HELIOSARES (ANR-09-BLAN-223)
Output format and data description

GCM –Ionosphere simulation model

Title:*	Output format and data description – GCM/Ionosphere model
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Distribution:*	*HELIOSARES project + MAVEN team*
Level:*	*low level*
Roles:*	

Version History

Version	Date	Released by	Detail
0.0	18/02/2014	R. Modolo	draft
0.1	20/02/2014	JY. Chaufray, F. leblanc	correction
0.2	15/07/2014	R. Modolo	Change after PSG discussion
1.0	28/07/2017	R. Modolo	Consolidated version

Content

1-Data accessibility and data description

1.1- Data description

Information about the model is discussed in several papers:

- For the **lower atmosphere** :

Forget, F., F. Hourdin, R. Fournier, C. Hourdin, and O. Talagrand (1999), Improved general circulation models of the Martian atmosphere from the surface to above 80 km, J. Geophys. Res., 104, 24,155– 24,175.

- For the **lower atmosphere-thermosphere**

Gonzalez-Galindo, F., F. Forget, M. A. Lopez-Valverde, M. Angelats i Coll, and E. Millour (2009), A ground-to-exosphere Martian general circulation model: 1. Seasonal, diurnal, and solar cycle variation of thermospheric temperatures, J. Geophys. Res., 114, E04001, doi:10.1029/2008JE003246

- For the **Ionosphere in the chemical equilibrium region (below 180 km)**

González-Galindo, F., J.-Y. Chaufray, M. A. López-Valverde, G. Gilli, F. Forget, F. Leblanc, R. Modolo, S. Hess, *and* M. Yagi *(*2013*),* Three-dimensional Martian ionosphere model: I. The photochemical ionosphere below 180 km, J. Geophys. Res. Planets, 118, *2105-2123, doi:*10.1002/jgre.20150.

- For the **Ionosphere from chemical equilibrium region to higher altitude (includes transport)**

Chaufray JY, F. González-Galindo , Francois Forget , Miguel López-Valverde , Francois Leblanc , R. Modolo , Sébastien Hess , Manabu Yagi , Pierre-Louis Blelly , Olivier G. Witasse, 3D Martian Ionosphere model : II Effect of transport processes due to pressure gradients, J. Geophys. Res. Planets, Accepted

Limitations :
The **ionospheric** model includes **transport related to pressure gradient force and neutral wind effects**. Transport related to magnetic forces are not taken into account in the current state of the model and simulation results.

Coordinate system:
Simulations have been performed in planetocentric latitude with longitude increasing to the east coordinate system. A “hybrid” coordinate is used on the vertical grid equivalent to a terrain following coordinate for the lower atmosphere and a pressure coordinate for the upper atmosphere and ionosphere. 50 vertical layers are used, with an uneven sampling to allow for a higher vertical resolution in the lower layers. The 30 upper layers correspond to a vertical spacing of about 7 km in the upper atmosphere.

For simplification, all quantities are provided on a single grid. The grid is a spherical grid.
Table 1 provide information on the grid structure

Variable name	Information	Min and Max	Resolution
Latitude	Latitude values of grid point	-90° to +90°	3.75°
Longitude	Longitude values of grid point	-180° to +180°	5.625°
Altitude	Altitude values of grid point	100km to 250km	2.5km

Table 1: Variables related to the grid structure

The data files include information for dominant neutral and ionic species. All species (ions, electrons and neutral) have information about the density. Zonal velocity, the meridional velocity, relative vertical velocity, and temperature (neutral, ions and electrons) are provided for the neutral atmosphere.

All neutrals have the same velocity and same temperature.
The different species stored in the output files are summarized in table 2.

Quantity	Neutral species	Charged particles
	O (atomic oxygen), CO2 (carbon dioxide), H (atomic hydrogen), H2 (molecular hydrogen)	Electrons*, O+ , CO2+, O2+
Density	**X**	X
Temperature	**X**	X
Velocity (Un,Vn,Wn)	**X**	-

Table 2: species described in the output file

* only a subset of ion species included in the model are provided in the output file (dominant species), therefore, locally we can have a slight difference between electron density and the sum of ion densities.

2.- Output format

Archived outputs files are saved in the “netCDF” format (http://www.unidata.ucar.edu/software/netcdf/).
This format is well documented and largely adopted in numerical and data archives.

General information concerning each file can be accessed through netcdf functionalities. For instance in a terminal window the command “ncdump –h Heliosares_Ionos_Ls270_SolMean1_12_02_13.nc” returns information concerning the “Heliosares_XXXX.nc” file (assuming that the netcdf package has been installed on the local machine). It is composed of three parts: 1- dimensions of variables of the files, 2- the name of the variables, their data type and dimension, 3- the attribute of the file.

To have access to the value of a specific variable, the command “ncdump –v variable_name Heliosares_Ionos_Ls270_SolMean1_12_02_13.nc” return the requested information.

Ex : If we want the Sun-Mars distance (in AU)
ncdump –v dsm Heliosares_Ionos_Ls270_SolMean1_12_02_13.nc
>>dsm = 1.388682;

In front of each line we have indicated information about the variable. Only a subset of the header is provided in table 3.

netcdf Heliosares_Ionos_Ls270_SolMean1_12_02_13 { dimensions:	
dim_scalar = 1 ;	Dimension of a scalar
AltN = 61 ;	Number of point for Altitude
nLong = 65 ;	Number of point for Longitude (or Local Time)
nLat = 49 ;	Number of point for Latitude
Numb_coef = 5 ;	Number of coefficient per reactions
variables:	
float reaction1XX(Numb_coef) ; reaction1XX:title = "h + o2 + co2 --> ho2 + co2" ;	Information about reaction 1 and coefficient used for the reaction
….	Information about reaction 61 and coefficient used for the reaction
float sunactiv(dim_scalar) ; sunactiv:units = "year" ; sunactiv:title = "Solar Activity" ;	Solar activity (in Martian year reference)
float zls(dim_scalar) ; zls:units = "rad" ; zls:title = "Solar Longitude" ;	Solar longitude
float dsm(dim_scalar) ; dsm:units = "UA" ; dsm:title = "Sun distance" ;	Sun distance
float dec(dim_scalar) ; dec:units = "rad" ; dec:title = "Declination" ;	Declination
float longsubsol(dim_scalar) ; longsubsol:units = "rad" ; longsubsol:title = "Subsolar longitude" ;	Subsloar longitude
float Longitude(nLong) ; Longitude:units = "degrees east" ; Longitude:title = "East Longitude" ;	Longitude array
float Latitude(nLat) ; Latitude:units = "degrees north" ; Latitude:title = "North Latitude" ;	Latitude array
float Altitude(AltN) ; Altitude:units = "km" ; Altitude:title = "Altitude" ;	Altitude array
float LocalTime(nLong) ; LocalTime:units = "h" ; LocalTime:title = "Local Time" ;	Local Time array
float SZA(nLat, nLong) ; SZA:units = "rad" ; SZA:title = "Solar Zenith Angle" ;	Solar zenith Angle Array
float co2(AltN, nLat, nLong) ; co2:units = "cm-3" ; co2:title = "CO2 neutral density" ;	Density array for co2
float o(AltN, nLat, nLong) ; o:units = "cm-3" ; o:title = "O neutral density" ;	Density array for O
float h(AltN, nLat, nLong) ; h:units = "cm-3" ; h:title = "H neutral density" ;	Density array for H
float h2(AltN, nLat, nLong) ;	Density array for H2

h2:units = "cm-3" ; h2:title = "H2 neutral density" ;	
float o2plus(AltN, nLat, nLong) ; o2plus:units = "cm-3" ; o2plus:title = "O2+ ion density" ;	Density array for O2+
float oplus(AltN, nLat, nLong) ; oplus:units = "cm-3" ; oplus:title = "O+ ion density" ;	Density array for O+
float co2plus(AltN, nLat, nLong) ; co2plus:units = "cm-3" ; co2plus:title = "CO2+ ion density" ;	Density array for CO2+
float elec(AltN, nLat, nLong) ; elec:units = "cm-3" ; elec:title = "e- density" ;	Density array for electrons
float Temperature(AltN, nLat, nLong) ; Temperature:units = "K" ; Temperature:title = "Tn neutral temperature" ;	Temperature array for neutrals atmospheric species
float Temp_elec(AltN, nLat, nLong) ; Temp_elec:units = "K" ; Temp_elec:title = "Te electron temperature" ;	Temperature array for electrons (Viking profile)
float Temp_ion(AltN, nLat, nLong) ; Temp_ion:units = "K" ; Temp_ion:title = "Ti ion temperature" ;	Temperature array for ions (Viking profile)
float Zonal_vel(AltN, nLat, nLong) ; Zonal_vel:units = "m.s-1" ; Zonal_vel:title = "Un Zonal Velocity neutral" ;	Zonal velocity , Un wind component
float Merid_vel(AltN, nLat, nLong) ; Merid_vel:units = "m.s-1" ; Merid_vel:title = "Vn Meridional Velocity neutral" ;	Meridional velocity, Vn wind component
float Vert_vel(AltN, nLat, nLong) ; Vert_vel:units = "m.s-1" ; Vert_vel:title = "Wn Vertical Velocity neutral" ;	Vertical velocity, Wn wind component

// global attributes:
:file_format = "NetCDF" ;
:file_format_version = 1.4f ;
:Conventions =
"http://www.unidata.ucar.edu/software/netcdf/" ;
:Program = "LMD-GCM/Ionosphere" ;
:Date = "11_07_14" ;
}	

3.- IDL reader

An example of IDL reader is shown below. It reads and extracts only part of variables stored in the file. However it is relatively easy to extend it to complementary data set recorded.

```
;==========================================

; IDL Reader for LMD GCM Ionospheric output files

;------------------------------------------

; This Reader extracts information from output file

; of the LMD GCM Ionosphere simulation model

;------------------------------------------

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; jean-yves.chaufray@latmos.ipsl.fr

; LATMOS / UVSQ / CNRS

; Created : February, 14th 2014
```

```
; Modified: July, 11th 2014
;=========================================
@C:\Users\modolo\Documents\MISSION\MAVEN\MAVEN_weblibrary\colorbar
@C:\Users\modolo\Documents\MISSION\MAVEN\MAVEN_weblibrary\map_lt_lon
@C:\Users\modolo\Documents\MISSION\MAVEN\MAVEN_weblibrary\map_lt_lon_velvect
@C:\Users\modolo\Documents\MISSION\MAVEN\MAVEN_weblibrary\plot_density_profile
@C:\Users\modolo\Documents\MISSION\MAVEN\MAVEN_weblibrary\plot_temperature_profile
@C:\Users\modolo\Documents\MISSION\MAVEN\MAVEN_weblibrary\legend

PRO Read_Heliosares_atmosphere_Ionosphere
close,/all
common data,tab,lat,lon,alt
common val,color_level,fig_title
common data1D, alt_profile, profile1,profile2,profile3,profile4,profile5,alt_profile_new
common data2D,tab2,LTime
common data3,Lat_new,Lon_new,Compzonal,Compmerid

set_plot,'win'
loadct,39
!P.font=-1

!x.thick=2
!y.thick=2

device,decomposed=0

Pi = acos(-1.0)

iwindow = 0
Alt_val = 200.; km
```

```
path = 'C:\Users\modolo\Documents\MISSION\MAVEN\MAVEN_weblibrary'
filename ='Heliosares_Ionos_Ls270_SolMean1_12_02_13.nc'

Id1=ncdf_open(path+'\'+filename,/NOWRITE)

; Reading IDs of the different variables (labels)
; Reading IDs of the different variables (labels)
Rid1 =ncdf_varid(Id1,'sunactiv')
Rid2 =ncdf_varid(Id1,'zls')
Rid3 =ncdf_varid(Id1,'dec')
Rid4 =ncdf_varid(Id1,'dsm')
Rid5 =ncdf_varid(Id1,'longsubsol')
Rid6 =ncdf_varid(Id1,'Latitude')
Rid7 =ncdf_varid(Id1,'Longitude')
Rid8 =ncdf_varid(Id1,'Altitude')
Rid9 = ncdf_varid(Id1,'LocalTime')
Rid10 = ncdf_varid(Id1,'SZA')
;;-- Reading neutral density
Rid11 =ncdf_varid(Id1,'co2')
Rid12 =ncdf_varid(Id1,'o')
Rid13 =ncdf_varid(Id1,'h')
Rid14 =ncdf_varid(Id1,'h2')
;;-- Reading ion and electron density
Rid15 =ncdf_varid(Id1,'o2plus')
Rid16 =ncdf_varid(Id1,'oplus')
Rid17 =ncdf_varid(Id1,'co2plus')
Rid18 =ncdf_varid(Id1,'elec')
;;- Reading Temperature
Rid19 =ncdf_varid(Id1,'Temperature')
Rid20 =ncdf_varid(Id1,'Temp_elec')
Rid21 =ncdf_varid(Id1,'Temp_ion')
```

```
;;-- Reading velocity
Rid22 =ncdf_varid(Id1,'Zonal_vel')
Rid23 =ncdf_varid(Id1,'Merid_vel')
Rid24 =ncdf_varid(Id1,'Vert_vel')
;Importing the selected data set
ncdf_varget,Id1,Rid1,sunactiv
ncdf_varget,Id1,Rid2,zls
ncdf_varget,Id1,Rid3,dec
ncdf_varget,Id1,Rid4,dsm
ncdf_varget,Id1,Rid5,longsubsol
ncdf_varget,Id1,Rid6,latitude
ncdf_varget,Id1,Rid7,longitude
ncdf_varget,Id1,Rid8,altitude
ncdf_varget,Id1,Rid9,Local_Time
ncdf_varget,Id1,Rid10,SZA

ncdf_varget,Id1,Rid11,co2
ncdf_varget,Id1,Rid12,o
ncdf_varget,Id1,Rid13,h
ncdf_varget,Id1,Rid14,h2

ncdf_varget,Id1,Rid15,o2plus
ncdf_varget,Id1,Rid16,oplus
ncdf_varget,Id1,Rid17,co2plus
ncdf_varget,Id1,Rid18,elec

ncdf_varget,Id1,Rid19,Tn
ncdf_varget,Id1,Rid20,Te
ncdf_varget,Id1,Rid21,Ti

ncdf_varget,Id1,Rid22,Un
```

```
ncdf_varget,Id1,Rid23,Vn

ncdf_varget,Id1,Rid24,Wn
```

4.- IDL visualization example

Different examples of data visualization are proposed in order to cross check that the file has been correctly read and data have been correctly displayed.

The file Heliosares_Ionos_Ls270_SolMean1_12_02_13.nc has been used to create the following figures.

4.1- O+ Density map @200km

The following script allows reforming the density map of O+ ions. The map is displayed in Latitude vs Local Time.

```
;;******************* Figure 1 *********************
;==Plotting the density map of O+ @ Alt_val
nlon = N_ELEMENTS(longitude)
nlat = N_ELEMENTS(latitude)
lat = REBIN(TRANSPOSE(latitude),nlon,nlat)
lon = REBIN(longitude,nlon,nlat)
LTime  = REBIN(Local_Time,nlon,nlat)
tab = FLTARR(nlon,nlat)


FOR ilon=0,nlon-1 DO BEGIN
 FOR ilat = 0,nlat-1 DO BEGIN
  ; find the altitude value in the Altitude map
   near = MIN(ABS(Altitude(*)-Alt_val),index)
   IF (FINITE(oplus(ilon,ilat,index),/NAN) EQ 0) THEN BEGIN ;  check if it NaN
     tab(ilon,ilat) = oplus(ilon,ilat,index)
   ENDIF ELSE BEGIN
     tab(ilon,ilat) = 0/0
   ENDELSE
 ENDFOR
ENDFOR

iwindow = iwindow+1
WINDOW,iwindow

tab = alog10(tab)
minval =-2.
maxval = 5.
color_level = FINDGEN(128)/127.*(maxval-minval)+minval
fig_title = 'Density map [log10(cm-3)] of O+ @'+STRING(Alt_val,FORMAT='(f4.0)')+' km'
map_lt_lon; IDL routine based on CONTOUR IDL function
```

O+ density map is presented in figure 3

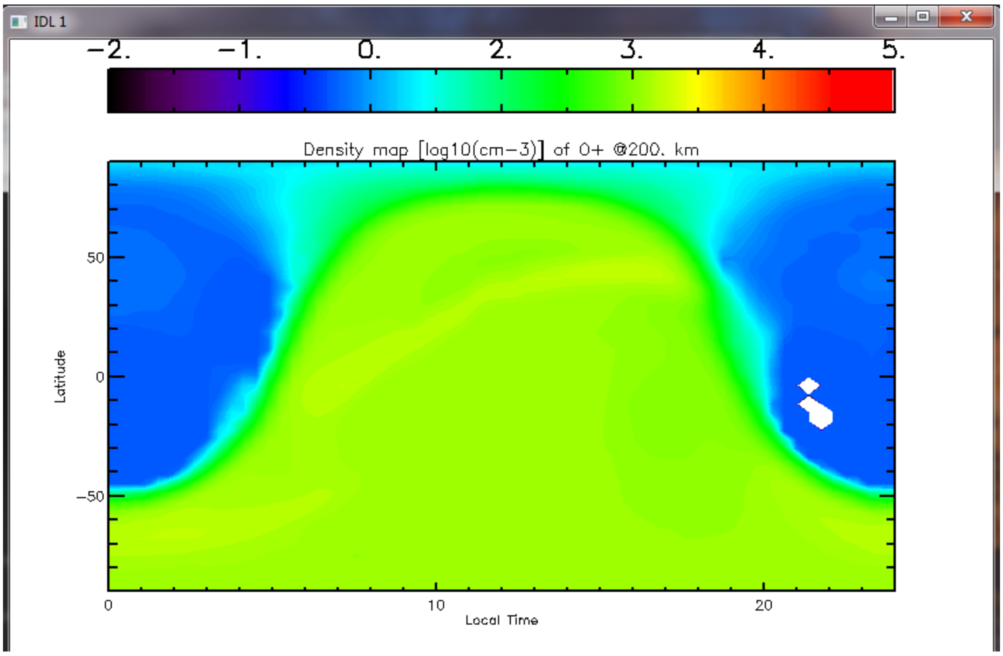

Figure 1: O+ Density map in function of latitude and local time for file Heliosares_Ionos_Ls270_SolMean1_12_02_13.nc

The density of O+ ions is expected to be larger in the dayside region (between local time 6 and 18h). Since Ls=270° the illuminated hemisphere is the Southern hemisphere therefore we also expect a North/south asymmetry with larger density values in the Southern hemisphere (negative latitude values).

4.2- Ionospheric density profile

The following script allows displaying the ioopsheric density profiles at Latitude =0° and Local Time = 12h.

```
;;;****************** Figure 2 ********************
;;==Plotting the density profile pof ionospheric species versus altitude
ilt = FIX(nlon/2.)
ilat = FIX(nlat/2)

;; Extracting profiles for LT = Local_Time(ilt) and latitude = latitude(ilat)
nalt = N_ELEMENTS(Altitude(*))

profile1    = FLTARR(nalt)
profile2    = FLTARR(nalt)
profile3    = FLTARR(nalt)
profile4    = FLTARR(nalt)
profile5    = FLTARR(nalt)

alt_profile = Altitude
profile1(*)    = elec(ilt,ilat,*)
profile2(*)    = o2plus(ilt,ilat,*)
profile3(*)    = oplus(ilt,ilat,*)
profile4(*)    = co2plus(ilt,ilat,*)


iwindow = iwindow+1
WINDOW,iwindow
```

```
fig_title = 'Density profiles [cm-3]  @ LAT = '+STRING(latitude(ilat),FORMAT='(f4.0)')+' °, LT = '+STRING(Local_Time(ilt),FORMAT='(f5.0)')+' h'
plot_density_profile
```

Figure 4 shows ionospheric density profile

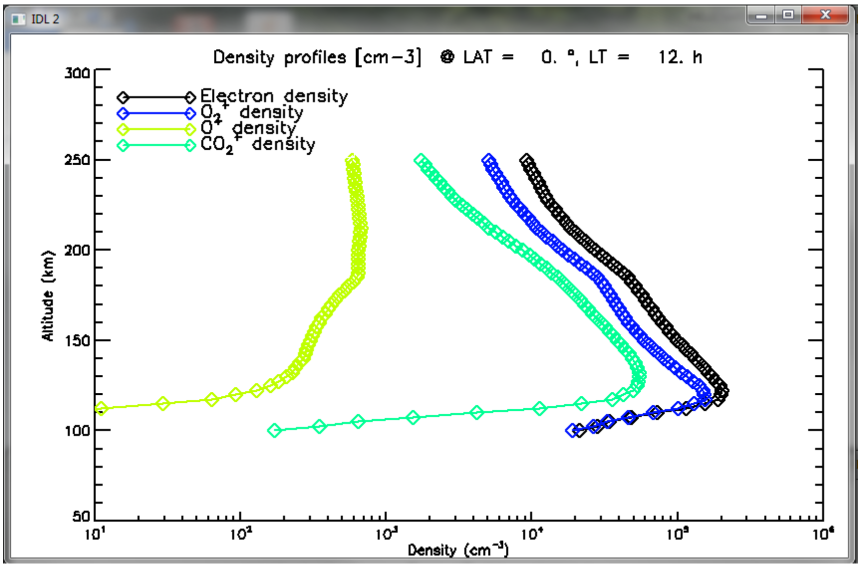

Figure 2: Ionospheric density profile with the Heliosares_Ionos_ls270_SolMean1_12_02_13.nc file

O2+ ion density is the major ion species in the ionosphere as expected. A peak density of few 10^5 cm-3, mainly due to O2+ ions, and located at about 120 km height is emphasized as expected.

4.3- Density map of Temperature at 200 km

The following IDL script presents the neutral temperature at 200 km.

```
;;;**************** Figure 3 ********************
;;== Plotting the Tn density map @ Alt_val

tab = FLTARR(nlon,nlat)


FOR ilon=0,nlon-1 DO BEGIN
  FOR ilat = 0,nlat-1 DO BEGIN
   ; find the altitude value in the Altitude map
    near = MIN(ABS(Altitude(*)-Alt_val),index)
    IF (FINITE(Tn(ilon,ilat,index),/NAN) EQ 0) THEN BEGIN ;  check if it NaN
      tab(ilon,ilat) = Tn(ilon,ilat,index)
    ENDIF ELSE BEGIN
      tab(ilon,ilat) = 0/0
    ENDELSE
  ENDFOR
ENDFOR
```

```
iwindow = iwindow+1
WINDOW,iwindow


minval =100.
maxval = 350.
color_level = FINDGEN(128)/127.*(maxval-minval)+minval
fig_title = 'Neutral Temperature map [K]  @'+STRING(Alt_val,FORMAT='(f4.0)')+' km'
map_lt_lon
```

Figure 5 presents the result obtained for the neutral temperature map.

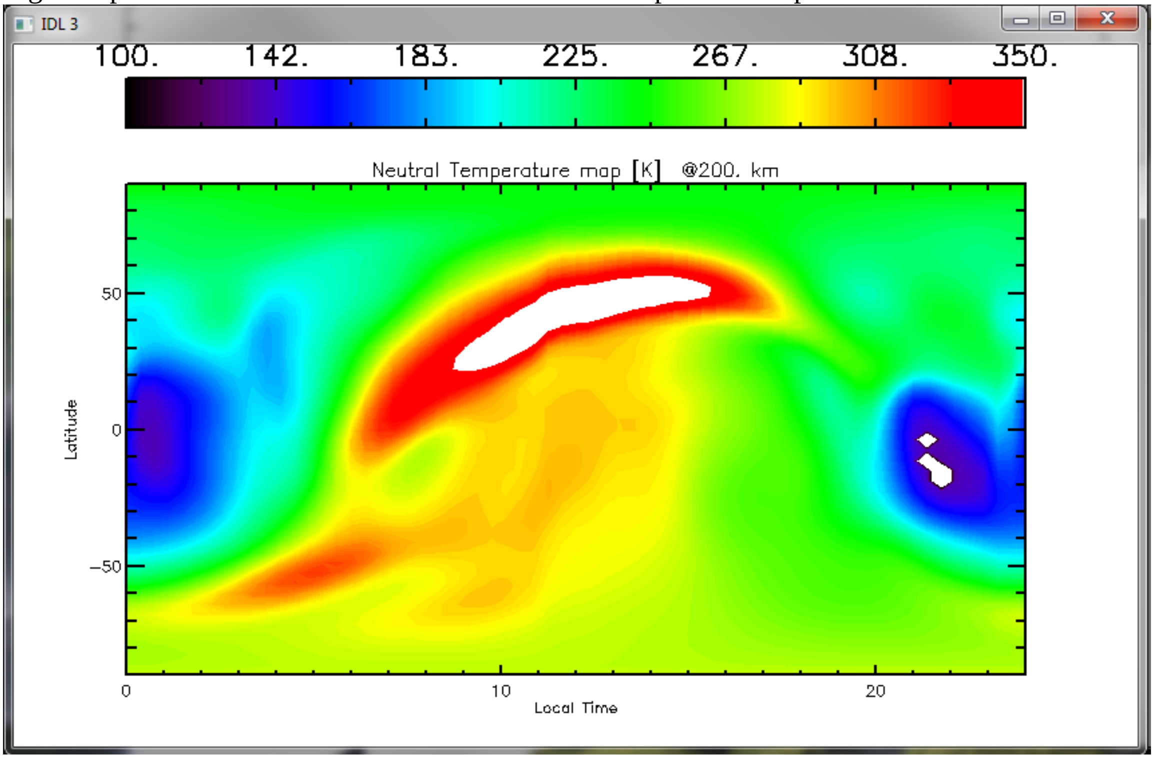

Figure 3: Temperature map of at 200 km

4.4- Temperature profiles

The following IDL script shows ions, electrons and neutral temperature profiles. Ions and electrons profiles used in the code are the Viking measurements.

```
;;******************* Figure 4 ***********************

;;== Plotting Temperature profile

ilt = FIX(nlon/2)

ilat = FIX(nlat/2)

; Extracting profiles for localtime = Local_Time(ilt) and latitude = latitude(ilat)

profile1    = FLTARR(nalt)
```

```
profile2    = FLTARR(nalt)

alt_profile = Altitude

profile1(*)    = Tn(ilt,ilat,*)

profile2(*)    = Te(ilt,ilat,*)

profile3(*)    = Ti(ilt,ilat,*)

iwindow = iwindow+1

WINDOW,iwindow

fig_title = 'Temperature profiles [K]  @ LAT = '+STRING(latitude(ilat),FORMAT='(f4.0)')+' °, LT = '+STRING(Local_Time(ilt),FORMAT='(f5.1)')+' h'

plot_temperature_profile
```

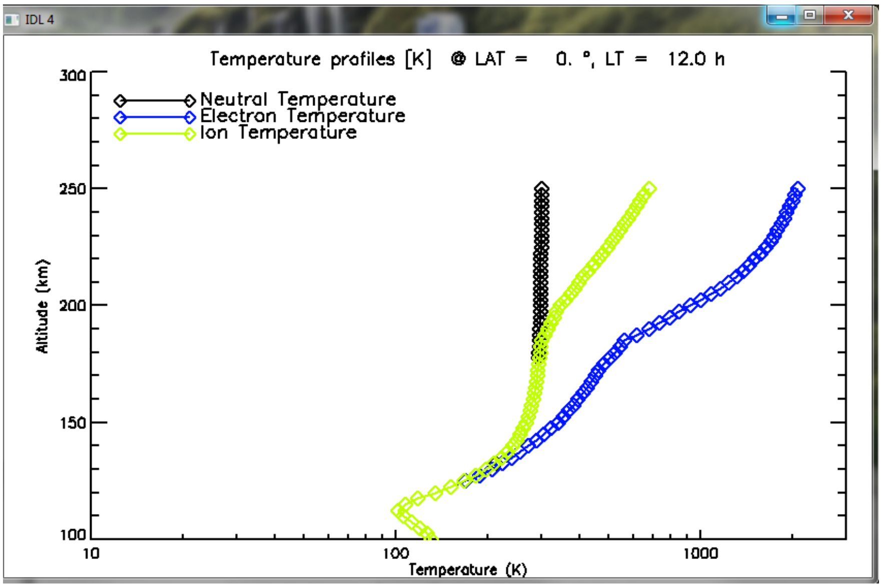

Figure 4: Temperature profles for neutrals, electrons and ions

4.5 Zonal velocity (Un) map @ 200km

```
;;******************* Figure 5 *********************

;==Plotting the Zonalvelocity map of neutrals @ Alt_val

tab = FLTARR(nlon,nlat)

FOR ilon=0,nlon-1 DO BEGIN

  FOR ilat = 0,nlat-1 DO BEGIN

   ; find the altitude value in the Altitude map

    near = MIN(ABS(Altitude(*)-Alt_val),index)
```

```
    IF (FINITE(Un(ilon,ilat,index),/NAN) EQ 0) THEN BEGIN ;  check if it NaN
     tab(ilon,ilat) = Un(ilon,ilat,index)
    ENDIF ELSE BEGIN
     tab(ilon,ilat) = 0/0
    ENDELSE
  ENDFOR
ENDFOR
iwindow = iwindow+1
WINDOW,iwindow
minval =MIN(tab)
maxval =MAX(tab)
color_level = FINDGEN(128)/127.*(maxval-minval)+minval
fig_title = 'Zonal velocity map [m.s-1] of neutral winds @'+STRING(Alt_val,FORMAT='(f4.0)')+' km'
map_lt_lon
```

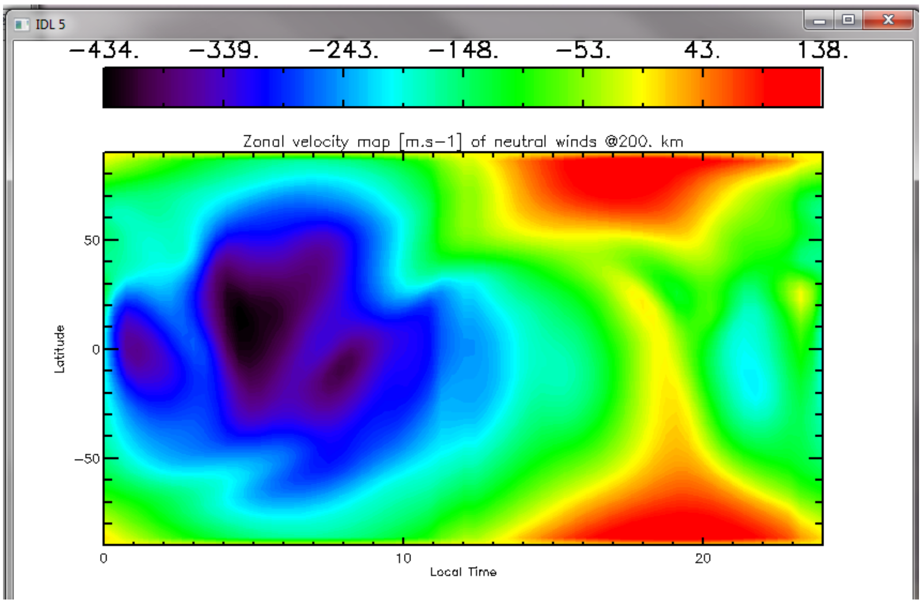

Figure 5: Zonal velocity map (Un) of neutrals at 200 km