Atmospheric Fronts off the East Coast of Taiwan Studied by ERS Synthetic Aperture Radar Imagery

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Abstract— **Synthetic aperture radar (SAR) images acquired by the European Remote Sensing satellites ERS-1 and ERS- 2 over the east coast of Taiwan around 10:30 local time often show frontal features that are located typically 50 km off the coast. We show that they are not sea surface manifestations of a land breeze front, but of a quasi-stationary atmospheric front that persists over the whole day or even over the next day(s). Evidence for this interpretation is obtained mainly from the comparison of the SAR images with sequences of cloud images acquired by the Japanese Geostationary Meteorological Satellite GMS-4.**

Keywords-component; coastal atmospheric front, synthetic aperture radar, cloud image, Taiwan

I. INTRODUCTION

Frontal features located off the east coast of Taiwan are often visible on synthetic aperture radar (SAR) images acquired by the European Remote Sensing satellites ERS- 1 and ERS- 2 around 10:30 local time. These frontal features have previously been misinterpreted as being sea surface manifestations of the Kuroshio front (an oceanic front), but here we show that they are sea surface manifestations of quasi-stationary atmospheric fronts. The fronts run quasi-parallel to the coast line, but vary strongly in distance from the coast (20-70 km), in strength (difference in wind stress before and behind the front), and width (sharpness). The formation of quasi-stationary fronts off the east coast of Taiwan is due to the unique environment: the high steep mountain chain bordering the coast (average height: 2500 m) and the warm Kuroshio flowing in a northward direction along the coast. Evidence for the interpretation that the frontal features which are often visible on ERS SAR images acquired over the east coast of Taiwan are indeed sea surface manifestations of quasi-stationary atmospheric fronts is obtained from the comparison of the SAR images with sequences of cloud images taken from the GMS-4 geostationary satellite, with weather maps, and with radiosonde data. Quasi-stationary coastal fronts have been studied before in other parts of the world, see, e. g., [1], and [2]), but, to our knowledge, never at the east coast of Taiwan.

Note that SAR is the only instrument capable of revealing fine-scale structures of atmospheric fronts, like the distribution of rain cells embedded in fronts.

II. EXAMPLES OF QUASI-STATIONARY FRONTS

A. The 18 January 1999 front

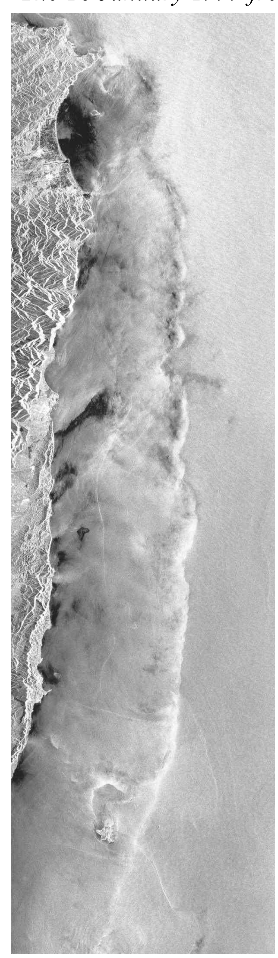


Figure 1. ERS-2 SAR strip acquired on 18 January 1999 at 2:25 UTC or 10:25 local time (LT) along the east coast of Taiwan. Imaged area is 380 km x 100 km. © ESA

The ERS-2 SAR image depicted in Fig.1 shows a frontal line along the east coast of Taiwan at a distance approximately 50 km offshore. In the lower (southern) section, the image intensity, and thus the small-scale sea surface roughness, is strongly enhanced in the frontal area due to flow convergence caused by opposing winds. The semi-circular features with dark patches in the middle visible in the upper (northern) section of the image are sea surface manifestations of convective rain cells.

The surface weather map of 18 January 1999 at 00:00 UTC shows east of Taiwan winds of 5 ms^{-1} from E, cloud coverage of 7/8, and rain showers. West of Taiwan it shows winds of 2.5 ms^{-1} from NNE.

The radiosonde launched at Hualien on 18 January at 0:00 UTC measured at a height of 174 m a wind speed of 2.4 ms^{-1}, a wind direction of 264^0, an air temperature of 16.7^0 C, and a relative humidity of 94%. The wind speed remained below

5 ms^{-1} up to a height of 2300 m where the wind direction was 203^0. Then the wind speed increased to 10 ms^{-1} at a height 3500 m where the wind direction was 237^0, and to 19 ms^{-1} at a height of 4700 m where the wind direction was 250^0. The high relative humidity (varying between 86% and 100%) was maintained up to a height of 4700 m, where it suddenly dropped to 37 %.
Fig. 2 shows two cloud images taken from the Japanese Geostationary Meteorological Satellite GMS-4 in the visible band. The image on the left of Fig.2 was taken only 8 minutes after the ERS-2 SAR data acquisition and shows a 60 km wide cloud band adjacent to the east coast of Taiwan. Its eastern boundary follows closely the frontal line visible on the ERS-2 SAR image. All other GMS-4 cloud images taken on that day between 7:32 LT and 15:32 LT also show cloud bands parallel to the coastline, see the image taken at 13:33 LT which is depicted on the right of Fig.2.

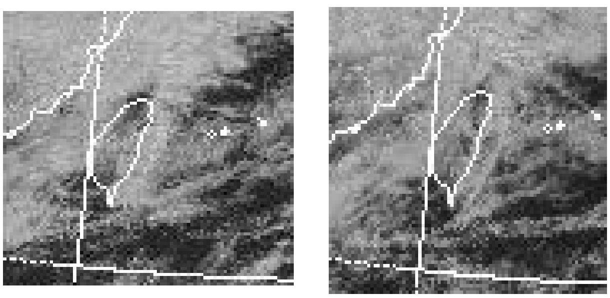
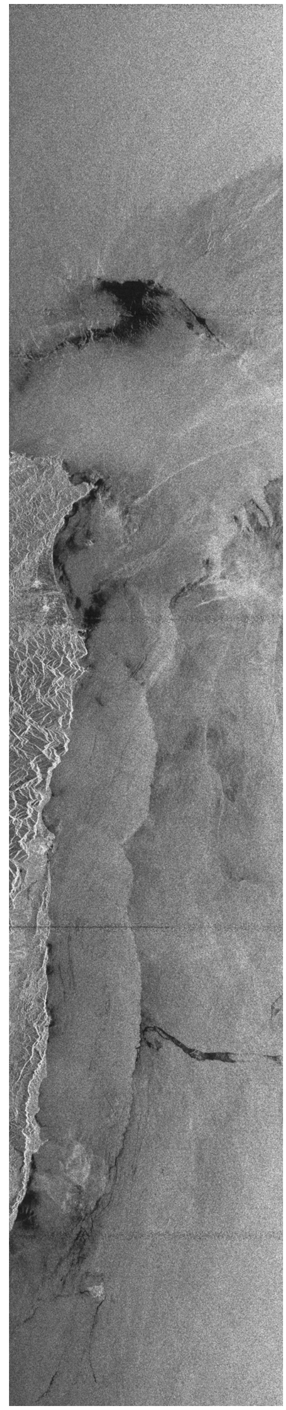


Figure 2. Cloud images obtained by the Japanese Geostationary Meteorological Satellite GMS-4 in the visible band on 18 January 1999 at 10:33 LT (left image) and at 13:33 LT (right image).

The sequence of cloud images show that the width of the coastal cloud band increases from sunrise to sunset. At 7:32 LT the cloud band was approximately 20 km wide and at 15:32 LT it was 80 km wide. Note, that coastal cloud bands cannot be detected when there is complete cloud cover..
From the data analysis of the 18 January 1999 event we conclude: (1) The front is formed by the collision of two air masses, a warm air mass advancing from the east over the warm waters of the Kuroshio, and a cold air mass coming from the west, i. e., from the mountain range. (2) The time at which the frontal feature was captured by the ERS SAR (10:25 LT) is well beyond the time at which land sea breeze and katabatic wind fronts occur. Thus we exclude that the frontal feature visible on the ERS-2 SAR image is the sea surface manifestation of a land sea breeze/katabatic wind front. This is further substantiated by the analysis of a sequence of cloud images showing that a coastal cloud band was present during the whole day. (3) Since the water temperature of the Kuroshio (around 25^0 C in January) was much higher than the air temperature (16.7^0 C), the air-sea interface was highly unstable. This gave rise to strong turbulence and thus to enhanced generation of ripple waves as well as to inhomogeneities in the ripple wave field causing inhomogeneities in the gray level in the SAR image. Furthermore, probably also convective rain cells developed.

B. The 7 April 1996 front



This ERS-1 SAR image depicted in Fig.3 shows a frontal line along the east coast of Taiwan at a distance of approximately 30 km offshore. When comparing this SAR image with the SAR image depicted in Fig. 1, one notes that the roughness band parallel to the coast has a much more homogeneous appearance. Note that an oil spill is deflected eastwards.
The surface weather map of 7 April 1996 at 00:00 UTC shows east of Taiwan winds of 2.5 ms^{-1}s from SE, and alto cumulus clouds. It shows further that at the weather station at Taitung (at the east coast of Taiwan), the wind speed was below 1 ms^{-1} and was blowing from NW, the air temperature was 23^0 C, the dew point temperature 21^0 C, and the lower cloud level between 600 and 1000 m. This implies that the clouds near the coast and over the open ocean must have been of different origin, i.e., the clouds near the coast must have been generated locally. Six hours later, at 6:00 UTC, the air temperature at Taitung was 26^0 C, which is very close to the sea surface temperature, which, according to climatological data, is at this time of the year between 26^0 C and 27^0 C.
The radiosonde launched at Hualien on 7 April 1996 at 00:00 UTC measured at a height of 152 m a wind speed of 1.1 ms^{-1} w, a wind direction of 251^0 , an air temperature of 21.1^0 C, and a relative humidity of 98%. The wind speed was always below 1.6 ms^{-1} at heights between 152 m and 2300 m where the wind direction varied between 185^0 and 266^0. (Note, however, that the accuracy of wind direction is very

Figure 3. ERS-1 SAR strip acquired on 7 April 1996 at 2:25 UTC or 10:25 LT along the east coast of Taiwan. Imaged area is 540 km x 100 km. © ESA

poor if the wind speed is below 2 ms^{-1}). From there the wind speed increased to 10.2 ms^{-1} at a height of 4400 m, where the wind direction was 268^0.
The GMS-4 cloud images acquired on 7 April 1996 at 2:01 UTC or 10:01 LT, i.e., 24 minutes before the ERS-2 SAR data

acquisition, shows also a cloud band adjacent to the east coast of Taiwan. Its eastern boundary follows closely the frontal line visible on the ERS-1 SAR image.

From the data analysis of the 7 April 1996 front we conclude: (1) The fact that the oil trail visible in the lower part of the image (which is a typical oil spill originating from a ship) is deflected and bended around, is indicative of an opposing wind, i.e., of a wind blowing from the mountains onto the sea. (2) Since the air temperature was only slightly cooler than the sea surface temperature, the air-sea interface may have been only slightly unstable or neutrally stable, which explains the quite homogeneous coastal band in the SAR image.

C. The 7 January 2002 front

The ERS-2 SAR image depicted in Fig. 4 shows off the coast a broad jagged frontal feature with embedded dark patches, which extends from the center of the image southwards. We interpret the dark patches as being sea surface manifestations of rain cells. In the lower left-hand section of the SAR image wind streaks oriented in NW-SE direction are visible suggesting that a wind was blowing approximately in this direction.

The cloud images acquired 7 minutes later by the GMS-4 satellite (not shown here) and 45 minutes later by the MODIS sensor onboard the Terra satellite (Fig. 5) show clouds east of Taiwan which are separated from the coastline by a cloud-free area. The sequence of hourly GMS-4 cloud images acquired in the visible band reveals that this cloud-free band persisted during the whole day and was also present the day before. The sequences of GMS-4 cloud images acquired in the infrared bands on 6 and 7 January 2002 reveal that high level clouds coming from a westerly direction were blown over Taiwan. These clouds were unaffected by the mountain chain and were clouds associated with a cold front of a cyclone centered over the Sea of Japan.

On 7 January 2002 measurements of the sea surface wind field were carried by the scatterometer onboard the Quikscat satellite (spatial resolution: 25 km) at 05:42 LT and 18:06 LT. The wind field measured at 05:42 LT is depicted in Figure 6. Note that Quikscat cannot measure wind fields close to the coast because there the radar backscatter from a resolution cell is contaminated by radar backscatter from land. This map shows that 4 hours and 43 minutes before the SAR data acquisition the wind was blowing in the southern section of the imaged area with a speed of 4-6 ms^{-1} from an easterly direction, and further north with a speed of 10–14 ms^{-1} from a northwesterly direction. The Quikscat wind field map at 18:06 LT (not reproduced here) shows that at this time the wind was blowing in the whole coastal region with an almost uniform speed of 10-14 ms^{-1} from a northerly direction. We interpret the absence of a visible atmospheric front in the northern section of the SAR image as being caused by the strong synoptic wind, which destroys or masks the front.

From the data analysis of the 7 January 2002 event we conclude: (1) The absence of clouds near the coast suggests that dry air coming from the mountains was blowing away the moist air farther east, (2) In the confluence zone where the dry air from the mountains meets the moisture-laden air from the sea, convective rains cells developed. (3) The shape of the frontal feature with embedded dark patches suggests the presence of convective rain cells. This is substantiated by the MODIS cloud image which shows that clouds were present where rain cells are visible on the SAR image. (4) The dark wind tongues visible at the coastline indicate wind shadowing and suggest a (weak) eastward directed surface wind.

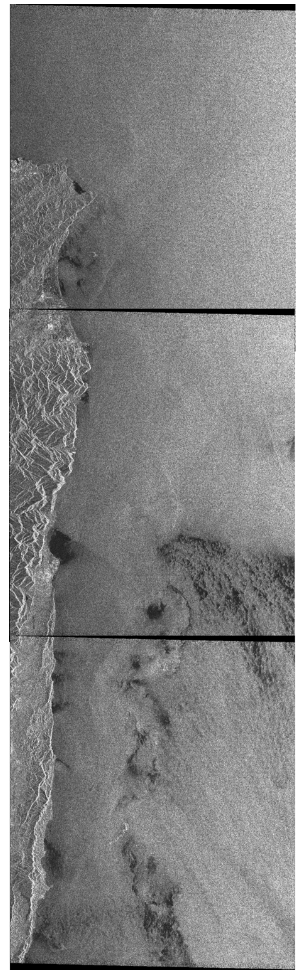


Figure 4. ERS-2 SAR strip acquired on 7 January 2002 at 2:25 UTC (10:25 LT) along the east coast of Taiwan. Imaged area is 330 km x 100 km. © ESA

Figure 5. MODIS image acquired on 7 January 2002 at 03:10 UTC (11:10 LT) over Taiwan and adjacent sea areas.

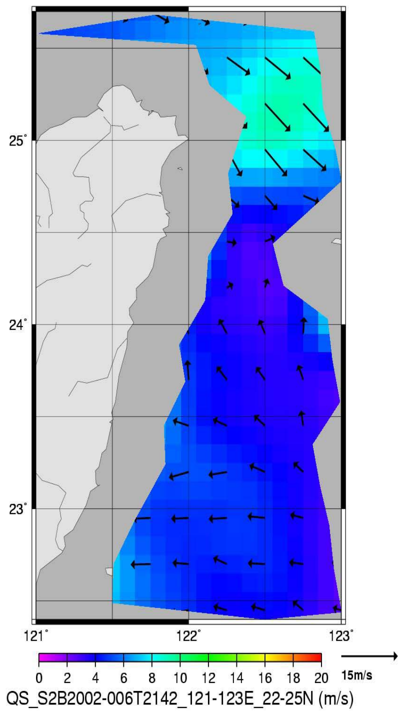


Figure 6. Wind field map derived from Quikscat data acquired on 7 January 2002 at 05:42 LT.

D. The 3 May1999 front

The ERS-2 SAR image depicted in Fig. 7 shows a frontal line along the east coast of Taiwan at a distance of approximately 50 km offshore. On the average, the 50 km wide frontal band exhibits a lower radar backscatter than the sea area farther east.

The surface weather map of 3 May 1999 at 00:00 UTC shows east of Taiwan winds of 5 ms^{-1} from an easterly direction, 7/8 cloud cover (2/8 of the clouds were low-level cumulus clouds (300-600 m above sea level) and 5/8 of them were high clouds). At the coast the air temperature was 27^0 C, which was probably higher than the sea surface temperature.

The cloud image acquired 7 minutes later by the GMS-4 satellite at 10:32 LT (not shown here) show in the area imaged by the SAR a cloud cover of approximately 80% and a very distinct line of dense clouds following closely the frontal line visible on the SAR image. We interpret this as being caused by moist air coming from the east which is lifted upwards when it collides with the air from the mountains.

The sequences of GMS-4 cloud images acquired in the infrared bands on 2 and 3 May 1999 reveal that high level clouds were blown from the west over Taiwan where they were not affected by the Central Mountain Chain. The sequences of GMS-4 images show further that a cumulus cloud developed over the Taiwan Strait which then moved towards the island where it dissolved over the land.

III. CONCLUSIONS

The analysis of the ERS SAR images presented in the last section and of a large number of other ERS SAR data acquired around 10:30 local time over the east coast of Taiwan in conjunction with other data yield the following results: (1) Strong quasi-stationary atmospheric fronts off the east coast of Taiwan are generated when a weak easterly synoptic-scale wind blows against the steep coastal mountain chain where it is blocked and where it encounters an opposing westerly local wind blowing from the mountains. (2) The blockage causes an uplift of the moist air which often gives rise to rain. (3) Quasi-stationary fronts are usually associated with a cloud boundary separating cloud-covered and cloud-free areas or they are associated with a cloud line. (4) In the frontal area often rain cells are encountered, (4) The generation of quasi-stationary fronts off the coast seems not to require the absence of clouds over the mountain range, i.e., "radiation weather". (5) Quasi-stationary fronts have been detected in all seasons, but the strongest fronts seem to occur during the winter months when the air-sea temperature difference is large, (6) For those frontal events analyzed in detail in this investigation, we have noted that always a strong westerly wind was blowing over the mountains. This wind may have been instrumental in triggering the flow of cold air downhill.

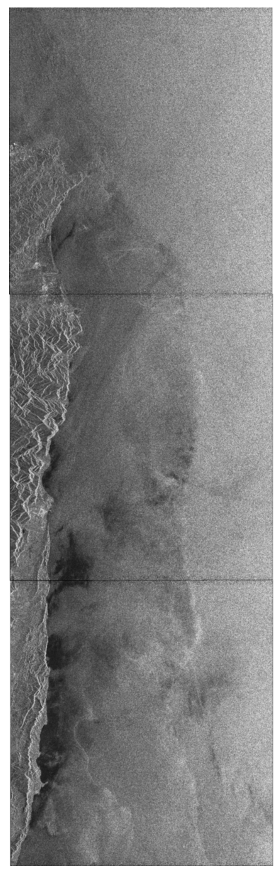


Figure 7. ERS-2 SAR strip acquired on 3 May 1999 at 2:25 UTC (10:25 LT) along the east coast of Taiwan. Imaged area: 300 km x 100 km. © ESA

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