OBSERVATIONS OF ATMOSPHERIC GRAVITY WAVES OVER THE CHINESE SEAS BY SPACEBORNE SYNTHETIC APERTURE RADAR

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ABSTRACT

On synthetic aperture radar (SAR) images acquired over the ocean often sea surface signatures of atmospheric gravity waves (AGWs) as well as of oceanic internal waves are visible. They often look quite similar and it is not always easy to decide whether the wave-like patterns result from AGWs or from oceanic internal waves. In this paper we present criteria how to discriminate between these two phenomena on SAR images of the sea surface.

We present 4 SAR images acquired by the Advanced Synthetic Aperture Radar (ASAR) onboard the European Envisat satellite over the China Seas showing sea surface signatures of AGWs. By using other satellite data and radiosonde data, we show that the wave-like patterns visible on the SAR images are indeed sea surface signatures of AGWs. From the SAR images quantitative information on the sea surface wind fluctuations induced by the secondary airflow associated with the AGWs are derived.

1. INTRODUCTION

Gravity waves are a common phenomenon in the atmosphere [1], [2]. Atmospheric gravity waves (AGWs), as we shall call them in the following, which are generated in the troposphere can propagate upward or they can remain in the troposphere and get trapped there [3], [4]. Trapping requires a specific state of the atmosphere. AGWs cannot only be trapped vertically, but also horizontally by some kind of horizontally boundaries. Thus the AGWs are confined to a waveguide and can propagate horizontally over distances of more than hundred kilometres, which is confirmed by satellite observations. AGWs can be generated by several mechanisms, e.g., by airflow over mountain ranges or over mountainous islands, in which case they are called atmospheric lee waves (see, e.g., [5]), by horizontal or vertical wind shear [6], or by atmospheric fronts [7], [8].

AGWs in the marine boundary layer become visible on synthetic aperture radar (SAR) by changes of the sea surface roughness [7]-[10], [15] AGWs which propagate in the lower atmosphere are associated with a spatially variable surface wind (or more precisely, with a variable wind stress) which modulates the short-scale sea surface roughness and thus the backscattered radar power or the normalized radar cross section (NRCS) [16]. This modulation of the sea surface roughness generates the sea surface signature of the AGWs and the associated modulation of the NRCS or radar signature. However, unfortunately not only a variable wind stress associated with AGWs modulates the sea surface roughness and gives rise to wave-like patterns on SAR image, but also a variable surface current associated with oceanic phenomena, like oceanic internal waves and tidal flow over periodic sandbanks. The strength of the sea surface roughness modulation caused by these oceanic phenomena has often the same magnitude as the surface roughness modulation caused by AGWs. Furthermore, the spatial scales of the radar signatures of these oceanic phenomena and of AGWs are often similar. Therefore it is often difficult to identify unambiguously wave-like patterns visible on SAR images of the sea surface as radar signatures of AGWs, of oceanic internal waves, or of underwater sandbanks. To discriminate between them usually requires several criteria. We will show in the next section that there exist some characteristic differences in the radar signatures of AGWs and of oceanic internal waves which in many cases are sufficient for discrimination. They follow from previously developed theories of SAR imaging mechanisms of AGWs and of oceanic internal waves (see, e.g., [7], [17]).

The paper is structured as follows: In section 2 we describe the physical mechanisms generating the radar signatures of AGWs and of oceanic internal waves and discuss what differences in the shape of the radar signatures follows from them. In section 3 we briefly describe how AGWs are trapped in the lower troposphere. In sections 4 we present 4 examples of SAR images acquired by the Advanced Synthetic Aperture Radar (ASAR) onboard the European Envisat satellite over the China Seas showing sea surface signatures of AGWs. We analyze them in conjunction with other satellite and in-situ data and derive quantitative information on the sea surface wind fluctuations associated with the secondary airflow generated by AGWs. Finally in section 5 we present the conclusions.
2. RADAR SIGNATURES OF ATMOSPHERIC GRAVITY WAVES AND OF OCEANIC INTERNAL WAVES

Wave patterns visible on SAR images of the sea surface can be sea surface signatures of AGWs, of oceanic internal waves, of underwater sandbanks, or of atmospheric boundary layer rolls. Sea surface signatures originating from sandbanks or of atmospheric boundary layer rolls can, in general, quite easily be identified and will not be treated in this section in detail (see, e.g., [18] - [20]). When the sea surface signatures result from sandbanks, they can only occur over shallow sea areas where periodically spaced sandbanks and strong currents (usually tidal currents) are known to exist. When the wave pattern results from boundary layer rolls, then the pattern is aligned approximately in wind direction (not perpendicular to it as the wave pattern of AGWs) and the spacing between the individual rolls forming this quasi-periodic pattern increases with distance from the source. For more information see http://earth.esa.int/applications/ERS-SARtropical/ or (identical) www.ifm.uni-hamburg.de/ers-sar/, where many examples of these radar signatures can be found. However, the situation is quite different for sea surface signatures of AGWs and oceanic internal waves, which, at first sight, look quite similar and which often give rise to misinterpretations. Therefore we briefly review in this section the basics of the SAR imaging mechanisms of both types of waves.

2.1. Radar signatures of atmospheric gravity waves

AGWs become visible on SAR images because they are associated with variations of the wind stress at the sea surface. The wind stress depends on the wind speed at the sea surface and on the stability of the air-sea interface. Variations of the wind speed at the sea surface disturb the small-scale sea surface roughness and thus give rise to sea surface signatures visible on the SAR image as variations of the normalized radar cross section (NRCS or \( \sigma \)) or of the SAR image intensity. Model functions which relate the NRCS to the wind vector \( \mathbf{U} \) for a neutrally stable atmosphere at a height of 10 m above the sea surface, have been developed by several research groups. The model function which is most often used for inferring sea surface wind speed from NRCS data of the ASAR onboard the Envisat satellite is the “C-band Wind Scatterometer Model Function 4”, abbreviated CMOD4 [21] or the CMOD_IFR2 model developed by IFREMER [22]. However, quantitative information on the sea surface wind speed can only be extracted from SAR image of when the wind direction is known. The wind direction is sometimes inferred from the SAR image itself, e.g., from the direction of the wind streaks (Horstmann and Koch, 2005) or from the direction of wind shadows behind mountainous islands. Another way to obtain wind direction is from atmospheric models, like the one developed by the National Centers for Environmental Prediction (NCEP). Both methods will be used in our analyses of ASAR images showing sea surface signatures of AGWs (see section 4). AGWs are associated with air motion, which, for the cases analyzed in this paper, reach to the sea surface, where they modify the sea surface wind speed and thus the backscattered radar power. A schematic plot of this air motion together with the streamlines and the deformation of the isolines of potential temperature associated with a linear AGW propagating in a stably stratified three-layer atmosphere can be found in [7] or at the website http://www.ifm.uni-hamburg.de/ers-sar/Sdata/atal.setPositiveButton(364,1157,385,1163)/atmospheric/grwaves/intro/index.html. However, quite often the AGWs are nonlinear and appear as wave packets and are described in terms of soliton theory. When nonlinear AGWs are generated by atmospheric fronts or by airflow over mountains, the isolines of potential temperature are elevated at the front of the packet] [7], [26].

![Schematic plot of the streamlines of a nonlinear atmospheric gravity wave](image)

**Fig. 1.** (a) Schematic plot of the streamlines of a nonlinear atmospheric gravity wave (b) Schematic plot of the variation of the normalized radar cross section \( \sigma \) caused by the wave induced variation of the surface wind speed.

In the terminology of soliton theory one says that the leading soliton in a wave packet is a “soliton of elevation". Under a soliton of elevation the total surface wind speed (vector sum of the ambient wind...
speed and the wind speed associated with the soliton of elevation) is reduced relative to the ambient wind. From Fig. 1 we see that the direction of the air motion associated with the AGW is alternating at the surface. Under the wave crest the air motion is directed in wave propagation direction and under the wave trough it is directed in opposite direction. This wave-induced airflow is superimposed on the ambient airflow. Since the NRCS is a monotonic function of the sea surface wind speed, this leads to alternating bands of reduced and increased NRCS and thus to alternating bands of reduced and increased image intensity relative to the background.

The nonlinearity manifests itself in the shape of the streamline field. The areas where the total wind speed at the surface is reduced is much narrower than the area where the wind speed is increased. The resulting modulation of the normalized radar cross section, $\sigma$, has thus the shape shown in Fig. 1b. Here $\sigma_0$ denotes the NRCS value associated with the background wind field. Therefore, extrapolated to two dimensions, a nonlinear atmospheric gravity wave appears on a SAR image as a broad bright band sandwiched-in between two narrow dark bands.

Typical radar signatures of nonlinear AGWs are depicted in Fig. 2.

Figure 2. Typical radar signatures of atmospheric gravity waves, (a) Quasi-linear wave, ERS-1 SAR image, 17 August 1994, Melville Island (northern Canada), Arctic Ocean; (b) Nonlinear wave packet, ERS-1 SAR image, Caspian Sea, 12 May 1996, 0723 UTC. (http://www.ifm.uni-hamburg.de/ers-sar/Sdata/atmospheric/grwaves/252302781ERS1.html).

2.2. Radar signatures of oceanic internal waves

Oceanic internal waves become visible on SAR images acquired over non-slick infested sea areas because they are associated with variations of the surface current caused by wave-induced water motions which modify the sea surface roughness. A schematic plot of the water motion together with the streamlines and the deformation of the isotherms associated with a linear oceanic internal wave propagating in a water column, which consists of two layers of different densities separated by a thermocline, can be found in [17] or at the website http://www.ifm.uni-hamburg.de/ers-sar/Sdata/oceanic/intwaves/intro/index.html.

The variable surface current associated with the internal waves generates convergent and divergent flow regimes at the sea surface. As shown in [17] and [24] the amplitude of the Bragg waves increases in convergent flow regions and decreases in divergent flow regions. As a consequence, the radar signatures of oceanic internal waves consist of alternating bright and dark bands on a uniform background.

Oceanic internal waves, in particular those generated by tidal flow over shallow underwater bottom topography, are most often nonlinear and occur in wave packets. The distance between the waves and the amplitude of the waves in a wave packet decrease from front to rear. As in the case of nonlinear AGWs, nonlinear oceanic internal waves are often described in terms of soliton theories. Soliton theories applicable to the description of the generation and propagation of internal solitary waves or soliton in the ocean predict that, if the depth of the upper (lighter) layer is smaller than the depth of the lower (denser) layer, then the internal solitary waves must be "solitary waves of depression". This means that the thermocline or pycnocline is pushed downward as depicted schematically in Fig. 3. The leading edge of a solitary wave of depression is always associated with a convergent flow region and the trailing edge with a divergent flow region. Thus the leading edge of a solitary wave of depression is always associated with an increased NRCS and the rear with a decreased NRCS relative to the background [17]. This implies that the radar signature of an oceanic solitary wave of depression consists of a bright band in front followed by a dark band (Fig. 4a).

Usually the depth of the upper layer is in the ocean is much smaller than the depth of the lower layer. But in exceptional cases it can also be larger, in which case the internal solitary waves become "solitary waves of elevation". Solitary waves of elevation have been observed over the shelf of the South China [25]. These solitary waves of elevation transform from solitary waves of depression when travelling from the deep ocean (west of the Luzon Strait) into the shallow region of the shelf of South China Sea.

But there exist also other radar signatures of internal waves that deviate from this scheme. Sometimes radar signatures consist only of bright bands or only of dark bands. Only bright bands are encountered when the
wind speed is below threshold for Bragg wave generation. In these cases the solitary oceanic internal waves generate roughness bands that cannot be described by weak nonlinear hydrodynamic interaction theory (see Fig. 3b). Sometimes only dark bands are visible. In these cases surface films (usually of natural origin) are present which accumulate in the convergent flow regimes where they damp the Bragg waves [23].

Figure 3. (a) Shape of the pycnocline (thermocline), (b) Sea surface roughness pattern, and (c) SAR image intensity associated with an internal solitary wave packet consisting solitary waves (solitons) of depression of decreasing amplitude from front to rear.

Fig. 4 Typical radar signatures of nonlinear oceanic internal waves. (a) ERS-2 SAR image, Sulu Sea, 30 January 1998, 0224 UTC (http://www.ifm.uni-hamburg.de/ers-sar/Sdata/oceanic/intwaves/sulusea/145293483ERS2.html), (b) ERS-1 SAR image, Andaman Sea, 22 December 1993, 1603 UTC. (http://www.ifm.uni-hamburg.de/ers-sar/Sdata/oceanic/intwaves/andsea). © ESA

2.3. Discrimination between radar signatures of atmospheric gravity waves and of oceanic internal waves

In order to identify unambiguously wave patterns visible on SAR images of the sea surface as sea surface signatures of AGWs or of oceanic internal waves one needs, in general, auxiliary information, e.g., on the geographical location of the wave pattern, on the state of the ocean and the atmosphere, on coastal topography, and on underwater bottom topography.

But often one can decide already, with a high degree of confidence, from the shape of the radar signature whether the wave pattern originates from AGWs or from oceanic internal waves. If the radar signature consists of broad bright bands surrounded by narrow dark bands, then it very likely originates from an AGW (see section 2.1).

Furthermore, if the radar signature of the leading edge of a wave pattern consists of a dark band followed by a bright band, and if the pattern is not located in a sea area where 1) solitary oceanic internal waves of elevation can exist or where 2) surface slicks are present, then it very likely originates from an AGW.

But there exist also other criteria by which the origin of the wave pattern can be determined with a high degree of confidence:

The wave pattern originates very likely from AGWs if 1) the pattern is located in the lee of a mountainous island or a mountainous coast, 2) the pattern is located near an atmospheric front (usually cold front) or near a strong wind shear zone, 3) the pattern is located in a sea area where a) the water column is not stratified such that no oceanic internal waves can be supported and b) there are no shallow underwater sandbanks, 4) there exist quasi-simultaneously acquired cloud images which show wave patterns with the same wavelength.

Conversely, the wave originates very likely from oceanic internal waves if the pattern 1) is located in a sea area a) where the water column is strongly stratified, where there are shallow underwater ridges, sea mounts, or steep shelf breaks and c) where strong tidal currents are known to exist., 2) consists of regularly spaced wave packets with an inter-packet separation ranging from 20 to 100 km between them.

Regularly spaced wave packets are observed when the internal oceanic waves are tidally generated (usually by the semi-diurnal tide which has a period of 12.4 hours).

In order to increase the confidence level about the origin of the radar signature further, one should check the state of the atmosphere by using radiosonde data. These data are available online from the University of Wyoming

http://weather.uwyo.edu/upperair/sounding.html

If the state of the atmosphere is such that it can support AGWs in the lower troposphere, the presence of AGWs is likely.

In section 4 we shall apply these criteria to identify unambiguously the wave patterns visible on the 4 ASAR images presented in this section as sea surface signatures of AGWs.
3. TRAPPING OF ATMOSPHERIC GRAVITY WAVES IN THE LOWER TROPOSPHERE

When AGWs become visible on SAR images of the sea surface, the airflow associated with these waves (also called secondary flow) must reach to the sea surface. Since AGWs can only exist in stably stratified atmospheric layers, the lower layer of the atmosphere, which reaches down to the sea surface must be stably stratified. Above this layer there must be a boundary present which prevents the AGWs to escape into higher levels, possibly into the mesosphere, where they may break, generate turbulence and finally generate heat. Thus the AGWs visible on SAR images must be waves which are trapped in an atmospheric waveguide or wave duct whose lower boundary is the sea surface and whose upper boundary is of an a-priori unknown origin [4]. Such an upper boundary, which reflects the AGWs generated in the lower troposphere, can be present if the vertical profile of the air density and the wind speed fulfills certain conditions, e. g., when a deep neutrally stable layer is overlying the surface-based stable layer [2] or when a strong vertical wind shear layer borders this stable layer. In the horizontal plane the AGWs are often trapped within horizontal wind shear layers generated by wind jets.

4. EXAMPLES OF ATMOSPHERIC GRAVITY WAVES OVER THE CHINESE SEAS

4.1 The 9 November 2005 event

Fig. 5 shows an ASAR image acquired in the image mode (IM) (swath width: 100 km) on 9 November 2005 at 1343 UTC over the Yellow Sea east of Qingdao. At this time of the year the Yellow Sea is, at this location, not stratified, i. e., there exists no thermocline. Therefore the wave pattern visible on this ASAR image cannot originate from oceanic internal waves. The radiosonde data acquired at Qingdao on this day at 1200 UTC show that a layer of lower stability was overlaying the surface-based stable layer and that a temperature inversion was present below 800 m. Thus the atmosphere was able to support AGWs in the lower troposphere. Therefore we interpret the wave pattern visible on the ASAR image as sea surface signatures of an AGW. This interpretation is supported also by the MERIS image acquired 11 hours and 45 minutes earlier (on 9 November 2005 at 0228 UTC), which is depicted in Fig. 6 and which shows periodic patterns in the cloud distribution which have approximately the same wavelength (10 km) as the wave pattern visible on the ASAR image depicted in Fig. 5. The AGWs were generated by a south westerly wind of 10 ms⁻¹ interacting with coastal mountains located on a peninsula in the Laoshan mountain area. The AGW is a trapped lee wave propagating upwind in a westerly direction. Its shape resembles the shape of a transverse wave in a ship wake Fig. 7 shows the variation of the sea surface wind speed along the transect (white line) inserted in Fig. 5 by using the CMOD4 model. The wind direction was taken from the NCEP model (at 1200 UTC) and from Quikscat data (at 1030 UTC). Fig. 7 shows that, due the presence of the AGW, the wind speed varied between 6 and 11 ms⁻¹.

Figure 5. ASAR IM image (swath width: 100 km) acquired on 9 November 2005 at 1343 UTC over the Yellow Sea east of Qingdao. The wind blows from the left and the atmospheric gravity wave packet propagates from right to left (against the wind). The inserted white line denotes the transect along which the wind speed has been calculated using the CMOD4 model. © ESA

Figure 6. Sub-scene of a MERIS image acquired on 9 November 2005 at 0228 UTC over the Yellow Sea near Qingdao showing wave patterns in the cloud distribution.
Figure 7. Sea surface wind speed variation induced by the AGWs calculated along the transect inserted in Fig. 5 as a white line. The wavelength of the AGW is approximately 10 km.

4.2. The 27 May 2007 event

Fig. 8 shows an ASAR image acquired in the image mode (IM) (swath width: 100 km) on 27 May 2007 at 0230 UTC over the Bohai Sea. Visible is in the upper right hand section the southern tip of Liaoning Peninsula and in the lower section the Dazhushan Dao islands. The AGW packet in the upper section of the image has been generated by wind shear caused by interaction of the easterly synoptic-scale wind with the southern tip of Liaoning Peninsula. Weaker AGWs have been generated behind the Dazhushan Dao islands. In Fig. 9 the wind speed map derived from this ASAR image is depicted. The wind direction was taken from the NCEP model. The wind speed map shows that wind speed variation caused by this AGW was quite strong ranging from 6 to 12 ms\(^{-1}\). The radiosonde data acquired at Dalian on 27 May 2007 at 0000 UTC, which are depicted in Fig. 10, show that up to a height of 1400 m the temperature decreased very little and that there was no inversion layer. However, the wind profile depicted in Fig. 11 shows a change in wind direction at a height of 1000 m. Thus we suspect that the wind shear layer at this height formed the upper boundary for the wave guide.

Figure 8. ASAR IM image (swath width: 100 km) acquired on 27 May 2007 at 0230 UTC over the Bohai Sea. Visible is in the upper right hand corner is the southern tip of Liaoning Peninsula and in the lower section the Dazhushan Dao islands. Atmospheric lee waves have been generated behind the peninsula and the mountainous islands. © ESA

Figure 9. Sea surface wind field derived from the ASAR image of 27 May 2007 at 0230 UTC (Fig. 8) by taking the wind direction from the operational forecast model NCEP and by using the CMOD4 wind scatterometer model. (courtesy: Knut-Frode Dagestad, NERSC, Bergen).
4.3. The 27 February 2007 event

Fig. 12 shows an ASAR image acquired in the alternating polarization mode (APM) (swath width: 100 km) on 27 February 2007 at 0202 UTC over the Hangzhou Bay (Wangpang Yang). Visible is in the lower right-hand section a wave pattern consisting of three dark lines. Since to the north of the wave pattern the image intensity is brighter than further south (suggesting a wind front) and since the wave pattern does not have the shape of sea surface signatures of an oceanic internal wave, we suspect that the wave pattern results from an AGW. This interpretation is substantiated also by cloud images obtained by the MERIS sensor on 27 February at 0200 UTC and the MODIS sensor at 0325 UTC which both show a cloud band approximately at the location of the wave pattern visible on the ASAR image (not reproduced here). The wind was blowing with a speed of 8 to 10 ms\(^{-1}\) from a north easterly direction. We have obtained these values from the NCEP model (at 0000 UTC) as well as from Quikscat data (at 1018 UTC).

The sounding data of Shanghai on 27 February at 0000 UTC show a very strong inversion at a height of approximately 800 m, see Fig. 13. We have taken the sounding data of Shanghai and not of Hangzhou (which is closer), since Shanghai is located upstream of the phenomenon.

This AGW is an upstream AGW generated by flow impeded by a mountain. The north easterly airflow interacts with a mountain which is located on the peninsula bordering the Hangzhou Bay to the south and which is 1017 m high (Hemudu Wenhua Yizhi).

Figure 10. Vertical temperature (right curve) and dew point temperature (left curve) profiles measured by a radiosonde launched at Dalian on 27 May 2007 at 0000 UTC. These profiles are plotted as skew-T diagrams. Note that up to height of 1400 m the air temperature decreases very little.

Figure 11. Vertical profile of the wind component in the east-west (wake) direction calculated from the radiosonde data of Dalian on 27 May 2007 at 0000 UTC.

Figure 12. ASAR APM image (swath width: 100 km) acquired on 27 February 2007 at 0202 UTC over the Hangzhou Bay (Wangpang Yang). Visible are sea surface signatures of an upstream AGW generated by flow impeded by a mountain located on the peninsula to the south. © ESA

Figure 13. Vertical temperature (right curve) and dew point temperature (left curve) profiles measured by a radiosonde launched at Shanghai on 27 February 2007 at 0000 UTC. These profiles are plotted as skew-T diagrams. Note that the very strong inversion at a height of 837 m.
Such upstream AGWs have been described previously by Li et al. [14]. They occur when the Froude number has a value around 1. Fig. 14 shows the streamlines in x-z space along the wind direction (based on the NCEP wind field). The airflow from the north (on the right) is blocked by the mountains located on the peninsula to the south (blue area on the left).

4.4. The 9 April 2005 event

Fig. 14 shows an ASAR image acquired in the alternating polarization mode (APM) (swath width: 100 km) on 9 April 2005 at 1406 UTC over the Strait of Taiwan near the Chinese town Raoping (between Shantou and Xiamen). It shows sea surface signatures of AGWs which have wavelength around 10 km. This interpretation is also substantiated by the MODIS image acquired at 0240 UTC which shows adjacent to the coast wave-like cloud patterns which have approximately the same wavelength of 10 km (not reproduced here). The sounding data of Shantou (a coastal town located SW of the imaged area) at 1200 UTC from this day show at a height of 100 m a south westerly wind of 4 ms$^{-1}$ which increases to 13 ms$^{-1}$ at a height of 600 m. Thus a strong wind shear layer was present at a low altitude which probably has caused the trapping of the AGW. A very peculiar feature visible on this ASAR image are the thin bright lines in the dark areas of the wave pattern. We suspect that they are sea surface signatures of sub-rotors as described by Doyle and Durran [26]. According to these authors sub-rotors develop along the leading edge of “parent” rotors due to parallel shear instability. Rotors are rotating eddies with horizontal axes found on the lee side of mountain ranges when atmospheric lee waves are present. They usually are encountered under the first wave crest of a wave packet, but sometimes also under subsequent wave crests. Note also in the lower section of the ASAR image the wave pattern which result from under water sand banks in the Taiwan Strait (Taiwan Tan).

5. CONCLUSIONS

SAR images acquired over the Chinese Seas often show sea surface signatures of oceanic internal waves as well as of AGWs. The sea surface signatures often have quite similar shapes and it often not easy to discriminate between them. In this paper we have presented 4 SAR images acquired by the Advanced Synthetic Aperture Radar (ASAR) over the Yellow Sea, the Bohai Sea, the East China Sea and the South China Sea (Strait of Taiwan), which definitively show sea surface signatures of atmospheric gravity waves. Criteria how to distinguish between these two types phenomena have been presented. A prime criterion for a sea surface signature to originate from solitary AGWs is that usually it consists of a narrow dark band in front followed by a broad bright and again a narrow dark band. On the other hand, a prime criterion that it originates from solitary oceanic internal waves is that, in general, it consists of a broad bright band in front followed by a weak dark band. These criteria should be of great help for scientists who are given the task to determine whether wave-like patterns visible on SAR images of the sea surface result from oceanic internal waves or from atmospheric gravity waves.
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6. REFERENCES