The kinetic energy spectrum in the free atmosphere—1 second to 5 years

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(Manuscript received June 9, 1969; revised version January 16, 1970)

ABSTRACT

An energy spectrum of wind speed at altitudes from 3 to 20 km is constructed from rawinsonde and aircraft data originating in the U.S.A. and the U.S.S.R. Most of the observations are concentrated near 40° N and cover periods from 1 sec to 5 year. The spectrum is subdivided into three major regions separated by gaps: a sharp annual maximum, a synoptic (or macroscale) maximum at periods from 1–2 months to 3–4 days, and a microscale maximum with periods of 1–3 min. It is shown that the microscale maximum is not a permanent feature of the spectrum. Usually high frequency turbulence is supressed by stable stratification in the free atmosphere and its energy is negligibly small. Spectra in the free atmosphere and near the ground are compared. An attempt is made to relate frequency and wave number spectra at synoptic scales.

I. Introduction

The intensive study of turbulence in the free atmosphere during the past ten years has concentrated on the microscale subrange of eddies which affect aircraft. As a result, there are thousands of turbulence spectra at scales ranging from 10–50 m to 600–2000 m obtained in Australia, England, the United States, and the Soviet Union at altitudes from 1–2 to 20–25 km.

Experimental data in other subranges of atmospheric turbulence are by comparison rare. Pinus (1964) and Kao & Woods (1964) investigated the mesoscale region (scales from 3–4 to 50–100 km) using aircraft. Angell (1958) and Mantis (1963) studied subsynoptic and mesoscale turbulence (periods from 10 min to 7 days) with superpressure constant level balloons. Pinus (1969) and Wan-cheng Chiu (1959) investigated synoptic scales of turbulence (periods up to 2 months) with rawinsonde data from some aerological stations. Data from the dissipation subrange of turbulence in the free atmosphere are virtually non-existent.

All these data do not yet provide the answers to two important questions: Is there a wavelength band in which the spectrum is constant? Is there a significant gap between synoptic scales and the microturbulent range?

An attempt is made in this paper to construct the spectrum of turbulence in the free atmosphere for a wide range of scales and periods using all the available data. Some important features of the resulting spectrum are discussed.

II. Spectrum of turbulence at very low frequencies

The longest periods previously available in analyses of zonal (E–W) and meridional (N–S) components of atmospheric motion are those of two days to two months obtained by Wan-cheng Chiu (1959) for winds at seven levels between 3 and 20 km at Belmar, New Jersey. While spectra of the N–S component clearly show a saturation, being nearly constant at periods longer than 20 days, the spectra of the E–W component continue to increase with period throughout the range with a slope of approximately -1 in a doubly logarithmic representation.

Therefore, to clarify the behavior of spectra at the lowest frequencies, monthly averaged winds have been used over the Washington,

[1] The work presented here was performed while the author was an Exchange Fellow in the Department of Meteorology of The Pennsylvania State University.

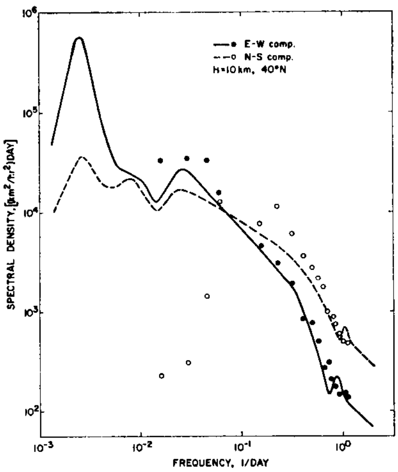

Fig. 1. Spectral density of E–W (solid line) and N–S (dashed line) wind components at 10 km altitude over Washington, D.C. station. Solid and open circles represent a replot of Figure 2 data (see text).

D.C. station[1] for the period from 1952 to 1968 for 8 levels between 3 and 20 km (U.S. Weather Bureau, Climatological Data, National Summary).

The computed spectra reveal a sharp maximum at a period of one year for the E–W component and much smaller (but still pronounced) maximum for the N–S component.

It is usually impossible to match precisely spectra obtained at different locations and for non-overlapping frequencies. On the average, the matching of spectra obtained over Washington, D.C. and Belmar, New Jersey was fairly good at all levels. To determine more accurately the shape of the spectrum, it was calculated for the whole range of low frequencies using only Washington, D.C. data at 10 km altitude.

Fig. 1 shows a log–log plot of the resulting spectral densities of the E–W (solid line) and the N–S (dashed line) wind components at 10 km altitude over Washington, D.C. for periods from 12 hours to 2 years. Three sets of overlapping data have been used to calculate these spectra: monthly averaged winds for the period from 1952 to 1968, daily winds for the period from January 1957 to January 1963 and 6-hour-interval winds for the period from 1 March 1960 to 12 November 1960.

It is worth noting a problem at this point. The spectrum in Fig. 1 is presented in terms of frequency for one particular station. But some authors have studied the kinetic energy in the free atmosphere as a function of wave number around selected parallels of latitude. It is interesting to compare two kinds of spectra and their relationship.

At small periods ($T < T_m$) and at small scales ($L < L_m$) Taylor's hypothesis of "frozen turbulence" is valid and the following relations are true (Monin & Yaglom, 1967)

$$\frac{2\pi f}{\bar{U}} = k \tag{1}$$

where f is the frequency in cycles per unit time, $\bar{U}$ is the mean wind speed and k is a wave number in radians per length. The time (or frequency) spectrum $S(f)$ is related to the spatial (or wave number) spectrum $S(k)$ by

$$S(k) = \frac{\bar{U}}{2\pi} S(f) \tag{2}$$

The hypothesis is that all the turbulent eddies smaller than L_m are transported with a constant speed $\bar{U}$ and, therefore, geometrical shapes of $S(k)$ and $S(f)$ are identical.[2]

But for long periods and large scales this is no longer true. The speed of large eddies is not a constant but depends on the size of the eddies. Hence, the geometrical shapes of $S(k)$ and $S(f)$ are different. This situation is illustrated by 2 which shows a log–log plot of the spectral density for the E–W and N–S components of wind at 10 km altitude for 40° N parallel obtained by Benton & Kahn (1958) as a function of wave number. It is easily seen that the shapes of the spectra of Figs. 1 and 2 are quite different.

Thus, in order to relate time and space spectra for larger scales, it is necessary to determine the dependence of energy propagation on scale. Unfortunately, direct evidence is

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[1] Belmar, New Jersey station is not listed now in U.S. Weather Bureau, Northern Hemisphere Data Tabulations and in National Summary of Climatological Data. Washington, D.C. station has been chosen as nearest to Belmar, New Jersey.

[2] Values of T_m and L_m are not accurately known, especially in the free atmosphere. Experimental tests of Taylor's hypothesis (Monin & Yaglom, 1967) show that $L_m \simeq 1$ km in the planetary boundary layer. Some authors (Pinus, 1964; Kao & Woods, 1964) use this hypothesis up to $L \sim 50$ km in the free atmosphere.

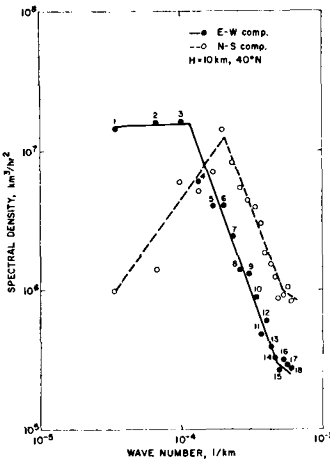

Fig. 2. Spectral density of E–W (solid circles and line) and N–S (open circles and dashed line) geostrophic wind components as revealed by wave number analysis along the 40° N parallel at 10 km altitude (after Benton & Kahn, 1958). Numbers 1–18 indicate wave numbers along the parallel.

not available from observations; however, reasonable estimates of energy propagation can be made from simple models of the atmoshere (Yeh, 1949).

The simplest atmosphere model i.e. a barotropic layer bounded above and below by flat rigid surfaces, contains periodic wave solutions identical to Rossby waves. While the agreement of the model with wave movement in the atmosphere is good for large wave numbers, its agreement for small wave numbers is poor because it incorrectly indicates rapid upstream propagation.

A more reasonable simulation of long waves can be achieved (Dr. J. B. Hovermale, private communication) with a barotropic model whose upper surface has freedom of movement. Even better agreement is possible when this free surface is capped by a quiescent layer. The model in effect simulates a barotropic troposphere under the modifying buoyancy effect of a less dense stratosphere.

Periodic solutions in this model can be characterized by wave velocities, C, of the form

$$C = \bar{U} + \frac{\beta + \alpha^2 U}{k^2 + \alpha^2} \tag{3}$$

The new symbols above are defined by

$$\beta = \frac{\partial f}{\partial y} \text{ and } \alpha^2 = f^2 \varrho_0/(\varrho_0 - \varrho_1)\, gH$$

where f is the Coriolis parameter, ϱ_1 and ϱ_0 are the densities of the upper and lower layers respectively, g is the acceleration due to gravity and H is the mean depth of the lower layer.

This formula indicates movement at large wave numbers similar to that of Rossby waves. At small wave numbers however, where the Rossby wave becomes unrealistic, the above formula gives a more reasonably answer by stabilizing (slowing down) wave movement.

Since waves represented by (3) are dispersive, individual waves in the system move at different speeds than the energy. The energy carrying or group velocity can be related to wave velocities and scale by the well-known formula

$$C_g = C + k\frac{\partial C}{\partial k} \tag{4}$$

which, applied to (3) gives

$$C_g = \bar{U} + \frac{(\beta + \alpha^2 U)}{(k^2 + \alpha^2)^2}(k^2 - \alpha^2) \tag{5}$$

which, in terms of wave velocity, becomes

$$C_g = \bar{U} + (\bar{U} - C)\frac{(k^2 - \alpha^2)}{(k^2 + \alpha^2)} \tag{6}$$

Thus it is C_g rather than C or $\bar{U}$ that should be most closely related to the movement of energy in the atmosphere. In order to compare $S(k)$ and $S(f)$ for large scales and periods, it is possible to use (2), providing C_g replaces $\bar{U}$.

Equations (5) and (6) are identical if C is given by (3). But if C is determined in other ways, e.g. from observational evidence, (5) and (6) will yield different energy velocities.

Values of group velocities for wave numbers from 1 to 18 have been computed using C as given by (3) ($C_g^{(2)}$ in Table 1) and using C as revealed by observations of Astling *et al.* (1962) ($C_g^{(1)}$ in Table 1).

One can try to compare these theoretical values of group velocity with empirical evidence taking into account the observation that the spectra in Figs. 1 and 2 have two corresponding points. The first is the intersection of the E–W and the N–S curves on both graphs, which

Table 1. *Dependence of energy propagation velocities on wave number*

See text for explanation

Wave no.[a]	Wavelength $\times 10^3$ km	$C_g^{(1)}$ m/sec	$C_g^{(2)}$ m/sec	C_{BF} m/sec
1	30	−1.7	−21.5	5.5
2	15	7.6	−2.0	5.5
3	10	13.5	11.9	5.5
4	7.5	18.1	18.7	5.5
5	6	20.2	21.2	10
6	5	20.4	21.7	13.5
7	4.3	20.1	21.4	16
8	3.7	21.8	20.8	17.5
9	3.3	21.9	20.2	18.5
10	3	24.7	19.7	19.5
11	2.7	24.5	19.2	20
12	2.5	24.3	18.8	20.5
13	2.3	24.1	18.4	21.0
14	2.1	23.8	18.1	21.5
15	2	23.5	17.9	22.0
16	1.9	23.2	17.6	22.5
17	1.8	22.8	17.4	23.0
18	1.7	22.4	17.3	23.0

[a] With respect to the parallel circle at 40° N.

gives a correspondence between wave number $k \simeq 1.5 \cdot 10^{-4}$ km^{-1} (Fig. 2) and frequency $f \simeq 7 \cdot 10^{-2}$ day^{-1} (Fig. 1) and hence $Cg \simeq 5.5$ m/sec. The other point of reference (not so distinct as the former) is the point of slope change on the right sides of Figs. 1 and 2 which provides a correspondence between $k \simeq 5 \cdot 10^{-4}$ km^{-1} and $f \simeq 1$ day^{-1} and gives us $C_g \simeq 23$ m/sec.

Between those two reference points the values of energy propagation velocity (C_{BF} in Table 1) might be chosen so as to provide the best geometrical fit between the E–W spectrum in Fig. 1 and the E–W spectrum calculated from that of Fig. 2 with (1) and (2), providing C_{BF} replaces $\bar{U}$. Closed and open circles in Fig. 1 show the result of this calculation. Considering the crude method of comparison and the time lapse of over 10 years between the two sets of data, the coincidence of the two kinds of analysis is remarkable.

Roughly the same results could be achieved with $C_g^{(1)}$ or $C_g^{(2)}$ from Table 1, except for the lowest wave numbers. It should be emphasized that the equations (5) and (6) do not account for factors related to the curvature of the earth, so that the indicated wave movement and energy propagation of the largest waves may still be questionable.

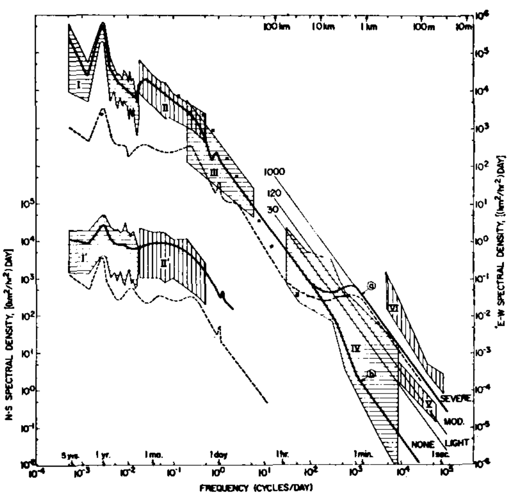

Fig. 3. Average spectra of E–W and N–S wind components (solid lines) in the free atmosphere (see Table 2). Dashed lines are corresponding spectra near the ground (after Van Der Hoven, 1957 and Oort & Taylor, 1969). Solid squares are Mantis' (1963) Lagrangian data.

The conclusion that may be reached from the evidence presented above is that the relationship between space spectra and time spectra of synoptic scale winds is best described in terms of group velocity.[1]

III. Construction of the spectrum

Spectra of atmospheric turbulence from different sources and for different ranges of frequencies have been combined in Fig. 3, with km^2 hr^{-2} day as the basic unit for spectral density and day^{-1} for frequency. The sources and characteristics of the various data plotted schematically as "maximum–minimum" boxes in this figure are listed in Table 2. For the E–W component the available data cover all the periods from 5 years to 1 sec (with the exception of a gap between ~40 min and 4 hours). For the N–S component, only periods from 5 years to 2 days are covered at altitudes from 3 to 20 km (see Table 2). The data of Fig. 1 are used to plot the N–S spectrum up to the 12-hour period.

The solid lines in Fig. 3 are drawn for each component of wind through the mean values of

[1] The comparison of the spectra in Figs. 1 and 2 using theoretical and empirical values of phase velocity C did not show any reasonable matching of the curves.

spectral density in each box. At frequencies higher than 10^2 day^{-1}, the E–W spectral density is split into two branches "*a*" and "*b*". The reason for this will be discussed later.

For the purpose of comparison, the E–W and N–S spectra of winds near the ground are plotted by dashed lines (Van der Hoven, 1957; Oort & Taylor, 1969).

The " $-5/3$" slope lines plotted in the high frequency part of Fig. 3 correspond to values of energy dissipation equal to 30, 120 and 1000 cm^2/sec^3, which approximately separate regions of "no", "light", "moderate", and "severe" turbulence in terms of aircraft bumpiness (Vinnichenko *et al.*, 1968).

From the evidence presented in Fig. 3 we may draw several conclusions:

Table 2. *Power spectra of turbulence in the free atmosphere*

Box no.	Source	Altitudes (km)	Periods covered	Location	Data characteristics	Number of spectra in the box
I, I′	This paper	3, 6, 10, 12 14, 16, 18, 20	1952–1968	Washington, D.C., USA	Monthly averaged rawinsonde winds	8
II, II′	Wan-cheng Chiu, 1959	3, 6, 10, 12 14, 16, 20	1.1.53–30.4.54	Belmar, New Jersey, USA	Daily rawinsonde winds	7
III	Vinnichenko *et al.*, 1968	3, 5, 7, 9, 12, 15, 18	July 1966 January 1967	Kharkov, Ukraine, USSR	2 hour interval rawinsonde winds during each month	14
IV[a]	Vinnichenko *et al.*, 1969	1, 3, 5, 7, 9	July 1966 January 1967	Kharkov Ukraine, USSR	Doppler navigator and hot-wire. IL-18 aircraft	60
V[a]	Mather, 1968	Jet stream level	February 1968	Denver, Colorado, USA	Doppler navigator, pressure and vanes probe. T-33 aircraft	7
VI[a]	Steiner & Rhyne, 1964	5–13 (thunder-storms)	1960–1961	USA	Accelerometer and flow vane probe. T-33 aircraft	5 (inside Cb clouds)

[a] These data represent longitudinal spectra with respect to course of aircraft.

1. There is a strong annual maximum in the spectrum of wind speed in the free atmosphere which is about two orders of magnitude larger than near the ground.

2. The annual maximum, naturally, cannot be associated with a geographic scale, but represents a deep low frequency modulation of relatively small scale turbulence.

3. The energy spectrum reaches saturation at periods of about 1–2 months and at scales of about 5–10 thousand kilometers.

4. The slope of the spectrum at synoptic periods between 2 months and 2–3 days is approximately " -1" with a sharp drop up to the period of 1 day.[1]

5. The mesoscale (periods from 1 day to ~ 10 min) spectrum follows the " $-5/3$" law fairly well.[2]

6. There is generally not enough energy at synoptic and mesoscale wavelengths to cause small scale turbulence hazardous for aircraft if the only source of higher frequency energy is the cascade of energy from synoptic through meso- to microscale wavelengths.

Ogura (1958), using results of Benton & Kahn (1958) showed that wind fields could be considered as quasi two-dimensional and isotropic at scales much larger than an effective thickness of the earth's atmosphere (~ 10 km). This leads to the following relation between the E–W and the N–S spectra at scales less than $5–10 \times 10^3$ km (Fig. 2) and much larger than 10 km:

$$S_{N-S}(k_1) = -k_1 \frac{dS_{E-W}(k_1)}{dk_1} \tag{7}$$

[1] There is not enough evidence that the daily maximum revealed on Figures 3 and 5 really exists in the free atmosphere and is not caused by aliasing of rawinsonde data.

[2] Data derived from superpressure balloon flights (Mantis, 1963) show (solid squares in Fig. 3) that no significant maxima or minima occur in the gap region between 4 hr and ~ 40 min. Mantis' spectrum has a much steeper slope due to the fact that his data represent Lagrangian behavior of turbulence (Inoue, 1951).

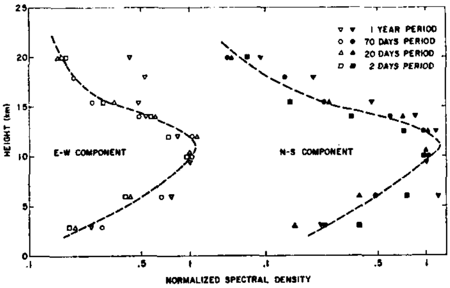

Fig. 4. Height dependence of spectral density at synoptic periods in the free atmosphere.

From Figs. 1 and 3 we can draw the conclusion that two-dimensional isotropy exists in the free atmosphere at periods from ~4–6 days to 10–20 min (see also Mantis, 1963).

At scales much less than 10 km and at periods much shorter than 10 min the flow becomes three-dimensionally isotropic, and the spectral densities of lateral components are 4/3 times larger than those of the longitudinal one (Monin & Yaglom, 1967). Therefore, for practically all scales and periods except the transitional region at scales ~1–~20 km (periods of ~1–~20 min), we can estimate the value of the spectrum of any component of the turbulence by measuring only one of them.

It is of interest to determine whether there is any dependence of spectral density on height at different periods. Fig. 4 shows the height dependence of spectral densities for periods 1 year, 70, 20, and 2 days normalized at 10 km altitude. It is obvious that both the E–W and the N–S components reach maxima of spectral density at 10–12 km. At shorter periods (less than 1 hour) the clear dependence of the spectral density on height is usually not observed during a single aircraft experiment. In contrast, there is clear evidence of a height dependence of aircraft bumpiness probabilities similar to that shown in Fig. 4 (see e.g. Pinus & Shmeter, 1962) assuming that at least a seasonal statistical summary of the CAT bumpiness is provided.

This implies that although there is a more or less distinct relation between energies involved in the climatological and synoptic periods (from 1 year to 2 days), energetics of mesoscale and microscale turbulence (periods shorter than ~40 min) are not necessarily related directly to the energies at longer periods. The most we can say is that the larger the kinetic energy at synoptic scales the larger is the probability of encountering strong microscale turbulence.

This leads us directly to the discussion of an existence of spectral gap at mesoscale in the free atmosphere.

IV. Spectral gap at mesoscale

The existence of the so-called mesometeorological minimum (or gap) in the spectrum of wind speed near the ground was first shown by Panofsky and Van der Hoven (1955) and Van der Hoven (1957). This gap is usually centered on periods of one hour and covers periods from 10–7 hours to 20–5 min (for more complete discussion of gap in the spectra of velocity, temperature, and pressure near the ground see e.g. Monin & Yaglom, 1967).

Until now only occasional data have been available on the existence of mesoscale gaps in the free atmosphere (Mantis, 1963; Reiter & Burns, 1965; Vinnichenko *et al.*, 1968). No definite conclusion could be drawn from these data due to lack of reliable spectral estimates at subsynoptic and synoptic scales. The data in Fig. 3 present an opportunity to discuss this problem.

Fig. 5 shows a replot of the E–W spectra in the free atmosphere and near the ground on a semilogarithmic graph where spectral estimate times frequency is plotted against log of frequency. The numbers on this graph indicate minimum and maximum values of $f \cdot S(f)$ at some periods calculated from the position of upper and lower limits of corresponding "boxes" in Fig. 3 (at periods of ~1 hour and ~1.5 min only maximum values are given as the minimum values are practically zero).

The most important feature of Fig. 5 is that the energy involved in the annual, synoptic and mesoscale variations of wind in the free atmosphere is much larger than that near the ground. For example, the total energy at synoptic scales (periods from ~3 months to ~1 day) near the ground is less than six percent of the total energy at the same scales at altitudes of 6 to 14 km and reaches about 20 percent of the energies at 3 and 20 km.

In contrast, the micrometerological maximum at periods of about 1 min in the free atmosphere is not much larger than the corresponding maximum near the ground in spite of the fact that this maximum is plotted for the case of

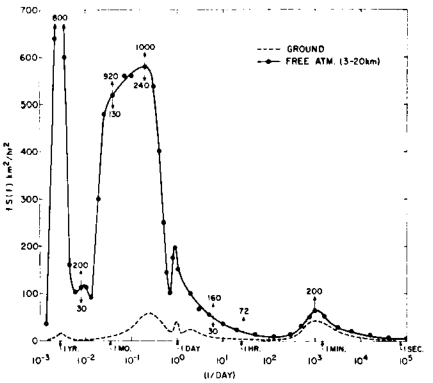

Fig. 5. Average kinetic energy of E–W wind component in the free atmosphere (solid line) and near the ground (dashed line). Numbers indicate maximum values of kinetic energy at particular periods (see Fig. 3).

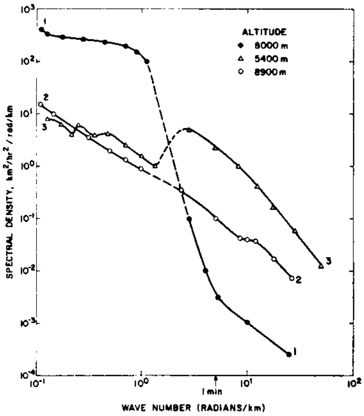

Fig. 6. Three types of transition zones between meso- and microscale spectra in the free atmosphere.

vrey severe turbulence with $\varepsilon \sim 1000$ cm^2/sec^3 (see Fig. 3, branch "*a*"). Therefore, we can say that in the free atmosphere the energy involved in the microturbulence process is insignificant compared with energetics of synoptic scales.

But even this relatively small microscale maximum does not exist all the time in the free atmosphere. The three kinds of spectra which are typically observed in the transitional region between meso- and microscale are shown in Fig. 6 (Vinnichenko *et al.*, 1968). These composite longitudinal wind spectra obtained in the upper troposphere simultaneously cover the mesoscale (wave numbers $\leqslant 1$ rad/km) and the microscale (wave numbers $\geqslant 3$ rad/km). Spectra similar in shape to No. 1 are the most frequent and usually correspond to smooth flight conditions. The main feature of this kind of spectrum is a sharp decay of energy between meso- and microscale with a slope of -2 to -3 and a region of very weak microturbulence with a $-5/3$ slope. Spectrum No. 1 has unusually large energy at mesoscale which shows once more that there is no direct connection between energy of two-dimensional flow and three-dimensional turbulence.

Spectra similar to No. 2 usually correspond to "none-light" bumpiness of aircraft and have a $-5/3$ slope through the whole meso- and microscale region without any gap in between.

Spectra of No. 3 type are fairly rare and have enough energy at microscale to cause serious effects for aircraft. These spectra usually have a gap between meso- and microscale. Thus, the probability of gap occurrence in the cloudless atmosphere should correspond approximately to the probability of aircraft bumpiness which is less than 20% for light turbulence, less than 7% for moderate and less than 0.5% for severe bumpiness (Colson, 1968).

Therefore, returning to Fig. 3, we would say that in the free atmosphere the spectral density curve is usually similar to branch "*b*" without any gap and only in relatively rare occasions when wind shear and stability are favorable for the breakdown of mesoscale motion, does the spectrum display a gap (branch "*a*", Fig. 3).[1]

If we extrapolate the mesoscale part of the spectrum in Fig. 3 starting from 10^2 day^{-1} into the high frequency region following a "$-5/3$" law, we would find $\varepsilon \sim 5$ cm^2/sec^3. Assuming that this value is valid in the upper troposphere and lower stratosphere (8–14 km), we can estimate that the energy dissipation in this region is about 1.2 watt/m^2, which is in fairly good agreement with results of Panofsky & Trout (1968), and those of Kung (1966) obtained using independent methods.

This shows that on an average over several synoptic periods or scales the free atmosphere maintains a constant rate of energy dissipation

[1] Recently Goldman (1968) repeated Van der Hoven's experiment on the 177 m tower in Oklahoma and did not find a gap in the spectrum covering periods from 20 hrs to 2 min. This indicates that even in boundary layer the mesoscale gap is not a permanent feature of the spectrum. It is worth noting here that high frequency part of Van der Hoven's spectrum was measured under hurricane conditions.

by the cascade mechanism of energy transfer to the high frequency end of the spectrum. But at particular locations and times, the instantaneous energy dissipation could vary from a fraction of 1 cm^2/sec^3 to several thousands, depending on the actual wind and temperature stratification.

V. Conlusion

Analysis of aerological and aircraft data on turbulence in the free atmosphere over a wide range of scales permitted construction of an energy spectrum covering periods from ~ 5 years to ~ 1 sec.

This spectrum reveals a strong synoptic maximum (at periods from ~ 2 months to ~ 1 day) deeply modulated by annual variations.

It is shown that frequency spectrum at one station is consistent with a wave number analysis along a parallel circle.

Spectral density values at long periods (more than 2 days) depend strongly on height with a maximum at 10–12 km for both E–W and N–S components.

The micrometeorological maximum is not a permanent feature of the spectrum and the probability of its occurrence in clear skies is less than 30%.

Mesoscale variations in the free atmosphere contain much more energy than those near the ground (presumably due to internal gravity waves). Therefore even if a microscale maximum exists it is not separated from synoptic motions by as deep and wide a gap at mesoscale as it is near the ground.

Most of the time the development of three-dimensional microturbulence is supressed by strong stability of the free atmosphere and the total high frequency energy is negligibly small.

On the average the total energy dissipation in the free atmosphere at altitudes 8–14 km equals about 1 $watt/m^2$.

This study shows once more an urgent need for theoretical and experimental investigation of the processes and conditions leading to generation of small-scale turbulence by instability of quasi two-dimensional mesoscale flow.

ACKNOWLEDGMENTS

This paper was prepared during an extended visit at the Department of Meteorology, The Pennsylvania State University. During that time, the author benefitted from the advice and wisdom of Profs. H. A. Panofsky and A. K. Blackadar, and from his collaborative work with Profs. J. A. Dutton and J. B. Hovermale. The hospitality of the entire department was a considerable encouragement to scientific endeavors.

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СПЕКТР КИНЕТИЧЕСКОЙ ЭНЕРГИИ В СВОБОДНОЙ АТМОСФЕРЕ ДЛЯ ПЕРИОДОВ ОТ 1 СЕКУНДЫ ДО 5 ЛЕТ

Из радиозондовых и самолетных данных, полученных в США и СССР, построен энергетический спектр скорости ветра для высот от 3 до 20 км. Большая часть наблюдений концентрируется вблизи 40° с. ш. и покрывает периоды от 1 секунды до 1 года. Спектр подразделяется на три основных области, разделенных провалами: резкий годовой максимум, синоптический (или макромасштабный) максимум на периодах от 1–2 месяцев до 3–4 дней и микромасштабный максимум с периодами 1–3 минут. Показано, что микромасштабный максимум не является постоянной особенностью спектра. Обычно высокочастотная турбулентность подавлена устойчивой стратификацией в свободной атмосфере и ее интенсивность пренебрежимо мала. Спектры в свободной атмосфере сравниваются со спектрами вблизи поверхности. Делается попытка связать частотные и пространственные спектры для синоптических масштабов.