# "Planetary Atmospheric Dynamics"

**Brian D. McNoldy**

Lycoming College

Department of Astronomy and Physics

1997-1998

*Project Advisor:*

Dr. Richard Erickson

*Honors Committee:*

Dr. David Fisher

Dr. Stephen Griffith

Dr. David Wolfe

Department of Astronomy and Physics

ASTR 490, ASTR 491

Departmental Honors Project Approval

1997-1998

Brian D. McNoldy

"Planetary Atmospheric Dynamics"

Project Advisor: **Richard Erickson** Richard R. Erickson

Committee Member: **David Fisher** David G. Fisher

Committee Member: **Stephen Griffith** Stephen R Griffith

Committee Member: **David Wolfe** David H. Wolfe

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ngle of n (1-15) order sinusoid          a138 = 0.0000000
de of n (1-15) order sinusoid            a139 = 0.0000000
ngle of n (1-15) order sinusoid          a140 = 0.0000000
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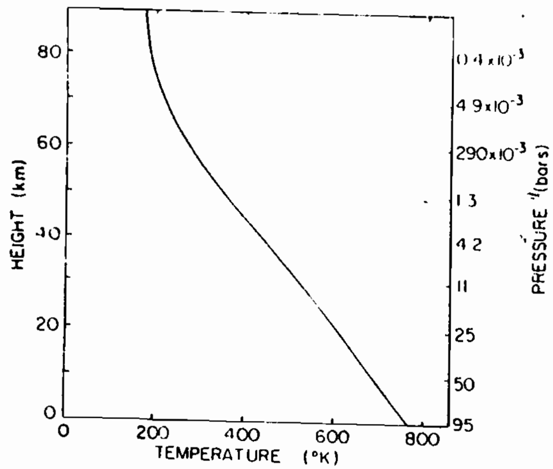



**Fig. 1.14** Temperature profile of Venus' atmosphere. [This model is the NASA 1972 standard atmosphere. NASA Report S.P. 8001.]

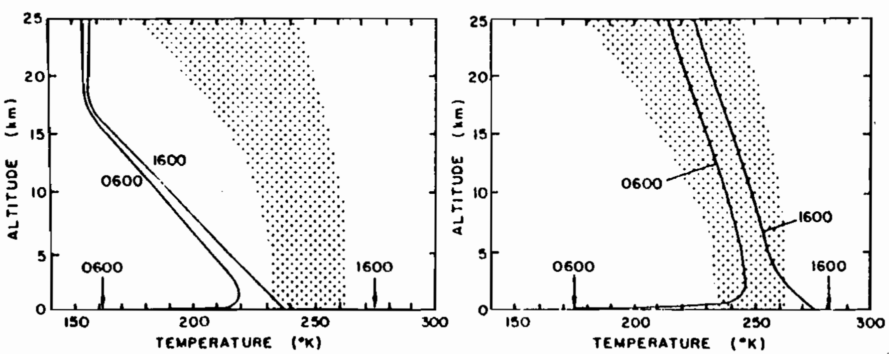



**Fig. 1.16** Temperature profiles for Mars showing the effect of direct solar heating due to dust absorption. The shaded areas show the region of Mariner 6 and 7 observations. The curves at the left are calculated for a clear $CO_2$ atmosphere and at the right for one containing dust. [Calculations are due to GIERASCH and GOODY (1972).]

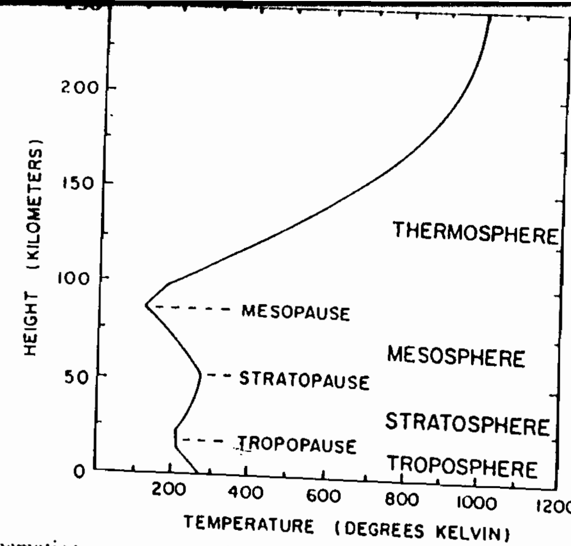



**Fig. 1.1** Schematic temperature profile for Earth's atmosphere showing the various regimes defined by the temperature gradient.

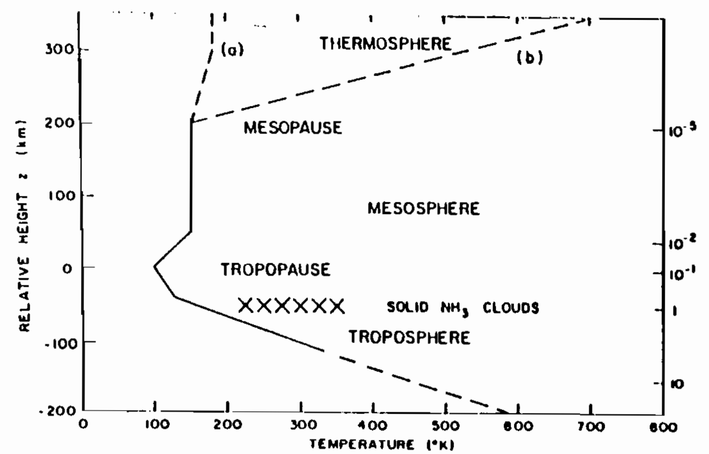
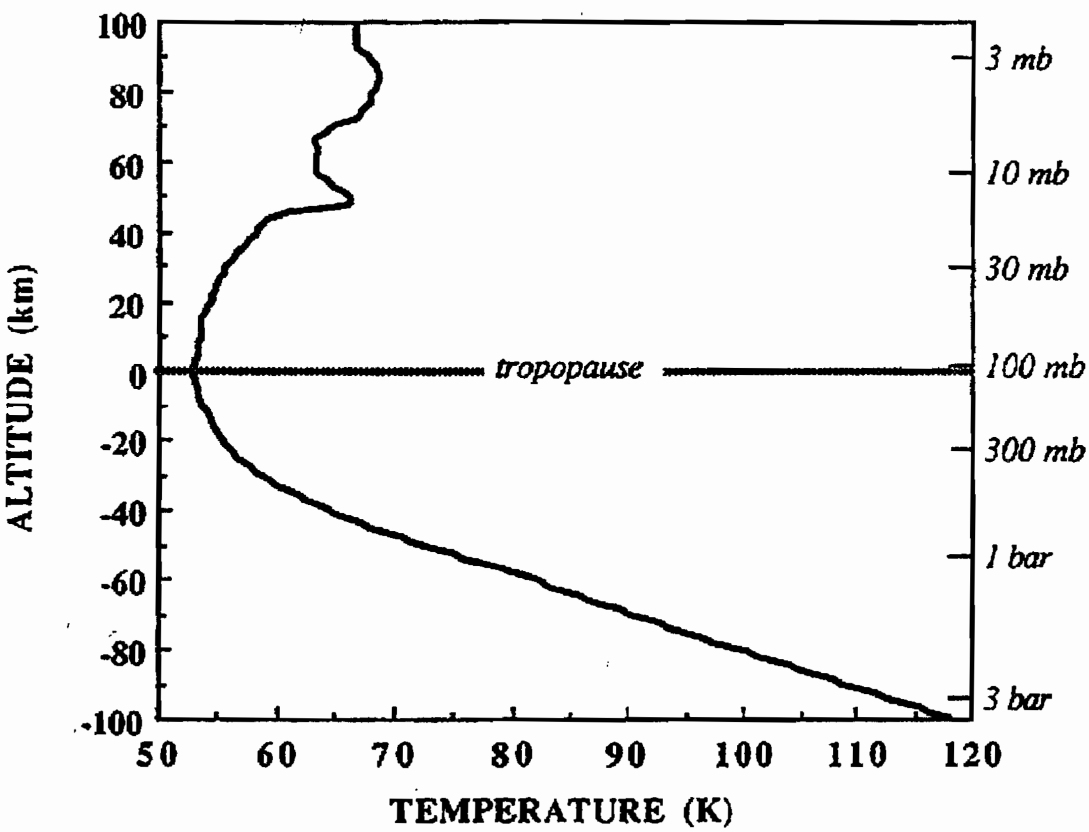



**Fig. 1.19** Schematic structure of the Jovian atmosphere. Even the adiabatic curve for the troposphere is uncertain, since it depends on the $H_2$/He mixture and the role of moist convection; also at low $T$, $\gamma$ for $H_2$ is sensitive to $T$. Here we have taken a lapse rate of 2.9 K km corresponding to $\gamma \approx 1.6$. The tropopause occurs at a minimum $T$ of 100–120 K. A stratosphere is not shown because the profile is not known accurately enough for one to be sure that there is a temperature decrease above the tropopause. In the region just above the tropopause, $T$ probably increases because of direct solar absorption, with a low level of infrared activity providing radiative cooling. At the mesopause the main vibrational relaxation occurs in $C_2H_2$ and $CH_4$. In the thermosphere, curve (a) is the expected profile for heating by solar extreme ultraviolet and curve (b) is a profile inferred from the Pioneer 10 radio occultation. The discrepancy presumably indicates an additional heat source for the atmosphere.

# ALTITUDE – PRESSURE – TEMPERATURE
## Profile for Uranus



| Species | Molecular Wt. | Earth | Venus | Mars | Jupiter |
|---|---|---|---|---|---|
| $H_2$ | 2 | 5(−7) | — | 5(−5) ? | 0.8-0.95(?) |
| He | 4 | 5(−6) | | — | 0.05−0.2(?) |
| $CH_4$ | 16 | 2(−6) | | <1(−3) ? | ~1(−3) |
| $NH_3$ | 17 | 4(−9) | -- | <2(−4) ? | ~2(−4) |
| $H_2O$ | 18 | 1(−3)-1(−2) | ~1(−3) | ~~4(−4)~~ .0003 | 1(−6) |
| HF | 20 | — | 5(−9) | — | — |
| CO | 28 | 2(−7) | 5(−5) | ~~8(−4)~~ .0007 | 2(−9) |
| $N_2$ | 28 | 0.78 | — .035 | ~~2.4(−2)~~ .027 | — |
| NO | 30 | 5(−10) | — | 1(−9)−1(−8) ? | — |
| $O_2$ | 32 | 0.21 | — | ~~1.6(−3)~~ .0013 | — |
| HCl | 36; 38 | — | 6(−7) | — | — |
| Ar | 40 | 9(−3) | — | ~~1.5(−2)~~ .016 | — |
| $CO_2$ | 44 | 3(−4) | ~~0.97~~ .96 | ~~0.95−0.99(?)~~ .9532 | — |
| $O_3$ | 48 | 4(−7) | — | ~~1(−8)~~ .00000003 | — |
| Ne | 20 | | | .0000025 | |

* A number $a \times 10^b$ is written $a(b)$. See Appendix III for more detail on Earth's atmosphere.

U.S. Standard Atmosphere, 1976

TABLE III.1 *Model Atmosphere*

| Height $z$ (km) | Geopotential Height $\Phi/g_0$ (km) | Temperature $T$ (°K) | Pressure $p$ (mb) | Number Density $N$ (cm$^{-3}$) | Mean Molecular Wt. $\langle\mu\rangle$ (gm mole) | Pressure Scale Height $H$ (km) | Accel. of Gravity $g$ (cm sec$^{-2}$) |
|---|---|---|---|---|---|---|---|
| 0 | 0 | 288 | 1.013(3) | 2.547(19) | 28.96 | 8.434 | 980.7 |
| 5 | 4.996 | 256 | 5.405(2) | 1.531(19) | 28.96 | 7.496 | 979.1 |
| 10 | 9.98 | 223 | 2.650(2) | 8.598(18) | 28.96 | 6.555 | 977.6 |
| 15 | 14.97 | 217 | 1.211(2) | 4.049(18) | 28.96 | 6.372 | 976.1 |
| 20 | 19.94 | 217 | 5.529(1) | 1.849(18) | 28.96 | 6.382 | 974.5 |
| 25 | 24.90 | 222 | 2.549(1) | 8.334(17) | 28.96 | 6.536 | 973.0 |
| 30 | 29.86 | 227 | 1.197(1) | 3.828(17) | 28.96 | 6.693 | 971.5 |
| 35 | 34.81 | 237 | 5.746(0) | 1.760(17) | 28.96 | 7.000 | 970.0 |
| 40 | 39.75 | 250 | 2.871(0) | 8.308(16) | 28.96 | 7.421 | 968.4 |
| 45 | 44.68 | 264 | 1.491(0) | 4.088(16) | 28.96 | 7.842 | 966.9 |
| 50 | 49.61 | 271 | 7.978(−1) | 2.135(16) | 28.96 | 8.047 | 965.4 |
| 55 | 54.53 | 261 | 4.253(−1) | 1.181(16) | 28.96 | 7.766 | 963.9 |
| 60 | 59.44 | 247 | 2.196(−1) | 6.439(15) | 28.96 | 7.368 | 962.4 |
| 65 | 64.34 | 233 | 1.093(−1) | 3.393(15) | 28.96 | 6.969 | 960.9 |
| 70 | 69.24 | 220 | 5.221(−2) | 1.722(15) | 28.96 | 6.570 | 959.4 |
| 75 | 74.13 | 208 | 2.388(−2) | 8.300(14) | 28.96 | 6.245 | 957.9 |
| 80 | 79.00 | 198 | 1.052(−2) | 3.838(14) | 28.96 | 5.962 | 956.4 |
| 85 | 83.89 | 189 | 4.457(−3) | 1.709(14) | 28.96 | 5.678 | 955.0 |
| 86 | 84.85 | 187 | 3.734(−3) | 1.447(14) | 28.95 | 5.621 | 954.7 |
| 90 | 88.74 | 187 | 1.836(−3) | 7.12(13) | 28.91 | 5.64 | 953 |
| 95 | 93.60 | 189 | 7.597(−4) | 2.92(13) | 28.73 | 5.73 | 952 |
| 100 | 98.45 | 195 | 3.201(−4) | 1.19(13) | 28.40 | 6.01 | 951 |
| 110 | 108.13 | 240 | 7.104(−5) | 2.14(12) | 27.27 | 7.72 | 948 |
| 120 | 117.78 | 360 | 2.538(−5) | 5.11(11) | 26.20 | 12.09 | 945 |
| 130 | 127.40 | 469 | 1.250(−5) | 1.93(11) | 25.44 | 16.29 | 942 |
| 140 | 136.98 | 560 | 5.403(−6) | 9.32(10) | 24.75 | 20.03 | 939 |
| 150 | 146.54 | 634 | 4.542(−6) | 5.19(10) | 24.10 | 23.38 | 936 |
| 160 | 156.07 | 696 | 3.040(−6) | 3.16(10) | 23.49 | 26.41 | 933 |
| 180 | 175.04 | 790 | 1.527(−6) | 1.40(10) | 22.34 | 31.70 | 927 |
| 200 | 193.90 | 855 | 8.474(−7) | 7.189(9) | 21.30 | 36.18 | 922 |
| 220 | 212.64 | 899 | 5.015(−7) | 4.049(9) | 20.37 | 40.04 | 916 |
| 240 | 231.27 | 930 | 3.106(−7) | 2.429(9) | 19.56 | 43.41 | 911 |
| 260 | 249.78 | 951 | 1.989(−7) | 1.529(9) | 18.85 | 46.35 | 905 |
| 280 | 268.19 | 966 | 1.308(−7) | 9.818(8) | 18.24 | 48.93 | 900 |
| 300 | 286.48 | 976 | 8.770(−8) | 6.518(8) | 17.73 | 51.19 | 894 |
| 350 | 331.74 | 990 | 3.450(−8) | 2.528(8) | 16.64 | 55.83 | 881 |
| 400 | 376.32 | 996 | 1.452(−8) | 1.068(8) | 15.98 | 59.68 | 868 |
| 450 | 420.25 | 998 | 6.248(−9) | 4.687(7) | 15.25 | 63.64 | 855 |
| 500 | 463.54 | 999 | 3.024(−9) | 2.197(7) | 14.33 | 68.79 | 843 |
| 750 | 670.85 | 1000 | 2.260(−10) | 1.646(6) | 6.58 | 161.1 | 785 |
| 1000 | 864.07 | 1000 | 7.514(−11) | 5.445(5) | 3.94 | 288.2 | 732 |

# Planetary Atmospheric Dynamics
# 1st-Semester Summary

## *Progress*

### Past:

Read several books on Planetary Atmospheres, Fluid Dynamics, Atmospheric Physics, etc.

Researched valid sites from which I could get detailed text- and graphic-based GOES satellite data. Managed to get some useful data, but what was available did not seem very practical.

Found altitude-dependent graphical data on temperature, pressure, particle density, composition for Earth and even some for Mars, Venus, and Jupiter. Most is from 1978, but I'm currently searching to patch it up with more recent data.

### Current:

Writing a program that will calculate a "standard atmosphere" for Earth. Fairly interactive... it asks for several input parameters for initial conditions. The program is dependent on the fact that Earth's atmosphere is neatly stratified into distinct layers with distinct properties.

Looking for up-to-date data for Earth, Mars, and Venus regarding temperaure and pressure profiles.

Constantly finding ways to increase the accuracy and portability (use on other bodies) of the standard atmosphere routine.

### Future:

Get a working and accurate version of the program for Earth, Mars, and maybe Venus too (using up-to-date Magellan, Pathfinder, and MGS data for V and M). Once I'm certain I know what the tricks and obstacles are, I want to attempt to model Titan's atmosphere. This will be interesting because details of it's atmosphere are relatively unknown. The Cassini orbiter *will* :) drop the Huygens probe into Titan's atmosphere (and surface?) in November 2004, then my model will truly be put to the test.

Depending on how long the program takes to 'perfect' for the various bodies, I would then like to look at atmospheric electrification. Lightning interests me a great deal and I think it would be fascinating to see what I can learn about how the process differs in different atmosphers with bizarre conditions.

If there is still time left, it probably means I came back for a fifth year!

Brian McNoldy

# ***Planetary Atmospheric Dynamics***

Astronomy and Physics Departmental Honors Project

**-- Brian D. McNoldy --**

This year-long honors project was inspired by an internship I held during the summer of 1997 at NASA's Goddard Space Flight Center. The topic of my research there was mesoscale properties of tropical convective systems. By analyzing radar and infrared satellite measurements, one can learn quite a bit about the relationship between cloud coverage and the underlying precipitation. Radar data is not very cheap or convenient to collect in most locations of the world (especially in oceanic regions); however, satellite data can be collected for any site in the world at least once a day. The amount of cloud coverage and rainfall over the tropical oceans greatly affects major weather patterns such as ENSO (El Niño Southern Oscillation).

Stepping back from the relatively specific focus of the internship, I began the honors project with the very general goal of learning about the planetary-scale structure and dynamics of various solar system bodies' (including Earth, Venus, Mars, and Saturn's moon Titan) atmospheres. Earth would serve as an excellent standard model because its structure is moderately well-understood and I could base computer model programming off of it. Venus was chosen because it has a very dense and uniform atmosphere. On the other hand, Mars has a sparse and more-layered atmosphere. Titan (the only moon known to have a substantial atmosphere) has never been studied experimentally, so modeling it will be a much greater challenge. The *Cassini* mission currently en route to the Saturnian system will drop a probe (*Huygens*) into Titan's nitrogen-rich atmosphere in November 2004; only then will my model truly be put to the test.

The computer model I have written is currently designed for Earth. It allows altitude-dependent calculations of pressure and temperature to be made, using user-defined parameters. At the present time, my model matches reality up to about 20 km (tropopause) for pressure and up to about 150 km (lower thermosphere) for temperature. My goal is to correctly model up to 1000 km (thermopause).

During the second half of the honors project (this semester), I plan to continue modeling the temperature and pressure of Earth, Venus, Mars, and Titan. Depending on how long that takes, I will then investigate atmospheric electrification. Lightning has been observed on Earth, Venus, and Jupiter and almost certainly exists on Saturn and Titan. I would like to focus on the different processes involved with electrification on each of the different bodies.

## Useful Terms:

**mesoscale-** a weather feature that is defined to be 20-200 km in size and 12-36 hours in duration.

**convective-** a weather system is said to be convective if its dynamics are driven by updrafts and downdrafts due to warm/cool or moist/dry boundaries.

**El Niño-** a major oscillation in global atmospheric energy resulting in reversed wind flow and increased temperatures in the equatorial Pacific Ocean. This in turn affects the weather of most of North and South America.

**troposphere-** the lowest layer of our atmosphere. All weather occurs in this layer which extends up to ~20 km above the surface of the Earth; the temperature decreases with height.

**tropopause-** the boundary between the troposphere and the stratosphere. It occupies a thin region at about 20 km above the surface.

**stratosphere-** the second layer of our atmosphere. Characterized by very little verticle air movement. Exists between ~20-52 km and the temperature increases with height.

**stratopause-** the boundary between the stratosphere and the mesosphere. It occupies a thin region about 52 km above the surface.

**mesosphere-** the third distinctive layer of the atmosphere. It occupies the region between 52 km and 88 km. Temperature decreases with height once again.

**mesopause-** the boundary between the mesosphere and the thermosphere. It occupies the region at about 88 km above the surface.

**thermosphere-** the next-to-last layer of the atmosphere. The rarefied air particles are ionized by the constant bombardment of cosmic (X- and $\gamma$-) rays from space. Due to this absorption and high atomic energies, temperatures in the thermosphere climb with altitude, reaching as high as 2500°F during the daytime. Extends from ~88-800 km.

```
/*
   Brian D. McNoldy
   Departmental Honors Project, 1997-98
   "Planetary Atmospheric Dynamics"
   Advisor: Dr. Richard Erickson
   Committee: Drs. David Fisher, Stephen Griffith, David Wolfe

   Calculates the temp, pressure, and grav. accel. at incremental altitudes.
   User specifies initial height, final height, height increment.
*/

#include <iostream.h>
#include <math.h>
#include <fstream.h>

int main(){
  int n;                   //number of heights to calculate
  float P;                 //pressure (Pa)
  float T;                 //temperature (K)
  float dT;                //temp gradient within each h interval (K m^-1)
  float rho=0.0422923; //density at z_init (mol L^-1) (.083689 kg m^-3)
  float R=8314.51;         //ideal gas constant (L Pa K^-1 mol^-1)
  float g;                 //gravitational acceleration (m s^-2)
    /*
    float G=6.67259x10^-11;  gravitational constant (kg m^3 s^-2)
    float M=5.9742x10^24;    mass of Earth (kg)
    */
  long double c=398633871800000.0; //the product of G*M
    /*
    float m=4.810x10^-26;     mean mass of molecules (kg)...only accounting
                               for N2(78%), O2(21%), and Ar(.93%); 28.95g/mol
    float k=1.38066x10^-23;   Boltzmann Constant (J K^-1)
    */
  float C1=0.003484;     //ratio of m/k
  float C2=0.002759;     //accounts for decrease in average mass of particles
  float C3=0.001935;     //"  "
  float C4=0.001011;     //"  "
  long double r=6378140.0;  //radius of Earth (m)
  float e=2.7182818;     //exponential
  float z;               //height above "sea level" (m)
  float z_init;          //initial height to begin calculations
  float z_max;           //max height to calculate (m)
  float h;               //height of each increment (m)
  char flag=0;           //0 to remain in program, 1 to exit
  char quit;             //checks to see if another calculation is desired
  char type=0;           //checks for correct input at the exit prompt
```

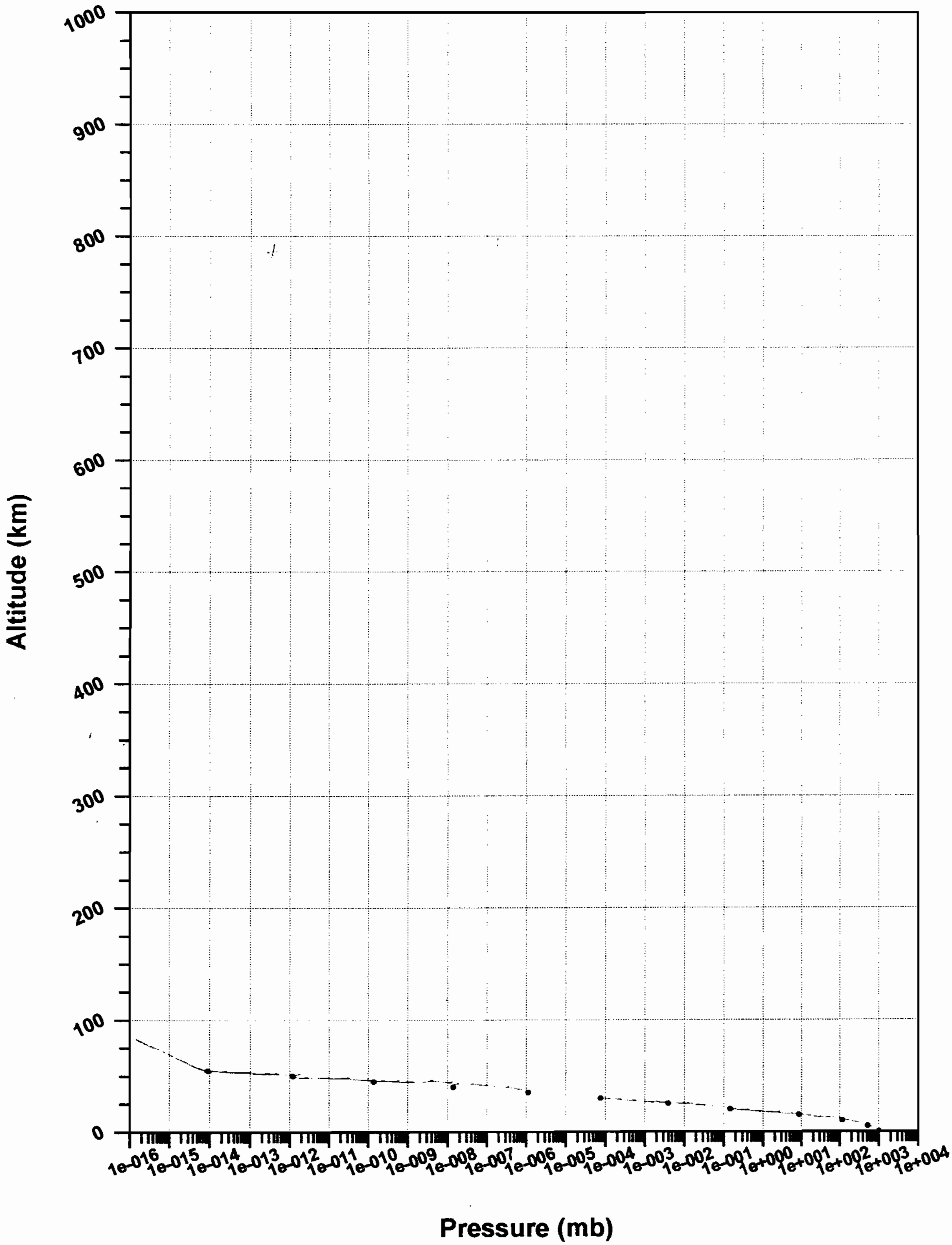
```
//user inputs initial conditions
while(flag==0){
  cout<<char(27)<<"[H"<<char(27)<<"[2J";
  cout<<endl<<endl;
  cout<<"Initial height (in m): ";
  cin>>z_init;
    if (z_init<0){
      cout<<endl<<endl<<"Initial height must be greater than 0 km."<<endl;
      cout<<"Exiting program..."<<endl<<endl;
      flag=1;
      break;
    }
    if (z_init>=1000000){
      cout<<endl<<endl<<"Initial height must be less than 1000 km."<<endl;
      cout<<"Exiting program..."<<endl<<endl;
      flag=1;
      break;
    }
  cout<<endl;
  cout<<"Maximum height (in m): ";
  cin>>z_max;
    if (z_max<=0){
      cout<<endl<<endl<<"Maximum height must be greater than 0 km."<<endl;
      cout<<"Exiting program..."<<endl<<endl;
      flag=1;
      break;
    }
    if (z_max>1000000){
      cout<<endl<<endl<<"The maximum altitude this algorithm can "<<endl;
      cout<<"accurately process is 1000 km.  Exiting program..."<<endl<<endl;
      flag=1;
      break;
    }
    if (z_init>=z_max){
      cout<<endl<<endl<<"Maximum height cannot be greater than initial height."<<endl;
      cout<<"Exiting program..."<<endl<<endl;
      flag=1;
      break;
    }
  cout<<endl;
  cout<<"Height of each increment (in m): ";
  cin>>h;
    if (h<=0){
      cout<<endl<<endl<<"The height increment must be greater than 0 km."<<endl;
      cout<<"Exiting program..."<<endl<<endl;
      flag=1;
      break;
    }
  cout<<endl;
  cout<<"Initial temperature (in K): ";
  cin>>T;
    if (T<0){
      cout<<endl<<endl<<"Temperature cannot be below 0 K."<<endl;
      cout<<"Exiting program..."<<endl<<endl;
      flag=1;
      break;
    }
```

```
z=z_init;       //accuracy is increased if z_init~0
P=rho*R*T;      //find pressure at inital altitude before entering loop

ofstream out;
out.open("atmos.txt");

while(z<=z_max){

 cout<<endl;
 cout<<"_______"<<"\t\t"<<"______"<<"\t\t"<<"______"<<"\t\t"<<"______"<<"\n";
 cout<<"z (km) "<<"\t\t"<<"T (K) "<<"\t\t"<<"P(mb)"<<"\t\t"<<"g(ms^-2)"<<"\n";
 cout<<"_______"<<"\t\t"<<"______"<<"\t\t"<<"______"<<"\t\t"<<"______"<<"\n\n";
 g=c/(pow((z+r),2));


/****TROPOSPHERE****/
while(z<=18500.0){
  if ((z>18500.0)||(z>z_max))
    break;
  cout <<z/1000.0 <<"\t\t" <<T <<"\t\t" <<P/100.0 <<"\t\t" <<g <<"\n";
  out <<z/1000.0 <<"\t" <<T <<"\t" <<P/100.0 <<"\n";
  dT=-0.0061;  //due to H2O cooling
  T+=dT*h;
  z+=h;
  g=c/(pow((z+r),2.0));
  P*=pow(e,-(C1*g*(z-z_init))/(T));
  //P*=pow(((T+dT*h)/T),(-g/(0.001*R*dT)));
} //end troposphere loop

/****STRATOSPHERE****/
while(z>18500.0){
  if ((z>52000.0)||(z>z_max))
    break;
  cout <<z/1000.0 <<"\t\t" <<T <<"\t\t" <<P/100.0 <<"\t\t" <<g <<"\n";
  out <<z/1000.0 <<"\t" <<T <<"\t" <<P/100.0 <<"\n";
  dT=0.0038;  //due to O3 heating
  T+=dT*h;
  z+=h;
  g=c/(pow((z+r),2.0));
  P*=pow(e,-(C2*g*(z-z_init))/(T));
  //P*=pow(((T+dT*h)/T),(-g/(0.001*R*dT)));
} //end stratosphere loop

/****MESOSPHERE****/
while(z>52000.0){
  if ((z>88000.0)||(z>z_max))
    break;
  cout <<z/1000.0 <<"\t\t" <<T <<"\t\t" <<P/100.0 <<"\t\t "<<g <<"\n";
  out <<z/1000.0 <<"\t" <<T <<"\t" <<P/100.0 <<"\n";
  dT=-0.0040;  //due to CO2 cooling
  T+=dT*h;
  z+=h;
  g=c/(pow((z+r),2.0));
  P*=pow(e,-(C3*g*(z-z_init))/(T));
  //P*=pow(((T+dT*h)/T),(-g/(0.001*R*dT)));
} //end mesosphere loop
```

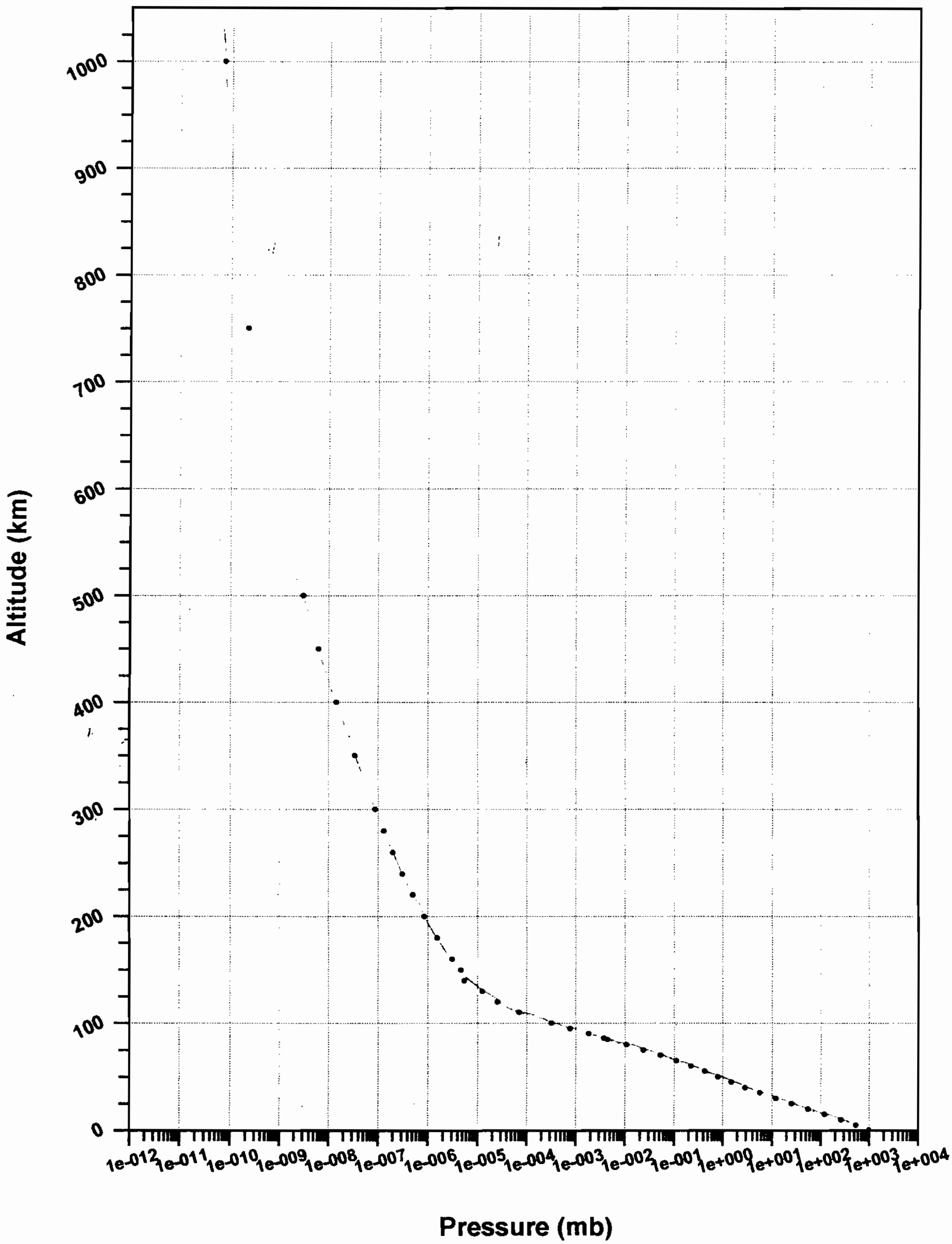
```
    /****THERMOSPHERE****/
    while(z>88000.0){
      if ((z>1000000.0)||(z>z_max))
        break;
      cout <<z/1000.0 <<"\t\t" <<T <<"\t\t" <<P/100.0 <<"\t\t" <<g <<"\n";
      out <<z/1000.0 <<"\t" <<T <<"\t" <<P/100.0 <<"\n";
      dT=(1.1*T/z)*pow(e,-z/1000000.0);  //due to UV heating
      T+=dT*h;
      z+=h;
      g=c/(pow((z+r),2.0));
      P*=pow(e,-(C4*g*(z-z_init))/(T));
      //P*=pow(((T+dT*h)/T),(-g/(0.001*R*dT)));
    } //end thermosphere loop

  } //end altitude check (z<z_max)

    out.close();
    cout<<"_______"<<"\t\t"<<"______"<<"\t\t"<<"______"<<"\t\t"<<"______"<<"\n";
    cout<<"z (km) "<<"\t\t"<<"T (K) "<<"\t\t"<<"P (mb)"<<"\t\t"<<"g(ms^-2)"<<"\n";
    cout<<"_______"<<"\t\t"<<"______"<<"\t\t"<<"______"<<"\t\t"<<"______"<<"\n\n";
    cout<<"Number of increments="<<(z_max-z_init)/h<<endl;
    cout<<"Generated data written to 'atmos.txt' in current directory.\n";
    cout<<"Finished.\n\n";

    while (type==0){
      cout<<"Another calculation (y/n)? ";
      cin>>quit;
        if ((quit=='y')||(quit=='Y')){
          flag=0;
          break;
        }
        else if ((quit=='n')||(quit=='N')){
          flag=1;
          break;
        }
        else if (((quit!='y')||(quit!='Y'))&&((quit!='n')||(quit!='N'))){
          cout<<"Enter either (y)es or (n)o."<<endl;
          type=0;
        }
    } //end correct input check
  } //end exit program check
} //end main
```

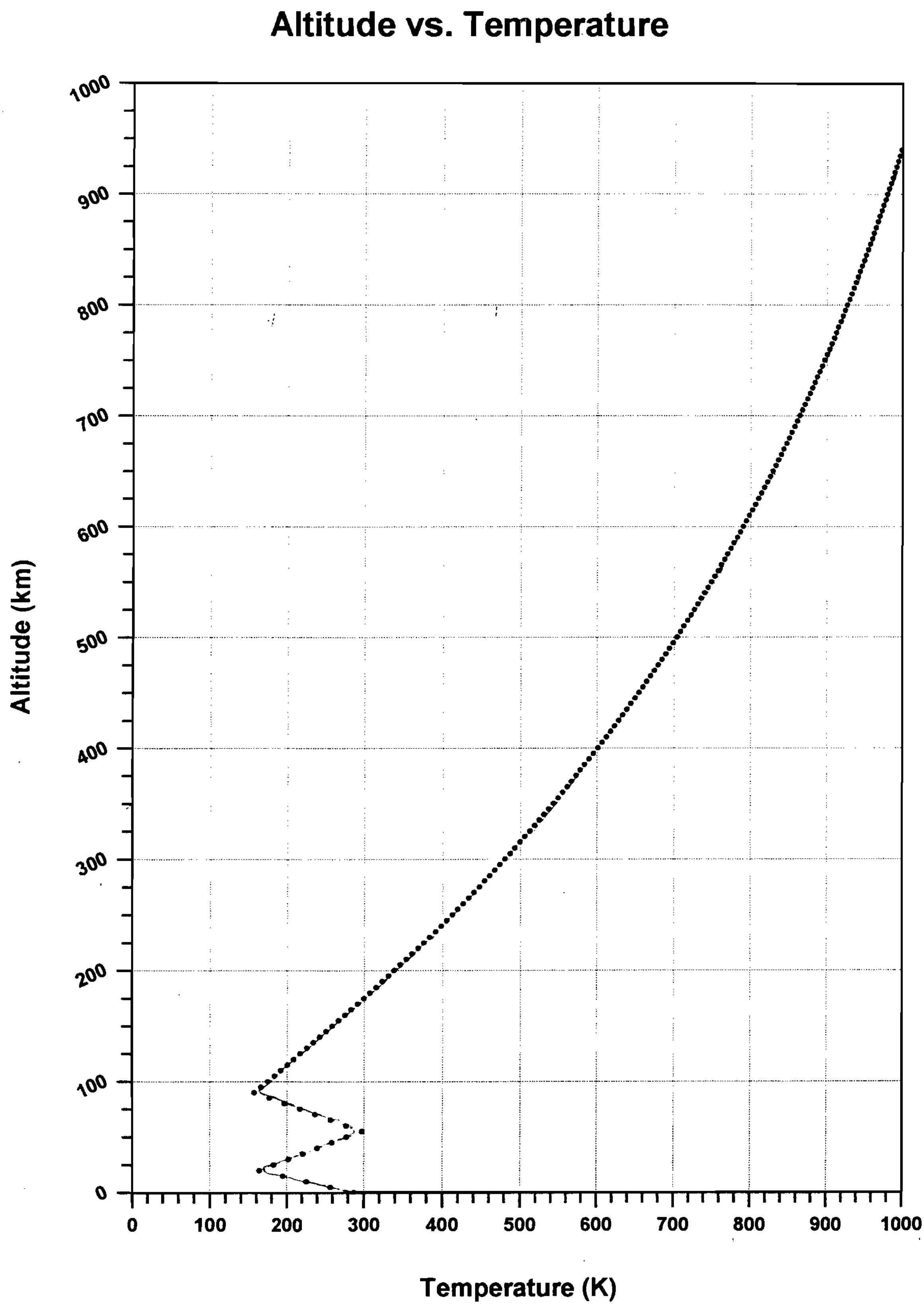
| | | |
|---|---|---|
| 0 | 288 | 1012.72 |
| 5 | 257.5 | 522.446 |
| 10 | 227 | 116.66 |
| 15 | 196.5 | 8.71777 |
| 20 | 166 | 0.146282 |
| 25 | 185 | 0.00389827 |
| 30 | 204 | 7.59129e-05 |
| 35 | 223 | 1.14168e-06 |
| 40 | 242 | 1.38332e-08 |
| 45 | 261 | 1.39573e-10 |
| 50 | 280 | 1.20393e-12 |
| 55 | 299 | 9.06929e-15 |
| 60 | 279 | 1.65771e-16 |
| 65 | 259 | 1.56443e-18 |
| 70 | 239 | 6.83252e-21 |
| 75 | 219 | 1.20123e-23 |
| 80 | 199 | 7.09048e-27 |
| 85 | 179 | 1.10278e-30 |
| 90 | 159 | 3.23677e-35 |
| 95 | 167.88 | 1.40072e-37 |
| 100 | 176.719 | 6.11331e-40 |
| 105 | 185.514 | 2.68728e-42 |
| 110 | 194.262 | 1.1883e-44 |
| 115 | 202.964 | 5.60519e-47 |
| 120 | 211.616 | 0 |
| | . | |
| | . | |
| | . | |
| 250 | 417.347 | 0 |
| 255 | 424.497 | 0 |
| 260 | 431.592 | 0 |
| 265 | 438.632 | 0 |
| 270 | 445.616 | 0 |
| 275 | 452.546 | 0 |
| 280 | 459.421 | 0 |
| 285 | 466.241 | 0 |
| 290 | 473.008 | 0 |
| 295 | 479.72 | 0 |
| 300 | 486.379 | 0 |
| 305 | 492.985 | 0 |
| 310 | 499.538 | 0 |
| 315 | 506.038 | 0 |
| 320 | 512.486 | 0 |
| 325 | 518.883 | 0 |
| 330 | 525.227 | 0 |
| 335 | 531.52 | 0 |
| 340 | 537.763 | 0 |
| 345 | 543.955 | 0 |
| 350 | 550.096 | 0 |
| | . | |
| | . | |
| | . | |
| 950 | 1016.01 | 0 |
| 955 | 1018.28 | 0 |
| 960 | 1020.54 | 0 |
| 965 | 1022.78 | 0 |
| 970 | 1025 | 0 |
| 975 | 1027.2 | 0 |
| 980 | 1029.39 | 0 |
| 985 | 1031.56 | 0 |
| 990 | 1033.71 | 0 |
| 995 | 1035.84 | 0 |
| 1000 | 1037.96 | 0 |

# Altitude vs. Pressure

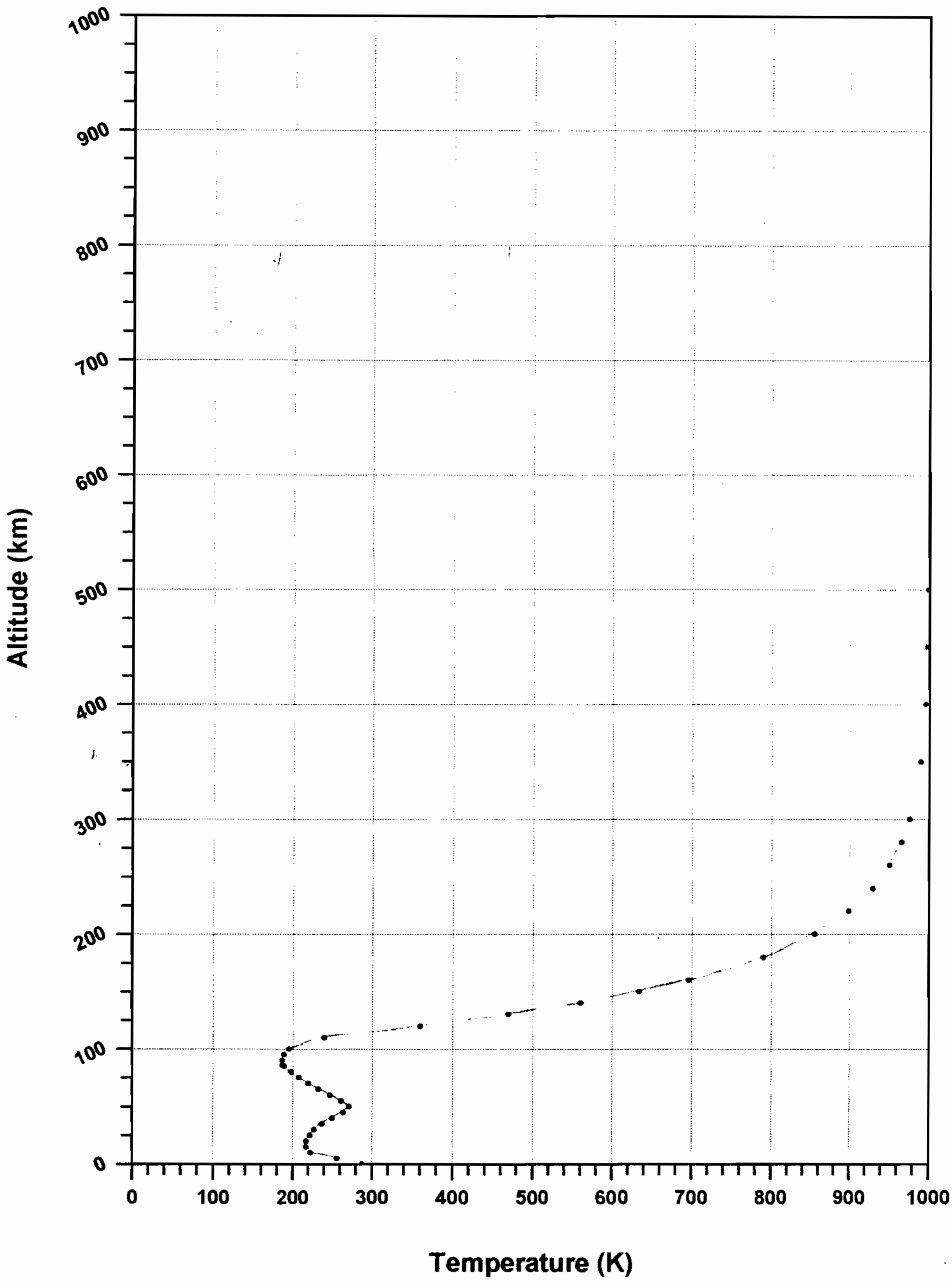


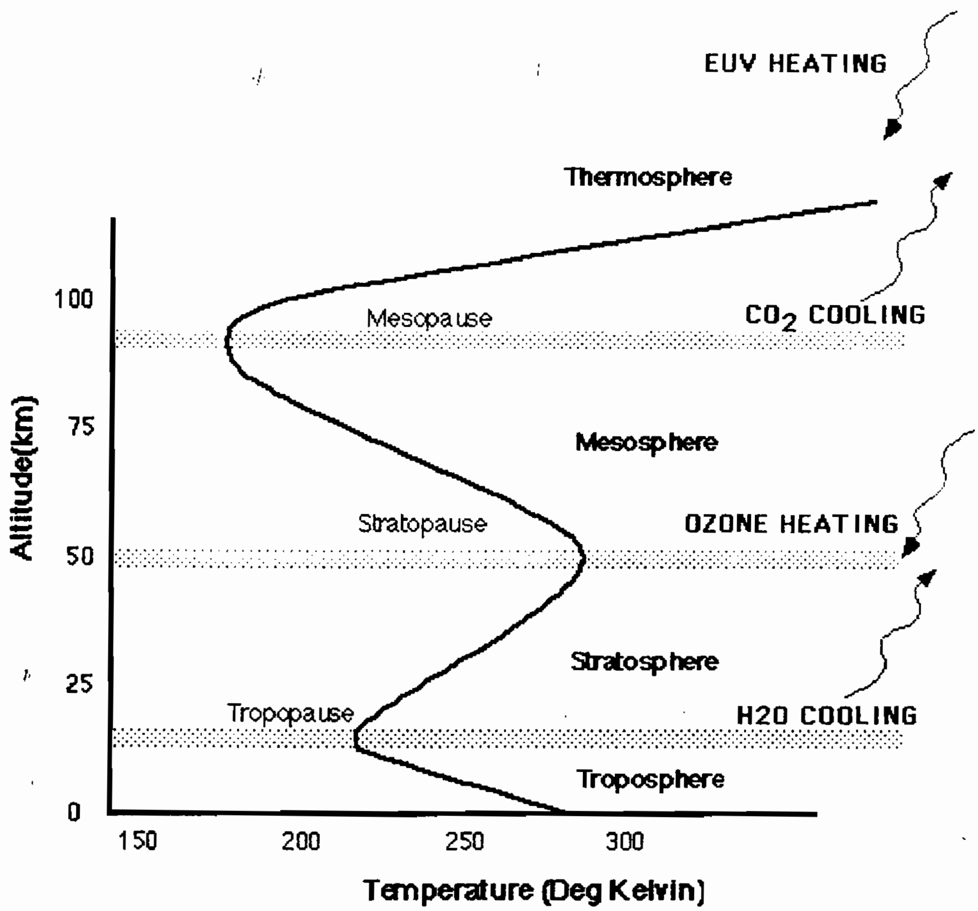
# Altitude vs. Pressure



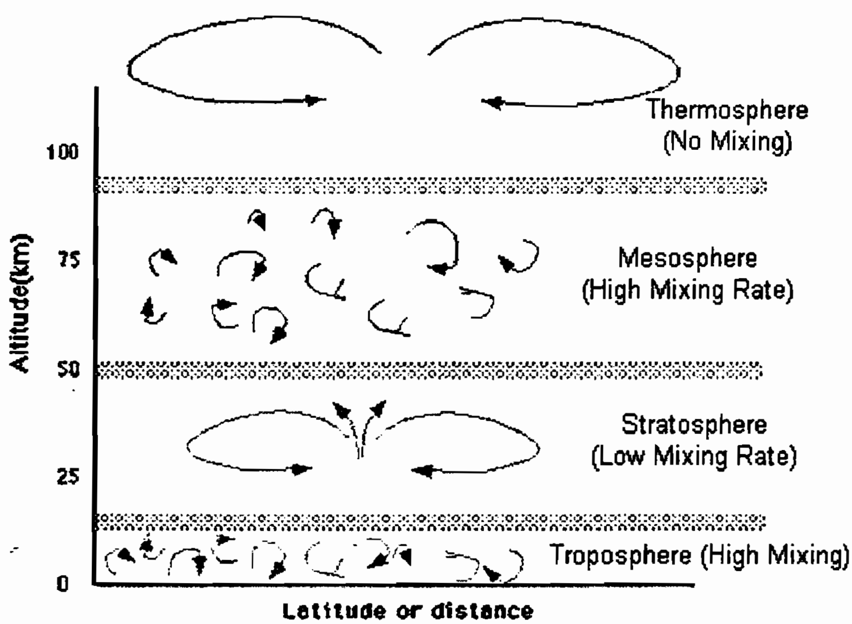

Altitude vs. Temperature
Altitude (km)
0
100
200
300
400
500
600
700
800
900
1000
Temperature (K)
0
100
200
300
400
500
600
700
800
900
1000

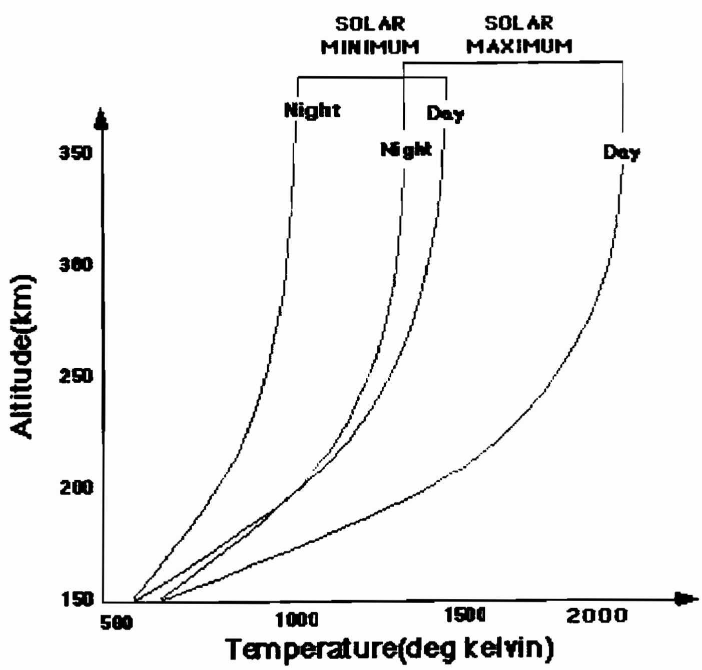
# Altitude vs. Temperature





EUV HEATING
Thermosphere
100
Mesopause
CO2 COOLING
75
Mesosphere
Altitude(km)
Stratopause
OZONE HEATING
50
Stratosphere
25
Tropopause
H2O COOLING
Troposphere
0
150
200
250
300
Temperature (Deg Kelvin)


Thermosphere
(No Mixing)
Mesosphere
(High Mixing Rate)
Stratosphere
(Low Mixing Rate)
Troposphere (High Mixing)
100
75
50
25
0
Altitude(km)
Latitude or distance


SOLAR MINIMUM
SOLAR MAXIMUM
Night
Day
Night
Day
350
300
250
200
150
Altitude(km)
500
1000
1500
2000
Temperature(deg kelvin)