From Atkinson
Meso-Scale Atmospheric Circulations

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The Meso-scale

I. Introduction

Most meteorologists agree that a major problem in atmospheric science is the full explanation of atmospheric motion. This problem has confronted physical scientists for over three centuries and even today is not fully solved. Over these centuries the general atmospheric circulation has been shown to be exceedingly complicated and indeed the complexity seems to increase with every new massive observational onslaught on the atmosphere. In the face of such complexity it is perhaps natural that meteorologists have attempted to "break down" the global atmosphere into parts that may be more easily examined and understood. These "parts" are frequently known as "motion systems", configurations of motion which have different sizes and lifetimes—or alternatively different scales. This appreciation of scale soon became recognized as vital to any real understanding of atmospheric circulation. It is fundamental to the contents of this book and the remainder of this chapter reviews the scale concept in the light of both observational and theoretical evidence, with particular reference to the meaning of the traditional threefold classification of macro-, meso- and micro-scales. Space scales and time scales are described in terms of wavelengths and periods respectively. Thus the "wavelength" is the average distance from one updraught to the next updraught, or from one high pressure centre to the next. Similarly, the "period" is the average time from one gust to the next gust, or from one temperature maximum to the next.

II. Observation

The most immediately obvious air movements are those that make themselves felt to the individual, whether it be in the observation of curling cigarette smoke or in the risk of being blown over by a strong wind. Such movements are generally recognized by meteorologists to be of "micro-scale", with characteristic dimensions ranging from millimetres to hundreds of metres. More familiar meteorological features such as cumuliform clouds and valley fogs have come to be known as "local" phenomena, with characteristic dimensions of a few kilometres. The introduction of instruments, and more particularly, networks of instruments, allowed the identification of larger motion systems, notably cyclones and anticyclones. Such systems have characteristic horizontal dimensions of over at least 1000 km and are known as "synoptic scale" systems. Many meteorologists recognize a yet larger type of system, typified by the Rossby wave, with characteristic horizontal dimensions of 3000–6000 km.

Appreciation of the above hierarchy of motion systems was consolidated in the period 1920–50. In the first of those three decades the Bergen school of meteorologists presented its classical model of the synoptic scale, frontal cyclone (Bjerknes and Solberg, 1921, 1922). At the same time micro-scale motions came under close scrutiny with the opening of the British Chemical Defence Establishment (CDE) near Porton Down, Wiltshire, UK. One of the important projects of CDE was to increase our understanding of diffusion mechanisms in the atmosphere and largely under this stimulus the foundations of micro-meteorology were laid. The emphasis was upon the diffusion of particles or gases over distances of the order of tens of metres and consequently much of the research was directed towards the nature of small scale turbulence. Since the initiation of CDE effort, many institutions in many countries have become interested in turbulence in its own right as a vital mechanism in transferring heat, water and momentum within the atmosphere and between the earth and atmosphere. The theory and practice of micro-meteorology up to 1950 was well summarized by Sutton (1953) and Pasquill (1974) has covered developments since that date.

At the other extreme, the planetary waves, so brilliantly analysed by Rossby (1939, 1940), were at last clearly revealed in the 1940s. Rossby's work, together with that of Sutcliffe (1938, 1947), Bjerknes and Holmboe (1944) and Eady (1949) elucidated some of the links between the planetary waves and the smaller cyclones and anticyclones. By 1950 meteorology had the scientific and technological knowledge to sketch an initial description and dynamical understanding of the large scale flows in the mid-latitude atmosphere.

In contrast to the major developments outlined above, "local" studies changed little in both their number and character. They remained essentially observational boundary-layer studies, usually over areas extending horizontally for no more than a few kilometres: typical topics of interest were frost hollows and urban areas (the latter particularly in central Europe). The main reason for this interest in the boundary layer at the expense of small scale, free atmospheric circulations was probably the ease of observing the former when compared with the latter. So, although meteorologists prior to 1950 were aware that many local or slightly larger scale features, other than those in the boundary layer, awaited their full attention, they were largely prevented from analysing them for want of the appropriate observational tools. After 1950 such tools became available.

Within the last 30 years four new methods of observation have facilitated the identification and analysis of motion systems of a size between the large, or macro-scale, and the small, or local and micro-scale, i.e. the middle, or meso-scale. The four new tools are radar, instrumented aircraft, satellites and very dense, surface instrumental networks. Of these, satellites are the most recent and probably the least useful. In contrast, weather radars became available shortly after World War II and, despite their early crudity for meteorological purposes, immediately made accessible to analysis precisely those systems that were beyond the reach of pre-War meteorologists. In a review of the achievements of and prospects for radar in meteorology Ligda (1951, p. 1281) wrote:

> It is anticipated that radar will provide useful information concerning the structure and behaviour of that portion of the atmosphere which is not covered by either micro- or synoptic meteorological studies. We have already observed with radar that precipitation formations which are undoubtedly of significance occur on a scale too gross to be observed from a single station, yet too small to appear even on sectional synoptic charts. Phenomena of this size might well be designated meso-meteorological.

By 1953 Swingle and Rosenberg (1953) used the adjective in the title of a paper given at the first weather radar conference and by the mid-1950s the prefix "meso-" was well established, replacing "micro-" as used by Fujita (1951) in what was essentially a meso-scale study.

The accumulation of evidence from radars and special surface observational networks, particularly from the Severe Local Storms Unit of the US Weather Bureau (the forerunner of today's National Oceanic and Atmospheric Administration), clearly substantiated Ligda's claim, leading to the production of a handbook on meso-analysis by Fujita, Newstein and Tepper (1956). This was followed up by Tepper (1959) who spelled out to a wider public the importance of "Meso meteorology—the link between macroscale atmospheric motions and local weather", to quote the title of his paper. He appreciated that his threefold division (see Table 1(a)) into macro-meso- and micro-scale was somewhat crude, and indeed to some extent arbitrary, but found it convenient to make his point that (Tepper, 1959, p. 57) "the emphasis on the larger scale motions and the deliberate disregard of the smaller scale motions has become well ingrained among meteorologists". With direct reference to the work of Sutcliffe and Charney, Tepper claimed that motions smaller than macro-scale are not "meteorologically insignificant" nor "meteorological noise". Rather, they are vital to the local forecaster and probably to the flow of energy within the whole circulation of the atmosphere. Tepper's words are rather harsh if applied to today's forecasting techniques. The smaller scale motions are not "deliberately disregarded" in current numerical forecast models: even if they are not dealt with explicitly, their effects are represented in various ways. Nevertheless two decades ago Tepper's point had some validity and five years later, in a Presidential Address to the Royal Meteorological Society, Sawyer (1964) reiterated the case, particularly in the context of severe convective storms, in a masterly appraisal of meteorological analytical techniques on all scales. In many subsequent articles the essence of Tepper's threefold subdivision reappeared, exemplified by Fiedler and Panofsky's (1970) results shown in Table 1(b).

Table 1 Three scales of atmospheric motion

Scale	Macro-	Meso-	Local
(a) Characteristic dimension (km)†‡	>483	16–160	<8
Scale	**Synoptic**	**Meso-**	**Micro-**
(b) Period (h)§	>48	1–48	<1
Wavelength (km)§	>500	20–500	<20

† *Note:* Dimensions have been converted from non-metric units.
‡ *Source:* Tepper (1959).
§ *Source:* Fiedler and Panofsky (1970).

The somewhat arbitrary "feel" for a threefold division of scale of atmospheric motion has been further investigated by the methods of spectral analysis (see Panofsky, 1955). The spectrum measures the distribution of variance of a variable over wavelengths or periods. If the variable is a velocity component, the spectrum also describes the distribution of kinetic energy over wavelengths or periods. Two types of spectra are useful: space spectra and time spectra. In the first case observations are made at many places simultaneously, or nearly so; the spectrum (or power density) is then plotted as a function of wavelength, or its reciprocal, the wave number. In the second case, observations are made at a point, at frequent intervals, and the spectrum is plotted as a function of period, or its reciprocal, the frequency. If large ranges of period or wavelength are to be considered, it is convenient to plot period or wavelength as abscissa on a logarithmic scale, from right to left, and the ratio of the computed spectrum to period or wavelength as ordinate (Fig. 1). In this case, the area under the curve between two periods or wavelengths represents the variance contributed by the interval between these periods or wavelengths to the total variance. In the schematic Fig. 1, most of the variance is due to fluctuations with periods between 10 s and 1000 s or between 12 h and 100 days; but very little of the variance comes from between 1000 s and 12 h.

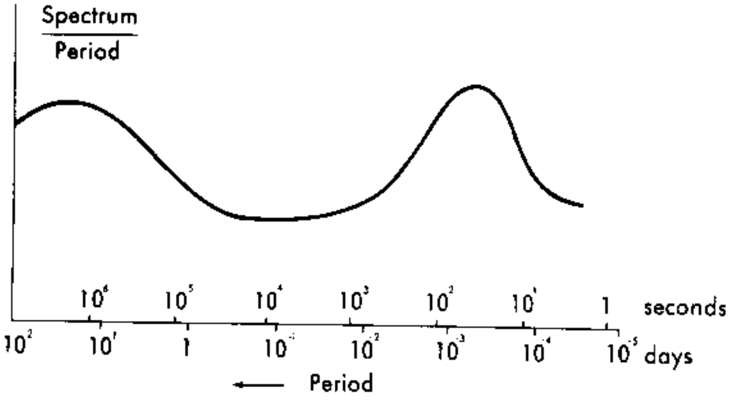

FIG. 1. Schematic frequency spectrum. (After Fiedler and Panofsky, 1970.)

Time spectra and space spectra are not independent of each other. Frequently, particularly for the smaller scales, it is possible to interpret variations at a point as a function of time by assuming that a pattern varying in space is moving past the observer with a known velocity, say c. Then the periods in the time spectrum are given by the wavelengths in the space spectrum divided by c. For the smaller scales, the speed c is essentially the wind speed.

With the aid of spectral analysis, van der Hoven (1957) appeared to provide substantial observational support for the threefold scale division. He produced a variance spectrum of horizontal wind speed in the frequency range from 0.0007 to 900 cycles per hour (periods of 2 months to 4 s) which showed two main peaks, one at periods of 3–4 days and one at periods of a few seconds separated by a minimum of variance at periods from 10 min to 5 h. This result appeared to confirm those of the earlier paper by Panofsky and van der Hoven (1955) which had paid particular attention to meso-scale periods and associated wavelengths. Van der Hoven produced six more spectra from different locations, all revealing a minimum of variance at the same order of magnitude of period. As the variance of wind speed is proportional to the kinetic energy of the speed fluctuations, van der Hoven (1957, p. 162) concluded that "the lack of physical process which could support eddy energy in the atmosphere is ... the reason for the spectral gap in this range". This conclusion led to the construction of many spectra in later years in an attempt to establish the existence or otherwise of the so-called

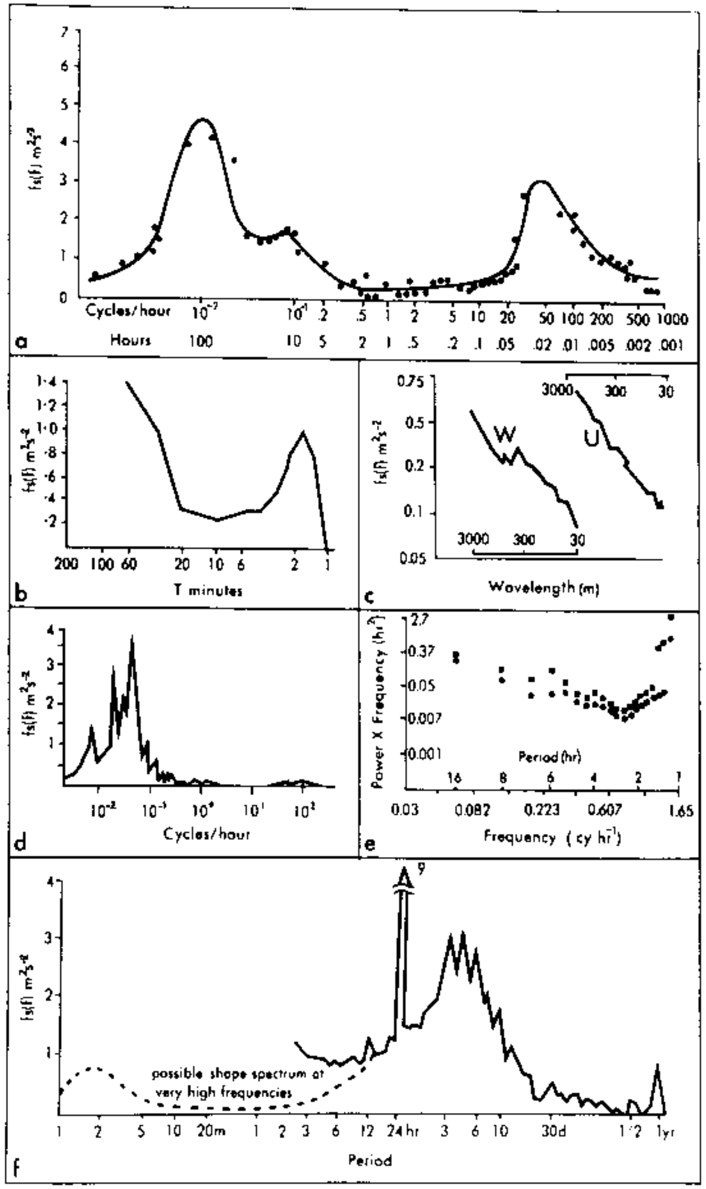

FIG. 2. Typical spectra of horizontal wind speed that show a "gap". (a) Brookhaven National Laboratory at a height of about 100 m. (After van der Hoven, 1957.) (b) Minnesota at a height of about 9 km. (After Mantis, 1963.) (c) Australia at heights between 9 and 11 km. (After Reiter and Burns, 1965.) (d) Oregon at surface. (After Frye *et al.*, 1972.) (e) Nevada at height of about 450 m—data from both a tower and radar-tracked balloons. (After Cornett and Brundidge, 1970.) (f) Maine at surface. (After Oort and Taylor, 1969.)

"spectral gap". Support for van der Hoven's results appears in papers by Mantis (1963), Reiter and Burns (1965), Oort and Taylor (1969), Cornett and Brundidge (1970), Hess and Clarke (1973), Smedman-Hogström and Hogström (1975) and Frye *et al.* (1972) (Fig. 2). Although these spectra were taken in different parts of the atmosphere in different conditions, each one contains a suggestion of a minimum of energy density on time scales from 10 min to 1 day and space scales from 5 to 150 km or so, depending upon whether frequency or wave number was used for the construction of the spectrum.

In direct contrast, Goldman (1968) refuted the results of van der Hoven, claiming that the maximum of energy at high frequencies was primarily due to van der Hoven's use of data collected in hurricane conditions. Goldman's carefully collected data from a tower in Oklahoma suggested that the

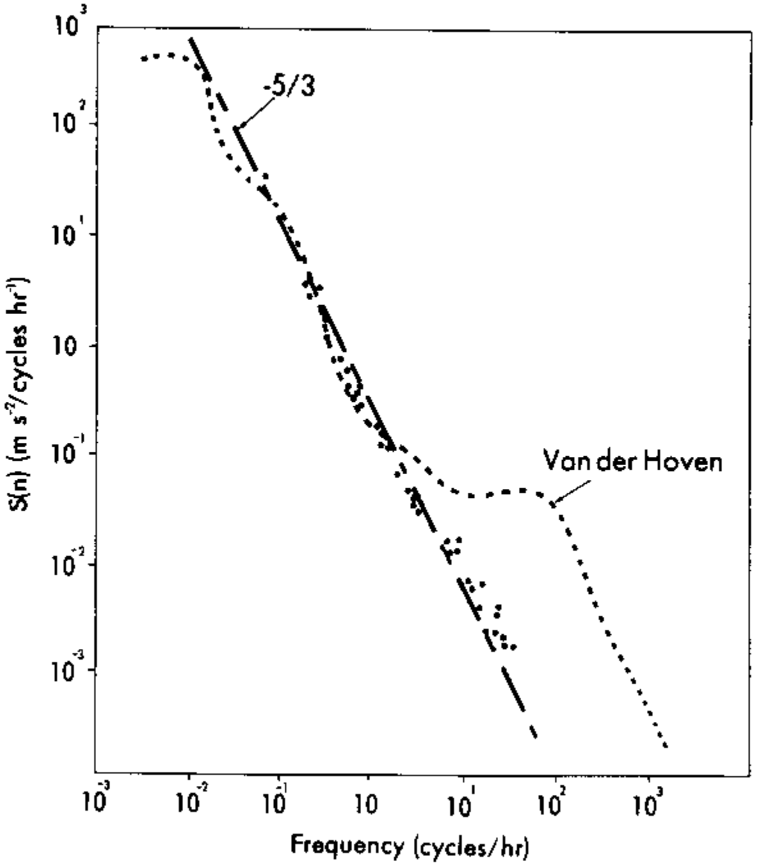

FIG. 3. Spectrum of horizontal wind speed—Oklahoma at height of 177 m. (After Goldman, 1968.)

variance curve follows the "$-5/3$ power law" predicted by Kolmogorov (1941) (Fig. 3). Further observational evidence to support Goldman's results was provided by Kao and Woods (1964), Pinus *et al.* (1967), Hseuh (1968), Hwang (1970), Vinnichenko and Dutton (1969) and Vinnichenko (1970).

Clearly the shape of spectra of both horizontal and vertical winds is not yet firmly established. Sufficient spectra have now been computed to show that they vary with location, season of the year, altitude, synoptic situation and values of indicative parameters such as the Richardson number. Vinnichenko (1970) combined several spectra in a further attempt to summarize the energy distribution of the atmosphere (Fig. 4) and he recognized the difference of opinion about the gap. Figure 4 illustrates the spectrum on both a log–log plot (Fig. 4(a)) and semi-log plot (Fig. 4(b)), the latter showing only that spectrum involving curve a in Fig. 4(a). The energy density of the mean wind in the free atmosphere is about two orders of magnitude larger than near the ground. In contrast to that in the free atmosphere, the energy density of micro-scale turbulence is small in all parts of the atmosphere. The meso-scale variations in the free atmosphere contain much more energy than variations near the ground so that, even if a micro-scale maximum exists, it is not separated from synoptic motions by so deep and wide a meso-scale gap as occurs near the ground.

It is tempting to believe wholeheartedly in the spectral gap as it so conveniently divides the atmosphere into three types of motion, depending on different types of dynamics dominant at the three scales: in particular, synoptic scales (quasi-geostrophic and hydrostatic), local and micro-scale (non-geostrophic, non-hydrostatic and turbulent) and meso-scale (non-geostrophic and hydrostatic). From another viewpoint, "the synoptic scales represent the scales of horizontal heterogeneities in radiation and the micro-scales represent the scales of the vertical heterogeneities of the temperature and wind fields" (Panofsky, 1969, p. 1101). But two closely associated changes of thinking have occurred since van der Hoven concluded that the meso-scale gap was empty for lack of suitably sized atmospheric circulations to fill it. First, in an analysis of the spectral distribution of energy and atmospheric predictability, Robinson (1967, p. 417) noted: "...I find unconvincing the argument that disturbances on scales between the cyclone and the thunderstorm do not exist because we do not regularly see them on synoptic charts". Robinson saw meso-scale circulations as a vital link in the atmospheric energy cascade from very large to very small scales. Second, Robinson made the important point that most spectra, rather than displaying an anomalous minimum in the meso-scale range, display an anomalous maximum in the micro-scale range. This apparently simple, yet fundamentally different mode of thought was soon appreciated in the literature. As mentioned earlier, Goldman (1968) could find no "hump" and therefore no gap, but Bretherton (1969) recognized that gaps do appear, as shown above, in certain types of

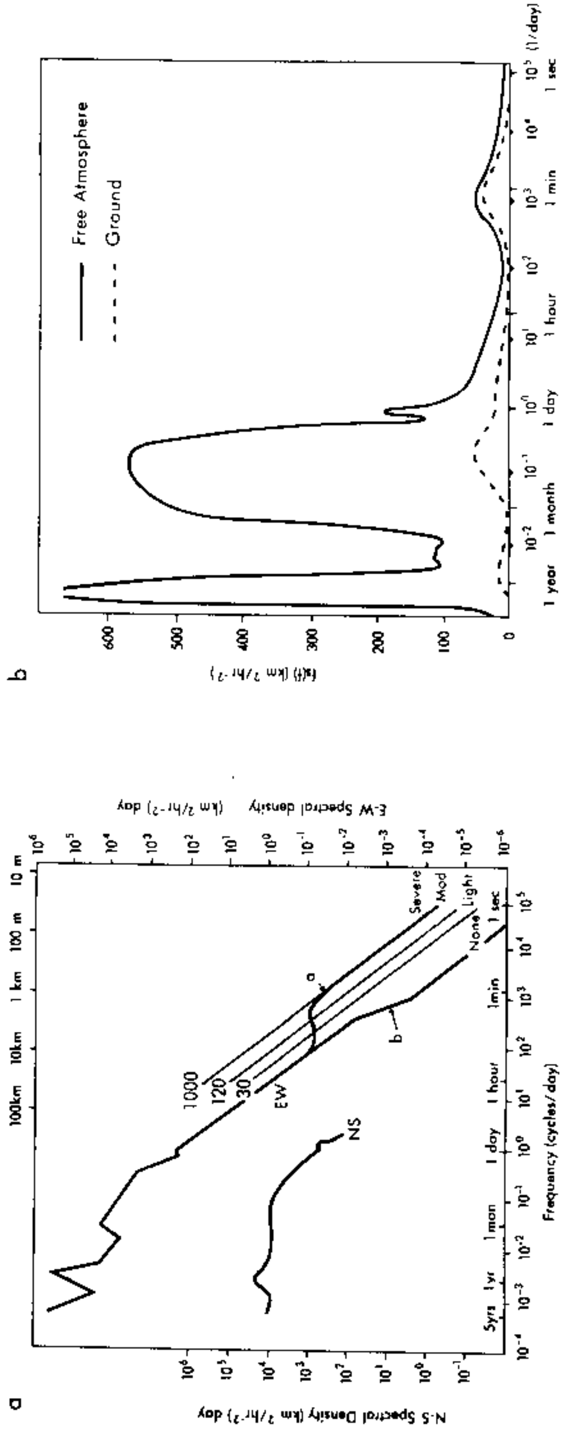

FIG. 4. (a) Log–log plot of spectra of zonal (E–W) and meridional (N–S) atmospheric motion in upper troposphere. Note that the scales for zonal and meridional flow are offset. The lines with a slope $-5/3$ shown in the high frequency part of the spectrum correspond to values of energy dissipation rate equal to 30, 120 and 1000 $\mathrm{cm^2\,s^{-3}}$, which give approximate separations between regions of "no", "light", "moderate" and "severe turbulence" as generally reported on basis of reactions of aircraft encountering turbulence. (After Vinnichenko, 1970.)
(b) Semi-log plot of curve a of zonal flow part (a). Solid line, free atmosphere from 3 to 20 km; dashed line, near the ground. (After Vinnichenko, 1970.)