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A first look at wavenumber spectra from GASP data

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ABSTRACT

A preliminary analysis of Global Atmospheric Sampling Program (GASP) data has been made to explore the character of mesoscale atmospheric wavenumber spectra. The results show a $k^{-5/3}$ spectral slope over spatial scales ranging from about 100 km to about 400–700 km. At larger scales there is evidence of a transition to steeper wavenumber dependence. These results are briefly discussed in terms of two-dimensional stratified turbulence and internal waves.

1. Introduction

Since the work of Vinnichenko (1970) and Pinus (1966, 1977) meteorologists have searched for an explanation for the organized appearance of atmospheric spectra at scales beyond the microscale. For scales less than a few hundred meters there is common acceptance that spectra are due to conventional isotropic three-dimensional turbulence as described by the theory of Kolmogoroff (1941). However, for scales greater than a few kilometers, the observed spectra of horizontal velocity also appear to be due to turbulence, although they cannot be turbulent in the classical sense of Kolmogoroff. To date there have been two explanations offered for the behaviour of atmospheric spectra on these larger scales. The first is to invoke the concept of a reverse cascading two-dimensional turbulence (Kraichnan, 1967; Gage, 1979; Lilly, 1983). The second is to invoke the concept of a spectrum of internal waves (Dewan, 1979; VanZandt, 1982). This latter explanation follows in the spirit of Garrett and Munk (1972) in modelling ocean spectra.

The empirical basis for our understanding of atmospheric spectra on the mesoscale is very sketchy. Large-scale frequency spectra are easily obtained from rawinsonde data but they give no information about the mesoscale. Recently, nearly continuous wind measurements have become available which enable the examination of atmospheric spectra over time scales ranging from a few minutes to many days (Balsley and Carter, 1982; Larsen et al., 1982). However, single station measurements do not permit a direct examination of atmospheric wavenumber spectra. The latter have been inferred by assuming the spectra are due to turbulence and applying the Taylor transformation. Brown and Robinson (1979) established the validity of the Taylor transformation for scales in the range 500–1000 km by comparing frequency and wavenumber spectra over Eastern Europe.

In this paper we present wavenumber spectra obtained from an analysis of GASP wind data measured by aircraft. A corresponding analysis of other aircraft data is given by Lilly and Petersen (1983). We make the usual assumption that the airplane speed is large compared to the propagation velocity of the atmospheric disturbances. Comparison of our results with past results, which are mostly transformed frequency spectra over the range of scales from about 50 to 10^3 km permits an evaluation of the Taylor transformation at scales less than about 10^3 km and enables us to construct a tentative picture of the form of the atmospheric wavenumber spectra at mesoscales.

2. The GASP data set

The Global Atmospheric Sampling Program (Perkins, 1976, Papathakos and Briehl, 1981) was conducted by NASA to gather data near the tropopause on minor constituents and meteorological variables. Data were collected automatically on cassette tapes on specially instrumented Boeing 747 aircraft in routine commercial service, with most measurements made between about 9 and 14 km. Wind data were taken from the onboard computer linked with the inertial navigation system and were recorded to the nearest knot (about 0.5 m/s) and degree. These winds have a random error of about 5% of the reported value, due largely to inaccuracies in the true air speed measurement. At high frequencies (of the order of 0.1 Hz or higher) the inertial and aerodynamic response of the aircraft to small wind changes is less than 100%; however, the error due to this effect at frequencies below 0.1 Hz is relatively small compared with the combined uncertainty of the 5% random error and the ± one-half knot recording resolution (R. Kuntzmann, The Boeing Company; personal communication). The winds also have a sinusoidal (Schuler) error of period 84 minutes and random amplitude from 0 to 2.5 m s^{-1}, which arises from electronic tuning of the gyroscopes and accelerometers. The spectra to be presented below show no evidence of this effect.

Data were recorded in two modes. Under normal conditions, recordings were made at 5-minute intervals (about 75 km at 250 m s^{-1} air speed). Data for each flight were processed into segments. Within each segment the airplane altitude did not change more than about 500 m, the tropopause interpolated from NMC gridded data was not crossed, moderate or greater turbulence was not encountered, and the latitude did not change by more than 4 degrees. Segments were retained for analysis only if they were at least 2400 km long. Along each segment thus retained, the zonal and meridional wind components were computed and interpolated with a cubic spline routine to 75 km intervals relative to the ground in preparation for the spectral analysis. About 60% of the segments retained were from west-to-east flights and, due to the length requirement, about 85% of them were from trans-oceanic flights (America to Europe or Asia).

Small-scale data were recorded whenever the plane encountered moderate or greater turbulence, that is, whenever the vertical accelerometer reading was outside the range 0.8 to 1.2 times the acceleration due to gravity. In these cases the system automatically recorded data each 4 seconds (about 1 km at 250 ms^{-1}) until one minute after the last turbulence encounter. Data for each "episode" were used only if the tropopause was not crossed, if the airplane altitude changed by less than about 500 m, and if the episode was more than 17 km long. Lateral and longitudinal wind components relative to the mean over each "episode" were computed and interpolated to 1 km intervals. About 70% of the "episodes" used occurred over the oceans. This is nearly the same as the percentage of total time spent over the oceans by GASP flights, and so shows no obvious bias toward more (or less) occurrence of turbulence over land. For this pilot study, no effort was made to separate "episodes" according to their proximity to mountains, although we note that Pinus (1979) found enhanced wind energy over rough terrain.

The data collection phase of GASP lasted from 1975 to 1979, and all data are available on magnetic tape from the National Climatic Center, Asheville North Carolina. There are over 6900 flights in the GASP data set, made during all seasons and covering a wide variety of latitudes and longitudes. For this pilot study we have used only a few hundred flight segments, selected as described above and limited to the extratropics during fall through early spring (October through April for latitudes $\geq 25°$ N). While there may be seasonal or latitudinal dependencies in the winds' variability, no effort to resolve them has been made yet. All wind data, and temperature and minor constituent data, will be included in a future more complete study.

3. Results of the spectral analysis

The results of the large-scale spectral analysis of winds for October through April for latitudes greater than 25° N are shown in Fig. 1. The flights are distributed evenly among months and about 80% of them are between 30° N and 55° N. These spectra cover wavelengths ranging from 150 km to 4800 km. Zonal and meridional winds are analyzed separately both for the troposphere and for the stratosphere. For each flight, the autocorrelation function (R) was computed for lags 0, 75, ..., 2400 km, and then the cosine transform of R was computed and smoothed using a Hanning filter. The results in Fig. 1 represent the average values of

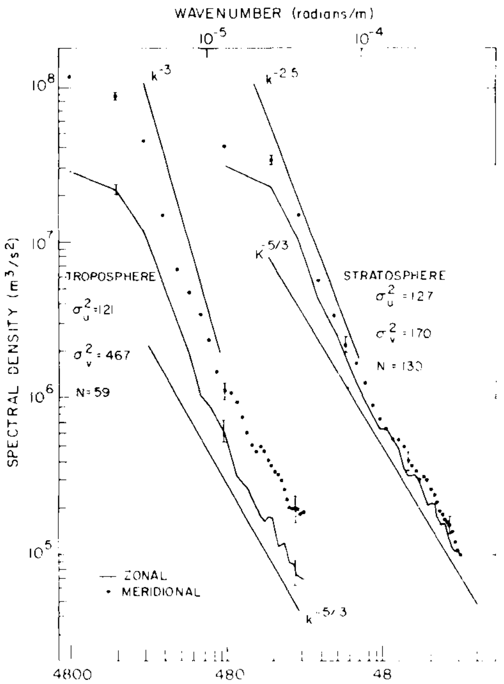

Fig. 1. Kinetic energy spectra from GASP data. Stratospheric spectra are shifted one decade to the right.

all N flights ($N = 50$ in the troposphere and 130 in the stratosphere). The vertical bars that are plotted at a few wavenumbers represent the variability (the standard deviation divided by $N^{1/2}$) of the spectra over the N flights. The relatively lower energy at the longest wavelength (λ) is an artifact due to the smoothing filter used.

The tropospheric spectra are shown on the left of Fig. 1. It is clear that, while the shape of the zonal and meridional spectra are approximately the same, the spectral density of the meridional component exceeds that of the zonal component by a factor of 2 to 4 at all wavenumbers. The total variance (σ^2) of the meridional wind is about 3.8 times that of the zonal wind. In the stratosphere the variance of the zonal wind is nearly the same as in the troposphere, while the meridional winds' variance in the stratosphere is less than half the tropospheric value. The spectral densities given by Lilly and Petersen (1983) are also larger for the meridional component at wavelengths greater than about 300 km, but the difference appears less striking than in Fig. 1. There seem to be several possible explanations for the relatively high spectral densities of the tropospheric meridional wind. First, they may reflect a genuine difference between the stratosphere and troposphere. We checked the repeatability of this feature by analyzing an additional 296 flight segments in the troposphere, chosen using the same criteria as before except the minimum length required was reduced to 1200 km, and obtained results nearly identical to those in Fig. 1 for the troposphere at wavelengths less than about 1200 km. Second, they may reflect a variation with latitude, as the stratospheric flight segments are biased toward higher latitudes relative to the tropospheric flight segments. Or, there may be another explanation. Resolution of this question is clearly beyond the scope of the present pilot study.

In Fig. 1, both zonal and meridional spectra exhibit a change in slope near 500–700 km wavelength. For wavelengths less than about 400–700 km, the data suggest a $-5/3$ slope in all cases, fitting lines by eye. A steeper slope appears appropriate at longer wavelengths (ignoring the values for the longest wavelength). The tropospheric zonal wind spectrum at scales larger than about 400 km and the stratospheric meridional wind spectrum at scales larger than about 700 km suggest a 2.5 slope. The tropospheric meridional wind spectrum at scales larger than 600 km seems to fit a -3 line, and the stratospheric zonal wind spectrum at scales larger than about 500 km seems to fit a -2.2 line. Of course, the slope of the best-fit line depends upon the range of wavelengths chosen for fitting. For example, if one limits attention to λ 800 km (above about the Rossby radius of deformation) and ignores the two longest wavelengths (to insure no filtering effects), then a -3 slope fits all spectra fairly well, which would be consistent with the k^{-3} behaviour predicted for geostrophic turbulence (Charney, 1971). But, this may be fortuitous and perhaps the main point to be drawn at this time from Fig. 1 is simply that the long λ portions of the spectra are steeper than the shorter λ portions.

Average spectra of the small scale winds obtained during turbulence episodes appear in Fig. 2. Here the wind is separated into lateral and longitudinal components relative to the mean wind. Note the variances of the lateral and longitudinal components are comparable in magnitude. Since no significant differences were found between tropo-

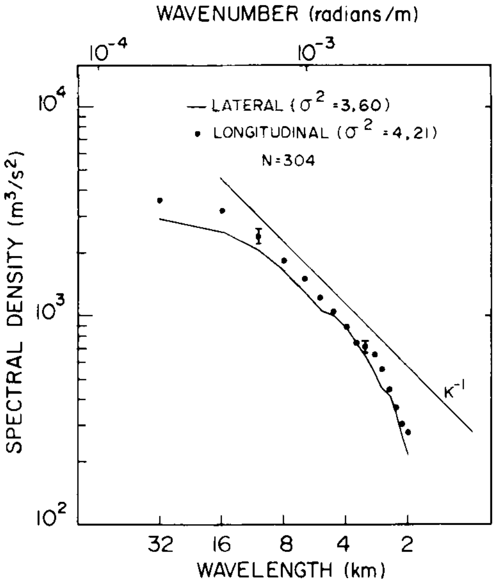

Fig. 2. Kinetic energy spectra from high-resolution GASP data associated with episodes of moderate turbulence.

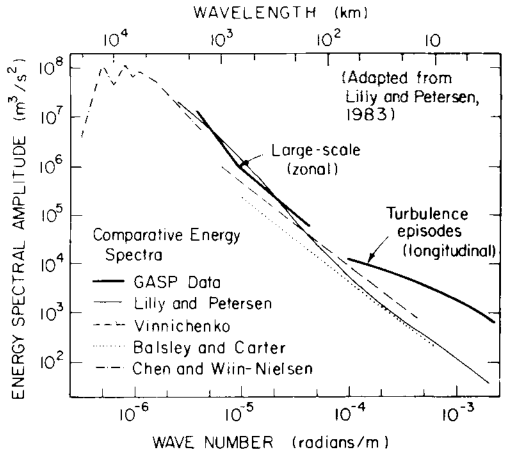

Fig. 3. Composite horizontal energy spectra (adapted from Lilly and Petersen, 1983).

spheric and stratospheric spectra, they have been averaged together.

The spectra of Fig. 2 do not fit any particular overall spectral slope. For λ from about 3 to 10 km, the spectra nearly follow k^{-1} and for λ less than a few kilometers the spectra are closer to k^{-3}. While the lower energy at longest λ is due to the smoothing filter used, the remaining fall-off in slope at the long λ end is perhaps due to relatively lower energy at long λ during moderate turbulence episodes. However, the spectra given by Pinus (1977), which range from 2 km to 50 km in λ and are based on data taken under presumably quiet conditions, also show a decrease in slope at long λ. Thus, explanation of this feature remains uncertain at this time. At the short wavelength end of the spectra the filtering effect of the measurement system (e.g., inertial response of the aircraft and data recording resolution) may contribute to the sharp fall-off in spectral energy for λ less than a few kilometers.

4. Discussion

In this paper we have presented a first look at the wavenumber spectrum of atmospheric motions as deduced from GASP aircraft wind measurements. These wavenumber spectra complement the frequency spectra of Vinnichenko (1970) and Balsley and Carter (1982) and extend to mesoscales the wavenumber spectra reported by Chen and Wiin-Nielsen (1978).

With the aid of the wavenumber spectra presented here it is possible to construct a tentative picture of the atmospheric wavenumber spectra over a wide range of scales. This picture builds upon the conceptual framework of Gage (1979), and Lilly (1983). In Fig. 3 we present a composite spectra (adapted from Lilly and Petersen (1983)) comprising the results of Vinnichenko (1970), Chen and Wiin-Nielsen (1978), Balsley and Carter (1982) and Lilly and Petersen (1983), together with some of the present results. The spectra of Vinnichenko (1970) and Balsley and Carter (1982) have been transferred to the wavenumber domain by use of the Taylor transformation as described by Lilly and Petersen (1983). An advection velocity of 23 m s^{-1} was used to transform the Vinnichenko spectrum and an advection velocity of 10 m s^{-1} was used to transform the Balsley and Carter spectrum.

The composite spectra of Fig. 3 show clearly the demarcation of two different power laws for length scales above and below a transition scale in the range 300–700 km. These spectra clearly show a $k^{-5/3}$ power law dependence for mesoscales and a steeper power law dependence for large-scales. The Lilly and Petersen spectrum shows a transition beginning at a few hundred kilometers while the present results show a transition near 700 km.

The overall spectral shape described above is not inconsistent with the suggestion of Gage (1979) that mesoscale atmospheric spectra are a manifestation of the reverse energy cascading $k^{-5/3}$ inertial range of two-dimensional turbulence (Kraichnan, 1967). Presumably the large-scale spectra are due to the enstrophy cascading inertial range of geostrophic turbulence (Charney, 1971). The enstrophy cascade is associated with large-scale baroclinic instability at low wavenumbers while the reverse energy cascade originates from small scale turbulence, thunderstorms, etc.

Another feature evident in Fig. 3 is the near universality of the spectra. Considering the diverse sources of these spectra, it is remarkable that there is so little scatter. VanZandt (1982) has recently drawn attention to the universal nature of atmospheric spectra.

There has been a long running debate concerning the relative contribution of waves and turbulence to atmospheric spectra (Stewart, 1969) and several suggestions have been made to distinguish between the two kinds of motion. While there are cases when waves are easily distinguished from turbulence (Axford, 1971), the general picture remains confused. For example, the spectral shapes in Fig. 3 can be easily interpreted in terms of turbulence. However, the K_z-spectra of wind and temperature profiles are more easily interpreted in terms of a spectrum of internal waves (VanZandt, 1982).

A recent analysis of Riley et al. (1981) has shown that waves and two-dimensional turbulence are governed by two different sets of equations under conditions of stable stratification. Lilly (1983) has extended these results and argued that waves and turbulence must coexist. Waves can radiate out of the fluid and leave a residual two-dimensional turbulence which he calls stratified turbulence. Lilly shows that only a small amount of the energy in small-scale turbulence needs to cascade to larger scales to explain the mesoscale spectrum of atmospheric motions.

In summary, the spatial spectra based on GASP data help to bridge an important part of the energy spectrum where little data has been available heretofore. Resolution of several important issues, especially an assessment of the relative contributions of turbulence and gravity waves to the observed spectra, remain as key tasks for the future.

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