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# Ship wave signature at the cloud top of deep convective storms

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ABSTRACT

We identify certain features atop some thunderstorms observed by meteorological satellites as ship wave-like. A few examples of satellite visible images are shown and the ship wave signature patterns in them are identified and discussed. The presence of ship wave signatures implies the existence of a dynamical mechanism in the storm that behaves like an obstacle to the ambient flow. We use a numerical storm model simulation to show that this mechanism is due to the strong updraft and divergence in the upper part of the storm.


## 1. Introduction

Meteorological satellite observations provide valuable information of atmospheric conditions that are often impossible to obtain by conventional means. One of the most useful aspects of satellite data is their wide spatial and temporal coverage that includes remote locations where no other kinds of observations are available. This is especially important for monitoring deep convective storms (only "storms" or "thunderstorm" from now on, in the rest of the paper) that may occur in such remote areas. However, satellite storm data need to be correctly interpreted to render them useful to scientists. One way to interpret satellite data is to examine specific features that appear at the top of storms and explain the physical mechanisms that produce them. If this can be done, then it is possible to relate these features to useful meteorological variables. This paper examines one of these features, the ship wave signature, at the cloud top of deep convective clouds as observed by meteorological satellites and the mechanism that generates it.

Ship wave patterns have been observed in the atmosphere for a long time and a more comprehensive study was performed by Sharman and Wurtele (1983). They (and other investigators cited by them) are concerned with the waves generated by air moving past some stationary obstacles on the surface such as an island or isolated mountain. Thus far there appears to be no scientific discussions of ship waves generated by deep convective storms whose circulation near the overshooting tops serve as an obstacle to storm-relative upper level winds.

In this paper, we identify certain features observed by meteorological satellites atop some thunderstorms as ship wave signatures (henceforth abbreviated as SWS). The observational evidence and examples will be presented in the next section. A simple cloud model interpretation of it and a brief conclusion will be given following that.

## 2. Satellite observations

At any instant there are a multitude of mechanisms operating at the top of a thunderstorm, some of which can produce various forms of wave patterns. These wave patterns often interfere with each other, making it difficult to

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distinguish SWS from other cloud top features in satellite imagery. If the upper level storm-relative winds have been unsteady and changed direction substantially, or when the wave-generating overshooting tops are short-lived only and keep penetrating the storm top at somewhat different locations, the ship wave pattern may not be obvious, either. There are also times when the SWS generating mechanism is weak or absent, and hence no such wave pattern can be observed. Often we do detect patterns in satellite imagery that can be identified as SWS. Moreover, since the ship wave features are best observed in visible and near IR imagery, their identification is easier at lower sun elevations (due to more distinct shadows).

Fig. 1 shows an example of the storm top SWS. This heavy precipitating and high-wind storm system occurred on 5 April 2007, near Ouagadougou, Burkina Faso (for further details on this case see http://oiswww.eumetsat.org/WEBOPS/iotm/iotm/20070405_ouaga/20070405_ouaga.html).

The SWS here appear to be associated with the storm top plumes which make the chevron feature of the wave visible. The plume level wind direction appears to be approximately from left (West) to right (East) as judged from satellite video loop of this storm system. For a discussion of the storm top plumes, the readers are referred to Setvak and Doswell (1991) or Levizzani and Setvak (1996). The wave crests in the north branch have more obvious curvature while those in the south branch appear to be straighter. This could indicate that upper level winds had changed somewhat during the formation of the waves as the pattern looks somewhat similar to the waves created by a ship when it changes direction, or it could be caused by horizontal shear (north–south component) in the ambient flow. At present this is unclear and further studies are needed. The overshooting top (already gone at the time of the satellite overpass) showed up at the location where the plume initially emerged, but it had disappeared shortly before this particular image was taken. The movie files for this case documenting the evolution can also be found at the web address above.

Fig. 2 shows another SWS example. This is a MODIS/Aqua band-1 image of a storm system which occurred in Greece and southern Adriatic Sea at 1155 UTC on 14 September 2008. There is an extensive ship wave signature system on top of the storm cells (a few of the wave crests are indicated by white dashed curves in the inset). The ship wave pattern associated with the south-most cell is seen to overlap (possibly lie above) the quasi-concentric ripple-like gravity waves on the anvil.

Certain storm top features also exhibit ship wave characteristics. Fig. 3 shows the satellite visible image of a storm over Bretagne in northwest France with a distinct two-beam plume which may be called a “diverging plume”. Each of the two plume beams shows similar curvature as that could be found for ship waves.

Note that common ship waves have two modes: diverging mode and transverse mode. All the examples in satellite images we have seen so far seem to show only the diverging mode. Further discussion of this point is given in Section 4.

## 3. Mechanism of storm top ship wave signature generation

Strictly speaking, ship waves are not simple waves but rather an interference pattern of waves. Kelvin (1891) derived a simple two-dimensional ship wave solution based on a pressure perturbation (the “ship”) with a constant velocity on a water of infinite depth. He demonstrated that the resulting waves are confined to a wedge-shaped region with a semi-apex angle of 19.5° independent of the velocity (see, e.g., Whitham, 1974). Later investigators improved on Kelvin's simple model and obtained results with wider validity (Havelock, 1908; Inui, 1935; Ursell, 1960; Plesset and Wu,

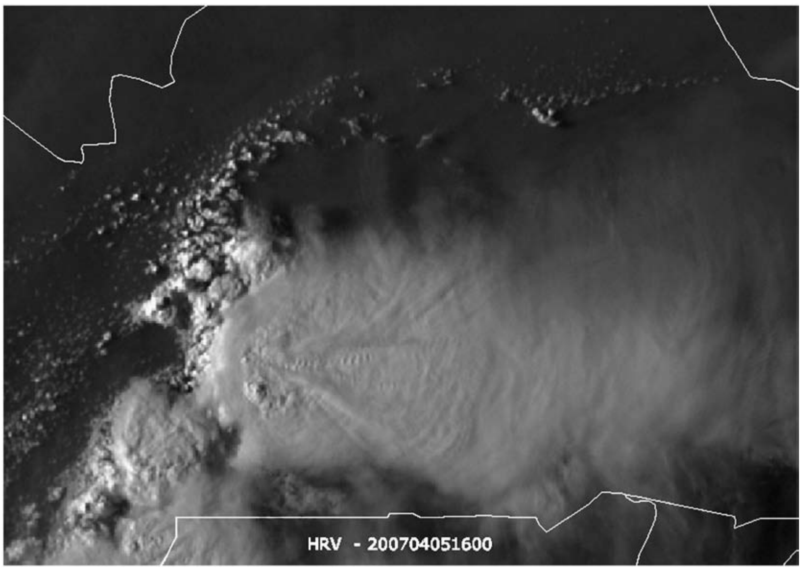


**Fig. 1.** Meteosat Second Generation (MSG) High Resolution Visible (HRV, band 12) image of storms above Burkina Faso, 5 April 2007, 1600 UTC. Image provided by Hans-Peter Roesli and EUMETSAT.