THE NCAR TGCM'S: PAST, PRESENT, AND FUTURE

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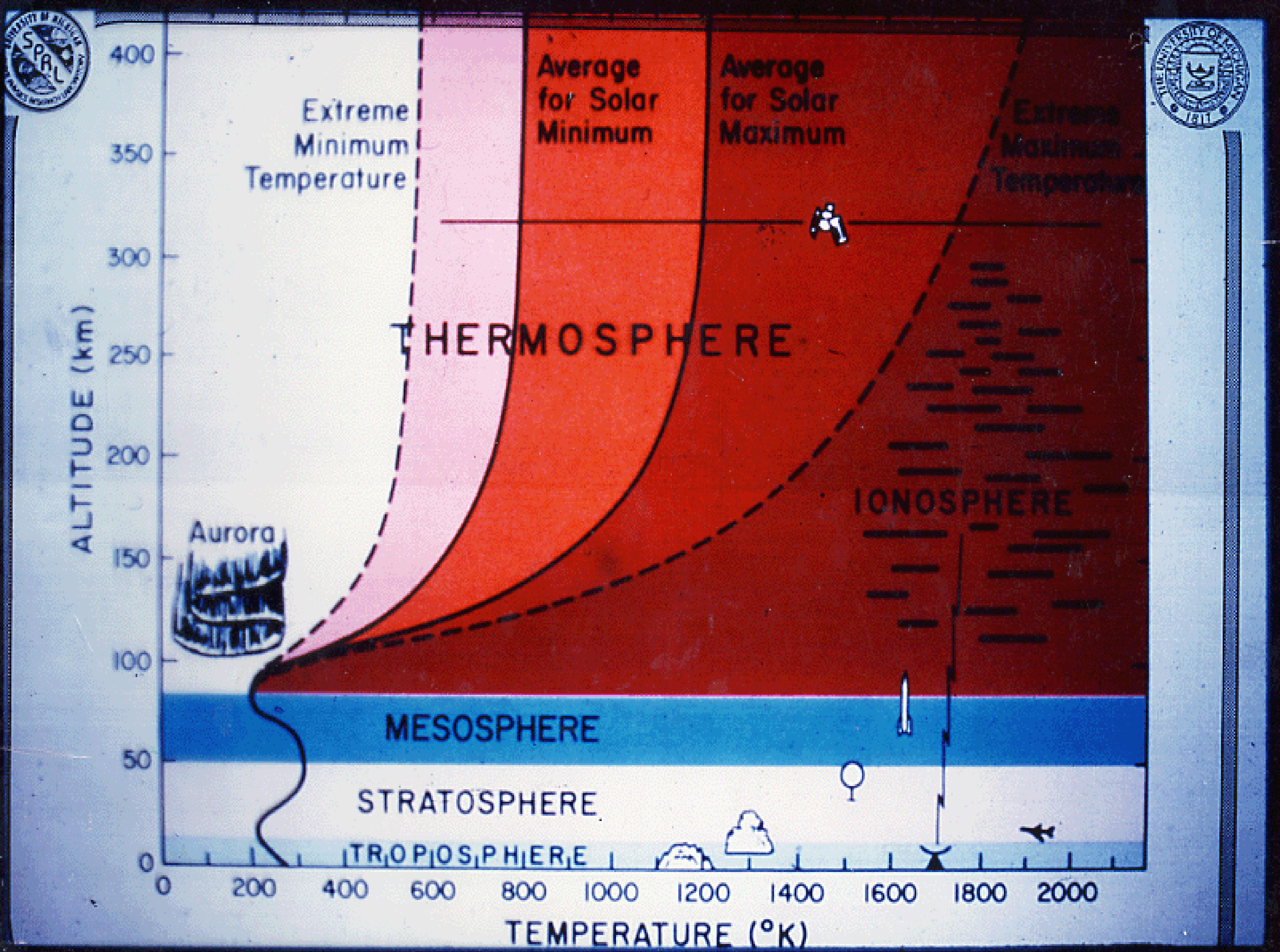
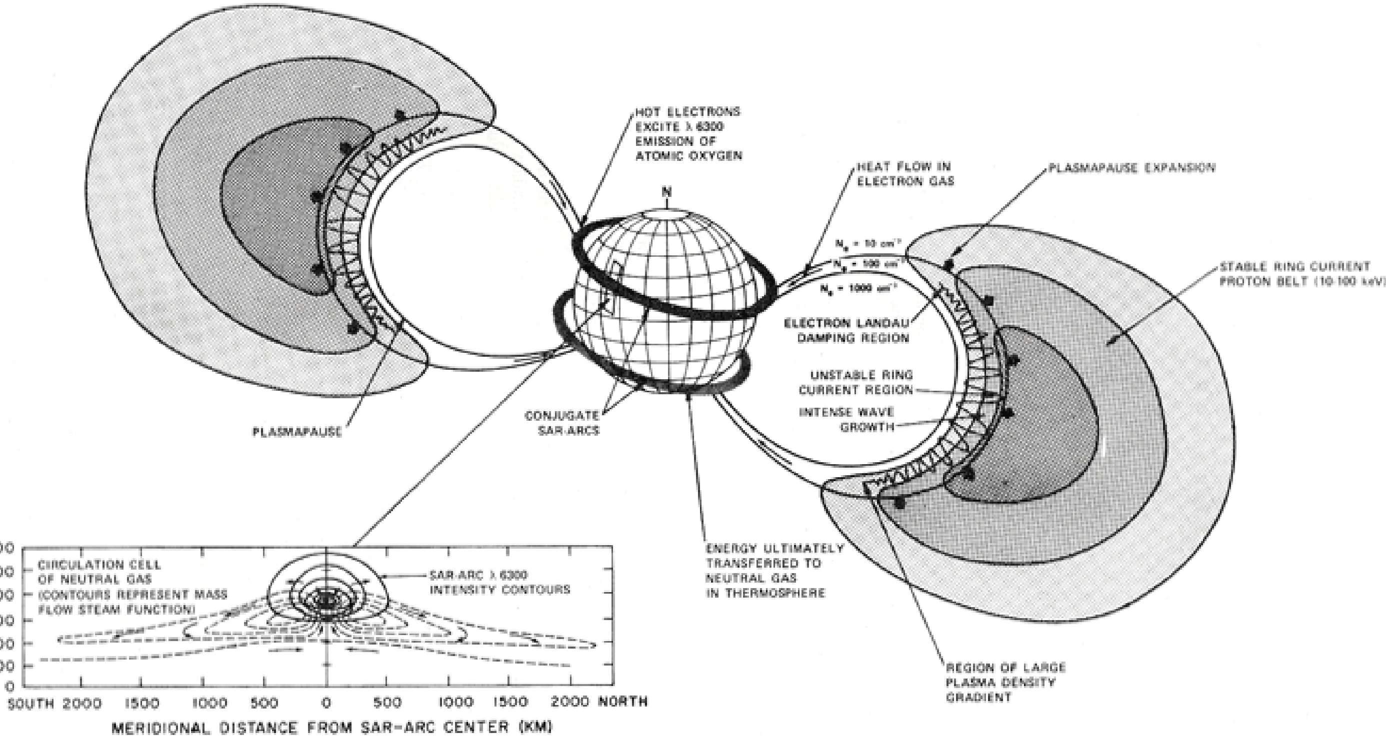
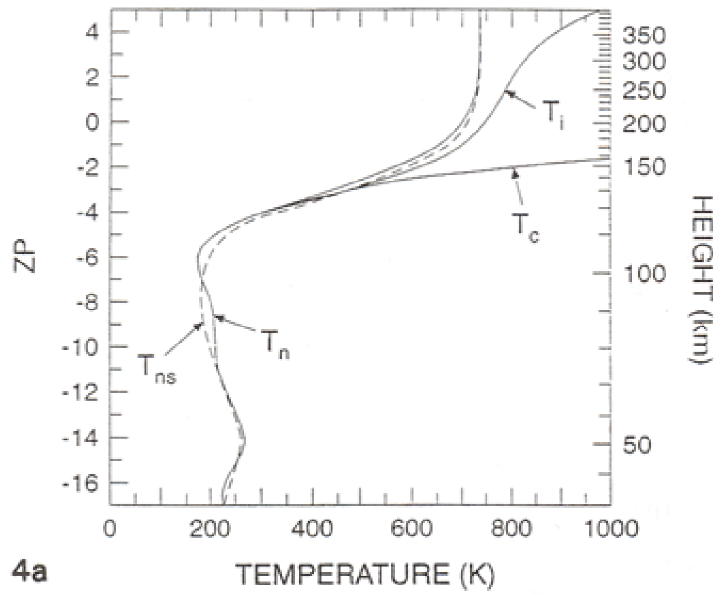


ALTITUDE (km)
400
350
300
250
200
150
100
50
0
Extreme Minimum Temperature
Average for Solar Minimum
Average for Solar Maximum
Extreme Maximum Temperature
THERMOSPHERE
IONOSPHERE
Aurora
MESOSPHERE
STRATOSPHERE
TROPOSPHERE
0
200
400
600
800
1000
1200
1400
1600
1800
2000
TEMPERATURE (°K)

Talk outline

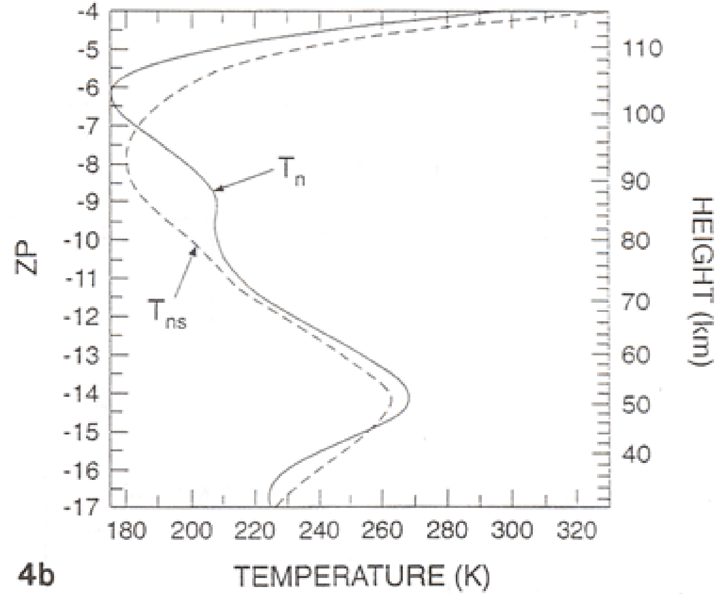
- How and why the TGCM's were developed at NCAR.
- Their present day capability and how they are being used in CEDAR.
- The future modeling efforts in a changing Climate.


HOT ELECTRONS
EXCITE λ 6300
EMISSION OF
ATOMIC OXYGEN
N
HEAT FLOW IN
ELECTRON GAS
PLASMAPAUSE EXPANSION
N_e = 10 cm^{-3}
N_e = 100 cm^{-3}
N_e = 1000 cm^{-3}
STABLE RING CURRENT
PROTON BELT (10-100 keV)
ELECTRON LANDAU
DAMPING REGION
UNSTABLE RING
CURRENT REGION
INTENSE WAVE
GROWTH
PLASMAPAUSE
CONJUGATE
SAR-ARCS
ENERGY ULTIMATELY
TRANSFERRED TO
NEUTRAL GAS
IN THERMOSPHERE
REGION OF LARGE
PLASMA DENSITY
GRADIENT
CIRCULATION CELL
OF NEUTRAL GAS
(CONTOURS REPRESENT MASS
FLOW STEAM FUNCTION)
SAR-ARC λ 6300
INTENSITY CONTOURS
HEIGHT (KM)
600
500
400
300
200
100
0
SOUTH 2000 1500 1000 500 0 500 1000 1500 2000 NORTH
MERIDIONAL DISTANCE FROM SAR-ARC CENTER (KM)



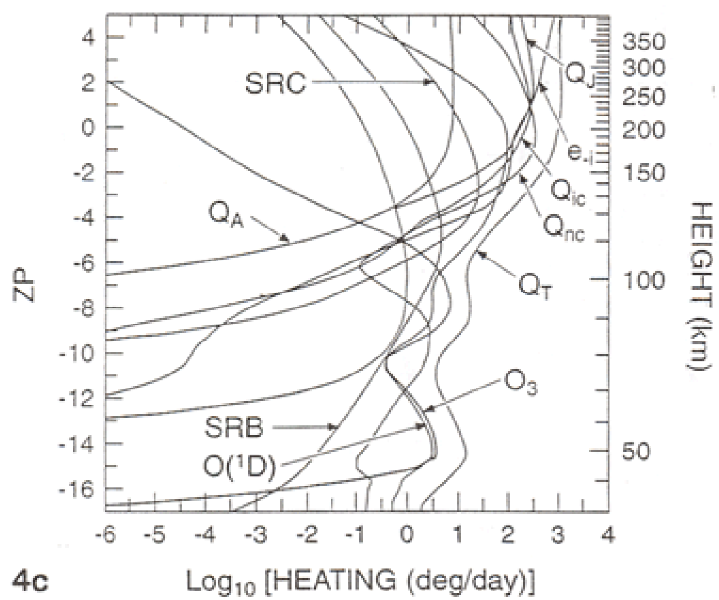
ZP
HEIGHT (km)
TEMPERATURE (K)
T_i
T_c
T_n
T_{ns}

4a



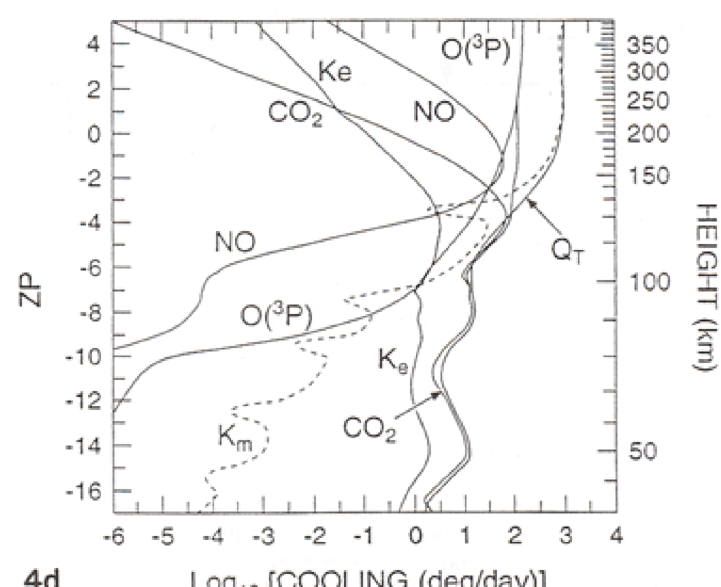
ZP
HEIGHT (km)
TEMPERATURE (K)
T_n
T_{ns}

4b



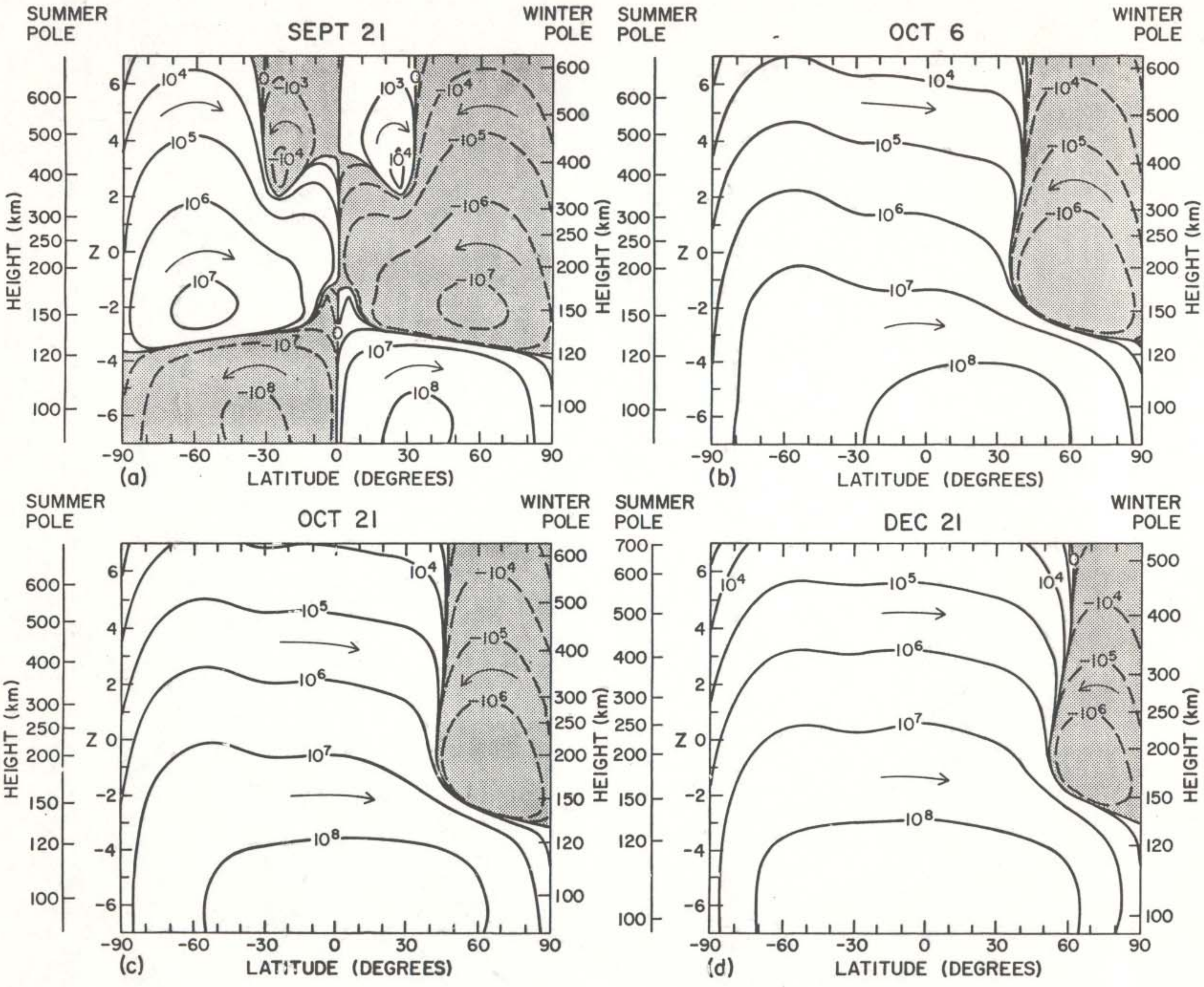
ZP
HEIGHT (km)
Log_{10} [HEATING (deg/day)]
SRC
Q_J
e_{-i}
Q_{ic}
Q_{nc}
Q_A
Q_T
O_3
SRB
$O(^1D)$

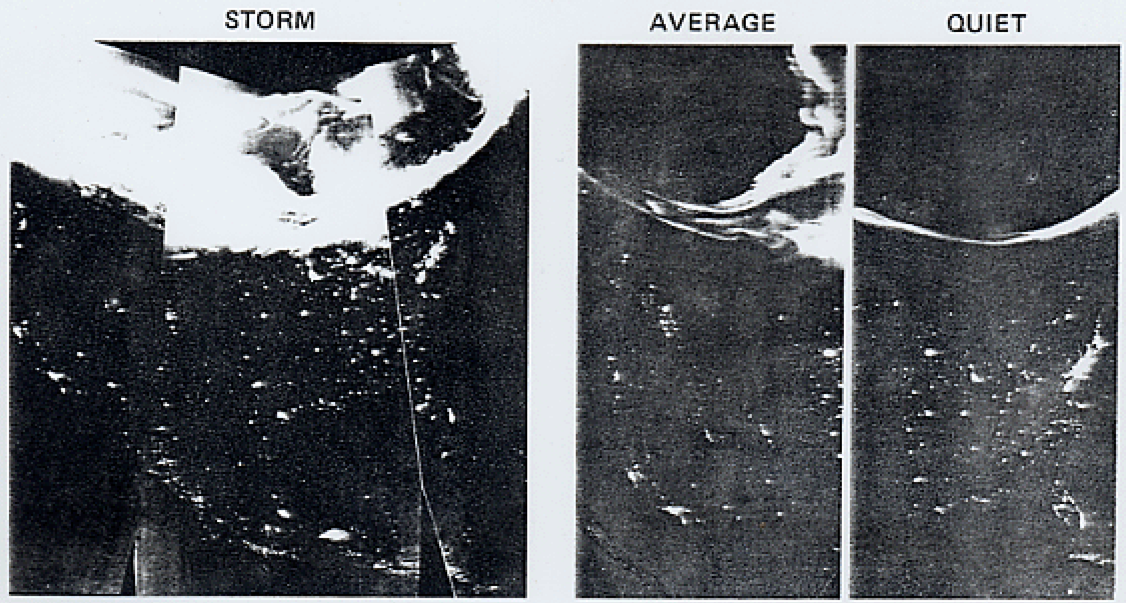
4c

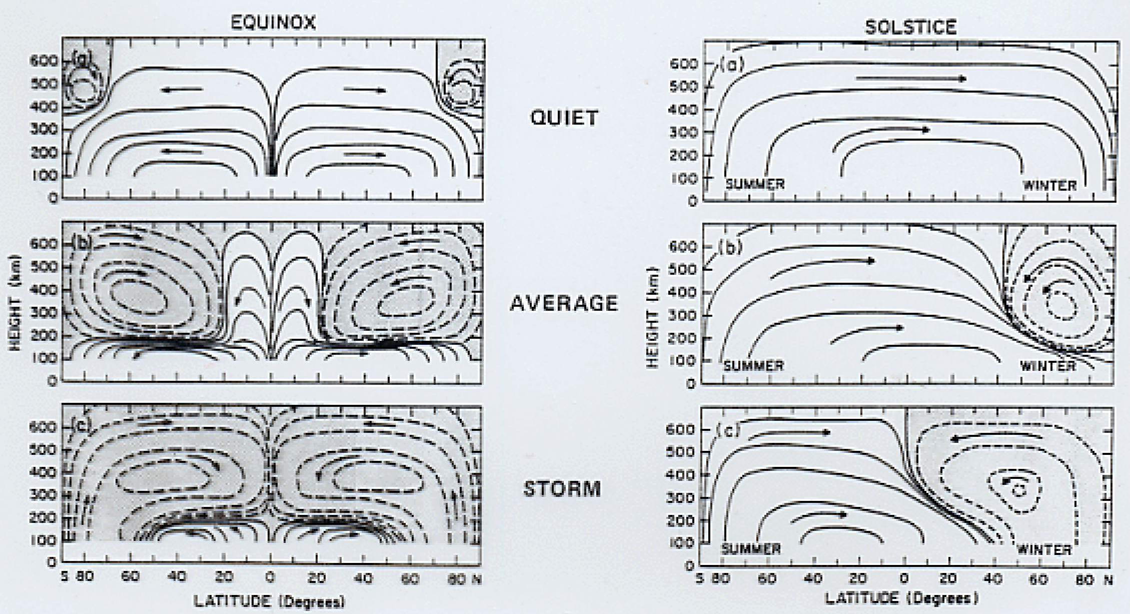


ZP
HEIGHT (km)
Log_{10} [COOLING (deg/day)]
$O(^3P)$
Ke
CO_2
NO
NO
Q_T
$O(^3P)$
K_e
CO_2
K_m

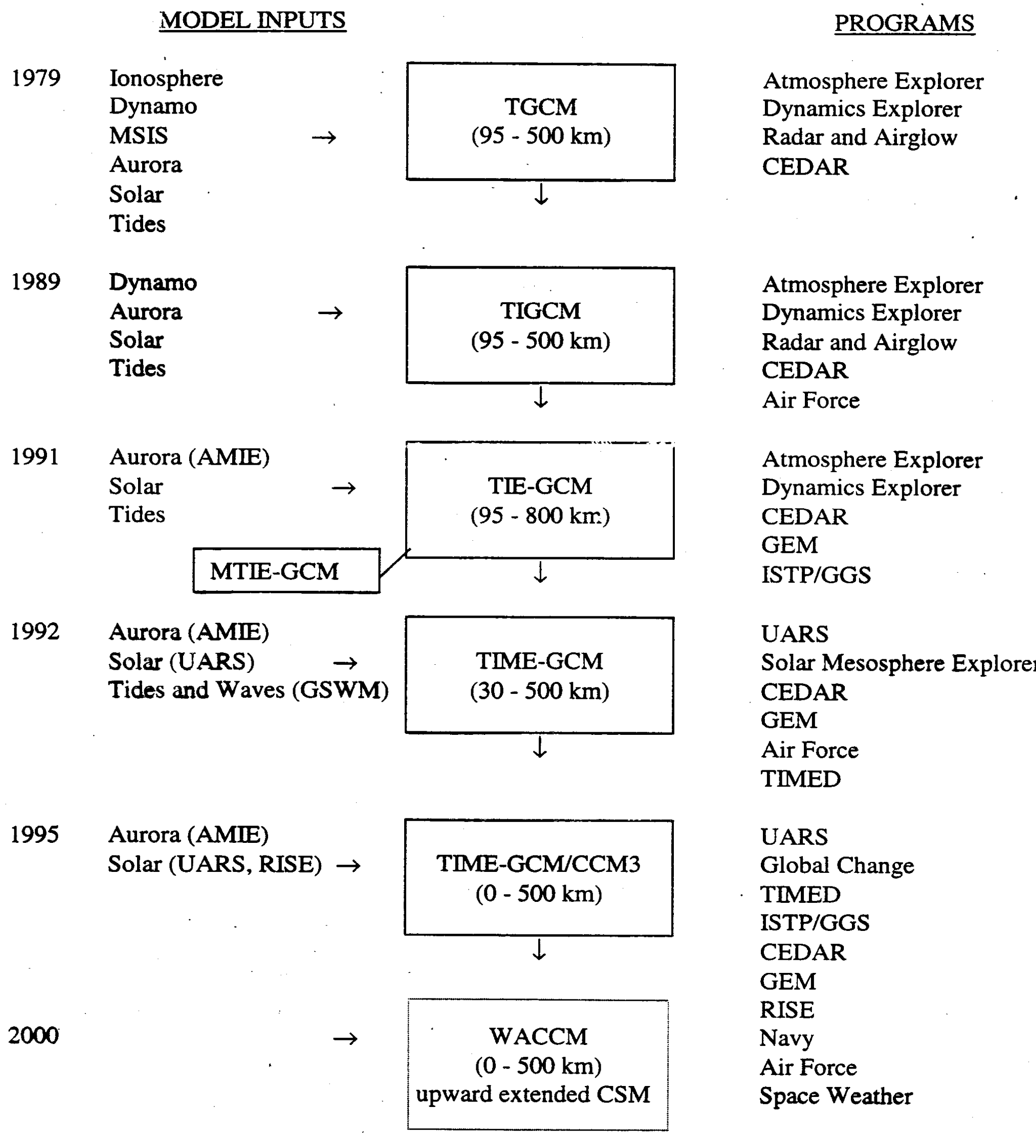
4d


SUMMER POLE
SEPT 21
WINTER POLE
HEIGHT (km)
LATITUDE (DEGREES)
(a)
SUMMER POLE
OCT 6
WINTER POLE
HEIGHT (km)
LATITUDE (DEGREES)
(b)
SUMMER POLE
OCT 21
WINTER POLE
HEIGHT (km)
LATITUDE (DEGREES)
(c)
SUMMER POLE
DEC 21
WINTER POLE
HEIGHT (km)
LATITUDE (DEGREES)
(d)


STORM
AVERAGE
QUIET

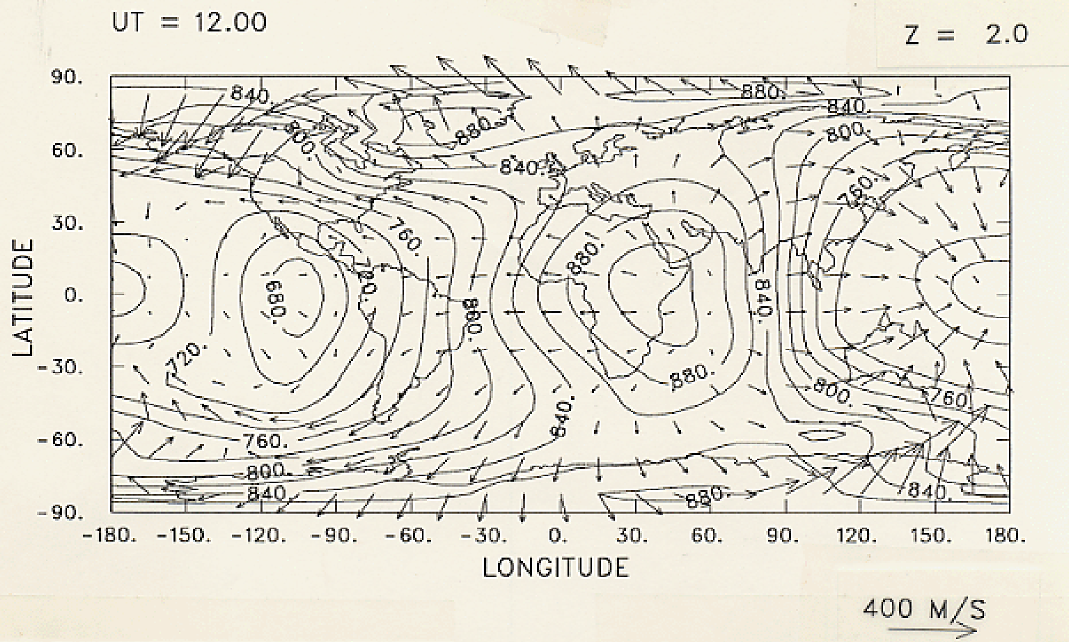

EQUINOX
SOLSTICE
QUIET
AVERAGE
STORM
(a)
(b)
(c)
HEIGHT (km)
SUMMER
WINTER
0
100
200
300
400
500
600
S 80
60
40
20
0
20
40
60
80 N
LATITUDE (Degrees)

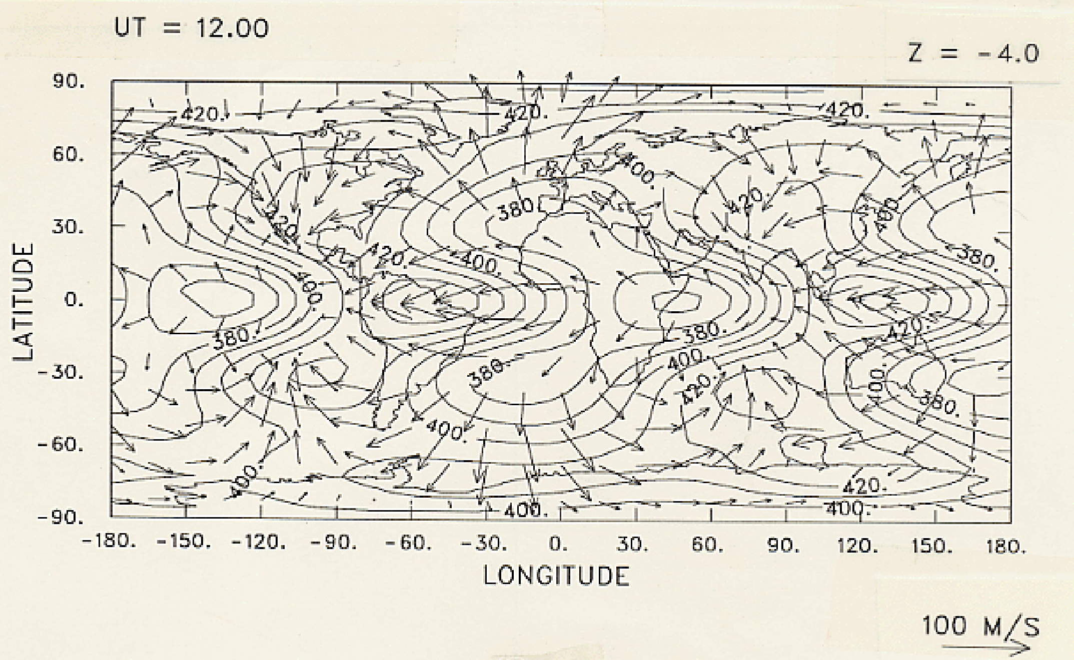
LONG RANGE TGCM MODEL DEVELOPMENT

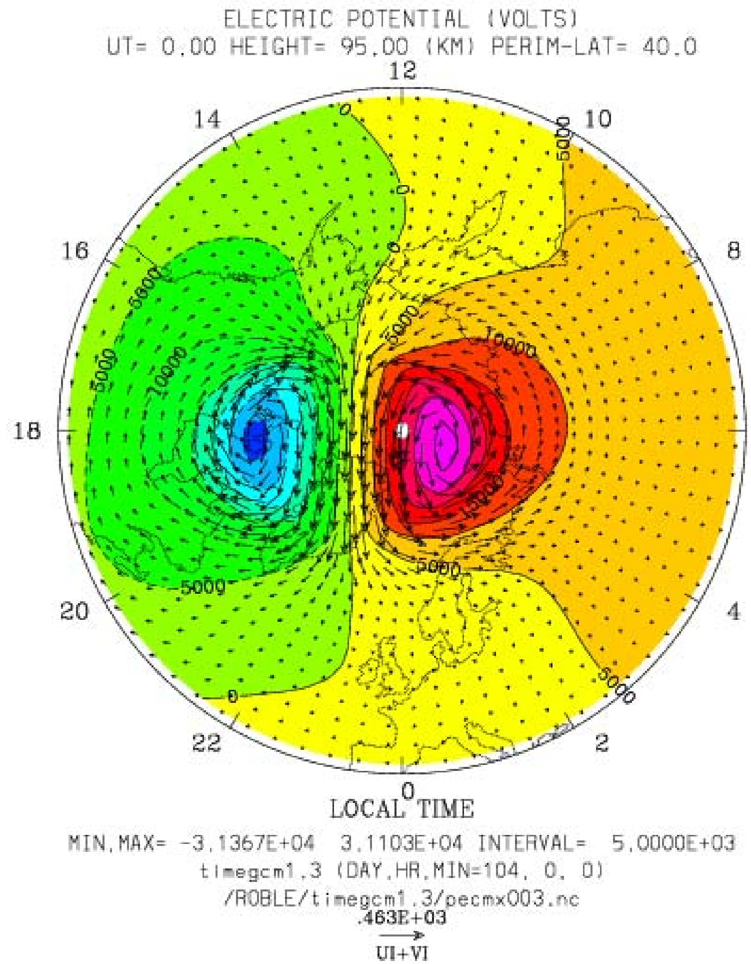


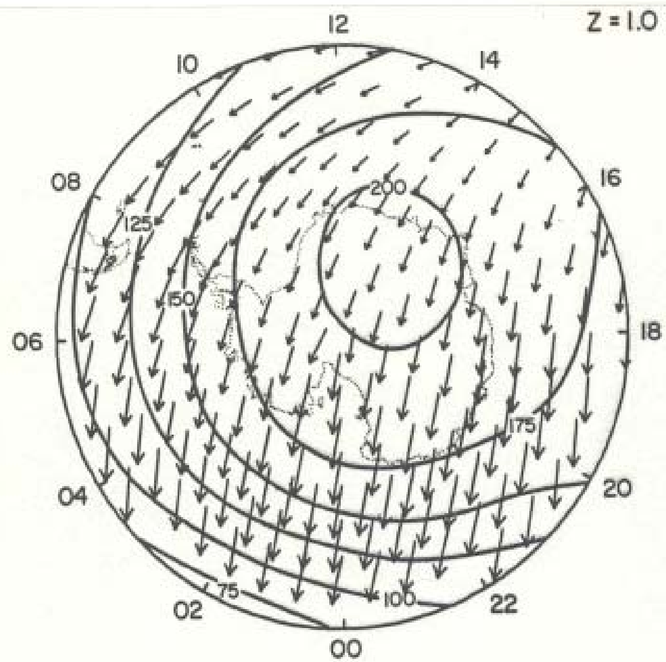
Schematic illustrating past and future TGCM development. The year of model development and diminishing dependence on empirical specification is given on the left of the boxes and the programs and data sources used for GCM validation and scientific studies is given on the right. CCM refers to the NCAR Community Climate Model.

EARTH

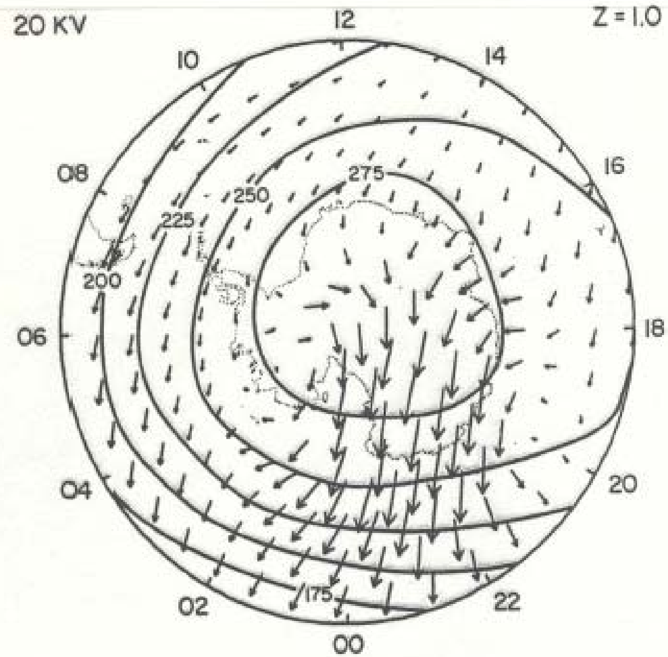

UT = 12.00
Z = 2.0
LATITUDE
LONGITUDE
400 M/S
90.
60.
30.
0.
-30.
-60.
-90.
-180. -150. -120. -90. -60. -30. 0. 30. 60. 90. 120. 150. 180.
840.
800.
880.
760.
720.
680.


UT = 12.00
Z = -4.0
LATITUDE
LONGITUDE
100 M/S
90.
60.
30.
0.
-30.
-60.
-90.
-180. -150. -120. -90. -60. -30. 0. 30. 60. 90. 120. 150. 180.
420.
400.
380.

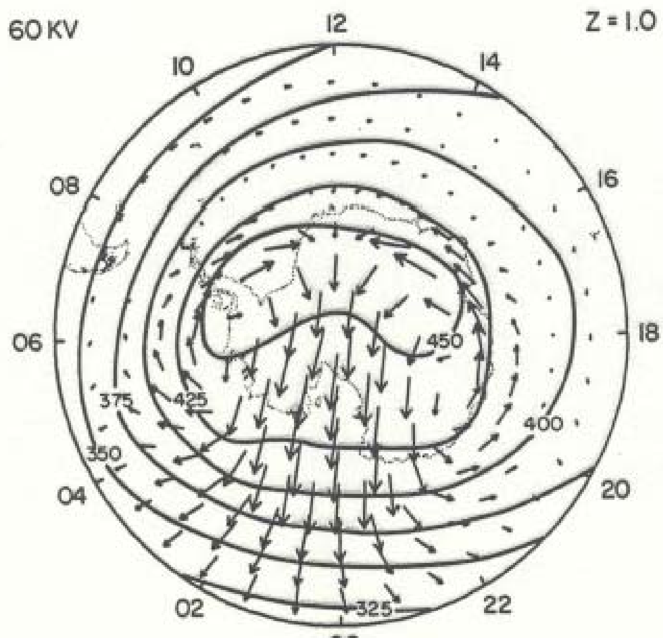

ELECTRIC POTENTIAL (VOLTS)
UT= 0.00 HEIGHT= 95.00 (KM) PERIM-LAT= 40.0
12
14
10
16
8
18
6
20
4
22
2
0
5000
10000
-5000
LOCAL TIME
MIN,MAX= -3.1367E+04 3.1103E+04 INTERVAL= 5.0000E+03
timegcm1.3 (DAY,HR,MIN=104, 0, 0)
/ROBLE/timegcm1.3/pecmx003.nc
.463E+03
UI+VI

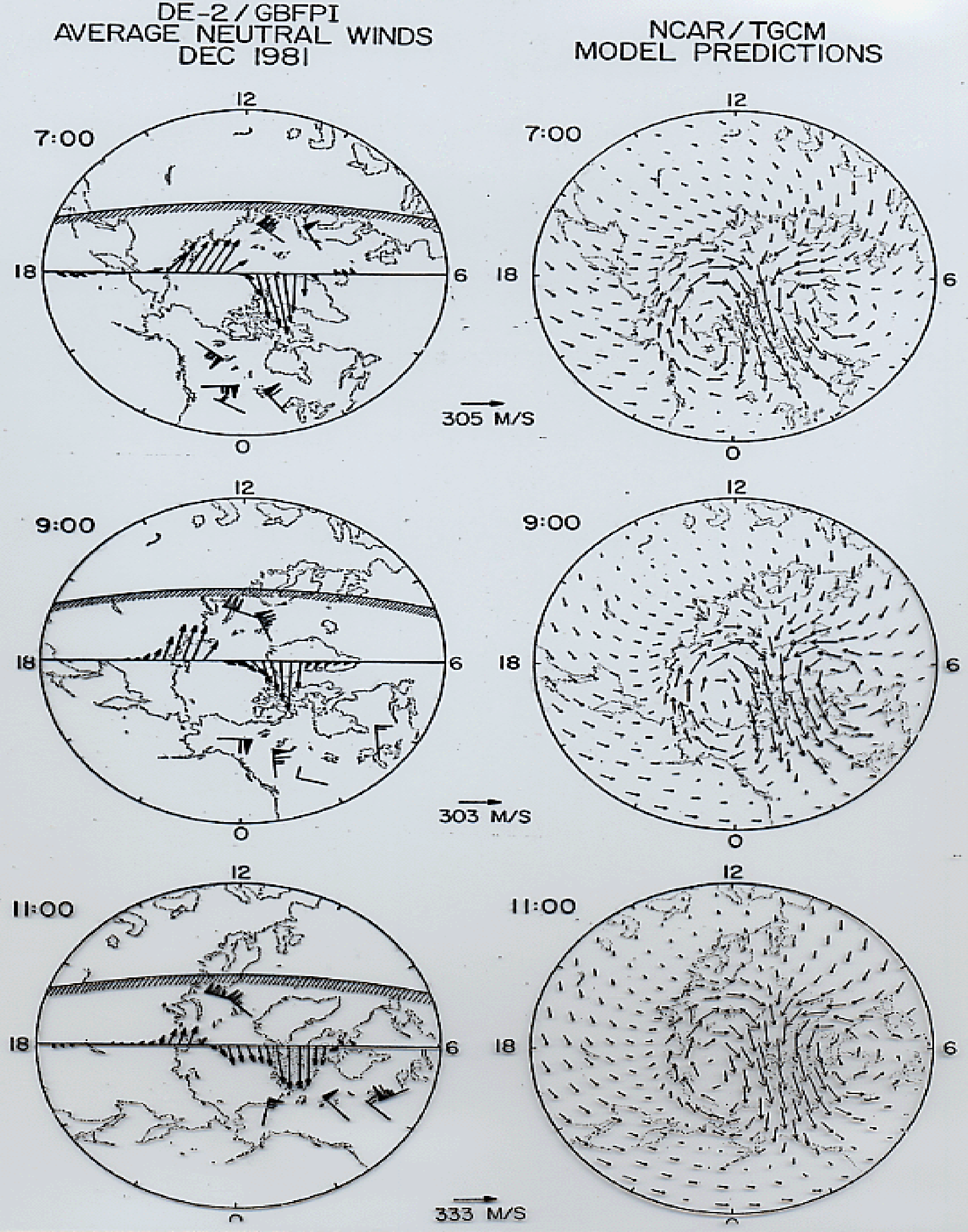

Z = 1.0
20 KV
12
14
16
18
20
22
00
02
04
06
08
10
200
175
150
125
100
75
LOCAL TIME

(a)

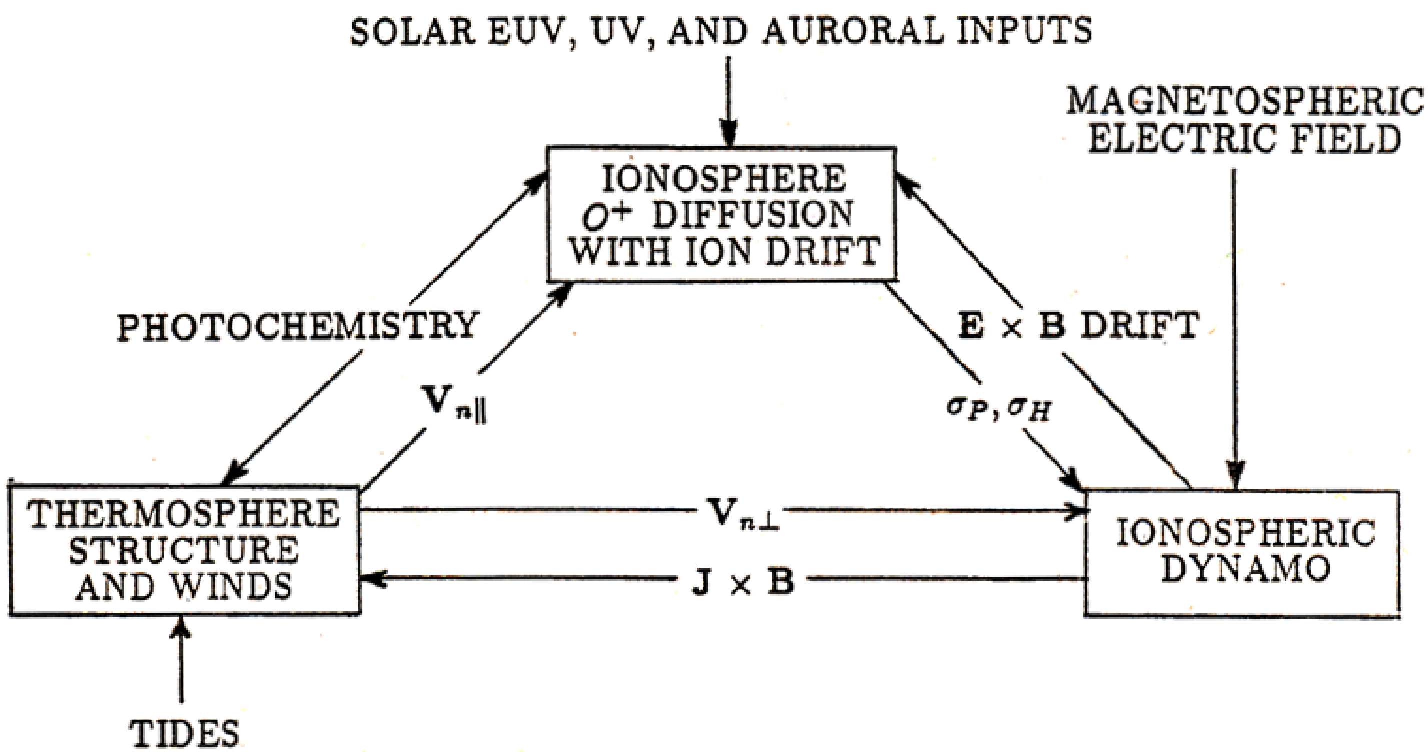

Z = 1.0
12
14
16
18
20
22
00
02
04
06
08
10
275
250
225
200
175
LOCAL TIME

(b)


60 KV
Z = 1.0
12
14
16
18
20
22
02
04
06
08
10
450
425
400
375
350
325


DE-2/GBFPI
AVERAGE NEUTRAL WINDS
DEC 1981
NCAR/TGCM
MODEL PREDICTIONS
7:00
9:00
11:00
12
18
6
0
305 M/S
303 M/S
333 M/S

TIE-GCM



SOLAR EUV, UV, AND AURORAL INPUTS
MAGNETOSPHERIC ELECTRIC FIELD
IONOSPHERE
O^+ DIFFUSION
WITH ION DRIFT
PHOTOCHEMISTRY
$\mathbf{V}_{n\parallel}$
$\mathbf{E} \times \mathbf{B}$ DRIFT
σ_P, σ_H
THERMOSPHERE
STRUCTURE
AND WINDS
$\mathbf{V}_{n\perp}$
$\mathbf{J} \times \mathbf{B}$
IONOSPHERIC
DYNAMO
TIDES

TIE-GCM
350 km, 0 UT, Equinox, Solar Maximum

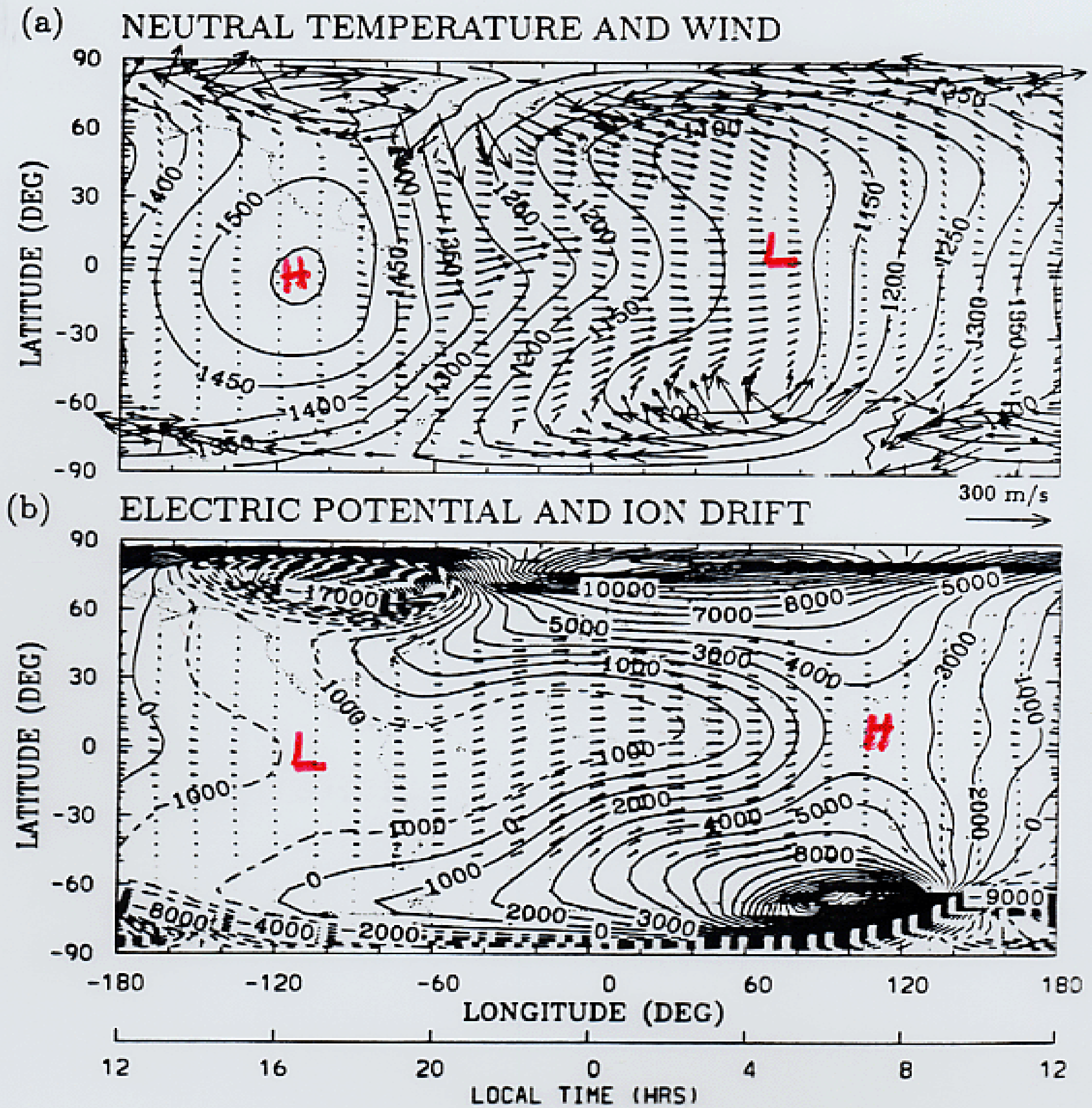
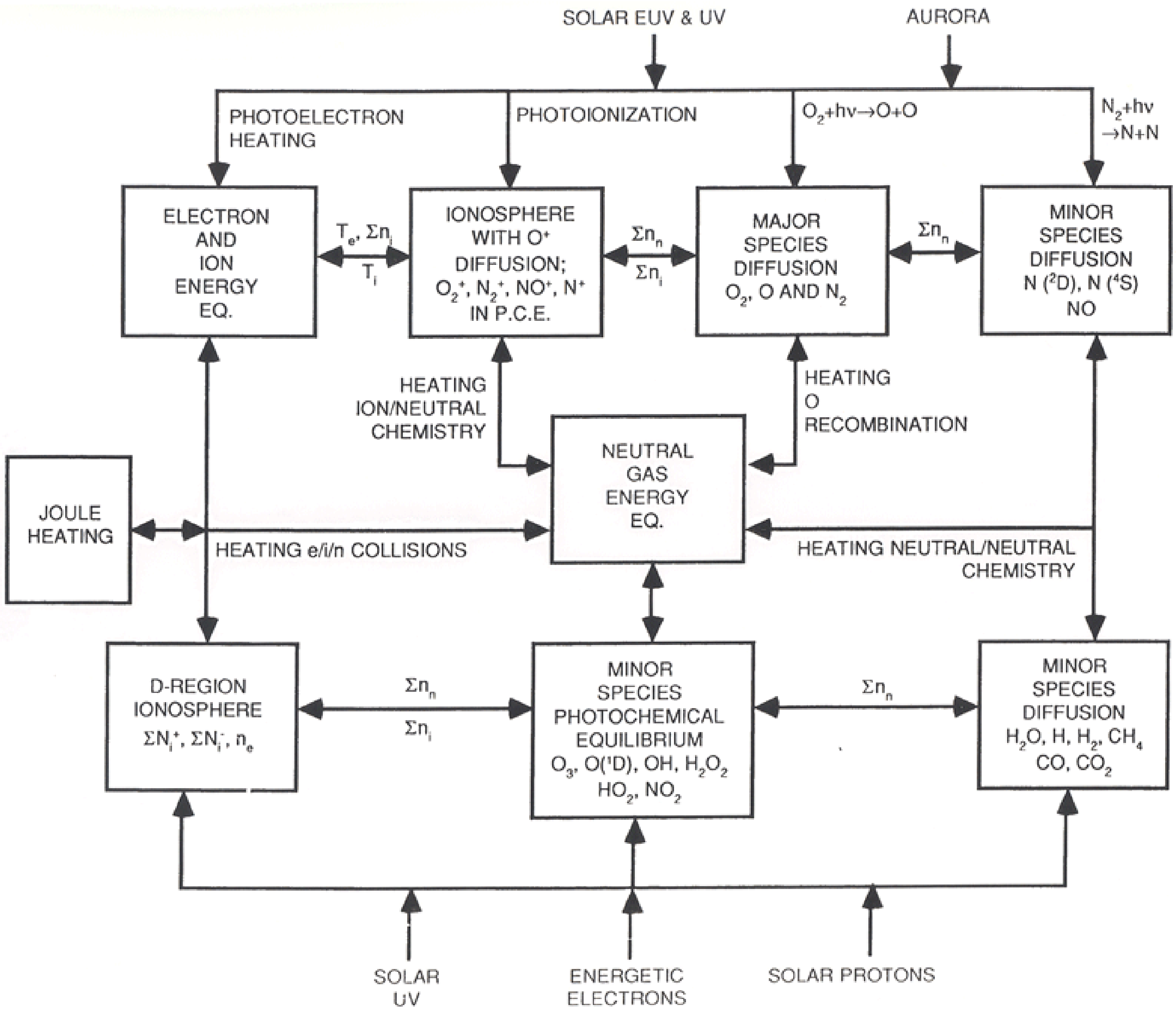
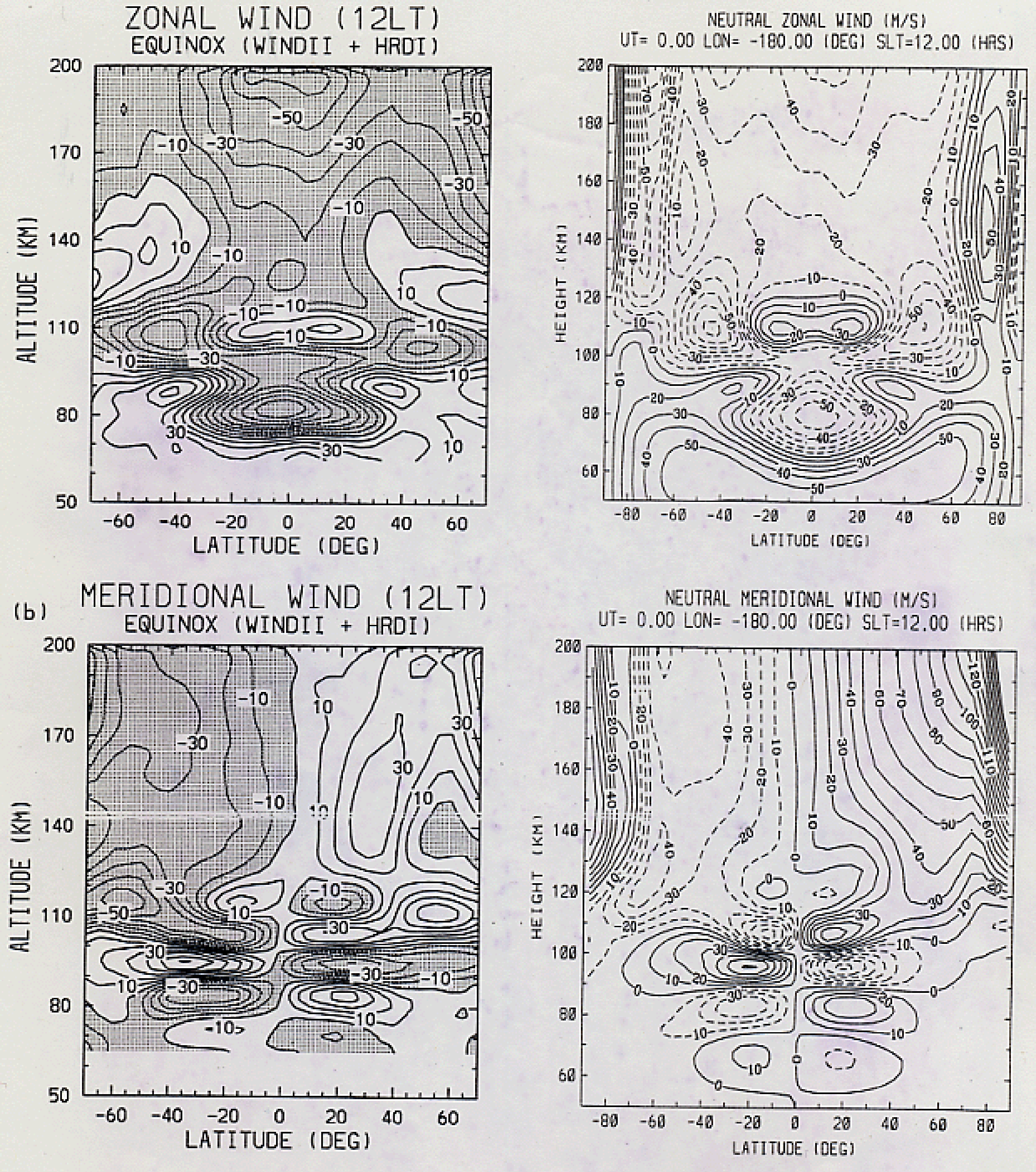
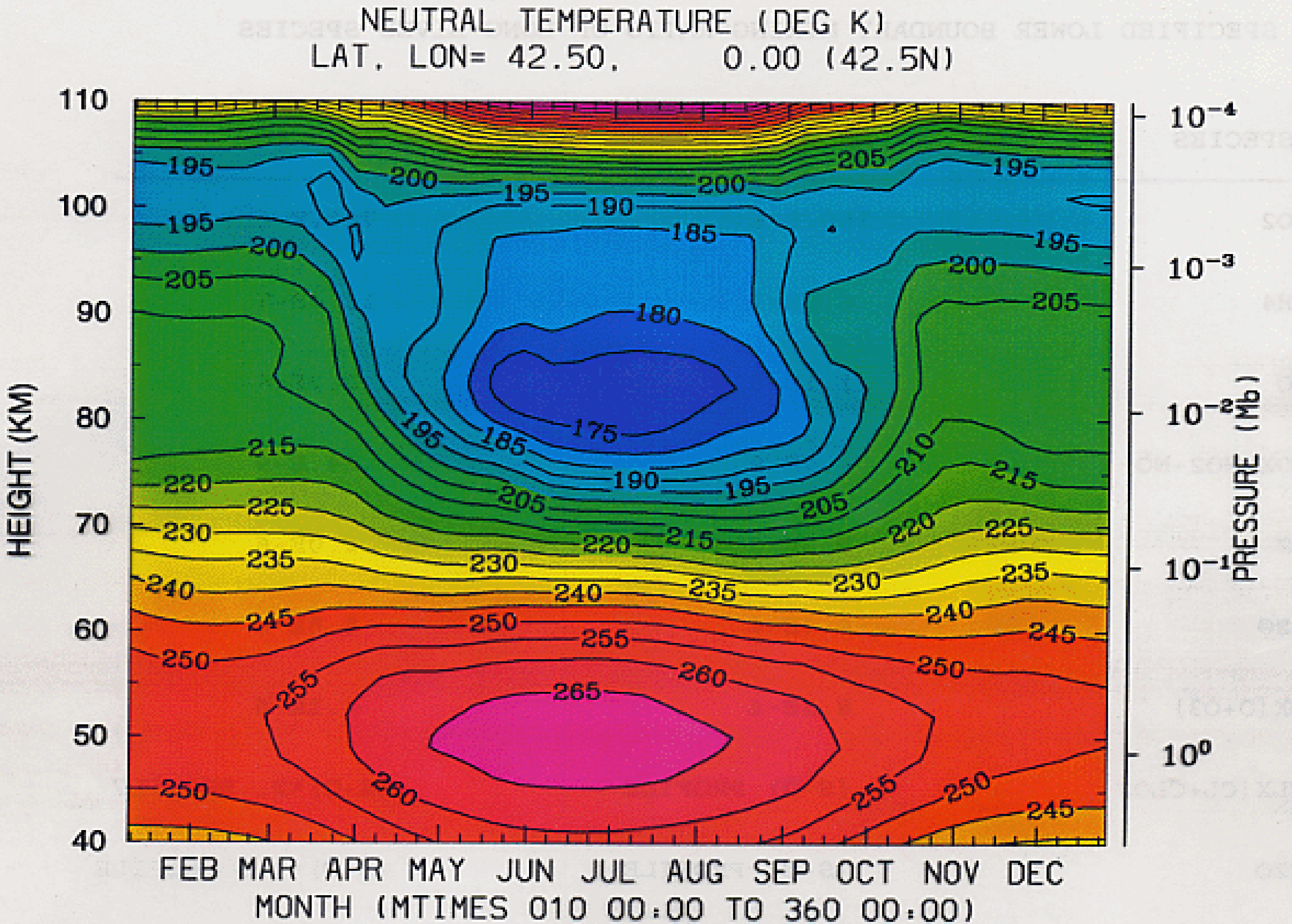


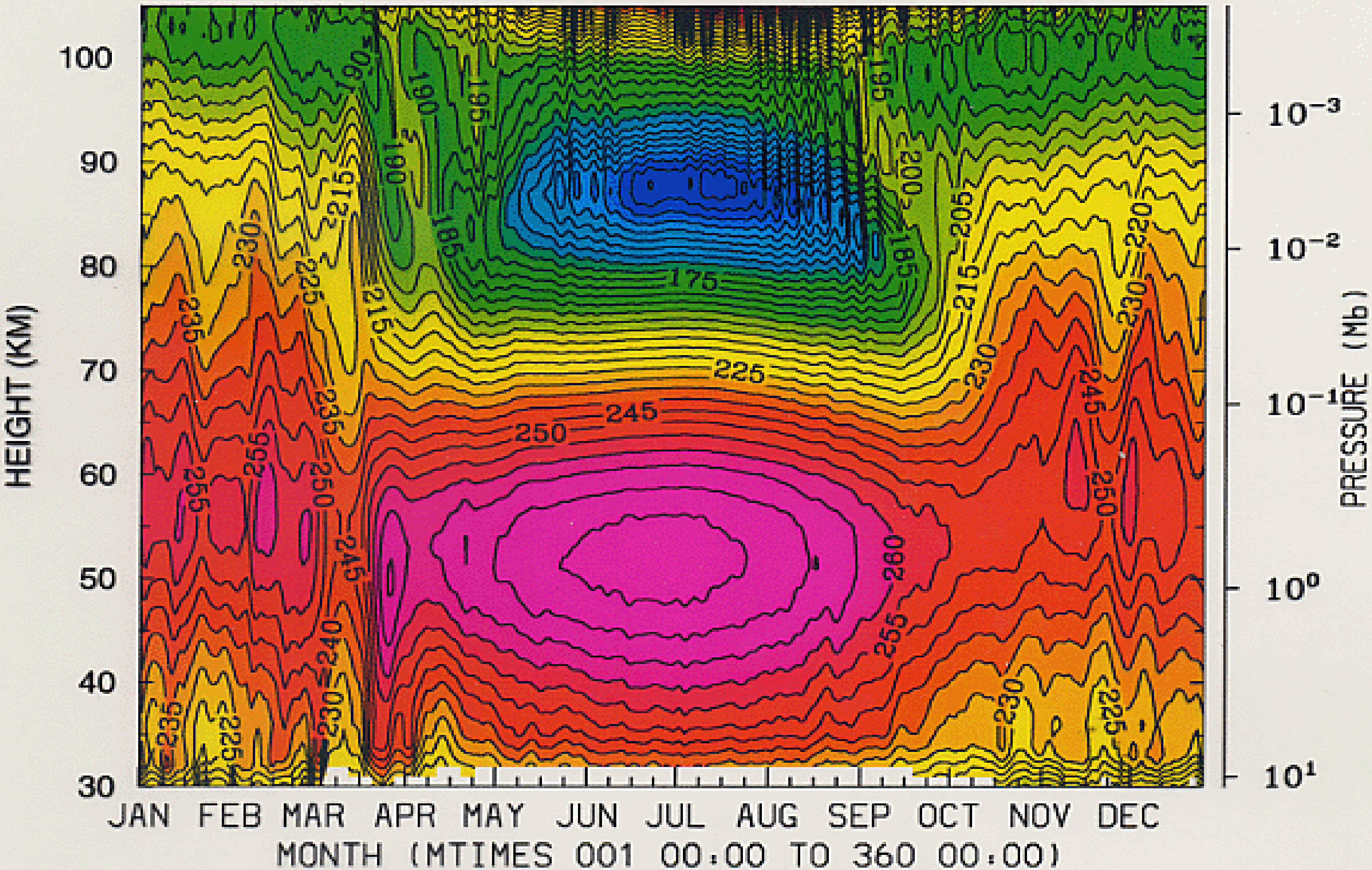
Figure 2

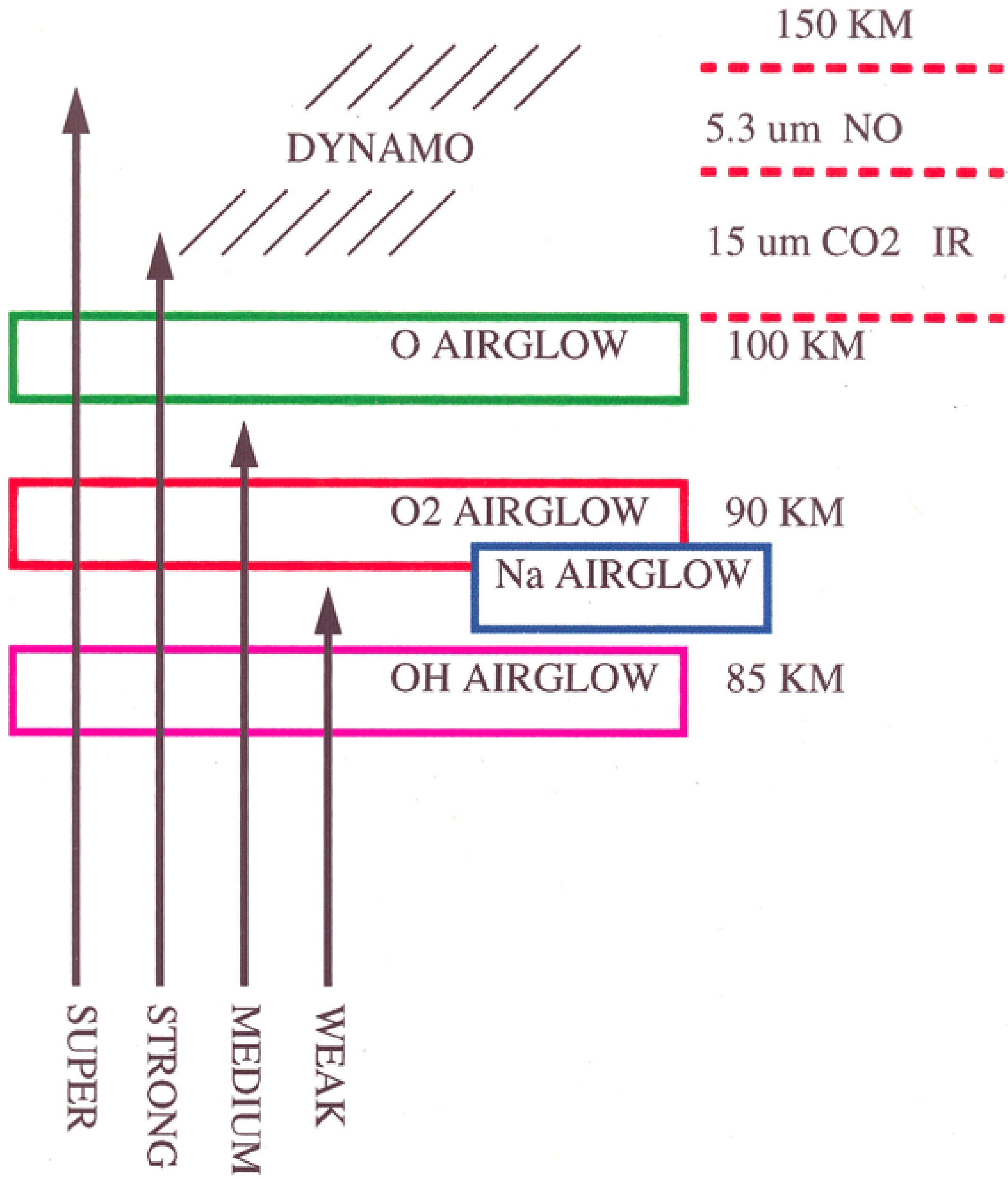

SOLAR EUV & UV
AURORA
PHOTOELECTRON HEATING
PHOTOIONIZATION
$O_2+h\nu \rightarrow O+O$
$N_2+h\nu \rightarrow N+N$
ELECTRON AND ION ENERGY EQ.
T_e, Σn_i
T_i
IONOSPHERE WITH O^+ DIFFUSION; O_2^+, N_2^+, NO^+, N^+ IN P.C.E.
Σn_n
Σn_i
MAJOR SPECIES DIFFUSION O_2, O AND N_2
Σn_n
MINOR SPECIES DIFFUSION N (^{2}D), N (^{4}S) NO
HEATING ION/NEUTRAL CHEMISTRY
HEATING O RECOMBINATION
NEUTRAL GAS ENERGY EQ.
JOULE HEATING
HEATING e/i/n COLLISIONS
HEATING NEUTRAL/NEUTRAL CHEMISTRY
D-REGION IONOSPHERE ΣN_i^+, ΣN_i^-, n_e
Σn_n
Σn_i
MINOR SPECIES PHOTOCHEMICAL EQUILIBRIUM O_3, O(^{1}D), OH, H_2O_2 HO_2, NO_2
Σn_n
MINOR SPECIES DIFFUSION H_2O, H, H_2, CH_4 CO, CO_2
SOLAR UV
ENERGETIC ELECTRONS
SOLAR PROTONS


ZONAL WIND (12LT)
EQUINOX (WINDII + HRDI)
ALTITUDE (KM)
LATITUDE (DEG)
NEUTRAL ZONAL WIND (M/S)
UT= 0.00 LON= -180.00 (DEG) SLT=12.00 (HRS)
HEIGHT (KM)
LATITUDE (DEG)
(b)
MERIDIONAL WIND (12LT)
EQUINOX (WINDII + HRDI)
ALTITUDE (KM)
LATITUDE (DEG)
NEUTRAL MERIDIONAL WIND (M/S)
UT= 0.00 LON= -180.00 (DEG) SLT=12.00 (HRS)
HEIGHT (KM)
LATITUDE (DEG)

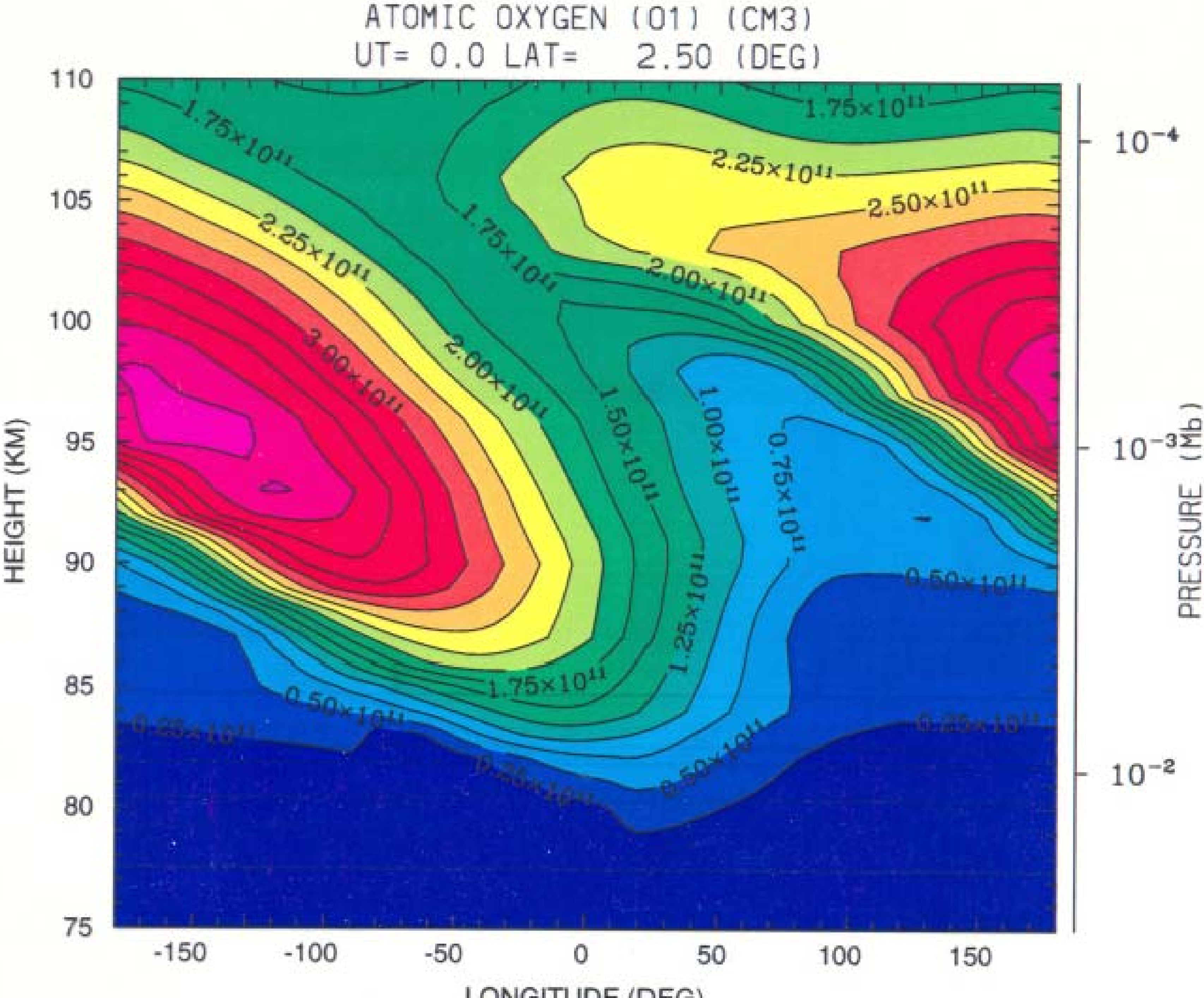

NEUTRAL TEMPERATURE (DEG K)
LAT, LON= 42.50, 0.00 (42.5N)
HEIGHT (KM)
PRESSURE (Mb)
FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
MONTH (MTIMES 010 00:00 TO 360 00:00)

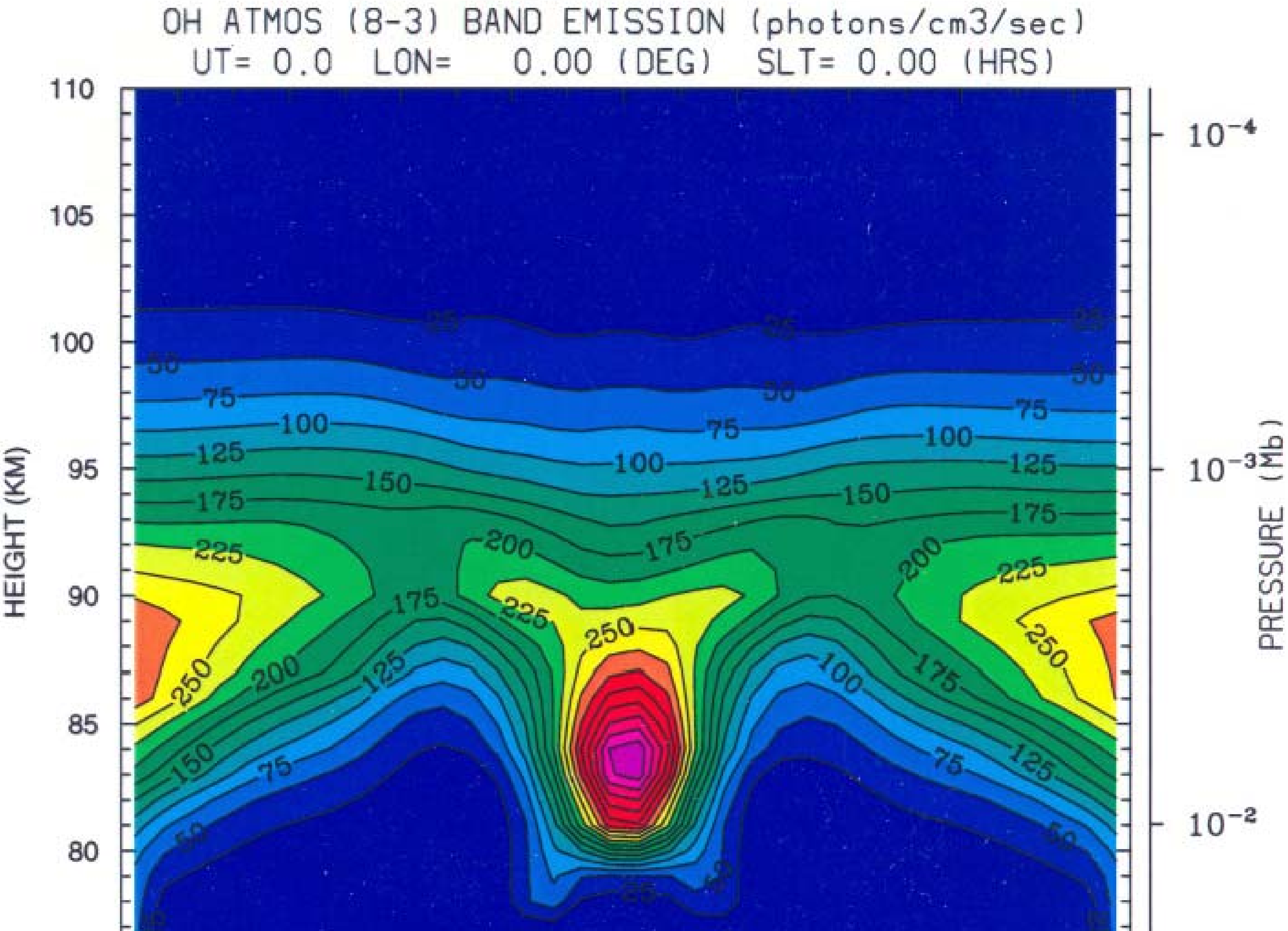
NEUTRAL TEMPERATURE (DEG K)
LAT, LON= 67.50, -50.00 (SONDRSTROM FJORD)



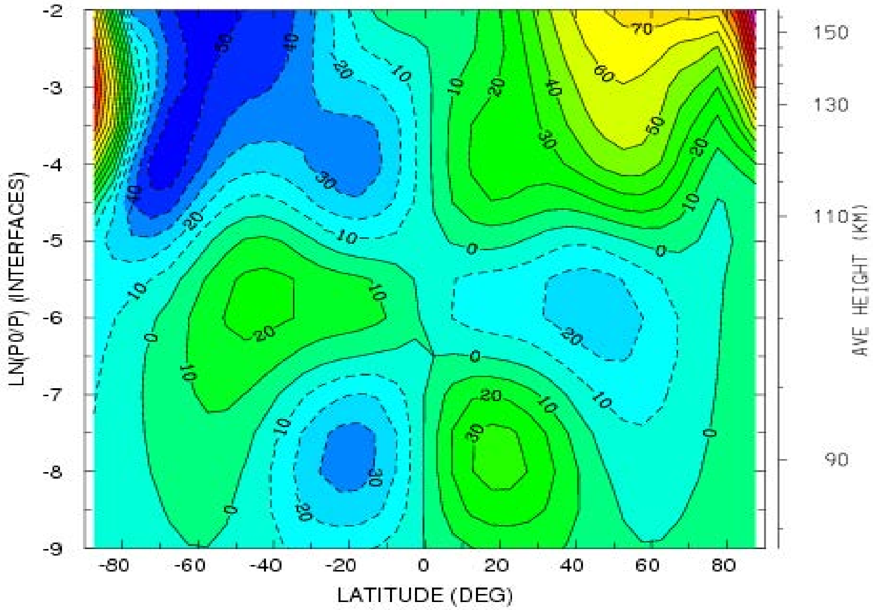


DIURNAL TIDE

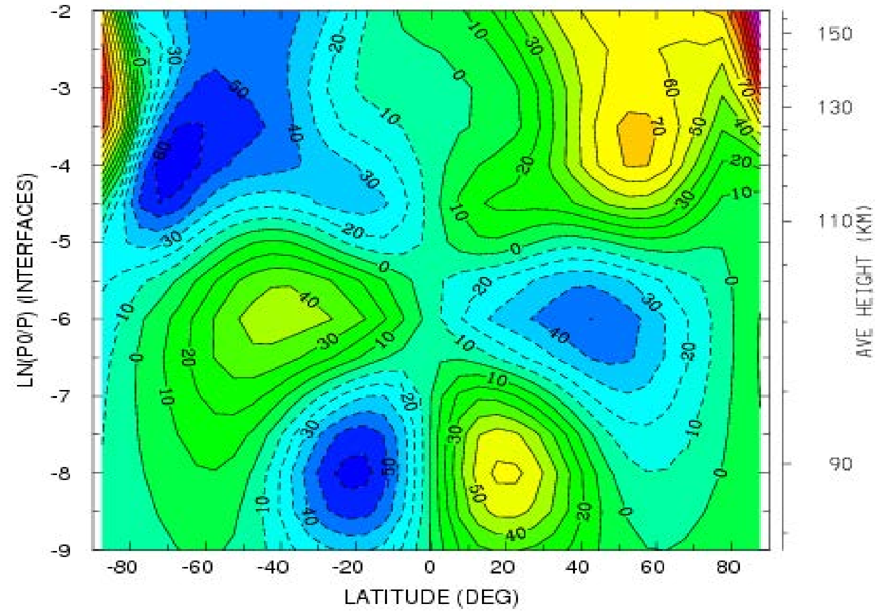

ATOMIC OXYGEN (O1) (CM3)
UT= 0.0 LAT= 2.50 (DEG)
HEIGHT (KM)
110
105
100
95
90
85
80
75
PRESSURE (Mb)
10⁻⁴
10⁻³
10⁻²
-150
-100
-50
0
50
100
150
1.75x10¹¹
2.25x10¹¹
2.50x10¹¹
2.00x10¹¹
3.00x10¹¹
1.50x10¹¹
1.25x10¹¹
1.00x10¹¹
0.75x10¹¹
0.50x10¹¹
0.25x10¹¹


OH ATMOS (8-3) BAND EMISSION (photons/cm3/sec)
UT= 0.0 LON= 0.00 (DEG) SLT= 0.00 (HRS)
HEIGHT (KM)
110
105
100
95
90
85
80
PRESSURE (Mb)
10^{-4}
10^{-3}
10^{-2}
25
50
75
100
125
150
175
200
225
250

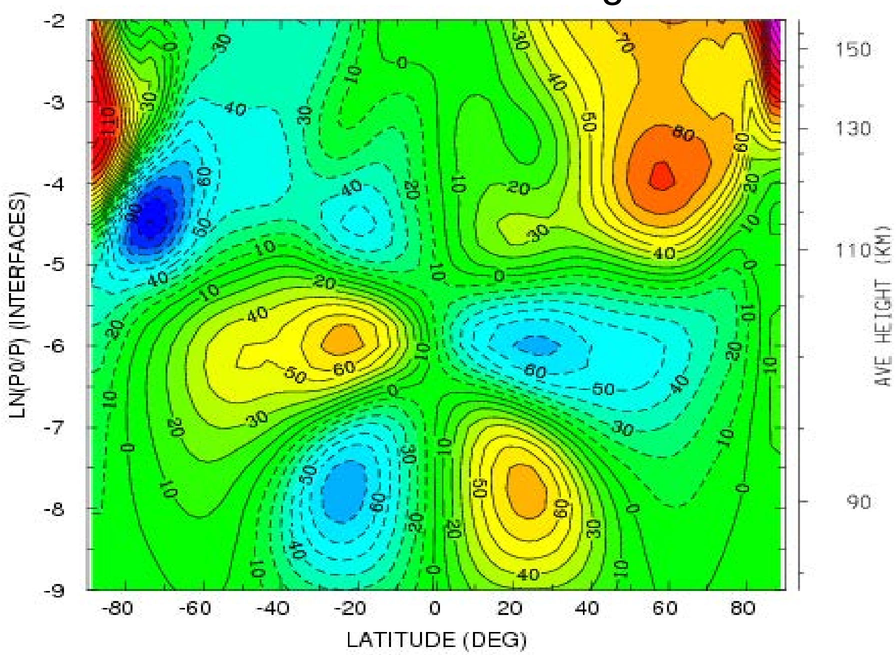
VN SLT=12 AMPLITUDE*1



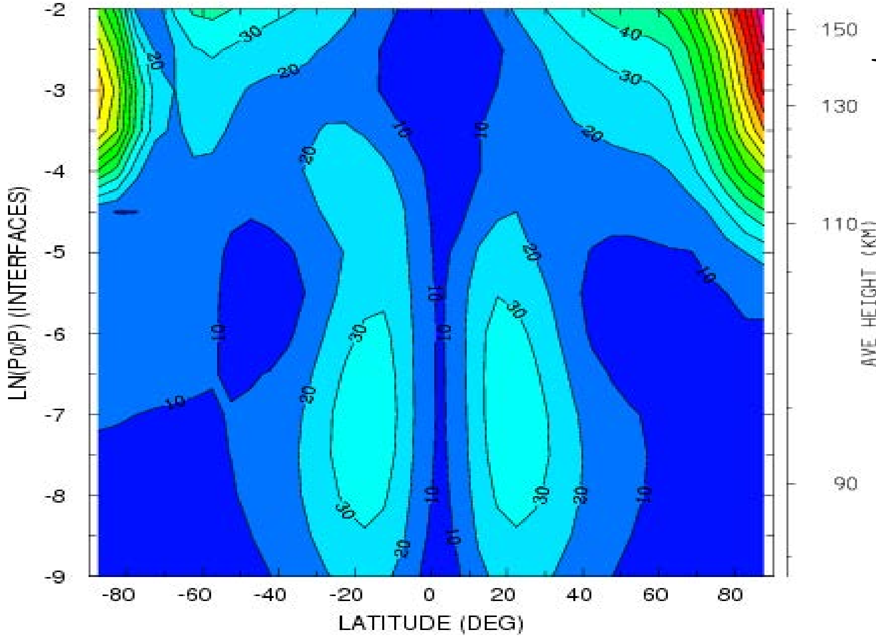
VN SLT=12 AMPLITUDE*2



VN SLT=12 2.5 deg

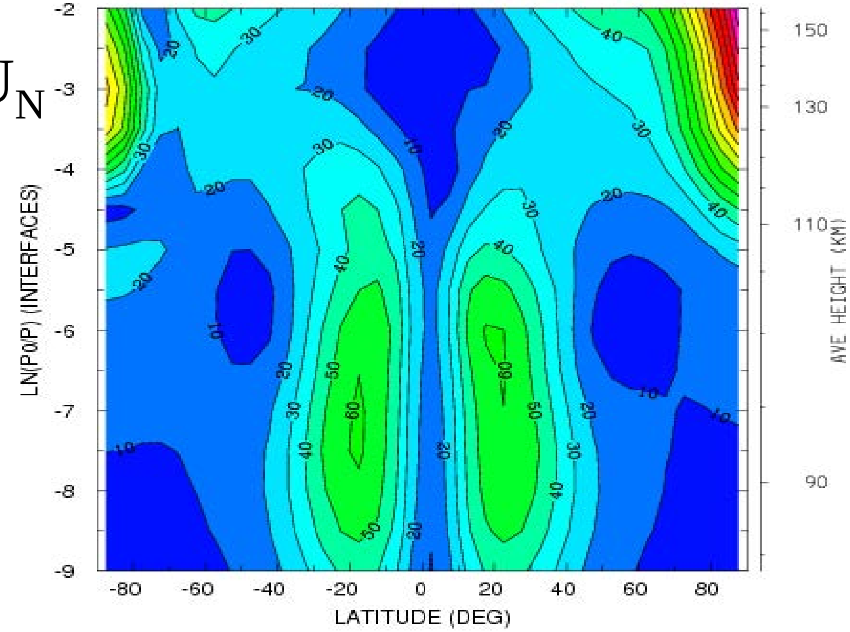


VN WAVE 1 AMPLITUDE*1

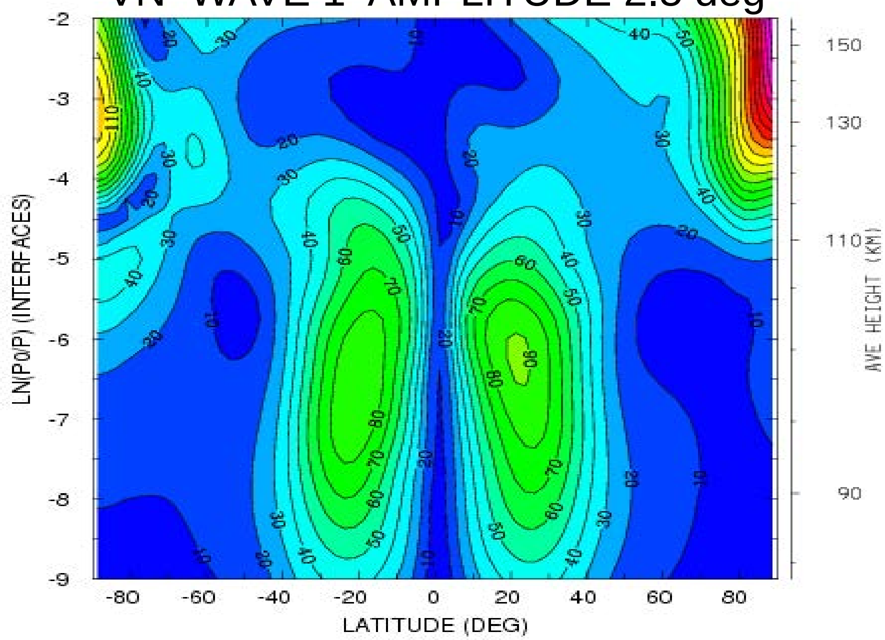


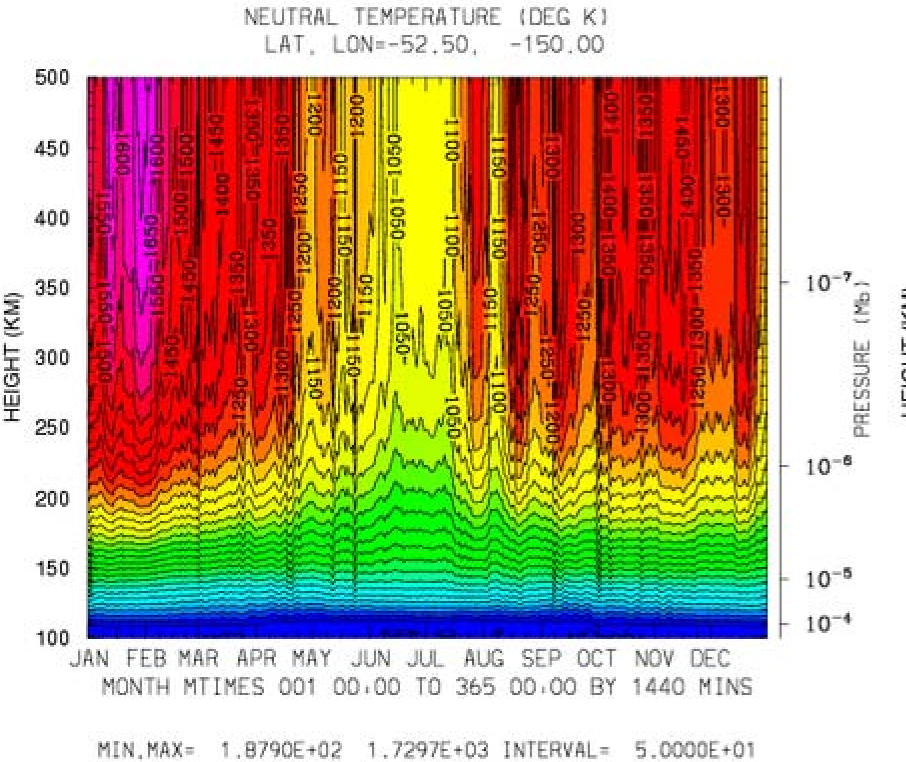
VN WAVE 1 AMPLITUDE*2

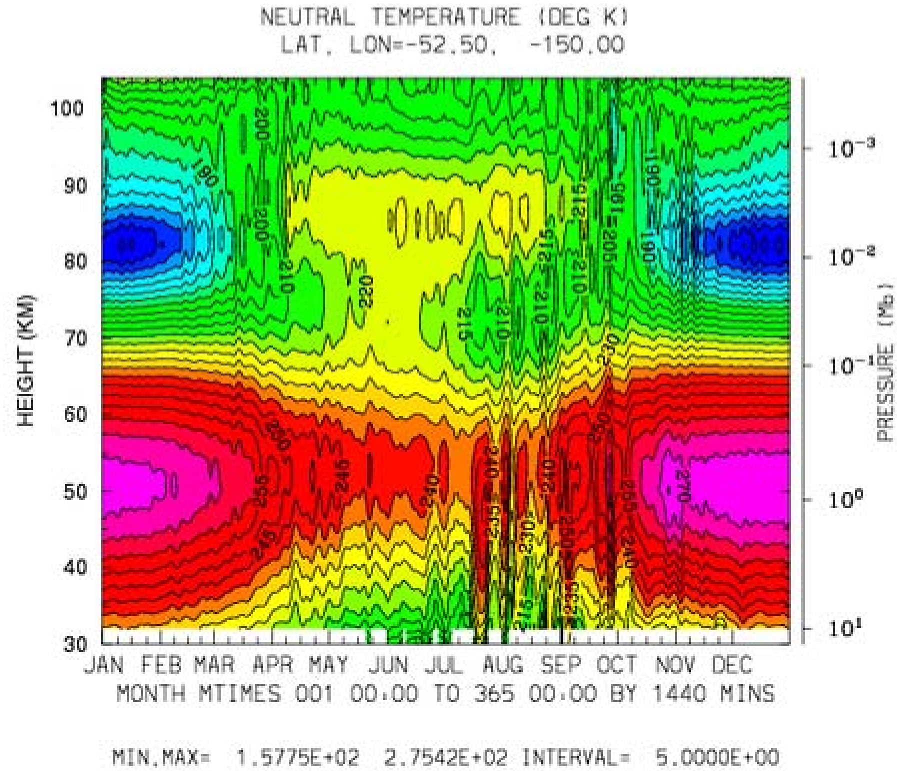
U_N



VN WAVE 1 AMPLITUDE 2.5 deg

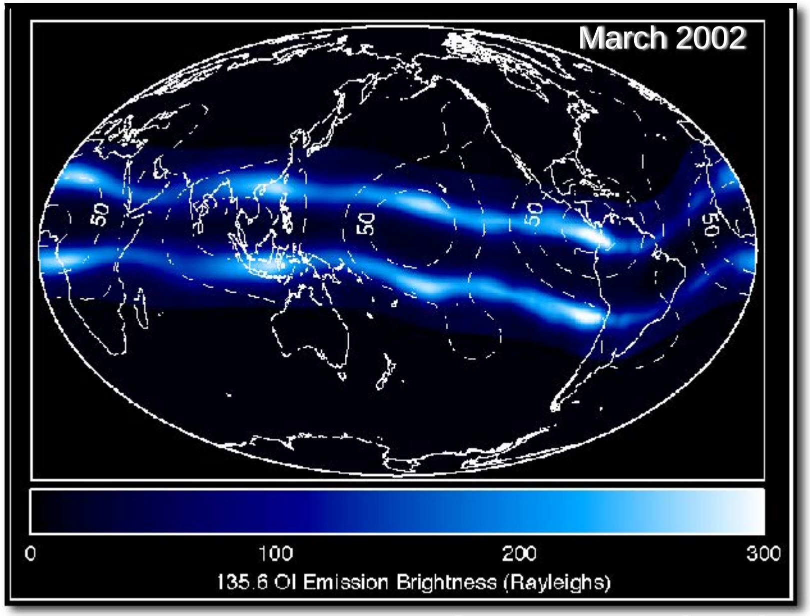



NEUTRAL TEMPERATURE (DEG K)
LAT, LON=-52.50, -150.00
HEIGHT (KM)
PRESSURE (Mb)
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
MONTH MTIMES 001 00:00 TO 365 00:00 BY 1440 MINS
MIN,MAX= 1.8790E+02 1.7297E+03 INTERVAL= 5.0000E+01


NEUTRAL TEMPERATURE (DEG K)
LAT, LON=-52.50, -150.00
HEIGHT (KM)
PRESSURE (Mb)
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
MONTH MTIMES 001 00:00 TO 365 00:00 BY 1440 MINS
MIN,MAX= 1.5775E+02 2.7542E+02 INTERVAL= 5.0000E+00

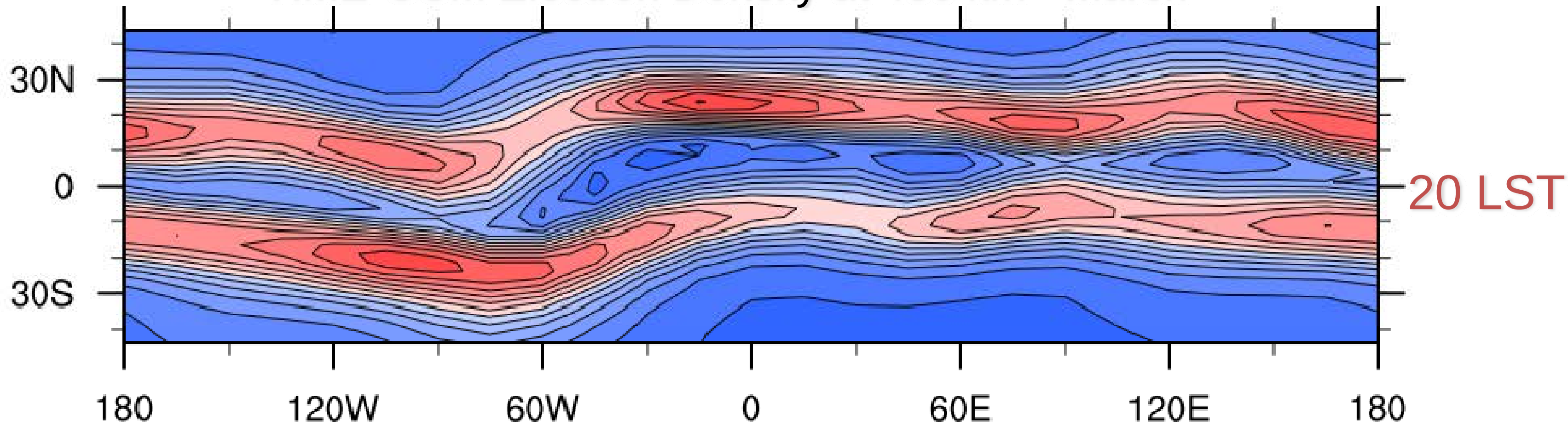
Tropospheric Tidal Effects in the Earth's Ionosphere

IMAGE FUV Ionospheric Emission

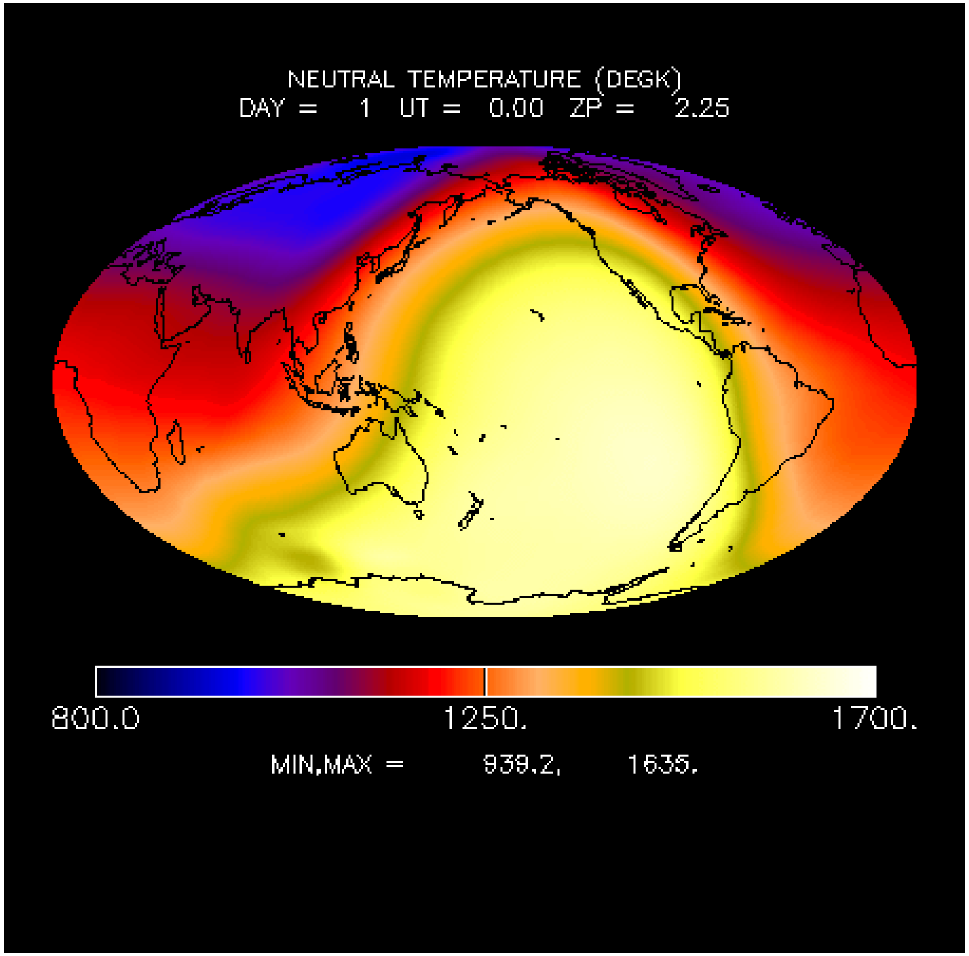


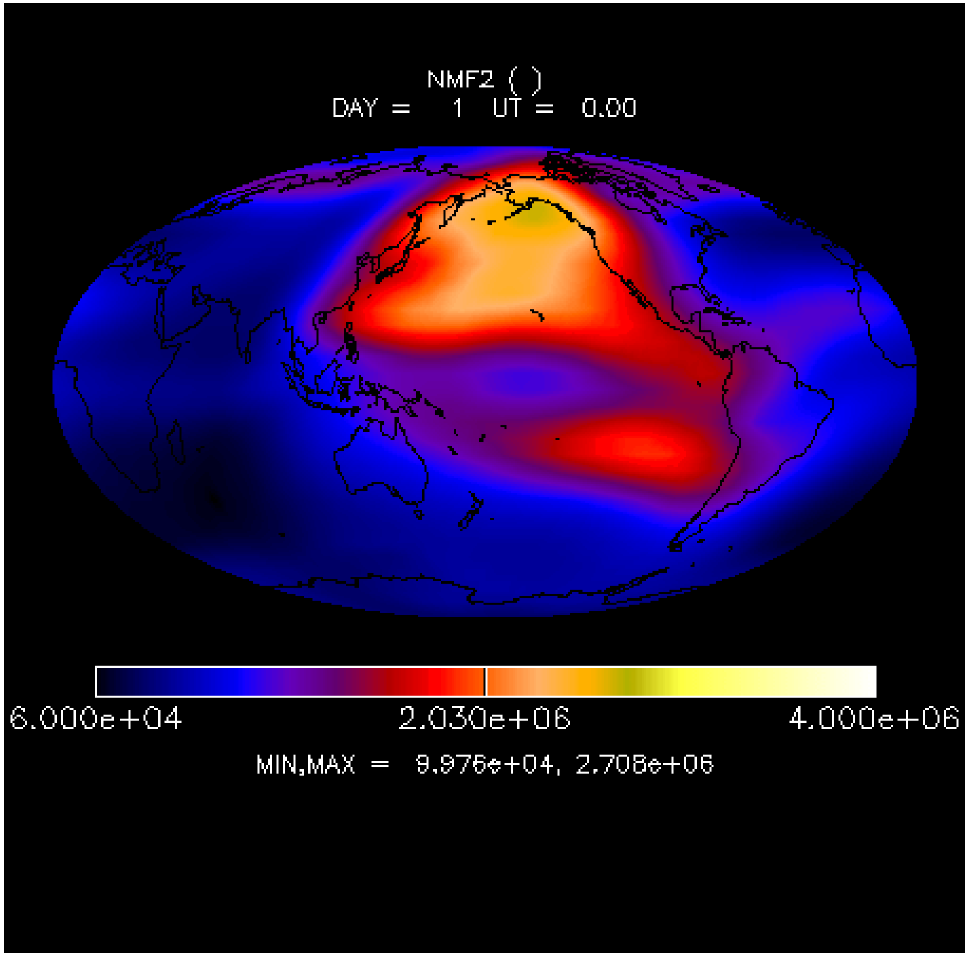
after Immel et al. (2006)

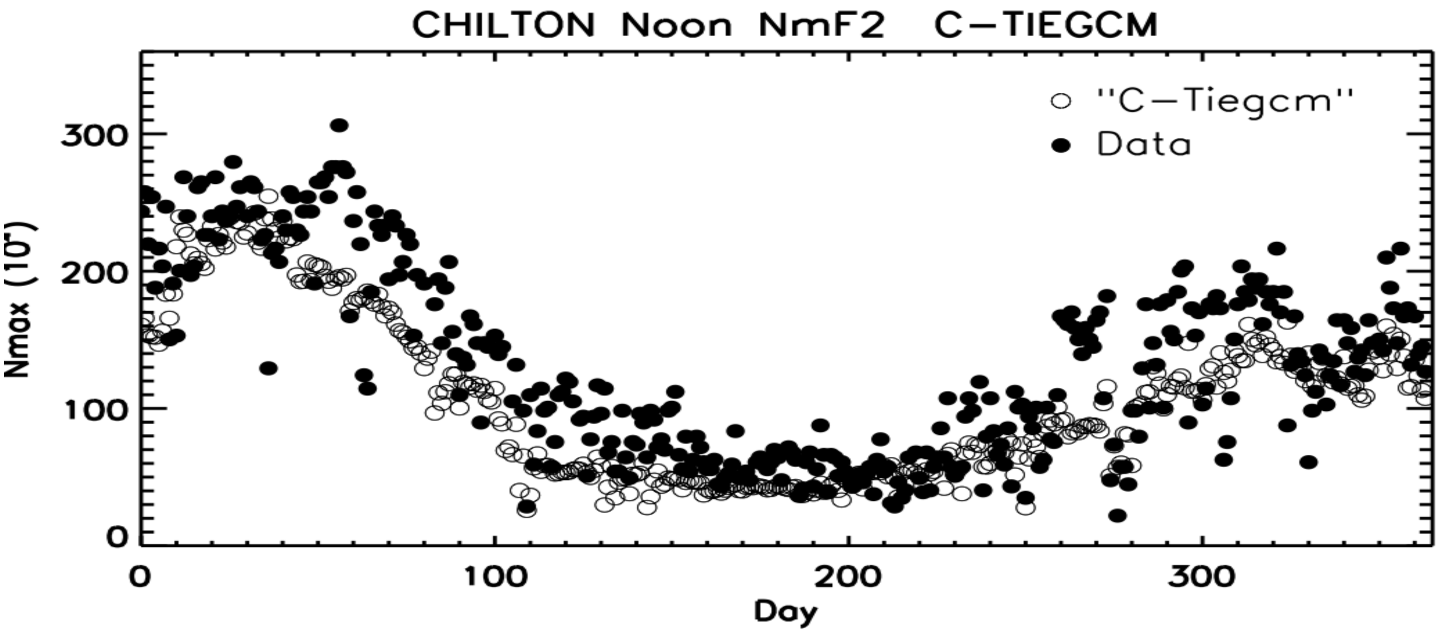
TIME-GCM Electron Density at 450 km - March

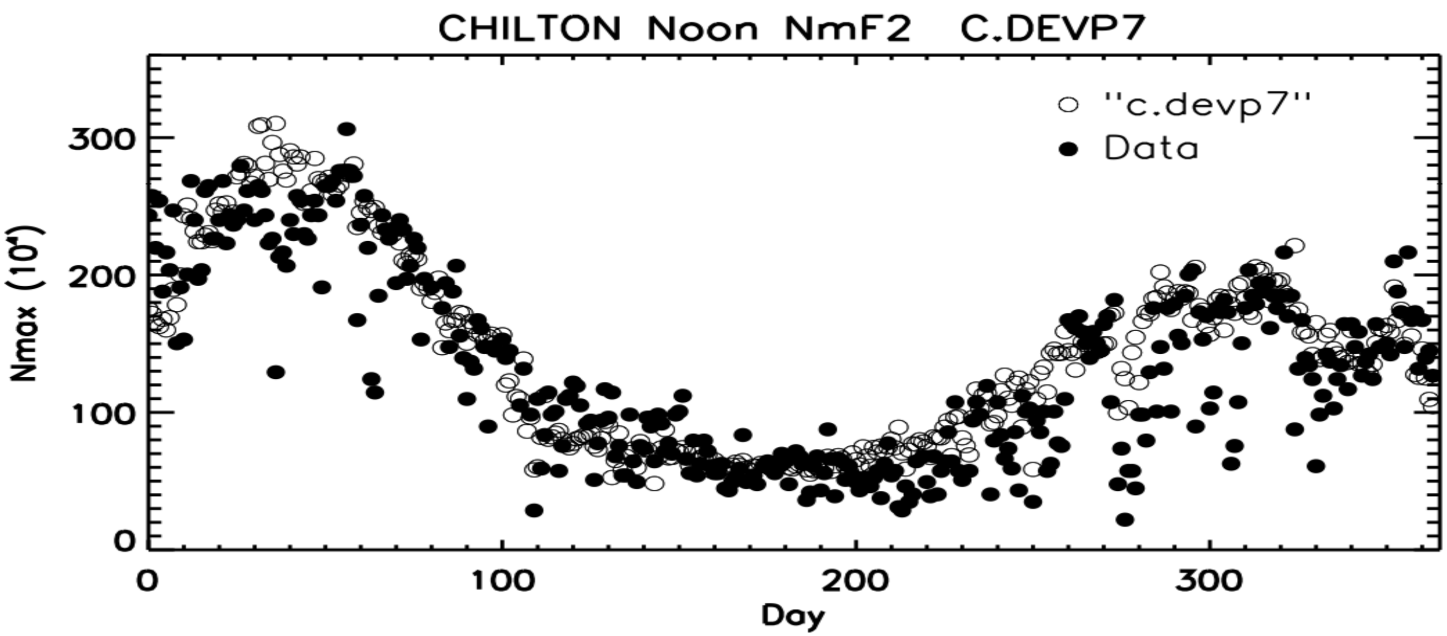


after *Hagan et al.* [2007]

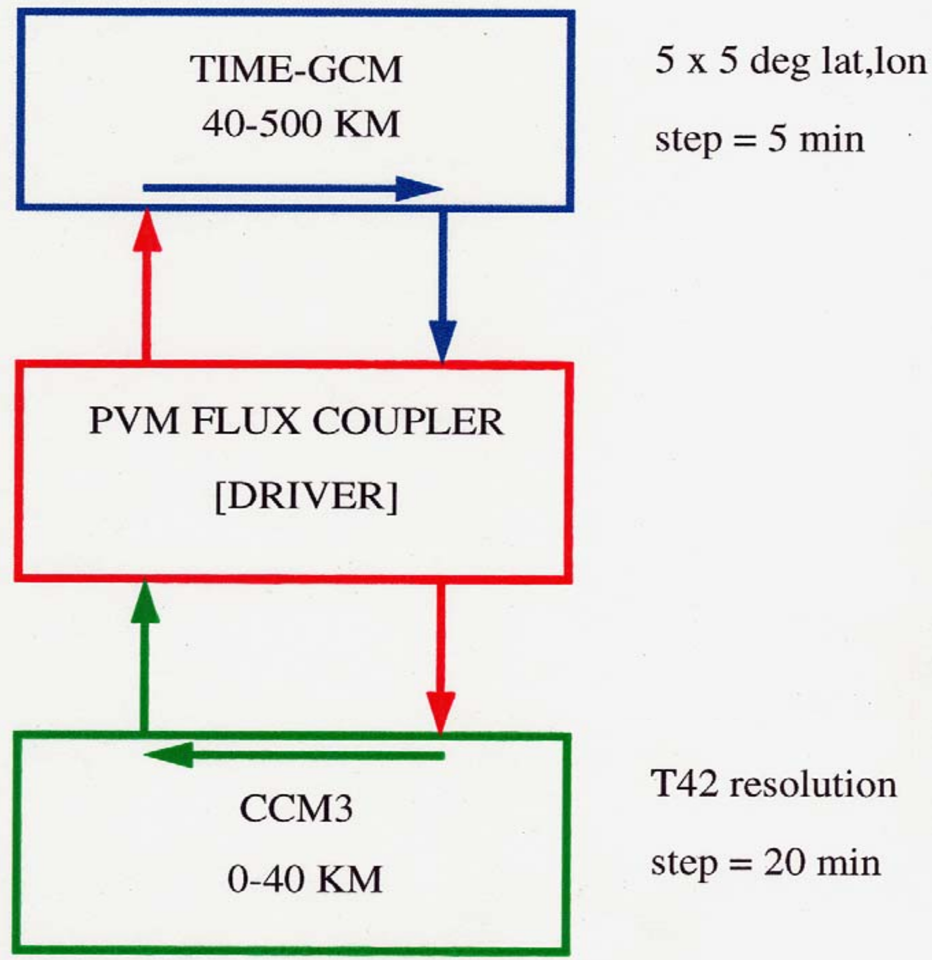

NEUTRAL TEMPERATURE (DEGK)
DAY = 1 UT = 0.00 ZP = 2.25
800.0
1250.
1700.
MIN,MAX = 939.2, 1635.


NMF2 ( )
DAY = 1 UT = 0.00
6.000e+04
2.030e+06
4.000e+06
MIN,MAX = 9.976e+04, 2.708e+06

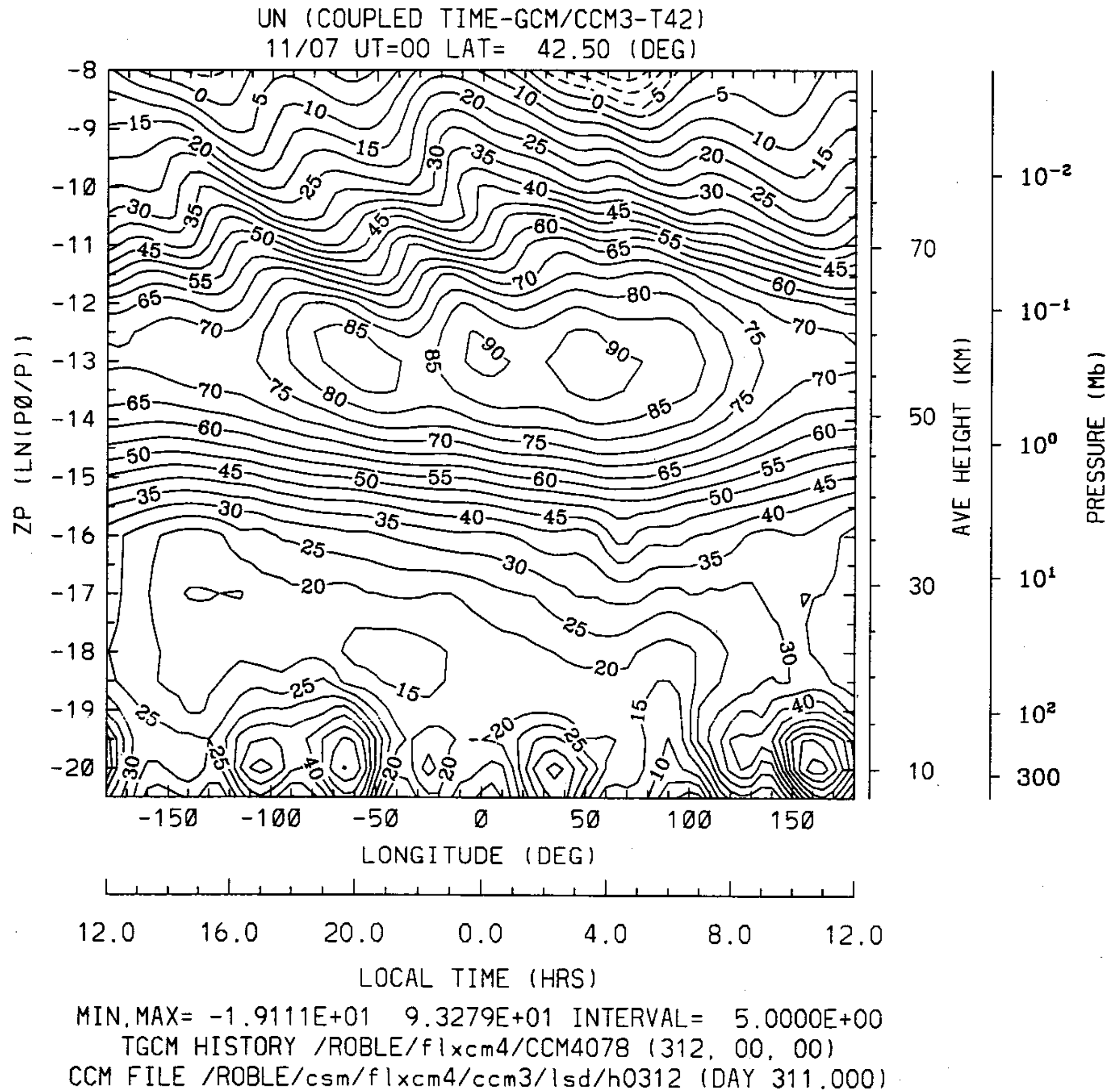

CHILTON Noon NmF2 C-TIEGCM
"C-Tiegcm"
Data
Nmax
0
100
200
300
Day

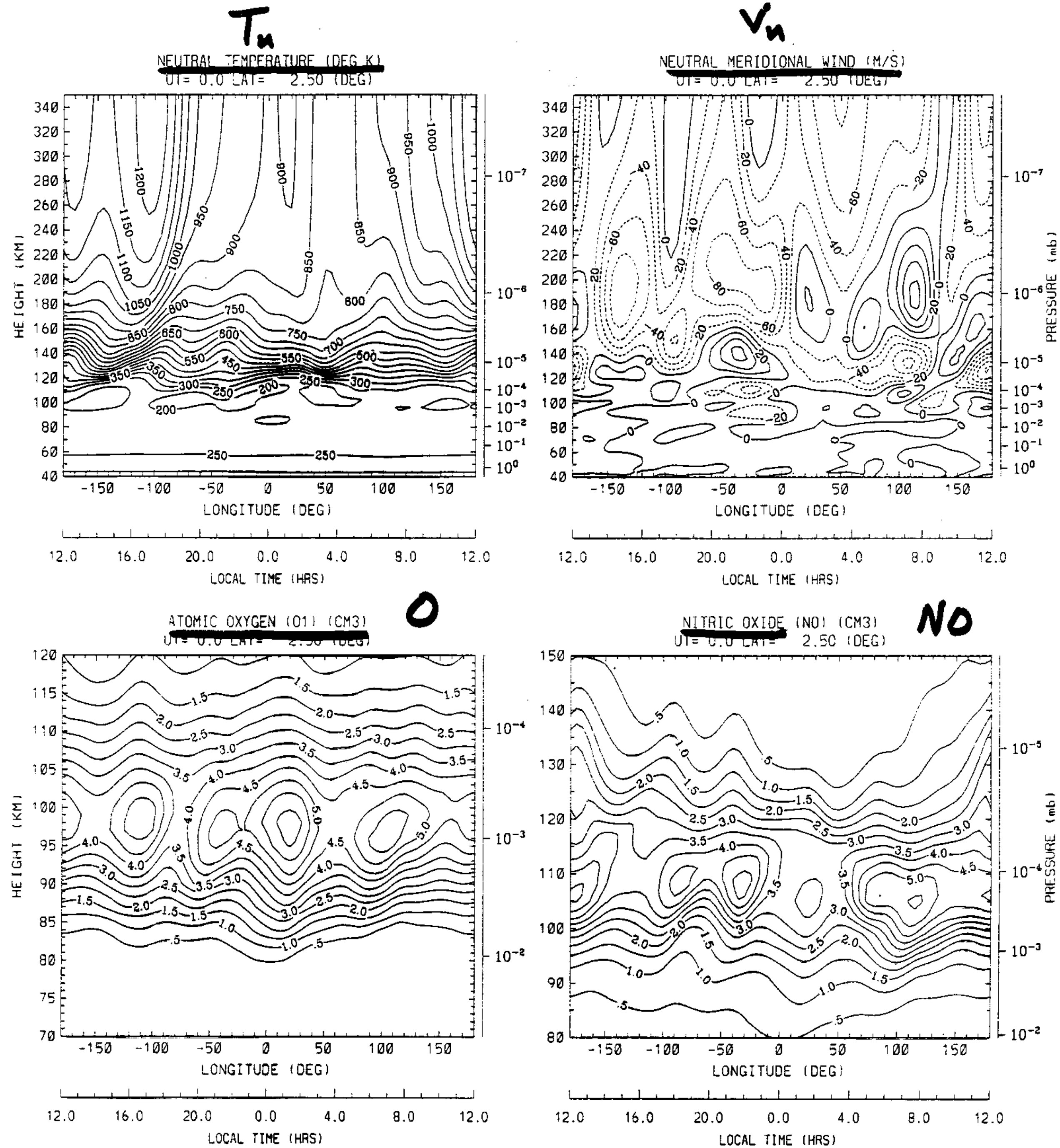

CHILTON Noon NmF2 C.DEVP7
"c.devp7"
Data
Nmax
0
100
200
300
Day

TIME-GCM / CCM3 (0-500 KM)

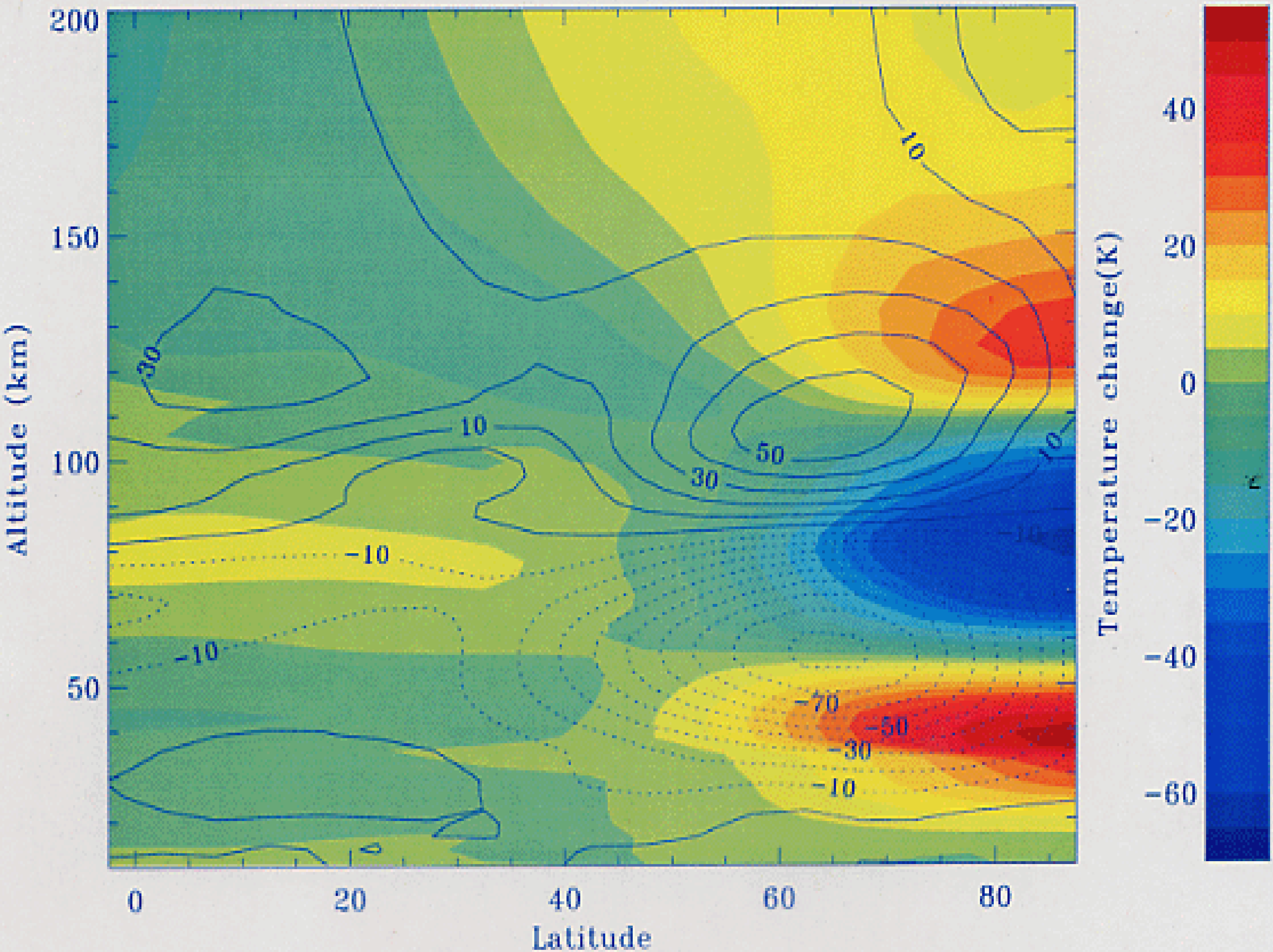


Fields exchanged: T, U, V, H, W, H_2O, CH_4


UN (COUPLED TIME-GCM/CCM3-T42)
11/07 UT=00 LAT= 42.50 (DEG)
ZP (LN(PØ/P))
AVE HEIGHT (KM)
PRESSURE (Mb)
LONGITUDE (DEG)
LOCAL TIME (HRS)
MIN,MAX= -1.9111E+01 9.3279E+01 INTERVAL= 5.0000E+00
TGCM HISTORY /ROBLE/flxcm4/CCM4078 (312, 00, 00)
CCM FILE /ROBLE/csm/flxcm4/ccm3/lsd/h0312 (DAY 311.000)

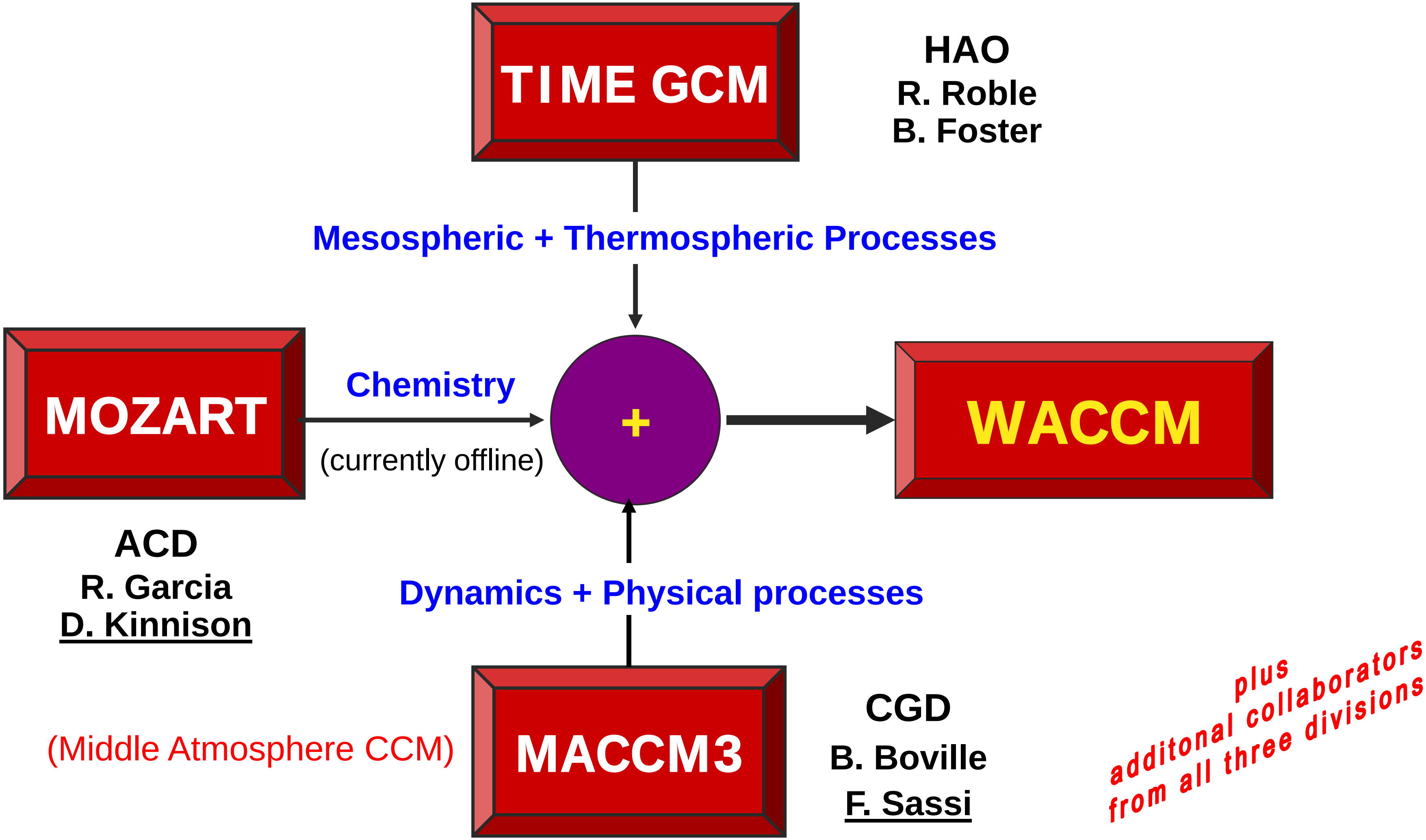


Tn
NEUTRAL TEMPERATURE (DEG K)
UT= 0.0 LAT= 2.50 (DEG)
HEIGHT (KM)
LONGITUDE (DEG)
LOCAL TIME (HRS)
Vn
NEUTRAL MERIDIONAL WIND (M/S)
UT= 0.0 LAT= 2.50 (DEG)
PRESSURE (mb)
LONGITUDE (DEG)
LOCAL TIME (HRS)
O
ATOMIC OXYGEN (O1) (CM3)
HEIGHT (KM)
LONGITUDE (DEG)
LOCAL TIME (HRS)
NO
NITRIC OXIDE (NO) (CM3)
UT= 0.0 LAT= 2.50 (DEG)
PRESSURE (mb)
LONGITUDE (DEG)
LOCAL TIME (HRS)

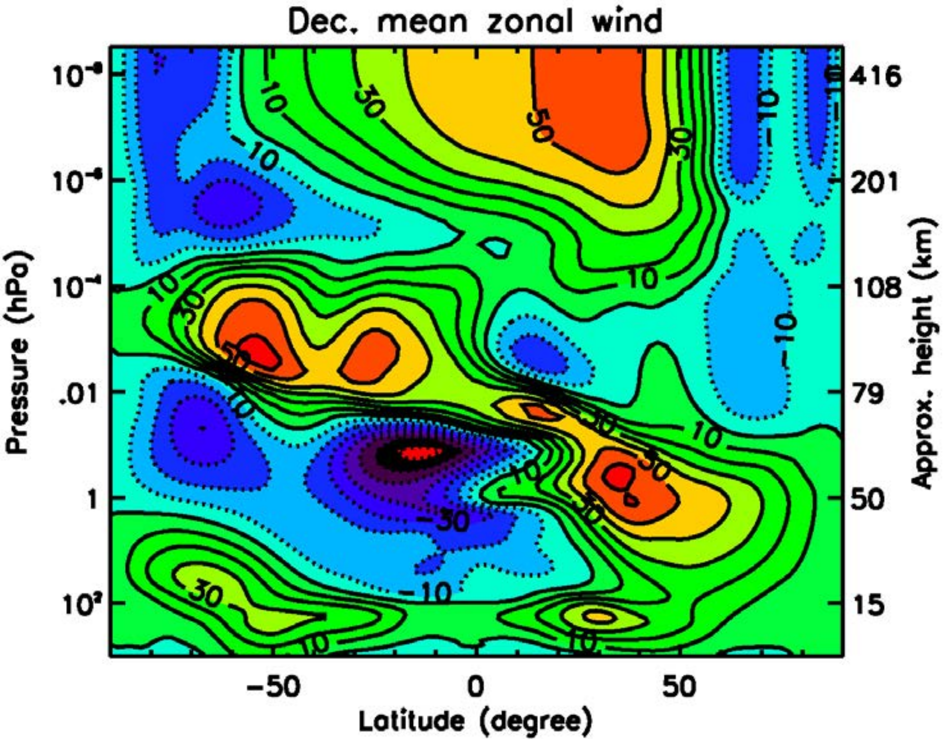


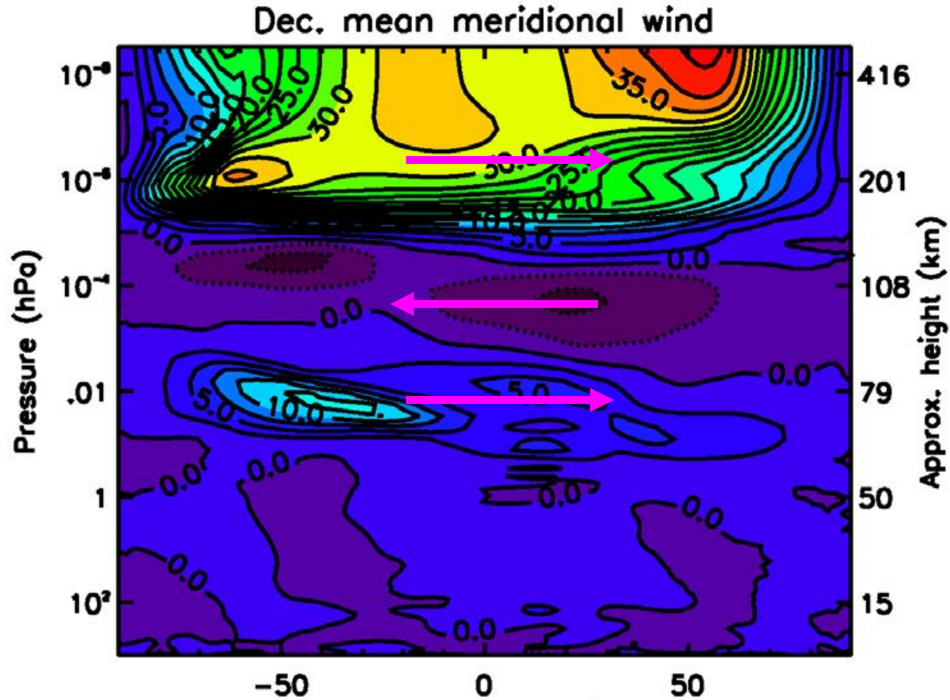
200
150
100
50
Altitude (km)
0
20
40
60
80
Latitude
10
30
50
-10
-70
-50
-30
Temperature change(K)
40
20
0
-20
-40
-60

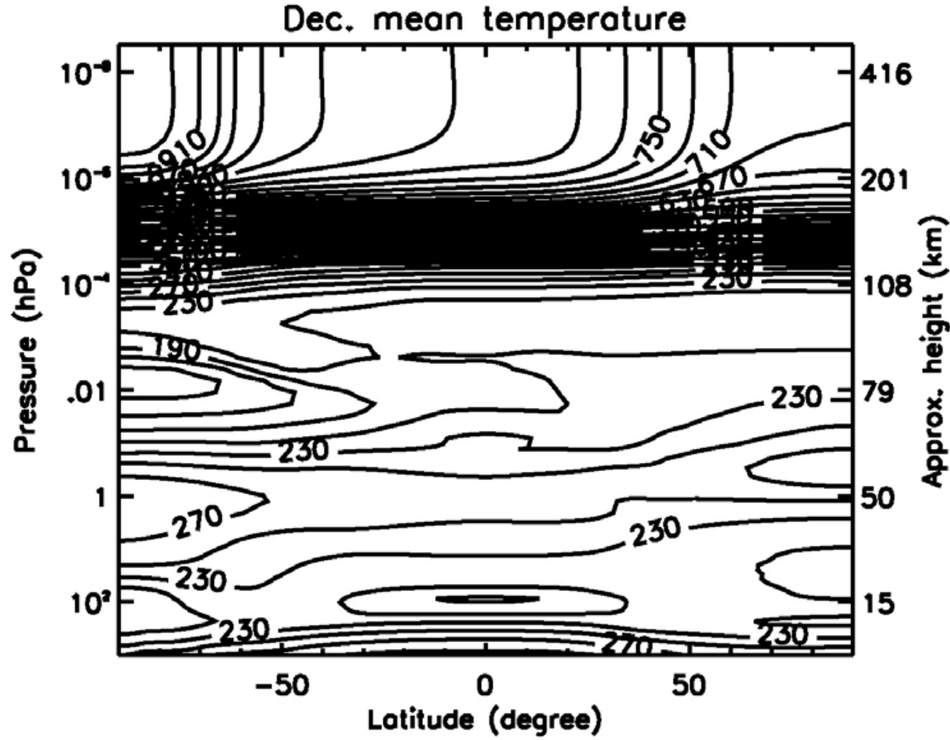
WACCM Components:
A collaboration among 3 NCAR Divisions

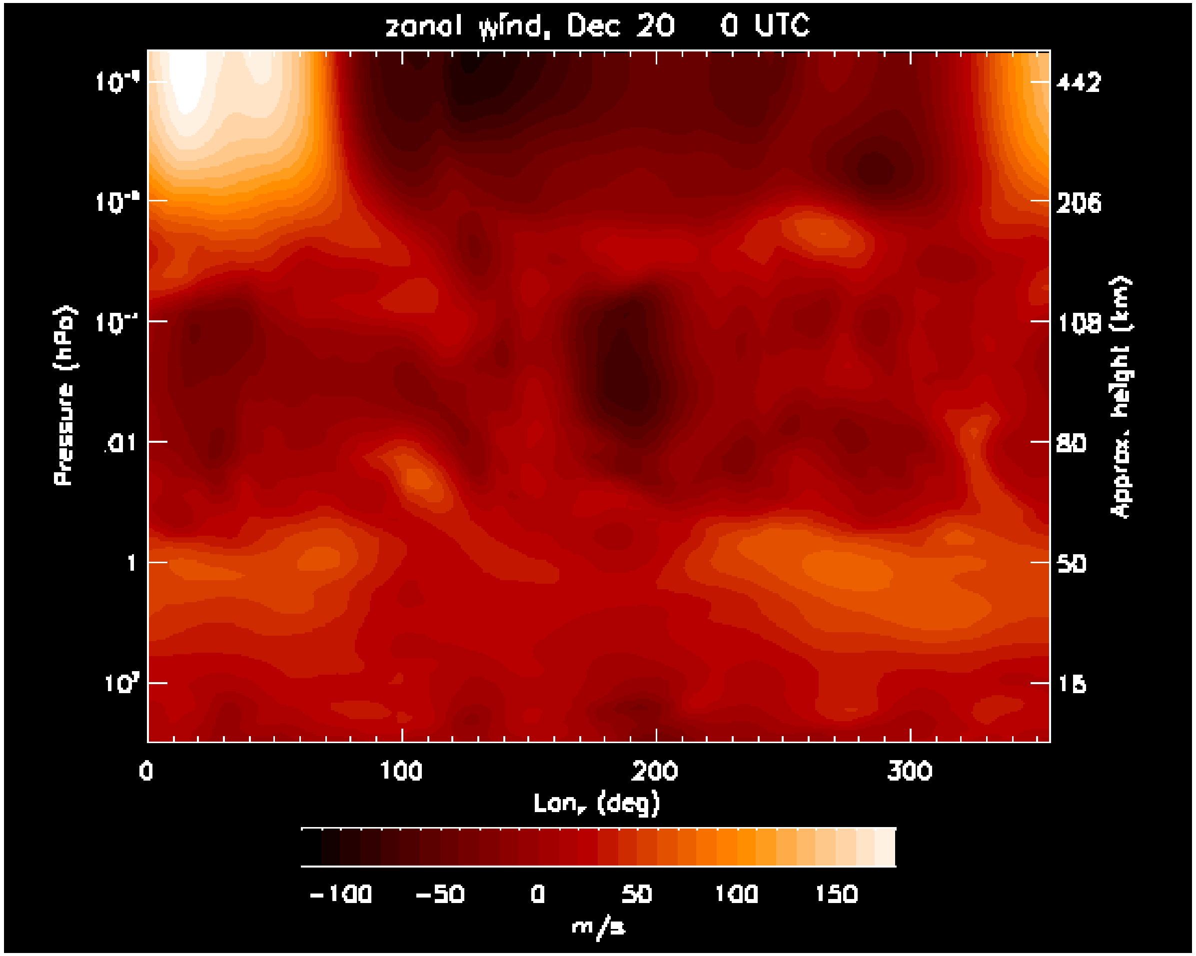


WACCM: Winds and Temperature (December)









zonal wind, Dec 20 0 UTC
Pressure (hPa)
Approx. height (km)
Lon. (deg)
m/s

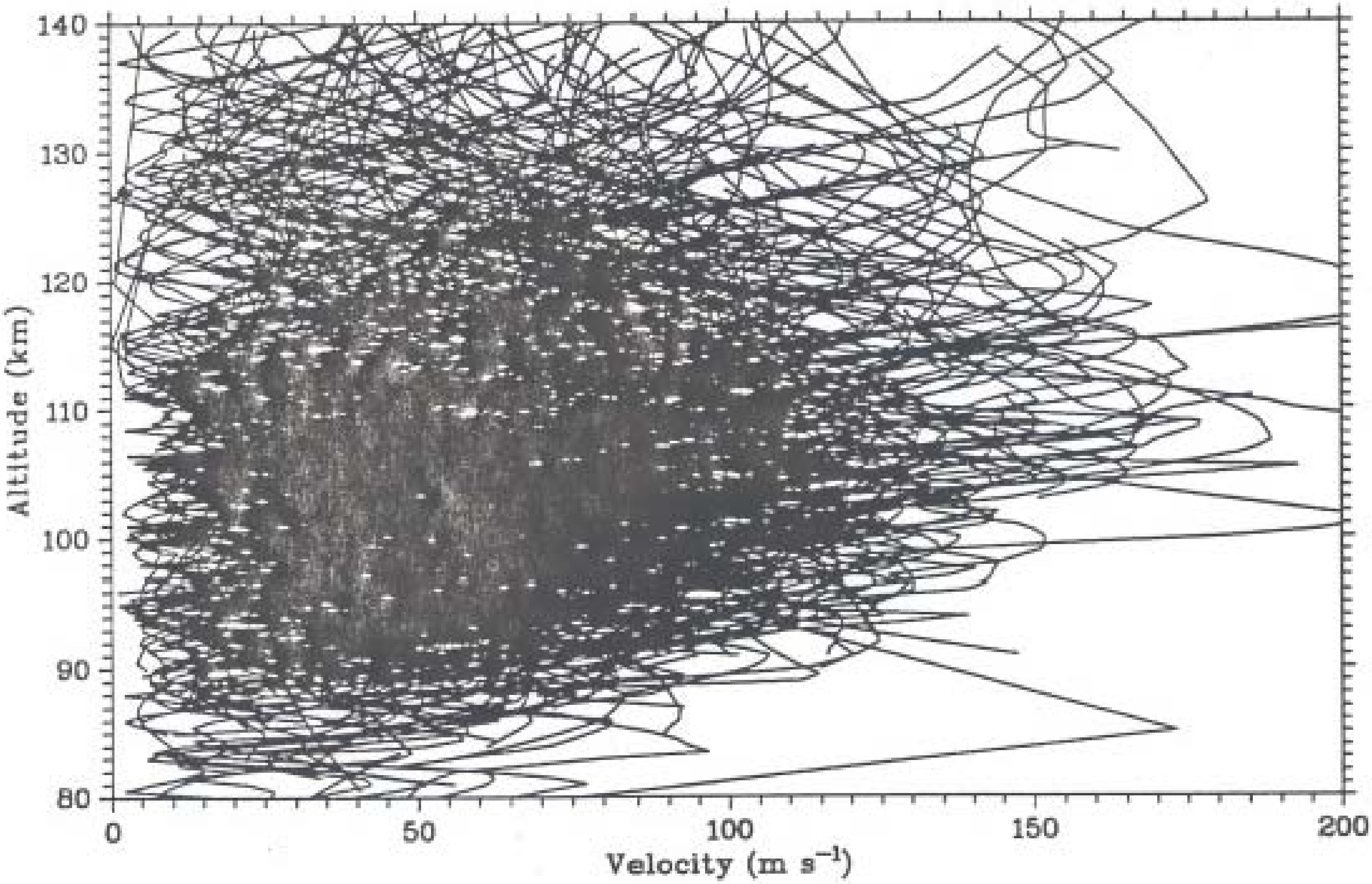
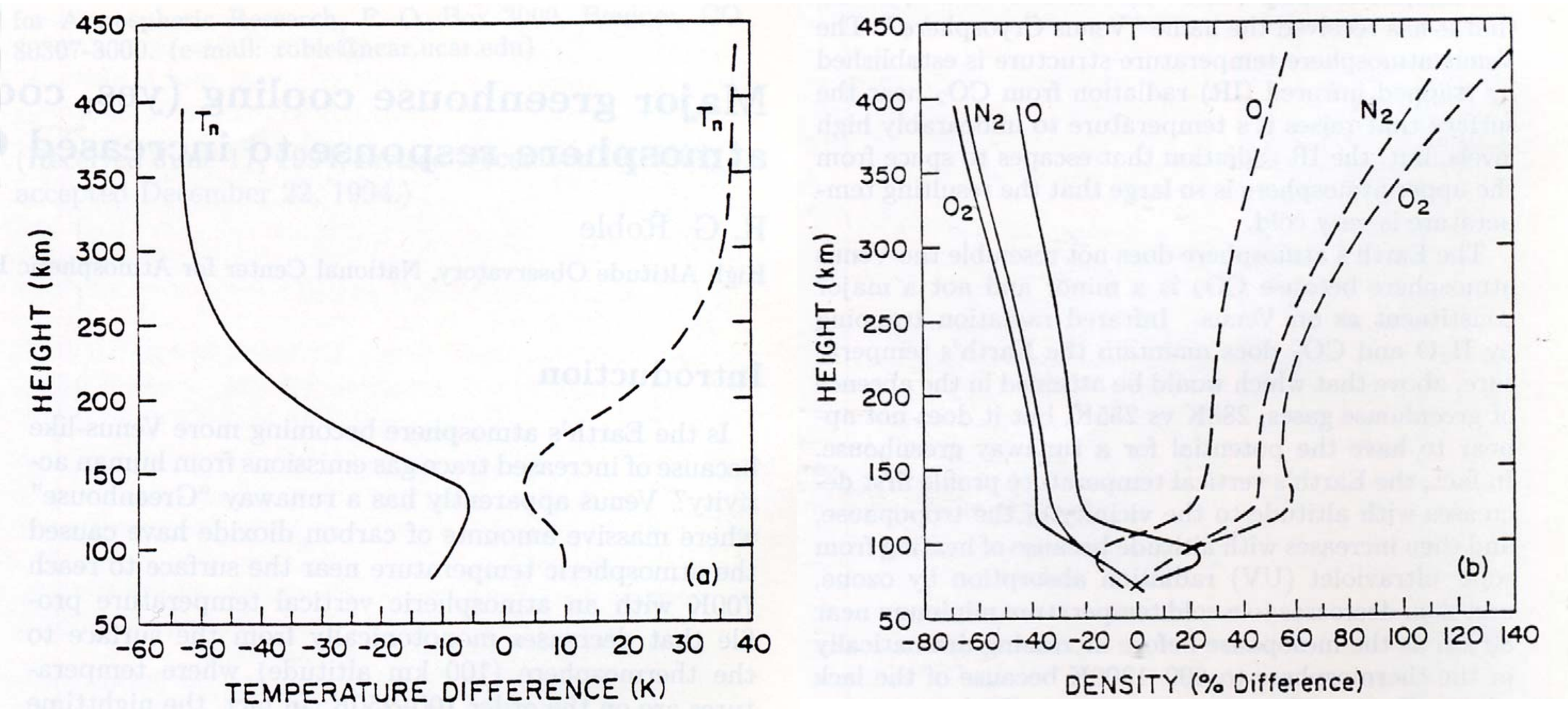


Figure 2. Superposition of the wind speed profiles for all the mid- and low-latitude chemical release wind profile data.

WACCM STUDIES

- There are 2 versions of WACCM: Ground-to-140km and Ground-to-500km
- WACCM shows that considerable lower atmospheric variability propagates and affects the upper atmosphere and ionosphere
- WACCM is a free running climate model whereas TIME-GCM is a campaign model using data at the lower boundary to force the observational period for comparison with ground-based and satellite data

Roble and Dickinson (1989)



Aeronomy of Cooling Processes

- **The thermosphere is cooled primarily through radiation from CO_2, NO, and $O(^3P)$**
  - CO_2 radiation in 15 μm band; NO radiation in 5.3 μm band modulates solar cycle change
- **Primary change in recent model estimates is due to increased levels of NO**
  - Older model estimates were tuned to measurements of NO from SME

    Soft X-ray fluxes based on AE-era measurements
  - More recent measurements (HALOE, SNOE, ISSAC, HIRASS) ~5 times higher

    E.g., peak solar minimum low-latitude density ~$3x10^7$ instead of ~$6x10^6$

    Revised solar soft X-ray fluxes based on TIMED/SEE, SNOE, rockets (EUVAC)

    Model with revised ionization and chemistry in agreement with NO measurements
  - Key uncertainties in chemical rates pertain to branching between $N(^2D)$, $N(^4S)$

    N_2+e*, NO^++e^-, $N(^2D)$+O

    Temperature dependence of $N(^4S)+O_2$ and NO+N reactions also important
  - All of the cooling reactions are modulated by O, so atomic/molecular balance important
- **Current model rate coefficients:**

  CO_2+O excitation rate:

    $1.56x10^{-12}$ for $T_n < 260$

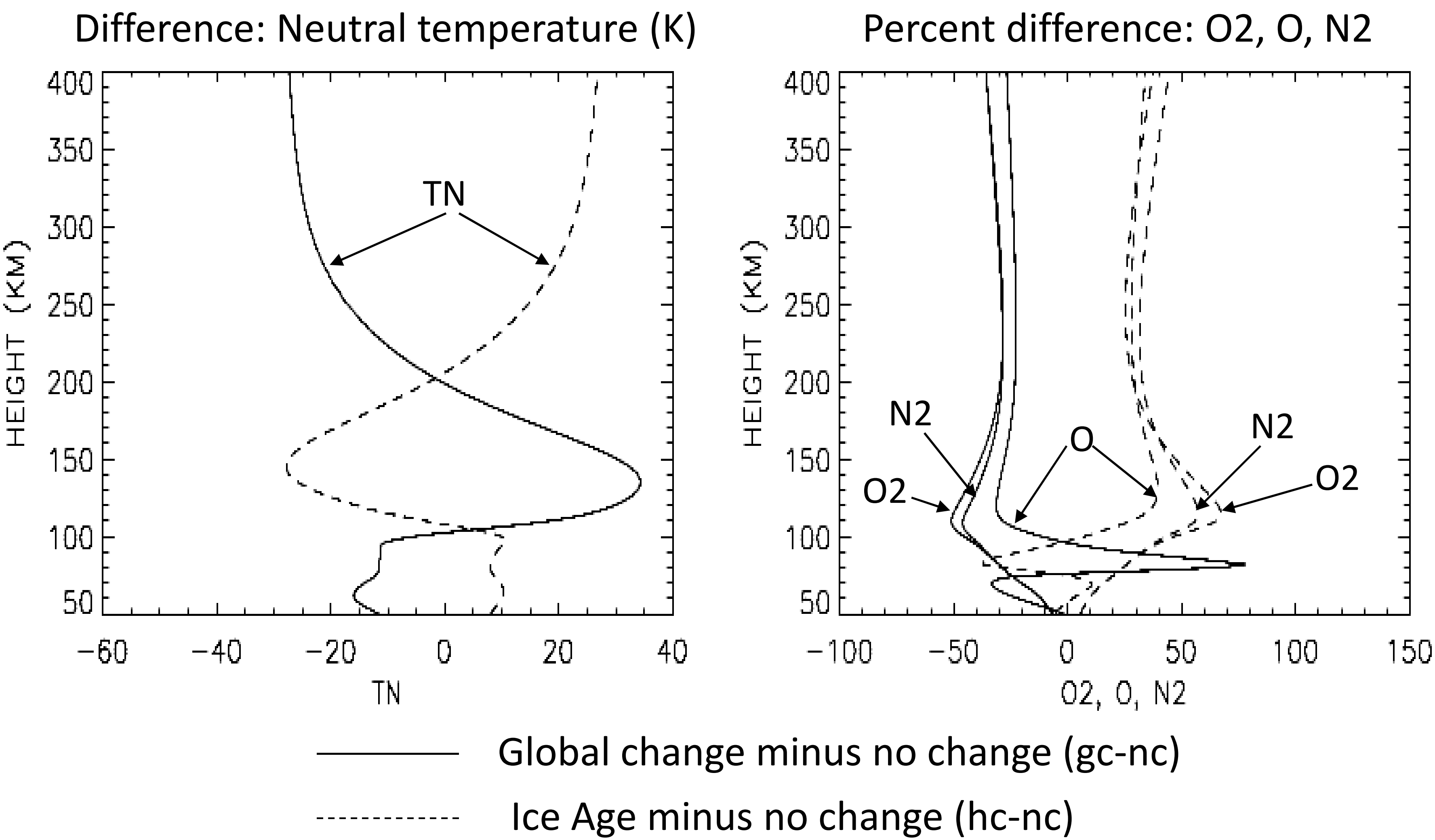
    $(2.6-0.004*T_n)x10^{-12}$ for 260<Tn<300

    $1.4x10^{-12}$ for $T_n>300$

  NO+O excitation rate:

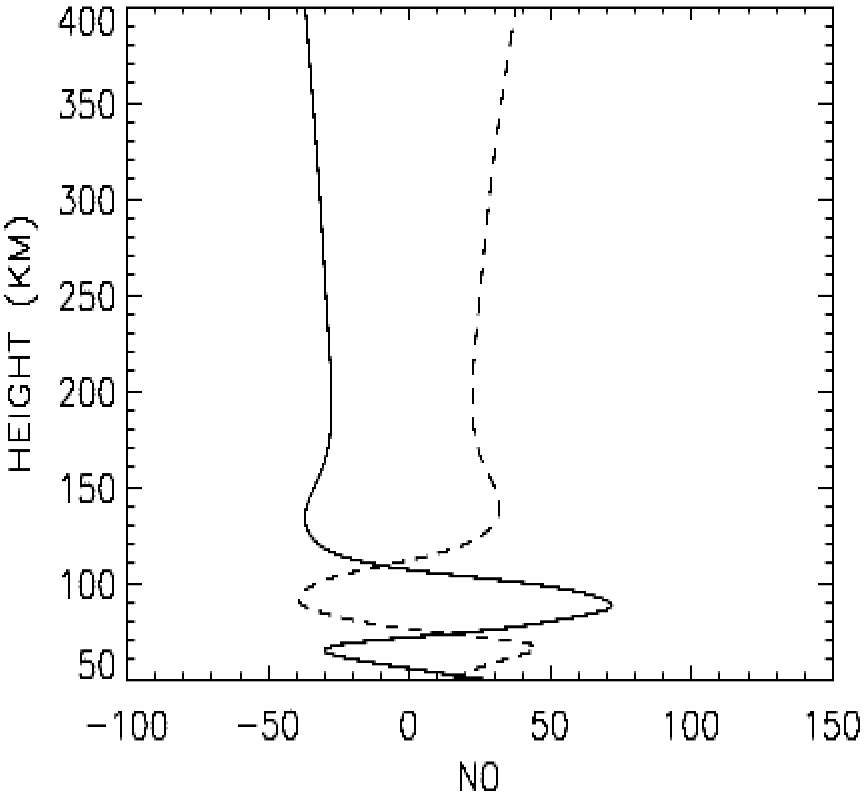
    $4.2x10^{-11}$

Solar Medium

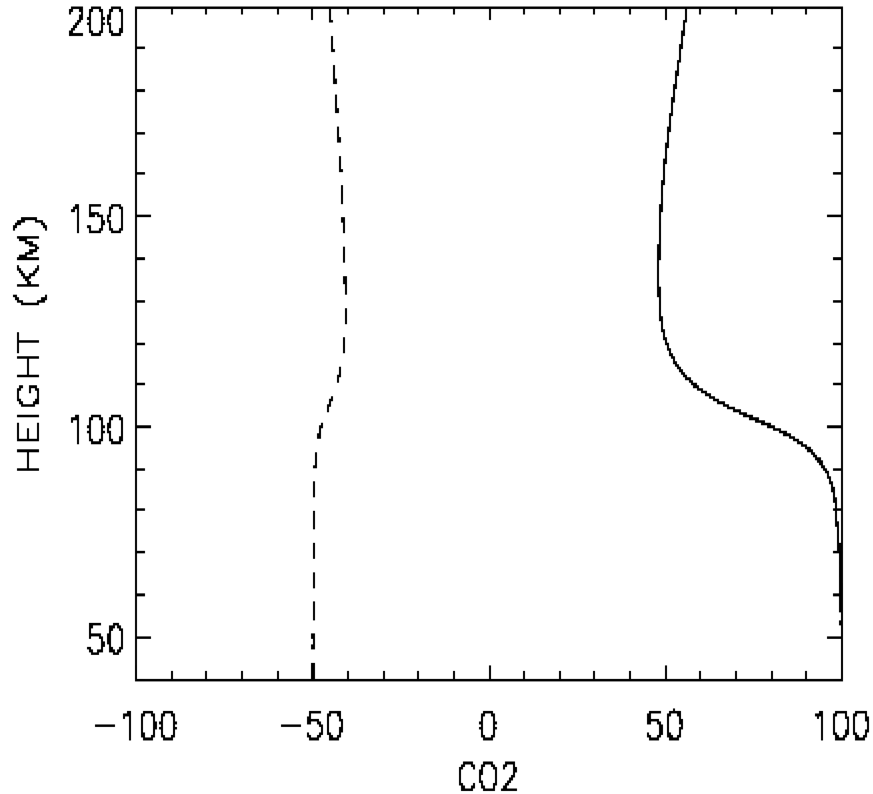


Solar Medium

Percent difference: NO



Percent difference: CO2

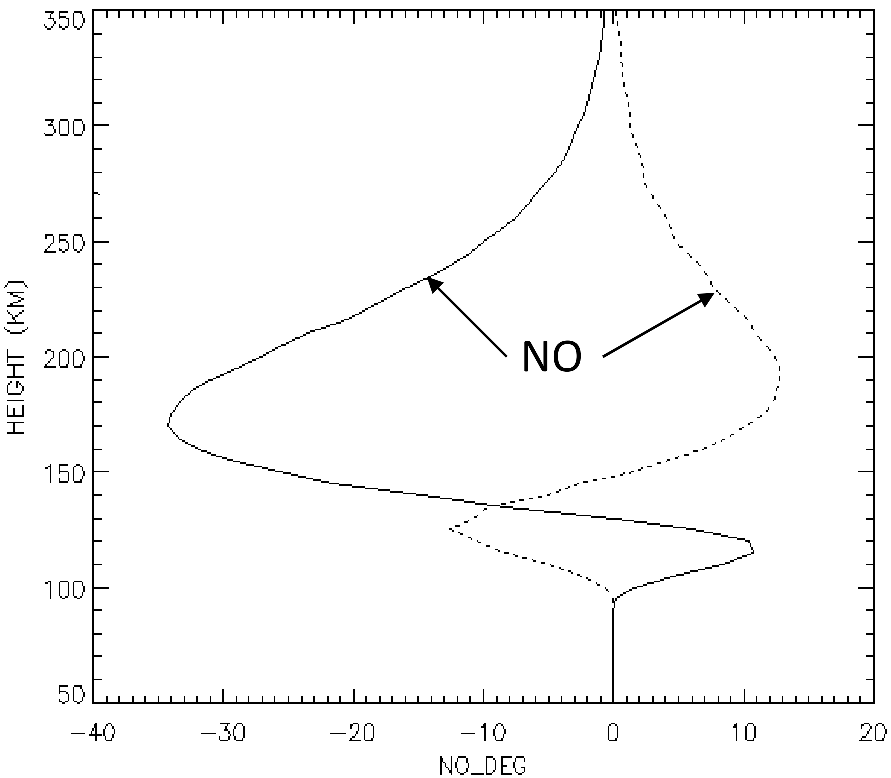


——— Global change minus no change (gc-nc)

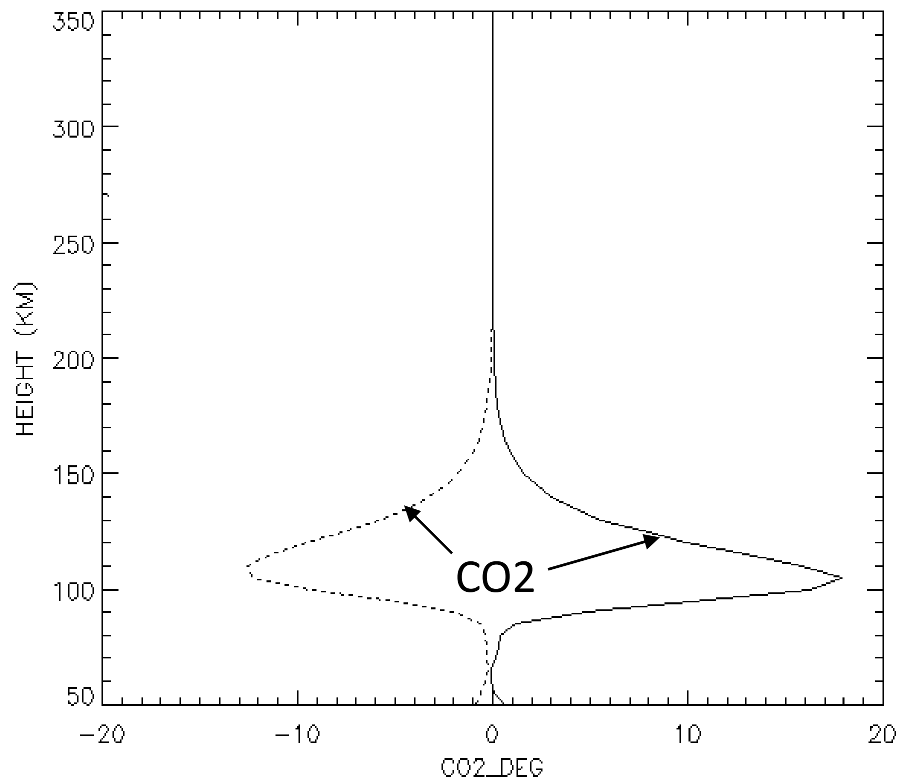
- - - - - - Ice Age minus no change (hc-nc)

Change in NO and CO2 cooling

5.3 micron NO cooling (deg/day)



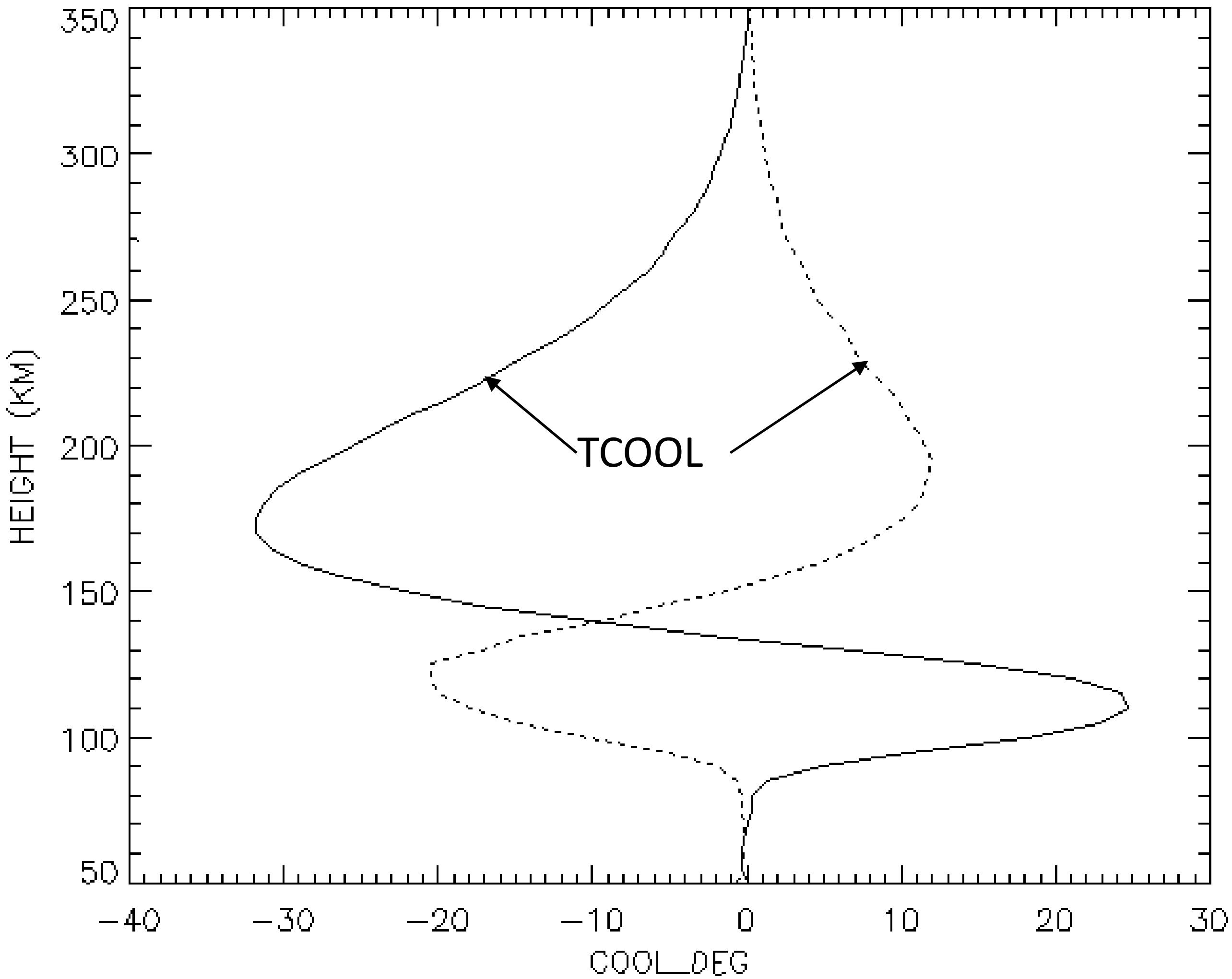
15 micron CO2 cooling (deg/day)



——— Global change minus no change

- - - - - - Ice Age minus no change

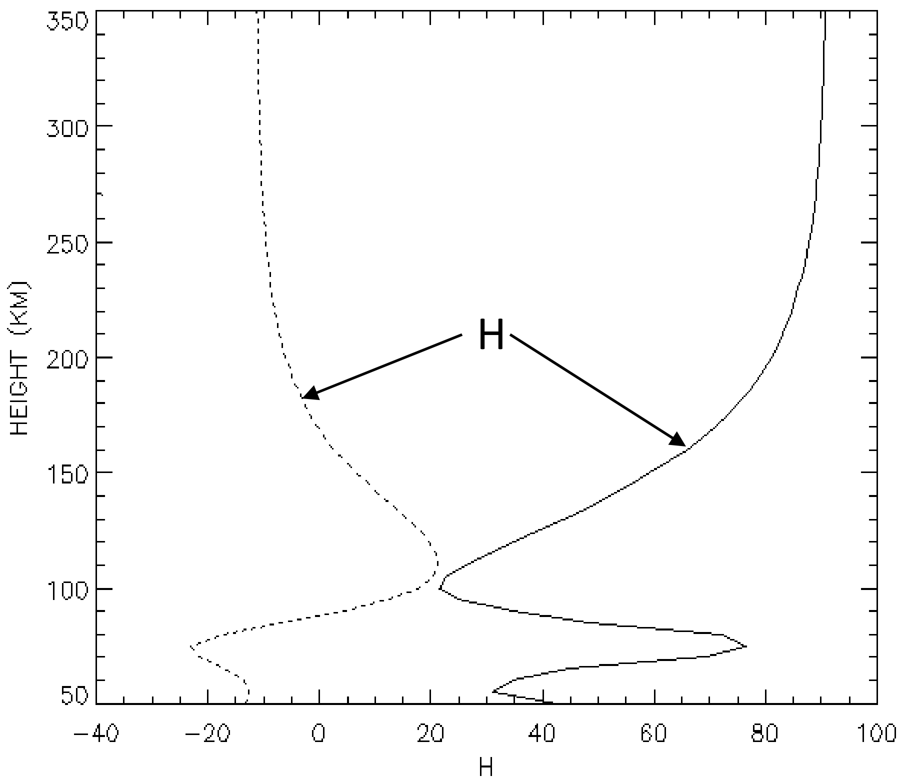
Change in total cooling (deg/day)



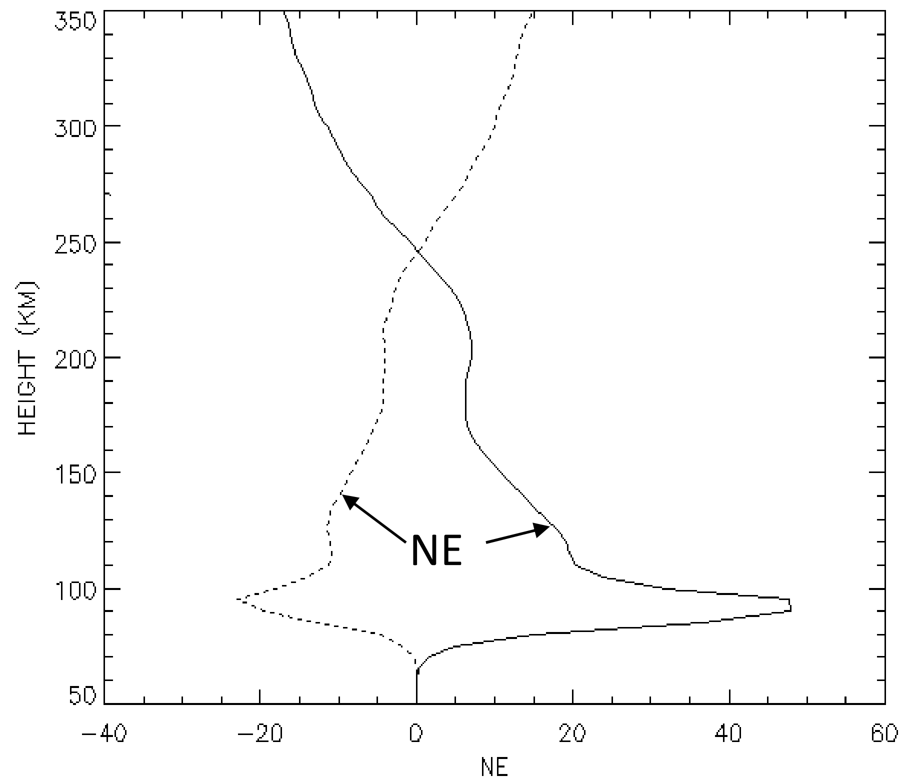
——— Global change minus no change

- - - - - Ice Age minus no change

Percent change: H (cm3)



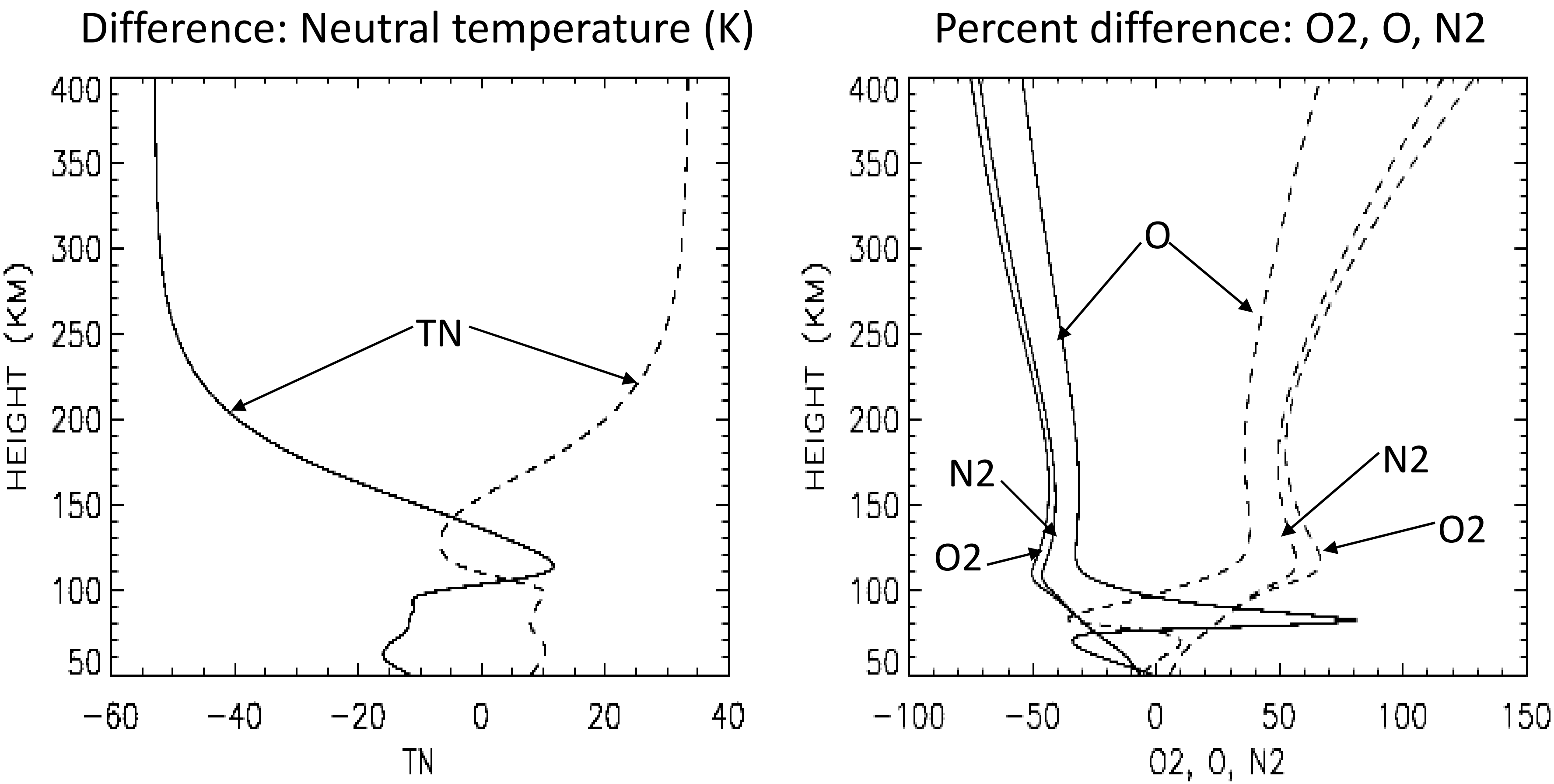
Percent change: NE (cm3)



Global change minus no change

Ice Age minus no change

Solar Minimum



——— Global change minus no change (gc-nc)

- - - - - - Ice Age minus no change (hc-nc)

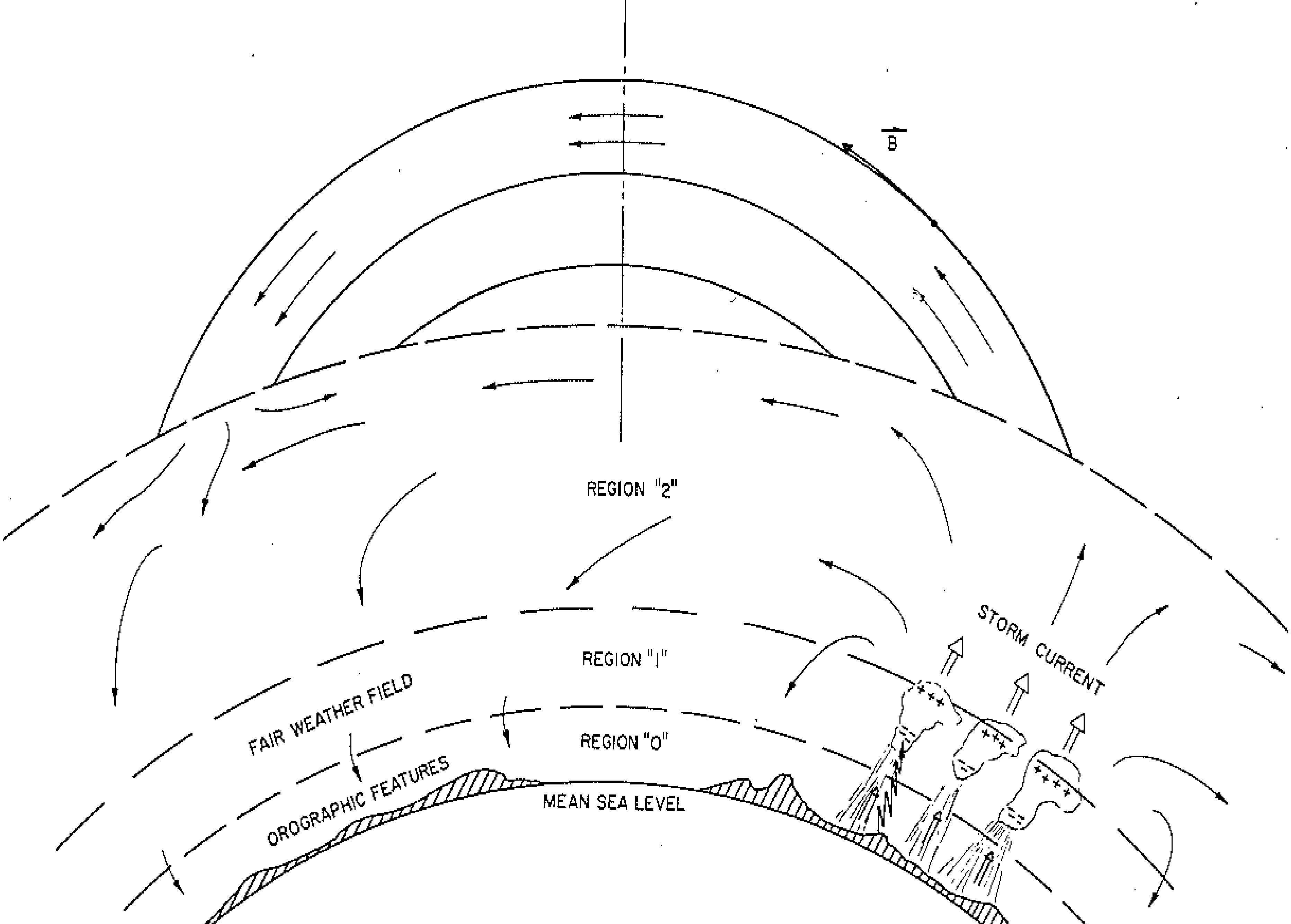
Conclusions

• Increased CO_2 and CH_4 levels will cool and contract the upper atmosphere, but the effects vary as a function of altitude, with some altitudes actually warming.

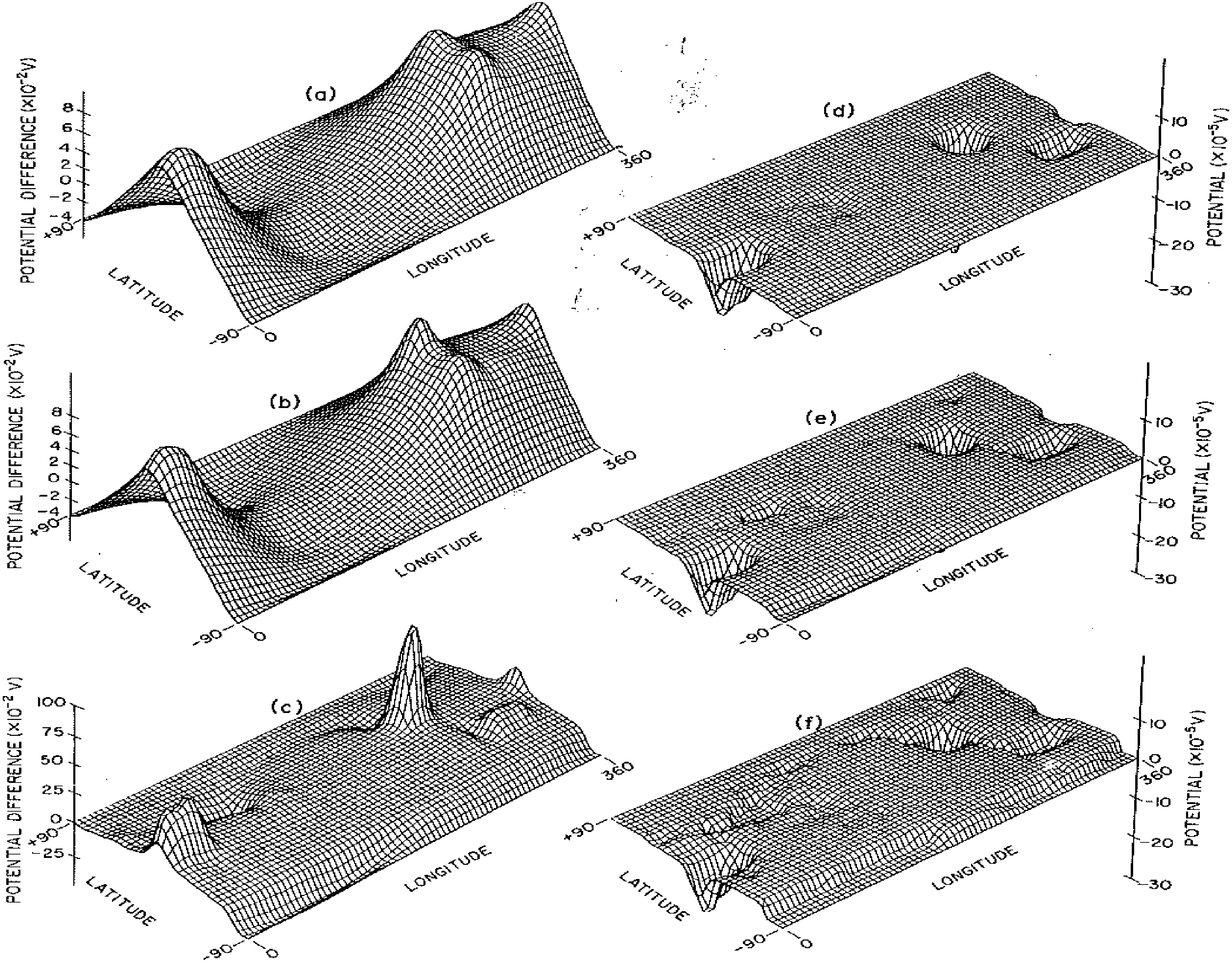
• Effects of NO cooling and chemical heating modulate the thermospheric response to global change as well as to the solar cycle.

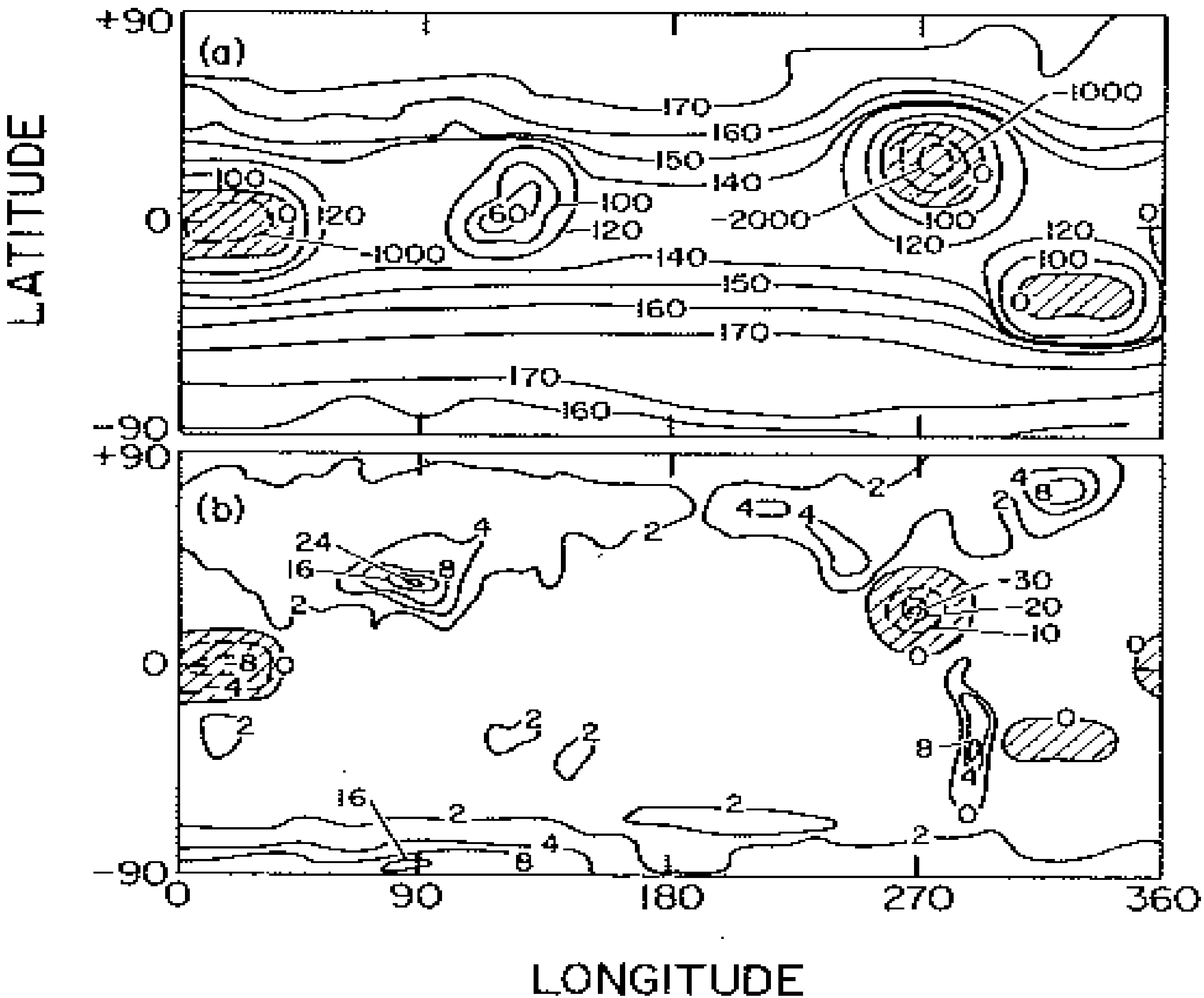
• Largest changes are predicted to occur during solar minimum conditions.

• These findings may be commensurate with early inference of density changes from satellite orbit analysis.



GLOBAL ELECTROSTATIC MODEL


(a)
POTENTIAL DIFFERENCE (x10^{-2}V)
8
6
4
2
0
-2
-4
+90
LATITUDE
LONGITUDE
-90
0
360
(b)
POTENTIAL DIFFERENCE (x10^{-2}V)
8
6
4
2
0
-2
-4
+90
LATITUDE
LONGITUDE
-90
0
360
(c)
POTENTIAL DIFFERENCE (x10^{-2} V)
100
75
50
25
0
-25
+90
LATITUDE
LONGITUDE
-90
0
360
(d)
POTENTIAL (x10^{-5}V)
10
0
-10
-20
-30
+90
LATITUDE
LONGITUDE
-90
0
360
(e)
POTENTIAL (x10^{-5}V)
10
0
-10
-20
-30
+90
LATITUDE
LONGITUDE
-90
0
360
(f)
POTENTIAL (x10^{-5}V)
10
0
-10
-20
-30
+90
LATITUDE
LONGITUDE
-90
0
360



(a)
(b)
LATITUDE
LONGITUDE
+90
0
-90
0
90
180
270
360
170
160
150
140
100
120
60
-1000
-2000
24
16
8
4
2
-30
-20
-10