

## **Soil moisture responses to vapour pressure deficit in polytunnel-grown tomato under soil moisture triggered irrigation control**

M. S. Goodchild, K. D. Kühn & M. D. Jenkins

Delta-T Devices Ltd., 130 Low Road, Burwell, Cambridge, CB25 0EJ, UK

### **Abstract**

The aim of this work has been to investigate soil-to-atmosphere water transport in potted tomato plants by measuring and processing high-resolution soil moisture data against the environmental driver of vapour pressure deficit (VPD). Whilst many researchers have successfully employed sap flow sensors to determine water uptake by roots and transport through the canopy, the installation of sap flow sensors is non-trivial. This work presents an alternative method that can be integrated with irrigation controllers and data loggers that employ soil moisture feedback which can allow water uptake to be evaluated against environmental drivers such as VPD between irrigation events. In order to investigate water uptake against VPD, soil moisture measurements were taken with a resolution of 2 decimal places - and soil moisture, air temperature and relative humidity measurements were logged every 2 minutes. Data processing of the soil moisture was performed in an Excel spread sheet where changes in water transport were derived from the rate of change of soil moisture using the Slope function over 5 soil moisture readings. Results are presented from a small scale experiment using a GP2-based irrigation controller and data logger. Soil moisture feedback is provided from a single SM300 soil moisture sensor in order to regulate the soil moisture level and to assess the water flow from potted tomato plants between irrigation events. Soil moisture levels were set to avoid drainage water losses. By determining the rate of change in soil moisture between irrigation events, over a 16 day period whilst the tomato plant was in flower, it has been possible to observe very good correlation between soil water uptake and VPD - illustrating the link between plant physiology and environmental conditions. Further data is presented for a second potted tomato plant where the soil moisture level is switched between the level that avoids drainage losses and a significantly lower level. This data illustrates the possibility that rate-of-change of soil moisture and VPD measurement could be employed to highlight plant stress conditions.

## Introduction and method

The primary aim of this work has been to investigate soil-to-atmosphere water transport in potted tomato plants by measuring and processing high-resolution soil moisture data against the environmental driver of vapour pressure deficit (VPD). A secondary aim has been to assess if this method is sensitive enough to be used as a means of identifying water stress.

Transpiration rate measurements have been made by weighing tomato and cucumber plants that show linear relationships with VPD for values greater than 3kPa under high ( $<20\text{MJ m}^{-2} \text{d}^{-1}$ ) and low ( $<9\text{MJ m}^{-2} \text{d}^{-1}$ ) incident radiation levels (Medrano 2003 & 2005). Whilst many researchers have successfully employed sap flow sensors to determine water uptake by roots and transport through the canopy, a method which has also been considered as a means of scheduling irrigation (Jones), the installation of sap flow sensors is non-trivial (Smith and Allen). However, with careful consideration of installation and calibration of sap flow measurement has been shown by Chu et al. to be sufficiently sensitive to measure transient responses to wind speed. More recently, the comparison of diurnal sap flow enhanced thermal diffusivity and VPD measurements have shown potential to enable growers to identify early signs of water stress and enable plant-based irrigation scheduling (Skinner).

The method described in this paper does not attempt to make quantitative measurements of water transport but does attempt to show that rate of change of soil moisture measurements are sensitive enough to detect changes in water transport under atmospheric loading as indicated by in-canopy VPD measurements. Furthermore, the experimental arrangement presented in this paper aims to assess the potential for soil moisture derived water transport and VPD measurements to help identify early signs of water stress. This additional functionality could be integrated relatively easily with irrigation control equipment.

The starting point for this measurement method is the Richards flow equation for the movement of water in unsaturated soils (Tuzet et al.) where the water uptake in soil is derived from the rate of change of soil moisture in a contained soil environment, assuming there is negligible drainage or run-off. By measuring air temperature and relative humidity close to the plant canopy it is possible to determine the VPD in kPa (Allen et al. and Murray), which in this evaluation is considered the most significant driver of water transport.

In order to investigate the relationship between water uptake and VPD soil moisture measurements were taken with a resolution of 2 decimal places. Soil moisture, air temperature and relative humidity measurements were logged every 2 minutes. Data processing of the soil moisture was performed in an Excel spread sheet where the rate of change of soil moisture was derived using the Slope function over 5 soil moisture readings.

The irrigation controller arrangement employs a low-volume high-frequency (LVHF) algorithm using a soil moisture sensor similar to that described by R. Muñoz-Carpena et al., irrigation water delivery volumes were adjusted to achieve a maximum soil moisture change of 2% Vol. In the experimental work shown below we have created a very simple irrigation controller using a soil moisture sensor with a DeltaLINK 3.0 Script. The GP2 also collects data from relative humidity and air temperature sensors and calculates vapour pressure deficit, with a second DeltaLINK 3.0 Script. These user defined scripts provide additional functionality within the GP2, as shown in Figure 1, and enables soil moisture and VPD data to be logged in real-time allowing the relationship between rates of change in soil moisture and VPD to be more easily investigated.

### **Irrigation control implemented using DeltaLINK 3.0 Script Editor**

The GP2-based irrigation controller employs the DeltaLINK 3.0 Script Editor to implement the following simple GP2 relay control algorithm:

Turn Irrigation Valve ON when:

- SM300 Soil Moisture < Soil Moisture Trigger Threshold

Turn Irrigation Valve OFF when:

- Timer ≥ Irrigation Duration

where:

- Soil Moisture Trigger Threshold: 30% Vol. and 20% Vol.
- Irrigation Duration Limit: 5 seconds
- Minimum Irrigation Interval: 2 minutes

The Irrigation Duration Limit was set at 5 seconds in order to achieve a 1.5% to 2% Vol. change in soil moisture. Irrigation water volume was typically 50 to 60ml, delivered via a single dripper to each plant.

### **Calculation of vapour pressure deficit using DeltaLINK 3.0 Script Editor**

The calculation of VPD from air temperature and humidity data was implemented with a second DeltaLINK 3.0 Script in the GP2 using equations (1) and (2) below (Allen et al. and Murray).

$$e_s = 0.6108 \exp\left[\frac{17.27T}{T+237.3}\right] \quad (1)$$

where:

$e_s$  is saturated vapour pressure at temperature T (kPa)

$T$  is air temperature ( $^{\circ}\text{C}$ )

and,

$$VPD = e_s - \frac{RH \times e_s}{100} \quad (2)$$

where:

RH is relative humidity (%).

The calculations above, used to determine VPD, were applied to each set of air temperature and relative humidity data providing VPD measurements every 2 minutes. Water deliver volume was typically 50ml to 60ml.

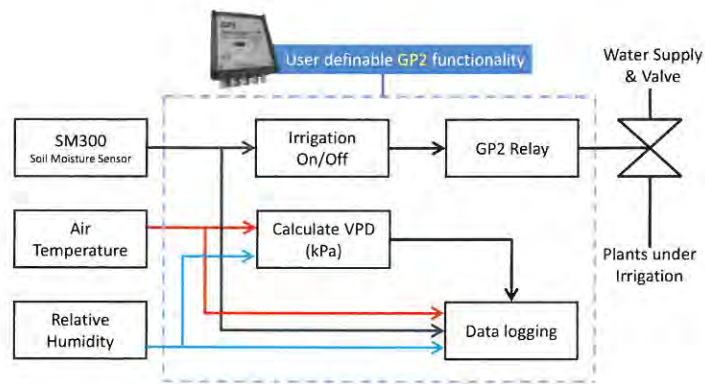


Fig 1 – Block diagram showing irrigation control, VPD calculation and data logging functions implemented in the GP2

### Experimental arrangement

In this experiment 6 tomato plants were grown in individual pots containing 8.5 litres of John Innes No.1 compost under a polytunnel at Delta-T Devices Ltd. (Burwell, UK, latitude  $53^{\circ}18' \text{ N}$ , longitude  $0^{\circ}02' \text{ E}$ ). Each pot was irrigated with a single dripper and irrigation control was achieved using a GP2 Data Logger and Controller. The GP2 was configured to provide 2 independent irrigation controllers (3 pots per irrigation controller) using an SM300 soil moisture sensor feedback in each case. The 2 independent irrigations of 3 tomato plants were arranged as follows:

1. irrigation set-point,  $\theta_{\text{ref}}$ , was chosen to: avoid drainage from the pots following an irrigation event and remained fixed during the 16 day trial, (Reference tomato plant)

2. irrigation set-point was switched between:  $\theta_{ref}-10\%$ ,  $\theta_{ref}$  and  $\theta_{ref}-10\%$ , (2<sup>nd</sup> tomato plant)

The arrangement of the dripper and SM300 soil moisture sensor is shown in Figure 2 below where the SM300 has been partially buried so that the soil moisture measurement is made within the root zone at an approximate depth of 4cm to 9cm in a 9 litre plant pot. In both irrigation treatments the SM300 soil moisture sensors employed the generic Mineral calibration.



Fig. 2 – The experimental arrangement showing the close proximity of SM300 soil moisture sensor to the root zone of the tomato plant and the irrigation dripper.

Air temperature and relative humidity was measured using an RHT 4n1 RH and Air Temperature Sensor which was placed in close proximity to the canopy of the tomato plants, as shown in Figure 3 below. Due to the restricted nature of ventilation in the polytunnel near 100% humidity occurred overnight resulting in close to zero VPD as well as condensation forming on the inside of the polytunnel.

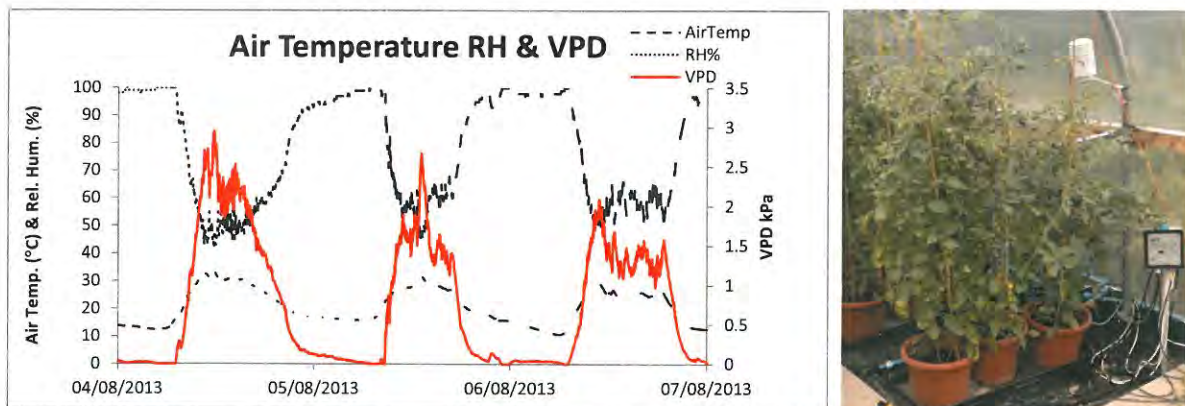


Fig. 3 – The experimental arrangement in the Delta-T polytunnel showing the close proximity of the air temperature and relative humidity sensor to the canopy together with air temperature and RH data over a 3 day period, used to calculate VPD by the GP2 Data Logger and Controller.

### Soil moisture responses to vapour pressure deficit

The data collected over a 16 day period is shown in Figure 4 where the GP2 based irrigation controller with feedback from an SM300 soil moisture sensor (black line) has maintained the soil moisture between 30% and 32%. VPD data is also presented against soil moisture in Figure 4. Data processing of the soil moisture was performed in an Excel spreadsheet where the rate of change of soil moisture was derived using the Slope function over 5 soil moisture readings. The rate of change of soil moisture between irrigations data is shown in Figure 5 with VPD data.

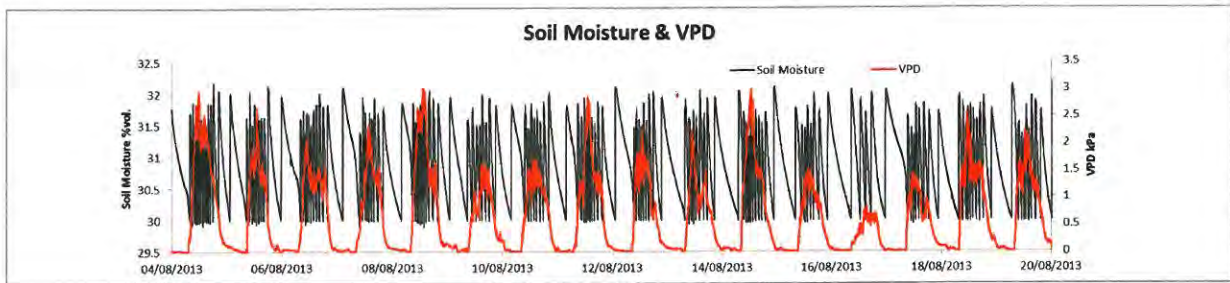


Fig. 4 – SM300 (Irrigation Control) and vapour pressure deficit responses (Reference tomato plant)

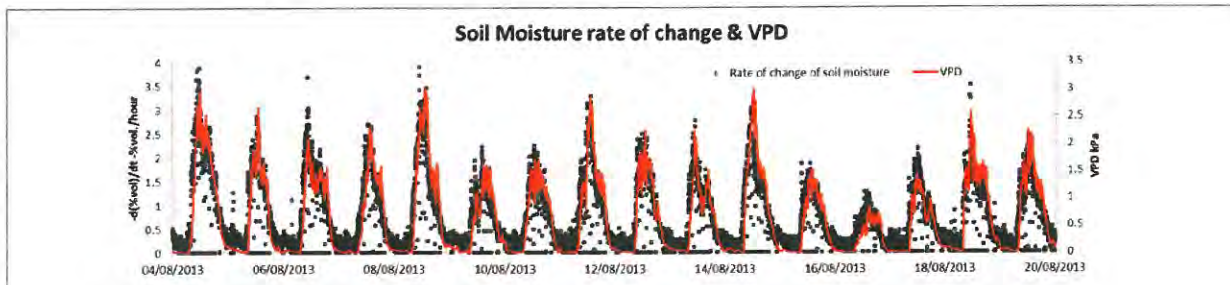


Fig. 5 – Rate of change of soil moisture and vapour pressure deficit responses (Reference tomato plant)

In Figure 5 it can be seen that the rate of change of soil moisture between irrigation events is well aligned with the diurnal VPD cycles and that the relative amplitudes of these responses also correlate. To further investigate this correlation the rate of change of soil moisture is plotted against VPD in Figure 6. From this data, where the measurement interval is 2 minutes over a 16 day period, it would appear that a linear relationship exists for VPD < 3kPa and when the soil moisture is maintained between 30% and 32% Vol. At these VPD levels it would appear that stomatal closure that would regulate water flow is not taking place.

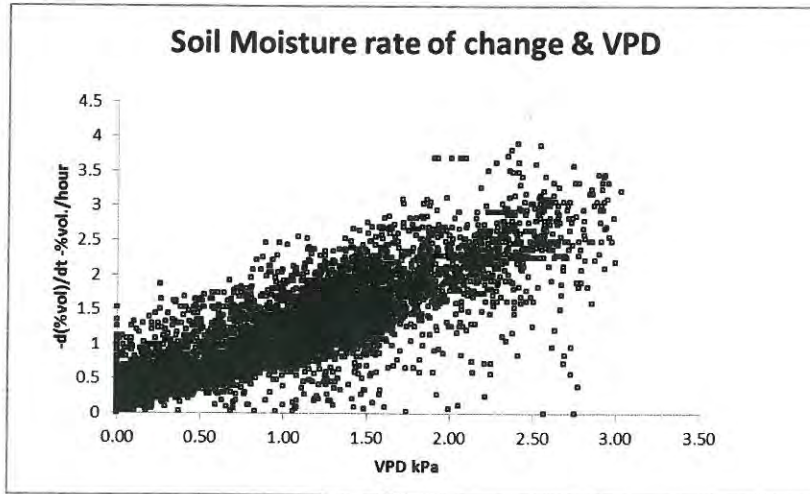


Fig 6 – Rate of change of soil moisture plotted against VPD where the soil moisture is maintained at 30% Vol. (Reference tomato plant)

Figure 7 shows data collected over the same 16 day period as in Figures 4 and 5 for a 2<sup>nd</sup> tomato plant where the soil moisture has been alternated between 20 and 22%, 30 and 32% and back to 20 and 22% by the GP2 based irrigation controller with feedback from an SM300 soil moisture sensor (black line).

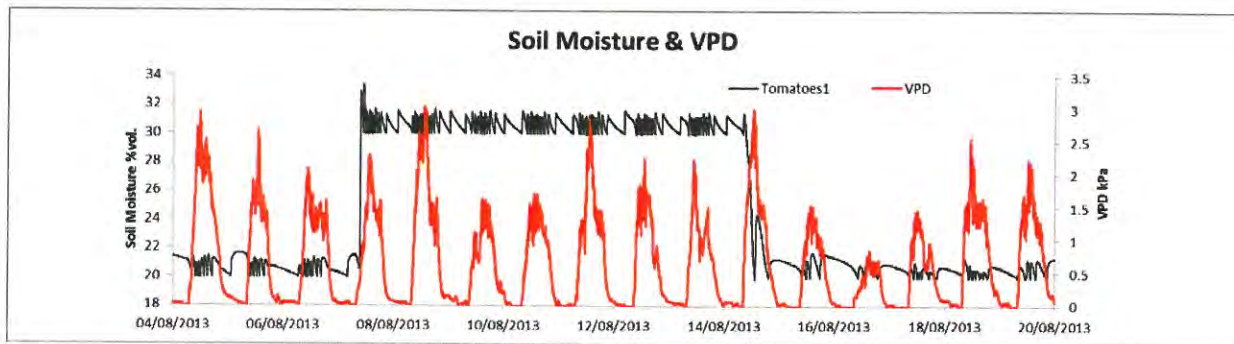


Fig. 7 – SM300 (Irrigation Control) and vapour pressure deficit responses (2<sup>nd</sup> tomato plant)

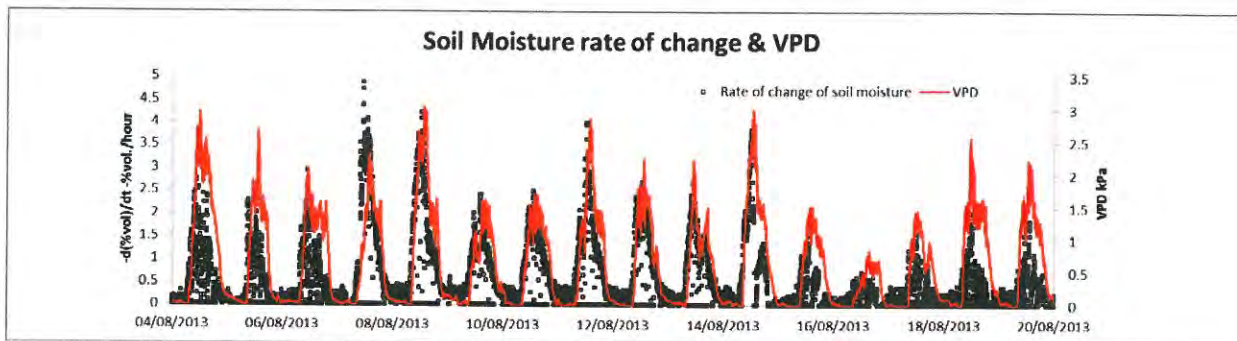


Fig. 8 – Rate of change of soil moisture and vapour pressure deficit responses (2<sup>nd</sup> tomato plant)

Upon first inspection it would appear that all is well with in both soil moisture regimes as the irrigation events are well aligned with the diurnal VPD cycle. However, a repeat of the data processing of the soil moisture data to derive the rate of change of soil moisture between irrigation events, as shown in Figure 8, suggests water uptake may have changed at the lower soil moisture levels. In Figure 8 it can be seen that when the soil moisture is maintained between 30 and 32% Vol. the rate of change of soil moisture between irrigation events is well aligned with diurnal VPD cycles and that the relative amplitudes of these responses also correlate, similar to the responses shown in Figure 5. However, when the soil moisture is maintained between 20 and 22% Vol. the rate of change of soil moisture responses indicate a different relationship with VPD. From the inspection of the data in Figure 8 it appears that the rate of change of soil moisture is aligned with initial daily increase in VPD but does not follow the peaks in VPD and tends to decrease during the periods of non-zero VDP. One possible explanation for this type of response is that when the soil moisture is between 20% and 22% Vol. the tomato plant experiences water stress and is limited in its ability to respond to increasing VDP. The initial peaks in the rate of change of soil moisture maybe due to an overnight water recharge within the root zone which cannot be maintained hydraulically (at this level of soil moisture) as a result of increasing water demands of the tomato plant. The overall reduction of water flow, indicated by the rate of change of soil moisture data, is supported by the reduction in the number of irrigations per day when the soil moisture is maintained between 20% and 22% Vol. To further investigate these responses the rate of change of soil moisture is plotted against VPD in Figure 9 for both soil moisture regimes.

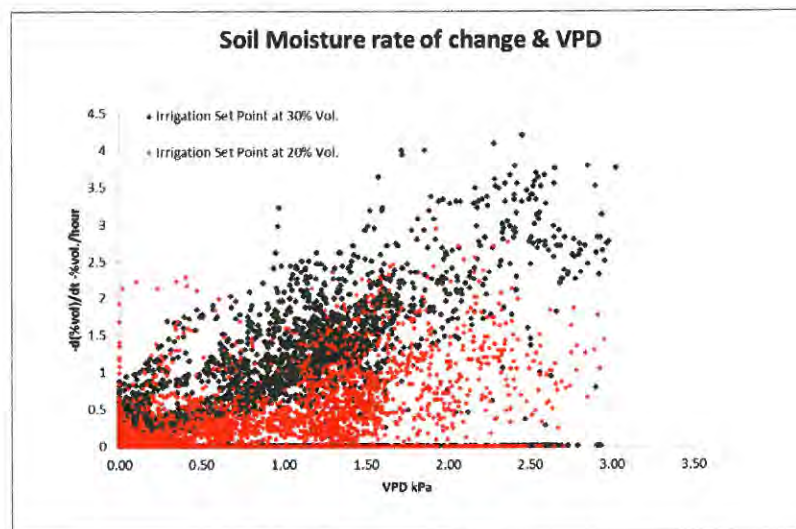


Fig 9 – Rate of change of soil moisture plotted against VPD where the soil moisture has been alternated between 20%Vol. and 30% Vol. (2<sup>nd</sup> tomato plant)



From this data, it again appears that there is a linear relationship for VPD < 3kPa when the soil moisture is maintained between 30% and 32% Vol. (black diamonds). However, when the soil moisture is maintained between 20% and 22% Vol. (red circles) the relationship no longer looks to be linear for VPD < 1kPa. Above 1kPa it appears that the rate of change of soil moisture is suppressed with respect to the measurements taken when the soil moisture was maintained between 30% and 32% Vol.

Whilst the method described in this paper does not attempt to make quantitative measurements of water transport, the data presented above does show that soil moisture based measurements are sensitive enough to detect changes in water transport under atmospheric loading as indicated by in-canopy VPD measurements. Furthermore, the experimental data collected in this paper illustrates the potential for soil moisture derived water transport and VPD measurements to help identify early signs of water stress by either:

- comparing the rate-of-change of soil moisture and VPD responses over time, or by,
- assessing the linearity of the rate-of-change of soil moisture and VPD relationship.

### **Conclusions**

A small scale experiment using a GP2-based irrigation controller with feedback from a single SM300 soil moisture sensor was employed to regulate the soil moisture level and assess the water flow from a potted tomato plant between irrigation events. By determining the rate of change in soil moisture between irrigation events it has been possible to observe very good correlation between water transport, using rate of change of soil moisture data, and vapour pressure deficit, illustrating the link between plant physiology and environmental conditions. Comparison of data collected from a 2<sup>nd</sup> potted tomato plant where the irrigation trigger points were set at 30% and 20% Vol. illustrates the possibility for soil moisture derived water transport and VPD measurements to help identify early signs of water stress.

## References

- Allen, R. G., Pereira, L. S., Raes, D., and Smith, M., 1998, Crop evapotranspiration. Guidelines for computing crop water requirements, FAO Irrigation and Drainage, Paper No. 56, FAO, Rome.
- Chu, R.C., Hsieh, C., Wu, S., and Phillips, N.G., 2009, Transient response of sap flow to wind speed. *Journal of Experimental Botany*, Vol. 60, No. 1, pp. 249-255
- Jones, H. G., 2004, Irrigation scheduling: advantages and pitfalls of plant-based methods, *Journal of Experimental Botany*, Vol. 55, No. 407, pp. 2427-2436
- Medrano, E., Sánchez-Guerrero, M.C. and Lorenzo, P. 2003, Influence of vapour pressure deficit on tomato crop transpiration. *Acta Hort. (ISHS)* 614:613-618 [http://www.actahort.org/books/614/614\\_91.htm](http://www.actahort.org/books/614/614_91.htm)
- Medrano, E., Lorenzo, P., Sánchez-Guerrero, M.C. and Montero J.I., 2005, Evaluation and modelling of greenhouse cucumber-crop transpiration under high and low radiation conditions, *Scientia Horticulturae*, 105, pp 163-175
- Muñoz-Carpena R., Bryan H., Klassen W. and Dukes M. D., 2003, Automatic soil moisture-based drip irrigation for improving tomato production. *Proc. Fla. State Hort. Soc.* 115, 80-85
- Murray, F. W., 1967: On the Computation of Saturation Vapor Pressure. *J. Appl. Meteor.*, 6, 203-204
- Skinner A., 2013. Engineering a sap flow sensor for irrigators, *Acta Hort. (ISHS)* 991:67-75  
[http://www.actahort.org/books/991/991\\_8.htm](http://www.actahort.org/books/991/991_8.htm)
- Smith D.M. and Allen S.J., 1996, Measurement of sap flow in plant stems, *Journal of Experimental Botany*, Vol. 47, No. 305, pp. 1833-1844
- Tuzet A., Perrier A. and Leuning R., 2003, A coupled model of stomatal conductance, photosynthesis and transpiration, *Plant, Cell & Env.*, 26, 1097-1116