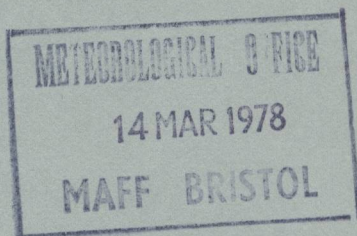


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THE ATMOSPHERES OF THE PLANETS*

By B. J. MASON

(DIRECTOR-GENERAL, METEOROLOGICAL OFFICE)

I am deeply honoured to be giving this year's Halley Lecture in memory of one of the greatest scientists of the seventeenth century, eclipsed perhaps only by Newton himself. I have no real qualifications for this task because, although Halley did write an important paper in 1686 on the structure and origin of the trade winds and monsoons, and contributed substantially to the study of meteorological optics and the aurora, his outstanding contributions were in fields of which I have little real knowledge. But Halley was always ready to tackle new subjects, and this opportunity has encouraged me to escape temporarily from the more pressing problems of the Earth's atmosphere and study the atmospheres of Venus, Mars and Jupiter. The subject is timely because our knowledge has increased greatly during the last few years through measurements made by American and Russian spacecraft during close approaches to all three planets and through landings on Venus and Mars. Because of the great differences in their physical parameters (see Table I) and in the relative importance of dynamical, radiative and thermodynamical processes, the meteorology of the three planets is entirely distinct and very different from that of the Earth.

VENUS

Some general features. Although Venus, our nearest planetary neighbour and the brightest planet in the sky, has a mass and radius very similar to those of the Earth, the constitution of its atmosphere and its meteorology are completely different.

Venus is the nearest planet to the Sun to possess an atmosphere. This is more than 100 times as massive as the Earth's atmosphere and is composed almost

* A written version of the Halley Lecture for 1977 which was delivered in Oxford on 17 May 1977; this paper is a modified form of one with the same title published in the December 1977 issue of *The Observatory (London)*.

TABLE I—BASIC PARAMETERS OF THE PLANETS

	Venus	Mars	Jupiter
Mean distance from the Sun (10^6 km)	107	226	773
Sidereal period	225 days	687 days	11.86 years
Rotation period about axis	—243 days	1.03 days	9 h 55½ min
Mass (relative to Earth)	0.81	0.11	318
Radius (km)	6050	3380	71 350 (equator)
Mean density (g/cm^3)	5.1	3.97	1.33
Surface gravity (m/s^2)	8.90	3.70	26
Solar irradiance (W/m^2)	2600	600	10
Effective radiation temp. (K)	230	216	130
Average surface pressure	90 bar	7–8 mb	20 bar } arbitrary reference level
Average surface temp. (K)	760	230	400
Cloud cover (per cent)	100	5	100
Albedo	0.77	0.20	0.42
Adiabatic lapse rate (K/km)	10.5	4.4	1.9
Scale height (km)	5	11	17
Atmospheric composition	CO ₂ traces HCl, HF, CO, H ₂ O	CO ₂ traces H ₂ O, O ₂ , CO, A, Kr	Mainly H ₂ He, CH ₄ , NH ₃ , PH ₃
Cloud composition	droplets H ₂ SO ₄	water ice	ammonia crystals particles of NH ₄ SH, water and ice ≈ 10 ⁸
Radiative relaxation time (s)	10 ⁹ (surface) 10 ⁵ (80 km)	2 × 10 ⁵	
Dynamical relaxation time (s)	6 × 10 ⁸ (surface) 2 × 10 ⁵ (80 km)	8 × 10 ³	5 × 10 ³

entirely of carbon dioxide. The incoming solar energy flux of 2600 W/m^2 nearly twice that received by the Earth, is largely trapped by the carbon dioxide to produce very high surface temperatures of about 760 K. Observations of Venus, especially of its surface and lower atmosphere, have long been hindered by its unbroken layer of yellowish cloud whose top extends up to about 70 km above the ground and which reflects nearly 80 per cent of the incident sunlight. This is in complete contrast to the Earth, which has an average cloud cover of only 50 per cent that reflects about 30 per cent of the incident sunlight. However, during recent years, our knowledge of the atmosphere of Venus has been greatly extended by observations from United States MARINER spacecraft (1971–72) which have orbited within 6000 km of the planet's surface and from the Russian VENERA probes (1969–73) which have penetrated the atmosphere itself.

Another remarkable feature of Venus strongly affecting its meteorology is its very slow period of rotation (243 Earth days) and the great length of day (120 Earth days) but, even so, the surface temperatures are remarkably uniform, with very little latitudinal or diurnal variation. This speaks for the efficiency of the atmospheric motions in transporting heat and reducing the temperature contrasts that would otherwise be impressed by differential solar heating. The radiative relaxation time (the time taken for a temperature perturbation to be reduced to 1/e of its initial value by radiative processes) is estimated to be very long, about 10^9 s, in the lower atmosphere, where atmospheric motions would achieve the same result in about 10^7 s. In the high atmosphere, in the upper parts of the cloud layer, the radiative and dynamical relaxation times are more nearly

equal at about 10^5 s so that heat transfer by radiation and by the winds are more nearly equal. Moreover, since the radiative relaxation time near the surface is much greater than the length of day (10^7 s), the night-time does not last long enough for appreciable cooling to occur, and diurnal temperature effects are very small. By contrast, in the upper atmosphere, both latitudinal and diurnal temperature contrasts have an important influence on atmospheric motions.

Composition of the atmosphere. For many years the only gas definitely identified in the atmosphere of Venus was CO_2 , discovered by Adams and Dunham in 1932, but recently HCl, HF, CO and H_2O have been detected spectroscopically in low concentrations. It is thought that whereas during the formation of the Earth's atmosphere, by the out-gassing of rocks, the CO_2 was largely dissolved in the oceans to form carbonates or used up in photosynthesis, on Venus the surface temperature was too high to allow condensation of water vapour or to support plant life, and so the CO_2 accumulated to form a high-density atmosphere that absorbed solar radiation by the greenhouse effect to produce the high temperatures now measured.

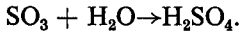
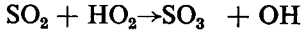
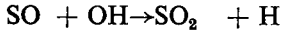
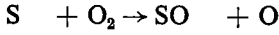
Water vapour was probably lost in the high troposphere in reactions with SO_2 and its derivatives to form droplets of H_2SO_4 (see later) and also, at higher levels, by photolytic dissociation, with the H_2 escaping to space. However, additional hydrogen may be produced at very high levels by the solar wind.

The variation in the number-density of cloud particles with height, as deduced from measurements of optical transmission by the VENERA 8 probe, is plotted in Figure 1. The particle concentration reaches a maximum value of rather more than $1000/\text{cm}^3$ at 45 km but falls off rapidly at lower levels to form a sharp cloud base at 30 km and more gradually at higher levels to form a diffuse cloud top at about 70 km. There is also some evidence for a lower, more tenuous cloud layer below 10 km.

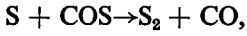
Constitution and formation of the clouds of Venus. Detailed analysis of the polarization of reflected sunlight from the clouds reveals them to consist of spherical particles, probably liquid, of refractive index 1.44 and of remarkably uniform size with a mean radius of 1 micrometre. This uniformity of particle size, which appears to extend over the whole planet, is not characteristic of terrestrial clouds.

The cloud droplets most probably consist of 75 per cent H_2SO_4 and 25 per cent of H_2O , i.e. concentrated sulphuric acid, which would give a refractive index of 1.44 and, at the same time, account for the very low measured concentrations of water vapour (relative humidities of only 1–10 per cent in the vicinity of the cloud top). The infra-red spectrum of Venus, with a strong emission band at 11.2 micrometres, and the blackness of the planet at 4 micrometres, would also be consistent with the clouds being largely composed of H_2SO_4 . The lemon-yellow hue of the clouds is, however, not so easily explained. This could be due to the solution in the droplets of a contaminant that absorbs blue light but, more likely, to particles of elemental sulphur. In fact, of the many possible substances examined in the laboratory, only solid elemental sulphur matches the absorption spectra of the clouds on Venus. Since it also absorbs strongly near the peak of the solar spectrum, a solid sulphur aerosol may play a significant role in the heating of the upper atmosphere.

The photochemical processes responsible for producing the cloud droplets of H_2SO_4 , and which remove atomic sulphur from the atmosphere, are thought to occur mainly at heights above 65 km according to the following reactions:



At the same time elemental sulphur may be produced by



COS being formed at levels below 50 km and temperatures above 350 K, for example by

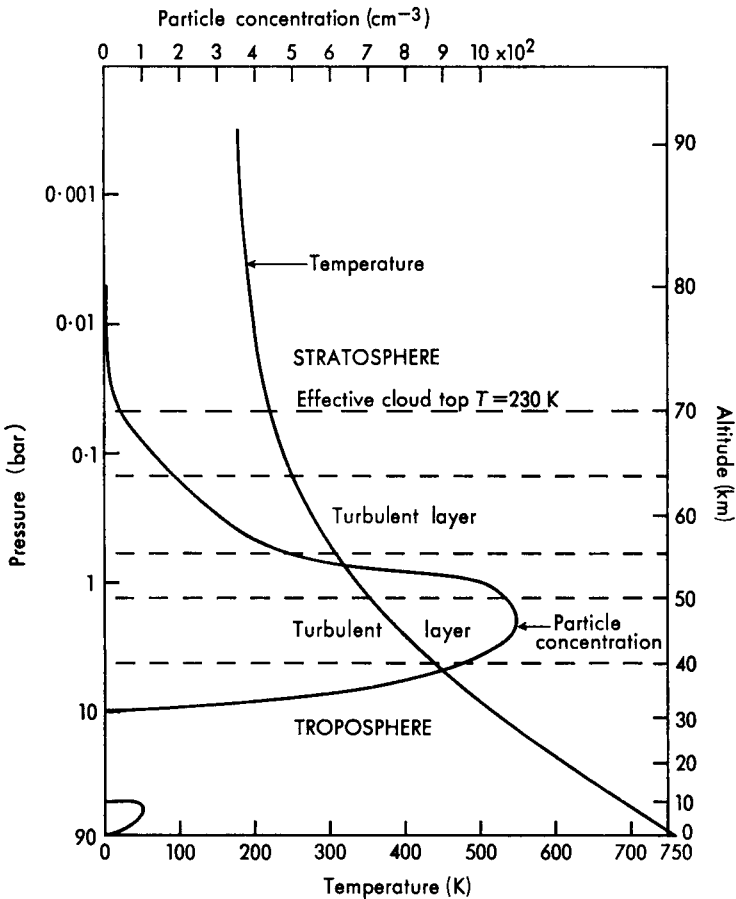
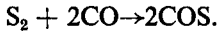


FIGURE 1—VERTICAL PROFILES OF TEMPERATURE AND CLOUD PARTICLE DENSITY FOR THE ATMOSPHERE OF VENUS

Droplets of concentrated H_2SO_4 would, of course, be much more stable than water clouds and would grow or evaporate much more slowly in response to vertical atmospheric motions than do terrestrial clouds. This may largely explain the unbroken and uniform character of the cloud deck on Venus. It has been suggested that the rapidly changing dark features revealed on ultra-violet photographs of the clouds mark the presence of ultra-violet-absorbing sulphur particles whereas in the bright areas the cloud droplets consist of almost pure sulphuric acid. If so, the dark features might mark regions of ascending convective motions bringing up from lower levels the COS required to form the elemental sulphur particles. High-resolution pictures of the planet's disc taken by the MARINER 10 television camera indicate the presence of tenuous haze layers high in the stratosphere at altitudes between 80 and 90 km. At least two distinct layers, separated by a few kilometres in altitude, appear in pictures taken both in orange and in ultra-violet light, and they extend laterally from the equator to high latitudes. If the particles are assumed to be transparent, with radius 1 micrometre, measurements of optical density would suggest number densities of the order of $0.1/\text{cm}^3$.

The vertical structure of the atmosphere. The vertical temperature profile of the atmosphere of Venus, based on measurements of temperature, pressure and altitude made respectively with resistance thermometers, aneroids and capacitor sensors, and a pulsed radio altimeter on the VENERA probes, is shown in Figure 1. The temperature, 760 K at the surface, falls off linearly with height at the rate of 8 K/km up to 50 km, where it reaches 360 K, and thereafter more slowly to become nearly isothermal above 80 km (200 K). The lapse rate in the deep atmosphere is therefore less than the adiabatic value of 10.5 K/km.

The general shape of the temperature profile has been reproduced by radiative-transfer calculations involving the computation at successive levels of both the incoming solar radiation and the infra-red transfer. The net flux of solar radiation as a function of altitude and solar zenith angle, taking into account scattering and absorption by both aerosols and gases, is calculated in such a way as to be consistent with the VENERA 8 photometer measurements of the downward component of solar flux and the observed wavelength dependence of the planetary reflectivity (albedo). The size, concentration and nature of the cloud droplets and aerosol particles, assumed to occupy a layer between about 30 and 60 km, are chosen to be consistent with the optical and spectroscopic data described above. The net infra-red flux, and hence the radiative cooling and radiative equilibrium temperatures, is then calculated for each level. These procedures lead to temperatures that are much too high and also to too steep a lapse rate in the deep atmosphere but, when convective energy transport is introduced to bring the lapse rate down to the adiabatic value while maintaining radiative equilibrium at these levels, the resulting overall temperature profile for radiative-convective equilibrium agrees quite well with observation. The model calculations indicate that about 3 per cent of the incident solar radiation reaches the surface of the planet, compared with 1.5 per cent measured by VENERA 8, and this is sufficient to produce strong heating by the greenhouse effect and account for the observed high surface temperature.

The horizontal winds, observed by Doppler measurements of the radial velocity of the VENERA 8 probe, are plotted as a function of altitude in Figure 2. They increase steadily from only a few m/s in the deep atmosphere to

about 50 m/s at 40 km and then rise quite sharply to about 100 m/s at 50 km. These winds are zonal in direction, blowing roughly along lines of latitude.

Atmospheric motions. Information on atmospheric motions has been provided by movements of cloud features seen in ultra-violet light as observed both from the ground and from MARINER 10, by Doppler shifts in reflected sunlight and in the CO₂ lines of the atmosphere, and by drift measurements of the VENERA probes as they entered the atmosphere.

Global views of the planet in ultra-violet light reveal dark Y- or C-shaped features near the equator, which vanish at one limb, and reappear at the other, suggesting a rotation period of about 4 days for the clouds. This implies a relative velocity between the clouds and the surface of about 100 m/s, which is very high compared with the slow rotation rate of the planet but is consistent with the strong zonal easterly winds, blowing in the retrograde direction of rotation of the planet, that were measured by VENERA 8 at altitudes above 50 km. In the low troposphere, below 10 km, the zonal velocities are only a few m/s and the meridional velocities are only about 2 m/s. Fluctuations in the radio signals received from the MARINER spacecraft indicated the existence of two layers of intense turbulence, each about 10 km thick, centred at about 45 km and 60 km with a preferred horizontal eddy size of about 5 km. The turbulence at 45 km may be caused by instabilities in a zone of strong winds and wind shear. The turbulent layer at 60 km is probably due to small-scale convection set up by strong solar heating of the cloud at this level but limited to a shallow layer near the tropopause by relatively stable layers above.

The 3400 photographs taken by MARINER 10 over 8 days, with resolution from about 100 m to about 130 km, revealed a subsolar disturbance (SSD) spanning some 20° of latitude and 80° of longitude, locked to the Sun-Venus line and continuously generated in response to maximum solar heating. The SSD shows cellular features, the largest of which are about 500 km across, with a good deal of interior structure. The cells, which last a few hours, move with the wind and change markedly from hour to hour, are almost certainly a manifestation of large-scale convection. The photographs also show a circumequatorial

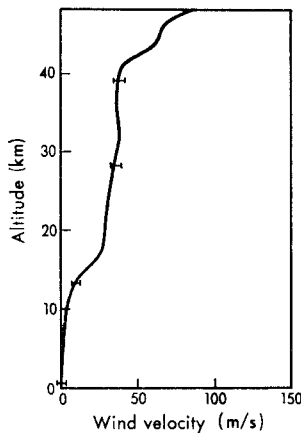


FIGURE 2—HORIZONTAL WIND VELOCITY MEASURED BY VENERA 8 AS A FUNCTION OF ALTITUDE

band containing cells of 100–500 km in diameter. These are also probably of convective origin, resulting from interaction between the high-pressure SSD and the zonal wind. Since the atmospheric pressure falls off from the SSD towards the poles, the zonal winds are accelerated towards high latitudes. The spiral streaks may perhaps be interpreted as associated 'jet streams'. The kinetic energy of these motions is eventually dissipated in the low-pressure polar vortices. In the virtual absence of Coriolis forces on Venus, temperature gradients may exist parallel to the zonal flow and hence parallel to the direction of the vertical wind shear. In this situation the flow may become unstable and break up into roll vortices with axes parallel to the mean flow, with wavelengths of the same order as the scale height (5 km) and growth times of a few days. Such instabilities, which probably account for the small-scale zonal streaks on the MARINER photographs, will draw energy from the mean flow, and thereby tend to destroy the shear and the horizontal temperature gradients and stabilize the vertical lapse rate.

Motions on the planetary scale. The driving force for the planetary circulation is the differential heating between the equator and the poles produced, in the upper atmosphere, by the differential absorption of solar radiation in the cloud layer and, in the lower atmosphere, by the residual radiation which reaches the planetary surface and produces high surface temperatures through the greenhouse effect. The intervening atmosphere is therefore heated both from above and from below. In the upper atmosphere, at cloud level, both radiative and dynamical processes are important in heat transfer and in reducing the horizontal temperature gradients whilst, in the deep atmosphere, the dynamical processes dominate. In the latter case the simplest circulation would be a convective cell with rising motions near the subsolar point and sinking motions near the anti-solar point, similar to the Hadley cell of the Earth's tropical atmosphere. Such a circulation, depicted in Figure 3, would transport heat meridionally as well as vertically in a direction depending on the static stability. The cell will transport heat polewards only if the gradient of potential temperature is positive, i.e. $\theta_1 > \theta_2$, so that the mean lapse rate is rather less than the adiabatic value, as is observed to be the case. Detailed analysis, based on the assumption that dynamical heating (or cooling) of the air due to the vertical motions is balanced by radiative cooling (or heating) when averaged vertically and latitudinally, leads to reasonable values for the horizontal and vertical gradients of potential temperature and shows that the Hadley circulation could maintain a lapse rate close to the adiabatic value without the help of small-scale convective or turbulent heat transfer. In these conditions of near static stability, the Hadley cell produces temperature differences between pole and equator of only about 0.1 K. These very small temperature gradients, and the fact that the lapse rate is nearly adiabatic, speak for the efficiency of the motions in redistributing the heat even though the zonal and meridional winds in the lower atmosphere are only of the order of 1 m/s and the vertical motions are only about 1 cm/s.

The vertical extent of the Hadley circulation in the atmosphere of Venus is not known, nor the extent to which it is linked to the stratospheric circulation. The latter, being driven by the absorption of most of the incident solar radiation in the cloud layers at about 50–60 km altitude, shows the influence of diurnal heating, and is apparently quite distinct from the tropospheric flow. The main problem is to explain the rapid motion of the cloud features which both Doppler and VENERA probe drift measurements show to be due to real winds of about

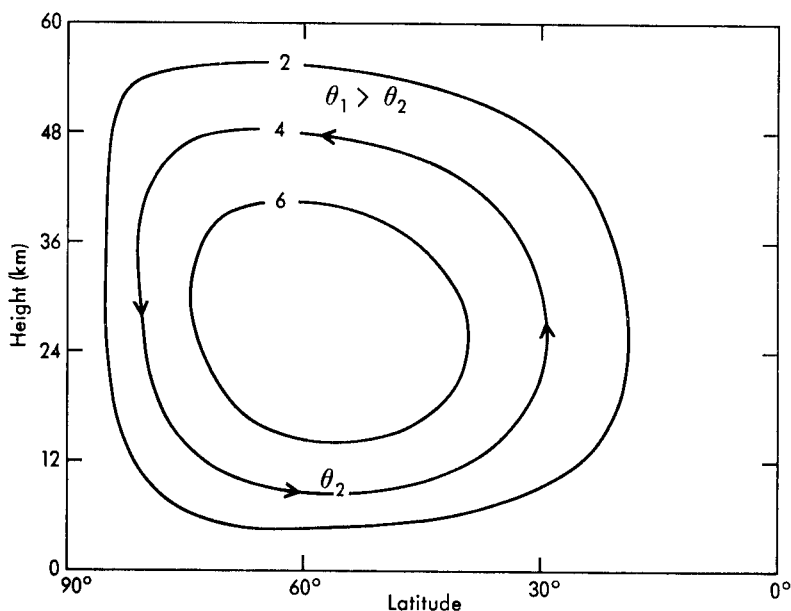


FIGURE 3—A POSTULATED HADLEY-CELL CIRCULATION FOR THE LOWER ATMOSPHERE OF VENUS

100 m/s travelling in the opposite direction to, and 20 times as fast as, the overhead motion of the Sun relative to a fixed point on the surface.

The most likely explanation for this strong 4-day circulation is the so-called 'moving-flame effect' proposed by Schubert and Whitehead. If a flame or other compact heat source is moved in a circular path beneath a pan of liquid*, motions are induced as shown in Figure 4. The moving source induces a thermal wave which lags behind the source by an amount which increases with height above the bottom of the fluid because of the finite time required for the heat to be conducted upwards. This produces tilted convection cells giving a net motion at the top of the fluid which is opposite to the direction of motion of the heat source. This portrays what might be expected to happen in the atmosphere of Venus if it were heated from below. In fact the heating occurs mainly in the upper atmosphere in the cloud layers so that the thermal lag, being greatest at the lower levels, might be expected to produce an opposite tilt of the cells and a net motion in the *same* direction as the Sun. However, a more detailed analysis by Plumb shows that the direction of tilt depends rather critically on the static stability, and in the stable upper atmosphere of Venus where internal gravity waves are probably responsible for the vertical transport of heat, the cells should indeed tilt so as to produce a net motion in the opposite direction to that of the Sun. Moreover, the theory indicates that mean motions much faster than the

* This experiment was first suggested by James Thomson in his 1892 Bakerian Lecture to the Royal Society following a much earlier but incorrect suggestion by Halley (1686) that the Trade Winds on the Earth were caused by the diurnal revolution of the Sun from east to west over the equatorial zone.

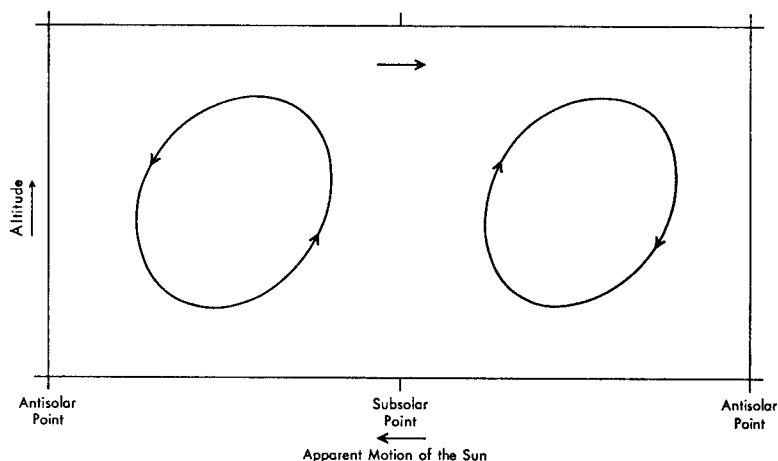


FIGURE 4—THE VERTICAL CIRCULATION TO BE EXPECTED IN AN ATMOSPHERE HEATED FROM BELOW BY A MOVING HEAT SOURCE

speed of the heat source may be generated, and that this magnification factor is independent of the length of the solar day but is largely determined by the deviation of the vertical lapse rate of temperature from the adiabatic value and by the distribution of radiative heating and cooling in the planetary atmosphere. Strong zonal retrograde motions of about 100 m/s are reproduced at heights of about 60 km in a three-dimensional, 16-level model of the atmospheric circulation of Venus described recently by Young and Pollock (*J Atmos Sci*, 34, 1977, pp. 1315–1351). The model produces planetary-scale waves and eddies in the high atmospheres, initially as a result of the meridional temperature gradient and the slow rotation of the planet. The large eddies release potential energy that is apparently converted into mean zonal kinetic energy through a non-linear instability which thereby amplifies the planetary waves and zonal winds.

It is planned that in December 1978 a United States PIONEER spacecraft will land on Venus and that a second craft will be inserted into an elliptical orbit passing within 200 km of the surface every 24 hours. This second vehicle will carry an infra-red spectrometer supplied by the Atmospheric Physics Department of Oxford University which, in measuring emissions from CO₂ in the 15-micrometre band, will provide atmospheric temperature profiles from the outer fringes of the atmosphere down to the top of the cloud deck. Global daily maps of the temperature field should reveal new information on planetary atmospheric wave motions, including the 4-day rotation, and increase considerably our knowledge and understanding of the upper atmosphere of Venus.

MARS

Mars, about half the diameter of the Earth, has a very tenuous atmosphere composed mainly of CO₂ which, exerting a total pressure of only 6–8 mb, has less than 1 per cent of the mass of the terrestrial atmosphere. The incoming solar flux of 600 W/m², about half that received by the Earth, experiences little

absorption in the atmosphere and, with only 20 per cent reflected by the planetary surface, implies a mean equilibrium temperature of 216 K, in reasonable agreement with direct measurement. During the winter months a thin sheet of cloud, the so-called 'polar hood', composed of ice crystals, gradually spreads from the polar regions to middle latitudes. During the remainder of the year the planet is mainly free of cloud but the surface is sometimes obscured for a month or more at a time by dust veils raised from the surface by the wind.

Our knowledge of the Martian atmosphere and of its surface, including the polar ice caps, has been greatly extended in recent years by observations from the United States MARINER spacecraft and especially by the VIKING landing vehicles.

Composition and temperatures of the Martian atmosphere. The Martian atmosphere is composed largely of CO_2 , with H_2O , CO , O_2 as minor constituents whilst, in the upper atmosphere, traces of A, Kr, Xe, O and NO have been detected by mass spectrometers carried on the VIKING spacecraft.

The temperature of the atmosphere below 30 km (0.1 mb) was determined during the descent of the VIKING V2 which landed at 48°N , 226°W , carrying an infra-red thermal radiometer to measure the thermal emission of CO_2 in several narrow channels in the 15-micrometre band. This remote method of temperature sensing was checked by direct measurements in the lower atmosphere and on the surface. The vertical temperature profile, as deduced from such measurements made on an early summer morning after the lower atmosphere had cooled overnight by radiation, is plotted in Figure 5, the altitude of the vehicle being measured by a radio altimeter. The atmosphere is seen to be isothermal from 1.5 to 4 km, and thereafter the temperature falls not quite linearly with increasing height with an average lapse rate of about 1.3 K/km. The vertical temperature profile, as determined by infra-red remote sensing from orbiting spacecraft, exhibited waves of wavelength 15–25 km, the amplitude of which grew with increasing altitude to reach about 25 K at 90 km. These are thought to be gravity waves excited by diurnal heating and cooling of the planet's surface and lower atmosphere. The temperatures of the lower atmosphere in summer are too high to allow condensation of CO_2 , so that the haze seen at middle latitudes in the northern summer is probably caused by the condensation of water vapour.

At levels above 100 km the mass spectrometers on VIKINGs V1 and V2 measured the densities of CO_2 from which vertical profiles of temperature were deduced up to heights of 200 km from the hydrostatic equation. The measured densities of N_2 and A also yield vertical profiles of the eddy diffusion coefficient over the same height range. The atmosphere is well mixed to heights in excess of 120 km, with eddy diffusivities a hundred to a thousand times larger than those obtaining at similar heights above the Earth. The upper atmosphere was found to be surprisingly cold and variable, with average temperatures well below 200 K and reaching a minimum of about 130 K at 130 km. These temperatures are significantly lower than those derived from airglow observations made from MARINER spacecraft when Mars was near perihelion.

Surface weather. At the VIKING 2 landing site the air temperature 1.6 m above the ground showed strong seasonal and diurnal variations. In late summer, when temperatures were highest, the mean daily temperature was 223 K with maximum and minimum values of 263 K and 185 K respectively. The mean diurnal range was 240 K to 190 K. In May, when the temperatures

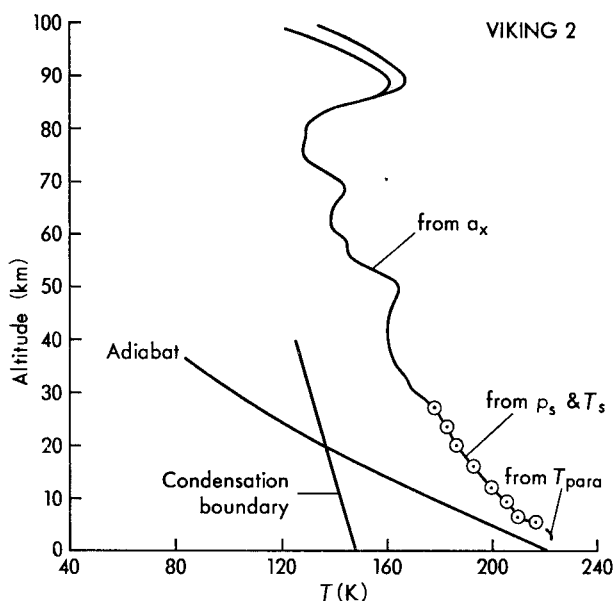


FIGURE 5—VERTICAL TEMPERATURE PROFILE OF THE MARTIAN ATMOSPHERE AS MEASURED BY VIKING 2 DURING ITS DESCENT TO THE PLANETARY SURFACE

The temperatures above 30 km (marked a_x) were derived from readings of accelerometers on the spacecraft. At lower levels they were inferred from direct measurements of pressure (p_s) and temperature (T_s) made from the spacecraft, while T_{para} refers to measurements made on the parachute supporting the craft on its final descent.

were lowest, the mean daily value was 163 K with extremes of 190 K and 150 K. In winter, the surface temperatures were low enough to produce night-time frosts of solid CO_2 which disappeared in the day time.

In summer the winds were rather constant from day to day. The daily mean vector wind was 0.7 m/s from the south-east with a diurnal amplitude of 3 m/s. The winds became gusty after sunrise and remained so until mid-afternoon as the lowest layers became convectively unstable. Peak gusts were 17 m/s. The winds were generally too light to raise dust, but observations from the MARINER 9 orbiting spacecraft suggested that the winds are much stronger in winter. The surface pressure at the VIKING 2 site varied between 7 and 8 mb with a diurnal range of 0.3 mb. The large seasonal variation may have been partly due to the condensation of a substantial fraction of the CO_2 on the polar cap.

The Martian polar ice cap. More than 700 high-resolution photographs taken of the north polar ice cap by VIKING 2 in October 1976 revealed the central area to be covered by layered deposits. The areas of the caps expand greatly to about 55° latitude in the local winter but contract again to about 85° in the summer. The long-standing controversy of whether the caps are composed mainly of water ice or of solid CO_2 has now been settled beyond all reasonable doubt by measurements from MARINER 9 and VIKINGs V1 and V2. According to the V2 measurements of the strength of the 1.38-micrometre emission band of water vapour, the total column densities reached a maximum value at $70\text{--}80^\circ\text{N}$ in the northern midsummer equivalent to 75 micrometres of precipitable

water. This requires near-surface temperatures above 200 K which, together with the fact that the residual ice cap had a brightness temperature of 205 K, is incompatible with the survival of a cap of solid CO_2 which would require a surface temperature below 150 K at a total surface pressure of 6 mb. Thus the residual (summer) ice cap must consist largely of water ice the thickness of which is estimated to be between 1 m and 1 km. However, the reflectivity of the residual cap was appreciably less than that for clean terrestrial snow, suggesting that it was mixed with a good deal of dust.

During the local winter, when surface temperatures fall as low as 125 K, condensation of both water vapour and CO_2 is possible, so that the greatly expanded caps consist of a mixture of water ice and solid CO_2 . An upper limit to the quantity of water ice that may be deposited on the polar cap is set by the total atmospheric water vapour in the winter hemisphere. This is equivalent to about 20 micrometres of precipitable water which, if spread uniformly over a cap covering 1 per cent of the hemisphere, would produce a layer 2 mm thick. Much of this would evaporate in the summer and perhaps be transported to the other polar cap.

It seems likely that the water-vapour content of the Martian atmosphere is maintained by a large reservoir of water ice in the form of a permafrost layer which, in winter, covers most of the planet but which, in the spring and summer, slowly recedes towards the poles releasing substantial quantities of water vapour into the atmosphere.

Atmospheric circulation of Mars. Because of its small mass, the Martian atmosphere responds rapidly, by radiative and convective processes, to changes in the surface temperature. The characteristic radiative response time being only about two days compared with 100 days on Earth, the large-scale atmospheric motions are under strong solar control. However, because the atmosphere is so tenuous, heat transport by the winds is inefficient and so large temperature contrasts exist. Complicating factors in the dynamics of the planetary circulations are the release of latent heat when CO_2 and water vapour condense to form the polar caps, and the raising of dust palls that affect both the thermal balance and the stability of the atmosphere.

Pollock, Leovy and Mintz have adapted a simplified numerical model of the Earth's atmosphere to the Martian atmosphere assumed to consist of pure CO_2 and to be initially isothermal at 200 K and at rest with a surface pressure of 5.8 mb. The circulation is thermally driven as a result of convective and infrared radiative heat transfer associated with the latitudinal variation of surface temperature. The model allows CO_2 to condense when the surface temperature falls below the frost-point, the thermal effects of the latent heat released and the reflectivity of the advancing ice cover being taken into account. In solstitial conditions, the model predicts strong zonal westerly winds in the middle latitudes of the winter hemisphere increasing in strength from 20 m/s near the surface to more than 60 m/s at 10 km altitude. They develop long standing waves induced by the larger mountains and also, as a consequence of the strong meridional temperature gradients between latitudes 20° and 60° (the edge of the ice cap), cyclonic and anticyclonic disturbances similar to those observed on Earth. Other features are a strong thermally driven mean meridional circulation across the equator, but only weak easterlies over much of the summer hemisphere.

Dust storms on Mars. A typical dust storm develops in three phases. In Phase 1, which lasts about 5 days, the storm begins as bright spots or cores with

diameters of less than 400 km and which show signs of diurnal regeneration with overnight decay. Phase 2, lasting for 5–30 days, and which may be accompanied by the appearance of blue-white peripheral clouds and the development of secondary bright cores at new locations, is the expansion phase. The dust veil spreads first in the E–W direction, encircles the whole planet in less than 20 days, and then sometimes spreads polewards to cover most of the planet in 20–30 days. Finally in Phase 3, the decay phase, clearing usually starts near the poles and spreads to lower latitudes.

There are evidently favoured sites for the development of the bright cores, notably the elevated plateaux between latitudes 20° and 40° S. They tend to occur just before the southern-hemisphere solstice, which is close to perihelion. Measurements of CO₂ pressure by infra-red detectors on the MARINER 9 orbiter showed the Hellas basin to be full of a dust pall for about 30 days before the great dust storm of 1971. Television pictures showed that dust became well mixed in the vertical direction up to heights of at least 30–40 km; infra-red radiometers indicated that this caused major changes in the vertical temperature profiles, which became almost isothermal, consistent with strong absorption of solar radiation by the suspended dust.

It seems that the dust storms tend to start in the southern hemisphere just before the solstice at a time when the Leovy–Mintz model predicts only weak easterly winds over much of the hemisphere. These would probably not be strong enough to raise dust, but local enhancement by thermal tides and topographic features may produce local winds and small vortices capable of raising sufficient dust to be responsible for the first phase of the storm. Phase 2 is then assumed to occur when the strong cross-equatorial cell builds up to maximum strength near the solstice, giving winds capable of raising large quantities of dust over a wide area. The radiative effects of the dust pall reduce the vertical temperature gradient thereby stabilizing the atmosphere, weakening the circulation and initiating the decay phase of the storm.

An alternative explanation by Gierasch and Goody invokes a feedback mechanism whereby an incipient dust storm generates its own high winds, thus enabling the storm to grow and become self-sustaining. The starting conditions are assumed to be an extensive low-level dust pall with light general winds and strong solar heating. Provided that there is some pre-existing cyclonic vorticity in the flow, and that the site is far enough from the equator for the Coriolis force to be an important influence, cyclonic inflow within the boundary layer will produce vertical motion which will raise the top of the dust cloud. Solar heating of the dust then raises the temperature, reduces the surface pressure and increases the vorticity. Intensification continues until the vortex can raise dust unaided by the weaker background circulation, and during this phase there will be diurnal regeneration and overnight relaxation. During the next stage the strong vortex continues to raise dust until settling from the stratosphere fills the lower atmosphere over a wide area. Horizontal temperature gradients then weaken and the storm enters the decay phase.

JUPITER

General features. Jupiter, having a mean density of only 1.33 g/cm³, is composed almost entirely of light elements, probably in their primordial abundance, with hydrogen predominant. Since the outer layers of the planetary mass are fluid, there is no sharply defined material surface, but the density increases with

depth and the pressure at the centre of the planet is estimated to be about 3×10^7 bar. Under these conditions the core probably consists of liquid metallic hydrogen, the conductivity and motion of which produce the observed strong planetary magnetic field.

Jupiter is enveloped in three layers of cloud suspended in a deep and well-stirred atmosphere composed largely of hydrogen and helium. The measured effective radiative temperature of the upper cloud deck, having an average reflectivity of 0.42, is 130 K. This is about 30 K higher than would be produced by the incoming solar flux of only 10 W/m^2 and suggests the presence of an internal heat source of about the same strength as the solar radiation. The total mass of the atmosphere is much greater than that of the Earth, the pressure 100 km below the upper cloud layer being 10 bar and the temperature about 350 K.

An important dynamical feature of Jupiter is its rapid (supersonic) rate of rotation, the length of day being only 10 hours. The atmosphere is therefore dynamically rather than thermally controlled, sustaining only small horizontal and diurnal temperature differences.

Our present knowledge of the Jovian atmosphere rests largely on observations made by the PIONEER 10 and 11 spacecraft during the nearest approaches to within about 10^6 km in December 1973 and December 1974.

Composition of the Jovian atmosphere. The Jovian atmosphere is composed largely of hydrogen. Helium was first detected by PIONEER 10 in November 1973. The measurements indicated an He/H_2 ratio of 0.18—very close to the solar value—suggesting that the planet has a composition similar to that of the primordial nebula. The evolution of the atmosphere has probably been slow because of the low temperatures existing at high levels (150 K at 200 km), and the fact that the planet is so massive that even the hydrogen is able to escape only very slowly. Other gases that have been detected are water, ammonia and methane, with traces of ethane, acetylene and phosphine. Analysis by ground-based spectroscopy of the infra-red bands in the sunlight reflected from the clouds gives column densities, assuming a common level of line formation ($p = 1.7$ bar, $T = 200$ K) that corresponds to the top of the water cloud. The ratios of the abundances of the major constituents H_2 , CH_4 and NH_3 are consistent with the atmosphere's having a solar composition, which would require the abundances shown in Table II.

TABLE II—RELATIVE NUMBER DENSITIES CORRESPONDING TO SOLAR COMPOSITION

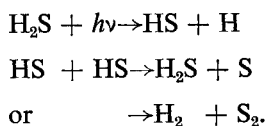
Constituent	H_2	He	H_2O	CH_4	NH_3	H_2S
Number density (per cent)	88.6	11.2	0.1	0.06	0.015	0.003

Of the compounds featured in Table II, only H_2S has not yet been detected in Jupiter's atmosphere. The strength of the H_2O lines in the 5-micrometre infra-red window suggests a humidity mixing ratio of about 10^{-6} , the saturation vapour pressure at the top of the water-cloud layer being very low. Such a low concentration would suggest a thousandfold depletion of water vapour on Jupiter relative to the solar abundance. However, the distribution of water vapour does not appear to be uniform over the planetary disc, and the measurements are probably not yet sufficiently reliable for such conclusions to be drawn with confidence.

Constitution and formation of Jovian clouds. On the assumption that the Jovian atmosphere is effectively mixed to great depths with a temperature lapse rate that is adiabatic, it is possible to compute its chemical composition as a function of altitude. The simplest model, developed by Lewis and his collaborators, assumes that the atmospheric species are in thermochemical equilibrium below the tropopause ($p = 100$ mb, $z = 160$ km, $T = 100$ K). Starting with a parcel containing more than 50 volatile constituents in solar abundance at a reference level of $p = 2 \times 10^5$ bar, $T = 2000$ K, this is allowed to ascend adiabatically, and the levels at which the various liquid and solid phases condense out are calculated, making due allowance for the latent heats released. The condensates are assumed to remain as aerosols at these levels. For example, quartz is calculated to precipitate at temperatures below 1500 K, whilst ammonium chloride, bromide and iodide are condensed below 460 K. The densest clouds, of water and ice, are calculated to form at $T = 270$ K, 60 km above the 'surface' reference level where $p = 20$ bar. Near the 200 K (90 km) level, H_2S is thought to react with NH_3 to form a cloud of solid NH_4SH particles and to provide the main source of particulates in the atmosphere. Finally, white crystals of ammonia precipitate at 155 K ($p = 700$ mb, $z = 120$ km) to produce the visible upper cloud layer, this being confirmed by the appearance in Jupiter's emission spectrum of lines characteristic of solid ammonia. It is, however, important to realize that the predictions of the models are quite sensitive to the assumed concentrations of the various species, and that if these are changed significantly, large changes in the predicted cloud structure may result. Thus if the concentrations of NH_3 , H_2O and H_2S are all increased five-fold, the predicted cloud bases are lower, the clouds much denser, and aqueous ammonia condenses out at 300 K to form a cloud of liquid droplets beneath the water/ice cloud with base at 270 K.

In general there is good agreement between the abundances calculated from the models and those estimated from spectroscopic data except that the model produces about 10^3 times as much water as the observations suggest, and that H_2S has not been detected experimentally. Moreover, the model calculations so far described provide no explanation for the marked coloration of Jupiter. For these additional features it seems reasonable to look to irreversible chemical reactions caused perhaps by photolysis, lightning discharges etc.

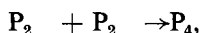
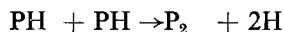
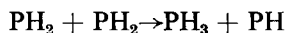
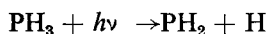
It is possible that the observed ethane and acetylene are produced by the ultra-violet photolysis of methane. While at high levels most of the H_2S is probably removed by condensation with NH_3 to form the cloud of NH_4SH particles, at levels below 90 km ($T = 200$ K) it may well be dissociated by ultra-violet light, so initiating the following reactions leading to the production of elemental sulphur:



The sulphur would then be available for further reactions leading to hydrogen polysulphide H_xS_y , or ammonium polysulphide NH_xS_y , which are generally yellow, orange and brown in colour and may therefore account for some of Jupiter's colours. The coloured bands, usually brown tinged with blue, tend to

coincide with the latitudinal belts that are free of the upper white ammonia-crystal cloud where the ultra-violet radiation could perhaps penetrate to the intermediate layer of NH_4SH cloud and photolyse the H_2S quite efficiently.

The existence of phosphine, PH_3 , is difficult to explain if the atmosphere were to contain as much water as the models predict, because most of it would be oxidized to form P_4O_6 which would dissolve in the water cloud droplets. However, if the water content were three orders of magnitude smaller, as suggested by the observations, this would probably be insufficient to oxidize more than a small fraction of the PH_3 . If then phosphine is present above the level of the ammonia-crystal cloud, it is likely to be dissociated by ultra-violet light and eventually produce red phosphorus crystals according to:



which could conceivably account for the colour of the Great Red Spot, the top of which rises several kilometres above the general level of the ammonia-crystal clouds.

Vertical temperature profile of Jovian atmosphere. Measurements by infra-red radiometers on the PIONEER vehicles give a mean effective radiative temperature for the planet of 130 K on both the dark and sunlit sides, which speaks for rapid heat transport by the atmospheric motions and very small diurnal temperature changes. Moreover, the measurements show that the planet emits about twice as much energy as it receives from the Sun. The additional heating is believed by some to be produced by a slow contraction of the planet—a rate of only 1 mm/year would apparently suffice. This extra heat is radiated outwards from the planetary 'surface' through the atmosphere, so that Jovian meteorology is largely internally driven.

The temperature structures of the atmosphere above the $p = 1$ bar, $z = 110$ km level, as deduced from measurements on the infra-red emission bands of H_2 , NH_3 and CH_4 , made both from Earth and from the PIONEER vehicles, agree in locating a temperature minimum of about 100 K at the 100 mb, 160 km level. Above this the temperature rises in the stratosphere to reach 150 K at 10 mb (see Figure 6). The derived pressure at the 130 K level is 0.48 bar, with $T = 165$ K at $p = 1$ bar. The vertical temperature profile below $p = 1$ bar, derived mainly from microwave (1–20 cm) emissions of NH_3 and infra-red emissions of H_2 (about 5 micrometres), is nearly linear, with a mean lapse rate of about 2 K/km. These measurements are quite consistent among themselves and allow a model adiabatic atmosphere of solar composition to be followed down to at least the $p = 20$ bar, $T = 400$ K level, which we may arbitrarily define as the 'effective surface' of the planet.

There is also consistency between cloud-free radiative models, which show most of the infra-red flux to be emitted from levels between 700 and 150 mb, and the chemical cloud model which places the base of the upper layer of ammonia-crystal cloud at 700 mb.

Cloud structure. The simple parcel method described above predicts the levels of cloud formation and their densities but provides no information on the horizontal distribution of cloud, which is determined largely by the air motion.



PLATE I—AWARDS TO CAPTAINS AND NAVIGATORS OF CIVIL AIRLINES

From left to right: Captain D. H. Mackie and Mrs Mackie, Director-General of the Meteorological Office, Mrs L. C. Williams and Navigation Officer L. C. Williams (see page 97).



PLATE II—AWARD WINNERS WITH MAJOR AND MRS K. G. GROVES

From left to right: Dr S. J. Caughey, Flight Lieutenant E. D. Peet, Mrs Groves, Major K. G. Groves, Flight Lieutenant A. N. White, Dr A. J. Gadd (see page 96).



**PLATE III—MAJOR K. G. GROVES PRESENTING THE 1977 METEOROLOGY
PRIZE TO DR A. J. GADD**
(See page 96.)



**PLATE IV—MAJOR K. G. GROVES PRESENTING THE SECOND MEMORIAL
AWARD FOR 1977 TO DR S. J. CAUGHEY**
(See page 97.)

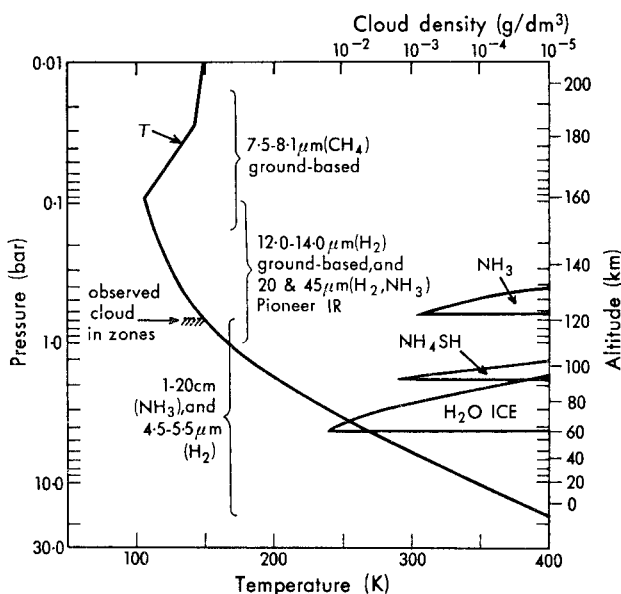


FIGURE 6—VERTICAL TEMPERATURE PROFILE OF THE JOVIAN ATMOSPHERE WITH THE POSITIONS OF THE THREE CLOUD LAYERS

Pictures from PIONEER 11, taken at its closest approach to within about 10^6 km, have a resolution of about 200 km and confirm and extend results of ground-based studies of the horizontal arrangements of clouds in Jupiter's atmosphere and their motions. They reveal seven or eight distinct bright cloud bands (zones) running parallel to the equator and separated by darker belts. The equatorial zone is some 20 000 km wide but the zonal width decreases towards higher latitudes. The bright zones, which the infra-red radiometers show to be colder (and therefore higher) than the dark belts, are interpreted as the upper surface of the ammonia-crystal cloud layer formed as the result of ascending motions, the dark belts being regions of descent and cloud dispersal. The zones and belts are not entirely regular. Dark patches often appear in the bright zones, indicating that the ammonia-cloud cover is not always complete, and the boundaries between the zones are often serrated owing, as high-resolution pictures show, to chains of vortices 5000–10 000 km in diameter. The outstanding feature is the 'permanent' Great Red Spot in the centre of the tropical zone of the southern hemisphere (see below).

A remarkable feature of the Jovian cloud patterns is their longevity. On Earth, a particular cloud system rarely persists for more than a few days unless tied to a topographical feature; but Jupiter's surface, being fluid, has no topographical feature and yet the cloud configurations persist for at least a year. One reason may be that, because the temperatures, infra-red fluxes and emissions of the gases at cloud level are all much lower than on Earth (with radiative cooling rates of only about 10 K/year compared with about 1 K/day on Earth), the radiative relaxation time is of order 10 years, which implies that temperature anomalies are likely to take a very long time to disappear by radiative processes.

Another remarkable feature is the axisymmetric organization of the Jovian

clouds along lines of latitude, which does not occur on Earth or on Venus. This may be partly due to lack of topographical features and the absence of large surface-pressure differences which cannot be supported by a fluid surface, but is mainly due to the strong control exerted by the rapidly rotating massive planet on the atmospheric circulation.

Atmospheric circulation on Jupiter. The fact that PIONEER 11 found that thermal emissions from the planet in high latitudes did not differ by more than a few per cent from those in low latitudes, despite the large excess of solar irradiation at the equator, suggests that either the atmospheric circulation is very effective in transporting heat from the equator to the poles or that the solar imbalance is largely counterbalanced by an internal heat source.

On Earth the poleward heat transfer is largely accomplished by baroclinic waves (cyclones and anticyclones) embedded in the middle-latitude westerlies, but these appear to have no counterpart in the axisymmetric Jovian circulation, which suggests that the meteorology of Jupiter is quite different from that of Earth. In the first place, the influence of the planet's rotation is much stronger on Jupiter. The rapid rotation of such a massive planet results in a mainly horizontal circulation with little vertical motion—rather like that of the deep oceans on Earth. The strong zonal flow, running parallel to lines of latitude, is almost in the Jovian equivalent of geostrophic balance. These motions are thermal winds driven by pressure differences set up by the meridional temperature gradients, their strength increasing with height at a rate proportional to the thermal gradient but, since they blow perpendicularly to the thermal gradient, they are unable to transport much heat and therefore cannot account for the observed small equator–pole contrast. However, the banded structure of the clouds suggests that the axisymmetric vortex develops instabilities with wavelength of order 10 000 km and, although these must be of a different character from that of the Earth's baroclinic waves, they may nevertheless transport heat from the relatively warm cloud-filled zones to the cooler intermediate belts and, overall, towards the poles. The most likely mechanism is shear instability leading to the development of inertial waves as a consequence of an imbalance between the centripetal and pressure-gradient forces which divide the axisymmetric vortex into a series of zonal toroidal cells corresponding to the zones and belts, as depicted in Figure 7. The circulation, involving meridional flow from zones to belts at high levels, is completed by vertical motions which release latent heat of condensation in the zones and so enhance the temperature contrasts. These temperature differences, observed to be about 3 K between zones and belts, set up pressure differences with the zones becoming regions of high pressure and anticyclonic vorticity and the belts becoming regions of low pressure and cyclonic vorticity as shown in Figure 7, and these, in turn, produce alternate bands of easterly and westerly winds. Both observations and numerical models indicate that these zonal winds tend to become concentrated in narrow jets on the boundaries of the cloud bands so that the edges of adjacent bands travel in opposite directions. The zonal winds are strongest near the equator where there is a westerly jet of about 100 m/s. The strong wind shears associated with these jets, together with the enhanced temperature gradients in the zones, may well allow the development of inertial waves of shorter wavelength, about 5000 km, than those responsible for the bands themselves and account for the rows of vortices seen on the edges of the cloud bands in the high-resolution photographs.

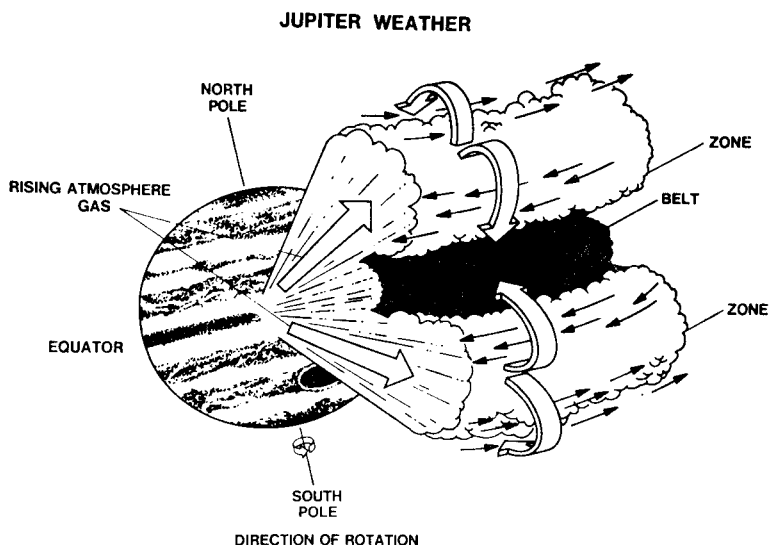


FIGURE 7—THE STRUCTURE AND CIRCULATION OF THE UPPER ATMOSPHERE OF JUPITER

The Great Red Spot. The outstanding feature of Jupiter, the Great Red Spot in the southern tropical zone, was first observed by Hooke or Cassini in 1664. An oval, stretching 25 000 km longitudinally and 12 000 km latitudinally, its area is roughly equal to that of the whole Earth's surface. Its rate of rotation about the axis of Jupiter is remarkably constant; during the last century its period has varied by only 7 seconds in nearly 10 hours. Although it has wandered in longitude over some 1200° in the last 100 years, it has varied by less than 1° in latitude during that time. It oscillates in longitude with an amplitude of about 1° and a period of about 90 days. The motions of much smaller spots in the zones and around the Great Red Spot give some information on the atmospheric motions relative to the Spot. If the movements of the small spots are not greatly affected by wave motions, they imply zonal wind speeds in the southern tropical zone of about 2 m/s relative to the Great Red Spot and circulation velocities near the spot of 20–60 m/s in the counterclockwise direction.

The mechanism responsible for the formation and maintenance of the Great Red Spot is still unknown. Hide has proposed it to be a Taylor column such as forms over a topographic obstacle in a rapidly rotating fluid. The obstacle sets up a disturbance which propagates upwards and appears at the top of the fluid as an eddy. However, since the Jovian surface is likely to have no topographic features that could anchor such a column, and it is not at all clear how such an eddy could be maintained against dissipative forces for hundreds of years, this does not seem a very likely explanation.

In a recent computer simulation of Jupiter's atmospheric circulation, Williams finds that a special type of large eddy, reminiscent of the Great Red Spot, appears between two adjacent jet streams in which smaller eddies coalesce and form a large, long-lived eddy. The absence of a solid underlying surface so reduces the energy dissipation that most features of the circulation, including the

eddies, last for much longer than similar features on Earth. However, the maintenance of a large eddy for about 40 days in a model, though providing some interesting hints and insights, does not constitute a convincing explanation of the Great Red Spot, which has lasted for hundreds of years.

CONCLUDING REMARKS

The remarkable recent increase in our knowledge of planetary atmospheres, gained largely but not entirely from space probes, has allowed planetary meteorology to develop on sound lines, mainly by comparison of the results of numerical models with observations as in terrestrial meteorology.

Studies of the atmospheres of the other planets are not only of great intrinsic scientific interest in themselves but, because they exhibit such marked differences, broaden our perspectives and provide greater insight into planetary fluid dynamics as a whole and therefore a deeper understanding of the Earth's weather and climate in particular.

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FORECASTING SEA-BREEZES AT ESKMEALS

By O. W. BRITTAIN

(Meteorological Office, Bracknell)

SUMMARY

Sea-breezes at Eskmeals ($54^{\circ} 19'N$, $03^{\circ} 24'W$) are complicated because of the mountainous coastal regions involved. The various types of sea-breeze are described and a diagram for forecasting them in the summer half of the year is obtained. The diagram is mainly based on (a) the difference between the screen temperature at Eskmeals (T_L) and the sea surface temperature (T_S) and (b) the free-stream wind V_L . Results of a test on the diagram carried out by forecasters at Eskmeals under operational conditions are presented.

THE TOPOGRAPHY OF THE ESKMEALS AREA

Eskmeals is situated on fairly flat sandy ground about one kilometre inland from the sea. The meteorological site is on well-drained land which lies about 8 metres above mean sea level. The coastline near Eskmeals lies roughly north to south and the joint tidal estuary of three rivers, the Irt, Mite and Esk, is about one kilometre to the north. Beyond this estuary the coastline lies south-east to north-west for about 22 km to St Bees Head (see Figures 1(a) and 1(b)). Apart from Eskdale, an enclosed valley to the north-east of Eskmeals, there is extensive high ground from 155° through east and north to 335° . Much of the mountainous surround rises to 400–600 metres but to the north-east and north-north-east a prominent cluster of peaks, including Scafell Pike, rises to nearly 1000 metres. The steep escarpment to the fells lies about 6 km to the east of Eskmeals and slightly further to the south-east. To the north-north-west, the rise to higher ground is more gradual. Apart from a range of hills 3 to 4 km distant to the north-east rising to 150–250 metres, fairly flat ground extends from the sea to the fells.

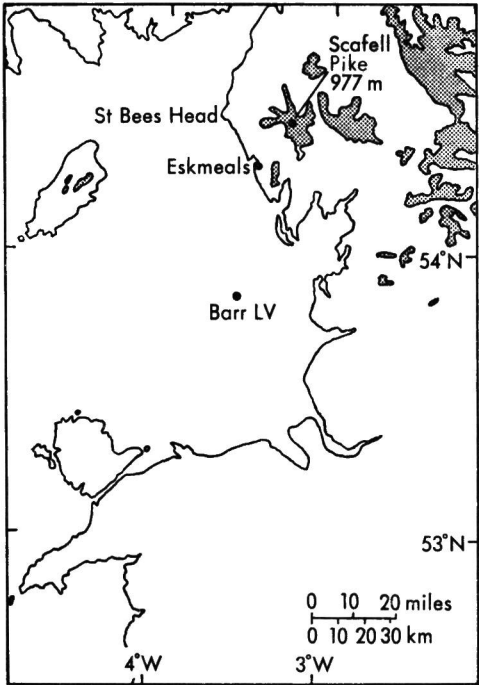


FIGURE 1(a)—THE LOCATION OF ESKMEALS
Shading indicates ground over 400 metres above mean sea level.

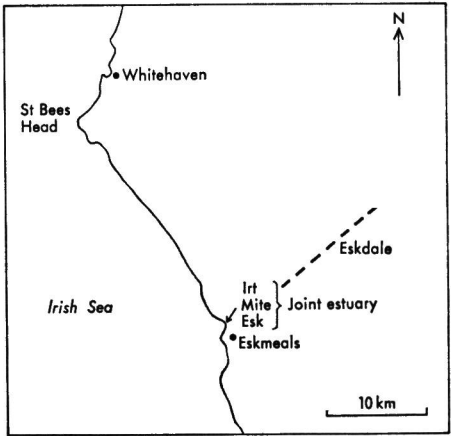


FIGURE 1(b)—MAP OF COASTAL AREA AROUND ESKMEALS

DEFINITION OF A SEA-BREEZE AT ESKMEALS

A sea-breeze at Eskmeals was essentially defined as a surface wind with a direction between 190° and 310° , that is to say an onshore wind. To eliminate onshore winds which had no association with sea-breeze effects, the definition was further limited to occasions when the onshore component of the surface wind, resolved in the direction $270-090^\circ$, that is to say normal to the coastline, exceeded the onshore component of the free-stream wind resolved in a similar manner. This second restriction fails to eliminate occasions of ordinary backing of the surface wind in a northerly gradient. However, on such occasions the surface wind is north-easterly at first (a valley effect) becoming north-westerly but $>310^\circ$, which does not satisfy the first restriction.

THE DATA USED

A study of sea-breezes for the period 1960-75 was made in order to distinguish between the various types which occur at Eskmeals, depending on the direction of the free-stream wind.

A method of forecasting whether or not a sea-breeze will occur was based on data for the 10 year period 1964-73. The main indicators used were (a) the difference between the air temperature at screen level over land and the sea temperature ($T_L - T_S$) which is generally accepted as being closely associated with the occurrence of a sea-breeze, which only sets in when $T_L - T_S$ is positive, and (b) the free-stream wind V_f .

TYPES OF SEA-BREEZE AT ESKMEALS

(a) During calms or light free-stream winds from any direction, the sea-breeze usually sets in from 270° . It then veers gradually at about 10 degrees an hour by 20 to 40° , in response to the Coriolis effect, followed by a prolonged spell from $290-310^\circ$. (*Note.* Anabatic and katabatic winds as well as sea-breezes and land-breezes occur in the mountainous coastal regions in which Eskmeals is situated. In particular, with clear skies and light winds, an anabatic wind sometimes sets in at Eskmeals from $210-230^\circ$, some hours after dawn. This is often before there are suitable conditions for the onset of a sea-breeze, that is to say when T_L exceeds T_S .)

(b) With measurable free-stream winds from 270° to 020° (through north) the onset of the sea-breeze is marked by a strengthening and change in direction of the surface wind which eventually becomes $290-310^\circ$. The final direction is the same as for type (a) sea-breezes but type (b) sea-breezes are usually much stronger.

(c) With free-stream winds from $020-070^\circ$, sea-breezes often occur even with strong free-stream winds. This is considered to be due to the sheltering effect of the hills on the lower layers. The direction of the surface wind usually becomes $210-230^\circ$.

(d) With free-stream winds from $070-140^\circ$, the sea-breeze usually blows from $270-310^\circ$ and can occur with free-stream winds of up to 22 knots. It is possible that 'sea-breezes' associated with the stronger winds are sometimes caused by lee standing eddies set off by the hills.

(e) With free-stream winds from $140-210^\circ$, the onset of the sea-breeze is usually marked by a gradual veer and decrease in the surface wind which on many occasions eventually becomes $290-310^\circ$. During the veering process, the surface wind direction at Eskmeals often remains $210-230^\circ$ for several hours.

The stronger the initial flow, the smaller the sea-breeze effect, so that on a few occasions the surface wind only veers to about $190\text{--}230^\circ$.

(f) With free-stream winds from $210\text{--}270^\circ$, the onset of the sea-breeze is occasionally marked by a small shift in surface wind direction towards west; there is usually little change in speed.

THE EFFECT OF STABILITY

From a study of upper-air soundings at Eskmeals and at stations in the main radiosonde network it was found that (1) sea-breezes will not develop until any nocturnally generated surface-based inversion has completely broken down and that (2) no particular depth of convection governs their occurrence, in contrast to experience in Lincolnshire where sea-breezes at Manby do not occur unless there is convection to 5000 ft over land (Brittain, 1966).

THE FREE-STREAM WIND (V_f) AND THE SCREEN TEMPERATURE (T_L)

The free-stream wind is usually estimated by using a geostrophic scale on surface isobars but these are difficult to draw with confidence in the Eskmeals area because of the sparse network of surface pressure observations over land and the even sparser network over the Irish Sea. Therefore on most occasions the free-stream wind was taken to be the wind speed and direction at 600 metres obtained from radar wind soundings made at Eskmeals at various times during the day, mainly between 1000 and 1530 clock time. Routine soundings made at 0715 clock time could not at first be used to obtain the 600 m wind because of the high rate of ascent, but during summer 1974 more efficient radar equipment was installed and early location of the ascending sonde was made easier. On a few occasions when radar winds were not available, V_f was estimated from surface isobars drawn on the hourly MOLFAX charts of the British Isles. For each value of V_f a synchronous value of the screen temperature at Eskmeals (T_L) was obtained.

THE SEA TEMPERATURE (T_s)

During the first year (1972) in which sea-breezes at Eskmeals were studied, values of the sea temperature reported by the Barr Light Vessel, situated almost 40 km from Eskmeals (see Figure 1) were used. During 1973, since reports from the Barr Light Vessel were no longer available, values of T_s were obtained from the 5-day mean sea temperature (MOLFAX) charts. For the earlier period 1964–71, the sea temperature for the summer half of the year was obtained from the pecked line on Figure 2 which is a curve drawn through values obtained for 1972, plotted as open circles, and for 1973, plotted as dots. For the winter half of the year the sea temperature was obtained from the solid line which was derived from an atlas of 50-year mean monthly sea surface temperatures (CPIEM, 1960).

THE FORECASTING DIAGRAM

Values of $T_L - T_s$ were plotted against the simultaneous free-stream wind speed and direction on a polar diagram, similar to that shown in Figure 3, for various times during the day when radar wind soundings were made. The symbols used indicated (1) when a sea-breeze was neither blowing at the time nor noted as having developed within the next 30 minutes, (2) when a sea-breeze which had

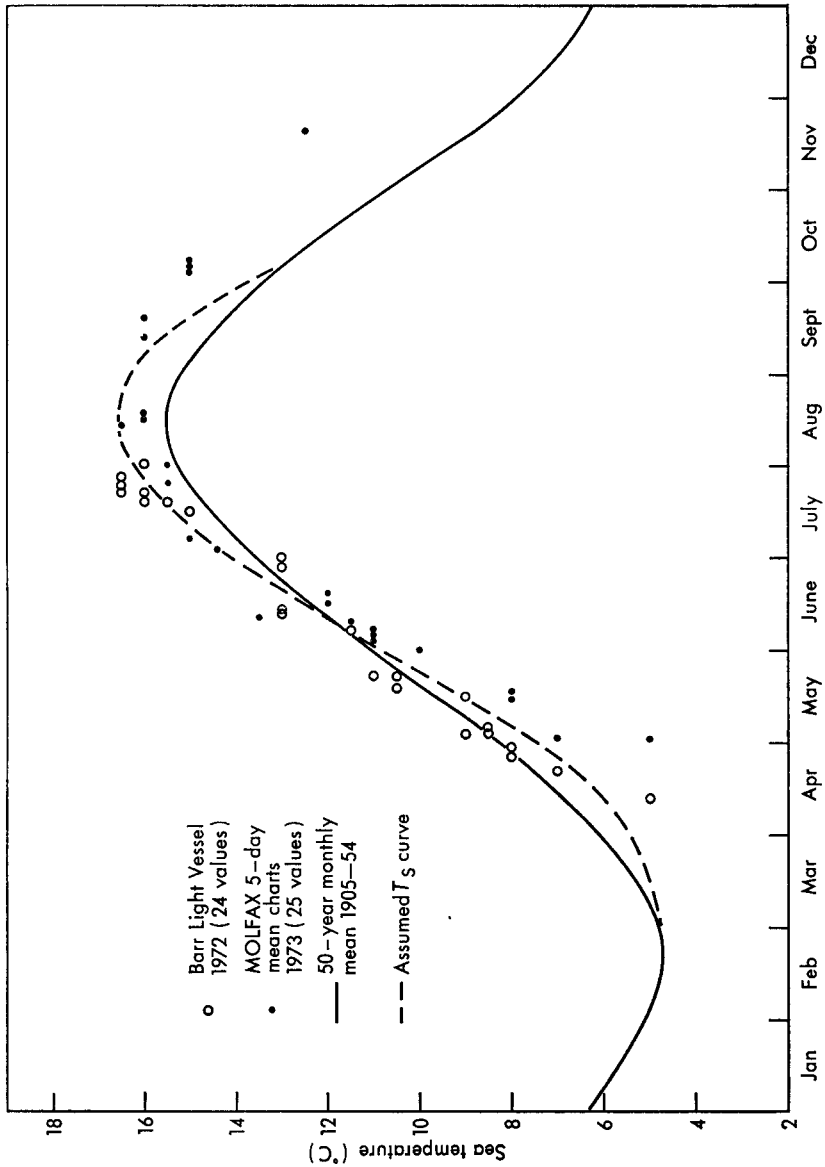


FIGURE 2—SEA TEMPERATURES IN THE ESKMEALS REGION

previously set in continued for at least 30 minutes and (3) when one subsequently developed within 30 minutes. There was a total of 654 plots of which 293 were associated with a sea-breeze and 361 were not. Figure 3 shows the resulting isopleths of $T_L - T_S$ in relation to V_f . The isopleths indicate the boundary conditions between occurrence and non-occurrence of a sea-breeze at Eskmeals, provided that there is no surface inversion of temperature. Of the 654 plots, 138 failed to fit the isopleths and the resulting contingency table is shown below.

	Sea-breeze indicated	Sea-breeze not indicated	Total
Sea-breeze occurred	207	86	293
No sea-breeze	52	309	361
Total	259	395	654

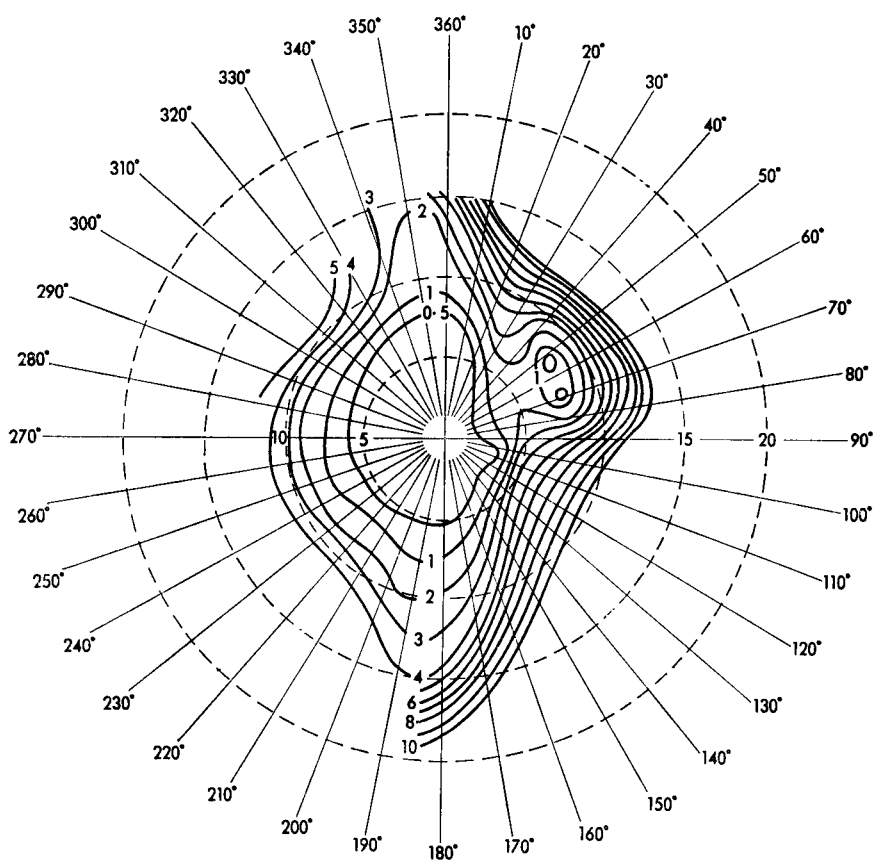


FIGURE 3—SEA-BREEZE FORECASTING DIAGRAM FOR ESKMEALS

Continuous isopleths indicate the temperature excess in degrees Celsius of the land temperature over that of the sea ($T_L - T_S$) required for a sea-breeze to develop for different values of the free-stream wind (dashed circles, speed measured in knots). Once an appropriate combination occurs a sea-breeze is likely to occur at Eskmeals within 30 minutes.

This represents a value for the Hanssen and Kuipers Index (Hanssen and Kuipers, 1965) of 0.56 and an equivalent 78 per cent success in the indication of a sea-breeze if there had been equal numbers of sea-breeze and no-sea-breeze events. However, the plots are not all independent since individual days are often associated with more than one plot. Woodcock (1976) has discussed the Hanssen and Kuipers Index in relation to other plausible measures of skill and has shown that it is superior in practical utility to χ^2 and is independent of varying trial conditions i.e. different mixtures of event and non-event days. The index is defined as follows:

Given a 2×2 contingency table of the form

	Forecast		
	Yes	Yes	No
Observed	No	a	b
		c	d

then

$$\text{Index} = \frac{ad - bc}{(a + b)(c + d)}.$$

AN OPERATIONAL TEST OF THE FORECASTING DIAGRAM

During the period February to October 1975, the Eskmeals forecasters used the diagram to prepare a forecast stating whether or not a sea-breeze would occur during the day. The forecast had to be completed by 0815 clock time and covered the period from 0715 or 0815 GMT to dusk. Since most sea-breezes in the summer months set in between 07 and 09 GMT at Eskmeals the routine radar wind sounding made at 0715 clock time each day was used to obtain the 600 m wind and T_L was measured at 0730 clock time. T_s was obtained from the 5-day mean sea surface temperature chart received on MOLFAX the previous day. As part of the normal forecasting processes, changes in V_t and T_L were predicted to cover the period up to dusk. The values of V_t and $T_L - T_s$ were then applied to the diagram in order to establish whether or not a sea-breeze would occur. If a sea-breeze set in before a prediction was made, no entry was made for that day. Over the whole period, 182 forecasts were made, the results of which are shown in the following contingency table:

	Sea-breeze forecast	Sea-breeze not forecast	Total
Sea-breeze occurred	52	13	65
No sea-breeze	7	110	117
Total	59	123	182

This represents a value for the Index of 0.74 and an equivalent 87 per cent success in the forecasting of a sea-breeze if there had been an equal number of sea-breeze and no-sea-breeze events. Of the 20 incorrect forecasts, it was considered that 2 were due to the failure of the diagram and 18 to errors in forecasting the indicators. For the individual months, the Index ranged from 0.32 for February to 0.87 for May which corresponds to an equivalent success rate of 66 per cent for February and 93 per cent for May.

FURTHER ASPECTS OF THE SEA-BREEZE

(a) Table I shows the number of days with a sea-breeze during each month for the years 1971 to 1975. For the years 1971 to 1974, the numbers are based on the

working week, that is to say omitting week-ends, but they have been adjusted in proportion to allow for this, throwing to the nearest whole number. The numbers for 1975 refer to complete months and did not require adjustment.

TABLE I—NUMBER OF DAYS WITH A SEA-BREEZE AT ESKMEALS DURING EACH MONTH FOR THE YEARS 1971–75

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1971	4	1	7	17	17	11	25	11	13	1	1	3
1972	0	3	4	14	14	10	17	12	15	8	1	1
1973	0	6	14	11	7	17	17	12	8	0	0	0
1974	0	3	10	20	11	17	6	10	1	7	1	0
1975	0	5	6	8	17	19	15	14	3	6	0	0
Total	4	18	41	70	66	74	80	59	40	22	3	4
Per cent	0.8	3.7	8.5	14.6	13.7	15.4	16.6	12.3	8.3	4.6	0.6	0.8

Some 73 per cent of the sea-breeze days occurred in the months April–August.

(b) The time of onset of the sea-breeze was 3 to 5 hours after sunrise on 75 per cent of occasions but ranged from 2 to 10 hours after sunrise.

(c) The time of cessation was nil to 4 hours before sunset on 83 per cent of occasions but ranged from 9 hours before to 1 hour after sunset.

(d) The maximum gust during the sea-breeze occurred during the period from 1 hour before noon to 3 hours after noon on 73 per cent of occasions.

(e) The mean strength of the sea-breeze was 0.6–3.5 knots on 19 per cent of occasions; between 3.6 and 6.5 knots on 54 per cent; between 6.6 and 9.5 knots on 19 per cent; between 9.6 and 12.5 knots on 6 per cent and greater than 12.5 knots on 3 per cent.

(f) The strength of the sea-breeze did not at any time appear to be governed by the size of the term $T_L - T_s$.

CONCLUSIONS

Although sea-breezes at Eskmeals are complicated because of the high ground in the region, a sea-breeze forecasting diagram based on $T_L - T_s$ and the free-stream wind gave good results when used in practice by Eskmeals forecasters. An important consideration is that the sea-breeze will not set in until any nocturnally generated surface-based inversion has completely broken down. On the other hand, no particular depth of convection governs their occurrence, in contrast to experience in Lincolnshire. The strength of the sea-breeze does not appear to be governed by the size of the term $T_L - T_s$. Over the period 1971–75, some 73 per cent of sea-breeze days occurred in the months April–August.

ACKNOWLEDGEMENT

The author wishes to thank Mr C. L. Hawson and Mr C. A. S. Lowndes of the Special Investigations Branch of the Meteorological Office at Bracknell and his former colleagues at Eskmeals for their help, especially Mr J. H. Davies.

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AWARDS

L. G. Groves Memorial Prizes and Awards

The annual award of prizes took place on Friday 25 November 1977 at the Main Building, Ministry of Defence, Whitehall. The Air Member for Personnel, Air Chief Marshal Sir John Aiken, K.C.B., presided and the awards were presented by Major K. G. Groves. As well as Mrs Groves, several other members of Major Groves's family were present, which served to enhance the personal nature of this annual event in a most agreeable way. In view of the strike of lift maintenance workers it was perhaps fortunate that the beautifully decorated Historic Room in which the ceremony took place was no more than two floors above ground level. (See Plates II-IV.)

The 1977 Aircraft Safety Prize was awarded to Flight Lieutenant A. N. White of Royal Air Force Scampton with the following citation:

'Flight Lieutenant White's "Vulcan Miscellany" presents to all Vulcan aircrew, in an easily readable style, a unique and permanent collection of the significant accidents, incidents and handling aspects which have occurred over the years. As a result Vulcan crews are aware of the many problems encountered in the past and how they were handled. With this valuable knowledge they can prepare their own reactions to potential emergencies with confidence. It also shows how current operating procedures and orders have been developed and what can happen in certain circumstances if they are ignored; apart from re-emphasizing their validity, it also provokes thought on their future development. The miscellany is also an idea capable of further development beyond the flight safety aspects of systems operations into the field of operational training.

It is in recognition of his initiative and practical contribution to the safety of Vulcan aircrew and the possibility of the idea being applied to other aircraft that Flight Lieutenant White has been awarded the 1977 L. G. Groves Aircraft Safety Prize.'

The 1977 Meteorology Prize was awarded to Dr A. J. Gadd of the Meteorological Office with the following citation:

'For the past ten years Dr Gadd has been engaged in the development of numerical forecasting models and of their practical applications. He has been responsible for the incorporation of many significant improvements into operational routines especially in the fields of initialization, time integration and output. His work on the split explicit time integration scheme recently incorporated into the main operational model has led to substantial savings of computer time and greater flexibility in the numerical forecasting system.

Dr Gadd has been concerned with refinements in the modelling of temperature and wind and with adaptations of computer output which have had direct application in the provision of meteorological services for aviation. These include the output of forecast data in grid point form for use in computers used by airlines and air traffic control authorities in flight planning and in the direction of aircraft operations. In his contacts with members of the aviation industry Dr Gadd's evident authority, depth of expertise and co-operative approach have invariably led to the appreciation of the users and to confidence in the solutions found to their problems.'

The 1977 Meteorological Observer's Award was awarded to Flight Lieutenant E. D. Peet of the Meteorological Research Flight, RAE Farnborough with the following citation:

'Flight Lieutenant Peet has served with the Meteorological Research Flight as a pilot for the last four years and has identified himself to an unusual degree with the scientific tasks of the Flight. This has enabled him to make a positive and worthwhile contribution to the planning of the flights and to the development of both the Hercules and Canberra aircraft as tools for research. During actual flying operations his keen interest, relevant comments and general helpfulness have done much to ensure that each flight has been conducted in such a way as to make maximum use of its opportunities for the scientific study of weather phenomena.'

The 1977 Second Memorial Award was awarded to Dr S. J. Caughey of the Meteorological Research Unit at Cardington with the following citation:

'For the past three years Dr Caughey has been the leader of the team at Cardington engaged on the experimental and theoretical study of the boundary layer. He has made many contributions to the analysis and interpretation of data from major field experiments, helping to present a more ordered picture of the complex processes at work in the lower atmosphere.

He has been quick to develop and exploit the potential of new methods of observation, in particular the use of sound pulses to study the small-scale pattern of wind and temperature fluctuations. The careful experiments of the Cardington team have established a firm quantitative foundation for this technique and pointed the way to important practical applications in measuring such things as wind shear and fog-top height.'

Meteorological Office awards to captains and navigators of civil airlines

Since 1954 the Director-General of the Meteorological Office has made awards annually to encourage in-flight and post-flight weather reporting by captains and navigators on the staff of civil airlines. The awards have been of two kinds: books, suitably inscribed, have been awarded to captains and navigators who have provided the best series of reports during the year under review, and captains (and exceptionally navigators) who have given long and meritorious service in the provision of air reports have been given brief-cases.

For a number of reasons including the trend towards self-briefing, remote briefing facilities at air terminals, and the introduction of the practice of designating aircraft to provide AIREPs on Atlantic routes, it has become increasingly difficult to maintain a workable and fair system of marking as a basis for the awards. In the circumstances it has been decided that the system should be wound up and that the awards for 1976 will be the last. Since the scheme began there have been 46 awards of brief-cases and 439 book awards.

The final presentation of brief-cases took place at the Meteorological Office College, Shinfield Park, near Reading on 25 October 1977 when the Director-General presented the awards to Captain D. H. Mackie, formerly of British Airways, and to Navigation Officer L. C. Williams, formerly of British Caledonian Airways. This was only the second occasion on which a brief-case had been awarded to a navigator. (See Plate I.)

REVIEW

Meteorology for glider pilots, third international edition, by C. E. Wallington, 240 mm × 140 mm, pp. xi + 331, *illus.* London, John Murray, 1977. Price: £8.50.

The first edition of this book was published in 1961. It was the outcome of a decade which had seen much fruitful interplay between meteorologists and pilots in the developing sport of cross-country gliding. The book was firmly based on the author's own experience in the air, as well as on his theoretical knowledge and meteorological instinct. Written in a style that was at once personal yet authoritative it became, and has remained, the popular standard work on meteorology for the gliding movement in this country.

For this new edition there has been a major reshaping of the original text. It is still recognizably the old 'Wallington' though there have been many changes in text, diagrams and plates. The description 'international' is justified by the inclusion of many southern-hemisphere weather maps and other material drawn from the author's recent experience in Australia, where he now lives, and elsewhere.

The book is now arranged in four distinct parts of which the first is entitled 'General meteorology'. This is a basic course on the elements of meteorology addressed to amateur pilots. It differs little from many other such courses, though it includes a chapter on tropical weather which is new to this edition.

The second part entitled 'Gliding meteorology' will be the kernel of the book for most meteorologists. It has chapters on Airflow over hills; Dry thermals; Cumulus convection; Convective storms; Sea-breezes; and Lee waves. All these topics were covered in the first edition and much of the original text is still intact, since most of the nuts and bolts of gliding weather were well understood by 1961. It is interesting to consider how far we have advanced since then, especially in our knowledge of the variability of convective phenomena on the 'meso' scale. In this country at least it has seemed that the gradual improvement in the performance of gliders over the past sixteen years has been accompanied by a corresponding decrease in the meteorological feedback.

From his international vantage point Wallington has been able to shed a little new light, but in general it is clear that the advances of recent years have been small. However, the new sections describing the simultaneous occurrence of thermals and lee waves are a very welcome corrective to older ideas that these two phenomena were mutually exclusive. Other new material includes a note on the cellular organization of thermals over flat terrain in Australia, and a description of some interesting orographic convergence effects in the USA. Although the chapters on 'Convective storms' and 'Sea-breezes' have little that is essentially new, the latter does contain some recent case studies which are a welcome change from the generalized descriptions that form the bulk of the text.

The final two parts are quite short. 'Weather forecasts' gives practical advice to pilots on obtaining forecasts from a national meteorological service that are tailored to the needs of gliding. 'Technical notes' is a short appendix where such subjects as geostrophic winds and tephigrams can be kept at a safe distance from those readers who like 'weather' but are allergic to 'meteorology'.

The book has been written for glider pilots, and its reshaping has been done to make it more attractive to that audience. From his different standpoint, the meteorologist can applaud the new layout, but he will regret that there has been some decrease in scientific content, deliberate though this may have been. Those who knew the older editions will find that beyond the rearrangement and expansion of the text, this edition has rather little to report that is substantially new. But to those who have never yet delved into 'Wallington' there can be no hesitation in recommending it as an excellent exposition, in popular but authoritative style.

P. G. WICKHAM

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LETTER TO THE EDITOR

The exceptional heat-wave of 23 June to 8 July 1976

Mr Shaw's interesting article, in the October 1977 *Meteorological Magazine*, on the hot spell of 23 June to 8 July, is just a bit misleading in the matter of low humidities. While it was indeed unusual for relative humidities of less than 20 per cent to occur as they did, e.g. on 30 June 1976, over a wide stretch of lowland England, Mr Shaw seems to go a bit astray when he considers these occurrences in the context of previous occasions. It is doubtful if a value of 4 per cent relative humidity has, this century, occurred only in March 1965, and in that month it was recorded at other places than Manchester Airport and Great Dun Fell; indeed it seems to have got down to 2 per cent at Strachan in Kincardineshire (Green, 1966). But the records of Ben Nevis Observatory show that very low relative humidities were (and undoubtedly still are) not so very rare on that summit; with the help of some of the staff of the Meteorological Office, I documented two cases (Green, 1967) where the relative humidity was apparently zero.

Inspection of the daily aerological records shows that occasions when there is dry air not far above the surface are fairly common, but the boundary layer usually insulates them from the surface, except on hill-tops. The dryness is, not surprisingly, usually greatest in winter anticyclones, and the Ben Nevis records show that occurrences of low relative humidity at the Observatory were commonest in winter. There was a secondary maximum in May–June, and this is the period when low relative humidities are commonest in the lowlands; diurnal heating, in warm anticyclonic conditions in early summer, easily transforms *rather* low relative humidity, during the day, to *very* low relative humidity.

F. H. W. GREEN

*Department of Agricultural Science,
University of Oxford,
Parks Road,
Oxford OX1 3PF*

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Mr Shaw has commented on the above letter as follows:

‘The section on low humidities was intended as an item of extra interest and was in no way as exhaustively researched as the sections on temperature records. I should be surprised if serious objections to the latter were raised, but it does not surprise me at all that someone who has himself written articles specifically on cases of very low relative humidity should be able to raise critical comment. My phrase ‘believed to be the lowest recorded this century’ was taken, as far as I remember, from one of the references quoted and in retrospect, I suppose, it invited comment such as that of Mr Green.

‘My main comparison was with the list given in the *Climatological Atlas* covering a 22 year period and I assumed that such a list *had* been fairly well researched. The ‘4%’ item was thrown in as an extra, perhaps rashly. Mr Green’s last sentence surprises me a little. I did not know of the tendencies to low humidities in May–June but if ‘rather’ low R.H. was easily transformed into ‘very’ low R.H. there would surely be many more instances recorded at our low-level stations. It would seem from my brief look at the subject that while R.H. of the order of 25–30% may not be uncommon in hot weather, values below 20% are rare at low levels.’

EDITOR

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