Met Office
Hadley Centre

Monitoring of mean radiant temperature for man

For the Climate Monitoring and Attribution team
September 2012
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1. Introduction

Heat waves and cold spells are often associated with increases in mortality and morbidity rates. Information on human heat stress during such events is therefore important to health authorities and policy makers. Currently, the United Kingdom's (UK) heat wave and cold weather warning thresholds are set against surface air temperature: typical thresholds of 30°C day maximum and 15°C night minimum temperatures are used for heat waves, 2°C mean temperature is used for cold weather warnings. However, air temperature is only one of the terms of human heat balance and mean radiant temperature is arguably an important contributor to heat stress.

Various thermal comfort and heat stress indices can be calculated from meteorological data including radiant temperature. A sensitivity analysis of the Universal Thermal Climate Index (UTCI)[1] demonstrates the relative importance of radiant temperature compared to air temperature: at lower air temperatures and high radiant temperatures, air temperature has relatively no effect on the UTCI (figure 1). The equation for the often used Wet Bulb Globe Temperature (WBGT)[2] also places more importance on radiant

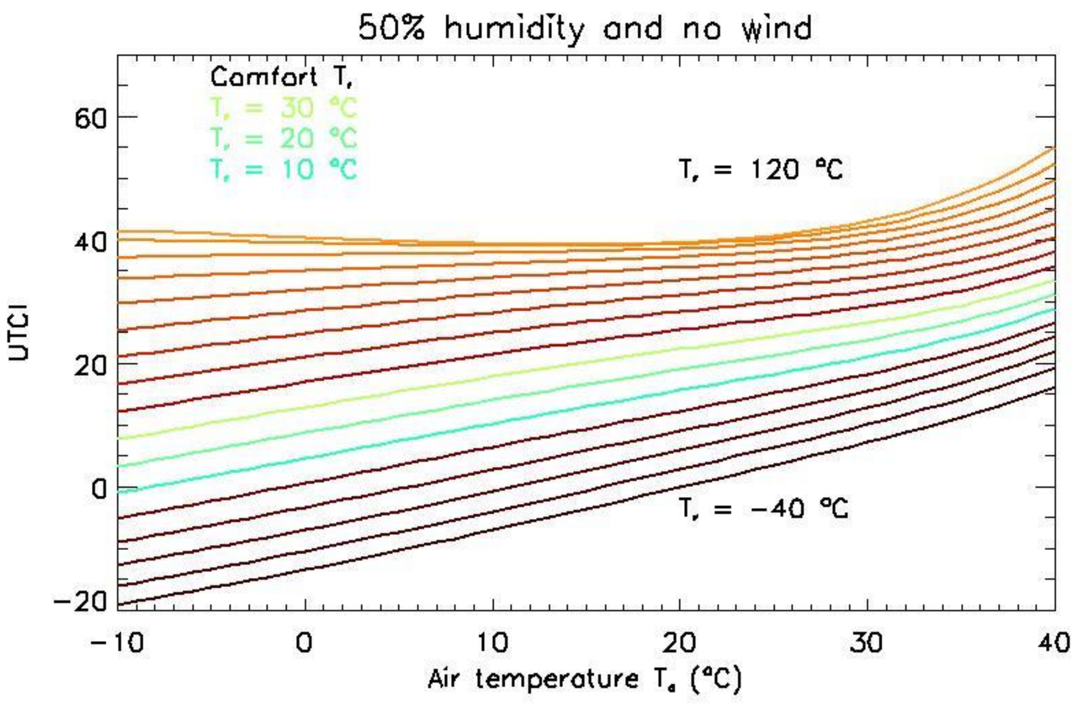

Figure 1. Sensitivity plot of the Universal Thermal Climate Index (UTCI) against air temperature T_a for different values of radiant temperature T_r.

temperature T_r than air temperature T_a though the predominant term is the wet bulb temperature T_w (how this affects thermal balance strongly depends on clothing and it should be noted that the WBGT was designed for military khaki):

$$WBGT = 0.7T_w + 0.2T_r + 0.1T_a \qquad \text{equation 1}$$

There are few ground-based stations with the capability to take observations of radiant temperature. Furthermore, mean radiant temperature is a parameter that depends on the shape of the surface to which it is applied: it will be different for man to other applications such as vegetation, animals or ground. However, measurements by satellite instruments provide the retrievals necessary for the calculation of mean radiant temperature: retrievals from the SEVIRI instrument (Spinning Enhanced Visible and Infra-Red Imager) include down-welling short-wave radiation (DSSF), down-welling long-wave radiation (DSLF), albedo and Land Surface Temperature (LST), and these are sufficient for an estimation of mean radiant temperature for man.

2. Derivation of the mean radiant temperature equation

Many of the steps for the derivation of Mean Radiant Temperature (MRT) for man can be found in Monteith and Unsworth (1990)[3] that provides a more detailed analysis for some of the steps. Man is assumed to be standing on an empty and flat plain of uniform albedo ρ and emissivity ε, and is approximated by a vertical cylinder of height h and radius r. The mean radiant temperature T_{mr} is obtained from the sum of total short and long wave radiation fluxes, S_{tot} and L_{tot}, respectively, absorbed by the body. This is given by equation 2 using the Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8}$ W/m^2/K:

$$\sigma T_{mr}^4 = (1-\rho_h)S_{tot} + L_{tot} \qquad \text{equ. 2}$$

ρ_h is the body's mean albedo which reflects some of the short-wave radiation. Average short-wave reflection coefficients for man range from 0.35 to 0.18 ([a]) while assumed reflectivity for man of 0.15 have been used for radiation balance estimations. However, ρ_h is neglected here (i.e. $\rho_h = 0$) because it will depend on the individual's clothing and behaviour.

[a] c.f. short-wave reflection coefficients for Man listed in section 3(a) of Table 6.1(i) on page 81 of Monteith and Unsworth (1990)[3]

The total short-wave radiation flux at the surface of the cylinder is expressed by equation 3 given down-welling components of direct S_b and diffuse S_d Solar radiation:

$$S_{tot} = \underbrace{\frac{A_h}{A} S_b}_{\text{direct}} + \underbrace{\frac{S_d}{2}}_{\text{diffuse}} + \underbrace{\frac{\rho}{2}(S_b + S_d)}_{\text{reflected}} \qquad \text{equ. 3}$$

The first term of equation 3 is the radiation received from direct sunlight and requires a shape factor A_h/A dependent on the Solar zenith angle ψ. The second term is the radiation received from diffuse sunlight from the upper hemisphere surrounding man. The third term is the radiation received from the reflected sunlight (direct and diffuse) from the lower hemisphere surrounding man. For reflected sunlight, the ground surface has somewhat different albedo values for direct and diffuse sunlight. The spectral Directional-Hemispherical (DH) albedo ρ_{DH} also known as black-sky albedo is used for direct sunlight and the spectral Bi-Hemispherical (BH) albedo ρ_{BH} also known as white-sky albedo is used for diffuse sunlight[4]. As a result, equation 3 can be rewritten as:

$$S_{tot} = \left(\frac{A_h}{A} + \frac{\rho_{DH}}{2}\right) S_b + \frac{1+\rho_{BH}}{2} S_d \qquad \text{equ. 4}$$

The shape factor is the ratio of the surface area of shadow (for direct sunlight) cast by a solid and the total surface area of the solid. The shape factor for a vertical cylinder is given by equation 5. For an average human, $h/r \approx 14$ (equivalent to a height of 1.65 m and a radius of 0.117 m). In this case, A_h/A is no more than 0.034 when the Sun is at the zenith ($\psi = 0°$) and tends to infinity at sunset and sunrise ($\psi = 90°$) (figure 2).

$$\frac{A_h}{A} = \frac{\frac{1}{2} + \frac{h}{r}\frac{\tan\psi}{\pi}}{1 + \frac{h}{r}} \qquad \text{equ. 5}$$

In cloudless conditions, down-welling direct Solar radiation may be estimated from the turbidity τ of the atmosphere and the Solar zenith angle ψ by equation 6.

$$\begin{cases} S_b = S_{p0} e^{-\frac{\tau}{\cos\psi}} \cos\psi & \text{if } \psi < 90° \\ S_b = 0 & \text{if } \psi \geq 90° \end{cases} \qquad \text{equ. 6}$$

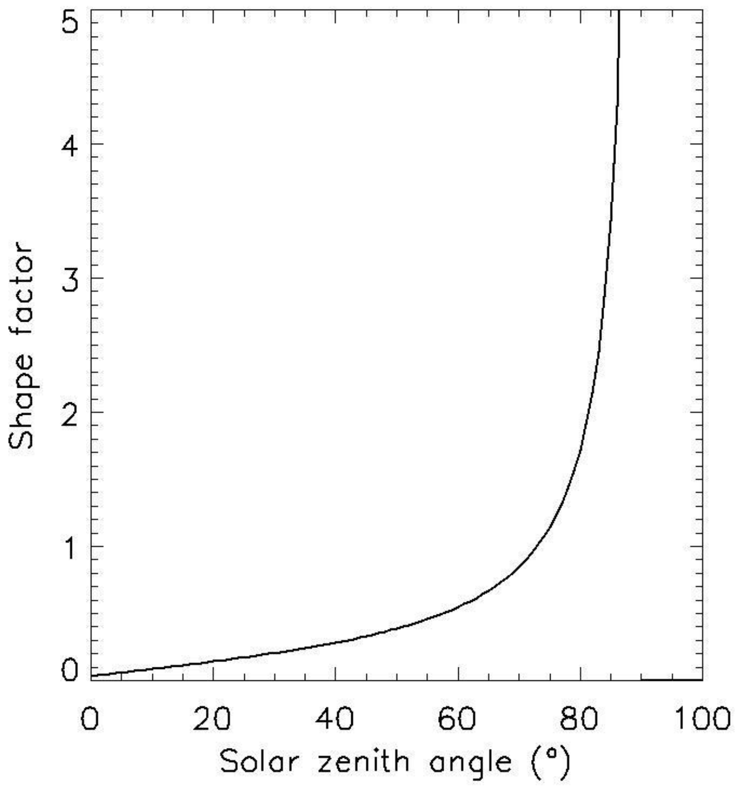

Figure 2. Dependency of the shape factor A_h/A on the Solar zenith angle ψ.

S_{p0} is the maximum direct Solar radiation that is expected through a layer of clean air ($\tau = 0$) when the Sun is at the zenith ($\psi = 0°$) and is typically 75% of the Solar constant, $S_{p0} \approx 1030\ \mathrm{W/m^2}$. From measurement, turbidity τ in Britain is expected to range from 0.07 (Ben Nevis) to 0.6 (Midlands).

The total long-wave radiation flux at the surface of the cylinder is expressed by equation 7 given down-welling long-wave radiation L_d from the atmosphere (from the upper hemisphere surrounding man) and up-welling long-wave radiation from the ground (from the lower hemisphere surrounding man); this latter is derived from the land surface temperature T_{LS} and depends on the ground's emissivity ε which is around 0.9 to 0.95 for soils: minerals range from 0.67 (quartz) to 0.94 (marble), while leaves range from 0.938 (French bean) to 0.995 (sugar cane).

$$L_{tot} = \frac{L_d + \varepsilon\sigma T_{LS}^4}{2} \qquad \text{equ. 7}$$

Mean radiant temperature should include an additional term for the radiation emitted by the human body using a measure of mean skin temperature and emissivity: however, skin temperature is transient and dependent on activity and clothing, emissivity is also dependent on clothing, and both vary between individuals. Therefore this term has been ignored and here mean radiant temperature for man is defined for incoming radiation only.

3. Application to SEVIRI satellite retrievals

The Land Surface Analysis (LSA) Satellite Application Facility (SAF)[b] provides a number of retrievals from the Meteosat Second Generation (MSG) satellite using the SEVIRI radiometer. These include:

- Fraction of Vegetation Cover (FVC) (may be used to estimate emissivity)
- Surface albedo
- Land Surface Temperature (LST)
- Down-welling surface short-wave radiation flux (DSSF)
- Down-welling surface long-wave radiation flux (DSLF)

All of these are received in near-real time (1 to 2 h delay) at the Met Office through the Eumetcast system.

At present, the use of SEVIRI retrievals for the monitoring of the mean radiant temperature is dependent on the availability of DSSF data (down-welling short-wave radiation). The DSSF retrieval is the total down-welling short-wave radiation, direct and diffuse together. As can be deducted from equation 4, the DSSF needs to be split into its direct S_b and diffuse S_d parts; and direct Solar radiation S_b can be estimated from the turbidity τ and Solar zenith angle ψ using equation 6. The DSSF product manual[5] refers to the atmospheric transmittance factor T given by:

$$T = \frac{T_A}{1 - A_S A_A} \qquad \text{equ. 8}$$

A_A is the spherical albedo of the atmosphere and is given a constant value for the DSSF retrieval: $A_A = 0.0880228$

A_S is a function of the white-sky albedo ρ_{BH} and of the Solar zenith angle ψ [6]:

[b] http://landsaf.meteo.pt/

$$A_S = \rho_{BH} \frac{1.4}{1 + 0.8 \times \cos\psi} \qquad \text{equ. 9}$$

T_A is the transmittance of the atmosphere and is given by[7]:

$$T_A = e^{-\tau_{H2O}} e^{-\tau_{O3}} e^{-\tau_{Aer+CO2+O2}} \qquad \text{equ. 10}$$

Assuming that the turbidity can be identified as $\tau = \tau_{H2O} + \tau_{O3} + \tau_{Aer+CO2+O2}$ and that the Solar zenith angle dependent transmittance used in equation 6 with S_{p0} can be equated to the transmittance T_A with the Solar constant as described in the DSSF manual, the turbidity τ may be estimated as:

$$\tau = \ln \frac{S_{p0} \cos\psi}{DSSF\left(1 - A_A A_S\right)} \cos\psi \qquad \text{equ. 11}$$

This derivation for τ however is imperfect and further work is required to provide a better estimate of turbidity – despite this, under clear sky conditions, turbidity τ provides a suitable means of splitting the DSSF into a direct S_b and a diffuse S_d sunlight component. The albedo retrieval closest in time to and within 3 days of the DSSF measurement time is used.

The DSLF provides the down-welling long-wave radiation from the atmosphere, L_d of equation 7, while the LST is the Land Surface Temperature and T_{LS} of equation 7. For both DSLF and LST, the retrieval closest in time to and within 1 hour of the DSSF measurement time is used. At present, the land surface emissivity ε is assumed to be unity ($\varepsilon = 1$): this is an approximation made for convenience as for soils the emissivity is more likely to be around 0.9 to 0.95 and for leaves between 0.938 and 0.995 – in most cases it would seem that $\varepsilon > 0.9$. Fraction of Vegetation Cover (FVC) retrievals are based on land surface emissivity[8] and could provide useful emissivity values that change over time (as FVC undergoes seasonal changes).

Finally, this derivation of Mean Radiant Temperature (MRT) for man from SEVIRI retrievals is applicable to clear skies only as LST retrievals are available only for cloud free areas. In addition to quality checks of the DSSF data, a mask is created for clear sky land areas using the LST quality control information[9].

4. Examples

Near-real time monitoring of the mean radiant temperature for man is now available at the Met Office. Two examples of retrievals and derived data are presented here: (1) the daytime heat wave conditions at 12 h GMT on 18th August 2012; (2) relatively cooler night-time conditions at 3 h GMT on 7th September 2012. Radiation flux data are plotted with the same colour scale as temperature using the σT^4 transform to obtain radiation flux from temperature T: under this scheme, 400 W/m^2 is equivalent to 17°C and 1000 W/m^2 is equivalent to 91°C.

For 18th August 2012, figure 3 shows the short (DSSF) and long (DSLF) wave radiation retrievals over Europe from SEVIRI, along with the Land Surface Temperature (LST) for 12 h GMT on 18th August. A reduction in sunlight on the DSSF map can be seen towards the east as it is later in the afternoon in that area than in western Europe. The DSLF retrieval shows a distinctively cooler atmosphere over the Alps than in western France or northern Italy. Spatial variations of LST can also be observed. Figure 4 shows the two albedo retrievals, the white-sky albedo (BH) having slightly higher values than the black-sky albedo (DH). The approach for operational albedo retrieval consists of a decomposition of the bi-directional reflectance factor into several geometric kernel functions associated to the dominant light scattering processes[4]. Figure 5 illustrates the derivation of turbidity τ from DSSF and albedo which results in the down-welling direct Solar radiation S_b map; a map of the shape factor A_h/A used to calculate mean direct Solar radiation on the body is also shown. As can be expected under clear sky conditions, most of the DSSF is direct Solar radiation. Finally, figure 6 maps the total short-wave radiation S_{tot} and total long-wave radiation L_{tot} on man and the sum of these that provides the measure of Mean Radiant Temperature (MRT) for man. It can be seen that most of the contribution to MRT is from long-wave radiation even though DSLF values are much smaller than DSSF during the day-time. This is because the shape factor reduces the contribution of direct Solar radiation by a factor of up to 30, while the contribution from diffuse terms (diffuse Solar radiation, DSLF and LST) remain unaffected.

Figures 7 to 10 offer the same illustration of SEVIRI retrievals and derived data for night-time (3 h GMT) 7th September 2012. Of note dawn sunlight can be seen at the very east of the DSSF map (figure 7): consequently, turbidity is only computed where there is sunlight and the shape factor only takes values where the Sun is risen (figure 9). Snow

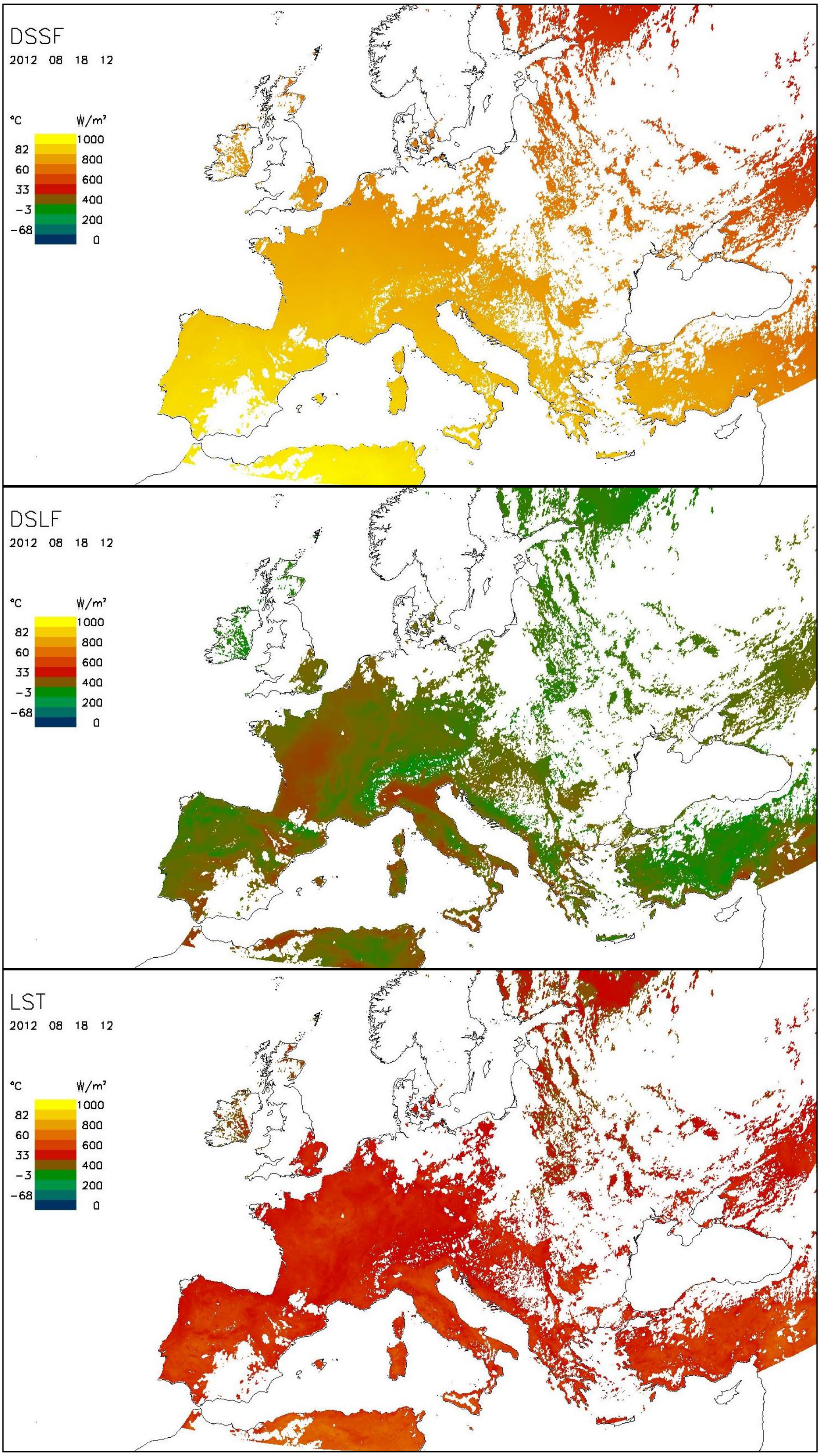

Figure 3. Down-welling short-wave DSSF and long-wave DSLF radiation retrievals and Land Surface Temperature (LST) retrieval over Europe from SEVIRI for 12 h GMT on 18th August 2012.

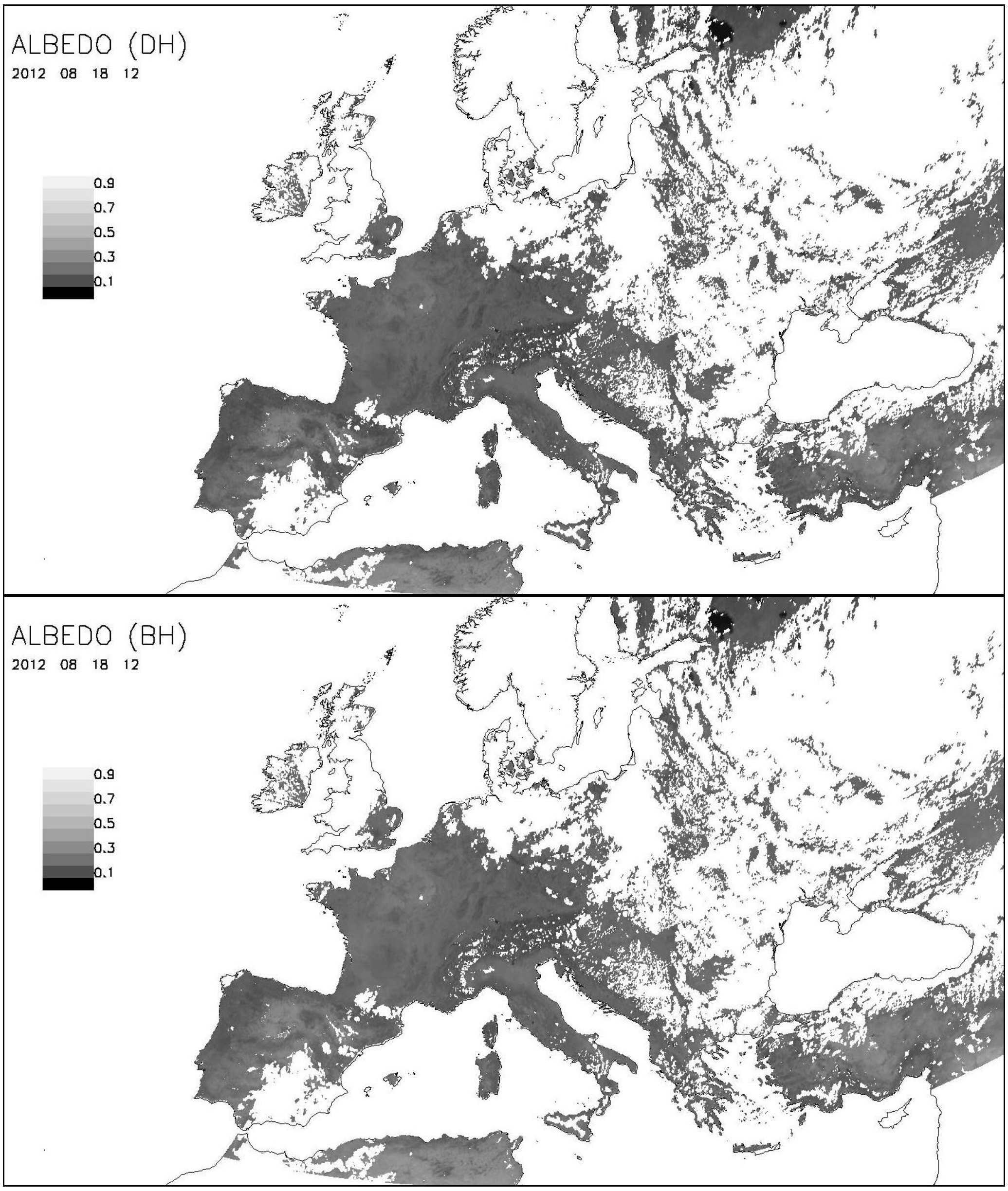

Figure 4. Directional-Hemispherical (DH) and Bi-Hemispherical (BH) albedo retrievals over Europe from SEVIRI for 12 h GMT on 18th August 2012.

on the Alps can be seen from the albedo maps of figure 8. The LST remains relatively high all along the Mediterranean, Adriatic and Aegean coasts, and combined with the dawn in the east, the resulting MRT is relatively high along the coast and where there is sunlight (figure 10).

5. Recommendations

There are a number of ways the work described here can be improved upon and used. In terms of improvements, two items that have already been described in this report are:

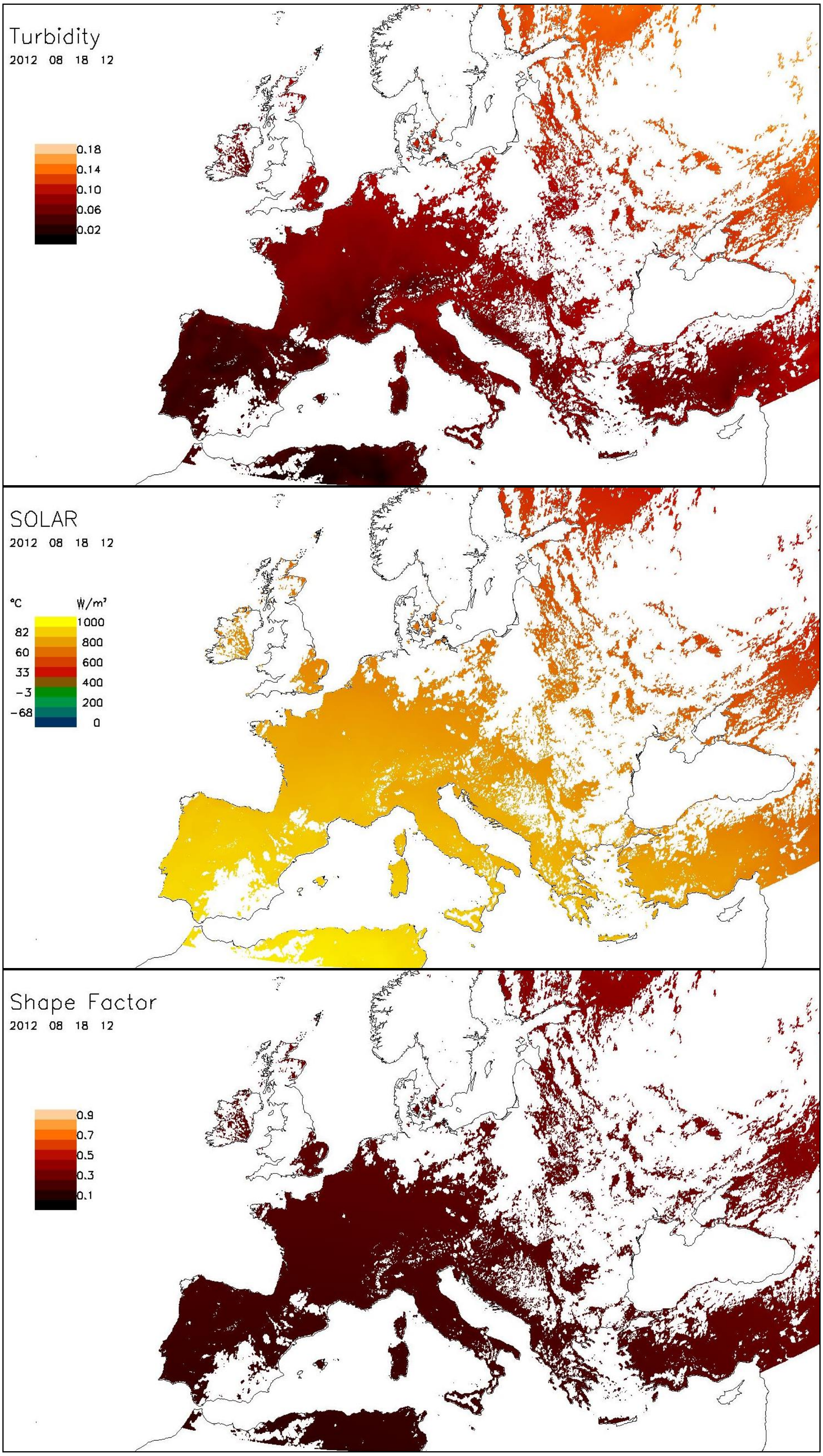

Figure 5. Turbidity and direct Solar radiation derived from DSSF, and shape factor, over Europe for 12 h GMT on 18th August 2012.

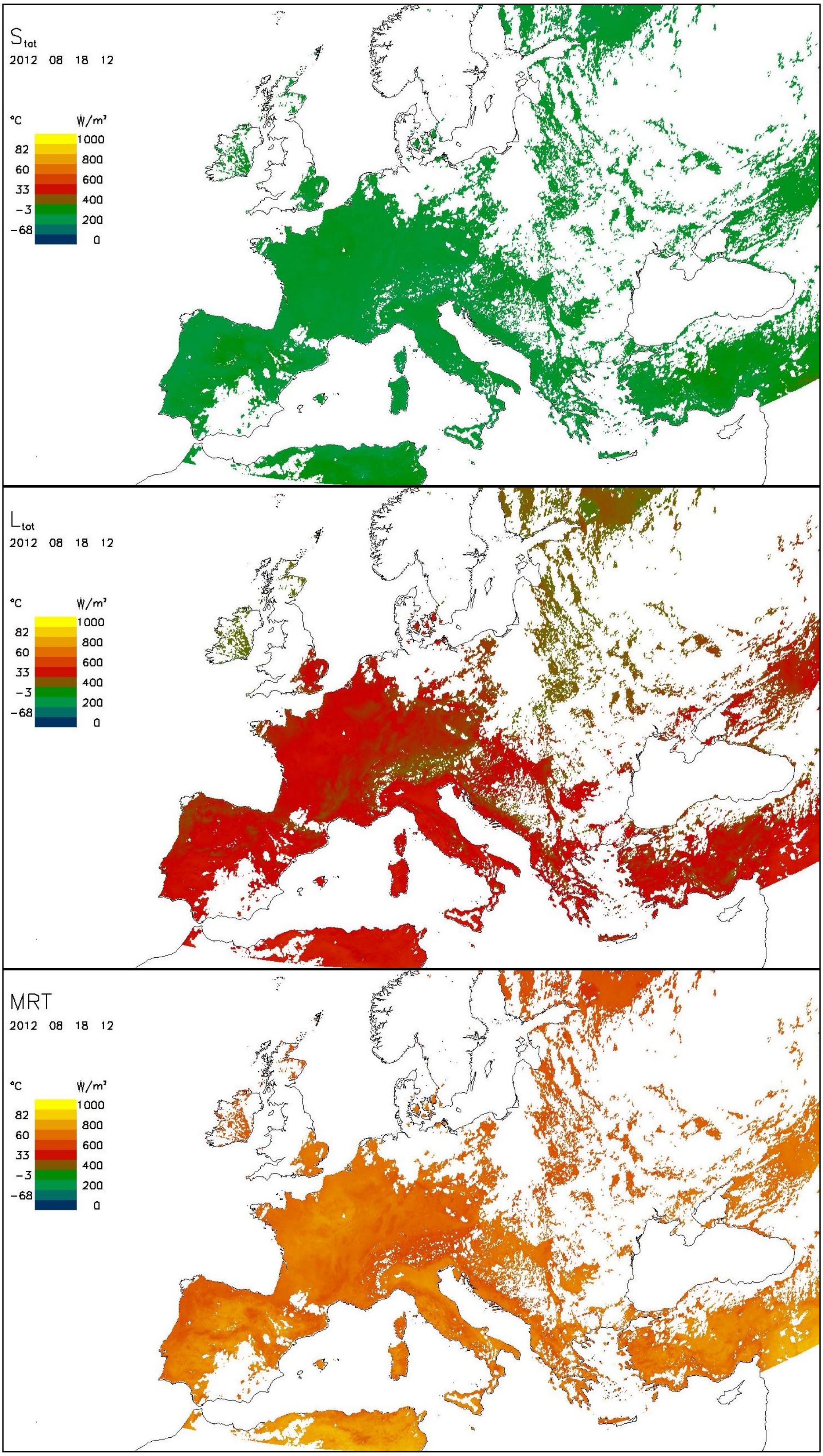

Figure 6. Total short-wave and long-wave radiation on man and Mean Radiant Temperature (MRT) for man derived from SEVIRI retrievals over Europe for 12 h GMT on 18th August 2012.

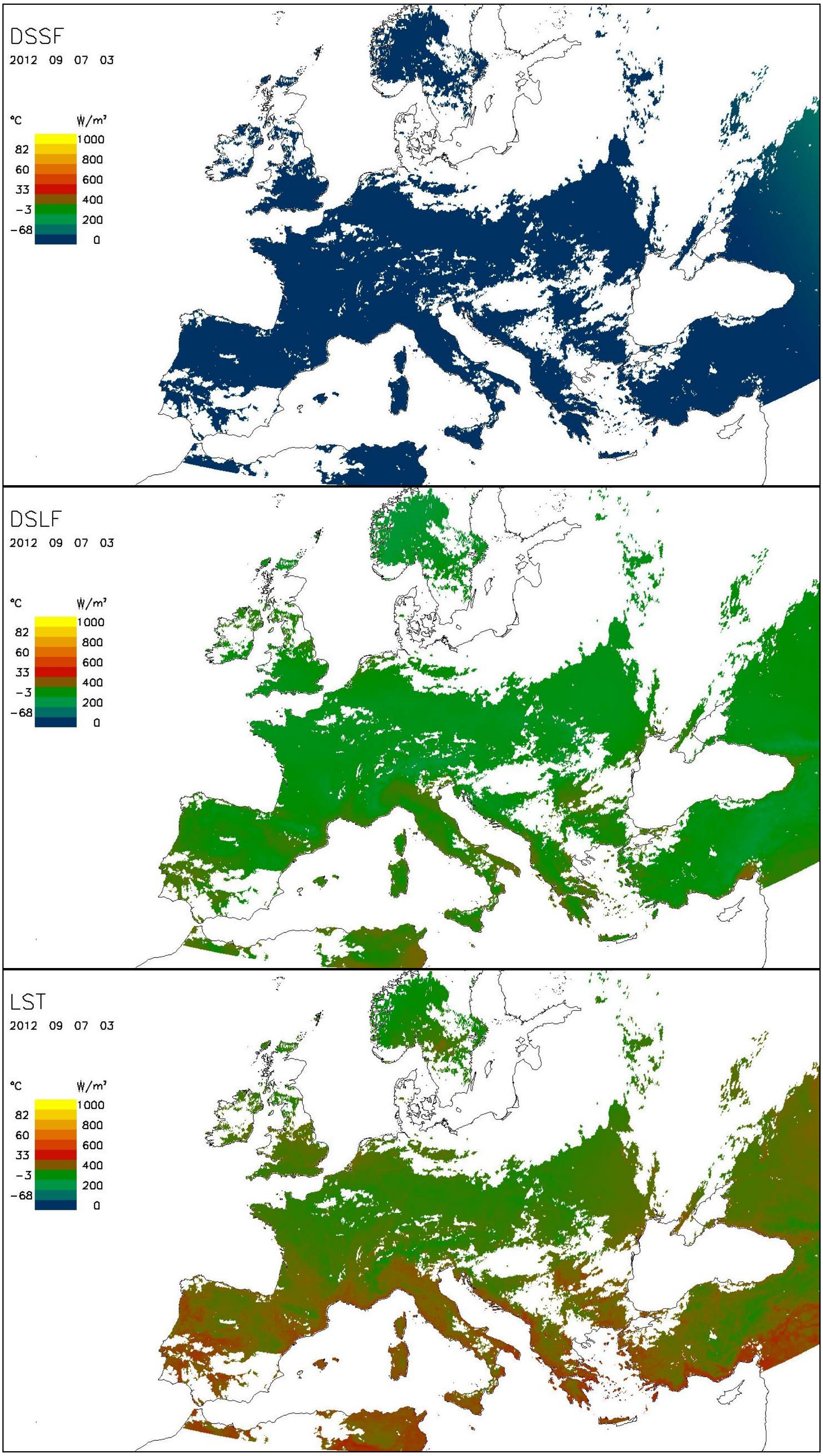

Figure 7. Down-welling short-wave DSSF and long-wave DSLF radiation retrievals and Land Surface Temperature (LST) retrieval over Europe from SEVIRI for 3 h GMT on 7th September 2012.

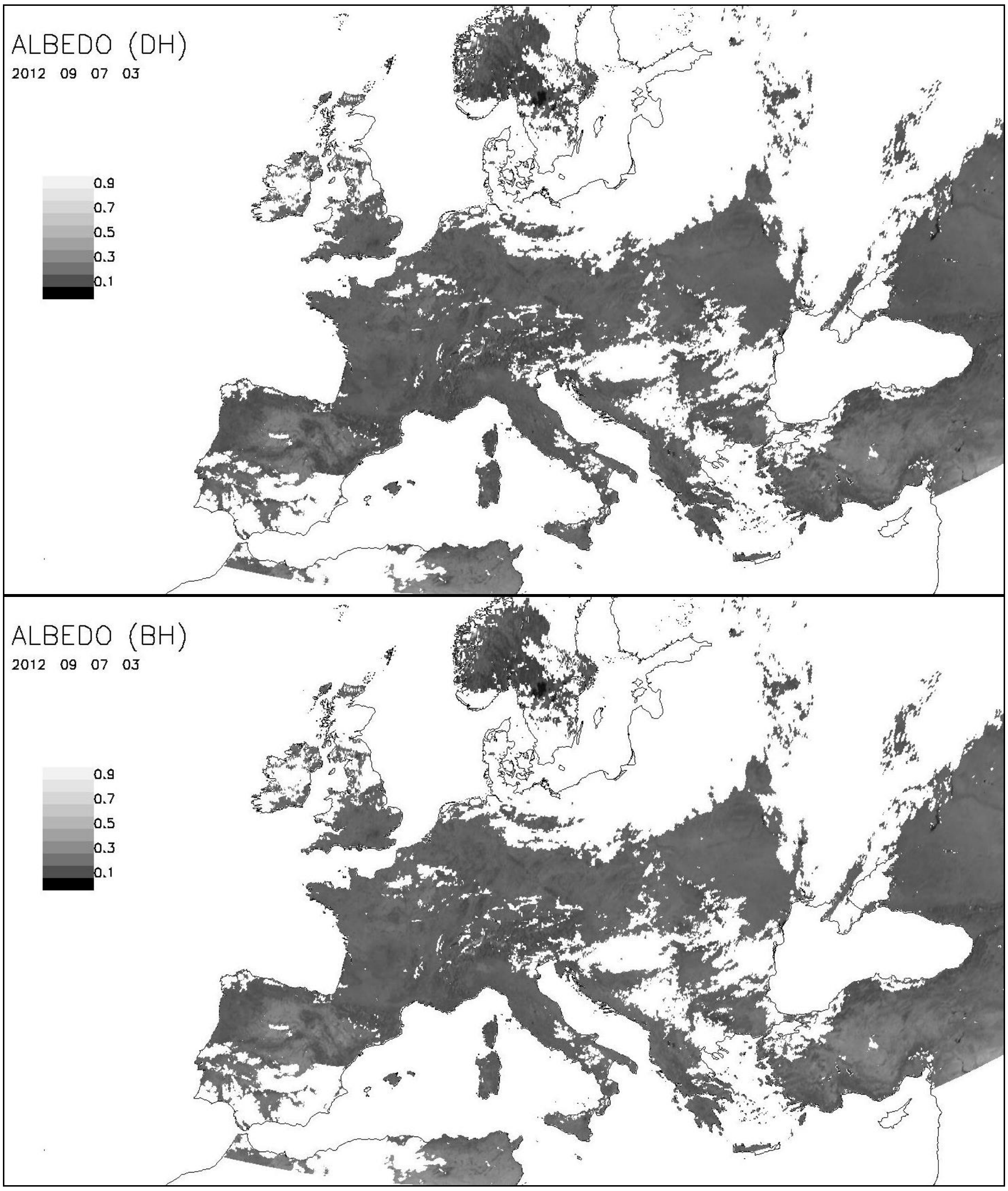

Figure 8. Directional-Hemispherical (DH) and Bi-Hemispherical (BH) albedo retrievals over Europe from SEVIRI for 3 h GMT on 7th September 2012.

- improvement to the derivation of the turbidity τ by a further understanding of how it relates to the DSSF, the maximum available sunlight and the different albedo parameters;
- use of an emissivity ε derived from the Fraction of Vegetation Cover (FVC) retrieval using existing soil and vegetation emissivity maps, to correctly calculate the long-wave radiation contribution from Land Surface Temperature (LST).

Currently, the Mean Radiant Temperature (MRT) for man is available as a near-real time satellite monitoring product over Europe, restricted to clear sky conditions. To take this work forward:

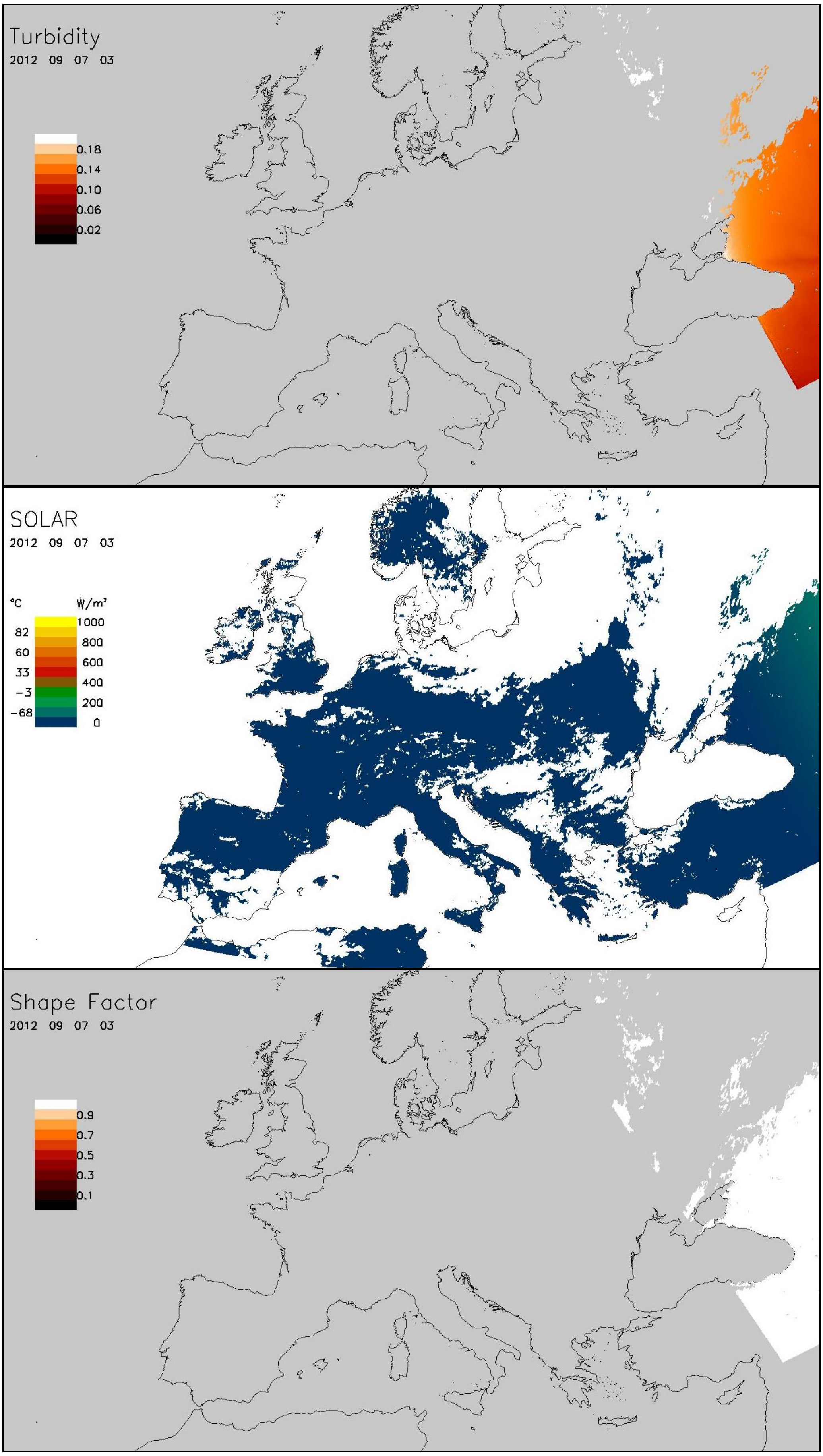

Figure 9. Turbidity and direct Solar radiation derived from DSSF, and shape factor, over Europe for 3 h GMT on 7th September 2012.

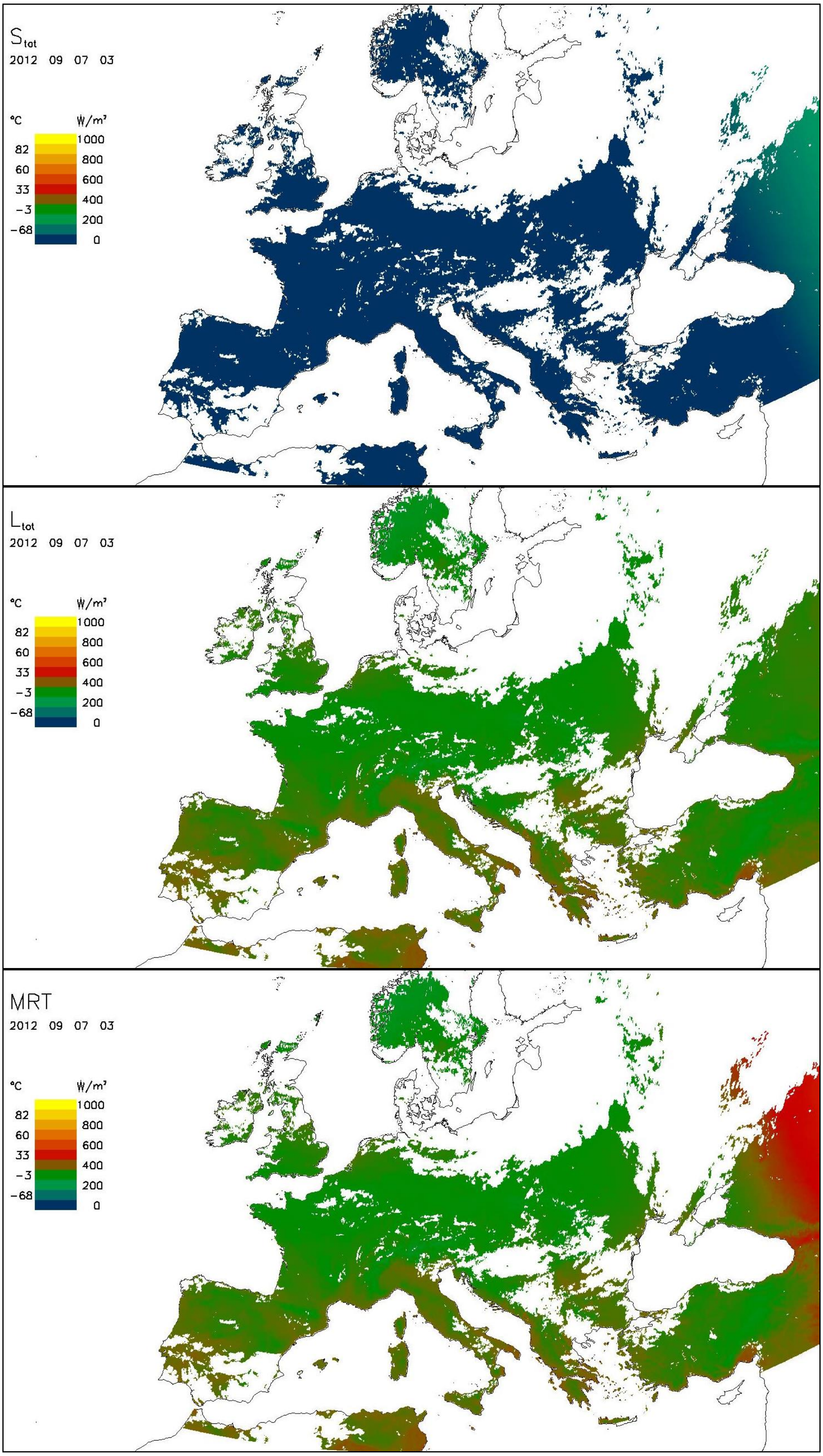

Figure 10. Total short-wave and long-wave radiation on man and Mean Radiant Temperature (MRT) for man derived from SEVIRI retrievals over Europe for 3 h GMT on 7th September 2012.

(A) Due to the geostationary position of the MSG satellite, good quality SEVIRI retrievals are available over Africa and an MRT monitoring product for Africa could be particularly useful for heat stress assessments. This could be provided if relevant stakeholders express an interest.

(B) To remove the restriction to clear sky areas, the MRT could be calculated from nowcast and forecast model fields. As long as the relevant fields (short-wave and long-wave radiation, cloud cover, ground temperature, emissivity and albedo) are available, the derivation of MRT from model data would also enable the further derivation of heat stress indices (UTCI, WBGT, etc.) using other fields available from models such as air temperature, humidity and wind speed that are not obtainable from satellite retrievals. Furthermore, the use of forecast models could provide critical heat stress information in advance of heat wave and cold weather conditions.

(C) The daily mapping of isochrones of heat stress could provide useful information to stakeholders, i.e. information that would be acted upon to mitigate the impact of particularly hot or cold weather.

[1] Fiala, D., Havenith, G., Brode, P., Kampmann, B., and Jendritzky, G., 2012: UTCI-Fiala multi-node model of human heat transfer and temperature regulation. *International Journal of Biometeorology*, **56**, 429-441.
[2] Parsons, K.C., 2003: Human thermal environments. London, Taylor and Francis.
[3] Montieth, J.L., and Unsworth, M.H., 1990: Principles of environmental physics. London, Edward Arnold.
[4] LSA SAF, 2012: Product user manual (PUM) – land surface albedo. Lisboa, LSA SAF. http://landsaf.meteo.pt/GetDocument.do?id=465 (accessed 11-9-2012) Reference Number: SAF/LAND/MF/PUM_Al/1.6v2
[5] LSA SAF, 2011: Product user manual – down-welling surface shortwave flux (DSSF). Lisboa, LSA SAF. http://landsaf.meteo.pt/GetDocument.do?id=449 (accessed 10-9-2012) Reference Number: SAF/LAND/MF/PUM_DSSF/2.6v2
[6] Briegleb, B.P., Minnis, P., Ramanathan, V., and Harrison, E., 1986: Comparison of regional clear-sky albedos inferred from satellite observations and model computations. *Journal of Climate and Applied Meteorology*, **25**, 214-226.
[7] Frouin, R., Lingner, D.W., Gautier, C., Baker, K.S., and Smith, R.C., 1989: A simple analytical formula to compute clear sky total and photosynthetically available Solar irradiance at the ocean surface. *Journal of Geophysical Research*, **94**, 9731-9742.
[8] Caselles, V., Valor, E., Coll, C., and Rubio, E., 1997: Thermal band selection for the PRISM instrument – 1. analysis of emissivity-temperature separation algorithms. *Journal of Geophysical Research*, **102**, 11145-11164.
[9] LSA SAF, 2010: Product user manual – land surface temperature (LST). Lisboa, LSA SAF. http://landsaf.meteo.pt/GetDocument.do?id=304 (accessed 12-9-2012) Reference Number: SAF/LAND/IM/PUM_LST/2.5

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