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Micro-climate influence on reference evapotranspiration estimates in wetlands

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ABSTRACT
Temperature and relative humidity measurements were made within and outside a lowland fen in eastern England during 2009 and 2010. Summer temperatures were found to be on average 0.24°C lower within the fen than outside, whilst summer vapour pressures were found to be on average 0.074 kPa higher within the fen. In contrast, winter temperatures were found to be higher within the fen by an average of 0.03°C. These differences may be expected to influence evapotranspiration estimates derived using data from each of the sites. The influence of the location of meteorological measurements on evapotranspiration estimates was therefore evaluated. The existence of a wetland micro-climate results in up to a 7% reduction in annual reference evapotranspiration compared to a site surrounded by arable farmland only 5.5 km away.

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1 Introduction

1.1 Background

The presence of water at or near the surface of a wetland for significant periods of time creates the saturated soil and distinctive micro-organisms and plant and animal communities that differentiate it from other, drier habitats (Acreman and Mountford 2009). Because of this frequent wetness, evapotranspiration from wetlands is often much greater than other land cover types (Bullock and Acreman 2003). For example, reed-beds may evaporate 20% more than short grass (Gilman *et al*. 1998). In many wetlands evapotranspiration dominates the water balance (Hammer and Kadlec 1986), particularly in wet heath and raised bogs, where the water balance is controlled by the balance between rainfall and evaporation (Acreman *et al*. 2009). In river-fed wetlands, evapotranspiration can exceed 5 mm d^{-1} (Gardner 1991) and make it a significant factor in a wetland's water budget. Consequently, quantitative estimates of evapotranspiration are vital for wetland site management and for water resources management in catchments containing wetlands (Acreman and Miller 2007). An essential prerequisite is an understanding of the feedback relationships between hydrometeorological factors and evaporation.

1.2 Examples of wetland ET

The rate of evaporation from wetlands depends on meteorological factors, radiation, wind speed, temperature and humidity and surface characteristics, such as the plant type, surface roughness and wetness of the soil (Oke 2002, Harding and Lloyd 2008). Wetlands tend to evaporate more water than other land types, such as forests, savannah grassland or arable land (Bullock and Acreman 2003) due to the dense vegetation and saturated or inundated soils. For example, Acreman *et al.* (2003) reported evapotranspiration rates from a reed-bed to be 14% higher than that of a nearby wet grassland over a five month period. Previous studies have demonstrated a range of evapotranspiration rates for different wetland environments. For example, sedge meadows in South Africa were found to evaporate between 0.6 and 9.8 mm d^{-1} during the summer, whilst nearby reed-bed evapotranspiration was found to be between 0.2 and 3.3 mm d^{-1} during the same period (Smithers *et al.* 1995). Within the UK, extreme values for reed-beds of 13.4 mm d^{-1} have been reported (Fermor *et al.* 2001) although lower values between 0.5 and 5 mm d^{-1} were found by Peacock and Hess (2004). For UK wet grasslands, rates between 0.6 mm d^{-1} during a very wet period to 6.4 mm d^{-1} during a hot dry spell have been reported from the Pevensey Levels, Sussex (Gasca-Tucker and Acreman 2000) and between 1 and 5.5 mm d^{-1} at Yarnton Mead, Oxfordshire (Gardner 1991). Mould *et al.* (2010) recorded up to 5.5 mm d^{-1} on the floodplain at Otmoor in Oxfordshire. Harding and Lloyd (2008) estimated an annual evaporation for wet grassland at Tadham Moor, Somerset, of 630 mm – 50 mm greater than the estimate for a grass surface.

1.3 Estimating wetland ET

Drexler *et al.* (2004) reviewed a range of techniques employed to estimate wetland evapotranspiration *in situ*, including diurnal water-table fluctuations, Bowen-ratio energy balance, surface renewal and the eddy-covariance approach. Due to the requirement for sensitive micrometeorological measurements, these techniques are often of limited use to research applications (Allen *et al.* 1998, Drexler *et al.* 2004), therefore, for practical wetland creation and management, estimates of wetland evapotranspiration are based on potential

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evaporation from an open water surface, E_O, (Penman 1948), or evapotranspiration from a hypothetical reference surface, ET_O, (Allen *et al.* 1998). These are then adjusted by an empirical canopy factor that reflects the ratio of wetland evapotranspiration to the reference value, and depends on the properties of the surface (especially the canopy resistance), the area of open water in the wetland and the depth to the water table (Mohamed *et al.* 2012). ET_O has been used as a reference in many wetland studies (e.g. Gasca-Tucker *et al.* 2007, Drexler *et al.* 2008, Anda *et al.* 2014), but by definition, it is not measured but derived from meteorological data.

The potential evapotranspiration of a hypothetical reference surface estimated from the Food and Agriculture Organization of the United Nations (FAO) Penman-Monteith equation, ET_O, has been adopted as a standard reference by many international organisations (e.g. Allen *et al.* 1994, 1998, 2005). It is determined from locally relevant data on temperature, solar radiation, humidity and wind speed (Allen *et al.* 1998). Whilst in research studies these may be measured within the wetland, practical wetland creation and management usually relies on data collected at standard meteorological stations sited in accordance with international guidance.

1.4 Microclimate effects

It is well recognised that wetlands create local microclimates. Přibáň and Ondok (1978) observed lower air temperatures within wet grassland communities than outside the wetlands. Comparison of the two wetland areas revealed that the difference in evapotranspiration rates was attributable to differing biomasses and ground heat fluxes. The different ground heat fluxes were attributed to differences in thermal conductivity of the soils between the two wetlands and differences in soil-moisture content (Přibáň and Ondok 1978). Brom and Pokorný (2009) reported smaller diurnal temperature variations and temperature amplitudes in wetlands in the Czech Republic relative to drained pastures. Huryna *et al.* (2014) measured 30% more evaporation from a wet meadow than from pasture and arable fields, suggesting this contributes significantly to the cooling of agricultural landscapes. Acreman *et al.* (2011) identified a lower temperature within the Somerset Levels and Moors, UK, compared to outside the wetland as a result of higher evapotranspiration and Raney *et al.* (2014) identified significantly different soil temperatures within temperate fens relative to surrounding uplands.

Several studies have reported different evapotranspiration estimates when using meteorological data collected within wetlands and from nearby weather stations located outside the wetland. For example, Gardner (1991) found monthly potential evapotranspiration totals were up to 25 mm higher when estimated using meteorological data from outside the wetland. Gasca-Tucker *et al.* (2007) report a similar finding, in which potential evapotranspiration estimated using data from outside the wetland was higher than that estimated from within the wetland for values above 2 mm d^{-1}. Although both studies acknowledge that the differing evapotranspiration estimates may have been a result of inconsistencies in data collection or calculation procedures, there is also the implication that they may result from microclimates within the wetland.

We therefore hypothesise that microclimates created within wetlands affect the drivers of evapotranspiration to an extent that estimates of reference evapotranspiration derived from weather stations unaffected by the presence of the wetland—for example historical data collected prior to wetland creation, or data from nearby synoptic weather stations—may be inappropriate for use in practical wetland hydrological management. This paper aims to compare air temperature and humidity within; on the edge of; and outwith a wetland in southern England in order to evaluate the impact of location of meteorological conditions on estimated reference evapotranspiration.

2 Methods

2.1 Study site

The study was conducted at Wicken Fen, Cambridgeshire, in eastern England (52.31°N, 0.28°E). Wicken Fen is a peat wetland covering approximately 323 ha and comprises a mosaic of vegetation communities, including reed-beds (dominated by *Phragmites australis*) and fen meadows (dominated by *Molina caerulea – Cirsium dissectum)*. It is a remnant island of once wider peat wetlands in the region, most of which have been drained for arable agriculture. The diverse communities at Wicken Fen represent different stages in the succession of a fenland habitat and have resulted in the Fen being designated as a site of national and international importance to conservation (Bennett and Friday 1997, Friday and Harvey 1997, McCartney and De La Hera 2004, Mountford *et al.* 2005). A previous hydrological study of Wicken Fen concluded that rainfall and evapotranspiration dominate the water balance. Annual evapotranspiration was estimated to average 417 mm for the period 1995 to 1999 (McCartney *et al.* 2001) whereas average annual precipitation is 567 mm.

Three automatic weather stations were sited at increasing distance from the centre of the Wicken Fen Reserve (Fig. 1, Table 1). Sedge Fen, near the centre of Wicken Fen, is a managed wetland with groundwater levels typically within 1 m of the surface throughout the year and large areas of standing water during the winter (McCartney and De La Hera 2004). Adventurers' Fen (on the edge of Wicken Fen) is reclaimed agricultural land now managed as a habitat for bird and invertebrate species. The hydrological regime at this site is one of winter flooding and below-surface water levels during summer. For ecological management purposes, the area of Adventurers' Fen under consideration has been divided into blocks separated by embankments (Bennett and Friday 1997). The weather station is situated atop one of these embankments. The Oily Hall weather station is situated amidst arable farmland that has been drained and reclaimed for agriculture. It is not only drier, but up to four metres lower in elevation, due to peat wastage (Waltham 2000). The transect was aligned with the prevailing wind direction (south-westerly) so as to ensure the off-fen instrumentation

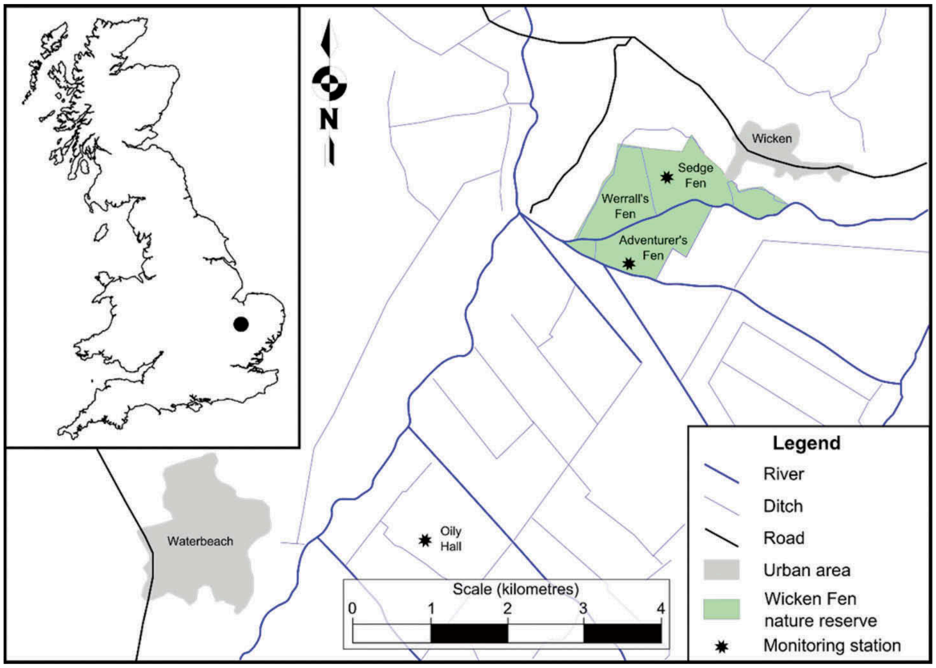

Figure 1. Location of Wicken Fen and monitoring stations at Sedge Fen, Adventurers' Fen and Oily Hall.

Table 1. Summary of recording station locations.

Site name	Latitude (ºN)	Longitude (ºE)	Distance from Sedge Fen (km)	Vegetation description
Sedge Fen	52.31	0.28		*C. mariscus* fen
Adventurers' Fen	52.30	0.27	0.95	Reedbed
Oily Hall	52.27	0.23	5.50	Fallow

was upwind of the wetland to minimise any influence of the wetland on humidity at the off-fen sites.

2.2 Instrumentation and data

All measurements cover the period 3 August 2008–27 September 2009. Temperature and relative humidity measurements were taken at the three locations (summarised in Table 1) using HMP45C temperature probes (Campbell Scientific, Logan, UT, USA). Data from the HMP45C probes were stored as half-hourly averages on a CR200 micrologger (Campbell Scientific, Logan, UT, USA). Solar radiation and wind-speed data were also recorded at Sedge Fen. The solar radiation was recorded using a Kipp & Zonen CNR1 radiometer (Campbell Scientific, Logan, UT, USA) and the wind speed at a height of 3.08 m using a DWR-201 cup anemometer (Didcot Instruments, London, UK). Data from both instruments were also stored as 30-minute averages, from which daily totals were derived. Given that incident solar radiation is not affected by the presence of the wetland and the close proximity of the stations, the solar radiation estimated at Sedge Fen was assumed to be representative of all sites. Using the equations of Wong and Chow (2001) the effect of latitude and vapour pressure would reduce solar radiation at Oily Hall and Adventurers' Fen by only 0.17% and 0.01%, respectively. Little spatial variation in direct beam, diffused and global horizontal radiation was apparent across distances of 500 m in Singapore (Jayaraman and Maskell 2012). It is well-known that wind speed can change with factors such as altitude (e.g. Justus and Mikhail 1976), but little is published on spatial patterns. The measurements sites are at the same altitude and not influenced by tall trees or buildings, so we considered that wind speed data from Sedge Fen could be applied at Oily Hall and Adventurers' Fen. This was confirmed by a comparison between Sedge Fen wind-speed data and data from Baker's Fen (1 km away – collected by Leicester University for a carbon flux experiment) for which there was very little difference in daily or 30 minute time series for March to August 2010. Furthermore, reference evapotranspiration is insensitive to small variations in wind speed. Therefore, in the reference evapotranspiration calculations, only the temperature and relative humidity data are unique to each site.

Prior to deployment, the three HMP45C probes used within this study were installed adjacent to one another at one meteorological station. The 30-minute temperature and relative humidity data from the Adventurers' Fen and Oily Hall probes were compared to that from the Sedge Fen probe by means of linear regression and subsequent measurements were corrected so as to remove the effects of systematic errors from the data. A second calibration was undertaken following the completion of the measurement campaign to ascertain whether the regression parameters had changed during the measurement period (Appendix). The regressions applied to the Adventurers' Fen and Oily Hall temperature and relative humidity data have an inherent error that may be quantified as the mean square error, MSE, from which it is possible to derive the 95% confidence interval, CI, defining the range within which observed differences between the Sedge Fen and Adventurers' Fen or Oily Hall data may be attributed to errors within the regressions applied to the data from the probes. Any differences lying outside of these confidence intervals are likely to indicate actual differences in the variable of interest at the two sites under consideration.

2.3 Data processing and analysis

Data are presented as weekly mean anomalies relative to Sedge Fen, representing the difference in the variable of interest between the site of interest and Sedge Fen. Daily reference evapotranspiration, ET_O (mm), was calculated using the Penman-Monteith method (equation 1) described by Allen *et al.* (1998) using the AWSET software (Hess 2002). Analysis of all data was performed using R version 3.0.1 (The R Foundation for Statistical computing 2013).

$$ET_o = \frac{\Delta}{\Delta + \gamma^*}\frac{(R_n - G)}{\lambda} + \frac{86.4}{\lambda}\frac{1}{\Delta + \gamma^*}\frac{\rho cp}{ra}(ea - ed) \quad (1)$$

where Δ is the slope of vapour pressure curve (kPa °C^{-1}), λ is the latent heat of vapourisation (MJ kg^{-1}), ρ is the atmospheric density (kg m^{-3}), cp is the specific heat of moist air 1.013 kJ kg^{-1}°C^{-1}, ea is the mean saturation vapour pressure (kPa) and ed the actual vapour pressure (kPa). Net radiation, R_n (MJ m^{-2} d^{-1}), is estimated from measured shortwave radiation, assuming a fixed albedo of 0.23 for the reference surface, and longwave radiation estimated from sunshine fraction, air temperature and vapour pressure (Allen *et al.* 1998). Soil heat-flux, under the reference surface G (MJ m^{-2} d^{-1}), is estimated from change in daily mean air temperature (Wright and Jensen 1972). Aerodynamic resistance, ra (s m^{-1}), is estimated from wind speed using fixed roughness parameters for heat, water vapour and momentum for the reference surface (Allen *et al.* 1998). γ^* is the modified psychrometric constant (equation 2),

$$\gamma^* = \gamma\left(1 + \frac{rc}{ra}\right) \quad (2)$$

where γ is the psychrometric constant (kPa°C^{-1}) and rc is the bulk surface resistance for the reference surface (70 s m^{-1}).

3 Results

3.1 Air temperature

The weekly mean temperature data from Adventurers' Fen and Oily Hall are presented as anomalies relative to the Sedge Fen temperature data in Fig. 2. Similar trends are observed at both Adventurers' Fen and Oily Hall. The temperatures at each site are slightly higher than those at Sedge Fen during the summer months (June–October) and slightly lower during the winter months (November–May). Although the general trends at Adventurers' Fen and Oily Hall are similar, the temperatures at Oily Hall exhibit greater positive anomalies during summer and greater negative anomalies during winter than those at Adventurers' Fen relative to the temperatures at Sedge Fen. The Adventurers' Fen temperature anomaly data show a greater tendency to fall within the confidence interval than the Oily Hall temperature anomaly data, particularly during the winter period. Only during the summer period do the temperature anomalies for both stations lie outside the confidence intervals for sustained periods.

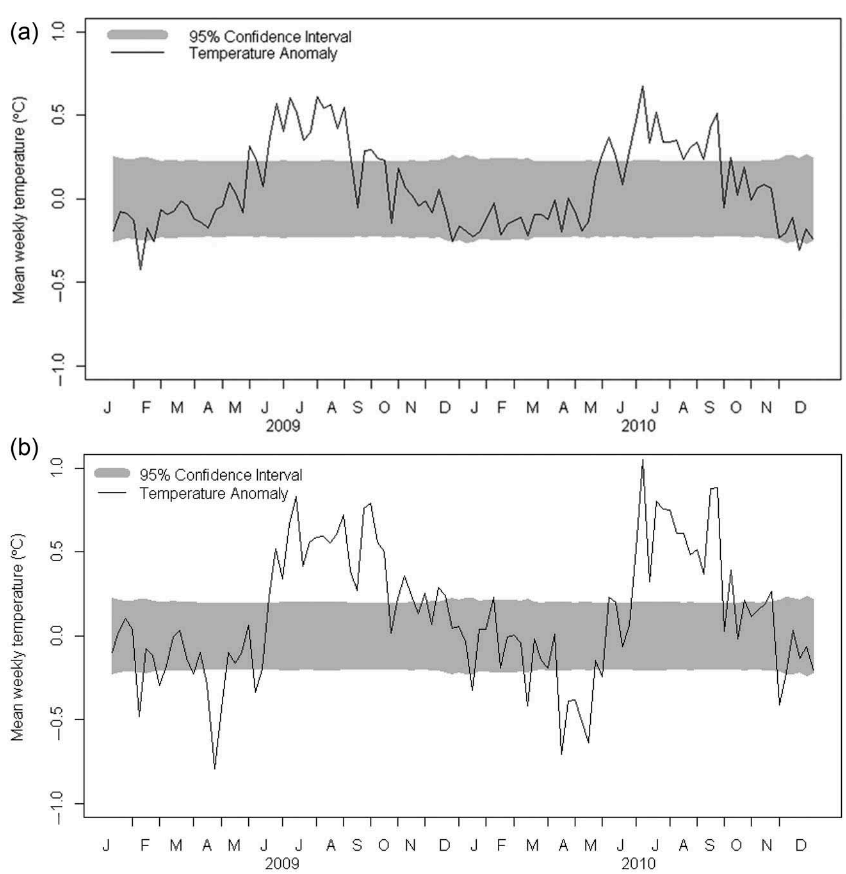

Figure 2. Weekly mean temperature anomalies relative to Sedge Fen at (a) Adventurers' Fen and (b) Oily Hall.

The daily mean temperature data from Adventurers' Fen and Oily Hall were compared to the daily mean temperature data from Sedge Fen by means of a Mann-Whitney U-test (Mann and Whitney 1947). The median values of daily mean temperature at Adventurers' Fen and Oily Hall were both significantly different ($P < 0.01$) from Sedge Fen.

The 30-minute mean temperature anomalies at Adventurers' Fen and Oily Hall relative to Sedge Fen are presented in Fig. 3. The 30-minute temperature anomalies for Adventurers' Fen demonstrate that the temperature at Adventurers' Fen exceeds that at Sedge Fen between approximately 16:00 and 06:00. For the remainder of the day, the Sedge Fen temperature is higher than the temperature at Adventurers' Fen. Most of the 30-minute Adventurers' Fen anomalies lie within the 95% confidence interval, the exceptions being the anomalies between approximately 19:00–22:00 which lie just outside the confidence interval. The Oily Hall 30-minute temperature anomalies exhibit the same trends as the Adventurers' Fen anomalies. However, the Oily Hall anomalies demonstrate a larger amplitude, resulting in much of the data lying outside the confidence interval. The positive anomalies (indicating that the Oily Hall temperature exceeds that at Sedge Fen) lie outside the confidence interval between approximately 17:00 and 05:00, whilst the negative anomalies (indicating that the Sedge Fen temperature exceeds that at Oily Hall) lie outside the confidence interval between approximately 07:00 and 15:00.

The mean weekly diurnal temperature ranges for Adventurers' Fen and Oily Hall are summarised as anomalies relative to those at Sedge Fen in Fig. 4. A general seasonal trend is evident in which the diurnal temperature range at Sedge Fen is greater than that at Adventurers' Fen during the summer, but similar in the winter. The diurnal temperature range at Sedge Fen is generally greater than that at Oily Hall throughout the year, although the differences during the winter are lower than those observed during the summer.

3.2 Vapour pressure

The weekly mean vapour pressure data from Adventurers' Fen and Oily Hall are presented as anomalies relative to the Sedge Fen vapour-pressure data in Fig. 5. The vapour pressures at Adventurers' Fen are typically slightly lower than those at Sedge Fen, although the Adventurers' Fen anomalies generally lie within the confidence interval. The anomalies only lie outside the confidence interval for a sustained period from March to May 2010. By contrast, the vapour pressure at Oily Hall is consistently lower than that at Sedge Fen and typically lies outside the confidence interval. During 2010, the

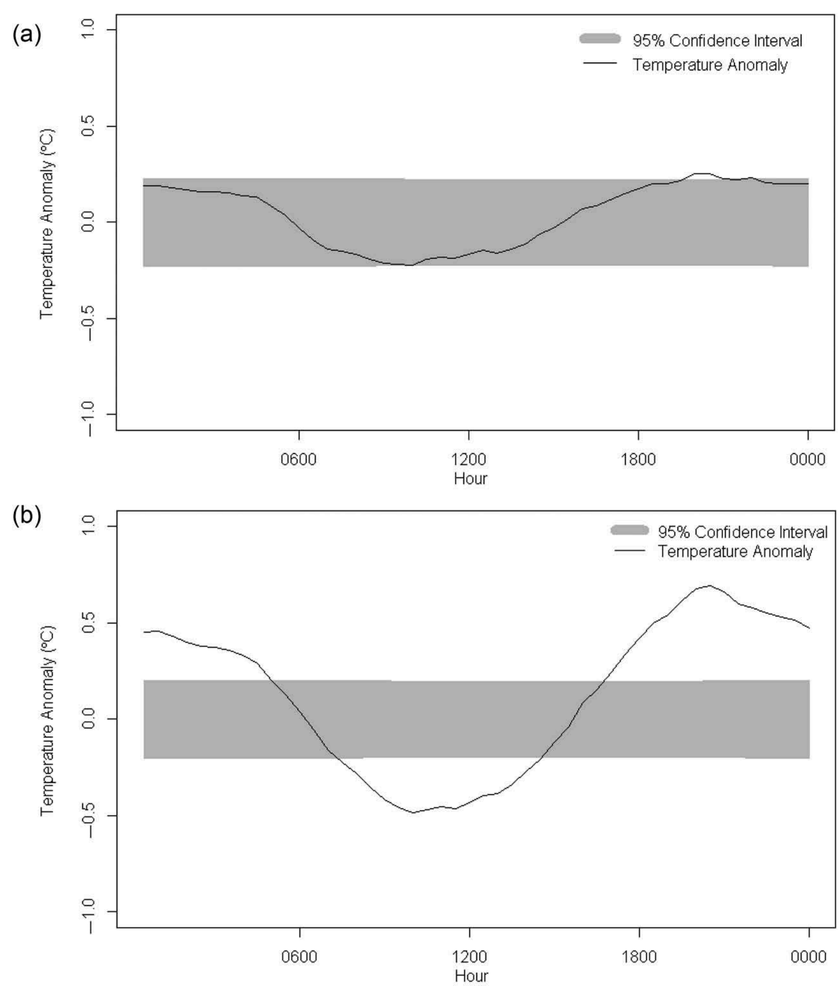

Figure 3. 30-minute mean temperature anomalies relative to Sedge Fen at (a) Adventurers' Fen and (b) Oily Hall.

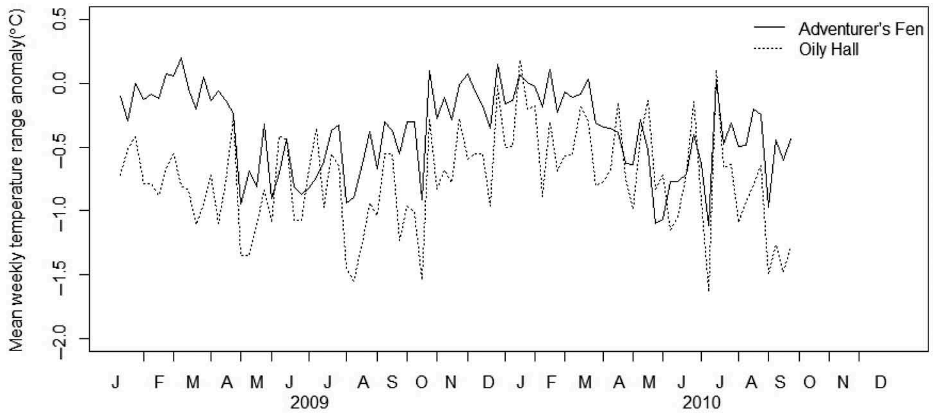

Figure 4. Weekly mean diurnal temperature range anomalies relative to Sedge Fen at Adventurers' Fen and Oily Hall.

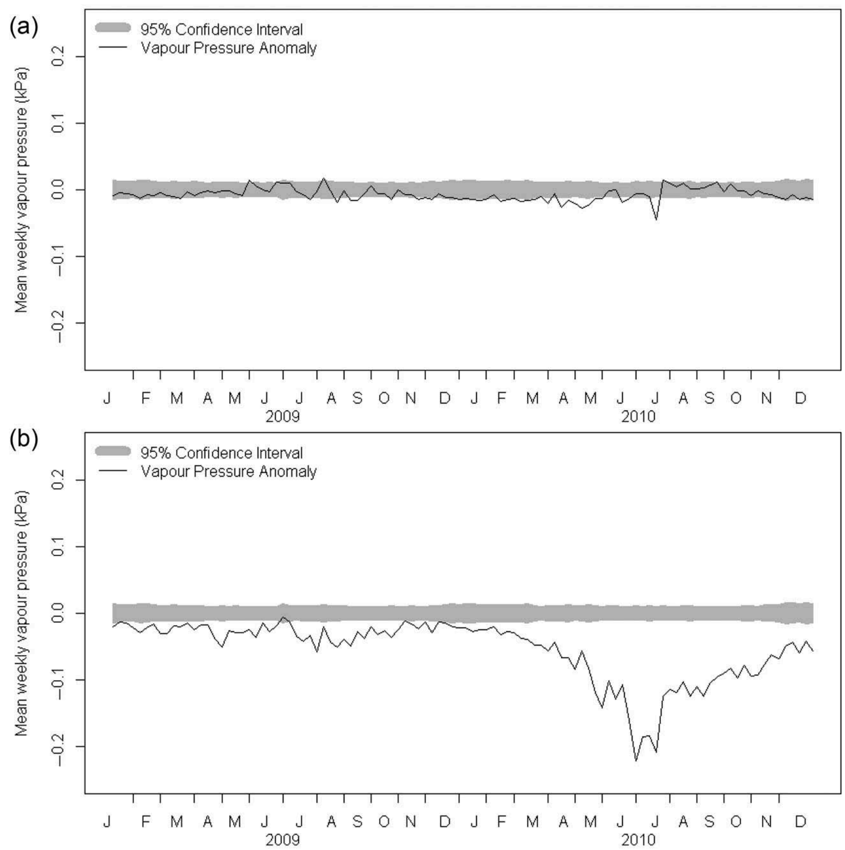

Figure 5. Mean weekly vapour pressure anomalies relative to Sedge Fen at (a) Adventurers' Fen and (b) Oily Hall.

negative vapour pressure anomaly observed at Oily Hall is greater than that observed during 2009.

The daily mean vapour-pressure data from Adventurers' Fen and Oily Hall were compared to the daily mean vapour pressure data from Sedge Fen by means of a paired Mann-Whitney U-test. The results demonstrate that the differences in the mean daily vapour pressure at both Adventurers' Fen and Oily Hall are statistically significant ($P < 0.01$).

The enhanced vapour pressure anomaly observed at Oily Hall during summer 2010 may have been due to instrumental drift. The vapour pressure anomalies for both stations were recalculated using the 2011 calibrations (Section 2.2) and are presented alongside the anomalies calculated using the 2008 calibrations (Fig. 6).

The Adventurers' Fen anomalies based on the 2011 regressions show a general agreement with those based on the 2008 regressions, differing by an average of 0.0028 kPa during the study period. The obvious exceptions are the large variations in the anomalies based upon the 2011 regressions from March to May 2010. By contrast, the Oily Hall vapour pressure anomalies based on the 2011 regressions show a marked disagreement with those based on the 2008 regressions. For the Oily Hall probe, the vapour pressure anomalies based on the 2011 regressions are on average 0.0808 kPa higher than

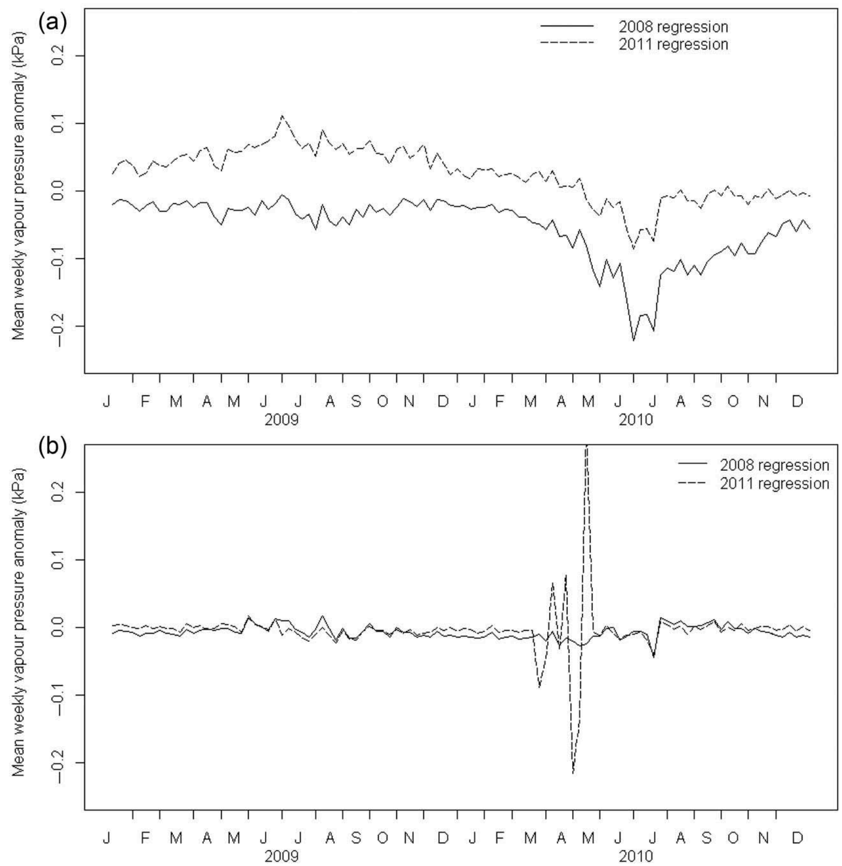

Figure 6. Comparisons of mean weekly vapour pressure anomalies relative to Sedge Fen using 2008 regressions (Table 3) and 2011 regressions (Table 4) for (a) Oily Hall and (b) Adventurers' Fen.

those based on the 2008 regressions. The magnitude of the summer 2010 vapour pressure anomalies at Oily Hall calculated according to the 2011 regressions are comparable with the magnitudes of the summer 2009 anomalies calculated according to the 2008 regressions.

3.3 Reference evapotranspiration

The annual reference evapotranspiration totals for Adventurers' Fen and Oily Hall using both sets of calibration parameters and for Sedge Fen using the 2008 calibrations are summarised in Table 2.

Weekly mean reference evapotranspiration estimates for Adventurers' Fen and Oily Hall are presented as anomalies relative to Sedge Fen reference evapotranspiration estimates in Fig. 7. The reference evapotranspiration at Sedge Fen is generally lower than both Adventurers' Fen and Oily Hall. The reference evapotranspiration anomalies peak during the summer at both sites. The reference evapotranspiration estimates at Oily Hall are greater than those at Adventurers' Fen for most of the observation period. The only exceptions are in the April–June period, when the Oily Hall reference evapotranspiration estimates are lower than those for Adventurers' Fen. The largest anomalies are observed at Oily Hall during summer 2010.

The annual reference evapotranspiration estimate for Adventurers' Fen is insensitive to the calibration parameters used and in both years was 2.5% greater than for Sedge Fen. However, the estimate for Oily Hall showed a 7% difference in annual reference evapotranspiration between the two calibrations. As a result, using the 2008 calibration parameters, estimated annual reference evapotranspiration at Oily Hall was greater than the other two stations in both years, whereas using the 2011 calibration parameters in 2009, it was the lowest of the three and in 2010 was similar to Adventurers' Fen.

Table 2. Summary of reference evapotranspiration data at all stations, 2009 and 2010.

	Sedge Fen		Adventurers' Fen		Oily Hall	
	2009	2010	2009	2010	2009	2010
Total ET_O (mm) 2008 calibrations	603.6	578.1	618.4	592.8	633.3	639.6
Total ET_O (mm) 2011 calibrations			618.2	592.8	586.0	596.5

4 Discussion

The temperatures data reveal the weekly mean temperature at Adventurers' Fen and Oily Hall to be higher than those at Sedge Fen during the summer months (by an average of 0.24°C) and lower during the winter (by an average of 0.03°C). Furthermore, Oily Hall exhibits greater temperature anomalies relative to Sedge Fen than Adventurers' Fen. Statistical comparison of the daily mean temperatures showed the data from Adventurers' Fen and Oily Hall to be significantly different from those at Sedge Fen. The temperature anomalies

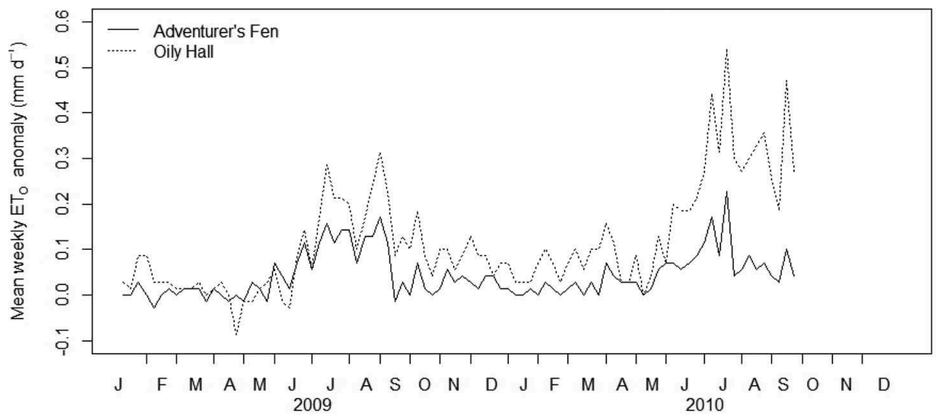

Figure 7. Weekly mean reference evapotranspiration anomalies relative to Sedge Fen at Adventurers' Fen and Oily Hall

at Adventurers' Fen exhibit a tendency to lie within the 95% confidence interval during the winter period and to lie outside the confidence interval for a sustained period only during the summer. This suggests that Sedge Fen only experiences a summer microclimate relative to Adventurers' Fen, in which temperatures are suppressed at Sedge Fen. The anomalies at Oily Hall exhibit a greater amplitude than those at Adventurers' Fen, as well as an enhanced tendency to lie outside the confidence interval. These results reinforce the aforementioned suggestion of suppressed summer temperatures at Sedge Fen as well as indicating that Sedge Fen temperatures may be enhanced relative to those at Oily Hall during the late winter period (i.e. April and May).

The 30-minute mean temperature anomalies at Adventurers' Fen and Oily Hall relative to Sedge Fen demonstrate that temperatures at Sedge Fen are higher than those at the other sites during much of the daylight period and lower overnight. These findings are therefore indicative of a larger diurnal temperature range at Sedge Fen than either Adventurers' Fen or Oily Hall. However, only the Oily Hall 30-minute anomalies lie outside the 95% confidence intervals for much of the day. Therefore, the diurnal temperature ranges at Sedge Fen and Adventurers' Fen cannot definitively be said to be different, since the observed anomalies may be attributable to the linear corrections applied to the Adventurers' Fen temperature data. The similar diurnal temperature ranges at these sites may be a reflection of the location of Adventurers' Fen on the edge of the wetland site. Since many of the Oily Hall 30-minute temperature anomalies lie outside the confidence intervals, it is reasonable to conclude that the diurnal temperature range at Sedge Fen is greater than the range at Oily Hall. This contrasts with the findings of Brom and Pokorný (2009), who reported narrower temperature ranges at wetland sites relative to drained pastures. This suggests that reduced temperature ranges are not a universal feature of wetland microclimates, although further investigation will be required in order to ascertain the mechanisms controlling diurnal temperature ranges in wetlands.

The diurnal temperature range anomalies relative to Sedge Fen exhibit a seasonal pattern. During the summer months the diurnal temperature range is greater than that at Adventurers' Fen and Oily Hall. The weekly mean temperatures previously commented upon indicated a tendency for Adventurers' Fen and Oily Hall to be slightly warmer than Sedge Fen during the summer. When considered in the context of larger diurnal temperature ranges at Sedge Fen than the other sites, it would seem that the summer daily minimum temperatures are lower at Sedge Fen than either of the other sites. Thus, overnight cooling within the wetland is greater than outside during the summer months, whilst the daytime maxima at all sites during the summer are similar. This may be indicative of overnight temperatures being stabilised by the release of stored heat within the surface layer outside of the wetland, implying that incident energy is either not stored within the surface layer at the wetland or that stored energy is not released overnight in the wetland. However, surface energy budget measurements would be required at all three sites to further investigate these possible explanations.

The weekly mean vapour pressure anomalies reveal a tendency for all sites to experience similar winter regimes, whilst Oily Hall and Adventurers' Fen are less humid than Sedge Fen in the summer, by an average of 0.074 kPa and 0.004 kPa, respectively. The vapour pressure anomalies at Adventurers' Fen lie within the confidence interval for most of the observation period so cannot definitively be said to differ from the vapour pressures observed at Sedge Fen. In contrast, the Oily Hall vapour pressure anomalies lie outside the confidence intervals for almost the entire duration of the observation period and are therefore indicative of heightened atmospheric vapour pressures within the wetland compared to outside. Unlike the temperature anomalies, the magnitude of the Oily Hall vapour pressure anomaly differs in successive years. The 2010 average vapour pressure anomaly is 0.064 kPa greater than that during 2009. Investigation of the vapour pressure data from all sites revealed that the vapour pressures at Sedge Fen and Adventurers' Fen are comparable in both years, whilst the vapour pressure at Oily Hall is lower in 2009 than 2010. Therefore, the differences observed in the Oily Hall vapour pressure anomalies are attributed to annual differences in the Oily Hall vapour pressure data. This suggests that the vapour pressure is more stable on an annual basis within the wetland than outside. The generally higher vapour pressures observed at the wetland may represent the greater availability of water for evapotranspiration at this site. If actual evapotranspiration is greater within the wetland than outside, this may account for the more humid atmosphere observed at Sedge Fen compared to that at Oily Hall.

However, the differences observed in the Oily Hall vapour-pressure data may also imply that the relative humidity probe at Oily Hall has drifted from the calibration parameters defined in Section 2.2. The regression parameters derived prior to the commencement of the deployment of the instruments have been shown to alter during the study period. This is indicative of an alteration in the response characteristics of either one or both sensors in each pairing during the measurement campaign. In future studies it would be expedient to deploy duplicate sensors at each site. The Adventurers' Fen vapour pressure anomalies are similar whether the 2008 or 2011 regressions are applied, implying that the response characteristics of the probes at Sedge Fen and Adventurers' Fen remain stable relative to one another. The large variation observed during spring 2010 when applying the 2011 regression to the Adventurers' Fen vapour pressure data coincides with a similar variation in the temperature data when using the same regression parameters. Since the vapour-pressure data are derived from temperature data (equations A4 and A5), it would seem that the large variation of vapour pressure anomalies are attributable to variations of the temperature anomalies.

No such stability is observed within the Oily Hall vapour-pressure data when applying the 2008 and 2011 regression data. The relative responses of the Oily Hall and Sedge Fen probes have therefore altered during the measurement campaign. It is likely that the response characteristics of the sensors changed gradually, rather than as an instantaneous step change, although positively identifying the rate of this change is impossible on the basis of the data available. Furthermore, the response characteristics may have continued to change between the end of the data-collection period in December 2010 and the comparison undertaken in July 2011. However, it is reasonable to assume that the 2008 regression parameters are representative of the earlier part of the data collection period, whilst the 2011 regression parameters are representative of the latter part. The remainder of the discussion shall assume this to be the case.

A case may therefore be made for the apparently large negative vapour-pressure anomaly observed at Oily Hall during summer 2010 being an artefact of the application of inappropriate regression parameters arising from instrumental drift rather than evidence of a significantly drier atmosphere during this period. This would necessitate the downward revision of the reference evapotranspiration estimate for 2010 at Oily Hall so as to reflect the reduced vapour-pressure deficit. However, this does not necessarily imply that the identification of a wetland microclimate at Sedge Fen with respect to summer vapour pressure is erroneous. Given the similarity in magnitudes of the vapour pressure anomalies at Oily Hall when applying the 2008 regressions to the summer 2009 data and the 2011 regressions to the 2010 data, it is feasible that a change in the sensor responses may have occurred during the intervening winter period.

Table 3. Comparison of half-hourly temperature and relative humidity data from HMP45Cs at Adventurers' Fen and Oily Hall, relative to that installed on Sedge Fen (5 and 6 June 2008).

	Adventurers' Fen		Oily Hall	
	Temperature	Relative Humidity	Temperature	Relative Humidity
Gradient	1.024	1.003	1.024	0.999
Standard error	0.005	0.004	0.004	0.004
p-value	<0.01	<0.01	<0.01	<0.01
y-intercept (°C/%)	−0.284	−0.330	−0.341	−0.028
Standard error	0.058	0.332	0.052	0.307
p-value	<0.01	0.327	<0.01	0.928
R^2	0.999	0.999	0.999	0.999

However, not all of the anomalies presented within this study are necessarily indicative of a wetland microclimate as some of the temperature anomalies and most of the Adventurers' Fen vapour pressure anomalies lie within the error margins resulting from the application of the regressions detailed in Tables 3 and 4. The Oily Hall data exhibits a greater tendency to lie outside the error margins, therefore a wetland microclimate characterised by lower summer temperatures, higher winter temperatures and consistently higher vapour pressures is most evident when comparing the Oily Hall and Sedge Fen data, although this is likely partially attributable to the aforementioned sensor drift. The tendency for the Adventurers' Fen data to show greater affinity with the Sedge Fen data is likely due to the location of the Adventurers' Fen station on the edge of the wetland.

The magnitudes of seasonal average anomalies compare favourably with those of Li *et al.* (2009), in which atmospheric variables and surface fluxes were measured at a 900 km^2 reed-bed wetland and an arable plantation. Enhanced air temperatures at the wetland were reported, averaging 0.3°C over a year. Also, the vapour pressure deficits reported showed that during the growing season the atmosphere at the reed-bed wetland was more humid than that at the arable site by an average of 0.07 kPa. The magnitudes of the temperature and humidity differences reported within this study and that of Li *et al.* (2009) would seem to suggest that similar effects are observed in both cases irrespective of wetland size. However, Li *et al.* (2009) did not evaluate the potential inconsistencies between sensors. As this work has shown, the precision of individual sensors must be considered when dealing with such small differences. Wicken Fen may also be said to be providing a climate regulation ecosystem service, as identified by Acreman *et al.* (2011).

Table 4. Comparison of half-hourly temperature and relative humidity data from HMP45Cs at Adventurers' Fen and Oily Hall, relative to that installed on Sedge Fen (15 and 29 July 2011).

	Adventurers' Fen		Oily Hall	
	Temperature	Relative Humidity	Temperature	Relative Humidity
Gradient	0.996	0.955	0.999	0.97
Standard error	0.003	0.004	0.005	0.008
p-value	<0.01	<0.01	<0.01	<0.01
y-intercept (°C/%)	0.073	3.536	0.046	7.785
Standard error	0.051	0.307	0.069	0.589
p-value	0.154	<0.01	0.499	<0.01
R^2	0.993	0.99	0.987	0.99

5 Conclusion

The reference evapotranspiration estimates (ET_O) based on the temperature and relative humidity data gathered at the three sites imply that lower reference evapotranspiration can be expected at Sedge Fen than Adventurers' Fen and Oily Hall. During the study period, the ET_O estimates for Adventurers' Fen and Oily Hall were 2.5% and up to 7.7% higher than for Sedge Fen, respectively, which is consistent with the warmer, drier atmospheres observed at Adventurers' Fen and Oily Hall stimulating a greater atmospheric "demand" for evapotranspiration by enhancing the vapour pressure deficit term within the Penman-Monteith equation.

A possible wetland microclimate has been identified in the peat wetland at Sedge Fen, characterised by lower summer mean temperatures, higher winter mean temperatures and a larger diurnal temperature range than at nearby sites in arable farmland outside the wetland. The vapour pressure was also consistently higher (although this may have been an artefact of instrumental drift in the case of the Oily Hall station). This creates a dilemma for wetland evapotranspiration studies. When seeking to calculate reference evapotranspiration, meteorological data should ideally be collected within wetlands so as to capture microclimate effects accurately. However in situations where this is not possible, meteorological data sourced from locations outside the wetland may not be sufficiently proximate to represent atmospheric conditions at the wetland adequately.

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No potential conflict of interest was reported by the authors.

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Appendix

Sensor calibration and confidence interval

The regressions of temperature and relative humidity measurements from the three sensors prior to deployment (Table 3) demonstrate that the gradients derived for temperature and relative humidity are statistically significant at the 0.01 level, although all gradients show minimal deviation from unity. Only the temperature data exhibit statistically significant values for the y-intercept. The high R^2 values indicate that almost all the variance in data between the probe at Sedge Fen and those at Adventurers' Fen and Oily Hall are explained by the linear relationships detailed in Table 3. Following the completion of the measurement campaign a second calibration was performed using the same method. This showed that the regression parameters of all relationships have changed since the original comparison. The greatest differences between the 2008 and 2011 regression parameters are in the y-intercepts, and in particular those of the relative humidity regressions.

The equations used to define the mean square error and confidence interval are presented below.

The variables referred to throughout this study are defined as follows:

$$\mathrm{MSE} = \frac{\sum (y - y_i)^2}{n-2} \tag{A1}$$

where:

y = variable measured by Sedge Fen probe during calibration
y_i = variable predicted from Adventurers' Fen or Oily Hall probe during calibration
n = number of calibration measurements

$$\mathrm{CI} = \pm t_{(n-2)} \sqrt{\mathrm{MSE}\left[1 + \frac{1}{n} + \frac{(y_k - \bar{y})^2}{\sum (y_i - \bar{y})^2}\right]} \tag{A2}$$

where:

y_k = variable measured by probe at Adventurers' Fen or Oily Hall
y_i = mean of variable predicted during calibration
$t_{(n\text{-}2)}$ = t-statistic for *n-2* degrees of freedom at the 95% confidence limit

$$T_{\mathrm{mean}} = \frac{T_{\mathrm{max}} + T_{\mathrm{min}}}{2} \tag{A3}$$

where:

T_{mean} = Mean daily air temperature (°C)
T_{max} = Maximum daily air temperature (°C)
T_{min} = Minimum daily air temperature (°C)

$$e_s(T) = 0.6107 e^{\frac{17.27T}{T+237.3}} \tag{A4}$$

where:

$e_s(T)$ = Saturation vapour pressure (kPa) at air temperature T (°C)

$$e = \frac{\mathrm{RH}}{100}\left(\frac{e_S(T_{\mathrm{min}}) + e_S(T_{\mathrm{max}})}{2}\right) \tag{A5}$$

where:

e = Vapour pressure (kPa)
RH = Relative humidity (%)