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Aircraft measurements of atmospheric kinetic energy spectra

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ABSTRACT

Wind velocity data obtained from a jet airliner have been used to construct kinetic energy spectra over the range of wavelengths from 2.5 to 2500 km. The spectra exhibit an approximate −5/3 slope for wavelengths of less than about 150 km, steepening to about −2.2 at larger scales. These results support and extend the measurements of spatial and temporal spectra of Vinnichenko and Dutton (1969), Brown and Robinson (1979), and Balsley and Carter (1982), and are generally consistent with the recent results of Nastrom and Gage (1983).

1. Introduction

The statistical structure of atmospheric variables has been observed and studied rather extensively for large (planetary and synoptic) scales and more selectively for scales of a few kilometers and less. The mesoscale range from a few to about a thousand kilometers in wavelength has been somewhat neglected, due to the scarcity of appropriate measurement techniques. The analysis of kinetic energy spectra by Vinnichenko (1970; see also Vinnichenko and Dutton, 1969, and Vinnichenko et al., 1973) utilized mainly sonde network data for the large scales and aircraft turbulence measurements for smaller scales, with the mesoscale spectra interpolated across the data gap. For several years, however, aircraft data of appropriate quality have been available to help fill the gap. In this note we present a spectral analysis of a particularly homogeneous and well controlled set of aircraft-observed motion data. This data set does not fully fill the gap, due to its geographic, seasonal, and altitude limitations. A much larger set of similar but somewhat less well-controlled data with generally longer sampling intervals is available from commercial and military aircraft, together with smaller but more accurate and complete sets from research aircraft.

2. Data and procedures applied

The data utilized here were obtained from a Boeing 747 jet aircraft operated by Continental Airlines on passenger routes between Chicago (41°59′ N, 87°54′ W), Los Angeles (33°56′ N, 118°24′ W), and Honolulu (21°20′ N, 157°55′ W) during the fall and early winter of 1973–4. Horizontal winds were determined from the routine navigation system (Central Air Data Computer), based on data from an inertial navigation system (Litton LTN 51) and conventional dynamic and static pressure sensors. No side slip angle measurement was available, so that parameter was assumed to be zero. The data were tape recorded for a program sponsored jointly by Continental Airlines and the National Center for Atmospheric Research. The wind data were abstracted from the aircraft tape at 5 s intervals in conventional fashion and some obviously bad data points (extreme outliers) were removed, generally consisting of less than 1% of the data. These points are believed to be mostly produced by electronic noise unrelated to the actual air motion field. Each flight tape

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(containing about three hours of flight data) was then subject to a standard spectral processing technique, in which the mean and linear trends were removed, the outer 5% of the data points on each end "tapered" to make the set appear periodic, and the data then passed through a standard Fast Fourier Transform analysis code. The spectral amplitudes (squares of the Fourier amplitude coefficients) were then summed and averaged in 17 wave number bins with approximate logarithmic spacing. The first two bins are each filled by the amplitude from a single frequency, while all others consist of averages of two or more spectral amplitudes. The 17th bin always has a central frequency a little smaller than the Nyquist frequency, 0.1 Hz.

The temporal spectra can be converted to spatial spectra by applying the Taylor (frozen turbulence) hypothesis, thus dividing the frequencies and multiplying the spectral amplitudes by an appropriate sensor speed. The optimal value of sensor speed to use is somewhat uncertain, however. For the smaller scales of motion, 100 km and less, one might suppose that features move with the mean wind, so that the true air speed, usually about 240 m s^{-1}, would seem most appropriate. Wavelengths of greater than 100 km are probably related to baroclinic disturbances, which typically move at the speed of the mean level of non-divergence, thus slower than the wind speed at the aircraft flight pressure levels of around 250 mb. For these modes, the appropriate sensor speed should be somewhere between the true air speed and ground speed. Since the ratio of wind speed to air speed was usually about 10% and the spectral amplitude levels between different flights varied by a factor of two or more, it was decided to apply a single arbitrary sensor speed, 240 m s^{-1}, for all flights. This is believed to produce errors of not over 20% for any flight, with these errors largely cancelling out in the overall mean, since flights were divided about equally between the upwind (westward) and downwind (eastward) directions. A total of 26 flight tapes were so analyzed, of which 22 were made on the Los Angeles–Honolulu route and four on the Los Angeles–Chicago route. For purposes of presentation, the spectral amplitudes and wave numbers in each of the 17 bins were considered as samples from the same population, and their averages are plotted against the average wave number for each bin on Fig. 1. Since the length of the flight tapes

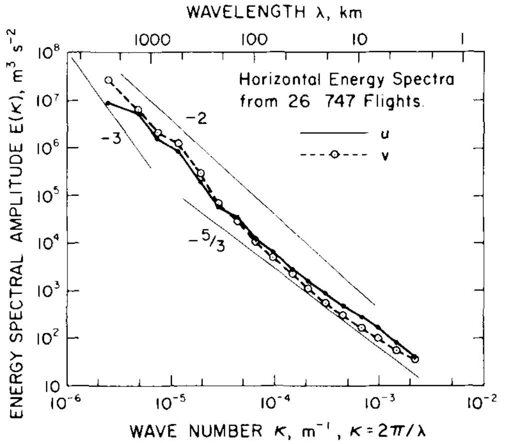

Fig. 1. One-dimensional spatial spectra of the westerly (u) and southerly (v) wind components obtained from 26 flight tapes from a Boeing 747 jet airliner operated by Continental Airlines on routes between Chicago, Los Angeles, and Honolulu. Various spectral slopes are shown for comparison.

varies by up to a factor of two, this procedure produces some additional scatter and perhaps a slight (upward) bias in the means of the low wave numbers.

3. Results

The solid curve in Fig. 1 corresponds to the spectra for the east–west wind component, while the dashed curve shows the north–south component spectrum. Since the average aircraft flight directions were about 070° or 250°, these component spectra are fairly close to the downwind and crosswind spectra, but the latter have not been recomputed. It may be seen that the v-component amplitudes are higher for wavelengths greater than 200 km and the u-component amplitudes higher at the smaller scales. Since incompressible isotropy for two-dimensional flow requires that the component in the direction of flight should be significantly less than that across it, the implication is that the east–west spectra at high wave numbers are considerably enhanced over isotropy. The standard deviations of the bin-averaged spectral amplitudes are about the same as their mean values, or a little larger for the low wave number components. If the sample mean of each spectral amplitude is distributed as a χ^2 variable (consistent

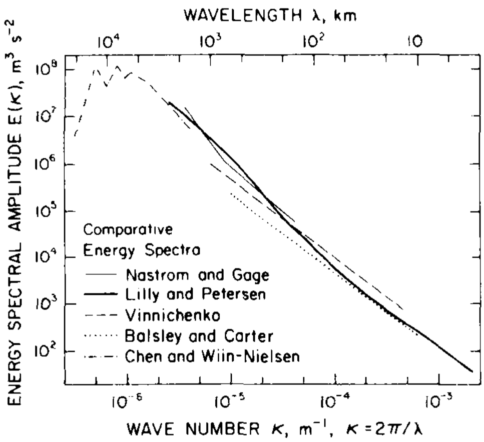

Fig. 2. Comparisons of our aircraft spectra with others presented previously and concurrently. The heavy solid line is a smoothed average of the u and v spectra from Fig. 1. The Nastrom and Gage spectra are obtained in a similar way from aircraft operating in other upper tropospheric environments. The Vinnichenko and Balsley and Carter spectra have been converted from temporal spectra of the u-component using the Taylor hypothesis. The Chen and Wiin-Nielsen spectrum is a scalar spectrum of the two-dimensionally incompressible flow component over the northern hemisphere.

with the Fourier coefficients being distributed as Gaussian variables), then the standard deviation of the spectral amplitude mean is $(2/26)^{1/2} \approx 0.28$ times the standard deviation of each amplitude.

On Fig. 2, the average of the u and v component spectra (equal to the one-dimensional spectrum of horizontal kinetic energy) is shown for comparison with other spectra. The dashed curve is taken from that shown by Vinnichenko (1970), while the dotted curve is taken from the spectrum by Balsley and Carter (1982) of Doppler-derived winds during the summer 1979 at Poker Flat (near Fairbanks), Alaska. A fourth spectrum, shown as the dash-dotted curve, is the two-dimensional energy spectrum obtained for large-scale atmospheric motions, analyzed from rawinsonde data by Chen and Wiin-Neilssen (1978).

These spectra were originally presented in a variety of different forms, so it seems appropriate to describe the process of conversion to a common plot. Vinnichenko showed a temporal spectrum of the westerly velocity component, plotted in abscissa units of cycles/day and ordinate units of (km^2 h^{-2}) day. Based on comparisons with spatial spectra he estimated an appropriate Taylor advection velocity to be 23 m s^{-1} for wavelengths less than 1800 km. For conversion into spatial spectra, we therefore divided the abscissa by (86,400 s day^{-1}) $\times$ (23 m s^{-1})/(2π) and multiplied the ordinate by (10^6 m^2 km^{-2}) $\times$ (24 h day^{-1}) $\times$ (23 m s^{-1})/($2\pi \times$ 3600 s h^{-1}). Balsley and Carter also exhibited a temporal spectrum of the westerly wind component, with abscissa and ordinate units of Hz and m^2 s^{-2} Hz^{-1}, respectively. From Monthly Climatic Data for the World (WMO-NOAA, 1979), we found that the mean vector wind speed for Fairbanks for the observational period was 7 m s^{-1} and the mean scalar speed 14 m s^{-1}. We assumed the appropriate advection velocity to be 10 m s^{-1}, multiplied the abscissa by (2π/10 m s^{-1}) and the ordinate by the inverse. The Chen and Wiin-Nielsen spectrum was based on spherical harmonic analysis of the two-dimensionally non-divergent wind field. The amplitudes were then integrated over the mass of the atmosphere, apparently from the 100 to 1000 mb pressure surfaces. The spectral abscissa was given as the surface spherical harmonic index (the degree of the Legendre polynomial) and the ordinate was calibrated in units of joules m^{-2} = kg s^{-2}. We converted the index number to wave number by division by the earth's radius, 6.2×10^6 m, and converted the ordinate to kinematic units by division by the atmospheric mass/unit area below 100 mb, 9000 kg m^{-2}, and then multiplied by the earth's radius.

From Fig. 2, it is apparent that all the spectra are reasonably compatible with each other, despite rather wide differences in environment and data treatment. The Chen and Wiin-Nielsen curve is a scalar spectrum of non-divergent horizontal kinetic energy, and is thus equivalent to the integral of the spectral amplitudes lying on a circle in two-dimensional space of both the horizontal velocity components, while the other two curves are one-dimensional spectra of the westerly component only. For accurate comparison, the Chen and Wiin-Nielsen spectrum should be reduced relative to the others by a factor of two to three at the high frequency end. On the other hand, it is a total tropospheric average, while the others are more heavily weighted toward the upper tropospheric wind maximum. An independently-obtained large-scale spectrum, calculated by Desbois (1975) from constant volume balloons floating at the 200 mb level in the Southern Hemisphere, shows very similar features and amplitudes.

Our spectra, which were made from data taken at altitudes near the tropospheric wind maximum in winter but mostly in subtropical latitudes, differ from the others, and from the spectra obtained from aircraft data by Nastrom and Gage (1983), principally in their steeper slope in the 100–1000 km wavelengths. A portion of this steepening can perhaps be accounted for by the effects of airflow over the high mountain regions of the western U.S. Even though only four of the 26 flights were made over this region, their spectral amplitudes for wavelengths greater than 100 km were three to six times greater than those of the over-water flights and thus affected the means significantly. Smaller scale parts of the spectrum were also increased in the continental flight legs, but mostly by less than a factor of two. Because of the small number of such flights, it is not known whether these differences are typical or anomalous. In any event, the over-water flights alone show a spectral steepening at about the same scale, though not so strongly.

Our data largely support the hypothesis of a mesoscale spectral slope of −5/3, made by Brown and Robinson (1979), Gage (1979), and concurrently from similar aircraft data sources by Nastrom and Gage (1983). Attempts to explain this spectral shape have recently been made by Gage (1979), Lilly (1982), and Van Zandt (1982), using gravity wave and turbulence analysis techniques. In order to more adequately compare and test these and other theoretical models, it is important to extend and present analysis to include the spectra of vertical velocity, temperature and/or displacement, and one or more passive scalars, and also to extend the spectra to wavelengths within the inertial range of three-dimensional turbulence, usually 100 meters or less. The rich sources of data available from commercial wide-body jets and research aircraft as used by Nastrom and Gage should make such analysis possible in the not distant future.

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