UNIFIED MODEL DOCUMENTATION PAPER NO 29

CALCULATION OF SATURATED SPECIFIC HUMIDITY AND LARGE - SCALE CLOUD

by

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17 November 1999

Version 4.1

Model Version 4.5

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Modification Record		
Document version	**Author**	**Description...................**
2	R.N.B.Smith	Brought up to date with model versions 3.n Iteration procedure in cloud scheme described
3	A.C.Bushell	2A cloud scheme description added
4	S.Cusack	Brought up to date with UM version 4.5
4.1	C.Wilson	Equations P291.2 and P291.3 corrected

OUTLINE

(1) INTRODUCTION

This paper documents calculations of quantities which are required by several components or need to be calculated several times within a component of the Unified Model. These are:

(1) Saturation specific humidity at a given temperature and pressure

(2) Large-scale cloud

(2) CALCULATION OF SATURATED SPECIFIC HUMIDITY (P291)

(a) Theory

Saturated specific humidity q_s (kg kg^{-1}) is assumed to be given by

$$q_s(T,p) = \varepsilon\, e_s(T)/p \qquad \text{(P291.1)}$$

where e_s is the saturation vapour pressure of water vapour (Pa)

p is atmospheric pressure (Pa)

T is temperature (K)

and ε is the ratio of the molecular weights of water and dry air (=0.62198)

Values of the saturation vapour pressure are obtained from the Goff-Gratch formula adopted by the World Meteorological Organisation (Landolt-Bornstein (1987)). Saturation vapour pressure over liquid water, $e_{s,w}$ is given by,

$$\begin{aligned}\log_{10} e_{s,w} = {} & 10.79574\left(1 - T_t/T\right) - 5.028\log_{10}\left(T/T_t\right) \\ & + 1.50475\,x\,10^{-4}\left(1 - 10^{(-8.2969(T/T_t - 1))}\right) \\ & + 0.42873\,x\,10^{-3}\left(10^{(4.76955(1 - T_t/T))} - 1\right) \\ & + 0.78614 + 2.0\end{aligned} \qquad \text{(P291.2)}$$

for temperatures in the range 223 < T < 373, where T_t = 273.16K, the triple point of water.

Saturation vapour pressure over ice $e_{s,i}$ is given by,

$$\begin{aligned}\log_{10} e_{s,i} = {} & -9.09685\left(T_t/T - 1\right) - 3.56654\log_{10}\left(T_t/T\right) \\ & + 0.87682\left(1 - T/T_t\right) + 0.78614 + 2.0\end{aligned} \qquad \text{(P291.3)}$$

for temperatures in the range 173 < T < 273.15.

(b) Implementation in the model

Equations (P291.2) and (P291.3) are used to calculate values for the saturation vapour pressure of water every 0.1K between 183.16K and 338.16K. These are shown in Table 1 and are held in DATA statements in the model code. More accurate values are calculated by in the model using linear interpolation between the tabulated values. For temperatures below and above this range the first and last values in the DATA statements are used respectively.

Two routines for calculating saturated specific humidity are present in the model library. Routine QSAT has values of saturation vapour pressure over ice below 273.15K while routine

QSAT_WAT has values over water below the same temperature. The latter is included for use in inverting dew points measured by radiosondes which are always reported with respect to water. Both routines return a saturated specific humidity using temperature and pressure as inputs.

(3) LARGE-SCALE CLOUD (P292)

(a) The way the cloud scheme operates

The formulation of models which do not incorporate cloud water variables allows condensation only when grid-scale supersaturation is reached and then converts the excess water vapour directly to precipitation. In the cloud scheme described here condensation can occur before grid-scale supersaturation and the vapour is condensed to cloud water. Also, the conversion from vapour to liquid or frozen cloud water is reversible. Before describing the details of the cloud scheme an outline of how it is used in the model is presented. In some respects this resembles the way the traditional schemes for large-scale precipitation are used, which can be represented as:

$$\left\{\begin{matrix} T \\ q \end{matrix}\right\} \frac{\text{Processes operating}}{\text{over model timestep}} \triangleright \left\{\begin{matrix} T^* \\ q^* \end{matrix}\right\} \frac{\text{Removal of any}}{\text{supersaturation}} \triangleright \left\{\begin{matrix} T^{**} = \text{fn}(T^*, q^*) \\ q^{**} = \text{fn}(T^*, q^*) \\ \text{ppn} = q^* - q^{**} \end{matrix}\right.$$

The adjustment back to saturation step in the above uses the variables as incremented by the other processes represented in the model (superscript * values). Although this adjustment changes prognostic variables it is diagnostic in the sense that no timestep is involved in the functions giving T^{**} and q^{**}. For this reason the step to remove supersaturation could be applied after each process (as long as the precipitation were accumulated) but to save computing time it is done only once each timestep.

The large-scale cloud scheme operates in a similar way to the large-scale precipitation scheme in models without prognostic cloud water variables. A main difference is that it calculates cloud amount and water content (rather than precipitation) from thermodynamic and water content variables which are conserved during changes of state of cloud water (rather than from temperature and specific humidity). The definitions of these "cloud-conserved" variables are:

the liquid/frozen water temperature

$$T_L = T - \frac{L_c}{c_P} q_c^{(L)} - \frac{(L_C + L_F)}{c_P} q_c^{(F)} \qquad \text{(P292.1)}$$

and the total water content

$$q_t = q + q_C^{(L)} + q_C^{(F)} = q + q_C \qquad \text{(P292.2)}$$

$q_C^{(L)}$ and $q_C^{(F)}$ are the liquid and frozen cloud water contents respectively. The large-scale cloud scheme is used in two similar ways which can be represented as:

$$\begin{Bmatrix} T \\ q \\ q_C^{(L)} \\ q_C^{(F)} \end{Bmatrix} \xrightarrow{\text{Process(es)}} \triangleright \begin{Bmatrix} T^* \\ q^* \\ q_C^{(L)*} \\ q_C^{(F)*} \end{Bmatrix} \frac{\text{Calculations}}{\text{using defns.}} \triangleright \begin{Bmatrix} q_t^* \\ T_L^* \end{Bmatrix} \frac{\text{Cloud}}{\text{Scheme}} \triangleright \begin{Bmatrix} T^{**} = T_L^* + (L/c_P)\, q_C^{**} \\ q^{**} = q_t^* - q_C^{**} \\ q_C^{**} = q_C(T_L^*, q_t^*) \\ C^{**} = C(T_L^*, q_t^*) \end{Bmatrix}$$

$$\text{(P 292.1 \& 2)}$$

or

$$\begin{Bmatrix} T \\ q \\ q_C^{(L)} \\ q_C^{(F)} \end{Bmatrix} \frac{\text{Calculations}}{\text{using defns.}} \triangleright \begin{Bmatrix} q_t \\ T_L \end{Bmatrix} \xrightarrow{\text{Process(es)}} \triangleright \begin{Bmatrix} q_t^* \\ T_L^* \end{Bmatrix} \frac{\text{Cloud}}{\text{Scheme}} \triangleright \begin{Bmatrix} T^{**} \\ q^{**} \\ q_C^{**} \\ C^{**} \end{Bmatrix} \text{as above}$$

$$\text{(P 292.1 \& 2)}$$

The functions giving C^{**} and q_C^{**} are derived below and given in Appendix A. The cloud water content q_C^{**} is partitioned into liquid and frozen components by the cloud scheme and the appropriate latent heat used in the calculation of T^{**} (see Appendix A).

The second version of the above diagram is appropriate for those model processes which directly increment the cloud-conserved variables T_L and q_C, such as advection (P12) and the turbulent mixing scheme for the boundary layer (P24). The cloud scheme operates diagnostically in the same sense as the traditional type of large-scale precipitation scheme - no timestep is involved in the calculations. It requires the values of the cloud-conserved variables after they have been incremented using the prognostic equations for the other model processes (i.e. superscript * values). Though the cloud scheme does not change the values of the cloud-conserved quantities, the variables T, q, $q_C^{(L)}$ and $q_C^{(F)}$ are changed if there is any change of state of water. Like the traditional type of large-scale precipitation scheme, the cloud scheme could be applied after every model process, but this is not necessary. However, after any process which increments the cloud-conserved variables directly, it is necessary to use it in order to obtain the new values of T, q, $q_C^{(L)}$ and $q_C^{(F)}$. The next section describes how q_C^{**} and C^{**} in the above diagrams are obtained from the cloud-conserved quantities.

(b) The calculation of cloud amount and water content

The calculation of cloud amount and cloud water content uses the cloud distribution concepts developed by Sommeria and Deardorff (1977) and Mellor (1977). A statistical distribution of the cloud-conserved variables about their grid-box mean is assumed.

In the mean the amount of cloud and its water content must clearly depend on the difference between the specific total water content and the saturation specific humidity. The grid-box mean of this difference in terms of conserved variables is

$$Q_C = a_L \left(q_t - q_s(T_L, p) \right) \qquad \text{(P292.3)}$$

and the local deviation from the mean is

$$s = a_L \left(q_t' - \alpha_L T_L' \right) \qquad \text{(P292.4)}$$

Initial estimates of a_L and α_L are given by

$$\alpha_L^{(1)} = \left. \frac{\partial q_s}{\partial T} \right|_{T=T_L} = \frac{\varepsilon L q_s(T_L, p)}{R T_L^2} \qquad \text{(P292.5)}$$

$$a_L^{(1)} = \frac{1}{\left(1 + \frac{L}{c_P} \alpha_L^{(1)} \right)} \qquad \text{(P292.6)}$$

where L is set to L_C if $T_L > T_M$ and $L_C + L_F$ otherwise. The values of a_L and α_L are iteratively refined as described later.

The fluctuations represented here are not necessarily due to turbulence alone but rather to any unresolved motion. The grid-box mean of s is zero since $\overline{q_t'}$ and $\overline{T_L'}$ are zero.

The standard deviation of s is

$$\sigma_s = a_L \left(\overline{q_t'^2} - 2\alpha_L \overline{q_t' T_L'} + \alpha_L^2 \overline{T_L'^2} \right)^{1/2} \qquad \text{(P292.7)}$$

Higher order moments are similarly defined. The statistics of s are completely defined by its distribution function G which must satisfy

$$\int_{-\infty}^{\infty} G(s)\,ds = 1 \quad , \quad \int_{-\infty}^{\infty} s G(s)\,ds = 0$$

Now the local cloud water content is

$$q_C' = \begin{cases} 0 & s \le -Q_C \\ Q_C + s & s > -Q_C \end{cases} \qquad \text{(P292.8)}$$

The mean cloud fraction is obviously the fraction of the grid-box with cloud water content greater than zero. In terms of G,

$$C = \int_{-Q_C}^{\infty} G(s)\,ds \qquad \text{(P292.9)}$$

The grid-box mean cloud water content is similarly given by

$$q_C = \int_{-Q_C}^{\infty} (Q_C + s)\, G(s)\, ds \qquad \text{(P292.10)}$$

To close the system G must be specified. Here a pragmatic choice is made to use the symmetric triangular function with standard deviation $\sigma_s = b_s/\sqrt{6}$ shown in Figure 1. Evaluating the integrals on the r.h.s. of (P292.9) and (P292.10) with this G gives simple polynomial functions of Q_C and b_s for the cloud fraction and water content (see Appendix A).

The sub-gridscale fluctuations whose distribution are given by G are, in a larger-scale model, due not only to small-scale turbulence but also to mesoscale effects. So using a higher order turbulence closure scheme to predict $\overline{q_t'^2}$ etc. may not be appropriate for a grid-box large enough to contain other unresolved motions.

To examine the role of b_s in the cloud scheme we set Q_C to the value at which cloud just forms, i.e. $-b_s$, to obtain a threshold relative humidity for cloud,

$$RH_C = 1 - \frac{b_S}{a_L q_s(T_L, p)} \qquad \text{(P292.11)}$$

where the r.h.s. is evaluated for T_L=T and it has been assumed in the derivation of (P292.11) that q_C=0 and q_t=q=$RH_C q_s(T_L,p)$. For RH_C to be a specifiable constant or function, without any temperature or pressure dependence determined by the q_s function, b_s must have the form

$$b_s = A a_L q_s(T_L, p)\, f(q_t / q_s(T_L, p)) \qquad \text{(P292.12)}$$

where f is an arbitrary function. Substituting (P292.12) into (P292.11) gives

$$A = \frac{(1 - RH_C)}{f(RH_C)}$$

For simplicity f = 1 has been chosen so that

$$b_s = (1 - RH_C) a_L q_s(T_L, p) \qquad \text{(P292.14)}$$

In versions 1A and 2A, the vertical profile of RH_C is set via the user interface. The appropriate values should depend on vertical resolution and may need to be tuned. In version 2B the values of RH_c are calculated as set out in Appendix D.

With b_s specified by (P292.14), $Q_N = Q_C/b_s$ (see Appendix A) can be written as

$$Q_N = \frac{\left(\frac{q_t}{q_s(T_L, p)} - 1\right)}{(1 - RH_C)} \qquad \text{(P292.15)}$$

and it can be seen that this does not depend on α_L or a_L. Consequently the cloud fraction, C, and the normalised cloud water content, q_C/b_s, do not depend on α_L or a_L (see P292.A1 & A2) in Appendix A). The actual (unnornalised) cloud water content does depend on a_L via b_s. Because Q_N, C and q_C/b_s do not depend on α_L or a_L they are not affected by the iterative refinement of the latter parameters which is now described.

The values of $\alpha_L^{(1)}$ or $a_L^{(1)}$ given by (P292.5 and 6) are used to calculate first estimates of $q_C^{(F)}$, $q_C^{(L)}$, q and T using the algorithm in Appendix A. (nth estimates are denoted by superscript (n) in the following.) For subsequent estimates the chord between $T^{(n)}$ and T_L on the q_s curve is used to obtain $\alpha_L^{(n)}$, i.e.,

$$\alpha_L^{(n)} = \frac{\left(q_s(T^{(n-1)}, p) - q_s(T_L, p)\right)}{T^{(n-1)} - T_L} \qquad \text{(P292.16)}$$

This iterative process can be written as

$$\alpha_L^{(n)} = F\left(\alpha_L^{(n-1)}\right) \qquad \text{(P292.17)}$$

and for convergence $|F'|$ must be < 1 in the vicinity of the solution α_L (which satisfies $\alpha_L = F(\alpha_L)$). F is given by

$$F(\alpha_L) = \frac{\left[q_s(T, p) - q_s(T - \beta\, a_L(\alpha_L), p)\right]}{\beta\, a_L(\alpha_L)} \qquad \text{(P292.18)}$$

where

$$a_L(\alpha_L) = \frac{1}{\left(1 + \frac{L}{c_P}\alpha_L\right)} \qquad \text{(P292.19)}$$

$$\beta(Q_N) = \frac{L}{c_P}(1 - RH_C)\, f_{qc}(Q_N) \qquad \text{(P292.20)}$$

and f_{qc} is the function which gives q_C/b_s in terms of Q_N, i.e. (P292.A2). T is the temperature which gives α_L when substituted in the r.h.s. of (P292.16).

The iteration converges quickly since

$$\frac{dF}{d\alpha_L} = \frac{da_L}{d\alpha_L}\frac{dF}{da_L} = \frac{L}{c_P} a_L\left(\alpha_L - \frac{dq_s}{dT}\right)$$
$$\approx \frac{-L}{c_P}\frac{\beta a_L^2}{2}\frac{d^2 q_s}{dT^2} \qquad \text{(P292.21)}$$

and for ranges of temperatures and pressures occurring naturally $F'(\alpha_L) \cong -10^{-2}$ to -10^{-1}. This convergence process is illustrated schematically in Figure 2(a). The convergence is accelerated further by choosing to replace $\alpha_L^{(n)}$ by $\hat{\alpha}^{(n)} = W\alpha_L^{(n)} + (1-W)\alpha_L^{(n-1)}$ where W is set to 0.75. This forces convergence from one side (see Figure 2(b)).

The cloud fraction C^{**} given by the scheme is related to the relative humidity $RH^{**}=q^{**}/q_s(T^{**},p)$ (see Appendix B). However, the cloud fraction is not calculated from the relative humidity as we do not know either until the cloud scheme has been used.

Appendix C describes a method of initialising the prognostic cloud water variables if the initial data dump does not contain them.

(c) The implementation of the cloud scheme in the model code (subroutine LS_CLD)

The subroutine can be called to to do calculations for JLEVS (1 ≤ JLEVS ≤ Q_LEVELS) adjacent model layers. (Q_LEVELS is the number of model layers with water content variables, the so-called "wet" layers.) The subroutine starts at layer KLEV (1 ≤ KLEV ≤ Q_LEVELS-JLEVS+1) and proceeds upwards. In practice the subroutine is called with KLEV = 1 and JLEVS = Q_LEVELS after the dynamics subroutines and with KLEV = 1 and JLEVS = BL_LEVELS as part of the surface and boundary layer processes component (P24). (BL_LEVELS is the number of model layers whose variables can be changed by the boundary layer subroutine.)

The cloud-conserved variables T_L and q_t are input to the subroutine, having previously been calculated and updated (see diagrams in (a) above). (Surface pressure is also input so that pressure can be calculated and used in the q_s function.) Q_N is calculated using (P292.15), or (P292.A4) if $RH_C = 1$, to determine which points have cloud in them. These points are compressed down to smaller vectors and the iterative process to obtain C, $q_C^{(L)}$, $q_C^{(F)}$, q and T is only done for points which have non-zero cloud. The number of iterations is currently set to 3. The calculation of temperature requires partition of the cloud water into liquid and frozen components. The algorithm for doing this is given in Appendix A.

(d) Version 2A implementation of cloud scheme.

This version of the cloud scheme accompanies the 3A version of the Large-Scale Precipitation routine, which introduces ice microphysics and a prognostic cloud ice content, advected separately from the remaining moisture variables.

i) Removal of cloud ice phase from water content calculations.

Separation of the frozen and fluid components of the grid-box mean total water content requires new 'cloud-conserved' variables, defined below, to replace equations P292.1 and P292.2:

$$T_{LL} = T - \frac{L_C}{C_P} q_C^{(L)} \quad \text{(P292.22)}$$

$$q_{TL} = q + q_C^{(L)} \quad \text{(P292.23)}$$

where T = grid-box mean temperature, q = grid-box mean humidity (in kg/kg) and $q_C^{(L)}$ = grid-box mean cloud liquid water content.

Once again, the PDF approach is used to calculate the liquid cloud fraction and cloud water content from the new conserved variables, using a width set from P292.14 where q_S is taken with respect to water only. The calculations are simpler because knowing $q_C^{(L)}$ enables q to be calculated from q_{TL} and T from T_{LL} directly without further having to partition the cloud water between ice and liquid phases. The same iterative process is used, but the q_S function is again taken to be with respect to water, rather than ice, at all temperatures.

ii) Diagnosis of ice cloud fraction and total cloud fraction.

The ice-free cloud calculation described above clearly returns a cloud cover that no longer represents the effects of frozen cloud water. This leaves a double problem; first, how to produce a frozen cloud fraction and, secondly, how to combine such a fraction with the liquid cloud fraction to produce a total cover. The individual fractions are required in order to produce in-cloud water contents for the precipitation processes whereas the total is needed for the radiation clear-sky calculations.

For consistency with the 1A cloud scheme, the frozen cloud fraction is calculated from equation P292.A1 using a value of Q_N derived by inverting P292.A2. In this case, q_C is taken from the prognostic $q_C^{(F)}$ and b_s is estimated:

$$b_s = (1 - RH_{crit})\, q_S(T, p) \qquad \text{(P292.24)}$$

to allow calculation of $q_N = q_C^{(F)} / b_s$ and hence:

$$Q_N = \begin{cases} \text{undefined but} \le -1 & \ldots 0 = q_N \\ \sqrt[3]{6\, q_N} - 1 & \ldots < q_N \le \frac{1}{6} \\ 1 + 2\sqrt{2}\cos[\frac{1}{3}\cos^{-1}[\frac{3(1-q_N)}{2\sqrt{2}}] + \frac{4\pi}{3}] & \ldots \frac{1}{6} < q_N < 1 \\ q_N & \ldots q_N \ge 1 \end{cases} \qquad \text{(P292.25)}$$

Although Q_N is undefined when $q_N = 0$, this is not a problem as the cloud fraction is by definition zero when there is no cloud frozen water content. The cloud fraction which is obtained in this fashion will have a value close to that which would have been returned by the 1A scheme in the pure ice cloud case for the same frozen cloud water content. However, the grid-box humidity in the two cases may be significantly different because the PDF scheme has not been used to relate the grid-box mean cloud water and total water contents in the 2A version.

When mixed-phase cloud exists, both liquid and frozen ice cloud fractions will be non-zero. The total cloud cover is calculated on the basis of a simple minimum overlap assumption:

$$C(Total) = \mathrm{MIN}(\,(C^{(F)} + C^{(L)}), 1\,) \qquad \text{(P292.26)}$$

The main differences in the 2A routine from the 1A, therefore, are that non-zero cloud liquid water contents at temperatures below T_M are possible and the relationships between grid-box mean total water content, total cloud fraction and total cloud water content are less closely constrained when ice cloud is present, potentially allowing cloud to form in sub-critical relative humidity conditions.

APPENDIX A.

THE CALCULATION OF CLOUD FRACTION, CLOUD WATER CONTENT, HUMIDITY AND TEMPERATURE FROM CLOUD CONSERVED VARIABLES.

The cloud fraction and water content derived assuming the triangular distribution function with standard deviation $\sigma_s = b_s/\sqrt{6}$ are given in terms of Q_C and B_s by:

$$C = \begin{cases} 0 & Q_N \leq 1 \\ \frac{1}{2}(1 + Q_N)^2 & -1 < Q_N \leq 0 \\ 1 - \frac{1}{2}(1 - Q_N)^2 & 0 < Q_N < 1 \\ 1 & 1 \leq Q_N \end{cases} \tag{P292.A1}$$

$$q_C / b_s = \begin{cases} 0 & Q_N \leq -1 \\ \frac{1}{6}(1 + Q_N)^3 & -1 < Q_N \leq 0 \\ Q_N + \frac{1}{6}(1 - Q_N)^3 & 0 < Q_N < 1 \\ Q_N & 1 \leq Q_N \end{cases} \tag{P292.A2}$$

where

$$Q_N = Q_C / b_s \tag{P292.A3}$$

The code calculates q_C and C using (P292.A1) and (P292.A2) unless $RH_C = 1$ in which case

$$Q_N = q_t - q_s(T_L, p) \tag{P292.A4}$$

and

$$C = \begin{cases} 0 & Q_N \leq 0 \\ 1 & Q_N > 0 \end{cases} \tag{P292.A5}$$

$$q_C / a_L = \begin{cases} 0 & Q_N \leq 0 \\ Q_N & Q_N > 0 \end{cases} \tag{P292.A6}$$

After q_C is known specific humidity is calculated from

$$q = q_t \;\; q_C \tag{P292.A7}$$

The calculation of temperature requires a thermodynamic partition of the cloud water into liquid and frozen components, $q_C^{(L)}$ and $q_C^{(F)}$ respectively. The components are also required as outputs so that thermodynamically consistent calculations can be done in other parts of the model. An initial "test" temperature, T', is set assuming all the cloud water is liquid:

$$T' = T_L + (L_C/c_P)q_C$$

The algorithm for partitioning cloud water and calculating the temperature continues as follows:

If $T' > T_M$ then { the assumption that all the cloud water is liquid is correct so }

$q_C^{(F)} = 0$

$q_C^{(L)} = q_C$

$T = T'$

else { i.e. $T' \leq T_M$ and so if T was set to T' we would have a contradiction so set a new test temperature, T'', assuming all the cloud water is frozen }

$T'' = T' + (L_F/c_P)q_C$

if $T'' < T_M$ then { the assumption that all the cloud water is frozen is correct so }

$q_C^{(F)} = q_C$

$q_C^{(L)} = 0$

$T = T''$

else { i.e. $T' \leq T_M$ and $T'' \geq T_M$ so T must be equal to T_M and a mixture of liquid and frozen cloud water must be present }

$q_C^{(F)} = (T_M - T').(c_P/L_F)$

$q_C^{(L)} = q_C - q_C^{(F)}$

$T = T_M$

endif

endif.

APPENDIX B.

THE RELATIONSHIP BETWEEN CLOUD FRACTION AND RELATIVE HUMIDITY.

The cloud fraction can be written in terms of the grid-box mean relative humidity, $RH = q/q_s(T,p)$, which is calculated with the temperature and specific humidity found by using the algorithm in Appendix A.

For $RH \le RH_C$,

$$C = 0 \qquad \text{(P292.B1)}$$

for $RH_C < RH < (5+RH_C)/6$,

$$C = (1/2)R^2 \qquad \text{(P292.B2)}$$

where R satisfies

$$R^3 - 6R + 6\left(\frac{RH - RH_C}{1 - RH_C}\right) = 0 \qquad \text{(P292.B3)}$$

The physically realistic root of this cubic gives

$$C = 4\cos^2(\pi/3 + \varphi/3) \qquad \text{(P292.B4)}$$

where

$$\varphi = \cos^{-1}\left[\frac{3}{2^{3/2}}\left(\frac{RH - RH_C}{1 - RH_C}\right)\right] \qquad \text{(P292.B5)}$$

for $(5+RH_C)/6 \le RH \le 1$,

$$C = 1 - \left[\frac{3}{2^{3/2}}\left(\frac{1 - RH}{1 - RH_C}\right)\right]^{2/3} \qquad \text{(P292.B6)}$$

At $RH = (5+RH_C)/6$ both (P292.B4-5) and (P292.B6) give C = 0.5 and so the function given by (P292.B1-6) is continuous.

APPENDIX C.

THE INITIALISATION OF CLOUD FRACTION AND WATER CONTENT.

If the initial fields for a model forecast or simulation do not contain the prognostic cloud water content variables, $q_C^{(L)}$ and $q_C^{(F)}$, then a method of initialising them is needed. The relationships given in Appendices A and B above provide one such method using the temperature and specific humidity fields as a starting point.

Firstly the relative humidity is calculated from T and q and then the cloud fraction is derived using (P292.B1)-(P292.B6). For $0 \le C < 1$ the following expressions for $q_C^{(L)}$ and $q_C^{(F)}$ in terms of C, T and p can be derived using (P292.A1)-(P292.A4):

$$\left. \begin{aligned} q_C^{(L)} &= 0 \\ q_C^{(F)} &= \frac{F(C)\, q_s(T,p)}{\left[1 + \left(RH + F(C)\right)\left(L_C + L_F\right)\dfrac{\alpha}{c_P}\right]} \end{aligned} \right\} \quad \text{for } T \le T_M \qquad \text{(P292.C1)}$$

$$\left. \begin{aligned} q_C^{(L)} &= \frac{F(C)\, q_s(T,p)}{\left[1 + \left(RH + F(C)\right) L_C \dfrac{\alpha}{c_P}\right]} \\ q_C^{(F)} &= 0 \end{aligned} \right\} \quad \text{for } T > T_M \qquad \text{(P292.C2)}$$

where $\alpha = \partial q_s / \partial T = \varepsilon L q_s(T,p) / RT^2$ (L being the appropriate latent heat) and $F(C)$ is given by,

$$\frac{F(C)}{(1-RH_C)} = \begin{cases} \dfrac{(2C)^{3/2}}{6} & 0 \le C \le \dfrac{1}{2} \\ 1-[2(1-C)]^{1/2} + \dfrac{[2(1-C)]^{3/2}}{6} & \dfrac{1}{2} < C < 1 \end{cases} \qquad \text{(P292.C3)}$$

When there is complete cloud cover, i.e. $C = 1$, no unique cloud water content can be derived using this method. Physically this is because the cloud water content is determined by the relative rates of condensation and precipitation formation when $C = 1$. However, tests have shown that for $T \le T_M$, (P292.C1) with $F(1) = (1-RH_C)$ gives good initial values for $q_C^{(F)}$. The same prescription for $T > T_M$ did not give large enough values for $q_C^{(L)}$ but the use of a tuned value of 0.25 for F(1) gave better results.

The tests involved taking model dumps containing cloud water, diagnosing values for the cloud water variables as described above and comparing the diagnosed and model-predicted fields. Exact agreement cannot be obtained (if it could there would be no need for cloud water to be prognostic!) but the initial field generated by this method enables the model to produce realistic cloud and precipitation fields within 2 to 3 hours from the start of the forecast or simulation. Normally this initialisation need not be used, a previous simulation or forecast/assimilation will give the cloud water fields.

APPENDIX D

The parametrization of critical relative humidity

Version 2B of the layer cloud scheme is the same as version 2A, with the additional functionality of calculating the value of the critical relative humidity (RH_c) uniquely in every grid-cell. The option of calculating RH_c is not available with version 1A.

(a) The calculation of RH_c

The basis of the parametrization is that there is a relationship between the subgrid variability of saturation and the variability resolved on a 3*3 grid centred on the grid-box of interest - i.e. that larger scale variability can be used to determine the variability of saturation on the smaller scale. Cusack et al. (1998) discuss this idea in detail.
Using the definition of Q_c in (P292.3), the variability of grid-box mean saturation on a 3*3 region of boxes, $\sigma^2_{3,3}$ is given by

$$\sigma^2_{3,3} = \frac{\sum_{x=1}^{3}\sum_{y=1}^{3}(Q_{c_{x,y}} - \overline{Q_c})^2}{9} \quad \text{, where} \qquad \text{(P292.D1)}$$

$$\overline{Q_c} = \frac{\sum_{x=1}^{3}\sum_{y=1}^{3} Q_{c_{x,y}}}{9} \qquad \text{(P292.D2)}$$

and x and y are the indices for the latitude and longitude direction respectively.

The standard deviation of saturation in one climate grid box is given by

$$\sigma_{clim} = A(p) * \sigma^2_{3,3} \qquad \text{(P292.D3)}$$

$$A(p) = c_0 + c_1 * \left(\frac{p - c_2}{c_3 + \mathrm{I}p - c_2\mathrm{I}} \right) \qquad \text{(P292.D4)}$$

where

and c_0=0.522, c_1=0.122, c_2=1.75*10^4 Pa, c_3=2500 Pa and p is the pressure in Pa.

Finally,

$$RH_c = 1 - \frac{\sqrt{6}\,\sigma_{clim}}{a_L q_s(T_L, p)} \qquad \text{(P292.D5)}$$

Some extra processing of the 8 neighbouring values of Q_c is performed to reject statistical outliers from the estimate of the standard deviation of Q_c over the 3*3 region.
In the boundary layer (from level 1 to BL_LEVELS) only the neighbouring grid-boxes which have a surface which 'matches' the surface of the central grid-box are used to estimate $\sigma^2_{3,3}$. The criteria for 'surface matching' is that ocean points do not match with the land and sea-ice, and that land and sea-ice do match. Once the initial value of $\sigma^2_{3,3}$ is estimated, it is used as a basis for the rejection of statistical outliers. If

$$\left| Q_{c_{x,y}} - \overline{Q_c} \right| > (\ 3 * \sigma_{3,3}(i)\ )$$

where $\sigma_{3,3}(i)$ is the initial estimate of the 3*3 standard deviation of saturation, then the point (x,y) is removed from the second, and final estimate of the large-scale variability of saturation (if the surfaces do not match, then they are excluded from this extra processing).

(b) Implementation in the UM

This parametrization has been included in version 4.5 of the UM. Note that the value of the constants in (P292.D4) are only suitable for the climate configuration of the UM: the parametrization has not yet been tested in the operational configurations.
All calls to GLUE_CLD in the UM now pass in an extra variable defined for all grid-cells. In version 2B of the cloud scheme this new variable contains the value of RH_c in every grid-cell, whereas in earlier versions it is a dummy variable. Only in version 2B of GLUE_CLD is this new variable passed to subroutine LS_CLD: all calculations within the new 2B version of LS_CLD use the RH_c values defined at every grid-cell. The constants in (P292.D4) are defined in the comdeck RHCCON2B.
The subroutine RHCRIT_CALC calculates the value of RH_c in every grid-cell, and stores the values in a part of the D1 array which is not written to the model dump (much like the liquid condensate variable at vn4.5). During a model integration RHCRIT_CALC is called once every timestep by CLD_CTL, and this is the only time in a time-step that the RH_c values are updated. However, there are two other subroutines that call RHCRIT_CALC, namely SETCONA and SETLSCLD. In the timestep order of the UM, GLUE_CLD is called before the actual call by the cloud scheme in the physics sections: therefore, in the first timestep of a run RH_c values need initialised before the cloud scheme is called. This is done by calling RHCRIT_CALC in SETCONA. To ensure bit comparison, one must call RHCRIT_CALC whenever a model dump is written: this is done in SETLSCLD. Note that different model dump periods will not give bit-reproducible answers for RH_c: this has been a feature of the cloud scheme for several years, so it is not a problem at vn4.5. A logical protects every call to RHCRIT_CALC: if false, then this subroutine is not called.

APPENDIX E

The cloud area parametrization

The cloud area parametrization is an option only available with versions 2A and 2B of the cloud scheme: in addition, radiation schemes earlier than 3A at vn4.5 have not been made compatible with this scheme. The cloud scheme calculates the cloud volume in a grid-cell, which is the important quantity for precipitation microphysics (so that in-cloud condensate can be determined). However, for the purpose of the radiation calculations it is cloud area, and not cloud volume, which is important. It has been assumed for radiation calculations in all previous UM versions that the cloud area equals the cloud volume, or equivalently, that any cloud which exists in a grid-cell occupies its full depth. This can give optically thick clouds when the cloud volume is small, and the vertical resolution is poor. The cloud area parametrization creates a pseudo-increase in vertical resolution, and so allows optically thinner clouds when the cloud volume is small. Only the radiation calculations use this cloud area quantity.

(a) The calculation of cloud area

Versions 2A and 2B of the cloud scheme require inputs such as temperature, water vapour+liquid condensate, and ice-phase condensate to be specified for each layer on input. The cloud area parametrization splits each layer into three sub-layers, and specifies the required input quantities as means for each of these three sub-layers using an interpolation algorithm described below.
To calculate the sub-layer values of a quantity X, the layer mean values are used to linearly interpolate (in pressure) the value of X to half-levels. The profile of X within one layer is assumed to consist of 2 straight lines: one from the upper half-level to the mid-layer positi on, and another from the mid-level to the lower half-level. What remains is to determine the mid-layer value of X. The constraint on the profile shape together with the added constraint that X must be conserved (i.e. the vertical integral of X in the layer is the same) defines a mid-layer value of X: therefore, the vertical profile of X is fully specified.
The layer is split into three sub-layers of equal thickness in pressure, and the mean values of the input quantities to the cloud scheme are specified for each sub-layer from the vertical profile of the quantity. Then, the cloud scheme operates on each sub-layer, in an identical fashion to what it does for layer mean quantities when the cloud area parametrization is excluded.
Exceptions are made to the above general algorithm, if the change in saturation between 2 adjacent layers, *i* and *i-1*, exceed a critical value, namely

$$\left| \left[\frac{(q_T - q_{SAT}}{q_{SAT}} \right]_i - \left[\frac{q_T - q_{SAT}}{q_{SAT}} \right]_{i-1} \right| > 0.3 \qquad \text{(P292.E1)}$$

In this case we use a 'one'sided' interpolation method: the value of X at level *i-1/2* is different for each of the 2 layers. For layer *i* the value of X at the half level *i-1/2* is extrapolated from using the gradient of X between layers *i* and *i+1*. For layer *i-1*, the value of X at level *i-1/2* is extrapolated from the gradient of X between layers *i-1* and *i-2*.
If in one layer both the gradient above and below satisfy (P292.E1) then the profile of quantity X is assumed to be uniform with height.

It should also be noted that if the mean value of ice-phase condensate in a layer is zero, the only means of one sub-layer having greater than zero ice condensate is if another sub-layer has a negative amount (because conservation of quantities is required) which is obviously unrealistic: therefore it is asserted that if the ice condensate in a layer is zero, all sub-layers also have a zero amount.

The cloud volume, required for the parametrization of precipitation processes, is defined as the mean of the three sub-layer values: similarly, the grid-box mean value of liquid-phase condensate output by the cloud scheme is defined to be the mean of the values in the three sub-layers. Cloud area in a layer, required by the radiation section, is defined to be the maximum value of the three sub-layers' cloud volume.

(b) Implementation in the UM

The cloud area variable is only required by the radiation code. It is most naturally calculated by the cloud scheme, which fortunately is called just before the call to the radiation scheme. A new 3-D variable storing the cloud area in every grid-cell is created in ATM_PHYS, and passed to CLD_CTL where it is an intent OUT variable. The call is then made to RAD_CTL and this new variable is passed to radiation: notice that RAD_CTL also requires the cloud volume, for some microphysics calculations done in version 3A of the radiation.

In CLD_CTL, a logical (L_CLD_AREA) protects the use of the cloud area parametrization: if true then cloud area is calculated according to the method described in part A; if false then the cloud scheme performs the calculations it did before this code was introduced, and it sets the cloud area variable to equal cloud volume (this is because parts of the radiation code at vn4.5 use cloud area regardless of the value of L_CLD_AREA). If L_CLD_AREA is set to true then the call to GLUE_CLD in CLD_CTL is replaced by a call to AREA_CLD.

REFERENCES

Landolt-Bornstein, 1987: Numerical data and functional relationships in science and technology. Group V/ Vol 4B Meteorology. Physical and chemical properties of air, p35.

Mellor,G.L., 1977: The Gaussian cloud model relations. J. Atmos. Sci., **34**, 356-358,1483-1484.

Sommeria,G. and Deardorff, J.W., 1977: Subgrid-scale condensation in models of non-precipitating clouds. J. Atmos. Sci., **34**, 344-355.

Cusack, S., J. M. Edwards and R. Kershaw, 1998: A parametrization of the subgrid-scale variability of saturation for use in GCM cloud schemes. To be submitted to Q. J. Royal Met. Soc.

LIST OF FIGURES AND TABLES

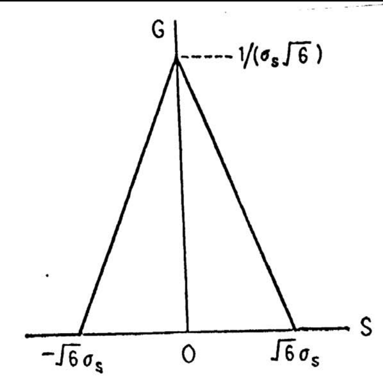

Figure 1. The symmetric triangular probability distribution function with standard deviation σ_s used in the cloud model.

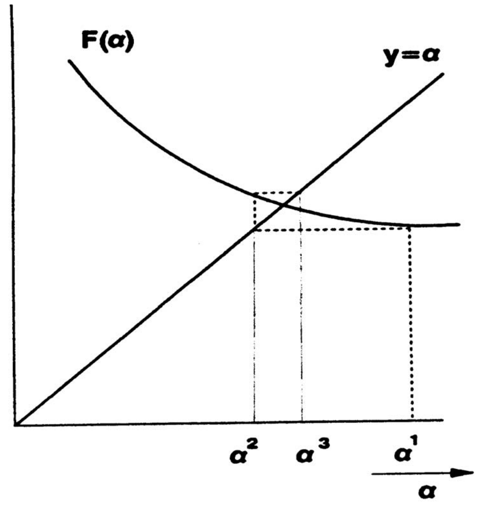

Fig. 2a Unweighted scheme

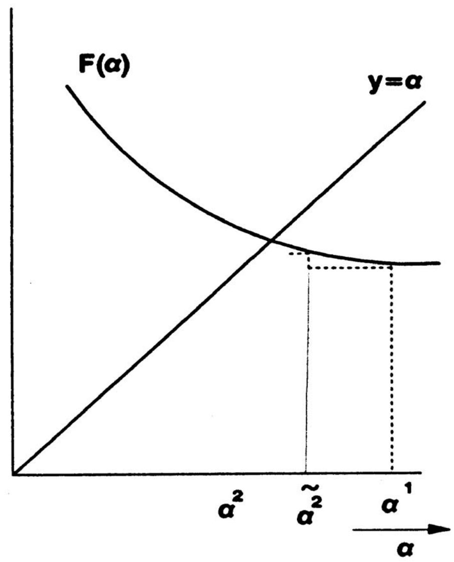

Fig 2b Weighted scheme

Fig. 2 Schematic iteration procedures

TABLE 1. SATURATION WATER VAPOUR PRESSURE:

ABOVE 0 DEG C VALUES ARE OVER WATER,

BELOW 0 DEC C VALUES ARE OVER ICE.

T(degC)	+0.0	0.1	0.2	0.3	0.4
-90.0	0.966483E-02	0.984279E-02	0.100240E-01	0.102082E-01	0.103957E-01
-89.5	0.105865E-01	0.107803E-01	0.109777E-01	0.111784E-01	0.113825E-01
-89.0	0.115902E-01	0.118016E-01	0.120164E-01	0.122348E-01	0.124572E-01
-88.5	0.126831E-01	0.129132E-01	0.131470E-01	0.133846E-01	0.136264E-01
-88.0	0.138724E-01	0.141225E-01	0.143771E-01	0.146356E-01	0.148985E-01
-87.5	0.151661E-01	0.154379E-01	0.157145E-01	0.159958E-01	0.162817E-01
-87.0	0.165725E-01	0.168680E-01	0.171684E-01	0.174742E-01	0.177847E-01
-86.5	0.181008E-01	0.184216E-01	0.187481E-01	0.190801E-01	0.194175E-01
-86.0	0.197608E-01	0.201094E-01	0.204637E-01	0.208242E-01	0.211906E-01
-85.5	0.215631E-01	0.219416E-01	0.223263E-01	0.227172E-01	0.231146E-01
-85.0	0.235188E-01	0.239296E-01	0.243465E-01	0.247708E-01	0.252019E-01
-84.5	0.256405E-01	0.260857E-01	0.265385E-01	0.269979E-01	0.274656E-01
-84.0	0.279405E-01	0.284232E-01	0.289142E-01	0.294124E-01	0.299192E-01
-83.5	0.304341E-01	0.309571E-01	0.314886E-01	0.320285E-01	0.325769E-01
-83.0	0.331348E-01	0.337014E-01	0.342771E-01	0.348618E-01	0.354557E-01
-82.5	0.360598E-01	0.366727E-01	0.372958E-01	0.379289E-01	0.385717E-01
-82.0	0.392248E-01	0.398889E-01	0.405633E-01	0.412474E-01	0.419430E-01
-81.5	0.426505E-01	0.433678E-01	0.440974E-01	0.448374E-01	0.455896E-01
-81.0	0.463545E-01	0.471303E-01	0.479191E-01	0.487190E-01	0.495322E-01
-80.5	0.503591E-01	0.511977E-01	0.520490E-01	0.529145E-01	0.537931E-01
-80.0	0.546854E-01	0.555924E-01	0.565119E-01	0.574467E-01	0.583959E-01
-79.5	0.593592E-01	0.603387E-01	0.613316E-01	0.623409E-01	0.633655E-01
-79.0	0.644053E-01	0.654624E-01	0.665358E-01	0.676233E-01	0.687302E-01
-78.5	0.698524E-01	0.709929E-01	0.721490E-01	0.733238E-01	0.745180E-01
-78.0	0.757281E-01	0.769578E-01	0.782061E-01	0.794728E-01	0.807583E-01
-77.5	0.820647E-01	0.833905E-01	0.847358E-01	0.861028E-01	0.874882E-01
-77.0	0.888957E-01	0.903243E-01	0.917736E-01	0.932464E-01	0.947407E-01
-76.5	0.962571E-01	0.977955E-01	0.993584E-01	0.100942E+00	0.102551E+00
-76.0	0.104186E+00	0.105842E+00	0.107524E+00	0.109231E+00	0.110963E+00
-75.5	0.112722E+00	0.114506E+00	0.116317E+00	0.118153E+00	0.120019E+00
-75.0	0.121911E+00	0.123831E+00	0.125778E+00	0.127755E+00	0.129761E+00
-74.5	0.131796E+00	0.133863E+00	0.135956E+00	0.138082E+00	0.140241E+00
-74.0	0.142428E+00	0.144649E+00	0.146902E+00	0.149190E+00	0.151506E+00
-73.5	0.153859E+00	0.156245E+00	0.158669E+00	0.161126E+00	0.163618E+00
-73.0	0.166145E+00	0.168711E+00	0.171313E+00	0.173951E+00	0.176626E+00
-72.5	0.179342E+00	0.182096E+00	0.184893E+00	0.187724E+00	0.190600E+00
-72.0	0.193518E+00	0.196473E+00	0.199474E+00	0.202516E+00	0.205604E+00
-71.5	0.208730E+00	0.211905E+00	0.215127E+00	0.218389E+00	0.221701E+00
-71.0	0.225063E+00	0.228466E+00	0.231920E+00	0.235421E+00	0.238976E+00
-70.5	0.242580E+00	0.246232E+00	0.249933E+00	0.253691E+00	0.257499E+00
-70.0	0.261359E+00	0.265278E+00	0.269249E+00	0.273274E+00	0.277358E+00
-69.5	0.281498E+00	0.285694E+00	0.289952E+00	0.294268E+00	0.298641E+00
-69.0	0.303078E+00	0.307577E+00	0.312135E+00	0.316753E+00	0.321440E+00
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-62.5	0.767052E+00	0.777741E+00	0.788576E+00	0.799549E+00	0.810656E+00
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-61.5	0.880404E+00	0.892575E+00	0.904877E+00	0.917350E+00	0.929974E+00
-61.0	0.942771E+00	0.955724E+00	0.968837E+00	0.982127E+00	0.995600E+00
-60.5	0.100921E+01	0.102304E+01	0.103700E+01	0.105116E+01	0.106549E+01

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-60.0 0.108002E+01,0.109471E+01,0.110962E+01,0.112469E+01,0.113995E+01,
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-49.5 0.418343E+01,0.423514E+01,0.428746E+01,0.434034E+01,0.439389E+01,
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-43.0 0.909567E+01,0.920172E+01,0.930909E+01,0.941765E+01,0.952730E+01,
-42.5 0.963821E+01,0.975022E+01,0.986352E+01,0.997793E+01,0.100937E+02,
-42.0 0.102105E+02,0.103287E+02,0.104481E+02,0.105688E+02,0.106909E+02,
-41.5 0.108143E+02,0.109387E+02,0.110647E+02,0.111921E+02,0.113207E+02,
-41.0 0.114508E+02,0.115821E+02,0.117149E+02,0.118490E+02,0.119847E+02,
-40.5 0.121216E+02,0.122601E+02,0.124002E+02,0.125416E+02,0.126846E+02,

-40.0 0.128290E+02,0.129747E+02,0.131224E+02,0.132712E+02,0.134220E+02,
-39.5 0.135742E+02,0.137278E+02,0.138831E+02,0.140403E+02,0.141989E+02,
-39.0 0.143589E+02,0.145211E+02,0.146845E+02,0.148501E+02,0.150172E+02,
-38.5 0.151858E+02,0.153564E+02,0.155288E+02,0.157029E+02,0.158786E+02,
-38.0 0.160562E+02,0.162358E+02,0.164174E+02,0.166004E+02,0.167858E+02,
-37.5 0.169728E+02,0.171620E+02,0.173528E+02,0.175455E+02,0.177406E+02,
-37.0 0.179372E+02,0.181363E+02,0.183372E+02,0.185400E+02,0.187453E+02,
-36.5 0.189523E+02,0.191613E+02,0.193728E+02,0.195866E+02,0.198024E+02,
-36.0 0.200200E+02,0.202401E+02,0.204626E+02,0.206871E+02,0.209140E+02,
-35.5 0.211430E+02,0.213744E+02,0.216085E+02,0.218446E+02,0.220828E+02,
-35.0 0.223241E+02,0.225671E+02,0.228132E+02,0.230615E+02,0.233120E+02,
-34.5 0.235651E+02,0.238211E+02,0.240794E+02,0.243404E+02,0.246042E+02,
-34.0 0.248704E+02,0.251390E+02,0.254109E+02,0.256847E+02,0.259620E+02,
-33.5 0.262418E+02,0.265240E+02,0.268092E+02,0.270975E+02,0.273883E+02,
-33.0 0.276822E+02,0.279792E+02,0.282789E+02,0.285812E+02,0.288867E+02,
-32.5 0.291954E+02,0.295075E+02,0.298222E+02,0.301398E+02,0.304606E+02,
-32.0 0.307848E+02,0.311119E+02,0.314424E+02,0.317763E+02,0.321133E+02,
-31.5 0.324536E+02,0.327971E+02,0.331440E+02,0.334940E+02,0.338475E+02,
-31.0 0.342050E+02,0.345654E+02,0.349295E+02,0.352975E+02,0.356687E+02,
-30.5 0.360430E+02,0.364221E+02,0.368042E+02,0.371896E+02,0.375790E+02,

-30.0 0.379725E+02,0.383692E+02,0.387702E+02,0.391744E+02,0.395839E+02,
-29.5 0.399958E+02,0.404118E+02,0.408325E+02,0.412574E+02,0.416858E+02,
-29.0 0.421188E+02,0.425551E+02,0.429962E+02,0.434407E+02,0.438910E+02,
-28.5 0.443439E+02,0.448024E+02,0.452648E+02,0.457308E+02,0.462018E+02,
-28.0 0.466775E+02,0.471582E+02,0.476428E+02,0.481313E+02,0.486249E+02,
-27.5 0.491235E+02,0.496272E+02,0.501349E+02,0.506479E+02,0.511652E+02,
-27.0 0.516876E+02,0.522142E+02,0.527474E+02,0.532836E+02,0.538266E+02,
-26.5 0.543737E+02,0.549254E+02,0.554839E+02,0.560456E+02,0.566142E+02,
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-25.0 0.632204E+02,0.638550E+02,0.644959E+02,0.651418E+02,0.657942E+02,
-24.5 0.664516E+02,0.671158E+02,0.677864E+02,0.684624E+02,0.691451E+02,
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-23.0 0.770791E+02,0.778394E+02,0.786088E+02,0.793824E+02,0.801653E+02,
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-17.0 0.137109E+03,0.138402E+03,0.139700E+03,0.141017E+03,0.142338E+03,
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  7.0 0.100120E+04,0.100810E+04,0.101502E+04,0.102201E+04,0.102902E+04,
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 9.5 0.118658E+04,0.119459E+04,0.120264E+04,0.121074E+04,0.121888E+04,

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39.0 0.699292E+04,0.703061E+04,0.706837E+04,0.710639E+04,0.714451E+04,
39.5 0.718289E+04,0.722143E+04,0.726009E+04,0.729903E+04,0.733802E+04,

40.0 0.737729E+04,0.741676E+04,0.745631E+04,0.749612E+04,0.753602E+04,
40.5 0.757622E+04,0.761659E+04,0.765705E+04,0.769780E+04,0.773863E+04,
41.0 0.777975E+04,0.782106E+04,0.786246E+04,0.790412E+04,0.794593E+04,
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41.5 0.798802E+04,0.803028E+04,0.807259E+04,0.811525E+04,0.815798E+04,
42.0 0.820102E+04,0.824427E+04,0.828757E+04,0.833120E+04,0.837493E+04,
42.5 0.841895E+04,0.846313E+04,0.850744E+04,0.855208E+04,0.859678E+04,
43.0 0.864179E+04,0.868705E+04,0.873237E+04,0.877800E+04,0.882374E+04,
43.5 0.886979E+04,0.891603E+04,0.896237E+04,0.900904E+04,0.905579E+04,
44.0 0.910288E+04,0.915018E+04,0.919758E+04,0.924529E+04,0.929310E+04,
44.5 0.934122E+04,0.938959E+04,0.943804E+04,0.948687E+04,0.953575E+04,
45.0 0.958494E+04,0.963442E+04,0.968395E+04,0.973384E+04,0.978383E+04,
45.5 0.983412E+04,0.988468E+04,0.993534E+04,0.998630E+04,0.100374E+05,
46.0 0.100888E+05,0.101406E+05,0.101923E+05,0.102444E+05,0.102966E+05,
46.5 0.103492E+05,0.104020E+05,0.104550E+05,0.105082E+05,0.105616E+05,
47.0 0.106153E+05,0.106693E+05,0.107234E+05,0.107779E+05,0.108325E+05,
47.5 0.108874E+05,0.109425E+05,0.109978E+05,0.110535E+05,0.111092E+05,
48.0 0.111653E+05,0.112217E+05,0.112782E+05,0.113350E+05,0.113920E+05,
48.5 0.114493E+05,0.115070E+05,0.115646E+05,0.116228E+05,0.116809E+05,
49.0 0.117396E+05,0.117984E+05,0.118574E+05,0.119167E+05,0.119762E+05,
49.5 0.120360E+05,0.120962E+05,0.121564E+05,0.122170E+05,0.122778E+05,

50.0 0.123389E+05,0.124004E+05,0.124619E+05,0.125238E+05,0.125859E+05,
50.5 0.126484E+05,0.127111E+05,0.127739E+05,0.128372E+05,0.129006E+05,
51.0 0.129644E+05,0.130285E+05,0.130927E+05,0.131573E+05,0.132220E+05,
51.5 0.132872E+05,0.133526E+05,0.134182E+05,0.134842E+05,0.135503E+05,
52.0 0.136168E+05,0.136836E+05,0.137505E+05,0.138180E+05,0.138854E+05,
52.5 0.139534E+05,0.140216E+05,0.140900E+05,0.141588E+05,0.142277E+05,
53.0 0.142971E+05,0.143668E+05,0.144366E+05,0.145069E+05,0.145773E+05,
53.5 0.146481E+05,0.147192E+05,0.147905E+05,0.148622E+05,0.149341E+05,
54.0 0.150064E+05,0.150790E+05,0.151517E+05,0.152250E+05,0.152983E+05,
54.5 0.153721E+05,0.154462E+05,0.155205E+05,0.155952E+05,0.156701E+05,
55.0 0.157454E+05,0.158211E+05,0.158969E+05,0.159732E+05,0.160496E+05,
55.5 0.161265E+05,0.162037E+05,0.162811E+05,0.163589E+05,0.164369E+05,
56.0 0.165154E+05,0.165942E+05,0.166732E+05,0.167526E+05,0.168322E+05,
56.5 0.169123E+05,0.169927E+05,0.170733E+05,0.171543E+05,0.172356E+05,
57.0 0.173173E+05,0.173993E+05,0.174815E+05,0.175643E+05,0.176471E+05,
57.5 0.177305E+05,0.178143E+05,0.178981E+05,0.179826E+05,0.180671E+05,
58.0 0.181522E+05,0.182377E+05,0.183232E+05,0.184093E+05,0.184955E+05,
58.5 0.185823E+05,0.186695E+05,0.187568E+05,0.188447E+05,0.189326E+05,
59.0 0.190212E+05,0.191101E+05,0.191991E+05,0.192887E+05,0.193785E+05,
59.5 0.194688E+05,0.195595E+05,0.196503E+05,0.197417E+05,0.198332E+05,

60.0 0.199253E+05,0.200178E+05,0.201105E+05,0.202036E+05,0.202971E+05,
60.5 0.203910E+05,0.204853E+05,0.205798E+05,0.206749E+05,0.207701E+05,
61.0 0.208659E+05,0.209621E+05,0.210584E+05,0.211554E+05,0.212524E+05,
61.5 0.213501E+05,0.214482E+05,0.215465E+05,0.216452E+05,0.217442E+05,
62.0 0.218439E+05,0.219439E+05,0.220440E+05,0.221449E+05,0.222457E+05,
62.5 0.223473E+05,0.224494E+05,0.225514E+05,0.226542E+05,0.227571E+05,
63.0 0.228606E+05,0.229646E+05,0.230687E+05,0.231734E+05,0.232783E+05,
63.5 0.233839E+05,0.234898E+05,0.235960E+05,0.237027E+05,0.238097E+05,
64.0 0.239173E+05,0.240254E+05,0.241335E+05,0.242424E+05,0.243514E+05,
64.5 0.244611E+05,0.245712E+05,0.246814E+05,0.247923E+05,0.249034E+05,
65.0 0.250152E+05
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TABLE 2. SATURATION WATER VAPOUR PRESSURE:

VALUES ABOVE AND BELOW ZERO DEGREES CELSIUS ARE OVER WATER,

(VALUES BELOW -50 DEG C ARE OUTSIDE FORMAL RANGE OF WMO ADOPTED FORMULA. HOWEVER IT IS STANDARD PRACTISE TO USE THESE VALUES.)

T(degC)	+0.0	0.1	0.2	0.3	0.4
-90.0	0.186905E-01	0.190449E-01	0.194059E-01	0.197727E-01	0.201462E-01
-89.5	0.205261E-01	0.209122E-01	0.213052E-01	0.217050E-01	0.221116E-01
-89.0	0.225252E-01	0.229463E-01	0.233740E-01	0.238090E-01	0.242518E-01
-88.5	0.247017E-01	0.251595E-01	0.256252E-01	0.260981E-01	0.265795E-01
-88.0	0.270691E-01	0.275667E-01	0.280733E-01	0.285876E-01	0.291105E-01
-87.5	0.296429E-01	0.301835E-01	0.307336E-01	0.312927E-01	0.318611E-01
-87.0	0.324390E-01	0.330262E-01	0.336232E-01	0.342306E-01	0.348472E-01
-86.5	0.354748E-01	0.361117E-01	0.367599E-01	0.374185E-01	0.380879E-01
-86.0	0.387689E-01	0.394602E-01	0.401626E-01	0.408771E-01	0.416033E-01
-85.5	0.423411E-01	0.430908E-01	0.438524E-01	0.446263E-01	0.454124E-01
-85.0	0.462122E-01	0.470247E-01	0.478491E-01	0.486874E-01	0.495393E-01
-84.5	0.504057E-01	0.512847E-01	0.521784E-01	0.530853E-01	0.540076E-01
-84.0	0.549444E-01	0.558959E-01	0.568633E-01	0.578448E-01	0.588428E-01
-83.5	0.598566E-01	0.608858E-01	0.619313E-01	0.629926E-01	0.640706E-01
-83.0	0.651665E-01	0.662795E-01	0.674095E-01	0.685570E-01	0.697219E-01
-82.5	0.709063E-01	0.721076E-01	0.733284E-01	0.745679E-01	0.758265E-01
-82.0	0.771039E-01	0.784026E-01	0.797212E-01	0.810577E-01	0.824164E-01
-81.5	0.837971E-01	0.851970E-01	0.866198E-01	0.880620E-01	0.895281E-01
-81.0	0.910178E-01	0.925278E-01	0.940622E-01	0.956177E-01	0.971984E-01
-80.5	0.988051E-01	0.100433E+00	0.102085E+00	0.103764E+00	0.105467E+00
-80.0	0.107196E+00	0.108953E+00	0.110732E+00	0.112541E+00	0.114376E+00
-79.5	0.116238E+00	0.118130E+00	0.120046E+00	0.121993E+00	0.123969E+00
-79.0	0.125973E+00	0.128009E+00	0.130075E+00	0.132167E+00	0.134296E+00
-78.5	0.136452E+00	0.138642E+00	0.140861E+00	0.143115E+00	0.145404E+00
-78.0	0.147723E+00	0.150078E+00	0.152466E+00	0.154889E+00	0.157346E+00
-77.5	0.159841E+00	0.162372E+00	0.164939E+00	0.167545E+00	0.170185E+00
-77.0	0.172866E+00	0.175584E+00	0.178340E+00	0.181139E+00	0.183977E+00
-76.5	0.186855E+00	0.189773E+00	0.192737E+00	0.195736E+00	0.198783E+00
-76.0	0.201875E+00	0.205007E+00	0.208186E+00	0.211409E+00	0.214676E+00
-75.5	0.217993E+00	0.221355E+00	0.224764E+00	0.228220E+00	0.231728E+00
-75.0	0.235284E+00	0.238888E+00	0.242542E+00	0.246251E+00	0.250010E+00
-74.5	0.253821E+00	0.257688E+00	0.261602E+00	0.265575E+00	0.269607E+00
-74.0	0.273689E+00	0.277830E+00	0.282027E+00	0.286287E+00	0.290598E+00
-73.5	0.294972E+00	0.299405E+00	0.303904E+00	0.308462E+00	0.313082E+00
-73.0	0.317763E+00	0.322512E+00	0.327324E+00	0.332201E+00	0.337141E+00
-72.5	0.342154E+00	0.347234E+00	0.352387E+00	0.357601E+00	0.362889E+00
-72.0	0.368257E+00	0.373685E+00	0.379194E+00	0.384773E+00	0.390433E+00
-71.5	0.396159E+00	0.401968E+00	0.407861E+00	0.413820E+00	0.419866E+00
-71.0	0.425999E+00	0.432203E+00	0.438494E+00	0.444867E+00	0.451332E+00
-70.5	0.457879E+00	0.464510E+00	0.471226E+00	0.478037E+00	0.484935E+00
-70.0	0.491920E+00	0.499005E+00	0.506181E+00	0.513447E+00	0.520816E+00
-69.5	0.528279E+00	0.535835E+00	0.543497E+00	0.551256E+00	0.559113E+00
-69.0	0.567081E+00	0.575147E+00	0.583315E+00	0.591585E+00	0.599970E+00
-68.5	0.608472E+00	0.617069E+00	0.625785E+00	0.634609E+00	0.643556E+00
-68.0	0.652611E+00	0.661782E+00	0.671077E+00	0.680487E+00	0.690015E+00
-67.5	0.699656E+00	0.709433E+00	0.719344E+00	0.729363E+00	0.739518E+00
-67.0	0.749795E+00	0.760217E+00	0.770763E+00	0.781454E+00	0.792258E+00
-66.5	0.803208E+00	0.814309E+00	0.825528E+00	0.836914E+00	0.848422E+00
-66.0	0.860086E+00	0.871891E+00	0.883837E+00	0.895944E+00	0.908214E+00
-65.5	0.920611E+00	0.933175E+00	0.945890E+00	0.958776E+00	0.971812E+00
-65.0	0.985027E+00	0.998379E+00	0.101193E+01	0.102561E+01	0.103949E+01
-64.5	0.105352E+01	0.106774E+01	0.108213E+01	0.109669E+01	0.111144E+01
-64.0	0.112636E+01	0.114148E+01	0.115676E+01	0.117226E+01	0.118791E+01
-63.5	0.120377E+01	0.121984E+01	0.123608E+01	0.125252E+01	0.126919E+01
-63.0	0.128604E+01	0.130309E+01	0.132036E+01	0.133782E+01	0.135549E+01
-62.5	0.137339E+01	0.139150E+01	0.140984E+01	0.142839E+01	0.144715E+01
-62.0	0.146616E+01	0.148538E+01	0.150482E+01	0.152450E+01	0.154445E+01

-61.5 0.156459E+01,0.158502E+01,0.160564E+01,0.162654E+01,0.164766E+01,
-61.0 0.166906E+01,0.169070E+01,0.171257E+01,0.173473E+01,0.175718E+01,
-60.5 0.177984E+01,0.180282E+01,0.182602E+01,0.184951E+01,0.187327E+01,

-60.0 0.189733E+01,0.192165E+01,0.194629E+01,0.197118E+01,0.199636E+01,
-59.5 0.202185E+01,0.204762E+01,0.207372E+01,0.210010E+01,0.212678E+01,
-59.0 0.215379E+01,0.218109E+01,0.220873E+01,0.223668E+01,0.226497E+01,
-58.5 0.229357E+01,0.232249E+01,0.235176E+01,0.238134E+01,0.241129E+01,
-58.0 0.244157E+01,0.247217E+01,0.250316E+01,0.253447E+01,0.256617E+01,
-57.5 0.259821E+01,0.263064E+01,0.266341E+01,0.269661E+01,0.273009E+01,
-57.0 0.276403E+01,0.279834E+01,0.283302E+01,0.286811E+01,0.290358E+01,
-56.5 0.293943E+01,0.297571E+01,0.301236E+01,0.304946E+01,0.308702E+01,
-56.0 0.312491E+01,0.316326E+01,0.320208E+01,0.324130E+01,0.328092E+01,
-55.5 0.332102E+01,0.336162E+01,0.340264E+01,0.344407E+01,0.348601E+01,
-55.0 0.352838E+01,0.357118E+01,0.361449E+01,0.365834E+01,0.370264E+01,
-54.5 0.374737E+01,0.379265E+01,0.383839E+01,0.388469E+01,0.393144E+01,
-54.0 0.397876E+01,0.402656E+01,0.407492E+01,0.412378E+01,0.417313E+01,
-53.5 0.422306E+01,0.427359E+01,0.432454E+01,0.437617E+01,0.442834E+01,
-53.0 0.448102E+01,0.453433E+01,0.458816E+01,0.464253E+01,0.469764E+01,
-52.5 0.475321E+01,0.480942E+01,0.486629E+01,0.492372E+01,0.498173E+01,
-52.0 0.504041E+01,0.509967E+01,0.515962E+01,0.522029E+01,0.528142E+01,
-51.5 0.534337E+01,0.540595E+01,0.546912E+01,0.553292E+01,0.559757E+01,
-51.0 0.566273E+01,0.572864E+01,0.579532E+01,0.586266E+01,0.593075E+01,
-50.5 0.599952E+01,0.606895E+01,0.613918E+01,0.621021E+01,0.628191E+01,

-50.0 0.635433E+01,0.642755E+01,0.650162E+01,0.657639E+01,0.665188E+01,
-49.5 0.672823E+01,0.680532E+01,0.688329E+01,0.696198E+01,0.704157E+01,
-49.0 0.712206E+01,0.720319E+01,0.728534E+01,0.736829E+01,0.745204E+01,
-48.5 0.753671E+01,0.762218E+01,0.770860E+01,0.779588E+01,0.788408E+01,
-48.0 0.797314E+01,0.806318E+01,0.815408E+01,0.824599E+01,0.833874E+01,
-47.5 0.843254E+01,0.852721E+01,0.862293E+01,0.871954E+01,0.881724E+01,
-47.0 0.891579E+01,0.901547E+01,0.911624E+01,0.921778E+01,0.932061E+01,
-46.5 0.942438E+01,0.952910E+01,0.963497E+01,0.974181E+01,0.984982E+01,
-46.0 0.995887E+01,0.100690E+02,0.101804E+02,0.102926E+02,0.104063E+02,
-45.5 0.105210E+02,0.106367E+02,0.107536E+02,0.108719E+02,0.109912E+02,
-45.0 0.111116E+02,0.112333E+02,0.113563E+02,0.114804E+02,0.116056E+02,
-44.5 0.117325E+02,0.118602E+02,0.119892E+02,0.121197E+02,0.122513E+02,
-44.0 0.123844E+02,0.125186E+02,0.126543E+02,0.127912E+02,0.129295E+02,
-43.5 0.130691E+02,0.132101E+02,0.133527E+02,0.134965E+02,0.136415E+02,
-43.0 0.137882E+02,0.139361E+02,0.140855E+02,0.142366E+02,0.143889E+02,
-42.5 0.145429E+02,0.146982E+02,0.148552E+02,0.150135E+02,0.151735E+02,
-42.0 0.153349E+02,0.154979E+02,0.156624E+02,0.158286E+02,0.159965E+02,
-41.5 0.161659E+02,0.163367E+02,0.165094E+02,0.166838E+02,0.168597E+02,
-41.0 0.170375E+02,0.172168E+02,0.173979E+02,0.175806E+02,0.177651E+02,
-40.5 0.179513E+02,0.181394E+02,0.183293E+02,0.185210E+02,0.187146E+02,

-40.0 0.189098E+02,0.191066E+02,0.193059E+02,0.195065E+02,0.197095E+02,
-39.5 0.199142E+02,0.201206E+02,0.203291E+02,0.205397E+02,0.207522E+02,
-39.0 0.209664E+02,0.211831E+02,0.214013E+02,0.216221E+02,0.218448E+02,
-38.5 0.220692E+02,0.222959E+02,0.225250E+02,0.227559E+02,0.229887E+02,
-38.0 0.232239E+02,0.234614E+02,0.237014E+02,0.239428E+02,0.241872E+02,
-37.5 0.244335E+02,0.246824E+02,0.249332E+02,0.251860E+02,0.254419E+02,
-37.0 0.256993E+02,0.259600E+02,0.262225E+02,0.264873E+02,0.267552E+02,
-36.5 0.270248E+02,0.272970E+02,0.275719E+02,0.278497E+02,0.281295E+02,
-36.0 0.284117E+02,0.286965E+02,0.289843E+02,0.292743E+02,0.295671E+02,
-35.5 0.298624E+02,0.301605E+02,0.304616E+02,0.307650E+02,0.310708E+02,
-35.0 0.313803E+02,0.316915E+02,0.320064E+02,0.323238E+02,0.326437E+02,
-34.5 0.329666E+02,0.332928E+02,0.336215E+02,0.339534E+02,0.342885E+02,
-34.0 0.346263E+02,0.349666E+02,0.353109E+02,0.356572E+02,0.360076E+02,
-33.5 0.363606E+02,0.367164E+02,0.370757E+02,0.374383E+02,0.378038E+02,
-33.0 0.381727E+02,0.385453E+02,0.389206E+02,0.392989E+02,0.396807E+02,
-32.5 0.400663E+02,0.404555E+02,0.408478E+02,0.412428E+02,0.416417E+02,
-32.0 0.420445E+02,0.424502E+02,0.428600E+02,0.432733E+02,0.436900E+02,
-31.5 0.441106E+02,0.445343E+02,0.449620E+02,0.453930E+02,0.458280E+02,
-31.0 0.462672E+02,0.467096E+02,0.471561E+02,0.476070E+02,0.480610E+02,
-30.5 0.485186E+02,0.489813E+02,0.494474E+02,0.499170E+02,0.503909E+02,
-30.0 0.508693E+02,0.513511E+02,0.518376E+02,0.523277E+02,0.528232E+02,
-29.5 0.533213E+02,0.538240E+02,0.543315E+02,0.548437E+02,0.553596E+02,
-29.0 0.558802E+02,0.564046E+02,0.569340E+02,0.574672E+02,0.580061E+02,
-28.5 0.585481E+02,0.590963E+02,0.596482E+02,0.602041E+02,0.607649E+02,
-28.0 0.613311E+02,0.619025E+02,0.624779E+02,0.630574E+02,0.636422E+02,

-27.5	0.642324E+02	0.648280E+02	0.654278E+02	0.660332E+02	0.666426E+02
-27.0	0.672577E+02	0.678771E+02	0.685034E+02	0.691328E+02	0.697694E+02
-26.5	0.704103E+02	0.710556E+02	0.717081E+02	0.723639E+02	0.730269E+02
-26.0	0.736945E+02	0.743681E+02	0.750463E+02	0.757309E+02	0.764214E+02
-25.5	0.771167E+02	0.778182E+02	0.785246E+02	0.792373E+02	0.799564E+02
-25.0	0.806804E+02	0.814109E+02	0.821479E+02	0.828898E+02	0.836384E+02
-24.5	0.843922E+02	0.851525E+02	0.859198E+02	0.866920E+02	0.874712E+02
-24.0	0.882574E+02	0.890486E+02	0.898470E+02	0.906525E+02	0.914634E+02
-23.5	0.922814E+02	0.931048E+02	0.939356E+02	0.947736E+02	0.956171E+02
-23.0	0.964681E+02	0.973246E+02	0.981907E+02	0.990605E+02	0.999399E+02
-22.5	0.100825E+03	0.101718E+03	0.102617E+03	0.103523E+03	0.104438E+03
-22.0	0.105358E+03	0.106287E+03	0.107221E+03	0.108166E+03	0.109115E+03
-21.5	0.110074E+03	0.111039E+03	0.112012E+03	0.112992E+03	0.113981E+03
-21.0	0.114978E+03	0.115981E+03	0.116993E+03	0.118013E+03	0.119041E+03
-20.5	0.120077E+03	0.121122E+03	0.122173E+03	0.123234E+03	0.124301E+03
-20.0	0.125377E+03	0.126463E+03	0.127556E+03	0.128657E+03	0.129769E+03
-19.5	0.130889E+03	0.132017E+03	0.133152E+03	0.134299E+03	0.135453E+03
-19.0	0.136614E+03	0.137786E+03	0.138967E+03	0.140158E+03	0.141356E+03
-18.5	0.142565E+03	0.143781E+03	0.145010E+03	0.146247E+03	0.147491E+03
-18.0	0.148746E+03	0.150011E+03	0.151284E+03	0.152571E+03	0.153862E+03
-17.5	0.155168E+03	0.156481E+03	0.157805E+03	0.159137E+03	0.160478E+03
-17.0	0.161832E+03	0.163198E+03	0.164569E+03	0.165958E+03	0.167348E+03
-16.5	0.168757E+03	0.170174E+03	0.171599E+03	0.173037E+03	0.174483E+03
-16.0	0.175944E+03	0.177414E+03	0.178892E+03	0.180387E+03	0.181886E+03
-15.5	0.183402E+03	0.184930E+03	0.186463E+03	0.188012E+03	0.189571E+03
-15.0	0.191146E+03	0.192730E+03	0.194320E+03	0.195930E+03	0.197546E+03
-14.5	0.199175E+03	0.200821E+03	0.202473E+03	0.204142E+03	0.205817E+03
-14.0	0.207510E+03	0.209216E+03	0.210928E+03	0.212658E+03	0.214398E+03
-13.5	0.216152E+03	0.217920E+03	0.219698E+03	0.221495E+03	0.223297E+03
-13.0	0.225119E+03	0.226951E+03	0.228793E+03	0.230654E+03	0.232522E+03
-12.5	0.234413E+03	0.236311E+03	0.238223E+03	0.240151E+03	0.242090E+03
-12.0	0.244049E+03	0.246019E+03	0.248000E+03	0.249996E+03	0.252009E+03
-11.5	0.254037E+03	0.256077E+03	0.258128E+03	0.260200E+03	0.262284E+03
-11.0	0.264384E+03	0.266500E+03	0.268629E+03	0.270779E+03	0.272936E+03
-10.5	0.275110E+03	0.277306E+03	0.279509E+03	0.281734E+03	0.283966E+03
-10.0	0.286227E+03	0.288494E+03	0.290780E+03	0.293083E+03	0.295398E+03
-9.5	0.297737E+03	0.300089E+03	0.302453E+03	0.304841E+03	0.307237E+03
-9.0	0.309656E+03	0.312095E+03	0.314541E+03	0.317012E+03	0.319496E+03
-8.5	0.322005E+03	0.324527E+03	0.327063E+03	0.329618E+03	0.332193E+03
-8.0	0.334788E+03	0.337396E+03	0.340025E+03	0.342673E+03	0.345329E+03
-7.5	0.348019E+03	0.350722E+03	0.353440E+03	0.356178E+03	0.358938E+03
-7.0	0.361718E+03	0.364513E+03	0.367322E+03	0.370160E+03	0.373012E+03
-6.5	0.375885E+03	0.378788E+03	0.381691E+03	0.384631E+03	0.387579E+03
-6.0	0.390556E+03	0.393556E+03	0.396563E+03	0.399601E+03	0.402646E+03
-5.5	0.405730E+03	0.408829E+03	0.411944E+03	0.415083E+03	0.418236E+03
-5.0	0.421422E+03	0.424632E+03	0.427849E+03	0.431099E+03	0.434365E+03
-4.5	0.437655E+03	0.440970E+03	0.444301E+03	0.447666E+03	0.451038E+03
-4.0	0.454445E+03	0.457876E+03	0.461316E+03	0.464790E+03	0.468281E+03
-3.5	0.471798E+03	0.475342E+03	0.478902E+03	0.482497E+03	0.486101E+03
-3.0	0.489741E+03	0.493408E+03	0.497083E+03	0.500804E+03	0.504524E+03
-2.5	0.508290E+03	0.512074E+03	0.515877E+03	0.519717E+03	0.523566E+03
-2.0	0.527462E+03	0.531367E+03	0.535301E+03	0.539264E+03	0.543245E+03
-1.5	0.547265E+03	0.551305E+03	0.555363E+03	0.559462E+03	0.563579E+03
-1.0	0.567727E+03	0.571905E+03	0.576102E+03	0.580329E+03	0.584576E+03
-0.5	0.588865E+03	0.593185E+03	0.597514E+03	0.601885E+03	0.606276E+03

0.0 0.610699E+03; values for 0.1 and above as in Table 1.