STUDY OF LOCAL WINDS IN MOUNTAINOUS COASTAL AREAS BY MULTI-SENSOR SATELLITE DATA

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ABSTRACT

Local winds in mountainous coastal areas are usually subject to large variations on spatial scales of the order of kilometers to tens of kilometers. Over the ocean, these wind fields cannot be resolved by scatterometers flown on satellites. We show that spaceborne synthetic aperture radars are well suited to study these local wind fields, in particular when used in combination with other spaceborne sensors, like MODIS, MERIS, and Quikscat, and with weather radars. As an example we show how SAR images acquired by the Advanced Synthetic Aperture Radar (ASAR) onboard the Envisat satellite, together with data from the above mentioned sensors, can be used to study off-shore atmospheric fronts generated by the reflection of onshore airflow by a coastal mountain range.

1. INTRODUCTION

Local winds in mountainous coastal areas are in general strongly variable on spatial scales of the order of kilometers to tens of kilometers. The spatial resolution of spaceborne scatterometers (typically 25 – 50 km) is usually not fine enough to resolve these local wind fields over coastal waters. We show in this paper that the synthetic aperture radar (SAR) is a very valuable instrument for studying these local sea surface wind fields. However, optimum information can be extracted from SAR data only when they are used in conjunction with data other from other high resolution spaceborne and ground-based instruments and with results from model calculations. Very useful are data from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra and Aqua satellites and the Medium Resolution Imaging Spectrometer (MERIS) onboard the Envisat satellite, and data from ground-based weather radars.

Examples of local winds in mountainous coastal areas are katabatic winds, boras, gap winds, and winds generated by the reflection of onshore airflow by a coastal mountain range, which often give rise to the formation of off-shore atmospheric fronts. In this paper mentioned winds, since studies of katabatic winds and boras using spaceborne SAR images have been reported previously [1,2].

Off-shore local atmospheric fronts generated by local coastal winds have been observed in several parts of the world, e.g., off the island of Hawaii [3,4] and off the east coast of Taiwan [5, 6]. Here present new data acquired by the above mentioned sensors over the east coast of Taiwan which strongly support the hypothesis that the meso-scale atmospheric front, which is often encountered off the east coast of Taiwan, is generated by the interaction of an onshore synoptic-scale wind with a local offshore wind generated by the reflection of the onshore airflow by the coastal mountain range. This hypothesis is further validated by simulations carried out with the meso-scale MM5 atmospheric model [7]. In a previous study [5] we were not sure whether the off-shore wind was caused by katabatic wind or by reflected on-shore airflow.

2. THE AIRFLOW MODEL

A schematic plot showing the airflow system where the offshore airflow is caused by re-circulation of air Reflected from the mountain range is depicted in Fig. 1. When impinging on the mountain range, the

Figure 1. Schematic plot of the airflow for the case that re-circulation of air causes the formation of the coast-parallel atmospheric front. The two vertical lines with the horizontal arrows attached denote the horizontal components of the wind vectors: 1) close to the shoreline (left) and 2) east of the convergence line (right).
Synoptic airflow splits into two vertical directions. The downward part forms the return flow, whereas the upward part climbs up the mountains and forms clouds. If it were purely katabatic winds to generate the front, the whole air would flow down along the mountain slope and no clouds would be formed inland at the coast.

3. EXAMPLES OF COSTAL OFFFRONTs

3.1 The 30 September 2005 front

On 30 September 2005 a northeasterly wind with a speed of about 8 m/s was blowing against the east coast of Taiwan. This gave rise to the formation of an atmospheric front as evident from the ASAR and MODIS Terra images depicted in Fig. 2. On the ASAR image (left) an eliptically-shaped area attached to the island can be delineated, which has a slightly different image brightness (corresponding to a different sea surface roughness) than the sea area further east. The boundary between these two areas constitutes the atmospheric front. The frontal line visible on the ASAR image coincides approximately with the line separating the cloud-free area at the east coast of Taiwan visible on the MODIS image (right). This complies with the model described in the previous section (see Fig. 1).

3.1 The 11 December 2006 front

The sea surface wind field map retrieved from Quikscat data [8] acquired on 30 September at 10:48 UTC, which is depicted in Fig. 3, shows that a westerly wind with a speed of about 10 m/s was blowing against the east coast of Taiwan, see Fig. 3.

The ASAR image depicted in Fig. 4, which only shows the sea area around the southern section of Taiwan, was acquired 3 hours and 12 minutes later (at 14:01 UTC). It shows a distinct area of reduced image brightness adjacent to the southeastern coast of Taiwan. Its boundary constitutes the atmospheric front. Note the dark lines behind the islands south of Taiwan which result from wind shadowing. From the orientation of these lines the wind direction can be determined. Fig. 4 shows the area around the southern section of Taiwan in greater detail. Two small islands are visible as
bright spots in the right-hand section of the image and also 5 ships aligned along the front as small bright spots. Furthermore, gap winds are visible on the west side of the southern section of Taiwan (the bright elongated patches). They are winds that blow from the eastern side over the island through gaps in the mountain range.

On 11 December 2006 the sea area east of Taiwan was almost completely covered with clouds. On the MODIS image acquired on this day at 3:10 UTC (not reproduced here), a very small increase in cloud density along a line parallel to the east of Taiwan is visible. However, this frontal line is much better visible on the MODIS image acquired the next day, on 12 December at 2:15 UTC, see left image of Fig. 6. The right image of Fig. 6 shows a weather radar image acquired 15 minutes before the MODIS image was acquired. Note that the rain band follows closely the band of increased cloud density.

Using the MM5 meso-scale atmospheric model, numerical simulations have been carried out with the aim of obtaining the airflow around Taiwan for the time of the ASAR data acquisition. The plot depicted on the left of Fig. 7 shows the result (courtesy of J.-P. Chen of the National Taiwan University). It shows that the airflow from the east associated with the synoptic-scale wind is deflected in a southward direction by the high mountain range located at the east coast of Taiwan. As a consequence, a frontal line is generated at the east coast of Taiwan. For comparison, we added to this plot the weather radar image of 14:00 UTC (right image of Fig. 7) showing the rain band. The MM5 simulations yield the existence of an atmospheric front east of Taiwan, but its distance from the coast is somewhat smaller than observed.

On 8 November 2006 an easterly wind with a speed of about 8 m/s was blowing against the east coast of Taiwan. An ASAR Wide Swath ASAR image was acquired at 01:52 UTC which shows an atmospheric front, see left image of Fig. 8. At the same time a cloud image was acquired by the MERIS sensor (flying like ASAR also on Envisat), see the right image of Fig. 8. It shows a broad cloud band whose outer boundary roughly matches the frontal line visible on the ASAR image. Only 38 minutes later (at 02:30 UTC), another cloud image was taken by the MODIS sensor onboard the Terra satellite, see left image of Fig. 9, and again 3 hours and 48 minutes later by the MODIS sensor onboard the Aqua satellite, see right image of Fig. 9.
comparison of these cloud images show that the cloud pattern is rapidly changing, but it seems to be affected by the presence of a local atmospheric front off the east coast of Taiwan.

![Cloud Images](image1.png)

Figure 8: Envisat ASAR image acquired on 8 November 2006 at 01:52 UTC in the Wide Swath Mode. Right: Envisat MERIS image acquired on 8 November 2006 at 01:52 UTC. © ESA

![Cloud Images](image2.png)

Figure 9: Left: MODIS Terra image (visible composite) acquired on 8 November 2006 at 02:30 UTC. Right: MODIS Aqua image (visible composite) acquired on 8 November 2006 at 05:40 UTC.

4. EXAMPLE OF KATABATIC WIND FIELDS

As mentioned in the introduction, also the hypothesis has also been made that katabatic are responsible for the generation of the atmospheric front off the east coast of Taiwan. \[5,6\]. Katabatic winds are caused by cold air generated by radiative cooling of air late in the evening and at night over the mountains. The cold air then flows downhill as a gravity current. Katabatic winds are usually encountered when the weather is calm weather when the sky is cloud-free. In coastal regions, the airflow is funneled through the valleys of the coastal mountain range. When it flows onto the sea, it generates sea surface roughness patterns that mirror the coastal topography. In Figs. 10 two ASAR images are presented showing sea surface manifestations of katabatic wind fields. The ASAR image depicted on the left in shows a katabatic wind field at the east coast of Taiwan which was acquired during clear skies on 29 July 2004 at 13:48 UTC, i.e., at 21:48 local time. The ASAR image depicted in Fig. 11 shows a katabatic wind field at the east coast of the Black Sea which was acquired during clear skies on 19 September 2006 at 19:18 UTC, i.e., at 22:18 local time.

![ASAR Images](image3.png)

Figure 10. ASAR images showing sea surface manifestations of katabatic winds. Left: ASAR image acquired in the image mode on 29 July 2004 at 21:48 local time over the east coast of Taiwan (The width of the imaged area is 100 km). Right: ASAR image acquired in the Wide Swath Mode on 19 September 2006 at 22:18 local time over the east coast of the Black Sea.

These two ASAR images clearly show that the wind field of katabatic winds over the coastal waters is strongly influenced by coastal topography. One can see on the left image of Fig.10 that the katabatic wind reaches out about 10 km onto the sea. This distance is much smaller than the distance of the atmospheric front east of Taiwan which we have determined from the ASAR images (typically between 25 and 70 km). Furthermore, there is no clear frontal line field visible in the ASAR images depicted in Fig. 10 that separates the katabatic wind field from the ambient wind field. These observations do not comply with the hypothesis that katabatic winds are the main cause of the generation of the atmospheric fronts east of Taiwan. However, they may have a modulating effect on its generation.
4. CONCLUSION

Our analysis of ASAR, MODIS, MERIS and weather radar data acquired over the east coast of Taiwan strongly favors the interpretation that the frontal line, which is often observed east of Taiwan, is generated by an offshore airflow, which has its origin in air reflected from the mountain range and which collides with the onshore synoptic-scale wind. From our analysis of time sequences of weather radar images we conclude that the along-shore atmospheric front east of Taiwan is a quasi-stationary atmospheric front which is primarily caused by re-circulation of blocked air, but modulated also by katabatic winds. This interpretation is also supported by simulations carried out with the MM 5 meso-scale atmospheric model.

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REFERENCES


7. [http://www.mmm.ucar.edu/mm5/overview.htm](http://www.mmm.ucar.edu/mm5/overview.htm)