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# The spatial distribution of the vertical energy fluxes over a desert lake area

Jörg M. Hacker, Flinders Institute for Atmospheric and Marine Sciences,
The Flinders University of South Australia

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**The influence of a group of shallow lakes in a desert environment on the spatial distribution of the vertical turbulent energy fluxes was investigated. Observations were made in the Coongie Lakes area in northern South Australia during a four-day pilot study using an instrumented aircraft. By subdividing the flight path into characteristic sections, it was possible to arrive at typical estimates for the energy fluxes for the immediate lake area, the area between the lakes, the dry desert country surrounding the lakes, a swamp area, a salt lake and the area just downwind of the downwind edges of the lakes.**

**The results show that the largest values for both —sensible and latent — heat fluxes occur over the swamp area; the latent heat flux shows a secondary maximum just downwind of the lakes. The diurnal cycle of the fluxes over the saltlake with high evaporation and a small sensible heat flux in the morning against large sensible heat fluxes and near zero evaporation in the afternoon shows the importance of the availability of surface water for the relation between these fluxes.**

## Introduction

Most boundary layer experiments held during recent years can be classified into two categories: either they took place in horizontally homogeneous areas with the aim of understanding and parametrising the processes in the boundary layer under various conditions; or the emphasis was on the change of the structure of the boundary layer in response to a rapid change in surface roughness (water/land) or thermal properties (urban/rural). Few investigators tried to examine the influence of complex terrain on the structure of the boundary layer in detail, because many simultaneous observations over different sites are necessary for such a study. The logistic problems connected with such detailed observations in a complex and possibly remote area are normally prohibitive. These problems can be overcome by using an instrumented aircraft which is able to measure all of the relevant parameters during traverses over the area of interest within a reasonably short time interval.

Examples of such studies are Lenschow and Dutton (1964) and Holmes (1969) who studied the surface temperature over different surface types and its influence on the overlying air using aircraft data. Holmes (1969), at a flying height of 15 m, found air temperature differences of up to 3 K between air over agricultural land with a surface temperature of about 45°C and air over lakes with a surface temperature of about 20°C. In a later study of several areas in Canada (Holmes and Wright 1978), humidity variations and variations in the vertical energy fluxes were included in the observations. One result was that the latent heat flux over irrigated land was about double that over the surrounding non-irrigated areas. Desjardins et al. (1985) and Schuepp et al. (1987) investigated differences in evapotranspiration from various wheat crops in Canada using aircraft measurements for the estimation of regional water use efficiency and found good agreement between the airborne and the ground-based methods.

In this paper results are presented from a pilot study using an instrumented research aircraft (Grob G109B) as the only observational platform. The study took place in the Coongie Lakes area in the remote north of South Australia where it would have been well nigh impossible to use ground-based instrumentation to yield the same detailed results. The parameters studied were the surface temperature and the vertical turbulent fluxes of sensible and latent heat.

In the following sections, the area of the investigation and the strategy of the measurements is described, followed by a discussion of the aircraft instrumentation and the data processing methods. The results of the study are then presented, with the main emphasis on the horizontal distribution of the vertical energy fluxes.

## The experiment

The Coongie Lakes area in northern South Australia is a green oasis in a very dry desert environment. The lakes are a result of occasional waterflow along the northern branch of the Cooper Creek and some of them seem to be lakes with permanent water. Some others hold water only during some years, while most lakes in the area are normally dry. For a general description of the region, see Sinclair (1987).

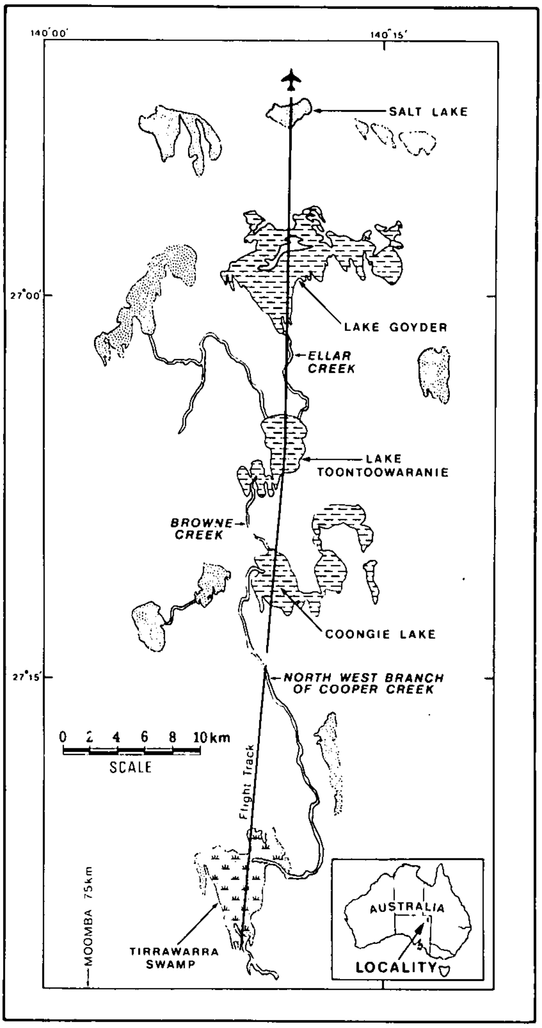
Although the hydrology of the lakes has not yet been studied thoroughly, it is clear that evaporation plays an important role in their water budget. As the area is part of the Great Artesian Basin which is important for the water supply of mining communities like Moomba (see Fig. 1) and for the ecology of the region in general, all terms of the hydrological budget should be determined as accurately as possible. Due to the remoteness of the area and its complexity, it is very difficult to use ground-based methods for estimating an average evaporation for the lakes as well as for the surrounding desert country.

Meteorologically the area is of interest, because it is likely that the strong contrast between the immediate lakes area and the surrounding desert country strongly influences various parameters in the lower boundary layer. To get a first impression of this influence, the FIAMS (Flinders Institute for Atmospheric and Marine Sciences) research aircraft was flown over the area in May 1987 during a four-day pilot study.

Figure 1 shows a map of the area of the experiment. The chosen flight path was an almost straight line from the southern end of Tirrawarra Swamp to the northern end of the small dry salt lake marked in Fig. 1, covering a total distance of 60.5 km. The flight pattern consisted of two traverses, one flown from south to north at a mean height of approximately 20 m above the ground, the other from north to south at about 150 m. This pattern, preceded and followed by a vertical sounding, was flown once during morning and afternoon of 21 and 22 May 1987.

As can be seen on the map, the flight path initially crossed Tirrawarra Swamp before entering an area dominated by sand dunes with an average height of about 15-20 m. Some of the dunes were completely bare sand, others had some sparse vegetation, mainly low shrubs and some spinifex. The depressions between the dunes were partially covered with some shrubs and a few very low trees. Approximately 16 km north of Tirrawarra Swamp, Cooper Creek was crossed which was flowing at the time of the experiment over a width of about 20 m. The banks of the creek were covered with dense vegetation. The flight path then continued over more sand dunes to the southern edge of Lake Coongie. A small dry salt pan just south of Lake Coongie was crossed before traversing over the centre of the lake which had an average water depth of about 2 to 3 m. From the northern edge of Lake Coongie to the southern edge of Lake Toontoowaranie, a flat and nearly dry area was flown over. Lake Toontoowaranie is similiar to Lake Coongie except that in its centre there is a stretch with very shallow water. The area between Lake Toontoowaranie and Lake Goyder, the next lake to the north, is similiar to the previous

**Fig. 1** Map of the area of the experiment. The thick line represents the flight track across the lakes. Dashed lakes contained water during the time of the experiment, stippled lakes were dry.



inter-lake area. Lake Goyder is shallower than the other two lakes with an average depth of only 1 to 2 m. A large sandbank in its northern part was permanently exposed. North of Lake Goyder, dry sand dune country with dunes as high as 25 m was overflown. At the northern end of the flight path, a small dry salt lake was crossed.

The synoptic situation was dominated by a large high pressure cell located in the Great Australian Bight which led to a light southeasterly wind over the area of the experiment. During the night, the clear sky led to a strong nocturnal inversion which was only slowly eroded during the morning. Later in the day, shallow convection formed up to a height of about 500 m. No convective clouds were observed in the area, but during the second day, a thin layer of cirrostratus cloud covered parts of the area. No rain had been observed in the area for the previous two weeks.

Even though these flights took place at different times on two successive days, they were combined to form the diurnal cycle of the computed parameters.

## Instrumentation and data processing

All data were sampled onboard the research aircraft; its instrumentation and the standard methods for evaluating the data are described in detail in Hacker (1988). Air temperature was measured using a fast PT100-based sensor; a Lyman-α hygrometer and a dew-point mirror were used to measure humidity; the vertical component of the wind was measured with an air motion sensing system consisting of a five-hole probe (three-dimensional wind components in the aircraft system) and an attitude and heading reference system (three dimensional attitude and accelerations of the aircraft); the mean horizontal wind was measured with an Omega/VLF navigation system; a radar altimeter measured the absolute height above the terrain while an infrared radiometer monitored the surface temperature.

All parameters except the horizontal wind were sampled at a rate of 13 samples per second which corresponds to a spatial resolution of approximately 6 m. The vertical turbulent fluxes of sensible and latent heat H and E can be defined as

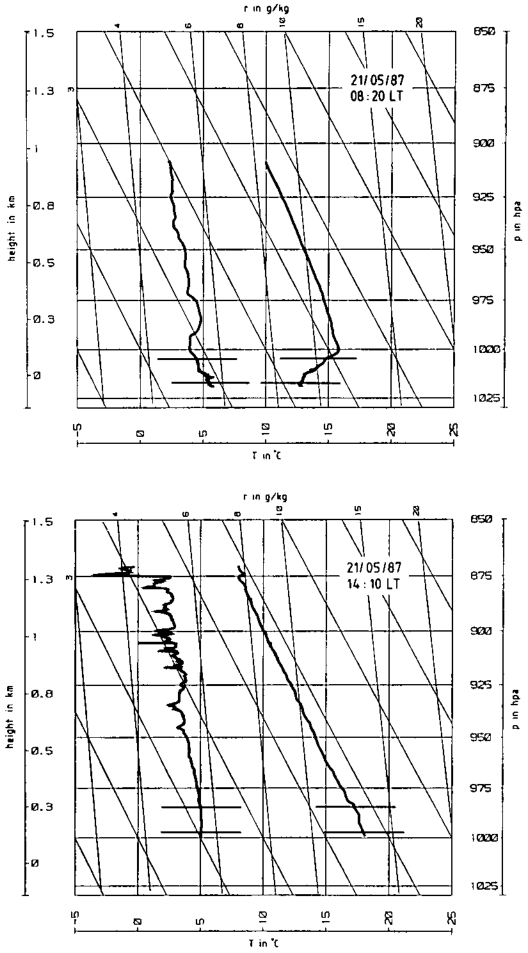
$$H = \rho c_p \overline{w'\theta'} \text{ and } E = \rho L \overline{w'q'}, \text{ respectively,}$$

where $\rho$, $c_p$ and L denote air density, specific heat for constant pressure and specific heat of vaporisation, respectively; w', θ' and q' are the deviations of the original time-series of vertical wind, potential temperature and specific humidity from the low-pass filtered series with a cut-off wavelength of 4 km. Averages denoted by the overbar were taken over various length intervals as described in the results.

## Results

Figure 2 shows two of the vertical soundings obtained before and after the traverses with the mean flying heights marked as horizontal bars. At 8.20 local time ('LT') in the morning, a strong nocturnal inversion is still visible between 60 m and 150 m above the ground with a temperature increase of 4 K. A shallow mixed layer has formed in the lowest 60 m. During the morning flights, this inversion was gradually eroded and disappeared at about 10.00 LT. The afternoon sounding shows a well-mixed layer with a slightly stable stratification. At approximately 1100 m above

**Fig. 2 Vertical profiles of temperature T and mixing ratio r. Horizontal bars at 20 m and 150 m mark the average flying heights above the mean ground level for the two traverses. 'LT' means 'local time'. The height scale refers to the International Standard Atmosphere. Approximately 10 min were needed for a complete sounding.**



ground, a weak temperature inversion and slight drop in humidity can be seen. The top of the haze layer as observed from the aircraft during the soundings was found at approximately 500 m and above this altitude the gradual diminuition of turbulence indicated that this was the top of the convection layer.

Table 1 gives the surface temperatures and its standard deviations measured from the aircraft using the infrared radiometer. Due to the low flying altitude and the rather dry conditions, no corrections for atmospheric absorption of infrared radiation were applied to these measurements. The standard deviations were obtained from the fluctuations of the original time-series. As the lakes are shallow and their water is so muddy that the lake floor was not visible, the thermal regime of the water layer at the top is subject to a strong diurnal cycle with around 13 to 14°C in the early morning and 15 to 18°C in the afternoon, depending on the cloud cover.

The effect of the above mentioned thin cirrostratus layer on 22 May can be seen in the rather low values for the lakes for 14.00 LT. There was no cloud cover over the swamp and the saltlake and only some cirrus patches over the dunes. The surface temperatures of the Tirrawarra Swamp area are similiar to those of the dunes, except that they show a lower maximum in the afternoon due to the high evapotranspiration of the dense vegetation. The surface temperature of the saltlake in the north shows the biggest increase during the morning which can be related to some surface moisture there, as will be discussed later.

Figure 3 shows the diurnal cycle of the sensible and latent heat flux H and E as a mean for the total traverse in both flying heights. In the early morning, significant vertical fluxes were observed only at the 20 m level which is in accordance with the soundings. The flights at the 150 m level were well within the inversion layer which suppressed vertical motions. Later in the morning, after the nocturnal inversion had been eroded away, the fluxes reached higher values at all levels, decreasing with height. During the early afternoon, the convection reached its maximum intensity with the highest flux values at both levels.

To quantify the influence of the various surfaces along the flight pattern on H and E, the flight path was divided into several parts, for which the fluxes were computed separately.

**Fig. 3** Latent and sensible heat fluxes E and H for the total area.

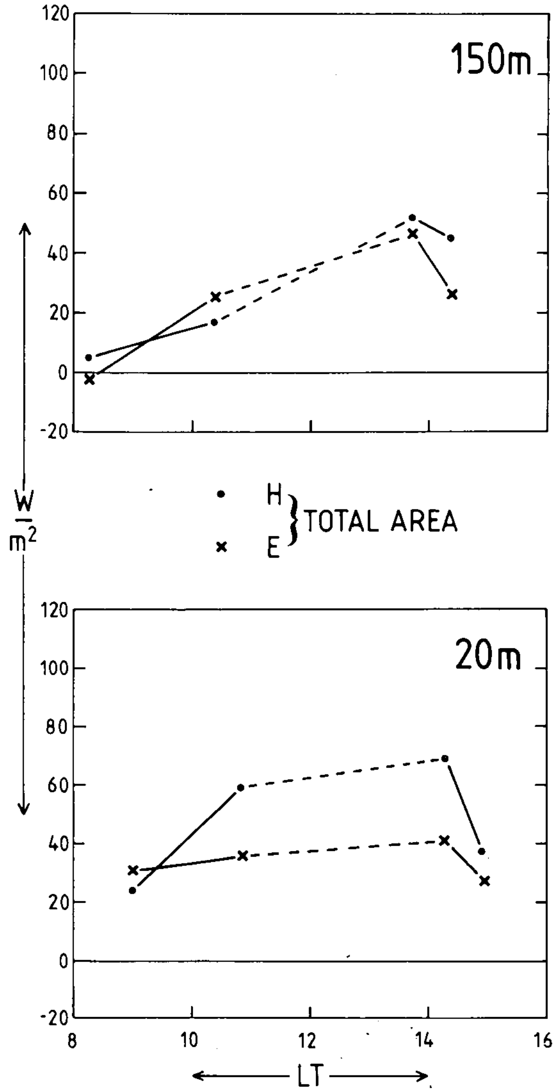


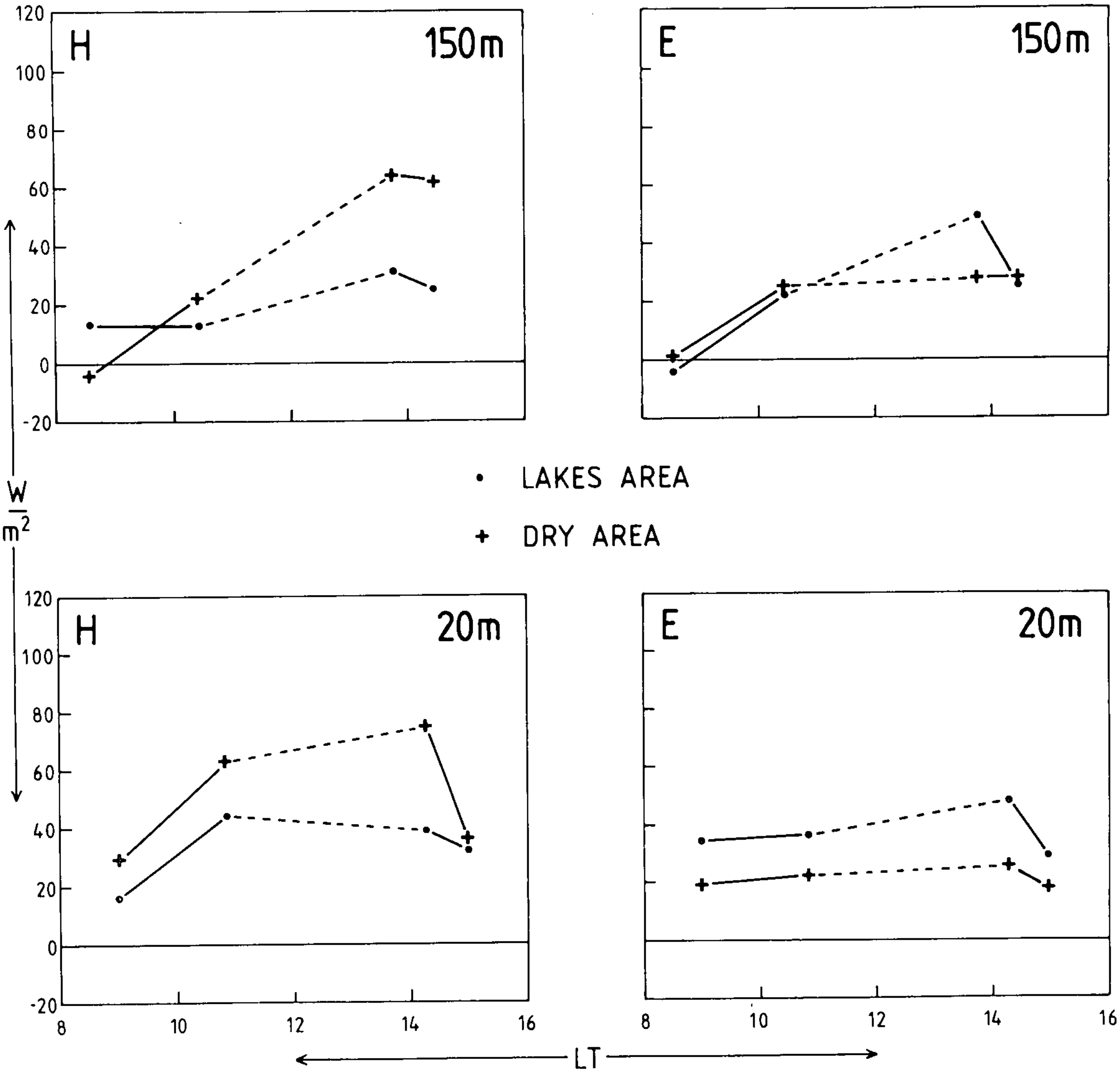
**Table 1. Surface temperatures and standard deviations in °C for the different areas as explained in the text.**

| *Date/Time* | *Coongie* | *Toont.* | *Goyder* | *Swamp* | *Saltlake* | *Dunes* |
|---|---|---|---|---|---|---|
| 22-5-87/08:35 | 14.2±0.1 | 14.2±0.1 | 13.3±0.1 | 13.4±1.2 | 14.0±0.7 | 13.9±1.6 |
| 21-5-87/10:35 | 15.4±0.2 | 15.5±0.3 | 16.6±0.8 | 22.1±2.8 | 25.9±0.7 | 22.8±3.2 |
| 22-5-87/14.00 | 15.6±0.2 | 15.6±0.1 | 15.0±0.1 | 24.9±3.6 | 28.3±1.1 | 25.6±3.5 |
| 21-5-87/14.45 | 17.9±0.7 | 17.3±0.5 | 16.1±0.3 | 24.3±3.2 | 28.1±1.3 | 24.3±2.8 |

At first, the area was divided into a 'lakes area' and a 'dry area', with the 'lakes area' being represented by the area influenced by the lakes and the 'dry area' by that outside of the 'lakes area', but excluding Tirrawarra Swamp in the south and the saltlake in the north. Figure 4 shows that at the 20 m level during the whole day H for the 'dry area' exceeds H for the 'lakes area' whereas the reverse is true for E. The same relation was observed at the 150 m level, except for the early morning traverse. As already mentioned, the 150 m flight level was well inside the nocturnal inversion for this flight and special phenomena like wave motions were existent in this layer which tended to decouple the derived fluxes from the underlying surface.

In a second subdivision, the flight path was split up into four areas, 'the swamp' covering the Tirrawarra Swamp exclusively, 'the lakes' covering the immediate area of Lakes Coongie, Toontoowaranie and Goyder, 'the dunes' covering the area between the three lakes, between Lake Goyder and the saltlake and between Tirrawarra Swamp and Lake Coongie and 'the saltlake' covering the area of the small dry saltlake at the northern end of the flight path. The fluxes for the

**Fig. 4 Latent and sensible heat fluxes E and H for the area of the lakes ('LAKES AREA') and the surrounding dry areas ('DRY AREA'). For the definition of the areas see text.**



areas of this subdivision are shown in Fig. 5. The most conspicuous feature is that during all flights 'the swamp' shows the highest values for both, the sensible and latent heat flux. This applies especially to the 20 m level, where both fluxes are about twice as large as the mean fluxes for the whole area (see Fig. 3). Tirrawarra Swamp thus seems to be convectively the most active region along the flight path. This can be explained by the strong contrast of surfaces close together within the swamp area, where narrow channels of open water are closely intermingled with dense, dark vegetation and a few bare spots of land. This high degree of variability in surface type and cover is visible also in the high variability of the observed surface temperatures (see Table 1).

The difference in flux values between 'the lakes' and 'the dunes' is quite substantial, with the exception of the latent heat flux in the 20 m level. During nearly the whole day, the sensible heat flux is slightly negative over the lakes thus transferring heat from the warm air above to the cooler water of the lakes; this downward flux reaches a maximum at the time of the highest air

**Fig. 5 Latent and sensible heat fluxes E and H for the area of the swamp ('SWAMP'), the immediate lakes ('LAKES'), the dunes ('DUNES') and the saltlake ('SALTLAKE'). For the definition of the areas see text.**

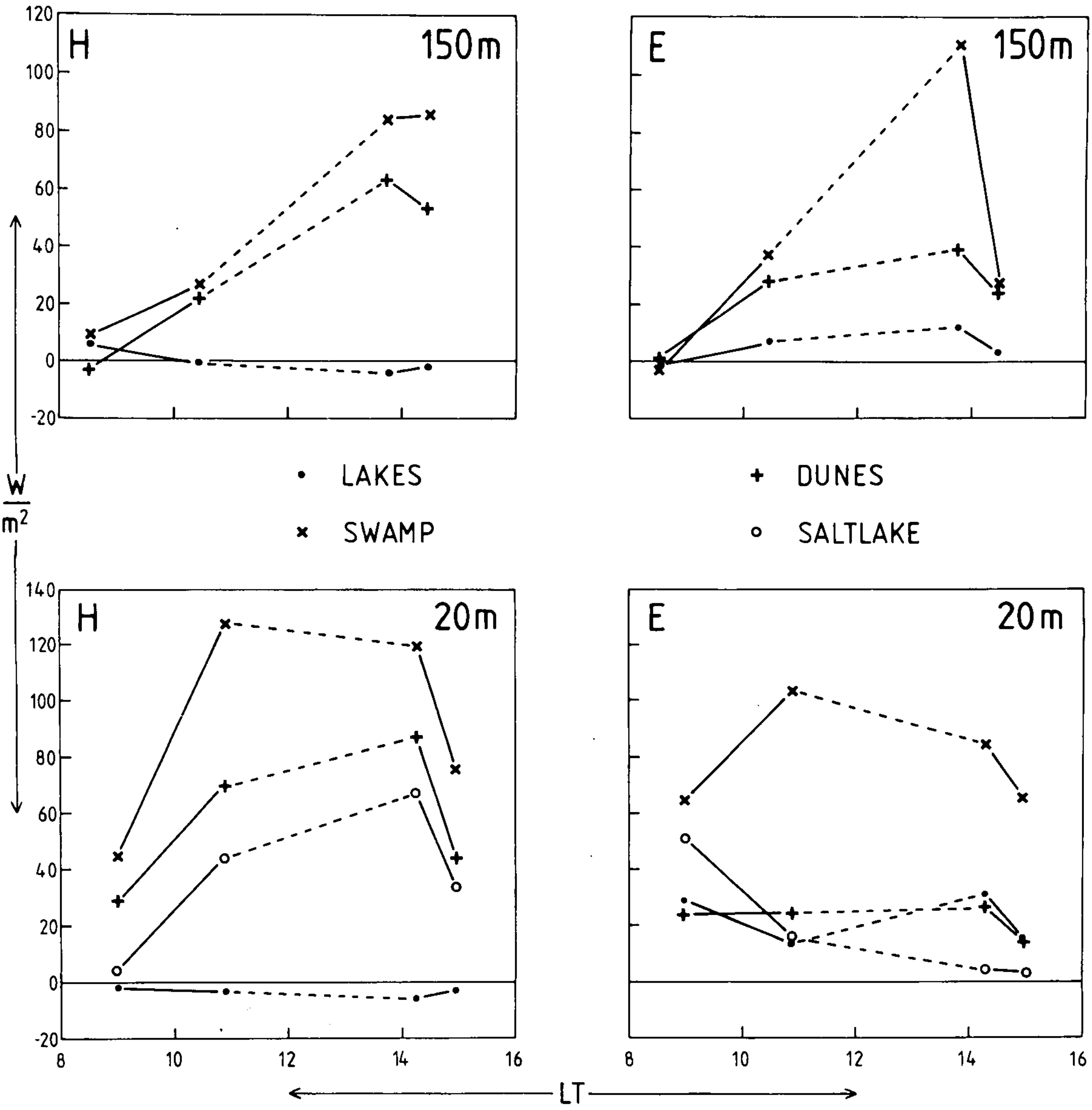
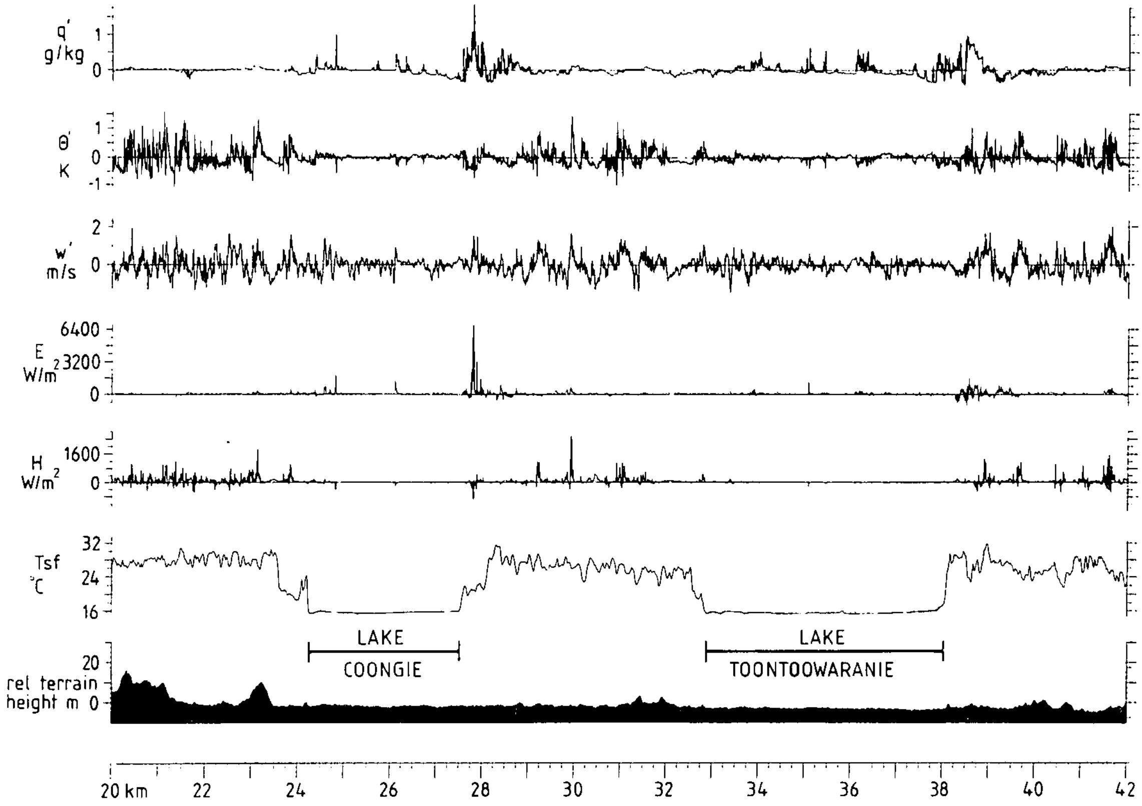


**Fig. 6 Series of various parameters along a part of the flight track. Top to bottom: Fluctuations of specific humidity q; fluctuations of potential temperature θ; fluctuations of vertical wind w; instantaneous latent heat flux E; instantaneous sensible heat flux H; surface temperature $T_{sf}$; relative terrain height along the flight path. For further explanations see text.**



temperatures. Similiar downward heat fluxes were found by McBean and Paterson (1975) for warm air moving over the cooler waters of Lake Ontario and also by Hacker et al. (1988) for hot inland air moving over the cool oceanic waters off the South Australian coast. In the dunes area, H reaches approximately 2/3 of the values for 'the swamp'. The latent heat flux in the 20 m level shows similiar values for 'the lakes' and 'the dunes' which will be explained below.

The fluxes for 'the saltlake' are given for the 20 m level only, because the lake was rather small (approximately 1.75 km in diameter) and fetch problems would have influenced the results at higher levels. In the morning, E is much larger than H, pointing to the availability of water at the surface of this lake; from ground observations at Moomba it can be assumed that dew had possibly formed during the night. Another possibility is that water had risen from below during the night and quickly evaporated in the morning, as soon as enough incoming radiation was available. After this water had evaporated, the lake-bed obviously dried out completely and the dominating energy transport during the remainder of the day was the sensible heat flux.

Figure 6 shows series of various parameters along a section of the flight path for the 20 m level in the afternoon of the second day. The parameters shown are the relative terrain height computed as difference between pressure altitude and radar altitude, the surface temperature measured by the infrared radiometer, the deviations of vertical wind speed w', potential temperature θ' and specific humidity q', and the instantaneous latent and sensible heat fluxes as products between w' and θ' and w' and q', multiplied by $\rho c_p$ and $\rho L$, respectively. Averages over these products yield the sensible and latent heat fluxes for the various areas as defined above.

The series of the instantaneous fluxes shown in Fig. 6 indicate that increased latent heat fluxes occur in the areas around the northern edges of the lakes (27.75 km - 29.00 km and 38.00 km - 40.00 km). This can be explained by the combination of two effects, the influence of the stability in the lowest layers of the atmosphere and the prevailing wind. Due to the cooler water in the lakes, a stable atmospheric sub-layer forms which tends to suppress convectively generated turbulence and hence vertical energy fluxes. Closer to the shoreline of the lakes, the water becomes shallower and merges with exposed drier areas. There, this stable layer gradually becomes eroded and finally gives way to a superadiabatic sub-layer near the ground. It can thus be hypothesised, that the water vapour which has been evaporated from the lake becomes transported in a very shallow layer towards the northern edge of the lakes with the prevailing southeasterly wind and only there transported upwards by convective motions. A similiar effect was found in studies of the evaporation from beaches and tidal flats in the Upper Spencer Gulf area in South Australia by Hacker et al. (1988).

This effect can be seen more quantitatively in Fig. 7 showing H and E for the area just downwind of the northern edges of the lakes (between 2 and 4 km downwind, depending on surface characteristics), called 'downwind of lakes', and the areas between the lakes (called 'dry inter-lake'), but excluding this immediate downwind area. This subdivision clearly shows that during the whole day E is larger than H in the downwind area and H is larger than E in the dry inter-lake area.

## Conclusion

In summary it can be stated that even this rather limited pilot study yields detailed quantitative results on the spatial variation of the vertical heat transport over this highly complex area. The ideal approach to obtain estimates for the evaporation and other parameters in the area would be the deployment of one or two fixed stations on the ground measuring energy fluxes and basic meteorological parameters with simultaneous airborne measurements covering the whole of the area of interest. With several observation periods spread over the different seasons and synoptic situations, it should be possible to get reasonable estimates for the evaporation from the lakes area and its surroundings for a relatively small logistic effort.

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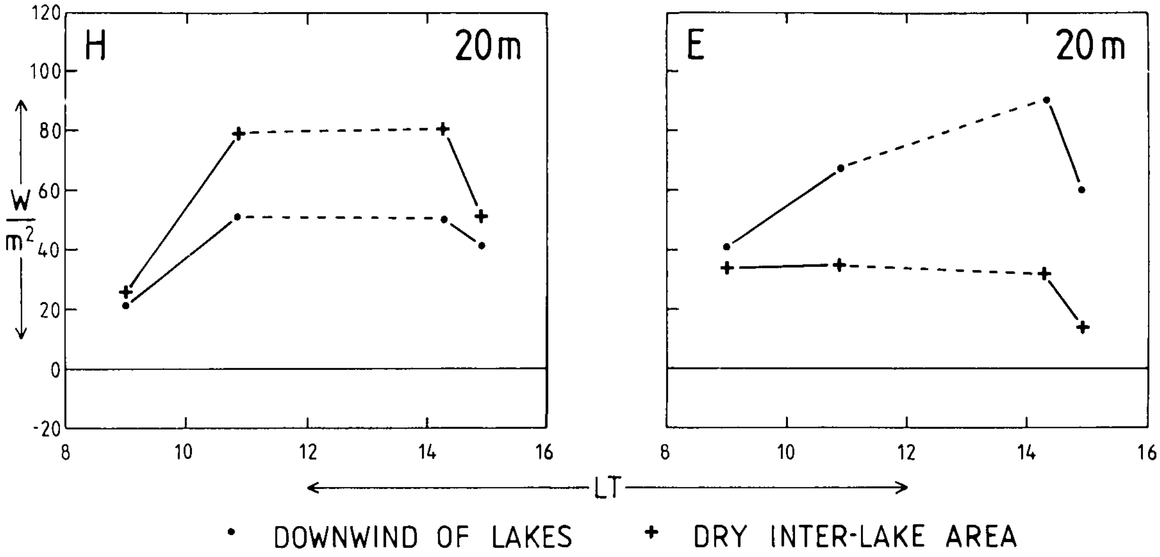
**Fig. 7** Latent and sensible heat fluxes E and H for the area immediately downwind of the lakes ('DOWNWIND OF LAKES') and for the dry area between the lakes, but excluding the immediate downwind area ('DRY INTER-LAKE AREA'). For the definition of the areas see text.



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