PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Winds and Temperatures in the Auroral Zone and their Relations to Geomagnetic Activity [and Discussion]

D. Rees, H. Rishbeth and T. R. Kaiser

Phil. Trans. R. Soc. Lond. A 1972 **271**, 563-575
doi: 10.1098/rsta.1972.0024

Phil. Trans. R. Soc. Lond. A. **271**, 563–575 (1972) [563]
Printed in Great Britain

Winds and temperatures in the auroral zone and their relations to geomagnetic activity

By D. Rees
Department of Physics, University College London

Measurements of neutral wind velocity and neutral atmospheric temperature above 90 km in the auroral zone have shown distinct correlations with local and global geomagnetic activity respectively.

Individual magnetic substorms have been observed to produce neutral wind speeds of over 500 m s^{-1} at 130 to 150 km. Ion-neutral particle drag is a likely accelerating mechanism with enhanced meridional electric fields and electron density. These wind disturbances can theoretically propagate to mid-latitudes in the night hemisphere and produce anomalously high neutral wind speeds on a global scale especially during geomagnetic storm conditions. Such anomalously high wind speeds have been observed on several occasions at mid-latitude sites during disturbed conditions.

Neutral temperature values in the auroral zone show a positive correlation with geomagnetic activity with a relatively slow decay following heating. The temperature dependence upon the C9 index (which is representative of $\overline{K_p}$) is altitude dependent, increasing from a value near to the global mean (25 K per unit C9) at 140 km to an enhanced value of 50 K per unit C9 at 165 km.

Auroral zone measurements are only possible during the period September to April inclusive; however, in this period, during quiet geomagnetic conditions and between 130 and 200 km, there is a decrease of neutral temperature of 150 ± 50 K between mid-latitudes (30° N) and the auroral zone (70° N) which is significantly greater than the polewards decrease of temperature predicted from satellite drag density data.

1. Introduction

The measurements of neutral wind velocity and temperature reported in this paper are based on the rocket programmes of University College London (U.C.L.) at high latitude (Esrange, Kiruna, 68° N) and mid-latitude (Woomera, 31° S) during the period 1968 to 1970 – a period of high solar activity. Additionally, many other measurements were made during rocket experiments of the Max Planck Institute for Extraterrestrial Physics, Munich.

The two U.C.L. programmes were intended to constitute a balanced programme with the following objectives:

(i) To extend measurements of thermospheric winds to high latitude since before 1968 almost all observations were at latitudes lower than 40°.

(ii) To investigate the auroral zone thermosphere and to make comparisons of its structure during both geomagnetically quiet and disturbed periods.

(iii) To extend thermospheric measurements to include neutral temperature and density as well as wind speed.

(iv) To make comparisons between thermospheric structure at mid-latitude and high latitude and to examine the response of each to geomagnetic activity and other parameters.

Before the U.C.L. programme the response of the upper atmosphere to geomagnetic activity had not been resolved, other than by the review of Jacchia, Slowey & Verniani (1967) giving the mean global response to geomagnetic heating and a mean time delay between activity and the resulting heating. The resolution of geomagnetic effects from satellite data analysis has been successively improved since then in reviews by Jacchia (1970), Roemer (1970) and Moe (1970). These later results have described the thermal and density changes as functions of geomagnetic activity, time of day and latitude, but without describing the detailed dynamic response of the auroral thermosphere to geomagnetic activity, or explaining the diurnal variations or the delay between activity and heating.

This paper attempts to fit the still scanty data recently available from rocket experiments and ground-based measurements (see, for example, Roble, Hays & Nagy 1970) into a description of the thermal and dynamic reactions of the lower thermosphere to geomagnetic activity.

2. Neutral winds in the auroral zone lower thermosphere

Rees (1971*a*) has made a number of measurements of neutral wind profiles in the auroral zone above 90 km using trimethyl aluminium trails and closely spaced grenade cloud releases.

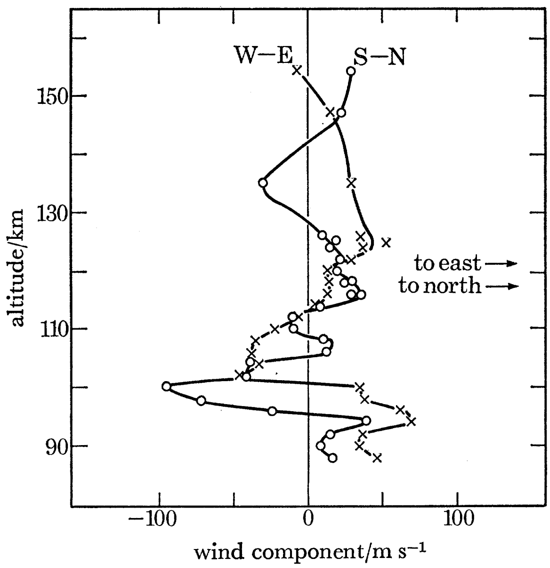

Figure 1. S–N and W–E neutral wind components on 1 February 1968, 06h42 C.E.T.

Figures 1 and 2 show neutral wind profiles obtained above Esrange on 1 and 4 February 1968 at morning twilight. The eastward bias of the latter wind profile (200 m s^{-1}) is attributable to the negative bay disturbance preceding the launch. The several wind profiles shown in figure 3 occurred following three evening positive bay disturbances, while one with a fairly strong eastward wind was on a quiet evening. The four launches were on successive nights, 15 to 18 March 1969. The east–west wind velocities obtained during eight experiments up to March 1969 at a height of about 150 km have been plotted in figure 4 against the mean S–N magnetic perturbation component (ΔX) for the previous 2 h before launch.

The following major points arise from the data:

(i) A strong correlation between the E–W neutral wind speed (V_{NY} m s^{-1}) and the mean local S–N ground magnetic perturbation (ΔX, nT) of the previous 2 h. The correlation is highest between 120 and 150 km, where the highest wind speeds are observed following geomagnetic bay disturbances, and can be expressed as

$$V_{NY} = -2.5\,\Delta X\ (\text{nT}). \qquad (1)$$

The direction is such that a 2 to 3 h, 200 nT positive bay disturbance will produce a westward neutral wind speed of about 500 to 600 m s^{-1}.

(ii) The correlation expressed in (i) above results from the locally enhanced ionospheric electric fields and electron density. The product of these factors drives the auroral electrojet, and also accelerates the neutral gas via ion-neutral collisions. The ions are driven by a meridional electric field when the corresponding ionospheric Hall current causes the ground magnetic perturbation.

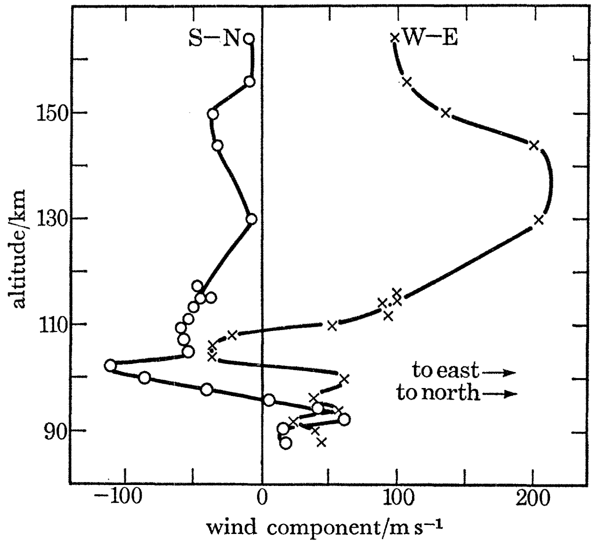

FIGURE 2. S–N and W–E neutral wind components on 4 February 1968, 06h33 C.E.T.

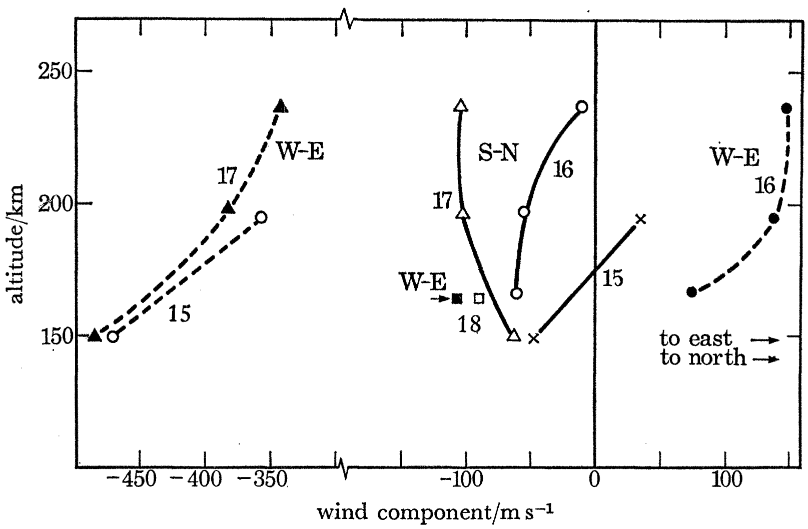

FIGURE 3. S–N and W–E neutral wind components during March 1969: 15, 15 March 18h55 C.E.T.; 16, 16 March 19h05 C.E.T.; 17, 17 March 19h10 C.E.T.; 18, 18 March 19h16 C.E.T.

(iii) Below 120 km the ions are increasingly constrained by ion-neutral collisions. This process is reflected in a rotation through about 90° of the resulting perturbed neutral wind vector down to about 105 km, below which the correlation and mechanism expressed above fail to operate. In addition, during intense negative bays, high energy particle precipitation causes high electron densities and therefore a large part of the ionospheric current flow below 120 km. The resulting neutral wind acceleration between 120 and 150 km may then be somewhat less than that expressed by equation (1).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

(iv) The wind disturbances generated in the auroral zone may have velocities exceeding the local sonic velocity (about 300 m s^{-1} at 120 km and 500 m s^{-1} at 150 km). Additionally, below the night time F region (say up to 200 km) and in the night hemisphere, the only effective modifying forces once the air has been accelerated out of the auroral zone are Coriolis and viscous drag from lower non-accelerated air layers (below 110 km). The former effect is mainly

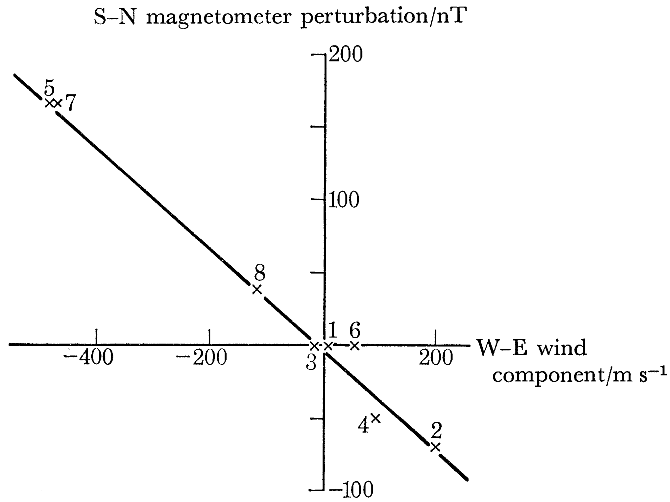

FIGURE 4. W–E neutral wind component (above 150 km generally) plotted against S–N ground magnetometer perturbation for eight launches during 1968–9: (1) 1 February 1968, 06h42 C.E.T.; (2) 4 February 1968, 06h33 C.E.T.; (3) 15 October 1968, 17h32 C.E.T.; (4) 1 November 1968, 05h40 C.E.T.; (5) 15 March 1969, 18h55 C.E.T.; (6) 16 March 1969, 19h05 C.E.T.; (7) 17 March 1969, 19h10 C.E.T.; (8) 18 March 1969, 19h16 C.E.T.

to rotate the wind vector, while the latter is probably rather ineffective due to the relatively low kinetic viscosity near 110 km.

(v) The spatial scale of the accelerating region for a geomagnetic activity level of $K_p = 4$ would appear to be 2000 to 3000 km E–W and 200 to 500 km N–S. The time scale of this acceleration should be about 2 to 3 h and, inside that region, the average neutral air speed between 120 and 150 km altitude should be close to 500 m s^{-1}.

(vi) Above 240 km a somewhat different acceleration process can be effective. Strong (25 mV m^{-1}) electric fields can be observed in the vicinity of the instantaneous auroral oval under quiet magnetic conditions at ground level when the E-region electron density is low. In the F region the neutral gas can be accelerated due to the region's higher (about 10^5 cm^{-3}) electron density. At 300 km, winds of 200 to 300 m s^{-1} have been seen in the absence of a significant ground magnetic perturbation, but in the presence of a high ionospheric electric field. During strong geomagnetic bay disturbances, the neutral winds at 300 km may, as at 150 km, become even higher due to the corresponding enhanced electric field.

3. A proposed model for global air circulation in the thermosphere induced by the auroral electrojet

Neutral wind observations made at mid-latitude around 150 km altitude during geomagnetically disturbed periods can be found in table 1. The wind speeds at mid-latitude are higher than those generally found during quiet periods (cf. Bedinger 1966). An additional significant

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

feature of the disturbed day profiles is that the wind vector above 140 km has a nearly constant direction, as is found with disturbed wind profiles in the auroral zone (figure 4). On quiet days, however, a rotation of the wind vector with increasing height is generally observed until over 200 km altitude both at mid-latitude and in the auroral zone.

A model for the global neutral wind circulation at about 150 km altitude, induced by neutral gas acceleration in the auroral zone by ion drag, was constructed on the following hypotheses.

(i) Acceleration of the neutral gas only occurred due to ion drag in hypothetical equal and constant eastward and westward auroral electrojets.

Table 1. Neutral winds during disturbed periods

date	place	K_p index	wind velocity m s^{-1}	direction toward	altitude km	source
17 Aug. 1959 a.m.	Wallops Is. (38° N)	8	150	SW	150	Bedinger (1966)
24 May 1960 p.m.	Wallops Is. (38° N)	5	100	W	140	
6 Mar. 1961 p.m.	Woomera (31° S)	7	160	NW	180	Jarrett *et al.* (1963)
20 Feb. 1963 p.m.	Wallops Is. (38° N)	4	135	S	150	Bedinger (1966)
16 Jan. 1964 a.m.	Wallops Is. (38° N)	5	225	SW	140	
1 Nov. 1964 midnight	Fort Churchill (59° N)	4+	240	W	110	
16 June 1965 p.m.	Kauai (22° N)	C 9 = 7	227	E	150	Smith (1968)
unknown	Eglin (30° N)	7+	210–265	SW	200	Haerendel (1970)

(ii) A 2 to 3 h bay disturbance of 200–300 nT corresponding to $K_p \approx 4$, existed for which electric fields in the vicinity of the electrojets were about 50 V km^{-1}, with peak electron density near 120 to 130 km of about 3×10^{11} electron m^{-3}. Computed auroral zone winds for such a disturbance, of 500 m s^{-1}, agreed well with actual observed winds (Rees 1971 *a*). The horizontal extent of the accelerating region was taken to be about 2000 to 3000 km E–W and 500 km N–S.

(iii) A strong ion drag constraint existed in the day hemisphere effectively restricting the neutral gas motion to the night hemisphere where, outside the auroral region, the E-region electron density is low and therefore only pressure gradients and Coriolis forces are appreciable. The day/night terminators were thus taken to be zero flux boundaries.

(iv) In calculating the global propagation of the auroral winds only those pressure gradients set up by the wind pattern itself and the momentum of the accelerated wind were taken into account. The effects of the normal quiet day global pressure pattern and modifications to this pattern due to geomagnetic heating associated with the bay disturbance were not considered (see §4).

(v) No energy transportation via ion-acoustic or acoustic-gravity waves set up in the auroral zone by supersonic ion or neutral motions was considered.

Figure 5 represents the schematic wind circulation pattern as a function of local time and latitude. The wind velocities shown are, however, relative to the Earth's surface at any locality.

It has been pointed out that the time lag due to the transit times of air from the auroral zone to a particular place outside the auroral zone will be comparable with the duration of a particular substorm and the rate of change of local time.

Cole (1971) has examined the rate of transfer of momentum at F-region heights (300 km) from the auroral electrojet to mid-latitudes. He proposes a very fast and efficient momentum diffusion mechanism due to spatial and temporal variation of electric field and electron density in the auroral electrojet and arrives at a time constant of momentum transfer to mid-latitudes of the order of 1000 s. There are no wind measurements at 300 km altitude to test this prediction. However, some of the mid-latitude observations of table 1 (e.g. Woomera, 6 March 1961) were within 1 to 2 h of the start of a disturbed period.

This time delay after the start of a disturbed magnetic period is comparable with the delay observed (Rees 1971 *a*) in the auroral zone, while figure 5 would show that air 'originating' in

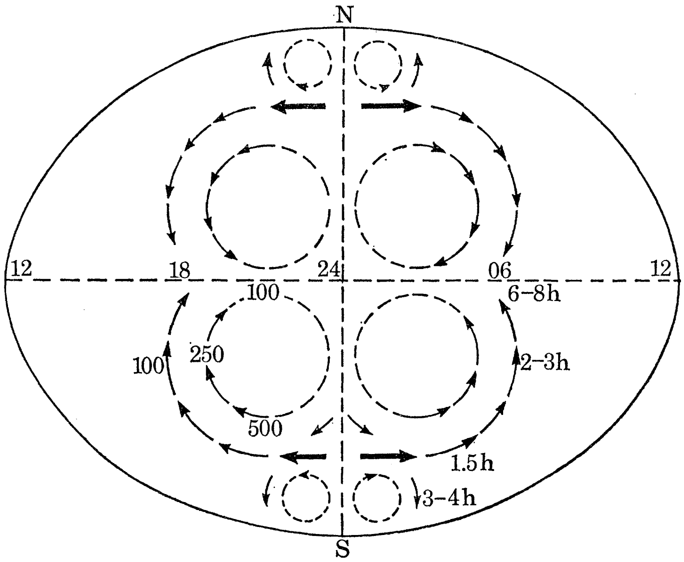

Figure 5. Schematic diagram of neutral circulation above 150 km following a 2 to 3 h substorm event. Typical disturbance velocities (m s^{-1}) and time scales (h). Arrows represent velocity vectors relative to the ground and not streamlines.

the auroral zone should arrive at 40° magnetic latitude more than 3 h after the start of the magnetic disturbance, and may indicate that the enhanced momentum transfer mechanism that Cole predicts does occur.

If the Cole mechanism occurs, figure 5 may be indicative of the circulation stream lines. At mid-latitude, the arrival of heated air from the auroral zone may then lag the observation of high wind speeds by a few hours.

It is possible that the direct 'auroral zone' circulation cell may break up at mid-latitude and that heated auroral zone air may never reach the equator during disturbed geomagnetic periods given the latitudinal variations of the geomagnetic activity effect on thermospheric temperature shown by Roemer (1970) and Moe (1970).

The high wind speeds seen at Kauai in June 1965 (Smith 1968) could be part of the auroral cell, or a secondary equatorial cell induced in a mid-latitude break-up region of the auroral circulation cell. Temperature measurements which might distinguish between heated auroral zone air and normal equatorial air were not made on this occasion.

4. The thermal response of the auroral thermosphere to geomagnetic activity

Jacchia (1970) and Roemer (1970) have reviewed satellite drag data to investigate the reaction of the upper atmosphere to geomagnetic activity. Roemer has derived the latitude dependence of the K_p associated heating between 200 and 800 km altitude. He finds a general

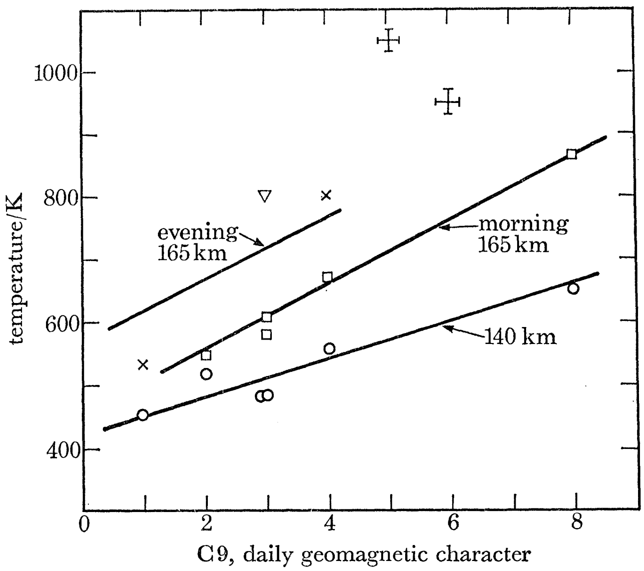

Figure 6. Temperatures at 140 and 165 km with corresponding C9 values. ○, 140 km; ×, 165 km evening; □, 165 km morning; ▽, 202 km evening; ╪, 160 km (Poloskov *et al.* 1970).

enhancement of the heating toward high latitude, which is approximately a factor of two near the auroral zone, given by

$$T = (17.9 + (21.4 \pm 8.3) \sin |\phi|)\,\overline{K_p} + 0.03 \exp \overline{K_p} \quad (\mathrm{K}).$$

Of interest also is the delay between geomagnetic activity and the observation of enhanced thermospheric heating. The satellite results show a delay which increases from the order of 1 h at high latitude to about 8 or 9 h near the equator. The data from air glow analysis (thermal broadening of the 630 nm oxygen line) (see, for example, Roble *et al.* 1970) would seem to agree with the heating rates and response times derived from satellite observations (Jacchia 1970). In addition, these measurements are of temperature and do not have to be computed from air density as are the satellite drag data.

Rees (1971*b*) and Poloskov, Toulinov, Chanin & Maillard (1970) have recently published temperature data for the altitude range 120 to 200 km in the auroral zone from chemical release experiments at Esrange, Sweden and Heiss Island, U.S.S.R. respectively. In figure 6 the data at altitudes of 140 and 165 km have been plotted against the relevant C9 index (which is representative of K_p averaged over 24 h). The temperature dependence on the C9 index can be expressed approximately as

$$T(140) = 420 + 25 \times \mathrm{C}9 \quad (\mathrm{K})$$

$$T(165) = 450 + 50 \times \mathrm{C}9 \quad (\mathrm{K})$$

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

at morning twilight. At evening twilight, the temperatures at 165 km are approximately 100 K higher.

As these measurements are only made at local twilight, detailed studies of the response times to geomagnetic activity are not readily obtainable. The observed temperatures, however, correlated very poorly with the 3 h mean index K_p, with local magnetic activity, and with the solar 10.7 cm flux, while the correlation obtained (figure 6) with C9 would tend to indicate a rather slow increase of temperature in the 130 to 165 km region followed by a 12 to 24 h decay period. The decay period observed here, up to 200 km, is perhaps longer than that observed above 200 km from satellite observations.

One feature is observed in the temperature measurements in the immediate vicinity of auroral forms (Rees 1971 *b*, Poloskov *et al.* 1970) – a rapid rise and subsequent decay of the order of 100 to 200 K in a period of a couple of minutes, superimposed on the overall mean temperature profile. It is not clear whether this rapid fluctuation reflects intense localized energetic particle heating, or is possibly due to non-thermal excitation of aluminium oxide and other contaminant gases.

One rocket launch in Pakistan (25° N) on 29 November 1967 (Rees 1971 *b*) following a $K_p = 4$ disturbance showed no significant temperature differences in the region 120 to 160 km compared with our other quiet condition rocket experiments.

It would seem significant that the delay periods reported variously from satellite and airglow observations are of the same order as the circulation travel times of locally heated and accelerated auroral zone air proposed in figure 5, based on the observations of high neutral wind speeds in the auroral zone.

5. Global temperature structure in the lower thermosphere

The temperature data of Rees (1971 *b*), Poloskov *et al.* (1970), Rees, Roper, Lloyd & Low (1972) and recent, as yet unpublished data from Woomera rocket range, have been used to obtain a global model of temperature in the lower thermosphere.

Figure 7 shows a model for 170 km which uses satellite data (Jacchia *et al.* 1967) to obtain the equatorial diurnal variation, and the recent mid-latitude and auroral zone rocket temperature measurements at local twilight. The model is constructed for the equinox and for a mean level of solar activity corresponding to 1968–70 during which rocket measurements have been made.

The principal features of the model are:

(i) A much greater decrease of temperature towards the pole than that apparent from the satellite models at the 170 km level, such that the global minimum temperatures occur near the poles and not at the equator in the early morning.

(ii) At 200 km altitude, from a smaller data sample, the isotherm distribution would appear to be similar, though with a general global increase of between 100 and 200 K.

(iii) No significant temperature variations in the auroral zone greater than 50 K have appeared in the period September to April when chemical release experiments at Esrange are possible (Rees 1971 *b*). At Woomera, however, a summer to winter decrease at both morning and evening twilight of the order of 100 K appears possible from a small data sample. Earlier data reported by Ivanova, Kokin & Chizhov (1969) also show low temperatures in the lower thermosphere at high latitude.

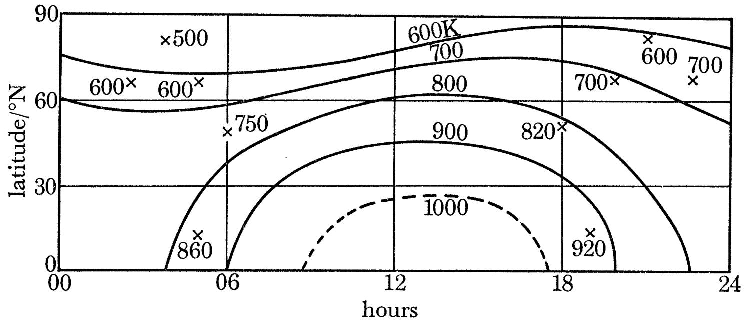

FIGURE 7. Global temperature pattern for 170 km during quiet magnetic conditions 1968–70 for the equinox. Temperatures in kelvins.

6. Global thermospheric wind patterns

Geisler (1967), Kohl & King (1967) and Challinor (1969) have each computed models of the diurnal variation of the global wind system in the thermosphere. Only the last has been able to predict a net eastward neutral wind flow, maximized in the evening, at mid-latitude above 200 km, while all have used C.I.R.A. 1965 or U.S. Standard Atmosphere Supplements 1966 model atmospheres for the global pressure system as the basis of the wind computations.

Mean air density measurements from chemical release experiments at Kiruna (68° N) (Rees 1971*c*) under quiet geomagnetic conditions are certainly not greater than at Woomera (31° S), at 170 km being approximately 0.7×10^{-9} kg m^{-3} and 0.8 to 1.1×10^{-9} kg m^{-3} respectively.

When combined with the air temperature model described above, a global pressure distribution would be obtained always having a negative pressure gradient with increasing (south and north) latitude, while the earlier models (Jacchia 1965) showed a pressure gradient reversal during the night.

In detailed computations of thermospheric motions attention needs to be given to the pressure model used if realistic comparisons are to be made with King-Hele & Scott's (1967) results from satellite orbital inclination changes and recent neutral wind measurements above 200 km (Rees *et al.* 1972). A geostrophic wind produced by the global pressure gradient system (similar to figure 7) will be directed eastward in both northern and southern hemispheres. A true geostrophic wind will not occur in practice, air motions being severely constrained by ion drag in daytime and by viscous drag.

7. Conclusions

The results of rocket experiments reported here show that major dynamic and thermal changes occur in the lower thermosphere in the auroral region in association with geomagnetic activity. Acceleration of the neutral gas above 120 km in the immediate vicinity of the auroral electrojet occurs in a short (2 h) time scale, whereas the altitude-dependent thermal response of the atmosphere above 120 km is related to the 12 to 24 h mean global geomagnetic activity. It is proposed that the neutral wind disturbances initiated in the night time auroral zone propagate and cause a global circulation of air initially heated in the auroral regions. This circulation system may partly explain the delayed thermal response at lower latitudes to global geomagnetic activity, and be intimately related to some ionospheric perturbations observed at mid-latitude during geomagnetic storms.

A global temperature map of the lower thermosphere derived from chemical release experiments has a significantly different isotherm distribution from that of earlier models derived from satellite drag data. A major feature is that of a global minimum of temperature occurring near the poles during quiet geomagnetic periods.

Pressure is expected to show a similar global distribution to temperature as there is no evidence from chemical release experiments of a significant increase of density with latitude to compensate for the decrease of temperature.

Most of the experimental data presented here has originated from the Esro sounding rocket programme, the U.K. national programmes at Woomera and Esrange and the German national space research programme. The contributions of very many people to the success of these experiments are greatly appreciated. The data preparation and analysis has been carried out by the Space Science and Upper Atmosphere Research Group at University College London supported by grants from the Science Research Council and the United States Air Force European Office of Aerospace Research.

I would like also to acknowledge many inspiring discussions with Mr K. H. Lloyd, Dr G. Haerendel and Professor G. V. Groves.

References (Rees)

Bedinger, J. F. 1966 Compendium of wind data from the vapor trail technique. *Geophys. Corp. America Tech. Rep.* no. 66-7-N, Bedford, Mass.
Challinor, R. A. 1969 *Planet. Space Sci.* **17**, 1097.
Cole, K. D. 1971 *Planet. Space Sci.* **19**, 59.
COSPAR Working Group IV 1965 COSPAR International Reference Atmosphere. Amsterdam: North-Holland.
Geisler, J. E. 1967 *J. atmos. terr. Phys.* **29**, 1469.
Haerendel, G. 1970 Electric fields and their effects in the ionosphere. Presented at STP Symposium Leningrad.
Ivanova, I. N., Kokin, G. A. & Chizhov, A. F. 1969 *Space research IX* (eds. K. S. W. Champion, P. A. Smith and R. L. Smith-Rose), p. 514. Amsterdam: North-Holland.
Jacchia, L. G. 1965 *Smithsonian Contr. Astrophys.* **8**, 215.
Jacchia, L. G. 1970 *Space research X* (eds. T. M. Donahue, P. A. Smith and L. Thomas), p. 367. Amsterdam: North-Holland.
Jacchia, L. G., Slowey, J. & Verniani, F. 1967 *J. geophys. Res.* **72**, 1423.
Jarrett, A. H., McGrattan, G. J. & Smith, F. J. 1963 *Planet. Space Sci.* **11**, 1319.
King-Hele, D. G. & Scott, D. W. 1967 *Planet. Space Sci.* **15**, 1913.
Kohl, H. & King, J. W. 1967 *J. atmos. terr. Phys.* **29**, 1045.
Moe, K. 1970 Orbital atmospheric model development. NASA Report MDC G0574, McDonnel Douglas Corp.
Poloskov, S. M., Toulinov, G. F., Chanin, M. L. & Maillard, M. 1970 Summary of temperature measurements of the upper atmosphere in the northern polar zone. Presented at COSPAR, Leningrad.
Rees, D. 1971*a* *J. Br. interplanet. Soc.* **24**, 233.
Rees, D. 1971*b* *Planet. Space Sci.* **19**, 233.
Rees, D. 1971*c* *J. Br. interplanet. Soc.* **24**, 643.
Rees, D., Roper, R. G., Lloyd, K. H. & Low, C. 1972 *Phil. Trans. R. Soc. Lond.* A **271**, 631.
Roble, R. G., Hays, P. B. & Nagy, A. F. 1970 *Planet. Space Sci.* **18**, 431.
Roemer, M. 1970 Geomagnetic activity effect in the 250 to 800 km altitude region. Presented at COSPAR, Leningrad.
Smith, L. B. 1968 *J. geophys. Res.* **73**, 4959.
U.S. Government Printing Office 1966 U.S. Standard Atmosphere Supplements, Washington D.C.

Discussion

H. Rishbeth (*Radio and Space Research Station, Ditton Park, Slough*)

Dr Rees showed a map of the global wind pattern above 150 km resulting from auroral-zone disturbances. At mid-latitudes this pattern shows equatorward winds at some local times. Recent work at Slough (*J. atmos terr. Phys.* **33**, 379, 391, March 1971) indicates that equatorward winds could produce the increases of F-region electron concentration sometimes observed during storms. It would be interesting to study ionospheric data for the specific occasions for which Dr Rees has data.

D. Rees

Experimental evidence at both morning and evening twilight at mid-latitude stations such as Wallops Island and Woomera indicates that high neutral wind speeds with an equatorward component of some hundreds of metres per second do occur during severe geomagnetic disturbances ($K_p > 4$) at altitudes above 150 km. What is not presently clear is whether these wind speeds and directions, or the circulation pattern I have devised from a simple model of electric field gas acceleration in the auroral zone, correctly depict the situation near the midnight sector.

Similarly, daytime conditions and the timescale of induction of mid-latitude circulation after the onset of auroral zone gas acceleration are unclear from the present neutral wind data.

The comparison of ionospheric predictions and observations for certain days when wind patterns at twilight have been experimentally determined could provide the necessary experimental link between F-region electron density enhancement and neutral gas movements, such that night time F-region behaviour could, with confidence, be used to determine the night time thermospheric wind pattern during disturbed periods.

Prediction of the F-region neutral wind pattern in areas which are not amenable to present direct measurement, such as near the summer pole, could additionally be used to optimize the experimental investigation by daytime direct techniques during the next few years, when these daytime wind determination methods come into widespread use.

T. R. Kaiser (*Department of Physics, The University, Sheffield* 10)

Much of the data on winds and drifts are derived from apparent motions of ionized irregularities; I am thinking especially of the ionospheric drifts, the motions of meteor trains and also rocket releases of ion clouds. It may therefore be helpful to summarize the expected behaviour of an ion cloud under the influence of steady neutral winds and electric fields. I should explain that this does not include the effects of wave-like phenomena discussed by Professor Hines.

For the present purposes we can divide the atmosphere into three altitude regions:

(i) Below 95 km. Here both the electron and ion collision frequencies (ν_e, ν_i) are less than their cyclotron frequencies (ω_e, ω_i) and thus gyromagnetic effects are not pronounced. An ion cloud thus moves with the neutral wind and electric field drifts are minimal.

(ii) 95 to 130 km. In this region $\nu_e < \omega_e$ but $\nu_i > \omega_i$.

(iii) above 130 km. Both ν_e and ν_i are small compared with ω_e and ω_i respectively.

In region (iii) the neutral wind cannot produce significant motion across the field lines and hence the cloud moves with the appropriate wind component along the field lines. The electron and ion Hall velocities are equal and hence, under the influence of an electric field $\boldsymbol{E}$, the whole cloud will move with velocity $(\boldsymbol{E}\wedge\boldsymbol{B})/B^2$ where $\boldsymbol{B}$ is the Earth's magnetic field.

In region (ii), which is particularly relevant to the present meeting, the behaviour of an ion cloud depends critically on its geometrical configuration. If it is greatly elongated in the magnetic field direction or, for planar irregularities, if they are alined to the magnetic field within a fraction of one degree or less, then it is the electrons which determine the cloud behaviour (diffusion and motion). Otherwise this is determined by the ions. Thus, for sufficiently field-alined irregularities, neutral winds cause motion only along the field lines and electric fields produce a drift at the electron Hall velocity, $(\boldsymbol{E}\wedge\boldsymbol{B})/B^2$. For $E = 50$ mV m^{-1} this is about 1000 m s^{-1} which is typical of the motion of field-alined irregularities observed in the radio-aurora. Non field-alined irregularities move with the neutral wind (since $\nu_i \ll \omega_i$) and drift at the ion Hall velocity equal to (ω_i/ν_i) $(\boldsymbol{E}\wedge\boldsymbol{B})/B^2$; in the $\boldsymbol{E}$ region this is 2 to 3 orders of magnitude less than the electron Hall velocity.

In both regions (ii) and (iii), ion-neutral drag can result from electric fields but, in the former case, this will occur only for highly field-alined structures.

Reference

Kaiser, T. R., Pickering, W. M. & Watkins, C. D. 1969 Ambipolar diffusion and motion of ion-clouds in the Earth's magnetic field. *Planet. Space Sci.* **17**, 519–522.

D. Rees

Apart from the use of direct tracer materials by rocket releases for measuring electric fields and winds, the several radio techniques for monitoring neutral and ion motions in the atmosphere have recently come under sharp scrutiny by a Working Group set up under the auspices of I.U.C.S.T.P.

We have conducted recent experiments in Australia at Woomera in collaboration with members of Adelaide University to compare both meteor radar drifts and E- and F-region partial reflexion drifts with those from direct rocket trail, cloud, barium ion cloud and electric field probe measurements.

Our measurements, to be published shortly, have demonstrated that extreme care is necessary to interpret the indirect measurements as movements of the neutral gas or ionosphere.

As I interpret the S.T.P. recommendation and our own measurements, F-region reflexions (also including Thomson scatter measurements) are contaminated by atmospheric waves which interfere in a complex manner with simultaneous particle motions.

At lower heights (radar meteor and E-region drifts), there is a direct conflict between field-alined irregularities and field-alined instability, i.e. under what conditions can a field-alined irregularity exist stably? If such irregularities are stable then the type of motion Professor Kaiser has described in the region below 95 km may operate. If, however, small-scale field-alined irregularities are more correctly instabilities, the observed motion may, as at higher levels, partially reflect the development of the instability.

The closest analogy is the apparent streaming of bright rays along a rayed arc aurora. Such a rayed arc may show 'motions' of 1 to 3 km s^{-1}, while we also now appreciate that neutral wind speeds of perhaps 1 km s^{-1} and plasma $(\boldsymbol{E}\wedge\boldsymbol{B})$ drifts of 1 to 3 km s^{-1} may coexist. I would hesitate, however, to ascribe the apparent visual velocities of the auroral rays, which may be indistinguishable in radio auroral measurements, to either the neutral gas or plasma drifts, although the altitude of these active rays, about 95 to 110 km at the lower boundary, could include either of the cases Professor Kaiser ascribes to level (ii) 95 to 130 km.

Similarly, meteor-radar and radio-reflexion techniques show neutral winds, $\boldsymbol{E} \wedge \boldsymbol{B}$ drifts and 'tides' which are macroscopically similar to those derived from tracer techniques. However, a differentiation between particle movement and the phase velocity of a propagating wave may be necessary for a correct interpretation of the experimental data.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES