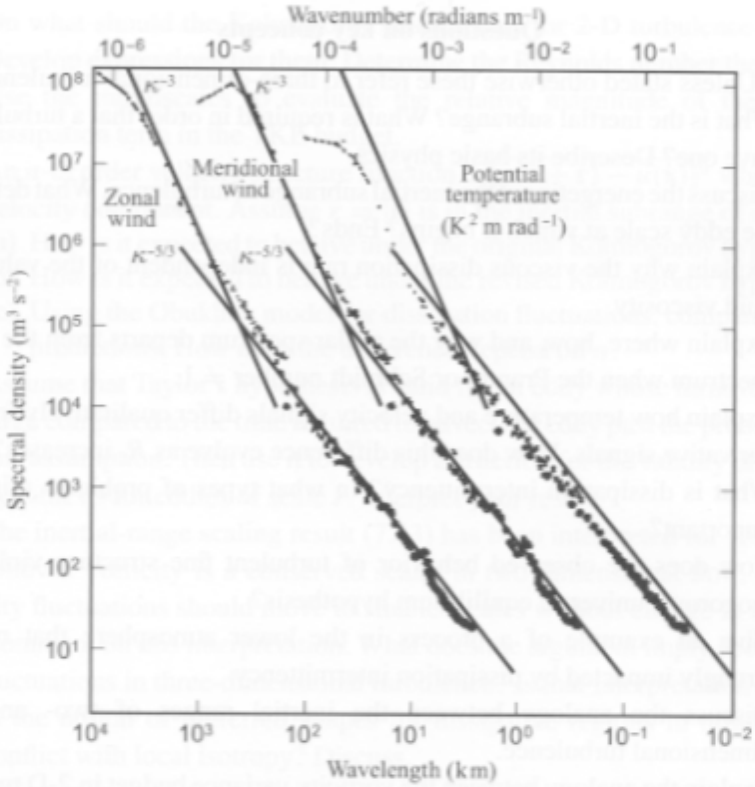

Figure 7.6 Spectra of horizontal velocity components and temperature in the upper atmosphere. From Nastrom and Gage (1985).

7.5.5 Atmospheric observations

Perhaps the most complete observations of velocity spectra above the boundary layer are those reported by Nastrom and Gage (1985). Their results, which are based on measurements made during more than 6000 commercial aircraft flights, are summarized in Figure 7.6. At the smaller wavenumbers the spectra fall as κ^{-3} for perhaps a half-decade, and at larger wavenumbers they show an extended $\kappa^{-5/3}$ range. According to Vallis (2006) the -3 range may be associated with a forward enstrophy cascade, but the origin of the $\kappa^{-5/3}$ range at smaller scales is not clear. But Gage (1979) has hypothesized that two-dimensional turbulence can exhibit a $\kappa^{-5/3}$ range due to an inverse energy cascade, and Gage and Nastrom (1986) state that it seems reasonable to assume that "breaking waves" are an important part of its small-scale energy source. Lilly (1989) shows that turbulence closure models indicate that such forward enstrophy and inverse energy cascades can coexist in two-dimensional turbulence with energy sources at both large and small scales.