Evidence of upstream and downstream solitary wavetrains coexistence in the real atmosphere

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From a true color image of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) onboard the Orbview-2 satellite, we observed two packets of orderly wave clouds on two sides of Hainan Island in the South China Sea. A packet of 23 wave clouds stretches southward from the island. A second packet of more than 20 wave clouds stretches northeastward off the northeast coast of the island. The concave orientation of the wave cloud lines implies that both packets are propagating away from the island. A chart of geopotential height and velocity at 850 mb shows a southwesterly air flow over the island; hence the two wave cloud packets propagate upstream and downstream, simultaneously. Thus, we have found new evidence of the coexistence of both upstream and downstream solitary wavetrains generated in the real atmosphere by land topographic disturbances. Comparison with theoretical results supports this conclusion.

1. Introduction

In recent years, solitary wave packets (Zheng et al., 1998a), mountain waves (Eckermann and Preusse, 1999), coastal lee waves (Zheng et al., 1998b; Li et al., 2001), island lee waves (Vachon et al., 1994), gravity waves (Chunchuzov et al., 2000), vortex streets (Li et al., 2000), and upstream wave packets (Li et al., 2002) in the atmosphere have all been identified from satellite images. Most of these waves are generated by airflow over a topographic (or dynamical) obstacle, constitute a single wave packet, and propagate in one direction only. Theories developed by Grimshaw and Smyth (1986), Wu (1987), and Shen (1993), among others; however, predicted that perturbation of a topographic obstacle could generate two separate wave packets.
packets arranged on two sides of the topography. Recently, Porter and Smyth (2002) simulated the morning glory of the Gulf of Carpentaria, Australia, using numerical solution of the Benjamin-Ono equation. Their model indeed generated two solitary wavetrains propagating in two opposite directions on two sides of the topography. Farmer and Armi (1999) and Armi and Farmer (2002) measured the behavior of stratified water flow over bottom topography in Knight Inlet, British Columbia, Canada. Their measurements also showed that an upstream solitary wavetrain was indeed generated by the topography. Here we report a new case, which appears on satellite images and provides striking evidence of the coexistence of both upstream and downstream solitary wavetrains in the real atmosphere. In order to confirm this conclusion, we will also show the comparison between the observed case with theoretical models derived by Grimshaw and Smyth (1986).

2. Satellite Images

The SeaWiFS onboard the Orbview-2 satellite is an 8 band (6 visible and 2 near infrared) optical scanner and was launched into a sun-synchronous orbit at 705-km altitude on August 1, 1997 (McClain et al., 1998). The images are produced by the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) and distributed by the Distributed Active Archive Center (DAAC). There are two kinds of image products with different coverage for users’ choices: Local Area Coverage (LAC) SeaWiFS images with a swath width of 2801 km and a spatial resolution at nadir of 1.1 km, and Global Area Coverage (GAC) SeaWiFS images with a swath width of 1502 km and a spatial resolution at nadir of 4.5 km. The images used for this study are LAC images.
3. Interpretation

The case of interest is shown in figure 1. Previously studies suggest that all undular cloud patterns represent signatures of atmospheric waves (Zheng et al., 1998a; Eckermann and Preusse, 1999; Li et al., 2001). A digitally orthorectified version of figure 1 (in black and white and not shown here) was used to obtain accurate measurements of the phenomena. The packet stretching southward from the island (P1) contains 23 waves. The concave orientation of the wave cloud lines in P1 implies that the wave packet propagates southward. The average separation distance (or wavelength) between solitons is 6.4 km. The maximum length of the crest lines is 330 km. The packet located northeastward 200 km off the northeast coast of the Island (P2) contains more than 20 waves. The concave orientation of the wave cloud lines in P2 again implies that the wave packet propagates northward. The average wavelength of the first ten solitons is 9.8 km. The maximum length of crest lines is 370 km. Figure 2 shows charts of sea surface pressure and wind velocity (upper) and geopotential height and velocity at 850 mb (lower) on the same date and indicates a low pressure center moving southeastward from South China toward the study area. At the sea surface, the wind is southerly at 5 ms\(^{-1}\). At 850 mb, it is southwesterly and around 10 ms\(^{-1}\). These observations provide additional evidence that wave packet P1 propagates upstream and P2 downstream, respectively.

Figure 3 shows a cross section taken along the red line in Figure 1. Shown at the bottom of the figure is the topography of Hainan Island with a 1/12\(^{\circ}\) by 1/12\(^{\circ}\) resolution. Most of the island is covered by the Wuzhi Mountain with a peak at 1867 m above sea level located at 109\(^{\circ}\)42’E 18°54’N near the center of the island. Shown at the top of the figure are the gray value
curves of the wave clouds. The gray values are related to cloud top altitudes, but are not calibrated. In Figure 3, \( P_1 \) is just in front of a steep topographic elevation rising from the ocean surface, which constitutes a sudden obstruction in the way of the airflow, producing favorable conditions for generating upstream solitons. \( P_2 \) is distributed on the downstream side located 200 km off the coast of the island.

4. Comparison with Theoretical Models

In order to confirm relationship between the two coexisting atmospheric wave packets shown on Figure 1 and to determine their dynamical features, we decide to compare the observed case with available theoretical results. In the non-resonant case of continuously stratified flow of an inviscid incompressible fluid over topography, Grimshaw and Smyth (1986) found a wave motion solution in the form of

\[
A_s = -\frac{c_s^2}{c_s^2 - V^2} G_s(X) + \frac{c_s}{2c_s^2} G_s(X - c_s^+ T) + \frac{c_s}{2c_s^2} G_s(X + c_s^- T), \quad \text{for } 0 \pi T \pi \infty, \quad (1)
\]

where \( c_s = 2N h / \pi \), in which \( N \) is the Brunt-Väisälä frequency and \( h \) is the vertical dimension of the waveguide, and is the long-wave phase speed relative to a basic state at rest, \( V \) is a constant horizontal velocity from left to right, \( G_s(X) \) is the normalized background topography, \( c_s^\pm = c_s \pm V \), \( G_s(X - c_s^+ T) \) and \( G_s(X + c_s^- T) \) represent two coexisting, freely propagating long waves, respectively, \( X \) is the slow space variable positive right, and \( T \) is the slow time variable. Those waves \( G_s(X - c_s^+ T) \) with phase speed \( c_s^+ \) propagate downstream, while those waves \( G_s(X + c_s^- T) \) with speed \( c_s^- \) propagate upstream for subcritical flow, \( V \pi c_s \), and propagate downstream for supercritical flow, \( V \phi c_s \). This solution is derived based on the following assumptions of lengthscales: a) the amplitude of the topography to be much less than the vertical
dimension of the waveguide; \(b\) the wave amplitude to be much less than the vertical dimension of the waveguide; and \(c\) the horizontal lengthscale of the topography to be much greater than the vertical dimension of the waveguide. The solution also predicts that, on a long timescale, the freely propagating waves will be affected by nonlinearity and dispersion, and will evolve either into a finite number of solitary waves, or into an oscillatory wavetrain.

In our case, the topography is imposed by the Hainan Island. The horizontal lengthscale of the island is 250 km and the average amplitude of a mountain ridge along 19° N is 600 m. The satellite image (figure 1) shows bands of clouds forming large clusters, 300-400 km in extent. The morphology of these features indicates that the clouds are stratocumulus, a sort of low-level cloud with the cloud top height lower than 3 km (Kidder and Vonder Haar, 1995). This implies that the vertical dimension of the waveguide is less than 3 km. Cloud images have solitary wave packet features the same as the case observed in the north Arabian Sea (Zheng et al., 1998a). Hence, according to classification of atmospheric solitary waves by Rottman and Grimshaw (2002), the waves we observed belong to the class of low-level solitary waves. The lengthscales of our case meet assumption \(c\), probably meet assumption \(a\), but do not include the wave amplitude scale. Here we consider assumption \(b\) to be met so that we may compare our case with theoretical solution (1). On the basis of solution (1), our case should be generated by subcritical flow, because a wave packet propagates upstream and another downstream, simultaneously. If the two wave packets coexist, in other words they were generated at the same time, the following relation must be true:

\[
\frac{L_u}{c_s^-} = \frac{L_d}{c_s^+}, \tag{2}
\]

where \(L_u\) and \(L_d\) are upstream and downstream distances from the mountain ridge to the upstream and downstream packets, respectively. From the digitally orthorectified version of
Figure 1 (not shown here), we measure $L_u = 140$ km and $L_d = 370$ km. Substituting these values into (2) yields

$$\frac{c^+}{c^-} = \frac{c_s + V}{c_s - V} = 2.64. \quad (3)$$

From Figure 2, we determine $V = 10$ m s$^{-1}$. Thus, we obtain $c_s / V = 2.2$, and $c_s = 22$ m s$^{-1}$. Both the ratio $c_s / V$ and the value of $c_s$ are close to that of morning glory cases (Rottman and Grimshaw, 2002). In other words, they are within a reasonable range. Therefore, we believe that relation (2) stands in our case. This confirms the coexistence of upstream and downstream solitary wavetrains.

Solution (1) also gives the normalized amplitudes of upstream ($A_u$) and downstream ($A_d$) solitary wavetrains. Substituting values of $c_s$, $c_s^+$, and $c_s^-$ into (1) yields $A_u = 1.83$, and $A_d = 0.69$. Although we can determine the ratio of these amplitudes based on satellite images, we cannot determine their absolute values. The amplitude of a soliton is inversely proportional to the square of the characteristic half width (Zheng et al., 2001), and the latter is directly proportional to the width of a cloud image line no matter what imaging mechanisms. Therefore, the ratio of $A_u$ and $A_d$, $a_{ud}$, can be estimated from the satellite image. In our case we measure the average image width of leading soliton of upstream wavetrain as 3.5 km, and that of the last soliton of downstream wavetrain as 5.6 km, thus $a_{ud} = 2.6$. On the other hand, the theories give $a_{ud}$ as 2.65. Both values are almost the same. This further confirms the coexistence of upstream and downstream solitary wavetrains.

Using the above data, we calculate the generation time of the waves as of 3.2 hr earlier. The vertical dimension of a waveguide can be calculated using $h = \pi c_s / 2N$. If we take the Brunt-Väisälä frequency $N$ as 0.02 s$^{-1}$, a typical value for the low-level atmosphere (Rottman...
and Grimshaw, 2002), we obtain an estimate for $h$ of 1.7 km, which is close to the cases of morning glory (Noonan and Smith, 1985). We also obtain an estimate for the Froude number $(V/Nh)$ of 0.3, implying subcritical flow in this case.

5. Conclusions

From SeaWiFS satellite images we observed two packets of orderly wave clouds on two sides of Hainan Island in the South China Sea. Weather charts and the concave orientations of the wave cloud lines imply that the packets propagate both upstream and downstream in the wind direction simultaneously. Our observation and interpretation are well supported by the wave solutions derived by (Grimshaw and Smyth, 1986). Therefore, we conclude that this case provides evidence for the coexistence of upstream and downstream solitary wavetrains generated in the real atmosphere by topographic disturbances.

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References


Figure legends

Figure 1. A true color SeaWiFS image taken on March 19, 1999. The waters of the northern South China Sea are shown in dark blue. Aerosol contamination is evident to the west of the Hainan Island. Two groups of wave clouds in white arrayed on the two sides of the island are interpreted as signatures of upstream ($P_1$) and downstream ($P_2$) solitary wavetrains generated in the real atmosphere by topographic disturbances. The red line represents the wind direction at 850 mb.

Figure 2. Weather charts for the observation area on March 19, 1999 (NCEP/NCAR Reanalysis data taken from NOAA website). (a). Sea surface pressure and wind velocity. Units of color code are Pa. Arrows represent the wind field. In the study area, the sea surface wind is southerly and about 5 m s$^{-1}$. (b). Geopotential height and wind velocity at 850mb isobaric level. Units of color code are in m. Arrows represent the wind field. In the study area, the wind is southwesterly and about 10 m s$^{-1}$.

Figure 3. Cross section along the red line shown in Figure 1. The topography of Hainan Island (extracted from ETOPO5 5°×5° Navy bathymetry data taken from NAVY website) is shown at the bottom. The grey value curves of wave packets $P_1$ and $P_2$ with arrows showing the propagation directions are shown at the top.