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Abstract. The seasonal variation of the eddy diffusion coefficient is deduced for a height of 94 km at 23^{o}S based on two independent methods of analysis. One of these methods, already used in the past, is related to indirect measurements of atomic oxygen and the other one is a new method related to measurements of the density of upper atmospheric sodium. The results are mutually consistent giving a maximum eddy diffusion coefficient during summer.

Introduction

The possible causes of the production and propagation of turbulence have been discussed by several authors (see, for example, Shimazaki, 1971, and references therein). Among these causes are oscillatory motions of small and/or large periods, irregular winds, and wind shears. An acceptable overall theory for turbulence, turbulent transport, and related eddy diffusion coefficient, K, is not yet available, but the adoption of an effective diffusion coefficient and the corresponding eddy flux has been necessary to explain the distribution of minor atmospheric constituents in the mesosphere and lower thermosphere (Shimazaki and Laird, 1970). A review on the topic has been given by Hunten (1975), showing that K is expected to be of the order of 10^6 cm^2 s^{-1} in the lower thermosphere, and Lindzen (1971) has argued that between the stratosphere and the lower thermosphere, K should increase exponentially with a scale height of the order of twice the neutral density scale height. As pointed out by Hunten (1975), measurements of the mixing ratio gradient of some tracers are not enough for the determination of the absolute value of K which requires also estimates of the associated eddy flux through model calculations. Estimates of the eddy diffusion coefficient,for example, have been obtained from calculations of the worldwide continuity in the heat budget by Johnson and Gottlieb (1970), who obtained 10^6 cm^2 s^{-1} at 92 km, and from OGO 6 airglow observations of the atomic oxygen green line by Donahue et al., (1973) who obtained coefficients in the range 2×10^6 cm^2 s^{-1} to 8×10^6 cm^2 s^{-1} depending on some model input parameters. More recently, Allen et al. (1981) have deduced a K profile through modelling of several long lived species for which measurements were available in different height ranges.

The neutral sodium (Na) layer which has its peak density at about 94 km is expected to be very sensitive to the eddy diffusion coefficient, since eddy diffusion is presumably responsible for the transport of Na between a source at about the peak of the layer and a sink at lower heights. The region above the peak is expected to be

chemically inactive (Kirchhoff and Clemesha, 1982). Solution of the flux equation (Hunten, 1975) shows that this is a region where the density is proportional to the flux. This is easy to see in the special case of a narrow layer source located above the loss region. Between source and sink a constant downward flux, equal to the integrated production of the source, will exist. Thus, for a given influx at the source the maximum Na density, Na_m, is practically fixed by the absolute value of the eddy diffusion coefficient and not by the loss processes, the detailed nature of which is unimportant. Since at our latitude (-23^o) the shape of the layer remains virtually unchanged through the seasons, the above conclusion can be extended also to the Na abundance (height integral of Na density), and seasonal variations in Na_m (or abundance) can be related to seasonal variations of the eddy diffusion coefficient. In this analysis we neglect the possible effects of ionization. It should be noted that Hunten's (1981) model, in which ionization results in a lifetime of only about 12 hours for free Na atoms has been shown to be invalid by Clemesha et al. (1981).

Except for differences in the production and loss processes and the regions in which they take place, a somewhat similar argument can be applied to the atomic oxygen layer. The aim of this work is to deduce the seasonal variations of K through the variations observed in the peak densities of Na and O, and to show that they are mutually consistent.

Derivation of K

The basic idea of the determination of K is to compare the eddy flux given by the diffusion equation,

$$\phi = - K(dn/dz + n/H) \qquad (1)$$

where n is the density of the flowing constituent and H is the density scale height of the neutral atmospheric density, to the flux given in the case of atomic oxygen by the continuity equation,

$$\phi_z - \phi_{z_0} = \int_{z_0}^{z} (P - L)dz \qquad (2)$$

where P and L are respectively the chemical production and loss terms of the constituent of density n and where the integration is carried over the height region z. Atomic oxygen data have been analysed in this way (Donahue et al., 1973; Colegrove et al., 1965). In this work we also use neutral atmospheric sodium data, for which the seasonal variation of the density is well known. As mentioned previously, the lifetime of the Na atoms above the peak of the layer (94 km) is very long. Temperature profiles having the shape of the US Standard Atmosphere, but normalized at 84 km to a temperature deduced from measurements of OH rotational temperature, were adopted. On the basis of seasonal variations of this parameter and the Na densities, we will deduce the variations of K assuming the input flux rate to be constant. Junge et al. (1962) estimate a total Na influx from meteoroid deposition of 1.3×10^4 cm^{-2} s^{-1} but caution to a possible uncertainty of up to two orders of magnitude. An earlier estimate of this input rate, due to Cabannes et al. (1938), is 2.4×10^3 cm^{-2} s^{-1}, and a more recent one of Hughes (1975) is 1.6×10^4 cm^{-2} s^{-1}. Since there is a rather large uncertainty about this flux value, we have chosen to normalize the Na results to the O results for winter. The necessary flux in this case is 5.4×10^3 cm^{-2} s^{-1} as shown in Table 2.

The atomic oxygen density data are determined indirectly from intensity data of the 5577 Å line of O (Takahashi et al., 1977) using the technique of Reed and Chandra (1975). The values of photodissociation rates as well as the relevant loss rates are calculated using a comprehensive time dependent atmospheric model which extends between 30 and 140 km. The eddy diffusion coefficient is assumed to have a height profile whose amplitude is adjusted such that at a given seasonal period the calculated maximum O density equals the maximum density deduced from the green line. Details of the atmospheric model are given in Kirchhoff and Clemesha (1982). The results are given in Table 1, where the eddy diffusion coefficient is shown to vary

between a minimum of 4.5×10^5 cm^2 s^{-1} during fall and a maximum of 12.3×10^5 cm^2 s^{-1} during summer.

From a 5 year data set of laser radar measurements at 23°S (Simonich et al., 1979) it is known that the Na abundance (or Na_m) increases from summer to winter by a factor of about 2. The number of data points during summer is much less than during winter, but the trend is consistent from year to year. From April to August, the average abundance stays practically constant. It decreases more or less steadily towards December, where it presents its lowest magnitude of about 2.5×10^9 Na atoms cm^{-2}, and through March it stays below 3.5×10^9 Na atoms cm^{-2}. The maximum densities and the temperatures at 94 km, for the different seasonal periods, as well as the calculated values of K are shown in Table 2. The seasonal variation obtained for K is shown in Figure 1.

Discussion

Ebel (1980) points out that eddies of different scales seem to affect the distribution of heat, momentum, and minor constituents in different ways, which complicates comparison between different models. His model, based on meteorological parameters, derives values of K for the different seasons, varying between 2.2×10^6 cm^2 s^{-1} in summer and 8.9×10^6 cm^2 s^{-1} in winter, for our latitude (23°S). The absolute values of K, however, depend on a normalization adopted in this case at 100 km at 50°N.

Blum et al. (1978) have developed a semi-empirical model of the atmosphere based on satellite-borne mass spectrometer measurements in the thermosphere. The periodic density variations observed in the measurements were interpreted as the result of the combined action of variations in the exospheric temperature and turbopause height, which in turn can be related to the eddy diffusion coefficient. On this basis, Blum and Schuchardt (1978) have deduced a seasonal-latitudinal variation of the eddy diffusion coefficient. It

is important to note, on the other hand, that these density variations observed in the thermosphere have also been interpreted as the result of a global thermal wind system (Mayr and Volland, 1972). While the global wind circulation model does not consider variations of the eddy diffusion coefficient, the moving turbopause model does not include effects of horizontal winds, but apparently both are successful in describing the observed density variations of the lower thermosphere.

In the Blum and Schuchardt model the height dependence of the eddy diffusion coefficient is such that above and below the maximum there is a constant height gradient and the annual variation is determined by the variation of height and magnitude of the maximum. Above the peak, the magnitude decreases by a factor of 100 in 11 km, and below the peak the increase with height is a factor of 10 in 25 km. The eddy diffusion coefficients for 25^{o}S (K. Schuchardt, 1979, private communication) are shown in Figure 2 for January, April, and July, (dashed line), where we show the height interval 30-110 km, but numerical values in this case should not be extrapolated to heigths lower than 70 km. The values of K deduced from Na and given in Table 2 are shown in Figure 2 for summer (S) and Winter (W) by the heavy dots. For comparison we also show the eddy diffusion profiles used by other authors. Megie and Blamont (1977) (MB) adopted a profile very similar to the worldwide average eddy coefficients deduced from the continuity in the heat budget by Johnson and Gottlieb (1970). The dashed lines designated BS are Blum and Schuchardt's extreme profiles, the largest for summer and the smallest for fall. The continuous line H is the profile of Hunten (1975), and the dotted profile is from Allen et al. (1981).

From the foregoing it is clear that the seasonal variations in sodium which would follow from calculations of the Na layer using the BS eddy diffusion profiles, are very much larger than those observed in practice. This is true also for the atomic oxygen. It applies also to middle and high latitudes. It is likely, therefore, that the Blum and Schuchardt interpretation of the satellite

measurements in terms of an eddy diffusion model, produces enhanced variations in K, and that the seasonal variations in K are actually smaller. This result is apparently consistent with calculations of combined diffusion-wind models (Schuchardt and Blum, 1980) which require lower seasonal variations of the eddy diffusion coefficient.

The sensitivity of the atomic oxygen layer to eddy transport has been previously recognized by Colegrove et al. (1965). These authors have deduced a height independent eddy diffusion coefficient based on mass spectrometer measurements of the ratio O/O_2 at about 120 km, and model calculations in the height range of 70 to 130 km. They arrived at a value of 4.0×10^6 cm^2 s^{-1}. It is interesting to note, however, that their photodissociation coefficient of O_2 at zero optical depth of 5.6×10^{-6} s^{-1} is much larger than that used in more recent models, as for example in Liu et al. (1976), who use 1.26×10^{-6} s^{-1}. Furthermore, the loss rate for O may have been underestimated. Additional loss and smaller photodissociation values both act in the sense of decreasing the value of K that was deduced by Colegrove et al.. An updated value would probably be within the range 3×10^5 cm^2 s^{-1} to 9×10^5 cm^2 s^{-1}.

The absolute values for K that we have deduced depend ultimately on the solar flux data and reaction rates that we have used in our model. The variations for the different seasons, however, do not depend on the absolute values of these quantities. In the case of Na a variation in the extraterrestrial influx rate, caused perhaps by the occurence of meteoroid showers or the inclination of the earth's axis, would modify the deduced variation for K, although this modification should be small if the yearly variation is similar to the data of Ellyett and Keay (1961) which show radar meteor rates smaller in July than in December by a factor of about 1.5. It should be noted, finally, that K for summer is larger than for winter, at our latitude (-23^o), as has been obtained also at a mid northern latitude on the basis of incoherent scatter measurements of temperature (Alcayde et al., 1979).

Summary

We have discussed a new method to deduce information about the eddy diffusion coefficient at a height of about 94 km,and a numerical application was made for sodium data taken at 23°S in order to deduce the seasonal variation. The uncertainty in the value of the sodium influx rate prevents us from calculating the absolute value of the eddy diffusion coefficient but, by assuming that the influx is roughly constant we have derived a seasonal variation. We have also derived eddy diffusion coefficients from measurements of the 5577 Å atomic oxygen emission, and find that the seasonal variations obtained from Na and O are mutually consistent, which lends weight to our assumption that the sodium influx is roughly constant. The absolute value of this flux, obtained by normalization to the atomic oxygen calculations is within the range of estimated values. A minimum K is obtained between fall and winter, increasing toward spring, and being maximum during summer. The variation between minimum and maximum is a factor of 3, which is much less than estimates obtained from other methods.

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Table 1. Eddy diffusion coefficients at 94 km deduced from seasonal variations of atomic oxygen at 23^{o}S.

	Summer	Fall	Winter	Spring
T(K)	209	204	194	204
$O_m(10^{11}\ cm^{-3})$	3.25	4.6	3.0	3.85
$K(10^5\ cm^2\ s^{-1})$	12.3	4.5	7.6	7.6

Table 2. Eddy diffusion coefficients at 94 km deduced from seasonal variations of sodium at 23^{o}S.

	Summer	Fall	Winter	Spring
T(K)	209	204	194	204
$Na_m(10^3\ cm^{-3})$	2.5	4.0	4.0	3.6
$\phi(10^3\ cm^{-2}\ s^{-1})$	5.4	5.4	5.4	5.4
$K(10^5\ cm^2\ s^{-1})$	13.2	8.1	7.6	9.2

Figure Captions

Figure 1. The seasonal variations obtained for K. Dashed lines are for O, and continuous lines for Na.

Figure 2. Eddy diffusion coefficients in the height range 30-110 km. The values calculated in this work are shown by the heavy dots at 94 km. The other profiles are shown for comparison. H from Hunten (1975); BS from Blum and Schuchardt (1978); and MB from Megie and Blamont (1977). The dotted line is from Allen et al. (1981).

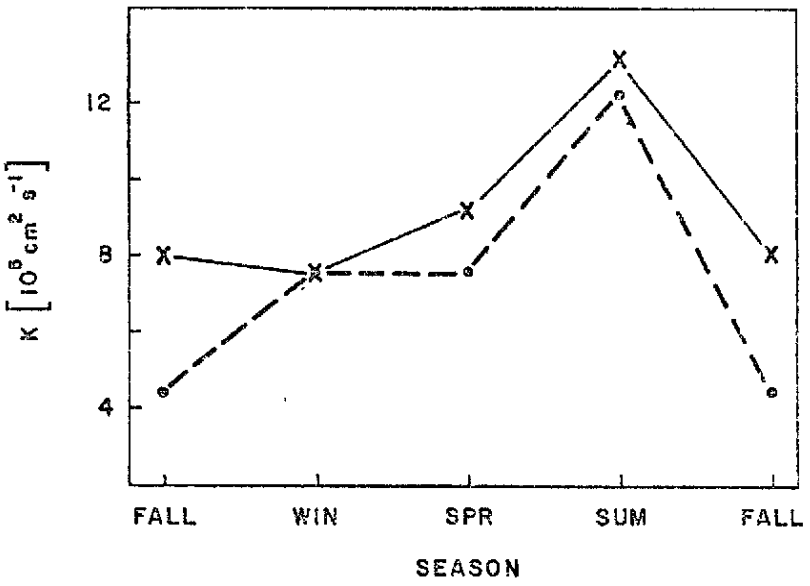
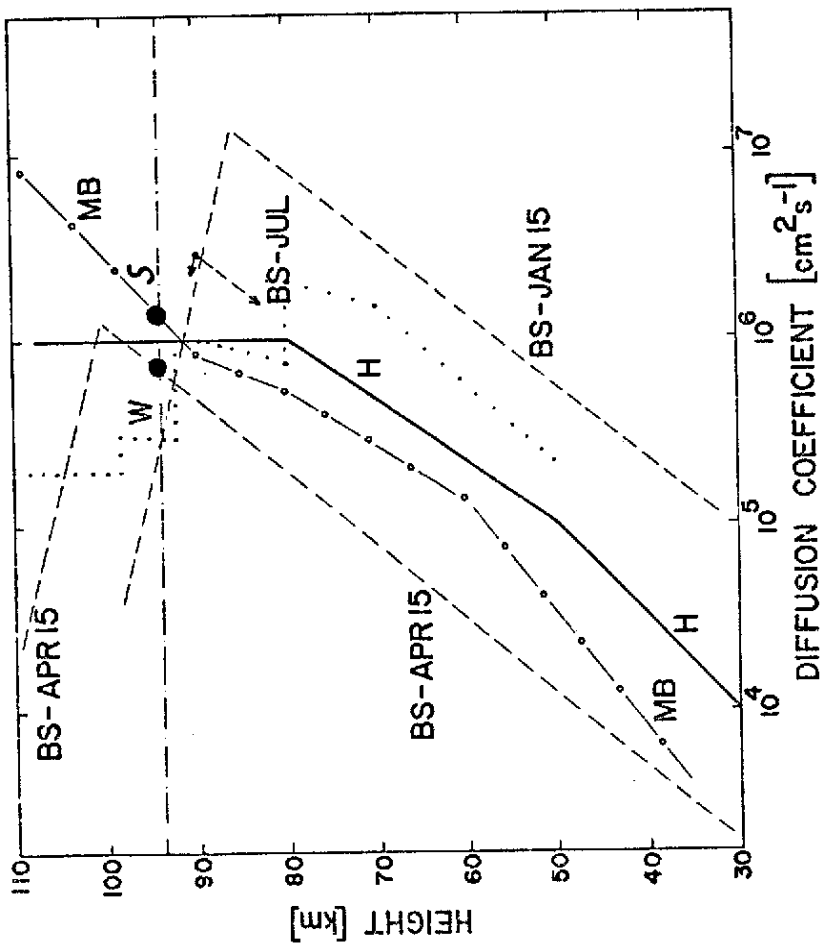


Fig. 1 - The seasonal variations obtained for K. Dashed lines are for O, and continuous lines for Na.



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