Coexistence of Atmospheric Gravity Waves and Boundary Layer Rolls Observed by SAR*

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ABSTRACT

Both atmospheric gravity waves (AGW) and marine atmospheric boundary layer (MABL) rolls are simultaneously observed on an *Environmental Satellite (Envisat)* advanced synthetic aperture radar (ASAR) image acquired along the China coast on 22 May 2005. The synthetic aperture radar (SAR) image covers about 400 km $\times$ 400 km of a coastal area of the Yellow Sea. The sea surface imprints of AGW show the patterns of both a transverse wave along the coastal plain and a diverging wave in the lee of Mount Laoshan (1133-m peak), which indicate that terrain forcing affects the formation of AGW. The AGW have a wavelength of 8–10 km and extend about 100 km offshore. Model simulation shows that these waves have an amplitude over 3 km. Finer-scale ($\sim$ 2 km) brushlike roughness features perpendicular to the coast are also observed, and they are interpreted as MABL rolls. The FFT analysis shows that the roll wavelengths vary spatially. The two-way interactive, triply nested grid (9–3–1 km) Weather Research and Forecasting Model (WRF) simulation reproduces AGW-generated wind perturbations that are in phase at all levels, reaching up to the 700-hPa level for the diverging AGW and the 900-hPa level for the transverse AGW. The WRF simulation also reveals that dynamic instability, rather than thermodynamic instability, is the cause for the MABL roll generation. Differences in atmospheric inflection-point level and instability at different locations are reasons why the roll wavelengths vary spatially.

1. Introduction

Mesoscale marine atmospheric boundary layer (MABL) phenomena are frequently observed by satellite sensors. They appear either as organized cloud patterns in visible–infrared satellite images or as coherent patterns on the sea surface in microwave synthetic aperture radar (SAR) images. Since the 1990s, abundant high-resolution and wide-swath SAR images have become available from

European Remote Sensing Satellites-1 and -2 (ERS-1/2), Radar Satellite-1 and -2 (RADARSAT-1/2), Environmental Satellite (Envisat), and other satellites. These SAR images provide detailed observations of sea surface imprints of many MABL phenomena in all weather and day–night conditions. SAR measures the variation in normalized radar cross section (NRCS) from the wind-roughened sea surface. Any wind variation associated with MABL phenomena will change the sea surface roughness, and as a result they can be imaged by SAR through the Bragg resonant-scattering mechanism (Valenzuela 1978).

In the literature, SAR-imaged MABL phenomena include various types of atmospheric gravity waves (AGW) (Vachon et al. 1994; Zheng et al. 1998; Chunchuzov et al. 2000; Li et al. 2004; Li 2004; Gan et al. 2008; X. Li et al. 2011), vortex streets (Li et al. 2000, 2008), coastal katabatic winds (Alpers et al. 1998; Li et al. 2007), boundary layer rolls (Alpers and Brümmer 1994; Levy 2001), gap

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FIG. 1. An *Envisat* ASAR WSM image acquired at 0204:25 UTC 22 May 2005 showed alternate bright–dark patterns off the Yellow Sea coast of China in the vicinity of Qingdao. These 8.5-km wavelength wavelike patterns are interpreted as sea surface imprints of AGW. Smaller 1.5–2-km-scale atmospheric boundary rolls are also presented in the SAR image seen in Fig. 7 and the roll's orientation is perpendicular to that of the AGW. Boxes A and B are referenced in Fig. 7.

winds (Pan and Smith 1999), tropical storms and polar mesoscale cyclones (Atlas 1994; Sikora et al. 2000; Li et al. 2012), coastal jets (Sandvik and Furevik 2002; Shimada and Kawamura 2004; Winstead et al. 2006; Isoguchi et al. 2011), fronts and eddies (Ivanov et al. 2004; Young et al. 2005; Young and Winstead 2005), atmospheric convective cells (Ufermann and Romeiser 1999; Babin et al. 2003; Romeiser et al. 2004; Sikora et al. 2011; H. Li et al. 2011), and cold-air outbreaks (CAO) (Mourad and Walter 1996), among others.

Interactions among different MABL phenomena—that is, between roll and CAO (Müller et al. 1999), AGW and CAO (Winstead et al. 2002), and wind and atmospheric eddy (Alpers et al. 2011)—were also observed by SAR. In this study, we present a unique observation of different types of AGW and MABL rolls on an *Envisat* wide-swath-mode SAR image, covering the Yellow Sea coast of China (Fig. 1). Both transverse and diverging types of AGW are shown in the image. The transverse AGW appears along the coastline, and the diverging

AGW appears on the lee side of Mount Laoshan (1133 m). MABL rolls also simultaneously exist near the coast. Their scale is much smaller and the direction is perpendicular to that of the AGW.

To understand the characteristics of MABL phenomena, we can convert NRCS measured from calibrated SAR to measurements of the sea surface wind field using the existing geophysical model functions (GMFs)—that is, the C-band Model Function, version 5 (CMOD5) for C-band SAR (Hersbach et al. 2007)—with good accuracy (Yang et al. 2010, 2011). In this sense, a SAR image not only shows the MABL phenomena patterns but also provides direct measurement of sea surface wind speed and its variation associated with the phenomena. The winds from SAR measurements make SAR a useful tool for quantitative MABL phenomena study. However, since all current SAR satellites are not operational satellites, these SAR observations are generally limited to one or two snapshots during the evolution of a MABL phenomenon. Visible–infrared images from operational

polar-orbiting and geostationary weather satellites have been also used to complement SAR observations in MABL phenomena studies (Ivanov et al. 2004). The visible–infrared images have better temporal coverage, but their spatial resolutions are usually one order of magnitude lower than that of SAR.

Limited snapshots of MABL phenomena by remote sensing sensors cannot typically reveal the generation and life span evolution of a MABL phenomenon. One of the recent developments in this research field is to take advantage of the rapidly advancing Community Atmosphere Mesoscale Model capabilities. The state-of-the-art fine-resolution (subkilometer spatial resolution) numerical weather prediction (NWP) model simulations can lead to improved understanding of MABL phenomena. In the past, we have implemented the community fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5) (Grell et al. 1995) and the Weather Research and Forecasting Model (WRF) (Skamarock et al. 2008) NWP models to simulate SAR-observed katabatic winds (Li et al. 2007), vortex streets (Li et al. 2008), and AGW (X. Li et al. 2011), and have obtained insight concerning the generation mechanism and evolution of these MABL phenomena. However, NWP simulation of extra-finescale MABL structures—that is, MABL rolls—is still a challenge because of model spatial resolution even with nested-domain model implementations. Nevertheless, model simulations provide background information necessary to help us understand the entire physical process. In this study, our results show that the generation mechanisms for the AGW and the rolls are different. Terrain forcing is the generation mechanism for AGW, but atmospheric dynamic instability, not the conventional thermal instability, is the generation mechanism for rolls.

This paper is organized as follows, we first present the *Envisat* SAR observation of AGW and MABL rolls in section 2. Next, in section 3, we study the transverse and diverging types of AGW using SAR-derived surface winds and time series of environmental variables from WRF simulation. In section 4, the standard FFT method is used to extract MABL roll characteristics, including dominant wavelength and associated wind direction. Using WRF simulation results, we analyze the generation mechanism of MABL rolls and the cause of the spatial variation of roll wavelength. Discussions and conclusions are in section 5.

2. Satellite SAR observation

The SAR image (Fig. 1) used in this study is an *Envisat* wide-swath mode (WSM) image acquired at 0204:25 UTC

22 May 2005. The WSM SAR provides a medium-resolution (75-m pixel spacing and 150-m spatial resolution) image with a swath of 405 km, at either horizontal (HH) or vertical polarization (VV). Figure 1 is a VV image. The image center is at about 35.0°N, 120.5°E, and it covers the Yellow Sea coast of China.

MABL phenomena development is common in this area (Liu et al. 2010), especially during the spring season because of the existence of a stable MABL. AGW were observed in the lee of Mount Laoshan (X. Li et al. 2011) and along an atmospheric front (Liu et al. 2010). In Fig. 1, there are three phenomena contained in this image: 1) a distinguished diverging AGW on the lee side of Mount Laoshan at the top of the image; 2) an alternate bright–dark transverse AGW in the middle part of the image; and 3) a brushlike wind pattern perpendicular to the coastline that existed in both AGW regions. The transverse and diverging AGW have a similar wavelength of 8–10 km. The diverging angle between the two arms of the diverging AGW is about 25°, and the transverse AGW is perpendicular to the local wind direction and more or less parallel to the coastline. The length of the transverse AGW crest is about 150 km. The brushlike wind roll pattern is the sea surface imprint of MABL rolls. The rolls' spatial scale (~2 km) is small so that they are less pronounced than the AGW patterns, but their characteristics are shown very clearly in the spectral domain (see analysis in section 4).

3. Atmospheric gravity waves

a. SAR-derived sea surface winds associated with AGW

AGW changes the low-level atmospheric pressure, temperature, and wind fields. Among these parameters, SAR can image periodical oscillation of winds over the sea surface directly. In Fig. 1, the sea surface imprints of both transverse and diverging types of AGW are shown. As we pointed out in the introduction, a well-calibrated SAR image can also be converted to a wind image as shown in Fig. 2a. For computing winds, we first average the NRCS values from all SAR pixels within a 1 km × 1 km cell to reduce the SAR speckle noise and then generate a 1-km SAR wind image using standard National Oceanic and Atmospheric Administration (NOAA) SAR wind processing procedures (Li et al. 2007; X. Li et al. 2011). To derive SAR wind speed, the NOAA National Centers for Environmental Prediction (NCEP) operational Global Forecast System (GFS) model wind directions closest to the SAR imaging time are used. The GFS model wind has a 1° × 1° resolution. We further interpolate the wind directions to each averaged SAR area

FIG. 2. Sea surface wind field (at 10-m height) derived from (a) SAR measurements and (b) WRF simulation. The WRF result is at 0200:00 UTC 22 May 2005.

and then apply the CMOD geophysical model function to derive a SAR-wind image. Wind directions from other independent sources can also be used for SAR-wind retrievals. In this case, the surface winds from the operational NOAA GFS and higher-resolution WRF (shown in section 3b) agree that wind direction was in the offshore direction at the SAR imaging time. Sea surface wind retrieval from C-band SAR is within a 2 m s^{-1} error range when validated against other measurements from scatterometer, buoy, and outputs from weather models (Yang et al. 2010, 2011). In the coastal region between 34° and 36°N , the sea surface winds (at 10-m height) associated with transverse AGW vary between about 4 and 20 m s^{-1} . The wind in the

diverging area is slightly higher, and the wind associated with the left arm is higher than that with the right arm. The wind pattern extends to about 100 km offshore.

b. AGW simulation with WRF

To understand the dynamic mechanisms that induce this phenomenon, we implement the WRF version 3 (Skamarock et al. 2008) to simulate the actual low-level atmospheric circulation associated with this group of AGW. We use a two-way interactive, triply nested grid technique. The center of the computation domain is located at 35.50°N , 120.50°E , and the configuration consists of a 9-km outer coarse domain with a horizontal

FIG. 3. WRF domain used in this case study. Three red boxes represent a triple nested grid with spatial resolutions of 9, 3, and 1 km, respectively.

grid of 280×251 grid points, a 3-km medium domain with a horizontal grid of 310×301 grid points, and an inner high-resolution 1-km domain with a horizontal grid of 271×262 grid points. The model domain is shown in Fig. 3. Mount Laoshan is in the middle of the smallest box. A total of 27 full σ levels in the vertical axis are used with the model top at a level of 50 hPa. The physical parameterizations of the model are the same as those contained in our previous studies (Li et al. 2007; X. Li et al. 2011). The outermost coarse-mesh lateral boundary conditions are specified by linearly interpolating the NCEP 6-hourly final analyses (FNL) at a resolution of $1^\circ \times 1^\circ$. The model begins at 1200 UTC 21 May 2005 and then integrates continuously for 24 h.

In the SAR coverage domain, the sea surface wind field simulated by the WRF at 0200 UTC (a few minutes before the SAR imaging time) is shown in Fig. 2b. In general, the WRF-simulated sea surface wind (at 10-m height) clearly shows that the AGW patterns resemble the SAR observation.

Figure 4 shows the histograms of winds retrieved from the SAR image and simulated with WRF. One can see that the two histograms are similar in shape but there is a mean bias of about 3 m s^{-1} . This systematic difference

between the winds from these two independent sources is understandable since both retrieval schemes are complex in nature. WRF shows more distinct AGW patterns, reaching farther offshore than that observed by SAR. The brushlike wind pattern associated with atmospheric boundary layer rolls is very clear, but the detailed boundary layer roll spacing is not well resolved

FIG. 4. Histogram of sea surface winds from WRF simulation and SAR retrieval.

FIG. 5. Vertical wind field at 950 mb simulated by WRF at 0200:00 UTC 22 May 2005. Land is marked in green.

since the WRF resolution is not as high as that of the SAR image.

Figure 5 shows the 950-hPa vertical wind velocity field at 0200 UTC simulated by WRF. The strongest perturbation induced by AGW happens near Mount Laoshan, which peaks at 1133 m above sea level. Two arms of diverging AGW are clearly visible, and the amplitude of diverging AGW gradually reduces away from the coast. SAR only clearly observed one arm of the diverging AGW, and this is due to the SAR instrument-viewing geometry with respect to the AGW orientation. The asymmetry of the two arms of diverging AGW on a SAR image is similar to the asymmetry of V-shaped Kelvin ship wakes in SAR images (Hennings et al. 1999). The vertical velocity along any crest of a transverse AGW is not uniform. There are some valleys in the transverse AGW pattern. This is due to the strong low-level offshore horizontal wind cutting through the AGW.

Figure 6 shows the WRF-simulated horizontal wind field at different heights. Ambient wind speed increases with altitude, but the wind direction remains the same at all levels. While the transverse AGW reaches up to the 900-hPa level (~ 1000 m), the diverging AGW reaches a much higher altitude—to the level of 700 hPa (~ 3000 m), about 3 times the height of Mount Laoshan. The shape of the shadow of the diverging AGW remains the same at all levels. The upward perturbation in the diverging AGW region is due to the stronger vertical wind perturbation associated with it (Fig. 3).

One of the basic characteristics of AGW is that both transverse and diverging AGW are standing waves

(X. Li et al. 2011). In this case, the WRF simulation reveals that the AGW pattern reacts to the synoptic wind direction change (shown in the movie loop in the supplemental material at the Journals Online website: <http://dx.doi.org/10.1175/JAS-D-12-0347.s1>). Both the transverse and diverging AGW patterns align with the mean wind direction. When the mean synoptic wind direction changes, the reorientation of AGW patterns follows instantaneously. However, the wavelength and wind speed perturbation as well as the AGW location with respect to the coastline do not change.

4. Marine atmospheric boundary layer rolls

As we discussed in section 2, there is brushlike wind pattern superposed on the AGW. A zoomed full-resolution SAR sub-image is shown in Fig. 7a. Quasi-periodic streaks are clearly seen on the sea surface. These features are interpreted as the sea surface imprint of atmospheric boundary layer rolls, and they are aligned with the mean wind direction from the WRF simulation. A SAR image can be used to detect the MABL rolls, because rolls modulate the sea surface roughness on the centimeter scale that is sensed by SAR via the change of the Bragg wave spectrum (Alpers and Brümmer 1994; Mourad and Walter 1996; Müller et al. 1999; Levy 2001). Roughness is related to the wind speed and thus from the calibrated NRCS, the wind direction and the wind speed can be derived from the SAR image. The streak pattern in sea surface roughness can be explained by a change in the surface wind speed due to the formation of boundary layer rolls.

FIG. 6. WRF-simulated low-level atmospheric circulations at different heights associated with the atmospheric gravity waves at 0200:00 UTC 22 May 2005.

MABL rolls are quasi-helical secondary circulations superimposed on the mean wind within the MABL (Alpers and Brümmer 1994) capped by the inversion layer. The mechanisms for generating atmospheric boundary layer rolls can be attributed to dynamic or thermodynamic instability in the boundary layer. Thermodynamic and dynamic instabilities refer to the rising (sinking) air motion at the bottom (top) of the MABL due to diabatic heating (cooling) and the vertical wind shear in the MABL, respectively. Using the FFT method, we show in Fig. 7b the wavelengths of the rolls in boxes A and B (in Fig. 1) to be 2267 and 1697 m, respectively. This indicates that the MABL roll wavelength varies greatly in the study area. The orientations of these rolls in boxes A and B are the same, 57.2° with respect to north.

To investigate the mechanisms of the roll formation and its spatial variation, the WRF simulation outputs are analyzed. Figure 8 shows the vertical profiles of temperature averaged over the area of boxes A and B 1 h

before the SAR image was taken. The radiosonde measurements at Qingdao Station in China at 0000 UTC 22 May 2005 are also plotted on the figure to show that model results and measurements are consistent. The mean sea surface temperatures are also shown on the horizontal axis. It is noticed first that the sea surface temperature is lower than the near-surface air temperature, indicating that the boundary layer investigated here is stable. A not-well-defined mixed layer is noticed in box A. No capping inversion layer existed in either box A or B. This thermodynamic condition suggests that the rolls detected by the SAR image were not driven by thermodynamic instability (Etling and Brown 1993; Young et al. 2002). We thus hypothesize that the rolls were generated by the dynamic instability (i.e., the inflection-point instability). Inflection-point instability related to boundary layer shear flow has been well documented in previous theoretical papers (Lilly 1966; Brown 1972; LeMone 1973; Brown 1980). Detailed equations on MABL roll development due to inflection-point instability can be

FIG. 7. (a). Full-resolution SAR subimages of scene in Fig. 1. Box B in Fig. 1 shows the brushlike atmospheric boundary roll patterns. (b) FFT analysis of the subimages of boxes A and B in Fig. 1 showing the dominant orientation and wavelength of atmospheric boundary layer rolls.

found in the review paper by Brown (1972). Figure 9 shows the mean WRF-simulated wind profiles averaged over the area of boxes A and B, and the wind data from the same radiosonde measurements as in Fig. 8. It shows that there is a clear inflection point in the wind profiles at heights of 1800 and 1200 m, respectively. This confirms our above-mentioned hypothesis that the inflection instability plays a key role in the formation of rolls in this case. The height of the inflection point in box A is higher than that in box B, which may be one of the reasons why the wavelength of the rolls in box A is longer than that in

box B according to the roll theory (Brown 1980). Another reason for the longer wavelength in box A is that the boundary layer in box A is more stable than that in box B. A stable boundary layer tends to suppress the development of rolls (Wippermann et al. 1978). It is also possible that rolls interact with the gravity wave. As the wavelength of the gravity wave is much larger than that of the rolls, the large-scale flow may transfer energy to the relatively small coherent structure and generate large eddies.

In this study, the WRF simulation does not reveal the MABL rolls directly. Although the finest horizontal

FIG. 8. Vertical profiles of mean temperature averaged over the area of boxes A and B. Mean sea surface temperature and the two boxes are also shown. Dashed line is the radiosonde measurements made at Qingdao station at 0000 UTC 22 May 2005.

FIG. 9. Vertical profiles of mean wind speed averaged over the area of boxes A and B. Dashed line is the radiosonde measurements made at Qingdao station at 0000 UTC 22 May 2005.

resolution of the WRF grid is 1 km, the resolution is usually not sufficient to capture the rolls with a wavelength of 2 km. Moreover, in order to simulate a physical phenomenon, the “physics” of this phenomenon must be built into the model. Simulations with different standard model settings were performed, and it appears that the roll cannot be simulated directly for this case.

5. Discussion and conclusions

In this study, transverse and diverging patterns of AGW are observed in an *Envisat* SAR image off the Yellow Sea coast of China at 0204:25 UTC 22 May 2005. Terrain forcing by Mount Laoshan causes the diverging AGW pattern. The vertical wind perturbation is strongest, reaching up to 1.5 m s^{-1} and the 700-hPa level (Fig. 3), near the mountain and gradually reduces away from the coast. The WRF simulation study shows that AGW are standing waves with fixed wavelength and orientation with respect to the local ambient wind. When the local wind direction changes because of a change in the synoptic weather system, the diverging AGW retains its shape but its orientation changes accordingly. In the coastal plain area, AGW show a transverse pattern that is parallel to the coastline. The vertical wind perturbation associated with the transverse AGW reaches up to the 900-hPa level (Fig. 5), which is much lower than the 700-hPa level reached by the diverging AGW near the mountain.

The vertical wind perturbation varies along any transverse wave crest. Collectively, it looks like the offshore wind blows across the transverse wave train and creates valleys that are perpendicular to the transverse wave

crests. It is clearly seen that a brushlike wind pattern is superposed on the transverse AGW. The brushlike wind pattern is the secondary circulation associated with MABL rolls, whose scale also varies at different locations. The WRF simulation shows that no atmospheric inversion layer existed when the SAR image was taken. This fact suggests that dynamic inflection-point instability is the cause for MABL roll generation. In addition, the atmospheric inflection-point level and instability vary greatly at different locations. These are possible reasons why MABL roll wavelengths vary spatially as shown in Fig. 7b.

Cross sections of Scorer and Richardson numbers calculated from the WRF simulation along the east–west cross section centered at the location of Mount Laoshan (36.19°N , 120.59°E) are given in Figs. 10 and 11, respectively. Theoretically, when the Scorer number is sufficiently small, the associated AGW energy does not propagate upward and is trapped within a waveguide (Da Silva and Magalhães 2009). Figure 10 shows that the Scorer number varies along the cross section in the low-level atmosphere because of the existence of AGW. At the 3-km level, the Scorer number is close to zero, meaning that the AGW is trapped between the sea surface and an altitude of 3 km.

The Richardson number (Ri) is the ratio of the static stability (Brunt–Väisälä frequency N^2) to the square of the wind shear (dU/dz). When $Ri < 0$, the atmosphere is unstable and demonstrates convective instability. When $Ri > 0.25$, the atmosphere is dynamically stable. For $0 \leq Ri \leq 0.25$, the airflow is in dynamic instability (Nappo 2002). Dynamic instability can happen even in a statically stable flow, when the wind shear is strong enough

FIG. 10. Cross section of the Scorer number ($\times 10^{-6} \text{ m}^{-2}$) calculated from the WRF simulation along the east–west cross section centered at the location of Mount Laoshan. Gray no-data area represents the shape of the mountain.

to break up the stable layer. In the $0 \leq \text{Ri} \leq 0.25$ range, the heat and momentum fluxes become large and the turbulence feeds the momentum and energy from the background flow into AGW, causing the AGW amplitude to increase (Chimonas 1972). Figure 11 shows that $0 \leq \text{Ri} \leq 0.25$ at low levels in the atmosphere. The background meteorological condition is favorable for the generation of AGW. This is consistent with our

analysis of the atmospheric boundary layer roll generation mechanism.

In this study, we demonstrate the advantage of wide-swath (400–500-km swath) SAR in MABL phenomena studies, as it covers multiple MABL phenomena in one synoptic view with high spatial resolution. In general, the WRF-simulated sea surface winds and SAR-derived winds match very well (Fig. 2). The advantage of WRF

FIG. 11. As in Fig. 10, but for the Richardson number.

simulation is that it reveals the vertical perturbations and time series of the AGW process, which cannot be observed by SAR. The advantage of SAR is that it can observe even smaller MABL phenomena that cannot be simulated by WRF. Although WRF cannot simulate small-scale MABL rolls directly, it can provide additional background information that can be used to understand the generation mechanism and spatial variation of MABL rolls. This study shows that synergy between SAR observation and community WRF simulation reveals the entire life span of these MABL phenomena.

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