2024 CESM Tutorial

WACCM: The High-Top Configuration of CESM

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Whole Atmosphere Community Climate Model (WACCM)

Model lid

WACCM-X

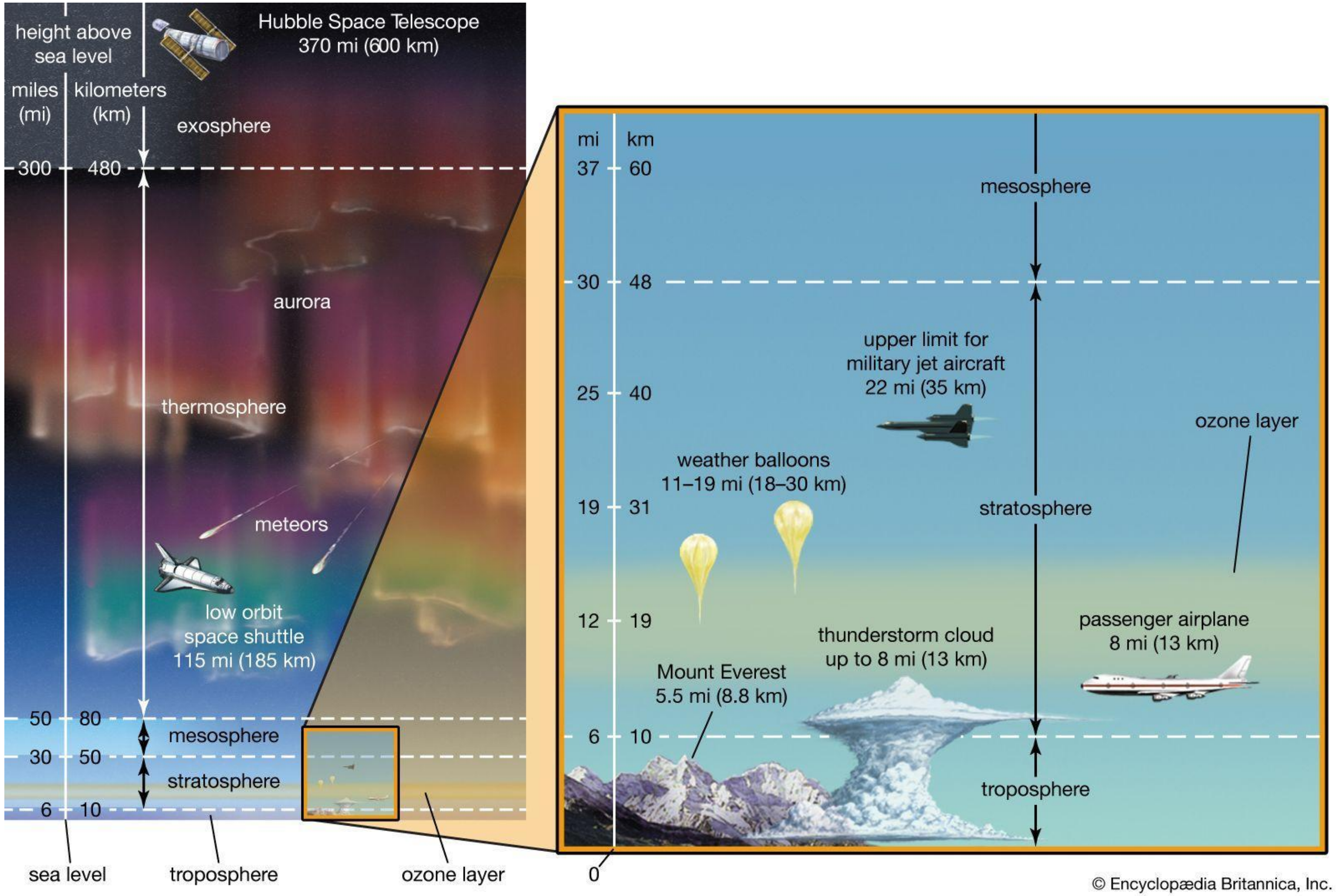
500-700 km

WACCM

140 km

CAM

42 km



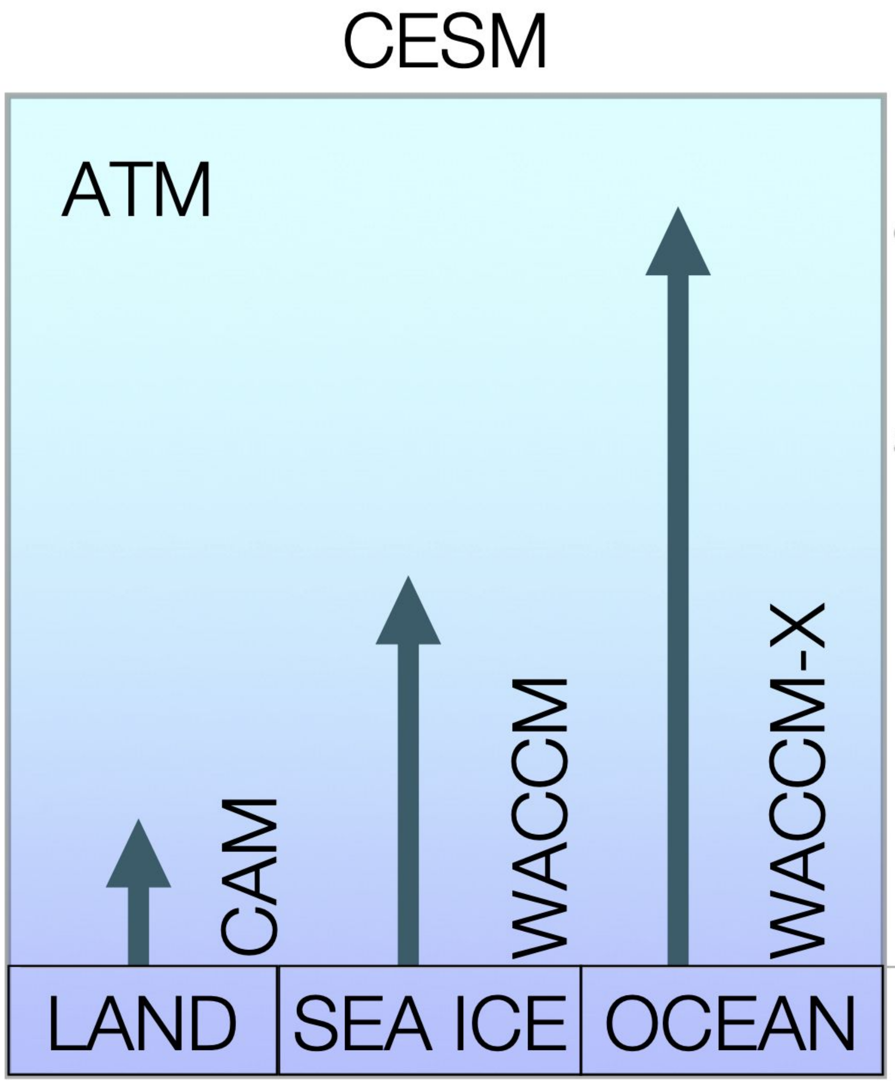
https://cdn.britannica.com/42/90442-050-6CB42E65/layers-atmosphere-Earth-phenomena-heights.jpg

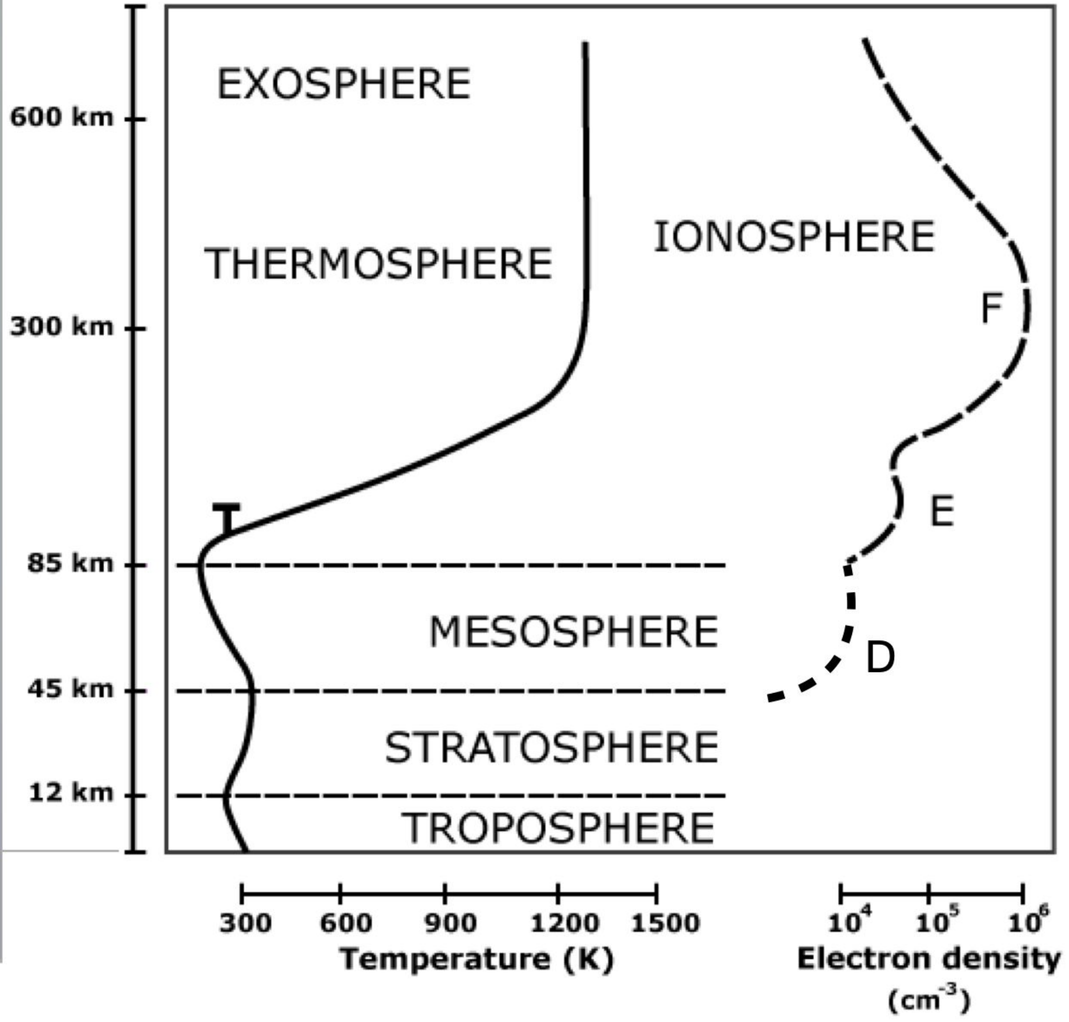
Progressively higher model lids require more comprehensive physics.

What physics do we need to resolve the atmosphere up to 140 km?

Why does this part of the atmosphere matter?

CESM Atmospheric Components





WACCM-X

500-700 km

WACCM

140 km

CAM

42 km

Motivation for WACCM

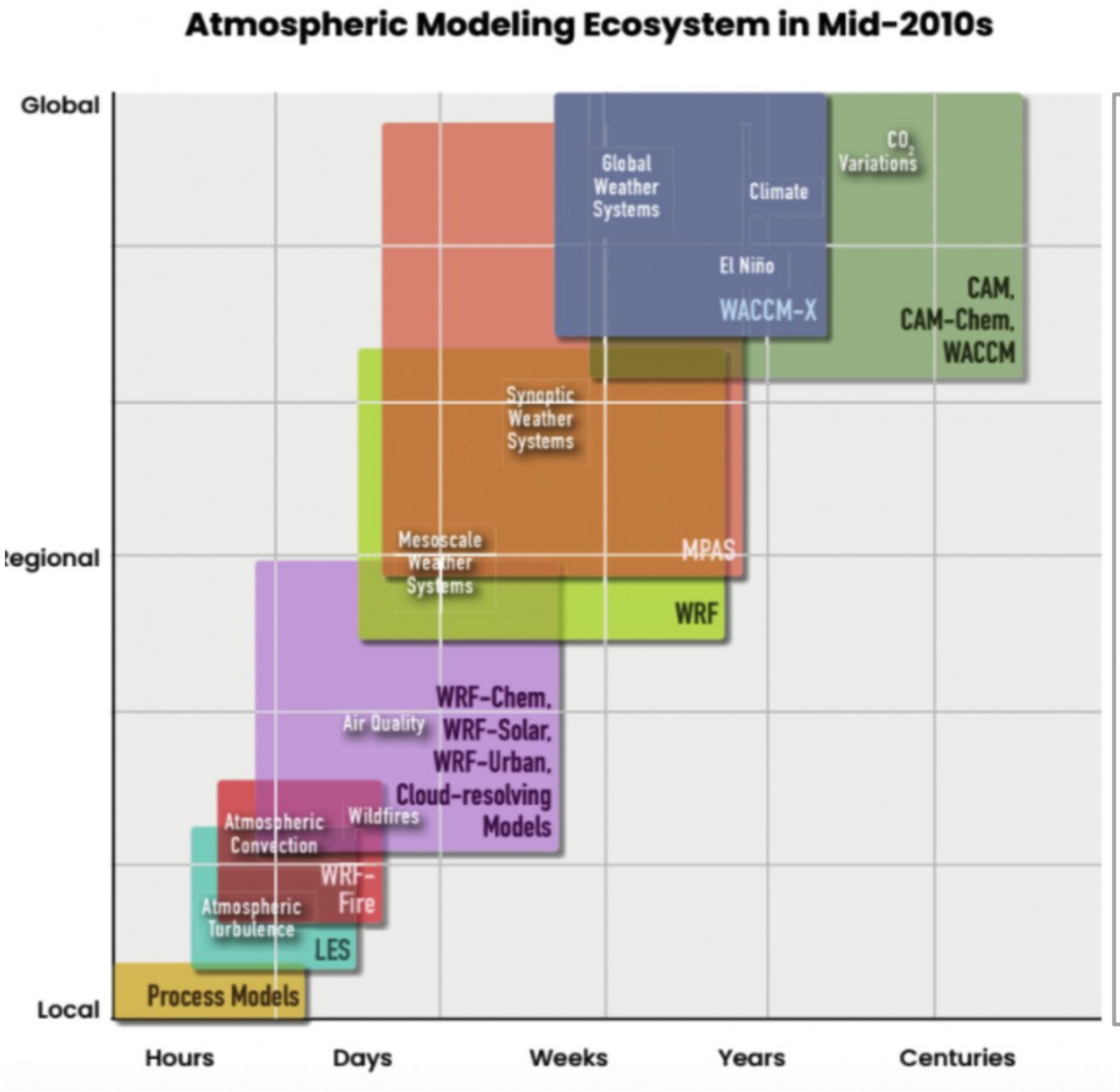


Image from a presentation by Mary Barth

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
  - Chemistry, aerosols, circulation and radiation
- We need a model that can simulate this coupling on short (weather/subseasonal-to-seasonal) and long (climate/paleoclimate) timescales

How WACCM fits into CESM

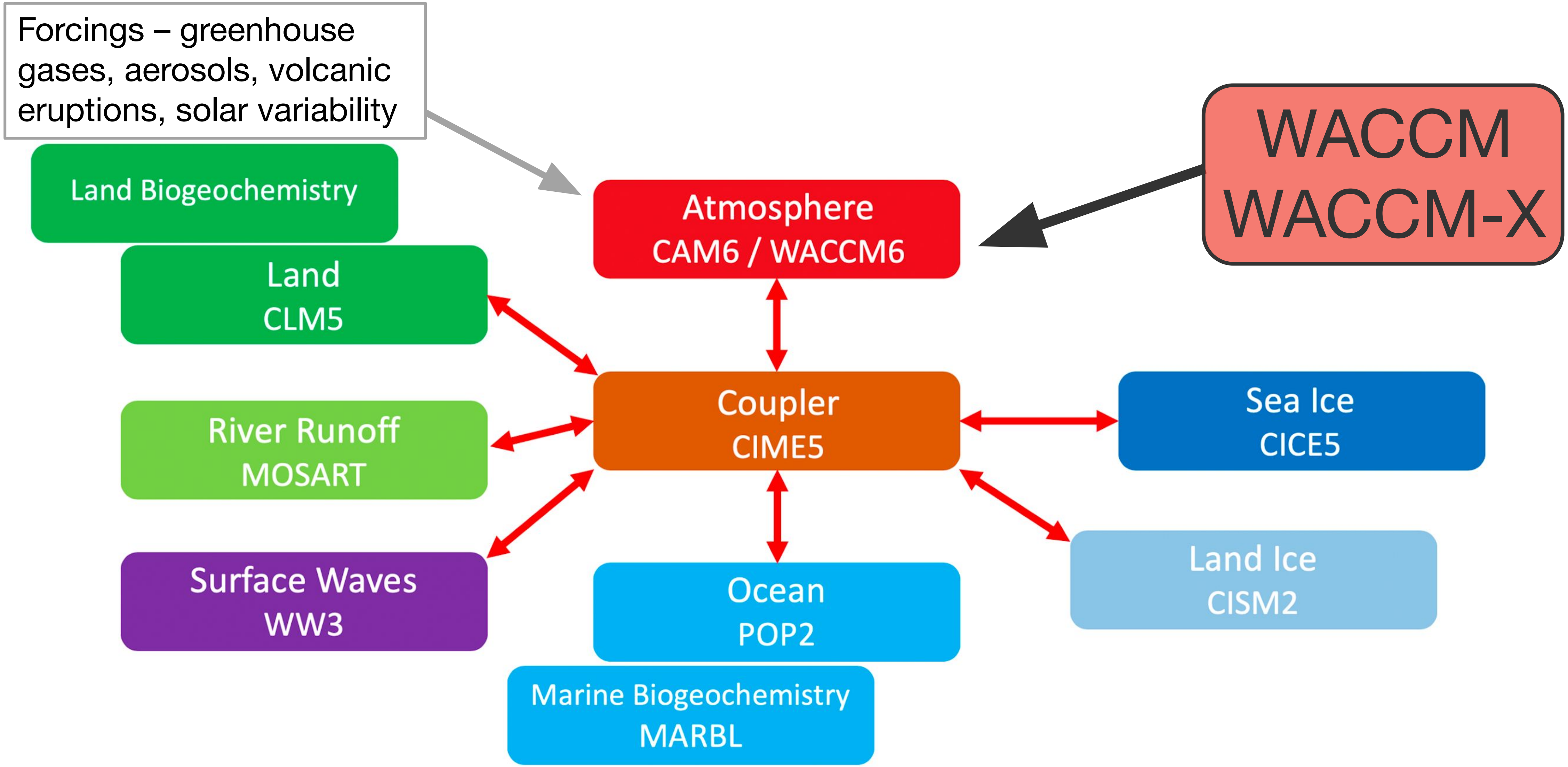


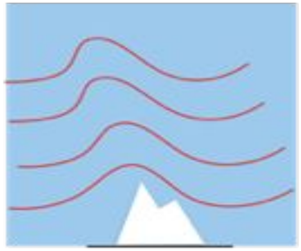
Figure 1. Schematic of the CESM2 component models (Danabasoglu et al., 2020)

Gravity wave physics

- Three primary gravity wave schemes
  - **Orographic**: primarily affecting the stratospheric polar vortex
  - **Frontal**: primarily affecting the polar vortex and mesopause region
  - **Convective**: driving the QBO, impacting the mesopause region
- Schemes apply theoretical frameworks to trigger gravity wave generation and determine forcing

1. Orographic GWs:

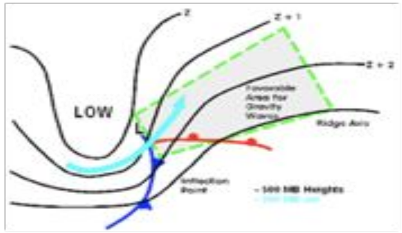
Uncertain: Efficiency



Orographic GWs:
- McFarlane (1987)
- 1 wave with $c = 0$
- Amplitude dependent on orography height and wean wind

2. Frontally generated GWs:

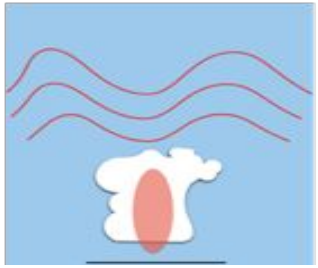
Uncertain: Efficiency, amplitude, phase speeds



- 40 waves with $-100 < c < 100$ m/s
- Gaussian distribution in phase speed centered at U 600 mb
- Constant wave amplitude

3. Convectively generated GWs:

Uncertain: Efficiency, amplitude conversion



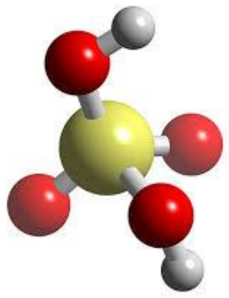
- 40 waves with $-100 < c < 100$ m/s
- Dominant c related to h (depth of heating)
- Wave Amplitude $\propto Q^2$
- Wave spectrum impacted by wind in heating

Beres et al. 2004 (Beres = Richter)

WACCM versus CAM

WACCM inherits the dycore 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
- Gravity wave drag deposition from vertically propagating GWs generated by orography, fronts, and convection
- Interactive QBO (quasi-biennial oscillation) derived from gravity and resolved wave forcing
- Molecular diffusion and constituent separation
- Thermosphere extension (WACCM-X) to ~500-700 km

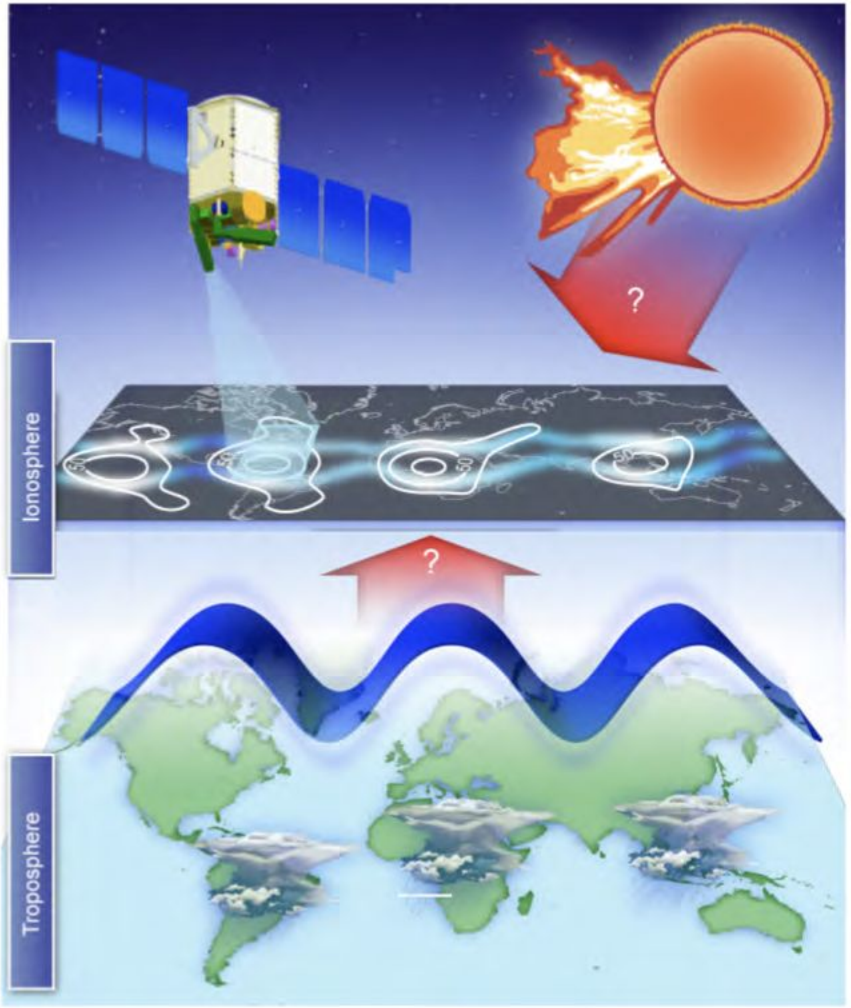


H_2SO_4

Whole Atmosphere Community Climate Model with thermosphere and ionosphere eXtension (WACCM-X)

WACCM-X is a model of the entire atmosphere that extends into the thermosphere to ~500-700 km altitude, and includes the ionosphere. Because the thermosphere ionosphere system responds to variability from the Earth's lower atmosphere as well as solar-driven "space weather" Including:

- Waves and tides
- Tropospheric weather
- Middle-atmosphere events
- Seasonal variations
- Anthropogenic trace gases

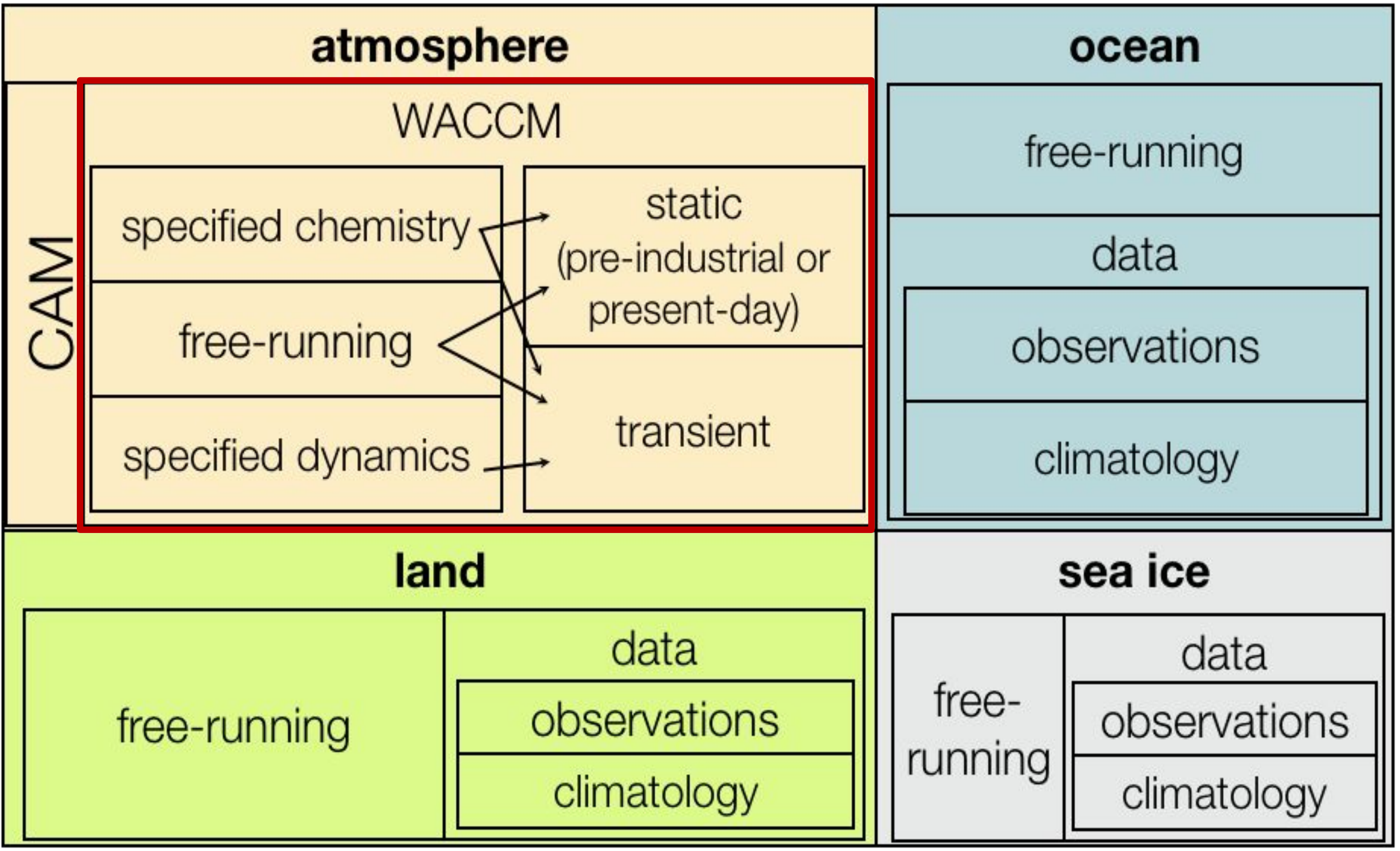


https://www2.hao.ucar.edu/modeling/waccm-x

WACCM versus WACCM-X

	WACCM6	WACCM-X v2
Vertical Levels	70, 88(SD), 110	126, 145(SD)
Model Top	$6x10^{-6}$ hPa (~140 km)	$4x10^{-10}$ hPa (500-700 km)
Horizontal Resolution	0.95°x1.25°, 1.9°x2.5°	1.9°x2.5°
Time step	30 minutes	5 minutes
Specified Dynamics	SD-WACCM6 option, or nudging_nml	SD-WACCM-X option, or nudging_nml
Chemistry	TSMLT (233), MA (99), SC (37)	MA (76)
QBO	0.95°x1.25° or 1.9°x2.5°	Nudged
Tropospheric Physics	CAM6	CAM4
Radiation	RRTMG	CAM-RT
Tropospheric Aerosol	Interactive MAM4	Prescribed Bulk
Stratospheric Aerosol	Interactive MAM4	Prescribed
Non-orographic GW	Yes	Yes
Molecular Diffusion	minor	minor and major
Auroral Physics	Yes	Yes
Ions	E-region or E&D-region	E-region
Ion transport	No	Yes
E Dynamo	No	Yes

Possible WACCM configurations



WACCM can be run with

- interactive or specified chemistry
- a free running atmosphere, or an atmosphere constrained to historical or specified meteorology via the specified dynamics scheme
  - Old approach: “SD” compsets
  - New approach: nudging namelist available in all atmospheric configurations and compsets
  - GEOS5, MERRA2 meteorology is available on GLADE

Scientifically supported WACCM atmosphere compsets

Scientifically supported WACCM atmosphere configurations for CESM2.0 use TSMLT1 chemistry (see chemical mechanisms) and 0.95° latitude x 1.25° longitude horizontal resolution (f09_f09_mg17).

Compset	Resolution	Description	Period
FW1850	f09_f09_mg17	Pre-industrial control WACCM6 using 1-degree FV dycore, TSMLT1, CMIP6 piControl emissions, year 1850 SSTs, coupled to interactive land and MEGAN2.1	1850
FWHIST	f09_f09_mg17	Historical WACCM6 using 1-degree FV dycore, TSMLT1, CMIP6 emissions, historical SSTs, coupled to interactive land and MEGAN2.1	1974 to 2015
FW2000	f09_f09_mg17	Year 2000 WACCM6 1deg compset using 1-degree FV dycore, TSMLT1, year 2000 CMIP6 emissions, year 2000 SSTs, coupled to interactive land and MEGAN2.1	2000
FWSD	f09_f09_mg17	Historical SD-WACCM6 using GEOS5 analysis with a 50-hour relaxation, TSMLT1, CMIP6 emissions, historical SSTs, coupled to interactive land and MEGAN2.1	2005 to 2015
FWscHIST	f09_f09_mg17	Historical SC-WACCM6 using 1-degree FV dycore, specified chemistry, historical SSTs	1976 to 2015

https://ncar.github.io/CAM

WACCM chemical mechanisms

CESM2.0 supports 6 chemical mechanism. The CESM chemical mechanism is a set used to calculate chemical reactions using the chemical preprocessor (http://www.cesm.ucar.edu/working_groups/Chemistry/chemistry.preprocessor.pdf).

Mechanism (pre-processor code)	Model: Chemistry Description	#Species	#Reactions
TSMLT1 (pp_waccm_tsmlt_mam4)	WACCM: Troposphere, stratosphere, mesosphere, and lower thermosphere	231 solution, 2 invariant	583 (433 kinetic, 150 photolysis)
TS1 (pp_trop_strat_mam4_vbs)	CAM-chem: Troposphere and stratosphere	221 solution, 3 invariant	528 (405 kinetic, 123 photolysis)
MA (pp_waccm_ma_mam4)	WACCM: Middle atmosphere (stratosphere, mesosphere, and lower thermosphere)	98 solution, 2 invariant	298 (207 kinetic, 91 photolysis)
MAD (pp_waccm_mad_mam4)	WACCM: Middle atmosphere plus D-region ion chemistry	135 solution, 2 invariant	593 (489 kinetic, 104 photolysis)
SC (pp_waccm_sc_mam4)	WACCM: Specified chemistry	29 solution, 8 invariant	12 (11 kinetic, 1 photolysis)
CAM	CAM: Aerosol chemistry	25 solution, 7 invariant	7 (6 kinetic, 1 photolysis)

T1 (comprehensive troposphere)

TSMLT1(T1 with middle atmosphere, stratosphere-mesosphere-lower thermosphere chemistry)

TS1 (T1 with comprehensive stratosphere)

https://ncar.github.io/CAM

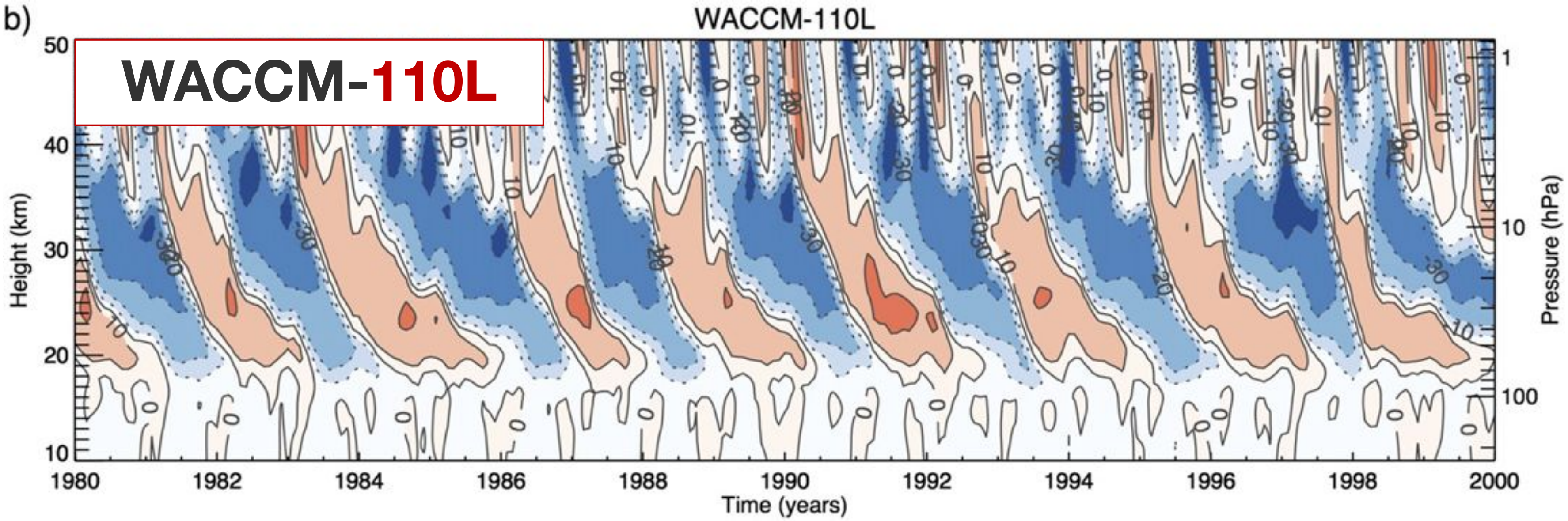
Scientifically supported WACCM-X compsets

WACCM-X has three compsets/resolutions which are supported scientifically. These compsets are based on version 4 of CAM/WACCM.

Compset Name	Supported Resolution	Description	Period
FXHIST	f19_f19_mg16	Historical WACCM-X based on CAM4 using 2 degree FV dycore, MA chemistry, CCMI emissions, historical SSTs, coupled to land, prescribed ice, river	2000 to 2015
FX2000	f19_f19_mg16	Year 2000 WACCM-X based on CAM4 2 degree FV dycore, using MA chemistry, year 2000 CCMI emissions and SSTs, coupled to interactive land, prescribed ice, river	2000
FXSD	f19_f19_mg16	Historical SD-WACCM-X based on CAM4 using 2 degree FV dycore, MERRA1 with a 50-hour relaxation, MA chemistry, CCMI emissions, historical SSTs, coupled to interactive land, prescribed ice, river	2000 to 2015

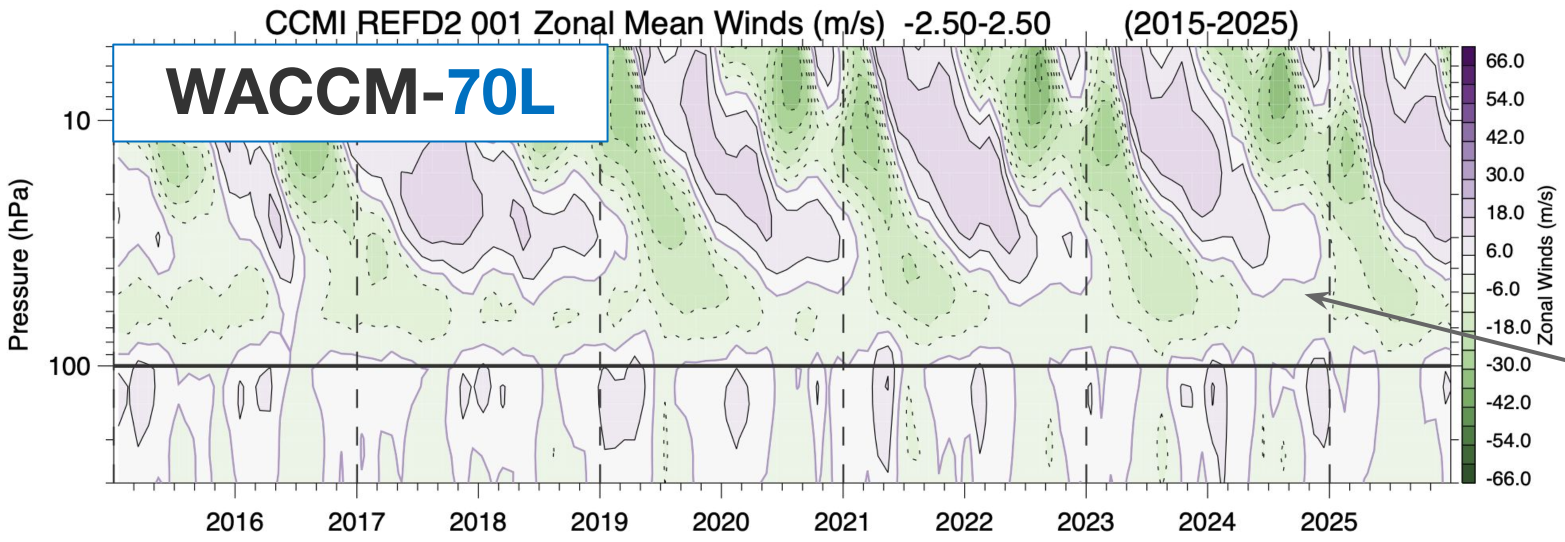
https://ncar.github.io/CAM

Stratospheric Quasi-Biennial Oscillation (QBO)



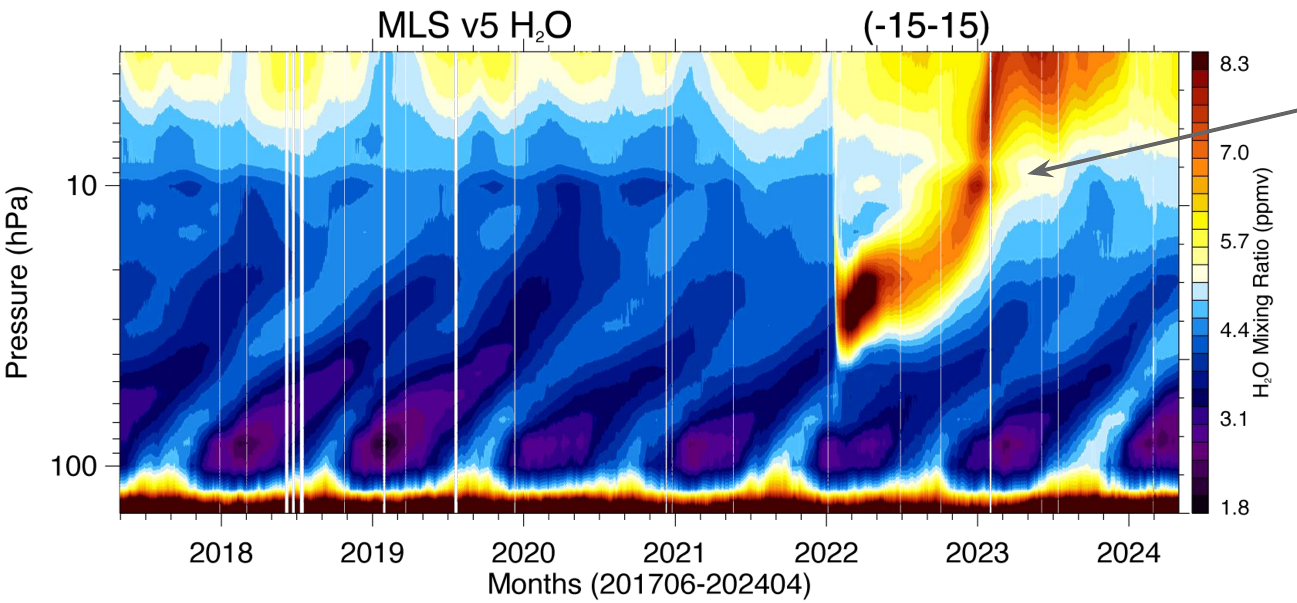
Successful simulation of the QBO

- adequate horizontal and vertical resolution, a realistic simulation of tropical convection and a means of describing the effects of mesoscale gravity waves [Garcia and Richter, 2019].



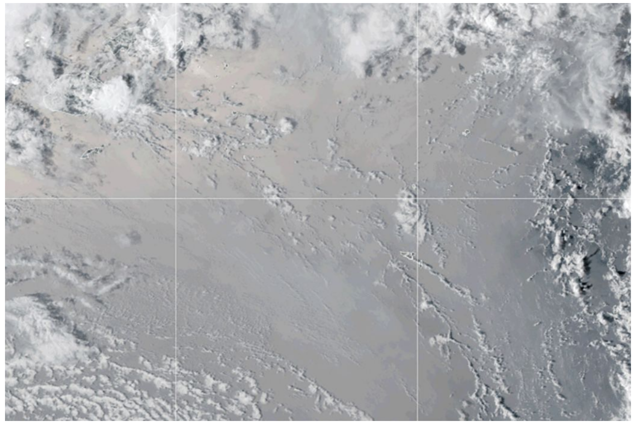
The QBO westerly does not come down to lower altitudes.

Water Vapor – Hunga Tonga Eruption

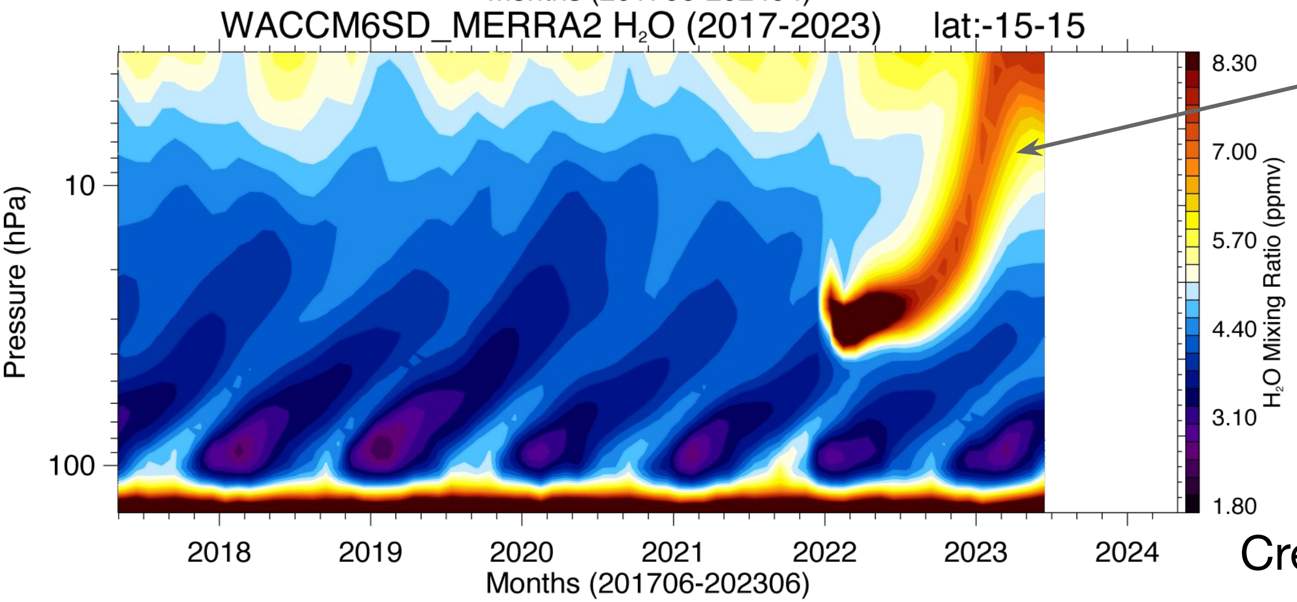


Hunga Tonga (Jan 2022)

MLS Satellite



The underwater eruption of the Hunga Tonga-Hunga Ha'apai volcano on Jan. 15, 2022 (GOES-17 satellite imagery, NOAA)



WACCM6 (SD)

WACCM6 is able to simulate the Hunga Tonga volcanic eruption.

Credit: WACCM simulations (Jun Zhang)

Chemistry Contribution to Stratospheric Ozone Depletion After the Unprecedented Water-Rich Hunga Tonga Eruption

- Following the Hunga Tonga–Hunga Ha'apai (HTHH) eruption in January 2022, stratospheric ozone depletion was observed at SH mid-latitudes and over Antarctica during the 2022 austral wintertime and springtime, respectively.
- Most of the ozone depletion is attributed to internal variability and dynamical changes forced by the eruption.
- Both the modeling and observations show a significant NOx reduction associated with the HTHH aerosol plume, indicating enhanced dinitrogen pentoxide (N_2O_5) hydrolysis on sulfate aerosol.

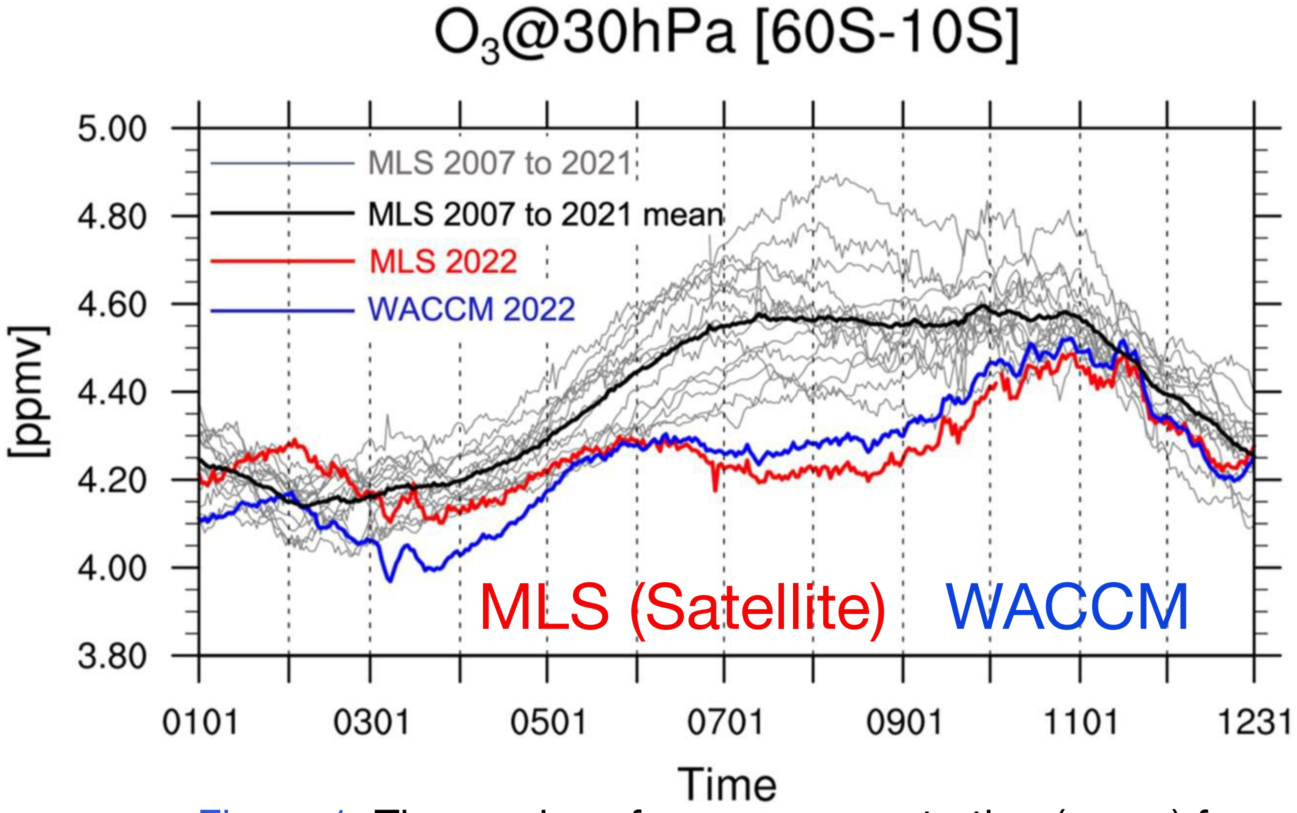


Figure 1. Time series of ozone concentration (ppmv) for midlatitudes and tropics (10ºS–60ºS) at 30 hPa.

Zhang et al. (2024, DOI:10.1029/2023GL105762)

Contributions of Parameterized Gravity Waves and Resolved Equatorial Waves to the QBO Period in a Future Climate of CESM2

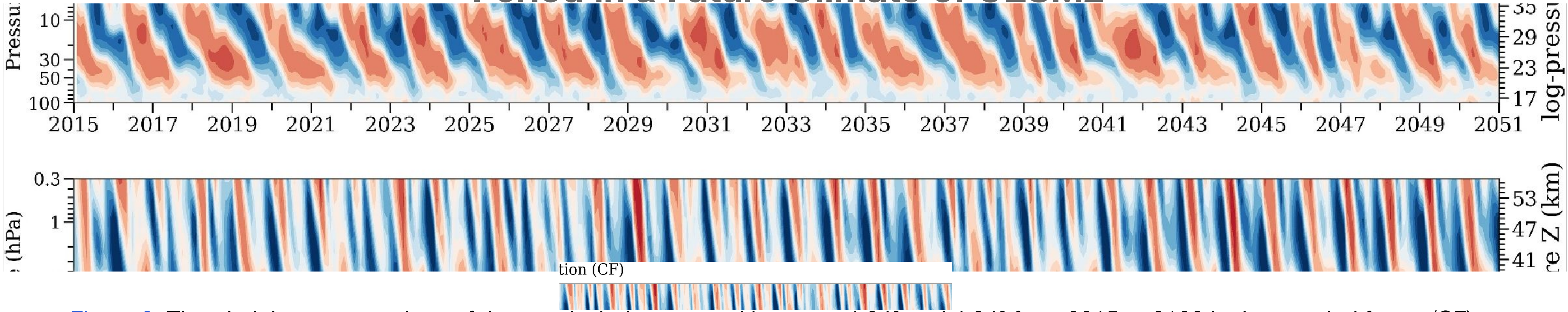


Figure 2. Time-height cross sections of the zonal winds averaged between 4.24° and 4.24° from 2015 to 2100 in the coupled future (CF) simulation. The tick marks on the x-axis indicate January for each year.

- The QBO period in the future simulation is much shorter: 21.6 (2015–2050) and 12 months (2065–2100), than in the historical simulations (23.5–30.9 months). The shortened QBO period in the future is primarily due to increases in both resolved wave forcing and parameterized gravity wave drag (GWD) in the stratosphere, with a more significant contribution by the GWD.

- As convective activity becomes stronger in the future simulation, the momentum flux of parameterized convective gravity waves at the cloud top increases, resulting in stronger GWD in the stratosphere.

Lee et al. (2024, DOI:10.1029/2024JD040744)

Climate, Variability, and Climate Sensitivity of "Middle Atmosphere" Chemistry Configurations of the Community Earth System Model Version 2, Whole Atmosphere Community Climate Model Version 6 (CESM2(WACCM6))

- Analyzed two CESM2(WACCM6) with simplified "middle atmosphere" chemistry at nominal 1° and 2° horizontal resolutions.

- 2° configurations generally reproduce the climate, variability, and climate sensitivity of the 1° nominal horizontal resolution configuration with comprehensive chemistry.

- For any purposes other than those needing an accurate representation of tropospheric organic chemistry and secondary organic aerosols, these simplified chemistry configurations deliver reliable simulations of the whole atmosphere that require 35% and 86% fewer computational resources at nominal 1 and 2° horizontal resolution, respectively.

Figure 3. Stratospheric polar vortex strength assessed from the zonal mean zonal wind at 60 and 10 hPa for the (left column) NH and (right column) SH.

Davis et al. (2023, DOI: 10.1029/2022MS003579)

Effects of Forcing Uncertainties on the Thermospheric and Ionospheric States During Geomagnetic Storm and Quiet Periods

- Ensemble simulations of a whole atmospheric model, the WACCM-X, with various kinds of forcing perturbation is used to evaluate the upper atmosphere's response to the uncertainties of different forcings.

- The results show that the impact of high-latitude electric potential uncertainty is significant globally during the 2013 St. Patrick's Day storm. The lower atmospheric wave and tide forcing uncertainties result in a global impact on the upper atmosphere in the model.

- The sensitivity of the upper atmosphere to both uncertainties is approximately the combination of the two individually, though the combined effects are not a linear sum, indicating non-linearities in the ionosphere and thermosphere response to forcing uncertainties.

Figure 4. The standard deviation (STD) of electric potential from the WACCM-X ensemble.

Hsu & Pedatella (2023, DOI: 10.1029/2022SW003216)

Effects of denitrification on the distributions of trace gas abundances in the polar regions: a comparison of WACCM with observations

- Nitric acid trihydrate (NAT) particles have been shown to lead to denitrification of the lower stratosphere.

- This study evaluates the probability density functions of various gaseous species in the polar vortex using the Whole Atmosphere Community Climate Model (WACCM), and compare these with measurements by the Michelson Interferometer for Passive Atmospheric Sounding onboard the Environmental Satellite (MIPAS/Envisat) and two ozonesonde stations for a range of years and in both hemispheres.

- The average difference between WACCM and ozonesondes supports the need to reduce the NAT number density in the model. Therefore, this study suggests using a NAT number density of 5×10^{-4} cm^{-3} for future simulations with WACCM.

Figure 3. HNO_3 PDFs within the polar vortex for MIPAS and the sensitivity simulations of WACCM for the NH (a–c) and SH (d–f) spring months

Weimer et al. (2023, DOI:10.5194/acp-23-6849-2023)

Potential Non-Linearities in the High Latitude Circulation and Ozone Response to Stratospheric Aerosol Injection

- We use a set of CESM2(WACCM6) Stratospheric Aerosol Injection (SAI) simulations achieving three different levels of global mean surface cooling and demonstrate that the SAI-induced changes in the high latitude circulation and ozone are more complex and could be non-linear.

- This manifests in our simulations by disproportionally larger Antarctic springtime ozone loss, significantly larger intra-ensemble spread of the Arctic stratospheric jet and ozone responses, and non-linear impacts on the extratropical modes of surface climate variability under the strongest-cooling SAI scenario compared to the weakest one.

- These potential non-linearities may add to uncertainties in projections of regional surface impacts under SAI.

Figure 4. Impacts on the Arctic and Antarctic ozone (d–i) Correlation between seasonal mean changes in (d–f) polar ozone and stratospheric vortex strength, and between changes in (g–i) polar ozone and polar SAD at 170 hPa.

Bednarz et al. (2023, DOI:10.1029/2023GL104726)

What do you want to do?

- WACCM6 is one of the most advanced configurations of CESM2, because it resolves
  - a greater vertical extent of the atmosphere
  - chemistry and aerosols
  - middle and upper atmosphere physics
  - vertical coupling by virtue of higher vertical resolution

- Many of our most pressing fundamental and applied scientific questions are at the intersection of multiple disciplines, with coupling across time and space
  - The WACCM enterprise at NCAR is a cross-lab endeavor between ACOM, CGD, and HAO, with broad external community involvement

https://www.dreamstime.com

QuESTIONS ?

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