Roll Clouds Associated with an East Asian Cold Front

Tsing-Chang Chen,* Ming-Cheng Yen,+ Shih-Yu Wang,+ and Raymond W. Arritt#

ABSTRACT

On 11 January 1998, a cold front formed in southeast China as a result of a cold-air outbreak in northeast Asia. During this synoptic development, a series of roll clouds (along the SW–NE direction) was observed in East Asia; some of the clouds stretched for over a thousand kilometers. This roll cloud formation moved southeastward across Taiwan, the Ryukyu Islands, and Japan, and eventually into the open ocean. In order to explore the possible cause of these roll clouds the following preliminary analyses were made in this study:

1) the location of roll clouds relative to the cold front was determined in terms of the contrast between the infrared images of the Geostationary Meteorological Satellite of Japan and surface charts issued by the Japan Meteorological Agency,
2) the intrusion of the density current was identified using upper-air soundings at Taipei, and
3) the migrations of roll clouds and the cold front were judged by comparing the arrival time of the first roll cloud and the front with time series of surface meteorological variables measured at a surface station in northwest Taiwan.

These observations imply that the series of roll clouds formed in association with solitary wave disturbances generated on the density current (i.e., the outflow from the cold-air break) but behind its leading edge.

1. Introduction

After sunset, a stable low-level inversion layer may be formed by nocturnal radiational cooling. An undular atmospheric bore, a series of solitary waves, or a modified gravity current may develop on or behind the inversion layer when it is blocked by the advancing cold air from thunderstorm outflow, a cold front, or downslope katabatic flow. That is, the leading edge of the stable inversion layer may move away from or get caught up by the gravity current of cold-air outflow. The undular atmospheric bore or borelike disturbances are sometimes accompanied by a series of roll clouds if sufficient moisture exists ahead of the gravity current. Numerous observations, diagnoses, and simulations have been conducted to examine different aspects of the undular bore waves/borelike disturbances and the associated roll clouds in northern Australia near the southern coasts of the Gulf of Carpentaria region (Smith 1988; Christie 1992) and in the United States Midwest (Locatelli et al. 1998).

In northern Australia, the roll cloud formation with the undular atmospheric bore is known as a “morning glory.” The morning glory bore waves originate from two directions: the northeast and the south. From the northeast, they are generated by the intrusion of cold air transported by the sea breeze from the hilly east coast of the Cape York Peninsula toward a nocturnally formed maritime inversion layer. In contrast, the

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southerly morning glory bore waves are generated by a cause different from that of the northeasterly ones (Smith et al. 1995). Between two high pressure systems centered in southwest and east Australia, a cold front may appear over a heat low in northern Australia and an extratropical one in south-central Australia. As the front propagates northward, the southerly morning glory bore waves may form at the leading edge of the frontal zone and move on the preexisting maritime inversion layer.

Over the U.S. Midwest, a nocturnal inversion layer may form ahead of the cold-air outflow from thunderstorms and a gust front (with a wind shift line) may exist south of a synoptic-scale cold front and north of a prefrontal trough. In the vicinity of this trough an undular atmospheric bore can form on a nocturnal inversion layer. Some roll clouds may appear along the bore waves (e.g., Clarke 1998). Sometimes, undular disturbances with roll clouds may occur on the density current behind the leading edge of the stable inversion layer (e.g., Shreffler and Binkowski 1981; Haase and Smith 1984; Fulton et al. 1990), because the speed of solitary wave disturbances is slower than the density current intruding on the stable inversion layer.

During the cold season, the outflow from cold fronts in East Asia often moves southeastward to meet the maritime air mass, just as cold fronts across northern Australia and the U.S. Midwest. According to the *Monthly Weather Outlook* issued by the Weather Bureau of Taiwan, this synoptic situation occurs frequently during the cold season. The undular atmospheric borelike disturbances accompanied by roll clouds may be generated over East Asia. To our knowledge, no documentation of this lower-tropospheric phenomenon can be found in the literature. To bridge this gap, we report observations of a roll cloud formation propagating with a cold front from southeast China to Taiwan in the past (1997/98) winter. The infrared imagery of the Geostationary Meteorological Satellite (GMS) of Japan, surface charts issued by the Japan Meteorological Society (JMA) for East Asia, and surface observations along the upper-air soundings in Taiwan were used to depict the chronological evolution of the roll cloud formation. The purpose of this paper is not only to document a series of roll clouds formed behind the leading edge of a cold density current in East Asia but also to call attention to the meteorological community concerning this interesting phenomenon. Hopefully, future research will concentrate on the further exploration of the East Asian roll cloud formation and the detailed structure of the associated cold front and undular borelike disturbances.

2. Roll clouds

At about 1400 local standard time (LST) on 11 January 1998, a spectacular roll cloud oriented in the NE–SW direction reached the northwest coast of Taiwan. A picture of the cloud (Fig. 1) was taken at a distance of approximately 15 km from the campus of National Central University (NCU), Chung-Li (the location of this city is marked by an open circle in Fig. 2), Taiwan. As revealed in Fig. 1, this picture is actually composed of *four* shots with the camera facing the NW direction (almost perpendicular to the roll cloud) and positioned next to a pentagonal radar antenna (at the left end of Fig. 1) mounted on the roof of the NCU Atmospheric Sciences Department building. Based on the distance (~15 km) between the camera and the roll cloud, we have estimated that the NE–SW horizontal extent of this cloud is about 60 km from the coast near the NCU campus to the northern tip of Taiwan, and the vertical extent is about 2–3 km. The appearance of this roll cloud resembles the morning

FIG. 1. The roll cloud picture, which is composed of four shots taken at the campus of National Central University (NCU), Taiwan, at 1400 LST (0600 UTC) 11 January 1998. The camera was positioned on the roof of the NCU Atmospheric Sciences Department building (next to the pentagonal radar antenna in the left end of the picture) facing west. This roll cloud is oriented SW–NE along the northwest coast of Taiwan about 15 km away from the NCU campus.

glory in northern Australia (e.g., Clarke 1972; Clarke et al. 1981; Smith et al. 1982; Reeder et al. 1995) and the cloud bands accompanying the undular atmospheric bore waves in the U.S. Midwest (e.g., Locatelli et al. 1998). According to local residents on the northwest coast of Taiwan, this type of roll cloud has been seen occasionally during the cold season: however, this type of roll cloud has not been documented even by local meteorological journals in Taiwan. The East Asian region is covered by the GMS, so that a better view of its geometric structure and life cycle may be obtained from the GMS imagery. Previous observations found that many morning glories of northern Australia (e.g., Smith 1988) and the cloud bands of the U.S. Midwest undular atmospheric bore (e.g., Clarke 1998) are nearly invisible on the infrared image. However, Erickson and Whitney (1973) found that the infrared channel of the Very High Resolution Radiometer (VHRR) was able to pick up the wave cloud formation of moving gravity waves propagating out from a severe thunderstorm region in the U.S. Midwest. We scanned both the visible and infrared GMS images with a resolution of 5 km × 5 km and found that the East Asian roll cloud was more discernable on infrared images than on visible ones.

Shown in Fig. 3 is the chronological evolution of the roll cloud formation visible in the GMS infrared images. A single roll cloud appeared after sunset in southeast China at about 1900 LST on 10 January 1998 (not shown). While propagating southeastward, it grew into a series of roll cloud bands. At 0330 LST on 11 January (the top-left panel of Fig. 3), the roll cloud formation became well organized and arrived at the east coast of China, south of the Yangtze River. Five hours later (at 0030 UTC or 0830 LST on 11 January), the northeastern end of the roll cloud bands reached Kyushu, Japan; some roll clouds stretched over a thousand kilometers from Kyushu to southeast China, and cloud bands became thicker toward Japan. As seen in the infrared image at 1330 LST on 11 January (the top-right panel of Fig. 3), a northeastward-oriented (SW–NE) roll cloud longer than 400 km was approaching Taiwan. The roll cloud picture taken at 1400 LST from the NCU campus (Fig. 1) is a part of this cloud band. Compared to the cloud image at 0830 LST, the cloud band became thicker as it moved closer to Taiwan. Was this caused by the increase of the moisture supply, or by some other reason? The answer to this question is not clear to us at this stage. Less than a half hour after the picture was taken (at 1400 LST), the southwest tail of the cloud band moved into Taiwan (indicated by the image at 1430 LST—the lower-right panel of Fig. 3). Some roll clouds started to dissipate, but others could still be identified even at 1730 LST in the Taiwan Strait.

Observations of the East Asian roll clouds shown in Fig. 3 reveal some differences from those observed in northern Australia and the U.S. Midwest:

1) The morning glory of northern Australia and the cloud bands of the undular atmospheric bore in the U.S. Midwest generally decay as soon as the nocturnally formed stable inversion layer is destroyed by daytime convective mixing. The series of East Asian cloud bands started to develop after sunset over the cold landmass, but they did not dissipate

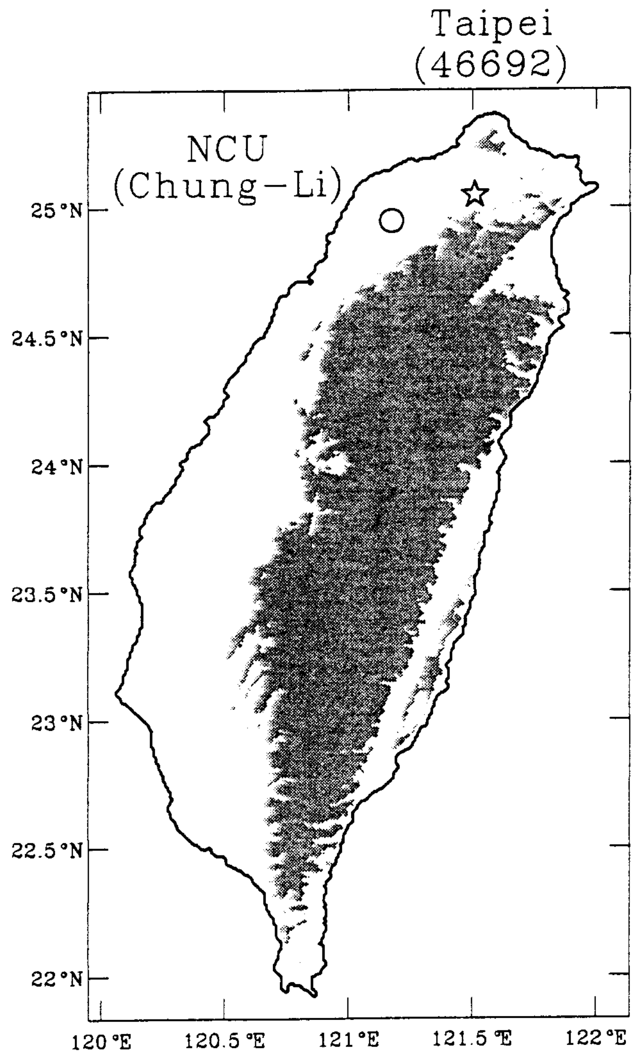

Fig. 2. Displayed on this map are locations of a surface station at the NCU campus, Chung-Li, and the radiosonde launching station at Taipei, Taiwan. Elevations higher than 500 m are stippled.

even after 1430 LST (the lower-right panel of Fig. 3) over the open ocean. Evidently, the life cycle of this East Asian roll cloud formation is *longer* than those in the other regions. Compared to the large East Asian landmass, diurnal heating over the ocean is much weaker and in turn, the development of a nocturnal inversion layer over the ocean is also less likely (as will be shown in section 3a). Is the longevity of the East Asian roll clouds related to the lack of a maritime inversion layer? This question warrants future study.

2) Cloud bands of the southerly morning glory (Fig. 24 of Smith et al. 1995) are parallel with each other and uniform in their intensity. In the central United States, some cloud bands associated with the undular atmospheric bore may radiate out from the active thunderstorm region to form a long arc (Fig. 1 of Clarke 1998). In contrast, the East Asian roll clouds shown in Fig. 3 are thicker in the northeastern end (north of the surface low center; referred to in Fig. 4) than they are in the southwestern end. The East Asian roll clouds are also *longer* in comparison to most of those in northern Australia and the central United States.

These comparisons may suggest that the cause of the East Asian roll cloud formation may not be exactly the same as those in northern Australia and the U.S. Midwest. However, some inference of the formation cause may be derived from the synoptic environment in which the East Asian roll clouds are embedded.

3. Synoptic environment

a. Synoptics

The synoptic environment over northeast Asia during the entire episode of the East Asian roll clouds

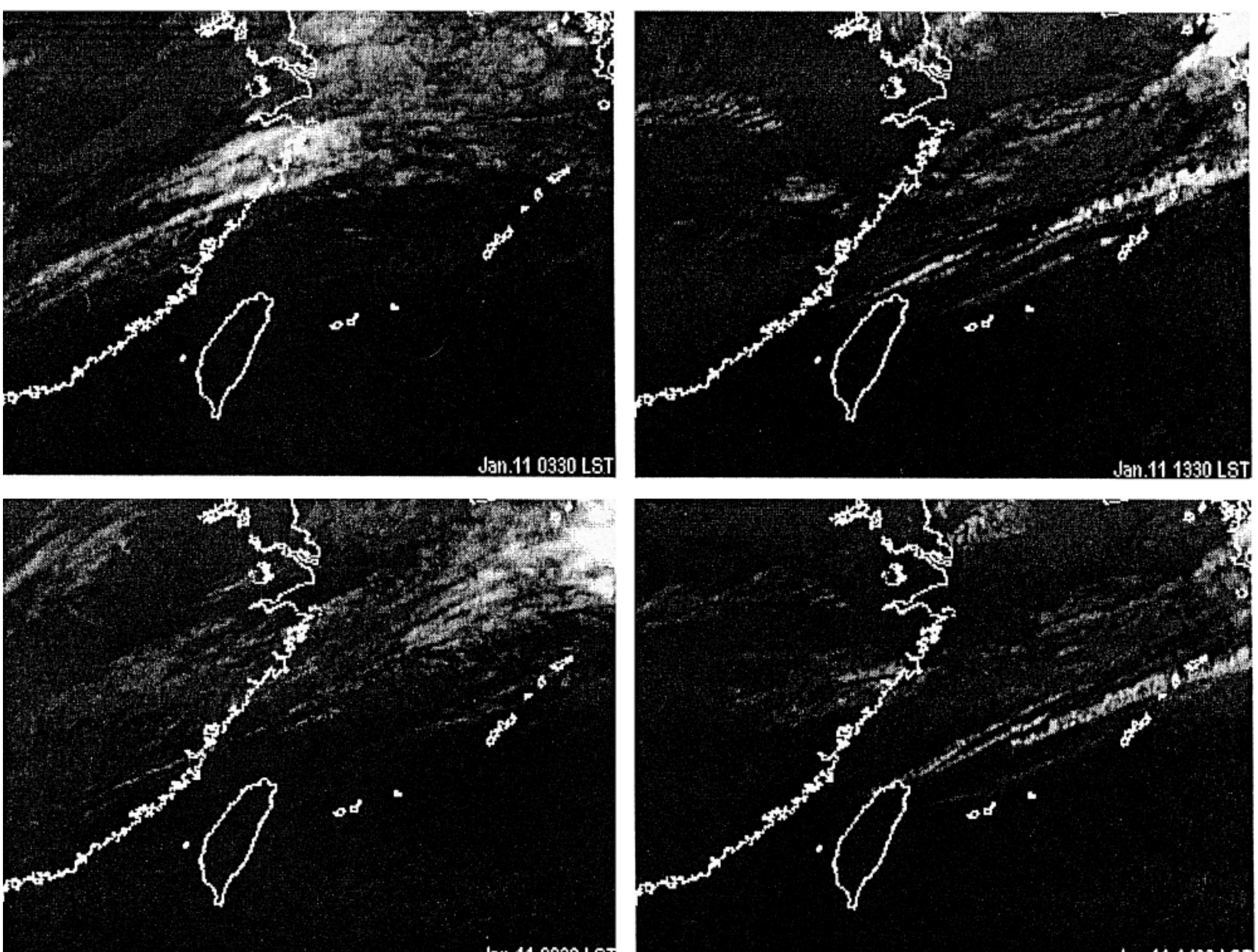

FIG. 3. The infrared images of the roll cloud formation taken on 11 January 1998 by the Geostationary Meteorological Satellite of Japan at four local standard times (LST), which are shown on the lower-right corner of each image.

(10–12 January 1998) was dominated by a dipole structure of surface pressure consisting of a developing Siberian high in northeast Asia and a midlatitude low system containing several low centers over the region between the Sea of Okhotsk and the Bering Sea. Following the development of the Siberian high, a cold-air outbreak occurred on 10 January 1998 (not shown). The high pressure cold air swept southeastward through the Korean Peninsula, the Japan Sea, and Japan, and established a mesohigh east of the Ryuku Islands and south of Japan. West of this mesohigh, a cold front originated in southeast China and extended across the East China Sea to reach the Ryuku Islands.

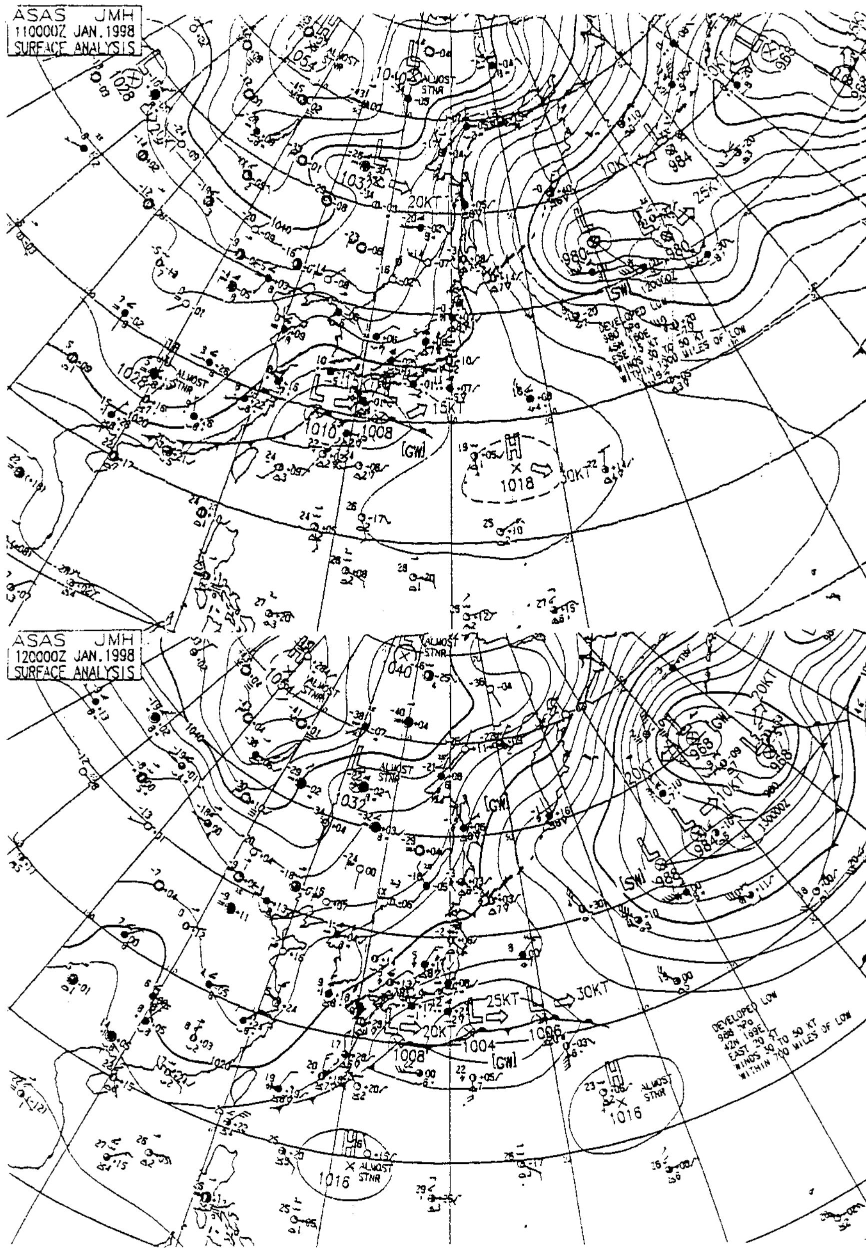

FIG. 4. Surface synoptic charts at 0000 UTC (0800 LST) 11 January 1998 and 0000 UTC (0800 LST) 12 January 1998, issued by the Japan Meteorological Agency, are shown.

The mesohigh formed by the outflow from the northeast Asian cold-air mass continued to move farther southward into the open western subtropical Pacific. At 0000 UTC (i.e., 0800 LST) on 11 January (the top panel of Fig. 4), the cold front was located slightly north of Taiwan with a low pressure system of about 2000 km in its horizontal scale appearing at its east end. Rainfall occurred over the entire region along the 1020-mb isobar behind the cold front, while the surface southwesterlies prevailed ahead of the front. The couplet of the Siberian high and the midlatitude low system migrated somewhat eastward in the next 24 h. After being cut off from the major cold-air mass of the northeast Asian high by an eastward-propagating medium-scale cyclone, at 0000 UTC on 12 January 1998 (the bottom panel of Fig. 4) the mesohigh eventually broke into two fragmental mesohighs over the western subtropical Pacific. In addition to a further deepening, the medium-scale cyclone propagated eastward to the region south of Japan and east of Ryukyu. At this stage, the cold front attached to this low pressure system was over the open ocean east of Taiwan and Ryukyu. Taiwan was then embedded in the high pressure cold-air mass behind this front where the prevailing surface winds were northeasterly.

The roll clouds associated with the southerly undular bore in northern Australia propagate northeastward ahead of a subtropical cold front (Smith et al. 1995), while some cloud bands with the U.S. Midwest undular bore move ahead of the gravity current from a thunderstorm outflow (Locatelli et al. 1998). Based upon the schematic classification of the undular borelike disturbances given by Locatelli et al. (1998), these cloud bands are attached to the "true" atmospheric bore. However, the contrast between the infrared images of the East Asian roll clouds (in the bottom left panel of Fig. 3 at 0030 UTC or 0830 LST on 11 January) and the location of the cold front northeast of Taiwan (in the top panel of Fig. 4—the surface chart at 0000 UTC or 0800 LST on 11 January) indicates that these roll clouds are actually located behind the cold front. As observed in Oklahoma by Fulton et al. (1990) and illustrated schematically by Locatelli et al. (1998), the East Asian roll clouds displayed in Fig. 3 essentially were formed by the *modified gravity current.*

When the phase speed of solitary waves propagating on a stable layer is slower than the gravity current intrusion on this stable layer, undular disturbances may be formed behind the leading edge of the gravity current. Note that the maritime surface temperatures ahead of the cold front at 0000 UTC (i.e., 0800 LST) shown in Fig. 4 were warmer than 20°C, and the diurnal heating is small over ocean. Can a stable inversion layer form nocturnally over the ocean? The upper-air soundings at Taipei (marked by an open asterisk in Fig. 2 and located about 20 km away from the coast) may give us some answers to this question. The soundings of two synoptic times are available: 0000 UTC and 1200 UTC (which correspond to 0800 and 2000 LST, respectively) on 11 January. Although the sun rose at approximately 0700 LST, the temperature observed by the surface station at the NCU campus did not exhibit any significant daily increase by 0800 LST (0000 UTC) in the morning (as will be shown later). In other words, the characteristic of the nocturnally formed inversion layer, if it existed, might not have significantly decayed at 0800 LST.

As revealed from the skew-*T* analysis in the left panel of Fig. 5 (at 0000 UTC on 11 January), a very shallow maritime inversion layer may have formed before dawn. It will be shown later in this section that the cold front passed through the NCU campus at about 1300 LST (i.e., 0500 UTC) on 11 January. The inversion layer (reaching 700 mb) shown by the sounding at 1200 UTC on 11 January (the right panel of Fig. 5) was established by the intrusion of cold air following the advance of the cold front. The comparison between these two soundings supports the argument that the series of roll clouds shown in Fig. 3 were formed by the undular disturbances of a modified gravity current.

b. Station observations

We have already showed in this study that the roll clouds formed behind the cold front might migrate with the gravity current. Nevertheless, a better understanding of the temporal evolution of the synoptic environment in which the cold front and roll clouds

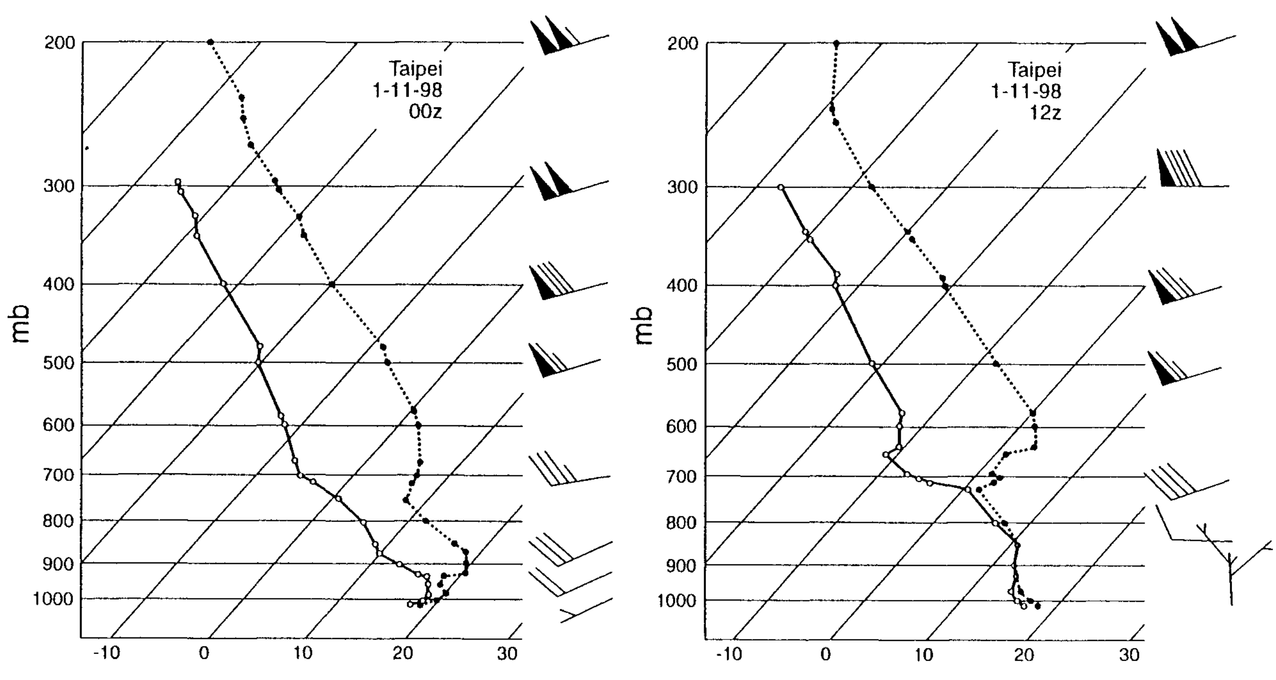

FIG. 5. Skew-*T* analyses from Taipei 0000 UTC and 1200 UTC on 11 January 1999 are displayed.

were embedded would be of use to our future search for the cause of the East Asian roll cloud formation. Observations at the surface station in the NCU campus may serve this purpose. Before proceeding with the detailed analysis of station observations, a brief description of some background work by previous studies is presented.

1) The synoptic condition during the passage of a synoptic cold front is characterized by rapid changes in some meteorological variables in northern Australia (e.g., Smith et al. 1995) and the U.S. Midwest (e.g., Locatelli et al. 1998): an abrupt drop in temperature and humidity; a sudden increase of wind speed (with a rapid change in its direction) and pressure.
2) The typical diurnal variations of meteorological variables at the NCU station (Chen et al. 1998, 1999) are that T_s (RH_s) increases (decreases) after sunrise, while the reverse situation occurs after sunset. The p_s exhibits a distinct semidiurnal variation with its maxima (minima) occurring at 1000 (0400) and 2200 (1600) LST.

The variations of the meteorological variables pressure (p_s), temperature (T_s), relative humidity (RH_s), wind speed (v_s), and wind direction (θ_s) during the passage of the cold front and the associated roll clouds observed at the NCU surface station are shown in Fig. 6. The prominent features of these variations are highlighted below.

1) Prefrontal passage

As indicated by the sudden changes in T_s, RH_s, and p_s and the switch of surface wind direction in this figure, the passage of the cold front through the NCU campus occurred at 1300 LST on 11 January, an hour before the picture of the roll cloud (Fig. 1) was taken. This observation supports our previous conclusion that the roll clouds were formed behind the cold front.[1] Six hours before the frontal passage, T_s (RH_s) increased (decreased) as is typical of its diurnal variation, but combined with interesting changes in some variables right after sunrise at 0700 LST: T_s increased 20°C, RH_s dropped 10%, v_s exhibited a peak increase, and p_s underwent a step change within an hour. In contrast, p_s was on its falling trend [since 0000 UTC on 10 January (not shown)] because of the approaching cold front. Perhaps, due to its semidiurnal component, p_s exhibited a minor maximum at 1000 LST. Accompanying pronounced changes in T_s, RH_s, and p_s, the surface wind speed (v_s) underwent a significant increase after 0800 LST (0000 UTC on 11 January, several hours before the frontal passage) but strangely v_s started to decrease notably as the front became closer to the NCU station.

2) Postfrontal passage

(i) Overall change

Immediately after the frontal passage at 1300 LST, T_s dropped 7°C, RH_s increased 26%, and p_s showed a jump of 0.5 mb. In the next seven hours, p_s (T_s) exhibited a relatively steady increase (decrease) in a manner differing from the tropical diurnal variation. The sudden rise in RH_s and the continuous decline of T_s are caused by the intrusion of a cold-air mass. This RH_s increase also occurs in the U.S. Midwest (Smith et al. 1995; Locatelli et al. 1998) but is not observed in northern Australia (e.g., Smith et al. 1995). The abundant moisture available over East Asia may be one of the major factors facilitating the roll cloud formation and prolonging its life span over the open ocean. Actually, the passage of cold front through the NCU surface station is signified not only by abrupt changes in T_s, RH_s, p_s, and v_s but also by the switch of wind direction from SW to NE.

(ii) Short-time oscillation

Analyzing the undular borelike disturbances with a nocturnal thunderstorm density current, Fulton et al.

[1]According to the laboratory experiment of Wood and Simpson (1984) and the numerical modeling by Haase and Smith (1989), the largest amplitude disturbance of the gravity current is located close to the leading edge of the current and the following undulations have successively smaller amplitudes. If the East Asian roll clouds displayed in Fig. 3 are formed by the modified gravity current, why should the roll cloud shown in Fig. 1 be found about one hour after the passage of the cold front? Checking the GMS IR images at 1330 LST on 11 January 1998 (the top-right panel of Fig. 3), one can easily find that at least *three* roll clouds appeared ahead of the one shown in Fig. 1. Evidently, several undular disturbances occurred before the one passed through the NCU campus. Since the three undular disturbances were not detected by the NCU surface station, it is obvious that these disturbances did not extend far enough southwestward to reach Taiwan. In contrast, the one shown in Fig. 1 stretched sufficiently to affect Taiwan. The following question is raised: Why is there such a difference between the lengths of the undular disturbances (perpendicular to the propagation)? At this stage the cause of this length difference is beyond our understanding.

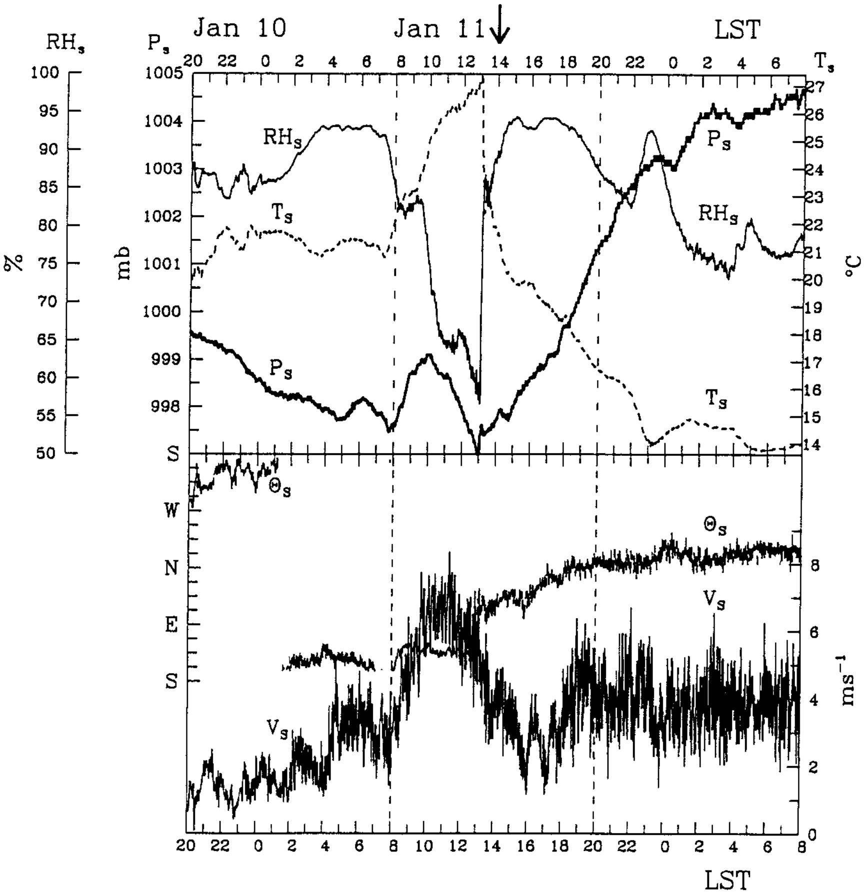

FIG. 6. Pressure (p_s), temperature (T_s), relative humidity (RH$_s$), wind speed (v_s), and wind direction (θ_s) observed by the NCU surface station for the period from 10 January 1998 at 1200 UTC to 12 January 1998 at 0000 UTC. The time of the roll cloud picture (Fig. 1) taken is indicated by an arrow at the top of the upper panel.

(1990) were able to identify solitary wave perturbations with observations at a 444-m tower. Actually, these perturbations were vaguely revealed from surface observations in Oklahoma. Nevertheless, some indication of the oscillation associated with the East Asian roll clouds may be perceived, but not distinctively, from time series of surface observations (Fig. 6) by the NCU surface station between 1400 and 2000 LST. Both T_s and p_s underwent step changes almost every hour within the first five hours after the frontal passage. Distinct oscillations stand out in the v_s time series (with a period of almost an hour) in concert with the step changes of T_s and p_s. Also, RH$_s$ exhibited some variation but with no clear oscillation. It may be difficult, if not impossible, to trace every wave disturbance inferred from infrared images (Fig. 3) and match them with surface observations. Nevertheless, the coincidence between the arrival time of the roll cloud (Fig. 1) and changes of T_s, p_s, and v_s (consisting of a step change of T_s, a p_s jump, and a v_s oscillation) indicated their link to an undular disturbance. Estimated with locations of the East Asian cold front between two synoptic times in Fig. 4, the eastward propagation speed of this cold front is about 10 m s^{-1}. The observation by one of the authors (S.-Y. Wang)[2] showed that it took the roll cloud (Fig. 1) about 20–30 min to pass over the NCU Atmospheric Science Building. The wavelength of the roll cloud may be within the range of 10–20 km. The undular disturbances of the true atmospheric bore (e.g., Smith et al. 1995; Locatelli et al. 1998) and the modified density current (e.g., Fulton et al. 1990) have an oscillation period of approximately 10 min and a wavelength of 10 km along their propagation direction. The oscillation period of v_s and the wavelength of undular borelike disturbances in this study seem to be somewhat longer than those measured by Fulton et al. (1990) in the U.S. Midwest. The large-scale winter circulation in East Asia is dominated by the northeast winter monsoon. The cold front linked to a medium-scale cycle generally follows a cold-air outbreak. Can it be possible for the East Asian borelike disturbances to behave somewhat differently from those in the U.S. Great Plains, because of the dif-

[2]S.-Y. Wang (third author) took the roll cloud picture (Fig. 1) from the roof of the NCU Atmospheric Science Building. This provided him with a chance to witness the passage of the roll cloud. According to his observation, the sky was cloudless with calm winds before the passage. However, the approaching roll cloud contained strong rotation with upward motion on the forward side like the roll vortex at the front of the cold outflow current observed by Fulton et al. (1990, their Fig. 7). During the passage, temperatures dropped rapidly and winds became gusty from the southwest. The entire episode took about 20–30 min. The sky was clear again after the passage, although the visibility was lower than that before the passage.

ferent synoptic environment? More accurate measurements and detailed analyses are needed to answer this question.

4. Concluding remarks

In this study, we analyzed a series of cloud bands associated with undular borelike disturbances observed on 11 January 1998 in East Asia. Several interesting features of this lower-tropospheric phenomenon were discovered from our analysis. They include the following.

1) The contrast between the GMS infrared images of roll clouds and the JMA surface charts revealed clearly that some cloud bands are located behind the cold front.
2) As shown by the upper-air soundings at Taipei, a very shallow nocturnally formed inversion layer at 0000 UTC (i.e., 0800 LST) prior to the passage of the cold front was replaced by a well-developed thick one at 1200 UTC (i.e., 2000 LST) after the frontal passage.
3) The first roll cloud was observed at 1400 LST at the NCU campus one hour after the passage of the cold front through the NCU surface station at 1300 LST.

These observations suggest that the undular borelike disturbances documented in this study were generated by the *modified density current* (Fulton et al. 1990; Locatelli et al. 1998).

Fulton et al. (1990) made a detailed analysis of undular disturbances initiated by a nocturnal thunderstorm density current in Oklahoma. However, some differences exist between some characteristics of the U.S. Midwest and East Asian undular disturbances.

1) The SW–NE extents of some cloud bands in East Asia can stretch over a thousand kilometers. The dimensions of roll clouds along their propagation direction are thin in their SW end but become thicker to the NE end toward the medium-scale cyclone. The horizontal dimensions of the U.S. Midwest solitary disturbances seem to be shorter.
2) Humidity increases and temperature drops after the cold front passage in northern Australia and the U.S. Midwest; however, humidity increased over the next several hours after the frontal passage in the East Asian case observed at the NCU station.
3) The life cycle and wavelength of the undular borelike disturbances are somewhat *longer* in East Asia than those observed by Fulton et al. (1990) over the U.S. Midwest.

These comparisons lead us to speculate that the different synoptic environment between East Asia and the U.S. Midwest may be related to the differences described above. Since only one case was investigated in this study, future efforts will be needed to explore in further detail the cloud bands and their associated undular borelike disturbances for other cases.

In addition to the academic interest, the roll clouds may have practical consequences. The location of the Taipei international airport is about 5–6 km northwest of the NCU campus and about 10 km east of the northwest coast of Taiwan. The runway of this airport is oriented along the SW–NE direction, almost parallel with the roll clouds (namely, the undular borelike disturbances). These cloud bands and undular borelike disturbances may possibly be hazardous to air traffic. Thus, our understanding of this lower-tropospheric phenomenon may be helpful in improving forecasts for the regional weather systems so that warnings can be accurately issued. Although the region west of Taiwan is a 100-km-wide strait, some existing meteorological facilities in northwestern Taiwan can be applied to engage more extensive observation of this phenomenon. These facilities include a Weather Surveillance Radar-1988 Doppler system (Crum and Alberty 1993) in northern Taiwan, a vertical profiler (Carter et al. 1995) on the NCU campus, a radiosonde launching station at Taipei, a receiver station of the GMS images in the Remote Sensing Center at NCU, an Automatic Rainfall and Meteorological Telemetry System (Hsu 1998; Chen et al. 1998b) administered by the Taiwan Weather Bureau, and autonomous aerosondes (Holland et al. 1992) owned by the National Science Council of Taiwan. A successful Central Australian Fronts Experiment was executed in 1991 (Smith et al. 1995) to explore the temporal evaluation of the cold front from central Australia and its link with the southerly morning glory. In view of this success, we suggest that the available facilities in northern Taiwan be used to launch a field experiment so that the roll clouds and the associated undular borelike disturbances in East Asia can be better understood.

The cold surge in East Asia, which results from the cold air outbreak, is one of the most extensively researched aspects of the East Asian winter monsoon. As reflected by some previous review articles (e.g., Boyle and Chen 1987; Lau and Chang 1987), the linkage of cold surge with the large-scale winter monsoon circulation in East Asia has been the primary research focus in the East Asian meteorological community. Actually, the winter monsoon research should include not only the upscale interaction but also the downscale one. The current study showed that the temporal evolution of cold fronts and their relationship with mesoscale systems such as roll clouds and undular borelike disturbances should be integral parts of winter monsoon research.

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