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Upper Layer Observations and Simulation Using Kraus and Turner's Model in the Gulf of Finland

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There are strong seasonal variations in the depth of the thermocline and in the sea surface temperature in the western part of the Gulf of Finland. A numerical model, developed by Kraus and Turner, was used to calculate the depth of the thermocline and the temperature of the mixed layer from June to October in 1969 and 1974. Observed daily mean values of total incoming radiation, air temperature, wind velocity, air humidity and cloudiness were used as input data from which the thermal energy balance on the sea surface was calculated. The model is sensitive to the drag coefficient of the wind and to the absorption coefficient of the solar radiation for which the values $c_D = 0.8 . 10^{-3}$ and $\beta = 0.25 \text{ m}^{-1}$ were used in this work. For the mixed layer temperature the results of the model are 2-4^0 C too small. The depth of the thermocline can be predicted with an accuracy of ±5 meters.

Introduction

The annual trend in the seasonal thermocline has been successfully modelled by Kraus and Turner (1967). This model was later improved by Denman (1973) with the aim of achieving more accurate results in the synoptic scale of weather disturbances. Denman and Miyake (1973) have applied the model, with good results, in the northeast Pacific Ocean.

This article first presents observational material to provide a general picture of the annual vertical temperature changes in the western Gulf of Finland. The main object of this work is, to apply Kraus and Turner's model to the daily measured values of total incoming radiation, air temperature, wind speed, air humidity and cloudiness in 1969 and 1974, and to compare the calculated values of the mixed layer temperature and the depth of the thermocline with observations made at sea.

The Annual Trend in the Thermocline in the Western Gulf of Finland

The bathythermograms used to investigate the annual changes in sea temperatures originate from fifteen different years. They are taken in central areas of the Gulf of Finland, where the depth varies between 60 and 90 meters (Fig.1). It has been shown that changing currents and large movements of water masses are characteristic of this sea area (Palmén 1930, Palmén and Laurila 1938). There are very few bathythermograms from single stations. Therefore to provide a general picture of its development a larger investigational area was chosen.

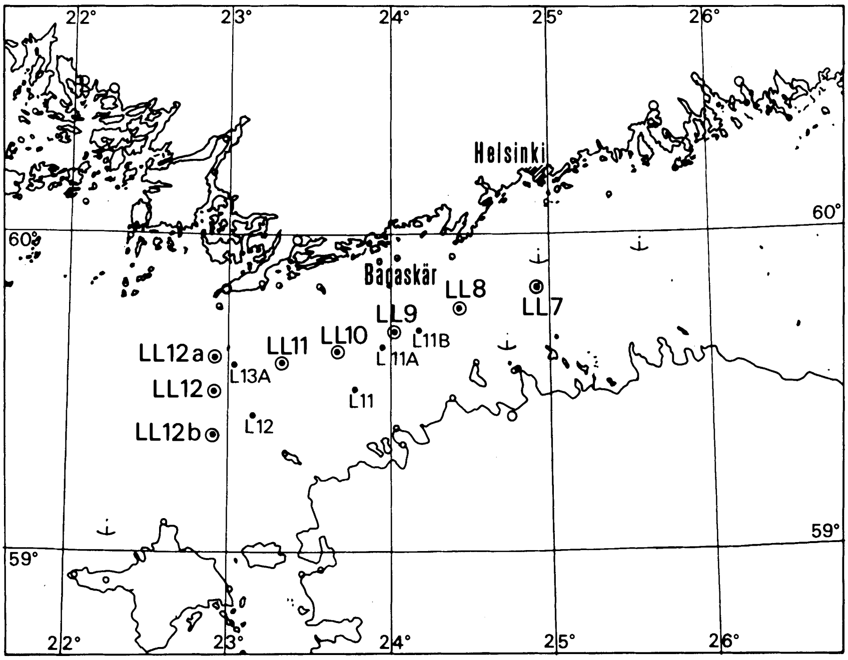

Fig. 1. Map of the investigated area on the Gulf of Finland with observation stations.

A measured temperature profile with definitions of the parameters are shown in Fig. 2. The parameters are defined visually from enlarged bathythermogram curves. In 70% of the curves the thermocline was well shaped. 25% of the temperature curves had transient thermoclines above the seasonal one. If the uppermost transient was visually of the same size or greater than the lower thermoclines, it was chosen. In 5% of the curves it was impossible to make the definitions.

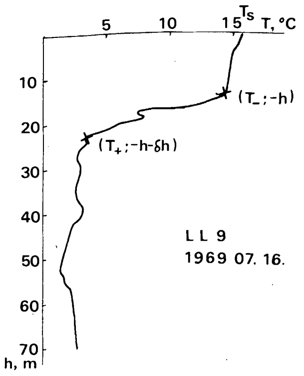

Fig. 2. Parameters of the bathythermogram curve. T_S is the surface temperature, T_- temperature in the upper part of the thermocline, T_+ temperature in the lower part of the thermocline, h is the depth of the thermocline and δh the thickness of the thermocline.

Figs. 3-7 present the parameters read from the bathytermograph curves, the surface temperature T_S, the temperature in the lower part of the mixed layer $T_-$and in the lower part of the thermocline T_+, the depths of the upper and lower parts of the thermocline h and $h + \delta h$. These parameters show the average variation in temperature in summer and autumn in the western Gulf of Finland, and thus also the decay in the depth of the thermocline. The curves in Figs. 3 and 4 do not differ much, which means that the mixed layer is on average homogeneous. The temperature in the lower part of the thermocline grows by about 3 degrees during the summer due to diffusion, breacking of internal waves and advection (Fig. 5).

Fig.6 shows that the range of variation in the depth of the thermocline in the area varies with time from 5 to 15 meters. Two separate phases can be seen as the thermocline deepens. From the middle of June until the middle of September this deepening becomes slower, i.e. about 6 meters a month. From mid-September onwards the deepening gets faster, i.e. 20 meters a month. The increase in the rate of deepening is due to increasingly strong winds in the autumn, and to convection as the surface waters cool and sink into deeper water layers. Fig. 7 shows the deepening of the lower part of the thermocline during summer and autumn.

The vertical height (δh) of the thermocline has an average value of 10 meters during summer. Single bathythermograph measurements give an average value of 0.5±0.3 for the ratio of the vertical height of the thermocline to the depth of the thermocline, $\delta h/h$.

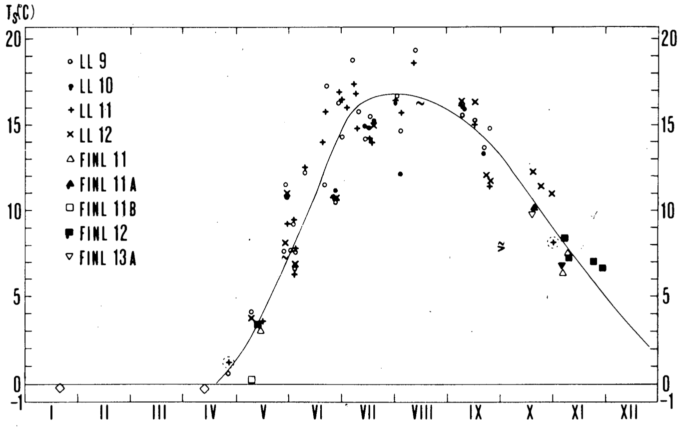

Fig. 3. Surface temperature observations as a function of time from fifteen different years in the western Gulf of Finland. The different marks mean the various stations as listed to the right.

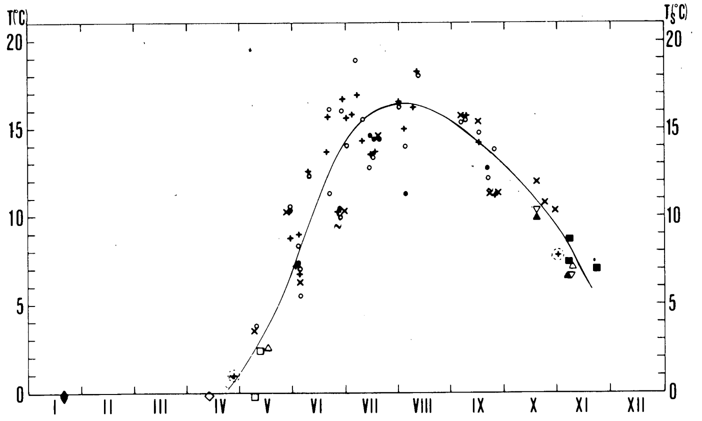

Fig. 4. Temperature in the upper part of the thermocline as a function of time. Observations from fifteen different years in the western Gulf of Finland.

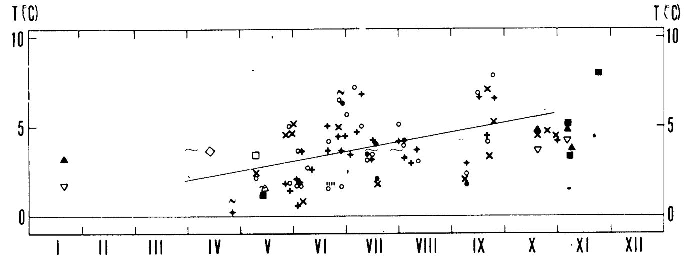

Fig. 5. Temperature in the lower part of the thermocline as a function of time. Observations from fifteen different years in the western Gulf of Finland.

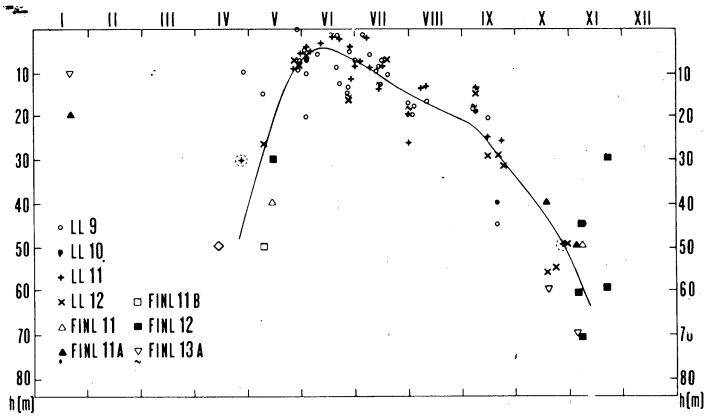

Fig. 6. The depth of the upper part of the thermocline as a function of time. Observations from fifteen different years in the western Gulf of Finland.

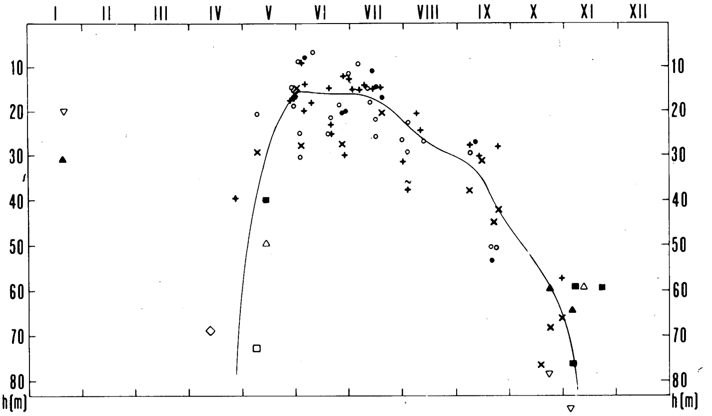

Fig. 7. The depth of the lower part of the thermocline as a function of time. Observations from fifteen different years in the western Gulf of Finland.

This value has a slight decreasing trend during the summer. The value is greater than that ($\delta h/h=0.1$) used by Kitaigorodskii (1977) in his theoretical treatment of mixed layer deepening.

Application of the Kraus and Turner Model

In their one-dimensional model of the deepening of the thermocline Kraus and Turner (1967) use the turbulent kinetic energy equation instead of the total kinetic energy equation to describe the mixed layer. The equations of heat and mechanical energy are approximatively connected according to the two-layer model. The resulting equations for the surface temperature and the thermocline depth changes are

$$\frac{dT_s}{dt} = \frac{2}{h^2}\,[Q_n h - (G + \frac{Q_s}{\beta})] \tag{1}$$

$$\Lambda \frac{dh}{dt} \equiv \frac{1}{(T_s - T_+)h}\,[2(G + \frac{Q_s}{\beta}) - Q_n h] \tag{2}$$

Q_n is the net balance of heat (see Eq. (6)). Q_s is the total incoming radiation, ß the coefficient of extinction. Λ is the Heaviside unit function defined by $\Lambda = \Lambda(dh/dt) = 1/0$ for $dh/dt \gtrless 0$.

G is the kinetic energy input from the wind

$$G \equiv (\frac{\rho_a}{\rho_w})^{\frac{3}{2}}\,\frac{c_D^{\frac{3}{2}}\,\bar{u}^3}{g\alpha} \tag{3}$$

Where ρ_w, ρ_a are the densities of water and air, c_D the drag coefficient of wind, u mean wind velocity and α the coefficient of expansion.

As the thermocline rises $\Lambda = 0$, the right hand side of Eq. (2) has the value zero and h can be calculated from the equation

$$h \equiv 2\,\frac{G - (Q_s/\beta)}{Q_n} \tag{4}$$

The introduction of Eq. (4) into Eq. (1) gives

$$\frac{dT_s}{dt} = \frac{1}{2}\,\frac{Q_n^2}{G + (Q_s/\beta)} \tag{5}$$

The energy dissipation term has been omitted in this treatment. Kraus and Turner consider the temperature below the thermocline (T_+) as constant. In this work T_+ was changed every month according to the observations (see Fig.5), using the values 3 (June), 3.8, 4.2, 5.0, 4.6 and 4.3°C (November).

Eqs. (1) to (5) include two experimental parameters: the coefficient of extinction ß and the drag coefficient of wind c_D.

The model can be applied with a chosen time step (in this study one day) to observed meteorological input parameters, in this case total incoming radiation (measured in Helsinki), air temperature, relative humidity, cloudiness and wind velocity (observations from Bågaskär). From these parameters the heat balance terms on the sea surface have been calculated using the equations given by Hankimo (1964). The equation of the net balance is

$$Q_n = Q_e + Q_c + Q_b + Q_r - Q_s \tag{6}$$

and the terms are

$$Q_e = 3{:}27\,(e_s - e_a)\,\bar{u}\ Wm^{-2}\,, \qquad \text{the flux of latent heat} \tag{7}$$

$$Q_c = 0.213\,(T_s - T_a)\,\bar{u}\ Wm^{-2}\,, \qquad \text{the flux of sensible heat} \tag{8}$$

$$Q_b = 0.484\,(297.0 - 1.86\,T_s - 0.95\,U_o)(1 - 0.0956\,C)\ Wm^{-2}\,, \quad \text{the effective back radiation} \tag{9}$$

$$Q_r = 0.484\,(0.15\,Q_s - 2.06\cdot 10^{-4}\,Q_s^2)\ Wm^{-2}\,, \quad \text{reflection back from the sea surface.} \tag{10}$$

e_s denotes the saturated water vapor pressure at the temperature of the water surface, e_a the water vapor pressure of the air at the altitude of 10 meters and $\bar{u}$ the wind velocity at the same altitude. The surface temperature T_s is that calculated by the model for the last day. U_o is the relative humidity, and C cloudiness.

Weather conditions during 1969 and 1974 are of a somewhat different character (Table 1).

Figs. 8 and 9 present the results of the model obtained from June to October in 1969 and 1974. The best values for the experimental extinction coefficient β and the drag coefficient of wind c_D are $\beta = 0.25\,m^{-1}$, $c_D = 0.8 \cdot 10^{-3}$. Denman and Miyake (1973) used the value $\beta = -0.3\ m^{-1}$. Lowering the value of the drag coefficient to $0.8 \cdot 10^{-3}$ effectively raised the sea surface temperature in this work. The extinction coefficient was chosen so that the mixed layer depth was satisfied in both years.

Table 1 Monthly sums of total incoming radiation Q_s at Helsinki and the monthly means of wind speed v_a, air temperature T_a, relative humidity U_o and cloudiness C at Bågaskär in the years 1969 and 1974 compared with each other. The corresponding daily mean values have been used as data in running the Kraus and Turner model.

	Helsinki		Bågaskär							
	Q_s, Wm^{-2}		v_a, ms^{-1}		T_a, °C		U_0, %		C (0-8)	
	1969	1974	1969	1974	1969	1974	1969	1974	1969	1974
J	7894	7533	3.7	5.3	14.5	13.7	71	77	3.2	4.3
J	7370	5997	4.5	5.5	15.7	15.7	79	85	3.5	5.6
A	6309	5692	5.1	4.0	17.4	14.1	72	90	2.6	4.0
S	2976	3049	6.8	4.7	11.0	13.5	83	87	5.8	4.9
O	1453	919	5.6	6.1	6.3	7.2	85	90	5.2	5.2

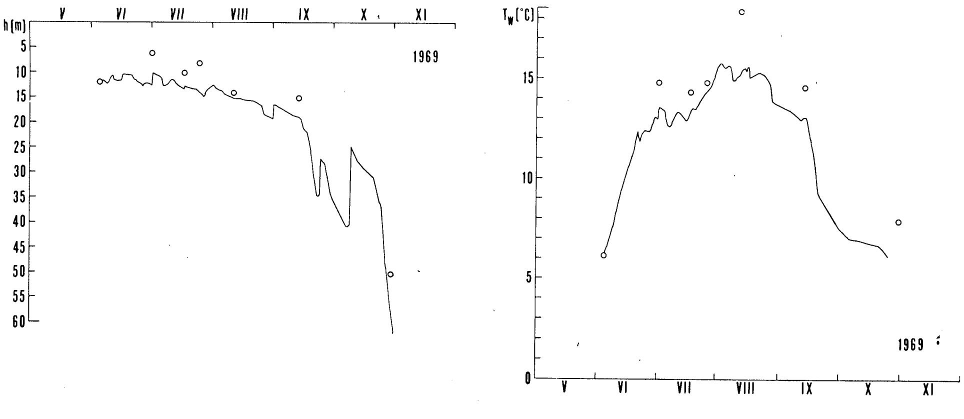

Fig. 8. Comparison of the model output (straight line) with the observed data (circles) from June to October in 1969. *h* is the depth of the thermocline and T_W the mixed layer temperature. The parameter values were $c_D=0.8\cdot10^{-3}$, ß = 0.25 m^{-1}.

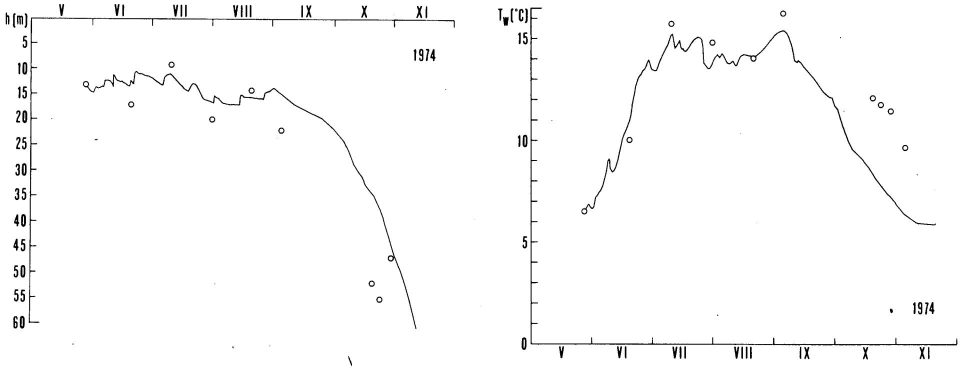

Fig. 9. Compaison of the model output (straight line) with the observed data (circles) from June to November in 1974. *h* is the depth of the thermocline and T_W the mixed layer temperature. The parameter values were $c_D= 0.8\cdot10^{-3}$, ß = 0,25 m^{-1}.

Kraus and Turner have chosen values $c_D = 0.80 + 0.114\ \mu\ 10$, ß = 0.05 – 0.1 m^{-1}, but they have not used larger data as a test for their validity.

Denman (1973) also proved that the depth of the thermocline is sensitive to changes in the experimental parameters. According to Denman and Miyake (1973) the extinction coefficient of the surface water might change during summer due to variations in the amount of plancton.

It has not been calculated here how well the heat balance equations (7-10) – using coastal meteorological input from Bågaskär and Helsinki – simulate weather conditions on the open sea. Checking and optimizing the coefficients of these equations might improve the efficency of the model.

In Table 2 the heat equation components calculated from Eqs. (7) to (10) are presented together with values given by Hela (1951) and Hankimo (1964). Tables 3 and 4 present the observational data used to check the results of the model. The great variation in thermocline depth at different stations can be seen, as a result of which the mean values depend on the number and location of observations available.

Conclusions

The Kraus and Turner model for calculating mixed layer depth and temperature gives qualitatively good results in the western Gulf of Finland. The mixed layer temperature can be predicted with an accuracy of 2-4°C, the predicted value beeing continuously too small. The depth of the mixed layer can be calculated with an accuracy of ± 5 meters, which is same presented by Denman and Miyake (1973). The predictions could obviously be improved by checking the coefficients of the heat balance equations. The fact that the meteorological observations are from coastal stations also has an influence on the heat balance terms. As far as the wind is concerned it might be useful to calculate the velocity from the synoptic air pressure charts with the geostrophic assumption.

One important factor in explaining the differences between the model results and observations, especially in autumn, could be the advection of warm water from the northern Baltic Sea. This can be verified using the results obtained by Palmen (1930) concerning current measurements from lightships on the Gulf of Finland during 1923-1927. Observations at sea and dynamical calculations from the last few years also show strong advective wind-dependent movements of water masses from the west into Gulf of Finland.

Table 2 Monthly mean values of heat balance terms of different works Bågaskär lies in the northern part of the Baltic Sea, Finngrundet in the southern part of the Bay of Bothnia. Q_e and Q_c are the fluxes of latent and sensible heat, Q_b the effective radiation, Q_r reflection back from the sea surface, Q_s the total incoming radiation and Q_n the net flux of energy from the sea surface.

	Q_e $\mathrm{Wm^{-2}}$					Q_c $\mathrm{Wm^{-2}}$			
	Hela Bågaskär 1923-38	Hankimo Finngrundet 1961	Tyrväinen G. of Finland 1969	1974		Hela Bågaskär 1923-38	Hankimo Finngrundet 1961	Tyrväinen G. of Finland 1969	1974
J	-11	3	9	4	*J*	-27	-17	-40	-40
J	12	17	28	20	*J*	-19	-5	-18	-15
A	59	47	46	23	*A*	-3	-5	-20	-2
S	55	52	61	27	*S*	5	-4	5	-1
O	51	50	16	41	*O*	17	2	-2	19

	Q_b $\mathrm{Wm^{-2}}$				Q_r $\mathrm{Wm^{-2}}$		
	Hankimo Finngrundet 1961	Tyrväinen G. of Finland 1969	1974		Hankimo Finngrundet 1961	Tyrväinen G. of Finland 1969	1974
J	52	72	56	*J*	27	23	23
J	42	62	41	*J*	20	23	20
A	48	74	55	*A*	23	21	20
S	52	44	52	*S*	14	12	13
O	45	46	33	*O*	7	7	4

	Q_s $\mathrm{Wm^{-2}}$				Q_n $\mathrm{Wm^{-2}}$		
	Hankimo Finngrundet 1961	Tyrväinen G. of Finland 1969	1974		Hankimo Finngrundet 1961	Tyrväinen G. of Finland 1969	1974
J	-321	-255	-251	*J*	-253	-190	-209
J	-188	-246	-193	*J*	-163	-152	-127
A	-212	-204	-184	*A*	-100	-83	-83
S	-127	-126	-102	*S*	11	23	-11
O	-56	-46	-30	*O*	44	0	66

Table 3 The observed data of mixed layer depth h and the mixed layer temperature T_W in 1969. The mean values are used to check the results of the Kraus and Turner model.

1969	4/6		1/7		16-17/7		23/7		11-12/8		13/9		31/10	
	h m	T_w ^oC	h m	T_w ^oC	h m	T_w ^oC	h m	T_w ^oC	h m	T_w ^oC	h m	T_w ^oC	h m	T_w ^oC
LL9	20	6.1	4	14.4	13	14.7	5	14.8	16	18.6	14	14.4		
LL10					8	14.8								
LL11	4	6.1	8	15.4	9	13.7	10	15.0	11	18.4	15	14.8	50	8.0
Mean	12	6.1	6	14.9	10	14.4	8	14.9	14	18.5	15	14.6	50	8.0

Table 4 The observed data of mixed layer depth h and mixed layer temperature T_W in 1974. The mean values are used to check the results of the Kraus and Turner model.

1974	27-28/5		19/6		9/7		1/8		19-20/8		4-5/9		19/10		23/10		29/10		5/11	
	h m	T_W ^oC	h m	T_W ^oC	h m	T_W ^oC	h m	T_W ^oC	h m	T_W ^oC	h m	T_W ^oC	h m	T_W ^oC	h m	T_W ^oC	h m	T_W ^oC	h m	T_W ^oC
LL7	15	6.3	7	11.0	10	15.7	14	14.2	5	11.6	19	15.1	44	11.8	44	10.9	40	10.6		9.0
LL8											25	16.0			55					
LL9	6	6.1	11	10.2			23	16.5	16	15.5	22	16.1	50	12.0	57	11.6	53	11.5		10.0
LL10											18	16.4								
LL11	10	6.8	25	9.5	8	15.8	23	15.5	20	15.4	12	16.6	58	12.6		12.8		11.6		10.1
LL12a			18	11.2							30	17.6					45	12.4		9.5
LL12	20	6.7	21	10.9							24	15.7	57	12.1	57	11.3	50	10.9		10.1
LL12b			18	10.6							24	17.9						11.9		
Mean	13	6.5	17	10.0	9	15.8	20	14.9	14	14.1	22	16.4	52	12.1	53	11.7	47	11.5		9.7

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