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Components of near-surface energy balance derived from satellite soundings – Part 2: Latent heat flux

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Abstract

This paper introduces a new method for recovering global fields of latent heat flux. The method focuses on specifying Bowen ratio fields through exploiting air temperature and vapour pressure measurements obtained from infra-red soundings of the AIRS (Atmospheric Infrared Sounder) sensor onboard the NASA-Aqua platform. Through combining these Bowen ratio retrievals with satellite surface net available energy data we have specified estimates of global surface latent heat flux at the 1° by 1° scale. These estimates were evaluated against data from 30 terrestrial tower flux sites covering a broad spectrum of biomes. Taking monthly average 13:30 local time (LT) data for 2003, this revealed a relatively good agreement between the satellite and tower measurements of latent heat flux, with a pooled root mean square deviation of 79 W m^{-2}, and no significant bias. The results show particular promise for this approach under warm, moist conditions, but weaknesses under arid or semi-arid conditions subject to high radiative loads.

1 Introduction

The specter of increasing global surface temperatures mean our ability to both monitor and predict changes in the activity of the water cycle becomes critical if we are to develop the adaptive capability needed to manage this change (Lawford et al., 2004). As a result, significant investments have been and are being made in developing both monitoring and modelling capacity in the related areas of water resource management (Nickel et al., 2005), flood and drought risk assessment (Lehner et al., 2006) and weather and climate prediction (Irannejad et al., 2003; Brennan and Lackmann, 2005). Of the various components of the water cycle, the accuracy with which evaporative fluxes, E, are both measured and hence modelled at scales relevant to decision making has been identified as an area where greater capacity is needed, particularly in order to evaluate and hence better constrain model performance (Chen and Dudhia, 2001; McCabe et al., 2008).

Satellites offer a potentially attractive source of data for calculating E at scales directly relevant to model development (Jiminez et al., 2009). Over the past 30 yr a variety of schemes for specifying E using remote sensing data have been developed and used to evaluate the spatio-temporal behaviour of evaporation for field (Tasumi et al., 2005), regional (Bastiaanssen et al., 1998; Mu et al., 2007; Mallick et al., 2007) and continental scales (Anderson et al., 2007). The methods employed thus far appear to fall into several categories. The most common approach centres on assuming a physical model of evaporation given many of the terms required for these models are available as satellite products (Choudhury and Di Girolamo, 1998; Mu et al., 2007). A number of studies have also tried to resolve λE indirectly by estimating evaporative fraction from the relationship between satellite derived albedo, vegetation indices, and land surface temperature (Verstraeten et al., 2005; Batra et al., 2006; Mallick et al., 2009).

What is common to all these approaches is that they rely to a greater or lesser extent on parameterization of surface characteristics in order to derive the estimates of E and, therefore, the products from these approaches are conditional on these parameterizations. For example, in schemes which exploit the Penman-Monteith equation both the aerodynamic and surface resistance terms require some form of calibration of surface characteristics, often involving vegetation indices, whether empirically (Mu et al., 2007) or through linking to photosynthesis (Anderson et al., 2008). This is obviously a confounding factor when one attempts to use these data to evaluate surface parameterisations in weather, climate and hydrological models, particularly when the models we wish to evaluate may contain very similar model descriptions for E. What is required therefore are methods for deriving E estimates from satellite data that do not rely unduly on surface parameterisation, so that they become a valid and valuable data source for model evaluation. One approach that appears to fulfill this requirement is where E is estimated from satellite data as a residual term in the energy balance equation (Tasumi et al., 2005; Mallick et al., 2007). However, this approach suffers from the effects of error propagation because all errors including any lack of observed closure of the regional energy budget are lumped into the estimate of E (Foken et al., 2006). From this we can see that something more akin to a satellite 'observation' would be attractive.

Global polar orbiting sounders like AIRS (Atmospheric Infrared Sounder) provide profiles of air temperature and relative humidity at different pressure levels from the surface to the upper troposphere, along with several other geophysical variables (for example surface temperature, near surface air temperature, precipitable water, cloudiness, surface emissivity, geopotential height etc.). Profile information like this points to the possibility of exploiting Bowen ratio methods to produce large scale estimates of E. Despite having been used to refine estimate of near surface air temperature over the oceans (e.g., Hsu, 1998), the use of Bowen ratio methods in conjunction with satellite sounder data somewhat surprisingly appears to have been overlooked as a method for estimating E. The reasons for this are probably be twofold. Firstly, the resolution of the temperature and humidity retrievals are assumed to be inadequate. Secondly, there can be reservations over the applicability of the underlying assumptions of this method on this scale. Although these appear valid concerns there are important counter arguments to consider. Firstly, the degree of signal integration going on at the scale of the satellite sounding should help relax the requirement on signal resolution. This will be aided by an effectively large sensor separation interval in the vertical. Secondly, studies over both ocean and land indicate that the Bowen ratio method can be relatively robust under non-ideal conditions (Tanner, 1961; Todd et al., 2000; Konda, 2004). Given the potential benefits of having non-parametric estimates of E at the scales and spatial coverage offered by satellites, we argue that the possibility of using sounder products within a Bowen ratio framework merits investigation.

This paper presents a preliminary development and evaluation of 1° by 1° AIRS sounder-Bowen ratio derived latent heat flux, λE. We focus on terrestrial systems because of the availability of an extensive tower-based flux measurement network against which we can evaluate the various satellite derived components. However, we see no

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reason to exclude the oceanic estimates and refer to these where relevant.

2 Methodology

2.1 Bowen ratio methodology

The Bowen ratio (β) is the ratio of sensible, H ($\mathrm{W\,m^{-2}}$), to latent, λE ($\mathrm{W\,m^{-2}}$), heat flux (Bowen, 1926),

$$\beta = \frac{\mathrm{H}}{\lambda E} \tag{1}$$

where λ is the latent heat of vaporization of water ($\mathrm{J\,kg^{-1}}$) and surface to atmosphere fluxes are positive. If the instantaneous energy balance of the plain across which H and λE are being considered is given by

$$\Phi = R_\mathrm{N} - G = H + \lambda E \tag{2}$$

where Φ ($\mathrm{W\,m^{-2}}$) is known as the net available energy, R_N ($\mathrm{W\,m^{-2}}$) is the net radiation across that plain and G ($\mathrm{W\,m^{-2}}$) is the rate of system heat accumulation below that plain, then combining Eqs. (1) and (2) one gets,

$$\lambda E = \frac{\Phi}{1+\beta} \tag{3}$$

Therefore, if Φ and β are available, λE can be computed (Dyer, 1974). The estimation of Φ from satellite data is covered in a companion paper (Jarvis et al., 2010). β was estimated as follows.

H and λE are assumed to be linearly related to the vertical gradients in air temperature and vapour partial pressure, $\partial T/\partial z$ and $\partial p/\partial z$,

$$\lambda E = \rho\lambda\varepsilon k_E \frac{\partial p}{\partial z} \tag{4a}$$

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and,

$$H = \rho c_P k_H \frac{\partial T}{\partial z} \tag{4b}$$

where ε is the ratio of the molecular weight of water vapor to that of dry air, ρ is air density (kg m^{-3}), c_p is air specific heat (J kg^{-1} K^{-1}), k_E and k_H are the effective transfer coefficients for water vapor and heat, respectively (m s^{-1}) (Fritschen and Fritschen, 2005). If heat and water vapour occupy the same transfer pathway and mechanism through a plain then $k_E \approx k_H$ (Verma et al., 1978) and Eqs. (1) and (4) reduce to,

$$\beta = \frac{c_P}{\varepsilon\lambda} \frac{\partial T}{\partial p} \tag{5}$$

suggesting β can be estimated from the relative vertical gradient in T and p (Bowen, 1926).

AIRS soundings for T and p are available for a range of pressure levels in the atmosphere (Tobin et al., 2006). Assuming the lowest available two pressure levels $P_{1,2}$ occur within a region of the planetary boundary layer within which Eq. (4a and b) hold, then a finite difference approximation of Eq. (5) gives,

$$\beta = \frac{c_P}{\varepsilon\lambda} \frac{(T_1 - T_2 + \Gamma)}{(p_1 - p_2)} \tag{6}$$

where Γ accounts for the adiabatic lapse rate in T which in this case will be significant. Here, the 1000 and 925 mb pressure levels soundings will be exploited so that we are considering fluxes within the lower 1000 m of the atmosphere. For example, considering a landscape at zero meters above sea level, the 1000 mb level would correspond to approximately 100 m and the 925 mb level to 750 m, thus Δz=650 m and the effective measurement height is, therefore, 425 m.

In the turbulent region of the atmosphere, eddy diffusivities for all the conserved scalars are generally assumed equal because they are carried by the same eddies

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and, therefore, are associated at source (Swinbank and Dyer, 1967). There is evidence to suggest k_H is greater than k_E under stable (early morning and late afternoon) conditions and when lateral advection can be significant (Verma et al., 1978). However, in the present study we use the 13:30 LT AIRS soundings to obtain T and p when the atmosphere will tend to be least stable and the average depth of the turbulent boundary layer should extend well beyond the 925 mb level (Fisch et al., 2004). Also, we have opted to use the AIRS sounding data rather than its higher resolution MODIS counterpart because we anticipate lateral advection should be less of an issue at the larger scale.

The reliability of the estimates of β clearly also depends on the accuracy and resolution of the measurements of the temperature and humidity gradients. The AIRS products are are quoted as having resolutions of ±1 K per km for T and ±20 percent per 2 km for p (Tobin et al., 2006). Given Bowen ratio studies are invariably applied to small sensor separations of the order of meters and at the point scale, precisions of ±0.01 °C for temperature and ±0.01 kPa for vapour pressure are required (Campbell Scientific, 2005), making the AIRS sensitivities appear untenable. However, as mentioned above, the effective sensor separation of the order of hundreds of meters allied to the sounding integrating at the 100 km scale should help lifting these restrictions.

Here we specify Γ following Eq. (6.15) in Salby (1996) which when rearranged gives:

$$\Gamma = \frac{\ln\left[T_2/T_1\right]\Gamma_d}{\ln\left[P_2/P_1\right]\kappa} \tag{7}$$

where Γ_d is the dry adiabatic lapse rate (~9.8 K km^{-1}) and κ is the ratio of the specific gas constant (J kg^{-1} K^{-1}) to the isobaric specific heat capacity (J kg^{-1} K^{-1}) (Salby, 1996).

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2.2 Satellite data sources

The AIRS sounder was carried by the NASA Aqua satellite, which was launched into a sun-synchronous low Earth orbit on May 4, 2002 as part of the NASA Earth Observing System (Tobin et al., 2006). It gives global, twice daily coverage at 1:30 a.m./p.m. from an altitude of 705 km. In the present study we have used AIRS level 3 standard monthly products from 2003, with a spatial resolution of 1° by 1°. The monthly products are simply the arithmetic mean, weighted by counts, of the daily data of each grid box. The monthly merged product have been used here because the infrared retrievals are not cloud proof and the monthly products gave decent spatial cover in light of missing cloudy sky data. The data products were obtained in hierarchical data format (HDF4) with associated latitude-longitude projection from the NASA Mirador data holdings (http://mirador.gsfc.nasa.gov/). These datasets included all the meteorological variables required to realise Eqs. (6) and (7).

2.3 Tower evaluation data

The satellite estimates of β, λE, and H were evaluated against 2003 data from 30 terrestrial FLUXNET eddy covariance towers (Baldocchi et al., 2001) covering 7 different biome classes. These tower sites were selected to cover a range of hydrometeorological environments in South America, North America, Europe, Asia, Oceania and Africa. A comprehensive list of the site characteristics and the site locations are given in a companion paper Jarvis et al. (2010) which describes the specification of the satellite net available energy used here.

Eddy covariance has largely replaced gradient-based methods like Bowen ratio as the preferred method for tower measurements of terrestrial water vapour and sensible heat flux and hence are ideal for the evaluation here given the two methods are independent. Sensible and latent heat flux measurements were used as reported in the FLUXNET data base, in other words no corrections for any lack in energy balance closure (Foken, 2008; Wohlfahrt et al., 2009) were applied. The spatial scale of tower eddy

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covariance is of the order of $<10\,km^2$ and hence are at least three orders of magnitude smaller scale than the $10\,000\,km^2$ satellite data, which obviously has implications in heterogeneous environments.

3 Results

3.1 Bowen ratio evaluation

Figure 1a shows the global distribution of annual average, 13:30 LT β for 2003. The missing data segments are due to two data rejection criteria. Firstly, there are missing data in the AIRS sounder profiles, which are particularly prominent at high latitudes where presumably it is difficult to profile the atmosphere reliably near the surface and over the mountain belts where the lower pressure levels are intercepted by the ground. Secondly, we have imposed our own data rejection for β when there is reversal of the vertical vapour pressure gradient under high radiative load. This condition is often encountered in hot, arid settings when large scale advection causes the assumptions behind Bowen ratio methodology to become invalid (Rider and Philip, 1960; Perez et al., 1999). This condition was particularly prevalent over Australia in summer 2003 (Feng et al., 2008) and hence this region is not covered particularly well.

The first thing to note from Fig. 1a is that there is a clear land-sea contrast with β being relatively low and uniform over the sea as expected. The values of β over the oceans are in the region of 0.1, in line with commonly quoted figures for the sea (Betts and Ridgway, 1989; Hoen et al., 2002). Over the tropical forest regions of Amazonia and the Congo β is in the range 0.1 to 0.3, which also compares with values reported for these areas (da Rocha et al., 2004, 2009; Russel et al., 2006). The more arid areas are also clearly delineated. Although somewhat variable, the Sahara gives a range of 1.5–3.5 which corresponds with the results of Kohler et al. (2010) and Wohlfahrt et al. (2009) for the Mojave Desert. The South American savanna gives a range between 0.5–1 which corresponds with values reported by Giambelluca et al. (2009). One no-table feature is the homogeneity of the β fields over the Americas in contrast to the heterogeneity over Eurasia. 2003 was associated with widespread drying over Europe (Fink et al., 2004) which may explain this feature.

Figure 2a shows the relationship between the satellite and tower derived estimates of evaporative fraction $\Lambda=(1+\beta)^{-1}$ (Shuttleworth et al., 1989). We have elected to evaluate β in terms of Λ because, unlike β, Λ is bounded and more linearly related to the tower fluxes from which it is derived. The evaluation in Fig. 2a reveals a significant (r=0.34±0.06) correlation between Λ(satellite) and Λ(tower), albeit one corrupted by significant variability. This is to be expected given β is defined as a ratio of either four uncertain soundings (for the satellite) or two uncertain fluxes (for the tower). Assuming both measures are co-related through some "true" intermediate scale variable then the relationship between the two for the data in Fig. 2a is given by Λ(satellite)=0.31(±0.02)Λ(tower)+0.49(±0.04). This suggests that the relationship is actually well defined, but that it is significantly different to 1:1 unless Λ(tower) is in the range 0.6 to 0.8 i.e. in dry environments the satellite soundings appears to overestimate Λ and hence under estimate β due to the effects of flux divergence in the satellite data (see below).

3.2 Latent and sensible heat evaluation

Figures 1b and 2b shows the geographical distribution of the average noontime net available energy and its evaluation for 2003 taken from Jarvis et al. (2010). The corresponding geographical distributions of λE and H are shown in Fig. 1c and d. Figure 2c shows the relationship between the satellite and tower λE for all 30 evaluation sites. This gives an overall correlation of r=0.75±0.04. Assuming both the tower and satellite data are linearly co-related through some "true" value, linear regression gave λE(satellite)=0.98(±0.02)λE(tower) with a root mean square deviation (RMSD) of 79 W m^{-2} (see Fig. 2c). The biome specific statistics for λE are given in Table 1 which reveals correlations ranging between r=0.41±0.22 (SAV) to r=0.76±0.10 (ENF), RMSD ranging between 61 (MF) to 141 (SAV) W m^{-2} and regression gains ranging be-

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tween 0.85±0.08 (CRO) to 2.00±0.28 (SAV).

The relationship between the satellite and tower H for all 30 evaluation sites is shown in Fig. 2d. Here, r=0.56±0.05 and H(satellite)=0.59(±0.02)H(tower) with an RMSD of 77 W m^{-2}. Again, the biome specific statistics for H are given in Table 1 and reveal correlations ranging between 0.43±0.15 (GRA) to 0.79±0.11 (CRO), RMSD ranging between 52 (CRO) to 149 (SAV) W m^{-2} and regression gains ranging between 0.45±0.05 (SAV) to 0.93±0.06 (CRO). Figure 3 shows some examples of monthly time series of λE for both the satellite and the towers for a range of sites. This shows that the individual site statistics given in Table 1 reflect the seasonality in the tower data. Time series of the monthly full global fields of Φ and λE are available on http://www.lancs.ac.uk/staff/bsaajj/NERC_project.html.

4 Discussion

In addition to β, the retrieval of λE also depends heavily on the the measure of Φ being used. For a detailed discussion of the efficacy of the satellite derived values of Φ we have used here the reader is referred to Jarvis et al. (2010). To summarise, in comparing the satellite derived Φ with the tower $H+\lambda E$, Jarvis et al. (2010) found that their satellite estimate underestimated the tower value by, on average, approximately 10 percent, i.e. Φ(satellite)≈0.90Φ(tower) (see Fig. 2b). Therefore, the approximately 2 percent underestimate in satellite λE seen here would indicate that we are getting an approximately 8 percent compensation error introduced by the overspecification of Λ(satellite) under dry conditions seen in Fig. 2a. The SAV biome data are clearly the largest contributor to this source of error, with the wetter environments producing much better agreement between Λ(satellite) and Λ(tower).

Given there appears to be widespread lack of energy balance closure of the order of 20 percent observed at most FLUXNET sites (Wilson et al., 2002), this implies a potential systematic under specification of λE(tower) (and/or H(tower)). However, by the same argument the evaluation between satellite and tower for Φ would change

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by a similar amount leading to little or no net change in the overall evaluation for λE. Jarvis et al. (2010) found that accommodating a 20 percent imbalance in Φ(tower) gave Φ(satellite)$\approx$0.72Φ(tower) and that this lack of agreement could be explained by the under specification of the downwelling shortwave radiation component of Φ(satellite). It is unlikely that the entire energy imbalance is attributable solely to λE(tower) (Foken, 2008). As a result, the likely range for the pooled gain between the satellite and tower λE is between 0.8 to 1.0, determined by the combination of under specification of the satellite downwelling shortwave combined with overspecification of satellite Λ.

The monthly infrared products of AIRS are, by definition, a sample of relatively cloud free conditions whilst the tower fluxes are for a mixtures of clear and cloudy atmospheric conditions. The inclusion/omission of cloudy conditions should have little or no impact on energy partitioning ratios such as β (Grimmond and Oke, 1995; Balogun et al., 2009). Furthermore, despite being biased low, the shortwave component of Φ specified by Jarvis et al. (2010) was for all-sky conditions whilst the IR components of Φ appeared to be somewhat insensitive to the clear sky sampling bias. As a result, the primary motivation for attempting to recover satellite estimates for all-sky conditions would appear to be for increasing the temporal resolution of the data, and not for removing bias from the monthly satellite estimates.

The landscape scale β (and hence Λ) estimated from sounder data relate to a location some few hundred meters above the surface, whilst the tower data relate to heights either meters (for GRA, CRO and SAV) to tens of meters (for EBF, MF, DF, EF) above the surface. These towers are designed to operate in the constant flux portion of the planetary boundary layer which, as a rule-of-thumb, occupies the lower 10 percent of the planetary boundary layer and where fluxes change by less than 10 percent with height (Stull, 1988). Above this layer there is a tendency of H to decrease with height due to the entrainment of warm air from aloft down into the mixed layer (Stull, 1988). This explains the results in Fig. 2d where H(satellite) is significantly less than H(tower). In contrast, λE often tends to be preserved with height by the entrainment dry air from aloft (Stull, 1988; Mahrt et al., 2001). While comparing ground eddy covariance fluxes with aircraft fluxes over diverse European regions, Gioli et al. (2004) found the value of H at an average height of 70 m was 35 percent less that those at ground level, whereas no such trend in λE was observed. Similarly, Migletta et al. (2009) found H lapsed by 36 percent as one moved from the surface to a height of 100 m. The same behaviour has also been frequently observed in both airborne and ground-based eddy covariance measurements in USA (e.g., Desjardins et al., 1992) and Europe (Torralba et al., 2008; Migletta et al., 2009). Because of the differing lapse properties of λE and H one would imagine β(satellite) should, on average, be less than β(tower) which, despite being somewhat uncertain, is what we observe even for the wetter environments.

Clearly scale is another obvious reason for any disagreement between tower and satellite data. The satellite derived fluxes aggregate at the 1° scale all the sub grid heterogeneity (surface geometry, roughness, vegetation index, land surface temperature, surface wetness, albedo etc.), whereas, the towers aggregate at the 1 km scale or less. Although towers are often installed in relatively homogenous terrain, characteristics such as surface wetness and temperature can still be highly heterogeneous surface characteristics (Kustas and Norman, 1999; McCabe and Wood, 2006; Li et al., 2008) whilst also exerting nonlinear effects on λE (Nykanen and Georgiou, 2001). If, for example, the probability of a tower being located in either a cool/wet or hot/dry patch is even, and yet the cool/wet regions contribute disproportionately to the satellite scale latent heat flux then, on average, there clearly is a tendency for the tower observed flux to be less than its satellite counterpart (Bastiaanssen et al., 1997). Because of the diversity of nonlinear effects of surface characteristics on λE it is hard to evaluate these in detail here. One general inference can be drawn however; the degree of agreement we see in the pooled evaluation would suggest that the general scaling from tower to satellite appears somewhat conserved, a feature that is no doubt greatly aided by investigating the monthly average data. Although a more detailed footprint analysis is required to confirm this, the results in Table 1 suggest that the data from the taller, more extensive forest towers are more closely related to their satellite counterparts.

The pooled RMSD of 79 W m^{-2} for the λE evaluation is comparable with the results reported elsewhere for moderate (1 km^2) and coarse (10 km^2) resolution satellite λE when compared with tower flux data. Mecikalski et al. (1999) reported errors in time integrated daily λE estimates in the range of 37 to 59 $W m^{-2}$ while estimating continental scale fluxes over the USA using GOES (Geostationary Operational Environmental Satellite) data. The RMSD of λE retrieval errors from a series of studies over the Southern Great Plains of USA were found to be in the range of 40 to 85 $W m^{-2}$ using high resolution aircraft (Anderson et al., 2008), NOAA AVHRR (Jiang and Islam, 2001; Batra et al., 2006) and MODIS Terra optical and thermal data (Batra et al., 2006). In addressing the effects of scaling and surface heterogeneity issues on λE, McCabe and Wood (2006) obtained an RMSD of 64 $W m^{-2}$ when comparing spatially aggregated LANDSAT derived λE and MODIS Terra λE in central Iowa, USA. Using the surface temperature verses vegetation index triangle approach with MSG (Meteosat Second Generation) SEVIRI (Spinning Enhanced Visible and Infrared Imager) data, Stisen et al. (2008) obtained an RMSD of 31 to 41 $W m^{-2}$ for the Senegal River basin of Africa. Finally, Prueger et al. (2005) obtained a disagreement of 45 $W m^{-2}$ in λE while comparing 40 m aircraft and 2 m ground eddy covariance λE measurements again in central Iowa.

Our analysis also highlighted the well documented deficiency of the Bowen ratio approach under hot, dry conditions (Perez et al., 1999). In dry, high radiative load environments the assumption that $k_E \approx k_H$ appears to break down because large scale regionally advected sensible heat desaturates the surface and, as a result, the vertical temperature gradient becomes very large whilst the vapour pressure gradient becomes very small or negative. Under these conditions k_H becomes 2 to 3 times higher than k_E (Verma et al., 1978), a condition that appeared to persist over Australia throughout the summer of 2003.

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5 Conclusions

We conclude that the combination of the satellite sounding data and the Bowen ratio methodology shows significant promise for retrieving spatial fields of λE when compared with tower ground truth data, and warrants further investigation and refinement. The specification of satellite net available energy, and its shortwave component in particular, requires further attention. There are also circumstances where the satellite Bowen ratio method is inapplicable, but these conditions could be easily flagged by internal checks on the sounding profiles. Where the method appears to work, this provides estimates of λE that would prove valuable in a range of applications. In particular, because no land surface model has been involved in their derivation, the estimates of λE we show can be used as independent data for evaluating land surface parameterisations in a broad range of spatially explicit hydrology, weather and climate models. Furthermore, the availability of sounding data at both 1° and 5 km resolution in conjunction with tower and scintillometer surface flux data would provide an excellent opportunity to explore robust scaling methods in these same models.

Throughout this paper little or no mention is made of the sea latent heat estimates we make because of the lack of appropriate evaluation data sets on which to test these. The SEAFLUX project initiated by the World Climate Research Programme (WCRP) Global Energy and Water Experiment (GEWEX) Radiation Panel is addressing this in the near future. If our sea estimates pass such an evaluation then, again, we would imagine they would be similarly useful in weather and climate model development. Given the Bowen ratio method should work best in these moist environments we predict the sea estimates of latent heat we show here are potentially more reliable than their terrestrial counterparts.

The advent of microwave sounding platforms such as Megha Tropiques will afford an opportunity to extend the methodology to persistent overcast conditions, allowing for more detailed process studies. This approach could also exploit high spatial and temporal resolution geostationary sounder platforms like GOES and, in the near future,

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GIFTS (Geosynchronous Interferometric Fourier Transform Spectrometer) and INSAT (Indian National Satellite)-3-D. We also expect that the high vertical resolution soundings these platforms will provide will improve the accuracy of the current approach, particularly over elevated terrain.

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Table 1. Error analysis of AIRS derived λE and H over diverse plant functional types (biomes) of FLUXNET eddy covariance network. Values in the parenthesis are one standard deviation except for the correlation (r) where the values in the parenthesis are the standard errors of r.

Biome	λE RMSD ($W\,m^{-2}$)	λE Slope	λE r	λE N	H RMSD ($W\,m^{-2}$)	H Slope	H r	H N
EBF	84.84	1.02 (±0.04)	0.70 (±0.09)	65	53.2	0.64 (±0.03)	0.73 (±0.09)	66
MF	60.66	0.92 (±0.09)	0.65 (±0.14)	32	87.9	0.50 (±0.04)	0.67 (±0.14)	30
GRA	78.39	0.87 (±0.08)	0.67 (±0.12)	42	55.82	0.79 (±0.09)	0.43 (±0.15)	39
CRO	69.76	0.85 (±0.08)	0.59 (±0.15)	31	51.74	0.93 (±0.06)	0.79 (±0.11)	31
ENF	67.64	1.02 (±0.07)	0.76 (±0.10)	43	95.14	0.52 (±0.04)	0.62 (±0.13)	37
DBF	65.19	0.86 (±0.06)	0.68 (±0.09)	74	73.19	0.59 (±0.04)	0.49 (±0.11)	70
SAV	140.78	2.00 (±0.28)	0.41 (±0.22)	19	148.52	0.45 (±0.05)	0.51 (±0.22)	18
Pooled	78.74	0.98 (±0.02)	0.75 (±0.04)	306	76.94	0.59 (±0.02)	0.56 (±0.05)	291

EBF=Evergreen broadleaf forest, MF=Mixed forest, GRA=Grassland, CRO=Cropland, ENF=Evergreen needleleaf forest, DBF=Deciduous broadleaf forest, SAV=Savanna

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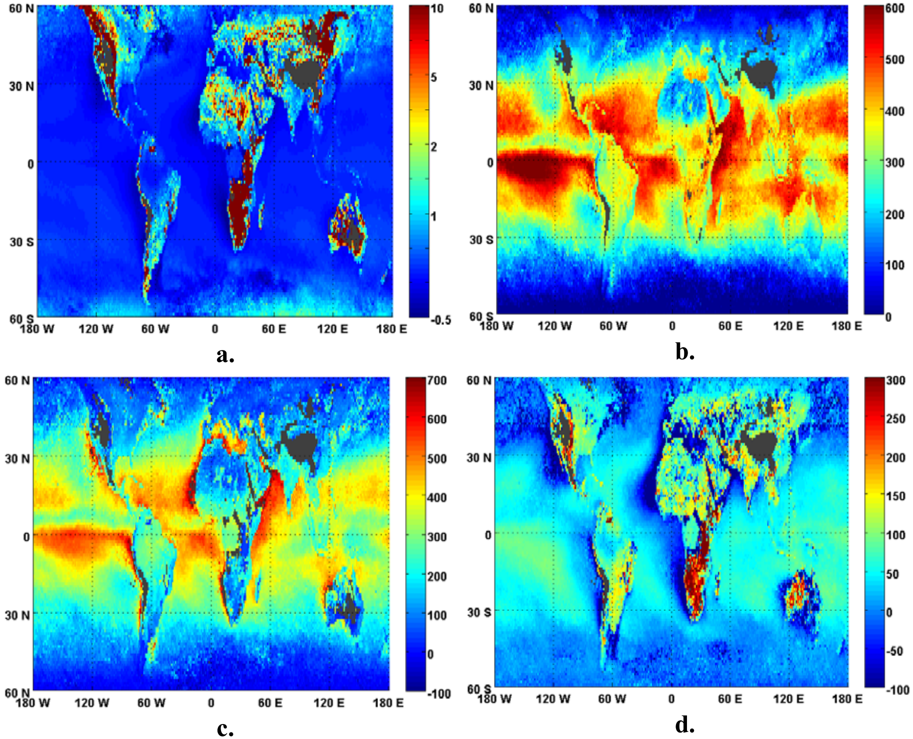

Fig. 1. Global fields of yearly average 13:30 LT derived from AIRS sounder observations for 2003. **(a)** Bowen ratio β (W m^{-2}/W m^{-2}). **(b)** Net available energy, Φ (W m^{-2}). **(c)** Latent heat flux, λE (W m^{-2}). **(d)** Sensible heat flux, H (W m^{-2}). Missing data are marked in grey.

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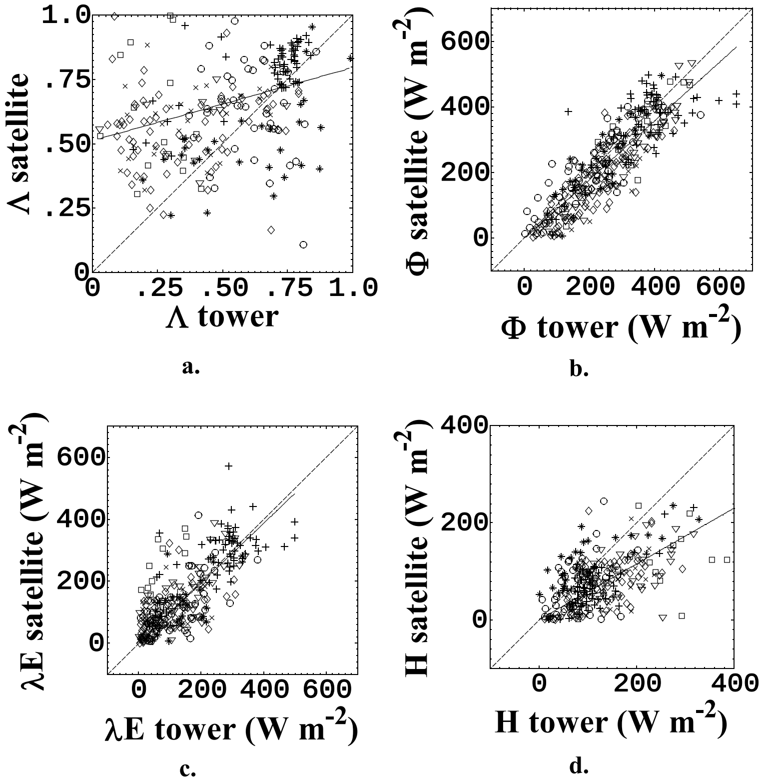

Fig. 2. The evaluation of the AIRS derived monthly 13:30 LT components against their tower equivalent. **(a)** Evaporative fraction, Λ. Here, the solid line denotes Λ(satellite)=0.31(±0.02)Λ(tower)+0.49(±0.04). **(b)** Net available energy, Φ. Here, the solid line denotes Φ(satellite)=0.90 (±0.03)Φ(tower)−2.43(±8.19) (see Jarvis et al., 2010). **(c)** latent heat flux, λE. **(d)** Sensible heat flux H. For regression statistics see Table 2. The dashed line is 1:1 in each case.
(+ EBF; × MF; ∘ GRA; ∗ CRO; ∇ ENF; ◊ DBF; □ SAV).

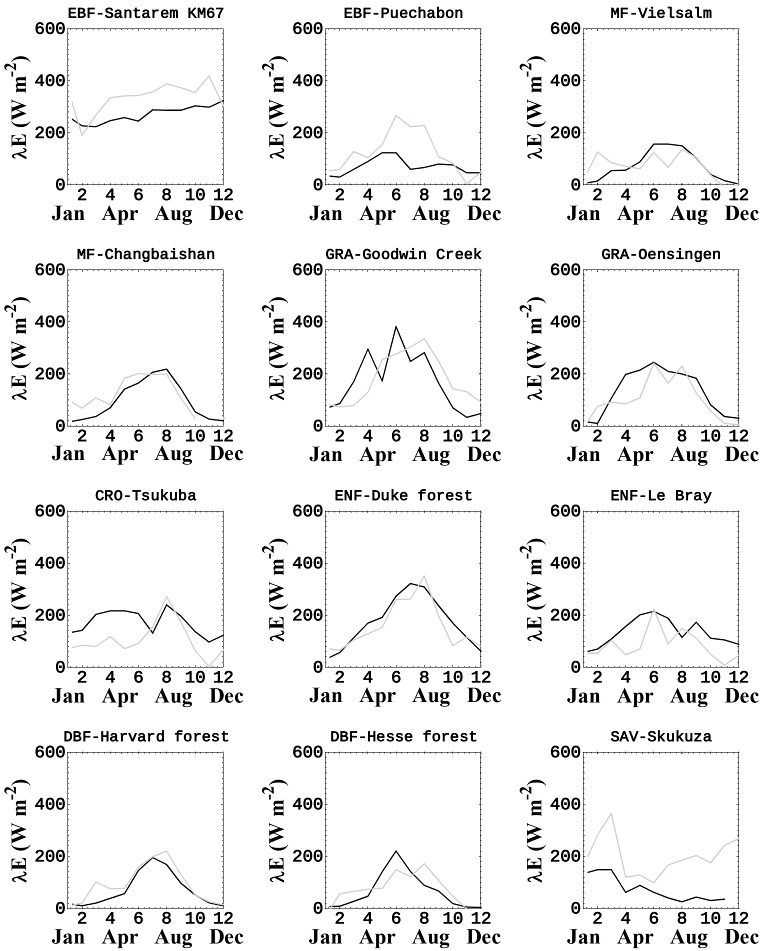

Fig. 3. Satellite (grey) and tower (black) time series of monthly average 13:30 LT latent heat flux, λE, for a selection of sites for 2003.