Detection of convective systems through surface wind gust estimation based on Sentinel-1 images: A new approach

Tran Vu La1 | Christophe Messager1 | Marc Honnorat1 | Claire Channelliere2

1EXWEXs, Brest, France
2TOTAL Exploration & Production, Courbevoie, France

Correspondence
Tran Vu La, EXWEXs, 2 Rue de Keraliou, Brest 29200, France.
Email: tvl@exwexs.fr

Funding information
Total, Grant/Award Number: SOLSTICE Project

Convective system (CS) tracking and identification are mainly based on the analyses of brightness temperature and precipitation. Few studies reported about the detection of CSs through surface wind gust estimation due to CS downdraft reaching sea surface. Based on high-resolution Sentinel-1 images, this study proposes the detection of CS signatures through an enhancement of surface wind magnitude in the vicinity of CSs. The CMOD5.N and Sapp’s model (CMOD-like function) are used for the retrieval of surface wind speed from VV-pol and HH-pol images, respectively. Based on numerous cases, the study presents the retrieved winds from two representative Sentinel-1 images acquired over the Gulf of Mexico, on which several types of CS effect on sea surface (i.e., round form, convection line) are detected. Wind gust produced by the downdraft associated to these CSs exceeds 20–25 m/s. In order to verify whether the detected wind gust is associated to CSs, moderate/heavy precipitation extracted from the Next-Generation Radar (NEXRAD) images is used as an additional assessment.

KEYWORDS
convective system detection, Sentinel-1, surface wind speed estimation

1 INTRODUCTION

Convective systems (CSs) produce many meteorological hazards, that is, heavy precipitation, wind gust, lightning, etc., everywhere including over marine areas. Under radar or satellite observations, CS signatures may be circular or seen as a line (squall), and they can occur at several scales (mesoscale, sub-mesoscale, convection cells). In spite of many typical features, the identification and tracking of CSs are performed through usually following one or two parameters, that is, brightness temperature (Fioletau and Roca, 2013) and heavy precipitation (Rochette and Moore, 1996), and based on infrared images and/or numerical weather prediction (NWP) models (Houze Jr., 2004). Few studies reported about CS detection through the estimation of surface wind gust magnitude (may exceed 20–25 m/s; Cotton, 1992) which is produced by CS downdraft on sea surface. The few number of studies about this subject can be explained by the lack of wind data for assessment, especially at a high spatial resolution.

The CS downdraft (a local effect) may reach the sea surface and then be deflected in several directions and the effect on resulting observed wind in term of intensity and direction is modulated by synoptic wind (synoptic effect). When local and synoptic winds blow in the same direction, the velocity of the local wind may be increased by a factor three (Yokoi et al., 2014) and usually exceeds 20–25 m/s (Cotton, 1992). The significant enhancement of wind speed leads to strong sea surface roughness which can be detected by the satellite images acquired at small scales (or high spatial resolution). Consequently, the CSs can be indirectly detected by high-resolution satellite images, for instance from Synthetic Aperture Radar (SAR) data, through their signatures on sea surface. As well as surface wind magnitude, CS downdraft can
change locally the direction of the environmental wind. However, unlike the wind magnitude, such modifications of wind direction are usually difficult to capture on SAR images, and thus, it is not the subject focused in this study.

Compared to the other wind sources, that is, buoys, scatterometers, NWP models, SAR sensors are selected for the estimation of surface wind gust, since they can offer high-resolution images on which CS signatures can be detected. In particular, C-band SAR sensors are not much affected by the meteorological factors, that is, cloud, rain, solar brightness, etc. This is important for the detection of CS signatures through surface wind gust estimation, since CS downdraft is regularly accompanied by moderate or heavy rainfall (although this does not always happen). In fact, impinging rain drops onto sea surface may increase or decrease surface roughness, and thereby radar backscattering, depending on rainfall and environmental wind as indicated in Alpers et al. (2016). This can contaminate surface wind gust estimation based on radar backscattering (extracted from SAR data). However, as concluded in Xu et al. (2015) and Contreras and Plant (2006), despite precipitation, in C-band wind-induced surface scattering is dominant in total scattering from the sea surface roughness. In other words, the impact of rainfall on surface wind speed estimation in C-band is quite small. Therefore, this subject is not discussed here. Among available C-band SAR, Sentinel-1A/B images are used for surface wind speed retrieval, since they satisfy the requirements of high spatial resolution, large coverage, and revisit frequency. In spite of many proposed studies (Mouche et al., 2012; Montuori et al., 2013), the scatterometry-based wind speed retrieval is still one of the most widely used methods, since it offers accurate wind speed estimates up to 25 m/s. In such approach, co-polarized radar backscattering, quantified through normalized radar cross section (NRCS), is empirically described as a function of wind speed, wind direction (relative to radar look), and the geometry of observations. This function is also called empirical geophysical model function (GMF). Therefore, once the NRCS, geometric parameters, and relative wind direction are determined, surface wind speed can be derived by inverting the GMF. In C-band, among the GMFs named C-band MODel (CMOD) functions, CMOD5.N (Hersbach, 2008) is selected here since it has been developed for the improvement of wind speed estimation, especially for strong wind. Since CMOD5.N is used for VV-pol wind speed estimation, a polarization ratio (PR; Horstmann et al., 2002) is normally proposed to derive wind speed from horizontal-polarization (HH-pol) data. Nevertheless, two models (Komarov et al., 2014; Sapp et al., 2016) have been recently proposed for the direct extraction of wind speed from HH-pol images. The Sapp’s model is used in this paper, since it is also based on the GMF as CMOD5.N (CMOD-like function).

There are several ways to obtain wind direction for wind speed estimation based on CMOD5.N and the Sapp’s model, such as extraction from SAR images (local gradient, fast Fourier transform), NWP models or sea buoys. This current study uses wind direction given by the global forecast system (GFS) numerical modeling provided by the National Centers for Environmental Prediction (NCEP). In spite of having small spatial scales, SAR-based wind direction was not used here, since its accuracy depends on the factors such as speckle noise, resampling ratio (La et al., 2017), and thereby it is not suitable for the processing of thousands of images. It is worth to note that there are no accurate and very high-resolution weather models able to reproduce correctly the small-scale convection (scale lower than 1 km), except the large Eddy simulation models, but only for local case studies and each time in a dedicated tuned version. As a result, there is no operational model correctly dealing convection at high resolution, over large areas where satellites may operate. Despite its coarse resolution (25 km), GFS wind direction is significantly convenient for processing in operational mode. Finally, the main aim of the paper is to provide a method to detect CSs through the enhancement of wind magnitude generated by CS downdraft at the ocean surface, in spite of wind direction.

The paper is organized as follow. Section 2 presents the description of CMOD and CMOD-like functions for wind speed estimation based on Sentinel-1 images. Section 3 describes the detection of CS effect on sea surface through wind maps derived from Sentinel-1 data. It is verified by the observations of radar reflectivity (or precipitation) extracted from the Next-Generation Radar (NEXRAD) images acquired by the surface radars in the Gulf of Mexico. Finally, section 4 is devoted for discussion and conclusion.

2 | DESCRIPTION OF CMOD AND CMOD-LIKE FUNCTIONS

The general form of the CMOD and CMOD-like functions is described as

$$
\sigma_{VV}^0 = A(\theta, U_{10})[1 + b_1(\theta, U_{10}) \times \cos \Phi_R + b_2(\theta, U_{10}) \times \cos 2\Phi_R]^B,
$$

where $\sigma_{VV}^0$ is the VV-pol NRCS of sea surface and $\Phi_R$ is the wind direction relative to radar look. The parameters $A$, $b_1$, $b_2$ are described as function of wind speed at the 10-m reference height $(U_{10})$ and incidence angle $\theta$, while the exponent $B$ is a fixed value. The values of $A$, $b_1$, $b_2$, and $B$ are different for each CMOD or CMOD-like function. They are determined based on the large collections of in situ measurements from sea buoys, scatterometers, and SAR data.

Figure 1 illustrates the sketch of wind speed estimation from Sentinel-1 images based on CMOD5.N and the Sapp’s model. The geometric parameters (incidence angle and radar
look) are first extracted from Level-1 data. They are then applied in Equation (1) with GFS wind direction and initial wind speed to yield NRCS. The calculated NRCS ($\sigma_{cal}$) is compared to that extracted from the preprocessed data ($\sigma_{obs}$). If the difference between $\sigma_{cal}$ and $\sigma_{obs}$ is inferior to the acceptable deviation ($\delta$), the initial wind speed is the obtained value. Otherwise, the input wind speed is increased one step, and the process of wind speed estimation is restarted. The $\delta$ value decides time calculation and the accuracy of wind speed estimates. Indeed, if $\delta$ is too small, time calculation is significantly long. Otherwise, if $\delta$ is too large, wind speed estimates may not be accurate.

3 | CS DETECTION THROUGH WIND SPEED ESTIMATION

3.1 | VV-pol Sentinel-1 image

Figure 2 presents the detection of a convection line (squall) moving eastward offshore the Gulf of Mexico, through surface wind speed estimation based on CMOD5.N from a VV-pol Sentinel-1 image acquired on first June 2017. Wind gust associated to the squall line in Figure 2a (Lat 28°N, Lon 93°–94°W) exceeds to 25–30 m/s, while it is not noted in Figure 2b, where wind map with 8–9 m/s is derived from the GFS. This is due to the large spatial grid of GFS wind speed (25 km). Indeed, Figure 2c presents a wind map consisting of the difference between CMOD5.N and GFS wind speeds. It highlights the CS signature, as well as the zones with and without the effect of CS downdraft.

As indicated above, CS downdraft is usually accompanied by moderate/heavy rain (although this does not always happen). Therefore, rainfall (or radar reflectivity) can be considered as an additional source to assess whether the strong-wind zones observed in Figure 2a are associated to the CS. For this approach, Figure 2d presents the radar reflectivity extracted from a NEXRAD image acquired by the surface radar installed in Houston, TX. It has the same coverage area and quite similar collection time as the Sentinel-1 image (only 1 min time gap). In the zones where wind gusts (20–30 m/s) are retrieved (Lat 28.5°N, Lon 94.5°–95°W and Lat 28°N, Lon 93°–94°W), high radar reflectivity of 40–50 dBZ (or heavy precipitation) is noted. This matches the typical features of CSs, that is, surface wind gust and heavy precipitation.

Wind field estimates in Figure 2 are compared to the in situ measurements given by the National Oceanic and Atmospheric Administration (NOAA) sea buoys (LUIT2, 42035, and 42047) in Table 1. The positions of these stations are illustrated in Figure 2a and Table 1. For an accurate comparison, the collection time of in situ measurements is closest as possible to that of the Sentinel-1 image. The GFS wind directions are close to the measured ones, despite their large spatial grid. This permits to expect good wind speed estimates. Indeed, the estimated wind speeds from the Sentinel-1 image are quite similar to the in situ measurements. The deviation of 0.4–0.8 m/s is largely lower than the reasonable threshold of 1 m/s for high-resolution wind maps and 2 m/s for larger ones.

3.2 | HH-pol Sentinel-1 image

In Figure 3, a CS signature (Lat 25.5°–25°N, Lon 83°–83.5°W) with the size of 0.5° (55 km) is identified offshore the Gulf of Mexico, through surface wind speed estimation based on the Sapp’s model from a HH-pol Sentinel-1 image acquired on September 26, 2016. The detected CS signature has a round form with a typical front associated to a downdraft (Figure 3a). Wind gust produced by the downdraft associated to this CS exceeds 20–25 m/s. As the previous case, the CS signature cannot be found on the GFS-derived wind map in Figure 3b, due to its coarse spatial grid (25 km). Meanwhile, it is well detected through surface wind speed estimation from Sentinel-1 image. This is shown in Figure 3c where CS signature is highlighted. Likewise, the zones with and without the effect of CS downdraft are clearly discriminated.

Figure 3d shows the radar reflectivity extracted from a NEXRAD image acquired by the radar in Tampa, FL. The time gap for data collection between Sentinel-1 and NEXRAD images is only 1 min. At Lat 25.5°–25°N and Lon 83.5°W, where wind gust exceeds 20–25 m/s, high radar reflectivity of 35–50 dBZ or (heavy rainfall) is noted. This permits to verify the CS signature detected in Figure 3a. Compared to the convection line noted in Figure 2a, the wind gust and precipitation of the detected CS in Figure 3a are less significant.

For validation, wind field estimates in Figure 3 are compared to the in situ measurements given by the NOAA sea buoys (42023, PL5F1, and KYWF1) in Table 2. The coordinates of these stations are illustrated in Figure 3a and Table 2. The GFS wind directions are close to the measured ones, despite their coarse spatial grid. As expected, wind
Speed estimates based on the Sapp’s model are quite similar to the in situ measurements. The deviation of 0–0.7 m/s is largely below the reasonable threshold of 1–2 m/s, depending on wind spatial resolutions.

4 DISCUSSION AND CONCLUSION

A new method for the detection of CS signatures based on high-resolution Sentinel-1 images has been proposed in this paper. When CS downdraft reaches sea surface, it enhances significantly surface local wind velocity. Surface wind gust due to CS downdraft exceeds regularly 20–25 m/s. Through wind gust estimation, the CS signatures on sea surface can be detected. There are two factors which may affect surface wind speed retrieval from Sentinel-1 images. First, moderate and/or heavy rainfall which is regularly accompanied by CS downdraft can modify radar backscattering, and thereby can contaminate wind speed estimation. However, as indicated in Xu et al. (2015) and Contreras and Plant (2006), in C-band, the impact of precipitation, even heavy rainfall, on radar backscattering is quite small. Second, the coarse spatial grid of GFS wind direction (25 km) may cause errors for wind speed retrieval. Nevertheless, as indicated in Tables 1 and 2, GFS wind directions are very close to the measured ones. Consequently, wind speed estimated by CMOD5.N and the Sapp’s model is quite similar to the in situ measurements. Additionally, wind speed estimates using the Komarov’s method (Komarov et al., 2014) (not shown here) without wind direction input have good agreement with
those based on the Sapp’s model. This demonstrates that the large scale of GFS wind direction does not invalidate the reliability of CS detection through wind gust estimation based on CMOD or CMOD-like functions.

Based on the retrieved wind maps from two representative images (VV-pol and HH-pol) at a high spatial resolution, a convection line (squall) and a CS signature in round shape were detected. Meanwhile, they were not identified on the wind maps based on GFS analyses due to coarse spatial grid (25 km). Since CS downdraft is usually accompanied by moderate and/or heavy rain, the surface radar observations of precipitation were considered as an additional source to assess whether the detected wind gust is associated to the CS signatures. In fact, in the zones where wind gust exceeds 20–30 m/s, precipitation or radar reflectivity is significant (40–50 dBZ). This permitted to conclude that the strong-wind zones originated from CS downdraft rather than synoptic weather events.

Finally, the proposed method shows that CSs can be indirectly identified through the detection of the enhancement of surface wind magnitude based on the SAR images. Although it worked accurately on two case studies, the presented approach must be tested more largely over hundreds of Sentinel-1 images acquired over the earth surface to exhibit some relevant statistic about reliability where some data exist (sea buoys for instances). Additionally, a deep study about the effect of CS downdraft on both surface wind magnitude and wind direction is ongoing.

| Station | Coordinates (°N, °W) | 10-m wind speed (m/s) | Wind direction | Sapp wind speed (1125 UTC) | GFS wind direction |
|---------|----------------------|-----------------------|----------------|----------------------------|-------------------|
| 42023   | 25.010, 83.066       | 4.0 (1130 UTC)        | 243°           | 4.0                        | 225°              |
| PLSF1   | 24.693, 82.773       | 3.2 (1120 UTC)        | 188°           | 3.9                        | 180°              |
| KYWF1   | 24.556, 81.808       | 0.6 (1124 UTC)        | 117°           | 0.5                        | 130°              |

FIGURE 3 Detection of a CS signature in round shape offshore the Gulf of Mexico, through surface wind speed estimation from a HH-pol Sentinel-1 image (IW1 mode) acquired on September, 29 2016 (11:25:47 UTC). (a) Sapp’s model-based wind speed estimates (pixel size = 125 m). (b) GFS-derived wind speed (25 km wind grid). (c) Comparison between Sapp’s model and GFS-based wind speed. (d) Radar reflectivity extracted from a NEXRAD image acquired by the surface radar in Tampa, FL at 11:27:00 UTC, September 19, 2016.

TABLE 2 Comparison between wind field estimates in Figure 3 and in situ measurements given by the NOAA sea buoys over the Gulf of Mexico (42023, PLSF1, and KYWF1)
ACKNOWLEDGEMENTS
This work was supported by the TOTAL Exploration & Production in the framework of SOLSTICE project and the CNES (Centre National d’Etudes Spatiales) in the framework of the PEPS (La Plateforme d’Exploitation des Produits Sentinel) program. The authors would like to thank the EU Copernicus Programme for the support of our researches. Sentinel-1A/B images are downloaded through https://scihub.copernicus.eu/ NEXRAD data are acquired from https://www.ncdc.noaa.gov/nexradinv/.

ORCID
Tran Vu La https://orcid.org/0000-0003-0712-093X

REFERENCES
Alpers, W., Zhang, B., Mouche, A., Zeng, K. and Chan, P.W. (2016) Rain footprints on C-band Synthetic Aperture Radar images of the ocean—revisited. Remote Sensing of Environment, 187, 169–185.
Contreras, R.F. and Plant, W.J. (2006) Surface effect of rain on microwave backscatter from the ocean; measurements and modeling. Journal of Geophysical Research, 111, C08S019.
Cotton, W.R. (1992) Mesoscale convective systems. Storm and Cloud Dynamics, Vol. 44, 1st Ed. USA: Academic Press.
Fiolleau, T. and Roca, R. (2013) An algorithm for the detection and tracking of tropical mesoscale CS using infrared images from geostationary satellite. IEEE Transactions on Geoscience and Remote Sensing, 51(7), 4302–4315.
Hersbach, H. (2008) CMOD5.N: a C-band geophysical model function for equivalent neutral wind. Reading: ECMWF. Technical memorandum 554.
Horstmann, J., Koch, W., Lehner, S. and Tonboe, R. (2002) Ocean winds from RADARSAT-1 ScanSAR. Canadian Journal of Remote Sensing, 28(3), 524–533.
Houze, R.A., Jr. (2004) Mesoscale convective systems. Reviews of Geophysics, 42(4), 1944–2015.
Komarov, A.S., Zabeline, V. and Barber, D.G. (2014) Ocean surface wind speed retrieval from C-band SAR images without wind direction input. IEEE Transactions on Geoscience and Remote Sensing, 52(2), 980–990.
La, T.V., Khenchaf, A., Combret, F. and Nahum, C. (2017) Exploitation of C-band Sentinel-1 images for high-resolution wind field retrieval in coastal zones (Iroise Coast, France). IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 10(12), 5458–5471.
Montuori, A., de Ruggiero, P., Migliaccio, M., Pietroni, S. and Spezie, G. (2013) X-band COSMO-SkyMed wind field retrieval, with application to coastal circulation modeling. Ocean Science, 9, 121–132.
Mouche, A.A., Collard, F., Chapron, B., Dagestad, K.-F., Guitton, G., Johannessen, J.A. and Kerbaol, V. (2012) On the use of Doppler shift for sea surface wind retrieval from SAR. IEEE Transactions on Geoscience and Remote Sensing, 50(7), 2901–2909.
Rochette, S.M. and Moore, J.T. (1996) Initiation of an elevated mesoscale convective system associated with heavy rainfall. Weather and Forecasting, 11(4), 443–457.
Sapp, J.W., Alsweiss, S.O., Jelenak, Z., Chang, P.S., Frasier, S.J. and Carswell, J. (2016) Airborne co-polarization and cross-polarization observations of the ocean-surface NRCS at C-band. IEEE Transactions on Geoscience and Remote Sensing, 54(10), 5975–5992.
Xu, F., Li, X., Wang, P., Yang, J., Pichel, W.G. and Jin, Y.Q. (2015) A backscattering model of rainfall over rough sea surface for Synthetic Aperture Radar. IEEE Transactions on Geoscience and Remote Sensing, 53(6), 3042–3054.
Yokoi, S., Katsumata, M. and Yoneyama, K. (2014) Variability in surface meteorology and air–sea fluxes due to cumulus convective systems observed during CINDY/DYNAMO. Journal of Geophysical Research: Atmospheres, 119, 2064–2078.

How to cite this article: La TV, Messager C, Honnorat M, Channelliere C. Detection of convective systems through surface wind gust estimation based on Sentinel-1 images: A new approach. Atmos Sci Lett. 2018;19:e863. https://doi.org/10.1002/asl.863