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2026 CESM Tutorial

WACCM/WACCM-X: Modeling the Whole Atmosphere

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Motivation for Whole Atmosphere Modeling

Whole Atmosphere Community Climate Model (WACCM)

- The middle atmosphere (stratosphere and mesosphere) couples the surface and lower atmosphere to the upper atmosphere and space
  - Microscale to planetary scale, microseconds to centuries
  - Dynamics, thermodynamics, chemistry, and radiation
- We need a model that can simulate this coupling on <u>short</u> (weather/ subseasonal - to - seasonal) and <u>long</u> (climate/paleoclimate) timescales

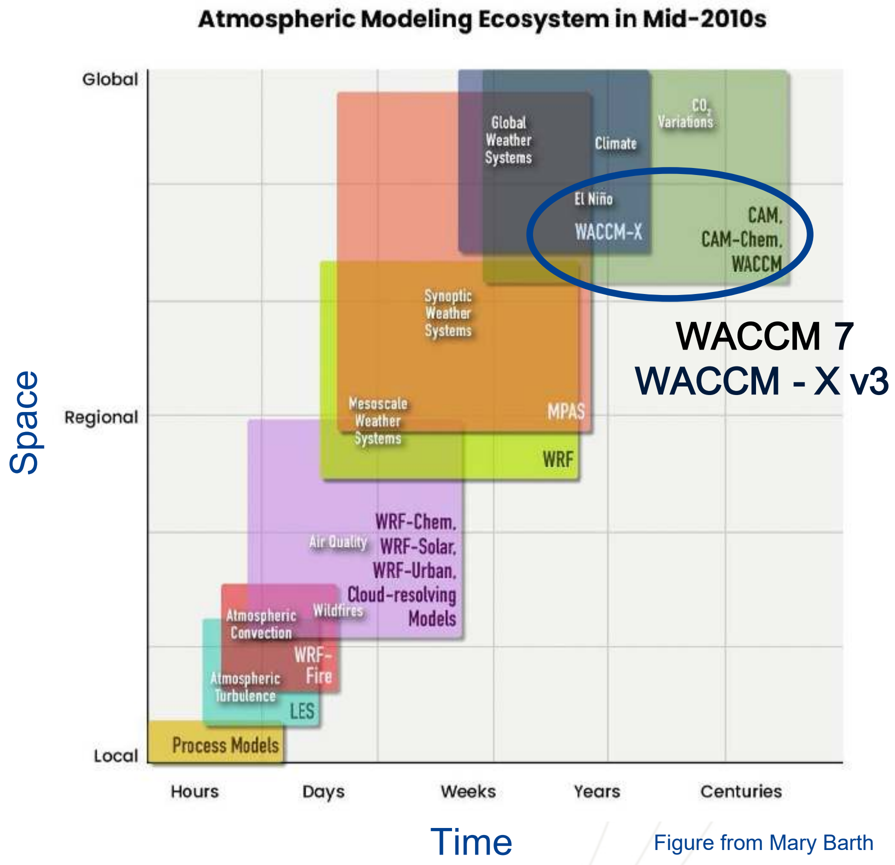
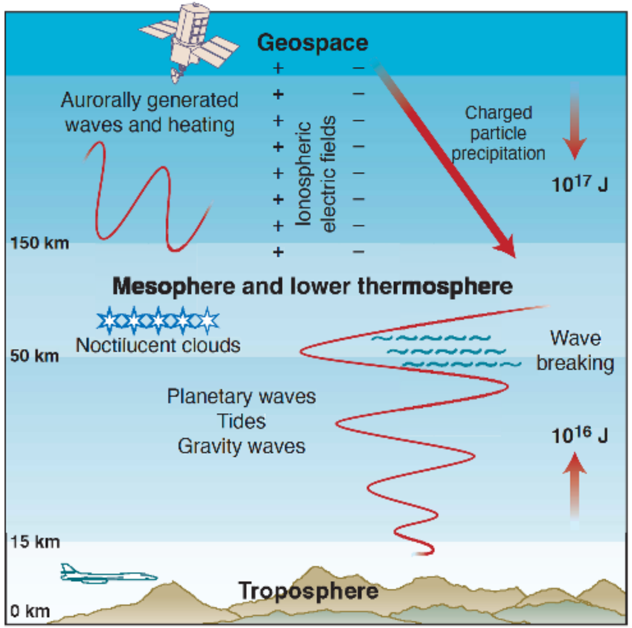


Figure from Mary Barth

Motivation for Whole Atmosphere Modeling

Energy propagates up in the form of waves and tides



Jarvis, "Bridging the Atmospheric Divide" Science, 2001

Geospace
(Ionosphere-Sun)

MLT
(50 - 150 km)

Stratosphere
(15-50 km)

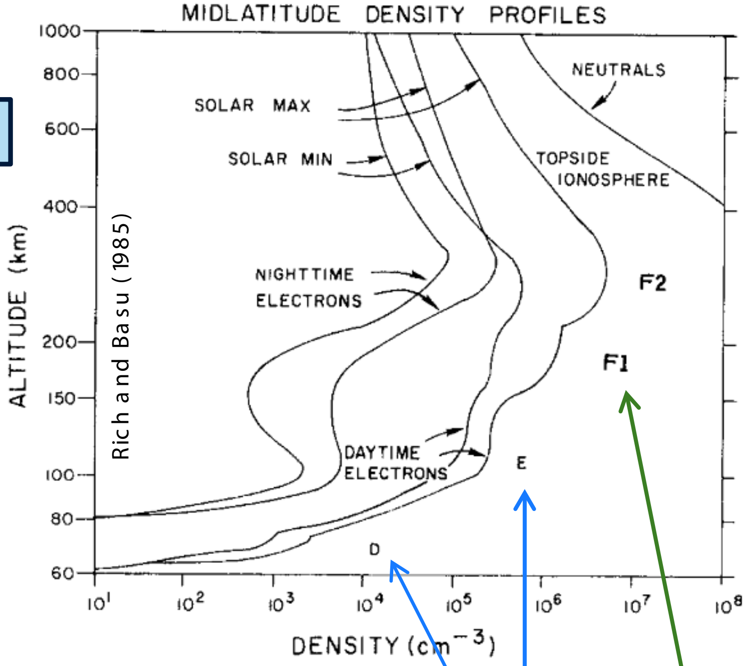
Troposphere
(0-15 km)

WACCM - X

~500 km

WACCM

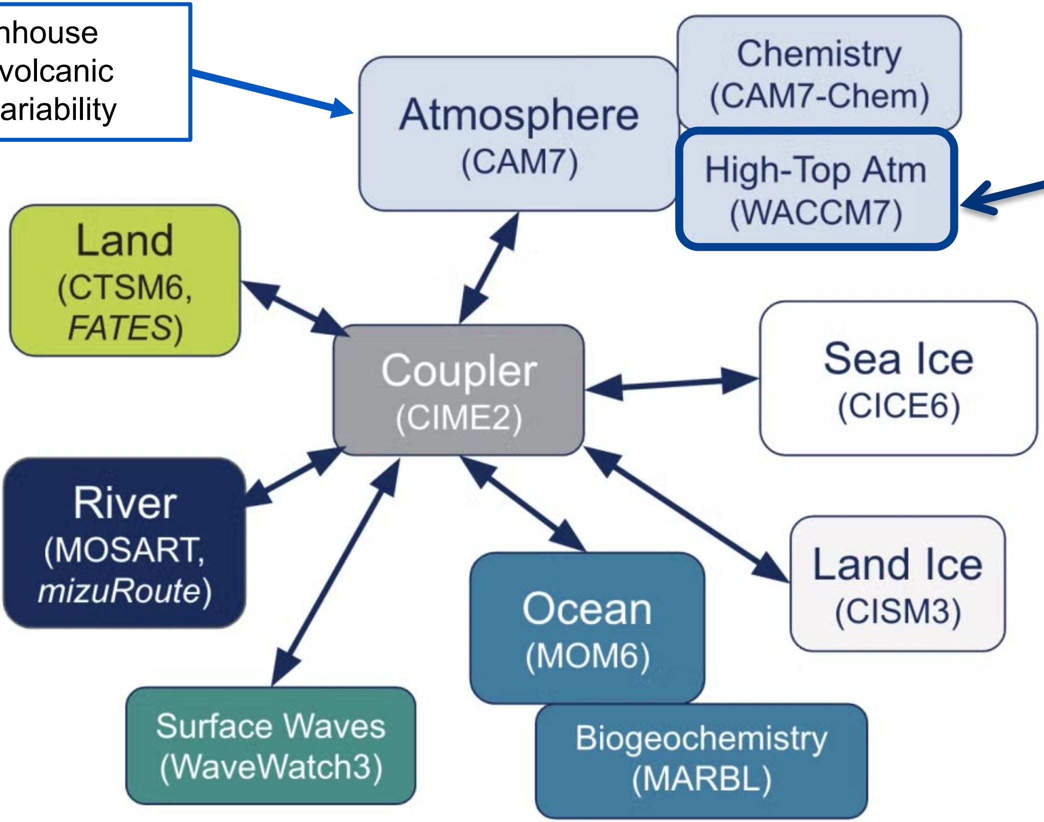
140 km



WACCM includes D & E regions
WACCM-X also includes F-region

How WACCM fits into CESM

Forcings – greenhouse gases, aerosols, volcanic eruptions, solar variability

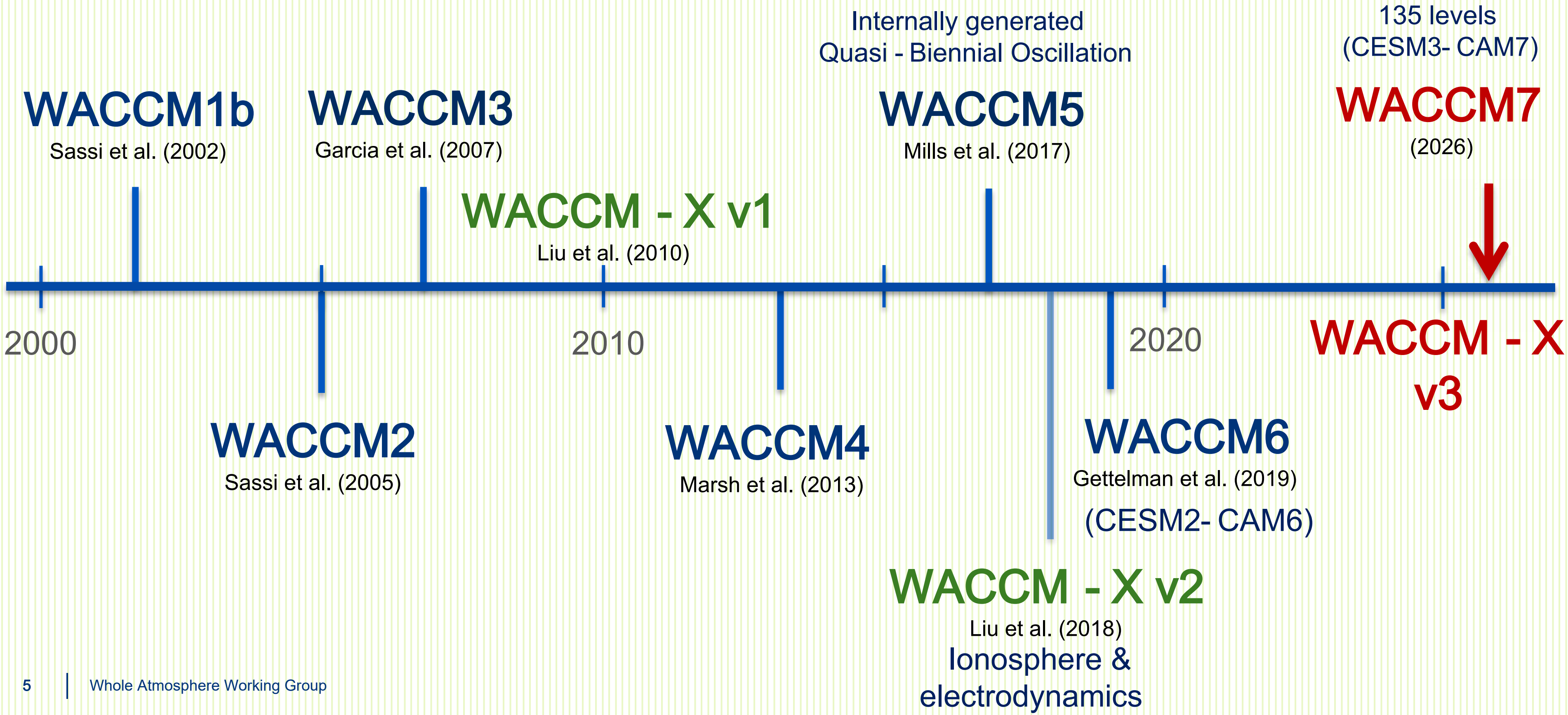


WACCM 7
WACCM - X v3

CESM3 component models

https:// www.cesm.ucar.edu

Whole Atmosphere Community Climate Model



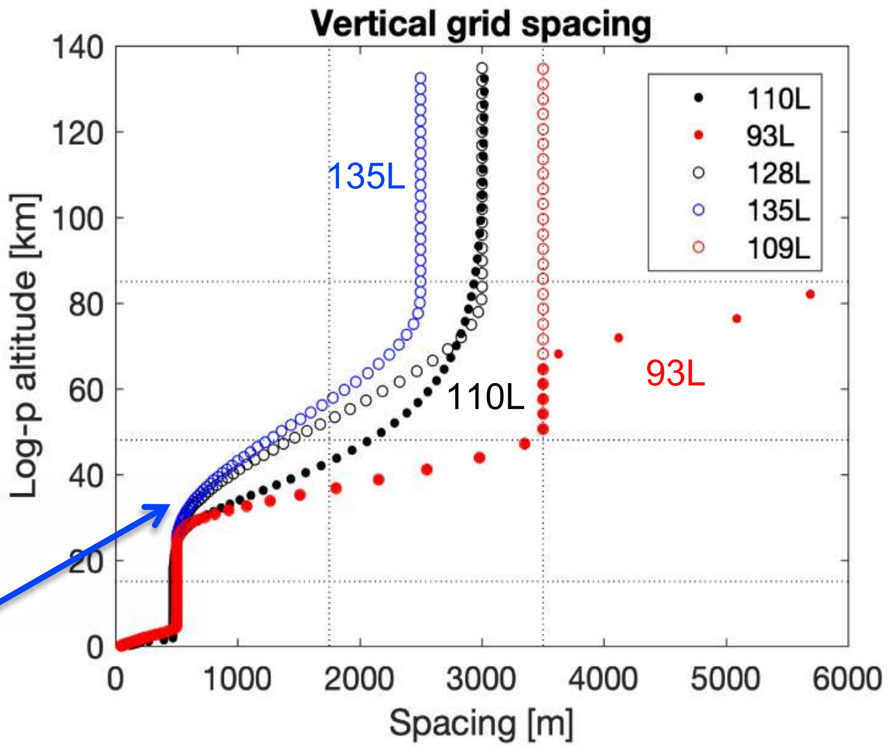
Vertical grid for WACCM7

CAM7 - MT (93L)

Increased resolution in the planetary boundary layer to lower the lowest model level to ~10 - 20 km (~52 km in CESM2)

WACCM6, Finite Volume (FV) - **110L**

WACCM7, Spectral Element (SE) - **135L**



From Nick Davis

WACCM *vs*. CAM

WACCM6

WACCM inherits the dynamical core and physics of CAM, and adds:

- Extension from surface to 6×10^{-6} hPa (~140 km), with 70 or 110 vertical levels
- Detailed neutral chemistry models
  - "middle atmosphere" (**MA**): catalytic cycles affecting ozone, heterogeneous chemistry on PSCs and sulfate aerosols, heating due to chemical reactions
  - "troposphere, stratosphere, mesosphere, and lower thermosphere" (**TSMLT**): adds chemistry affecting tropospheric air quality, organic chemistry
- Prognostic stratospheric aerosols derived from sulfur emissions
- Model of ion chemistry in the mesosphere/lower thermosphere (MLT), ion drag, auroral processes, and solar proton events
- EUV and non-LTE longwave radiation parameterizations

WACCM7

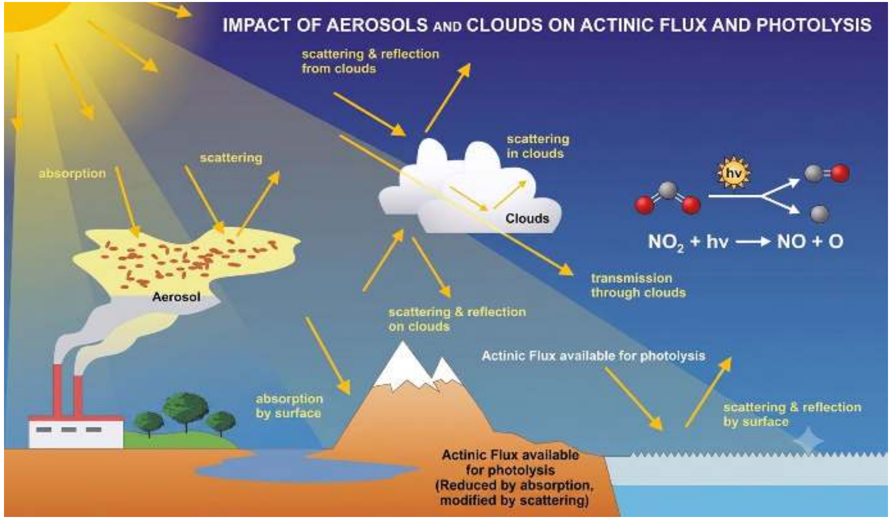
- Use **SE** dynamical core maintain consistency with CAM and enable high resolution simulations.
- 135 vertical levels
- Inline TUV-x to improve representation of photolysis and heating rates
- Chemical mechanisms: **TSMLT1**, **MA**, and **SC** (specified chemistry) chemistry

Tropospheric Ultraviolet and Visible (TUV)/TUV - x

Computes **photolysis rates**, which is important for ozone, nitrogen oxides and volatile organic compounds (VOCs), and **how much UV and visible light** reaches different altitudes. TUV directly controls the production of the hydroxyl radical (OH).

Feature/Capability	TUV	TUV-x (TUV-extended)
Computing Approach	Uses Look-Up Table (**LUT**), relies on pre-calculated data.	Calculates photolysis rates and atmospheric heating rates *in real-time*
Flexibility	Rigid; relies on predefined wavelengths and cross-sections.	Natively parses cross-sections and quantum yields to suit different chemical mechanisms used in the model
Aerosol & cloud coupling	Often approximated or treated via simplified methods in the LUT.	Accounts for the real-time impact of varying ozone and aerosol profiles (and partially clouds) on downwelling solar radiation and photolysis rates.
Implementation	**CESM2**	**CESM3**, the module is tied closely with the WACCM and the Model for Prediction Across Scales (MPAS) dynamical cores, improving both stratospheric and tropospheric chemistry representations.

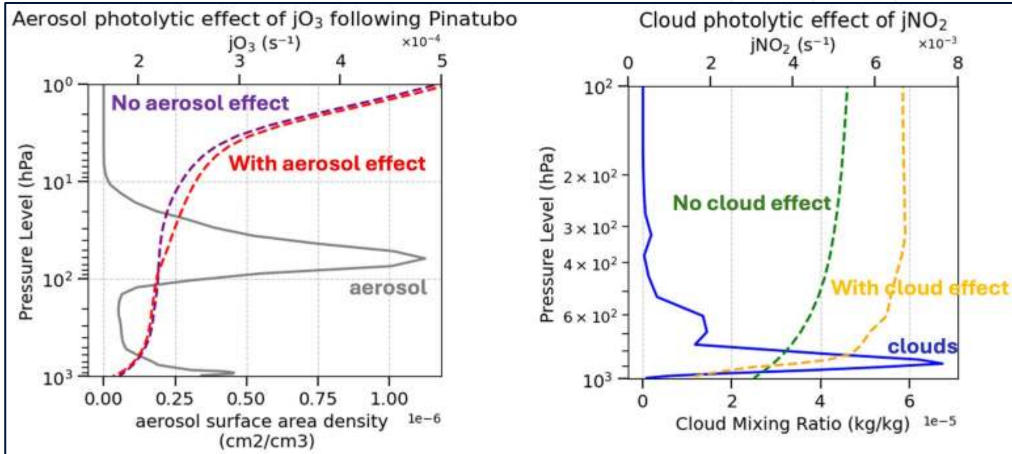
Inline photolysis scheme TUV - x in CESM3



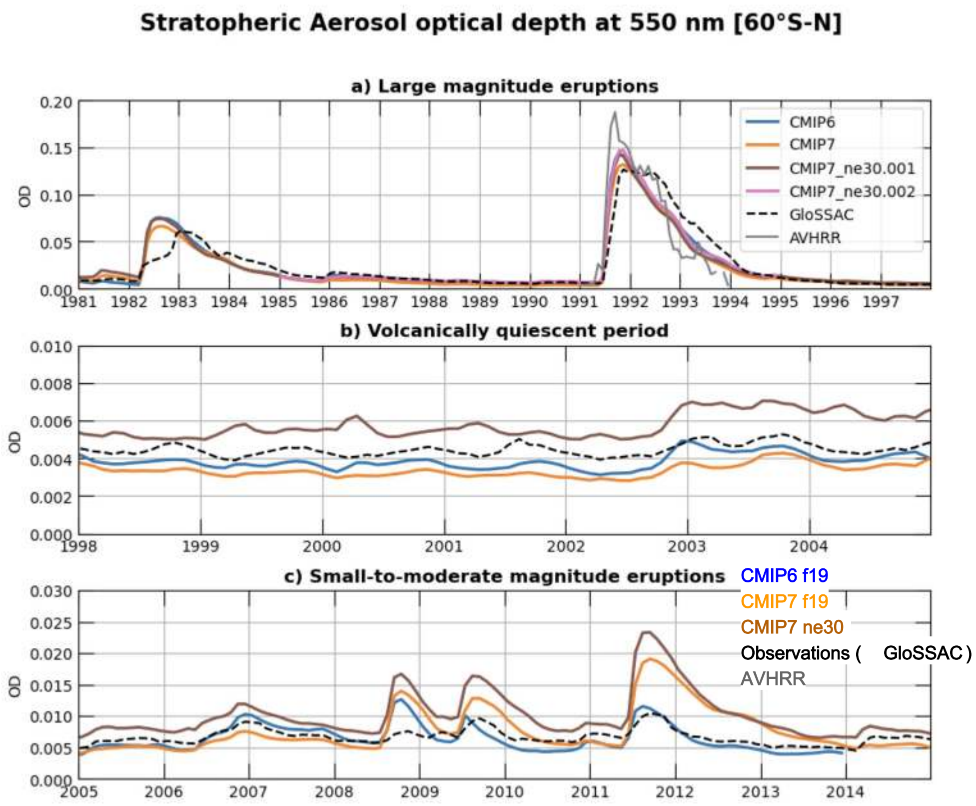
Aerosols and clouds redistribute solar radiation, enhancing photolysis above aerosol/cloud layers and reducing photolysis below through scattering and reflection effects.

https://atmos.eoc.dlr.de

- Dynamic online calculation of photolysis rates with in-line TUV-x. Photolysis drives key chemistry involving O_3 and NO_2
- Photolysis responds to real-time changes in aerosols, clouds, and ozone.
- Improves simulations of atmospheric oxidation, stratospheric ozone and air quality.
- Online calculation of impact relevant diagnostics, including UV-Index, cataract and skin cancer etc.



New Stratospheric Aerosol Emissions Database

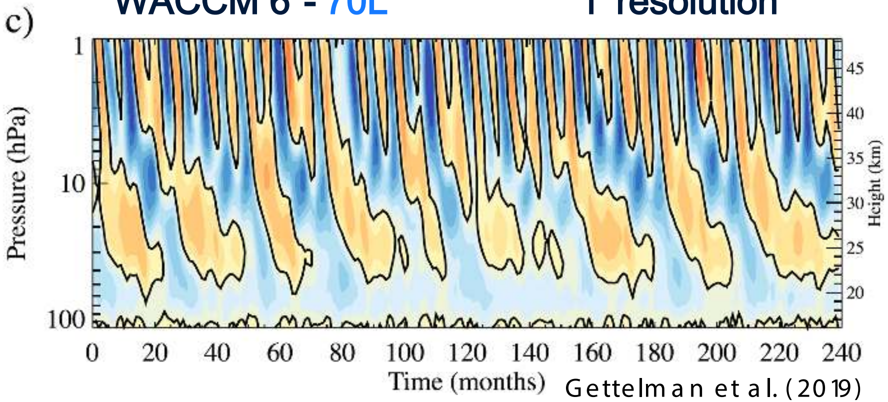


New CESM3 volcanic emissions database, with reduced altitude injections for large volcanoes and mass scaling

- Good AOD (and aerosol) representation of large magnitude volcanoes
- Slight overestimation in background aerosols compared to **GLoSSAC**
- Overestimation of some of the small to moderate magnitude eruptions
- In general better representation in stratospheric ozone and radiation than WACCM6

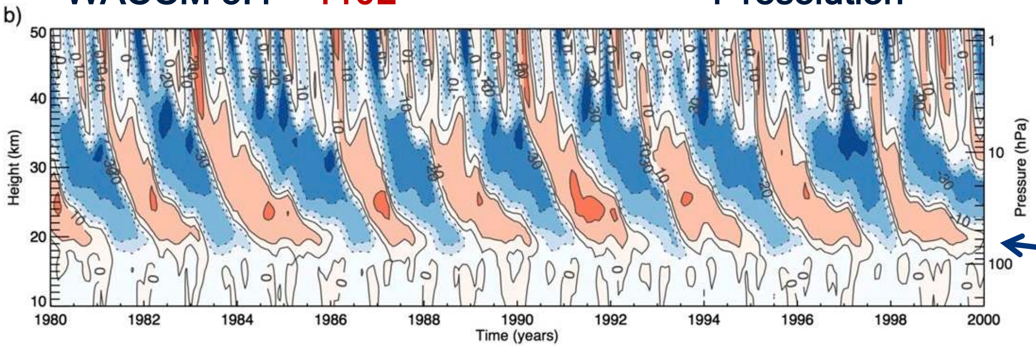
Quasi - Biennial Oscillation (QBO)

WACCM 6 - 70L 1° resolution



Gettelman et al. (2019)

WACCM 5.4 - 110L 1° resolution



Garcia and Richter (2019)

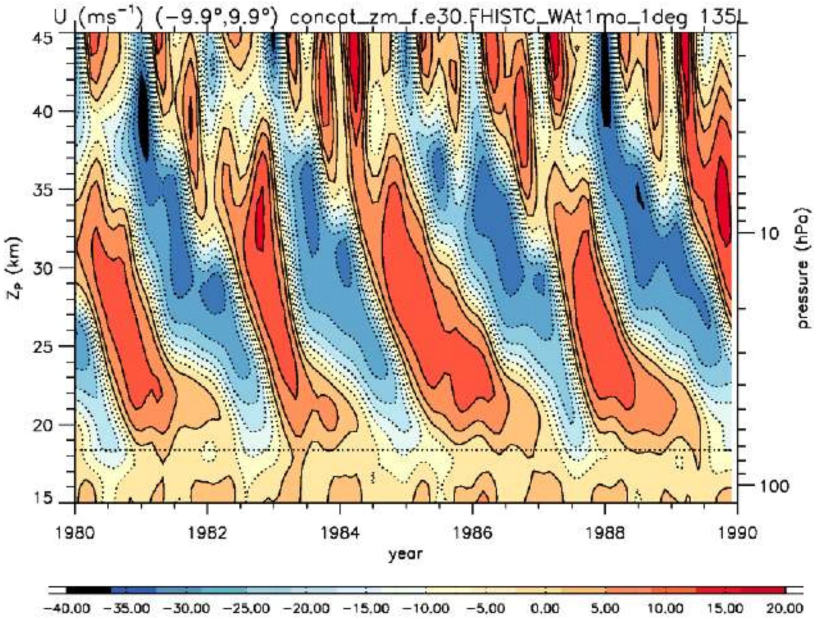
Successful simulation of the QBO:

Adequate horizontal and vertical **resolution**, a realistic simulation of tropical **convection** and a means of describing the effects of mesoscale **gravity waves**.

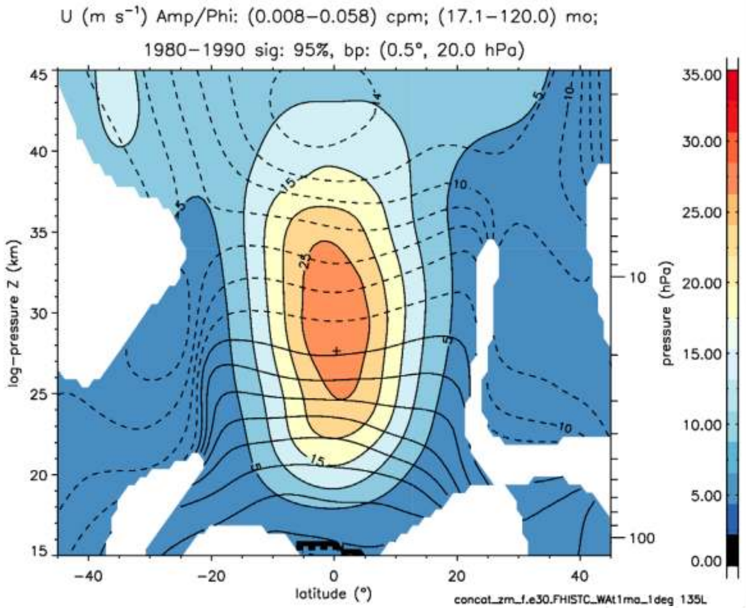
500 m vertical resolution in the upper troposphere lower stratosphere

Quasi - Biennial Oscillation (QBO) – WACCM7

Zonal mean zonal wind (10ºS - 10ºN)



QBO Amplitudes



QBO period & amplitude show good agreement with reanalyses (ERA5 & MERRA 2).

Figures from Rolando Garcia

WACCM with thermosphere - ionosphere eXtension (WACCM - X)

- WACCM - X extends WACCM into the thermosphere and ionosphere
- Additional processes: ion transport, electrodynamics, energetics
- WACCM - X Science goals:
  - Understand and quantify couplings between atmospheric layers through chemical, physical, and dynamical processes
  - Implications of the coupling to climate (downward coupling) and to the space environment (upward coupling)
  - Impacts of the Sun on the Earth System

WACCM - X coupling within atmosphere component

Extension of SE dynamical core into the thermosphere

- Dynamical core requires changes for thermosphere altitudes
- Modifications for species dependence and variable mean molecular weight as well as horizontal molecular viscosity/diffusion
- Efficient regridding using ESMF to map to/from geomagnetic grid for electrodynamics
- Enables high-resolution simulations from surface to space environment

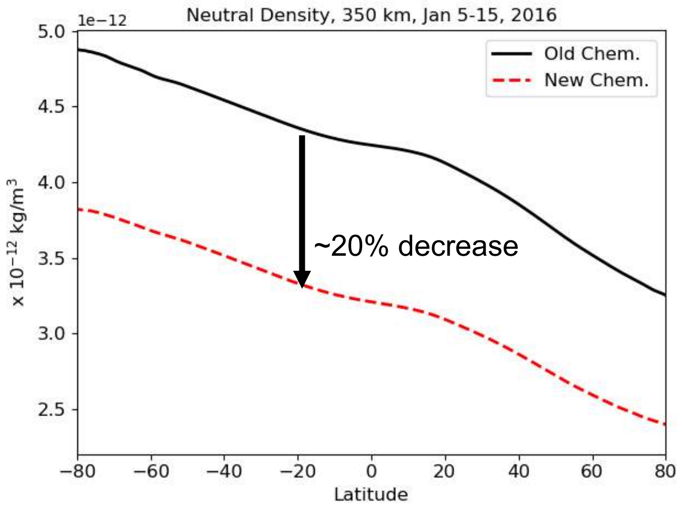
Hanli Liu (HAO) & Matt Rehme (CISL)

Chemistry updates for the mesosphere and thermosphere

	Reaction	Original Rate Constant (A, Ea/R)	Updated	Comment
Updated rates	$N(^4S) + O_2$ -> NO + O	JPL-19 3.3e-12, 3150	3-parameter fit	Fernandez et al., 1998
	$N(^2D) + O_2$ -> NO + $O(^1D)$	5e-12	K=6.2e-12 (T/300.)	Duff et al., 2003
New reactions	$N(^2D)$ + NO -> N_2 + $O(^1D)$	NA	K = 7.3e-11	Roble, 1995
	$N(^2D)$ -> $N(^4S)$ + hv	NA	K = 1.06e-5	Roble, 1995
	$N(^2D)$ + e -> $N(^4S)$ + e + 2.38 eV	NA	K = 3.6e-10_r8 * $(Te/300.0\_r8)^{1/2}$	Roble, 1995

Credit: Doug Kinnison, Jun Zhang (NSF - NCAR/ACOM)

WACCM - X simulated neutral densities with updated reaction rates show good agreement with observations



WACCM7/WACCM - X v3 Compsets

Short Names	Long Names <compset char>.<code base>.< compset shortname >.<res shortname >[.opt_desc_string].<nnn >[opt_char]
FHISTC_WAsc	HISTC_CAM70%WA%CSO_CLM60%SP_CICE%PRES_DOCN%DOM_MOSART_SGLC_SWAV
FHISTC_WAma	HISTC_CAM70%WA%CT0MA_CLM60%SP_CICE%PRES_DOCN%DOM_MOSART_SGLC_SWAV
FHISTC_WAt1ma	HISTC_CAM70%WA%CT1MA_CLM60%SP_CICE%PRES_DOCN%DOM_MOSART_SGLC_SWAV
FHISTC_WAt4ma	HISTC_CAM70%WA%CT4MA_CLM60%SP_CICE%PRES_DOCN%DOM_MOSART_SGLC_SWAV
FHISTC_WXma	HISTC_CAM70%WX%CT0MA_CLM60%SP_CICE%PRES_DOCN%DOM_MOSART_SGLC_SWAV

F: Active atmosphere and land, with prescribed sea-ice and ocean (using SST/ice data)
HISTC: historical time-varying simulations (1850 to near-present)

Specified Chemistry (SC). Ozone together with chemical and shortwave heating rates are simply prescribed in SC has 12 chemical reactions.
Middle Atmosphere (MA) chemistry, stratosphere, mesosphere and lower thermosphere, 298 chemical reactions
T1 mechanism: A comprehensive tropospheric chemistry scheme based on the Model for Ozone and Related chemical Tracers (MOZART) [Emmons et al., 2020].
T4 mechanism: a simplified, highly efficient tropospheric chemistry scheme, developed for long-term climate simulations (e.g., CMIP7)

Questions?

DiscussCesm Forums
(https:// bb.cgd.ucar.edu / cesm /)