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Surface energy exchanges over contrasting vegetation types on a sub-tropical sand island

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ABSTRACT

The surface energy balance of sub-tropical coastal vegetation has received little attention. Here we present a multi-year observational data set using the eddy covariance method to quantify, for the first time, the surface energy balance over three contrasting representative vegetation types on a sub-tropical sand island in eastern Australia: a periodically inundated sedge swamp, an exotic pine plantation and a palustrine wetland. On seasonal time scales, the palustrine wetland exhibited a Bowen ratio (β) ≈ 1, the pine plantation β > 1, and the swamp β varied from β ≤ 1 during wet seasons and inundation to β > 1 during dry seasons. The partitioning of energy is similar to a variety of Australian ecosystems and coastal vegetation types in other latitudes.

Energy fluxes responded to seasonal changes in background meteorology with the most important influences being net radiation and the surface layer temperature gradient, with the soil temperature-ambient temperature gradient, ground temperature, and vapour pressure deficit also important. Sites differed according to soil water content, with the remnant palustrine wetland and swamp having ready access to water but the exotic pine plantation having much drier soils. We conclude that should the current balance between vegetation types change, there would be a corresponding shift in the overall surface energy balance of the island, affecting its micrometeorology, and water table depth.

1. Introduction

The land surface interacts with the atmosphere in a multitude of ways depending on surface type and its ability to store and emit energy, or the availability of moisture for evapotranspiration. In coastal environments, variations in circulation on synoptic and local scales mean regular exposure to both terrestrial and marine air masses, with the contrasting thermodynamic properties affecting partitioning of available energy (Lafleur and Rouse, 1988; Trepekli et al., 2016). Combined with the pronounced changes in surface properties that occur across the shoreline, knowledge of the micrometeorology of coastal environments and associated land surface-atmosphere energetics is crucial in understanding development of local winds, cloud and precipitation. Coastal environments are also often subject to rapid environmental change due to urbanisation and land use change (Crossland et al., 2005), which may also modify hydrometeorological processes (Pielke et al., 2011).

Studies of the energy balance of coastal environs are more numerous for mid- to high-latitude settings. For example, herbaceous tundra in the coastal plains of northern Alaska (Vourlitis and Oechel, 1997); inundated sedge grasses near the Arctic Circle in the Hudson Bay region of Canada (Rouse et al., 1987); and dry and inundated grasses and sedges, and woodland on the coast of James Bay, Canada (Lafleur and Rouse, 1988). In the mid-latitudes, Li et al. (2009) made observations over maize and a seasonally flooded reed wetland in near-coastal locations in north-east China; Trepekli et al. (2016) studied energy fluxes at a coastal grassland in north-eastern Greece; and Moffett et al. (2010) conducted a short-term energy balance study of a tidal salt-marsh in the San Francisco Bay. Collectively, these authors found the energy balance to be typically influenced by combinations of net radiation (Q^*), precipitation, wind direction, vapour pressure deficit (e_d), ambient and soil temperature, availability of surface and subsurface water, and phenological changes in local vegetation. Wind direction is important due to the influence air mass origin has on e_d and temperature, with onshore winds typically reducing temperature and latent heat flux (Q_e) (Trepekli et al., 2016), thereby increasing the Bowen ratio (β) and ground heat flux (Q_g) (Lafleur and Rouse, 1988).

In the tropics, coastal environment energy balances remain largely undocumented. Sensible heat flux (Q_h) and Q_e have been found to be dominant in dry and wet seasons respectively at a site 30 km from the coast of southern China (Bi et al., 2007). Ramier et al. (2009) have

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shown that air mass characteristics remain important in inland monsoonal equatorial zones, but seasonal cycles of vegetation and soil water are equally as important. They observed dry season Q_h dominance, linked to soil surface temperature, and wet season Q_e dominance, resulting from high soil moisture. Guyot et al. (2012) noted that variability in energy partitioning on inter-annual time scales resulted from changes in wind direction and flux source area. They found changes in wind direction resulted in a switch between continental and monsoonal air masses; and changes in flux source area led to variation in surface conditions such as water availability, vegetation type and cover, and albedo. Studies of surface-atmosphere interactions in the sub-tropics have largely occurred at inland sites (e.g. Beringer and Tapper, 2000; Heilman et al., 2009; Posse et al., 2016; Sturman and McGowan, 2009) and observations from coastal locations remain scarce.

Mass and energy fluxes are commonly measured using the eddy covariance (EC) method. The largest collective body of work to date focuses on long-term monitoring over forests and grasslands (e.g. Ameriflux, Asiaflux, OzFlux; https://fluxnet.ornl.gov/). In Australia, most EC research has been concentrated in regions of tropical grassland, savanna and shrublands, and temperate broadleaf forests, with the focus being ecosystem productivity and water use (Beringer et al., 2016). Ecosystem function in Australia generally responds to water availability and can therefore show seasonal variation (Beringer et al., 2016) but energy balance analysis is less common. In the sub-tropics of eastern Australia, energy balance studies have been limited to over water on a coral cay in the southern Great Barrier Reef (MacKellar and McGowan, 2010; MacKellar et al., 2012; McGowan et al., 2010) and an irrigation reservoir (McGloin et al., 2015; McJannet et al., 2013).

In comparison to other sub-tropical ecosystems, little is known about the energy balance of terrestrial coastal environments in eastern Australia. Generally exposed to tropical maritime air masses in summer and sub-tropical continental air masses in winter (Sturman and Tapper, 2006), this region has a series of large barrier sand islands (Armstrong and Cox, 2002). The islands contain a wide range of groundwater dependent ecosystems (Eamus et al., 2006; Smolders et al., 2011) but are increasingly subject to urban development and recreational use, with their freshwater aquifers used to augment the regional potable water supply (Armstrong and Cox, 2002; Smolders et al., 2011; Taulis et al., 2011). When compared to all environments, there are few studies of the energetics of groundwater dependent ecosystems (Yuan et al., 2014). Improved knowledge of these environments is beneficial for the management of water resources (Cleverly et al., 2015).

Most of the large barrier sand islands in eastern Australia surround Moreton Bay, in south-east Queensland, a region that contains roughly 1100 km^2 of Ramsar-listed wetlands. One of the sand islands, Bribie Island (hereafter Bribie), has a coastal fringe containing roughly 45 km^2 of Ramsar wetlands; and the Ramsar area adjacent to Bribie is over 200 km^2 in area. Such Ramsar wetlands are hotspots of biodiversity and home to fundamental biogeochemical cycles (Ramsar Convention Secretariat, 2013). The Bribie sand mass contains two major hydrogeological features that strongly influence the local vegetation: a large sandy aquifer and a shallow water table (Smolders et al., 2011). Two key ecosystems on Bribie are unique remnant native vegetation assemblages: one a Ramsar-listed *Melaleuca quinquenervia* wetland, the other a coastal heath wetland. The remnant native vegetation found on Bribie also covers some 6100 km^2 of Queensland's coastal areas (Neldner et al., 2017). A third key ecosystem is a commercial pine plantation that has replaced remnant vegetation and is a similar ecosystem to > 3400 km^2 of plantations adjacent to the Queensland coast. There are > 10000 km^2 of commercial conifer plantations in Australia (Rhodes and Stephens, 2014) and globally there have been widespread increases in the extent of plantations, especially in the Southern Hemisphere (Franzese and Raffaele, 2017; Simberloff et al., 2010). The variety of vegetation found on Bribie is representative of large areas of coastal sub-tropical and tropical eastern Australia, but being concentrated in a small area means that direct comparison between surfaces can be uniquely made where each surface type has the same radiative input. Such simultaneous measurements over a range of surface types provide vital data sets for land-atmosphere model parameterisation (Pielke et al., 2011).

Past research into the environment of Bribie has focussed exclusively on the hydrogeology, groundwater, and surface water, with modelling of the groundwater flow aimed at enhancing sustainable management of the aquifer resource (Armstrong and Cox, 2002; Smolders et al., 2011; Taulis et al., 2011). More recent studies have examined groundwater and transpiration (Fan et al., 2014a; Fan et al., 2016; Guyot et al., 2017), and canopy interception and loss (Fan et al., 2015; Fan et al., 2014b), but those measurements were made at tree-scale and did not fully consider surface-atmosphere interactions. Thus, when considering evapotranspiration, and therefore Q_e, there remains an imbalance between tree-scale and stand-scale measurements. This imbalance extends to coastal tropical north Queensland, where groundwater fluctuations and transpiration of *Melaleuca quinquenervia* have been directly measured but the full energy balance has not (McJannet, 2008). Therefore, in order to adequately assess, and potentially enhance, existing water resource management practices there is a need to better quantify the groundwater-vegetation-atmosphere continuum in coastal eastern Australia.

Here we present a climatological study of surface energy fluxes based on simultaneous observations above three distinct ecosystems on Bribie. The datasets of up to 3-years in length represent the first direct measurements of the energy balance of a sub-tropical sand island. This study is also the first to examine surface-atmosphere interactions on Bribie from an atmospheric rather than surface-based perspective, thereby complementing and extending previous work for this Ramsar-listed shallow water table environment. By improving knowledge of eastern Australian groundwater-soil-vegetation-atmosphere processes it provides an observational data set from which existing water management practices may be assessed, and which may be used for the parameterisation of land-atmosphere models. It also establishes the context for more detailed examination of the nature of surface-atmosphere fluxes of energy on Bribie, and the quantification of an island-scale water balance, important for the sustainable management of both the groundwater dependent ecosystems and the aquifer itself. The key objectives are: 1) to quantify the energy fluxes of contrasting coastal vegetation assemblages in a sub-tropical sand island setting, on diurnal and seasonal time scales; 2) to determine the physical drivers, and the influence of changing hydrometeorological conditions, on the energy balances; and 3) relate variability in the energy balances between sites to vegetation types and surface conditions, and compare the seasonal energy partitioning with previously measured coastal locations from other parts of world.

2. Study site

Bribie is a sub-tropical sand island of approximately 149 km^2 at the northern edge of Moreton Bay, on the east coast of Australia (Fig. 1). The topography of Bribie is of low relief with most of the island 1–3 m above sea level (ASL) and almost all < 10 m (Geoscience Australia, 2015). The coastal fringes and a central swale are covered by remnant native vegetation with original vegetation replaced by commercial pine plantations in the remaining areas (Armstrong and Cox, 2002). On the southern fringe of the island there is a residential area of approximately 15 km^2.

Three EC sites were located within the major vegetation types on Bribie (Fig. 1). One EC system (referred to as the Wetland site, 26.959 °S, 153.144 °E, 2.5 m ASL) was installed in a Ramsar-listed *Melaleuca quinquenervia* dominated palustrine wetland, with an understory primarily of thick fern and sedges (Queensland Herbarium, 2013). In the Bribie region, *Melaleuca quinquenervia* has an average basal area of 32.4 m^2 ha^{-1} and average stem density of 588 stems ha^{-1} (Ryan, 2012). Tree height ranged from 5 to 14 m. A second EC system (the Swamp site, 26.988 °S, 153.130 °E, 2.5 m ASL) was located in a seasonally waterlogged north-