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

R.G. Roble
HAO/ESSL/NCAR
Boulder, Co
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.
LONG RANGE TGCM MODEL DEVELOPMENT

<table>
<thead>
<tr>
<th>MODEL INPUTS</th>
<th>PROGRAMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1979 Ionosphere, Dynamo</td>
<td>Atmosphere Explorer</td>
</tr>
<tr>
<td>MSIS</td>
<td>Dynamics Explorer</td>
</tr>
<tr>
<td>Aurora</td>
<td>Radar and Airglow</td>
</tr>
<tr>
<td>Solar</td>
<td>CEDAR</td>
</tr>
<tr>
<td>Tides</td>
<td>Air Force</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1989 Dynamo, Aurora, Solar, Tides</th>
<th>TIE-GCM (95 - 500 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Atmosphere Explorer</td>
</tr>
<tr>
<td></td>
<td>Dynamics Explorer</td>
</tr>
<tr>
<td></td>
<td>Radar and Airglow</td>
</tr>
<tr>
<td></td>
<td>CEDAR</td>
</tr>
<tr>
<td></td>
<td>Air Force</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1991 Aurora (AMIE), Solar, Tides</th>
<th>TIE-GCM (95 - 800 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Atmosphere Explorer</td>
</tr>
<tr>
<td></td>
<td>Dynamics Explorer</td>
</tr>
<tr>
<td></td>
<td>CEDAR</td>
</tr>
<tr>
<td></td>
<td>GEM</td>
</tr>
<tr>
<td></td>
<td>ISTP/GGS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1992 Aurora (AMIE), Solar (UARS), Tides and Waves (GSWM)</th>
<th>TIME-GCM (30 - 500 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UARS</td>
</tr>
<tr>
<td></td>
<td>Solar Mesosphere Explorer</td>
</tr>
<tr>
<td></td>
<td>CEDAR</td>
</tr>
<tr>
<td></td>
<td>GEM</td>
</tr>
<tr>
<td></td>
<td>Air Force</td>
</tr>
<tr>
<td></td>
<td>TIMED</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1995 Aurora (AMIE), Solar (UARS, RISE)</th>
<th>TIME-GCM/CCM3 (0 - 500 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UARS</td>
</tr>
<tr>
<td></td>
<td>Global Change</td>
</tr>
<tr>
<td></td>
<td>TIMED</td>
</tr>
<tr>
<td></td>
<td>ISTP/GGS</td>
</tr>
<tr>
<td></td>
<td>CEDAR</td>
</tr>
<tr>
<td></td>
<td>GEM</td>
</tr>
<tr>
<td></td>
<td>RISE</td>
</tr>
<tr>
<td></td>
<td>Navy</td>
</tr>
<tr>
<td></td>
<td>Air Force</td>
</tr>
<tr>
<td></td>
<td>Space Weather</td>
</tr>
</tbody>
</table>

2000 WACCM (0 - 500 km) upward extended CSM

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

(a) NEUTRAL TEMPERATURE AND WIND

(b) ELECTRIC POTENTIAL AND ION DRIFT

Figure 2
Tropospheric Tidal Effects in the Earth’s Ionosphere

IMAGE FUV Ionospheric Emission

March 2002

TIME-GCM Electron Density at 450 km - March

20 LST

after Immel et al. (2006)

after Hagan et al. [2007]
NEUTRAL TEMPERATURE (DEGK)
DAY =  1  UT =  0.00  ZP =  2.25

MIN,MAX =  839.2,  1635.
TIME-GCM / CCM3 (0-500 KM)

TIME-GCM
40-500 KM

5 x 5 deg lat,lon
step = 5 min

PVM FLUX COUPLER
[DRIVER]

CCM3
0-40 KM

T42 resolution
step = 20 min

Fields exchanged: T, U, V, H, W, H₂O, CH₄
UN (COUPLED TIME-GCM/CCM3-T42)
11/07 UT=00 LAT= 42.50 (DEG)

MIN.MAX = -1.9111E+01 9.3279E+01 INTERVAL = 5.0000E+00
TGM HISTORY /ROBLE/flxcm4/ccm4078 (312.00.00)
CCM FILE /ROBLE/csm/flxcm4/ccm3/lsd/h0312 (DAY 311.000)
WACCM Components:
A collaboration among 3 NCAR Divisions

TIME GCM

HAO
R. Roble
B. Foster

Mesospheric + Thermospheric Processes

MOZART
ACD
R. Garcia
D. Kinnison

(Middle Atmosphere CCM)

Chemistry
(currently offline)

Dynamics + Physical processes

MACCM3
CGD
B. Boville
F. Sassi

WACCM

plus additional collaborators from all three divisions
WACCM: Winds and Temperature (December)
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 CO₂, NO, and O(^3P)
  • CO₂ 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 ~3x10⁷ instead of ~6x10⁶
    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)
    N₂+e*, NO⁺+e⁻, N(^2D)+O
    Temperature dependence of N(^4S)+O₂ and NO+N reactions also important
  • All of the cooling reactions are modulated by O, so atomic/molecular balance important
• Current model rate coefficients:
  CO₂+O excitation rate:
    1.56x10⁻¹² for T_n < 260
    (2.6-0.004*T_n)x10⁻¹² for 260<T_n<300
    1.4x10⁻¹² for T_n>300
  NO+O excitation rate:
    4.2x10⁻¹¹
Solar Medium

Difference: Neutral temperature (K)

Percent difference: O2, O, N2

Global change minus no change (gc-nc)

Ice Age minus no change (hc-nc)
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)

- Global change minus no change
- Ice Age minus no change

Percent change: NE (cm³)
Solar Minimum

Difference: Neutral temperature (K)

Percent difference: O2, O, N2

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.