A numerical and theoretical study of the cirrus banding accompanying tropical cyclones

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Cirrus banding is defined as wave-like cirrus that typically form near a jet axis or an outflow region of tropical cyclones. Previous studies have suggested two possible mechanisms for the formation of the cirrus banding: the Kelvin-Helmholtz (KH) instability and the thermal-shear instability. However, the understandings of the cirrus banding is still limited because those previous works lacked observational evidences, quantitative evaluation of destabilization mechanisms, and stability analyses under a realistic basic state. To solve those issues, observational case studies, numerical experiments and a linear stability analysis were carried out.

Analyses of high-resolution radiosonde observations detected 27 cases of the cirrus banding. To increase the number of cases, those analyses targeted cirrus banding accompanying jet streams as well as tropical cyclones. The vertical profiles of all of the 27 cases shared a feature of a statically unstable layer within a cloudy layer in the upper troposphere. The vertical wind shear in the unstable layer was nearly parallel to the direction of the observed cloud bands, which is consistent with those emerging under the thermal-shear instability. The moist buoyancy frequency was close to zero, indicating that the moist processes were nonneligible even in the cold upper troposphere.

A cloud-system-resolving model, SCALE-RM, was used for simulating cirrus bands accompanying a tropical cyclone formed under an ideal condition. Roll-shaped convection cells were successfully generated inside cirrus banding on the outflow cirrus clouds. Statically unstable layers and vertical wind shear parallel to the banding clouds, found in the radiosonde observations, also appeared in this numerical experiment. An analysis of the heat budgets revealed that the radiative process heated the cloud bottom and cooled the cloud top by about 0.5 K/hour in the banding clouds. In a sensitivity experiment about the cloud-radiation interaction, where cloud optical properties were changed to be transparent to radiative processes, cirrus bands ceased to form within several hours. This result indicates that the radiative processes contribute to the formation and maintenance of cirrus bands, as suggested by previous studies.

A linear stability analysis was conducted to obtain growth rates of various modes under realistic basic states that were defined based on the radiosonde observations and the numerical experiments. The fastest growing mode was parallel to the vertical wind shear of the basic state and was vertically localized in the statically unstable layer, which was consistent with the radiosonde observations and the numerical experiments, and similar to the thermal-shear instability investigated by Asai (1970) in simpler basic states. The horizontal wavelength of the fastest-growing mode was 1 to 2 km, and this result can only explain the shortest portion of the wavelengths of the cirrus bands (1 km - 30 km) estimated from high-resolution polar-orbiting satellite images. The longer wavelength of the observed cirrus bands may be attributed to nonlinear effects.

Those results indicate that the cirrus banding consists of roll-shaped convection cells driven by the thermal-shear instability. This conclusion is consistent with recent modeling studies, and this study newly provides observational and theoretical evidences. Remaining issues include the following: establishing an objective method of the analyses of observational data, additional numerical sensitivity experiments on the intensity of the shortwave incidence and the microphysics parameterization, and a verification of nonlinear effects on the growth of the wavelength of the cirrus banding.

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