



The way the wind blows matters to ecosystem water use efficiency



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ABSTRACT

In many regions, atmospheric conditions change frequently with shifts of wind direction, extending maritime influences far inland or continental influences to coastal ecosystems. Climate models predict changes in both wind direction and velocity; these changes could potentially impact ecosystems mass and energy exchanges with the atmosphere. Using data on climate (wind speed and direction, air temperature and humidity) and ecosystem-scale fluxes (eddy-covariance evapotranspiration and CO₂ flux) from the Mediterranean island of Sardinia, we evaluated whether the frequency of certain wind characteristics, potentially affecting ecosystem CO₂ uptake, have changed over five decades, and whether these characteristics are indeed linked to ecosystem gas-exchange responses of the studied ecosystem. The analyses show that days dominated by summer Mistral winds decreased on average 3% per decade, and that wind direction affects biosphere-atmosphere exchange of carbon but not water. High velocity cool Mistral winds from continental Europe undergo limited thermal equilibration with the land surface after embarking on the land, trebling vapor pressure deficit (D) as they cross the island. In contrast, arriving with a similar D , lower velocity, warmer Saharan Sirocco winds heat up, thus increasing D 5-fold only 50 km inland. Over a mixed pasture-woodland (grass-wild olive), while soil moisture was low and constant, daytime net carbon exchange (NEE_d) averaged 2.3-fold higher ($p < 0.001$) in Mistral than Sirocco days, largely reflecting the theoretically expected response of canopy conductance (g_c) to variation of D . Because the product of g_c and D encodes the key ecosystem compensatory mechanism, the reciprocal g_c - D response maintained similar ecosystem evapotranspiration (E_e). Thus, summertime ecosystem water-use efficiency ($W_e = NEE_d/E_e$) was ~66% higher during Mistral than other days. The historical decrease of Mistral frequency reduced the estimated summertime $NEE_d > 30\%$. The analyses demonstrate that alteration of dominance of air masses predicted with future climate will amplify or negate the positive effect of increased atmospheric [CO₂] on W_e , and should be considered when assessing climate change impact on NEE .

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1. Introduction

In many locations, changes in weather conditions reflect interacting moist maritime and dryer continental air masses (Fosberger and Schroeder, 1966; Conil and Hall, 2006; Hughes and Hall, 2010). Attention is typically focused on the capacity of strong winds to fan regional fires, threatening human habitation and natural habitats, and reducing carbon (C) storage, net ecosystem CO₂ exchange (NEE) and latent heat flux. However, depending on their origin, winds can bring dry continental air to the coast [e.g., Santa Ana winds

along the southern California coast (Conil and Hall, 2006; Hughes and Hall, 2010)] or cool maritime air far inland (Venkatram, 1977; Stunder and Sethuraman, 1984; Garratt, 1985; Furberg et al., 2002). In these regions, water and carbon fluxes may respond to meso- and macroscale weather patterns (Haxeltine and Prentice, 1996; Schimel et al., 2001; Montaldo et al., 2013), yet the effects of wind direction have been explicitly considered only in footprint analyses, focusing mostly on <1 km around instrumented towers, and on the relationship between the characteristics of the contributing source/sink area and measured fluxes (Schmid, 2002; Detto et al., 2006; Oren et al., 2006). Thus, no explicit assessment has been made of the effects of coarse-scale weather phenomena and wind characteristics on biosphere-atmosphere exchanges of mass and energy.

Recent analysis of the positive effects of rising atmospheric [CO₂] on ecosystem-scale water-use efficiency (W_e , the amount

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of carbon captured by the ecosystem per unit of water it uses) excluded Mediterranean ecosystems because long-term $[\text{CO}_2]$ effects in these ecosystems are difficult to isolate from the effects of summer droughts (Keenan et al., 2013). However, the summer-dry nature of Mediterranean climate provides a background of stable soil moisture, uniquely suitable for assessing the effect of wind characteristics on W_e .

Popular awareness in many locations around the globe associates atmospheric conditions with the direction from which the winds arrive. In the western Mediterranean island of Sardinia, fast moving French Mistral winds bring relief from the summer heat (although can fan fires) as they travel on land, while slower Saharan Sirocco winds bring oppressive heat (Fig. 1, Lionello and Sanna, 2005; Burlando, 2009). As the weather changes with wind direction, decreasing stomatal conductance with increasing vapor pressure deficit (D) (above a threshold of usually 0.5–1 kPa, e.g., Duursma et al., 2008) may keep transpiration, the dominant component of evapotranspiration, relatively constant (Oren et al., 1999), if the canopy is well-coupled to the atmosphere (Kim et al., 2013). However, decreased stomatal conductance is likely to restrict CO_2 uptake, thus reducing W_e . Indeed, a decrease of W_e with increasing D is well-documented (Meinzer, 1982; Baldocchi et al., 1987; Berbigier et al., 2001), but the potential impact of such effect on NEE in the context of changing wind characteristics with climate is yet to be quantified.

The frequency of winds from different directions in the western Mediterranean summer is expected to change in frequency and extent with climate change (McInnes et al., 2011; Rasmussen et al., 2011). For example, models predict decreasing mean wind speed and summer Mistral frequency in southern France over the coming four decades (Najac et al., 2009, 2011). We obtained and analyzed historical wind data (five decades) for Sardinia in the Mediterranean basin, a key area for investigating global change impacts owing to its transitional climate and the high spatiotemporal variability of ecosystem function and biodiversity (Doblas-Miranda et al., 2015). We tested the hypothesis that (H1) the frequency of Mistral has already begun to decrease over the record period. Using output from MACC II re-analysis (Inness et al., 2013) available at the ECMWF (European Centre for Medium-Range Weather Forecasts), we focused primarily on Mistral and Sirocco winds embarking Sardinia evaluating the hypothesis that (H2) the high velocity Mistral winds are of lower D than the lower velocity Sirocco.

Air temperature (T_a) may decrease as the air mass (in the generated internal boundary layer) embarks the coast and travels over land where the elevation increases, and may rise depending on the contact time with the surface and the sensible heat flux from the surface (Venkatram, 1977; Raynor et al., 1979; Stunder and Sethuraman, 1984). We therefore assessed the changes in D due to the net effect of these processes on temperature as Mistral and Sirocco winds of different velocities climb on Sardinia reaching similar elevation near the coast of embarkation. Considering the thermal energy conservation equation integrated from the surface to the height of the entrainment zone (z_e assumed equal to 800 m), the change of T_a over time, t , to a reference horizontal distance from the coast, x , can be estimated with (Venkatram, 1977; Stunder and Sethuraman, 1984; Plant and Atkinson, 2002; Moene and van Dam, 2014, Anton Beljaars, personal communication):

$$\frac{\partial T_a}{\partial t} = u \frac{dT_a}{dx} = -\frac{1}{\rho c_p} \frac{\partial H}{\partial z} = \frac{H_s - H_e}{\rho c_p z_e} \quad (1)$$

where z is the vertical axis, H is the sensible heat flux, H_s is the sensible heat flux from the surface, H_e is the sensible heat flux from the entrainment zone (about 15% of H_s , e.g., Huang et al., 2011), u is the wind velocity, ρ is the air density and c_p is the specific heat capacity. Accounting in addition for the adiabatic cooling as the

air mass climbs the Sardinian mountain range to 600 m a.s.l., the change of T_a can be estimated in discrete form as:

$$\Delta T_a = \frac{H_s - H_e}{\rho c_p z_e} \frac{\Delta x}{u} - l_r z_{ms} \quad (2)$$

where l_r is the adiabatic lapse rate ($=0.75$ for average air saturation conditions) and z_{ms} is the height a.s.l., Δx is the distance between the coast and the reference point. One of the reference points (Orroli micrometeorological station, Fig. 1) was collocated with an eddy-covariance flux site providing measurements of H_s for ΔT_a estimates based on Eq. (2), as well as estimates of evapotranspiration and NEE over four years (2003–2006). Focusing on these years, we hypothesized that (H3) fast Mistral winds will remain cool as they climb the mountain range and cross the island, while the slow Sirocco winds will warm up over a short distance from the coast, thus further increasing in D .

During rainless periods in water-limited ecosystems, canopy transpiration is the dominant component of evapotranspiration (E_e , or latent heat flux calculated with eddy covariance instruments) because evaporation from wet surfaces and soil is negligible (Wetzel and Chang, 1987; Granger and Gray, 1989). Thus, E_e as surrogate of canopy transpiration is essentially the product of total canopy conductance, g_c , and atmospheric D :

$$E_e = g_c D, \quad (3)$$

assuming that leaf and air temperature are similar, and aerodynamic conductance is high relative to stomatal conductance (Jones, 1998; Novick et al., 2004), both safe assumptions considering the high u conditions involved (Kim et al., 2013). However, g_c is not independent of D , but decreases as the driving force of transpiration increases in a manner consistent with maintaining the hydraulic integrity and functionality of the water conduits of the xylem (Oren et al., 1999), avoiding the development of tension that might result in catastrophic cavitation. One expression of such relation is $g_c = g_{c,ref} - m \ln(D)$, where $g_{c,ref}$ is reference conductance at $D = 1$ kPa, and $m = 0.6g_{c,ref}$ for a large number of species (Oren et al., 1999), similar to predictions from leaf-level stomatal optimization theories (Katul et al., 2009). The stomatal conductance reduction with increasing D can compensate for the increased driving force (D), resulting in E_e remaining relatively invariant over a large portion of the range of D (Katul et al., 2009).

When soil moisture is low, it is also reasonable to assume that decomposition and CO_2 efflux from the soil surface are low (Oishi et al., 2013), and the daytime net flux of CO_2 across a plane above the canopy, F_c , is dominated by net canopy photosynthesis (A_c). Thus, F_c (expressed positively to reflect photosynthesis) as surrogate of A_c can be estimated following Fick's law of diffusion and adjusting g_c for the diffusivity ratio of $\text{CO}_2/\text{H}_2\text{O}$ (Cowan, 1978):

$$F_c = \frac{g_c}{1.6} C_a \left(1 - \frac{C_i}{C_a}\right) \quad (4)$$

where c_a and c_i are the CO_2 concentrations in the ambient atmosphere and in the intercellular space in the leaf, respectively. Combining the physiological relation described above, as D increases and g_c decreases, F_c should also decrease. Thus, while the offsetting response of stomata to changes in D should render E_e insensitive to wind-induced atmospheric changes, NEE_d (daytime net ecosystem carbon exchange, the sum of daytime F_c) should benefit from wind conditions that maintain cool air mass inland, but will decrease greatly (i.e. NEE_d approaches zero) when the air heats up. This hypothesis (H4) was tested with eddy covariance data obtained over the four summers at Orroli. Corollary to this hypothesis, $W_e (=NEE_d/E_e = c_a(1 - c_i/c_a)/1.6D)$; based on Eqs. (3) and (4), averaged over daytime) would decrease with D in proportion to the theoretical stomatal response, unless F_c is strongly

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