The general circulation of the atmosphere and its effects on the movement of trace substances. Part 2

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ABSTRACT

The assumption is made that the large-scale mixing properties of the atmosphere are related to the time and spatial variances of the winds. Data on the time standard deviations is presented for levels from the surface to about 75 km based on balloon and rocket soundings. The monthly and year to year variations in the 15–30 km region and the average seasonal variation for the 30–75 km region are examined. An attempt to relate the time and space distributions of some radioactive and airglow tracers to the wind data is made.

1. Introduction

At the Utrecht Symposium we discussed the large scale mixing properties of the atmosphere in terms of the variances of the meridional and vertical components of the wind; patterns in a meridional plane of the spatial and time variances were presented. Particular emphasis was given to the seasonal changes in these patterns and the seasonal changes in ozone and other trace substances in the lower stratosphere. It is our main intent at the present Symposium to continue this discussion with further data recently processed for longer time periods and extending to higher altitudes; no attempt will be made to reiterate the background information given previously (see NEWELL, 1963*b*).

It is worth recalling here that trace substances information provided the vital link between the various pieces of meteorological information available on the energy budget of the lower stratosphere. The budget in the form in which it is presently discussed was first debated at Utrecht and has since been elaborated in more detail (NEWELL, 1963*a*, 1964*b*; OORT, 1963, 1965; SHEPPARD, 1963). The concepts will be used below in our consideration of the relationship between trace substance information at higher levels and the meteorological observations. Primary attention will be given to the region between the tropopause and the mesopause.

2. Horizontal transports below 100 mb

(i) *Mean motions.* We have not performed further computations from direct observations. PALMEN & VUORELA (1963) have presented data for the winter season based on CRUTCHER's (1961) work which we commented on at Utrecht. In view of the uncertainties in the original data it seems that an approach which uses the equations of heat and momentum conservation and the eddy convergences can give more realistic results. DICKINSON (1962) and GILMAN (1964) have discussed such approaches and numerical results were given by NEWELL & MILLER (1964), but the eddy convergences and radiative effects are not yet known well enough to assess the reliability of the results. The general pattern was the same as that found by Palmer and Vuorela although the magnitudes were much smaller.

(ii) *Standing eddies.* The spatial standard deviations of the meridional wind component were computed from Crutcher's cross-sections which were drawn for every 10° of longitude. Results are shown in Tables 1*a*–*d*. The largest

TABLE 1*a*. *Standard deviation of meridional wind component. Zonal average from Crutcher's data. Units: meters sec*$^{-1}$. *Dec./Jan./Feb. Standing eddy component.*

Latitude ...	80	70	60	50	40	30	20	10
Level (mb)								
100	2.2	3.9	4.1	3.6	2.7	3.3	3.4	2.1
150	2.3	4.1	5.3	4.9	3.1	3.4	4.7	2.4
200	2.7	3.8	5.6	6.1	4.3	3.3	4.9	2.5
300	2.9	3.5	5.1	5.9	4.6	2.7	3.8	2.0
400	2.9	3.3	4.4	5.2	3.9	2.1	3.0	1.8
500	2.6	2.9	3.5	4.3	3.2	1.8	2.6	1.5
600	2.3	2.4	2.9	3.6	2.7	1.6	2.1	1.3
700	1.7	1.7	2.0	2.9	2.5	1.8	1.8	1.3
800	1.0	1.1	1.8	2.6	2.4	1.7	2.1	1.2

TABLE 1*b*. *Standard deviation of meridional wind component. Zonal average from Crutcher's data. Units: meters sec*$^{-1}$. *Mar./Apr./May. Standing eddy component.*

Latitude ...	80	70	60	50	40	30	20	10
Level (mb)								
100	1.4	1.9	1.7	1.5	1.5	2.5	2.2	1.6
150	1.0	1.7	2.4	2.7	2.4	2.4	2.5	1.9
200	1.0	1.8	2.8	3.1	2.9	2.3	2.6	2.1
300	1.5	2.0	3.0	3.3	2.8	2.3	2.2	1.5
400	1.5	2.2	2.9	3.0	2.6	1.7	1.7	1.2
500	1.4	2.1	2.4	2.6	2.3	1.3	1.8	0.9
600	1.1	1.7	1.9	2.3	2.0	1.4	1.6	0.9
700	0.7	1.2	1.5	2.1	1.6	1.6	1.7	1.1
800	0.4	0.6	1.2	1.7	1.5	1.6	1.8	1.1

TABLE 1*c*. *Standard deviation of meridional wind component. Zonal average from Crutcher's data. Units: meters sec*$^{-1}$. *June/July/Aug. Standing eddy component.*

Latitude ...	80	70	60	50	40	30	20	10
Level (mb)								
100	0.9	1.3	1.4	1.2	2.0	3.2	2.7	1.9
150	0.8	1.3	1.4	1.3	2.0	3.0	2.8	1.9
200	1.2	1.8	2.0	2.1	2.3	3.9	3.0	2.6
300	1.2	2.1	2.0	1.9	2.0	2.4	2.2	1.6
400	0.8	2.0	1.9	1.9	1.8	1.9	1.5	1.3
500	0.9	1.9	1.7	1.7	1.6	1.9	1.8	1.5
600	1.0	1.5	1.5	1.4	1.6	2.1	2.2	1.2
700	1.0	1.5	1.5	1.4	1.7	2.0	2.1	1.1
800	0.9	1.1	1.0	1.0	2.2	2.2	1.7	1.2

TABLE 1*d*. *Standard deviation of meridional wind component. Zonal average from Crutcher's data. Units: meters sec*$^{-1}$. *Sep./Oct./Nov. Standing eddy component.*

Latitude ...	80	70	60	50	40	30	20	10
Level (mb)								
100	1.2	2.0	2.3	2.2	2.0	2.4	2.2	2.5
150	1.3	1.9	2.2	2.3	2.0	2.3	1.8	2.5
200	2.0	3.1	3.8	3.7	3.2	2.6	2.3	1.3
300	2.2	3.6	4.0	3.6	2.8	2.3	2.4	1.1
400	2.4	3.2	3.5	2.8	2.2	1.9	1.7	1.2
500	2.2	2.3	2.6	2.5	2.0	1.8	1.7	1.2
600	1.8	1.6	2.2	2.3	1.8	1.6	1.5	1.4
700	1.6	1.2	1.9	2.0	1.6	1.4	1.4	1.6
800	1.2	0.7	1.7	1.7	1.7	1.3	1.1	1.3

TABLE 2*a*. *Standard deviation of meridional wind component. Zonal average from Crutcher's data. Units: meters sec*$^{-1}$. *Dec./Jan./Feb. Transient eddy component.*

Latitude ...	80	70	60	50	40	30	20	10
Level (mb)								
100	8.4	9.7	10.6	10.9	11.3	10.2	8.1	7.1
150	8.5	10.3	11.8	12.4	13.7	13.2	10.6	8.1
200	9.0	10.8	13.0	13.8	15.2	14.5	11.3	8.2
300	10.4	11.9	14.6	15.8	15.6	13.6	9.8	6.8
400	10.1	11.2	13.4	14.4	13.7	11.3	8.2	5.5
500	9.1	10.0	11.6	12.4	11.6	9.5	6.9	4.5
600	7.8	8.7	10.1	10.7	9.8	8.1	5.9	4.0
700	6.8	7.6	8.7	9.2	8.2	6.9	5.0	3.8
800	5.9	6.6	7.8	8.4	7.4	6.1	4.6	3.7

TABLE 2*b*. *Standard deviation of meridional wind component. Zonal average from Crutcher's data. Units: meters sec*$^{-1}$. *Mar./Apr./May. Transient eddy component.*

Latitude ...	80	70	60	50	40	30	20	10
Level (mb)								
100	5.6	5.9	6.8	7.9	8.8	8.9	7.1	5.8
150	6.4	8.2	9.7	11.1	12.2	11.8	9.5	6.9
200	7.5	9.6	11.6	13.4	14.2	12.9	10.0	7.0
300	10.2	11.6	14.3	15.5	14.6	11.8	8.5	6.0
400	10.0	11.1	12.9	13.7	12.5	9.8	6.8	4.7
500	8.9	9.6	10.9	11.6	10.6	8.3	5.6	3.9
600	7.6	8.1	9.3	9.8	8.8	7.1	4.9	3.7
700	6.6	7.0	8.1	8.5	7.7	6.4	4.5	3.6
800	5.6	6.2	7.2	7.7	7.1	5.8	4.3	3.6

TABLE 2*c*. *Standard deviation of meridional wind component. Zonal average from Crutcher's data. Units: meters sec*$^{-1}$. *June/July/Aug. Transient eddy component.*

Latitude ...	80	70	60	50	40	30	20	10
Level (mb)								
100	3.7	4.7	5.9	7.2	7.7	6.7	5.4	5.0
150	5.4	7.2	9.1	10.9	11.0	9.2	7.5	6.4
200	7.6	9.0	11.2	13.4	12.3	9.1	6.9	5.8
300	10.7	11.2	13.1	13.4	10.9	7.2	5.1	4.0
400	9.7	9.9	11.1	11.0	8.8	6.1	4.3	3.4
500	8.3	8.4	9.2	9.3	7.4	5.5	4.1	3.3
600	6.9	7.1	7.9	8.0	6.4	5.1	4.0	3.4
700	5.7	6.2	6.9	7.2	5.7	4.7	4.0	3.5
800	5.1	5.8	6.3	6.6	5.5	4.5	3.9	3.3

TABLE 2*d*. *Standard deviation of meridional wind component. Zonal average from Crutcher's data. Units: meters sec*$^{-1}$. *Sept./Oct./Nov. Transient eddy component.*

Latitude ...	80	70	60	50	40	30	20	10
Level (mb)								
100	6.3	7.2	8.1	8.7	8.7	7.6	6.2	5.3
150	7.3	8.8	10.8	12.2	12.2	10.5	8.3	6.6
200	8.1	10.2	12.9	14.7	14.3	11.5	8.5	6.4
300	9.2	11.7	14.9	15.9	13.8	10.0	6.7	4.7
400	8.8	10.8	13.2	13.9	11.5	8.2	5.4	3.9
500	8.1	9.3	11.2	11.9	9.7	7.0	4.7	3.6
600	7.3	8.0	9.4	10.1	8.4	6.3	4.5	3.5
700	6.4	7.0	8.1	8.6	7.3	5.6	4.4	3.5
800	5.6	6.3	7.4	7.9	6.7	5.2	4.1	3.5

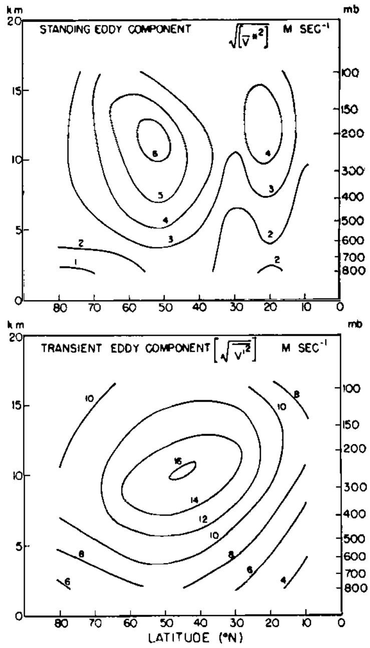

FIG. 1. A comparison of the eddy components of the meridional wind for the winter season (December–February) as a function of latitude and pressure.

values are associated with the meandering of the middle latitude jet stream in the winter season as might be expected. The smallest values occur in the lower troposphere of the tropics and polar regions throughout the year and in the polar lower stratosphere in the summer.

(iii) *Transient eddies.* The time standard deviations of the meridional wind averaged from Crutcher's data appear in Table 2*a–d*. Again the largest values are associated with the jet stream.

A comparison of Tables 1*a–d* and 2*a–d* indicates that the time standard deviations are generally greater than the spatial standard deviations. The spatial standard deviations (standing eddies) exhibit marked seasonal variability with a maximum in the winter, while there is much less annual variation in the transient eddy component. Fig. 1 is a comparison of the two terms for the winter season.

The data in item (iii) were discussed at Utrecht and the variances converted to equivalent eddy diffusion coefficients. In view of the recent interest in modelling large scale atmospheric diffusion processes (FRIEND *et al.*, 1962; KAO, 1962; PRABHAKARA, 1963; SUNDSTROM, 1964; REED & GERMAN, 1965) the basic data, rather than derived quantities, are presented here for completeness.

3. Horizontal transports 100–10 mb.

(i) *Mean motions* and (ii) *Standing eddies.* Results for the last six months of the IGY at 100, 50 and 30 mb are now available (PENG, 1965).

(iii) *Transient eddies.* Observations from a five year period of data which have been collected and preprocessed recently by the Planetary Circulations Project aided by the Travelers Research Center were available to us through the courtesy of Professor V. P. Starr. We have made use of them to study the monthly variations of momentum and heat fluxes in the stratosphere in connection with the biennial oscillation (WALLACE & NEWELL, 1965). The standard deviations of the meridional wind component in selected latitude belts are shown in Fig. 2*a–c*.

In the belt centered at 8° N (Fig. 2*a*) the standard deviations show only a slight trace of a seasonal variation and are generally small (5 m sec^{-1}). At 14° N the seasonal variation is quite strongly marked at 100 mb with largest values in the winter; smallest values appear to occur in the 20–50 mb region and these have little seasonal change. Figure 2*b* include data from 32° N and 37° N. Values are larger than in the tropics and the seasonal variation is evident at all heights. It is clear that the pattern also varies from year to year. Again the smallest values occur at intermediate heights which actually correspond to the transition zone between the westerly vortex of the upper troposphere and the vortex centered at stratopause levels. A further set of data for 47 and 52° N appear in Fig. 2*c* and show a similar trend of increases with latitude and quite large values at high altitudes.

It is evident from Fig. 2 that the mixing associated with transient eddies is generally less vigorous during the winters of 1958–59 and 1960–61 than during the adjacent winters. This tendency for alternating weak and strong

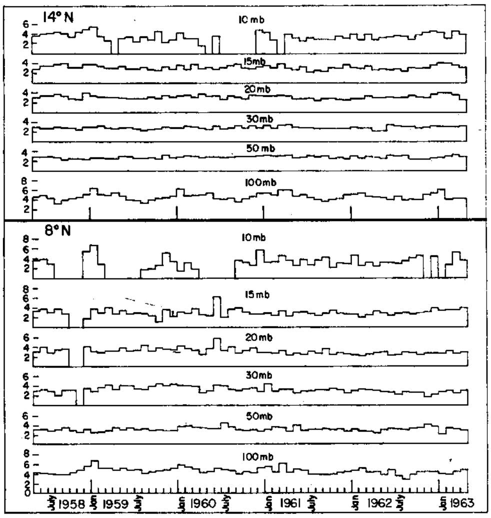

FIG. 2*a*. Time series of the transient eddy component of the meridional wind at 14° N and 8° N. Units in meters per second. Blank spaces denote months without sufficient data.

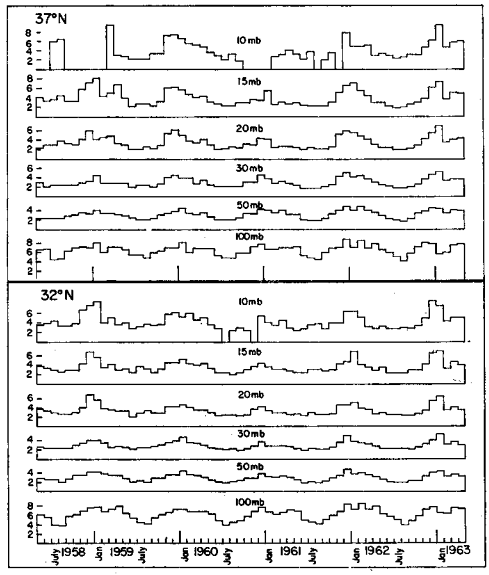

FIG. 2*b*. Time series of the transient eddy component of the meridional wind at 37° N and 32° N. Units in meters per second. Blank spaces denote months without sufficient data

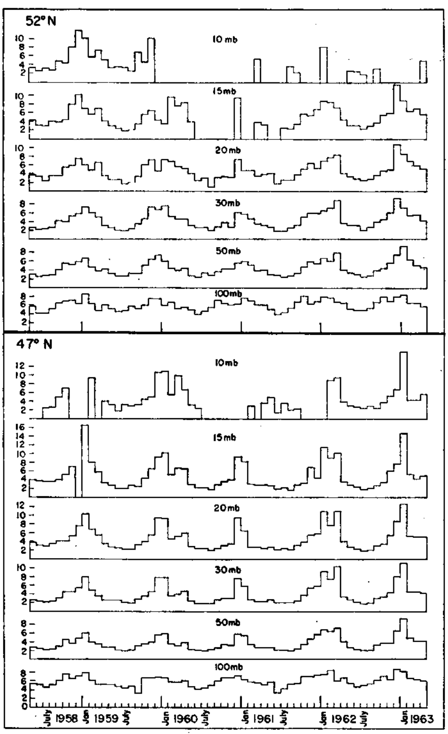

FIG. 2*c*. Time series of the transient eddy component of the meridional wind at 52° N and 47° N. Units in meters per second. Blank spaces denote months without sufficient data

winters is particularly marked in the transition zone around 30 mb at mid-latitudes. The monthly mean ozone amounts for three mid-latitude stations shown in Fig. 3 exhibit the same year to year variation. The effects of corresponding variations in heat and momentum transports from one winter to the next have been discussed in more detail elsewhere (WALLACE & NEWELL, 1965). Essentially we can regard high values of both ozone and standard deviation of the meridional wind component as a measure of a large flux of energy from the troposphere into

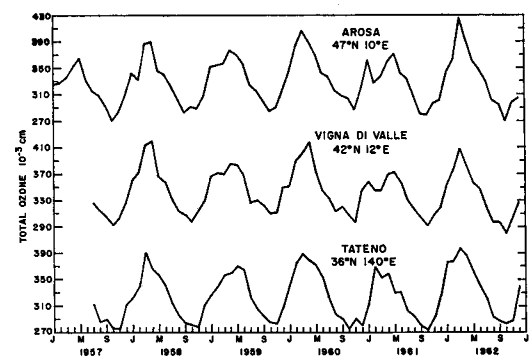

FIG. 3. Time series of total ozone for three mid-latitude stations.

the lower stratosphere and a concomitant high value of eddy activity.

We have argued elsewhere that the reason for a spring maximum in total ozone is essentially that more energy is propagated upward from the tropospheric heat engine in late winter. This excess of energy could produce either (or both) of the following effects in the stratosphere:

1. The level of eddy activity during these periods could be raised (NEWELL, 1964).

2. The average slopes of the eddy motions could be increased. NEWELL & MILLER (1964) have pointed out that the data of Hering for 1963 does show this effect.

The winter to winter differences in eddy activity are simply a manifestation of the first effect on a longer time scale and therefore should be accompanied by differences in the amounts of conservative trace substances transferred downwards (or upwards) through this zone.

4. Vertical Transports 100–30 mb

The standard deviations of the vertical velocity computed by the adiabatic method for the first year of the IGY were presented at Utrecht. Our colleague A. J. Miller will publish shortly similiar values for the last six months of the IGY together with an atlas encompassing the IGY in three-month seasons.

5. Horizontal transports above 10 mb

The most complete source of data for the 25–65 km region is the Meteorological Rocket Network. The mean zonal flow in the region based upon these data has been discussed by NEWELL (1963*a*, 1965*a*) and WEBB (1964); the station coverage is not yet sufficient to make meaningful statements about the magnitudes of mean motions and standing eddies. Calculations of the mean wind components and their standard deviations and covariances have been made for all the data up to October 1964. Three month averaging periods with the equinoxes and solstices as dividing dates have been used as well as two month periods with January and February coupled.

Cross-sections of the standard deviations of the meridional component are shown in Fig. 4. All the northern hemisphere stations have been used to draw the isolines shown with due weight being given to the number of observations per season; the number is larger than 200 for White Sands and larger than 100 for three other stations. Data is sparse at low latitudes and the data for Ascension Island at 8° S have been used as a guide to 8° N for the season displaced six months. Dashed lines represent the interpolated and extrapolated isolines. To illustrate the type of pattern which can be obtained from the rocket network stations above, the region below 30 km on these cross-sections is constructed from the radiosonde data included in the rocket data tabulations together with that from rocket firings that produced good data below 30 km. The fact that the main features below 30 km are similiar to those revealed by data from the global radiosonde network lends credence to the patterns above 30 km.

Figure 4*a* shows the season June 21 to September 20. There are large values (~ 10 m sec^{-1}) in the vicinity of the tropospheric jet stream but above this for a deep layer (~ 20–40 km) values are quite small. Above 40 km values increase to the highest levels attained by most of the standard rockets which are 60–65 km. The numbers listed in columns represent additional data for higher levels not plotted until after the isolines were drawn. The data at Fort Churchill are from the rocket grenade experiment; they include observations taken in 1964 and kindly supplied to the authors prior to publication by Dr. W. Nordberg. Points at Tonopah (38° N) and Johnston Island (18° N) were computed from observations of chaff by SMITH (1960*a*, *b*). It is recognized that these different techniques have different instrumental effects associated with them and that the data *in toto* is not a homogeneous sample; together with the sodium trail drift data it appears to be all that is presently available for this region. The inferences which may be drawn from the additional data will be discussed separately below.

The data for September 21 to December 20 are shown in Fig. 4*b*. The transition zone between the two systems is much smaller than in the summer and low values only occur over the sub-tropics. There is a general increase at all latitudes above 30 km with the largest change occurring over the polar regions where values now exceed those in the tropospheric jet.

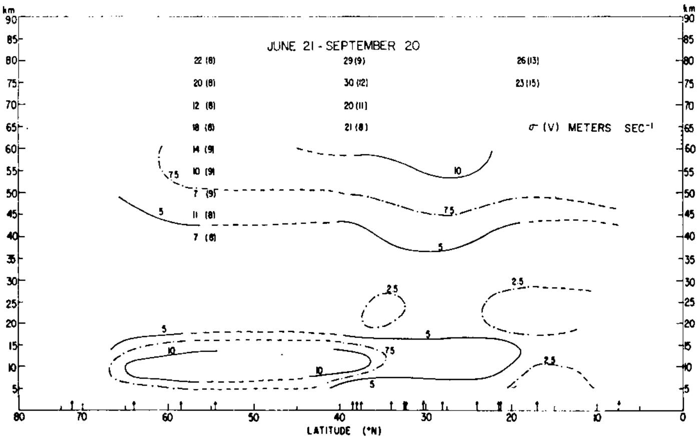

Fig. 4a. Temporal standard deviation of the meridional wind component for the summer season as deduced from Rocket Network data. Additional numerical values are from rocket grenade (left hand column) and chaff (other two columns) data.

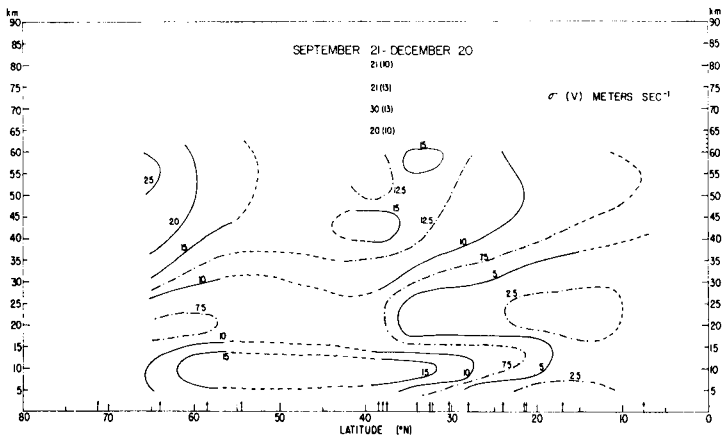

Fig. 4b. Temporal standard deviation of the meridional wind component for the autumn season as deduced from Rocket Network data. Additional numerical values refer to chaff data.

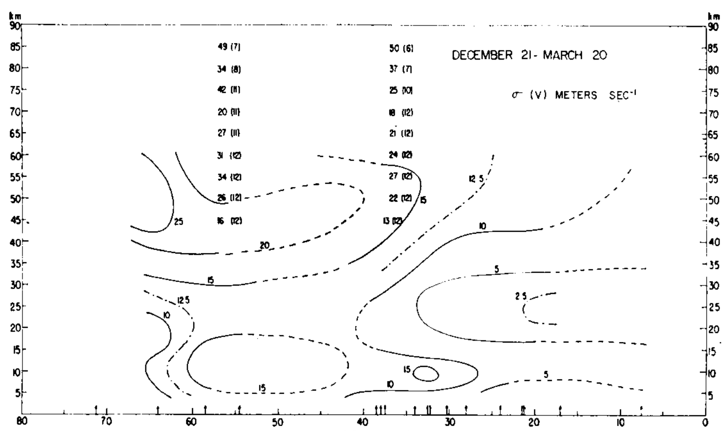

Fig 4c. Temporal standard deviation of the meridional wind component for the winter-season as deduced from Rocket Network data. Additional values refer to rocket grenade data for Ft. Churchill and Wallops Is.

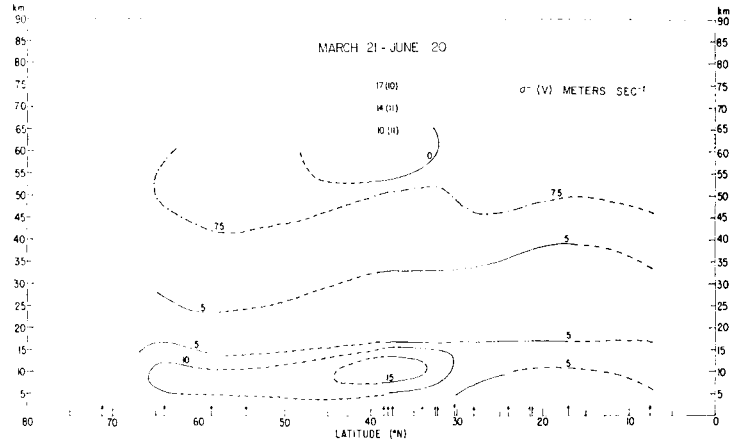

FIG. 4*d*. Temporal standard deviation of the meridional wind component for the spring season as deduced from Rocket Network data. Additional values refer to chaff data.

Values above the tropopause range from 2.5 m $\sec^{-1}$ at 20 km over the sub-tropics to 25 m $\sec^{-1}$ at 50 km over the poles which implies a range of two orders of magnitude in the quasi-horizontal mixing coefficient if this parameter is proportional to variance. Notice that the maximum standard deviation is not at the same latitude as the maximum zonal wind.

Figure 4*c* for December 21 to March 20 shows even larger values in the transition zone and a large region of high standard deviations (centered at 50–60 km) near the winter jet stream. There is some indication that a maximum may have been reached at about 50 km. Even at low latitudes near 50 km there are now values of about 10 m $\sec^{-1}$.

Values for March 21 to June 20, shown in Fig. 4*d*, are everywhere smaller than those in the late winter and the quiescent transient region is again evident.

Values for altitudes of 55, 50, 40 and 30 km for selected stations for bi-monthly averaging periods are shown in Fig. 5. The seasonal variability is a feature everywhere except at Ascension Island. At Fort Greely there is over a factor of five between the extremes. The factor does not vary greatly with height. On the other hand, at Cape Kennedy the largest variation is a factor of two at low altitudes.

We note that the associated vertical mixing coefficients cannot be determined as in the lower regions. There we made use of the variance of the adiabatically computed vertical velocity. REED & GERMAN (1965) have shown how the heat transports can be used to relate horizontal and vertical values of the coefficients but there is not yet reliable data on the heat transports for these higher levels.

The existence of a standing wave pattern in winter is suggested from consideration of the mean meridional wind components shown in Table 3*b* and 3*c*. These tables include the number of observations available and for these selected stations all data are included up to 65 km. NORDBERG *et al.* (1965) reported a similar standing wave pattern in their rocket grenade data; there are coherent patterns up to about 75 km where the smaller scale phenomena seem to become important. The data in Table 3*a* do not suggest standing wave features but a larger coverage in longitude is required before the existence or absence of low wave number features can be established.

6. Comparison with trace substance data

The standard deviation cross-sections provide a qualitative indication of the variation of quasi-horizontal mixing by large-scale motions. By analogy with the lower stratosphere and troposphere it can be argued that some measure of vertical mixing is also inherent in the data. The basic cause for increased transient eddy activity at high latitudes in winter is presumably the requirement to transport large amounts of heat polewards in the 30–50 km region in order to balance the heat budget. Radiative

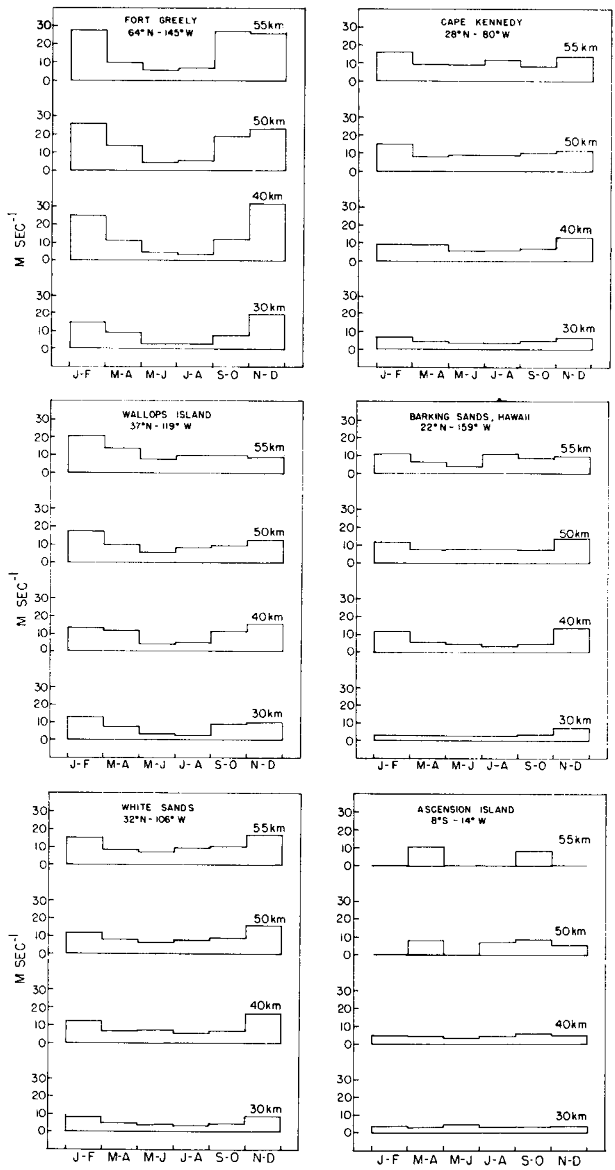

FIG. 5. Temporal standard deviations of the meridional wind component computed for two month time periods. Gaps indicate insufficient data.

processes are providing cooling in cold regions and warming in warm regions and the zonal available potential energy so produced is realised as kinetic energy of large scale eddies. Above about 55–60 km and between the equator and about 60° in winter the radiative processes are cooling warm regions and warming cold regions and hence destroying zonal available potential energy. There is thus a requirement for energy to be supplied from the 30–50 km layer and there must therefore exist inclined motions similar to those above the tropospheric jet with poleward-moving parcels descending and equatorward moving parcels ascending at angles greater than the slope of the mean isentropes. The exchange associated with this process, which may extend upward to the mesopause, will mix substances down their concentration

TABLE 3*a*. *Mean meridional wind component from rocket data. June 21 to September 20. Units: meters sec*$^{-1}$. *Number of observations in parentheses.*

Height (km) ...	65	62	60	55	50	45	40	35	30	25
Fort Greely,	−7.0	12.1	9.4	8.1	5.5	4.1	3.0	1.7	.2	.7
Alaska	(1)	(7)	(25)	(41)	(42)	(45)	(49)	(50)	(51)	(51)
Fort Churchill,	0	11.7	3.4	2.1	6.4	1.6	0	2.0	.1	.3
Canada	(0)	(3)	(5)	(13)	(16)	(18)	(20)	(25)	(27)	(29)
Wallops Island,	−6.3	6.5	2.2	5.2	5.5	3.5	.2	.7	.7	.4
Virginia	(3)	(15)	(23)	(45)	(81)	(100)	(114)	(118)	(112)	(106)
Point Mugu,	9.4	.6	.6	6.1	5.7	1.6	.4	1.0	.4	.5
California	(16)	(28)	(37)	(95)	(141)	(163)	(171)	(172)	(169)	(168)
White Sands,	7.3	5.2	5.3	5.9	6.0	4.7	.2	1.0	1.2	.4
New Mexico	(40)	(85)	(117)	(179)	(204)	(214)	(232)	(249)	(263)	(266)
Cape Kennedy,	3.6	6.5	5.0	6.2	5.6	2.0	1.6	.8	.6	−.2
Florida	(7)	(35)	(66)	(115)	(150)	(168)	(178)	(177)	(172)	(139)
Barking Sands,	12.7	3.3	.8	6.8	5.5	4.0	−.3	.8	1.3	1.0
Hawaii	(3)	(9)	(16)	(24)	(52)	(55)	(54)	(53)	(37)	(28)
Ascension Is.,	0	−7.4	−2.1	−1.4	−3.4	1.4	2.1	.8	.8	−1.4
BWI	(0)	(5)	(8)	(14)	(19)	(20)	(21)	(22)	(22)	(17)

TABLE 3*b*. *Mean meridional wind component from rocket data. September 21 to December 20. Units: meters sec*$^{-1}$. *Number of observations in parentheses.*

Height (km) ...	65	62	60	55	50	45	40	35	30	25
Fort Greely,	−12.0	−17.6	−16.2	−12.5	−11.6	−13.9	−10.6	−6.5	−2.6	.1
Alaska	(1)	(6)	(9)	(37)	(54)	(69)	(83)	(86)	(88)	(88)
Fort Churchill,	22.7	26.8	22.1	−.1	3.7	−1.7	−4.0	−6.4	−3.3	−1.2
Canada	(1)	(2)	(2)	(15)	(18)	(21)	(28)	(32)	(38)	(38)
Wallops Island,	13.2	12.1	12.6	10.5	13.2	12.0	8.8	5.4	5.3	2.5
Virginia	(6)	(13)	(16)	(32)	(69)	(78)	(89)	(88)	(81)	(69)
Point Mugu,	6.5	7.9	11.7	11.4	9.7	3.8	2.2	5.3	.5	−.1
California	(18)	(37)	(47)	(96)	(136)	(143)	(150)	(151)	(145)	(142)
White Sands,	8.8	12.1	8.9	9.1	9.9	7.3	2.9	4.1	3.1	.5
New Mexico	(34)	(84)	(135)	(183)	(204)	(213)	(225)	(229)	(237)	(240)
Cape Kennedy,	−16.0	4.5	4.0	6.9	11.1	6.5	4.0	1.9	2.3	1.0
Florida	(1)	(13)	(33)	(80)	(102)	(115)	(113)	(108)	(104)	(88)
Barking Sands,	10.0	−2.5	4.5	7.5	6.6	4.7	1.3	2.1	−.4	1.2
Hawaii	(2)	(4)	(11)	(41)	(61)	(62)	(63)	(62)	(63)	(59)
Ascension Is.,	−4.7	−5.3	−2.9	.1	−2.4	−1.4	.4	.5	.6	.1
BWI	(3)	(14)	(16)	(28)	(37)	(37)	(38)	(38)	(37)	(37)

gradients. The summer circulation may be laterally driven and have different mixing properties (NEWELL, 1965*b*). The actual wind data above 65 km are very sparse and the height at which small scale waves dominate over the large scale circulation processes is not known directly. This point is discussed further in Section 7. It is therefore quite important to examine all trace substance data which may be complementary to wind data, just as ozone and radioactive tungsten were complementary to wind information in the lower stratosphere several years ago. We therefore present below brief comments on the observations of seven trace substances pertinent to the transfer problems above 25 km.

(i) *Rh*^{102}

Rh^{102} was introduced into the atmosphere by a nuclear explosion at 43 km over Johnston Island (16° N) on August 11, 1958. Its distribution in time and space has been presented by

TABLE 3c. *Mean meridional wind component from rocket data. December 21 to March 20. Units: meters sec⁻¹. Number of observations in parentheses.*

Height (km) ...	65	62	60	55	50	45	40	35	30	25
Fort Greely,	0	−3.0	−11.2	−16.8	−16.4	−17.4	−16.9	−15.1	−12.6	−7.5
Alaska	(0)	(1)	(6)	(32)	(52)	(61)	(67)	(72)	(73)	(72)
Fort Churchill,	−74.0	−20.9	−17.2	−10.9	−7.6	−18.3	−12.2	−9.4	−7.5	−7.2
Canada	(1)	(2)	(3)	(7)	(12)	(15)	(21)	(26)	(29)	(33)
Wallops Island,	−11.0	−1.6	1.9	7.3	8.0	7.1	4.2	.8	3.4	.6
Virginia	(9)	(14)	(19)	(32)	(44)	(57)	(68)	(69)	(71)	(62)
Point Mugu,	−21.5	−.6	4.4	12.8	9.5	5.0	1.9	3.9	2.3	.7
California	(2)	(8)	(12)	(44)	(71)	(86)	(93)	(97)	(102)	(99)
White Sands,	6.4	6.6	8.6	10.2	9.6	7.1	2.8	1.2	1.6	.9
New Mexico	(35)	(76)	(96)	(120)	(132)	(145)	(161)	(176)	(180)	(181)
Cape Kennedy,	1.5	−1.3	6.1	6.6	7.5	6.5	4.9	4.3	3.9	2.0
Florida	(1)	(15)	(46)	(120)	(151)	(160)	(169)	(172)	(167)	(150)
Barking Sands,	0	1.8	−3.2	5.6	6.9	6.1	4.2	2.1	−.7	1.1
Hawaii	(0)	(4)	(5)	(20)	(21)	(21)	(21)	(21)	(21)	(20)
Ascension Is.,	10.5	8.5	13.0	8.2	7.0	1.2	1.6	.6	2.3	.5
BWI	(2)	(2)	(6)	(6)	(12)	(19)	(19)	(19)	(19)	(18)

TABLE 3d. *Mean meridional wind component from rocket data. March 21 to June 20. Units: meters sec⁻¹. Number of observations in parentheses.*

Height (km) ...	65	62	60	55	50	45	40	35	30	25
Fort Greely,	4.8	7.5	7.5	6.0	3.7	2.2	1.8	.4	0	.4
Alaska	(8)	(17)	(23)	(46)	(48)	(49)	(55)	(59)	(60)	(64)
Fort Churchill,	0	1.6	5.9	4.3	5.9	−.5	.8	−1.2	−.8	−.3
Canada	(0)	(2)	(3)	(4)	(7)	(6)	(11)	(13)	(18)	(22)
Wallops Island,	−6.2	2.5	2.6	2.2	2.8	5.0	1.1	.7	1.6	.4
Virginia	(5)	(8)	(17)	(45)	(67)	(73)	(86)	(87)	(85)	(82)
Point Mugu,	5.8	5.1	1.8	3.6	6.3	3.1	−.5	1.7	.5	.7
California	(12)	(18)	(27)	(94)	(139)	(145)	(150)	(150)	(150)	(144)
White Sands,	8.0	6.9	5.3	4.1	5.4	3.9	.1	.7	.9	.4
New Mexico	(53)	(103)	(129)	(158)	(181)	(190)	(202)	(204)	(205)	(216)
Cape Kennedy,	−4.7	6.3	4.8	3.5	5.3	2.0	.3	−.5	1.5	0
Florida	(3)	(18)	(44)	(116)	(164)	(178)	(186)	(185)	(182)	(156)
Barking Sands,	−1.6	−1.2	2.7	3.8	4.5	4.6	.6	1.1	.8	2.0
Hawaii	(5)	(10)	(15)	(39)	(51)	(51)	(53)	(52)	(40)	(37)
Ascension Is.,	0	−10.1	−5.8	−1.2	−.1	2.1	2.2	.8	1.0	−.3
BWI	(0)	(7)	(12)	(19)	(21)	(22)	(24)	(25)	(25)	(21)

KALKSTEIN (1962), FEELY *et al.* (1963) and TELEGADAS & LIST (1964). Consideration of particle sizes and sedimentation rates led KALKSTEIN (1962) and JUNGE (1963) to the suggestion that several months after the explosion much of the debris, which initially rose to altitudes of 100 km or more, was concentrated in a fairly thick layer centered at 55–60 km. A concentration gradient directed towards the equator was observed at 20 km in both hemispheres. The basic problem is to explain how intercommunication between 55 and 20 km, as shown by the observations, is related to the meteorological events. Kalkstein interpreted the data as indicating greater vertical mixing at high latitudes than at low latitudes and greater mixing in winter than summer. This interpretation is quite consistent with the data of Fig. 4; "vertical" mixing could be brought about by the inclined motions accomplishing the poleward heat transport.

Although the data are perhaps not adequate

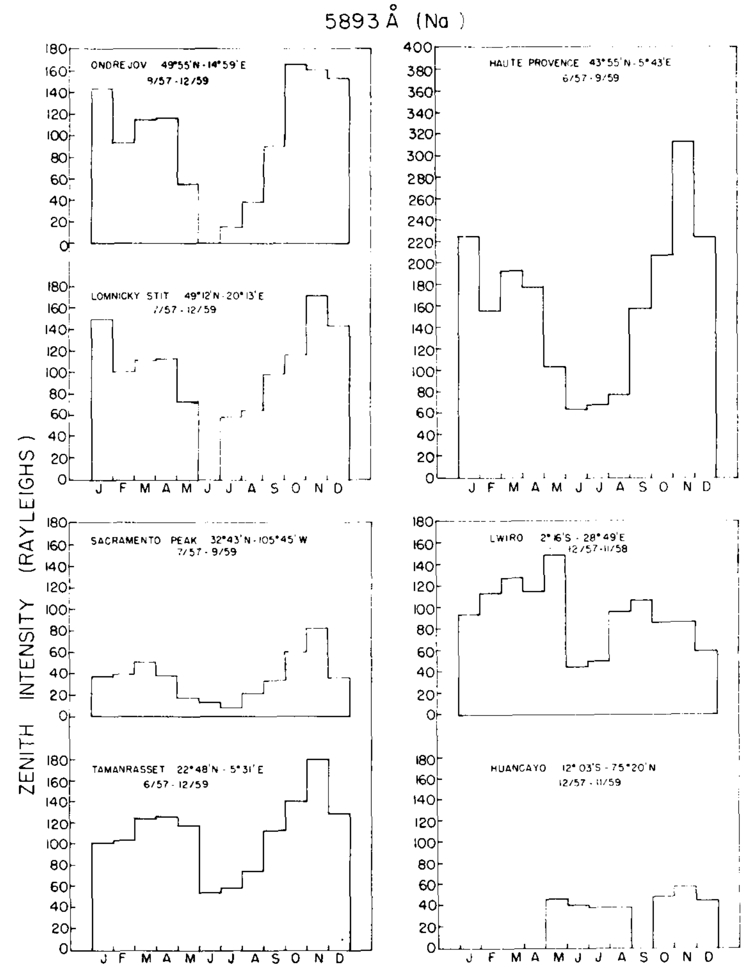

FIG. 6. Monthly values of the zenith intensity of the sodium component of nightglow. Blank months indicate insufficient data.

for definitive statements there is a suggestion that the relative increase in northern hemisphere values was greater in the 1959–60 winter than in the 1960–61 winter while in the southern hemisphere the mid-1960 winter had a larger relative increase than 1959 or 1961. A similar year to year variability was discussed in section 3.

(ii) *Cd*^{109} *and* (iii) *Pu*^{238}

Cd^{109} and Pu^{238} are two other radioactive isotopes that have been introduced artificially into the region of interest. Results of concentration measurements have been reported by SALTER (1965) and a comprehensive discussion of all available data was presented at the Visby Symposium by LIST *et al.* (1966). It is perhaps most appropriate to wait for the latter more extensive data before attempting interpretation in terms of Fig. 4.

(iv) *Na*

It has been recognized for some time that airglow radiation from sodium (5893 Å) is related to atmospheric circulation processes (see, for example, VALLENCE-JONES, 1963; HUNTEN, 1964; GADSDEN, 1964); the basic problem is the nature of this relationship. Sodium lines appear in the dayglow, the twilight emission and the nightglow. Nightglow data for a number of stations have been collected in the Annals of the IGY (YAO, 1962) and the

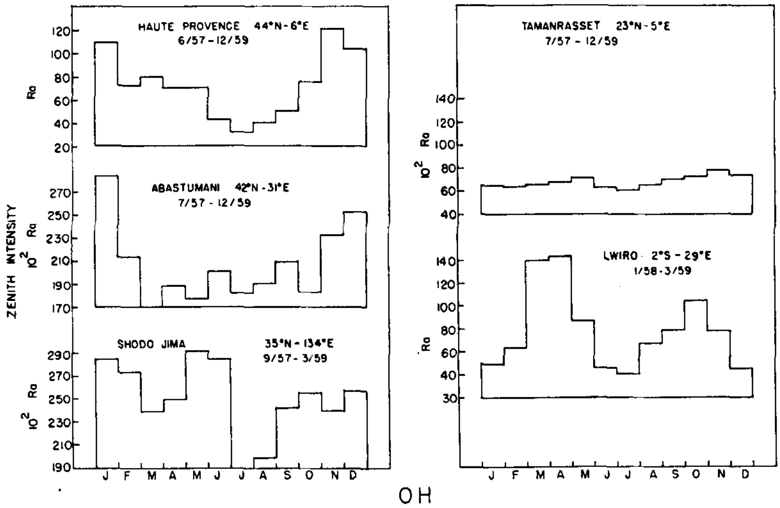

FIG. 7. Monthly values of the zenith intensity of the hydroxyl component of nightglow. Blank months indicate insufficient data.

monthly average values for several stations are shown in Fig. 6. The general feature of the seasonal variation, evident at all stations, is a maximum in the late fall and another smaller maximum in the spring in the northern hemisphere. It is difficult to deduce the variation with latitude from the IGY data because of the different techniques used at the various stations; a voyage with the same photometer between 60° N and 65° S suggests mid-latitude maxima in both hemispheres with the winter hemisphere showing the highest intensity (DAVIS & SMITH, 1965).

Dayglow observations (BLAMONT & DONAHUE, 1964) and twilight observations (HUNTEN, 1964) showed the same seasonal variation and the fact that the latter show an out-of-phase variation between the hemispheres suggests that meteorological processes are partly responsible. The ultimate origin of the sodium has been debated for many years (see for example the discussion by CHAMBERLAIN, 1961, and the work of JUNGE *et al.*, 1962). Whether ultimately the source is found to be meteor showers or sea salt the lack of a long term trend implies an overall balance between the amounts transferred into the 80–100 km region and the amounts lost by this region.

CHAPMAN (1939) originally suggested that the nightglow radiation originated from the photochemical reaction

$$NaO + O \rightarrow Na(^2P) + O_2$$

Possible additional reactions involved are:

$$Na + O_2 + M \rightarrow NaO_2 + M$$
$$Na + O + M \rightarrow NaO + M$$
$$Na + O_3 \rightarrow NaO + O_2$$
$$NaO_2 + O \rightarrow NaO + O_2$$

Changes in the sodium emission can thus be brought about by changes in the concentration of NaO or O in the emitting region or by changes in the reaction rate coefficient. Insofar as these concentrations are effected by the other reactions above, all the concentrations and rate coefficients involved are of pertinence. Possible dynamic effects will be noted briefly below.

(v) *OH*

Hydroxyl emission occurs in many portions of the spectrum of the nightglow. Several examples of the mean monthly zenith intensity are given in Fig. 7. There is evidently a similar variation to that of sodium with a maximum in the late fall and a minimum in summer. The southern hemisphere station shows an out-of-phase variation. The implication again is that some dynamical process is involved. Because of the different wavelengths and photo-

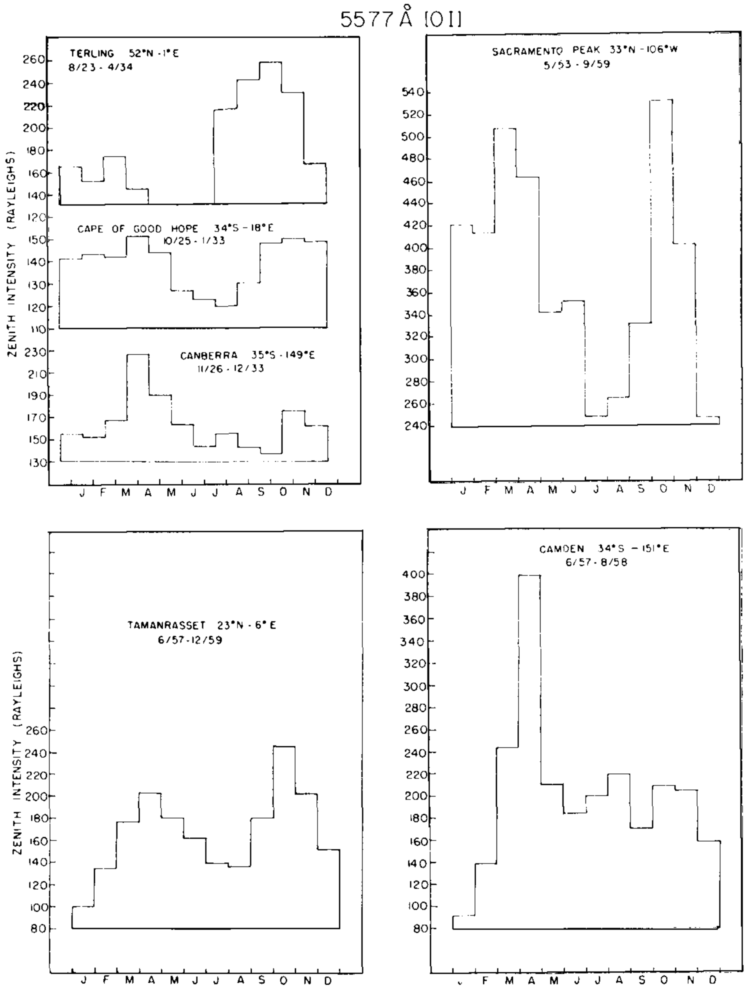

FIG. 8. Monthly values of the zenith intensity of the OI component of nightglow. Blank months indicate insufficient data.

meters involved it is not possible to deduce the variation with latitude from these data.

The reactions responsible for the emission are being actively debated in the literature (see for example KRASSOVSKY, 1963). A popular sequence is the following:

$$H + O_3 \rightarrow OH^* + O_2^*$$

$$OH^* \rightarrow OH + h\nu$$

$$OH + O \rightarrow H + O_2$$

in which free hydrogen (ultimately derived from water vapor or methane from below) simply acts as a catalyst.

(vi) *OI* (5577Å)

Data on this line are available for long periods from the work of Lord Rayleigh recently standardized by HERNANDEZ & SILVERMAN (1963) and for a long period at Sacramento Peak (IGY data supplemented by the compilation of HERNANDEZ, 1965, for 1953–57). Examples of the seasonal patterns appear in Fig. 8. It is again evident that maxima occur in the fall and spring with the former being the highest. The variation with latitude is such that maxima occur in middle latitudes.

While the possible reactions are again under discussion it appears that the emission is proportional to the concentration of atomic oxygen (raised to the third power for Chapman's mechanism and to the second power for Barth's mechanism, see TOHMATSU & NAGATA, 1963). Tohmatsu & Nagata have suggested a scheme of vertical motions that explains the variations with latitude and season.

JOHNSON (1964) has reviewed these three components of the airglow and made an attempt to relate them to what is known about the dynamics of the region between 50 and 100 km. Our comments below are based partly on his work and partly on the findings inherent in Fig. 4.

(vii) *Li*

Lithium has been monitored in the airglow for the past several years since it has become clear that it can be introduced by high altitude nuclear tests. Observations have been discussed by SULLIVAN & HUNTEN (1964) and GADSDEN (1964); the latter author has also attempted to fit the observations with a scheme of mean meridional circulations in the 80–100 km region.

7. General comments on the atmospheric circulation between 50 and 100 km

The observational material in the region influencing the distribution of the tracers discussed in Section 6 is very sparse. The rocket grenade experiment, sodium vapor trail drifts and meteor trail drifts are the principal sources of information. Data from the rocket grenade experiments show that large scale motions of the type evident in the Meteorological Rocket Network data and below dominate the circulation up to about 70–75 km (NORDBERG *et al.*, 1965). Above this range (evident also from Fig. 4) individual observations are influenced strongly by short period motions and tides, although the general flow pattern is still evident. Sodium cloud data have been divided into the three separate categories of gravity waves, tides and general drift in the 90 to 125 km region by KOCHANSKI (1964) and meteor winds are usually treated in terms of separate components (GREENHOW & NEUFELD, 1961; ELFORD, 1964). Recent studies of the detailed structure of the wind field between 30 and 70 km as determined by ROBIN falling sphere soundings (WEBB, 1965; NEWELL *et al.*, 1966) indicate that motions with short periods (several minutes to several hours) and small vertical scale (100 m to several km) are present in the region and their influence increases with altitude. Such motions have been studied theoretically by HINES (1963). While all types of motions may be present in the troposphere the large-scale long period motions propagate vertically only with great attenuation (CHARNEY & DRAZIN, 1961). The small scale motions in turn lose most of their energy by viscous dissipation before altitudes of about 150 km are achieved (see KOCHANSKI, 1964).

Possible atmospheric effects on the airglow constituents in the 75–100 km region are therefore (*a*) mean motions, (*b*) standing eddies, (*c*) transient eddies, (*d*) small-scale waves, (*e*) tidal motions.

(*a*) Mean motions have received much attention in the present context (TOHMATSU & NAGATA, JOHNSON, GADSDEN, loc. cit.). The meteor trail drift data at Jodrell Bank and Adelaide are cited as evidence for mean meridional motions insofar as both stations have components towards the winter pole in both July and December. However they also have predominantly westerly winds at both times; one might expect the Coriolis torque to ensure an easterly component at Jodrell in July and at Adelaide in December if these were genuine mean meridional motions.

(*b*) One can equally well cite the meteor wind evidence as being in favor of standing eddy circulations. Rocket Network data mean values and grenade experiment values have been similarly explained (NEWELL 1963*a*; NORDBERG *et al.*, 1965). If these standing waves influence the airglow constituents one would expect to observe strong variations in mean airglow intensity *with longitude* as there may well be a mean rising motion at one longitude and a mean sinking motion at another along the same latitude circle. The data mentioned previously are apparently not accurate enough for intercomparison. It is of some interest that the periods of change in the (standing wave) flow correspond to changes in the airglow emission. The vertical motions in the supposed waves are difficult to deduce until meteor data from other longitudes are available; this will also enable differentiation between mean motions and standing eddies to be made. The forced vertical motions accompanying the eddies which are part of the winter westerly jet would be such that poleward moving parcels would be subsiding and warming adiabatically in the 10–50° N region while equatorward moving parcels would be rising and cooling (NEWELL 1963*a*; 1964*a*). Essentially these motions in the 55–75 km region are thought to be coupled to the driving motions in the 25–50 km region in a similar manner to the coupling between the troposphere and the 15–25 km region.

(*c*) The motions which are classed as transient eddies by the present classification process are perhaps more properly envisaged as oscillations in strength and displacement in position of large scale semi-permanent features at these levels. When the transient eddy activity increases in September from its summer minimum the associated vertical motions would presumably transfer material both into and out of the lower portions of the airglow region. It is possible that this transfer is responsible for the increases in nightglow in October and November. The spring maximum would then have to be related to a corresponding increase in the southern hemisphere and rapid lateral mixing. The vertical extent of these transient eddies is difficult to assess with the present data. The momentum transport appear to reach a maximum in the vicinity of 50–60 km (NEWELL, 1965*b*) and much of the data of Fig. 4 likewise suggests decreases above 55 km. It is of interest to note that if the forced motions extend up to the mesopause there may be occasions in winter when very low temperatures are achieved in rising air in equatorial regions; such conditions together with the appropriate moisture might be expected to produce noctilucent clouds.

(*d*) Meteor trail turbulence at Adelaide has shown an indication of peak intensities in March and September with minima in May and November (ROPER & ELFORD, 1963). This is the only monitor of the small scale wave activity at present available and does not completely fit the airglow pattern.

(*e*) Tidal motions have long been recognized as an important component of the wind patterns in the mesosphere and above. Recent rocket data suggest the possibility of a significant diurnal tide in the 40–55 km region (MIERS, 1965). The possible existence of such a tide greatly complicates the interpretation of rocket wind data, for with the limited amount of data presently available it is difficult to distinguish between standing eddies and tidal effects. We are not yet in a position to speculate as to what effects such tidal motions might have upon mixing. The contribution of these tidal components to the observed standard deviations, to the calculated momentum fluxes and to the airglow variations can be assessed when sufficient rocket data for different times during the day has accumulated.

It is clear that a network of intercalibrated airglow photometers and a more extensive sampling program for radioactive trace substances would be of great assistance in unravelling the properties of the atmospheric circulation in the mesopause region just as ozone and tungsten observations have been very helpful in studies of the lower stratosphere.

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REFERENCES

BLAMONT, J. E., and DONAHUE, T. M., 1964, Sodium dayglow: observation and interpretation of a large diurnal variation. *J. Geophys. Res.*, **69**, pp. 4093–4127.

CHAMBERLAIN, J. W., 1961, *Physics of the Aurora and Airglow*. International Geophysics Series, Vol. 2, Academic Press, New York.

CHAPMAN, S., 1939, Notes on atmospheric sodium. *Astrophysical J.*, **90**, pp. 309–316.

CHARNEY, J. G., and DRAZIN, P. G., 1961, Propagation of planetary-scale disturbances from the lower into the upper atmosphere. *J. Geophys. Res.*, **66**, pp. 83–109.

CRUTCHER, HAROLD L., 1961, Meridional cross-sections, upper winds over the northern hemisphere. Technical Paper No. 41. U.S. Weather Bureau.

DAVIS, T. N., and SMITH, L. L., 1965, Latitudinal and seasonal variations in the night airglow. *J. Geophys. Res.*, **70**, pp. 1127–1138.

DICKINSON, R. E., 1962, Momentum balance of the stratosphere during the IGY. Unpublished S.M.

thesis, Dept. of Meteorology, M.I.T. Also in Final Report Studies of the Stratospheric General Circulation. Contract No. AF19(604)-5223, Planetary Circulations Project, Dept. of Meteorology, M.I.T., 132–167.

ELFORD, W. G., 1964, Seasonal and diurnal variations in winds at 90 km. Paper presented at the Annual Meeting of the A.G.U., Washington, April 21–24, 1964.

FEELY, H. W., *et al.*, 1963, Ninth Quarterly Report on PROJECT STAR DUST. DASA 1309.

FRIEND, J. P., FEELY, H. W., FISHER, E. L., and DAVIDSON, B., 1962, Project Star Dust Third Quarterly Rept. and subsequent repts. in series. DASA 1303.

GADSDEN, M., 1964, On the twilight sodium emission. 1: Observations from a southern hemisphere station. *Annales de Geophysique*, **20**, pp. 261–271.

GADSDEN, M., 1964, On the twilight sodium emission. 2: A theoretical model of sodium abundance. *Annales de Geophysique*, **20**, pp. 383–396.

GILMAN, P. A., 1964, On the mean meridional circulation in the presence of a steady state, symmetric, circumpolar vortex. *Tellus*, **16**, pp. 160–167.

GREENHOW, J. S., and NEUFELD, E. L., 1961, Winds in the upper atmosphere. *Quart. J. Royal Meteor. Soc.*, **87**, pp. 472–489.

HERNANDEZ, G. J., 1965, Data previous to the International Geophysical Year I: 5577(OI) line at Sacramento Peak, New Mexico. Research Report. AFCRL-65-319.

HERNANDEZ, G. J., and SILVERMAN, S. M., 1963, A reexamination of Lord Rayleigh's data on the Airglow 5577A(OI) Emission. Research Report AFCRL-63-835.

HINES, C. O., 1963, The upper atmosphere in motion. *Quart. J. Royal Meteor. Soc.*, **89**, pp. 1–42.

HUNTEN, D. M., 1964, Metallic emissions from the upper atmosphere. *Science*, **145**, pp. 26–31.

JOHNSON, W. F., 1964, Relations between the airglow and the mesospheric circulation. S.M. thesis, Dept. of Meteorology, M.I.T.

JUNGE, C. E., *et al.*, 1962, On the origin of the sodium present in the upper atmosphere. *J. Geophys. Res.*, **67**, pp. 1027–1039.

JUNGE, C. E., 1963, *Air Chemistry and Radioactivity.* International Geophysics Series, Vol. 4, Academic Press, N.Y.

KALKSTEIN, M. I., 1962, Rhodium-102 high-altitude trace experiment. *Science*, **137**, pp. 1–8.

KAO, S.-K., 1962, Large-scale turbulent diffusion in a rotating fluid with applications to the atmosphere. *J. Geophys. Res.*, **67**, pp. 2347–2359.

KOCHANSKI, A., 1964, Atmospheric motions from sodium cloud drifts. *J. Geophys. Res.*, **69**, pp. 3651–3662.

KRASSOVSKY, V. I., 1963, Hydroxyl emission in the upper atmosphere. *Plan. Space Sci.*, **10**, pp. 7–17.

LIST, R. J., SALTER, L. P., and TELEGADAS, K., 1966, Radioactive debris as a tracer for investigating stratospheric motions. Paper presented at Visby CACR meeting and submitted to *Tellus* 339–348.

MIERS, B. T., 1965, Wind oscillations between 30 and 60 km over White Sands Missile Range, New Mexico. *J. Atmos. Sci.*, **22**, pp. 382–387.

NEWELL, R. E., 1963*a*, Preliminary study of quasi-horizontal eddy fluxes from Meteorological Rocket Network data. *J. Atmos. Sci.*, **20**, pp. 213–225.

NEWELL, R. E., 1963*b*, The general circulation of the atmosphere and its effects on the movement of trace substances. *J. Geophys. Res.*, **68**, pp. 3949–3962.

NEWELL, R. E., 1964*a*, The circulation of the upper atmosphere. *Scientific American*, **210**, pp. 62–74.

NEWELL, R. E., 1964*b*, Stratospheric energetics and mass transport. *Pure and Applied Geophysics*, **58**, pp. 145–156.

NEWELL, R. E., 1964*c*, Further ozone transport calculations and the spring maximum in ozone amount. *Pure and Applied Geophysics*, **59**, pp. 191–206.

NEWELL, R. E., 1965*a*, A review of studies of eddy fluxes in the stratosphere and mesosphere. Report No. 12, Planetary Circulations Project, Department of Meteorology, M.I.T., Contract No. AT(30-1)2241.

NEWELL, R. E., 1965*b*, The energy and momentum budget of the atmosphere above the tropopause. Paper presented to the Sixty International Space Science Symposium, Mar del Plata, Argentina, May 17, 1965. (Proceedings to be published.)

NEWELL, R. E., MAHONEY, J. R., and LENHARD, R. W., JR., 1966, A pilot study of small scale wind variations in the stratosphere and mesosphere. *Quart. J. Royal Meteor. Soc.*, **92**.

NEWELL, R. E., and MILLER, A. J., 1964, Some aspects of the general circulation of the lower stratosphere. Proceedings of the Second AEC Conference on radioactive fallout from nuclear weapons tests, November 3–6, 1964, United States Atomic Energy Commission, Symposium series 5, pp. 392–404.

NORDBERG, W., *et al.*, 1965, Rocket observations of the structure and dynamics of the mesosphere during the quiet sun period. Goddard Space Flight Center, Breenbelt, Maryland, X-651-65-154. Paper presented at Mar del Plata, Argentina Sixth COSPAR Meeting (to be published).

OORT, A. H., 1963, On the energy cycle in the lower stratosphere. Rept. No. 9, Dept. of Meteorology, M.I.T.

OORT, A. H., 1965, The climatology of the lower stratosphere during the IGY and its implications for the regime of circulation. *Archiv für Meteorologie, Geophysik und Bioklimatologie*, **14**, pp. 243–278.

PALMÉN, E., and VUORELA, L. A., 1963, On the mean meridional circulations in the northern hemisphere during the winter season. *Quart. J. Royal Meteor. Soc.*, **89**, pp. 131–138.

PENG, L., 1965, Stratospheric wind temperature and isobaric height conditions during the IGY period. Part III, Report No. 15, Planetary Circulations Project, Dept. of Meteorology, M.I.T., Contract No. AT(30-1)2241.

PRABHAKARA, C., 1963, Effects of non-photochemical processes on the meridional distribution and total amount of ozone in the atmosphere. *Monthly Weather Review*, **91**, pp. 411–431.

REED, R. J., and GERMAN, K. E., 1965, A contribution to the problem of stratospheric diffusion by large-scale mixing. *Monthly Weather Review*, **93**, pp. 313–321.

ROPER, R. G. and ELFORD, W. G., 1963, Seasonal variation of turbulence in the upper atmosphere. *Nature*, **197**, pp. 963–964.

SALTER, L. P., 1965, The early stratospheric distribution of debris from a SNAP-9A abort. HASL-158, 310–315, April 1, 1965.

SHEPPARD, P. A., 1963, Atmospheric tracers and the study of the general circulation of the atmosphere. *Rep. on Prog. in Phys.*, **26**, pp. 213–267.

SMITH, L. B., 1960*a*, Monthly observations of winds between 100,000 and 300,000 ft. Research Rept. SC-4482 (RR). Sandia Corp.

SMITH, L. B., 1960*b*, The measurement of winds between 100,000 and 300,000 ft. by use of Chaff rockets. *J. Meteor.*, **17**, pp. 296–310.

SULLIVAN, H. M., and HUNTEN, D. M., 1964, Lithium, sodium, potassium in the twilight airglow. *Canadian J. Phys.*, **42**, pp. 1325–1335.

SUNDSTROM, A., 1964, Stratospheric transports as deduced from tracers. FOA 4 Rpt. A 4377–4557. Inst. of Meteor. Univ. of Stockholm.

TELEGADAS, K., and LIST, R. J., 1964, Global history of the 1958 nuclear debris and its meteorological implications. *J. Geophys. Res.*, **69**, pp. 4741–4753.

TOHMATSU, T., and NAGATA, T., 1963, Dynamical studies of the oxygen green line in the airglow. *Plan. Space Sci.*, **10**, pp. 103–116.

VALLENCE-JONES, A., 1963, Metallic emissions in the twilight and their bearing on atmospheric dynamics. *Plan. Space Sci.*, **10**, pp. 117–127.

WALLACE, J. M., and NEWELL, R. E., 1965, Eddy fluxes and the biennial oscillation in the stratosphere. Rept. No. 14, Planetary Circulation Project, Dept. of Meteorology, M.I.T., Contract No. AT(30-1)2241.

WEBB, W. L., 1964, Stratospheric solar response. *J. Atmos. Sci.*, **21**, pp. 582–591.

WEBB, W. L., 1965, "Scale of Stratosphere Detail Structure". *Space Research V*. John Wiley & Sons, Inc., New York, pp. 997–1007.

YAO, I. G., 1962, Observations of the night airglow. *Annals of the IGY*, **24**.

ОБЩАЯ ЦИРКУЛЯЦИЯ АТМОСФЕРЫ И ЕЁ ВЛИЯНИЕ НА ДВИЖЕНИЕ ПРИМЕСЕЙ

Предполагается, что крупно-масштабные характеристики перемешивания в атмосфере связаны с временными и пространственными вариациями ветров. Представленные данные о временных средне-квадратичных отклонениях для слоя на высоте от поверхности земли до 75 км основаны на зондировании с помощью ракет и шаров. Исследованы месячные и годовые вариации в 15–30 км области и средне-сезонные изменения для 30–75 км зоны. Сделана попытка связать временное и пространственное распределение следов радиоактивности и свечения неба с данными о ветре.