Chapter 2:
The OASIS Experiments

Chapter Contents

2.1 Introduction

The 1994 and 1995 OASIS experiments fit within a sequence of large-scale land-atmosphere interaction studies conducted to address, amongst others, the twin issues of using patch scale observations to predict regional scale interaction and the reverse process of inferring patch scale interactions from regional scale observations. These issues are described as aggregation or "upscaling" and disaggregation or "downscaling" respectively (Anderson et al., 2003).

Although there were previous boundary-layer experiments, the thread begins with the Hydrologic Atmospheric Pilot Experiment and Modélisation du Bilan Hydrique (HAPEX-MOBILHY) in 1986 (André et al., 1986; André et al., 1988). The objective of HAPEX-MOBILHY was to study the hydrological budget and the latent heat flux over an area of 100 km by 100 km, the scale of a GCM grid square. The study was conducted over forest and mixed agricultural land in southwest France and was the first that integrated ground-based, airborne and satellite observations. HAPEX-MOBILHY provided a comprehensive data set of hydrological and meteorological quantities that continues to be used in model validation studies (Garratt et al., 2002) and demonstrated the feasibility and utility of multi-disciplinary field programmes.

The First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) continued the theme of integrating observations from many platforms at many spatial and temporal scales (Sellers et al., 1988; Sellers et al., 1992). The study was conducted over a 15 km by 15 km area of prairie grass in Kansas, United States of America (USA) and consisted of five intensive field campaigns, four in 1987 and one in 1989, embedded in a three year monitoring programme. The objectives of FIFE were to test the upscaling of soil-vegetation-atmosphere transport (SVAT) models and to investigate the role of remote sensing in initialising and validating these models. FIFE also introduced the routine observation of F_C in large-scale field experiments and provided the template for project coordination and data dissemination for later programmes. The outcomes of HAPEX-MOBILHY, FIFE and similar projects are summarised in the excellent review of Shuttleworth (1991), who also presents some sharp insights into the outstanding issues at the time of his review.

The European Field Experiment in Desertification-threatened Area (EFEDA) and the Hydrologic Atmospheric Pilot Experiment in the Sahel (HAPEX-Sahel) studied land-atmosphere exchange processes in semi-arid areas threatened with desertification (Bolle et al., 1993; Goutorbe et al., 1994; Goutorbe et al., 1997; Lloyd et al., 1997). EFEDA was conducted in Spain during 1991 and HAPEX-Sahel in the Sahel area of the Republic of Niger from 1991 to 1993. Both experiments were focussed on addressing processes such as soil-vegetation-atmosphere interaction and the parameterisation of these processes at the scale of a GCM grid. Their location reflected the growing recognition that areas threatened by desertification are particularly sensitive to changes in climate and land use.

The boreal forests of the Northern Hemisphere are important to the global carbon cycle because they exist at latitudes where climate change is predicted to be greatest, they represent a significant carbon store and they may form part of the missing terrestrial sink of anthropogenic CO_2 (Schimel et al., 2001). These roles were recognised in the establishment of the Boreal Ecosystem-Atmosphere Study (BOREAS) that was conducted in Manitoba and Saskatchewan, Canada from 1993 to 1996 (Sellers et al., 1997). As with FIFE, the experimental effort was split between long term monitoring and three intensive field campaigns in 1994 and 1996. Ground-based and airborne observations were concentrated on two study areas approximately 50 km by 50 km, which were embedded in a larger 1000 km by 1000 km BOREAS experimental domain. Remote sensing observations within and between the northern and southern study areas were obtained from aircraft and satellites.

There have been several other programmes that investigated land-atmosphere interaction since BOREAS. Hydrological and biogeochemical processes in the European boreal zone were examined in the Northern Hemisphere climate Processes land-surface Experiment (NOPEX) in 1994 and 1995 (Halldin et al., 1998; Halldin et al., 1999). The Southern Great Plains experiment (SGP97) was held in Oklahoma, USA in 1997 and combined detailed ground-based, airborne and satellite data to investigate the spatial and temporal variation in soil moisture (Famiglietti et al., 1999). The interaction of hydrologic, ecologic and atmospheric processes in a semi-arid area were re-visited in the Semi-Arid Land-Surface-Atmosphere (SALSA) programme held in the San Pedro river basin in Mexico and Arizona, USA, from 1997 to 1999 (Goodrich et al., 2000). This study made extensive use of the new generation of satellite and airborne hyper-spectral radiometers in addition to the traditional tools of ground-based meteorological, hydrological and ecological observations.

The 1994 and 1995 OASIS experiments share four key features with these studies (Leuning et al., 2004; Cleugh et al., 2004; Finkele et al., 2003; Isaac et al., 2004a; Isaac et al., 2004b). First, OASIS used observations at a range of different spatial and temporal scales, from chamber measurements to micrometeorological sites to research aircraft to satellites. Second, the experimental effort was concentrated into a short intensive observation period but covered a large spatial extent. Third, the planning and structure of the OASIS experiment recognised that the problems being addressed were too complex for a single group to resolve and that collecting the data to address these problems required the coordination of many groups from different disciplines. Fourth, in common with all of the above studies, OASIS was focussed on improving knowledge of the processes governing surface-atmosphere exchange in order to improve current modelling approaches. This is in contrast to the earlier generation of boundary-layer studies such as Minnesota and Kansas (USA), Hay, Wangara and Koorin (Australia) where the primary objective was basic understanding and not modelling (Kaimal and Wyngaard, 1990; Garratt and Hicks, 1990).

In addition to these common features, there were several unique aspects to the OASIS experiments. First, although there have been other large boundary layer studies in Australia, OASIS was the first to attempt integration of a wide range of disciplines and scales. Second, OASIS included the trace gases nitrous oxide (N_2O) and methane (CH_4) in addition to CO_2 and had the improvement of emissions inventories as one of the main experimental aims. Third, OASIS took place over a region with two clearly defined heterogeneities at different scales. Heterogeneity at the mesoscale was driven by the rainfall gradient, approximately 1 mm per kilometre. At the microscale, it was driven by different land cover (crop and pasture). This allowed comparison of boundary-layer response to differences in land cover and differences in soil moisture. Fourth, OASIS captured conditions of below-average and average rainfall in consecutive years permitting the observed differences to be ascribed to soil moisture alone since land cover did not change significantly.

This thesis will concentrate on the 1995 OASIS experiment. The annual and growing season (July to September) rainfall totals for the OASIS experimental domain in 1994 and 1995 are presented in Section 2.6.2. These show that rainfall was very low in the 1994 growing season and Leuning et al. (2004) demonstrate that the heterogeneity of the OASIS domain was suppressed in the drought conditions. In addition to the atypical nature of 1994, flight plans for 1995 were better optimised for investigating the response of the boundary-layer to surface heterogeneity and the instrument suite carried by the aircraft was upgraded to include radiometers and a reliable CO_2 sensor. For these reasons, the 1994 OASIS results were considered unsuitable for the analyses presented in later chapters and have not been used.

This chapter is intended to provide the background required for subsequent chapters in the thesis by describing the OASIS measurement programme, the data collected, relevant details of the data processing and the climatology and meteorology of the experimental domain. Unless otherwise stated, all analyses used in this chapter were performed by the author using data from the sources identified. Section 2.2 gives an overview of the OASIS experiments including the scientific objectives and the location of the experimental domain. The ground-based sites and instrumentation used in the 1995 OASIS experiment are described in Section 2.3, the aircraft program is discussed in Section 2.4 and details of the remote sensing data are presented in Section 2.5. The rainfall climatology of the OASIS domain and the meteorology of the 1995 OASIS observation period are discussed in Section 2.6. Conclusions are presented in Section 2.7.

2.2 Overview of OASIS

2.2.1 Scientific Objectives

The overall aim of the OASIS experiments was (Raupach et al., 1994):

> "to measure, interpret and model biosphere-atmosphere exchange processes in heterogeneous terrain at interlinking spatial scales from leaf to region, especially
>
> (1) the land-air fluxes of energy and water
>
> (2) the land-air fluxes of the greenhouse gases CO_2, N_2O and CH_4
>
> (3) the land-air discrimination fluxes of the stable isotopes ^{13}C and ^{18}O in CO_2".

The groups associated with investigations of the stable isotope concentrations in the air, soil and plant material were unable to participate fully in the OASIS experiments and this research focus was not developed.

There were three main components within the energy and water exchange focus. The first component examined the processes by which patch scale measurements could be aggregated to provide regional scale estimates (upscaling) and by which regional scale measurements could be disaggregated into patch scale estimates (downscaling). This component was designed to test our current ability to use observations at one scale to accurately infer fluxes at a different scale. Upscaling would use the averaging schemes proposed by McNaughton (1994) and Raupach (1995) while downscaling would use soil-vegetation-atmosphere-transport (SVAT) models to infer patch scale fluxes from regional scale meteorology and local surface properties. The second component was testing CBL budget techniques for estimating regional scale fluxes of heat, water vapour and trace gases. This component would use data from the aircraft, from tethered and free-ascent balloons, from flask samples taken throughout the CBL and from ground-based instruments to test 1-, 2- and 3-dimensional budget methods. The methods were to be tested for H_2O first and the most successful method would then be applied to CO_2 and other trace gases. The third component was developing relationships between surface properties and remotely sensed radiance at several wavelengths. This component would draw on data from the NOAA-9 Advanced Very High Resolution Radiometer (AVHRR) and Landsat 5 Thematic Mapper (TM) instruments as well as an airborne hyperspectral radiometer. The intention was to test methods of inferring regional scale patterns in surface properties and to monitor their change over time.

The trace gas exchange focus was motivated by the need to better define the surface fluxes of CO_2, N_2O and CH_4 so as to constrain greenhouse gas emission inventories. This focus had five components, three of which have been actively researched in the years following the experiments. The first of these was chamber measurements of trace gas exchange between the soil and the atmosphere. This component was to provide measurements of the soil fluxes of CO_2, N_2O and CH_4 that could be used directly to refine inventory predictions and could also be used to test and validate models of soil microbial activity. The second component was the measurement of trace gas fluxes at the patch scale using micrometeorological techniques and this component has received the most attention to date. The techniques adopted were eddy covariance measurement of CO_2 fluxes from tower and aircraft-mounted instruments, flux-gradient methods for estimating the fluxes of CO_2, N_2O and CH_4 from concentration profiles measured at seven heights on a 22 m tower and nocturnal boundary-layer budget methods. The third component was the estimation of regional-scale trace gas fluxes using CBL budget techniques developed as part of the energy and water exchange focus. The remaining two components, which have not been pursued, were the testing of inverse Lagrangian methods for separating the soil and vegetation contributions to the observed flux and testing methods for upscaling measurements of trace gas fluxes.

2.2.2 Location and Major Features

The OASIS experiments were conducted in southeast Australia near the city of Wagga Wagga (35° 7′ 33″ S, 145° 21′ 13″ E), see Figure 2.1a, in October 1994 and October 1995. The name Wagga Wagga will be used to refer to the city and the name Wagga will be used to refer to the micrometeorological site. The term OASIS domain will be used to refer to the 130 km by 50 km area centered on the OASIS transect that is covered by the Landsat 5 image described in Section 2.5.

The major features of the experiment area are the Great Dividing Range to the south and east, rising to maximum heights of 1500 m, the Hay Plains, an extensive area of flat semi-arid land to the west and the Murrumbidgee River which flows from east to west through the city of Wagga Wagga. see Figure 2.1b. The ground-based sites were located along an 96 km transect oriented east-north-east to west-south-west. The terrain slopes gently from 140 m at Urana to 210 m at Wagga.

Figure 2.1c shows an area of 110 by 30 km containing the OASIS transect. The major features within this area are the foothills of the Great Dividing Range to the south and east, the Murrumbidgee River in the north western corner, Mt Galore (380 m) 12 km north-northeast of the town of Lockhart and Lake Cullival at the western end of the transect. The area is part of the watershed of the Murrumbidgee River but the drainage pattern is divided by the low ridge that runs north to south, 10 km east of Lockhart. The area to the east of the ridge forms the Bullenbung Plain, which drains north to the Murrumbidgee River. The area to the west of the ridge forms the Brookong Plain and drains west into Lake Urana, the outflow of which is a north flowing creek system that empties into the Murrumbidgee River.

The Wagga site was located on the eastern side of a shallow valley approximately 10 km wide and bounded to the west by Malebo Ridge (330 m), a series of hills (300 m) to the east and opening to the Murrumbidgee River to the south. Normalised Difference Vegetation Index (*NDVI*) derived from a Landsat 5 TM image of the area around the site shows a mosaic of crop, pasture and fallow fields with typical dimensions of 300 to 500 m, see Figure 2.1f.

The Browning site was located on the western side of the low ridge separating the Bullenbung and Brookong Plains and at the head of a shallow basin containing several ephemeral creeks that drain southwest to Lake Cullival. Two other sites were established in addition to the crop and pasture sites at the Browning property. The first was over canola at the Cooinda property, about 1 km northeast of the Browning crop and pasture sites. The second was over wheat at The Wattles property, about 4.5 km southwest of the Browning sites. The surrounding terrain is dominated by Mt Galore, 7 km to the north of the Browning site, which rises 200 m above the surrounding area. The Landsat 5 TM image shows a mixture of crops, pasture and fallow fields with typical dimensions of 500 to 800 m, see Figure 2.1e.

The Urana site was located on the Brookong Plain, 3 km southwest of Lake Cullival. This area is very flat with terrain slopes of less than 20 m in 5 km (1 in 250). Lake Cullival, 5 km by 3 km, is an ephemeral lake that was dry at the time of the aircraft flights in mid-October 1995. The southwest edge of the lake appears as the dark area in the top right corner of Figure 2.1d. The Landsat 5 TM image shows a mosaic of crop, pasture and fallow fields similar to the areas around the Browning and Wagga sites but field sizes tend to be somewhat larger with typical dimensions of 1000 m. The general increase in *NDVI* from west to east is evident in the gradual brightening of the images in Figure 2.1d to f.

The area from Wagga Wagga to Urana is used for mixed agriculture with approximately 50% of the land devoted to pasture (some native grasses but predominantly improved pasture), 40% to cropping (wheat, oats, canola, triticale and barley), 5% to fallow land and 5% to remnant native vegetation.

Table 2.1 shows the location, leaf area index (L_{ai}) and canopy height (h_c) of the eight ground-based sites used during the 1995 OASIS experiment.

Table 2.1 Location, leaf area index (L_{ai}) and canopy height (h_c) for the ground-based sites during the 1995 OASIS experiment. The location is given in Australian Map Grid easting (E) and northing (N).

	Wagga		Browning		Cooinda	Wattles	Urana	
	Pasture	Triticale	Pasture	Oats	Canola	Wheat	Pasture	Wheat
E (km)	530.51	530.83	478.37	479.94	480.90	475.35	448.25	447.28
N (km)	6120.55	6120.55	6108.51	6108.06	6108.85	6104.93	6098.57	6098.04
L_{ai}	2.0	4.0	1.5	3.5	2.0	3.0	1.0	2.5
h_c	0.5	0.8	0.2	0.8	1.6	1.1	0.2	0.8

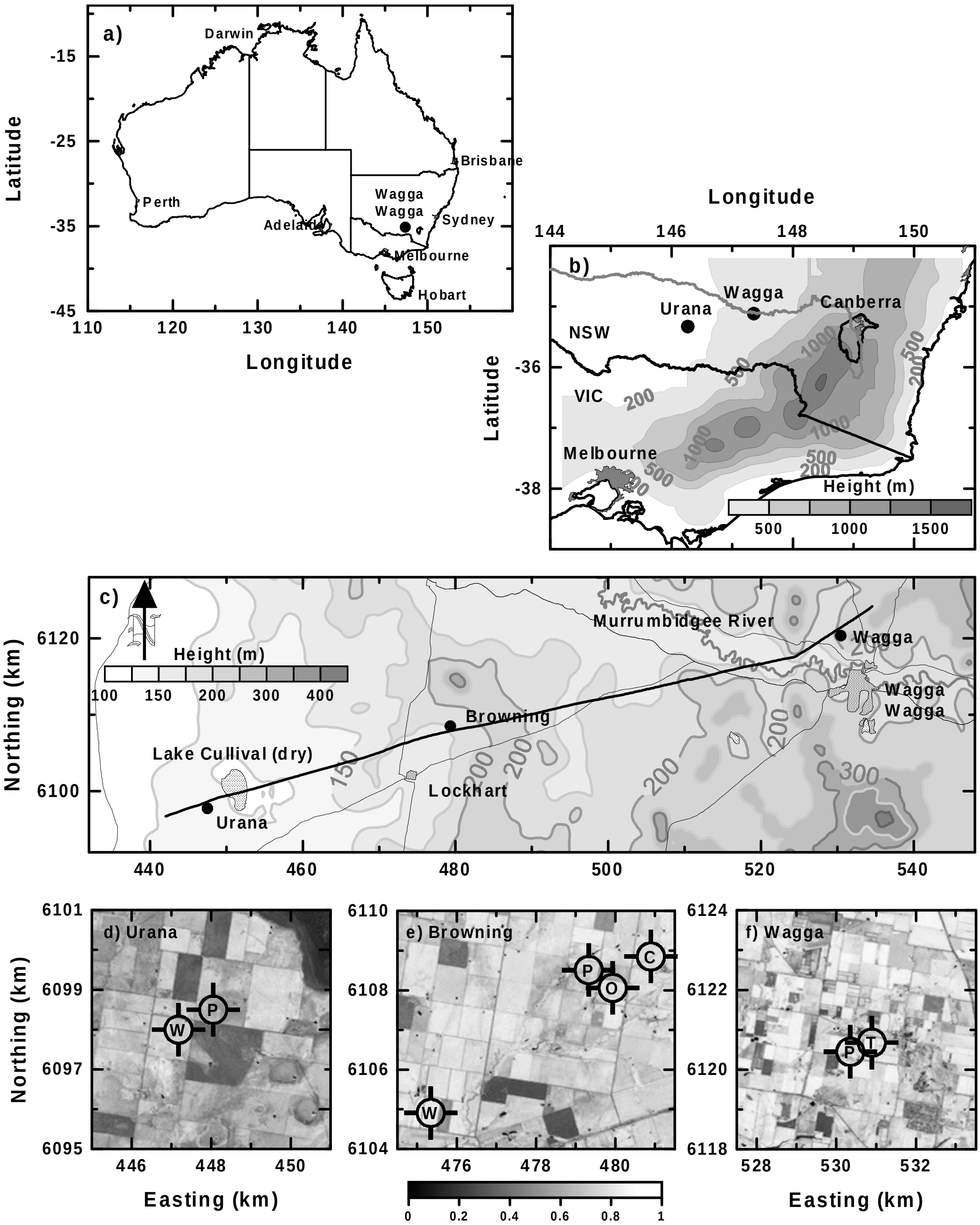

Figure 2.1 Location of the OASIS experiments, a) map of Australia showing the location of Wagga Wagga, b) map of south eastern Australia showing Wagga, Urana and the Murrumbidgee River (grey line), c) map of the OASIS domain showing Wagga, Browning, Urana, the aircraft transect (thick), major roads (thin) and Murrumbidgee River (grey line). Plots d), e) and f) are *NDVI* images of Urana, Browning and Wagga showing the locations of the crop ("W", wheat; "O", oats; "C", canola; "T", triticale) and pasture ("P") sites.

2.3 Description of the Ground-based Sites

2.3.1 General Remarks

The paired crop and pasture sites at Wagga, Browning and Urana are described in Leuning et al. (2004) and Griffith et al. (2002). The wheat site at The Wattles is described in Isaac and McAneney (1997) and Isaac et al. (2004a). The following sections give a brief outline of the instrumentation at the eight ground-based sites used during the 1995 OASIS experiment.

Data collection at the Wagga, Browning, Cooinda and Urana sites was done by Commonwealth Scientific and Industrial Research Organisation (CSIRO) Centre for Environmental Mechanics (CEM). The Wattles site was managed by The Horticulture and Food Research Institute of New Zealand Ltd (HortResearch). Processed data files were obtained from the principle investigators for each of these sites: Drs R. Leuning (Wagga), P. Coppin (Browning) and H. Cleugh (Cooinda and Urana) of CSIRO CEM and Dr J. McAneney (Wattles) of HortResearch. The processing involved collation of the raw data, coordinate rotation, trend removal and calculation of the variances and covariances from the turbulence data and basic quality control. The basic quality control consisted of removing periods when the instruments were being changed, calibrated or had failed.

2.3.2 Wagga

Wagga was the core site for both the 1994 and 1995 OASIS experiments. The site was located on a research farm operated by Charles Sturt University, Wagga Wagga. Micrometeorological observations were made over both crop (triticale) and pasture (lucerne) fields in 1995.

The pasture site consisted of a 22 m open lattice tower instrumented for profile measurements at 0.5, 1.0, 2.0, 4.0, 8.0, 14.0 and 22.0 m using cup anemometers and aspirated temperature and humidity sensors (Vaisala Oy, Helsinki, Finland). Eddy covariance measurements of latent heat, sensible heat and CO_2 flux were made at 2.0 m using a 3-axis sonic anemometer/thermometer (Coppin and Taylor, 1983) and an open-path infrared gas analyser (E009, Advanced Systems, Inc, Okayama, Japan).

Estimates of F_C were also made using observations of the CO_2 concentration profile from 0.5 to 2.0 m and from 0.5 to 4.0 m measured by a non-dispersive infrared gas analyser (LI-6262, LICOR Inc, Nebraska, USA). A Bowen ratio system was also installed on a separate mast in the pasture field and consisted of wet- and dry-bulb psychrometers with a vertical spacing of 1 m. The psychrometer position was reversed every 15 minutes and two consecutive periods averaged to give estimates of the fluxes every 30 minutes. A Fourier Transform Infrared (FTIR) spectrometer was also used to measure CO_2, N_2O and CH_4 profiles on the 22 m tower (Griffith et al., 2002).

The crop site consisted of a 4 m tower instrumented for profile measurements at 0.5, 2.0 and 4.0 m. Eddy covariance measurements of F_E, F_H and F_C were made at 2.0 m and Bowen ratio observations were also available. Instrumentation was identical to the pasture site. Soil heat flux was measured at 50 mm below the surface at both sites and corrected for storage using soil temperatures measured at 20 and 50 mm. Soil moisture was measured using Time Domain Reflectometry (TDR; Zegelin and White, 1988) at five (crop) and six (pasture) depths. Incoming and outgoing shortwave and net all wave radiation were measured at 2.0 m above both surfaces.

Mean and turbulent quantities were sampled at 0.1 and 20 Hz respectively and averaged over 15 minutes. Eddy covariance fluxes were calculated after coordinate rotation to force the mean crosswind and vertical components of the wind speed to zero and trace gas fluxes were corrected for density effects according to Webb et al. (1980). Data collection began on 13 October 1995 and stopped on 27 October 1995 with 21 and 22 October 1995 lost due to rainfall. Consecutive 15 minute periods were averaged to provide hourly data for the work in this thesis and the hourly data were subjected to a range of quality control checks. Only daytime hours, defined here as 0800 to 1700 inclusive, were used in the analyses in subsequent chapters. Within these times, a total of 98 hours of data was available for the crop site and 94 for the pasture site, representing 75% and 72% of the possible 130 hours respectively.

2.3.3 Browning

The 1994 OASIS experiment used the Bullenbung site (Leuning et al., 2004). This site was flooded in July 1995 after heavier than normal rains during the preceding three months and it was decided to relocate the site to the Browning property near Lockhart. Micrometeorological sites were established over fields of oats and pasture.

Eddy covariance measurements of F_E, F_H and F_C were made at 2.0 m above both crop and pasture sites with 3-axis sonic anemometer/thermometers (Coppin and Taylor, 1983; Solent, Gill Instruments Ltd, UK at the pasture site) and an open-path infrared gas analyser (Auble and Meyers, 1992). Cup anemometers and aspirated temperature and humidity sensors (Humitter, Vaisala Oy, Finland) provided measurements of mean quantities at 4.0 m. Soil heat flux was measured at a depth of 50 mm and corrected for heat storage using soil temperature measured at depths of 20 and 50 mm. Incoming and outgoing shortwave and net radiation were measured at 2.0 m above both surfaces. TDR measurements of soil moisture were attempted at both sites but no reliable data was collected.

Mean and turbulent quantities were sampled at 0.1 and 20 Hz respectively and averaged over 15 minutes. Eddy covariance fluxes were calculated after coordinate rotation to force the mean crosswind and vertical components of the wind speed to zero and trace gas fluxes were corrected for density effects according to Webb et al. (1980). Data collection began on 9 October 1995, ended on 27 October 1995 with 21 and 22 October 1995 lost due to rain. Hourly data were obtained by averaging consecutive 15 minute periods and the data were subjected to a range of quality control checks. A total of 154 hours of daytime data was available for the crop site and 164 for the pasture site, representing 81% and 86% of the possible 190 hours respectively.

2.3.4 Cooinda

Approximately 20% of the crops planted in the Lockhart area in 1995 were canola. Shortly before the start of the 1995 OASIS experiment, it was decided to establish a surface energy balance site over a canola field so that this surface type was represented in regional flux estimates. A suitable field was found on the Cooinda property, about 1.5 km northeast of the sites at Browning.

Eddy covariance measurements of sensible and latent heat flux were made at 4.0 m using a single-axis sonic anemometer/fine wire thermocouple (CA27T, Campbell Scientific, Utah, USA) and a Krypton hygrometer (KH2O, Campbell Scientific, Utah, USA). Mean quantities were also measured at 4.0 m using cup anemometers and aspirated temperature and humidity sensors (Humitter, Vaisala Oy, Finland). Soil heat flux plates (HFT3, Campbell Scientific Inc, Utah, USA) were buried at a depth of 70 mm and soil heat fluxes were corrected for storage using soil temperatures measured at four depths. Net radiation (Q7, Radiation and Energy Balance Systems (REBS) Inc, USA) was measured at 4.0 m.

Turbulence data was sampled at 10 Hz and averaged over 20 minutes. No coordinate rotation was possible due to the use of a single-axis sonic anemometer and the mean vertical velocity was simply removed before calculating the fluxes. Water vapour concentration derived from the Krypton hygrometer was corrected for O_2 absorption using the method of Tanner et al. (1993) and corrected for density effects following Webb et al. (1980). Collection of data for F_H and F_E began on 18 October 1995 and ended on 27 October 1995 with three days, 20, 21 and 22 October 1995, lost due to equipment failure and rainfall. A total of 47 daytime hours was available representing 67% of the possible 70 hours.

2.3.5 The Wattles

Two micrometeorological sites were established at The Wattles property, one over a field of oats and the other over a wheat field. Measurements of mean quantities were made on a third mast located in the wheat field. The beam of a large aperture scintillometer was directed across the diagonal of the wheat field. The original intention was to compare observations of F_H from the aircraft and the large aperture scintillometer at this site. This was prevented by a combination of the late arrival of the aircraft at the 1995 OASIS experiment and the failure of the scintillometer source on the second day of aircraft operations.

A single-axis sonic anemometer/fine wire thermocouple (CA27T, Campbell Scientific Inc, USA) and a Krypton hygrometer (KH20, Campbell Scientific Inc, USA) were mounted at heights of 4.5 m over the wheat crop and at 2.3 m over the oat crop. A two-dimensional drag anemometer (Green et al., 1994) provided measurements of the momentum flux over the wheat crop. Net radiation (Q6, REBS Inc, USA) was measured 1 m above the wheat crop. Two soil heat flux plates (HFT3, Campbell Scientific Inc, USA) were buried at a depth of 60 mm and the soil heat flux, F_G, estimated following Watts et al. (1990).

All turbulence data were sampled at 10 Hz and averaged over periods of 30 minutes. No coordinate rotation is possible due to the use of a single-axis sonic anemometer. For the latent heat flux, water vapour concentrations derived from the krypton hygrometers were corrected for O_2 absorption using the method of Tanner et al. (1993) and corrected for density effects following Webb et al. (1980). Data collection began on 10 October 1995 and ended on 25 October with three days data, 12, 21 and 22 October, lost due to rainfall. Data from a total of 104 daytime hours are available representing 80% of the possible 130.

2.3.6 Urana

Micrometeorological sites were established over fields of wheat and pasture for the 1995 OASIS experiment.

Eddy covariance measurements of F_E and F_H were made at 2.0 m above the crop and pasture sites with single-axis sonic anemometer/fine wire thermocouple (CA27T, Campbell Scientific Inc, USA) and a Krypton hygrometer (KH20, Campbell Scientific Inc, USA). Cup anemometers and aspirated temperature and humidity sensors (Humitter, Vaisala Oy, Finland) provided measurements of mean quantities at 2.0 m. Soil heat flux was measured at a depth of 50 mm and corrected for heat storage using soil temperature measured at depths of 20 and 50 mm. Incoming and outgoing shortwave and net radiation were measured at 2.0 m above both surfaces.

Mean and turbulent quantities were sampled at 0.1 and 10 Hz respectively and averaged over 15 minutes. No coordinate rotation is possible due to the use of a single-axis sonic anemometer. For the latent heat flux, water vapour concentrations derived from the krypton hygrometers were corrected for O_2 absorption using the method of Tanner et al. (1993) and corrected for density effects following Webb et al. (1980). Data collection began at both sites on 7 October 1995 but was ended prematurely at the wheat site by rainfall on 20 October 1995 and the subsequent collapse of the mast when a guy wire peg pulled out of the rain-softened soil (Dr. H. Cleugh, pers. comm.). Data collection at the pasture site was interrupted by rain on 20 October 1995 and resumed again on 25 October 1995. A total of 123 daytime hours are available for the pasture site representing 82% of the possible 150 hours. 98 hours of daytime data are available for the wheat site of which only 61 hours overlap with measurements at Wagga.

2.4 Description of the Aircraft Programme

2.4.1 General Remarks

There were three main objectives of the aircraft participation in the OASIS experiments. First, the aircraft were to provide the link between observations of the fluxes made by the ground-based instruments at patch scale and the estimates available from modelling and CBL budget techniques at the regional scale. Second, data from the aircraft would be used to assess the degree to which the ground-based sites were representative of their surroundings. Third, the aircraft would provide observations of mean quantities at regional scales that could be used to validate models and to test CBL budget techniques. Two aircraft were available to fulfil these objectives, a Cessna 340A *VH-EOS* and a Grob 109B *VH-HNK* operated by the Flinders Institute for Atmospheric and Marine Science (FIAMS), Flinders University of South Australia.

Experience from the 1994 OASIS experiment suggested that the utility of the aircraft data could be increased greatly if both aircraft were used in complementary roles that exploited their individual strengths. *EOS*, a twin-engine aircraft, flew at twice the airspeed of, and climbed twice as rapidly as the motorised glider, *HNK*. In contrast, the slower airspeed and better glide performance of *HNK* meant it was better suited to low-level operations at altitudes of less than 50 m. The 1995 OASIS experiment flight plan was tailored to use the features of both aircraft. *EOS* was to perform vertically stacked runs at each end of the transect with ferry flights between these at the top of the mixed layer to collect information on the entrainment dynamics. These flights would provide the top and sides of a 2-dimensional box enclosing the transect. *HNK* was to perform low-level flights along the transect to provide the bottom of the box. The measurements were expected to capture the entry of scalars into, and exit from, the 2-dimensional box via the surface fluxes, entrainment and advection.

VH-EOS was lost when both engines failed on approach to Parafield Airport, Adelaide, during a test flight immediately prior to departure for the 1995 OASIS experiment. The crew (Dr Jörg Hacker and Mr Ewan Mackenzie) was not seriously injured but the aircraft and the instrumentation were written off. Plans for the aircraft participation in the 1995 OASIS experiment were quickly revised and, several days late, *HNK* departed for Wagga Wagga on 13 October 1995. Dr Hacker did not attend the 1995 OASIS field experiment and in his absence, the author undertook all scientific and flight planning, coordination of aircraft logistics, preliminary data processing and liaison with other science groups at OASIS.

The amended flight plans are described in the remainder of this section. A total of 58 hours of data was collected during flights over eleven days in the period 16 to 29 October. Aircraft operations were prevented by rain on 21 and 22 October 1995 and 28 October 1995 was devoted to in-situ calibration of the aircraft instruments. The official end of the 1995 OASIS intensive observation period was 27 October 1995 and ground-based observations were stopped on this day. However, 29 October 1995 began without cloud and it was decided, given the late arrival of the aircraft at OASIS and the paucity of clear sky conditions, to collect one more day of aircraft data.

2.4.2 Low-level Flights

HNK performed a series of low-level flights over instrumented fields at the Wattles site, see Figure 2.2. The intention of these flights was to provide a data set that could be used to directly compare aircraft and ground-based observations of means, variances and covariances. The desire to compare means and variances meant that the aircraft height above ground level had to be as close as possible to the height of the ground-based instruments, about 4.5 m in the case of the eddy covariance measurements in the wheat field.

Figure 2.2 is an *NDVI* image of The Wattles property showing the location of the ground-based instruments and the aircraft flight tracks. Each low-level flight consisted of 10 to 14 runs along the north-south or east-west tracks at an altitude of between 4.5 and 6.0 m and with consecutive runs being flown on opposite headings. Nine flights were performed over seven days with each flight taking about 30 minutes to complete. Mean quantities used in the comparison at this site are averages over all of the passes comprising each flight and standard deviations for the whole flight have been calculated from the mean of the pass variances plus the variance of the pass means. Fluxes for an entire flight were calculated by averaging the fluxes for each pass. Averaging of values from each pass reduces the random error in the final figure by a factor of $1/\sqrt{N}$ where N is the number of passes.

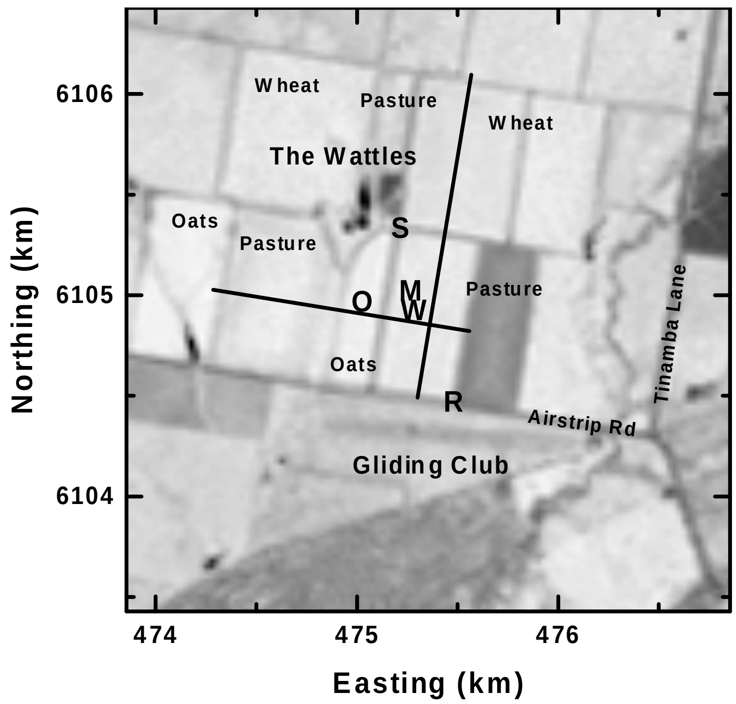

Figure 2.2 *NDVI* image of The Wattles property showing the location of the eddy covariance instruments in the wheat ("W") and oat ("O") fields, the location of the meteorological mast in the wheat field ("M"), the scintillometer source ("S") and receiver ("R") and the aircraft north-south and east-west flight tracks (black lines).

2.4.3 Grid Flights

One of the primary objectives of the aircraft during the 1995 OASIS experiment was to provide estimates of the regional scale fluxes of sensible and latent heat. Estimates of CBL fluxes from airborne instruments are subject to both random and systematic errors associated with the length over which the estimates are formed (Lenschow and Stankov, 1986; Mann and Lenschow, 1994; Mahrt, 1998). The random errors arise due to under-sampling of the transporting eddies and systematic errors arise due to incomplete resolution of long wavelength contributions when a short averaging length is used. Systematic errors can be reduced by flying at low altitude, for example, the error due to a 10 km averaging length is expected to be less than 4% at 20 m (Isaac et al., 2004b). Random errors can be reduced by flying repeated passes over the same track or by flying grid patterns consisting of several parallel legs. Data from a single grid pattern can be used to provide a spatially averaged flux at a given time or data from several grids over many days can be combined to provide a temporal average at a given location. Either method reduces the effect of transient mesoscale motions on the measured fluxes.

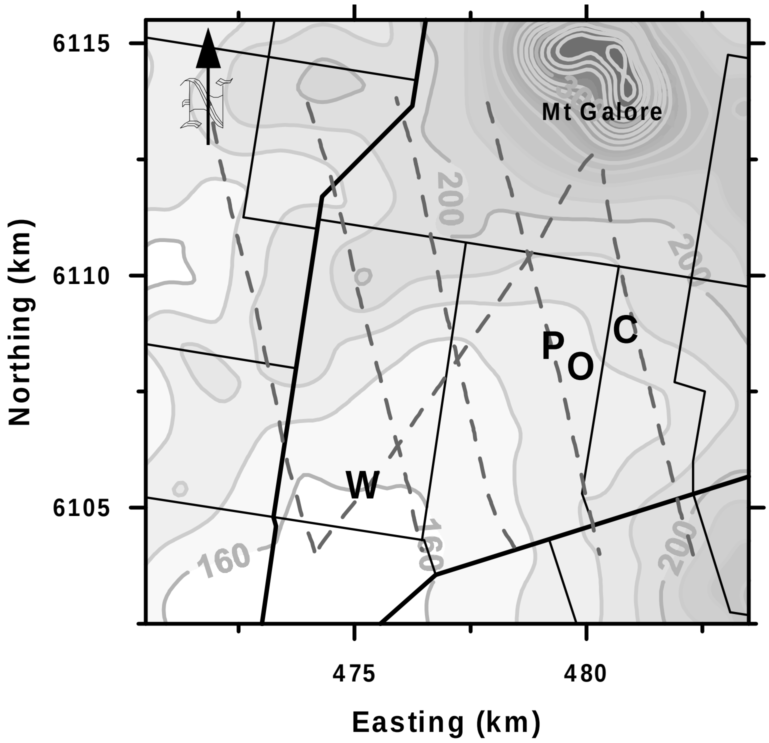

Figure 2.3 Schematic of the area around the Browning site showing the Browning oats ("O") and pasture ("P"), Cooinda canola ("C") and The Wattles wheat ("W") ground-based sites. The aircraft grid flight track (grey dashed line), major roads (thick black line) and minor roads (thin black line) are also shown. Terrain contours are at 10 m intervals.

Figure 2.3 shows a 13 by 13 km area north-west of the town of Lockhart containing the Browning, Cooinda and Wattles ground-based sites and the aircraft grid pattern used during the 1995 OASIS experiment. The grid consisted of six legs, each approximately 10 km long. Five of the legs were oriented north-northwest to south-southeast and were spaced about 2 km apart with the sixth leg along the diagonal from the northeast corner to the southwest corner of the grid. The grid pattern was generally started at the southwest corner with the aircraft returning to the starting point at the completion of the diagonal leg and was flown at three or four heights each day. Each grid pattern took approximately 40 minutes to complete and a total of 22 grids was flown on seven days. Table 2.2 lists details of the number and heights of the grid flights.

Table 2.2 The number of grid flights in each height range, the range of heights and the average height of each group.

Number	Range m	Average m
6	14 - 23	18
7	37 - 64	49
5	118 - 160	147
4	190 - 263	238

2.4.4 Transect Flights

Another primary objective of the aircraft flights was to assess the degree to which the ground-based sites were representative of the surrounding areas and to provide information on the spatial variation in F_E, F_H and F_C between the ground-based sites. This objective was met by flying repeated passes along a transect from Wagga to Urana.

Figure 2.4 is a map of the OASIS experiment domain showing the location of the ground-based sites and the aircraft transect and grid pattern flight tracks. The transect began 5 km northeast of Wagga, ended 5 km southwest of Urana and was 96 km in length. The extension beyond Wagga and Urana allowed flux estimates averaged over 10 km to be centred on these sites. The aircraft height during the transect flights was approximately 25 m and each transect pass took between 45 and 50 minutes. The transect flight path passed approximately 1 km north-west of the tower at the Wagga pasture site and passed directly over the Browning oats and Urana pasture sites. The small track deviation southwest of Wagga allowed the aircraft to pass close to the Wagga site without having to climb over Malebo Ridge. No sign of the gentle turn involved could be found in the turbulence data from the aircraft instruments.

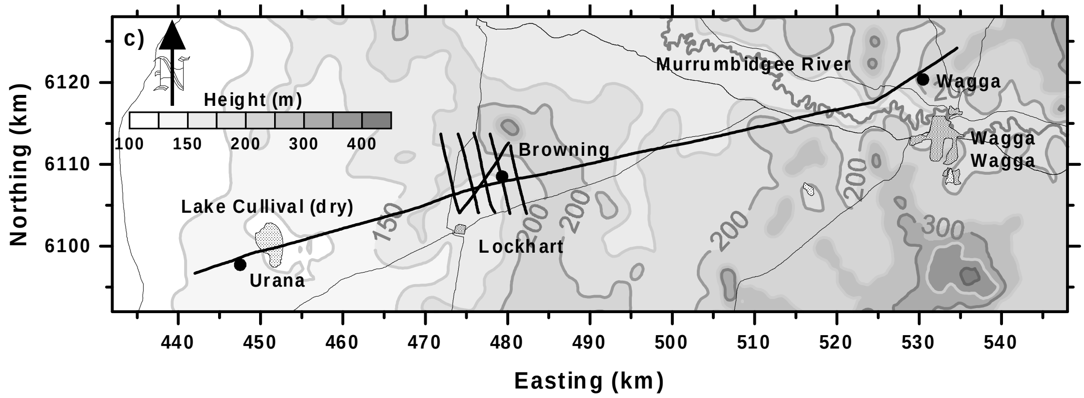

Figure 2.4 Map of the OASIS experiment domain showing the location of the ground-based sites and the aircraft transect and grid pattern flight tracks (black lines). Terrain contours are at 50 m intervals.

A total of twenty-two transect flights, ten of which were interrupted by grid patterns, were made over ten days from 16 to 29 October 1995. The outward (Wagga to Urana) transects and the western half of the return leg (Urana to Browning) occurred in the late morning to early afternoon. The eastern half of the return leg (Browning to Wagga) occurred in the late afternoon.

2.4.5 Profile/flask Flights

Regional scale fluxes of CO_2 can be estimated from temporal changes in the CO_2 concentration in the mixed layer of the convective boundary layer (Cleugh et al., 2004; Denmead et al., 1996; Raupach et al., 1992). The technique requires measurements of the CO_2 concentration in and above the mixed layer at different times of the day. For the 1995 OASIS experiment, this was to be achieved by a flask sampling system suspended beneath a large kite operated by a group from the University of Colorado, Colorado (USA) but problems were experienced in launching the kite and the method had to be abandoned.

The author considered the testing of CBL budget techniques for estimating regional scale fluxes to be an important objective for the 1995 OASIS experiment and offered *HNK* as an alternative sampling platform. Five flasks were mounted in a container, strapped into the right-hand seat in *HNK* and connected to a sampling port in the cabin roof by a length of Teflon tubing. The flasks were flushed and evacuated before use and samples taken at different heights by opening the valve at the neck of the flask. The flask contents were analysed by a second FTIR system based at Wagga. Details of the process and the results are given in Esler (1997) and Esler et al. (2000).

Flask flights were undertaken twice a day, in mid-morning and mid-afternoon, and all sampling was performed in the vicinity of Lockhart. The morning flights were dedicated to the flask sampling and involved out and return passes along the transect from Wagga to Browning, an ascent to about 2000 m and descent in five steps with samples taken at each step. Afternoon flights were slotted between other aircraft operations. Flasks were ferried by van to the Lockhart Gliding Club airstrip (see Figure 2.2), *HNK* landed at the strip, loaded the flasks in place of the observer and performed the ascent and descent to obtain the five samples which were then ferried back to Wagga for analysis. A total of 14 flask sampling flights were performed on eight days. Morning flights (7) took about 1 hour, afternoon flights about 45 minutes.

2.5 Description of Remote Sensing Data

2.5.1 Landsat Image

The 1995 OASIS field experiment was timed to coincide with two Landsat 5 passes over the area on 8 and 22 October 1995. The OASIS domain was covered by cloud during the pass on 22 October 1995 and data from this pass has not been used. The pass on 8 October 1995 coincided with clear skies over the OASIS domain. All analyses in this thesis use data from the 8 October 1995 pass. Details of the Landsat 5 pass are given in Table 2.3.

Table 2.3 Pass details for the Landsat 5 TM image.

Date	8 October 1995
Time	23:03:22 UTC
Path/row	92/84
Orbit	61720
Sun elevation	40.2 ^{o}
Sun azimuth	65.3 ^{o}
Centre latitude	34 ^{o} 36 ' 51 " S
Centre longitude	146 ^{o} 47 ' 01 " E

The data used in this thesis come from the Thematic Mapper sensor carried by the Landsat 5 satellite. This instrument uses a downward looking scanning radiometer to measure the radiance in seven wavelength bands with a pixel resolution of 30 m (bands 1 to 5 and 7) and 120 m (band 6). The region of the electro-magnetic spectrum occupied by the band and the wavelengths covered by the bands are given in Table 2.4.

Table 2.4 Region of the electro-magnetic spectrum covered by the 7 bands of the Landsat 5 Thematic Mapper.

TM Band	EM Region	Wavelength (μm)
1	Blue	0.45 - 0.52
2	Green	0.52 - 0.60
3	Red	0.63 - 0.69
4	Near IR	0.76 - 0.90
5	Middle IR	1.55 - 1.75
6	Thermal IR	10.40- 12.50
7	Middle IR	2.08 - 2.35

The image covers an area of 130 km by 50 km centred on a point halfway along the aircraft transect between the ground-based sites at Wagga and Urana (AMG easting 485000, AMG northing 6105000). It was supplied by the Australian Centre for Remote Sensing (ACRES) as an orthocorrected image resampled to a pixel size of 25 m (bands 1 to 5 and 7) with relative calibration of the 16 detectors per band to remove striping in the across track direction. The absolute radiometric calibration used to convert the digital count in each band to a spectral reflectance and the calculation of *NDVI* from the reflectance is described in Chapter Six.

2.6 Meteorology of the 1995 OASIS Experiment

2.6.1 General Remarks

Climate data for rainfall, air temperature, humidity, winds and sunshine are available for Wagga Wagga Airport and Urana Post Office from the Bureau of Meteorology, Australia. Wagga Wagga airport is 18 km southeast of the Wagga site at an elevation of 221 m and a 60 year record is available for this site. Urana Post Office is 16 km south-west of the Urana site at an elevation of 125 m. Rainfall is available for 120 years and temperature for 50 years at this site. Humidity and wind speed observations at Urana are only available for the last 5 years and this is too short to form a useful comparison with values from Wagga Wagga Airport.

Monthly average air temperatures at Wagga Wagga and Urana follow the same annual pattern with a mean difference of 1.1 °C, Urana being warmer than Wagga Wagga. This is close to the value of 0.94 °C expected due to the difference in elevation (96 m) between the two sites and suggests that, over the long term, there are no systematic differences in air temperature between Wagga Wagga and Urana. Systematic differences in the rainfall are discussed in the next section. Leuning et al. (2004) present a complementary analysis of meteorology during the 1994 and 1995 OASIS experiments.

2.6.2 Rainfall

Figure 2.5 shows plots of the annual total rainfall and monthly average rainfall for the period 1950 to 1995 for Wagga Wagga, Lockhart and Urana. Annual total rainfall is highly variable with maxima of >800 mm in wet years and minima of <300 mm in dry years. The drought in 1994 was considered severe but the rainfall record shows that there were five other years with similar or less annual rainfall in the 45 year period. The monthly average rainfall shows that most rainfall occurs from May to October, late autumn to spring in the Southern Hemisphere. There is a pronounced peak in rainfall amount in October for all three locations.

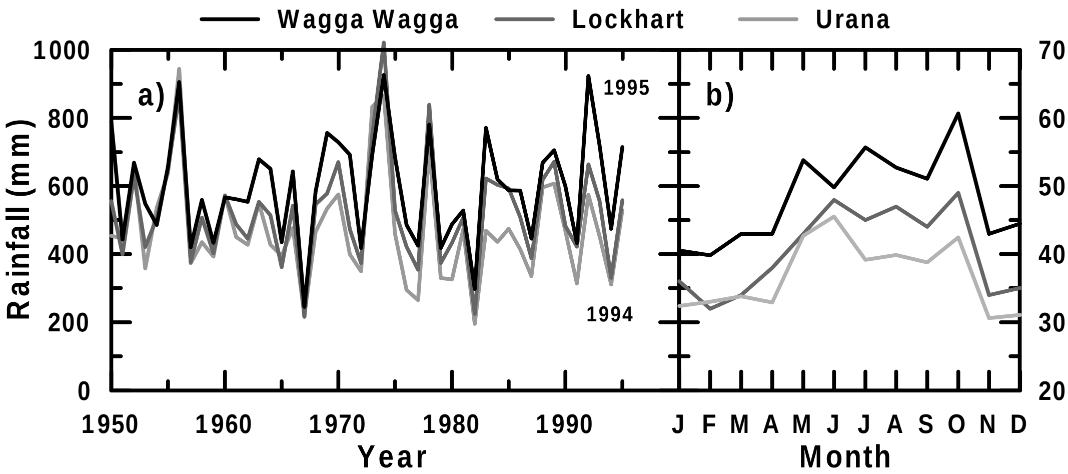

Figure 2.5 Plots showing a) annual total rainfall and b) monthly average rainfall for Wagga Wagga, Lockhart and Urana for the period 1950 to 1995.

Table 2.5 shows the annual and growing season (July to September) rainfall totals for the period 1950 to 1995 and for the years 1994 and 1995. The annual total for 1994 was between 65 and 79% of the long term value but growing season totals were less than 35% of the long term. Annual totals in 1995 were slightly above the long-term values as was the growing season value at Wagga Wagga. The 1995 growing seasons at Lockhart and Urana were drier than normal. The results suggest that differences between Wagga Wagga and the other two OASIS sites, Browning and Urana, may be more pronounced in 1995 than in the longer term.

Table 2.5 The annual and growing season rainfall totals for Wagga Wagga, Lockhart and Urana for the 1950 to 1995 period and for the year of 1995.

		Wagga Wagga	Lockhart	Urana
Annual	1950 - 1995	595.6	524.4	474.3
	1994	474.8	330.8	310.8
	1995	714.4	558.2	529.1
July to September	1950 - 1995	159.5	136.0	117.9
	1994	52.2	36.4	40.2
	1995	175.4	98.6	95.1

Figure 2.6 shows a plot of the cumulative rainfall for October 1995 for Wagga Wagga, Lockhart and Urana. Rain fell on two occasions during the 1995 OASIS experiment. The first was on 12 October 1995 (1.9, 5.7 and 7.4 mm at Wagga Wagga, Lockhart and Urana respectively) and the second was on 21 and 22 October 1995 (34.8, 48.9 and 43.0 mm at Wagga Wagga, Lockhart and Urana respectively).

The rainfall at Lockhart and Urana on these two days is close to the long-term average for October at these sites.

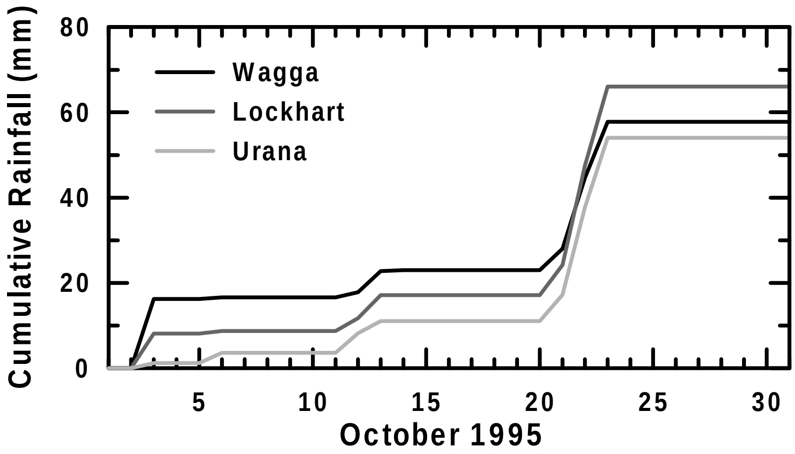

Figure 2.6 Plot of cumulative rainfall during October 1995 for Wagga Wagga, Lockhart and Urana.

Finkele et al. (2003) present results for the 1995 OASIS experiment from a coupled mesoscale-SVAT model. Their results predict a total rainfall over the two days of 22.5 mm at Browning, less than half of the observed rainfall of 48.9 mm. The discrepancy between the model results and the observations is of concern given the dominant role that water availability plays in determining evapotranspiration (Leuning et al., 2004). The effect of this is discussed later in the thesis.

2.6.3 Fluxes, Temperature, Humidity and Wind Speed

Figure 2.7 shows daily (0800 to 1700) averages of, and diurnal cycles in, the incoming shortwave radiation, the fluxes of sensible heat, latent heat and CO_2, air temperature, specific humidity and wind speed for 9 to 27 October 1995. Observations did not begin at Wagga until 13 October 1995.

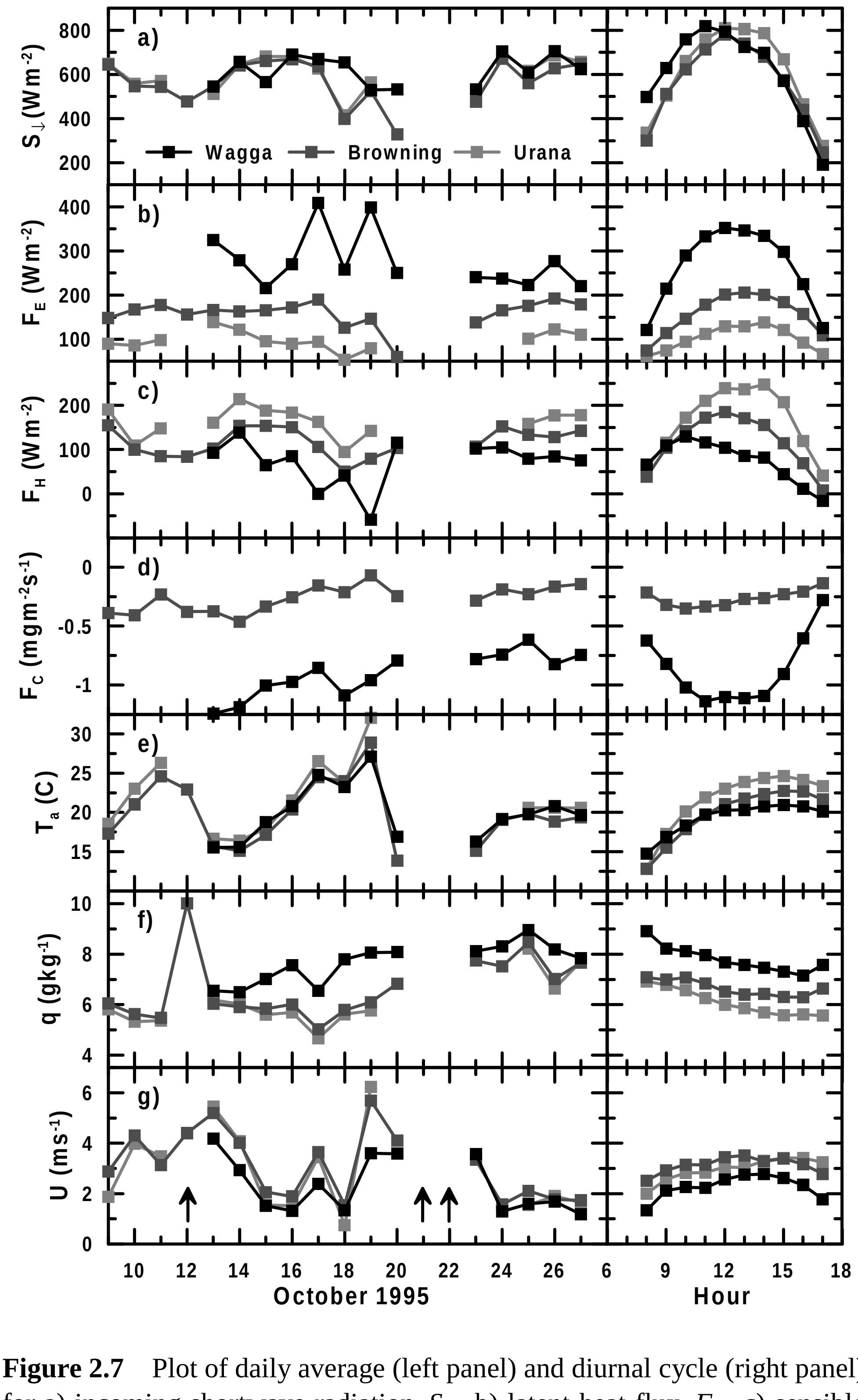

Figure 2.7 Plot of daily average (left panel) and diurnal cycle (right panel) for a) incoming shortwave radiation $S_\downarrow$, b) latent heat flux F_E, c) sensible heat flux F_H, d) CO_2 flux F_C, e) air temperature T_a, f) specific humidity q and g) wind speed U for the 1995 OASIS experiment at the Wagga (black), Browning (mid grey) and Urana (light grey) sites. Arrows indicate days of rainfall.

The synoptic conditions during the 1995 OASIS experiment were dominated by two cold fronts that passed over the area on 12 and 21 October 1995. The effect of these can be seen most clearly in the daily average air temperature, wind speed and incoming shortwave radiation. Daily average T_a and U rise ahead of the front and fall with the change of air mass behind the front. The trend in daily average $S_{\downarrow}$ reflects the cloudy conditions ahead of the front and the clearance behind. The fluxes of sensible and latent heat show responses to the changing synoptic conditions that depend on the site and, by implication, the soil moisture. At Browning and Urana, daily averaged F_E shows a decrease before the rainfall on 21 and 22 October 1995 and a pronounced increase after the rain while daily averaged F_H follows $S_{\downarrow}$. At Wagga, the daily averaged F_E and F_H both show strong responses to the hot, dry conditions on 17 and 19 October 1995. The daily averaged F_H at Wagga on these days was 0 and -59 W m^{-2} respectively, which indicates that evapotranspiration was maintained by advection in an "oasis" effect (Thom, 1975). This can only happen when sufficient water is available to the plants to prevent stomatal control of transpiration. The CO_2 flux does not exhibit a strong response to the synoptic conditions but shows a steady decline throughout the observation period. This reflects decreasing soil water levels and decreasing plant vigour as the growing season ends (Leuning et al., 2004).

The site-to-site differences are most clearly marked in the diurnal cycle of the latent heat, sensible heat and CO_2 fluxes, see the right hand panels of Figure 2.7b, c and d. Evapotranspiration and CO_2 uptake are greatest at Wagga and decrease from east to west along the transect in response to the observed rainfall gradient. Sensible heat loss by the surface shows the opposite trend with the highest values occurring at Urana and the lowest at Wagga. These trends reflect those in T_a and q where the lowest temperature and highest humidity occurs at Wagga. Note that the difference in afternoon temperatures between Wagga and Urana during the OASIS observational period was 3.6 °C, larger than expected given the 96 m height difference.

2.6.4 Spatial and Inter-annual Variability

Figure 2.8 shows the variation in $S_{\downarrow}$, $F_A = F_E + F_H$, F_E, F_H, F_C and T_{sfc} along the OASIS transect and between the years 1994 and 1995 derived from aircraft data. The values plotted are averages of all available transect flights in both years. The terrain elevation is also shown on each plot. Incoming shortwave radiation and CO_2 flux were only available for 1995.

There are no significant gradients in $S_{\downarrow}$ and $F_A = F_E + F_H$ along the transect but variations of ±50 W m^{-2} do exist in both quantities from location to location. These are likely to be an artefact of the small number of transects available for averaging in each year, 9 in 1994 and 10 in 1995.

There are strong gradients in F_E, F_H, F_C and T_{sfc} along the transect and significant variations in these quantities from 1994 to 1995, both of which reflect spatial and inter-annual differences in rainfall amount. There is a general trend from higher to lower values of F_E when going from east to west along the transect with corresponding trends in F_H, F_C and T_{sfc}. Values of F_E were much less in 1994 than in 1995 at all locations along the transect and this was reflected in higher values of both F_H and T_{sfc}. Spatial gradients in all of these quantities tended to be larger in 1995, when rainfall was larger, than in 1994. Site to site variation was also larger in 1995 with the exception of the Murrumbidgee River, whose influence on F_E, F_H and T_{sfc} was more noticeable in 1994 than in 1995.

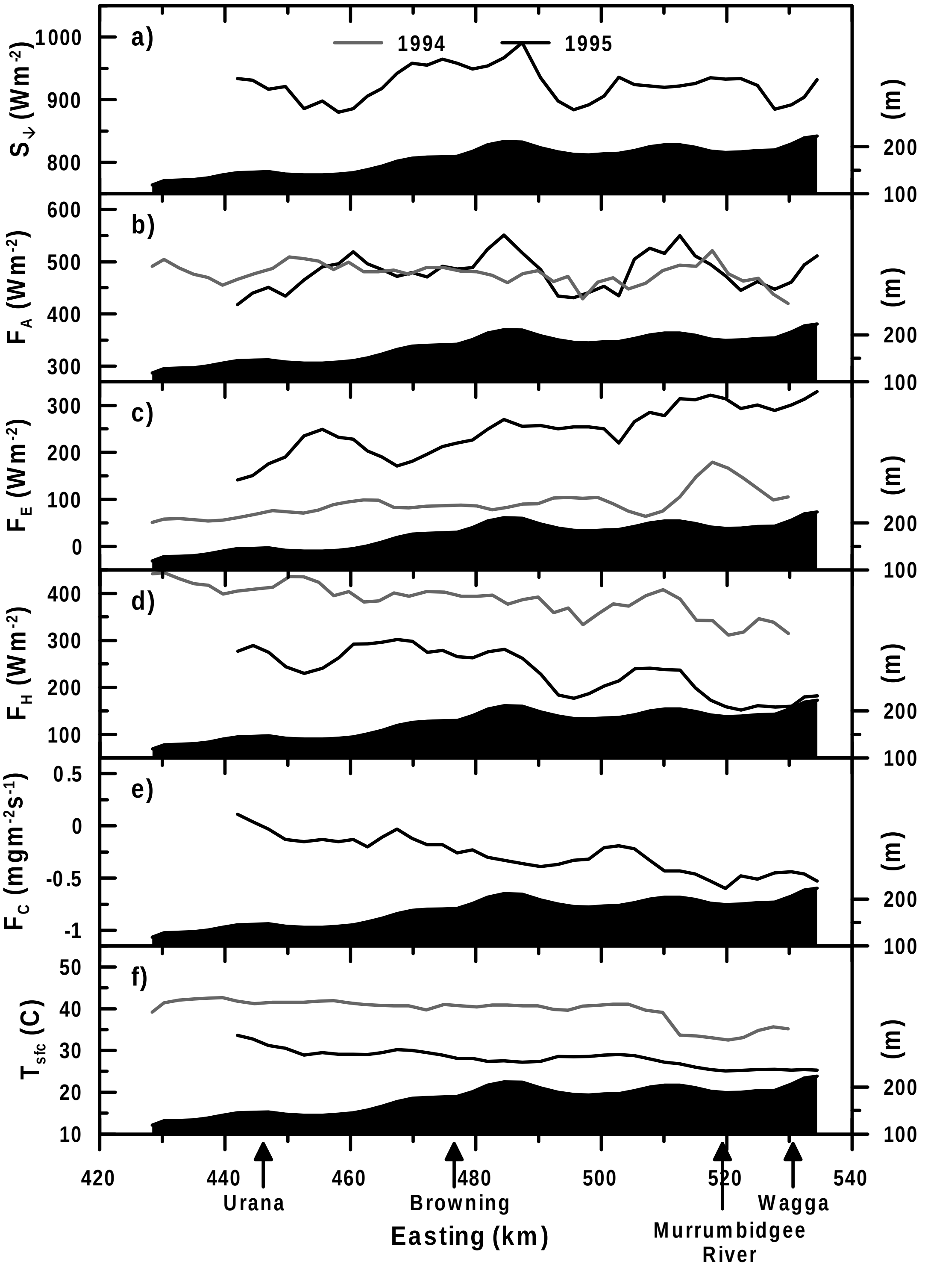

Figure 2.8 Aircraft observations of a) incoming shortwave radiation, $S_{\downarrow}$, b) available energy, $F_A = F_H + F_E$, c) latent heat flux, F_E, d) sensible heat flux, F_H, e) CO_2 flux, F_C and f) surface temperature, T_{sfc} for the OASIS transect in 1994 and 1995. $S_{\downarrow}$ and F_C were only available in 1995.

2.7 Concluding Remarks

Two multi-disciplinary field experiments were conducted in southeast Australia during the Austral springs of 1994 and 1995. Rainfall for the 1994 growing season was less than 35% of the long term average and the drought conditions, combined with a depleted instrument suite on *HNK* that year, led to the concentration of further analysis on the 1995 results. Leuning et al. (2004) presented an overview of the 1994 and 1995 experiments and described some of the results that have flowed from OASIS. Some additional points of relevance to the current work are discussed below.

Cleugh et al. (2004) applied CBL budget methods for estimating regional scale fluxes to the data available from the 1995 OASIS experiment and showed that the techniques were useful in a narrow range of conditions but argued for caution in their general application. In particular, they show that errors in the CBL budget methods are a function of the direction of the surface flux and the flux through the entrainment zone and that current measurement precision may be the limiting factor for trace gases such as CO_2, N_2O and CH_4. These findings are significant because they refine the limits of applicability for one method of estimating regional scale fluxes. Finkele et al. (2003) compared the 1995 OASIS observations with results from two coupled mesoscale-SVAT models in order to assess the differences in their treatment of the vegetation. Their results show that that the models do not accurately predict the intensity of the rainfall events, and hence short-term, local changes in soil moisture, during the 1995 OASIS experiment.

Isaac et al. (2004a) show that good agreement between aircraft and ground-based observations can be obtained when differences in measurement height and source area are minimised and when corrections for inadequate sensor response times are applied. Their results are of importance because of perceived bias in aircraft observations due, in part, to the tendency for previous comparisons to under-estimate F_H (Shuttleworth, 1991). In addition to this, measurements from ground-based and airborne instruments can only be integrated when there is confidence that both platforms are measuring the same quantity. Isaac et al. (2004b) proposed a method of integrating ground-based and aircraft observations to yield estimates of regional scale evapotranspiration that built on the complementary strengths of the two data sets. Their use of surface properties as the means to this integration foreshadows the work presented in this thesis.

Finally, two conclusions from the OASIS experiments presented in Leuning et al. (2004) are repeated here because of their importance to the current work. Firstly, the spatial and inter-annual variability in F_E, F_H and F_C is driven by soil moisture and, hence, rainfall gradients. The 1994 and 1995 OASIS results demonstrate that differences in the fluxes due to variability in soil moisture are greater than the differences between crop and pasture land uses. This is particularly significant given the inability of a coupled mesoscale-SVAT model that was carefully tuned to the OASIS conditions, to correctly simulate the observed rainfall in the 1995 experiment. The second important conclusion is that land cover classification alone is not enough to predict surface properties such as surface conductance. However, the combination of classification and rainfall, or some analogue such as $NDVI$, would correctly predict the surface properties across the OASIS domain (Wang et al., 2003).

To end this section, and with the benefit of hindsight, some useful conclusions can be stated regarding the execution of the OASIS experiments.

The most obvious gaps in the OASIS data set are the lack of CO_2 flux observations at Urana, the lack of soil moisture observations at Browning and Urana and the lack of soil evaporation observations at all sites. Wang et al. (2001) conclude that while observations of F_C are not necessary to calculate the parameters of a coupled evapotranspiration-photosynthesis model, the values of the parameters are sensitive to the combination of observations used in their estimation. Observations of F_C from Urana would have allowed consistent calculation of model parameters and may have confirmed the suggestion, based on the aircraft results, that the western end of the transect was a net CO_2 source. Measurements of soil moisture and soil evaporation would remove the uncertainty associated with estimating these quantities when determining stress functions for photosynthetic parameters and soil evaporation models (Wang et al., 2001; Wang and Leuning, 1998).

Several other additions or improvements would have produced significant benefits. Firstly, the lack of leaf scale observations meant that measurements were not made at the smallest scale planned. Secondly, there were problems with the aircraft observations of CO_2 concentration, described in Chapter Three. With the exception of the loss of *VH-EOS* prior to the 1995 experiment, the lack of reliable, fast response measurements of the turbulent fluctuations in CO_2 was the largest deficiency in the aircraft programme. Thirdly, the largest scale of measurements planned for the OASIS experiments were to have been provided by satellite remote sensing. A Landsat 5 Thematic Mapper (TM) image was obtained on 8 October 1995 but a second pass on 22 October 1995 was obscured by cloud and could not be used. Extensive use has been made of the available Landsat 5 image to examine the relationship between surface properties and *NDVI* , see Chapter Six. Access to more frequent images from the NOAA AVHRR instrument during the 1995 OASIS intensive observation period would have allowed the relationships to be tested over a greater range of conditions.