Estimating Surface-Atmosphere Exchange at Regional Scales

A thesis presented for the degree of
Doctor of Philosophy
by

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Symbol	Units	Eq.	Description
a	g m^{-3}	-	absolute humidity
$a_0(\lambda)$	-	6.1	Landsat 5 TM calibration offset at λ
$a_1(\lambda)$	-	6.1	Landsat 5 TM calibration slope at λ
A	-	3.19	PT100 time constant weight
B	-	3.19	reverse flow housing time constant weight
c_A	-	-	extinction coefficient in soil evaporation model
c_p	J kg^{-1} K^{-1}	1.1	specific heat at constant pressure
c_v	J kg^{-1} K^{-1}	-	specific heat at constant volume
c_Q	-	5.8	short wave radiation extinction coefficient
C	μmol mol^{-1}	-	CO_2 concentration
d	m	5.6	displacement height
d	-	6.2	ratio of actual to mean Sun-Earth distance
D	kg kg^{-1}	5.8	specific humidity deficit
D_0	kg kg^{-1}	5.8	empirical constant in model for g_{sx}
E	kg m^{-2} s^{-1}	1.4	evaporation
$E_s(\lambda)$	W m^{-2} μm^{-1}	6.2	solar radiance at wavelength λ
f	Hz	-	frequency
f	-	6.6	3-D source-area weight function
$fPAR$	-	-	fraction of photosynthetically active radiation absorbed by vegetation
$\bar{f}^y$	-	6.9	cross wind integrated source-area function
F_A	W m^{-2}	1.2	available energy
F_C	mg m^{-2} s^{-1}	5.3	CO_2 flux
F_E	W m^{-2}	1.2	latent heat flux
$F_{E,leaf}$	W m^{-2}	1.3	latent heat flux at the leaf surface
F_H	W m^{-2}	1.1	sensible heat flux

Symbol	Units	Eq.	Description
$F_{H,leaf}$	W m^{-2}	1.3	sensible heat flux at the leaf surface
F_G	W m^{-2}	1.2	ground heat flux
F_N	W m^{-2}	1.2	net radiation
$F_{N,leaf}$	W m^{-2}	1.3	net radiation at the leaf surface
F_{PAR}	W m^{-2}	-	flux of photosynthetically active radiation
F_s	-	4.1	flux of scalar s
g	m s^{-2}	1.1	acceleration due to gravity
g_s	m s^{-1}	-	stomatal conductance
g_{sx}	m s^{-1}	5.8	maximum stomatal conductance
GPP	tC ha^{-1} yr^{-1}	1.5	gross primary productivity
G_a	m s^{-1}	5.5	aerodynamic conductance
G_c	m s^{-1}	5.7	canopy conductance
G_i	m s^{-1}	5.5	isothermal conductance
G_s	m s^{-1}	5.5	surface conductance
G_{sx}	m s^{-1}	-	maximum surface conductance
h_c	m	-	canopy height
IAS	m s^{-1}	-	indicated airspeed
k	-	1.1	von Karman constant
K_p	-	3.3	static pressure correction factor
K_q	-	3.2	dynamic pressure correction factor
K_T	-	3.5	temperature correction factor (1-r)
K_α	-	3.8	angle of attack sensitivity
K_β	-	3.9	angle of sideslip sensitivity
L	m	1.1	Monin-Obukhov length
$L(\lambda)$	Wm^{-2}sr^{-1}μm^{-1}	6.1	spectral radiance at wavelength λ
L_{ai}	-	5.8	leaf area index

Symbol	Units	Eq.	Description
L_d	tC ha^{-1} yr^{-1}	1.7	CO_2 loss due to biome disturbance
L_s	m	4.1	integral length scale for scalar s
L_{ws}	m	4.1	integral length scale for ws covariance
$L_{\downarrow}$	W m^{-2}	1.2	incoming long wave radiation
$L_{\uparrow}$	W m^{-2}	1.2	outgoing long wave radiation
n	-	-	non-dimensionalised frequency
NBP	tC ha^{-1} yr^{-1}	1.7	net biome productivity
$NDVI$	-	-	normalised difference vegetation index
NEP	tC ha^{-1} yr^{-1}	1.6	net ecosystem productivity
p	kg m^{-2} s^{-1}	1.4	precipitation
p_a	hPa	-	pressure altitude
p_s	hPa	3.3	static pressure
$p_{s,m}$	hPa	3.3	measured static pressure
p_t	hPa	3.13	total pressure
P_{AV}	s	4.1	averaging period
P_{γ}	-	3.4	ratio of static to total pressure
q	kg kg^{-1}	-	specific humidity
q_c	hPa	3.2	dynamic pressure
$q_{c,m}$	hPa	3.2	measured dynamic pressure
q^*	kg kg^{-1}	-	saturation specific humidity deficit
$Q_{cal}(\lambda)$	-	6.1	byte value of pixel radiance at wavelength λ
r	-	-	temperature sensor recovery factor
r_a	s m^{-1}	5.13	aerodynamic resistance, single observation
r_C	-	-	correlation coefficient between w and C
r_d	s m^{-1}	5.13	deficit resistance, single observation
r_s	s m^{-1}	-	surface resistance, single observation

Symbol	Units	Eq.	Description
r_{ws}	-	4.1	correlation coefficient between w and s
R_a	tC ha^{-1} yr^{-1}	1.5	autotrophic respiration
R_a	s m^{-1}	5.14	aerodynamic resistance, average
R_d	s m^{-1}	5.14	deficit resistance, average
R_h	tC ha^{-1} yr^{-1}	1.6	heterotrophic respiration
R_s	s m^{-1}	-	surface resistance, average
$S_{\downarrow}$	W m^{-2}	1.2	incoming short wave radiation
$S_{\uparrow}$	W m^{-2}	1.2	outgoing short wave radiation
S_{50}	W m^{-2}	5.8	empirical constant in model for g_{sx}
SD_{ITCE76}	-	-	random error in difference between variance and covariance measurements during ITCE76
SD_{ran}	-	4.2	expected random error in difference between aircraft and ground-based measurements
T_a	°C	-	air temperature
T_F	°C	3.19	final temperature after step change
T_I	°C	3.19	initial temperature before step change
T_{leaf}	°C	-	leaf temperature
T_m	°C	3.19	measured temperature at time t
T_s	°C	3.6	static temperature
T_{sfc}	°C	-	surface radiometric temperature
T_t	°C	3.5	total temperature
$T_{t,m}$	°C	3.5	measured total temperature
u_{hdg}	m s^{-1}	3.12	along-heading component of wind speed
$u_{GS,hdg}$	m s^{-1}	3.12	along-heading component of ground-speed
u_*	m s^{-1}	1.1	friction velocity
$\mathbf{U}$	m s^{-1}	3.1	ambient wind vector
$\mathbf{U}_{GS}$	m s^{-1}	3.1	ground speed vector

Symbol	Units	Eq.	Description
$\mathbf{U}_{TAS}$	m s^{-1}	3.1	true airspeed vector
U	m s^{-1}	-	ambient wind magnitude
U_{GS}	m s^{-1}	3.10	ground speed magnitude
v_{hdg}	m s^{-1}	3.12	cross-heading component of wind speed
$v_{GS,hdg}$	m s^{-1}	3.12	cross-heading component of ground speed
W_{UE}	$mgCO_2g^{-1}H_2O$	5.3	water-use efficiency
WD	deg.	-	wind direction
w	m s^{-1}	-	vertical component of the wind speed
z	m	-	height
z_i	m	-	mixed layed depth
z_0	m	-	roughness length for momentum
z_{0h}	m	-	roughness length for heat
α	-	-	surface albedo
α	deg.	3.8	angle of attack
α_0	deg.	3.8	angle of attack offset
α_{E}	-	5.1	evaporative fraction
β	-	5.2	Bowen ratio
β	deg.	3.9	angle of sideslip
β_0	deg.	3.9	angle of sideslip offset
Δp_α	hPa	3.8	pressure difference across α ports
Δp_β	hPa	3.9	pressure difference across β ports
Δr	-	1.4	net runoff in the hydrological balance
ΔS	-	1.4	net storage in the hydrological balance
ε	-	5.7	change in latent heat content of saturated air with change in sensible heat content
ε_{s^2}	-	4.1	random error in variance of scalar s

Symbol	Units	Eq.	Description
ε_{ws}	-	4.1	random error in flux of scalar s
λ	J kg^{-1}	-	latent heat of vaporisation
ϕ	deg.	-	aircraft roll angle
ϕ'	deg. s^{-1}	-	aircraft roll rate
γ	-	3.4	Poisson's constant
Θ	rad.	6.2	solar zenith angle
ρ	kg m^{-3}	1.1	air density
$\rho(\lambda)$	-	6.2	spectral reflectance at wavelength λ
σ_C	μmol mol^{-1}	-	standard deviation of CO_2 concentration
σ_q	kg kg^{-1}	-	standard deviation of specific humidity
σ_s^2	-	4.1	variance of scalar s
σ_T	°C	-	standard deviation of temperature
σ_u	m s^{-1}	-	standard deviation of wind speed
σ_w	m s^{-1}	-	standard deviation of vertical wind speed
σ_{WD}	deg.	-	standard deviation of wind direction
σ_θ	K	-	standard deviation of potential temperature
θ	K	1.1	potential temperature
θ	deg.	-	aircraft pitch angle
θ'	deg. s^{-1}	-	aircraft pitch rate
τ	m s^{-1}	-	aircraft true airspeed
τ	-	5.7	fraction of available energy at soil surface
τ_1	s	3.19	PT100 sensing element time constant
τ_2	s	3.19	reverse flow housing time constant
ψ	deg.	-	aircraft yaw (heading) angle
ψ'	deg. s^{-1}	-	aircraft yaw rate

Abstract

This thesis examines a method for estimating the daytime fluxes of heat, water vapour and carbon dioxide at regional scales by using simple models to combine spatially resolved surface properties with bulk meteorological quantities measured at a central location. The central themes of this thesis are that the spatial and temporal variability of regional scale fluxes are contained in the surface properties and meteorology respectively and that the surface properties can be interpolated across a heterogeneous landscape using remotely sensed data. The regional scale fluxes estimated using this technique are compared to the values from three other methods and this allows some conclusions to be made regarding the relative strengths and weaknesses of each method. The surface property approach yields robust estimates of the fluxes that will be useful in researching exchange processes at regional scales, providing input parameters for, and validation of, the biosphere components of General Circulation Models and testing inventory estimates of CO_2 budgets.

The surface properties are derived using data from 33 aircraft flights and eight ground-based sites along a 96 km transect established during the 1995 Observations At Several Interacting Scales experiment held near Wagga Wagga, New South Wales, Australia. Surface properties examined are the evaporative fraction (ratio of evapotranspiration to available energy), the Bowen ratio (ratio of sensible heat flux to evapotranspiration), the maximum stomatal conductance (maximum stomatal opening under optimal conditions) and the water-use efficiency (ratio of CO_2 flux to evapotranspiration). Maximum stomatal conductance is calculated using a simple model of the stomatal response to light and water vapour deficit assuming soil evaporation occurs at the equilibrium rate. The diurnal trend and day-to-day variability in the surface properties is found to be significantly less than the spatial variability. All of the surface properties examined show some sensitivity to the synoptic conditions.

The relationships between the surface properties and the Normalised Difference Vegetation Index (*NDVI*) are examined using a 130 km by 50 km sub-scene from a Landsat 5 Thematic Mapper (TM) image obtained five days before the start of the experiment period. The ground-based and aircraft observations are used to calculate the source-area influencing each measurement and this is combined with the Landsat 5 TM data to produce an average, source-area weighted *NDVI* for each ground-based site and each aircraft location. The source-area model is important because it provides the link between the observations and the remotely sensed data by identifying the surface patch that influences the measurements. Linear relationships are found between the source-area weighted *NDVI* and the surface properties. The observed relationships are used to interpolate the surface properties over the region covered by the satellite image and spatial variations in water loss and CO_2 uptake by the surface vegetation are identified that are not resolved by the ground-based network.

Analysis of the ground-based data showed that the spatial variability of the bulk meteorological quantities used in the surface property approach was much less than the diurnal trend in these data. With the small temporal variation in the surface properties noted before, this confirms the utility of assigning the spatial and temporal variability of the fluxes to the surface properties and the meteorology respectively.

The combination of surface properties derived from the aircraft data and meteorology measured at a single location at the centre of the transect shows good skill in predicting the observed fluxes. Furthermore, the discrepancies between the predictions and the observations are explained by the different source-areas of the aircraft and ground-based data and much of the bias is removed when the surface properties are scaled from the *NDVI* of the aircraft source-area to the *NDVI* of the ground-based sites. Regional scale fluxes of heat and water vapour calculated using the surface property approach agree with averages of the ground-based data and this indicates that the ground-based network was representative of the OASIS region. Estimates of regional scale CO_2 fluxes are not available from the ground-based network due to the lack of measurements at the driest ground-based site but the surface property approach yields plausible values. The results demonstrate the utility of extrapolating surface properties across heterogeneous landscapes using remotely sensed data.

Statement

I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

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The appearance of my parents in the third paragraph does not rank their importance, for in this respect they are equal to the first two. They have at all times encouraged and supported me, particularly in this midlife crisis that become a PhD thesis. Sadly, my father did not live to see it complete but his presence saturates these pages. Thankfully my mother has outlasted my folly and now, perhaps, will see her son "settled, with a family and an education".

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