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Stable Isotope Composition of Water Vapor as an Indicator of Transpiration Fluxes From Rice Crops

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Measurements of the stable isotope composition (δ^2H and $\delta^{18}O$) of water vapor and associated micrometeorological parameters were made before and after full establishment of a rice crop in southeastern Australia. The aim of the experiment was to gain a better understanding of stable isotope variations of water vapor near the ground surface in response to local evaporation, local transpiration, regional scale vapor transport and the vertical stability of the atmospheric boundary layer. Vapor samples were collected at several heights within 9 m of the water surface during two separate sampling periods. The δ^2H values of the water vapor ranged over more than 60‰, reflecting major rapid changes in regional air mass sources, as well as variations in the stability of the lowest 10 m of the atmosphere. The influence of tropical and higher-latitude air masses resulted in local vapor compositions which were relatively enriched and depleted, respectively, in heavy isotopes. Vertical gradients in heavy isotope abundances were very large during stable conditions (as much as $\Delta\delta^2H = -27$‰ from 0.8 to 8.4 m), as the result of mixing between transpired water and regional air vapor. Transpiration fluxes calculated from the water vapor δ^2H gradient ranged from 5 to 7 mm d^{-1}, which was in good agreement with one-dimensional aerodynamic energy budget calculations of daytime vapor fluxes.

INTRODUCTION

Evapotranspiration is usually the dominant mode of loss of water in semiarid environments, with surface runoff and groundwater recharge representing very small fractions of annual precipitation. Although accurate estimation of this flux over periods of hours to days is quite difficult, one promising approach involves improved understanding of the turbulent regime of the atmospheric boundary layer as an integrator of processes over regional and watershed scales [*Brutsaert*, 1986]. The stable isotope composition of water vapor near the land surface should respond to local evapotranspiration as well as regional atmospheric circulation. Observations of stable isotope compositions of water vapor are also critical input parameters to model calculations of enrichment of heavy isotopes in surface waters during evaporation due to exchange of water molecules between vapor and liquid phases [*Gonfiantini*, 1986; *Simpson et al.*, 1987].

Despite potential advantages of using stable isotopes of water vapor, there have been relatively few studies of this nature, at least partly because of the experimental difficulties of collecting unfractionated vapor samples. Some examples of studies related to this subject include those of *Merlivat and Coantic* [1975] and *Merlivat* [1978], which involved laboratory experiments and the development of theory on the fractionation of stable isotopes of water during evaporation from a free water surface. *White and Gedzelman* [1984] found that the deuterium content of vapor samples collected within a few meters of the ground about 30 km northwest of New York City depended primarily on the origin of the air mass from which they were collected (i.e., large-scale air circulation patterns). *Bariac et al.* [1989] investigated short-term variations in stable isotope compositions of water in and above alfalfa crops during the course of the daily cycle of photosynthesis. Here we report observations of water vapor collected over an irrigated rice field in a semiarid climate, with stable isotope compositions integrated over daytime periods.

The aims of this work are threefold. The first is to study the interaction between regional air masses and local evapotranspiration by collecting vapor samples from various heights above an actively transpiring rice crop in an attempt to define some of the critical factors which regulate the stable isotope composition of water vapor in the lowest few meters of the atmosphere. The second is to verify that observed stable isotope compositions of water vapor near the ground surface are generally consistent with classical micrometeorology theory. Finally, if measured stable isotope composition profiles are consistent with micrometeorology theory, we will apply a modified Bowen ratio approach [*Bowen*, 1926] based on stable isotope gradients integrated over an entire day rather than averaging many short-term gradients of specific humidity. One possible advantage of such an approach is that the isotopic composition of the water undergoing evapotranspiration is likely to

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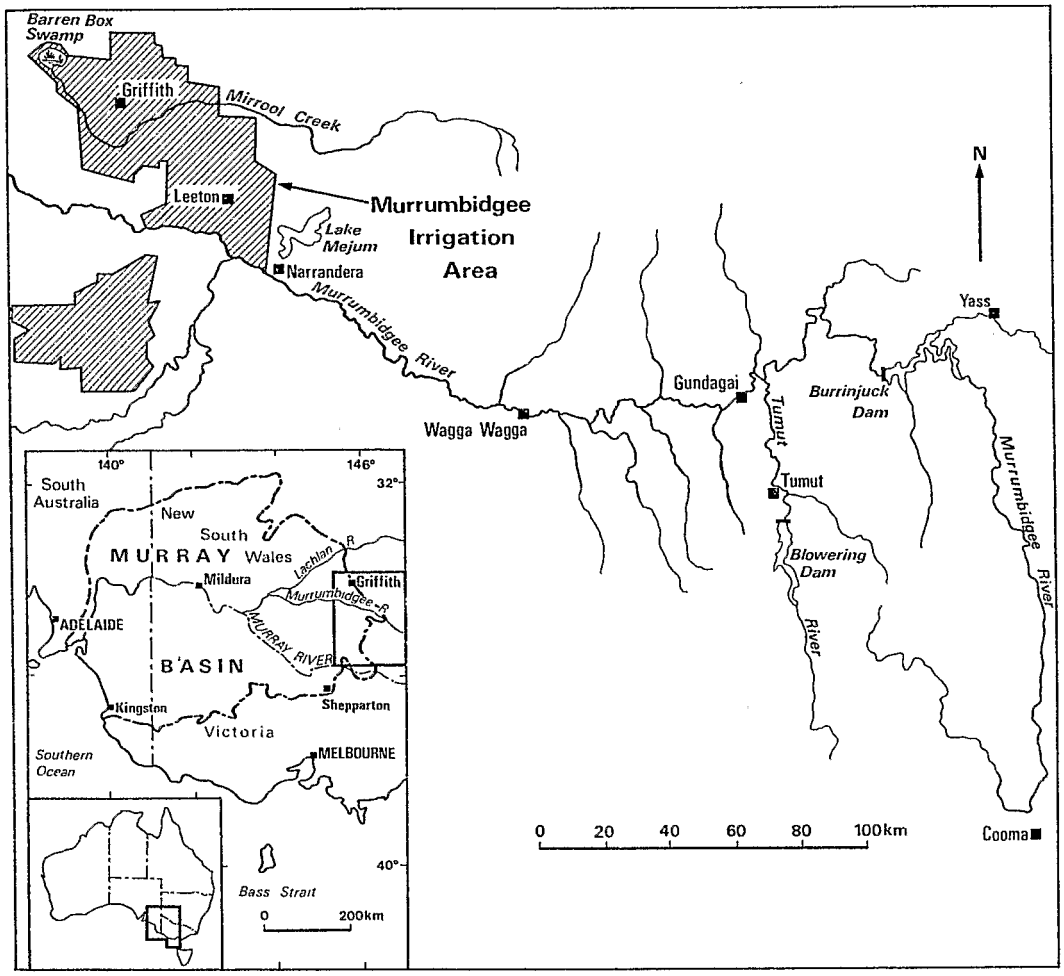

Fig. 1. Location of field site in the Murrumbidgee Irrigation Area (MIA) in southeastern Australia.

remain constant at least over time scales of days. Hence the gradient of stable isotopes in water vapor may be less subject to small-scale meteorological influences than those for some of the parameters commonly used in classical micrometeorology. Secondly, the method of collection provides flux-weighted vapor samples representative of most of an entire day of transpiration.

EXPERIMENTAL DESIGN

Field Environment

The field site of our data collection was about 12 km south of Griffith, New South Wales, within a region of irrigated agriculture (Murrumbidgee Irrigation Area, MIA) in southeastern Australia (Figure 1). Rice crops receive 60–80% of total annual irrigation water deliveries in this area [*Van der Lelij and Talsma*, 1978]. Our meteorological instruments and vapor sampling equipment were located within a contiguous area of approximately 120×10^4 m^2 of rice crops. Distances from the sampling site to the outer perimeter of these flooded fields were as follows: east and west, 10^3 m; north, 4×10^2 m; and south, 8×10^1 m. Within the rice sectors of the MIA, approximately 20–30% of the total surface area is flooded during the cropping months (October–March).

Periods of Measurement

We collected vapor samples and meteorological data during two time intervals. The first, from October 31 to November 2, 1989, began 11 days after initial flooding and aerial seeding of the local rice fields. The mean depth of water in the fields was about 1.5×10^{-1} m and no plants had emerged above the water surface. During this time period, the local flux of water vapor to the atmosphere should have been dominated by evaporation from free water surfaces.

The second sampling period was from January 31 to February 8, 1990, about 3.5 months after initial crop seeding and 1.5 months prior to harvest. The rice crop had reached approximately 6×10^{-1} m above the water surface, occupying almost the entire flooded area of the fields. Transpiration would be expected to dominate the local flux of water vapor to the atmosphere at this time. Nearly all of the interpretation of the stable isotope data reported here concerns samples collected during this second, transpiration-dominated period.

Sample Collection and Instrumentation

Water vapor samples were collected through segments of tubing attached to a mast at several heights above the water surface of the rice fields, by slowly pumping air (0.9×10^{-3}

$m^3\ min^{-1}$) through glass traps maintained at approximately −55° to −60°C with an electrical refrigeration unit. The sample collection apparatus for all of the rice field vapor samples was similar to that described by *Schoch-Fischer et al.* [1984]. At this flow rate we estimated that about 98% of the vapor was trapped. We did not correct the data reported here for any isotope fractionation occurring during sample collection due to incomplete trapping of vapor. Our estimate of the magnitude of this correction, based on both sequential trapping experiments and theoretical calculations, is less than −5‰ for δ^2H and less than −0.4‰ for $\delta^{18}O$ and would apply systematically to all our data. During each sampling period we collected vapor in separate cold traps from two or three heights simultaneously, with each sample representing vapor collected at a single height over 6–7 hours during the day. Water vapor samples were analyzed using conventional preparation and mass spectrometry techniques with sampling plus analytical precision based on replicate vapor samples being ±2‰ for δ^2H and ±0.2‰ for $\delta^{18}O$. All of the isotope composition data are reported in delta notation (δ,‰) relative to standard mean ocean water provided by the Vienna laboratory of the International Atomic Energy Agency (IAEA, V-SMOW) where

$$\delta = \frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}} \times 1000$$

where R is the ratio of the number of molecules containing one of the heavy isotopes ^2H or ^{18}O relative to the number of molecules containing only the lighter isotopes, ^1H and ^{16}O.

From a second sampling mast located about 10 m to the north of the vapor intake mast, air temperature and wind velocity were measured at two heights above the crop surface. Net incoming radiation was measured using the improved Funk-type radiometer (Swissteco) fixed on the mast at a height of 1.5 m above the surface of the crop. Heat flux at the interface between the soil and the water was measured directly by one heat flux plate (Middleton) buried 1 cm in the mud. Crop surface temperature was measured using two infrared sensors (Everest; spectral response, 7–20 μm; field of view, 5°). The sensors were facing downward at an angle of 45° in the east and west directions at a height of 1 m above the crop surface. Surface temperature of the water beneath the crop was measured using an IR thermometer with the same specifications, while temperature differences between the soil/water interface and the water surface were measured using a small thermocouple device. This allowed us to estimate net gains and losses of heat by the water within the rice field. Data from the sensors were sent every 30 s to a microcomputer through a 12-channel data logger, and then averaged over intervals of 10 min.

Measurements of relative humidity were also made in the rice field four times a day using an Assman psychrometer at 1.5 m above the crop surface. Daytime averages were calculated using an empirical correlation between the instantaneous relative humidity values measured on the site and hourly values reported for the Commonwealth Scientific and Industrial Research Organization (CSIRO) Griffith meteorological station 12 km from the field site. Relative humidity values above the rice fields during daytime hours were systematically higher than at the Griffith meteorological station, with specific humidity values ranging from about 10 to 40% greater for individual days during the experiment.

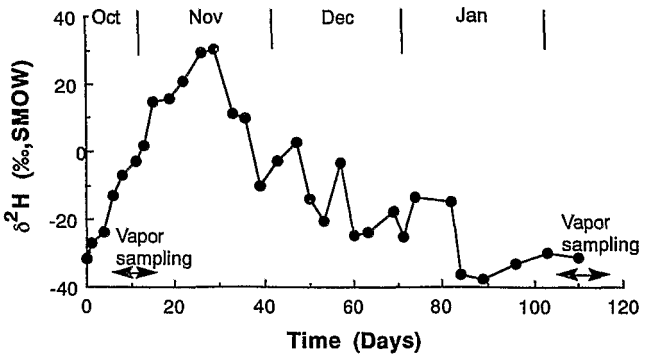

Fig. 2. Rice field δ^2H values for 3.5 months following initial flooding on October 20, 1989: input irrigation water δ^2H values were approximately −40‰ throughout this period.

General Features of Stable Isotope Observations

Stable Isotope Composition of Rice Field Surface Waters

The water used for irrigation in the MIA is derived primarily from surface runoff during winter and spring months in the Great Dividing Range that is collected in two large storage reservoirs and released for irrigation between late spring and early autumn. This input irrigation water from the Murrumbidgee River has a stable isotope composition of approximately $\delta^2H = -40‰$, $\delta^{18}O = -6.5‰$, which is relatively constant throughout the months of irrigation.

During the period of 4 months of flooding of the local rice crops, the water in the fields became progressively more enriched in heavy isotopes (δ^2H increased by about 70‰) over the first four weeks (Figure 2) and subsequently evolved toward a value of δ^2H only about 10‰ enriched over the input irrigation water ($\delta^2H = -40‰$). The most probable cause of this general trend was the dominance of evaporative loss (which causes enrichment in the heavy isotope abundance of residual waters) during the first month until the rice crop became established. Then a gradual shift to the dominance of transpiration losses (which do not result in significant heavy isotope enrichment of residual waters [*Zimmermann et al.*, 1967; *Dincer et al.*, 1979]), caused the water to approach a δ^2H value changed by only a small amount from that of the input irrigation water. The vapor sample data discussed here are representative of this latter transpiration-dominated stage. Our intention is not to analyze the evolution of the rice field stable isotope composition in detail (this subject will be examined elsewhere), but only to use the general trend as an indication of the dominance of transpiration over evaporation at the time of vapor sample collection during late January and early February.

Measured stable isotope values of rice field water during the week prior to collection of our second group of vapor samples were as follows: $\delta^2H = -30‰$, $\delta^{18}O = -4‰$. If all of the local influx of water vapor to the atmosphere was accomplished by transpiration, the vapor added would have this isotopic composition. If, however, it was all provided by evaporation, we could calculate an estimated composition of

TABLE 1. Collection Times and Stable Isotope Composition of Water Vapor Obtained After Initial Flooding but Prior to Rice Crop Emergence: October–November 1989

Date Start	Time Start	Total Collection Time, days	Height Above Water, m	δ^2H, ‰	$\delta^{18}O$, ‰
		Rice Field, Daytime Samples			
Oct. 31	1115	0.28	0.33	−76	−13.3
Oct. 31	1115	0.28	2.3	−83	−15.3
Nov. 1	1010	0.26	0.33	−77	−15.0
Nov. 1	1010	0.26	2.3	−83	−14.0
		Mean Values			
				−80	−14.4

The δ^2H and $\delta^{18}O$ values are relative to SMOW.

TABLE 2. Collection Times and Stable Isotope Composition of Daytime Water Vapor Samples Obtained 3.5 Months After Initial Crop Seeding: January–February 1990

Date Start	Time Start	Total Collection Time, days	Height Above Water, m	δD, ‰	$\delta^{18}O$, ‰
		Rice Field, Daytime Samples			
Jan. 31	1100	0.27	0.85	−71	−9.8
Jan. 31	1100	0.27	2.6	−78	−10.9
Jan. 31	1100	0.27	8.4	−84	−12.0
Feb. 1	0950	0.28	0.85	−90	−13.0
Feb. 1	0950	0.28	2.6	−91	
Feb. 1	0950	0.28	8.4	−91	−14.0
Feb. 2	1050	0.23	0.85	−113	−16.5
Feb. 2	1050	0.23	2.6	−127	−18.8
Feb. 2	1050	0.23	8.4	−126	−19.2
Feb. 3	0945	0.28	0.85	−96	−14.2
Feb. 3	0945	0.28	2.6	−110	−15.9
Feb. 3	0945	0.28	8.4	−110	−16.8
Feb. 4	1145	0.24	0.85	−109	−16.0
Feb. 4	1145	0.24	2.6	−116	−17.2
Feb. 4	1145	0.24	8.4	−122	−18.3
Feb. 5	0950	0.28	0.85	−97	−14.8
Feb. 5	0950	0.28	2.6	−100	−16.0
Feb. 5	0950	0.28	8.4	−119	−18.1
Feb. 6	1010	0.26	0.85	−83	−13.1
Feb. 6	1010	0.26	2.6	−110	−15.7
Feb. 6	1010	0.26	8.4	−110	−17.2
Feb. 7	1025	0.27	0.85	−76	−11.3
Feb. 7	1025	0.27	2.6	−91	−14.3
Feb. 7	1025	0.27	8.4	−103	−16.0
		Mean Day Values			
			0.85	−92	−13.6
			2.6	−103	−15.5
			8.4	−108	−16.5

the net vapor transferred to the atmosphere, based on laboratory measurements of equilibrium and kinetic fractionation during evaporation [*Majoube*, 1971; *Merlivat*, 1978], combined with the effects of exchange of atmospheric vapor with the liquid phase, controlled by the isotopic composition of the vapor and the ambient relative humidity [*Gonfiantini*, 1986].

Stable Isotope Composition of Water Vapor Samples

The stable isotopic composition of daytime water vapor samples collected over a period of 3 days less than 2 weeks after initial flooding of the rice fields is listed in Table 1. The mean δ^2H value for the four samples was −80‰ with a systematic vertical gradient between the 0.3 m and 2.3 m vapor samples of about −6‰. The vapor samples were more enriched in heavy isotopes than would be predicted for evaporation from a free water surface.

We attempted to calculate the effective isotopic composition of vapor evaporating from the surface of the flooded rice field, using a formulation summarized by *Gonfiantini* [1986, p. 131]. The critical environmental properties required for the calculation are the mean isotopic composition of the ambient vapor (δ^2H = −70‰) and the mean relative humidity (70%). Using this approach we obtained a value for the evaporating vapor of δ^2H = −130‰, which is substantially more depleted in deuterium than the vapor samples which were collected, and thus not consistent with the sign of the observed vertical gradients during the daytime hours. At present we cannot account for the processes which led to the presence of vapor over the flooded rice fields which was enriched in heavy isotopes substantially above the levels our calculations indicate would be expected for these evaporation-dominated conditions. During the same period of sampling we also collected three vapor samples from the Griffith laboratory site which averaged δ^2H = −91‰, about 23‰ more depleted in δ^2H than the time-weighted (24 hour) mean of the vapor samples above the flooded rice fields.

The stable isotope composition of water vapor samples collected at three heights over a period of 8 days after the rice crop had become well established is listed in Table 2. The mean δ^2H values were −92, −103 and −108‰, at 0.85, 2.6 and 8.4 m above the water surface, respectively. Over the period of 8 days, there was substantial variation in mean daily δ^2H values and in the gradient in δ^2H with height (Figure 3). The most depleted mean δ^2H values were for February 2–3, and the greatest difference in δ^2H between sampling heights occurred during the last three vapor sampling days (February 5–7). The large range of δ^2H values (−71 to −127‰) observed during January–February 1990 (Table 2) was also accompanied by considerable variation in $\delta^{18}O$ values (−9.8 to −19.2‰). The mean slope of δ^2H versus $\delta^{18}O$ for these samples was 6.2 (Figure 4), compared to a slope of 8 (world meteoric water line, WMWL) that defines the general trend for precipitation from throughout the world [*Craig*, 1961; *Yurtsever*, 1975]. Although there is some scatter in the composite of all the January/February

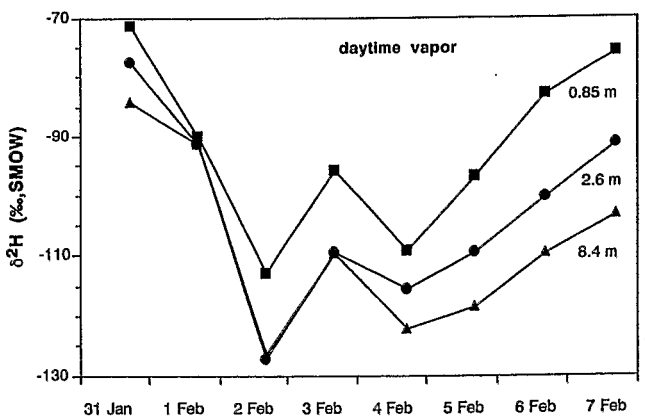

Fig. 3. Water vapor δ^2H values at three heights over a mature rice crop: 0.85, 2.6, and 8.4 m above the water surface measured from January 31 to February 7, 1990.

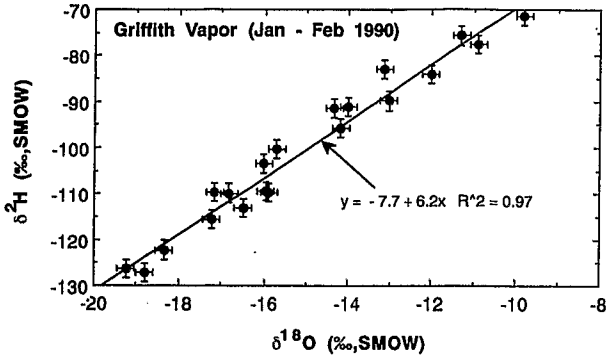

Fig. 4. Water vapor δ^2H versus $\delta^{18}O$ for all samples collected at the rice field after emergence of the crop above the water surface (January 31 to February 7, 1990).

stable isotope data, vapor data collected during the same sampling interval lie on straight lines parallel to the mean slope of 6.3. Therefore, short-term changes in meteorological conditions affected primarily the δ^2H value at the intercept with the $\delta^{18}O$ axis and not the variations in relative abundance of δ^2H and $\delta^{18}O$ with height during a given sampling interval.

The δ^2H values for the water vapor between January 31 and February 7 at three heights above the rice field (Figure 3) show two types of changes: (1) daily variations of the gradient in isotopic values between sampling heights, and (2) daily variations in the mean values of isotopic composition at any given height. We assume that these two types of variability are governed by processes having quite different spatial scales. Fluctuations in mean values of the isotopic composition of the water vapor for all samples on a given day should be related to large-scale air mass circulation, while the magnitude of the local vertical gradients should depend upon micrometeorological factors which determine mass and energy exchanges between the crop surface and the atmospheric boundary layer (ABL).

Influence of Large-Scale Meteorological Conditions on the Isotopic Composition of the Water Vapor Within the ABL

Large-scale meteorological observational summaries were extracted from daily regional pressure charts at the surface, 850-hPa and 500-hPa levels, as well as from daily aerological diagrams from the meteorological station in Wagga-Wagga, 150 km SE of Griffith. We will refer in the following discussion to the wet bulb potential temperature, θ_w which is defined as the wet bulb temperature that a sample of moist air would have if brought adiabatically to a pressure of 1000 hPa. This parameter is known to be a relatively conservative property of the core of an air mass and thus permits air masses of different origins to be distinguished.

To compare the isotopic composition of atmospheric water vapor near the land surface with the regional air circulation pattern we chose as a reference level for discussion the data from 8.4 m, the highest point above the rice field where vapor samples were obtained. On January 31, the isotopic composition of water vapor at this level was more enriched in heavy isotopes ($\delta^2H = -85‰$) than for any other day during the 8 days of sampling above the mature rice crop (Figure 3). Our interpretation of the regional meteorological map (Figure 5) is that the mean wind from the surface to the 500-hPa level was from the NE on January 31. The surface pressure chart (Figure 5) indicates that the regional source of this transport was from the south branch of a tropical cyclone being formed east of the coast of Queensland. The vertical profile of θ_w calculated from the aerological diagram at Wagga-Wagga shows a fairly homogeneous air mass from the surface up to 400 hPa (θ_w = 21°C).

The isotope composition of the water vapor at 8.4 m on February 1 indicates only a slight decrease in δ^2H value from the previous day. On February 2 the vapor was the most depleted in heavy isotopes for this period of 8 days, with δ^2H approaching −130‰. The surface synoptic chart (Figure 5) indicates that the tropical cyclone was well established by February 2 and had moved southwest to the coast of Queensland, just north of Brisbane. Over the same few days, a strong anticyclone had developed west of the Great Australian Bight. The Griffith region definitely experienced mean winds from the south on February 2. However, it is not obvious from the pressure chart alone whether these winds were primarily derived from the eastern branch of the anticyclone or from the region immediately south of the tropical cyclone (now called Nancy). Examination of the relevant aerological diagram and calculation of θ_w were therefore considered helpful. Between the surface and the 800-hPa level a distinct air mass (14°C < θ_w < 16°C) was observed to lie under the tropical air mass (19°C < θ_w < 21°C), indicating clearly that maritime air from higher latitudes had moved northward under the tropical air mass.

The trends from this set of vapor compositions for which air masses of tropical origin are substantially more enriched in heavy isotopes than air masses from higher latitudes are consistent with observations from near the east coast of North America [*White and Gedzelman*, 1984]. Thus the isotopic composition of water vapor, even very near the ground, can provide large-scale transport information relevant to the latitude of origin of air masses in the continental interior.

As the tropical cyclone moved southward, it approached closer to the site of our sample collection and an increasing component of tropical air was mixed with polar maritime air coming from the south. The stable isotope composition of the water vapor at 8.4 m, as well as large-scale transport pathway estimates based on analysis of the synoptic charts of pressure and aerological diagrams, reflects the relative importance of tropical air masses and polar maritime air masses over the following 5 days. Systematic changes are readily apparent from the evolution of the surface pressure between February 2 and February 7 (Figure 5). As a consequence of an increasing component of tropical air, the water vapor became progressively more enriched in heavy isotopes over a period of several days (Figure 3).

Estimation of Rice Crop Transpiration Rates Using Vertical Gradients in the Stable Isotope Composition of Water Vapor

In the following discussion, micrometeorological data are reported in terms of the height above the mean crop surface, while sampling heights for the water vapor stable isotope data are reported relative to the water surface. The mean height of the rice crop above the water surface during late

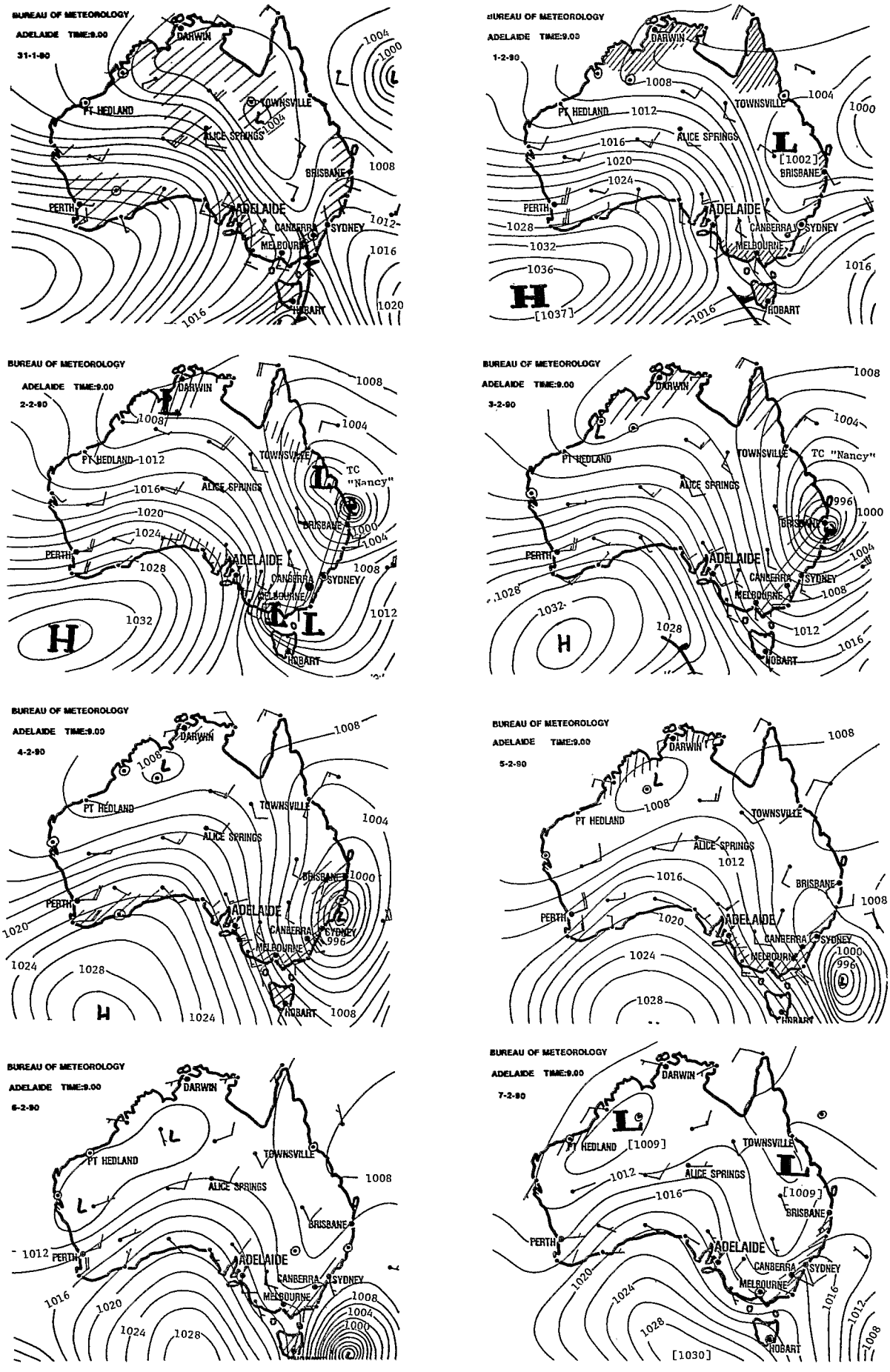

Fig. 5. Eastern Australia regional maps of surface pressure from January 31, 1990 to February 7, 1990.

January was approximately 0.6 m. For comparison to estimates of local evapotranspiration rates derived from gradients in the stable isotope content of water vapor it is useful to analyze our micrometeorological data in terms of the same conceptual framework. The following formulation seeks to link interpretation of the two types of measurements in a simple way.

Resistance Formulation

The concept of resistance to vapor transfer has been developed and applied in various forms [*Slatyer and McIlroy*, 1967; *Monteith*, 1973; *Cowan*, 1968; *Thom*, 1975]. The fluxes of water vapor, heat and momentum can be described by equations of the following form:

$$Q = \frac{c_s - c(z)}{r} \tag{1}$$

where Q is the relevant flux; c_s, the concentration at the canopy surface, $c(z)$, the concentration at height z; and r, the aerodynamic resistance between the canopy surface and height z. It is generally assumed that r is the same for a number of properties of interest [*Brutsaert*, 1982]. For heat, (1) becomes

$$H = \frac{\rho c_p (T_s - T)}{r} \tag{2}$$

while for water vapor, it becomes

$$E = \frac{\rho (q_s - q)}{r} \tag{3}$$

where H is the sensible heat flux, ρ is the density of air, C_p is the specific heat for constant pressure, T is the temperature, E is the evaporative mass flux of water and q is the specific humidity.

If movement of stable isotopes in the turbulent regime of the atmosphere is assumed to be nonfractionating, the flux of isotopes can be approximated by

$$Q_i = \frac{\rho (q_s R_s - qR)}{r} \tag{4}$$

where R is the ratio of the number of molecules containing one of the heavy isotopes to the number of water molecules containing only light isotopes. The ratio R can be replaced by delta notation

$$\delta = \frac{(R - R_0)}{R_0} \tag{5}$$

where R_0 is the value of R for the reference standard, V-SMOW. Moreover, we can define the isotopic content of the evapotranspiration source as

$$\delta_1 = \frac{Q_i}{R_0 E} - 1 \tag{6}$$

Using (4)–(6), we obtain

$$\delta_1 E = \frac{(q_s \delta_s - q\delta)}{r} \tag{7}$$

Using (3) and (7), we obtain

$$\delta = \delta_1 + \frac{q_s(\delta_s - \delta_1)}{q} \tag{8}$$

or alternatively

$$q = \frac{q_s(\delta_s - \delta_1)}{\delta - \delta_1} \tag{9}$$

Logarithmic Dependence With Height

We will use the approximation of *Choudury et al.* [1986] for the aerodynamic resistance:

$$r = \frac{\left\{\ln\left(\frac{(z-d)}{z_0}\right)\right\}^2}{k^2 U (1+\eta)^2} \tag{10}$$

where U is the wind velocity, z is the height of interest, and k is the von Karman constant (equal to 0.40). The values of the zero plane displacement d, the roughness length z_0, and η are calculated as follows [*Legg and Long*, 1975]:

$$d = 0.56h$$

$$z_0 = 0.3(h - d)$$

$$\eta = \frac{5(z-d)g(T_s - T)}{TU^2}$$

where h is the height of the rice crop and g is the gravity constant.

Experimentally, U has been found to increase logarithmically with height [*Brutsaert*, 1982]. If this form for U is used in (10), it leads to a logarithmic dependence with height of temperature, specific humidity and isotope concentration (qR) (strictly speaking, this is only true for neutral conditions, i.e., $\eta = 0$). If this logarithmic dependence is used in (8), the isotope delta value is seen not to have a logarithmic dependence with height, but a dependence of the form $a \ln x/(1 + a \ln x)$. Where Q/Q_s approaches unity, $a \ln x$ is small and hence δ is approximately logarithmic.

A measure of the degree of instability of the ABL that is based on the above logarithmic dependence is the friction velocity, U^* [*Brutsaert*, 1982], defined by

$$U^* = \frac{k(U_3 - U_2)}{\ln(z_3/z_2)} \tag{11}$$

The difference in δ^2H measured at two heights should be proportional to U^* calculated from the wind speeds measured at the same heights.

Estimation of Evapotranspiration

The basis of the estimation of evapotranspiration from a one-dimensional surface energy balance is as follows:

$$LE = R_n - G - \Delta Q_w - H \tag{12}$$

where L is the latent heat of evaporation, R_n is the net radiation above the canopy, G is the vertical downward heat flux measured at the interface between the water in the rice field and the soil and ΔQ_w is the change in the heat storage

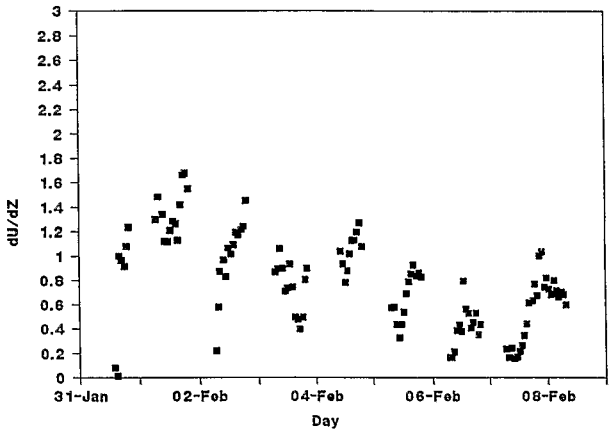

Fig. 6. Vertical gradient of hourly mean wind velocities over the rice crop between levels 0.2 and 2 m above the canopy, $[U(z_2) - U(z_1)]/(z_2 - z_1)$.

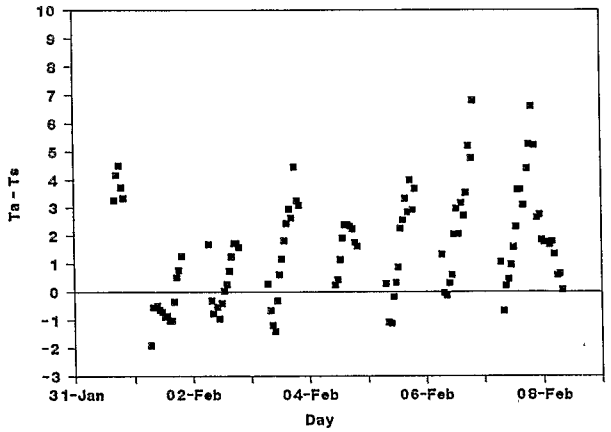

Fig. 7. Vertical gradient in hourly mean temperature between the air at 2.3 m and the rice crop surface.

of the water. ΔQ_w can be calculated using a calorimetric method,

$$\Delta Q_w = \int_{z_1}^{z_2} C_w \frac{\partial T}{\partial t}\, dz \tag{13}$$

where C_w is the volumetric heat capacity of the water, z_1 and z_2 are the top and bottom surfaces, respectively, of the water in the rice pond and T is the water temperature at level z and time t. The aerodynamic energy balance estimates evapotranspiration from the above equations using H calculated from (2) and (10). Another method of calculating the evapotranspiration which does not require an approximation (10) for the resistance term uses the Bowen ratio (Bo) defined by

$$\text{Bo} = \frac{C_p(T_2 - T_3)}{L(q_2 - q_3)} = \frac{H}{LE} \tag{14}$$

where the subscripts 2 and 3 refer to measurements at different heights above the ground. Combining (12) and (14), we obtain

$$LE = \frac{R_n - G - \Delta Q_w}{1 + \text{Bo}} \tag{15}$$

The Bowen ratio concept can be extended to any other admixture of the air such as CO_2 [*Brutsaert*, 1982]. Here we propose a modification of the Bowen ratio approach using the stable isotope content of water vapor. Equation (9) relates the specific humidity at any height to the stable isotope content at that same height. Suppose both q and δ are measured at the same height (denoted by subscript 2). Then

$$q_2 = \frac{q_s(\delta_s - \delta_1)}{\delta_2 - \delta_1} \tag{16}$$

The specific humidity at another height (denoted by subscript 3) can be estimated using δ measured at that height, i.e.

$$q_3 = \frac{q_2(\delta_2 - \delta_1)}{\delta_3 - \delta_1} \tag{17}$$

This estimate, together with the measured q_2 can be used in (14) and (15) to give an estimate of the rate of evapotranspiration.

Results and Discussion

Microclimatological conditions changed quite significantly during the 8-day experiment over the mature rice crop. Figures 6 and 7 show hourly wind velocity gradients between adjacent points of measurement, and temperature differences between the crop surface and the air at 2.3 m. These data (summarized as averages of daytime values in Table 3) show a simultaneous increase of the temperature difference and decrease of the wind speed gradient, reflecting increasing stable conditions in the ABL. Net radiation (Figure 8) remained fairly constant through the period of measurement except for February 1, which was cloudy and cool. Evapotranspiration during the daytime hours calculated from the energy budget values ranged from 8 mm to less than 2 mm but most values were between 5 and 7 mm. These are in reasonable agreement with values based on lysimeter measurements reported by *Lang et al.* [1974] for a rice crop in the same region during summer.

The stable isotope composition of water vapor at three

TABLE 3. Mean Daytime Values of Some Micrometeorological Parameters Measured Above the Rice Canopy: January–February 1990

Date	T_a, °C	T_s, °C	U_2, m s^{-1}	U_1, m s^{-1}	R_{net}, W m^{-2}
Jan. 31	31.4	28.1	3.7	2.6	340
Feb. 1	15.3	15.7	5.4	3.5	132
Feb. 2	18.7	18.3	4.2	2.8	324
Feb. 3	22.0	20.7	3.0	1.9	366
Feb. 4	24.7	23.1	3.8	2.3	298
Feb. 5	23.4	21.7	2.7	1.7	313
Feb. 6	24.2	21.9	1.9	1.3	350
Feb. 7	24.8	22.5	1.7	1.2	372

T_a is temperature at 2.3 m above the crop surface; T_s is temperature of the crop surface as measured by infrared sensors; U_2 is mean daytime wind velocity measured at a height of 2 m above the crop surface; U_1 is mean daytime wind velocity measured at a height of 0.2 m above the corp surface; and R_{net} is mean daytime net incoming radiation as measured 1.5 m above the crop surface.

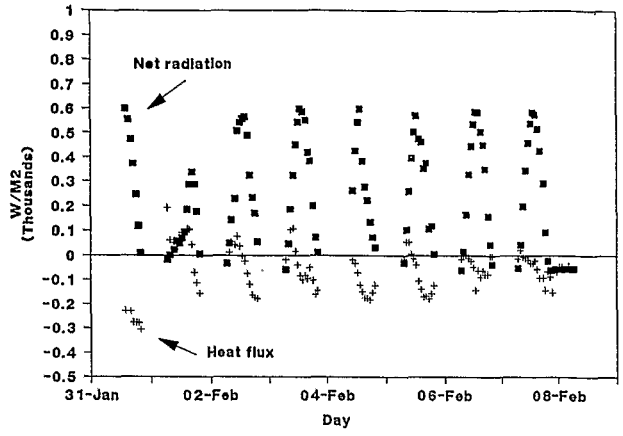

Fig. 8. Net radiation (R_n) and sensible heat flux (H) over the rice crop.

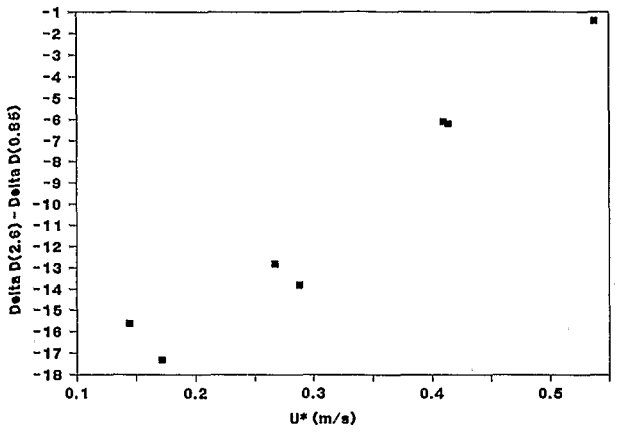

Fig. 10. Comparison of vertical gradients of δ^2H versus U^*.

levels above the rice canopy indicates a systematic gradient in δ^2H values from the lowest level to the highest level (Figure 3). Water vapor samples collected nearest to the rice canopy were systematically more enriched in heavy isotopes. The isotope composition at the three heights plotted against ln $((z - d)/z_0)$) (Figure 9) shows approximately a logarithmic dependence. One of our goals was to measure the magnitude of these near-surface gradients in stable isotope compositions and to attempt to use them to calculate mean daily transpiration by the rice crop.

Changes in the vertical gradients of δ^2H (Figure 3) closely reflect changes in micrometeorological parameters (Figures 6 and 7). These similarities can be examined by comparison of isotopic gradients versus U^* (Figure 10) where U^* is a measure of the degree of instability of the ABL and has been calculated from (11), where $U(z_2)$ and $U(z_1)$ are the wind speeds measured at 2.3 and 0.85 m respectively. The stable isotope gradient decreased in proportion to an increase in U^* and at least the lowest 10 m of the ABL was well mixed in terms of the stable isotope composition of water vapor for $U^* > 0.5$.

Comparison between evapotranspiration calculated from the aerodynamic energy budget method and the Bowen ratio method using gradients of stable isotope compositions is shown in Figure 11. The two methods show excellent agreement, indicating that our assumptions about a two-component vapor mixture are probably reasonable. In both sets of these calculations we have assumed that 90% of the local source vapor was derived from transpiration (δ^2H = −30‰) and 10% from evaporation from the local rice field water surface, yielding a local flux-weighted source δ^2H value of about −40‰. These calculations, and examination of individual profiles of stable isotope compositions, confirm that local transpiration contributes significant and readily measurable quantities of water vapor to the atmosphere above the rice crops, especially when relatively stable conditions exist in the ABL.

CONCLUSIONS

The stable isotope composition of water vapor collected at several heights above an irrigated rice crop were controlled by both regional air circulation and local evapotranspiration. Temporal variations in the stable isotopic composition of water vapor over rice crops at Griffith reflect contributions from air masses from source regions separated by large distances. Tropical air contributes vapor enriched in heavy isotopes (δ^2H > −70‰), while polar maritime-dominated air contributes light vapor (δ^2H < −130‰). The isotopic composition of water vapor above the rice canopy during unsta-

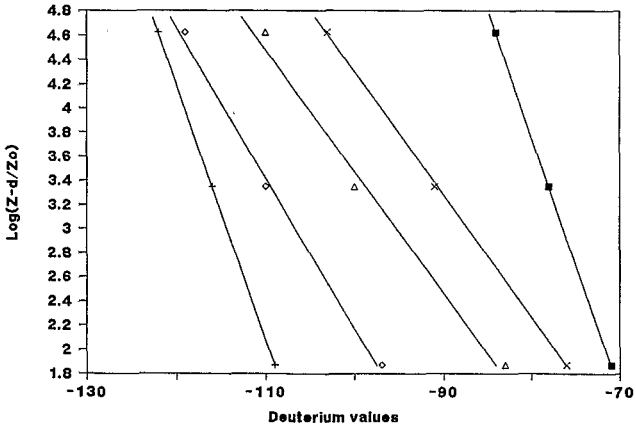

Fig. 9. Variation of daytime water vapor δ^2H values with the natural logarithm of height (adjusted for zero plane displacement) over the mature rice crop.

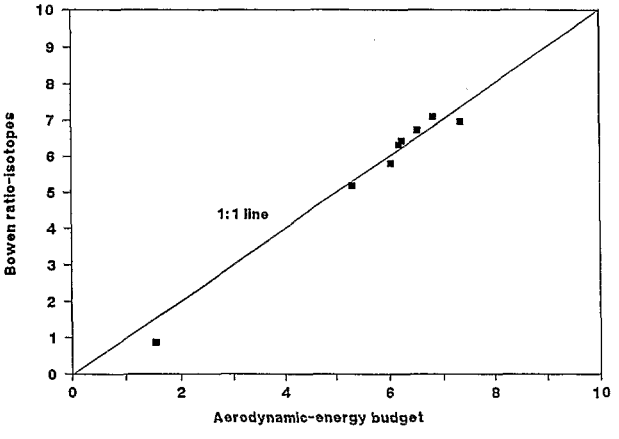

Fig. 11. Comparison of daytime evapotranspiration calculated from energy budgets and gradients in water vapor δ^2H.

ble conditions was dominated at all levels within the ABL by the regional air vapor properties. During stable conditions, the vertical isotope gradient was controlled by the rate of mixing between upper atmospheric air and local transpired water. The vertical profile of water vapor isotope composition was approximately logarithmic, similar to other parameters such as wind speed, mean temperature and mean specific humidity [*Brutsaert*, 1982]. The calculated evapotranspiration flux from stable isotope profiles using a Bowen ratio technique agrees well with energy budget calculations. However, this type of calculation can only be done with any confidence during stable conditions when water vapor stable isotope gradients are relatively high within the lowest 3 m of the atmosphere.

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