Sea surface imprints of coastal mountain lee waves imaged by synthetic aperture radar

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Received 7 September 2010; revised 26 October 2010; accepted 7 December 2010; published 12 February 2011.

[1] A group of mountain lee waves is observed on an Envisat advanced synthetic aperture radar (SAR) image on the lee side of Mountain Laoshan (1133 m) along the Yellow Sea coast of China. The lee waves are shown as alternating bright and dark patterns on the SAR image, indicating the ocean surface wind oscillation associated with atmospheric wavefield. The horizontal wind variation between wave crest and trough is from 7 to 17 m/s. A Moderate Resolution Imaging Spectroradiometer image acquired about 8.5 h prior to the SAR pass also showed the same group of standing lee waves. The cloud pattern matches the high-wind pattern in the SAR-derived wind image. The mesoscale Weather Research and Forecasting (WRF) model is used to simulate the lee wave phenomenon. We run the triply nested grid model with the highest horizontal resolution of 1 km. The WRF model successfully captures the characteristics of the lee wave. The waves are generated by the terrain forcing and the wave-induced perturbation propagates very strongly upward to the 500 hPa level. The event lasts about 24 h. Based on the WRF model wind results, we run a radar imaging model to simulate the SAR observation. The normalized radar cross section (NRCS) variations induced by the lee wave are compared between the radar simulation and the actual SAR observation. Reasonable agreement is reached.


1. Introduction

[2] Orographic effects on stratified airflow can lead to the development of atmospheric gravity waves (AGW) in the low-level atmosphere around these obstacles, i.e., isolated mountains or islands. These AGW, once generated, can exist in both upstream and downstream directions. Most of the observed AGW occur in the downstream direction and they are referred to as lee waves. A lee wave is a type of standing gravity wave which can have one of two different types of wave crest patterns: (1) the transverse type where the wave crests are perpendicular to the wind direction or (2) the diverging type where the wave crests are oriented outward from the center of the wake [Li et al., 1998]. As for which type of lee wave exists, the wavelength and the diverging wave orientation angle with respect to the mean flow depend upon the atmospheric Froude number (Fr) and the height of the obstacle [Baines, 1995]. Under a unique atmospheric condition where Fr = 1, AGW can also be generated in the form of a train of soliton pulses that propagate against the mean flow in the upstream direction [Li et al., 2004].

[3] Over the ocean, the low-level wind associated with the AGW modulates the sea surface capillary wave spectra, and thus, leave an alternating bright-dark roughness pattern associated with the wave crest-trough on the sea surface. This roughness pattern can be imaged by spaceborne synthetic aperture radar (SAR) through the Bragg resonant scattering mechanism [Valenzuela, 1978]. In the literature, the sea surface imprints of orographically generated AGW in transverse [Vachon et al., 1994], diverging [Li et al., 1998; Chunchuzov et al., 2000] and upstream [Li et al., 2004; Gan et al., 2008] forms have all been studied using spaceborne SAR images.

[4] Marine AGW are believed to be trapped in the marine atmospheric boundary layer (MABL) capped by the atmospheric inversion at a height of approximately 1 km. Diagnostic analysis of these SAR-observed AGWs is primarily based on conceptual layered analytical models. In the lee wave case, a linear wave-like solution can be obtained in a three-layer system [Chunchuzov et al., 2000]. In the upstream AGW case, the linear AGW solution breaks down because the Fr is close to 1, but the upstream wave solution can still be obtained by solving the forced KdV equation [Li et al., 2004]. These theoretical models are usually driven by radiosonde data measured within 100 km and 6 h of the SAR image. In order for a layered model to simulate the characteristics of AGW at the SAR imaging time, these radiosonde data are allowed to vary as much as 30% to
represent the actual atmospheric conditions [Chunchuzov et al., 2000]. Although conceptual models may provide some basic understanding of wave development within the range of some parameters and idealized topography, they have limitations in providing a complete understanding of the nature of the lee wave’s three-dimensional patterns and the time evolution of the AGW under actual atmospheric conditions with complex topography. In addition, only dynamic wave motion can usually be studied using the ideal theoretical model; the other environmental parameters, i.e., thermal and cloud parameters, cannot be addressed.

With the advance in atmospheric model development in recent years, researchers can now apply community weather models to simulate many types of SAR-observed MABL phenomena including island wakes [Pan and Smith, 1999], barrier jet and gap flow [Winstead et al., 2006], coastal katabatic winds [Li et al., 2007] and atmospheric vortex streets [Li et al., 2008] in great detail. It is the purpose of this study to further the SAR model study by using the state-of-the-art community Weather Research and Forecasting (WRF) model with actual atmospheric conditions as inputs to study a group of mountain-generated coastal lee waves observed by the advanced SAR (ASAR) onboard the European Space Agency’s Envisat. The WRF model reveals much more detailed AGW information than can be obtained using previous analytic models.

In this paper, section 2 presents the satellite observations of the AGW and their basic characteristics. In section 3, we describe the WRF model setup and AGW simulation results. Then, a M4S radar simulation model is used in section 4 to simulate the normalized radar cross section (NRCS) variations caused by sea surface wind field variations associated with the AGW. The wind field is given by the WRF model run at the SAR imaging time. Discussion and conclusions are given in section 5.

2. Satellite Observations

2.1. Coastal Mountain Lee Waves on a SAR Image

Figure 1 (top) is an Envisat ASAR image acquired on 9 November 2005 showing the sea surface manifestation of atmospheric gravity waves on the lee side of Mountain Laoshan (1133 m) off the Yellow Sea coast, China. (bottom) Ocean surface wind field derived from the ASAR image of Figure 1a. The CMOD5 geophysical model function is used to convert the calibrated normalized radar cross section measurements to a wind field. The blue arrow illustrates the wind direction from an operational meteorological model, NOGAPS. The NOGAPS model wind direction is used as input to calculate SAR wind.

In the SAR image, there is a group of eight alternated bright-dark features to the east of Mountain Laoshan. They are interpreted as atmospheric lee waves. The brighter area represents an area of higher roughness (higher NRCS value) associated with higher sea surface winds. The AGW orients in the east-west direction and its measured wavelength is about 12 km. The wave train extends over 100 km offshore.

The sea surface wind field can be derived from a calibrated SAR image. Unlike scatterometers, SAR instruments have only one view angle. Therefore, one NRCS value in a
SAR image may correspond to multiple pairs of wind speed and direction. In order to calculate a wind image based on the SAR image, one must first obtain wind direction from independent sources. In the SAR wind processing operational environment, wind directions from global meteorological models, i.e., NOAA’s Global Forecast System (GFS) model or the U.S. Navy Operational Global Atmospheric Prediction System (NOGAPS) model, are often used. The semi-theoretical and semiempirical geophysical model functions (GMFs) that convert calibrated NRCS to sea surface wind have long been developed and validated against in situ buoys. The GMF’s, i.e., CMOD4, CMOD5, and CMOD IRF2, wind retrieval accuracy from SAR is under 2 m/s standard deviation [Xu et al., 2010]. We process the SAR image (Figure 1, top) into a sea surface wind image (Figure 1, bottom) using the CMOD5 GMF with wind direction from the NOGAPS model. The NOGAPS wind has a 1° × 1° resolution and the model wind direction (blue arrow in Figure 1, bottom) at 36°N, 121°E grid point is used for SAR wind retrieval. AGW patterns are clearly seen in the SAR wind image. The horizontal sea surface wind oscillates between 7 and 17 m/s in the trough and peak areas, indicating this is a strong group of AGW.

2.2. Moderate Resolution Imaging Spectroradiometer Observation

[10] The low-level atmospheric circulation can also modify the cloud structure when the atmospheric moisture content is high. When wind and moisture content are high, cloud bands associated with the AGW will be generated and can then be viewed on satellite visible images [Mitchell et al., 1990; Li et al., 2001; Zheng et al., 2004; Gan et al., 2008]. Figure 2 is a 250 m resolution true color image composited using three visible bands from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument onboard the NASA Aqua satellite. The MODIS image was taken at 0515 UTC on 9 November 2005. In Figure 2, the remapped MODIS image covers an area between 35.5°–36.8°N and 120.2°–122°E. The color-coded semitransparent SAR wind image is overlaid on the MODIS image in Figure 2. Although these images are taken 8.5 h apart, there is a one-to-one correlation between the high-low wind band and the cloud band. The white cloud band corresponds to the orange higher-surface-wind band. This confirms that the AGW are stationary waves, and the atmospheric condition did not change greatly during the period of observation.

3. WRF Mesoscale Model Simulation

[11] In order to understand the dynamic mechanisms which induce this phenomenon, we use the WRF model version 3 [Skamarock et al., 2008] to simulate the actual low-level atmospheric circulation associated with this group of AGW. The WRF model is a limited area, nonhydrostatic, mesoscale weather model which has demonstrated capability to simulate or predict mesoscale atmospheric circulation. We use a two-way interactive, triply nested grid technique and the configuration consists of a 9 km outer coarse domain with a horizontal grid of 280 × 251 grid points, a 3 km medium domain with a horizontal grid of 310 ×
301 grid points, and an inner 1 km finest domain with a horizontal grid of 271 × 262 grid points. A total of 27 full \( \sigma \) levels in the vertical axis are used with the model top at a level of 50 hPa. The WRF model contains multiple options for the physics parameterizations. In this study, the primary model physics includes the Rapid Radiative Transfer Model (RRTM) longwave radiation, Dudhia shortwave radiation, Yonsei University (YSU) planetary boundary layer scheme, WRF Single Moment 3-Class (WSM) cloud microphysics, Kain–Fritsch (new Eta) convective parameterization employed only in coarse and medium domains, Monin-Obukhov surface-layer scheme, and unified Noah land-surface model. The outermost coarse mesh lateral boundary conditions are specified by linearly interpolating the National Centers for Environment Prediction (NCEP) 6 hourly final analyses (FNL) at a resolution of 1° × 1° degree. The sea surface temperature is updated every day according to the FNL data. The digital elevation of 30 s United States Geological Survey (USGS) topography data is used in the simulation. The model begins at 0000 UTC on 9 November 2005 and then integrates continuously for 24 h.

Figure 3. WRF simulation of the atmospheric circulation at 850 hPa in the study region at 1400 UTC: (a) horizontal wind speed, (b) vertical wind speed, (c) low cloud fraction (integrated cloud fraction in the low level of the model domain), (d) PBL height, (e) relative humidity, and (f) potential temperature.
Figure 3 shows atmospheric conditions in the lower troposphere (850 hPa) simulated by the WRF model at 1400 UTC. These simulated atmospheric parameters include horizontal wind speed (Figure 3a), vertical wind speed (Figure 3b), low cloud fraction (Figure 3c), planetary boundary layer (PBL) height (Figure 3d), relative humidity (Figure 3e), and potential temperature (Figure 3f). Figures 3a–3f show wave patterns similar to the satellite observations. We draw a line perpendicular to the wave crest from the coast near Mountain Laoshan and extract a cross section of the WRF-modeled horizontal wind field along the line. We then overlay this surface wind speed data with the independent SAR-measured wind field in Figure 4. The horizontal and vertical wind oscillation scale is the same, but there is some understandable systematic dynamical wind range difference. On average the SAR wind is about 2.64 m/s higher than that simulated by the WRF model. Compared to the horizontal wind field pattern, the vertical wind shows a much clearer wave-like motion. The strongest perturbation happens near Mountain Laoshan, gradually decaying away from the mountain. The cloud fraction pattern (Figure 3c) and relative humidity (Figure 3e) shows cloud and water vapor distribution that exactly matches the MODIS cloud image. The PBL is closely related to the AGW. It mediates the exchanges of momentum and mass between the sea surface and the atmosphere. The depth of the PBL is largely related to locally generated buoyancy fluxes and static stability as well as convective movement. One can see from Figure 3d, the PBL height field closely matches the vertical wind speed field. Potential temperature plot (Figure 3f) indicates that AGW motion induces the temperature variation at 850 hPa, which resembles the variations of other fields. Overall, the simulation captured all surface field variations associated with this group of AGW.

Figure 5 shows a cross section of vertical velocity and potential temperature along the white line in Figures 4b and 4c. The shape of the mountain is indicated in the lower left corner. The vertical velocity field shows that the AGW motion can reach above 10 km over the sea surface. The potential temperature contour lines show a similar but weaker pattern. Although the first and biggest wave can be seen at height of 5.5 km in the potential temperature chart, the whole group of AGW signatures is only observed at the 2.5 km height level. In the literature, the consensus is that the SAR-observed AGW are supposed to be trapped in the MABL with height of 1 to 2 km. They modulate airflow and generate cloud and sea surface roughness bands at the top and bottom of the MABL, respectively. The bands are shown in the satellite visible, infrared and microwave images. However, the results of this simulation show that AGW reach far higher in the upper atmosphere.

The time series of the WRF simulation (Figure 6) shows the AGW development and dissipation process. The left and right panels represent the time series of vertical velocity and cloud fraction in the lower troposphere throughout the day. The AGW is visible at 0600 UTC and it then becomes very distinguishable at 1200 UTC. The AGW weakens at 1800 UTC with broken cloud wave crest lines. The AGW dissipates further 6 h later. The life span of this wave is about one day. This is also confirmed by the satellite...
observations. The MODIS image taken at 0245 UTC the following day (not shown here) shows a clear sky in the study region with no wave-like cloud band.

4. Simulation of SAR Image

The WRF model simulation is performed independently from the SAR observation and the results reveal the AGW characteristics. Given the set of environmental conditions modeled by the WRF, the Envisat orbital parameters as well as radar parameters (C band, VV polarization, viewing geometry including incidence angle and radar look angle with respect to the mean wind direction), we can simulate SAR images using the community radar model: M4S (R. Romeiser, M4S 3.2.0 user’s manual, 2008, available at ftp://ftp.ifm.zmaw.de/outgoing/romeiser/M4S320/).

The M4S model can simulate the SAR image of a given surface current and wind field using different settings.

In this case, compared to the wind contribution to the modulation of NRCS, the effect from the background coastal ocean current is taken as small and uniform. Figure 7 shows the NRCS values simulated using the WRF model winds with the full composite surface model [Romeiser et al., 1997] and Elfouhaily et al.’s [1997] wave spectrum. Figure 7 (top) is the result from employing the composite model, and Figure 7 (bottom) is the same model run but with corresponding statistical noise properties. The simulated SAR NRCS images resemble the actual SAR observation and the AGW patterns are clearly seen.

Figure 8 shows the NRCS comparisons between the actual and M4S simulated SAR image along the white line in Figure 4b. The actual calibrated Envisat SAR radar cross section along the line is shown in blue. M4S simulation results with the full composite surface model using both Romeiser et al. [1997] (red) and Elfouhaily et al.’s [1997] (black) wave spectrum are presented. The 2.64 m/s systematic wind bias between the SAR retrieval and the WRF simulation is added to the M4S simulation. In general, the wave-like patterns agree well. The plot also shows a well-known fact that simulated NRCS values using Romeiser et al. [1997] and Elfouhaily et al.’s [1997] wave spectrum are usually higher and lower than the actual SAR calibrated NRCS value, respectively. The NRCS dynamic ranges for the simulation are much larger than that of Envisat SAR observation. This shows that the theoretical NRCS modulations are more sensitive to the wind input. The simulation results with the full composite surface model and Elfouhaily et al.’s [1997] wave spectrum are closer to the actual observation.

5. Discussion and Conclusions

In this study, a group of standing AGW was observed on the lee side of Mountain Laoshan along the Yellow Sea coast. The AGW happen in the local winter when the wind is strong and the atmosphere is in stable condition. The AGW wavelength is about 12 km and extends to over 100 km. Observations made by spaceborne SAR and MODIS sensors show that the AGW are indeed stationary waves. The cloud band is closely related to the high-wind band for 8.5 h. The horizontal wind variation between wave crest and trough is from 7 to 17 m/s.

Using the community WRF model, we successfully recaptured the low-level atmospheric circulation associated with the AGW. The AGW can be seen in the WRF model output fields including: horizontal wind speed, vertical wind speed, low cloud fraction, PBL height, relative humidity, and potential temperature. The 24 h WRF simulation also shows that the AGW is not trapped within the low-level waveguide capped by the atmospheric inversion layer usually at 1 km.
Figure 6. The time series (6 h interval starting at 0600 UTC on 9 November 2005) of WRF simulation of (left) vertical wind speed at 850 hPa and (right) low cloud fraction in the study region.
height, but waves generated at low altitudes leak upward to 10 km above sea level. The AGW has a clearer signature in wind data than in potential temperature data.

One of the most important parameters in mountain wave research is the atmospheric Scorer number, defined as ($\bar{\beta}^2$)

$$\bar{\beta}^2 = \frac{N(z)^2 \frac{\partial^2 u}{\partial z^2}}{u^2}.$$  

Where $N(z) = \left(\frac{g}{\theta} \frac{d\theta}{dz}\right)^{1/2}$ is the Brunt-Väisälä frequency and $u(z)$ is the wind speed. $\theta$ is potential temperature, $g$ is the local acceleration of gravity, and $z$ is geometric height. The cross section of $\bar{\beta}^2$ along the white line in Figures 4b and 4c is given in Figure 9. From the surface to 3 km, $\bar{\beta}^2$ is between 0.6 and $2 \times 10^{-6}$ m$^{-2}$, and its gradient is the largest, indicating a strong lee wave trapping mechanism in the troposphere [Teresa et al., 2010]. From about 3 to 10 km, $\bar{\beta}^2$ is small, between 0.1 and $0.2 \times 10^{-6}$ m$^{-2}$, and gradually decreases with height, a condition favorable for gravity waves to propagate upward in this region. In model simulation, the wave-like vertical wind field (Figure 5) is indeed shown at the height of 10 km. Therefore, there is a leaking part of the gravity waves that propagates upward. The wave propagation is in agreement with the vertical profile of the Scorer number. This is consistent with findings in the literature [Teresa et al., 2010]. Above a height of
10 km, $l^2$ increases slightly. In this region, our results confirm that there is no wave motion when $l^2$ increases with height [Scorer, 1954]. It is also worth noting in Figure 9 that the horizontal scale of the wave-like distribution of $l^2$ matches closely the shape of the mountain, a condition that leads to the development of large-amplitude mountain lee waves. The wave cross section shows that the waves are in phase at all levels, which explains why the MODIS cloud band and high-low-wind band are aligned at low altitude. The observation is made in local winter when the atmosphere is usually fairly stable. This geographic area is rich in developing atmospheric gravity waves in the winter and
spring seasons, because any disturbance to the strong northwesterly wind caused by mountains, atmospheric fronts, changing in surface roughness may provide favorable conditions for developing atmospheric gravity waves [Liu et al., 2010].

[21] WRF model results can also be used for SAR simulation with a SAR imaging model, such as M4S. The simulated SAR image resembles the actual SAR image but with NRCS discrepancy in both averaged value and dynamic range. The discrepancy is expected given that the input parameters to the M4S come from the WRF model output which contains systematic errors. There are also known uncertainties in the radar model. This study shows that the simulation with the full composite surface radar model using Elfouhaily et al.'s [1997] (black) wave spectrum is the closest to the actual SAR observations.

[22] This study adds to the body of our previous work on taking advantage of the synergy between satellite remote sensing and comparable high-spatial-resolution community weather forecast models to study atmospheric phenomena including: cloud line formation above the Gulf Stream [Li et al., 2004], katabatic winds [Li et al., 2007], atmospheric vortex streets [Li et al., 2008] and sea breeze circulation [Li et al., 2009]. With the rapid advance of community atmospheric mesoscale model capabilities, it has demonstrated that the high-resolution WRF model could be an ideal tool to study SAR-observed atmospheric phenomena in the MABL.

[23] Acknowledgments. The Envisat ASAR image was provided by the European Space Agency under Envisat projects 141 and 6133. The M4S radar simulation model was provided by R. Rromeiser from the University of Miami. The MODIS image was obtained courtesy of the MODIS Rapid Response Project at the NASA Goddard Space Flight Center. The views, opinions, and findings contained in this report are those of the authors and should not be construed as an official NOAA or U.S. government position, policy, or decision.

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