RAIN CELLS ASSOCIATED WITH ATMOSPHERIC FRONTS OVER THE OCEAN STUDIED BY SPACEBORNE SAR AND WEATHER RADAR DATA

Werner Alpers [(1)] and I-I Lin [(2)]

(1) Institut für Meereskunde, Universität Hamburg, Bundesstrasse 53, D-20146 Hamburg, Germany
(2) Department of Atmospheric Sciences, National Taiwan University, 1 Section 4, Roosevelt Road, Taipei, Taiwan 106

ABSTRACT

Spaceborne SAR images acquired over the ocean in conjunction with weather radar images are well suited to study atmospheric fronts in coastal areas. In this paper we confine ourselves to study quasi-stationary atmospheric fronts off the east coast of Taiwan which are located typically 30- 70 km offshore. These quasi-stationary atmospheric fronts were first detected on ERS SAR images [5]. In [5] we have compared mainly ERS SAR images with cloud images from a geostationary satellite, while here we compare Envisat ASAR and MODIS images mainly with weather radar images. Our analysis of three events presented in this paper lends further support to our hypothesis that these coastal quasi-stationary atmospheric fronts are generated by the collisions of the two airflows from opposing directions: one is associated with a weak to moderate easterly synoptic-scale wind blowing against the high coastal mountain range at the east coast of Taiwan and the other with a local offshore wind. The offshore wind results from re-circulated air flow from the synoptic-scale onshore wind and not primarily from a land breeze/katabatic wind system. However, this diurnally varying wind system has a modulating effect on the quasi-stationary atmospheric front.

1 INTRODUCTION

Atmospheric fronts over the tropical and subtropical oceans are often associated with rain cells. If the rain cells are sufficiently strong, then they can be delineated on SAR images of the ocean surface since the impinging rain drops modify the small-scale sea surface roughness and thus the radar backscattering, see, e. g., [1], [2]. Synoptic-scale atmospheric fronts as well as coastal atmospheric fronts over the ocean associated with rain cells have been studied before by using spaceborne synthetic aperture radar (SAR) images in conjunction with other data [3]-[5]. In this paper we confine ourselves to the investigation of rain cells associated with quasi- stationary atmospheric fronts off the east coast of Taiwan. They are often encountered typically 30- 70 km offshore when a weak to moderate synoptic-scale easterly wind blows against the steep mountain range at the east coast of Taiwan. These atmospheric fronts have first been delineated on SAR images acquired by the European Remote Sensing satellites ERS-1 and ERS-2 [5]. Comparisons of these ERS SAR images with other satellite data and with in-situ data indicate that these coastal atmospheric fronts are generated by the collisions of the two airflows from opposing directions: one is associated with a weak to moderate easterly synoptic-scale wind blowing against the high coastal mountain range at the east coast of Taiwan and the other with a local offshore wind. There are two hypotheses about the origin of the offshore wind. The first one is that it is a thermally driven land breeze/katabatic wind and the second one is that it is wind resulting from re-circulated air flow from the synoptic-scale onshore wind. Air blocked by the mountain range at low Froude numbers is re-circulated and flows at low levels back offshore. Our observations strongly favor the re-circulation hypothesis.
Evidence for this interpretation was obtained previously mainly from the comparison of the ERS SAR images with sequences of cloud images acquired by the Japanese Geostationary Meteorological Satellite GMS-4. In this paper we present more data which support this hypothesis by using mainly SAR images acquired by the Advanced Synthetic Aperture Radar (ASAR) on board the Envisat satellite, MODIS images acquired by the Terra satellite, and radar reflectivity images acquired by Taiwanese weather stations. Weather radar images are available every 30 minutes from the sea areas surrounding Taiwan and thus can give, like the cloud images from geostationary satellites, information on the temporal evolution of the atmospheric front. But one has to bear in mind that rain cells as well as clouds have their own dynamics and that they are not always encountered at

Proceedings of SEASAR 2006, 23-26 January 2006, Frascati, Italy,
(ESA SP-613, April 2006)

coastal fronts. In the following we shall present three events where coastal atmospheric fronts east of Taiwan are visible on Envisat ASAR images and/or MODIS images.

2 THE DATA SET

2.1 The 30 September 2005 event

In Fig. 1 an ERS-2 SAR image (left panel), a MODIS cloud image from the Terra satellite (central panel) and a weather radar image (right panel), which were acquired over the east coast ot Taiwan on 7 January 2002 at 02:29, 03:10, and 02:32 UTC, respectively, are depicted. The ERS-2 SAR image shows an oval-shaped area off the east coast of Taiwan, which has a distance of up to 70 km from the coast. The MODIS cloud image acquired from theTerra satellite 41 minutes later show a cloud-free area east of Taiwan, whose eastern boundary is located at its farthest point also about 70 km away from the coast. The cloud band at the eastern boundary of this area is associated with rain cells as evident from the weather radar image acquired 3 minute later (right panel). The weather radar image shows that some weak rain cells are embedded in the cloud band. The Quikscat sea surface wind map (not reproduced here) shows that, 4 hours and 43 minutes before the SAR data acquisition, the wind was blowing from a northeasterly direction with a speed between 5 and 10 m/s. These three images depicted in Fig. 1 are very unique since all of them give a coherent picture of the atmospheric front which is located quite far (up to 70 km) from the coast. This distance is too large for attributing its generation to the interaction of a land breeze/katabatic wind system with a synoptic-scale easterly wind. Land breeze/katabatic wind system is expected not to blow much farther than 20 km offshore.

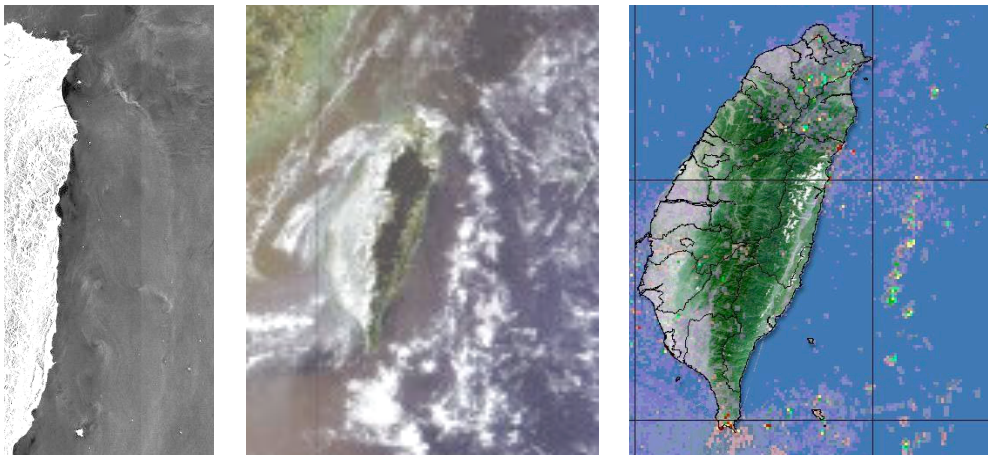

Fig. 1 ERS2 SAR, MODIS and weather radar images acquired on 30 September 2005 at 01:47, 02:55, and 02:00 UTC, respectively, over the east coast of Taiwan.

2.2 The 1 November 2005 event

In Fig. 2, left panel, an Envisat Wide Swath Mode ASAR image acquired over the east coast of Taiwan on 1 November 2005 at 01:42 UTC is depicted. It shows close to the coast a dark area, where the sea surface roughness is very low resulting from low wind velocities. In the sea area farther to the northeast, the sea surface roughness is higher. Visible are also wind streaks aligned in the NE-SW direction, which is indicative for the wind direction. Indeed, the surface weather map of that day (Fig. 4) shows that at 00:00 UTC a north easterly wind of 7.5 m/s was blowing. Also the sea surface wind map (Fig. 5) derived from Quikscat data acquired at 10:48 UTC shows east of Taiwan a north easterly wind of 5- 10 m/s.
The cloud images acquired from the Japanese geostationary satellite MTSAT at 02:00 UTC and at 04:00 UTC (Fig, 2, upper right panels) show broad cloud bands approximately at the position of the dividing line between

the dark and bright areas visible on the Envisat ASAR image. Note, that at 04:00 UTC the cloud band traces the frontal line better than at 02:00 UTC.
The two weather radar images depicted in the lower right panels of Fig. 2, which were also acquired at 02:00 UTC and 04:00 UTC, show distinctive rain bands located off the east coast of Taiwan. The rain band visible on the weather radar image of 02:00 UTC closely follows the dividing line (frontal line) between the dark and bright area visible on the Envisat ASAR image.
A sequence of 4 weather radar images acquired between 0:30 UTC and 03:30 UTC is depicted in Fig, 3. It shows that the rain band is quite persistent over this time period of three hours, but it is subject to slight changes in position and shape. Note that the rain band is still present at 12:00 LST (lower right image of Fig. 2), when the land breeze/katabatic wind system should have ceased blowing offshore.

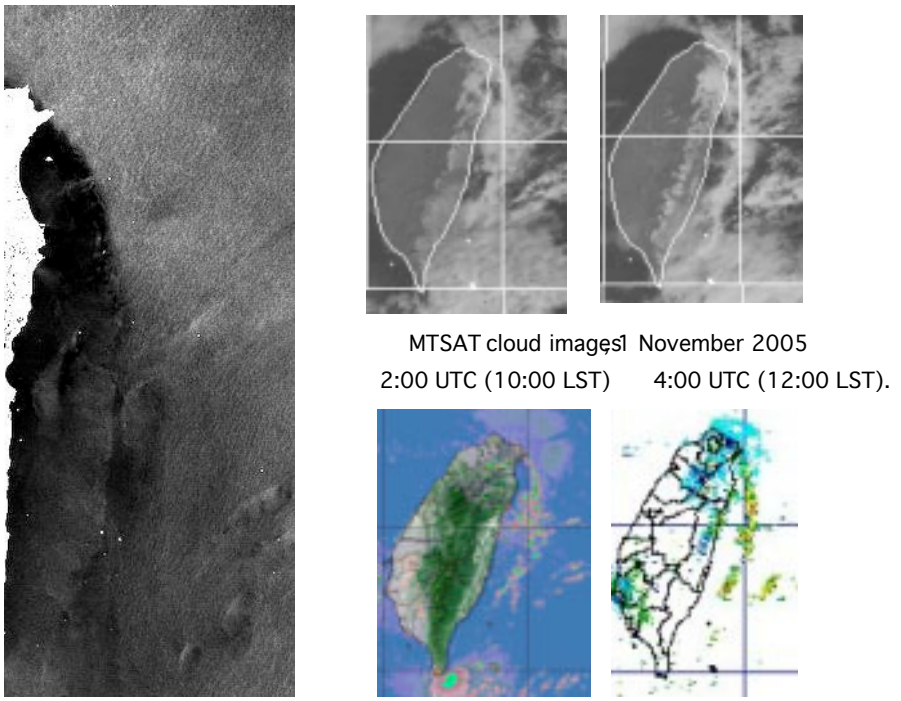

Fig. 2 Envisat Wide Swath Mode ASAR image acquired over the east coast of Taiwan on 1 November 2005 (left panel), cloud images acquired by the Japanese geostationary meteorological satellite MTSAT (upper right panels), and weather radar images acquired by Taiwanese weather stations (lower right panels). The times of the data acquisitions are given in the figure captions.

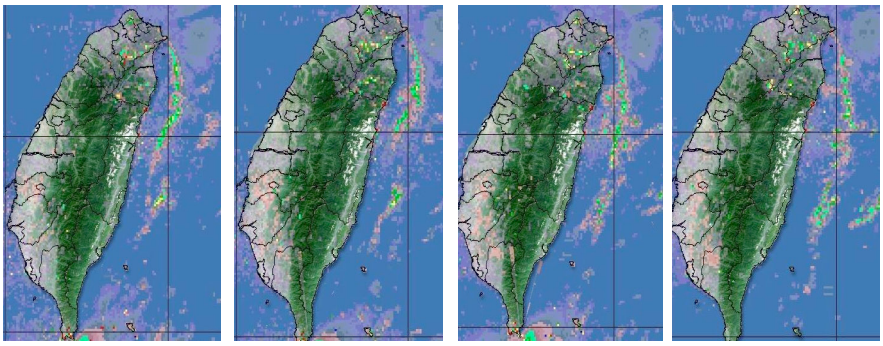

Fig. 3 Weather radar images acquired on 1 November 2005 at 00:30, 01:30, 02:30, and 03:30 UTC, respectively

.

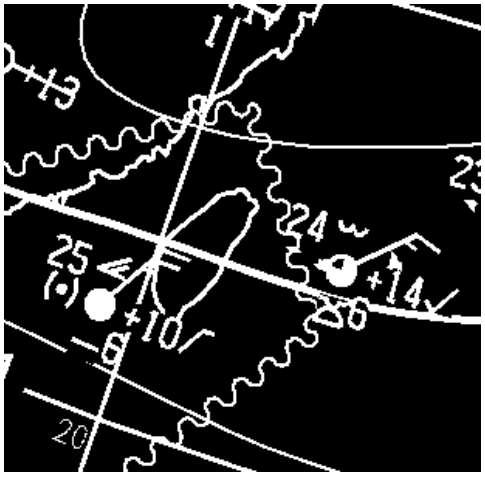

Fig.4 Surface weather map of 1 Nov. 2005 at 00:00 UTC around Taiwan.

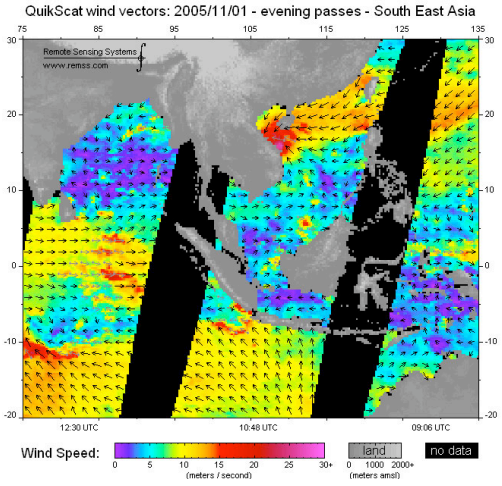

Fig. 5 Quikscat wind map of 1 Nov. 2005 at 10:48 UTC (Taiwan area)

2.1 The 20 April 2003 event

In the central panel of Fig. 6 a Terra MODIS image is depicted which was acquired on 20 April 2003 at 02:40 UTC, i.e., at 10:40 LST. The left panel shows the north east section of this MODIS image in more detail. Clearly visible is an area close to the coast where the image intensity is brighter than in the sea area farther east. This is caused by differences in the reflectivity of sunlight (sun glitter) from the sea surface and thus by differences in the sea surface roughness, which in turn is caused by differences in the sea surface wind velocity. This MODIS image clearly demonstrates that the quasi-stationary atmospheric front east of Taiwan can also become visible on optical images when the viewing angle of the optical sensor relative to the sun elevation angle is favourable. The weather radar image acquired at 03:00 UTC (right panel) shows a very faint rain band in the southern section, whose location correlates well with the location of the cloud band visible on the MODIS image (central panel). In Fig. 7 the sea surface wind map derived from Quikscat data acquired on 20 April 2003 at 09:54 UTC is depicted. Although this map was derived from Quikscat data acquired 7 hours and 14 minutes later than the MODIS image, it shows that also on this day an easterly wind of about 5 m/s was blowing against the mountain range at the east coast of Taiwan.

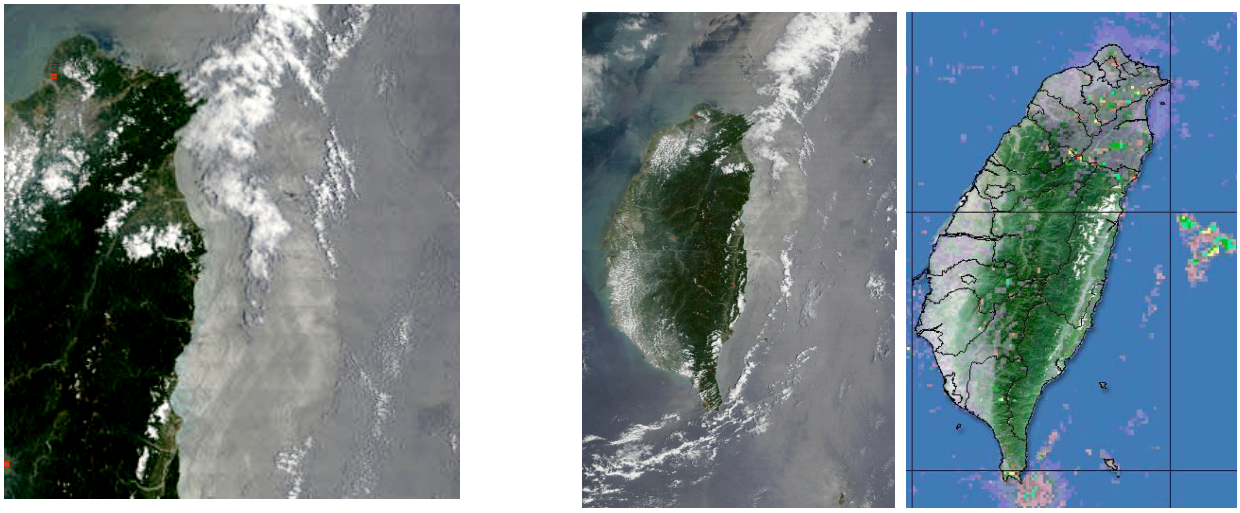

Fig. 6 MODIS image (left and central panels) and weather radar image (right panel) acquired over Taiwan on 20 April 2003 at 02:40 UTC and 03:00 UTC, respectively. The left panel shows a sub-area (northern section of the east coast of Taiwan) of the MODIS image depicted in the central panel, which highlights the differing sea surface reflectivity on both sides of the atmospheric front.

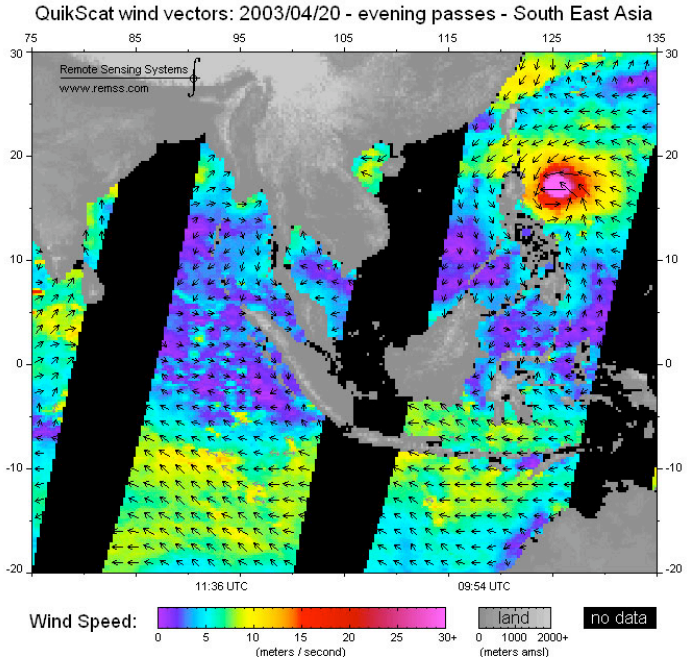

Fig. 7 Quikscat wind map of 20 April 2003 at 9:54 UTC (Taiwan area).

3. INTERPRETATION OF THE DATA

We interpret the data presented in the previous section as follows (see Fig. 9): The quasi-stationary atmospheric front east of Taiwan is generated by the collisions of the two airflows from opposing directions: one is associated with a weak to moderate easterly synoptic-scale wind blowing against the high coastal mountain range at the east coast of Taiwan and the other with a local offshore wind. At the convergence zone where both airflows collide air is forced to move upwards which often gives rise to the formation of coast-parallel cloud bands. There are two hypotheses about the origin of the offshore wind. The first one is that it is a thermally driven land

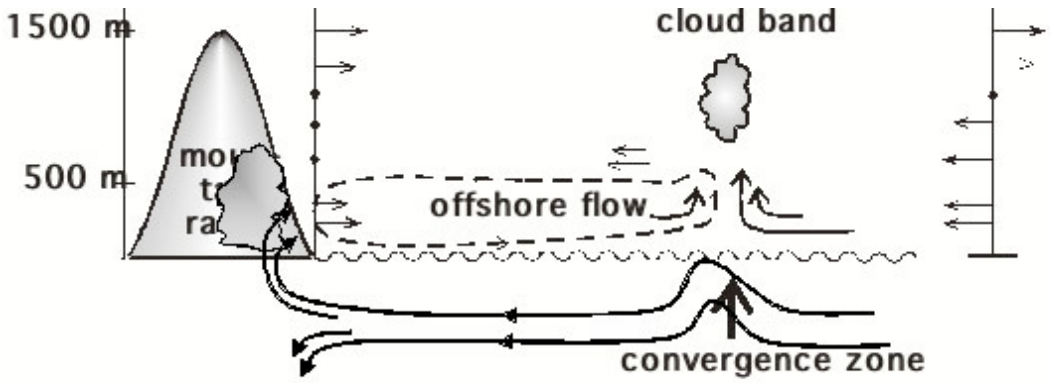

Fig. 8 Schematic plot of the airflow for the case that re-circulation of air causes the formation of the coast-parallel atmospheric front. The two vertical lines with the horizontal arrows attached denote the offshore components of the wind vectors 1) at the shoreline and 2) east of the convergence line.

breeze/katabatic wind system and the second one is that it is wind resulting from re-circulated air flow from the synoptic-scale onshore wind. Air blocked by the mountain range at low Froude numbers is re-circulated and flows at low levels back offshore. This mechanism was studied in detail with computer simulations by Smolarkiewicz et al. [6] and compared with observations of cloud bands off the Hawaiian island, where they found good agreement between theory and observations.

The data presented in this paper clearly favor the recirculation hypothesis. In particular, the frontal lines visible on the images of the 30 September 2005 (Fig. 1) and the 1 November 2005 (Fig. 2) events, which are located quite far from the coast line, suggest that land breeze/katabatic wind cannot be the main cause for the generation of the quasi-stationary atmospheric front east of Taiwan.

4 REFERENCES

[1] Atlas, D., "Footprints of storm on the sea. a view from a spaceborne synthetic aperture radar", *Journal of Geophysical Research*, 99, 7961–7969, 1994

[2] Melsheimer, C., W. Alpers, and M. Gade, "Simultaneous observations of rain cells over the ocean by the synthetic aperture radar aboard the ERS satellites and by surface-based weather radars", *J. Geophys. Res.*,106, 4556-4677, 2001.

[3] Ivanov, A. Yu., W. Alpers, K. Ts. Litovchenko, M.-X. He, Q.Feng, M. Fang, and X.-H. Yan, "Atmospheric front over the East China Sea studied by multi-sensor satellite and in-situ data", *J. Geophys. Res.*, 109(C12), C12001 doi:10.1029/2004JC002432, 2004.

[4] Alpers,W., C. M. Cheng, Y. Shao, and L.Yang, "Study of rain cells over the South China Sea by synergistic use of multi-sensor satellite and ground-based meteorological data", submitted to *Photogrammetric Engineering & Remote Sensing, 2006.*

[5] Alpers, W., J.-P. Chen, and I-I Lin: "Atmospheric fronts off the East Coast of Taiwan studied by ERS synthetic aperture radar imagery", *Proceedings of the 2005 International Geoscience and Remote Sensing Symposium (IGARSS'05),* Seoul, Korea, 25-29 July, 2005, IEEE, Piscataway, NJ, USA, 2005.

[6] Smolarkiewicz, P. K., R. M. Rasmussen, and T. L. Clark, "On the dynamics of Hawaiian cloud bands: island forcing", *J. Atmos. Sci.,* 45, 1872 – 1905, 1988.