AIRBORNE METEOROLOGICAL STUDIES AT FLINDERS UNIVERSITY

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INTRODUCTION

The atmospheric boundary layer and the processes which control its structure have been one of the major fields of research interest at the Flinders Institute for Atmospheric and Marine Sciences (F.I.A.M.S.) since its foundation in 1972. Numerous theoretical and observational studies have been carried out in this field, with field experiments being conducted in several areas, mainly within South Australia, e.g. Lyons and Schwerdtfeger (1975), Raupach (1976), Coppin (1977), Penney (1981) and Chen (1987). Experience from these studies showed it to be highly desirable to obtain access to an airborne observational platform which could explore a larger region, as well as the nature of specific sites within them in a relatively short time.

Through the generous donations of the late Dr. Don Schultz of Glen Osmond, S.A., a retired industrialist who followed research developments at F.I.A.M.S. with interest, during 1983-1984, the Institute was encouraged to formulate plans to purchase and equip a research aircraft for use in boundary layer research projects.

THE AIRCRAFT

Typical planned research projects included the study of the evaporation from different vegetated surfaces or from tidal flats and beaches, as well as the study of the structure of the thermal convection patterns occurring over the hot inland regions of Australia. Therefore, it was necessary to select an aircraft having facilities for safe operation within confined areas, while in slow, low-level flight but one which at the same time, would be capable of being operated in severe turbulence as could be anticipated during low-level flights over the hot Australian interior.

A dominant limitation on the selection of the aircraft and its instrumentation were the financial capabilities of F.I.A.M.S. to cover not only the capital cost, but its subsequent maintenance, particularly as it was (correctly) foreseen that the entire two-year development period (including the salary of the first author) would need to rely totally on private generosity.

It was decided that a Grob G-109B motorglider would fulfill all essential operational requirements and still leave sufficient funds to allow for the installation of comprehensive scientific instrumentation. The G-109B was delivered to the first author in May 1984 in Germany, and the remainder of 1984 was used to install and test its basic set of meteorological instrumentation in cooperation with the DFVLR (German Aero-space Agency) at Oberpfaffenhofen near Munchen. In November 1984, the G-109B was shipped to Australia, where it arrived in March 1985.

The dimensions and performance of the aircraft are summarized in Table 1.

Aircraft length:	8.10 m
Wingspan:	17.40 m
Max. take-off weight:	870 kg
Payload:	200 kg
Crew:	2
Normal cruising speed:	80-100 kts
Speed range for measurements:	40-100 kts (20- 50 m/s)
Range:	> 1000 km
Endurance:	> 10 h
Ceiling:	approx. 5000 m
Climb speed	2-3 m/s
Fuel economy:	approx. 15 l/h

Table 1: Dimensions and performance of the GROB G109B

The aircraft can be fitted with a variety of containers for mounting beneath both wings. The standard wing pods are the scientific instrumentation container under the left-hand wing and an additional fuel tank under the right-hand wing. The additional fuel tank can be exchanged with a pod for testing various items of scientific instrumentation, a video camera and a unit containing specialized radiometers.

The aircraft can operate under VFR/VMC during day and night everywhere in Australia. Its flying characteristics are not affected by rain, although not all of the sensors are then reliably functional. Even severe turbulence does not affect safety aspects, as the G-109B is designed to stand higher loads than normal single-engined aircraft. To be able to fly certain research missions (for instance over water, at night or lower than 500 feet above ground level), a number of special permits have been obtained from the Department of Aviation.

SCIENTIFIC INSTRUMENTATION

As mentioned above, the main field of research for which the instrumentation had to be designed was in the continuing investigation of the planetary boundary layer and the physical processes controlling its structure. For this reason, it was required to be able to measure the basic meteorological parameters, such as air temperature, humidity, atmospheric pressure and wind with a high degree of accuracy. To monitor vertical energy fluxes using the eddy-correlation method, sensors with a fast response time had to be selected to yield the desired resolution. For the first three of the above-mentioned parameters, state-of-the-art instruments with a proven design were selected, including two Pt100 (platinum wire-based) temperature sensor (one mounted in a reverse flow housing and a second one mounted in a housing optimized for fast response), a Lyman-alpha humidiometer combined with a dew-point system and a Rosemount Inc. pressure transducer.

To measure the three-dimensional wind vector from an aircraft, the wind vector relative to the aircraft, the aircraft's attitude (i.e. its orientation in space), and its position relative to the earth must be known at any time. The state-of-the-art method for obtaining this information is to use a combination of sensors measuring true air speed, the incidence angle of the wind relative to the aircraft and a laser-gyro-based inertial reference and/or navigation system (IRS/INS). After evaluation of various options, it was decided to use a five hole probe for measuring the incidence angles of the wind and its speed. The main reason for this choice lay in the ruggedness of this system, its proven performance and its availability. As the cost of laser-gyro-based IRS/INS was in excess of A$120,000, an attitude and heading reference system (AHRS) using a new sensor technology was chosen instead. Although this AHRS measures the attitude and the body acceleration of the aircraft with high accuracy, it is not accurate enough to determine the inertial movement of the aircraft by integration of its accelerations for longer than approximately 2 minutes without external updating. For movements in the vertical, an algorithm using pressure-altitude as additional information, can be used with sufficient accuracy. To update horizontal movements, however, more independent information (position fixing) is required.

Position fixes achieved by visual navigation using landmarks, such as railway lines, towns, etc. are often too inaccurate or in some cases, even impossible. For example, in the desert or over water. Also, in Australia some radio navaids are either not available (for example LORAN-C) or their coverage is limited, especially for flights at low altitude.

Based on these considerations, it was decided that the installation of an OMEGA-navigation system was the only feasible option at the time. The experience with the installed system has shown that the information from it is not only usable with certain limitations for wind computations, but is invaluable as an area navigation system for scientific missions and ferry flights.

To improve the accuracy of the navigation, in September 1988 a GPS navigation receiver (satellite-based Global Positioning System) has been installed. The position fixes based on this system give a three-dimensional resolution of about 20m which improves the aircraft's capabilities to measure the horizontal wind dramatically. Although the space vehicles required for this system are only available during 8 hours per day at the moment, 24 hour covered will be available by about 1991.

Two additional parameters of paramount importance for measurements in the atmospheric boundary layer are the surface temperature of the land or water below and the exact flying height above the ground. A compact radar altimeter yields the latter. Since most radiometers for measuring the surface temperature are rather bulky and heavy, a novel relatively small unit (Heimann) was preferred which has proven to be both reliable and sufficiently accurate for all applications so far.

• **high-res. static pressure transducer**	**Rosemount 1201F1**
• **barometric altitude transducer**	**Rosemount 1241M**
• **indicated airspeed transducer**	**Rosemount 1221D**
• **2 fast temperature sensors**	Pt100 (DFVLR) **thermocouple (meteolab)**
• relative **humidity sensor**	Vaisala Humicap
• 2 Lyman-**alpha** humidity sensors	AIR LA-1A ERC BLR
• dew-point **mirror** system	**meteolab** TP-3S
• infrared **radiometer** for surface temperature	**Heimann** KT-15
• **additional** radiometric **equipment**	(under development)
• radar altimeter	King KRA-10A
• 5-hole **probe** for **angle** of attack **and** sideslip	DFVLR
• 2 differential **pressure** transducers for 5-hole probe	Rosemount 1221F2VL
• **air data computer**	**F.I.A.M.S.**
providing:	
› **true air speed**	
• **attitude and heading reference system**	**Collins AHS 85**
providing:	
› **aircraft attitude angles (pitch, roll, heading),**	
› **3-dim. body accelerations and rates**	
• **OMEGA/VLF navigation system**	**Litton LTN 3000**
providing:	
› **aircraft position (latitude, longitude),**	
› **mean horizontal wind vector**	
› **aircraft ground speed**	
› **real time**	
• **GPS navigation receiver**	**Trimble TANS**
providing:	
› aircraft position (latitude, longitude, altitude),	
› 3-d aircraft **movement** (independent of positioning),	
› real **time** with an accuracy of µ-seconds	
• video-system	
consisting of:	
› CCD video **camera**	National F10
› remote control unit with viewfinder	National WV-RC35
› portable video recorder	National NV-180

Table 2: Scientific sensors and subsystems.

For some applications it is important to have an accurate record of either the weather conditions or the sppearance of the area being overflown. For this purpose, a video camera can be installed at any of several locations on the aircraft, either on top of the cockpit with a viewing field straight ahead, or on one of the wingtips, or in a specially designed pod located underneath the right hand wing with the camera looking forward or down.

Finally, it should be mentioned that one of the advantages of the aircraft is that special measurement requirements can be accommodated by installing the necessary instrumentation in a separate wing pod fitted to one of the two existing wing stations.

The sensors and scientific subsystems fitted to the aircraft and a summary of the accuracy, the resolution and the estimated response time for the basic measured parameters are listed in Tables 2 and 3, respectively.

parameter	units	instrument(s)	range	absolute accuracy	resolution	response time
st.pressure	hPa	a	1050 - 800	<0.2	<0.1	<0.02 s
press.alt.	ft	b	-1000 - 15000	10	3	<0.02 s
airspeed	kts	c	30 - 130	3	<0.1	<0.02 s
temperature	°C	d	-10 - 50	0.1	0.01	0.1 s
rel.humidity	%	e	0 - 100	3	0.5	0.3 s
abs.hum.	g/m**3	f	0 - 40	0.3	0.01	<0.05 s
dew point	°C	g	-40 - 50	<1.0	0.05	0.3 s
pitch	deg	j	-90 - 90	1	0.005	<0.05 s
roll	deg	j	-150 - 180	1	0.005	<0.05 s
heading	deg	j	0 - 360	1	0.05	<0.05 s
accelerations	g	j	-5 - 5	0.005	0.0003	<0.05 s
w(air)	m/s	bchij	-10 - 10	<0.5	<0.1	0.1 s
surface temp.	°C	k	-25 - 75	1.0	0.1	<1.0 s
radar alt.	ft	l	0 - 2500	10	3	0.2 s
u,v(air)	m/s	chijm	0 - 40	<2	<1	<0.4 s

a: high-res. static press. transd.
b: pressure altitude transducer
c: indicated airspeed transducer
d: temperature sensors
e: Vaisala Humicap
f: Lyman-alpha humidiometers
g: dew-point mirror system
h: 5-hole probe
i: diff. press. transd.
j: att.& hdg. ref. system
k: infrared radiometer
l: radar altimeter
m: OMEGA/VLF nav. system
n: GPS navigation system

Table 3: Measured parameters.

As the data-logger which was used during the test flights in Germany was not retained, a new data acquisition and logging system was designed and built at F.I.A.M.S. and especially tailored to give a wide range of users of the aircraft a reliable, easy to use and powerful means to sample, preprocess, display and log the measured parameters in flight and on the ground. This system enables the pilot and/or mission scientist to process and view the sampled parameters on-line on a 7" graphics monitor in the aircraft and, thus, decide already during the flight if certain alterations of the flight procedures are required.

RESEARCH ACTIVITIES

The first measurements made on a regular basis were the early morning temperature soundings during the National Gliding Championships at Gawler in January 1986. They proved to be an excellent test for more scientifically orientated flights, as numerous problems with the instrumentation could be rectified.

The first scientific flights followed during February and March 1986 for the Co-operative Sea-breeze Project over Adelaide in which the Regional Office of the Bureau of Meteorology and the S.A. Dept. of Environment and Planning participated. The study was aimed at a better understanding of the sea-breeze circulation in the Adelaide region. As the measurements required flights crossing the approach path into Adelaide Airport and flights lower than normally permitted over the city, special procedures and dispensations were negotiated with the Regional Office of the Dept. of Aviation, without whose very friendly cooperation many of the following research projects would not have been possible. For these flights the instrumentation of the aircraft was still very "fragile" and encountered many break-downs, some valuable first results were achieved.

The next field project was a pilot study for planned major research work in the Upper Spencer Gulf region in South Australia. Spencer Gulf has no source of fresh water at its head, and strong evaporation at the large tidal flats and beaches there has to be balanced by an inflow of sea water through the mouth of the Gulf, leading it to be aptly described as an "inverse estuary." To establish a salt and water balance of the Gulf, evaporation needs to be accurately estimated, a difficult problem with traditional methods. Therefore, an attempt was made to measure the vertical energy fluxes including evaporation of typical areas of the Gulf waters, tidal flats, beaches and the surrounding coast using the aircraft and its "mobile" eddy-correlation instrumentation. The flights and ground-based measurements were made in March 1986 showed that by far the largest rates of evaporation occurred over the tidal flats and beach areas with very low evaporation from the cooler Gulf waters themselves and decreasing values toward the dry inland where sensible heat fluxes became dominant. Detailed results of this pilot study are given in Hacker et al. (1988). Based on these results, a series of further field experiments was carried out in 1987 and 1988 (see below).

For several years, F.I.A.M.S. researchers had maintained an interest in the micro-climatological and micro-meteorological consequences of the clearing of native bush during the conversion of Eyre Peninsula in South Australia into a great grain producing region, a program of regional measurements (Schwerdtfeger, 1986). With the availability of the aircraft, more intense studies became feasible. First, a pilot study of local convective phenomena was carried out in early April 1986 (Williams, 1987, 1989). These first results were the starting point of a series of field experiments in the area which attracted the cooperation and involvement of several Divisions of the CSIRO. The first half of a major joint study took place in February and March 1988; the second one is planned for the summer 1988/89.

A most demanding research project was embarked upon in April and May 1986, being the study of the evaporation from the Coral Sea in the vicinity of John Brewer Reef 40nm northeast of Townsville in Queensland. The study was a joint project with the Dept. of Geography of the University of Tasmania in Hobart and had some logistic support from James Cook University in Townsville. The main aim of the study was to establish the representativity of evaporation measurements using bulk aerodynamic methods, based upon data obtained on a moored platform within John Brewer Reef lagoon, of the whole area around the reef. The study took place in cognizance of the overall aims of the worldwide TOGA experiment (Tropical Oceans and Global Atmosphere) of which one sub-experiment deals with the evaporation from the tropical ocean.

This study was a demanding test for the small research team. The aircraft, its sophisticated instrumentation, and required ground equipment were operated remotely from the back up facilities located in Adelaide. It had to be flown under quite hazardous conditions low over the ocean and up to 40nm off shore. This required another set of special procedures and dispensations from the Dept. of Aviation, for instance, the carrying of a life-raft, which was made available from the Royal Australian Air Force. The low-level flights, down to 50ft. (15m) under high wind conditions (up to 30kt) over the open ocean, even partially affected by sea spray, were a severe test for the ruggedness of the sensors. The aircraft itself had to be thoroughly hosed down after each flight to remove the salt crust from the wings and the fuselage.

The flying itself was highly exciting, as the typical mission required a take off from Townsville at first light in the morning, with low level cloud over the ocean over which the sun was rising. After a flight of about twenty minutes, the reef appeared through the holes in the cloud. The coral reefs in the turquoise water offered a fantastic view from the aircraft and were a worthwhile reward for the effort put into the preparations for the experiment.

Although all instruments and systems had worked perfectly during the experiment, the set back came a week later back home in Adelaide, when the hard disk of the ground system failed during transcription resulting in the loss of about 80% of the unique data. Unfortunately, lack of funds at the time had made it impossible to back up. However, the remaining 20% gave some valuable insight into the effects of the reef on evaporation and showed clearly the usefulness of the aircraft as a research tool for this kind of investigation. A repeat study was completed successfully in 1987.

In September and October 1986, the first part of the Australian Monsoon Experiment (AMEX) took place in and around Weipa on Cape York Peninsula in Far North Queensland. The aim was to study the development and the life cycle of North Australian cloudlines which form in the dry season over Cape York Peninsula and move westwards across the Gulf of Carpentaria. The planned task for Flinders' aircraft was to intercept the evolving cloudlines over the eastern parts of the Peninsula and trace them during their westward travel, but out of the blue bureaucratic trouble hit the operations and the aircraft was grounded indefinitely - in one of the most remote corners of the continent. The precise reasons for this were never revealed, but were clearly connected with the unusual classification of the G-109B as a motorglider. With only a temporary "field" telephone available, negotiations with Canberra were painfully difficult and 12 days elapsed before the aircraft was permitted back into the air. This did, however, not help much, as due to the fact that the aircraft and especially its inboard instrumentation had sat unprotected in hot, humid conditions for so long, the successful correction of the attendant problems coincided with the end of the organized experiment. Back in Adelaide, all problems were quickly resolved and since then, neither bureaucratic nor technical problems have occurred during any of the following operations.

Based on the encouraging results from the first part of the Co-operative Sea-breeze Project over Adelaide early in 1986, a second part was scheduled for the summer 1986/87. Several flights took place over the city and off-shore over the Gulf of St. Vincent and intense ground-based observations were made by the Bureau of Meteorology. A publication covering both parts of the study is in preparation. Of particular interest was the discovery that occasionally a very shallow layer of only a few tens of meters depth evolves over the Gulf, which decouples the rather strong sea breeze influence from the wind just above the sea surface. This potentially deceiving phenomenon can lead to forecasts of strong winds at the surface with reports from boats revealing nearly calm conditions.

In January 1987, the World Gliding Championships and the 20th OSTIV Conference took place at Benalla in Victoria. The G-109B and its instrumentation was, apart from being used for the early morning temperature soundings, demonstrated to a large international community of scientists dealing with airborne meteorological research. Some results from earlier studies were presented during the Conference sessions.

The first full involvement of the Flinders research team with a more hydrologically orientated study came in February 1987, when the group joined researchers from the CSIRO's Division of Water Resources (Adelaide and Perth) to investigate evaporation from areas covered by different types of vegatation in the Murray-Darling Basin near Wentworth, NSW. The ground-based measurements were made using ventilated chambers and chemical, piezometric and isotopic techniques. A publication describing the results of the study is in preparation.

A second field phase of the Upper Spencer Gulf study was carried out in April 1987, and a third, and for the moment, final field phase in February 1988, under much more favorable weather conditions. Results from both field phases confirm the preliminary findings of the pilot study in 1986, but have yielded much more detail.

South Australia is often referred to as the "driest state in the driest continent" and so the investigation of all possible sources of fresh water should be of paramount importance here. It is, therefore, surprising that the second largest surface water resource in the state, the Cooper Creek and the Coongie Lakes system in the far north, has been barely investigated in the 140 years since its discovery. With the generous support of Santos and Lloyd Aviation, companies which made their facilities at Moomba available, the Flinders research team was able to explore the meteorological and hydrological peculiarities around the Coongie Lakes. In May and in December 1987, two one-week pilot studies were carried out in preparation for more intense investigations planned for 1988-90. Results from the May study have already led to a publication describing interesting phenomena (Hacker, 1988). Another expedition to this area was made in the summer of 1988/89, yielding more comprehensive results.

The most exciting project in the summer of 1987/88 was, at least from the operational side, a study of the 'Gully wing' which is a well known vigorous, nocturnal down-slope wind on the western side of the Adelaide Hills. The project was another study carried out in co-operation with the Regional Office of the Bureau of Meteorology, which contributed ground-based observations. Missions were flown every three hours throughout the whole night across the Adelaide Hills giving spectacular views to the pilot and observer of the G-109B. Early results supported a theoretical hypothesis and the findings of a numerical study of the generation and structure of the 'Gully wind'.

During December 1988 to February 1989, numerous traverses were flown through strong sea breezes in the Coorong area of South Australia. These flights, initiated by a visiting scientist from Germany (Prof. Helmut Kraus, University of Bonn), led to exciting new views of secondary circulations within sea breeze fronts never before measured by airborne methods. A thorough evaluation of these data is in progress.

Photographs of the instrumentation, and some examples of results from the various research projects are given in the Appendix.

CONCLUSION

Although the small research team which operates the G-109B at F.I.A.M.S. had to overcome many financial, technical, operational, bureaucratic obstacles and set backs during the last four years, the research seen as a whole has proven to be very valuable and, for the members of the group, most of the time quite enjoyable. The research team has proven that it is possible to achieve high quality data sets and scientific findings with a very moderate level of funding. The aircraft itself has proven to be a very reliable and extremely economical vehicle and its small size has only in a very few cases been a serious restriction. The instrumentation has proven its high quality by comparing the measurements with independent observations, as well as its ruggedness under hazardous conditions like low flying over the open ocean under high wind conditions or under very dusty and hot conditions in Australia's interior in summer.

The Grob has become an indispensable research tool for meteorologists at F.I.A.M.S. and demonstrated its value and reliability by yielding results which under most circumstances could not reasonably have been obtained in any other way, particularly in extending the range and rate of monitoring in remote, inaccessible and non-uniform environments. There is no other way in which a sophisticated instrument-package can be transported while fully assembled and "ready to go," together with its scientific operators and utilized immediately on arrival at an area proposed for investigation. The aircraft constitutes the ideal bridge between local and remote sensing and offers many, otherwise earth-bound meteorologists to sense physically (and personally) atmospheric variations in space and time.

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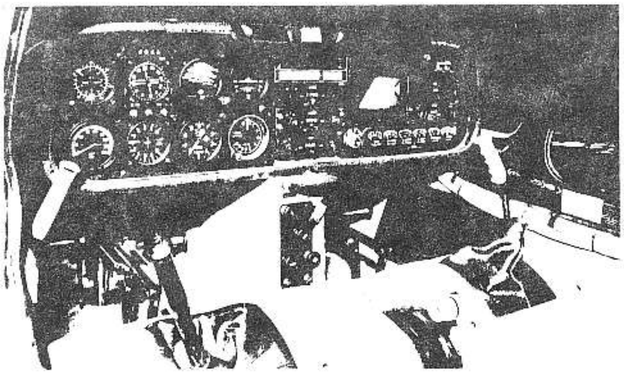
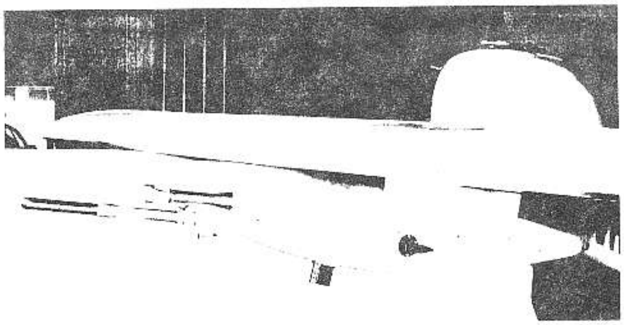
APPENDIX

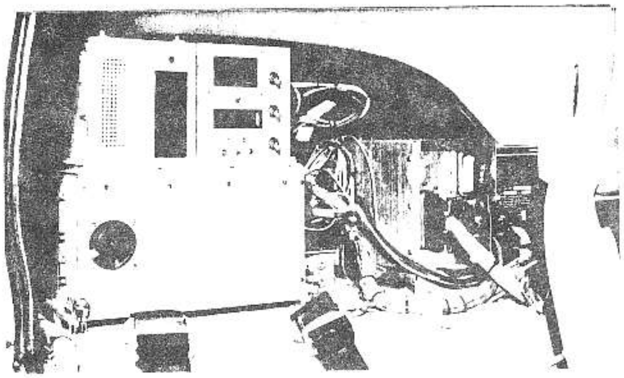
1. Photographs of the aircraft and its instrumentation.



Instrument panel of the G 109B. The basic flying instruments are located on the left-hand half of the panel (left to right, top row: air speed indicator, radio magnetic indicator, artificial horizon, turn and bank indicator; bottom row: engine RPM indicator, variometer, altimeter, radar altimeter). The display of the Omega/VLF navigation system is located at the top of the center panel with the two communications transceivers and the VOR receiver underneath. The graphics screen for displaying the scientific data on-line is located in the right-hand side of the panel. At the far right-hand side, the ADF receiver and the transponder are mounted. The row of small indicators along the bottom of the right-hand side are engine control instruments.



Instrument container mounted on the left hand wing. The reverse flow housing of the temperature sensor can be seen under the bottom of the pod.



Luggage bay of the G 109B. Units from left to right: Data acquisition system, emergency locator beacon, receiver/processor unit of the Omega/VLF navigation system, attitude and heading reference system.

2. Some examples of typical results from the field experiments.

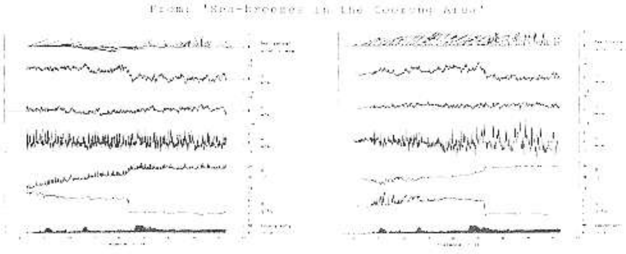

From: 'Sea-breezes in the Coorong Area'

FIGURE 1. Traverses through a sea-breeze front on 13 January 1989 at two altitudes: 35m AGL (left), 350m

AGL (right). The series shown from botom to top are: Topography as measured from the aircraft; specific humidity; potential temperature; vertical wind w; wind components perpendicular (v) and parallel to the front (u); horizontal wind vector. The coast is at 0km, the front is moving from left to right.

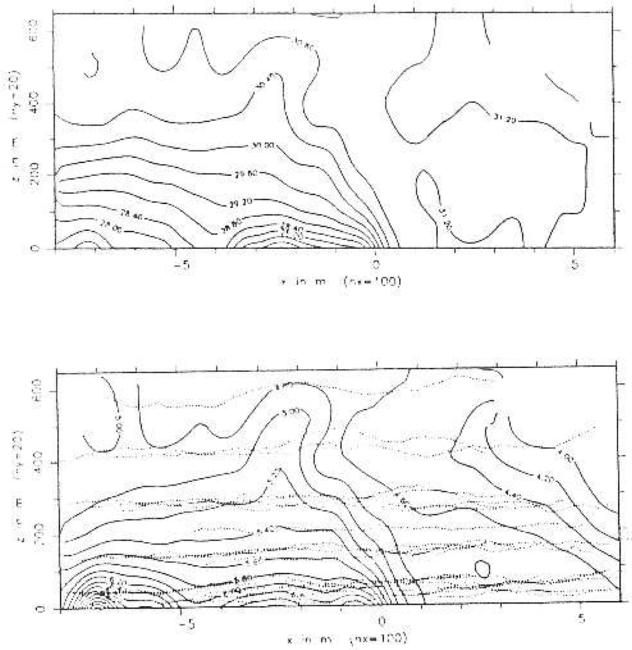


FIGURE 2. Cross-sections through a shallow sea-breeze on 24 January 1989 showing the fields of potential temperature (top) and specific humidity (bottom). The dotted lines in the lower diagram indicate the individual aircraft traverses. For further details, see text. Note that the abscissa is different from the one in Figure 1.

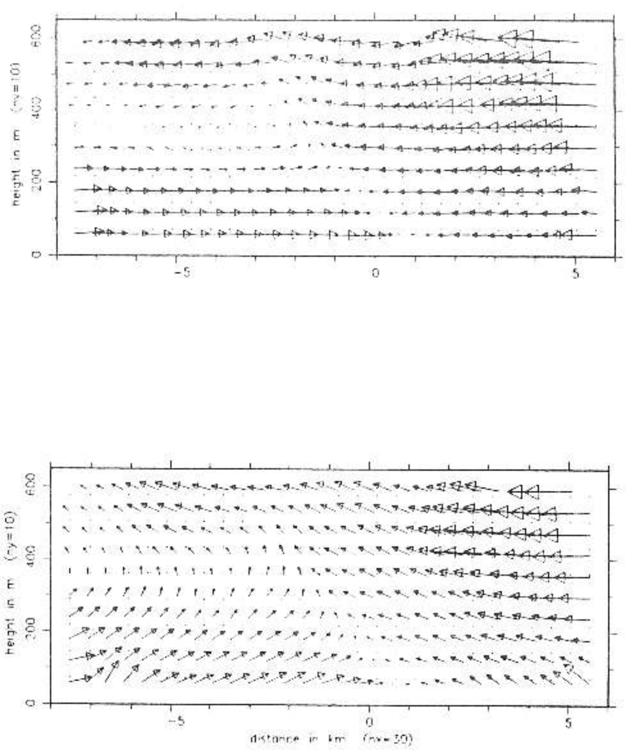


FIGURE 3. As Figure 2, but for the wind components. Top: vertical component and component perpendicular to the front; bottom: horizontal components. The dots show the regular grid onto which the original data was interpolated. For further details, see text.

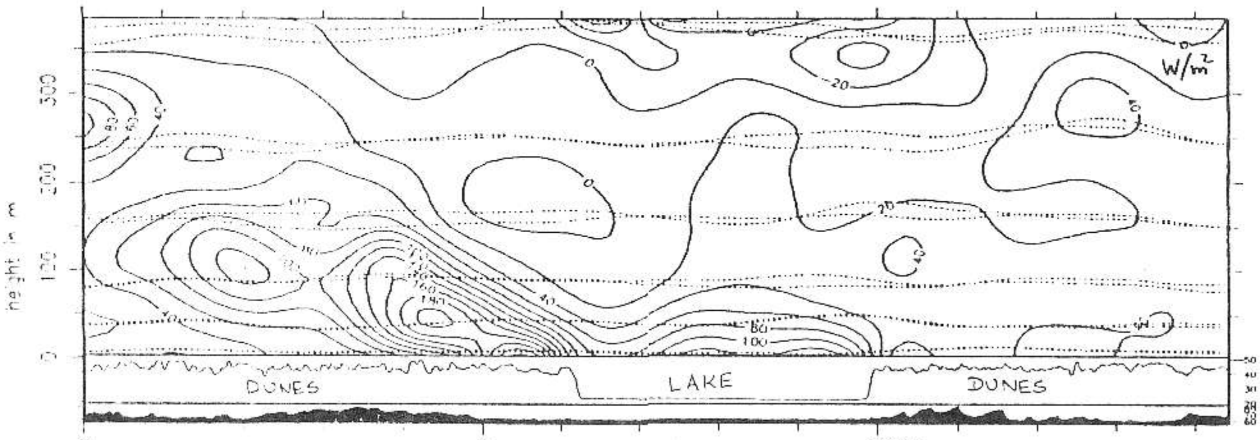


FIGURE 4. Vertical cross-section of the latent heat flux during the morning of 2 December 1988 over Lake Toontoowaranie. The two series at the bottom show the surface temperature and topography of the underlying surface as measured from the aircraft. For further details, see text.

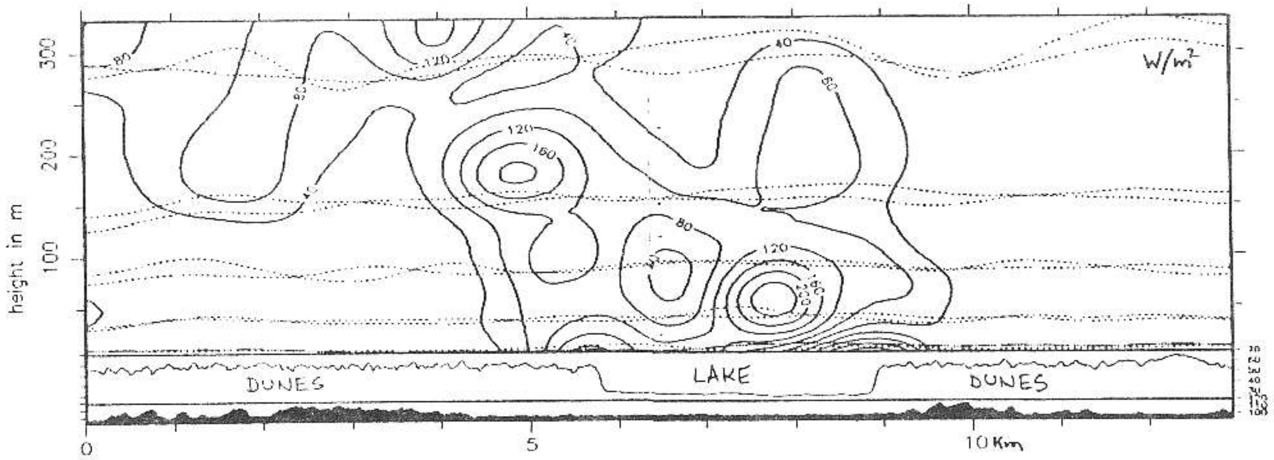


FIGURE 5. As Figure 4, but for midday of 1 December 1988.