The Role of Barrier Jet for the Development of Localized Heavy Precipitation over Northwestern Taiwan during the Mei-Yu Season

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1. Introduction

Hills and mountains affect the airflow in many different ways. Besides mechanically forced ascent on the windward slopes, the mountain also acts as a barrier to the approaching airflow and as a heat source (sink) during the day (night). In addition, low-level orographically induced strong winds are frequently observed along mountain barriers. The strong winds along the northwestern coast of Taiwan under the prefrontal southwesterly monsoon flow during the Mei-Yu season (e.g., the barrier jet) has been first reported by Chen and Hui (1992). They state: "Over the Taiwan area, the southwest flow ahead of the surface front....... interacted with the central mountain range, resulting in the windward ridge, leeside trough. Downstream of the blocked region, strong southwesterly winds (~15 m s^{-1}) developed in the lowest levels along the northwest coast, where the flow deflected by the mountain barrier merged with the undeflected southwest flow." In this present article, the structure and the development of the barrier jets along the northwestern Taiwan coast during the Mei-Yu season are reviewed. The orographic effects on the Mei-Yu frontal system over northwestern Taiwan and the role of enhanced convergence due to the interactions between the barrier jet and the jet/front system on the localized heavy rainfall are discussed.

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2. Development of the Barrier Jets

Our knowledge of the barrier jets along the northwestern Taiwan coast first comes from the analyses of aircraft data collected during TAMEX (Taiwan Area Mesoscale Experiment) IOP #5 (Chen and Li 1995a) and IOP #3 (Chen and Li, 1995b).

Chen and Li (1995a, b) show that because of orographic blocking, the low-level prefrontal southwesterly flow decelerates upstream off the southwestern coast of Taiwan. The low-level flow is then deflected by the island topography with a splitting flow over the southwestern coast. Along the western coast, the wind component parallel to the central mountain range increases northward down the orographically induced pressure gradient. The cross-isobar wind component reaches a maximum value > 14 m s^{-1}

at approximately 1-1.5 km (Chen and Li 1995b). Over the southern end of Taiwan, the mountains are relatively low. The airflow there crosses the island and descends in the lee. This descending airflow accelerates as it moves towards the lee-side trough (Chen and Li 1995b).

From the principal component analysis of the surface winds and pressure patterns over the Taiwan area during TAMEX, Chen and Li (1995b) show that the strongest southerly coast-parallel winds occur when the windward ridge (Wang 1986) is most significant (their fig. 12b).

3. An Overview of Barrier Jets during TAMEX

a. Observations

Li and Chen (1998) surveyed the occurrences of barrier jets during the entire TAMEX period. The southwesterly monsoon flow (or the low-level jet) strengthens near Taiwan when the low-level Mei-Yu trough moves towards the southeastern China coast. The barrier jet occurs along the northwestern Taiwan coast when the sub-synoptic-scale LLJ (Low-Level Jet) impinges on the central mountain range. A windward ridge/lee trough pressure pattern result from the stably stratified airflow past an island obstacle under a small-Froude number regime (Smith 1989; Sun et al. 1991). This occurs when the upstream Froude number ($Fr = U/Nh$) is about 0.2-0.5, where U, N and h are the upstream wind speed, Brunt-Vaisala frequency and barrier height, respectively (Chen and Li 1998). The observed barrier jet is a local feature. 90 km offshore, the magnitude of the alongshore wind component of the barrier jet is about 60% of its coastal value. For $Fr < 1$, the orographically induced wind and pressure perturbations will grow seaward up to a limit given by a Rossby radius $LR = U/f$ (Smith 1989). The Coriolis force inhibits the grow of perturbations far upstream of the island by forcing an adjustment to geostrophy. For the TAMEX barrier jet cases the Rossby radius is about 60-120 km.

During TAMEX, the barrier jets have an average maximum wind speed of 14 m s^{-1} at approximately 1 km above the surface, which is the top of the weakly stable boundary layer. The virtual potential temperature increases slightly with respect to height in the lowest 1 km because of vertical mixing. The barrier jets have an average vertical wind shear of about 10×10^{-3} s^{-1} below and 4×10^{-3} s^{-1} above the 1 km level. With limited aircraft data for the 21-22 May 1987 case, Li and Chen (1998) suggest that the force balance along the coastal jet over northwest Taiwan is dominated by the inertial and the pressure gradient force terms. They also suggest that although the pressure gradient along the western coast due to island blocking is the largest at the surface, boundary layer friction reduces the wind speed of the barrier jet in the lowest levels.

One of the unique features of the barrier jet over northwest Taiwan is that the jet is located north of the major mountain peaks, in contrast to mountain-parallel winds observed along the windward side of long mountain ranges (Schwerdtfeger 1975; Parish 1982; Forbes et al. 1987). Because the airflow and orography of Taiwan are three-dimensional, the dynamics of the barrier jet along the northwest coast of Taiwan are different from the classical theoretical studies of barrier winds from 2D models for long mountain ranges (Pierrehumbert and Wyman 1985; Xu 1990 and others). In the case of an isolated 3-D mountain, the airflow is different from 2-D flow because of horizontal streamline splitting (Miranda and James 1992). With an extra degree of freedom, the airflow is allowed to go around the orography for a low Froude number [$<O(1)$] flow regime (Smolarkiewicz et al. 1988; Smith 1989; Sun et al. 1991). It is apparent that the central mountain range is not long enough to force a mountain-parallel jet.

b. Numerical Simulations

Yeh and Chen (2003) study the airflow over the Taiwan area in the absence of radiative forcing, thermal forcing from the surface, and synoptic forcing using the NCAR/PSU MM5 model. Their model results reproduce the orographically induced low-level strong winds along the northwestern coast of Taiwan under the prefrontal southwesterly monsoon flow. Above the mixed layer, the along-shore force balance for the barrier jet is dominated by the inertial advection and the pressure gradient force terms as suggested by Li and Chen (1998). The significant Lagrangian flow acceleration of the northern branch of the deflected airflow along the northwest coast is mainly related to the pressure gradient force as the airflow moves down the orographically induced pressure ridge along the windward coast. Even though the along-shore pressure gradient force along the northwest coast is the largest at the surface, the observed and simulated wind profiles show that the wind speed maximum in the vertical of the barrier jet occurs at the top of the weakly stable boundary layer primarily due to frictional retardation in the lowest levels. Within the well-mixed layer, the along-shore force balance is a three-way balance between inertial advection, pressure gradient force, and frictional force. Normal to the northwest coast, the Coriolis force and the pressure gradient force are the two largest terms. In addition, the location and the strength of the orographically induced low-level strong winds along the northwest coast of Taiwan also depend on the impinging angle and the wind speed of the prevailing winds.

4. Barrier Jets and the Localized Heavy Rainfall along the Northwestern Coast

Under favorable large-scale conditions localized heavy rainfall could occur along the northwestern coastal areas of Taiwan due to the interactions between the Mei-Yu jet/front system and the barrier jet.

During IOP #13 of TAMEX, a heavy rainfall event occurred over northwestern Taiwan with the maximum localized rainfall > 231 mm day $^{-1}$ along the coast. Li et al. (1997) studied this heavy rainfall event. They show that for this case, the movement of the shallow low-level postfrontal cold air behind the Mei-Yu front is slowed down by the hilly terrain along the southeastern China coast as the Mei-Yu front advances southeastward toward the southeastern China coast. The low-level windshift line associated with the 850-hPa trough moves over the Taiwan Strait ahead of the surface front. A localized convergence zone occurs between the westerly flow behind the trough and the barrier jet along western Taiwan coast. A long-lived rainband develops within the localized convergence zone and moves southeastward toward the northwestern coast with the windshift line. There are several long-lived reflectivity maxima embedded within the rainband. They form on the southwestern tip of the rainband along the windshift line and intensify while moving northeastward along the convergence zone. The continuous generation of reflectivity maxima along the convergence zone maintains the rainband and produces persistent heavy rainfall along the northwestern coast as these reflectivity maxima move onshore.

Yeh and Chen (2003) studied a coastal rainfall (~ 40 mm h^{-1}) event along northwestern Taiwan during TAMEX IOP #3. This event was associated with the arrival of three moderate rainbands in succession. They formed within the Taiwan Straits ahead of an upper-level trough. There is a tendency for the most intense echoes to align in a northeast-southwest orientation off the northwestern coast where the orographically enhanced convergence zone occurs. The results from radar and numerical simulations suggest that the enhanced convergence off the coast is a combination of the sub-synoptical forcing (e.g., upper-level trough), orographic effects and feedback effects of the convection.

Our on-going work on the TAMEX IOP #2 case shows another type of interaction between the Mei-Yu jet/front system and the barrier jet. The localized heavy rainfall along the northwestern coastal areas (> 90 mm day^{-1}) occurs mainly during the passage of the Mei-Yu front at the surface. Most of the deep convection develops within the prefrontal southwesterly monsoon flow ahead of the upper-level trough and drifts northeastward with the southwesterly monsoon flow. They are enhanced either in the prefrontal region where the orographically deflected flow converges with the southwesterly flow within the Taiwan Straits or along the frontal boundary where the deflected southwesterly flow converges with the postfrontal northeasterly flow. However, the most intense radar echoes occur within the localized convergence zone along the frontal boundary.

Satellite and rainfall data during the Mei-Yu season show that statistically both the rainfall and deep convection along the northwestern coastal areas exhibit a weak early morning maximum. It appears that the island blocking of the prefrontal southwesterly flow and its interactions with the Mei-Yu systems from the north tend to be more significant in the early morning hours.

5. Summary

In this study, TAMEX results on barrier jets are reviewed. The locally strong coastal winds and the interactions between the orographically induced flow with the Mei-Yu jet/front systems frequently lead to localized heavy rainfall. These events won't be properly forecasted with the traditional synoptic-scale forecast techniques. Furthermore, without proper representation of orographic effects, these events also will be missed by regional weather models (Yeh and Chen 2002). Localized heavy rainfall events in regions of complex terrain will remain a significant challenge for scientific research as well as operational weather forecasting for many years to come.

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