4.2A THE MST RADAR TECHNIQUE: A TOOL FOR INVESTIGATIONS OF TURBULENCE SPECTRA

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INTRODUCTION

The MST radar technique has vastly improved our ability to measure turbulence spectra and turbulence intensity at all altitudes between the ground and the thermosphere, particularly at temporal scales characteristic of mesoscale motions. The only limitations have been the height resolution of the order of a hundred meters and the time resolution of the order of a minute. However, the instrument is still far superior to any other instrument used for this purpose in measuring frequency power spectra.

POWER SPECTRAL MEASUREMENTS

As an example, the Poker Flat radar has provided a data set that can be used to study turbulence at periods from a few minutes to several years at altitudes in the troposphere, stratosphere, and mesosphere. The only limitation of the technique is that since the radars are not scanning radars, velocity profiles are measured as a function of time and provide only frequency spectra. The frequency spectra then have to be related in some way to the wave number spectra since most of the theoretical results relate to wave number spectra and do not make any direct predictions about frequency spectra. Also, none of the spectra of the thermodynamic variables can be measured with the radar, but, on the other hand, vertical velocity spectra can be investigated, and that is difficult to do with any other instrument.

So far, only a few studies of turbulence spectra have been carried out using the radar data. LARSEN et al. (1982) calculated the frequency power spectra for 40 days of data from the Poker Flat, Alaska, MST radar. The height range covered was from 3.79- to 14.99-km altitude. The results showed that on the average, the spectral slope over that height range was -1.60 ± 0.24, very close to $-5/3$. BALSLEY and CARTER (1982) used a much longer time series from the same radar for both tropospheric and mesospheric winds. The much longer time series allowed a large number of spectra for shorter time frames to be composited in order to get a better estimate of the spectral slope. The details of how the spectra were produced are given in their paper. The resulting frequency power spectra at both 8- and 86-km altitude deviate very little from the $f^{-5/3}$ power law.

There have been a number of observations using other types of instruments that also found a $-5/3$ spectral power law at scales typical of the mesoscale. GAGE (1979) summarizes much of the observational evidence available at the time of his paper. LARSEN et al. (1982) cite further studies with similar results.

CHARACTERISTICS OF STRATOSPHERIC TURBULENCE

A different approach to the study of turbulence has been that of Dr. R. F. Woodman, formerly of the Arecibo Observatory in Puerto Rico. Together with Drs. T. Sato and P. Rastogi, he has been interested primarily in the frequency of occurrence of turbulent layers in the stratosphere. It has been known at least since the HICAT studies (LILLY et al., 1974) that turbulence in the stratosphere occurs in thin layers. HICAT involved turbulence measurements made with U2 aircraft. The 430-MHz radar at the Arecibo Observatory is capable of making observations with a height resolution of 300 m. The resolution is sufficiently good and the distribution of layers is such that generally only a single layer will be found within the sampling volume. The thickness of the layers is usually much less than the thickness of the sampling volume. The echo strengths can be used to study the frequency of occurrence of the layers and how they move as a function of time. Also, information on the distribution of layer thicknesses can be obtained (RASTOGI and WOODMAN, 1983).

WOODMAN et al. (1981) and RASTOGI and WOODMAN (1983) have used the data to investigate the effectiveness of stratospheric turbulent layers in mixing and transport processes. Calculations of the magnitude of the diffusion coefficient based on this approach have yielded values that are larger, perhaps by as much as an order of magnitude, than the values estimated originally by LILLY et al. (1974) based on HICAT data. The values derived from the new approach are in fact closer to the values needed to explain stratospheric residence times if large-scale circulation effects are neglected. However, the measured residence times have been attributed to large-scale transport processes in the past rather than diffusion. If diffusion really is more effective than had originally been thought, then how do we explain the role of the large-scale transport processes since they are also thought to be important? There is much room for more investigations of these problems, and the radar measurements will likely be a valuable tool.

TWO-DIMENSIONAL TURBULENCE VS. A UNIVERSAL SPECTRUM

Although it is generally agreed that the spectral slope of mesoscale horizontal velocity fluctuations lies near -5/3, the interpretation of the significance of this fact is far from resolved. GAGE (1979) summarized the data from various sources indicating the existence of a -5/3 slope. He then argued, based on scaling arguments, that mesoscale motions are more likely to be associated with a two-dimensional inertial subrange rather than a three-dimensional inertial subrange. The most important implication of two-dimensionally rather than three-dimensionally is that there is a reverse cascade of energy from small scales to large scales, the so-called red cascade as opposed to the blue cascade.

LILLY (1983) became interested in the problem and dealt more directly with the problem of where the energy sources for the cascade are located. He was also able to show that two-dimensional turbulence can exist in the presence of gravity waves and other three-dimensional structures. LILLY (1983) postulated that the source of energy is associated with convection, shear instabilities, mountain waves, and other small-scale dynamic structures. Although most of the energy from such a process will decay towards smaller scales, a small fraction of the energy may be able to reach larger scales to become part of a red cascade process. He estimated that even as little as 5-10% of the energy generated in this way would be enough to have a significant effect on mesoscale variance spectra. The general physical process proposed by LILLY (1983) is described in this way, but he also points out that there may be competing processes involved.

An alternative interpretation of the observed spectra was proposed by VANZANDT (1982). In his view, the -5/3 slope is only significant in that it represents the existence of a universal spectrum in analogy to the universal spectrum that has been found to exist in the oceans. The GARRETT-MUNK (1975) spectrum is an empirically derived description of the frequency spectra measured in the oceans, and the empirical spectrum has been found to fit the measurements made at a wide variety of locations and under a wide variety of conditions. Thus, it is really appropriate to characterize the spectrum as being universal.

Since the model is empirical, the physical basis for the model is not immediately evident. However, there is general agreement that in the oceans the spectrum is the result of a steady interaction of gravity waves. There is still discussion about the energy flow budget associated with such a spectrum. However, McCOMAS and MULLER (1980) have modeled the interactions of a spectrum of gravity waves, and the study showed that the energy flow was from large to small scales, the same as the energy flow direction in three-dimensional turbulence. See LeBLOND and MYSAK (1978) for a discussion of the dynamics of the GM spectrum.

NEED FOR FUTURE OBSERVATIONS

There are a number of important reasons for resolving the question of which model best represents mesoscale turbulent processes, aside from improving our general understanding of the dynamics of the atmosphere. A reverse energy cascade would create a serious limitation on our ability to make mesoscale forecasts. The implication is that to resolve scales of say a few hundred kilometers, we need to have good information about scales of motion that are much smaller than that.

At this point, I would like to be able to make a very specific list of the observations that are needed to distinguish between the two models. However, this is not possible. I can only describe some general considerations that might be used by anyone who is interested in pursuing the topic in the future.

A -5/3 spectral slope is a strong requirement for the existence of a two-dimensional inertial subrange, and the observations to date do seem to indicate that such a slope is representative of conditions on the average. However, the GM model does not make a prediction of what the slope should be. Therefore, a -5/3 slope is not contradictory to the model, though the slope is closer to -2 in the oceans. Once the spectral slope associated with the horizontal velocity fluctuations is known, the slopes for other quantities such as the vertical velocity, temperature etc., are given by the theory. But, if the atmospheric vertical velocity spectra are found to be consistent with the predictions of the GM model, that in itself does not argue against the existence of two-dimensional turbulence at that scale. Since two-dimensional turbulence theory does not consider vertical variations explicitly, any variability in that direction is incidental to the theory. It is clear that at this point it is not trivial to devise a test of the competing models. It may be that advancements in our understanding of the theory will have to take place first.

Suggestions made to date involve testing the basic premise of the interacting gravity-wave hypothesis. Gravity waves in the ocean are in some sense trapped by the imposed boundaries of the ocean floor and the water surface. Thus, it is possible for the waves to interact over long periods of time to establish a steady-state spectrum. Gravity waves generated in the atmosphere can propagate away vertically to be dissipated in the high atmosphere. It is crucial then to determine what the interaction time is and whether waves are propagating out of the troposphere before the interactions can take place. Another suggestion has been to test the universality of the spectrum in the atmosphere. Of course, if the spectral slope is found to vary to some extent, that would only prove that the interacting gravity-wave spectrum may be overwhelmed by other processes on occasion.

Although LILLY (1983) has proposed a model of two-dimensional mesoscale turbulence with energy flow from small to large scales, he qualifies this viewpoint by noting that if the motions really act as two-dimensional turbulent motions, they will eventually decorrelate in the vertical to the extent that instabilities will arise. The effect of such instabilities would be to reverse the flow of energy, and if such effects are too large, the proposed physical picture could be invalid. If the energy flow reversals associated with instabilities are not too large in magnitude then it may be possible that both processes can coexist.

MESOSCALE GAP

Throughout the last half of the sixties and first half of the seventies, there was another ongoing debate in the literature about the nature of mesoscale turbulence. Specifically, the argument centered on whether or not a gap in the energy spectrum at spatial scales charactertistic of the mesoscale actually exists. It was argued by proponents of the idea that since there are no real sources of energy for mesoscale motions, there should be a gap in the energy spectrum corresponding to those scales. The implication was that there is a clear separation between synoptic scale motions and microscale motions. The most surprising aspect of the argument was that both points of view were apparently supported by observational data. The most recent papers discussing the evidence for the existence of a mesoscale gap in the spectrum of turbulence were published between 1972 and 1975 (FRYE et al., 1972; HESS and CLARKE, 1973; SMEDMAN-HOGSTROM and HOGSTROM, 1975). The arguments and an excellent summary of the literature are presented in the introduction to the book by ATKINSON (1981) on mesoscale meteorology.

Proponents of the no-gap theory claimed that energy should decrease smoothly from large scales to small, as predicted by Kolmogoroff, according to the -5/3 power law, and they showed clear observational evidence of this type of behavior (e.g., VINNICHENKO and DUTTON, 1969; VINNICHENKO, 1970). There is now general agreement that there is no lack of energy at the mesoscale, and indeed, much of the present day research emphasis is on mesoscale motions (see LARSEN (1983) in this volume for further discussion and references).

Part of the "gap" controversy was fueled by a lack of adequate data. The mesoscale has always been the most difficult to observe, especially above the boundary layer. However, improvements in radar technology, instrumented aircraft, and satellites has made it possible to make an increasing number of measurements of turbulence spectra at these scales. The evidence is clearly in favor of the continuous energy distribution rather than the gap theory.

NONUNIVERSAL SPECTRA

The controversy was resolved when it was realized that the spectra that had been interpreted as being supportive of the gap model, in fact, showed an increase in energy above the normal level at small scales. The data used by VAN DER HOVEN (1957) was collected in hurricane conditions and had an energy peak at periods of a few minutes. It was the associated "valley" on the low frequency side of the anomalous peak that had been incorrectly interpreted as evidence of the mesoscale gap.

The arguments for and against the mesoscale gap are less interesting now, but not so the data that was used to support these arguments. There are clearly strong sources of energy at small scales, and the sources are evident in more than a few isolated cases. In fact, the -5/3 slope that has been found in the frequency spectra at different heights and different locations only appears if the mean behavior or the atmosphere is considered. Spectra usually have to be added, averaged, or composited in some way before consistent behavior appears. The oceans appear to be much less variable than the atmosphere in this respect. Anomalous peaks and deviant spectra should be considered along with the effort to improve our understanding of the mean or average turbulence spectra. It is possible that spectra measured at times when strong energy sources are present may hold the key to resolving the question of whether mesoscale turbulence is characterized by a universal gravity-wave spectrum or two-dimensional turbulence.

ACKNOWLEDGEMENTS

The author was supported by the National Aeronautics and Space Administration under grant NAGW 362 and by the National Science Foundation under grant ATM 81-08381.

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