Chapter 8:
Summary and Concluding Remarks

Chapter Contents

8.1 Preamble

Knowledge of the regional scale fluxes of water vapour and carbon dioxide is essential for understanding the exchange of these quantities between terrestrial and atmospheric stores. In the case of water vapour, the latent heat flux quantifies the rate at which the soil reservoir is depleted between rainfall events and through the surface energy budget, exerts a large degree of control on conditions in the convective boundary layer. In the case of CO_2, the flux quantifies the rate at which carbon is being stored in or lost from an ecosystem. The fluxes show large diurnal trends and spatial variability in response to the meteorological forcing and surface heterogeneity respectively and this makes it difficult to extrapolate them from measurements at the patch scale to regions.

Regional scale fluxes are required to validate models of surface-atmosphere exchange, to provide regionally-averaged input parameters to these models, to investigate water loss and carbon sequestration at catchment or biome scales and to verify inventory predictions of CO_2 uptake or emissions. This last point is very important in the Australian context. A great deal is known about the anthropogenic emissions of CO_2 and the emissions due to land-use change but very little is known about the uptake or loss of carbon by the Australian biosphere. Even less is known about the limitations that water availability, nutrient status or climate place on net primary productivity. The ability to estimate the regional scale fluxes of water vapour and CO_2 is an important tool in understanding and modelling these processes. This thesis sets out a new technique for estimating regional scale fluxes using surface properties inferred from remote sensing data and meteorology measured at a single location.

The major points in the thesis are summarised in Section 8.2 to provide an overview of the work undertaken and the conclusions reached. Section 8.3 revisits the thesis hypothesis stated in Chapter One, discusses its separate components and states the final conclusion as to the truth of the hypothesis. Section 8.4 presents some concluding remarks that point to possible future research.

8.2 Summary of Major Points

8.2.1 Aircraft and Ground-based Data

The instrument suite carried by *VH-HNK* was subjected to an extensive calibration programme as part of the work described in this thesis. This programme and the analysis of data collected during the 1995 OASIS experiment identified problems with the pneumatic lines to the dynamic pressure sensor, the fast-response temperature sensor and with the installation of the LICOR 6251 CO_2 analyser. Corrections for these problems were developed and applied successfully to the data.

A detailed comparison of aircraft and ground-based observations was made during the 1995 OASIS experiment. This was considered essential to address concerns that aircraft observations suffered from a systematic, unexplained bias (Shuttleworth, 1991) and to demonstrate the compatibility of measurements made by airborne and tower instruments. Resolution of these points was seen as an essential prelude to the integration of the aircraft and ground-based data.

The comparisons showed that mean wind speed, wind direction and air temperature from the aircraft and ground-based instruments systems were in good agreement. The variance of air temperature, specific humidity, and horizontal and vertical wind speed also agreed well between the two platforms once the aircraft measurements of air temperature were corrected for the effects of inadequate sensor response time. Aircraft and ground-based estimates of the sensible and latent heat fluxes were in excellent agreement after correcting the temperature data from the airborne instrument and allowing for the combined effect of differing source-areas and surface heterogeneity on the two sets of measurements. Net radiation measured by the aircraft instruments agreed with measurements from the ground-based instruments at Wagga, Browning and Urana but were 20% greater than values recorded at Wattles, consistent with an incorrect calibration for the net radiometer at the Wattles.

The aircraft observations of friction velocity were in reasonable agreement with the ground-based values when $z \le |L|$ but not when the aircraft height above ground level was greater than the Monin-Obukhov length. This result lead to the adoption of $|L|$ as the depth of the surface layer, placing a strong constraint on the maximum aircraft height at which surface layer quantities, such as the aerodynamic conductance, can be calculated from aircraft data.

Airborne measurements of F_C for a 10 km transect segment near the Browning site agreed with the ground-based values. However, airborne measurements of F_C for a 10 km by 8 km grid covering the Browning site and for a 10 km transect segment adjacent to the Wagga site under-estimated the ground-based values by 32% and 46% respectively. Subsequent analysis of an $NDVI$ image of the OASIS domain showed that the discrepancies were due to the differing source-areas of the aircraft and ground-based measurements and were not due to systematic errors in the aircraft measurement of CO_2 concentration.

The good agreement between the aircraft and ground-based observations demonstrates that data from the two platforms are equivalent, provided note is taken of their differing source-areas. This means that aircraft and ground-based data can be safely integrated into the same analysis.

8.2.2 Surface-atmosphere Exchange Parameters

The fluxes of heat, water vapour and CO_2 show large diurnal trends and are heavily influenced by synoptic conditions. These characteristics make it difficult to estimate the surface fluxes from infrequent aircraft passes and complicate the relationship between the fluxes and remotely sensed quantities. The evaporative fraction α_E, the Bowen ratio β, the maximum stomatal conductance g_{sx} and the water-use efficiency W_{UE} are properties of the surface and, as such, are expected to have little or no diurnal trend and to be insensitive to the synoptic conditions. This makes a robust relationship between the surface properties and $NDVI$ more likely than between $NDVI$ and the fluxes themselves.

Site-specific and spatially averaged values of α_E, β, g_{sx} and W_{UE} were calculated from the ground-based and aircraft data respectively. The values of α_E and g_{sx} derived from aircraft and ground-based observations proved to be sensitive to both systematic and random errors in the measurement of the surface energy balance. Systematic errors were corrected by adjusting the observations of F_H and F_E so as to achieve closure of the SEB on average while preserving the average Bowen ratio. The effect of random errors was reduced by averaging F_A, F_H, F_E and F_C and using these to calculate average values of α_E, β and W_{UE}. Average values of g_{sx} were obtained using a modification of the schemes described in McNaughton (1994) and Raupach (1995).

The evaporative fraction and maximum stomatal conductance show much less diurnal variation than fluxes of available energy, sensible heat and latent heat. With acceptable error, they may be considered constant throughout the day and this means that values derived from infrequent aircraft passes around midday and early afternoon are representative of the entire day. The situation is not clear for water-use efficiency due to the limited number of ground-based sites at which F_C was measured and the scatter in the observed diurnal variation of W_{UE}. Water-use efficiency remains within 10% of the daytime average between 1000 to 1500 at Wagga and between 1100 to 1600 at Browning. Assuming the measured W_{UE} applies to all hours between 0800 and 1700 results in an underestimation of F_C in the morning and an overestimation of F_C in the afternoon but the daily averages will be correct. The diurnal trend in β is too large for a single observation to serve as a daily value. All four surface properties show some sensitivity to synoptic conditions because the canopy response to changes in soil moisture, the changing role of soil evaporation and the occurrence of horizontal advection are not explicitly treated. This will cause the surface property approach to under-predict the day-to-day variability in the regional scale fluxes.

The spatial variability of the four surface properties along the OASIS transect is much larger than the diurnal trend and is larger than the day-to-day variability except when rainfall or horizontal advection occurs. The spatial variability reflects the rainfall gradient along the OASIS transect and the attendant gradient in soil moisture. The decrease in soil moisture during the 1995 OASIS experimental period is evident in the temporal trend of all surface properties. In general, α_E, g_{sx} and W_{UE}

faithfully indicate the effect of surface heterogeneity on the fluxes and this confirms the assertion that the spatial variability in the regional scale fluxes is largely contained in the surface properties.

The relationship between the surface properties and *NDVI* was investigated using a Landsat 5 TM image of a 130 km by 50 km area centred on the OASIS transect. A source-area model was used to calculate the weighting function for contributions from surface areas upwind of the ground-based and aircraft observations and this weighting function was then applied to the *NDVI* image to calculate the source-area weighted *NDVI* for each observation of the fluxes. By identifying the surface patch that most strongly influences the observation, the source-area model provides the link between the observations and remotely sensed data.

For unstable conditions, the source-area model predicts that the 80% contribution isopleth for tower observations has maximum dimensions of 100 m by 200 m compared to 400 m by 800 m for the aircraft data and this has some implications for the resolution of the remotely sensed image. The aircraft data must be averaged over several kilometres to produce stable estimates of the fluxes and the result is a footprint area of several km^2, larger than the 1 km^2 pixel size of AVHRR and MODIS images. In contrast, the tower footprint is much smaller than the pixel size of these images and this means that the microscale heterogeneity that influences the tower observations will not generally be resolved in the AVHRR or MODIS images. This means that a pixel size of 1 km by 1 km may be adequate for interpretation of aircraft data but greater resolution is needed when using data from towers.

Average values of the four surface properties calculated from ground-based and aircraft data were compared to the source-area weighted *NDVI*. These comparisons yielded linear relationships between the surface properties and *NDVI* with correlation coefficients of between 0.66 and 0.85. This allows the surface properties to be interpolated across the OASIS domain on the basis of *NDVI*.

8.2.3 Regional Scale Fluxes of Heat, Water Vapour and CO_2

Regional scale fluxes can be estimated by averaging data from a network of ground-based sites, from convective boundary-layer budget techniques and from coupled mesoscale-SVAT models. Ground-based sites provide good temporal resolution but have poor spatial coverage and this means that a network of surface sites is needed to estimate regional scale fluxes. These are prohibitively expensive for large areas because the density of the network must increase as the surface heterogeneity increases to ensure that all contributing surfaces are sampled. Integral CBL budget techniques (ICBL) require profiles of temperature and humidity from radiosonde flights and accurate measurements of scalar quantities in the mixed layer. They are also sensitive to subsidence and advection. Coupled mesoscale-SVAT models require regional scale values for input parameters such as the aerodynamic and surface conductances and suffer from simplistic surface schemes but even so, the input surface characteristics are often not available at the required spatial resolution.

An alternative approach has been examined here that relies on separating the spatial variability in the regional scale fluxes into spatial and temporal components contained in the surface properties and the meteorology respectively. Examination of the ground-based data showed that the bulk meteorological quantities required by this approach, $S_{\downarrow}$, F_A, D and G_a, have greater site-to-site correlation and less site-to-site variability than F_H, F_E and F_C. In particular, the site-to-site variability in these quantities is much less than the diurnal variation. This confirms the assertion that most temporal variability in the regional scale fluxes is contained in the meteorology.

Regional scale values of F_H, F_E and F_C were calculated using observations from the ground-based network and from the predictions of the coupled g_{sx}-PM model. Values of F_H and F_E were also available from the ICBL budget technique and from a coupled mesoscale-SVAT model. The results for F_H and F_E from the g_{sx}-PM model agree well with the observations for both the diurnal trend and the daily averages. The largest differences occur on days when rain fell and when there was strong warm-air advection, conditions that lie outside the range for which the g_{sx}-PM model approach is valid. The good agreement between the observations and the results from the coupled g_{sx}-PM model confirm that the ground-based sites captured most of the heterogeneity of the OASIS domain.

The results from the CBL budget method are in general agreement with the observations and with the results from the g_{sx}-PM approach but estimates from this technique are available for fewer days due to its greater sensitivity to non-ideal conditions.

Results from the coupled mesoscale-SVAT model show poor agreement with the estimates from the other techniques. This is because the three grid cells representing the Wagga, Browning and Urana sites were each assigned the same vegetation classification, and hence the same leaf area index, canopy height and maximum stomatal conductance, and the model was initialised with a spatially invariant soil moisture. This demonstrates a fundamental difficulty in using coupled mesoscale-SVAT models to calculate regional scale fluxes. The model can only reproduce the observed spatial variability in the fluxes if the spatial variability in the surface characteristics is represented faithfully in the parameters input to the model and this information is not generally available.

CO_2 fluxes were estimated using F_E predicted by the g_{sx}-PM method and values of the water-use efficiency interpolated across the OASIS domain on the basis of $NDVI$. Observations of F_C were only available from Wagga and Browning. There was good agreement between the observations and the predicted values when the model was restricted to an area bounded by the $NDVI$ values of Wagga and Browning. The lack of observations from Urana means that the regional scale F_C can not be estimated from the ground-based network and is only available using the surface property approach. The regional scale F_C from this method was 60% of the average of observations from Wagga and Browning.

It is useful to comment here on the relative merits of the α_E and g_{sx}-PM methods. Both surface properties show small diurnal change, small day to day variability, similar skill in predicting F_E and robust relationships to $NDVI$. The g_{sx}-PM method is the more conceptually pleasing because it attempts to deal with more fundamental physical processes. However, the α_E method is simpler and may be of greater use when simplicity is more important than outright accuracy.

8.3 Hypothesis Revisited

Having summarised the major points of this thesis, we are now in a position to assess the hypothesis set out in Chapter One. The four parts of the hypothesis are examined before the final conclusion is stated.

First, aircraft data have been shown to be compatible with ground-based data by direct comparison of means, variances and covariances and by the close agreement between aircraft and ground-based observations of the surface properties.

Second, the results presented in this thesis demonstrate that the spatial variability in the surface fluxes is contained mostly in the surface properties while the temporal variability is contained mostly in the meteorology. However, all of the surface properties examined show some sensitivity to synoptic conditions and this blurs the spatial and temporal separation at time scales longer than a few days. The lack of diurnal trend means that the surface properties can be derived as point values from ground-based observations or as spatial averages from infrequent airborne observations.

Third, the spatial variability of α_E, g_{sx} and W_{UE} is found to correlate well with the spatial variability of $NDVI$ for $1 \le L_{ai} \le 4$ and $0.53 \le NDVI \le 0.86$. This allows $NDVI$ to be used as the basis for interpolating measurements of the surface properties over areas of at least 5200 km^2.

Fourth, regional scale fluxes of F_E, F_H and F_C calculated using surface properties interpolated using $NDVI$ show good agreement with the available observations and with values from CBL budget techniques.

Overall, the hypothesis that regional scale fluxes can be calculated from spatially averaged or spatially-resolved values of surface properties and meteorology measured at a central location is found to be true for the fluxes of sensible heat, latent heat and CO_2.

8.4 Concluding Remarks

This thesis has presented a new technique that combines spatially resolved surface properties with meteorology measured at a central location to estimate the daytime, regional scale fluxes of sensible heat, latent heat and CO_2. The technique integrates ground-based, airborne and remotely sensed observations and provides a link between processes at the canopy and regional scales. The results from the method are more consistent with the available observations than an integral CBL budget technique and a coupled mesoscale-SVAT model when applied to the data from the 1995 OASIS experiment. The approach allows regional scale estimates of F_E, F_H and F_C to be obtained from a small observational network and an $NDVI$ image once the relationship between the surface properties and $NDVI$ has been established. With this work complete, a number of new directions for future research can be identified.

First, there are some problems that result from the choice of α_{E}, g_{sx} or W_{UE} for the surface properties and $NDVI$ for the remotely sensed quantity. There is certainly evidence in the literature that $NDVI$ is not a good predictor of vegetation type or of the turbulent fluxes. Also, all of the surface properties used have some diurnal variation and are sensitive to synoptic conditions. In addition, α_{E} and g_{sx} did not discriminate between crop and pasture at the same isohyet whereas $NDVI$ did. This suggests that the surface properties and $NDVI$ are not themselves directly related but are dependent on a third variable such as soil moisture or leaf area index. At the least, the relationship between the surface properties and $NDVI$ needs to be investigated over a much wider range of conditions for this work to have wider application.

A useful place to begin the search for a better choice of surface property would be with a coupled photosynthesis-transpiration model such as those proposed by Wang and Leuning (1998) and Tuzet et al. (2003). These models also account for soil moisture, removing some of the ambiguity of the current approach. Unfortunately, the increased sophistication carries the burden of increased data requirements but this penalty would be worth paying if general relationships between model parameters and remotely sensed data could be found. There have also been recent advances in hyper-spectral imaging from satellite, airborne and ground-based radiometers and these offer the possibility of remotely sensed quantities that are more directly related to photosynthetic activity than simple vegetation indices such as $NDVI$.

Second, the analysis presented in this thesis demonstrates the fundamental role played by soil moisture in determining the spatial variability of F_E and F_C across the OASIS domain. One plausible inference from the OASIS data set is that the availability and quality of soil moisture data already limit the fidelity of current modelling techniques. If this is the case, further refinement of the plant physiology sub-model will not improve the overall performance of the model without a similar refinement of the initialisation and treatment of soil moisture. Fortunately, there have also been recent advances in this field using both active and passive microwave radiometers to map the spatial variability of soil moisture at regional scales, albeit for a shallow layer close to the surface. Even so, the literature dealing with the measurement of regional scale soil moisture is only a fraction of that dealing with the measurement and modelling of regional scale fluxes and more effort will be required in this area if the full benefits of better physiological modelling are to be realised.

Finally, there is much more data available than has been used in this thesis. In particular, there is a network of observing sites across Australia that routinely report rainfall, wind speed, temperature, humidity and incoming solar radiation. There are techniques for interpolating this data on the basis of topography and land use that could reduce the errors associated with simply extrapolating the bulk meteorological quantities between measurement locations. There is also a wealth of existing remotely sensed data that has not been utilised in this study. We are not short of data, rather we are short of understanding in how to interpret and use the data available.