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4.1A DETERMINATION OF BILLOWS AND OTHER TURBULENT STRUCTURES

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INTRODUCTION

Billows are regular, wave-like arrays of cross-flow vortices that develop in stratified oceanic or atmospheric flows with large shear. Atmospheric billows can become manifest through condensation. Billows are frequently seen in their characteristic cloud forms in the lower atmosphere. Under suitable viewing conditions, billows can also be seen in noctilucent clouds that form near the polar mesosphere during the summer months. Excellent examples of these cloud forms have been catalogued by SCORER (1972).

Other turbulent structures -- related to billows -- are the Kelvin-Helmholtz instability (KHI) and cat's eye structures that occur in fully developed turbulent shear flows. Shear flows may contain perturbations at many different horizontal wavelengths and vertical scales. Realistic theoretical models have been constructed to study the stability and growth of these perturbations. For the purpose of this note, it will suffice to point out that, as the local gradient Richardson number Ri is reduced below a value of about 0.25, the most rapidly growing perturbations have a wavelength (λ) that is $\sim 2\pi$ times the initial thickness, h (TURNER, 1973; GOSSARD and HOOKE, 1975). As the layer becomes completely mixed, it may eventually acquire a thickness H $\sim$ 5h (SCORER, 1969; WOODS and WILEY, 1972). Stages in the growth of a shear-flow instability have been outlined by SCORER (1969), THORPE (1969), WOODS (1969) and READINGS (1973).

In this note we outline the extent to which billows and KHI have been observed in the atmosphere, principally with the use of radars. Most of these observations are confined to the troposphere. Suggestions are made for improved radar experiments that are required to detect these structures at higher altitudes.

BILLOW OBSERVATIONS IN THE ATMOSPHERE

High-power radars operating at GHz frequencies have a sufficiently fine spatial and temporal resolution to detect billows of $\sim$100-200 m thickness. Early radar observations of billow structures and KHI in the troposphere were reported by HICKS and ANGELL (1968), and HARDY and KATZ (1969).

ATLAS et al. (1970) have used a 2.9 GHz FM-CW radar, with a height resolution of $\sim$1 m, to observe the details of growth of a KHI in the boundary layer at 300-400 m, and its eventual decay into clear-air turbulence. JAMES and BROWNING (1981) have used a similar radar, with a $\sim$30 m range resolution and Doppler capability, to observe the development of secondary billows of 350 m wavelength on primary billows of 4.2 km wavelength at heights of 7-8 km.

VHF radars operating at a typical frequency of 50 MHz have a better altitude coverage ($\sim$5-25 km and 60-90 km), but their poor spatial resolution (typically 2-5 km in the vertical and horizontal directions) usually smears the fine structure in the shear regions. Few VHF radars make use of phase-coding and decoding techniques to achieve an improved height resolution of $\sim$150 m. UHF radars provide a narrow beam, and therefore an improved horizontal resolution. In either case, the horizontal resolution is often impaired by the integration time (∿1 min) and depends on the wind speed. For these reasons VHF and UHF radars have provided only limited evidence for billow structures in the middle atmosphere, and most of these observations are below the tropopause.

ROTTGER and SCHMIDT (1979) have used VHF observations with 150-m resolution and 30-m spacing to detect a Cat's eye structure at 4.5-km altitude. UHF observations with 150-m resolution at Arecibo (see e.g., RASTOGI, 1981) show vaguely defined large-vortex structures and bifurcating layers of turbulence in the troposphere.

In the above experiments the Doppler resolution is usually inadequate to resolve differential motions in a radar cell. WAND et al. (1983) have improved the radial velocity resolution to 4 cm s^{-1} in a UHF radar experiment, and have used this capability to detect the evolution of a KHI and a braided structure in the troposphere.

Radars, and other techniques e.g., balloon-borne sensors, have been ineffective in detecting the evolution of billow structures in the stratosphere, though estimates of CAT layer thickness are more readily obtained (BARAT, 1982; WOODMAN and RASTOGI, 1984). The CAT layer thickness can also be inferred in the mesosphere (∿0.1 to 1 km) using high-resolution VHF radars (ROTTGER et al., 1979). ROYRVIK (1983) has used an interferometric method with the Jicamarca VHF radar to infer that rotating, vortex-like, structures may occur in the mesosphere.

SUGGESTIONS FOR IMPROVED RADAR EXPERIMENTS

The existing VHF and UHF radars have provided scant results on the characteristics of billow structures in the atmosphere, due mainly to their poor vertical, horizontal and temporal resolution. It is clear that the thickness of fully grown CAT regions is usually less than 1 km.

To observe the growth of billows and KHI in CAT regions in the stratosphere and mesosphere, it is therefore necessary to:

1. Improve the vertical resolution to ∿100 m (or less) with the use of phase codes and decoding techniques,

2. reduce the horizontal smearing by limiting the beam width to 1°-2°,

3. reduce the horizontal smearing by limiting the integration time to 10-30 s, and

4. improve the Doppler resolution to ∿10 cm s^{-1} (or less) by spectral analysis of longer series of samples.

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