Rio Tinto Alcan

KMP SO_2 EEM Program – Technical Memo D03

Atmospheric Sulphur Dioxide Dry Deposition Velocity Manual

(Update to 2020 Technical Memo D03)

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1.0 Introduction

Under the Environmental Effects Monitoring (EEM) program, dry deposition of gaseous and particulate sulphur in the Kitimat valley is estimated from empirical observations of gaseous sulphur dioxide (SO_2) and particulate sulphate (pSO_4^{2-}; see Technical Memo F01, 2018) combined with modelled dry deposition velocities (V_d; see Technical Memo D01, 2016; Technical Memo D02, 2018). The 'DryDep' model developed by Environment and Climate Change Canada (ECCC; Zhang et al., 2001; 2003a; 2003b; Zhang and He, 2014) is used in the EEM program to estimate region-specific V_d in the Kitimat valley. The modelled V_d and estimated dry deposition of sulphur for the period 2016–2018 are reported in the comprehensive review (ESSA et al., 2020).

This manual describes the application of the DryDep model to estimate V_d for three sites in the Kitimat valley: Haul Road, Kitimat (latitude: 54.0293, longitude: –128.7019); Whitesail, Kitimat (latitude: 54.0669, longitude: –128.6391); and Terrace Airport (latitude: 54.47, longitude: –128.58). The primarily goal of the manual is to provide a description of the sources of the input data for 2019. The model code and structure of input and output files are described in Appendices 1–4.

The DryDep model was obtained from ECCC as a Fortran code (see Technical Memo D01, 2018). The code was revised to facilitate 'ease of use' for input and output file handling (see Appendix 1) and compiled as a Windows executable command line program. The model output provides hourly V_d for 31 gaseous species and 3 particulate size classes to 26 land cover types.

2.0 Input Data

The DryDep model requires two input files, (a) hourly meteorological forcing variables (see Appendix 2), and (b) a site-specific parameter file containing latitude and land cover fractions (see Appendix 3). On execution, DryDep produces two output files (a) *.aout, which contains average hourly V_d across the land cover fractions specified in the input parameter file for the 31 gaseous species and 3 particulate matter size classes (Appendix 4), and (b) *.out, which contains V_d for each landcover and gaseous species and particulate size class (contains 888 columns of data).

3.0 Data Sources

The DryDep model requires nine meteorological input variables on an hourly time step (Appendix 2). The following sub-sections outline the data sources for each input variables for 2019 at three study locations. A simple sensitivity analysis for each input variable (one-at-a-time) showing the degree of impact that each meteorological variable has on the modelled V_d was also assessed (see Appendix 5).

A note about measurement height, Z2: The reference height, Z2, is defined in the model as 10 m. If the reference height is not 10 m, this value should be changed as required in the parameter file (see Appendix 3). The same reference height should be used for both windspeed and temperature measurements; as this is not always the case, it is sufficient to use a different height for air temperature measurements, as long as the difference in temperature between the temperature measurement height (e.g., 2 m) and the windspeed measurement height (e.g., 10 m) is negligible. It is, however, important that the 'Temperature at Z2' and 'Surface Temperature' values differ (see respective sub-sections below).

3.1 Temperature at Z2

Temperature in degrees K recorded hourly (or the average of the previous hour), at Z2, i.e., the same height as windspeed measurements (typically 10 m). Temperature is typically recorded at 2 m; temperature measured at this height can be used if no measurements are available at windspeed measurement height. See Table 1 for temperature measurement sources and alternative sources.

Table 1: Temperature measurement sources and alternative sources.

Site	Source	Notes
Haul Road, Kitimat	BC Air Data Archive Website. Converted from °C to °K. Available at https://envistaweb.env.gov.bc.ca/	Primary source
	Rio Tinto Hourly Data, Haul Road. Available at http://67.231.17.48/clients/Rio_Tinto_Alcan/	Nearly identical data as primary source, but dataset may be less complete
	NADP Haul Road (site BC 22). Available at http://nadp.slh.wisc.edu/siteOps/ppt/default.aspx	Measurements consistently higher than above listed sources
Whitesail, Kitimat	Rio Tinto Hourly Data, Whitesail. Converted from °C to °K. Available at http://67.231.17.48/clients/Rio_Tinto_Alcan/	
Terrace Airport	Environment Canada, Terrace A meteorological station (Climate Station ID: 1068130). Converted from °C to °K. Available at https://climate.weather.gc.ca/historical_data/search_historic_data_e.html	
	Environment Canada, Terrace PCC meteorological station (Climate Station ID: 1068131). Available at https://climate.weather.gc.ca/historical_data/search_historic_data_e.html	Daily average data available only

3.2 Surface Temperature

Temperature in degrees K recorded hourly (or the average of the previous hour), recorded at ground-level, i.e., at the earth's surface. This is an uncommon measurement, except for some agricultural applications, and therefore must be estimated. To estimate surface temperature, we used existing known ratios of grass temperature (measured at the earth's surface) to air temperature (measured at 2 m) and multiplied those ratios by the known air temperature measurements for each of the study sites.

Grass temperature to air temperature ratio were determined for 15 sites at an hourly time-step over one year (June 2013–July 2014). The hourly ratios were averaged by month and hour to capture seasonal and diurnal patters (e.g. January 10:00 am). Each hourly air temperature for the Kitimat and Terrace study sites (Table 1) were multiplied by the corresponding month-hour ratio. The month-hour ratios can be found in Appendix 6.

Note: If temperature is measured at a site at heights of 10 m and 2 m, then these measurements can be used as the Temperature at Z2 and Surface Temperature parameters, respectively.

3.3 Windspeed

Windspeed, in m/s, averaged over the previous hour, recorded at Z2 (typically 10 m). See Table 2 for windspeed measurement sources.

Table 2: Windspeed measurement sources.

Site	Source
Haul Road, Kitimat	Rio Tinto Hourly Data, HaulRoad. Available at http://67.231.17.48/clients/Rio_Tinto_Alcan/
Whitesail, Kitimat	Rio Tinto Hourly Data, Whitesail. Available at http://67.231.17.48/clients/Rio_Tinto_Alcan/
Terrace Airport	Environment Canada, Terrace A meteorological station (Climate Station ID: 1068130). Converted from km/h to m/s. Available at https://climate.weather.gc.ca/historical_data/search_historic_data_e.html.

3.4 Relative Humidity

Relative humidity, as a fractional value 0−1, measured hourly. See Table 3 for measurement sources.

Table 3: Relative humidity measurement sources.

Site	Source
Haul Road, Kitimat	Rio Tinto Hourly Data, Whitesail. Converted from percent value to fraction. Available at http://67.231.17.48/clients/Rio_Tinto_Alcan/
Whitesail, Kitimat	Rio Tinto Hourly Data, Whitesail. Converted from percent value to fraction. Available at http://67.231.17.48/clients/Rio_Tinto_Alcan/
Terrace Airport	Environment Canada, Terrace A meteorological station (Climate Station ID: 1068130). Converted from percent value to fraction. Available at https://climate.weather.gc.ca/historical_data/search_historic_data_e.html

3.5 Solar Irradiance

Hourly solar irradiance, in W/m^2. Solar irradiance is not often available, but it can be estimated from daily sunshine duration or daily maximum and minimum temperature values. At the time of analysis, no solar irradiance data were available for the sites of interest, and so it was estimated from maximum and minimum daily temperature values using the Hargreaves and Samani (1982) method; this method was selected based on Aladenola and Madramootoo (2014). Daily solar irradiance was first determined in the R program package 'sirad' (Bojanowski, 2016) and then hourly solar irradiance was estimated from the daily values using the R package 'solaR' (Perpiñán, 2012). Detailed instructions and the R script for this process can be found in Appendix 7.

If daily solar irradiance values are known, the hourly values can be estimated using the R package 'solaR'.

3.6 Precipitation

Amount of hourly rainfall, in mm. Snowfall not included as precipitation. At the time of analysis, no hourly data was available for the Terrace A site, and so the daily Terrace rainfall data was disaggregated to an hourly timestep using the ratio of hourly to daily rainfall for the NADP Lakelse Lake monitoring site (site code BC 23). See Table 4 for measurement sources.

Table 4: Precipitation measurement sources.

Site	Source
Haul Road, Kitimat	NADP Haul Road precipitation (site code BC 22), where max temp > 0. Converted from inches to mm. Available at http://nadp.slh.wisc.edu/siteOps/ppt/default.aspx
Whitesail, Kitimat	NADP Haul Road precipitation (Site Code BC 22), where max temp > 0. Converted from inches to mm. Available at http://nadp.slh.wisc.edu/siteOps/ppt/default.aspx
Terrace Airport	Environment Canada, Terrace A meteorological station (Climate Station ID: 1068130), daily data, disaggregated by NADP Lakelse Lake hourly data (site code BC 23; where temp > 0; in converted to mm). Terrace A daily data available at https://climate.weather.gc.ca/historical_data/search_historic_data_e.html. Lakelse Lake hourly data available at http://nadp.slh.wisc.edu/siteOps/ppt/default.aspx.

3.7 Surface Pressure

Surface pressure, in mb, measured hourly. See Table 5 for measurement sources. If surface pressure is unknown at a given site, it can be estimated from the surface pressure at a known site following the pathway: Surface pressure at known site → surface pressure at sea level → surface pressure at unknown site. Ideally, some pressures should be available at the 'unknown' site, with which to calibrate the estimated results.

Table 5: Surface pressure measurement sources.

Site	Source	Notes
Haul Road, Kitimat	Rio Tinto Hourly Data, Haul Road. Converted from Pa to mb. Available at http://67.231.17.48/clients/Rio_Tinto_Alcan/	Primary source
	NADP Haul Road (site BC 22). Available at http://nadp.slh.wisc.edu/siteOps/ppt/default.aspx	Reports lower surface pressure than primary source but improves with a linear calibration of -5 mb.
Whitesail, Kitimat	Rio Tinto Hourly Data, Haul Road. Converted from Pa to mb. Available at http://67.231.17.48/clients/Rio_Tinto_Alcan/	
Terrace Airport	Environment Canada, Terrace A meteorological station (Climate Station ID: 1068130). Converted from kPa to mb. Available at https://climate.weather.gc.ca/historical_data/search_historic_data_e.html	

3.8 Snow Depth

Snow depth, in cm, measured hourly. Only daily snowpack was available at the selected sites, and so daily snowpack values were applied to all hours of the day. Where days were missing, the snow depth was estimated by stepping up (or down) in equal increments from one available value to the next. See Table 6 for measurement sources.

Table 6: Snow depth measurement sources.

Site	Source
Haul Road, Kitimat	Environment Canada, Kitimat Hatchery meteorological station (Climate Station ID: 106D289). Available at https://climate.weather.gc.ca/historical_data/search_historic_data_e.html
Whitesail, Kitimat	Environment Canada, Kitimat Hatchery meteorological station (Climate Station ID: 106D289). Available at https://climate.weather.gc.ca/historical_data/search_historic_data_e.html
Terrace Airport	Environment Canada, Terrace A meteorological station (Climate Station ID: 1068130). Available at https://climate.weather.gc.ca/historical_data/search_historic_data_e.html

3.9 Cloud Fraction

Cloud cover, as a fractional value 0−1, measured hourly. Cloud cover from Terrace A was used for all three sites, which is currently available only by request to Environment Canada by emailing ec.climatouest-climatewest.ec@canada.ca. Values were converted from a percent to a fraction. Cloud cover was available from the source at a 3-hr measurement interval, and missing hours were infilled with the averages of available measurement above and below. The cloud cover parameter does influence the model under the conditions found at the study sites (see Appendix 5).

References

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Appendix 1

```
C DryDep model V1.2c
C code revised by Trent University to allow external files to be loaded
C Command line execution: drydep.exe input.dat input.par output.out output.aout
C input.day: contains hourly data for nine meteorological variables
C input.par: contains site-specific parameters, e.g., latitude, land cover, etc
C output.out: modelled Vd for 31 gases and 3 particulate matter size ranges for 26
C land cover types
C output.aout: modelled Vd for 31 gases and 3 particulate matter size ranges
C for average site-specific land cover estimated from land cover proportions
C provided in the input.par file
C

      PROGRAM DRYDEP

      IMPLICIT REAL(A-H,O-Z),INTEGER(I-N)
      PARAMETER (NG=31)     ! number of gaseous species
      PARAMETER (NP=3)      ! number of particle species for dry deposition
      PARAMETER (NLUC=26)   ! number of land use category
      REAL VDG(NLUC,NG), VDP(NLUC,NP)
      REAL VDGavg(NG), VDPavg(NP)
      INTEGER KDAY(12), KDAY1(12)
      DATA KDAY/0,31,59,90,120,151,181,212,243,273,304,334/
      DATA KDAY1/31,28,31,30,31,30,31,31,30,31,30,31/
      CHARACTER SITEINFO*40
      CHARACTER METFILE*40
      CHARACTER OUTFILE*40
      CHARACTER AOUTFILE*40
      real Ra(NLUC), Ustar(NLUC), LAI_F(NLUC)
      REAL GLATIN, GLAT, Z2, WAT, ICE, LAK, ENT,
     & EBT, DNT, DBT, TBT, DDT, EBS, DSH, TSH, SGF, GRA, CRP,
     & RIC, SUG, MZE, COT, IRR, URB, TUN, SWA, DES, MWF, TRN
c Define the array
      REAL, DIMENSION(26) :: FLAND

c      DATA fland/0., 0., 0., 0., 0., 0.06, 0., 0., 0., 0., 0., 0.,
c     & 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0.29, 0.37,0.28, 0./

C  calculate Vd for one site each time
C
C  initialize site-dependent information
C      Z2=10.                    ! reference height (m)
C      GLAT=56.9688*3.14/180.    ! latitude for the site location, change according to
your site

C trentu: get site info
      PRINT*," "
      PRINT*,"DryDep is starting. This may take some time!"
      PRINT*," "

      CALL getarg(1,SITEINFO)
      OPEN(UNIT=12, FILE=SITEINFO)

      continue

      read(12,'(28F8.4)', END=475) Z2, GLATIN, WAT,
     & ICE, LAK, ENT, EBT, DNT, DBT, TBT,
     & DDT, EBS, DSH, TSH, SGF, GRA, CRP,
     & RIC, SUG, MZE, COT, IRR, URB, TUN,
     & SWA, DES, MWF, TRN
```

```
      FLAND= (/WAT, ICE, LAK, ENT,
     & EBT, DNT, DBT, TBT, DDT, EBS, DSH, TSH, SGF, GRA, CRP,
     & RIC, SUG, MZE, COT, IRR, URB, TUN, SWA, DES, MWF, TRN/)
      PRINT*, "...Running: ", SITEINFO
      PRINT*, "...Buffering ", NLUC

     continue

      CALL getarg(2,METFILE)
      OPEN(55, file=METFILE)
      read(55, '(A500)', ERR=475) line

475   continue

500   read(55, '(1I5,3I3,9F17.10)', END=525) IYR, IMO, ID, IH,
     & T2, Ts, U2, RH, SRAD, PREC, P0, SD, FCLD

     continue

C  create output files
      CALL getarg(3,OUTFILE)
      OPEN (22,file=OUTFILE)
      CALL getarg(4,AOUTFILE)
      OPEN (33,file=AOUTFILE)
C      OPEN (66, file="ERRORS.txt")

C  Get GLAT
      GLAT=GLATIN*3.14/180.

C  find Julian day
      JDAY=KDAY(IMO)+ID
      if (IMO.GT.2.and.MOD(IYR,4).EQ.0 ) JDAY=JDAY+1.

C  Calculate solar zenith angle
      hour=real(IH)
      DECLIN=ASIN(SIN(23.5*3.14159/180.)*
     &        SIN((JDAY-81.)*2.*3.14159/365.))
      SHORT1=SIN(GLAT)*SIN(DECLIN)
      SHORT2=COS(GLAT)*COS(DECLIN)
      COSZE=(HOUR-12)*3.14159/12.
      COSZEN=SHORT1+SHORT2*COS(COSZE)
      COSZEN= amax1(0.,COSZEN)

C  Call GasVd to calculate Vd for 31 gaseous species

      call GasVd (Z2, u2, sd, t2, ts, srad, rh, fcld, prec,  ! I
     &            COSZEN, P0, jday,                          ! I
     &            VDG, Ra, Ustar, LAI_F)                     ! O

      call PMVdBulk (Ra, Ustar, LAI_F, VDP)

      write(22,'(I4,3I3,1196F17.10)') IYR,IMO,ID,IH,
     &     ((VDG(I,J)*100,I=1,NLUC),J=1,NG),
     &     ((VDP(I,J)*100,I=1,NLUC),J=1,NP)  ! m/s -> cm/s

      CALL init1(VDGavg,NG)
      CALL init1(VDPavg,NP)

      DO J=1,NG
         DO I=1,NLUC
            VDGavg(J)= VDGavg(J) + VDG(I,J)*fland(I)
         ENDDO
```

```
      ENDDO
      DO J=1,NP
         DO I=1,NLUC
            VDPavg(J)= VDPavg(J) + VDP(I,J)*fland(I)
         ENDDO
      ENDDO

      write(33,'(I4,3I3,46F10.5)') IYR,IMO,ID,IH,
     &     (VDGavg(J)*100,J=1,NG),
     &     (VDPavg(J)*100,J=1,NP)  ! m/s -> cm/s

      goto 500
525   continue

      STOP

      END

      SUBROUTINE init1 (V, K1)
      real V(K1)
      do i=1,K1
        V(i)=0.
      end do
      return
      end
      SUBROUTINE init2 (V, K1)
      real V(K1)
      do i=1,K1
        V(i)=-0.9
      end do
      return
      end

      real function amin1 (x,y)
        amin1=x
        if (y.lt.x) amin1=y
      return
      end
      real function amax1 (x,y)
        amax1=x
        if (y.gt.x) amax1=y
      return
      end

      SUBROUTINE GasVd (  z2,     u2,     sd,
     &                    t2,     ts,    srad,    rh,
     &                  fcld,   prec,  COSZEN,   pmb,
     &                  iday, VDG, Ra, Ustar, LAI_F)
C
C  PURPOSE ---- Calculate dry deposition velocities for 31 gas species
C              and 3 aerosol species
C-----------------------------------------------------------------------
C  Reference for gas: Zhang et al., 2003. Atmos. Chem. Phys. 3, 2067-2082
C-----------------------------------------------------------------------
C     LUC No.     Vegetation type
C     =====       ===============
C       1         water
C       2         ice
C       3         inland lake
C       4         evergreen needleleaf trees
C       5         evergreen broadleaf trees
C       6         deciduous needleleaf trees
C       7         deciduous broadleaf trees
```

```
C       8         tropical broadleaf trees
C       9         drought deciduous trees
C       10        evergreen broadleaf shrub
C       11        deciduous shrubs
C       12        thorn shrubs
C       13        short grass and forbs
C       14        long grass
C       15        crops
C       16        rice
C       17        sugar
C       18        maize
C       19        cotton
C       20        irrigated crops
C       21        urban
C       22        tundra
C       23        swamp
C       24        desert
C       25        mixed wood forests
C       26        transitional forest
C-----------------------------------------------------------------------
C        KEY   VARIABLES
C-----------------------------------------------------------------------
C  alpha    | Scaling factor based on SO2 (no unit)
C  beta     | Scaling factor based on O3  (no unit)
C  brs      | Constant for stomatal resistance(W/m2)
C  bvpd     | Constant for water vapor pressure deficit  (kPa^-1)
C  coszen   | Cosine of solar zenith angle
C  fcld     | Cloud fraction (0.0-1.0)
C  fland    | fraction of Land types (%)
C  fsun     | fraction of sunlit leaves (0.0-LAI)
C  iday     | Julian day
C  lai      | Leaf area index  (no unit)
C  luc      | No. of land use category (26)
C  mw       | molecular weight for gaseous species
C           |   (g/mol)
C  ng       | No. of gaseous species dry deposited
C  pardir   | visible beam radiation (W/m2)
C  pardif   | diffuse visible radiation (W/m2)
C  pmb      | Surface pressure (mb)
C  prec     | hourly precipitation amount (mm/hour)
C  psi1     | Constant for leaf water potential(Mpa)
C  psi2     | Constant for leaf water potential(Mpa)
C  fsnow    | Snow fraction  (0.0-1.0)
C  ra       | Aerodynamic resistance (s/m)
C  rac      | IN-canopy aerodynamic resistance (s/m)
C  rb       | quasi-laminar resistance (s/m)
C  rc       | total surface resistance (s/m)
C  rcut     | cuticle resistance (s/m )
C  rcutdo   | Dry cuticle resistance for O3 (s/m)
C  rcutds   | Dry cuticle resistance for SO2 (s/m)
C  rcutwo   | Wet cuticle resistance for O3 (s/m)
C  rg       | Ground  resistance (s/m )
C  rgo      | Ground  resistance for O3 (s/m)
C  rgs      | Ground  resistance for SO2 (s/m)
C  rh       | relative humidity fraction (0.0-1.0)
C  rm       | mesophyll resistance (s/m)
C  rsmin    | minimum stomatal resistance (s/m)
C  rst      | Stomatal resistance (s/m)
C  sd       | Snow depth        (cm)
C  sdmax    | Maximum snow depth over which snow
C           |   fraction for leaves is 1 (cm )
C  srad     | Solar irradiance (w/m2)
C  t2       | Temperature  at first level (K)
```

```
C  ts       | Surface temperature (K)
C  tmin     | Minimum temperature for stomatal
C           |    opening (C)
C  tmax     | Maxmum temperature for stomatal
C           |    opening (C)
C  topt     | Optimum temperature for stomatal
C           |    opening (C)
C  u2       | wind speed at reference height z2(m/s)
C  ustar    | friction velocity (m/s)
C  VDF      | dry deposition velocity for one LUC
C  VDG      | gaseous dry deposition velocity (m/s)
C  wst      | fraction of stomatal closure under
C           |      wet conditions (0.0-0.5)
C  z0       | roughness length (m)
C-----------------------------------------------------------------------

      IMPLICIT REAL(A-H,O-Z),INTEGER(I-N)
      PARAMETER (ng=31)        ! NUMBER OF GAS SPECIES DRY DEPOSITED
      PARAMETER (luc=26)       ! NUMBER OF LAND-USE CATEGORIES
      PARAMETER (NSIZE=13)     ! NUMBER OF SIZE BINS
      PARAMETER (np=14)        ! NUMBER OF particle species

      REAL Ra(LUC)
C
C  parameters
C
      REAL Z01(LUC), Z02(LUC), ustar(LUC)
      REAL LAI(LUC,15),LAI_F(LUC)
C
C  parameters for gaseous Vd submodule
C
      REAL VDG(LUC,NG), ALPHA(NG),BETA(NG),RM(NG),MW(NG)
      REAL Rac1(LUC),   Rac2(LUC), RcutdO(LUC), RcutwO(LUC),
     &   RcutdS(LUC),   RgS(LUC),  RgO(LUC),  SDmax(LUC),
     &    Tmin(LUC),   Tmax(LUC),   TOPT(LUC),   BVPD(LUC),
     &    PSI1(LUC),   PSI2(LUC),  RSmin(LUC),    BRS(LUC)
      LOGICAL is_dew, is_rain
C
C  external functions
C
      external amin1, amax1
C
C   Surface Roughness Length [m].
C   Z01 and Z02 are minimum and maximum z0 for each LUC.
C
      DATA   Z01              /
     &  0.0 ,  0.01,  0.0 ,  0.9 ,  2.0 ,
     &  0.4 ,  0.4 ,  2.5 ,  0.6 ,  0.2 ,
     &  0.05,  0.2 ,  0.04,  0.02,  0.02,
     &  0.02,  0.02,  0.02,  0.02,  0.05,
     &  1.0 ,  0.03,  0.1 ,  0.04,  0.6 ,
     &  0.6    /
      DATA   Z02              /
     &  0.0 ,  0.01,  0.0 ,  0.9 ,  2.0 ,
     &  0.9 ,  1.0 ,  2.5 ,  0.6 ,  0.2 ,
     &  0.2 ,  0.2 ,  0.04,  0.1 ,  0.1 ,
     &  0.1 ,  0.1 ,  0.1 ,  0.2 ,  0.05,
     &  1.0 ,  0.03,  0.1 ,  0.04,  0.9 ,
     &  0.9    /
C
C   In-canopy aerodynamic resistance [s/m].
C   Rac1 and Rac2 are minimum and maximum Rac0 for each LUC.
C
```

```
      DATA   Rac1            /
     &  0   ,  0   ,  0   ,  100 ,  250 ,
     &  60  ,   60 ,  300 ,  100 ,  60  ,
     &  20  ,  40  ,  20  ,  10  ,  10  ,
     &  10  ,  10  ,  10  ,  10  ,  20  ,
     &  40  ,  0   ,  20  ,  0   ,  100 ,
     &  100    /
      DATA   Rac2            /
     &  0   ,  0   ,  0   ,  100 ,  250 ,
     &  100 ,  100 ,  300 ,  100 ,  60  ,
     &  60  ,  40  ,  20  ,  40  ,  40  ,
     &  40  ,  40  ,  50  ,  40  ,  20  ,
     &  40  ,  0   ,  20  ,  0   ,  100 ,
     &  100    /
C
C   Dry and wet cuticle resistance for O3 [s/m].
C
      DATA   RcutdO          /
     & -999 , -999 , -999 , 4000 , 6000 ,
     & 4000 , 6000 , 6000 , 8000 , 6000 ,
     & 5000 , 5000 , 4000 , 4000 , 4000 ,
     & 4000 , 4000 , 5000 , 5000 , 4000 ,
     & 6000 , 8000 , 5000 , -999 , 4000 ,
     & 4000    /
      DATA   RcutwO          /
     & -999 , -999 , -999 ,  200 ,  400 ,
     &  200 ,  400 ,  400 ,  400 ,  400 ,
     &  300 ,  300 ,  200 ,  200 ,  200 ,
     &  200 ,  200 ,  300 ,  300 ,  200 ,
     &  400 ,  400 ,  300 , -999 ,  200 ,
     &  200    /
C
C   Ground resistance for O3 [s/m].
C
      DATA   RgO            /
     & 2000 , 2000 , 2000 ,  200 ,  200 ,
     &  200 ,  200 ,  200 ,  200 ,  200 ,
     &  200 ,  200 ,  200 ,  200 ,  200 ,
     &  200 ,  200 ,  200 ,  200 ,  500 ,
     &  500 ,  500 ,  500 ,  500 ,  200 ,
     &  200    /
C
C   Dry cuticle resistance for SO2 [s/m].
C
      DATA   RcutdS          /
     & -999 , -999 , -999 , 2000 , 2500 ,
     & 2000 , 2500 , 2500 , 6000 , 2000 ,
     & 2000 , 2000 , 1000 , 1000 , 1500 ,
     & 1500 , 2000 , 2000 , 2000 , 2000 ,
     & 4000 , 2000 , 1500 , -999 , 2500 ,
     & 2500    /
C
c    & -999 , -999 , -999 , 1500 , 2500 ,
c    & 1000 , 2000 , 2000 , 6000 , 2000 ,
c    & 2000 , 2000 , 1000 , 1000 , 1500 ,
c    & 1000 , 2000 , 2000 , 2000 , 2000 ,
c    & 4000 , 2000 , 1000 , -999 , 2000 ,
c    & 2000    /
C
C   Ground resistance for SO2 [s/m].
C
      DATA   RgS            /
     &   20 ,   70 ,  20  ,  200 ,  100 ,
```

```
     &  200 ,  200 ,  100 ,  300 ,  200 ,
     &  200 ,  200 ,  200 ,  200 ,  200 ,
     &   50 ,  200 ,  200 ,  200 ,   50 ,
     &  300 ,  300 ,   50 ,  700 ,  200 ,
     &  200    /
C
C   Stomatal resistance related parameters.
C   In sequence: rsmin, brs, tmin, tmax, topt, bvpd, psi1, psi2
C
      DATA   rsmin            /
     & -999 , -999 , -999 ,  250 ,  150 ,
     &  250 ,  150 ,  150 ,  250 ,  150 ,
     &  150 ,  250 ,  150 ,  100 ,  120 ,
     &  120 ,  120 ,  250 ,  125 ,  150 ,
     &  200 ,  150 ,  150 , -999 ,  150 ,
     &  150   /
      DATA   brs              /
     & -999 , -999 , -999 ,   44 ,   40 ,
     &   44 ,   43 ,   40 ,   44 ,   40 ,
     &   44 ,   44 ,   50 ,   20 ,   40 ,
     &   40 ,   50 ,   65 ,   65 ,   40 ,
     &   42 ,   25 ,   40 , -999 ,   44 ,
     &   43   /
      DATA   tmin             /
     & -999 , -999 , -999 ,   -5 ,    0 ,
     &   -5 ,    0 ,    0 ,    0 ,    0 ,
     &   -5 ,    0 ,    5 ,    5 ,    5 ,
     &    5 ,    5 ,    5 ,   10 ,    5 ,
     &    0 ,   -5 ,    0 , -999 ,   -3 ,
     &    0   /
      DATA   tmax             /
     & -999 , -999 , -999 ,   40 ,   45 ,
     &   40 ,   45 ,   45 ,   45 ,   45 ,
     &   40 ,   45 ,   40 ,   45 ,   45 ,
     &   45 ,   45 ,   45 ,   45 ,   45 ,
     &   45 ,   40 ,   45 , -999 ,   42 ,
     &   45   /
      DATA   topt             /
     & -999 , -999 , -999 ,   15 ,   30 ,
     &   15 ,   27 ,   30 ,   25 ,   30 ,
     &   15 ,   25 ,   30 ,   25 ,   27 ,
     &   27 ,   25 ,   25 ,   30 ,   25 ,
     &   22 ,   20 ,   20 , -999 ,   21 ,
     &   25   /
      DATA   bvpd             /
     & -999 , -999 , -999 ,  0.31,  0.27,
     &  0.31,  0.36,  0.27,  0.31,  0.27,
     &  0.27,  0.27,  0.0 ,  0.0 ,  0.0 ,
     &  0.0 ,  0.0 ,  0.0 ,  0.0 ,  0.0 ,
     &  0.31,  0.24,  0.27, -999 ,  0.34,
     &  0.31   /
      DATA   psi1            /
     & -999 , -999 , -999 , -2.0 , -1.0 ,
     & -2.0 , -1.9 , -1.0 , -1.0 , -2.0 ,
     & -2.0 , -2.0 , -1.5 , -1.5 , -1.5 ,
     & -1.5 , -1.5 , -1.5 , -1.5 , -1.5 ,
     & -1.5 ,    0 , -1.5 , -999 , -2.0 ,
     & -2.0    /
      DATA   psi2            /
     & -999 , -999 , -999 , -2.5 , -5.0 ,
     & -2.5 , -2.5 , -5.0 , -4.0 , -4.0 ,
     & -4.0 , -3.5 , -2.5 , -2.5 , -2.5 ,
     & -2.5 , -2.5 , -2.5 , -2.5 , -2.5 ,
```

```
     & -3.0 , -1.5 , -2.5 , -999 , -2.5 ,
     & -3.0    /
C
C Leaf area index at the beginning of each month (im=1,13),
C  minimum LAI (im=14) and maximum LAI (im=15).
C Values of LAI are from GEM, provided by Stephane Belair and Judy St-James,
C with modifications for urban.
C
      DATA (LAI(6,im), im = 1, 15)/
     & 0.1  , 0.1  , 0.5  , 1.0  , 2.0  ,
     & 4.0  , 5.0  , 5.0  , 4.0  , 2.0  ,
     & 1.0  , 0.1  , 0.1  , 0.1  , 5.0  /
      DATA (LAI(7,im), im = 1, 15)/
     & 0.1  , 0.1  , 0.5  , 1.0  , 2.0  ,
     & 4.0  , 5.0  , 5.0  , 4.0  , 2.0  ,
     & 1.0  , 0.1  , 0.1  , 0.1  , 5.0  /
      DATA (LAI(11,im), im = 1, 15)/
     & 0.5  , 0.5  , 1.0  , 1.0  , 1.5  ,
     & 2.0  , 3.0  , 3.0  , 2.0  , 1.5  ,
     & 1.0  , 0.5  , 0.5  , 0.5  , 3.0  /
      DATA (LAI(14,im), im = 1, 15)/
     & 0.5  , 0.5  , 0.5  , 0.5  , 0.5  ,
     & 0.5  , 1.0  , 2.0  , 2.0  , 1.5  ,
     & 1.0  , 1.0  , 0.5  , 0.5  , 2.0  /
      DATA (LAI(15,im), im = 1, 15)/
     & 0.1  , 0.1  , 0.1  , 0.5  , 1.0  ,
     & 2.0  , 3.0  , 3.5  , 4.0  , 0.1  ,
     & 0.1  , 0.1  , 0.1  , 0.1  , 4.0  /
      DATA (LAI(16,im), im = 1, 15)/
     & 0.1  , 0.1  , 0.1  , 0.5  , 1.0  ,
     & 2.5  , 4.0  , 5.0  , 6.0  , 0.1  ,
     & 0.1  , 0.1  , 0.1  , 0.1  , 6.0  /
      DATA (LAI(17,im), im = 1, 15)/
     & 0.1  , 0.1  , 0.1  , 0.5  , 1.0  ,
     & 3.0  , 4.0  , 4.5  , 5.0  , 0.1  ,
     & 0.1  , 0.1  , 0.1  , 0.1  , 5.0  /
      DATA (LAI(18,im), im = 1, 15)/
     & 0.1  , 0.1  , 0.1  , 0.5  , 1.0  ,
     & 2.0  , 3.0  , 3.5  , 4.0  , 0.1  ,
     & 0.1  , 0.1  , 0.1  , 0.1  , 4.0  /
      DATA (LAI(19,im), im = 1, 15)/
     & 0.1  , 0.1  , 0.1  , 0.5  , 1.0  ,
     & 3.0  , 4.0  , 4.5  , 5.0  , 0.1  ,
     & 0.1  , 0.1  , 0.1  , 0.1  , 5.0  /
      DATA (LAI(21,im), im = 1, 15)/
     & 0.1  , 0.1  , 0.1  , 0.1  , 0.5  ,
     & 1.0  , 1.0  , 1.0  , 1.0  , 1.0  ,
     & 0.4  , 0.1  , 0.1  , 0.1  , 1.0  /
      DATA (LAI(22,im), im = 1, 15)/
     & 1.0  , 1.0  , 0.5  , 0.1  , 0.1  ,
     & 0.1  , 0.1  , 1.0  , 2.0  , 1.5  ,
     & 1.5  , 1.0  , 1.0  , 0.1  , 2.0  /
      DATA (LAI(25,im), im = 1, 15)/
     & 3.0  , 3.0  , 3.0  , 4.0  , 4.5  ,
     & 5.0  , 5.0  , 5.0  , 4.0  , 3.0  ,
     & 3.0  , 3.0  , 3.0  , 3.0  , 5.0  /
      DATA (LAI(26,im), im = 1, 15)/
     & 3.0  , 3.0  , 3.0  , 4.0  , 4.5  ,
     & 5.0  , 5.0  , 5.0  , 4.0  , 3.0  ,
     & 3.0  , 3.0  , 3.0  , 3.0  , 5.0  /
C
C  Gas Properties (Total 31 species)
C
```

```
C  Mesophyll resistance RM, scaling factors ALPHA and BETA, molecular weight.
C
      DATA   RM            /
     & 0.   , 0.   , 0.   ,  0.  ,  0.  ,
     & 0.   , 0.   , 0.   ,  0.  ,  0.  ,
     & 0.   , 0.   , 0.   ,  0.  ,  100.,
     & 100. , 100. , 100. ,  100.,  0.  ,
     & 100. , 0.   , 0.   ,  0.  ,  0.  ,
     & 0.   , 0.   , 0.   ,  0.  ,  100.,
     & 100.     /

      DATA   ALPHA          /
     & 1.   , 1.   , 0.   ,  0.  ,  1.  ,
     & 10.  , 2.   , 5.   ,  1.  ,  0.  ,
     & 0.   , 0.   , 0.   ,  0.8 ,  0.  ,
     & 0.   , 0.   , 0.   ,  0.  ,  0.  ,
     & 0.   , 0.01 , 0.6  ,  0.6 ,  0.4 ,
     & 0.01 , 2.   , 1.5  ,  0.1 ,  0.  ,
     & 0.       /

      DATA   BETA          /
     & 0.   , 1.   , 0.8  ,  1.  ,  1.  ,
     & 10.  , 2.   , 5.   ,  0.0 ,  0.6 ,
     & 0.6  , 0.8  , 0.3  ,  0.2 ,  0.05,
     & 0.05 , 0.05 , 0.05 ,  0.05,  0.05,
     & 0.05 , 0.   , 0.1  ,  0.  ,  0.  ,
     & 0.   , 0.   , 0.   ,  0.8 ,  0.5 ,
     & 0.5      /

      DATA   MW          /
     & 64.  , 98.  , 46.  ,  48. ,  34. ,
     & 63.  , 47.  , 79.  ,  17. ,  121.,
     & 135. , 183. , 147. ,  30. ,  44. ,
     & 58.  , 72.  , 128. ,  106.,  70. ,
     & 70.  , 72.  , 32.  ,  46. ,  60. ,
     & 104. , 46.  , 60.  ,  48. ,  77. ,
     & 147.     /
C
C  Maximum snow depth over which snow fraction for leaves is 1.0
C  Snow fraction for ground is treated 2 times of that for leaves
C
      DATA SDMAX  /
     &             9999. , 1.0   , 9999. ,  200. ,  400. ,
     &              200. , 200.  ,  400. ,  200. ,   50. ,
     &               50. ,  50.  ,   5.  ,   20. ,   10. ,
     &               10. ,  10.  ,  10.  ,   10. ,   10. ,
     &               50. ,   2.  ,  10.  ,    2. ,  200. ,
     &              200.        /

C  parameters for air dynamic properties
      DATA AA1/1.257/, AA2/0.4/, AA3/1.1/
      DATA AMFP /6.53E-8/, ROAROW/1.19/,
     &    BOLTZK/1.3806044503487214E-23/
C
C Define the function for saturation vapor pressure (mb)
C
      ES(TEMP) = 6.108*EXP(17.27*(TEMP - 273.16)/(TEMP - 35.86))
C
C   Some constants
C
      dair=0.369*29.+6.29
      dh2o=0.369*18.+6.29
```

```
C  Initialize Leaf Area Index for LUC with constant LAI values
      DO im=1, 15
      LAI(1,im)=0.
      LAI(2,im)=0.
      LAI(3,im)=0.
      LAI(4,im)=5.
      LAI(5,im)=6.
      LAI(8,im)=6.
      LAI(9,im)=4.
      LAI(10,im)=3.
      LAI(12,im)=3.
      LAI(13,im)=1.
      LAI(20,im)=1.
      LAI(23,im)=4.
      LAI(24,im)=0.
      END DO

      VDG=0.
C
C Loop 200 for LUC
C
      DO 200 I=1,LUC
C
C interpolate LAI
C
           IM = INT(iday / 30.5 ) + 1
           iday_M =iday - INT((IM-1)*30.5+0.5)
           IF (iday_M.EQ.0) THEN
           IM=IM-1
           iday_M =iday - (IM-1)*30.5
           END IF

           LAI_F(I)  = LAI(I,IM)
     &          + iday_M / 30.5 * (LAI(I,IM+1)-LAI(I,IM))
C
C    Set minimum wind speed as 0.8 m/s
           U2 = amax1(U2,0.8)
C    Potential temperature at reference height Z2
           T2P = T2 + Z2 * 0.0098
C
C  Calculating friction velocity and stability related varibles
C
C  for water surfaces (LUC 1, 3), z0 is a function of wind speed
C
      IF(I.EQ.1.OR.I.EQ.3)  THEN
             E = RH * ES(T2)
             Q = 0.622 * E/(PMB-E)
             T2PV = T2P * (1. + 0.61 * Q)
             E = ES(TS)
             QS = 0.622 * E / (PMB - E)
             TSV = TS * (1. + 0.61 * QS)
             DTHV = (T2PV - TSV)
             CUN=7.5E-4+6.7E-5*U2
             EL=9999.
             IF(ABS(DTHV).GT.1.0E-6)
     &       EL=T2PV*CUN**1.5*U2**2/(5.096E-3*DTHV)
             IF(EL.GT.0..AND.EL.LT.5.0) EL = 5.0
             IF(EL.GT.-5.0.AND.EL.LT.0) EL =-5.0
             ZL = Z2/EL

             IF(ZL.LT.0.0) THEN
                X=(1.0 - 15.0*ZL)**0.25
                PSIU=2.*ALOG(0.5*(1.0+X))+ALOG(0.5*(1.0+X*X))-
```

```
     &                  2.0*ATAN(X) + 0.5*3.1415926
               Y=SQRT(1.-9.*ZL)
               PSIT=2.*0.74*ALOG((1+Y)/2.)
            ELSE
               PSIU = -4.7*ZL
               PSIT = PSIU
            ENDIF

            Z0_F = 0.000002 * U2**2.5
            USTAR(I) = 0.4*U2/(ALOG(Z2/Z0_F) - PSIU)
           THSTAR = 0.4*(T2P-TS)/(0.74*ALOG(Z2/Z0_F)-PSIT)
c
C  for LUC other than water
C
      ELSE

            IF (Z02(I).GT.Z01(I)) THEN
             Z0_F=Z01(I)+(LAI_F(I)-LAI(I,14))/(LAI(I,15)-LAI(I,14))
     &                       *(Z02(I)-Z01(I))
            ELSE
             Z0_F=Z01(I)
            END IF
            RIB = 9.81*Z2*(T2P - TS)/(TS*U2**2)
            IF (SRAD.GT.0.0.AND.RIB.GT.0.0) RIB = 1.E-15
            DELTAT = T2P - TS
            IF(ABS(DELTAT).LT.1.E-10) DELTAT=SIGN(1.E-10,DELTAT)
            TBAR = 0.5*(T2P + TS)
            RATIOZ = Z2/Z0_F
            ASQ = 0.16/(ALOG(RATIOZ))**2

            IF(RIB.LE.0.)THEN
              AA = ASQ*9.4*SQRT(RATIOZ)
              CM = 7.4*AA
              CH = 5.3*AA
              FM = 1. - (9.4*RIB/(1. + CM*SQRT(ABS(RIB))))
              FH = 1. - (9.4*RIB/(1. + CH*SQRT(ABS(RIB))))
            ELSE
              FM = 1./((1. + 4.7*RIB)**2)
              FH = FM
            ENDIF

             USTARSQ = ASQ*U2**2*FM
             UTSTAR = ASQ*U2*DELTAT*FH/0.74
             USTAR(I) = SQRT(USTARSQ)
             THSTAR = UTSTAR/USTAR(I)
             EL = TBAR*USTARSQ/(0.4*9.81*THSTAR)
            IF(EL.GT.0..AND.EL.LT.5.0) EL = 5.0
            IF(EL.GT.-5.0.AND.EL.LT.0) EL =-5.0
             ZL=Z2/EL
      ENDIF
C
C  Aerodynamic resistance above canopy
C
      IF(ZL.GE.0.) THEN
          Ra(I)=(.74*ALOG(Z2/Z0_F)+4.7*ZL)/0.4/USTAR(I)
      ELSE
          Ra(I)=0.74/0.4/USTAR(I)*(ALOG(Z2/Z0_F)-
     &          2*ALOG((1+SQRT(1-9.*ZL))*0.5))
      ENDIF

      Ra(I)=amax1(Ra(I),5.0)
      if (I.EQ.1.OR.I.EQ.3) THEN
          Ra(I)=amin1(Ra(I),2000.)
```

```
      else
          Ra(I)=amin1(Ra(I),1000.)
      end if
C
C  STOMATAL RESISTANCE FOR WATER VAPOR ONLY. STEPS FOR CALCULATING:
C  1. Calculate direct and diffuse PAR from solar radiation
C  2. Calculate sunlit and shaded leaf area, PAR for sunlit and shaded leaves
C  3. Calculate stomatal conductance
C  4. Calculate stomatal resistance for water vapor
C
C  Set a big value for stomatal resistance when stomata are closed
   RST=99999.9
C
C  Only calculate stomatal resistance if there is solar radiation,
C  leaf area index is not zero, and within reasonable temperature range
C
      IF ( SRAD.GE.0.1             .AND.
     &     TS.LT.(Tmax(I)+273.15)  .AND.
     &     TS.GT.(Tmin(I)+273.15)  .AND.
     &     LAI_F(I).GT.0.001           .AND.
     &     COSZEN.GT.0.001               ) THEN

C  Calculate direct and diffuse PAR from solar radiation and solar zenith angle

      RDU=600.*EXP(-0.185/COSZEN)*COSZEN
      RDV=0.4*(600.-RDU)*COSZEN
      WW=-ALOG(COSZEN)/2.302585
      WW=-1.195+0.4459*WW-0.0345*WW**2
      WW=1320*10**WW
      RDM=(720.*EXP(-0.06/COSZEN)-WW)*COSZEN
      RDN=0.6*(720-RDM-WW)*COSZEN
      RV=amax1(0.1,RDU+RDV)
      RN=amax1(0.01,RDM+RDN)
      RATIO=amin1(0.9,SRAD/(RV+RN))
      SV=RATIO*RV                           ! Total PAR
      FV=amin1(0.99, (0.9-RATIO)/0.7)
      FV=amax1(0.01,RDU/RV*(1.0-FV**0.6667))  !fraction of PAR in the direct beam
      PARDIR=FV*SV                          ! PAR from direct radiation
      PARDIF=SV-PARDIR                      ! PAR from diffuse radiation
C
C Calculate sunlit and shaded leaf area, PAR for sunlit and shaded leaves
C
      IF (LAI_F(I).GT.2.5.AND.SRAD.GT.200.) THEN
      PSHAD=PARDIF*EXP(-0.5*LAI_F(I)**0.8)
     & +0.07*PARDIR*(1.1-0.1*LAI_F(I))*EXP(-COSZEN)
      PSUN=PARDIR**0.8*.5/COSZEN+PSHAD
      ELSE
      PSHAD=PARDIF*EXP(-0.5*LAI_F(I)**0.7)
     & +0.07*PARDIR*(1.1-0.1*LAI_F(I))*EXP(-COSZEN)
      PSUN=PARDIR*.5/COSZEN+PSHAD
      END IF
      RSHAD=RSmin(I)+BRS(I)*RSMIN(I)/PSHAD
      RSUN=RSmin(I)+BRS(I)*RSMIN(I)/PSUN
      GSHAD=1./RSHAD
      GSUN=1./RSUN
      FSUN=2*COSZEN*(1.-EXP(-0.5*LAI_F(I)/COSZEN))  ! Sunlit leaf area
      FSHAD=LAI_F(I)-FSUN                   ! Shaded leaf area

C  Stomatal conductance before including effects of temperature,
C                 vapor pressure deficit and water stress.

      GSPAR=FSUN*GSUN+FSHAD*GSHAD
```

```
C --  function for temperature effect
      T=TS-273.15
      BT=(Tmax(I)-TOPT(I))/(TOPT(I)-Tmin(I))
      GT=(Tmax(I)-T)/(TMAX(I)-TOPT(I))
      GT=GT**BT
      GT=GT*(T-Tmin(I))/(TOPT(I)-TMIN(I))
C --  function for vapor pressure deficit
      D0= ES(TS)*(1.- RH)/10.           !kPa
      GD=1.-BVPD(I)*D0
C --  function for water stress
      PSI=(-0.72-0.0013*SRAD)
c      PSI_S=(-0.395-0.043*(TS-273.15))*102.
      GW=(PSI-PSI2(I))/(PSI1(I)-PSI2(I))
      IF (GW.GT.1.0) GW=1.0
      IF (GW.LT.0.1) GW=0.1
      IF (GD.GT.1.0) GD=1.0
      IF (GD.LT.0.1) GD=0.1
C --  Stomatal resistance for water vapor
      RST=1.0/(GSPAR*GT*GD*GW)

      END IF
C
c  Decide if dew or rain occurs.
C
      IF (FCLD.LT.0.25) THEN
        Coedew=0.3
      ELSE  IF (FCLD.GE.0.25.AND.FCLD.LT.0.75) THEN
         Coedew=0.2
      ELSE
        Coedew=0.1
      END IF
         DQ=0.622/1000. * ES(TS)*(1.- RH)*1000.    ! unit g/kg
         DQ=amax1(0.0001,DQ)
         USMIN=1.5/DQ*Coedew

      IF (TS.GT.273.15 .AND. PREC.GT.0.20) then
        is_rain = .true.
        is_dew = .false.
      ELSE IF (TS.GT.273.15 .AND. USTAR(I).LT.USMIN)THEN
        is_dew = .true.
        is_rain = .false.
      ELSE
        is_rain = .false.
        is_dew = .false.
      END IF
C
C  Decide fraction of stomatal blocking due to wet conditions
C
      Wst=0.
      if ((is_dew.or.is_rain).and.SRAD.GT.200.) then
      Wst=(SRAD-200.)/800.
      Wst=amin1(Wst, 0.5)
      end if
C
C  In-canopy aerodynamic resistance
C
        Rac = Rac1(I)+(LAI_F(I)-LAI(I,14))/(LAI(I,15)-LAI(I,14)+1.E-10)
     &           *(Rac2(I)-Rac1(I))
        Rac = Rac*LAI_F(I)**0.25/USTAR(I)/USTAR(I)
C
C  Ground resistance for O3
C
      IF (I.GE.4.AND.TS.LT.272.15) THEN
```

```fortran
          RgO_F = amin1( RgO(I)*2., RgO(I) * exp(0.2*(272.15-TS)))
        ELSE
          RgO_F = RgO(I)
        END IF
C
C  Ground resistance for SO2
C
        IF (I.EQ.2) THEN
          RgS_F = AMIN1(RgS(I)*(275.15-TS), 500.)
          RgS_F = AMAX1(RgS(I), 100.)
        ELSE IF (I.GE.4.AND.is_rain) THEN
          RgS_F = 50.
        ELSE IF (I.GE.4.AND.is_dew) THEN
          RgS_F = 100.
        ELSE IF (I.GE.4.AND.TS.LT.272.15) THEN
          RgS_F = amin1( RgS(I)*2., RgS(I) * exp(0.2*(272.15-TS)))
        ELSE
          RgS_F =  RgS(I)
        END IF
C
C  Cuticle resistance for O3 AND SO2
C
        IF (RcutdO(I).LE.-1) THEN
          RcutO_F = 1.E25
          RcutS_F = 1.E25
        ELSE IF (is_rain) THEN
          RcutO_F = RcutwO(I)/LAI_F(I)**0.5/USTAR(I)
          RcutS_F = 50./LAI_F(I)**0.5/USTAR(I)
          RcutS_F = MAX (RcutS_F, 20.)
        ELSE IF (is_dew) THEN
          RcutO_F = RcutwO(I)/LAI_F(I)**0.5/USTAR(I)
          RcutS_F = 100./LAI_F(I)**0.5/USTAR(I)
          RcutS_F = MAX (RcutS_F, 20.)
        ELSE IF (TS.LT.272.15) THEN
          RcutO_F = RcutdO(I)/exp(3.*RH)/LAI_F(I)**0.25/USTAR(I)
          RcutS_F = RcutdS(I)/exp(3.*RH)/LAI_F(I)**0.25/USTAR(I)
          RcutO_F = amin1( RcutO_F*2., RcutO_F * exp(0.2*(272.15-TS)))
          RcutS_F = amin1( RcutS_F*2., RcutS_F * exp(0.2*(272.15-TS)))
          RcutO_F = MAX (RcutO_F,100.)
          RcutS_F = MAX (RcutS_F,100.)
        ELSE
          RcutO_F = RcutdO(I)/exp(3.*RH)/LAI_F(I)**0.25/USTAR(I)
          RcutS_F = RcutdS(I)/exp(3.*RH)/LAI_F(I)**0.25/USTAR(I)
          RcutO_F = MAX (RcutO_F,100.)
          RcutS_F = MAX (RcutS_F,100.)
        END IF
C
C  If snow occurs, Rg and Rcut are adjusted by snow cover fraction
C
          fsnow= sd/sdmax(i)
          fsnow= amin1(1.0, fsnow)   !snow cover fraction for leaves
        If (fsnow.GT.0.0001.and.I.GE.4) THEN
          RsnowS= AMIN1(70.*(275.15-TS), 500.)
          RsnowS= AMAX1(RSnowS, 100.)
          RcutS_F=1.0/((1.-fsnow)/RcutS_F+fsnow/RsnowS)
          RcutO_F=1.0/((1.-fsnow)/RcutO_F+fsnow/2000.)
          fsnow= amin1(1.0, fsnow*2.)   !snow cover fraction for ground
          RgS_F=1.0/((1.-fsnow)/RgS_F+fsnow/RsnowS)
          RgO_F=1.0/((1.-fsnow)/RgO_F+fsnow/2000.)
        END IF

C
C  Loop 100 for gas species
```

```
C
      DO 100 J=1,NG
C
C  Calculate diffusivity for each gas species
C
        dgas=0.369*MW(J)+6.29
        DI=0.001*TS**1.75*SQRT((29.+MW(J))/MW(J)/29.)
        DI=DI/1.0/(dair**0.3333+dgas**0.3333)**2
        VI=145.8*1.E-4*(TS*0.5+T2*0.5)**1.5/
     &                 (TS*0.5+T2*0.5+110.4)
        VI=VI/ROAROW
C
C  Calculate quasi-laminar resistance
C
        Rb  =5./USTAR(I)*(VI/DI)**.666667
C
C  Calculate stomatal resistance for each species from the ratio of
C  diffusity of water vapor to the gas species
C
        DVh2o=0.001*TS**1.75*SQRT((29.+18.)/29./18.)
        DVh2o=DVh2o/(dair**0.3333+dh2o**0.3333)**2
        RS=RST*DVh2o/DI+RM(J)
C
C  Scale cuticle and ground resistances for each species
C
        Rcut = 1./(ALPHA(J)/RcutS_F+BETA(J)/RcutO_F)
        Rg = 1./(ALPHA(J)/RgS_F+BETA(J)/RgO_F)
C
C  Calculate total surface resistance
C
        Rc = (1.-Wst)/Rs+1./(Rac+Rg)+1./Rcut
        Rc=amax1(10.0,1./Rc)        !Set minimum surface resistance as 10 s/m
C
C  Deposition velocity
C
        VDG(I,J) = 1./(RA(I)+RB+RC)

100   CONTINUE   ! end of gaseous species

200   CONTINUE   ! end of LUC

      RETURN
      END

      SUBROUTINE PMVdBulk (Ra, Ustar, LAI_F, VDP)

      IMPLICIT NONE
      INTEGER, PARAMETER :: NP=3        ! NUMBER OF particle species
      INTEGER, PARAMETER :: LUC=26      ! NUMBER OF landuse types
      REAL :: Ra(LUC), Ustar(LUC), LAI_F(LUC)    ! Input
      REAL :: VDP(LUC,NP)         ! Output

C  internal variables

      real  Vds1Fac(LUC)    ! Fitted factors for ground PM2.5    deposition.
      real  Vds2Fac(LUC,6)  ! Fitted factors for ground PM2.5-10 deposition.
      real  Vds3Fac(LUC,6)  ! Fitted factors for ground PM10+    deposition.

      real  VG(NP)          ! gravitational dry deposition for PM2.5, PM2.5-10 and
PM10+.
      real  zLAImax(LUC)    ! Maximum Leave Area Index (LAI) for 26 LUCs used for
fitted function.
```

```
      real :: xU1, xU2, xU3,fac, b
      integer :: I,J

C  for convinence purpose, I give maximum leaf are index for other LUCs equal to
999.00.
      DATA zLAImax / 999.00, 999.00, 999.00, 999.00, 999.00,
     &  5.00,
     &  5.00,
     &  999.00, 999.00, 999.00,
     &  3.00,
     &  999.00, 999.00,
     &  2.02,
     &  3.99,
     &  5.98,
     &  4.99,
     &  3.99,
     &  4.99,
     &  999.00, 999.00, 999.00, 999.00, 999.00, 999.00, 999.00/

      DATA VG  /3.673E-5, 1.782E-3, 3.447E-2/ ! m/s

      DATA (Vds1Fac(I), I=1,LUC)   /
     & 0.0069, 0.0043, 0.0069, 0.0043, 0.0043, 0.0043,
     & 0.0043, 0.0034, 0.0043, 0.0048, 0.0048, 0.0054,
     & 0.0054, 0.0048, 0.0054, 0.0054, 0.0054, 0.0048,
     & 0.0054, 0.0054, 0.0043, 0.0043, 0.0054, 0.0043,
     & 0.0043, 0.0043 /
      DATA ((Vds2Fac(I, J), J=1,6), I=1,LUC)   /
     &  0.25700,-1.31100, 2.96900, 0.00000,    0.00000,    0.00000,
     &  0.39490,-3.33800, 8.77900, 0.00000,    0.00000,    0.00000,
     &  0.25700,-1.31100, 2.96900, 0.00000,    0.00000,    0.00000,
     & -0.15540, 1.50100, 0.78330, 0.00000,    0.00000,    0.00000,
     &  0.01555, 0.33750, 0.44970, 0.00000,    0.00000,    0.00000,
     & -0.11600, 1.22800, 0.71300, 4.75200,   -5.09000,    1.75900,
     &  0.01555, 0.33750, 0.44970, 1.79200,   -0.19760,   -0.53120,
     & -0.05316, 0.65500, 0.67330, 0.00000,    0.00000,    0.00000,
     &  0.06689, 0.03170, 0.11650, 0.00000,    0.00000,    0.00000,
     &  0.05621, 0.15650, 0.27600, 0.00000,    0.00000,    0.00000,
     &  0.05621, 0.15650, 0.27600, 0.73640,    1.73300,   -1.37200,
     &  0.07450, 0.12410, 0.24050, 0.00000,    0.00000,    0.00000,
     &  0.07450, 0.12410, 0.24050, 0.00000,    0.00000,    0.00000,
     & -0.07851, 1.04900, 0.66010, 5.12400,   -4.23500,    0.98450,
     & -0.06025, 1.00700, 0.65040, 3.42400,   -2.37300,    0.33680,
     & -0.06021, 1.00500, 0.64930, 3.23700,   -2.11200,    0.22550,
     &  0.07461, 0.12350, 0.24000, 0.36030,    1.59500,   -1.11200,
     &  0.05638, 0.15550, 0.27530, 0.65670,    1.42500,   -1.14600,
     &  0.07461, 0.12350, 0.24000, 0.36030,    1.59500,   -1.11200,
     &  0.07450, 0.12410, 0.24050, 0.00000,    0.00000,    0.00000,
     &  0.07102, 0.00749, 0.05691, 0.00000,    0.00000,    0.00000,
     &  0.39490,-3.33800, 8.77900, 0.00000,    0.00000,    0.00000,
     &  0.09944,-0.01280, 0.04644, 0.00000,    0.00000,    0.00000,
     &  0.39490,-3.33800, 8.77900, 0.00000,    0.00000,    0.00000,
     &  0.01555, 0.33750, 0.44970, 0.00000,    0.00000,    0.00000,
     &  0.01555, 0.33750, 0.44970, 0.00000,    0.00000,    0.00000/

      DATA ((Vds3Fac(I, J), J=1,6), I=1,LUC)   /
     &  -0.87440, -5.52260, 98.82000, 0.00000,  0.00000,    0.00000,
     &  -7.30600, 46.27000, 93.52000, 0.00000,  0.00000,    0.00000,
     &  -0.87440, -5.52260, 98.82000, 0.00000,  0.00000,    0.00000,
     &  -0.97460, 71.17000,-19.49000, 0.00000,  0.00000,    0.00000,
     &  -2.23800, 39.11000, -6.72100, 0.00000,  0.00000,    0.00000,
     &  -1.58200, 66.41000,-17.33000, 7.74500,-14.79000,    7.80100,
     &  -2.23800, 39.11000, -6.72100, 6.19200,-11.68000,    6.14000,
```

```
     &  -1.65500, 51.94000,-11.74000, 0.00000,  0.00000,    0.00000,
     &  -1.27200, 12.71000,  0.53380, 0.00000,  0.00000,    0.00000,
     &  -2.16700, 27.08000, -2.65100, 0.00000,  0.00000,    0.00000,
     &  -2.16700, 27.08000, -2.65100, 7.66300,-14.22000,    7.42200,
     &  -2.07600, 24.28000, -1.82700, 0.00000,  0.00000,    0.00000,
     &  -2.07600, 24.28000, -1.82700, 0.00000,  0.00000,    0.00000,
     &  -1.95900, 62.94000,-15.79000,10.54000,-20.10000,   10.59000,
     &  -2.02900, 61.96000,-15.37000, 7.93600,-15.11000,    7.95800,
     &  -2.02900, 61.91000,-15.35000, 7.74600,-14.74000,    7.76200,
     &  -2.07400, 24.23000, -1.81700, 6.53000,-12.04000,    6.26700,
     &  -2.16900, 27.02000, -2.63400, 6.53500,-12.12000,    6.32700,
     &  -2.07400, 24.23000, -1.81700, 6.53000,-12.04000,    6.26700,
     &  -2.07600, 24.28000, -1.82700, 0.00000,  0.00000,    0.00000,
     &  -0.71960,  6.38500,  1.42800, 0.00000,  0.00000,    0.00000,
     &  -7.30600, 46.27000, 93.52000, 0.00000,  0.00000,    0.00000,
     &  -0.09826,  2.11500,  3.25500, 0.00000,  0.00000,    0.00000,
     &  -7.30600, 46.27000, 93.52000, 0.00000,  0.00000,    0.00000,
     &  -2.23800, 39.11000, -6.72100, 0.00000,  0.00000,    0.00000,
     &  -2.23800, 39.11000, -6.72100, 0.00000,  0.00000,    0.00000/

C  Loop 200 for LUC
      DO 200 I=1,LUC

      xU1 = amax1(USTAR(I), 0.15)
      xU1 = amin1(xU1, 1.5)
      xU2 = xU1 * xU1
      xU3 = xU1 * xU1 * xU1

C  Vd(PM2.5)
      VDP(I,1)  = VG(1) + 1.0/(Ra(I)+1.0/(Vds1Fac(I)*USTAR(I))) ! m/s

C  Vd(PM2.5-10)
      fac = Vds2Fac(I,1)*xU1 + Vds2Fac(I,2)*xU2 + Vds2Fac(I,3)*xU3
      b   = Vds2Fac(I,4)*xU1 + Vds2Fac(I,5)*xU2 + Vds2Fac(I,6)*xU3
      fac = fac * EXP( b * (LAI_F(I)/zLAImax(I) - 1.0) )
      if (fac .lt. 0) write(66,*), "fac<0 PM2.5-10 (", fac, ") on line ", I

      VDP(I,2)  = VG(2) + 1.0/(Ra(I)+1.0/(fac/100.))

C  Vd(PM10+)
      fac = Vds3Fac(I,1)*xU1 + Vds3Fac(I,2)*xU2 + Vds3Fac(I,3)*xU3
      b   = Vds3Fac(I,4)*xU1 + Vds3Fac(I,5)*xU2 + Vds3Fac(I,6)*xU3
      fac = fac * EXP( b * (LAI_F(I)/zLAImax(I) - 1.0) )
      if (fac .lt. 0) write(66,*), "fac<0 PM10+ (", fac, ") on line ", I

      VDP(I,3)  = VG(3) + 1.0/(Ra(I)+1.0/(fac/100.))

200   CONTINUE   ! end of LUC

      RETURN
      END SUBROUTINE PMVdBulk
```

Appendix 2

Meteorological data input file, data structure (1I5,3I3,9F17.10)

```
 1999  1  4  0        282.35000        281.35000         19.03444          0.63000
0.00000          0.00000        980.90000         0.00000          0.25000
```

Table A2. Description of 13 inputs in the meteorological data file. The file contains 1 line for each hour during the period of calculation, e.g., 8760 lines for one year.

Input data	Unit
Year	
Month	
Day	
Hour	LST
Temperature at Z2	K
Surface temperature	K
Windspeed at Z2	m s^{-1}
RH fraction	0–1
Solar irradiance	w m^{-2}
Precipitation rate	mm hr^{-1}
Surface pressure	mb
Snow depth	cm
Cloud fraction	0–1

Appendix 3

Parameter input file, data structure (28F8.4)

```
10.0000 54.2230 00.0000 00.0000 00.0000 01.0000 00.0000 00.0000 00.0000 00.0000
00.0000 00.0000 00.0000 00.0000 00.0000 00.0000 00.0000 00.0000 00.0000 00.0000
00.0000 00.0000 00.0000 00.0000 00.0000 00.0000 00.0000 00.0000
```

Table A3. Description of the 28 inputs in the parameter file

Parameter	Unit	Description
Z2	m	reference height
latitude	dd	study site
water	0–1	landcover fraction
ice	0–1	
inland lake	0–1	
evergreen needleleaf trees	0–1	
evergreen broadleaf trees	0–1	
deciduous needleleaf trees	0–1	
deciduous broadleaf trees	0–1	
tropical broadleaf trees	0–1	
drought deciduous trees	0–1	
evergreen broadleaf shrubs	0–1	
deciduous shrubs	0–1	
thorn shrubs	0–1	
short grass and forbs	0–1	
long grass	0–1	
crops	0–1	
rice	0–1	
sugar	0–1	
maize	0–1	
cotton	0–1	
irrigated crops	0–1	
urban	0–1	
tundra	0–1	
swamp	0–1	
desert	0–1	
mixed wood forests	0–1	
transitional forest	0–1	

Appendix 4

Table A4. Description of output file (*.aout) containing average hourly V_d across land cover fractions specified in the input parameter file (Appendix 2) for 31 gaseous species and 3 particulate matter size classes, data structure (I4,3I3,46F10.5).

No.	Output (symbol)	Output (name)
1	Yr	Year
2	Mn	Month
3	Dy	Day
4	Hr	Hour
5	SO_2	Sulphur dioxide
6	H_2SO_4	Sulphuric acid
7	NO_2	Nitrogen dioxide
8	O_3	Ozone
9	H_2O_2	Hydrogen peroxide
10	HNO_3	Nitric acid
11	HONO	Nitrous acid
12	HNO_4	Pernitric acid
13	NH_3	Ammonia
14	PAN	Peroxyacetylnitrate
15	PPN	Peroxypropylnitrate
16	APAN	Aromatic acylnitrate
17	MPAN	Peroxymethacrylic nitric anhydride
18	HCHO	Formaldehyde
19	MCHO	Acetaldehyde
20	PALD	C3 Carbonyls
21	C4A	C4-C5 Carbonyls
22	C7A	C6-C8 Carbonyls
23	ACHO	Aromatic carbonyls
24	MVK	Methyl-vinyl-ketone
25	MACR	Methacrolein
26	MGLY	Methylgloxal
27	MOH	Methyl alcohol
28	ETOH	Ethyl alcohol
29	POH	C3 alcohol
30	CRES	Cresol
31	FORM	Formic acid
32	ACAC	Acetic acid
33	ROOH	Organic peroxides
34	ONIT	Organic nitrates
35	INIT	Isoprene nitrate
36	$PM_{2.5}$	Particulate matter in bulk deposition
37	$PM_{2.5–10}$	Particulate matter in bulk deposition
38	PM_{10+}	Particulate matter in bulk deposition

Appendix 5

Sensitivity analysis of the meteorological input variables

To test the sensitivity of each meteorological input variable (n= 9; see Appendix 2), we increased the value of each variable by 30% in turn, holding the other input variables constant, and re-ran the DryDep model. We then repeated the exercise but decreased each input variable by 30%. In this way, we hoped to gain a better understanding of the contribution of each input variable to the modelled V_d and the potential influence of uncertainty in the input values to the model results. The modelled V_d are reported here for sulphur dioxide (SO_2; Table A5.1) and ammonia (NH_3; Table A5.2). There are limitations to this approach, predominantly due to the co-dependence of the meteorological variables, i.e., if one variable changes, other variables are likely to change simultaneously. Further, the likelihood of each of the variables to increase or decrease by 30% naturally varies between input variables. More importantly, the model contains non-linear responses. Therefore, these sensitivity tests should be considered a preliminary exploration only. Note: where increasing or decreasing a given value by 30% resulted in a non-sensical value (e.g., windspeed < 0, or fractional value > 1), the value was set at a limit of 0 or 1, where appropriate.

These sensitivity test suggests that temperature, surface temperature, windspeed, and relative humidity have the most influence on the modelled V_d for both SO_2 and NH_3, under the conditions tested. For the remaining input variables, the change in modelled V_d was 5% or less.

Table A5.1. Input variable sensitivity analysis for the dry deposition velocity (V_d) of sulphur dioxide (SO_2).

Input	Year	V_d (base)	V_d (+30%)	V_d (% change)	V_d (–30%)	V_d (% change)
temperature	2015	0.54	0.23	-57%	1.16	115%
	2016	0.52	0.23	-56%	1.11	113%
	2017	0.55	0.24	-56%	1.12	104%
	2018	0.54	0.24	-56%	1.04	93%
	average	0.54	0.24	-56%	1.11	106%
surface temperature	2015	0.54	0.98	81%	0.09	-83%
	2016	0.52	0.94	81%	0.09	-83%
	2017	0.55	0.97	76%	0.1	-82%
	2018	0.54	0.92	70%	0.1	-81%
	average	0.54	0.95	77%	0.10	-82%
windspeed	2015	0.54	0.66	22%	0.42	-22%
	2016	0.52	0.64	23%	0.41	-21%
	2017	0.55	0.68	24%	0.43	-22%
	2018	0.54	0.65	20%	0.44	-19%
	average	0.54	0.66	22%	0.43	-21%
relative humidity	2015	0.54	0.63	17%	0.45	-17%
	2016	0.52	0.64	23%	0.44	-15%
	2017	0.55	0.66	20%	0.46	-16%
	2018	0.54	0.63	17%	0.47	-13%
	average	0.54	0.64	19%	0.46	-15%
solar irradiance	2015	0.54	0.54	0%	0.53	-2%
	2016	0.52	0.52	0%	0.52	0%
	2017	0.55	0.55	0%	0.55	0%
	2018	0.54	0.54	0%	0.54	0%
	average	0.54	0.54	0%	0.54	0%
precipitation rate	2015	0.54	0.54	0%	0.51	-6%
	2016	0.52	0.52	0%	0.49	-6%
	2017	0.55	0.55	0%	0.52	-5%
	2018	0.54	0.54	0%	0.52	-4%
	average	0.54	0.54	0%	0.51	-5%
surface pressure	2015	0.54	0.54	0%	0.54	0%
	2016	0.52	0.52	0%	0.52	0%
	2017	0.55	0.55	0%	0.55	0%
	2018	0.54	0.54	0%	0.54	0%
	average	0.54	0.54	0%	0.54	0%
snow depth	2015	0.54	0.54	0%	0.54	0%
	2016	0.52	0.53	2%	0.52	0%
	2017	0.55	0.56	2%	0.55	0%
	2018	0.54	0.55	2%	0.53	-2%
	average	0.54	0.55	1%	0.54	0%
cloud fraction	2015	0.54	0.54	0%	0.54	0%
	2016	0.52	0.52	0%	0.52	0%
	2017	0.55	0.55	0%	0.55	0%
	2018	0.54	0.54	0%	0.54	0%
	average	0.54	0.54	0%	0.54	0%

Table A5.2. Input variable sensitivity analysis for the dry deposition velocity (V_d) of ammonia (NH_3).

Input	Year	V_d (base)	V_d (+30%)	V_d (% change)	V_d (–30%)	V_d (% change)
temperature	2015	0.62	0.26	-58%	1.27	105%
	2016	0.60	0.26	-57%	1.22	103%
	2017	0.63	0.27	-57%	1.22	94%
	2018	0.61	0.27	-56%	1.14	87%
	average	0.62	0.27	-57%	1.21	97%
surface temperature	2015	0.62	1.01	63%	0.09	-85%
	2016	0.60	0.97	62%	0.09	-85%
	2017	0.63	1	59%	0.1	-84%
	2018	0.61	0.95	56%	0.1	-84%
	average	0.62	0.98	60%	0.10	-85%
windspeed	2015	0.62	0.74	19%	0.49	-21%
	2016	0.60	0.72	20%	0.48	-20%
	2017	0.63	0.76	21%	0.5	-21%
	2018	0.61	0.72	18%	0.5	-18%
	average	0.62	0.74	20%	0.49	-20%
relative humidity	2015	0.62	0.71	15%	0.52	-16%
	2016	0.6	0.72	20%	0.5	-17%
	2017	0.63	0.74	17%	0.53	-16%
	2018	0.61	0.71	16%	0.53	-13%
	average	0.62	0.72	17%	0.52	-15%
solar irradiance	2015	0.62	0.61	-2%	0.6	-3%
	2016	0.6	0.6	0%	0.59	-2%
	2017	0.63	0.63	0%	0.62	-2%
	2018	0.61	0.61	0%	0.6	-2%
	average	0.62	0.61	0%	0.60	-2%
precipitation rate	2015	0.62	0.62	0%	0.58	-6%
	2016	0.6	0.6	0%	0.57	-5%
	2017	0.63	0.63	0%	0.6	-5%
	2018	0.61	0.61	0%	0.59	-3%
	average	0.62	0.62	0%	0.59	-5%
surface pressure	2015	0.62	0.62	0%	0.62	0%
	2016	0.6	0.6	0%	0.6	0%
	2017	0.63	0.63	0%	0.63	0%
	2018	0.61	0.61	0%	0.61	0%
	average	0.62	0.62	0%	0.62	0%
snow depth	2015	0.62	0.62	0%	0.61	-2%
	2016	0.6	0.6	0%	0.6	0%
	2017	0.63	0.63	0%	0.63	0%
	2018	0.61	0.62	2%	0.6	-2%
	average	0.62	0.62	0%	0.61	-1%
cloud fraction	2015	0.62	0.62	0%	0.62	0%
	2016	0.6	0.6	0%	0.6	0%
	2017	0.63	0.63	0%	0.63	0%
	2018	0.61	0.61	0%	0.61	0%
	average	0.62	0.62	0%	0.62	0%

Appendix 6

Table A6. Ratios of grass temperature to air temperature (2 m) used to estimate surface temperature from air temperature. The temperature values were averaged for a given hour of a month (e.g., all of the 2:00 am measurements for January) across 15 meteorological stations (June 2013-July 2014).

Hour	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
00:00	0.9950	0.9954	0.9946	0.9939	0.9956	0.9946	0.9943	0.9962	0.9958	0.9953	0.9946	0.9952
01:00	0.9951	0.9953	0.9951	0.9938	0.9955	0.9949	0.9946	0.9964	0.9960	0.9954	0.9946	0.9952
02:00	0.9950	0.9952	0.9952	0.9943	0.9957	0.9953	0.9949	0.9966	0.9961	0.9955	0.9947	0.9952
03:00	0.9952	0.9952	0.9955	0.9945	0.9962	0.9956	0.9950	0.9967	0.9963	0.9956	0.9947	0.9955
04:00	0.9951	0.9953	0.9956	0.9947	0.9966	0.9967	0.9956	0.9968	0.9964	0.9958	0.9947	0.9955
05:00	0.9952	0.9952	0.9958	0.9951	0.9992	1.0011	0.9992	0.9974	0.9964	0.9959	0.9948	0.9955
06:00	0.9953	0.9953	0.9962	0.9993	1.0044	1.0076	1.0057	1.0007	0.9974	0.9958	0.9948	0.9953
07:00	0.9954	0.9952	0.9985	1.0071	1.0102	1.0140	1.0129	1.0060	1.0016	0.9968	0.9947	0.9954
08:00	0.9954	0.9970	1.0038	1.0147	1.0153	1.0198	1.0190	1.0114	1.0071	1.0008	0.9963	0.9953
09:00	0.9968	1.0012	1.0089	1.0200	1.0199	1.0239	1.0235	1.0159	1.0117	1.0057	1.0009	0.9968
10:00	1.0001	1.0048	1.0118	1.0234	1.0222	1.0270	1.0264	1.0191	1.0145	1.0088	1.0054	0.9997
11:00	1.0028	1.0071	1.0141	1.0254	1.0239	1.0287	1.0287	1.0210	1.0161	1.0107	1.0073	1.0016
12:00	1.0037	1.0070	1.0150	1.0259	1.0251	1.0300	1.0297	1.0216	1.0170	1.0112	1.0072	1.0016
13:00	1.0034	1.0064	1.0147	1.0247	1.0240	1.0294	1.0291	1.0213	1.0163	1.0104	1.0053	1.0008
14:00	1.0022	1.0048	1.0136	1.0228	1.0225	1.0282	1.0277	1.0197	1.0147	1.0089	1.0031	0.9995
15:00	0.9994	1.0028	1.0112	1.0194	1.0191	1.0253	1.0249	1.0171	1.0116	1.0049	0.9994	0.9972
16:00	0.9957	0.9995	1.0076	1.0144	1.0154	1.0215	1.0206	1.0129	1.0074	0.9999	0.9951	0.9953
17:00	0.9943	0.9962	1.0020	1.0081	1.0105	1.0167	1.0160	1.0082	1.0023	0.9954	0.9940	0.9952
18:00	0.9944	0.9952	0.9958	1.0011	1.0053	1.0104	1.0094	1.0026	0.9969	0.9940	0.9940	0.9953
19:00	0.9946	0.9955	0.9940	0.9951	1.0000	1.0031	1.0020	0.9976	0.9948	0.9942	0.9941	0.9954
20:00	0.9947	0.9954	0.9942	0.9936	0.9962	0.9968	0.9959	0.9955	0.9951	0.9944	0.9943	0.9954
21:00	0.9947	0.9955	0.9943	0.9937	0.9953	0.9942	0.9940	0.9955	0.9954	0.9946	0.9943	0.9953
22:00	0.9947	0.9954	0.9943	0.9936	0.9955	0.9941	0.9941	0.9959	0.9956	0.9950	0.9944	0.9952
23:00	0.9949	0.9954	0.9944	0.9938	0.9956	0.9943	0.9944	0.9959	0.9958	0.9950	0.9945	0.9951

Appendix 7

```
# This R script is used to estimate solar irradiance for Rio Tinto sites
using the Hargreaves and Samani method.
# The script example is for 2019 data; replace dates and files where
indicated.

# Install and load the necessary packages.

install.packages('sirad') #for estimating daily solar irradiance from
sunshine duration or temperatures.
library('sirad')
install.packages('solaR') #for estimating hourly solar irradiance from daily.
library('solaR')
require(zoo)

# Solar irradiance using Envista Haul Road, Kitimat temperatures, 2019

# Create an object for the latitude and longitude of the study site

lat_HR_Envista <- 54.0293 #coordinates from Rio Tinto
lon_HR_Envista <- -128.7019

# Create POSIXct object containing the dates for running the model.
# NOTE: If the days that you are running the model are not consecutive (i.e.,
missing days here and there), you may have to get
# creative and import a list of the actual days for the 'BTd'

BTd_HR_Envista <- fBTd(mode = "serie", start = '01/01/2019', end =
'31/12/2019', format = '%d/%m/%Y')

# Import a file containing daily maximum and minimum temperatures (see
example file in Appendix 3 folder for formatting).
# Create vector objects for the maximum temperature, minimum temperatures,
and dates.

HR_temps_Envista <- read.csv("HR_Envista_2019_ha_input.csv", header = TRUE)
tmax_HR_Envista <- HR_temps_Envista$Tmax
tmin_HR_Envista <- HR_temps_Envista$Tmin
days_HR_Envista <- HR_temps_Envista$days

# Create an object for the sirad model output and run the model. Change out
the parameters for days, lat, long, Tmax, Tmin, and
# A and B coefficients as necessary.

HR_Envista_ha <- ha(days = days_HR_Envista, lat = lat_HR_Envista, lon =
lon_HR_Envista, extraT=NULL, A=0.18, B=0, Tmax=tmax_HR_Envista,
Tmin=tmin_HR_Envista)

# Create a .csv file of the model output.
write.csv(HR_Envista_ha, file = "HR_Envista_2019_ha_MJm2.csv")

# The ha output file is in MJ/m^2 and needs to be converted to Wh/m^2 (1MJ =
277.78 Wh)
```

```
# To prep the 'sirad' ha output file for the 'solaR' input meteo file, add a 'date' column, then convert the daily solar irradiance
# from MJ/m^2 to Wh/m^2 and name the column 'G0', then add a column called 'Ta' with average daily temperature.

# Import the meteo file using the readBD function.
BD_HR_Envista_ha <- readBD("HR_Envista_ha_meteo_2019.csv", lat = lat_HR_Envista, format = '%d/%m/%Y', header = TRUE, fill = TRUE,
                           dec = '.', sep = ',', dates.col = 'date')

# Work through the following steps to create the CompI output file. Change out the lat and BTd parameters as necessary.
Sol_HR_Envista_ha <- calcSol(lat = lat_HR_Envista, BTd = BTd_HR_Envista, sample = 'hour', keep.night = TRUE, method = 'michalsky')
CompD_HR_Envista_ha <- fCompD(sol = Sol_HR_Envista_ha, G0d = BD_HR_Envista_ha, corr = "CPR")

CompI_HR_Envista_ha <- fCompI(sol = Sol_HR_Envista_ha, compD = CompD_HR_Envista_ha, filter = TRUE)

write.csv(CompI_HR_Envista_ha, file = "HR_Envista_ha_CompI_2019.csv")

# The 'G0' column in the CompI output file is the one that contains the hourly solar irradiance values for the #DryDep model.
```