KRC Thermal Model

Hugh H. Kieffer   file= /hkieffer/xtex/tes/krc/krc.tex 2005nov18

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History of this LaTeX file:
  2002jul12-31 Write new atmosphere section
  2002sep17
  2004Jul18-22 upgrade description of atmosphere
  2005nov18 Add description of upper boundary condition for slpes and pits

1 Symbols

Code variable names are shown in text as `VARIAB` and in formulas as $\mathtt{VARIAB}$.
Program and routine names are shown as **PROGRM**.

2 Background

The TES Thermal Inertia routines can run with thermal models generated either by Mike Mellon or Hugh Kieffer. The thermal model described here is Hugh's. For the MGS production thermal inertia software, see MGSmodel.tex.

Hugh's MGS thermal model is derived from the Viking thermal model (Kieffer et al., 1976, JGR 82,p4249-4291, appendix), and later modifications to apply to comets. All the comet-related code has been removed, and on 2002jul13 the atmospheric interaction was substantially modified.

The KRC model development began when computing a single case for 19 latitudes at 40 seasons took an hour on a large university main frame computer. For this reason, the code was highly optomized for speed and uses layer thickness increasing exponentially downward and time steps that increase by factors of two deeper into the subsurface where stability criteria are met. The code is modularized based on time scale and function, and there is extensive use of Commons. For THEMIS, a "one-point" capability was included that allows input of a set of points defined by season, latitude, hour and a few major physical parameters; KRC will produces the surface kinetic temperature and planetary brightness temperature for these points.

In response to an oft-asked question, the acromyn KRC is simply K for conductivity, R for "rho" (ρ) for density, and C for specific heat; the three terms in thermal inertia.

The numerous input parameters that control the time-depth grid and convergence are based upon extensive testing done during the development of the TSEAS, TLATS and TDAY routines; be carefull changing them!

A guide to running KRC is in the file **helplist.txt**

3 Surface boundary condition

In **TDAY**, the frost-free surface condition is (see Eq. 13 for more detail):

$$W = (1. - A)S'_{(t)} + (1. - \alpha)\,\epsilon R_{\Downarrow t} + \frac{k}{X_2}(T_2 - T) - (1. - \alpha)\,\epsilon\sigma T^4 \tag{1}$$

where X_2 is the depth to the center of the first soil layer, $S'_{(t)}$ is the total solar radiation onto the surface, and $R_{\Downarrow t}$ is the downwelling thermal radiation (assumed isotropic).

Most constant terms are pre-computed, see Table 2.

Table 1: Fortran Code set

Name	description
	Primary routines
KRC	Planet surface thermal model; top routine, MGS-TES version
TSEAS	Advance one "season" along planets orbit for KRC system
TLATS	Latitude computations for the KRC thermal model system
TDAY	KRC day and layer computations
	Input / output routines
TCARD	Data input routine for KRC system
TDISK	Save/read results at the end of a season; Version with BINF5
TPRINT	Printed output routine
	Specific task routines
ALBVAR	Compute frost albedo as linear function of insolation
ALSUBS	Convert between L-sub-s and days into a Martian year
AVEDAY	Average daily exposure of surface to sunlight.
CO2PT	CO2 pressure/temperature relation
DEDING2	Delta-Eeddington solution for single homogeneous layer
EPRED	Exponetial Prediction of numerical iteration
TINT	Spherical integrals over globe
VLPRES	Viking lander pressure curves
	Orbit geometry routines
PORB	Computes planetary angles and location for specific time.
PORB0	Planetary orbit. Read pre-computed matrices and do rotation; minimal for KRC
ECCANOM	Iterative solution of Keplers equations for eccentric orbit
ORBIT	Compute radius and coordinates for elliptical orbit
	Utility routines listed in Makefile
Fortran	catime.o datime.o idarch.o sigma.o vaddsp.o xtreme.o binf5.o white1.o
C	b2b.o r2r.o u_move1.o u_move4.o u_swapn.o primio.o pio_bind_c.o
C	binf5_bind.o b_alloc.o b_c2fstr.o b_f2cstr.o b_free.o
	Other routines
IDLKRC	Interface to IDL. Planet surface thermal model MGS-TES version

The boundary condition is satisfied when W=0. A Newton iteration is done:

$$\frac{\partial W}{\partial T} = -F_7 - 4F_5T^3$$

thus estimate the change in surface temperature as

$$\Delta T = W/\left(F_7 + 4F_5T^3\right) \tag{2}$$

Subscript F indicates the values when frost is present. and the values in Eqn. 2 are replaced with ϵ_F, A_F, and T_F, and no iteration is done; leaving W as a non-zero quantity to change the forst amount. See Section 5.1.

Input: newatm

3.1 Insolation Implimented 2002jul13

Define one-layer atmosphere, grey in the solar and thermal regions.

The current local solar wavelength region atmospheric opacity of dust, τ can vary with atmospheric pressure: $\tau = \tau_0 \cdot P/P_0$

Direct and diffuse illumination are computed using a double-precision Delta-Eddington model, with single scattering albedo ϖ and Henyey-Greenstein asymmetry parameter G_H .

The incidence angle from zenith onto a horizontal surface is i. Direct (collimated) insolation is computed for the local surface, which may be sloped in any direction and has incidence angle i_2; direct insolation is zero when either i or i_2 is $> 90°$. Diffuse illumination is based on i, with the optional extension into twilight (see Section 3.1.1). For a sloped surface, the solid angle of skylight is reduced and light reflected off the regional surface (presumed Lambert) is added; the Delta-Eddington downward diffuse radiance is multiplied by `DIFAC` $= (1-\alpha) + \alpha A$, where α is fraction of the upper hemisphere obscured by ground.

The diurnal variation of insolation onto the surface at the bottom of the atmosphere is computed for the current season and latitude: Incidence angles are computed by:

$$\cos i = \sin\delta \sin\theta - \cos\delta \cos\theta \cos\phi \tag{3}$$

$$\cos i_2 = \sin\delta \sin\theta_2 - \cos\delta \cos\theta_2 \cos\phi_2 \tag{4}$$

where
δ = the solar declination ,
θ = latitude,
θ_2 = latitude + slope north,
ϕ = hour angle from midnight,
ϕ_2 = hour angle + slope east.

If a sloping surface is used, the regional surface is assumed to be at the same temperature (may be a poor approximation) and of the same albedo.

The incident flux at the top of atmosphere: $I = S_M \cos i$, where $S_M \equiv \frac{S_o}{U^2}$, S_o is the solar constant and U is heliocentric range of Mars.

Use Delta-Eddington model for atmosphere scattering and fluxes (`DEDING2.f`); output parameters are normalized to unit solar irradiance along the incident direction at the top of atmosphere; so they must be multiplied by S_M to get flux.
BOND Planetary (atm plus surface system) albedo
COLL Direct beam at bottom = collimated + aureole
RI(2,2) Diffuse irradiances:
(1,= I_0 = isotropic (2, = I_1 = asymmetric
,1)= at top of atmosphere ,2) = at bottom of atm

The net diffuse flux is $F = \pi * [I_0 \pm (2/3) * I_1]$ where + is down,$F^{\downarrow}$; - is up, $F^{\uparrow}$. [Shettle & Weinman eq. 8]

Solar heating of the atmosphere, by simple conservation of energy, is $H_V = S_M * \left(\mu_0 - F^{\uparrow}(0) - (1-A_s)\left[\mu_0 \mathrm{COLL} + F^{\downarrow}(\tau)\right]\right)$

3.1.1 Twilight

Twilight is allowed to account for having a turbid atmosphere. It is implimented as having the diffuse downward illumination depend upon an incidence angle scaled to go to 90° when the Sun is `TWILI` below the geometric horizon.

Because of the twilight extension, there can be a small negative energy balance near twilight. Physically, this is lateral scattering and does not strictly fit a one-layer model. There is no solar heating of the atmosphere during twilight.

3.1.2 Atmospheric IR radiation

Assume a gray IR spectrum with opacity $\tau_R = P/P_0 \cdot (C_1 + C_2\tau)$ where C_1 represents the opacity of the "clear" atmosphere, primarily due to the 15μm band, and C_2 is the IR/visual opacity ratio for dust.

The fractional thermal transmission of the atmosphere at zenith is $e^{-\tau_R}$. Define the fractional absorption $\beta \equiv 1. - e^{-\tau_R}$.

The fractional transmission of planetary (thermal) radiation in a hemisphere is:

$$e^{-\tau_e} \equiv \int_0^{90} e^{-\tau/\cos\theta} \cos\theta \sin\theta \; d\theta \tag{5}$$

Numerical integration in **hemi_int.pro** shows that the effective hemispheric opacity is, within about 0.05 in the factor,

$$\tau_e \sim [1.0 < (1.50307 - 0.121687 * \ln \tau_R) < 2.0]\, \tau_R \tag{6}$$

Define the effective absorption $\beta_e \equiv 1. - e^{-\tau_e}$.

The hemispheric downward (and upward) emission from a gray slab atmosphere is: $R_{\Downarrow t} = \sigma T_a^4 \beta_e$.

The IR heating of the atmosphere is: $H_R = \epsilon\sigma T_s^4(1. - e^{-\tau_e}) - 2R_{\Downarrow t} \quad = \quad \sigma\beta_e(\epsilon T_s^4 - 2T_a^4)$

3.1.3 Atmospheric temperature

Compute atmospheric temperature by simple perturbation: $\frac{\partial T_a}{\partial t} = \frac{H_R + H_V}{c_p M_a}$ where $M_a = P/G$ is the mass of the atmosphere and c_p is its specific heat at constant pressure.

Because the atmospheric temperature variation has significant time lag relative to the surface, one can use the surface temperature from the prior time step (typically 1/384 of a sol) with little error.

If the computed atmospheric temperature drops below the CO_2 saturation temperature for one scale height above the local surface, it is bounded at this value. This strictly does not conserve energy. SHOULD BE RECODED

The nadir planetary temperature is given by

$$\sigma T_P^4 = \epsilon\sigma T_S^4(e^{-\tau_R}) + \sigma T_a^4(1 - e^{-\tau_R}) \text{ or } T_P = \left[\epsilon(1. - \beta)T_S^4 + \beta T_a^4\right]^{1/4} \tag{7}$$

3.2 Starting Conditions: Day-average equilibrium

Atmosphere temperature balance, H_V is solar (Visible) heating of the atmosphere:

$$< H_V > +\epsilon\sigma < T_s^4 > (1. - e^{-\tau_e}) = 2(1. - e^{-\tau_e})\sigma < T_a^4 > \text{ or } < H_V > +\epsilon\sigma < T_s^4 > \beta_e = 2 < R_{\Downarrow t} > \quad [Eq:abal] \tag{8}$$

Surface energy balance, where I is the insolation onto the surface (ignoring diurnal-average sub-surface heat flow)

$$\epsilon\sigma < T_s^4 > -\epsilon\sigma(1. - e^{-\tau_e}) < T_a^4 >= (1 - A) < I > \tag{9}$$

Solve: replace $+\epsilon\sigma < T_s^4 >$ in Eq. 8, and use β_e :

$$< H_V > + \left[\epsilon\sigma\beta_e < T_a^4 > +(1 - A) < I >\right] \beta_e = 2\beta_e\sigma < T_a^4 > \tag{10}$$

$$< T_a^4 >= \frac{< H_V > /\beta_e + (1 - A) < I >}{\sigma(2 - \epsilon\beta_e)} \tag{11}$$

Substitute into Eq. 9 to get $< T_s >$:

$$< T_s^4 >= \beta_e < T_a^4 > + \frac{(1 - A) < I >}{\epsilon\sigma} \tag{12}$$

The planetary heating values can be based on the average surface temperatures from the prior season; this is similiar to allowing some long-term lag in atmospheric temperature response. They could be based on the prior day, but there is then some concern over numerical stability.

3.3 Liens

Note: as of 2004jul19 β is 1.- transmission

Atm_Cp. should be 860. in krcin master.inp *End of input: newatm*

4 Slopes and Conical Holes

The surface condition for a planar sloped surface or a flat-bottomed pit can be written as follows, using the crude assumption that the surfaces visible to the point of computation are at the same temperature and have the same brightness where illuminated.

$$W = (1 - A)S_M \left[D_1 \cos i_2 + \Omega D_2 + (1 - \Omega)A(G_1 D_1 + \Omega D_2)\right] + \Omega\epsilon R_{\Downarrow t} + \frac{k}{X_2}(T_2 - T) - \Omega\epsilon\sigma T^4 \tag{13}$$

Where Ω is visible fraction of the sky, D_1 is the collimated beam in the Delta-Eddington model and D_2 is the diffuse beam. G_1 is a geometric term for the solid angle of illuminated surface seen by the target surface of the pit. Within the [ ] for W,

the first term is `DIRECT` = the direct collimated beam,

the second is `DIFFUSE` = the diffuse skylight directly onto the target surface,

the third term is `BOUNCE` = light that has scattered once off the surrounding surface.

As a first approximation, for pits $G_1 = \min(1, (90 - i)/z')$ where z' is the slope of the pit walls. For a sloped surface, G_1 is unity. For a flat-bottomed pit, $i_2 = i$ when the sun is above the pit slope, and $\cos i_2 = 0$ when the sun is below the pit slope.

5 Pressure variation

P_0 = annual mean surface pressure at the reference elevation (input as `PTOTAL`).
P_g = the current global pressure `= PZREF`, can be any of the following:

1) constant at P_0
2) P_0 times the normalized Viking Lander pressure curve `VLPRES`
3) based on depletion of atmospheric CO_2 by growth of frost caps; $=P_0-$cap .

$P = P_g e^{-z/\mathcal{H}}$ `= PRES` is the current local total pressure at a specific elevation. The exponential term is `PFACTOR`

The initial partial pressure of CO_2 at zero elevation is $P_{c0} = P_0 \cdot (1.-$noncondensing fraction). `= PCO2M`

The current CO_2 partial pressure at zero elevation is $P_{cg} = P_{c0} + (P_g - P_0)$. `= PCO2G`

The nominal scale height is: $\mathcal{H} = T_a\mathcal{R}/\mathcal{M}G$; where T_a is the mean atmospheric temperature over prior day (or season), $\mathcal{R}$ is the universal gas constant, $\mathcal{M}$ is the mean molecular weight of the atmosphere (43.5, firm-coded), and G is the martian gravity.

Local current dust opacity scales with total pressure: $\tau = \tau_0 P/P_0$

5.1 CO_2 Frost condensation and Sublimation

The local frost condensation temperature `TFNOW` may be either fixed at an input value `TFROST`, or derived from $P_c = e^{-z/\mathcal{H}}P_{cg}$.

The relation between condensation/sublimation temperature and partial pressure is taken to be the Clausius-Clapeyron relation: $\ln P_c = a - b/T$, in **CO2PT** with a=27.9546 [Pascal] and b=3182.48 [1/Kelvin], derived from MARS page 959.

The code logic is: after subsurface layer calculations:

If frost is present $E = W \cdot \Delta t$ energy is used to modify the amount of frost; $\Delta M = -E/L$, where L is the latent heat of sublimation. And, the frost albedo may be variable, and there may be an exponential attenuation of the underlying ground albedo. E.g.,

If Frost then
    calc the change in frost amount, ΔM , apply it
        if $M \leq 0$, then
            set Frost false & set $M = 0$
    else
        calc unbalanced Power W based on prior T & determine ΔT to balance

if $T < T_F$ then
set Frost true & set $T = T_F$.

6 Subsurface

6.1 Diffusion theory for layered materials

Symbols used:

i = layer index, layer 1 is above the physical surface
subscript + is shorthand for $i+1$ and subscript - is shorthand for $i-1$
I = thermal inertia $\equiv \sqrt{k\rho C}$
k = thermal conductivity
ρ = bulk density
C_p or C = specific heat of the material
κ = Thermal diffusivity $\equiv \frac{k}{\rho C_p}$
B_i = thickness of layer i, or Δz
t = time
T = temperature
H = heat flow$=-k\frac{dT}{dz}$

Basic 2nd difference equation of heat flow:

$$\frac{\partial T}{\partial t} = \frac{-1}{\rho C}\frac{\partial}{\partial z}\left(-k\frac{\partial}{\partial z}\right) = \frac{k}{\rho C}\frac{\partial^2 T}{\partial z^2} \qquad \text{or} \qquad \frac{\Delta T_i}{\Delta t} = -\frac{H_{i+1/2} - H_{i-1/2}}{B_i \rho_i C_i} \tag{14}$$

Use steady-state relations to find heat flow at interface between two layers: $H = -k\nabla T$

$$H_{i+.5} = -\frac{T' - T_i}{B_i/2}k_i \ \text{ or } \ T' - T_i = -\frac{H_{i+.5}B_i}{2k_i}$$

where T' is the temperature at the interface.

$$\text{similarly } \ T_{i+1} - T' = -\frac{H_{i+.5}B_{i+1}}{2k_{i+1}}$$

$$\text{Thus } \ T_{i+1} - T_i = -\frac{H_{i+.5}}{2}\left(\frac{B_i}{k_i} + \frac{B_{i+1}}{k_{i+1}}\right)$$

$$\text{or } \ H_{i+.5} = -\frac{2(T_{i+1} - T_i)}{\frac{B_i}{k_i} + \frac{B_{i+1}}{k_{i+1}}}$$

$$\frac{\Delta T_i}{\Delta t} = \frac{2}{B_i \rho_i C_i}\left[\frac{T_+ - T_i}{\frac{B_i}{k_i} + \frac{B_+}{k_+}} - \frac{T_i - T_-}{\frac{B_i}{k_i} + \frac{B_-}{k_-}}\right] \tag{15}$$

Put into the form $\Delta T = F_{1_i}\left[T_+ + F_{2_i}T + F_{3_i}T_+\right]$ where $F_2 = -(1 + F_3)$.

$$F_{1_i} = \frac{k_i}{\rho_i C_i}\frac{\Delta t}{B_i^2}\frac{2}{1 + \frac{B_+ k_i}{B_i k_+}} \tag{16}$$

$$F_{3_i} = \frac{B_i/k_i \ + \ B_+/k_+}{B_-/k_- \ + \ B_i + k_i} = \frac{1 + \frac{B_+}{B_i}\frac{k_i}{k_+}}{1 + \frac{B_-}{B_i}\frac{k_i}{k_-}} \tag{17}$$

The classic convergence stability criterion is $\frac{\Delta t}{(\Delta Z)^2}\kappa < \frac{1}{2}$ or $(\Delta z)^2 \equiv B^2 > 2\Delta t\kappa$. [To be safe, at each layer should use the largest diffusivity of the 3 layers involved in the 2nd difference scheme]

If a discontinuity of physical properties is invoked, need to reset the layer thickness scheme at that point to maintain stability.

6.2 KRC code

The user inputs the thermal inertia I, the bulk density ρ, and the specific heat of the material C_p. Thermal conductivity k is computed from $I^2/[\rho C_p]$. The thermal diffusivity is $\kappa = \frac{k}{\rho C_p}$. While k, ρ, and C_p do not independantly influence the surface temperature for a homogeneous material, they set the spatial scale of the subsurface results; SCALE $= \sqrt{kP/\pi\rho C_p}$.

KRC uses layers that increase geometrically in thickness by a factor RLAY.

In order to simplify the innermost code loops, KRC places the surface between the first and second model layers. The input parameter FLAY specifies the thickness of this "virtual" layer is dimensionless units (in which the diurnal skin depth is 1.0), so that the scaled thickness of the uppermost layer in the soil is FLAY*RLAY, and the physical depth of its center in meters is 0.5*FLAY*RLAY*SCALE. Normally (LP2 set true) a table of layer thickness, depth, (both scaled and in meters), overlying mass, and numerical convergence factor is printed out at the start of a run.

R = RLAY = ratio of thickness of succeeding layers
X = X = scaled depth to middle of each layer
B = TLAY = scaled thickness of each layer. l_1 = FLAY
P = PERSEC = diurnal period in seconds

$$\mathrm{F4} = 1 + 1/R \tag{18}$$

$$B_i = B_1 * R^{i-1}\sqrt{\frac{k_i}{\rho_i C_p}\frac{P}{\pi}} \tag{19}$$

$$X_1 = -B_1/2 \qquad X_i = X_{i-1} + (B_{i-1} + B_i)/2 \tag{20}$$

$$\mathrm{FA}_i = \frac{2 \cdot k_i \cdot \Delta t}{\rho_i C_p \cdot B_i^2 \left(1 + \frac{B_{i+1}k_i}{B_i k_{i+1}}\right)} \tag{21}$$

$$\mathrm{FA3}_i = \frac{B_i/k_i \ + \ B_{i+1}/k_{i+1}}{B_i/k_i \ + \ B_{i-1}/k_{i-1}} \tag{22}$$

The convergence safety factor is $\Delta Z/\sqrt{2.\Delta t \cdot \kappa}$. If this is less than about 0.8, the process is numerically unstable. If possible, the routine will keep this larger than 2.

6.3 Layered Material

Beginning with layer IC, all lower layers can have their conductivity, density and volume specific heat reset to COND2, DENS2, and SPHT2 respectively. If LOCAL is set true, then the physical thickness of these layes scales with the local thermal diffusivity; otherwise, the geometric increase continues unaltered.

7 One-point Model 2002aug04

To support the THEMIS team, an interface to the KRC system was built that computes the temperature for a single condition. The user generates a file 'one.inp' that contains lines of specific times and conditions.

The input file `krcone_master.inp` is set to do one latitude for 2 seasons. It contains a change-card 10 which points to 'one.inp' as the file of specific points.

7.1 Code to accomodate One-point mode

krc.f:
  at the start of each case, sets IQ=1, which tells TSEAS to restart.
  after each season, calls TPRINT(9)

tseas.f
  does not report the time elapsed

tcard:
  Has a section for first item on change line being 11, which decodes the line into
    L_s,ALAT(1),HOURO,ELEV(1),ALB,SKRC,TAUD,SLOPE,SLOAZI
    computes DJUL for the desired L_s using **ALSUBS**
  does not call TPRINT to print changes

tprint(9):

Interpolates in hour, Prints one line of:

SUBS,ALAT(1),HOURO,ELEV(1),ALB,SKRC,TAUD,SLOPE,SLOAZI,touto,q4

touto is the surface kinetic temperature at the requested hour

q4 is planetary bolometric temperature

8 Evolution

8.1 2005nov18

Add the conincal pit option, which involves revising the illumination calculation to that of Equation 13. For test cases with no pit, FD(32)=0, related to the Phoenix Lander, with ice at no or several depths, temperature changes of runs before and after the code change had a mean of .0013 K and a StdDev of .014K, There were about 100 points each beyond .057K, with extremes of -.23 and +.34 K. The largest changes were in the bottom layers. T_planetary changes had mean .0007 and StdDev .046, there were 3 values each beyond 0.2, with extremes -.67 and +.97 .

8.2 2004jul20

Allow scale height to depend upon diurnal-average atmosphere temperature

Modify output type 52 to include atmospheric temperature, but only up to 5 cases. It now reduces file size to actual number of latitudes and seasons.

8.3 Symbols and variables

In table 2; computation frequency is indicated as:

C = Input constant
F = Firm-coded constant
O = Once
S = Every "season" (may be as frequent as each sol)
H = Every "Hour" (24 times per sol)
R = Rapid: every timestep (Nominal is 384 times per sol)
SR = every time step for one day each season

subscript f on these means when frost is present

* = Lien on how this is done

Subscript $[f]$ means that frost values are used if frost is present.

Table 2: Symbols and variables

Sym -bol	Name in Code	Input or Equation	Value +freq.	What and Basis
A	`AS`		S,R_f	Current bolometric albedo
c_p	`ATMCP`	Atm_Cp	860. C	Atm. specific heat at constant pressure J K^{-1} kg^{-1}, MARS p.855
C_1	`CABR`	CABR	0.18 C	Clear atmosphere IR absorption. Estimate
C_2	`TAURAT`		0.5 C	IR/vis relative opacity. Viking VIS & IRTM opacities. MARS p.1022,5
F_3	`FAC3`	$(1-A_{[f]})$	S,R_f	Surface solar absorbtance
F_4	`FAC4`	$1+1/\mathrm{RLAY}$	O	Layer factor
F_5	`FAC5`	$(1.-\alpha)\epsilon\sigma$	O	Surface thermal emission factor
$4F_5$	`FAC45`	$4(1.-\alpha)\epsilon\sigma$	O	Surface thermal emission factor
F_6	`FAC6`	$(1-\alpha)\epsilon_{[f]}$	O	Frost emission factor
F_7	`FAC7`	$\frac{k}{X_2}$	O	Layer scaling
F_8	`FAC8`	$e^{-\tau_R}\epsilon_{[f]}$	O	fraction of surface Blackbody reaching top-of-atm
F_9	`FAC9`	$\sigma(1-e^{-\tau_e})$	O	
G	`GRAV`	GRAV	3.727 C	Martian gravity, m s^{-1}
G_H	`GO`	ARC2	0.5 C	Henyey-Greenstein asymmetry. MARS p.1030
$\mathcal{H}$	`SCALEH`		S	Scale height in km. Based on TATM*
H_V	`ADGR`		SR	solar heating of atm Wm^{-2}
i			SR	incidence angle from zenith onto a horizontal surface
i_2			SR	incidence angle onto local slope; from SLOPE and SLOAZI
k	`COND`	COND	C	Thermal conductivity of the soil
$\mathcal{M}$	`AMW`		43.5 F	Atomic weight of general atmosphere (g/mole).
P_0	`PTOTAL`	PTOTAL	689.7 C	Global annual mean surface pressure, Pa
P_g	`PZREF`		S	Current pressure at reference level
P	`PRES`		S	Current local surface pressure
$R_{\Downarrow t}$	`ATMRAD`	$F_9T_a^4$	R	hemispheric emission from a gray slab atmosphere. Wm^{-2}
S_o	`SOLCON`	SOLCON	1368. C	Solar constant. Wm^{-2}
S_M	`SOL`	S_o/U^2	S	Solar flux at Mars. W/m^2
$S'_{(t)}$	`ASOL`		SR	total insolation onto slope surface Wm^{-2}
T	`TSUR`		R	Surface kinetic temperature
T_a	`TATM`	TATM	200. C*	Temperature of the atmosphere. Kelvin
T_a	`TATMJ`		R	Temperature of the atmosphere. Kelvin
T_P	`TPFH`		R	nadir planetary temperature
t			-	Time from midnight ("Hour")
U	`DAU`		S	Heliocentric range in Astronomical Units
W	`POWER`		R	Energy into the surface boundary
α	`1-SKYFAC`	$(1-\alpha)$	S	Fraction of upper hemisphere occupied by ground = slope/180
β	`BETA`	$1-e^{-\tau_R}$	S	vertical thermal absorption of atmosphere
β_e	`BETH`	$1-e^{-\tau_e}$	S	hemispheric thermal absorption of atmosphere
γ	`TWILFAC`		S	twilight extension factor = 90/(90+twilight)
δ	`[R]SDEC`		S	Solar declination.
ϵ	`EMIS`		S,R_f	Surface emissivity. FEMIS for frost
θ	`DLAT`		S	Latitude. θ_2 = latitude + slope north
μ_0	`COSI`		R	Cosine of the incidence angle
ϖ	`OMEGA`	DUSTA	0.9 C	Dust grain single scattering albedo. MARS p.1030
Ω	`SKYFAC`	$\equiv 1-\alpha$	SR	Fraction of the sky (upper hemisphere) that is visible to the surface
σ	`SIGSB`	5.67051e-8	F	Stephan-Boltzman constant W m^{-2} K^{-4}
τ_0	`TAUD`	TAUD	0.2 C	Nominal solar-range dust opacity
τ	`OPACITY`		S	Current local dust opacity
τ_e	`TAUEFF`		S	effective thermal opacity of the atmosphere
τ_R	`TAUIR`		S	thermal opacity, zenith
ϕ	`ANGLE`		R	Hour angle from midnight, ϕ_2 = hour angle + slope east
$<\_>$				diurnally-averaged value
	`TWILI`	TWILI	1.0 C	Central angle extension of twilight, degrees
	`DTAFAC`	$\Delta t/(c_p\frac{P}{g})$	O	Atmosphere heating factor
	`FEMIT`	$(1-\alpha)\epsilon_f\sigma T_f^4$	O	Frost thermal emission