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Hydrological implications of remotely sensed thermal inertia

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Abstract The potential of using the day/night temperature difference as an indicator of soil/canopy water content at short time-scales, based on AVHRR data, is considered. The goal of this approach is to evaluate the usefulness of introducing a soil thermal index in assessing the space–time variability of soil water content. Water balance model calibration, spatial models of precipitation, and flood forecasting (in the setting of initial conditions) may benefit from these results. Apparent Thermal Inertia (*ATI*), derived from AVHRR, was compared to daily precipitation and to an antecedent precipitation index to evaluate the evidence of time variability of *ATI* with regard to relative soil water content. Analysis of the spatial variability was also made to evaluate the robustness and the sensitivity of the *ATI* in the study area. Results from the computation of *ATI* over a 300 km^2 river basin in southern Italy indicate that this index can provide useful information related to an indirect estimate of soil moisture.
Key words ATI; AVHRR; Basilicata, Italy; soil moisture; remote sensing

REMOTE SENSING EVALUATION OF SOIL WETNESS

Techniques and methods for evaluation of soil water content pervade the literature of hydrological applications of Remote Sensing (e.g. Engman, 1995). The great potential of passive/active microwave methods for soil water content measurement (e.g. Schmugge, 1998; Engman & Chauhan, 1995) does not limit the usefulness of other indirect techniques, based on radiometric measures in the optical range. Poor spatial resolution still limits current applicability of passive microwave methods, while active microwave data are only available at low temporal frequency and at high cost. These factors constitute constraints to the practical application of such data for operational hydrological purposes. Hydrological applications of water budget or of flood frequency analysis at the regional scale require information on the changes in time and space of soil water availability. For the spatial scales of interest in river basin hydrology (from tens to hundreds of square kilometres) information from satellite platforms with adequate temporal frequency, and sufficient spatial resolution can provide important contributions to regional analyses. In this context, indirect measures of soil moisture are proposed, based on AVHRR (Advanced Very High Resolution Radiometer) observations. AVHRR is a scanning radiometer on board the NOAA satellites which, operating in parallel, guarantee at least four site re-visitations per day (around synoptic hours). This high repeat rate, together with its 1.1 km spatial resolution and spectral capabilities (five channels from the visible to the thermal infrared) make this sensor suitable for the above-mentioned purposes.

A number of approaches have been proposed for indirect evaluation of soil moisture through radiometric data in the optical range. A practical classification can distinguish: (a) use of visible and near-infrared reflectance measures (e.g. Musick & Pelletier, 1986; Becchi *et al*., 1998); (b) use of surface temperature evaluated in the infrared region (e.g. Price, 1980) and possibly integrated (Carlson *et al.*, 1995) with NDVI (Normalized Difference Vegetation Index). Our contribution should be viewed in the framework of methods based on the thermal inertia approach (e.g. Carlson, 1986) with specific attention to the minimum necessary ground data information, as required both by the "triangle method" (Carlson *et al.*, 1995), and by the "robust" approach to environmental monitoring by satellite introduced by Tramutoli (1998).

Our specific interest here is related to the re-evaluation of the role of thermal inertia as an index of soil moisture. This parameter may be viewed as information to be associated with, for instance, NDVI in the context of a long-term and wide-area evaluation of the variability of soil/canopy moisture content.

APPARENT THERMAL INERTIA (*ATI*) MEASUREMENTS BY AVHRR

Thermal inertia, *TI*, is a physical property of materials describing their impedance to temperature change. The equation $TI = (K\rho c)^{1/2}$, shows its dependence on the thermal conductivity K, density ρ, and specific heat c of the material. The change in temperature at the Earth's surface due to a given heat flux is inversely related to the thermal inertia of the exposed material. In particular, water bodies, having *TI* higher than dry soils and rocks, exhibit lower diurnal temperature fluctuations. As soil water content increases, thermal inertia also increases, reducing the diurnal temperature range. Present satellite remote sensing capabilities in measuring Earth surface temperature can be exploited in order to derive information on soil moisture, provided that the re-visitation time is adequate to follow the diurnal temperature cycle and the spectral resolution is sufficient to evaluate the net heat flux at the Earth surface.

An approximate (Apparent) value (*ATI*) of the actual *TI*, can be obtained from AVHRR measurements of the spectral surface albedo A and of the diurnal temperature range ΔT, as $ATI = (1 - A)/\Delta T$. We estimated both quantities following Xue & Cracknell (1996). Surface albedo A was obtained using visible ($R1$) and near-infrared ($R2$) reflectances from AVHRR channels 1 and 2 ($A = 0.423R1 + 0.577R2$). The diurnal temperature range ΔT is the difference between brightness temperatures, $T5$, measured in the AVHRR thermal infrared channel 5 at noon and midnight ($\Delta T = T5_{day} - T5_{night}$). Actual values of *TI* and measured *ATI* are variously affected by parameters related to space–time variability of observational, atmospheric, and surface conditions (e.g. time of the passes, satellite/solar zenith angles, transmittance, cloud cover, vegetation, permanent water bodies). In particular, brightness temperature is only vaguely related to ground surface temperature in the presence of dense vegetation.

Models that derive *TI* from *ATI* taking into account all these effects require considerable ancillary information which is frequently unavailable. In order to evaluate the potential of this approach based solely on the satellite data at hand, we preferred to use raw *ATI* measurements. Only the dependence on soil cover has been taken into account by checking for the presence of water bodies and tall vegetation in the study area.

COMPARISON BETWEEN *ATI* AND RELATIVE SOIL WETNESS

The study area was selected based on several requirements: (a) availability of daily rainfall and temperature data, and (b) homogeneity of land cover. The Basentello basin which was selected (in Basilicata, Italy) has an area of about 300 km^2 and presents a moderate relief, which helps in reducing the spatial variability of *ATI* data. Land cover is dominated by wheat cultivation (non-irrigated), as confirmed by the CORINE mapping (EU-DGXII). The basin is fairly dry, with an annual precipitation of 600 mm and an annual average temperature of 14.5°C. Total relief is about 400 m. The closure section of the basin is set by a small dam which produces a lake of about 2 km^2 surface area. Point measures of daily precipitation and minimum/maximum temperatures are made near the dam.

Owing to the moderate relief, spatial variability of precipitation is negligible, as was validated with station data from outside the basin. Based on the set of images available and the continuity of rainfall and temperature measurements, we selected images for April and June of two different years. Raw AVHRR data, routinely received at the IMAAA (Instituto di Metodologie Avanzate di Analisi Ambientale) Satellite Station in Tito Scalo (40°36′N, 15°43′E), have been calibrated in reflectance and brightness temperature following Lauritson *et al.* (1979), then geo-referenced and co-registered at 1 km accuracy, using an automatic procedure developed by Pergola & Tramutoli (2000). Only scenes which are cloud free over the study site have been processed for *ATI* determination. The Antecedent Precipitation Index, *API* (WMO, 1983) has also been computed in order to provide an indication of the relative moisture resulting from rainfall events during the preceding days. Daily maps of *ATI* were created for some days preceding and following precipitation, depending mainly on the degree of cloud cover.

Relying on the relative homogeneity of the land cover in the study area we decided to consider *ATI* data for the entire set of pixels included in the basin boundary, in order to obtain a sufficient data population for the spatial analysis. Since precipitation is a point measure, one representative *ATI* value must be selected for comparison with the relative moisture level. In this regard, the spatial average does not appear representative of the spatial sample because of the presence of outliers (see *ATI* values over 0.7 in Fig. 1). These high values were not removed or filtered, because the 10% percentile of the spatial sample was used as a robust indicator of the areal *ATI* values for any given day. This value is the one with rank 1/10 on the sorted *ATI* sample of each day. Selection of the 10% percentile as a representative value reduces the amplitude of the signal used for comparison with relative soil moisture and probably affects the correlation between *ATI* and *API*, as resulting from graphs in Figs 2 and 3 where the histograms of the rainfall events are also depicted. Nevertheless, the areal *ATI* is in sufficient agreement with the soil moisture indicator (*API*), and the relative homogeneity of the data sample substantiates this assertion. One also notices that greater distances between the spatial average and the 10% percentile occur after the rain events.

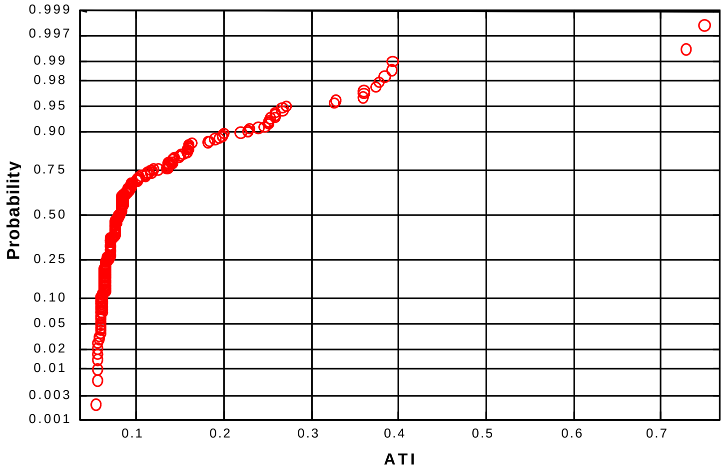

Fig. 1 Frequency distribution of *ATI* data on normal probability paper from the image of 8 June 1997.

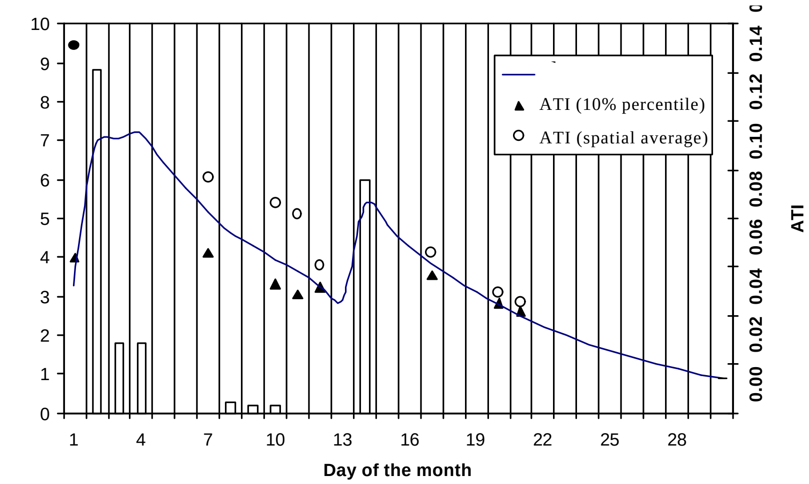

Fig. 2 Daily rainfall (histogram) and representative *ATI* values for April 1996. *API* index is in arbitrary units.

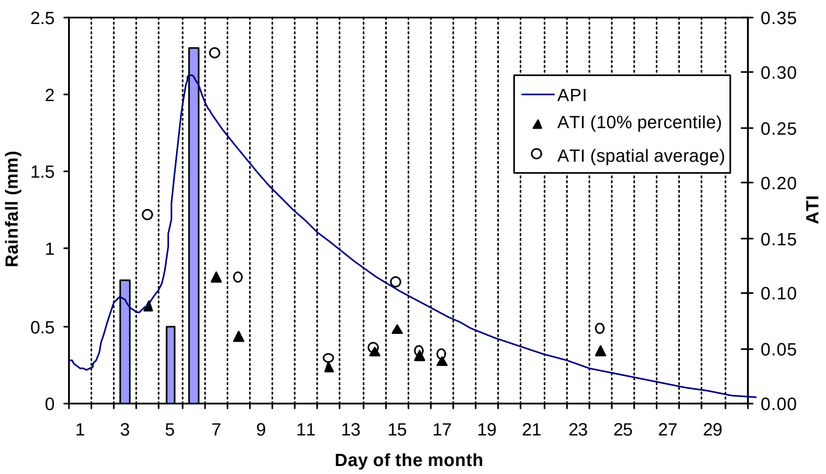

Fig. 3 Daily rainfall (histogram) and representative ATI values for June 1997. API index is in arbitrary units.

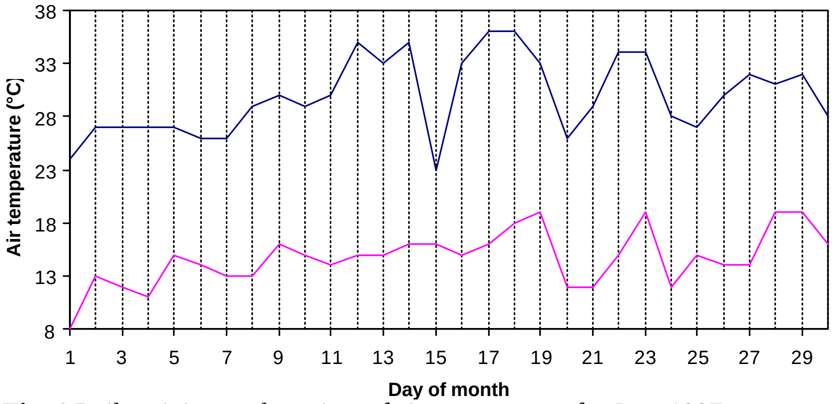

Fig. 4 Daily minima and maxima of air temperatures for June 1997.

On June 15 there are increases of *ATI* that are not preceded by rainfall. Looking at the temperatures during the corresponding day (Fig. 4), one can recognize a marked decrease in the maximum, possibly indicating prolonged cloud cover during the day (except around the time of the measurement), with a consequent abnormally low soil heating.

In conclusion, the overall behaviour of thermal inertia appears well related to precipitation (and related *API*) and can be linked reasonably to side effects if temperature data is available. Further analysis of the spatial variability of *ATI* may provide greater confidence in the signal to noise ratio, which may be important for estimates made in more heterogeneous land cover and to assess problems resulting from measuring temperature differences in areas of tall vegetation.

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