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Review on estimation methods of the Earth's surface energy balance components from ground and satellite measurements

MD MASUDUR RAHMAN[1,2] and WANCHANG ZHANG[1,*]

[1]*Key Laboratory of Digital Earth Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing 100 094, People's Republic of China.*
[2]*University of Chinese Academy of Sciences, Beijing 100 049, People's Republic of China.*
*Corresponding author. e-mail: zhangwc@radi.ac.cn

Accurate estimation of the Earth's surface energy balance (SEB) components is very much important for characterising the environmental, hydrological and bio-geophysical processes to predict the weather and climate or climate change. This narrative review summarises the basic theories of estimation methods of the solar (shortwave) radiation, thermal (longwave) radiation and evapotranspiration (latent heat flux) from both the ground and satellite measurements, which are inherently complex to measure at large scale. This paper discusses the reviews of prior and recent advances in the estimation methods and models by focusing their advantages, disadvantages and recommendations. Uncertainties associated with satellite estimations and some key directions for further studies are also discussed, including the status of ground-based measurements at regional and global scales and the advent of new satellite technologies for quantifying the SEB components more accurately. This study infers that the further advances in the satellite remote sensing and worldwide ground-based measurement networks will enhance the capabilities for the potential estimation of the SEB parameters as well as monitoring the global water and energy cycles to develop significant environmental studies for the betterment of living on the Earth.

Keywords. The Earth's surface; energy balance; solar radiation; thermal radiation; evapotranspiration; estimation methods.

1. Introduction

Sun is the primary source of energy on Earth. The incoming solar radiation is distributed in different components due to the scattering, reflecting, transmitting and absorbing characteristics of the Earth's surface and atmosphere. The net radiation is partitioned into sensible heat flux, latent heat flux and soil heat flux i.e. known as the surface energy balance (SEB) which is extremely vital to any land surface models for developing the hydrological, ecological and bio-geophysical processes. The very basic equation of SEB can be expressed as

$$R_\mathrm{n} = G + H + \mathrm{LE}, \tag{1}$$

where R_n is the net radiation in W m^{-2}, G is the soil heat flux, H is the sensible heat flux and LE is the latent heat flux. The land surface radiation budgets, i.e., the Earth's SEB between the incoming radiation in both short and longwave spectra

are characterised by the net radiation (R_n) which can be expressed as

$$R_\mathrm{n} = R_\mathrm{n}^\mathrm{s} + R_\mathrm{n}^\mathrm{l}, \tag{2}$$

$$R_\mathrm{n}^\mathrm{s} = (1 - \alpha) R^\mathrm{s}\!\downarrow, \tag{3}$$

$$R_\mathrm{n}^\mathrm{l} = \varepsilon R^\mathrm{l}\!\downarrow - \varepsilon\sigma T_\mathrm{s}^4, \tag{4}$$

where $R^\mathrm{s}\!\downarrow$ and $R^\mathrm{l}\!\downarrow$ are the incoming radiation of both shortwave (solar) and longwave (thermal) spectra, respectively, α is the albedo (unit less), ε is the atmospheric emissivity (unit less), T_s is the surface temperature (K) and σ is the Stefan–Boltzmann constant (W m^{-2} K^{-4}). Now the sensible heat flux (H) and latent heat flux (LE) can be written in the following equations:

$$H = \rho\, C_p\, \frac{\mathrm{d}T}{r_\mathrm{ah}}, \tag{5}$$

$$\mathrm{LE} = R_\mathrm{n} - G - H, \tag{6}$$

where ρ is the air density (kg m^{-3}), C_p is the air specific heat (J kg^{-1} K^{-1}), dT is the temperature difference between air and surface (K) and r_ah is the aerodynamic resistance (s m^{-1}). The above said components of Earth's SEB are responsible for heating or cooling of the land/soil (solar and thermal radiation), the heating and cooling of the air (sensible heat flux) and the evaporation of water from soil and vegetation (latent heat flux). Figure 1 shows an illustration of the Earth's surface radiation and energy flow among the space, atmosphere and Earth's surface.

Figure 1 shows that the incoming solar radiation is reflected and absorbed by the clouds, atmosphere and Earth's surface after that the cloud, atmosphere and Earth's surface emit the thermal radiation along with the other turbulent (soil, sensible and latent heat) fluxes. The net absorbed radiation plays a vital role in the environmental analysis and it should be zero, if not then heating effect for positive value and cooling for negative. To illustrate the energy flows at a global and local view, there were a lot of iconic diagrams that have been presented in the published articles and textbooks (Wild *et al.* 2009; Stephens and L'Ecuyer 2013; L'ecuyer *et al.* 2015) based on the conceptual background and several satellite and ground measurements. Trenberth *et al.* (2009) revealed the measurement of mean Earth's energy budget by a satellite sensor the Clouds and the Earth's Radiant Energy System

(CERES) for the March 2000 to May 2004 period and found that the net absorbed radiation was 0.9 W m^{-2}, which simply infers today's global warming issues.

Nowadays, there are more frequent weather anomalies as a consequence of global warming. Due to the interlinked systems, changes in single aspect of global process reverberate through the entire system, e.g., increasing surface temperatures modify the rainfall patterns and evaporation rates, which may lead to floods, droughts and storms, and hurricanes may intense due to the increase in sea surface temperatures. This is the common scenario over several parts of the world and has become an important research question. The study of energy flows between the Earth's surface, the atmosphere and space is of great importance for different types of environmental analysis (Krishnamurti and Biswas 2006; Wang and Liang 2008; Yingying *et al.* 2008; Xie *et al.* 2016), including climate change, disaster monitoring, plant water demand, plant growth, productivity, the irrigation management system and also in determining the large-scale atmosphere and ocean circulation patterns which eventually drive weather and climate (Slingo and Slingo 1988; Hartmann 1994; Lee *et al.* 2001; Schumacher *et al.* 2004; Bonan 2008). Therefore, we can feel that the effective estimation of land surface radiation and energy components is factually necessary for the Earth and environmental analysis to predict the weather and climate or climate change. However, the estimation of these components is very complex in nature due to the diverse characteristics of the atmosphere and Earth's surface.

To the best of our knowledge, the number of published review articles related to this review work is limited but the existing papers have presented very good and critical review works (Diak *et al.* 2004; Li *et al.* 2009; Liang *et al.* 2010; Nouri *et al.* 2013; Liou and Kar 2014; Shi *et al.* 2015; Zhang *et al.* 2016, etc.), which are reflecting the excellent state of art in the estimation techniques of surface energy fluxes. They reviewed the estimation methods of surface flux components in terms of history, measurement methods, merits and demerits of the methods and also focused on some experimental results. Most of the studies focused on one component such as evapotranspiration (ET, latent heat flux) based on the satellite estimation techniques, whereas we focus on the three important components (solar radiation, thermal radiation and ET)
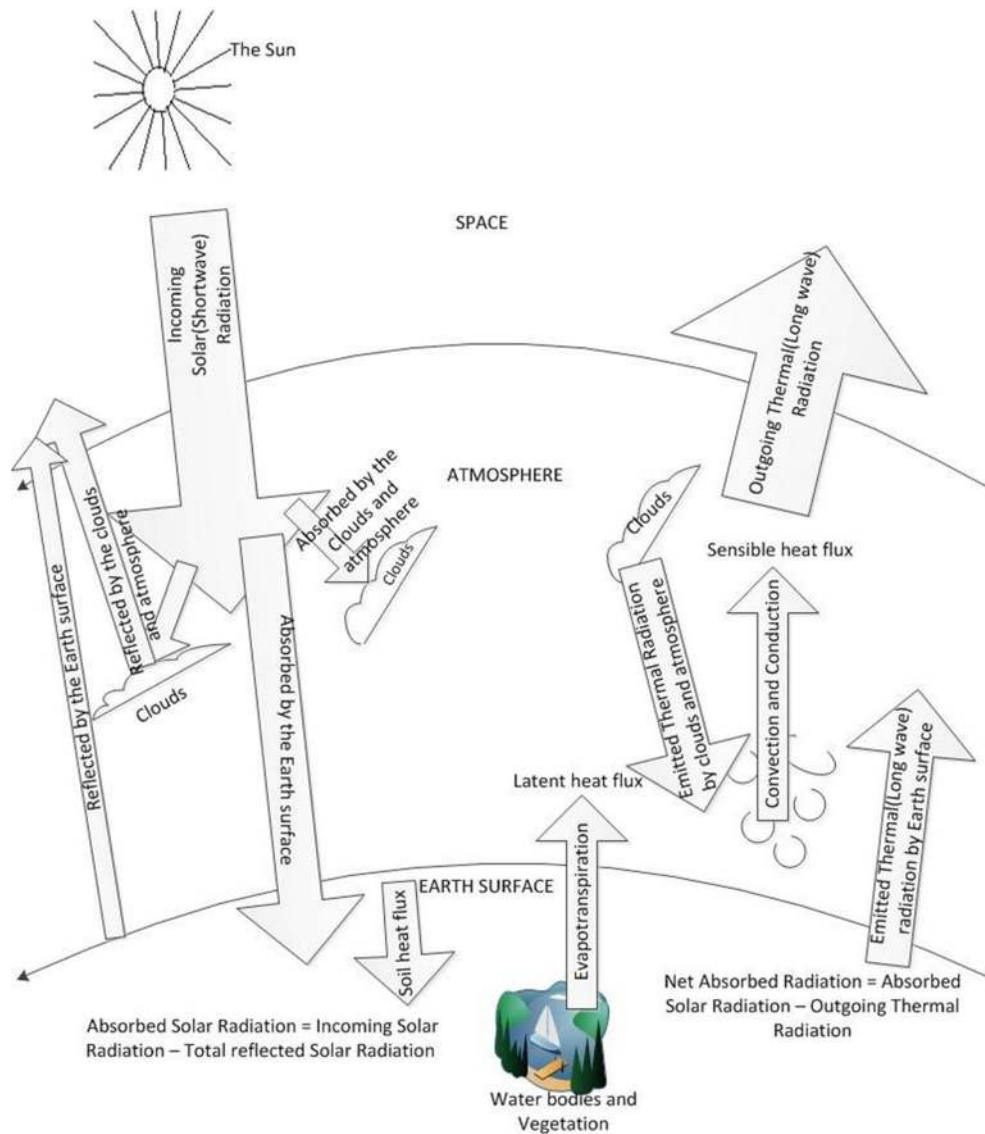
Figure 1. The conceptual diagram of the Earth's SEB phenomena among the space, atmosphere and the Earth's surface.

based on both the ground and satellite estimation techniques. The SEB has four main components as shown in equation (1), the net radiation (R_n) is the combined calculation of solar (shortwave) and thermal (longwave) radiation, the sensible (H) and latent (LE) heat fluxes are the results of atmospheric turbulences and soil/ground heat flux (G) which can be calculated as the function of net radiation, soil and vegetation characteristics (Bastiaanssen *et al.* 1998a, b). So, the estimation of net radiation using the solar and thermal radiations and estimation of any other heat flux using energy balance approach will have to go through the indirect estimation of all SEB components. As the energy balance is not closed (Foken 2008), therefore indirect estimation of a SEB component may lead to errors and uncertainties. Hence, the

individual estimation of sensible heat flux (H) and soil heat flux (G) can be studied further.

This study explains the fundamental and advanced estimation techniques of SEB components in more concise words and equations when compared with other reviews. However, an important purpose of this paper is to provide an overall idea to a reader, who is not specialist in this field. The meanings of all used symbols in this study are indicated in table 1 for quick reference. Along with the main concepts, advantages, disadvantages and uncertainties, we make some recommendations to the readers/researchers, where one can apply these methods. This paper aims to review the recent development in the estimation methods and models of three basic components of the Earth's SEB such as solar radiation, thermal radiation and the

Table 1. *The used symbols and their respective meanings.*

Symbols	Meanings
α	Surface albedo
γ	Psychrometric constant
ε	Atmospheric emissivity
Δ	Slope of saturated vapour pressure
ΔT	Vertical difference of temperature
Δq	Vertical difference of water vapour concentration
Δz	Vertical distance between two measurement points
λ	Latent heat of evaporation/vapourisation
ρ	Density of air
ρ_{dry}	Density of dry air
ρ_v	Density of water vapour
$\acute{\rho}_v$	Fluctuation in water vapour density
ρ_{wet}	Density of wet/moist air
σ	Stefan–Boltzmann constant
B	Bowen ratio
C_n^2	Refractive index fluctuation of air
C_p	Specific heat of air at constant pressure
DEM	Digital elevation model
$\mathrm{d}T$	Temperature difference between air and surface (temperature gradient)
e	Actual vapour pressure
e_{sat}	Saturated vapour pressure
E_{in}	Received radiation at the pyrgeometer/sensor surface
E_{m}	Measured radiation at the pyrgeometer/sensor surface
E_{out}	Emitted radiation at the pyrgeometer/sensor surface
EF	Evaporative fraction
$\mathrm{EF_r}$	Relative evaporative fraction
ET	Evapotranspiration
$\mathrm{ET_a}$	Actual evapotranspiration
$\mathrm{ET_{dry}}$	Evapotranspiration at dry reference pixel
$\mathrm{ET_r}$	Reference evapotranspiration
$\mathrm{ET_{wet}}$	Evapotranspiration at wet reference pixel
f_{c}	Fractional vegetation cover
G	Ground/soil heat flux
H	Sensible heat flux
H_{c}	Canopy sensible heat flux
H_{dry}	Sensible heat flux at dry reference pixel
H_{s}	Soil sensible heat flux
H_{wet}	Sensible heat flux at wet reference pixel
K_H	Coefficient of sensible heat transfer
K_V	Coefficient of latent heat transfer
L_{A}	Leaf area index
LE	Latent heat flux
$\mathrm{LE_{dry}}$	Latent heat flux at dry reference pixel
$\mathrm{LE_{wet}}$	Latent heat flux at wet reference pixel
NDVI	Normalised vegetation index
P	Atmospheric pressure
$R^{\mathrm{l}}\downarrow$	Incoming longwave radiation
$R^{\mathrm{l}}\uparrow$	Outgoing longwave radiation
R_{n}	Net radiation
$R_{\mathrm{n}}^{\mathrm{l}}$	Net longwave radiation
$R_{\mathrm{n}}^{\mathrm{s}}$	Net shortwave radiation
$R^{\mathrm{s}}\downarrow$	Incoming shortwave radiation

Table 1. *(Continued.)*

Symbols	Meanings
$R^{\mathrm{s}}\uparrow$	Outgoing shortwave radiation
r_{ah}	Aerodynamic resistance
$r_{\mathrm{ah\_c}}$	Canopy aerodynamic resistance
$r_{\mathrm{ah\_dry}}$	Aerodynamic resistance at dry reference pixel
$r_{\mathrm{ah\_wet}}$	Aerodynamic resistance at wet reference pixel
$r_{\mathrm{ah\_s}}$	Soil aerodynamic resistance
S	Sensitivity/calibration factor of instrument
T	Absolute temperature of pyrgeometer/sensor detector
$\acute{T}$	Fluctuation in air temperature
T_{a}	Air temperature
T_{c}	Canopy temperature
T_{H}	Maximum surface temperature in dry condition
T_{LE}	Minimum surface temperature in wet condition
T_{rad}	Directional radiometric surface temperature
T_{s}	Surface temperature/also used as soil temperature
$T_{\mathrm{s\ DEM}}$	Surface temperature adjusted to a standard elevation per pixel of the satellite image
$\acute{U}$	Fluctuation in vertical wind speed
V_{emf}	Output voltage of the pyrgeometer/sensor thermopile

ET, i.e., latent heat flux from satellite and ground measurements to achieve the present status and future directions in the study area.

2. Solar (shortwave) radiation

The solar radiation is the only significant energy source on the Earth that is transformed into various energy fluxes after entering into the atmosphere and Earth's surface. Basically, solar radiation has two acting parts: one is incoming (downward $R^{\mathrm{s}}\downarrow$) radiation on Earth's surface that depends on the atmospheric transmitivity, solar constant, solar altitude and incidence angle, and another part is outgoing (upward $R^{\mathrm{s}}\uparrow$) that is reflected back to space due to the combined effect of surface, clouds, aerosol, gases, etc. It is a measure of radiation received on a given area in a given time, usually indicated as the average irradiance in watts per square metre (W m^{-2}) that engenders in visible (VIS) and near-infrared (NIR) spectra (wavelength of 300–4000 nm).

2.1 *Ground measurement of solar radiation*

The basic science of solar irradiance is the detection of the optical electromagnetic radiation that is converted into electric signals, which can be measured by conventional techniques. There are two types of instruments available for measuring solar radiation such as pyrheliometer for direct irradiance and pyranometer for both direct and diffuse irradiances (Paulescu *et al.* 2013). The pyrheliometer is a broadband instrument that measures the direct beam of solar radiation. The pyranometer is a type of actinometer for measuring solar radiation (direct and diffuse) incoming from a 2π ($360°$) solid angle on a planar surface as shown in figure 2. These instruments are classified with respect to their quality by the International Standard ISO 9060/1990 that is also adopted by the World Meteorological Organization (WMO) (Guide to Meteorological Instruments and Methods of Observation, Seventh Edition 2008).

However, there are some worldwide and regional ground measurement networks for measuring the surface flux components as briefly described here. The WMO started the measurement of solar radiation from 1964 along with other components for surface radiation energy balance. The World Radiation Data Center (WRDC) is located at the Central Geophysical Observatory in St. Petersburg, Russia inside WMO that collects data from the large network with more than 1000 stations for monitoring solar radiation (Main Geophysical Observatory, World Radiation Data Center, St. Petersburg, Russia). The Baseline Surface Radiation Network (BSRN) (Ohmura *et al.* 1998) is a project under the umbrella of the World Climate Research Program (WCRP) (World Climate Research Programme n.d.) (n.d. stands for no date or year of publication, i.e., the citation is only
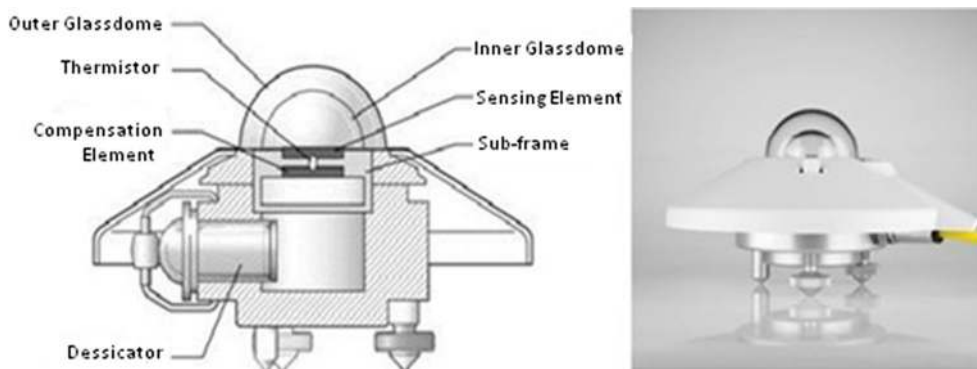
Figure 2. The schematic diagram (left) and photograph (right) of pyranometer (Solar Instruments/Atmospheric Science Instruments n.d.).

available on website/Internet) as a part of Global Energy and Water Cycle Exchange (GEWEX) (Global Energy and Water Cycle Exchange n.d.) for land surface radiation measurement with a small number of stations (currently 59 as of December 2016) covering a latitude range from 80°N to 90°S (Baseline surface radiation network n.d.). The Global Energy Balance Archive (GEBA) is a database established in 1985 at ETH Zurich for measuring the monthly means of surface energy fluxes (Gilgen and Ohmura 1999). The Surface Radiation Budget Network (SURFRAD) is a nation-wide network of US National Oceanic and Atmospheric Administration (NOAA) (Surface Radiation (SURFRAD) Network n.d.) to measure the surface radiation budgets over the United States since 1993 (Augustine *et al.* 2005). FLUXNET (Baldocchi *et al.* 2001) is a set of regional networks that coordinate regional and global analysis to measure the exchange of carbon dioxide (CO_2), water vapour and energy between terrestrial ecosystems and the atmosphere based on eddy-covariance method with 683 (as of April 2016) sites (FLUXNET A Global Network n.d.) over seven regions (AmeriFlux, CarboEurope, KoFlux, OzFlux, Fluxnet-Canada, AsiaFlux and ChinaFlux). Some other regional networks also exist and these networks have a set of stations to cover a desired area but the matter is that how much areas are covered and how these stations are distributed, i.e., the optimum distance between two stations. Cros and Wald (2003) showed that a station can cover an area of ∼30 km. Most of the measuring projects are using the Kipp and Zonen or Eppley or Hukseflux standard instruments to ensure the quality data collection.

2.2 *Satellite estimates of solar radiation*

Satellite remote sensing techniques are the only effective way to estimate the components of land SEB at both regional and global scales in contrast to the limited ground-based estimations. There has been a firm advancement in estimating the Earth's radiation budget since the first meteorological satellite was launched in the 1960s. Basically, these types of satellites measure the radiation of different wavelengths in the electromagnetic spectrum, i.e., collect images of different spectrum such as VIS, NIR, thermal infrared (TIR) and microwave range as radiation is the form of energy that can be transmitted without any material medium. However, the general procedure of satellite estimates of the Earth's SEB components is outlined in figure 3, which shows that we still need some ground measurement. The meteorological and solar radiation data are used for deriving some models and the surface energy components for accuracy measurements. Researchers are following the above illustrated procedure for estimating the surface fluxes and trying to use less ground data for deriving their methods/models to achieve the high accuracy with respect to ground measurements.

2.2.1 *Satellite sensors*

Various broadband radiometric sensors are on board in multiple satellite spacecrafts – the Earth Radiation Budget (ERB) sensor on Nimbus-7 (Jacobowitz and Tighe 1984); the Earth Radiation Budget Experiment (ERBE) sensor on three satellites which are NOAA-F, NOAA-G and another one with 57° inclination orbit which travels around the Earth once every 2 months (Barkstrom and
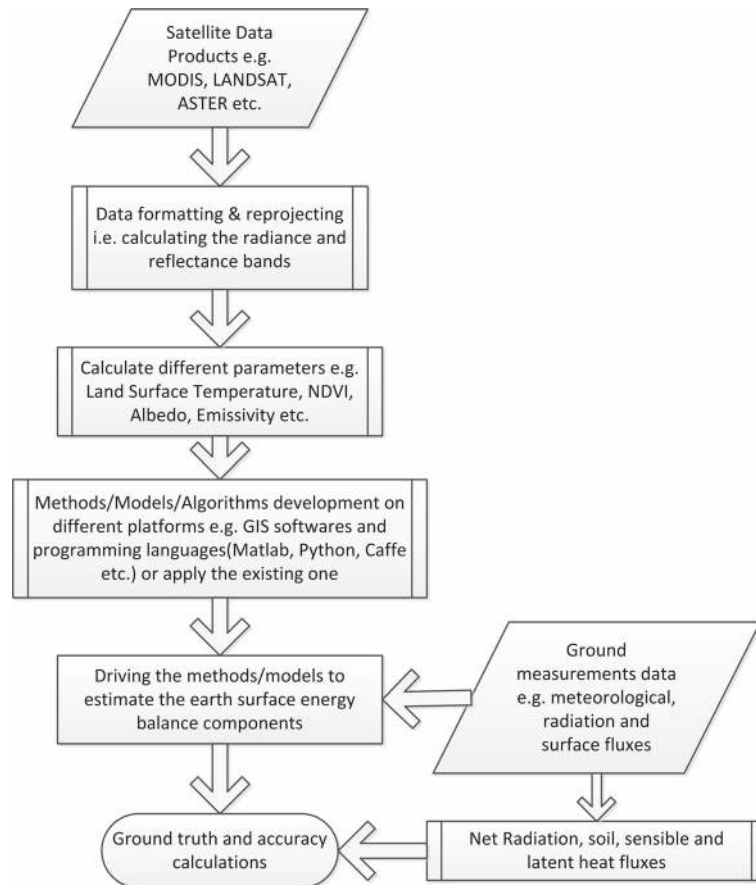
Figure 3. The flow chart of generalised estimation procedure of the Earth's SEB components from satellite measurements.

Smith 1986); the Clouds and the Earth's Radiant Energy System (CERES) (The Clouds and the Earth's Radiant Energy System n.d.) sensor which was 1st launched on Tropical Rainfall Measurement Mission (TRMM) in 1997 including European Space Agency's (EOS) Terra, Aqua and recently the Suomi National Polar Orbiting Partnership (S-NPP) (Soumi NPP n.d.); the Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) on Terra in 1999 (The Advanced Space-borne Thermal Emission and Reflection Radiometer n.d.) and the Geostationary Earth Radiation Budget (GERB) sensor on Meteosat-8 and Meteosat-9 launched in 2002 and 2007, respectively (Harries *et al.* 2005). There are also some sensors to produce surface radiation on both geostationary and orbiting satellites such as the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on Meteosat Second Generation (MSG) satellite (Schmetz *et al.* 2002); the Advanced Baseline Imager (ABI) sensor on Geostationary Operational Environmental Satellite (GOES) (The Geostationary Operational Environmental Satellite-Advanced Baseline Imager (ABI) n.d.) and

Moderate Resolution Imaging Spectro radiometer (MODIS) on Terra in 1999 and Aqua in 2002 (MODIS n.d.). In the case of data accumulation, the calibration of satellite instruments is mostly important but some missions did not have on-board calibration devices, which makes the data processing more complicated and another problem is the time gap like eight years between EREB and CERES. The meteorological satellites are able to collect the high temporal resolution (hourly) images over a large area, which are then further processed and compared with ground measurements to extract the desired information. It can derive the hourly irradiation most accurately at locations that are further 25 km away from a ground station (Zelenka *et al.* 1988).

2.2.2 *Estimation methods*

There are numerous methods for retrieving solar radiation from satellite signals. The development of these methods is still on going. At this stage, we can roughly classify these methods into three categories. First, the look-up-table (LUT) method

is a data structure that is developed based on the radiative transfer process (Liang *et al.* 2006; Lu *et al.* 2010; Huang *et al.* 2011). This method is extensively used to achieve high accuracy even it has some drawbacks such as computationally not economical and used in limited channel data. Second, the parameterisation methods that estimate solar radiation by establishing a model, i.e., the process of developing parametric equations with several parameters such as cloud, aerosol, gas and other atmospheric and surface variables (Kim and Ramanathan 2008; Wang and Pinker 2009; Lichun *et al.* 2015). Sometimes it is hard to keep the temporal resolution high due to the changing tendencies of some input parameters (e.g., cloud parameters). Third, the statistical method which is developed based on the statistical process and artificial neural network (ANN) that directly link the satellite observed signals to estimate solar radiation at regional scale (Lu *et al.* 2011; Hena *et al.* 2013). The most common disadvantage of these methods is the lack of generalisation. However, many researchers utilised the combination of the above stated methods (Rigollier *et al.* 2004; Kawai and Kawamura 2005; Yeom and Han 2010; Wang *et al.* 2014), which is known as the hybrid method. The summary of the above stated methods is listed in table 2.

3. Thermal (longwave) radiation

Longwave radiation is the electromagnetic radiation that is being emitted from the Earth's surface and atmosphere as infrared (4–100 μm) at low energy in the form of thermal radiation to space. It is measured in $W\,m^{-2}$ and mathematically expressed as in equation (4). The longwave radiation also has two parts: one is outgoing longwave radiation (the dominating part) which depends on the land surface characteristics such as surface temperature and emissivity and another is the incoming longwave radiation that depends on the cloud cover and humidity, i.e., the sky temperature and sky emissivity. The incoming solar radiation and outgoing longwave radiation are the key components of radiation balance. These are extremely important to develop any land surface and climate model because the Earth's surface and atmosphere gain energy by absorbing solar (shortwave) radiation, which is known as radiative heating, and lose energy by emitting thermal (longwave) radiation to balance the absorption of

Table 2. *Summary of the satellite-based estimation methods of solar radiation.*

Name of the methods and references	Main concepts	Advantages	Disadvantages	Recommendations
Look-up table (LUT) (Mueller *et al.* 2009; Ma and Pinker 2012; Zhang *et al.* 2014)	Radiative transfer model (RTM) based data structure	High accuracy No need to perform calculation for each pixel	Computationally not economical. The recalculation of LUT is very time consuming. The threshold for recalculation is high	The recalculation time/ the amount of RTM calculations can be reduced by using an eigenvector approach
Parameterization (Sun *et al.* 2012; Tang *et al.* 2016)	Developing parametric equations based on several atmospheric and surface parameters	Computationally cost effective	Hard to keep high temporal resolution due to the changing tendency of some input parameters	An extensive error analysis is recommended to improve the accuracy of shortwave radiative flux estimation from MODIS products
Statistical method (Lu *et al.* 2011; Yeom and Han 2010)	Statistical approach like ANN (artificial neural network) that directly link the satellite observed signal	Stable and efficient Simple algorithm	Semi automated in nature Time consuming for high temporal resolution	Highly recommended for geostationary satellite with enhanced revisiting ability

solar radiation, also known as radiative cooling (Kiehl and Trenberth 1997). The resultant of these two components is the net radiation that determines the ultimate heating or cooling of global system.

3.1 *Ground measurement of thermal radiation*

At surface, the longwave radiation is mainly measured by pyrgeometer. It is an electronic device that measures near surface infrared radiation spectrum according to the following mathematical relationships (Pyrgeometer n.d.):

$$E_{\mathrm{m}} = E_{\mathrm{in}} - E_{\mathrm{out}}, \qquad (7)$$

where E_{m} is the measured radiation at the pyrgeometer sensor surface in W m^{-2}, E_{in} is the longwave radiation received from the atmosphere and E_{out} is the longwave emitted by the sensor surface. Now, the generated radiation at the instrument sensor surface can be calculated as

$$E_{\mathrm{m}} = \frac{V_{\mathrm{emf}}}{S}, \qquad (8)$$

$$E_{\mathrm{out}} = \sigma T^4, \qquad (9)$$

where V_{emf} is the output voltage of the pyrgeometer thermopile in volts (V), S is the sensitivity/calibration factor of the instrument in V W^{-1} m^{-2}, σ is the Stefan–Boltzmann constant in W m^{-2} K^{-4} and T is the absolute temperature of pyrgeometer detector in K. Therefore, the longwave radiation can be calculated as

$$E_{\mathrm{in}} = \frac{V_{\mathrm{emf}}}{S} + \sigma T^4. \qquad (10)$$

A schematic diagram and photograph of pyrgeometer is shown in figure 4. However, the ground-based measurement networks as described in previous section such as BSRN, WRC, GEBA, FLUXNET, SURFRAD, etc. also collect the longwave radiation data over their coverage regions. The accuracy of longwave radiation measurement was set to 30 W m^{-2} as per BSRN standard, recent measured data are more faithful of ± 5 W m^{-2} (1.5%) and the quality check performed by updated BSRN tools (Long and Dutton 2002; Schmithüsen *et al.* 2012).

3.2 *Satellite estimates of thermal radiation*

Due to the limited coverage and maintenance complexity of ground measurements in large scale, the satellite retrieval of longwave radiation is very important for analysing the Earth's climate system. The measurement of longwave radiation flux is affected by the processes of scatterings, absorptions and emissions from clouds, aerosols, gases and the surface. The researchers are developing various algorithms based on different types of methods, which can be categorised roughly into three.

The first type is known as the empirical method based on the empirical functions using satellite-derived meteorological parameters such as surface temperature and water vapour burden (Ellingson *et al.* 1983; Wang and Liang 2009). This method with simple algorithms is sensitive to errors but widely used in numerous applications. The second type is the radiative transfer method (RTM; Schmetz 1989; Vázquez-Navarro *et al.* 2013) that calculates the radiation quantities using the atmosphere temperature and water vapour profiles, it can directly measure the downward longwave radiation using atmospheric profiles and the upward longwave radiation using land surface profiles as it has the strong validity of physics. The third type is known as the hybrid method (Wang and
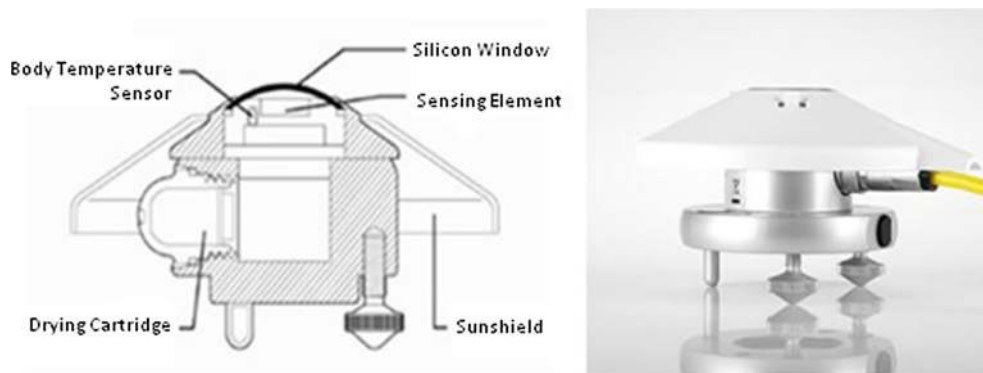

Figure 4. The schematic diagram (left) and photograph (right) of pyrgeometer (Solar Instruments/Atmospheric Science Instruments n.d.).

Liang 2010; Jiao *et al.* 2015) that is developed based on the combination of radiative transfer simulation and the statistical approaches such as ANN. The hybrid method indicates that there is a good generalisation and also the good accuracy. The summary of the above indicated methods is provided in table 3.

4. ET (latent heat flux)

ET is the vital component of the Earth SEB that is the collective value of evaporation from water bodies and the transpiration from vegetation and/or any other moisture containing living tissues, i.e., the processes of losing water from the Earth's surface to the atmosphere by both the evaporation and transpiration. This component is characterised by the latent heat flux of the Earth's surface as mathematically expressed in equation (6). This process cools the Earth's surface and moistens the atmosphere near surface which is why the estimation of ET is crucial for developing climatic, hydrological, bio-geophysical and ecological models to predict the weather and climate or climate change. A lot of efforts have been made for the accurate estimation procedure of ET as described in this section.

4.1 *Ground measurement of ET*

The potential ground measurement of ET has not been well observed with the common *in-situ* instruments and methods. Basically, micrometeorological measurement-based methods are vastly implemented to estimate ET (the latent heat flux) such as Bowen ratio energy balance (BREB), eddy covariance (EC) and Penman–Monteith (PM) method (Gavilán and Berengena 2007; Shi *et al.* 2015). ET can also be estimated based on weighing lysimeter (Gebler *et al.* 2015), providing the only direct measurement of water flux from vegetated area, i.e., the lysimeter water balance.

The BREB methodology is developed based on the SEB equation. The Bowen ratio (Bowen 1926) is defined as the ratio of the sensible heat flux (H) to the latent heat flux (LE) as expressed in the following equation:

$$B = \frac{H}{\text{LE}} = \frac{K_H \rho\, C_p\, \frac{\Delta T}{\Delta Z}}{K_V\, \lambda\, \frac{\Delta q}{\Delta Z}}, \qquad (11)$$

where K_H and K_V are the coefficient of sensible and latent heat transfer, ρ is the air density, C_p is the air specific heat, λ is the latent heat

Table 3. *Summary of satellite based thermal radiation estimation methods.*

| Name of the methods and references	Main concepts	Advantages	Disadvantages	Recommendations
Empirical method (Yu *et al.* 2014; Dutta *et al.* 2015)	Empirical functions based algorithm that developed using RS retrieved atmospheric parameters	Simple algorithm and easy to determine the coefficients	More error sensitive Significant positive error over arid region	Algorithm should be retrained with more perfect physical definition in extreme climate conditions
Radiative transfer method (Zhou *et al.* 2007; Park *et al.* 2015)	The radiative transfer simulation to calculate the radiation quantities using the atmospheric and land surface profiles	It has the strong validity of physics Applicable to all atmospheric profiles	The performance of the basic algorithm become degraded due to the common calculation of all sky	Algorithm should be improved by separating the calculation for clear and cloudy sky
Hybrid method (Yu *et al.* 2013; Yan *et al.* 2016)	This method developed on the combination of radiative transfer simulation and statistical approaches	A good generalization is observed in this method Widely accepted for good accuracy	Variable selection for statistical approaches is critical and crucial Large error appears, where the temperature is high such as for barren or desert surfaces	A correction method is required for model coefficients derivation from the high ground-air temperature difference to reduce the overestimation of longwave radiation
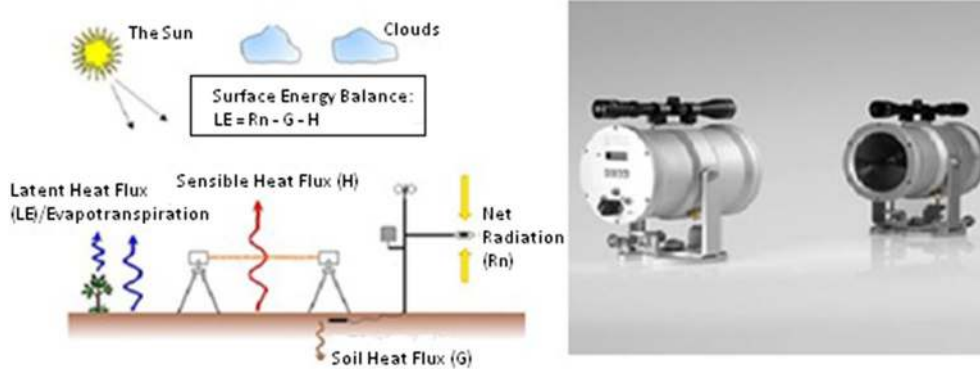
Figure 5. The operational diagram (left) and photograph (right) of the large aperture scintillometer (LAS) MkII ET System (Solar Instruments/Atmospheric Science Instruments n.d.).

of vapourisation, ΔT and Δq are the vertical differences of temperature and water vapour concentration and ΔZ is the vertical distance between the two measurement points. Now equation (6) can be rewritten as

$$\text{LE} = \frac{R_n - G}{1 + B}. \qquad (12)$$

In equation (12), if we have known B for a certain system then LE can be calculated from the measured net radiation (R_n) and soil heat flux (G).

The EC method (Pauwels and Samson 2006; Ha *et al.* 2015) estimates H and LE directly from the fluctuations of wind speed, temperature and water vapour. Observing the covariance between water vapour density and wind speed, we can calculate the latent heat flux as

$$\text{LE} = \lambda \overline{\acute{\rho}_v \acute{U}}, \qquad (13)$$

where λ is the latent heat of vapour, $\acute{\rho}_v$ is the fluctuation in water vapour density (kg m^{-3}), $\acute{U}$ is the fluctuation in vertical wind speed (m s^{-1}) and the overbar stands to indicate the average operation. Similarly, the sensible heat flux can be calculated as

$$H = \rho \, C_p \, \overline{\acute{T}\acute{U}}, \qquad (14)$$

where ρ is the density of the surrounding air and $\acute{T}$ is the fluctuation in air temperature (°C).

In recent years, the use of scintillometer has become popular for its large area coverage and good performance (Nieveen and Green 1998; Meijninger 2003; Ward and Evans 2015). Scintillometer is an electronic device that measures the sensible heat flux (H) of the surface and then calculates the latent heat flux (LE) using other climatic parameters (net radiation and soil heat flux) based on

the SEB. The basic principle is that it measures the turbulent intensity of the refractive index fluctuations (C_n^2) of air between a collimated light source (transmitter) and a detector (receiver). The transmitter sends a beam of light (electromagnetic radiation) at a known wavelength over a known distance of one to several kilometres and at the end of the path the receiver collects the travelled radiation and analyses the fluctuations of the radiation intensity to find out the turbulent heat fluxes. An operational diagram and photograph of large aperture scintillometer (LAS) is shown in figure 5. The estimated result of ET using this method shows a good agreement with the remote sensing-based estimation. Samain *et al.* (2012) presented the ET rates calculated per 10-day periods. It showed a good agreement between the remote sensing-based estimation and LAS-derived results with difference from 3.5% to 12.6%.

4.2 *Satellite estimates of ET*

Nowadays, satellite retrieval of ET has become a widespread area of interest to researchers for its highest cost effectiveness and large area coverage with revisiting capability as well as the reasonably good accuracy. The satellite-based estimation of ET started roughly from 1980 and is still developing based on various approaches and methods. It is hard to say which method or approach is the best because every aspect of these approaches/methods has its own merits and demerits. There are variety of models and methods for ET retrieval from satellite data such as the SEB-based methods (Kustas 1990), surface temperature vegetation indices (Ts-VI)-based methods (Tang *et al.* 2009), the Penman–Monteith (PM) method (Zhang *et al.* 2009), Priestley–Taylor (PT) method (Fisher *et al.*

2008), empirical method (Wang *et al.* 2007), water balance method (Wan *et al.* 2015) and other methods (Ryu *et al.* 2011; Wang and Bras 2011). These methods are further simplified and modified to improve their performance. The significant advantage of SEB methods is that these are using the energy balance approach, which can quantify surface fluxes and their water-use dynamics without reference to the source of water information as opposed to other models such as water-balance model, which requires detailed information of water sources. However, this paper focuses on various SEB-based methods and models.

4.2.1 *Surface energy balance index (SEBI)*

The SEBI model is based on the crop water stress index (CWSI), by scaling up the observed temperature in the maximum (max) temperature (dry condition) and the minimum (min) temperature (wet condition) (Jackson *et al.* 1981), which is the fundamental concept for all the SEB models. The observed max and min surface temperatures are interpolated to calculate the relative evaporative fraction (EF) then for a particular surface albedo and roughness, the pixelwise SEBI computes the regional ET from pixelwise max and min surface temperature redefined CWSI and relative EF. Due to the complexity in the determination of the max and min surface temperatures and poor accuracy of SEBI, it was further developed with a simplified form named simplified-SEBI (S-SEBI) (Roerink *et al.* 2000). Here, a reflectance (albedo)-dependent max and min surface temperatures are pointed out to determine the dry and wet conditions for partitioning the available energy into sensible and latent heat fluxes. The ET is calculated in terms of EF, which can be defined as the ratio of ET/latent heat flux (LE) to the available energy $(R_n - G)$. Under the dry and wet conditions, it can be formulated by interpolating the albedo-dependent surface temperatures as

$$EF = \frac{T_H - T_s}{T_H - T_{LE}}, \qquad (15)$$

where T_H is the max surface temperature at dry conditions and represents the max sensible heat flux and min latent heat flux, T_{LE} is the min surface temperature at wet conditions and represents the max latent heat flux and min sensible heat flux and T_s is the surface temperature.

4.2.2 *Surface energy balance system (SEBS)*

The SEBS was developed by Prof Dr Su in the Netherlands in 2002 to estimate the actual ET and other land surface heat fluxes in terms of atmospheric turbulent fluxes and EF from remote sensing (RS)-based data and some meteorological measurements (Su 2002; Su *et al.* 2003). Basically, it is the modified form of SEBI; here, the assumptions are: the latent heat flux is zero at the dry limit, i.e., the sensible heat flux (H_{dry}) is maximum (the available energy, $R_n - G$); on other hand, at wet limit, H_{wet} reaches at its minimum value as expressed:

$$H_{dry} = R_n - G, \qquad (16)$$

$$H_{wet} = \frac{(R_n - G)\gamma}{\gamma + \Delta} - \frac{\rho C_p (e_{sat} - e)}{r_{ah} (\gamma + \Delta)}, \quad (17)$$

$$\gamma = \frac{C_p P}{0.622\lambda}, \qquad (18)$$

where γ is the psychrometric constant (k Pa °C^{-1}), P is the atmospheric pressure (Pa), Δ is the slope of saturated vapour pressure as a function of T_a in k Pa °C^{-1}, e and e_{sat} are the actual and saturated vapour pressures, and r_{ah} is dependent on the Obukhov length which in turn is a function of the friction velocity and sensible heat flux. Now the relative evaporative fraction (EF$_r$) and EF can be expressed as

$$EF_r = \frac{H_{dry} - H}{H_{dry} - H_{wet}}, \qquad (19)$$

$$EF = \frac{EF_r * LE_{wet}}{R_n - G}. \qquad (20)$$

Here, to calculate the heat fluxes a distinction is made between the planetary boundary layer (PBL)/atmospheric boundary layer (ABL) and the atmospheric surface layer (ASL) to take the ABL height as a reference of potential air temperature. In SEBS, the parameters are derived from RS data and ground (meteorological and radiation) data are used as inputs to estimate the sensible heat flux and EF as well as the other components.

4.2.3 *Surface energy balance algorithm for land (SEBAL)*

The SEBAL was developed by Prof. Bastiaanssen in the Netherlands in 1998, which is one-layer image processing model (Bastiaanssen *et al.*

1998a, b). It estimates latent heat flux, i.e., ET as a residual of SEB and other land surface fluxes at both local and regional scales with minimum ground-based meteorological data. Basically, this model is a moderate approach based on both the empirical relationship and physical parameterisation scheme. Here, we need to collect the satellite imagery data of VIS, NIR, TIR spectra and also the land surface temperature (T_s), normalised vegetation index (NDVI) and albedo maps. The latent heat flux (LE) is estimated according to energy balance equation (6), where the net radiation (R_n) is computed from the balance of solar (shortwave) and thermal (longwave) radiation as indicated in equation (2), the soil heat flux (G) is calculated by the proposed equation of Bastiaanssen (2000), which is applicable to all categories of vegetation cover and land. The sensible heat flux (H) is computed according to equation (5), where SEBAL considers a linear relationship between the near surface-air temperature difference (dT) and the radiometric surface temperature (T_s) assuming the meteorological and surface conditions are homogeneous as expressed:

$$dT = cT_s + d, \tag{21}$$

where 'c' and 'd' are the empirical parameters obtained from the extreme evaporative condition, i.e., the 'anchor' pixel (Bastiaanssen 1995) for a given satellite image. The user can assign the dry/hot pixel and the wet/cold pixel to calculate dT on both conditions as

$$dT_{dry} = \frac{H_{dry} * r_{ah\_dry}}{\rho_{dry} * C_p}, \tag{22}$$

$$dT_{wet} = \frac{H_{wet} * r_{ah\_wet}}{\rho_{wet} * C_p}. \tag{23}$$

where r_{ah_dry} and r_{ah_wet} are the aerodynamic resistances at dry and wet conditions, respectively. In equation (22), the value of sensible heat flux is assumed to be maximum as $H_{dry} = R_n - G$ (maximum available energy) at dry pixel (taken from a pixel that located in an area that shows high surface temperature). In equation (23), the value of sensible heat flux H_{wet} is assumed to be zero at wet pixel (generally taken from a pixel located in deep water/water body), i.e., $dT_{wet} = 0$. After determining the value of dT at both wet and dry pixels, the values of 'c' and 'd' in equation (21) can be easily estimated. By using the values of 'c', 'd' and respective surface temperature (T_s) of each pixel, the air-surface temperature difference (dT) at every pixel is calculated using equation (21). Finally, the value of sensible heat flux (H) for each pixel is estimated iteratively with aerodynamic resistance corrected for stability using equation (5).

This method has been applied for ET estimation at both field and catchment scale in more than 30 countries such as Spain, Turkey, Egypt, India, Srilanka, China, USA, etc. over the world with an average accuracy of 85% (daily) and 95% (seasonal) at field scale (Bastiaanssen *et al.* 2010).

4.2.4 *Mapping evapotranspiration at high resolution with internalised calibration (METRIC)*

The METRIC is also an image processing tool (Allen *et al.* 2007) that is extended from SEBAL. The METRIC considers the slope aspect as T_s which relapses to $T_{s\ DEM}$ (the surface temperature adjusted to a standard elevation per pixel of the satellite image) through a common arbitrary datum, based on the image-specific lapse rate. This method uses the ASCE (American Society for Civil Engineers) standardised reference evapotranspiration (ET_r), which is calculated using the ASCE Penman–Monteith equation for alfalfa (about 0.5 m taller, rougher agricultural crop) field (ASCE-EWRI 2005). Here, the calibration via reference ET is done by choosing the dry pixel as $ET_{dry} = 0$ and the wet pixel as $ET_{wet} = 1.05ET_r$. However, this algorithm still suffers from the subjective specification of extreme pixels, i.e., dry and wet pixel selection.

4.2.5 *Two-source model (TSM)*

The TSM is also known as dual source model that was proposed by Norman *et al.* (1995) to improve the ET estimation accuracy from RS data (Sanchez *et al.* 2007). The basic concept of this model is to divide the composite radiometric temperature into two sources: one is soil and another is vegetative canopy, and to compute the sensible heat flux as the sum of canopy sensible heat flux (H_c) and soil sensible heat flux (H_s) is expressed as

$$H = H_c + H_s, \tag{24}$$

$$H_c = \rho_{air} \, C_p \frac{T_c - T_a}{r_{ah\_c}}, \tag{25}$$

$$H_s = \rho_{air} \, C_p \frac{T_s - T_a}{r_{ah\_s}}, \tag{26}$$

where T_c and T_s are the canopy and soil temperatures, respectively, T_a is the air temperature, and r_{ah_c} and r_{ah_s} are canopy and soil aerodynamic resistances, respectively. Here, T_c and T_s are related to the directional radiometric surface temperature T_{rad} as

$$T_{rad} = \left[f_c \cdot T_c^4 + (1 - f_c)^4 \right]^{1/4}, \qquad (27)$$

$$f_c = 1 - \exp \left(\frac{-0.5 \cdot \Omega \cdot L_A}{\cos \theta} \right), \qquad (28)$$

where f_c is the fractional vegetation cover, Ω is a factor that indicates the degree to which the vegetation is clumped (Kustas and Norman 1999), L_A is the leaf area index and θ is the viewing angle of the radiometer. This model experiences some uncertainties in determining the initial and corrected value of the PT coefficients as it utilises the PT parameterisation scheme for energy partitioning (Yang *et al.* 2015).

However, there are also some other methods and model for mapping regional and local ET such as recently the NP (non-parametric) approach (Liu *et al.* 2012; Pan *et al.* 2016) has been proposed by few researchers, where the net radiation, surface air temperature, land surface temperature and soil heat flux as the inputs without the need of parameterising resistance. After reviewing the detailed literature related to the estimation techniques of ET fluxes, we make a summarisation as listed in table 4.

5. Errors and uncertainties associated with satellite estimations

Several types of errors and uncertainties are found in satellite estimation of SEB components due to various problems and limitations in estimation methods and models, as well as the uneven characteristics of the atmosphere and Earth's surface. Some important sources of uncertainties and possible ways to reduce them are outlined here.

(1) *Errors associated with surface temperature retrieved from satellite measurement*: In the case of satellite estimation, most of the methods are using TIR radiation data to derive surface temperature. The atmospheric correction and surface emissivity affect the derivation of surface temperature; hence, the uncertainty is associated with the satellite measurement.

The surface temperature problem can be corrected using two methods, namely, direct and indirect methods, where the direct method uses the combination of atmospheric sounding and radiative transfer model but the indirect methods only use the satellite observations. The along track scanning radiometer (ATSR) observation can improve the estimation by performing the two nearly simultaneous measurements of brightness temperature from two different view angles. The consideration of both the directional radiometric surface temperature and emissivity on high spectral resolution (Norman *et al.* 1995) can reduce the uncertainty to some limit.

(2) *Uncertainties due to coverage problem of satellite data*: Different spatial and temporal scale SEB components are needed for several relevant departments at global and local scales. The simultaneous acquiring of high spatial and temporal resolution imagery is very hard because the satellites with high spatial coverage possess lower temporal frequency and vice versa. Also, the cloud covers obscure entire or parts of scene in an image, making it nearly impossible to obtain continuous coverage of an area. Hence, the spatio-temporal coverage problem may render the satellite estimation method impractical in relevant applications. There are some gap filling procedures (Anderson *et al.* 2007) and coupling models (Renzullo *et al.* 2008) to resolve this issue.

(3) *Uncertainties in net radiation estimation*: Net radiation is the key parameter of SEB, which quantifies the available energy $(R_n - G)$. However, the net radiation estimation may lead to errors due to the ignorance of diurnal variation and phase difference between the diurnal cycles of each individual component (short and longwaves). In most of the SEB methods, total R_n flux is considered without the relative functions of direct and diffuse radiation. It is necessary to consider the effects of diffuse radiation than only direct radiation (Roderick *et al.* 2001).

(4) *Uncertainties due to surface heterogeneity*: The satellite measurement of some land surface variables such as temperature, aerodynamic resistance, leaf area index, fractional vegetation coverage, plant height, etc. are highly sensitive to surface types. The observational angular effect is prominent over homogeneous

Table 4. *Summary of the satellite based evapotranspiration (latent heat flux) estimation models (surface energy balance based).*

Name of the models and references	Main concepts	Advantages	Disadvantages	Recommendations
Surface energy balance index (SEBI) (Choudhury and Menenti 1993)	Based on the crop water stress index (CWSI) by scaling up the max (dry condition) and min (wet condition) temperature	Direct effects of surface temperature and resistance on latent heat flux	Poor accuracy Ground based measurement is required	In this model, it is recommended to use of air potential temperature at the top of the Atmospheric Boundary Layer (ABL) instead of near surface temperature
Simplified SEBI (S-SEBI) (Roerink et al. 2000; Verstraeten et al. 2005)	The observation of temperature is albedo dependent to determine the max (dry condition) and min (wet condition)	Ground based measurement is not required	Extreme temperatures are location dependent	The desired RS image should contain the extreme values of surface temperature
Surface energy balance algorithm for land (SEBAL) (Bastiaanssen 2000; Bastiaanssen et al. 2005, 2010)	A moderate approach based on both the empirical relationship and parameterization scheme	Requires minimum ground based weather data Automatic internal correction of atmospheric effects on surface temperature	The user dependent specification of anchor pixels	The SEBAL is recommended to use under several climatic conditions at both field and catchment scales for solving water resources and irrigation problems
Surface energy balance system (SEBS) (Su 2002; Ma et al. 2013; Chen et al. 2013; Amatya et al. 2015)	Estimate the actual ET and other surface fluxes in terms of evaporative fraction and atmospheric turbulent fluxes	Good accuracy The roughness height for heat transfer can be calculated instead of constant value User friendly with RS and GIS software The uncertainties can be partially solved	Requires more parameters The solution of turbulent flux is relatively complex	This algorithm is recommended for some special irrigation area like Coleambally irrigation area (CIA) and also the topographic enhanced SEBS (TESEBS) is suggested for complex terrain areas
Mapping evapotranspiration at high resolution with internalized calibration (METRIC) (Allen et al. 2013; Carrillo-Rojas et al. 2016)	Extended from SEBAL with considering slope aspect	Slope aspect is considered	Uncertainties found in the determination of anchor pixels	This algorithm is highly recommended for higher resolution images
Two source model (TSM) (Li et al. 2005; Yang et al. 2015; Sun 2016)	It divides the composite radiometric temperatures into two sources – one is soil and another is vegetative canopy then sum-up the sensible heat fluxes for each	The view geometry is considered Empirical corrections are not required	Too many ground measurements are required	Two observation periods are recommended to perform the separate measurement of surface temperature

and dense vegetated surfaces but troublesome over heterogeneous surfaces (Carlson *et al.* 1994; Norman *et al.* 1995).

(5) *Inconsistency in satellite estimation models*: Different models are useful for different land surface types and meteorological conditions. Till date, there is no universal model, which could be used throughout the world. So, we need the modifications/improvements of the model to estimate SEB components at global scale, which leads to uncertainties.

(6) *Insufficient near surface meteorological and flux data*: Most of the satellite-based estimation models need the near surface meteorological data. Basically, the data from meteorological stations are obtained at a satellite pixel by spatial interpolation techniques. Different study regions have different climatic and terrain conditions with sparse/irregular meteorological and surface flux measurement stations. Therefore, the accuracy of the interpolation methods should be improved, as well as the ground-based meteorological and flux measurement networks also need further development.

(7) *Night-time transpiration and early morning dew*: If night-time transpiration occurs over a highly vegetated surface and this may be a significant error source in satellite estimation due to the nocturnal vapour pressure difference and wind speed (Dawson *et al.* 2007). Early morning dew over well-irrigated vegetation surface may affect the satellite measured radiant temperature (Pinter 1986). Hence, we should think about these issues before obtaining the satellite imagery.

In addition to the above-mentioned issues, other uncertainties in satellite measurements such as limitations of empirical vegetation index models, spatio-temporal scaling effects, lack of SEB components at satellite pixel for truth validation, etc. have been discussed in the literature (Wang *et al.* 2007; Kalma *et al.* 2008; Li *et al.* 2009).

6. Recommendations

In this study, we have discussed the advancements, limitations and uncertainties associated with different ground and satellite-based estimation methods and models and also provided some recommendations to researchers so that they can use these methods more specifically. The summarised

recommendations, as indicated in tables 2–4, can be explained in brief as follows to specify the key points for suitable applications of the respective methods and models:

(1) *Recommendations on solar radiation estimation methods*: Estimation of solar radiation at a large scale has many uses in the Earth system and photovoltaic power system applications. There are three categories of methods to estimate solar radiation. In the LUT method, a large number of radiative transfer model (RTM) calculations (10^5–10^7) are required if specified scientific approaches are not applied (Mueller *et al.* 2009), where eigenvector approach is useful to reduce the RTM calculations by several orders. So, the use of a scientific approach such as eigenvector approach is recommended for the RTM-based methods. The parametrisation scheme is implemented with MODIS data product needs for an extensive error analysis to find out the major error sources of the model (Wang and Pinker 2009). Hence, an extensive error analysis is needed for parameterisation scheme with moderate resolution images. The geostationary satellite with high temporal frequency such as multi-functional transport satellite (MTSAT) is more suitable for continuous estimation of solar radiation using the statistical method (Lu *et al.* 2011). For continuous estimation of solar radiation, the ANN-based statistical approaches are recommended using time-series images.

(2) *Recommendations on thermal radiation estimation methods*: Thermal (longwave) radiation is important for the radiative cooling process (Kiehl and Trenberth 1997) to balance the absorption of solar radiation. Here, we compile some recommendations on three major categories of estimation methods. The empirical method that combines the uses of satellite thermal data and atmospheric parameters is not perfect in extreme climate conditions (Yu *et al.* 2014). Hence, the re-training of algorithm is recommended where the empirical method uses both thermal and atmospheric parameters. If the RTM uses the common calculation of all skies, the model performance degrades (Zhou *et al.* 2007). Therefore, separate calculation for clear and cloudy sky is suggested. In the case of hybrid method, some statistical algorithms frequently overestimate the longwave

radiation over arid or desert surfaces where the ground-air temperature is high. Yu *et al.* (2013) used a correction method and found that the root means square error (RMSE) was substantially reduced. Therefore, a correction method is needed for model coefficients derivation from the ground-air temperature difference to reduce the overestimation of long-wave radiation.

(3) *Recommendations on ET estimation methods*: ET is a vitally important component of terrestrial energy, water and bio-geophysical cycle. We make some important recommendations on various SEB-based ET estimation methods. The SEBI model is the surface temperature-based parametrisation scheme to estimate the location-dependent ET, where the use of air temperature at the top of atmospheric boundary layer is recommended instead of near surface temperature (Choudhury and Menenti 1993). Simplified SEBI (S-SEBI) is the maximum and minimum temperature-based estimation method, where no additional meteorological data are needed if the surface extremes (max and min of surface temperature) are available (Roerink *et al.* 2000). Hence, the desired satellite image should contain the extreme value of surface temperature. The SEBAL model is an iterative and feedback-based numerical procedure that estimates surface fluxes using both the satellite and ground data. This model is widely accepted and recommended to use under several climatic conditions at both field and catchment scales for solving water resources and irrigation problems (Bastiaanssen *et al.* 2005). In SEBS, surface fluxes are estimated from satellite and ground data in terms of EF. This model is recommended to estimate ET for some special irrigation area such as Coleambally irrigation area (CIA) (Ma *et al.* 2013). The modified SEBS such as topographic enhanced SEBS (TESEBS) is suggested for areas with complex terrain (Chen *et al.* 2013; Amatya *et al.* 2015). The METRIC is an extension of SEBAL version with consideration of the slope aspect and is used for complex terrain areas with higher resolution satellite data (Carrillo-Rojas *et al.* 2016). This method is recommended for longer and higher mountainous areas with higher resolution satellite data. TSM model divides the composite radiometric temperature into two sources (soil and canopy), where

overestimation occurs due to the uncertainties that arise from the determination of PT coefficients and iteration procedure (Yang *et al.* 2015). Here, the careful selection of target criteria is suggested for iteration process, and two observation periods are also recommended to perform the separate measurement of surface temperature.

However, the above complied recommendations can be applied properly on the following considerations: estimation manner (instantaneous/continuous); study area's characteristics (land surface types, climate conditions); availability of satellite and ground data (spatial and temporal resolution, access criteria), etc.

7. Conclusions and perspectives

This paper reviews previous and recent studies on the estimation methods of the Earth's SEB components from ground and satellite measurements. We summarise the main scientific concepts, merits, demerits, errors and uncertainties of the studied methods and models and also provide some important recommendations to researchers on how to make use of these methods. In a broad sense, there has been a firm progress but this research area still faces many challenges.

The ground-based measurement instruments such as pyranometer, pyrgeometer, lysimeter, EC system and scintillometer have become more efficient and user friendly due to the rapid developments in electronics and communication technology. Therefore, the errors and uncertainties associated with ground measurements are negligible. But due to the limitation and lack of proper regional and global coverage, the worldwide ground measurement networks are not self-disciplined and unified. In the last three decades, satellite remote sensing technologies have developed significantly and the wide availability of satellite data products has enabled researchers to develop a wide spectrum of satellite-based estimation methods and models.

From this review work, we have observed that each method and model has its own advantages and disadvantages relative to other approaches, and there is no consensus on which one is the best. In reality, these are the important tools for estimating the SEB components at regional and global scales. There are several methods for satellite estimation of solar and thermal radiation. The RTM has a strong validity of physics (i.e., the RTM model

follows the basic theory of radiation physics) and can be applied to all atmospheric and land surface profiles. Among other methods and parameterisation schemes, the use of hybrid method may achieve a better generalisation, which is highly expected for universal applications. Most of the SEB-based models are estimating latent heat or sensible heat fluxes as the residual of SEB by using satellite data and some additional ground-based meteorological data. No additional data are needed in the S-SEBI model if the surface extremes (max and min surface temperatures) are present in the satellite imagery. In SEBAL, it is required to determine a constant temperature for dry and wet conditions because the extreme temperatures vary with reflectance changes as a consequence of the dry and wet conditions. It has some important advantages such as minimum ground-based data and automatic internal calibration within each processed image. The SEBS estimates H and LE distinctively under dry and wet limits in terms of EF for every pixel.

However, the accuracy of surface flux estimation using these methods varies from one model to another, one study area to another and one study period to another. Su *et al.* (2005) reported the accuracy of ET value estimated from SEBS was 10–15% with respect to ground-based measurement, where the EF ranged from 0.5 to 0.9. A maximum relative difference of 8% between measured and estimated EF was observed in the S-SEBI model (Roerink *et al.* 2000). The typical accuracy of SEBAL was tested under several climatic conditions at field scale and it was found to be 85% and 95% at daily and seasonal scales, respectively (Bastiaanssen 2000; Bastiaanssen *et al.* 2005). The SEBAL and SEBS have some limitations over mountainous area (Bastiaanssen *et al.* 2010; Chen *et al.* 2013). These limitations can be solved using METRIC and TESEBS models as they consider the slope aspect (Allen *et al.* 2007; Amatya *et al.* 2015). The TSM method is used for separate calculation of soil and canopy heat fluxes to improve the accuracy (Norman *et al.* 1995). Along with other uncertainties as described in the earlier section, uncertainties associated with the validation of satellite retrieved radiation quantities with the ground measurement are common in all satellite estimations. To overcome these uncertainties, the cross calibration within the same measurement network and among the different networks as well as the consistent processing and effective management of ground measurements is needed. Another

difficulty is in the inter-comparison of the error calculations between ground and satellite estimation as they use different error measuring variables used in different studies such as bias, mean bias, mean absolute error, RMSE, percentage error, standard deviation, etc.

Although the reviewed methods and models demonstrate an enough capability for surface flux estimations, but still have some limitations which lead to errors and uncertainties. Therefore, future research can be focused on several directions. Newly developed methods in acquisition of satellite and ground data are needed to solve the addressed uncertainties and limitations. Hybrid methods or integration of some methods can be used to take the advantage of their respective merits and compensating for their limitations. The use of data fusion and data assimilation techniques can be highly useful for integrated estimations. The satellite estimation methods also have a large area to be improved for using the recent high-resolution satellite data as relevant satellite data are rapidly growing.

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