Monitoring atmospheric gravity waves by means of SAR, MODIS imagery and high-resolution ETA atmospheric model: a case study

Maria Adamo¹, Giacomo De Carolis¹, Sandra Morelli² and Flavio Parmiggiani³

¹ CNR-ISSIA, Institute of Intelligent Systems for Automation, via Amendola 122/D-I, 70126 Bari, Italy;  
² University of Modena and Reggio Emilia, Department of Physics, via Campi 213/A, 41100 Modena, Italy;  
³ CNR-ISAC, Institute of Atmospheric Sciences and Climate, via Gobetti 101, 40129 Bologna, Italy;

ABSTRACT

A study aimed at retrieving sea surface wind fields of semi-enclosed basins from combined use of SAR imagery and a high resolution mesoscale numerical atmospheric model, is presented. Two consecutive ERS-2 SAR frames and a set of NOAA/AVHRR and MODIS images acquired over the North Tyrrhenian Sea on March 30, 2000 were used for the analysis. SAR wind speeds and directions at 10 m above the sea surface were retrieved using the semi-empirical backscatter model CMOD4. Surface wind vectors predicted by the meteorological ETA model were exploited as guess input to SAR wind inversion procedure. ETA is a three-dimensional, primitive equation, grid-point model currently operational at the National Centers for Environmental Prediction of the U.S. National Weather Service. The model was adapted to run with a resolution up to about 4.0 Km. It was found that the inversion methodology was not able to resolve wind speed modulations due to the action of an atmospheric gravity wave, called “lee wave”, which occurred in the analyzed area. A simple atmospheric wave propagation model was thus used to account for the SAR observed surface wind speed modulation. Synergy with ETA model outputs was further exploited in simulations where atmospheric parameters up-wind the atmospheric wave were provided as input to the lee wave propagation model.

1 INTRODUCTION

In the last few years scientific efforts of the remote sensing community are being focused on the capability of Synthetic Aperture Radar (SAR) imagery to provide high resolution (1–10 Km) wind fields in the marine environment. The geophysical relationship between the observed NRCS and the corresponding wind vector is provided by semi-empirical backscatter models belonging to the C-band MODels (CMOD) family [1]. As the wind field has two components, namely speed and direction, the inversion of the single SAR normalized radar cross section (NRCS) is however an undetermined problem. To solve it, two classes of SAR inversion procedures have been envisaged, both relying upon external wind information. The first class of inversion procedures is based on the a priori knowledge of the wind direction, usually gathered by anemometers located within the region of interest or estimated directly on the SAR image by means of the recognition of wind rows [2; 3]. Given the wind direction, the wind speed is retrieved as the optimal value which minimize the difference between the observed NRCS and the simulated one. The second class is instead based on the exploitation of mesoscale atmospheric model outputs [4]. Here the forecasted wind vector is used as guess to initialize the inversion procedure. While the measured wind vector is usually limited to a few instrumented sites scattered within the region of interest, wind fields predicted by mesoscale atmospheric models are able to capture the main features of the atmospheric flow over a regular grid whose size settles the spatial resolution of the SAR retrieved wind field. In contrast, mesoscale models may fail in predicting peculiar atmospheric processes of the lower atmospheric boundary layer, which superimpose to the main air flow and give rise to an additional NRCS modulation at spatial scales often comparable to that of the SAR wind inversion procedure. A remarkable example is represented by the internal atmospheric gravity waves, called “lee waves”. Commonly occurring in the lee side of terrain barriers, they are supported either by stably stratified lower troposphere or by vertical wind shears upstream the barrier [5]. The dominant wave length usually ranges from less than 1 Km to few tens of Km and may extend over several wave lengths downstream the barrier [6; 7]. In presence of stationary airflow, stationary atmospheric waves may develop, thereby lasting for several hours and causing the formation of spectacular cloud bands aligned with the wave vector and nearly perpendicular with the surface wind blowing upstream the barrier, documented by visible and thermal satellite imagery [8]. Over the sea surface, atmospheric waves modulate the horizontal wind speed blowing downstream the barrier, thus allowing their detection as periodic SAR NRCS modulation [6; 7; 9]. The formation and evolution of atmospheric gravity waves are mainly determined by the vertical structure of the atmospheric boundary layer upstream the disturbing topographic barrier. So far, radiosonde data were extensively used to study the spatial arrangement of lee waves, as demonstrated for the first time in [8]. However, it may only rarely happen that available radiosonde data are co-located both in space and time to a manifestation of atmospheric gravity wave train. In contrast, an accurate atmospheric model could provide the required atmospheric data at the desired space-time location to study the physical characteristics of the wave.
phenomenon. In this paper predictions from the numerical mesoscale atmospheric model ETA at high horizontal and vertical spatial resolutions are considered for twofold applications: 1) to drive a SAR surface wind inversion procedure over a selected area in the Northern Tyrrhenian Sea; 2) to assess SAR observation of an internal atmospheric wave visible in the same area by using the ETA predicted vertical profiles of atmospheric parameters. As horizontal and vertical structures predicted by ETA show little evidence of atmospheric wave pattern at the used resolutions, a specialized lee wave model is considered to validate SAR observations of wind modulation. The atmospheric wave pattern has also been compared with complementary MODIS and NOAA/AVHRR imagery in order to improve SAR image interpretation and to substantiate lee wave model feasibility with respect to the observed wave lengths.

2 ETA MODEL DESCRIPTION

The ETA atmospheric model is a three-dimensional, primitive-equation, grid-point model. It uses a rotated spherical coordinate system, and a semi-staggered Arakawa E grid. The vertical coordinate is the so-called $\eta$-coordinate, which represents a generalization of the usual $\sigma$ coordinate. The $\eta$ coordinate is defined as [10]:

$$\eta = \frac{p - p_{\text{ts}}}{p_{\text{tf}} - p_{\text{ts}}} \eta_s$$

where $\eta_s = (p_{\text{ref}} (z_s) - p_{\text{ts}})/(p_{\text{ref}} (0) - p_{\text{ts}})$. Here $p_{\text{ts}}$ and $p_{\text{tf}}$ are the model top and the surface pressure, respectively, $z$ is the geometric height and $p_{\text{ref}}(z)$ is a suitably defined reference pressure as a function of $z$. The $\eta$-coordinate surfaces are almost horizontal. However the model can perform run with terrain following coordinates as well. Prognostic variables are temperature, specific humidity, horizontal components of velocity, surface pressure, cloud water and turbulent kinetic energy. Physical parameterizations (including references for the various parameterizations) are presented in [11]. The model simulations, presented in this paper, are carried on with three nested domains in order to obtain the high horizontal resolution. The technique used is a one-way nesting. The European Centre for Medium Range Weather Forecasts (ECMWF) initialized analyses, at 0.5°×0.5° horizontal resolution, provided initial and boundary conditions for the lower resolution ETA model run. Initial conditions refer to 00:00 UTC 29 March 2000 and the simulations last 72 hours. Model outputs of the first domain are used as boundary conditions of the second grid run and this provides the boundary conditions for the finer grid run. Vertical resolution consists of 50 layers from sea surface to 25 hPa, with higher resolution near the bottom of the domain. Horizontal resolution is 0.125°×0.125 transformed degrees (about 20 Km×20 Km as approximate distance between two mass points on the semi-staggered Arakawa E grid) for the coarse grid, 0.05°×0.05 transformed degrees (about 4×4 Km²) for the second grid and 0.025°×0.025 transformed degrees (about 4×4 Km²) for the finer grid [11]. Model outputs for the finer grid are extracted every hour.

3 ATMOSPHERIC GRAVITY WAVES: MODEL DESCRIPTION

When air flow impinges upon a terrain obstacle, the disturbance causes displacement of the air from equilibrium position in the lee side of the obstacle. As a result, air parcels start to oscillate generating internal atmospheric waves restored by gravity. These waves, also called “lee waves”, are usually supported by stably stratified layers in the lower troposphere, which act as waveguide [5]. The occurrence of atmospheric waves is often associated with the formation of periodic cloud bands whose orientation is nearly perpendicular to the surface wind direction [12]. If lee waves propagate over the ocean surface, the corresponding wind speed variation modulates the local surface roughness, which in turn is detected as NRCS modulation on SAR images.

Purpose of this section is to review the simple lee wave model developed by Palm and Foldvik [13] which predicts the expected surface wind modulation. Air flow downstream the terrain barrier is modeled on the following assumptions: 1) the barrier is infinitely long and approximated by a bell-shaped function; 2) the wind blows parallel to the short side of the barrier. For the case studies herein presented, both conditions are only approximately fulfilled. The terrain barrier is represented by the peninsula north of Corsica, which is approximately stretched out into N-S direction with width/length ratio of about 1:3; besides, ETA provided a height-averaged wind speed components ratio $V/U \approx 0.32$. We thus expected that the lee wave model predictions can only partially support satellite observations.

In the reference bi-dimensional Cartesian space $x$-$z$, where $x$ is the downstream direction and $z$ is the vertical direction pointing upwards from the ground placed at $z=0$, the two-dimensional air parcel oscillations can be described by the Scorer parameter $l^2 = l(z)$ defined as follows [13]:

$$l^2 = \frac{S}{U^2} - \frac{1}{U} \frac{d^2U}{dz^2},$$
where $S = g \left( \frac{d\theta}{dz} \right) \theta$ is the atmospheric stability parameter; $U = U(z)$, $\theta(z)$ are the horizontal wind speed and the potential temperature upstream the barrier; $g$ is the acceleration due to gravity. The Scorer parameter in the lower atmosphere up to about 10 Km can be usually represented by the exponential function $\eta(z) = \eta(0) \exp(-cz)$, even if abrupt changes of $\eta$ due to thin inversion layers may occur.

As a result, the wave-like solution of the horizontal velocity $u$ modulating the upstream wind speed $U$ can be written as $[13; 14]$:

$$ u(x, z) = 2\pi HU(0) \phi \exp(-cz) \sum_{n=0}^{\infty} \left( \frac{1}{2} - 1 \right) U(z) \frac{\partial}{\partial z} J_{\nu_c} \left( \frac{\beta}{c} U(z) \right) - l(z) \frac{\partial}{\partial z} J_{\nu_c} \left( \frac{l(z)}{c} \right) \sin kx, \quad x > 0 $$

(3)

where $\beta$ is the exponent of the adiabatic atmosphere $\rho(z) = \rho(0) \exp(-\beta z)$. The Eq. 3 holds for a bell-shaped ridge $\zeta_d(x, 0) = H \beta^2 / (b^2 + x^2)$, where $H$ is its height and $b$ the half-width. The sum in Eq. 3 is performed on the resonant wavenumbers forming the lee wave pattern obtained as solution of the equation:

$$ J_{\frac{k}{c}}\left( \frac{l(0)}{c} \right) = 0, $$

(4)

where $J$ denotes the Bessel function of the first kind.

## 4 SAR WIND INVERSION PROCEDURE

Wind speed at 10 m above the mean sea level can be estimated from SAR imagery. Backscatter predictions of the CMOD4 [1] empirical model was herein considered for SAR inversion procedure. It is based on the following functional dependence:

$$ \sigma_b = b_e(W, \theta)[1 + b_1(W, \theta) \cos(\phi) + b_2(W, \theta) \cos(2\phi)]^n $$

(5)

where $\sigma_b$ is the SAR backscatter value, $(W, \phi)$ are the neutral 10 m wind speed and direction, $\theta$ is the incidence angle of the radar beam and $n$ has a value 1.6 for CMOD4 model. Parameters $b_i$'s were statistically determined after comparison with wind data from the ECMWF atmospheric model outputs.

SAR imagery was calibrated and then the averaged backscatter over the corresponding ETA wind cell was considered to retrieve the most probable wind vector that is obtained by the minimization of the cost function:

$$ J = \left( \frac{\sigma_b - \sigma_{\text{MODEL}}}{\Delta \sigma_b} \right)^2 + \left( \frac{U_{\text{ETA}} - U_{\text{TRIAL}}}{\Delta U_{\text{ETA}}} \right)^2 + \left( \frac{V_{\text{ETA}} - V_{\text{TRIAL}}}{\Delta V_{\text{ETA}}} \right)^2 $$

(6)

where $\sigma_b$ is the averaged SAR NRCS corresponding to the co-located ETA wind cell and $\sigma_{\text{MODEL}}$ is the simulated NRCS using the C band model functions with the trial wind vector $(U_{\text{TRIAL}}, V_{\text{TRIAL}})$. For a particular wind cell, the trial wind components $U_{\text{TRIAL}}$ and $V_{\text{TRIAL}}$ were allowed to vary over a wide range of values with step size of 0.1 ms$^{-1}$ around the corresponding ETA wind components $U_{\text{ETA}}$ and $V_{\text{ETA}}$. It was assumed that the uncertainty associated to the ETA wind vector $(U_{\text{ETA}}, V_{\text{ETA}})$ was $\Delta U_{\text{ETA}} = \Delta V_{\text{ETA}} = 1.73$ ms$^{-1}$ at the used horizontal resolution [4]. The error $\Delta \sigma_b$ represents the average NRCS variability and was found to obey the following relationship for the set of ERS images herein considered: $\Delta \sigma_b = 0.0754 \times \sigma_b$. The wind vector $(U_{\text{TRIAL}}, V_{\text{TRIAL}})$ that minimizes $J$ was retained as the best wind vector estimation for a particular wind cell.

## 5 THE EXPERIMENT

A pair of ERS-2 SAR Precision Images of the Northern Tyrrenhian Sea acquired on March 30, 2000 at 10:08 UTC (orbit: 25842, frames: 2727, 2745) and relevant to an area that extends from 42.2 N to 44.0 N and 8.8 E to 10.5 E was considered. On 10:40 UTC the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the EOS Terra satellite acquired an image including the SAR imaged area at 250 m resolution. Both SAR and MODIS images are shown in Fig. 1. MODIS image shows a clear periodic cloud band pattern that extends eastward from the Corsica peninsula. Co-located with the cloud pattern, a similar NRCS pattern can be seen on SAR image.
Fig. 1. Composite of ERS-2 SAR images (left) and MODIS image (right). The bottom plot shows averaged SAR and MODIS lines. The cloud pattern is put of phase with NRCS modulation.

Fig. 2. Scatter diagrams representing the performances of the SAR inversion procedure using CMOD4 model.

Fig. 3 shows SAR and MODIS insets of the common area along with the averaged azimuth profile. The periodic SAR backscatter modulation can be associated to a convective motion of air parcels generating the cloud band pattern to which corresponds a periodic, horizontal surface air flow [6]. Fig. 2 report the horizontal components $(U, V)$ of the retrieved wind vector (panels 1 and 2), wind speed (panel 3) and wind direction (panel 4) vs the corresponding ETA components for quantitative comparison. In general, the SAR inversion procedure corrected ETA wind speeds toward higher values. Specifically, an overall bias of about +5 ms$^{-1}$ resulted for wind cells whose residual value of the cost function was $J>10$ (black points in the panels of Fig. 2). They mainly correspond to SAR imaged areas located on the lee side of Corsica peninsula, where an atmospheric gravity wave is active, and, as expected, to areas close to the Ligurian coast [2]. For wind cells with residual $J<10$ (gray points in panels of Fig. 2), the retrieved SAR wind speeds resulted in average about 1.5-2.0 ms$^{-1}$ higher than ETA wind speeds. Assuming ETA wind vectors reasonably representative of the real wind vector, the corrective bias compares with the expected average rms uncertainty assigned to CMOD4's performances [2]. In contrast, the retrieved wind directions resulted not significantly different to ETA directions, regardless the residual $J$ value. This result may be twofold interpreted: 1) the main contribution of CMOD4 is relevant to wind speed since wind directions predicted by ETA model are within the CMOD4 direction accuracy of ±20°, according to the geophysical specification of the ERS-1/2 scatterometers [15]; or 2) the SAR inversion procedure is not able to correct the input wind direction, although the retrieved $U$ and $V$ components are individually modified. Although this aspect of the SAR inversion procedure deserves further investigation, for the purpose of the present paper it can be concluded that SAR detected complex atmospheric phenomena, such as atmospheric gravity waves, that superimpose to the main air flow predicted by mesoscale atmospheric modeling, should be properly handled. Another aspect of the SAR inversion procedure performance is the introduction of slight biases in the predicted CMOD4 NRCS, as drawn in the panel 5 of Fig. 2. It can be seen that for wind cells with $J<10$ (grey points in Fig. 2), the average NRCS bias between SAR and CMOD4 is about 0.32±0.19 dB for $\sigma^0_{\text{SAR}}$ ≥0.45 (~ -3.45 dB), i.e. for wind speeds not lower than about 11 ms$^{-1}$; the bias increases to 1.19±0.51 dB for wind cells with residual cost function $J>10$. The backscatter bias can be readily explained by considering that the couple $(U, V)$ for which $J$ assumes the minimum value does not necessarily minimize each term of the cost function. So, the backscatter bias is not surprising: the closer are the ETA wind components predictions to the true values, the lower the backscatter bias will result.

Fig. 3 shows the temporal sequence of four near-infrared/visible images gathered on March 30, 2000 since 03:17 UTC. They include the evolution of a periodic cloud pattern associated to a stationary atmospheric lee wave. The last image was acquired by MODIS at 10:40. Images gathered before 03:17 and after 10:40 do not show any cloud band structures, so we can assume the phenomenon lasted approximately seven hours. From visual inspection of the cloud pattern sequence, the maximum development occurred around 05:48; after then, a progressive attenuation of the cloud band is observed. SAR image was acquired at 10:08 when wave phenomenon was still active.
Literature about atmospheric gravity waves considered radiosonde soundings as reference upstream atmospheric data [6; 9]. In our case, the closest radiosonde station is located at Ajaccio, about 100 Km SW of Corsica peninsula, where soundings twice a day at 00:00 and 12:00 UTC are routinely collected. Therefore, we choose to use ETA predictions to analyze satellite observations. To assess the feasibility of ETA predictions on a statistical basis, we compared ETA outputs with co-located radio soundings gathered at Ajaccio station on March 29 and 30, 2000. A good agreement was found with little or negligible statistical differences [16]. Furthermore, some differences between ETA profiles extracted upstream Corsica peninsula and Ajaccio soundings at times closest to image acquisitions were found. These differences were assigned to the different atmospheric conditions over the faraway areas, thus stressing the choice to base quantitative interpretation of image observations on ETA outputs.

A SAR wind analysis of the NRCS modulation downwind the Corsica peninsula was carried out assuming the dominant surface wind direction aligned with the upstream wind direction (φ=45° from antenna upwind). CMOD4 predicted a total wind speed modulation of about 7.0 m/s in the range between 10.0 m/s to 17.0 m/s. The Scorer parameter profile at 10:00 UTC is a decreasing function of the height up to an altitude approximately corresponding to the maximum wind speed [13]. The following values of parameters were obtained: l(z)=0.760±0.095 Km and c=0.080±0.018 Km. In order to compare wind speed modulation with the predictions of the lee wave model, the corresponding cross-barrier wind speed component U was computed. Fig. 5 includes wind speed modulations predicted by the lee wave model for bell shaped barrier. Maximum and minimum wind speeds with their respective uncertainty were computed considering the errors associated to the parameters l(0) and c. The maximum wind speed was underestimated by about 1 m/s, while the minimum wind speed value is in agreement with CMOD4 results. Furthermore, it is worth noting that although the selected lee wave model only approximately matched the real atmospheric conditions and barrier shape, it was nonetheless able to capture the main features of the SAR observed wind speed modulation.

Finally, the expected dominant wavenumber of lee wave can be computed from Eq. 4 and then compared with corresponding observations based on satellite imagery shown in Fig. 4. Fig. 6 shows the result after conversion of wavenumbers in wave length. In particular, wave length estimation on SAR and MODIS images yield respectively 15.25±0.25 Km and 14.25±0.75 Km; the lee wave model coupled to ETA predictions at 10:00 and 11:00 UTC yield a wave length equal to 14.17±0.74 Km. A better agreement between the theoretical value and MODIS observation arose because the noisy SAR lee wave visibility led to a less robust wave length estimation.
**CONCLUSIONS**

Synergy between SAR imagery of the sea surface and predictions from a numerical mesoscale meteorological model can be utilized to correctly explain atmospheric phenomena occurring in the boundary planetary layer. In this paper high resolution atmospheric parameters predicted by the meteorological model ETA has been successfully exploited to capture the major atmospheric features detected by ERS-2 SAR imagery in an area of the North-West Mediterranean Sea.

First, ETA model was used to assess the SAR observed 10 m wind vector at 4.0 Km horizontal spatial resolution. SAR wind vector was estimated using an inversion procedure based on NRCS predictions of the semi-empirical backscatter model CMOD4. A periodic modulation of SAR NRCS associated to a cloud pattern observed on a MODIS image acquired about 30 minute after the SAR passage was detected. Both observations were explained as the effects of a quasi-stationary atmospheric gravity wave generated by the disturbing effect of the northern Corsica peninsula on the westerly air flow. Periodic cloud band formation frequently occurs as a result of the spatially periodic updraughts imposed by an atmospheric wave, which conveys humid air forming the cloud. In addition, the atmospheric wave affects the spatial distribution of the surface wind speed in the lee side of the terrain disturbance, thereby allowing its detection on SAR image. The temporal evolution of the cloud pattern from the very beginning was monitored by complementary NOAA/A VHRR imagery revealing that the atmospheric phenomenon lasted for at least 7 hours. ETA predictions did not show any atmospheric wave phenomena in that area at the used resolutions, but were able to accurately forecast atmospheric conditions upstream Corsica peninsula that resulted suitable for generation of an atmospheric gravity wave. A simple lee wave propagation model was indeed used as theoretical support to satellite observations. Although the formulation of the lee wave model did not exhaustively account for the real atmospheric conditions, the main features of the observed SAR wind speed modulation were nevertheless reproduced. As no surface wind information can be retrieved from near-infrared and visible satellite images, only estimates of cloud band wavelengths were carried out and successfully compared with lee wave model predictions. These results were accomplished using as input to lee wave model the atmospheric ETA parameters extracted at the closest time of every satellite acquisition.

**REFERENCES**

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