Monitoring space-time soil wetness variations by a multi-temporal microwave satellite records analysis.

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Abstract

In the last few years, remote sensing observations have become an useful tool for providing hydrological information, including the quantification of the main physical characteristics of the catchments, such as topography and land use, and of their variables, like soil moisture or snow cover. Moreover, satellite data have also been largely used in the framework of hydro-meteorological risk assessment and mitigation.
Recently, an innovative Soil Wetness Variation Index (SWVI) has been proposed, using data acquired by the microwave radiometer AMSU (Advanced Microwave Sounding Unit), flying aboard NOAA (National Oceanic and Atmospheric Administration) polar satellites.
The proposed index, developed by a multi-temporal analysis of AMSU records, seems able to reduce the problems related to vegetation and/or roughness effects. Such an approach has been tested, with promising results, on the analysis of some flooding events which occurred in Europe in past years.
In this paper, preliminary results obtained by the analysis of data related to the flooding event occurred in Europe during April 2006 are presented. Preliminary outcomes achieved seem to demonstrate the efficiency of the proposed indicator in detecting soil wetness variations in the space-time domain without the need of auxiliary or ancillary information.

Introduction

Soil moisture is a key parameter for many processes that occur along the soil-atmosphere interface: it mainly influences flux-exchange, evaporation and run-off generation process (Entekhabi et al., 1994, Wigneron et al., 1998). Hydrologist needs, in order to profitably use it, soil moisture information available regionally and at regular and frequent intervals. This is hardly achievable by direct surface measurements: the difficulties of field soil moisture mapping lie in the extreme spatial variability of point measurements and the impracticality of obtaining a sufficiently dense network of points to provide continuous information. Satellite measurements could help to overcome these gaps: large areas may be, in fact, observed in a single pass with temporal resolution varying from some minutes to several days (depending on the orbital features of the satellite platform).
Better soil moisture measurements have been carried out using data acquired in the microwave range of the electromagnetic spectrum (Schmugge, 1998). At these frequencies, in fact, it is possible to

achieve surface information both during the day and night, and also in presence of clouds. Moreover, there is a high sensitivity to the soil water presence. The dielectric contrast between dry soil and water in the microwave range is, in fact, at the basis of all the soil moisture retrieval techniques. In particular, a variation of soil water content produces variation in the slope of the soil emissivity plotted at different microwave frequencies (figure 1). By this way, a measurement of the gradient of soil emissivity, between higher and lower microwave channels, could lead to identify qualitative variations of soil water content. Such a gradient intensity is therefore related only on the differential contrast of soil emissivity in dry and wet conditions (which, although the decreasing of the real part of permittivity of water when frequencies increasing, still remains significant), regardless from the absolute value of the dielectric constant at a given frequency.

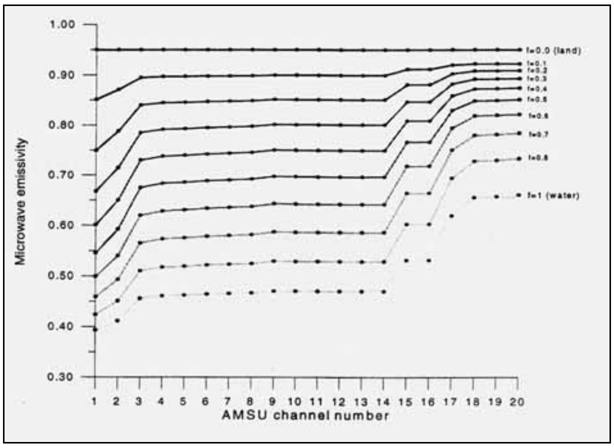

Fig. 1: Variation of the AMSU superficial emissivity for different amount of surface wetness (*f*) (adapted from Songyan et al., 2000).

Actually, there are some well-known problems which may limit soil moisture retrieval: vegetation cover can fully mask the soil and roughness effects may lead significant variation in soil emissivity, both reducing the sensitivity in the soil moisture retrieval (Wigneron et al., 2003). Besides, other effects, such as the presence of permanent water in the field of view (FOV) of the sensor and some atmospheric conditions, like water vapor fluctuations and scattering effect produced by the ice spheres in the upper portion of the raining clouds, are residual issues.

Usually, these problems have been limited using a huge amount of ancillary data (e.g. Ahmed, 1995; Jackson and Schmugge, 1991; Jackson, 1993) or combining data acquired by multi-configuration (multifrequency, dual-polarization or polarimetric, multiangular observations) satellite systems (e.g. Ahmed, 1995; Njoku and Entekhabi, 1996; Kim and Barros, 2002; Wigneron et al., 2003).

Methodology

Starting from the above considerations, an innovative AMSU Soil Wetness Variation Index (SWVI) has been recently proposed (Lacava et al., 2005). The SWVI is based on a general approach for multi-temporal satellite data analysis (RAT - Robust AVHRR Techniques, Tramutoli 1998). The RAT (Robust AVHRR Technique) approach is an automatic change-detection scheme that identifies signal anomalies in the space-time domain as deviations from a normal state that has been preliminarily identified (and usually given in terms of time average and standard deviation) on the basis of satellite observations collected during several years, under similar observational conditions for each image pixel.

The proposed formula for the innovative Soil Wetness Variation Index (SWVI) is:

$$SWVI(x,y,t) = \frac{SWI(x,y,t) - \mu_{SWI}(x,y)}{\sigma_{SWI}(x,y)} \qquad (1)$$

where: *SWI(x,y,t)* is a hypothetical soil wetness index defined as the difference (SWI=BT89GHz–BT23GHz) between the radiance (expressed in Brightness Temperature) measured in AMSU channels 15 (at 89 GHz) and 1 (at 23 GHz), respectively. As mentioned above, SWI may provide useful information about surface emissivity variations, but it is unable to discriminate the amount of these variations which are actually related to different soil water content from the ones possibly due to vegetation and/or roughness effects. $\mu_{SWI}(x,y)$ and $\sigma_{SWI}(x,y)$ are respectively the temporal average of SWI and its standard deviation, both computed on a selected, multi-annual AMSU imagery data-set composed by records collected during the same month of the year and acquired at around the same hour of the day. Therefore the *SWVI(x,y,t)* gives, at pixel level, the actual *SWI* excess compared to its unperturbed conditions (*SWI(x,y)* - $\mu_{SWI}(x,y)$), and compares this excess with the normal variability of *SWI(x,y,t)* ($\sigma_{SWI}(x,y)$), historically observed for the same site under similar observational conditions. In order for an anomaly to be significant, its magnitude should be greater (at least) than the normal fluctuation of the signal. The robustness of the method is by this way intrinsic, as the larger the natural observed fluctuation of the signal is, the harder it will be to identify anomalies statistically significant. This means that all the possible noisy effects, including the ones related to navigation and co-location processes or to the system configuration (e.g. different viewing angles, different path lengths, etc.) generally produce an increase of $\sigma_{SWI}(x,y)$ and, consequently, a decrease of *SWVI(x,y,t)* with a much-more selective identification of over-threshold events (Tramutoli, 1998).

However, working at pixel level, the main (noisy) site effects (e.g. vegetation, roughness, permanent water bodies within the field of view) are expected to be strongly reduced: the *SWVI(x,y,t)* index, in fact, is solely sensitive to SWI variations (for each place mainly depending on soil moisture) and not to its absolute value (strongly depending instead also on surface roughness and vegetation cover). We expect, then, that higher values of *SWVI(x,y,t)* are associated to a relative increase of soil wetness at each specific location. More specifically, positive *SWVI* values would indicate soils wetter than "normal" conditions.

Another possible problem affecting this kind of application is due to atmospheric water vapour that might influence radiances at sensor, especially at 23GHz, where an absorption band of water vapour is present. Actually, the differential nature of the proposed approach strongly reduces such an effect which is in fact, much less important if a brightness temperature difference is considered. Some studies and simulations have demonstrated that, although the absolute variation of the signal induced by fluctuations in water vapour may be significant, the relative effect in two different AMSU channels (like channel 1 and channel 15) is much less important (Songyan et al., 2000).

Furthermore, the possible residual effects due to water vapour fluctuations are taken into account by the proposed approach because, once more, they simply produces a more noisy signal and, then, a higher standard deviation with consequent increasing in *SWVI* robustness.

Results

The SWVI index has been already implemented and tested on several recent flooding events occurred in Europe (Lacava, 2004; Lacava et al., 2004; Lacava et al., 2005). In this paper, preliminary results obtained analyzing the flooding event which happened in Europe during April 2006 are presented.

Heavy floods hit central and eastern Europe since the end of March due to melting snow and intense rainfall (Brakenridge et al., 2006; International Federation of Red Cross and Red Crescent Societies, 2006). Swollen rivers and floodwaters have caused widespread damage and forced thousands of people to leave their homes (European Commission, 2006).

The main rain episode occurred during the last days of March, while during all the month of April some light precipitation still continued to provide power to the flow of the main European rivers. This effect is clearly visible in figure 2, where Precipitation Anomalies respect to the 1979-2000 mean, acquired from NCEP Climate Prediction Center, CAMS-OPI, are plotted for March 2006 (top) and April 2006 (bottom) (IRI, 2006). Note as large areas of Europe have been interested by rain especially in March (Meschiari, 2006a), while less precipitation have fallen in April, in particular, during the first ten days of April (Euronews, 2006).

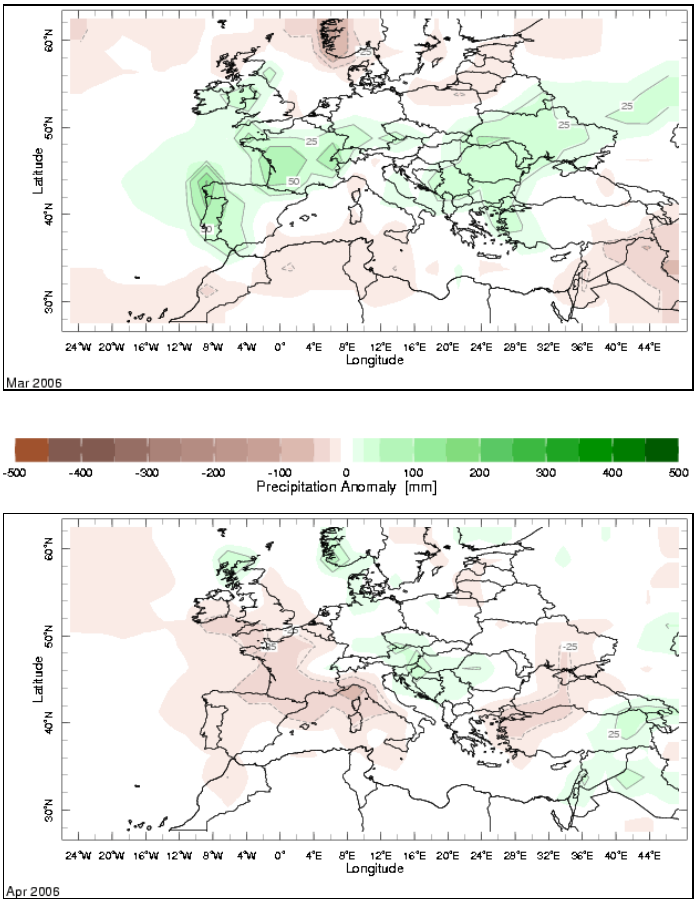

Fig. 2: Precipitation Anomalies (mm) for March 2006 (top) and April 2006 (bottom) respect to the 1979-2000 mean, with data from NCEP Climate Prediction Center, CAMS-OPI (adapted from IRI, 2006).

Probably the main effect which allowed the flood to have a long time-life, was the sudden and unusual increase in temperature over Europe at the begin of April, which produced large snowmelt over the mountains. In detail, after 4 months under the seasonal means, temperature recorded in April 2006 was about 2°C above the mean in almost all the European continent, resulting one of the most hot April of the last century (Meschiari, 2006b). In figure 3, Temperature Anomalies respect to the 1961-1990 mean, acquired from NCEP Climate Prediction Center, CAMS, are plotted for March 2006 (top) and April 2006 (bottom) (IRI, 2006). Note the net contrast in temperature moving from March to April, with a clear appearance of warmer temperatures over the areas interested by the flooding event.

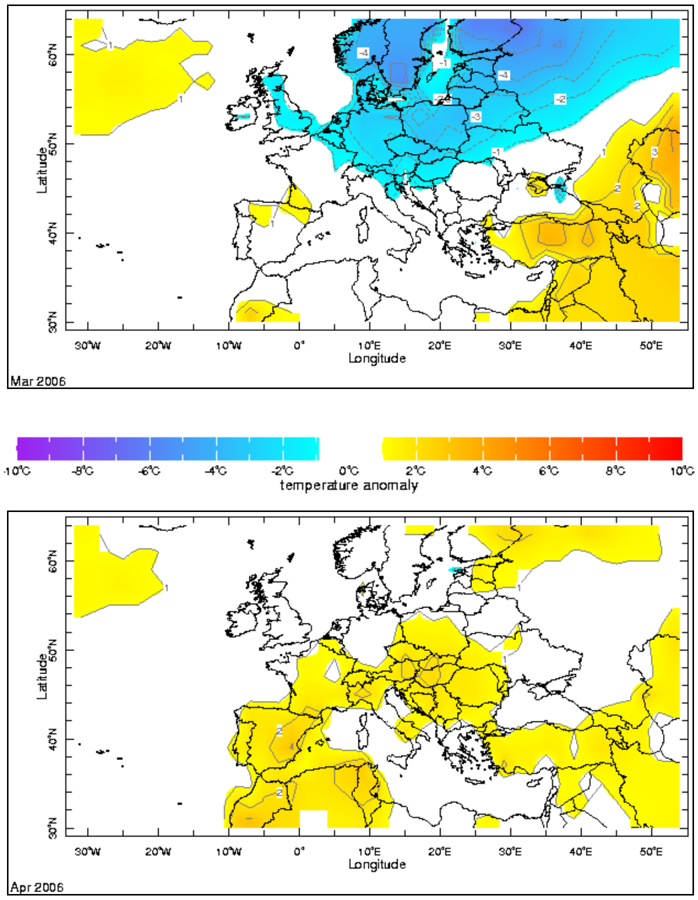

Fig. 3: Temperature Anomalies (°C) for March 2006 (top) and April 2006 (bottom) respect to the 1961-1990 mean, with data from NCEP Climate Prediction Center, CAMS (adapted from IRI, 2006).

The high level of risk connected to the event, is witnessed by the five activations of the "International Charter Space and Major Disasters" occurred between the 1 and the 19 of April 2006 (International Charter, 2006). The disaster hit seriously different European countries (European Commission, 2006):

• in Germany a state of emergency was declared on 1 April in five communities and about 1000 people were evacuated from Dresden and Meissen. Affected regions along the Elbe River included Mecklenburg-Vorpommern, Niedersachsen Brandenburg and Sachsen Anhalt (International Charter, 2006);

• in Austria, the level of the River Danube and of many rivers in the north of the country was critical during the weekend of 1 April. About 250 households were affected and Austria government reported three fatalities, dam failures and the disruption of rail connections in western Austria (International Charter, 2006);

• in the Czech Republic a state of emergency was declared for the whole area of the South Moravian department, where five towns were evacuated. The highest flood level alert, level 3, was declared at 45 sites across the country following the steady rise of the rivers Elbe (which climbed to 8.46 metres, more than four times its normal level), Vltava, Morava and Dyje among others (Associated Free Press, 2006). The regional authority declared a state of emergency on Saturday 1 April for the entire length of the river from 40 kilometres north of Prague to the German border (ReliefWeb, 2006). About 4200 people had to leave their homes. Five fatalities were confirmed (International Charter, 2006);
• the event hit Slovakia too, causing extensive flooding and two fatalities, a state of emergency was declared on 1 April at Trtice in the south-west of the country after the Cierna Voda River reached a dangerous level (International Charter, 2006);
• an emergency situation was declared in Hungary on 3 April 2006. The level of the River Danube rose to 861cm in the early hours of 5 April. This is the third highest level ever recorded (867cm in 1876 and 848 cm in 2002). Waters began to subside by 23 April. Hungary reported that its second largest river, the Tisza, reached a record level of 9.8 metres on 18 April, the Hungarian government extended a flood emergency to Hungary's three Koros rivers to the southeast of the country (International Charter, 2006);
• the increase of the Danube's level in Romania flooded 12 counties. Over 5,000 households had collapsed or flooded. The damage also counted some 500 km of roads, around 255 bridges and a total of over 80,000 hectares of farmland and grazing fields. Romanian government stated that the Danube reached its highest level since 1895, double its average volume for this time of year, flowing at a record 15,900 cubic meters/second. Over 15,000 people were evacuated from their homes (International Charter, 2006). Some farmland and forest areas have been deliberately flooded to protect towns (BBC News, 2006);
• Serbia is submerged by floods because of waters of Danube and Sava rivers reached record levels. At Belgrade, where there is the confluence of the two rivers, railway station and the roads were flooded after fifteen days of torrential rain, the emergency state was declared on 16 April for ten regions (Čekerevac, 2006);
• in Bulgaria the floods affected 23 localities, a state of emergency was declared in seven regions along the Danube and was cancelled on 10 May 2006 (European Commission, 2006).

In order to study this event, all the AMSU data acquired during April since 1999 to present (about 500 images) have been collect to generate the reference fields (i.e. $\mu_{SWI}(x,y)$ and $\sigma_{SWI}(x,y)$). In particular, two different data-sets (i.e. morning and afternoon NOAA pass) have been selected. After the pre-processing phase (including calibration, navigation, reprojection and co-location), an independent AMSU cloud screening test (Grody et al., 2000) has been applied in order to limit the problem due to the presence of raining clouds in the FOV, discarding from the successive steps all the pixels affected by raining clouds. This screening test derives from similar algorithms developed for SSM/I data (Grody et al., 1991; Ferraro et al., 1994&1998) based on the scattering effect produced by the ice spheres in the upper portion of the raining clouds which generates a clear depression of the BT at 89Ghz (Wilheit et al., 2003). Such a signal decreasing consequently generates lower *SWI* values (assuming that the lower channel is more transparent), and therefore protect us from false *SWVI* anomalies identification.
More significant results are shown in figure 4 and 5. In particular, figure 4 refers to the period from 30 March to 5 April , while in figure 5 the maps between 12 and 20 April are shown. In detail, the effects shown in figure 4 are probably mainly related to the intense rain which hit the area of interest during

the last days of March, while results achieved in figure 5 are more affected by the snowmelt caused by the increase in temperature which, coupled with the rains, has extended the time-length of the event.

The analysis of the *SWVI* maps in figure 4, in fact, shows the sudden response (in terms of soil wetness variations) of the soil to the heavy precipitation fallen at the end of March in some European regions. In the maps of 30 March it is possible to see large areas interested by high *SWVI* values (i.e. *SWVI > 4*, darker tones of blue) indicating the presence of anomalously wet soils. In particular, in the image acquired at 15:27 GMT is possible to note as a large part of East-Germany (where is located the Elba River), Austria, Czech Republic, Poland, Hungary and Slovakia, were characterized by high values of the index, which indicated the high vulnerability of the exposed soil in terms of soil wetness conditions. Regarding the maps relative to 1 April, it is possible to note as the anomalies extend aerially, involving in also Serbia and Romania. As said above, between 1 and 3 April many of these countries declared an emergency state, activating also the “International Charter Space and Major Disasters” at the European Community. The early indication, achieved in the SWVI map of 30 March at 15:27 GMT, two days before these events, might be, together with other hydro-meteorological data (meteorological forecast and nowcast, rain gauge, etc) an useful additional information for flood risk forecast systems. This map, in fact, already highlighted the vulnerability of the area (water satured soils) as a consequence of the rain fallen in the previous days, before the occurrence of new rains and/or impending, potentially hazardous, meteorological events (such as snowmelt). Looking at the next maps (from 2 to 5 April) a gradual decreasing of anomaly is evident (intensity of *SWVI* goes lower and areas involved are smaller). Such a behavior, may be justified assuming that this first “phase” of the flood, as above mentioned, is mainly related to the precipitation occurred over the area of interest during the last days of March (Blogeko, 2006). Unfortunately, being the event quite recent, detailed ground information confirming such an hypothesis are not yet available.

The maps reported in figure 5 refers to several days, from 12 April, in which, again, it is evident the presence of anomalous SWVI values. These effects are probably mainly due to snowmelt, which, coupled with some rainfall occurred over some European countries, has given new power to the flood event, involving regions not yet interested as Serbia, Romania and Bulgaria.

The effects shown in this SWVI maps sequence are less intense respect to those in figure 4: in fact, although some areas reached similar *SWVI* intensities, this occurs only on zones with limited extent and not for all the considered days. In particular, there is persistence in SWVI anomaly in Czech Republic, probably over the area around the Elba river courses, and a general trend toward Sud-East, which may be related to the spreading wave of Danube, which reached Romania and Bulgaria, as said above, in the second half of April (NASA - Earth Observatory, 2006). Again, the absence of detailed report about the ground conditions, limit the reliability of this preliminary results.

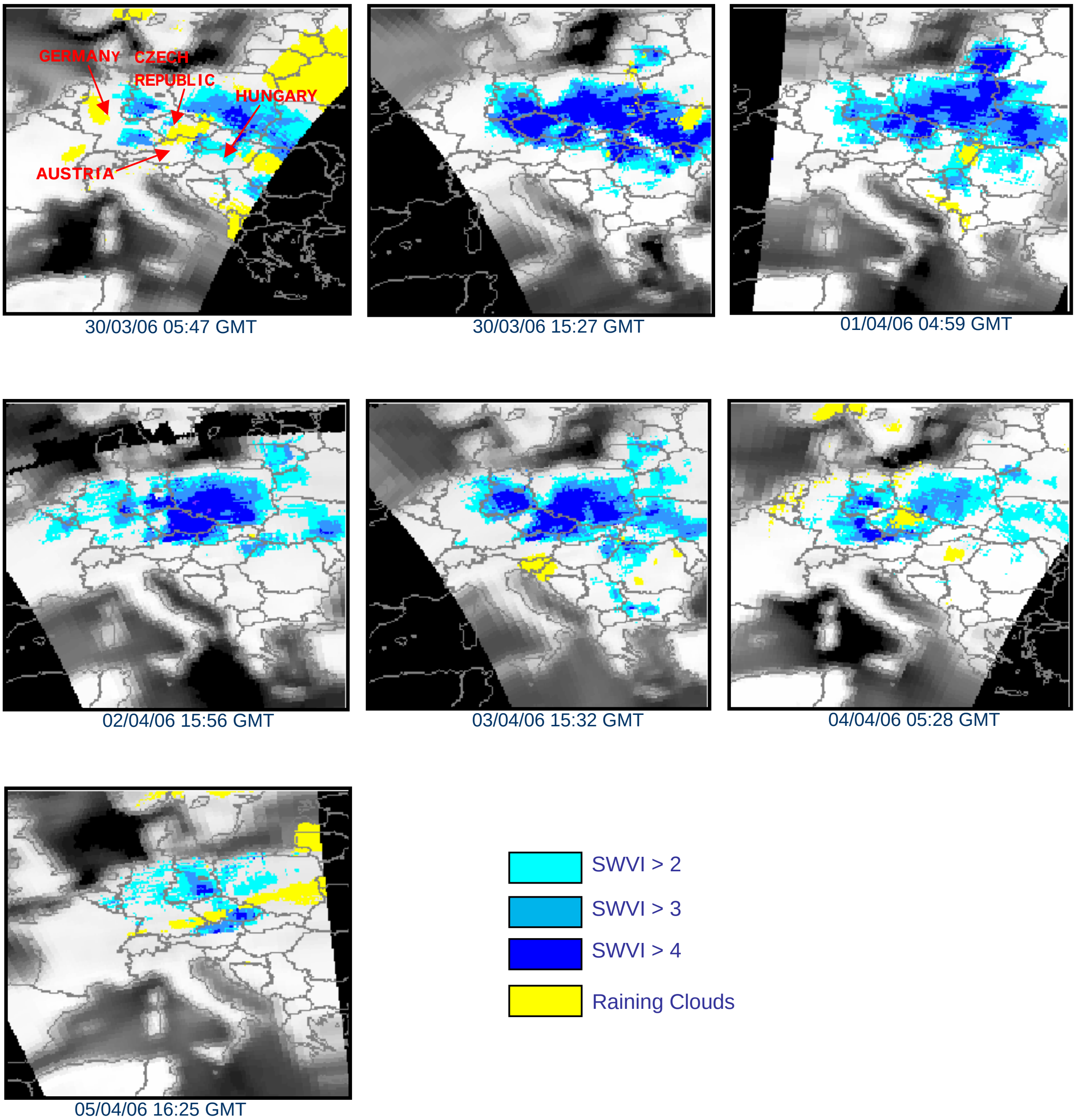

Fig. 4: SWVI maps on several days between the end of March and the beginning of April 2006. The resulting values of SWVI have been depicted in different blue tones (darker blue identifies wetter conditions), and raining clouds, identified by a screening test, in yellow; the results have been overlaid on the corresponding AMSU images (channel 1= 23.80 GHz) represented in gray tones (higher brightness temperatures are shown in brighter gray tones). Coastlines are depicted in dark grey.

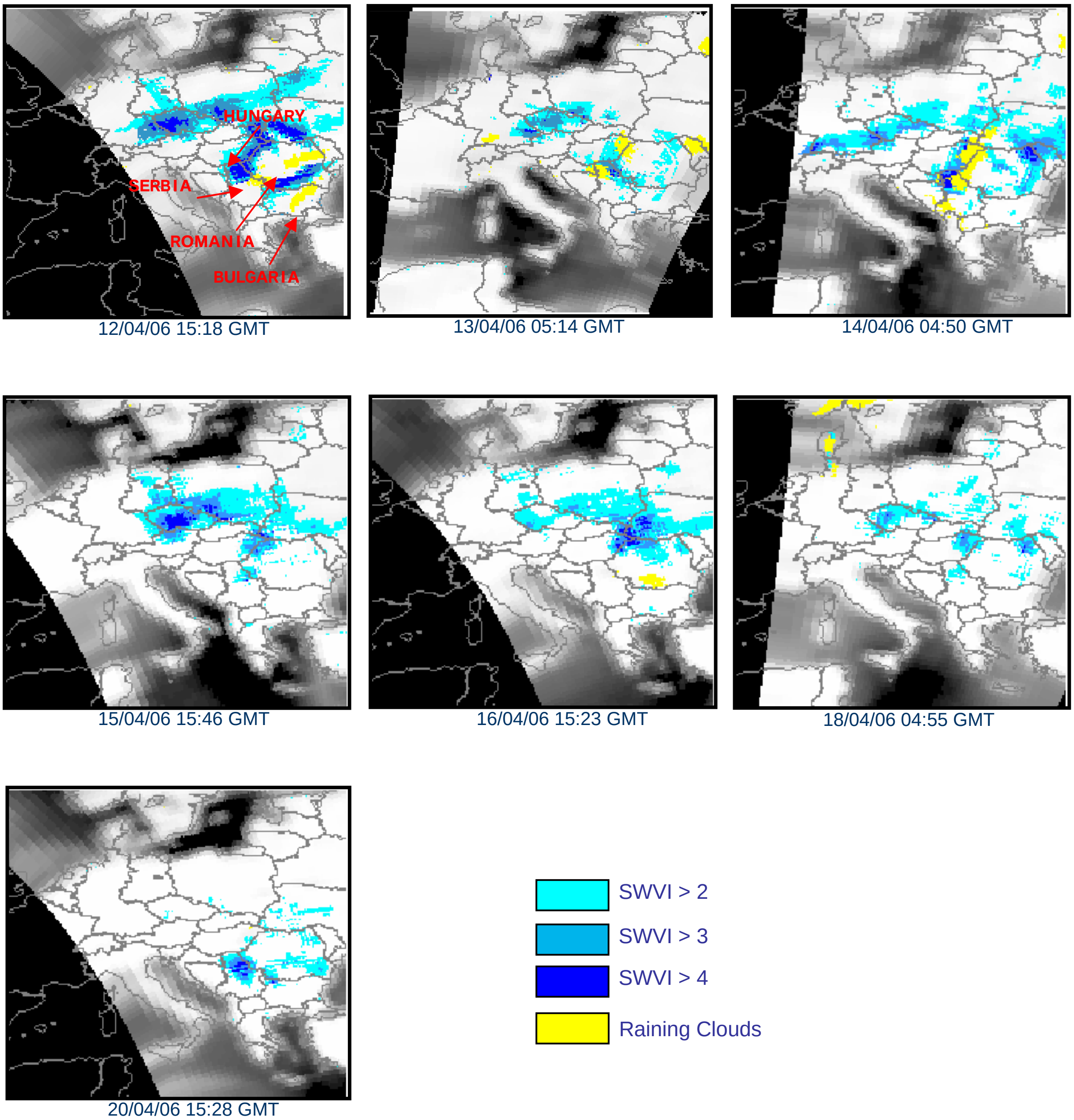

Fig. 5: As figure 4 for subsequent (i.e from 12 to 20) days of April 2006.

Conclusions

A recently proposed robust approach (RAT) has been used to define a Soil Wetness Variation Index (SWVI), aimed at the improvement of satellite soil wetness monitoring capabilities in the space-time domain and to possibly contribute to hydro-meteorological risk assessment and mitigation. The SWVI index has been implemented and tested on a recent flooding event occurred in Europe during April 2006.

Preliminary results achieved in this work, nevertheless quite satisfactory, need to be further investigate assessing their reliability with detailed ground information, which, up to now, are not yet available.

However, the suggested technique seems to be able to monitor the space-time evolution of all the flooding cycle, being the proposed SWVI indicator able to follow all the “wet-to-dry” phases for the considered events. In particular, the analysis of SWVI maps has revealed a good sensitivity of the indicator in identifying, timely and in automatic way, significant deviations from the "normal behavior" (in terms of soil wetness) due to the occurrence of heavy meteorological events. A sort of early signal, related to the rain that affected the study area before the AMSU pass, has also been observed about two days before the beginning of the main phase of the flooding event. Although requiring further investigations and additional confirmations, such a result might suggest the possibility to employ the SWVI as an additional (qualitative) parameter to support the definition of flooding hazard maps. When intense precipitation is forecasted, in fact, the knowledge of soil wetness conditions could be used to better define the hazard scenarios and the alert state of the involved area. Of course, more investigations are needed in order to better assess the usefulness of such a qualitative information before and, afterwards, additional efforts are required to possibly assimilate it into hydrological forecast model.

Further analyses, to be carried out also over an extended set of study cases (including no-extreme events), should be conducted in order to better assess the actual reliability and efficiency of such a technique. A possible future analysis can be devoted to a better evaluation of performances of the 22.5 GHz band, assessing the possible influence and impact of the water vapour absorption band in *SWVI* retrievals. A sensitivity analysis of the proposed *SWVI* is now in progress. This analysis, performed by comparison with ancillary data, like land cover maps, hydrological data, etc... will allow us to give a better evaluation of the reliability of *SWVI* in describing soil response to precipitations with different duration and intensity. Finally, the proposed methodology, now tested using AMSU data, is, for construction, easily exportable on other satellite sensors with better spatial/spectral/radiometric resolutions.

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