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

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Abstract. From a true colour 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 north-eastward off the north-east 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 mbar shows a south-westerly 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. 1998b).
2000), vortex streets (Li et al. 2000) and upstream wave packets (Li et al. 2004) 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 arranged on two sides of the obstacle. 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 topographic feature. Farmer and Armi (1999) and Armi and Farmer (2002) measured the behaviour 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 Sea-viewing Wide Field-of-view Sensor (SeaWiFS) onboard the Orbview-2 satellite is an eight-band (six visible and two near-infrared) optical scanner and was launched into a sun-synchronous orbit at an altitude of 705 km on 1 August 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. Previous 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 north-eastward 200 km off the north-east 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 10 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 mbar (lower) on the same date and indicates a low pressure centre moving south-eastward from South China toward the study area. At the sea surface, the wind is southerly at 5 m s\(^{-1}\). At 850 mbar, it is south-westerly and around 10 m s\(^{-1}\). These observations
provide additional evidence that wave packet $P_1$ propagates upstream and $P_2$ 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°42’ E, 18°54’ N near the centre of the island. Shown at the top of the figure are the grey value curves of the wave clouds. The grey 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 favourable 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 the relationship between the two coexisting atmospheric wave packets shown on figure 1 and to determine their dynamical features, we
Figure 2. Weather charts for the observation area on 19 March 1999 (National Centers for Environmental Prediction Reanalysis data taken from the NOAA web site). (a) Sea surface pressure and wind velocity. The units of the colour code are Pascals. 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 850 mbar isobaric level. The units of the colour code are metres. Arrows represent the wind field. In the study area, the wind is south-westerly and about 10 m s\(^{-1}\).
decided 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

\[ A_s \sim \frac{c_s}{2c_s} \frac{V}{2c_s} G_s(X) + \frac{c_s}{2c_s} G_s(X - c_s^+ T) + \frac{c_s}{2c_s} G_s(X - c_s^- T), \text{ for } 0 < T < \infty \]  

(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, \( V < c_s \), and propagate downstream for supercritical flow, \( V > c_s \). This solution is derived based on the following assumptions of length-scales: (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 length-scale 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 non-linearity 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 Hainan Island. The horizontal length-scale 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 length-scales 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:

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

(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 value into (2) yield

\[
\frac{c_s^+}{c_s^-} = \frac{c_s + V}{c_s - V} = 2.64
\]

(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 calculated the generation time of the waves as of 3.2 h 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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