

Space–time soil wetness variations monitoring by a multi-temporal microwave satellite records analysis

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Abstract

In the last few years, remote sensing observations have become a useful tool for providing hydrological information, including the quantification of the main physical characteristics of the catchment, such as topography and land use, and of its variables, like soil moisture or snow cover. Moreover, satellite data have also been largely used in the framework of hydro-meteorological risk mitigation.

Recently, an innovative Soil Wetness Variation Index (SWVI) has been proposed, using data acquired by the microwave radiometer AMSU (Advanced Microwave Sounding Unit) which flies aboard NOAA (National Oceanic and Atmospheric Administration) satellites.

SWVI is based on a general approach for multi-temporal satellite data analysis (RAT – Robust AVHRR Techniques). This approach exploits the analysis of long-term multi-temporal satellite records in order to obtain a former characterization of the measured signal, in term of expected value and natural variability, providing a further identification of signal anomalies by an automatic, unsupervised change-detection step. Such an approach has already demonstrated, in several studies carried out on extreme flooding events which occurred in Europe in the past few years, its capability in reducing spurious effects generated by natural/observational noise. In this paper, the proposed approach is applied to the analysis of the flooding event which occurred in Europe (primarily in NW Spain) in June 2000. Results obtained, in terms of reliability as well as efficiency in space–time monitoring of soil wetness variation, are presented. Future prospects, in terms of exportability of the methodology on the new dedicated satellite missions, like ESA-SMOS and NASA-HYDROS, are also discussed.

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1. Introduction

In the last few years many hydrological parameters have been investigated by remote sensing applications. The opportunity to observe large areas with a single pass has been seen, by the hydrologist, as a unique chance to obtain detailed information about the features of the catchments. Moreover, the possibility to periodically repeat this observation (with a revisiting time varying from a few hours to few weeks, depending on the orbital characteristics of the satellite platform) has been used to observe the space–tem-

poral dynamic of the main parameters of the hydrological cycle (CEOS, 2003).

One of the parameters mainly studied by satellite observations is the soil moisture. Soil moisture takes an essential role in many processes which occur along soil–atmosphere interface (Entekhabi et al., 1994). It influences evaporation, flux exchange and runoff generation process. In order for soil moisture information to be useful, it must be 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 sufficient dense network of points to provide continuous information. As mentioned before,

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satellite measurements could help to overcome these gaps. The scientific community has recognized the usefulness of satellite soil moisture measurements and, in fact, two new satellite missions have been scheduled to specifically measure soil moisture: the European Space Agency passive L-band Soil Moisture and Ocean Salinity (ESA-SMOS) mission (2007 launch) (Silvestrini et al., 2001) and the US National Aeronautics and Space Administration active/passive L-band HYDROSpheric states (NASA-HYDROS) mission (scheduled launch in 2010) (Entekhabi et al., 2004).

Most of the present satellite techniques for soil moisture/wetness measurement exploit data acquired in the microwave region of the electromagnetic spectrum. In this range, in fact, the measured radiances are strongly influenced by the superficial soil water content (Eagleman and Lin, 1976; Jackson et al., 1981). Moreover, the observations are mostly independent from the sun energy, as well as from the cloud presence (except in the presence of heavy raining clouds) allowing an all day and all weather capability (Schmugge, 1998). Better soil moisture information could be achieved in the lower part of the microwave region, where the effects due to the presence of rough or vegetated soil, the two main problems limiting satellite soil moisture measurements are less important, and the information come up from deeper soils (Choudhury et al., 1979; Wang et al., 1983; Jackson and Schmugge, 1989; Prigent et al., 1997; Schmugge et al., 2002). That is the reason why the above mentioned new planned satellite missions, specifically designed to measure soil moisture (i.e. the SMOS and HYDROS missions), are going to use L-band passive radiometers.

Unfortunately nowadays, soil moisture/wetness information may only be achieved using data acquired at frequencies higher than the L-Band, then corrections to the measurements are needed to take into account the effects of vegetation cover and soil roughness (Wigneron et al., 2003).

These corrections are often made using ancillary data, when they are available (Ahmed, 1995; Choudhury and Golus, 1988; Wang, 1985; Jackson and Schmugge, 1991; Jackson, 1993) and/or exploiting data acquired from different satellite sensors (Ahmed, 1995; Paloscia et al., 1993; Njoku and Entekhabi, 1996; Njoku and Li, 1999; Ruf and Zhang, 2001; Kim and Barros, 2002).

Change-detection methods might reduce the impact of these disturbing effects without the need of auxiliary data (Engman, 1991; Wagner et al., 1999; Singh et al., 2005). Typically, vegetation cover and surface roughness are parameters slightly variable with time, whereas soil emissivity fluctuations due to changes in soil moisture may occur within short times and in unpredictable ways. Then, if a multi-temporal satellite data analysis is performed, with satellite records acquired under similar observational conditions (i.e. in the same month of the year, at the same hour of the day, etc.) the effects of vegetation cover and/or surface roughness, can be considered negligible. Such an approach has recently been used by Lacava et al. (2005a)

who proposed a satellite-based Soil Wetness Variation Index (SWVI) to monitor soil wetness variations in the space–time domain during some flooding events which occurred in Europe in the past few years (Lacava, 2004; Lacava et al., 2004, 2005a), besides, a sensitivity analysis targeted to a first evaluation of the reliability of the SWVI in describing soil response to precipitation of different duration and intensity, is also in progress (Lacava et al., 2005b).

In this paper, preliminary results achieved for the flooding event which hit the Spain, southern France and the North-West of Italy in June 2000, are presented.

2. Data

AMSU (Advanced Microwave Sounding Unit), is a passive MW radiometer aboard NOAA (National and Oceanic and Atmospheric Administration) satellites since 1998. It consists of two separate modules: the AMSU-A covers the MW region between 23 and 89 GHz, through 15 channels with a spatial resolution of 48 km at nadir, whereas the AMSU-B is a five channel radiometer in the range between 89 and 183 GHz, with 16 km of spatial resolution.

Among all the 20 channels, which do not give polarization information, there are some localized in window regions (Goodrum et al., 1997), which may allow us to obtain information about superficial parameters, such as soil wetness variations (Grody, 2002; Songyan et al., 2000; Kongoli et al., 2006). In particular, these channels have been up to now used for surface emissivity, superficial temperature or snow cover measurements (Ferraro et al., 2005 and references herein).

Notwithstanding AMSU spectral features are not ideal for soil wetness monitoring, its spatial resolution is suitable for hydrometeorology and hydro-climatology studies. Moreover, the NOAA constellation configuration guarantees at least one image every 6 h, giving us the opportunity to follow the dynamics of parameter with high temporal variability, such as soil wetness. Furthermore, AMSU-A is also present aboard NASA Terra Satellite and it will be aboard the next European METOP mission, ensuring a long-term data collection, which is crucial for change-detection studies.

3. The methodology

In the microwave region there is a high contrast between the dielectric properties of water and soil (Eagleman and Lin, 1976; Jackson et al., 1981). This difference, which directly affects the emissivity of dry and wet soil, is at the basis of all studies devoted to measuring soil moisture/wetness from satellites.

In the presence of water, in fact, any surface could be viewed as the combination between dry soil and water, being f the fractional amount of the area covered by water within the considered pixel. Then the microwave emissivity

of wet soil in each pixel can be calculated as (Basist et al., 1998; Songyan et al., 2000):

$$\varepsilon_{ws} = (1 - f) * \varepsilon_{ds} + \varepsilon_w f = \varepsilon_{ds} - f(\varepsilon_{ds} - \varepsilon_w) \quad (1)$$

where ε_{ws} , ε_{ds} and ε_w are the emissivity of wet soil, dry soil and water, respectively. As the fractional amount of wet land increases, the emissivity decreases (this lowering is greatest at lower frequencies) so that the emissivity difference between low and high frequencies increases (Basist et al., 1998; Singh et al., 2005). A measurement of the gradient of soil emissivity between higher and lower frequencies, may give a good indication about variations of soil water content (Songyan et al., 2000; Grody, 2002). The problem still remains to discriminate the contribution which is actually related to soil water presence, from those due to vegetation cover or surface roughness.

The methodology recently proposed by Lacava et al. (2005a) is devoted to the overcoming of the abovementioned limits. As described in detail in previous papers (Lacava et al., 2004; Lacava et al., 2005a), it is based on a general strategy of satellite data analysis in the space–time domain (RAT – Robust AVHRR Techniques, Tramutoli, 1998) and it suggests the identification of soil wetness variations by means of an automatic change-detection tool. By the analysis of long-term multi-temporal AMSU records, acquired under similar observational conditions, the proposed approach suggests firstly computing the expected value of the signal (i.e. background signal) and its natural fluctuation in the space–time domain (i.e. standard deviation) under unperturbed conditions. Furthermore, an automatic change-detection step, carried out at pixel level, is applied in order to identify signal anomalies which may be possibly associated to significant soil wetness variations. By this way, specific site effects (like the ones due to vegetation cover and/or surface roughness) are strongly reduced, because the same site observed under the same observational conditions (same month of year, same time of day) is expected to have the same roughness and quite similar vegetation cover. As a consequence, the possible observed emissivity variations might mainly be attributed to moisture variations in the soil (Lacava et al., 2005a).

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

$$SWVI(x, y, t) = \frac{SWI(x, y, t) - \mu_{SWI}(x, y)}{\sigma_{SWI}(x, y)} \quad (2)$$

where $SWI(x, y, t)$ is a hypothetical soil wetness index defined as the difference ($SWI = BT_{89\text{ GHz}} - BT_{23\text{ GHz}}$) 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 which are mainly due to vegetation and/or roughness effects. $\mu_{SWI}(x, y)$ and $\sigma_{SWI}(x, y)$ are respec-

tively the temporal average of SWI and its standard deviation, both computed on a selected, multi-annual AMSU imagery dataset composed by records collected during the same month of the year and acquired at around the same hour of the day. Then 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, $\sigma_{SWI}(x, y)$ of $SWI(x, y, t)$, 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). On the other hand, such a trend may reveal a limited applicability of the approach over areas with an intrinsic high variability such as coastal zones. This effect should be taken into account in the analysis and interpretation of the SWVI maps.

However, working pixel by pixel, the main noisy site effects (e.g. vegetation, roughness, but also 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 23 GHz, 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 could 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.

As an example of the improved results to be expected by using such an approach, in Fig. 1 a comparison between

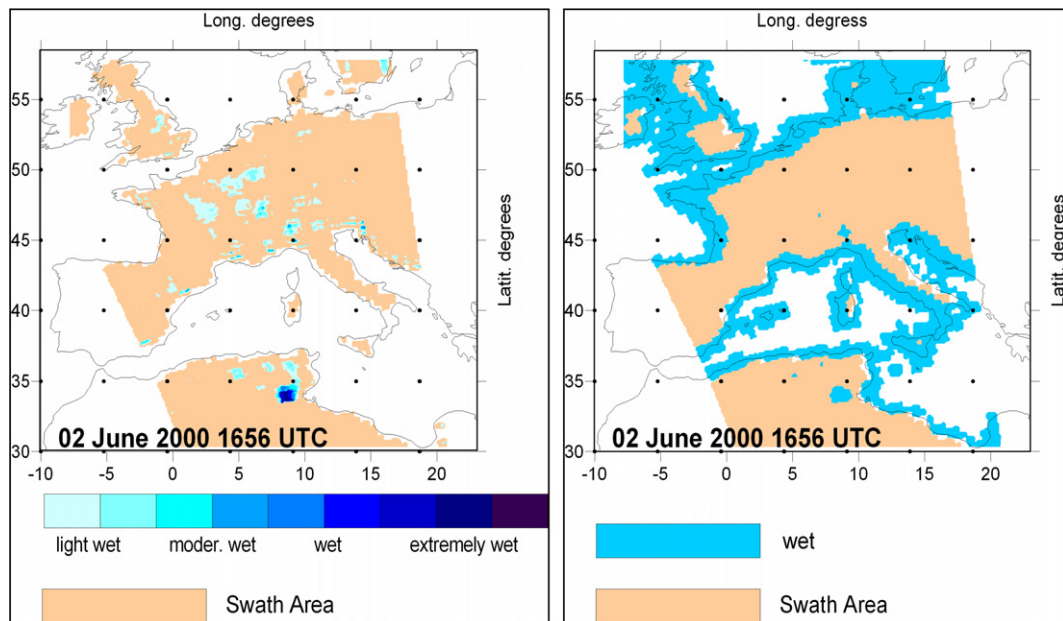


Fig. 1. On the left: SWVI map (see text) for the AMSU image of June 2, 2002 at 16:56 UTC. Different values of $SWVI(x, y, t)$ have been coloured in different shades of blue (higher SWVI values are shown in the darkest blue); On the right: SWI map (see text) for the same image: the areas identified as wet have been depicted in light blue. The AMSU swath is also shown in light orange in both panels.

the simple SWI and the proposed SWVI indicator is shown. In this picture, the AMSU swath area is highlighted in light orange, whereas, SWVI values, on the left, are represented in different shades of blue¹ (darker blue corresponds to higher soil wetness variations). On the right side, the simple SWI ($SWI = BT_{89\text{ GHz}} - BT_{23\text{ GHz}}$) map is shown. As above mentioned, the presence of water in the soil generates a decrease in the superficial emissivity which is higher at lower frequencies, so, in these circumstances, positive SWI values are expected: in light blue, in fact, all the pixels with positive SWI values (which should indicate soil emissivity variations) have been depicted. Large areas (all the coastal zones) corresponding to pixels including permanent water bodies (e.g. sea) are systematically identified as wet, independently from actual soil conditions. This circumstance obviously produces a general limitation, in terms of applicability, of the simple SWI index. On the other hand, comparing the two figures, it is quite evident as these site effects only marginally affect the SWVI index which automatically realizes that the coastal pixels, although presenting very high values of the signal, are also characterised by large fluctuations (i.e. high standard deviation), and, consequently, are identified as anomalies not statistically significant.

In order to try to attach to SWVI values a sort of (qualitative) physical meaning, we may classify as light wet (with respect to unperturbed conditions) all those pixels where SWVI values are in the range 1–2 (which simply means SWI values 1–2 sigma over the expected value), moderately

wet all those pixels with SWVI values between 2 and 3. Pixels with SWVI values in between 3 and 4 suggest (anomalous) wet conditions, whereas a SWVI greater than 4 should describe extremely wet conditions. However, it should be noted that, being SWVI a qualitative index describing relative, rather than absolute conditions, high positive SWVI does not necessarily identify soils close to the saturation state.

4. Event description

The proposed approach has been used in this paper, in order to assess its actual potential and efficiency, to study the flooding event which occurred in June 2000 primarily in Spain, and in sequence in southern France and in the North West region of Italy. The flood mainly hit the NE part of Spain, where the episode caused material damages estimated at over 65 000 000.00 euros (Llasat et al., 2003). A “flash flood” affected, in fact, the Spanish region of Catalonia, in particular Barcelona and the neighboring areas, on 9 and 10 June 2000. In some localities (especially in the Montserrat Basin), starting from the early morning of 9 June to the morning of 10 June, 224 mm of rain fell, causing the Llobregat river and its tributaries to overflow: 5 people died and hundreds were evacuated (Llasat et al., 2003; Mariani et al., 2005). Afterwards, the precipitation moved towards the south of France on 10 June, reaching the North-West of Italy the next day. In particular, the French areas mainly involved were the Rhone Alps, the Loire Valley’s Coise River, Toulouse and the whole Ariège region. In such regions the flood event caused 1 victim and hundreds of evacuees (Arnaud-Fassetta et al., 2005;

¹ For interpretation of colour in figures, the reader is referred to the Web version of this article.

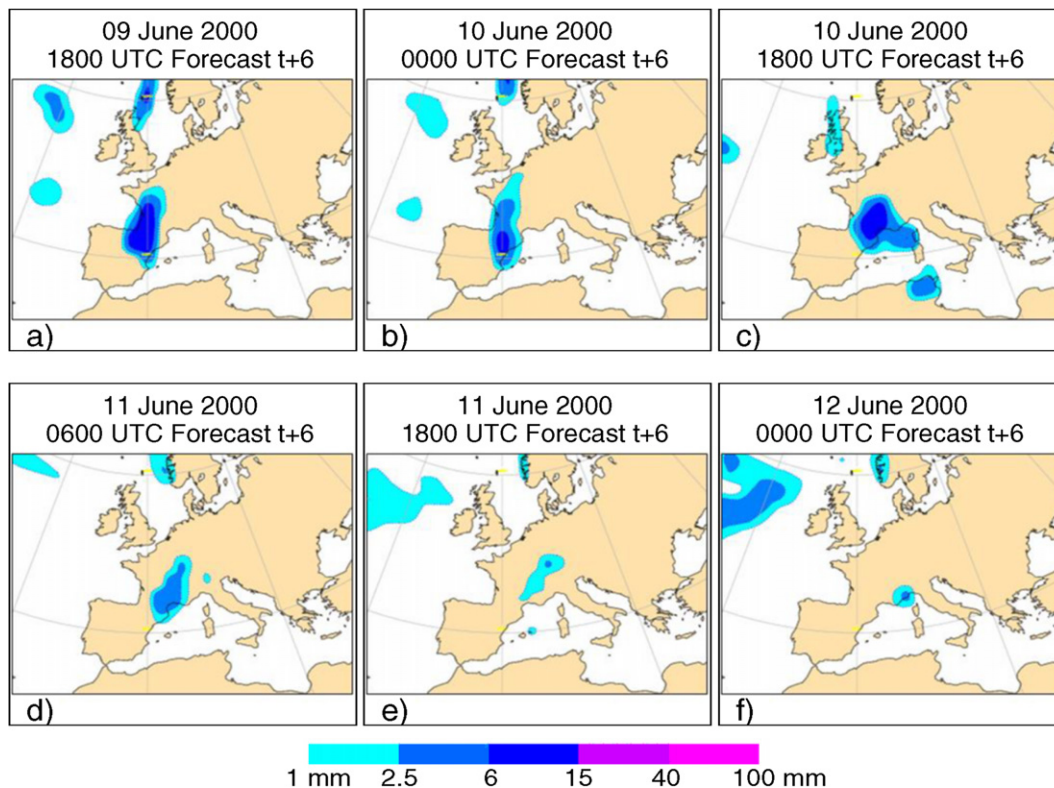


Fig. 2. ECMWF precipitation data (Re-Analysis ERA-40) (mm) on: (a) 9 June 2000, 18:00 UTC; (b) 10 June 2000, 00:00 UTC; (c) 10 June 2000, 18:00 UTC; (d) 11 June 2000, 06:00 UTC; (e) 11 June 2000, 18:00 UTC; (f) 12 June 2000, 00:00 UTC (from MARS Archive at ECMWF).

Associated Press, 2000). In Italy, the rain affected especially the Piedmont region, where about 220 mm of rain fell, causing enormous damages to infrastructures and to road networks (NimbusWeb, 2000; Turconi, 2001).

In Fig. 2, some of the re-analyzed forecast maps achieved from MARS (Meteorological Archival and Retrieval System) Archive (Re-Analysis ERA-40, Simmons and Gibson, 2000) at ECMWF (European Centre for Medium Range Weather Forecast) are shown (ECMWF, 2005). These maps describe the evolution of precipitation for the period between 9 and 12 June 2000. The space–time dynamic of the meteorological event appears clear. In fact, the rain first hit the Catalonia region during the night between 9 and 10 of June, and after moved towards France and Italy (10–11 June).

5. Implementation and results

Following RAT prescriptions, a prior collection of AMSU imagery has been carried out. Therefore, all the images acquired in the same month (June) of event occurrence (but in different years) have been selected, stratifying data also for hour of pass: two distinct homogeneous data series were produced, one (i.e. the “morning” data set) including all the passes acquired between 5:00 and 7:00 UTC, the other one (i.e. the “afternoon” series) gathering all the data collected between 15:00 and 18:00 UTC, respectively. Each of these two datasets consists of about 180

images (30 per year, for 6 years) acquired in the period 1998–2004 excluding, for each dataset, the year which was perturbed by the flooding event under investigation (i.e. 2000). 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 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, 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 89 GHz (Wilheit et al., 2003). Such a signal decrease consequently generates lower SWI values (assuming that the lower channel is more transparent), and therefore protect us from false SWVI anomalies identification. Nevertheless, possible failures in raining cloud detection as well as some residual problems potentially related to the presence of liquid water clouds might produce ambiguous results and then should be taken into account. Such an issue, which could be limited, for example, using specific algorithms to screening out also liquid water clouds or some kind of cloud mask, deserves further analysis.

Afterwards, for both the above described homogeneous datasets the previous defined reference fields (time average $\mu_{SWI}(x,y)$ and standard deviation $\sigma_{SWI}(x,y)$) were generated, at pixel level, for the whole scene.

Finally, the $SWVI(x,y,t)$ was computed according to Eq. (2) and used to automatically identify possible fluctuations of soil wetness in the space–time domain.

The SWVI maps generated for test cases are presented in Fig. 3. The areas hit by the flooding event have been ana-

lyzed before, during and after the selected events, in order to evaluate the reliability of the proposed index in following the space–time evolution of the flooding event. In the figure, raining clouds identified by the above mentioned screening test are also shown in brown (wherever they are

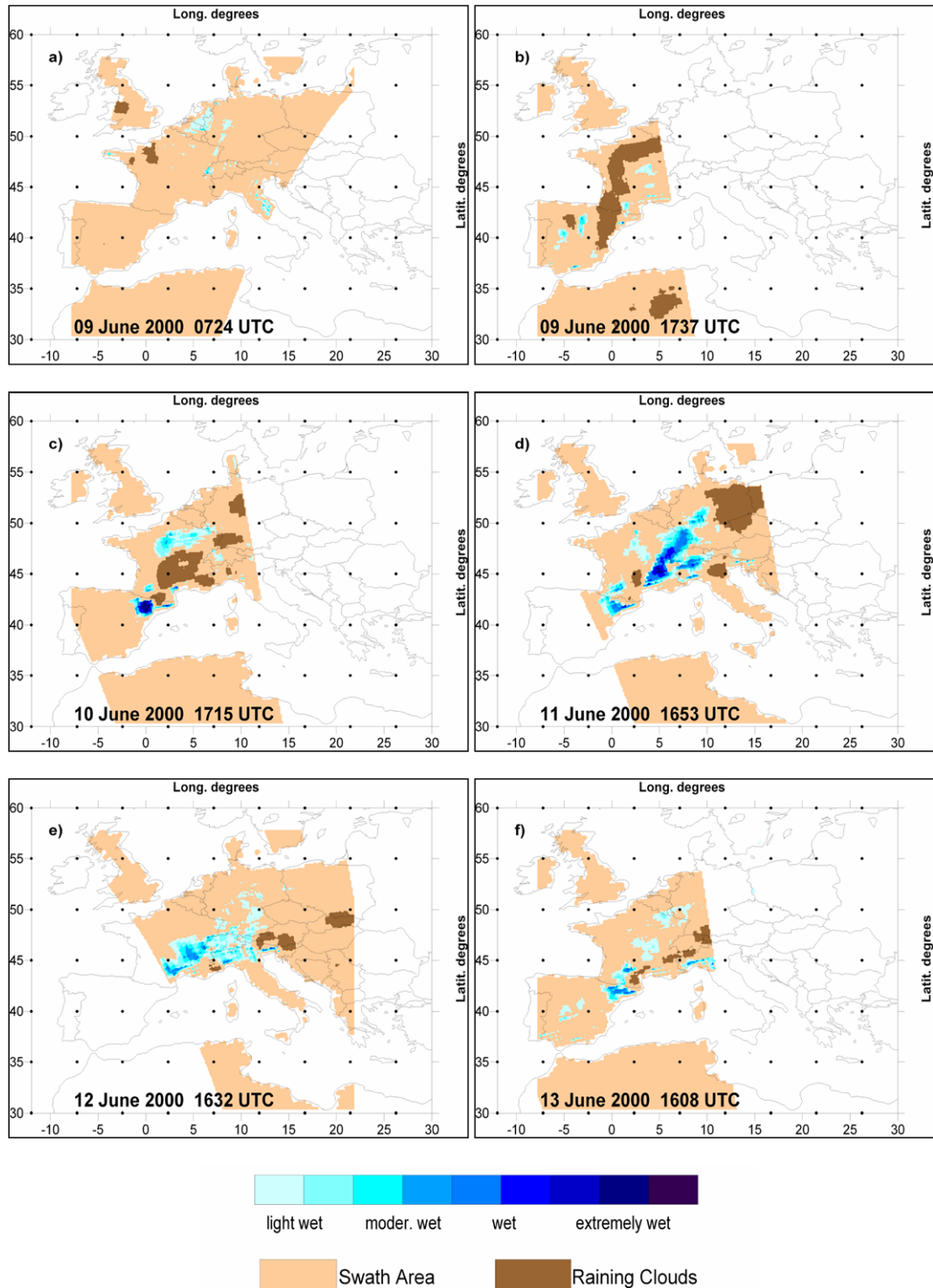


Fig. 3. Maps of $SWVI(x,y,t)$ for several days in June 2000. Panels from (a) to (i) respectively represent days from 9 to 18 June, 2000. Different values of $SWVI(x,y,t)$ have been coloured in different shades of blue (i.e. higher SWVI values are shown in the darkest blue). The AMSU swath is shown in light orange. Colour bars show the whole range of fluctuation for each field.

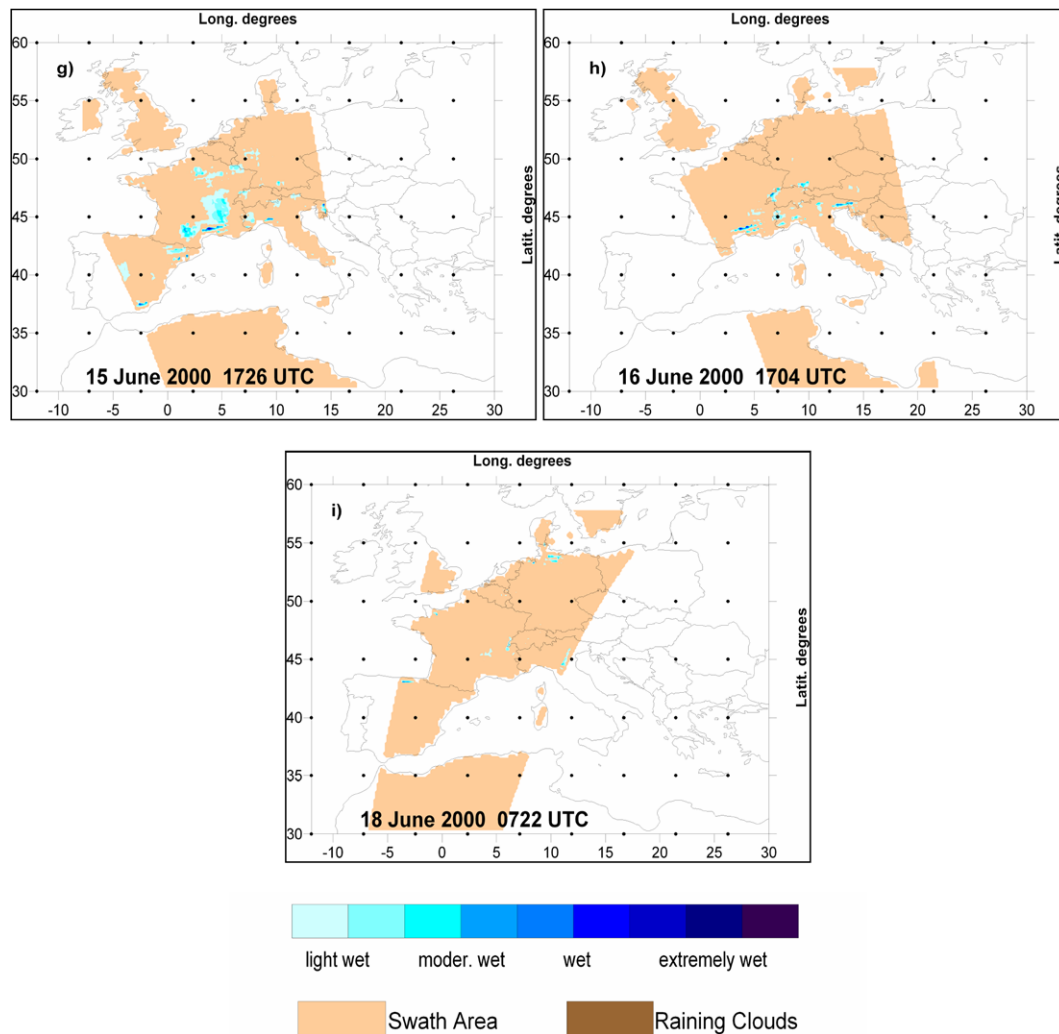


Fig. 3 (continued)

present). Results of the cloud screening test are in good agreement with the ECMWF forecast maps shown in Fig. 2, representing then an additional reliable and independent source of information about the precipitation evolution.

The analysis of the $SWVI(x,y,t)$ maps, reported in Fig. 3, shows that, before the main precipitation, on the morning of 9 June (panel a), the soil was characterized by “normal conditions” (i.e. no anomalies in terms of SWVI are identified over the studied scene). In the following two panels the sudden response (in terms of soil wetness variations) of the soils to the precipitation fallen between 9 and 10 of June in Spain (and partially in France) is possibly described by the (slight) SWVI anomalies which turn up over the affected region. In particular, on the map of 9 June at 17:37 UTC (panel b), clear weak positive anomalies in soil wetness are observed both in central Spain and in some region of France. Looking at this map, it is interesting to note as, although very limited in size and extension, the highest SWVI anomaly (with qualitative flags ranging from “wet” to “extremely wet”) is observed within an area very

close to Barcelona, just over the zone hit by the flash flood which started few hours later. This result might be regarded as an “early” sign of the anomalous wet conditions of the exposed soils shortly before the beginning of the main meteorological event. This sign is probably related to the precipitation which have already fell over the area during the morning and the afternoon of 9 June 2000, before the AMSU pass. The occurrence of precipitation that may probably drive such a SWVI response, is confirmed by both the ECMWF forecast map (Fig. 2, panel a) and by the Grody’s cloud screening test which detects a large area covered by raining clouds during the AMSU image acquisition (Fig. 3, panel b). In the next map, related to 10 June at 17:15 UTC (panel c), then after the end of the main precipitation event, a strong and large SWVI anomaly (both in size and intensity) appears within the same area of Spain, as a direct consequence of the precipitation which fell during the previous night. In the following days the effect in Spain decreases (see panels d,f,g) with a progressive decreasing of SWVI values and a contemporaneous continuous reduction of the extension of involved areas. With the

only exception of the map obtained for 12 June at 12:32 UTC (panel e), where the Catalonia region is out from the sensor swath and then no information is achievable from there, in the whole temporal sequence of SWVI maps a clear trend toward the normal conditions of soils is in fact easily observable. In the last two maps, for instance, obtained for 16 and 18 June (panels *h* and *i*), the Spanish area strongly affected by the flash flood appears to be came back to normal (unperturbed) soil wetness conditions. Moreover, looking at the sequence of the SWVI maps, the movement of the event toward France and Italy regions is also quite clear. The effects of heavy rain which shifted to South-Est of France and North-West Italy between 10 and 11 June, are clearly visible in panels from *d* to *g*, where, once more, the drying phase up to the restoration of apparent normal conditions observed on 18 June (panel *i*) is also well identifiable. Note the plain spatial persistence of the detected anomalies, just over the regions more affected by the flooding event. As mentioned before, after 16 June (panel *h*) the situation returns to a normal state, without any anomaly detected over the whole investigated area, confirming the reliability and robustness of the indicator also in unperturbed conditions (i.e. low rate of false alarms).

6. Conclusions

In this paper, a recently proposed AMSU-based Soil Wetness Variation Index (SWVI), aimed to improve soil wetness monitoring capabilities in the space–time domain and to possibly contribute to hydro-meteorological risk assessment and mitigation, has been implemented and tested on a flooding event which occurred in Europe in June 2000.

The results achieved in this paper represent a further confirmation of the efficiency of the proposed indicator in detecting soil wetness variations in the space–time domain.

The suggested technique reveals its capability to monitor the space–time evolution of the flooding cycle, being the proposed SWVI indicator able to follow all the “wet-to-dry” phases for the considered events. Moreover, the analysis carried out in this paper confirms the reliability of this method, as no “false positive” indications have been recorded during the whole considered period and over the whole investigated region. Both morning and afternoon passes have been analyzed, confirming an independence of the method on the observational conditions, as expected.

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 few hours before the beginning of the main phase of the meteorological event which caused the flash flood in the Catalonia region in Spain. Although requiring further investigations and addi-

tional 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 qualitative information before and, afterwards, additional efforts are required to possibly assimilate it into hydrological forecast model.

In order to do that some scientific issues which still remain opened and which may possibly limit the field of applicability of the proposed index, have to be carefully considered and addressed. For example atmospheric effects like residual cloud contamination, water vapor, liquid water cloud presence, etc. might affect the satellite measurement reducing the sensitivity of the approach in soil wetness variations retrieval.

Anyway, because of the high revisiting time of NOAA satellites (at least 6 h), a near-real-time monitoring of soil wetness is achievable, making SWVI a possible useful tool also in the nowcasting phase. Furthermore, because of the complete independence on the specific satellite platform, such a technique could be easily exported to the new generation of satellite microwave sensors, which may guarantee improved performances, like the present AMSR-E aboard EOS-Aqua, where, probably, it could be used to reduce the negative effects of Radio Frequencies Interference (Li et al., 2004).

Finally, the spatial and temporal resolutions of SWVI make it a possible useful information also for the incoming SMOS and HYDROS missions, which may perhaps benefits from such an indication for a preliminary qualitative validation of the improved products which are going to be achievable from these data.

References

- Ahmed, N.U., 1995. Estimating soil moisture from 6.6 GHz dual polarizations, and/or satellite derived vegetation index. *International Journal of Remote Sensing* 16 (4), 687–708.
- Arnaud-Fassetta, G., Cossart, E., Fort, M., 2005. Hydro-geomorphic hazards and impact of man-made structures during the catastrophic flood of June 2000 in the Upper Guil catchment (Queryas, Southern French Alps). *Geomorphology* 66, 41–67.
- Associated Press, 2000. Floods Force Hundreds Out Southern France...06/12/00. <http://www.mmmfiles.com/gc2000jun.htm>.
- Basist, A., Grody, N.C., Peterson, T.C., Williams, C.N., 1998. Using the special sensor microwave/imager to monitor land surface temperatures, wetness, and snow cover. *Journal of Applied Meteorology* 37, 888–911.
- CEOS (Committee on Earth Observation Satellites), 2003. Soil Moisture. *Heart Observation Handbook* (2003 Update): Earth Observation by Plans: Measurements, p. 83.
- Choudhury, B.J., Golus, R., 1988. Estimating soil wetness using satellite data. *International Journal of Remote Sensing* 9 (7), 1251–1257.
- Choudhury, B.J., Schmugge, T.J., Chang, A., Newton, R.W., 1979. Effects of surface roughness on the microwave emission from soil. *Journal of Geophysical Research* 84 (C9), 5699–5706.

- Eagleman, J.R., Lin, W.C., 1976. Remote sensing of soil moisture by a 21-cm passive radiometer. *Journal of Geophysical Research* 81, 3660–3666.
- ECMWF (European Centre for Medium-Range Weather Forecasts), 2005. MARS Archive. <http://www.ecmwf.int/index.html>.
- Engman, E.T., 1991. Application of microwave remote sensing of soil moisture for water resources and agriculture. *Remote Sensing of Environment* 35, 213–226.
- Entekhabi, D., Nakamura, H., Njoku, E.G., 1994. Solving the inverse problem for soil moisture and temperature profiles by sequential assimilation of multifrequency remotely sensed observations. *IEEE Transaction on Geoscience and Remote Sensing* 32 (2), 438–448.
- Entekhabi, D., Njoku, E.G., Houser, P., Spencer, M., Doiron, T., Kim, Y., Smith, J., Girard, R., Belair, S., Crow, W., Jackson, T.J., Kerr, Y.H., Kimball, J.S., Koster, R., McDonald, K.C., O'Neill, P.E., Pultz, T., Running, S.W., Shi, J., Wood, E., van Zyl, J., 2004. The hydrosphere state (hydros) satellite mission: an earth system pathfinder for global mapping of soil moisture and land freeze/thaw. *IEEE Transactions on Geoscience and Remote Sensing* 42 (10), 2184–2195.
- Ferraro, R.R., Grody, N.C., Marks, G.F., 1994. Effects of surface conditions on rain identification using the SSM/I. *Remote Sensing Reviews* 11, 195–209.
- Ferraro, R.R., Smith, E.A., Berg, W., Huffman, G., 1998. A review of screening techniques for passive microwave precipitation retrieval algorithms. *Journal of Atmospheric Science* 55, 1583–1600.
- Ferraro, R.R., Weng, F., Grody, N.C., Zhao, L., Meng, H., Kongoli, C., Pellegrino, P., Qiu, S., Dean, C., 2005. OAA operational hydrological products derived from the advanced microwave sounding unit. *IEEE Transactions on Geoscience and Remote Sensing* 43 (5), 1036–1049.
- Goodrum, G., Kidwell, K.B., Winston, W. (Eds.), 1997. NOAA KLM User's Guide. NOAA, NOAA-NESDIS/NCDC, Suitland, Maryland, USA.
- Grody, N.C., 1991. Classification of snow cover and precipitation using the special sensor microwave/imager (SSM/I). *Journal of Geophysics Research* 96, 7423–7435.
- Grody, N.C., 2002. An AMSU Soil Wetness Index, private communication.
- Grody, N.C., Weng, F., Ferraro, R.R., 2000. Application of AMSU for hydrological parameters. In: Pampaloni, P., Paloscia, S. (Eds.), *Microwave Radiometry and Remote Sensing of the Earth's Surface and Atmosphere*. VSP, The Netherlands, pp. 339–352.
- Jackson III, T.J., 1993. Measuring surface soil moisture using passive microwave remote sensing. *Hydrological Processes* 7, 139–152.
- Jackson, T.J., Schmugge, T.J., 1989. Passive microwave remote sensing system for soil moisture: some supporting research. *IEEE Transactions on Geoscience and Remote Sensing* 27, 225–235.
- Jackson, T.J., Schmugge, T.J., 1991. Vegetation effects on the microwave emission from soils. *Remote Sensing of Environment* 36, 203–212.
- Jackson, T.J., Schmugge, T.J., Nicks, A.D., Coleman, G.A., Engman, E.T., 1981. Soil moisture updating and microwave remote sensing for hydrological simulation. *Hydrological Sciences Bulletin* 26 (3), 305–319.
- Kim, G., Barros, A.P., 2002. Space-time characterization of soil moisture from passive microwave remotely sensed imagery and ancillary data. *Remote Sensing of Environment* 81, 393–403.
- Kongoli, C., Pellegrino, P., Weng, F., Ferraro, R.R., 2006. Evaluation of the AMSU land surface temperature algorithm for skin and shelter-air temperature retrievals. Extended abstract presented at the 14th Conference on Satellite Meteorology and Oceanography, part of the 86th AMS Annual Meeting, Atlanta, Georgia, January 2006.
- Lacava, T., 2004. Sviluppo di tecniche satellitari a microonde per il monitoraggio del rischio idrometeorologico, Ph.D. Thesis (available at University of Basilicata, Potenza, Italy).
- Lacava, T., Di Leo, E.V., Pergola, N., Romano, F., Sannazzaro F., Tramutoli, V., 2004. Analysis of multi-temporal satellite records for extreme flooding events monitoring. In: Testud, J., Mugnai, A., Santucci, J.F. (Eds.), *Proceedings of the 5th EGS Plinius Conference held at Ajaccio, Corsica, France, October 2003*, pp. 231–237.
- Lacava, T., Cuomo, V., Di Leo, E.V., Pergola, N., Romano, F., Tramutoli, V., 2005a. Improving soil wetness variations monitoring from passive microwave satellite data: the case of April 2000 Hungary flood. *Remote Sensing of Environment* 96 (2), 135–148.
- Lacava, T., Greco, M., Di Leo, E.V., Martino, G., Pergola, N., Romano, F., Sannazzaro, F., Tramutoli, V., 2005b. Assessing the potential of SWVI (Soil Wetness Variation Index) for hydrological risk monitoring by satellite microwave observations. *Advances in Geosciences* 2, 221–227.
- Li, L., Njoku, E.G., Im, E., Chang, P., St.Germain, K., 2004. A preliminary survey of radio-frequency interference over the US in Aqua AMSR-E Data. *IEEE Transactions on Geoscience and Remote Sensing* 42 (2), 380–390.
- Llasat, M.C., Rigo, T., Barriendos, M., 2003. The 'Montserrat-2000' flash flood event: a comparison with the floods that have occurred in the northeastern Iberian Peninsula since the 14th Century. *International Journal of Climatology* 23, 453–469.
- Mariani, S., Casaioli, M., Accadia, C., Llasat, M.C., Pasi, F., Davolio, S., Elementi, M., Ficca, G., Romero, R., 2005. A limited area model intercomparison on the "Montserrat-2000" flash-flood event using statistical and deterministic method. *Natural Hazards and Earth System Sciences* 5, 565–581.
- NimbusWeb, 2000. Diario meteorologico del mese di Giugno 2000. <http://www.nimbus.it/meteonews/meteodiario/diariometeogiugno.htm>.
- Njoku, E.G., Entekhabi, D., 1996. Passive microwave remote sensing of soil moisture. *Journal of Hydrology* 184, 101–129.
- Njoku, E.G., Li, L., 1999. Retrieval of land surface parameters using passive microwave measurements at 6–18 GHz. *IEEE Transactions on Geoscience and Remote Sensing* 37 (1), 79–93.
- Paloscia, S., Pampaloni, P., Chiarantini, L., Coppo, P., Gagliani, S., Luzi, G., 1993. Multifrequency passive remote sensing of soil moisture and roughness. *International Journal of Remote Sensing* 14 (3), 467–483.
- Prigent, C., Rossow, W.B., Matthews, E., 1997. Microwave land surface emissivity estimated from SSM/I. *Journal of Geophysical Research* 102 (21), 867–890.
- Ruf, C.S., Zhang, H., 2001. Performance evaluation of single and multichannel microwave radiometers for soil moisture retrieval. *Remote Sensing of Environmental* 75, 86–99.
- Schmugge, T.J., 1998. Applications of passive microwave observations of surface soil moisture. *Journal of Hydrology* 212–213, 188–197.
- Schmugge, T.J., Kustas, W.P., Ritchie, J.C., Jackson, T.J., Rango, A., 2002. Remote sensing in hydrology. *Advanced in Water Resources* 25, 1367–1385.
- Silvestrini, P., Berger, M., Kerr, Y.H., Font, J., 2001. ESA's Second Earth Explorer Opportunity Mission: The Soil Moisture and Ocean Salinity Mission – SMOS, *IEEE Geosci. Rem. Sens. Society Newsletter*, pp. 11–14, ISSN 0161-7869.
- Simmons, A.J., Gibson, J.K., 2000. ERA-40 Project Report Series No. 1. The ERA-40 Project Plan. ECMWF Publications.
- Singh, R.P., Oza, S.R., Chaudhari, K.N., Dadhwal, V.K., 2005. Spatial and temporal patterns of surface soil moisture over India estimated using surface wetness index from SSM/I microwave radiometer. *International Journal of Remote Sensing* 26 (6), 1269–1276.
- Songyan, G., Huilin, G., Yuanjing, Bolin Z., Wenjian, Z., Hong, Q., Maonong, R., 2000. Flood detection and Monitoring by using of AMSU-A microwave data. In: *Proceedings of the 20th International ATOVS Study Conference, Budapest, Hungary, 20–26 September 2000*.
- Tramutoli, V., 1998. Robust AVHRR Techniques (RAT) for Environmental Monitoring theory and applications, in *Earth Surface Remote Sensing II*, Giovanna Cecchi, Eugenio Zilioli (Eds.), SPIE 3496, pp. 101–113.
- Turconi, L., 2001. Opus 2000: sintesi monografica degli eventi di piena torrentizia. L'evento del 13 giugno 2000 nelle Alpi nord-occidentali. CNR-IRPI, Torino, Rapporto interno R.I. 01/08, 108p.
- Wagner, W., Lemoine, G., Rott, H., 1999. A method for estimating soil moisture from ERS scatterometer and soil data. *Remote Sensing of Environment* 70, 191–207.

- Wang, J.R., 1985. Effect of vegetation on soil moisture sensing observed from orbiting microwave radiometers. *Remote Sensing of Environment* 17, 141–151.
- Wang, J.R., O'Neill, P.E., Jackson, T.J., Engman, E.T., 1983. Multifrequency measurements of the effects of soil moisture, soil texture, and surface roughness. *IEEE Transactions on Geoscience and Remote Sensing* GE-21 (1), 44–51.
- Wigneron, J.P., Calvet, J.C., Pellarin, T., Van de Griend, A.A., Berger, M., Ferrazzoli, P., 2003. Retrieving near-surface soil moisture from microwave radiometric observations: current status and future plans. *Remote Sensing of Environment* 85, 489–506.
- Wilheit, T., Kummerow, C.D., Ferraro, R.R., 2003. Rainfall Algorithms for AMSR-E. *IEEE Transactions on Geoscience and Remote Sensing* 41 (2), 204–214.