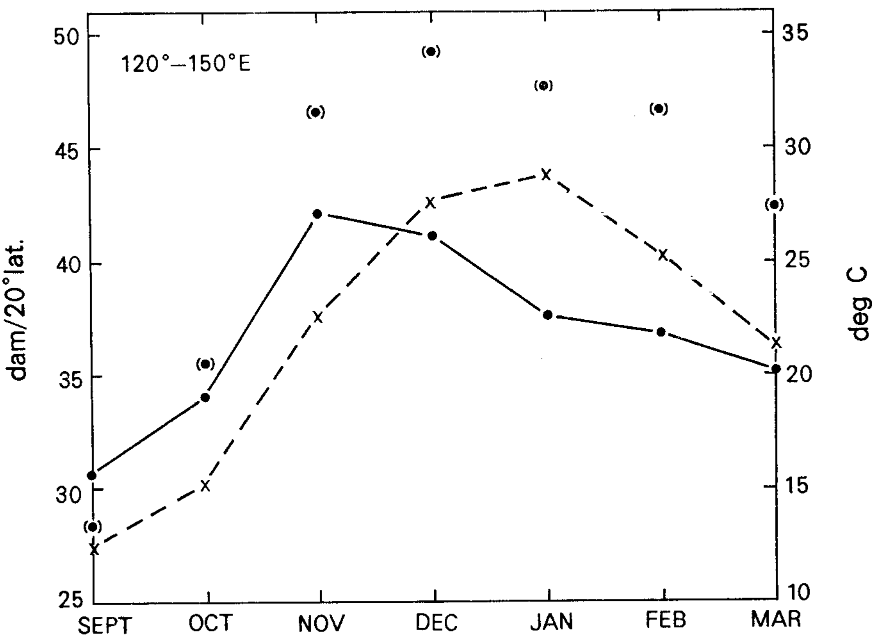


FIGURE 11—MERIDIONAL THICKNESS GRADIENT (1000/500 mb) BETWEEN 35°N AND 55°N (·——·) AND SURFACE TEMPERATURE DIFFERENCES (×- - -×) BETWEEN TWO STATIONS IN THE AREA OF THE WINTER EAST ASIAN TROUGH

(The scale for the temperature difference is on the right of the diagram.) Values of the thickness gradient for the band 30–50°N are plotted (·).

## 5. CONCLUSIONS

The following points emerge from this study:

1. The annual course of the zonal and meridional indices of the surface circulation in the northern hemisphere shows a maximum circulation in the winter half year. The peak of zonal flow occurs in December while the peak of the meridional flow is in January.

2. In the Pacific the westerlies fall to a very low value in July and August but increase more rapidly than the Atlantic westerlies in the autumn and early winter to reach a peak somewhat earlier. The difference in the two oceans is not easily to be explained by reference to the upwind thermal troughs.

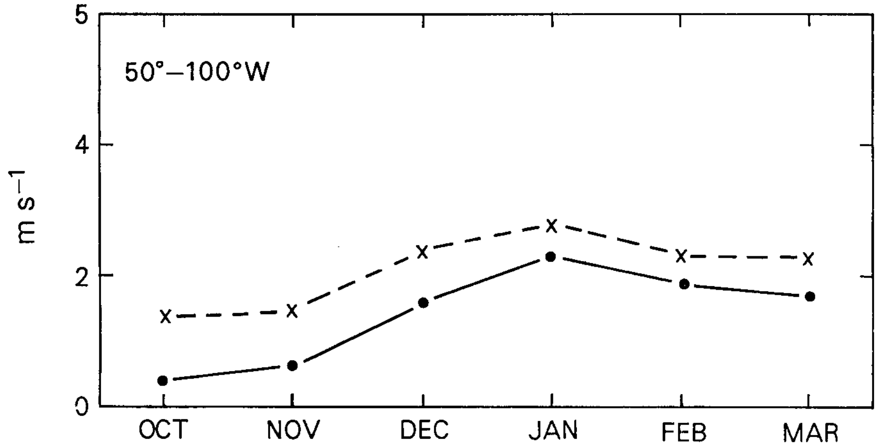


FIGURE 12—AVERAGE NORTHERLY GEOSTROPHIC WIND OVER TWO LATITUDE BANDS IN THE AREA OF THE WINTER AMERICAN TROUGH 50–100°W

(•——•) is for the latitude band 35–55°N.
(×- - -×) is for the latitude band 55–75°N.

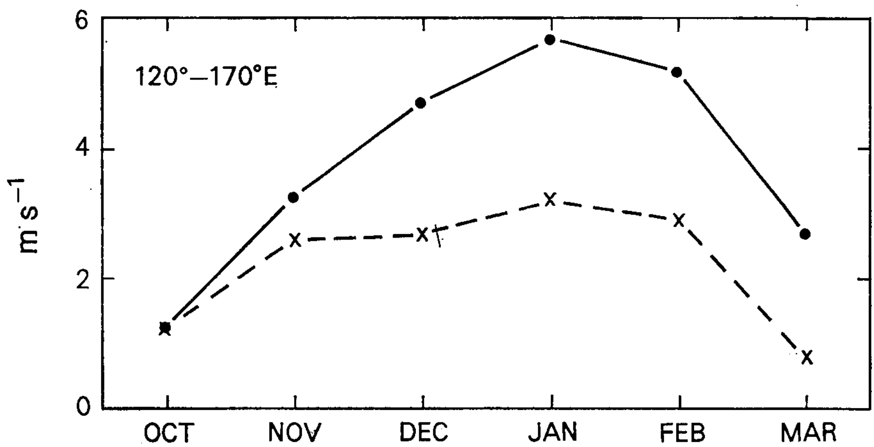


FIGURE 13—AVERAGE NORTHERLY GEOSTROPHIC WIND OVER TWO LATITUDE BANDS IN THE AREA OF THE WINTER EAST ASIAN TROUGH

(•——•) is for the latitude band 35–55°N.
(×- - -×) is for the latitude band 55–75°N.

3. The meridional thickness gradient over the oceans after being slightly less in summer than over the land areas increases more rapidly in the autumn. It reaches a peak in December whereas that over the land area has its maximum in February.

ACKNOWLEDGEMENT

The help of Mr P. R. Benwell, Mr P. Collison and Mr S. Lawson in writing the programs to obtain these indices is gratefully acknowledged.

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MILES, M. K. 1975 North Atlantic circulation and associated temperature gradients. Proceedings of WMO/IAMAP symposium on long-term climate fluctuations. WMO No. 421.

OORT, A. M. and RASMUSSON, E. M. 1971 Atmospheric circulation statistics. NOAA Prof. Paper, No. 5. US Department of Commerce.

## REVIEWS

*Radioisotopes and global transport in the atmosphere*, by I. L. Karol'. 245 mm × 175 mm, pp. xiii + 323, *illus.* (translated from the Russian by Israel Program for Scientific Translations, Jerusalem), John Wiley and Sons Ltd, Baffins Lane, Chichester, Susssex, 1975. Price £13·25.

This book is a presentation of Russian work on the use of both natural and artificial isotopes to study global transport mechanisms. As is natural in view of the stabilization altitude of the debris clouds from nuclear weapon tests, there is considerable emphasis on the lower stratosphere, and exchange processes across the tropopause.

The first chapter reviews in considerable detail observed fields and their fluctuations in time and space. The second chapter constructs, in spherical co-ordinates, a two-dimensional, meridional model of global transport between the planetary surface and 25 km. Chapter 3 deals with vertical transport, and removal processes for aerosols. Chapter 4 deals with the global distribution of zonal mean transport parameters appropriate to the model derived in Chapter 2. In Chapter 5 numerical models for solving the model equations are discussed, in Chapter 6 the model is used to examine the planetary distribution of radon and its decay products, and in Chapter 7 it is further used to examine the spread of debris from nuclear weapon tests, with particular reference to $W^{185}$ and $Mn^{54}$. Chapter 8 deploys the model upon the natural isotopes resulting from cosmic ray impact, such as $C^{14}$ and $Be^{7}$. The book ends with a three-page Conclusion, in which the major results are stated in a concise manner.

The subject is treated throughout in a quite detailed mathematical manner, equations being liberally interlarded with data tables. While making a valuable reference book for the specialist who needs a convenient compendium of the Russian work, this approach has the disadvantage of discouraging those looking for a readable, explanatory review of meridional transport processes. Such readers would be well advised to read the Introduction and skip to the Conclusion, wherein a clear concise statement of the book's results is given.

The date of the original Russian text is February 1972; in the four and a half years that have elapsed since then there has been considerable impetus given to the subject of meridional global transport, by the concern that aircraft flying in the stratosphere might cause chemical damage to the ozone there. This has rather badly dated the author's observation that three-dimensional models should be constructed. On the other hand, his conclusion that the mean climatic intensity of large-scale turbulent diffusion proved to be only a fraction of the values given in well-known estimates by western workers should provide food for thought in two-dimensional modelling circles. A point occurring to your reviewer in passing is that if the time taken to remove half the material of a nuclear blast from the lower stratosphere is that quoted of just barely less than a year, it is not easy to reconcile with lower estimates for the values of large-scale turbulent diffusion.

The book suffers from what has become an endemic fault of translations; in addition to being over four years old, it has no index. One assumes that the statement on page 47 'Thus, energywise, the lower troposphere is a refrigerating machine, . . .' includes an infelicitous translation of the Russian for stratosphere; pedants may also deduce with dismay the existence of a Russian equivalent of 'energywise'.

In conclusion, this should prove a useful book for the specialist, with some interesting results which warrant further study.

A. F. TUCK

## CORRECTION

*Meteorological Magazine*, November 1976, p. 343. The Jenkins (1969) reference should be

JENKINS, I. 1969 Increase in averages of sunshine in Greater London. *Weather*, **24**, pp. 52–54.

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### NOTICES

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Printed in England by Heffers Printers Ltd, Cambridge
and published by
HER MAJESTY'S STATIONERY OFFICE

**80p monthly** **Annual subscription £10.68 including postage**

Dd. 290748 K16 2/77 ISBN 0 11 724708 1