2025 CESM Tutorial

WACCM: The High-Top Configuration of CESM

MIJEONG PARK
ACOM, NSF NCAR & WACCM LIAISON

July 7-11, 2025

Thanks to Nick Davis, Mike Mills and Doug Kinnison

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UCAR Quarterly

UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH
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It's about TIME: A new upper-atmosphere model

by Carol Rasmussen

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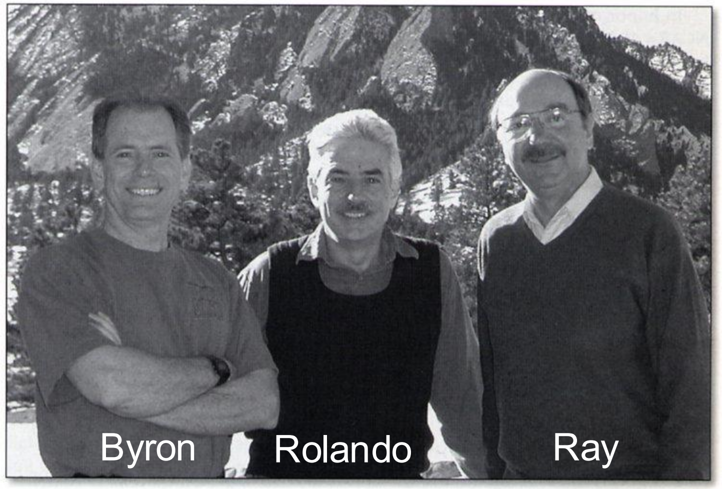
"A year from now, we expect to have a model that extends from the surface to 120 kilometers and includes ozone chemistry," says Boville. The yet-unnamed composite model will be one of only two or three general circulation models to reach that altitude. Some GCMs only extend to 30 km, including the troposphere and part of the lower stratosphere; a few have been extended into the mesosphere, with upper boundaries in the range of 60–80 km. The new model will include the entire mesosphere as well as the lower thermosphere. But the plan doesn't stop there. Further into the future, the scientists will add thermospheric and ionospheric dynamics and extend the model a few hundred kilometers higher.

A simple way to conceptualize the atmosphere is by its thermal structure, a sort of four-layer cake governed by radiative and dynamic processes. From the bottom up, each layer—troposphere, stratosphere, mesosphere, thermosphere—is alternately cooling or warming with altitude. The top layer has a more complicated structure, however, because the thermosphere coexists in space with the ionosphere, a region ruled by electric and magnetic fields. The electrically charged atoms and molecules of the ionosphere are ionized by solar radiation and aurora particle precipitation. This happens throughout the atmosphere, but in the denser air lower down, charged particles quickly bump into oppositely charged particles and recombine. In the sparsely populated ionosphere, ionized particles zip around for long distances without losing their charge.

"Most of the variability in the ionosphere and thermosphere has been attributed to variation in the aurora, heating due to dissipation of electric currents, and variability in the sun's ultraviolet and extreme ultraviolet radiation," says Roble—in other words, to processes within the upper atmosphere or coming from the sun. "But we have never been able to account for the observed variability in the lower part of the thermosphere, so we have not been able to model it." A few years ago, Roble attempted to

(Continued on p. 10)



Byron Boville, Rolando Garcia, and Ray Roble. (Photo by Carlye Calvin.)

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MOZART: An uncompromising global model

By Carol Rasmussen

A new version of NCAR's global chemical model is about to give atmospheric scientists a better look at the global budget and interactions of ozone and almost 50 other chemical species in the troposphere. From there, the model of ozone and related trace species (MOZART) is moving up all the way to 85 kilometers and expanding to encompass an additional 30 species.

"MOZART has been a major project in ACD for five years or more," says Atmospheric Chemistry Division director Guy Brasseur. "It is a theoretical tool that allows us to understand and quantify the global budget of chemicals and to look at changes in the chemical composition of the atmosphere in response to human activities."

In the troposphere, ozone is a greenhouse gas, harmful to people and animals. Before the 1970s, scientists thought that ozone was in the troposphere simply because it sank down from the stratosphere. Groundbreaking work by Paul Crutzen and William Chameides at that time showed that it is born out of reactions in the troposphere itself. Because some of the gas's precursors, including pollutants like the nitrogen oxides, are increasing, ozone concentrations are rising sharply in many parts of the world. However, scientists don't have all of the measurements they need to understand its reactions and transport, especially from the tropics and Southern Hemisphere. The answer is global modeling.

Atmospheric scientists in this country may not be as familiar with global chemical modeling as they are with global climate modeling; a large number of the world's 15 or so global chemical models are European. The United States is home to only five or six, with strong groups at NASA's Goddard Space Flight Center and Goddard Institute for Space Studies, Harvard University, and Lawrence Livermore National Laboratory, besides NCAR.

MOZART is "among the most detailed" of the global models, says Brasseur. "We have made very, very few compromises. We don't make many assumptions or simplifications." Because it requires high resolution (2.8° x 2.8°, with 34 vertical layers), 20-minute time steps, and a large number of species, MOZART is costly to run—ten times as expensive as NCAR's climate system model.

Users have done many types of studies using MOZART. For example, ACD researchers have reproduced the preindustrial chemical composition of the atmosphere by working backward from recent data, and they also have looked forward to 2050 and 2100 using IPCC scenarios of energy consumption, population, etc. "We have seen that the place where real perturbation will happen is the tropics," says Brasseur. "Also, in the upper troposphere [about 10 km] we expect a relatively large impact from airplane emissions."

MOZART version 2 incorporates an improved treatment of chemical transport and convection, as well as updated pollution information. It can use wind, temperature, and water vapor from climate models or from observational data to "push the chemicals around in the atmosphere," says Larry Horowitz, an ACD scientist involved in the model development. The ability to use different data sets will make MOZART useful in field campaigns. It will be fed with analyzed winds from the upcoming Tropospheric Ozone Production about the Spring Equinox experiment to help the TOPSE scientists understand their observations. For example, says Brasseur, "If as they fly north they suddenly have a peak of carbon monoxide, is that because they flew near a source, or was there an event that created that? We can answer those questions."

The model will make use of the daily measurements of carbon monoxide from the MOPITT (measurement of pollutants in the troposphere) instrument on Terra, the NASA Earth Observing System satellite launched on 18 December. Combining the

Orchestrating MOZART are, from left, Doug Kinnison, Claire Granier, Guy Brasseur, Louisa Emmons, Stacy Walters, and Larry Horowitz. (Photo by Carlye Calvin.)

1999 Winter

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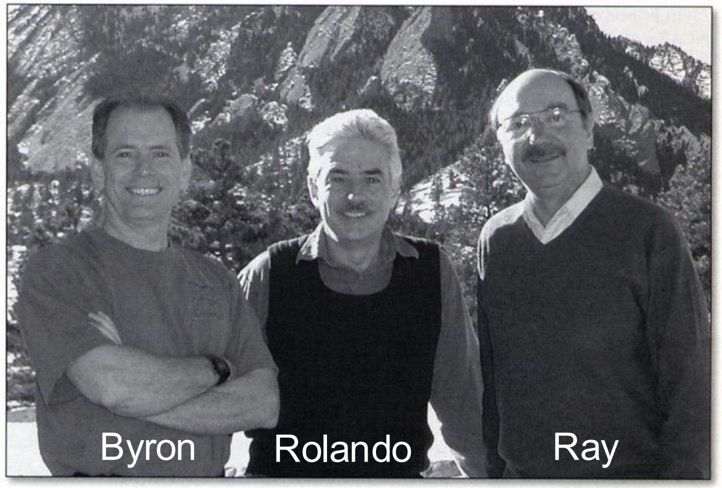

Byron Boville, Rolando Garcia, and Ray Roble. (Photo by Carlye Calvin.)

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Featured Alum: Byron Boville '79

Byron Arthur Boville received his BS degree in meteorology from McGill University and came to the UW to study with Jim Holton in 1975. Byron's father was also a meteorologist who was a professor at McGill and York Universities who did important work on the stratosphere and the ozone layer. Byron's PhD thesis was on wave, mean-flow interaction in the troposphere and baroclinic wave vacillation.

After receiving his PhD Byron moved to the National Center for Atmospheric Research in Boulder, Colorado where he made his career. His earliest work there was on the effect of the stratospheric polar night jet on tropospheric weather, a topic that has returned to prominence in recent years. He then became intimately involved with the development of the NCAR Community Climate System Model and became a leader in the development of CCSM and its vertically extended version, the Whole Atmosphere Community Climate Model (WACCM), which he pronounced "whack'em". Byron made fundamental contributions to understanding Earth's atmosphere and climate, while devoting substantial effort to model development. In May he was given the 2006 CCSM Distinguished Achievement Award *in recognition for Byron's critical leadership of the CCSM project at its inception, for his numerous contributions to the design and physics of the atmospheric model, and for his initiative in the collaborative development of the Whole Atmosphere Community Climate Model (WACCM), where WACCM represents a major move toward realizing NCAR's strategic goal of developing a comprehensive Earth System Model.* Byron is a Fellow of the American Meteorological Society. He was one of the invited speakers at the Holton Symposium in Atlanta this year.

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Doug, Mijeong and Rolando (July 9, 2025)

Atmospheric Circulation, Newsletter of the University of Washington Atmospheric Sciences Department, Autumn 2006

Motivation for WACCM

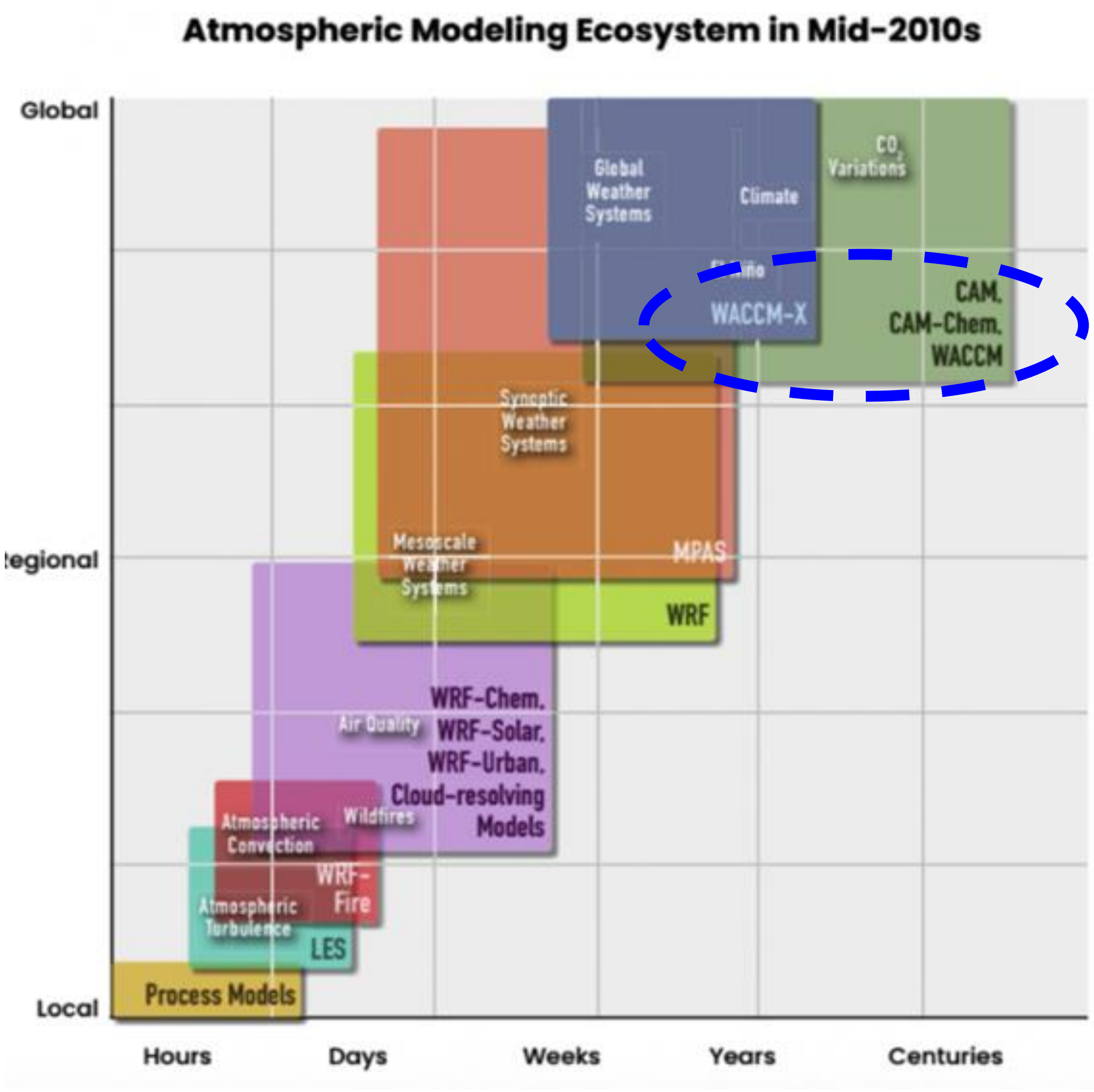
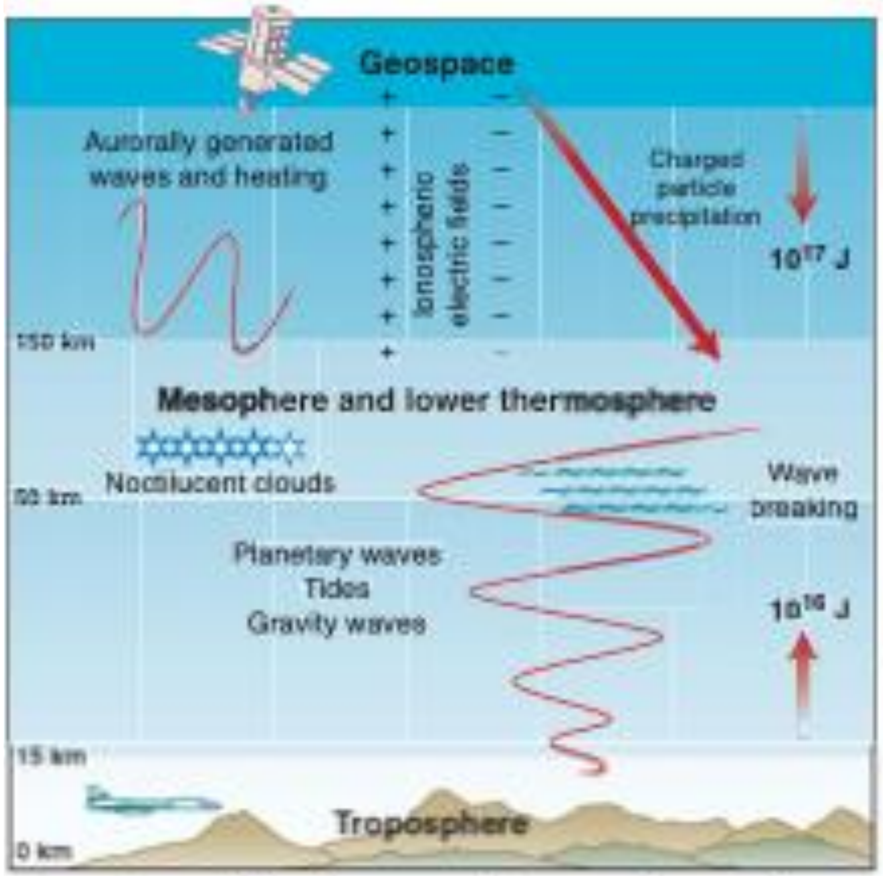


Image from Mary Barth

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

Vertical Structure of the Atmosphere



Energy transfer in the mesosphere and lower thermosphere. About 10^{16} J of energy propagates up daily from the atmosphere below in the form of waves and tides. During a geomagnetic storm (which occurs about every 5 days), about 10^{17} J is injected per day from space through auroral processes.

Jarvis, "Bridging the Atmospheric Divide" Science, 2001

Geosphere (Ionosphere-Sun)

MLT (50-150 km)

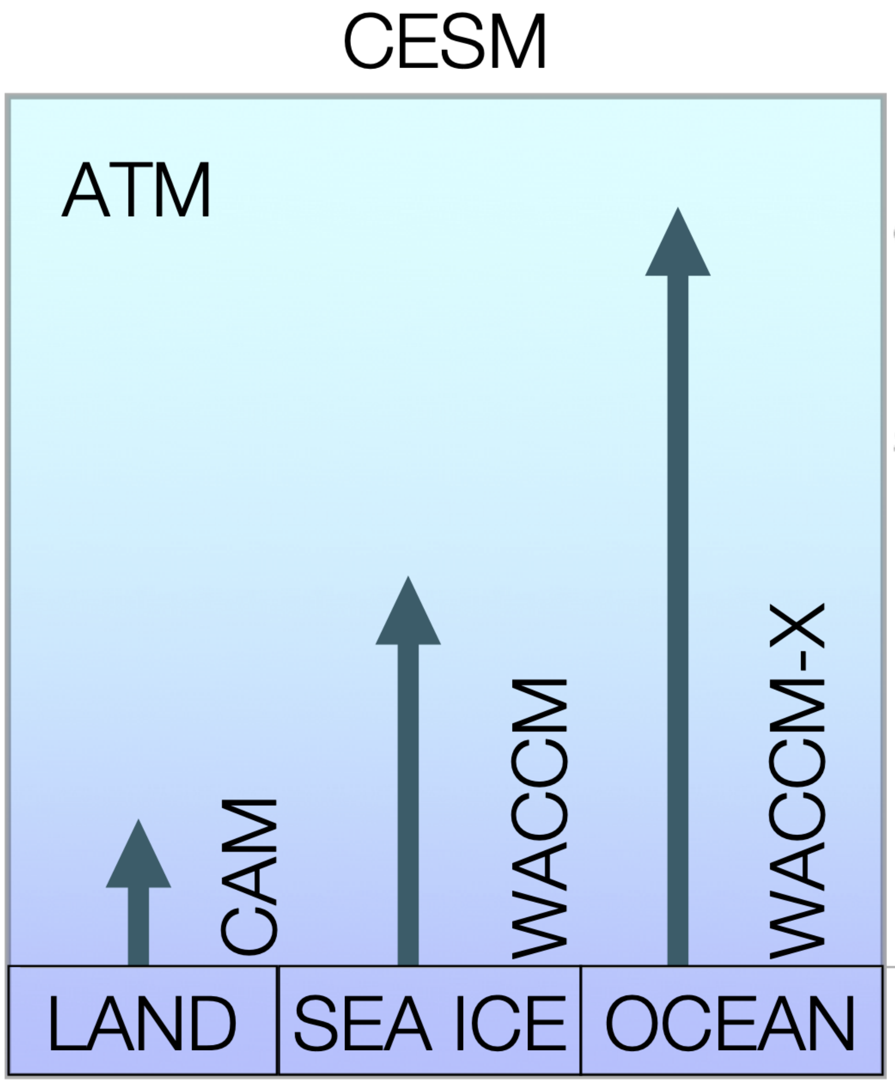
Stratosphere (15-50 km)

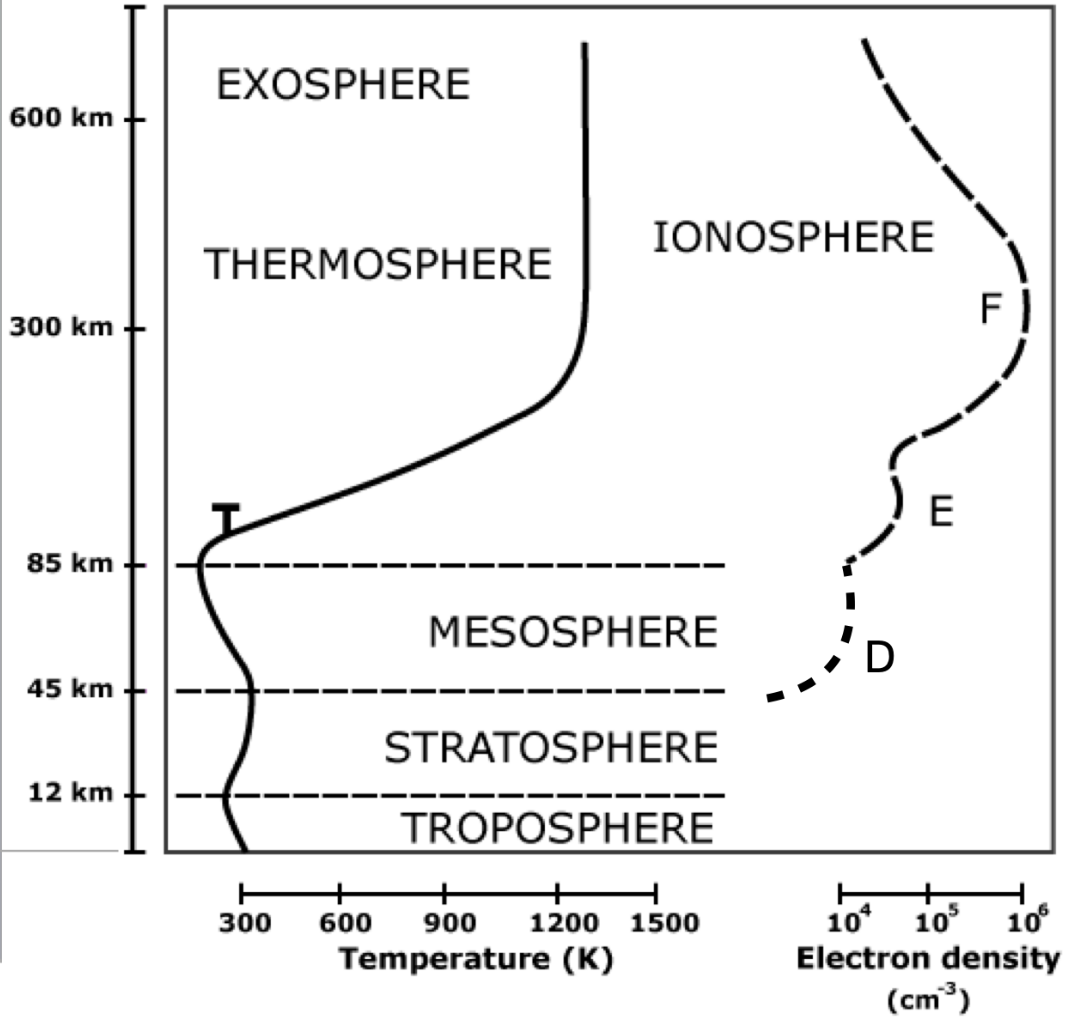
Troposphere (0-15 km)

The MLT is an important link in the vertical transfer of energy and material in the atmosphere, that mesospheric phenomena may be the most sensitive indicator of global temperature change [Jarvis, 2001].

<u>An ambitious modeling initiative</u>, the Whole Atmosphere Community Climate Model (WACCM), is under way at the National Center for Atmospheric Research in Boulder to bridge the gap and simulate the physics and chemistry of the atmosphere from the ground to 500 km.

CESM Atmospheric Components





Model lid

WACCM-X

500-700 km

WACCM

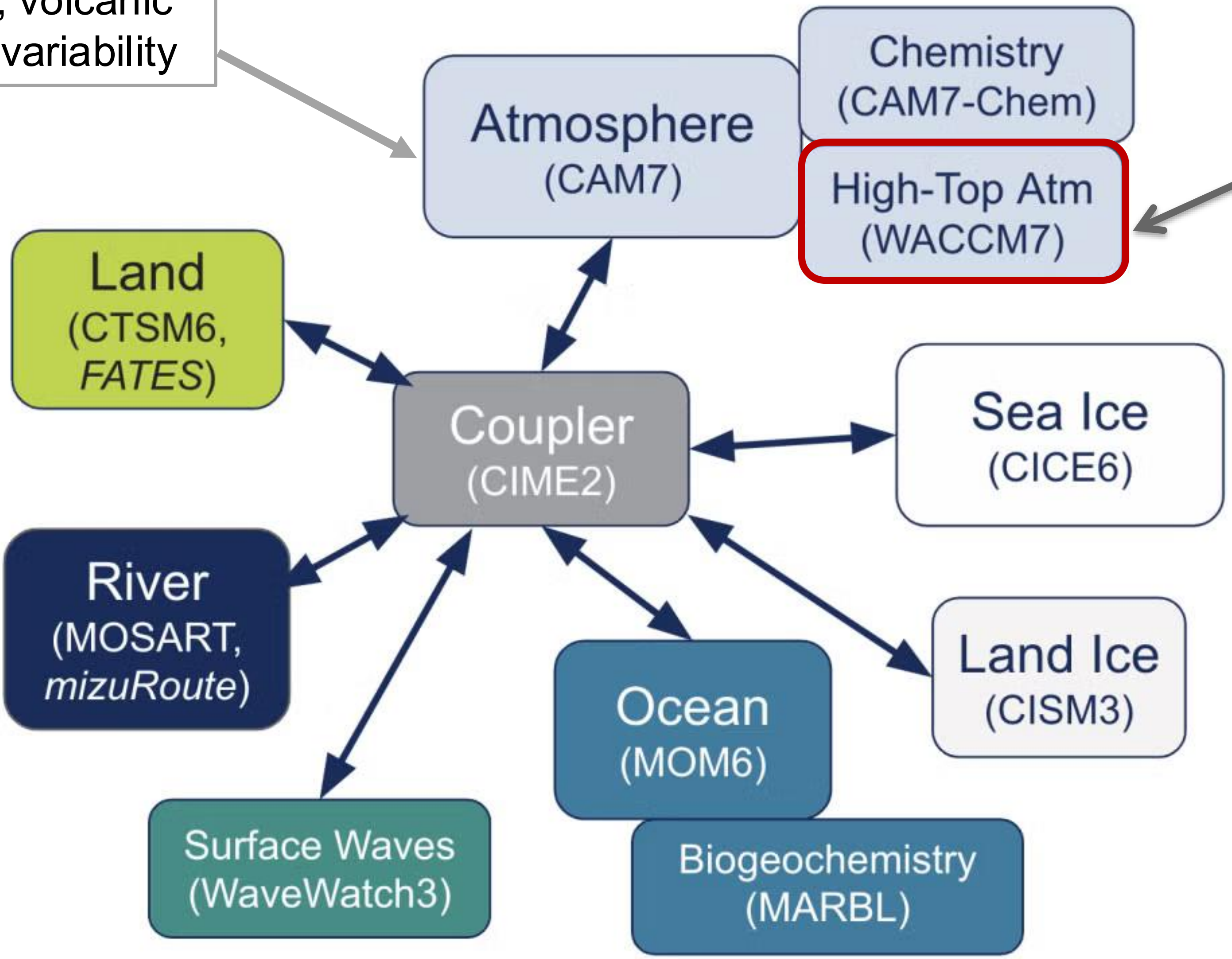
140 km

CAM

42 km

How WACCM fits into CESM

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



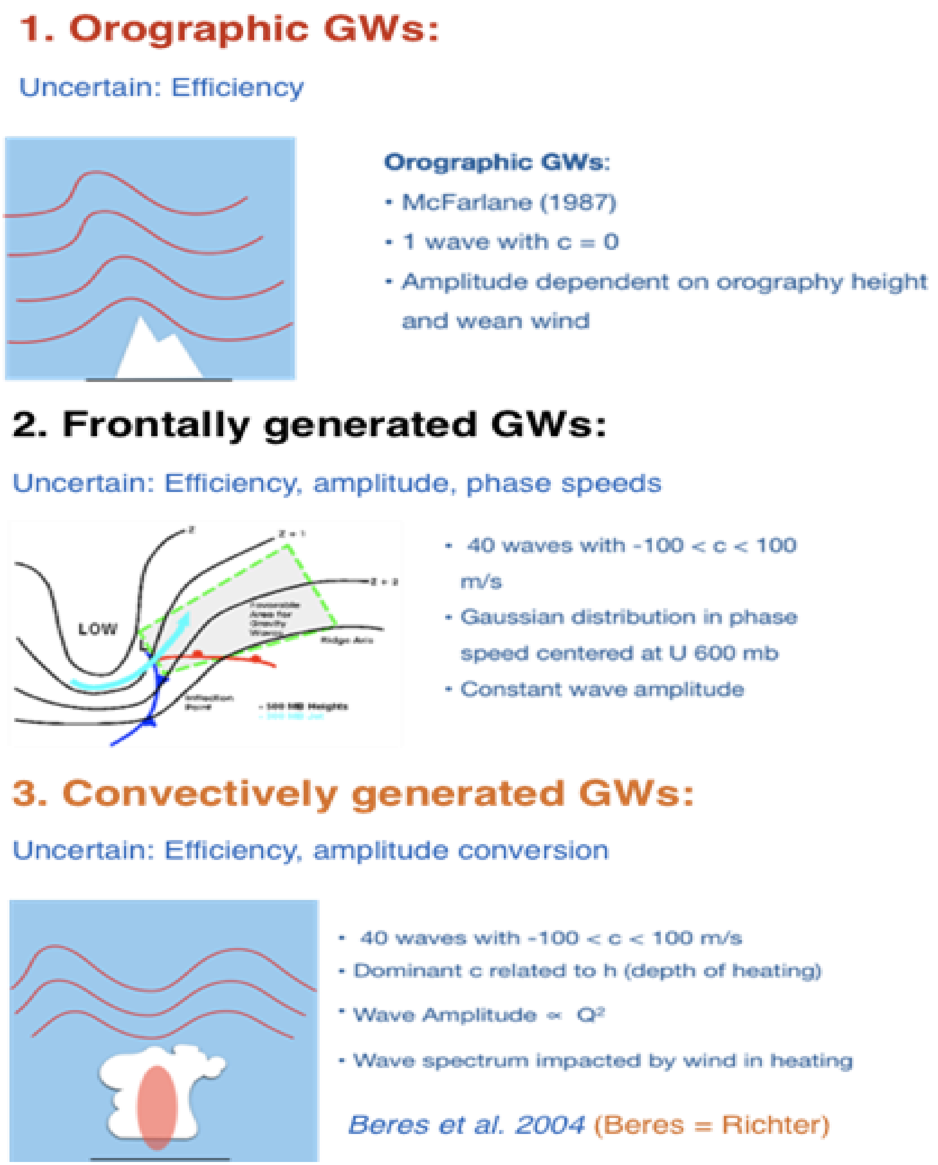
WACCM7
WACCM7-X

CESM3 component models

https://www.cesm.ucar.edu

Gravity wave physics

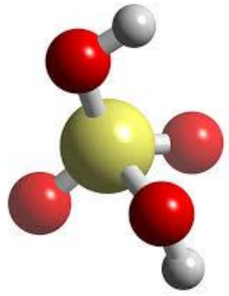
- Three primary gravity wave schemes
  - **Orographic**: primarily affecting the stratospheric polar vortex
  - **Frontal**: primarily affecting the polar vortex and mesopause region
  - **Convective**: driving the QBO, impacting the mesopause region
- Schemes apply theoretical frameworks to trigger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



WACCM *vs.* CAM

WACCM inherits the dycore and physics of CAM, and adds:

- Extension from surface to $6x10^{-6}$ 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

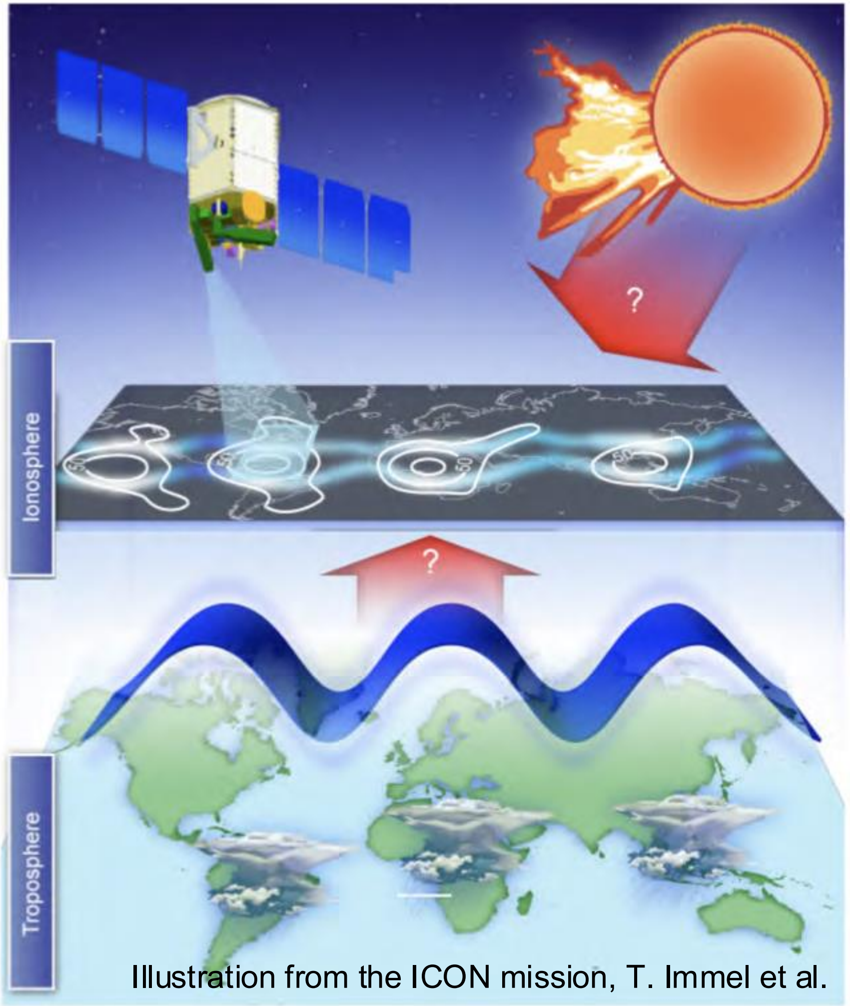


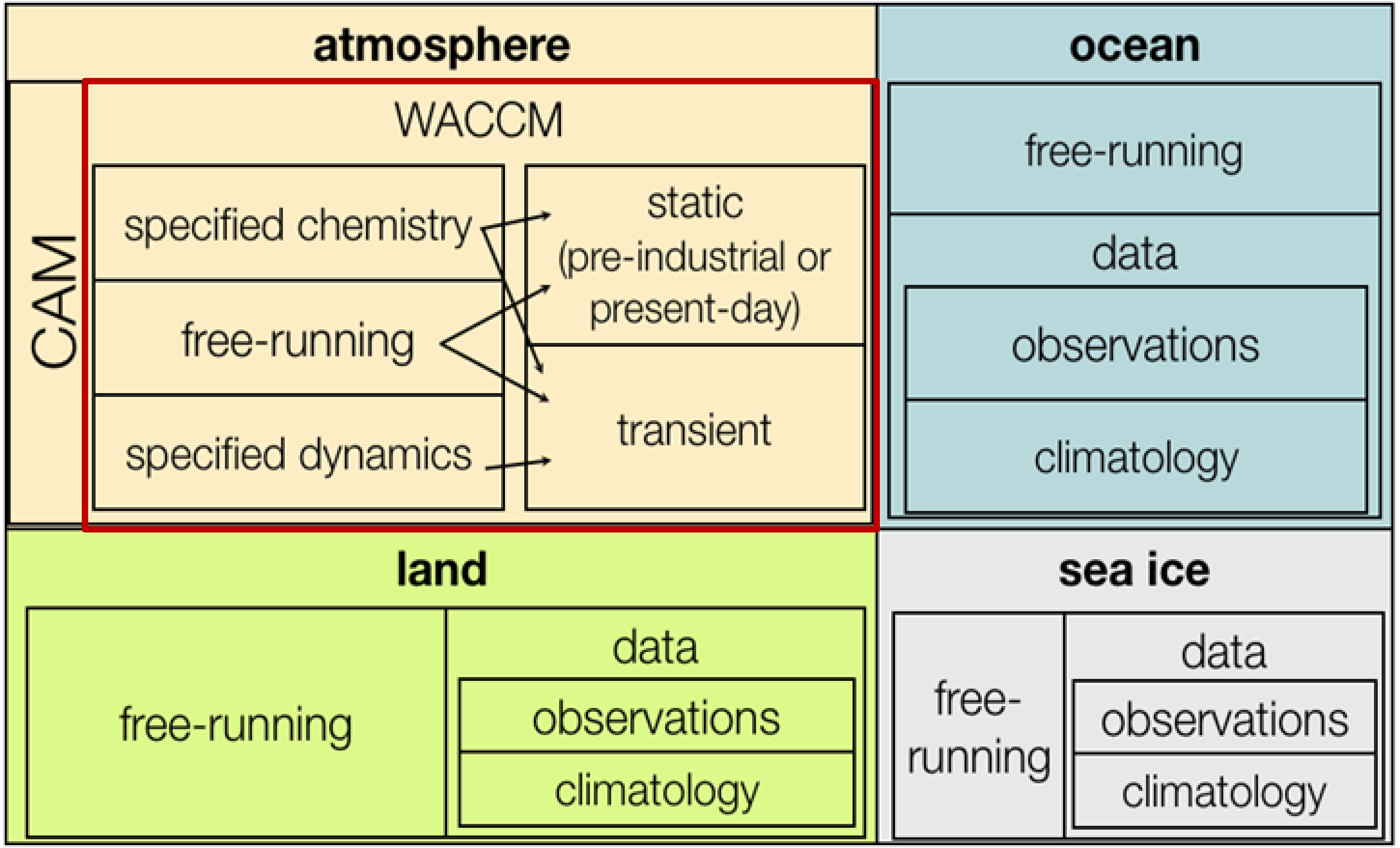
Illustration from the ICON mission, T. Immel et al.

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

WACCM *vs.* 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

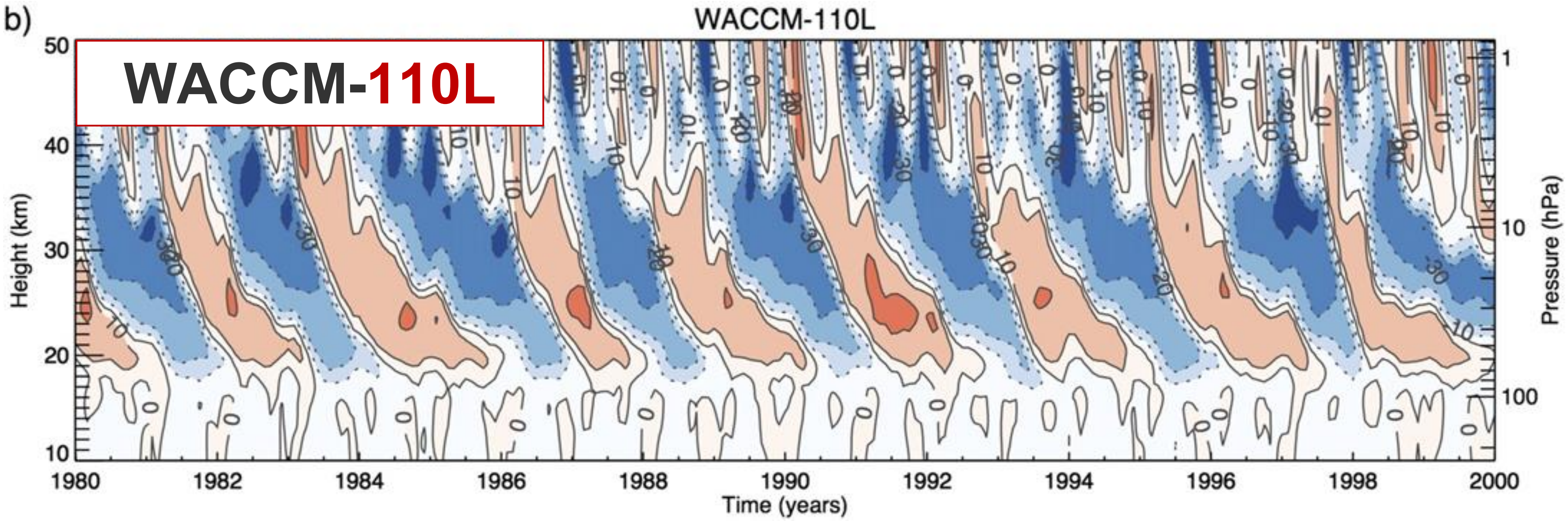
Scientifically supported WACCM-X compsets

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

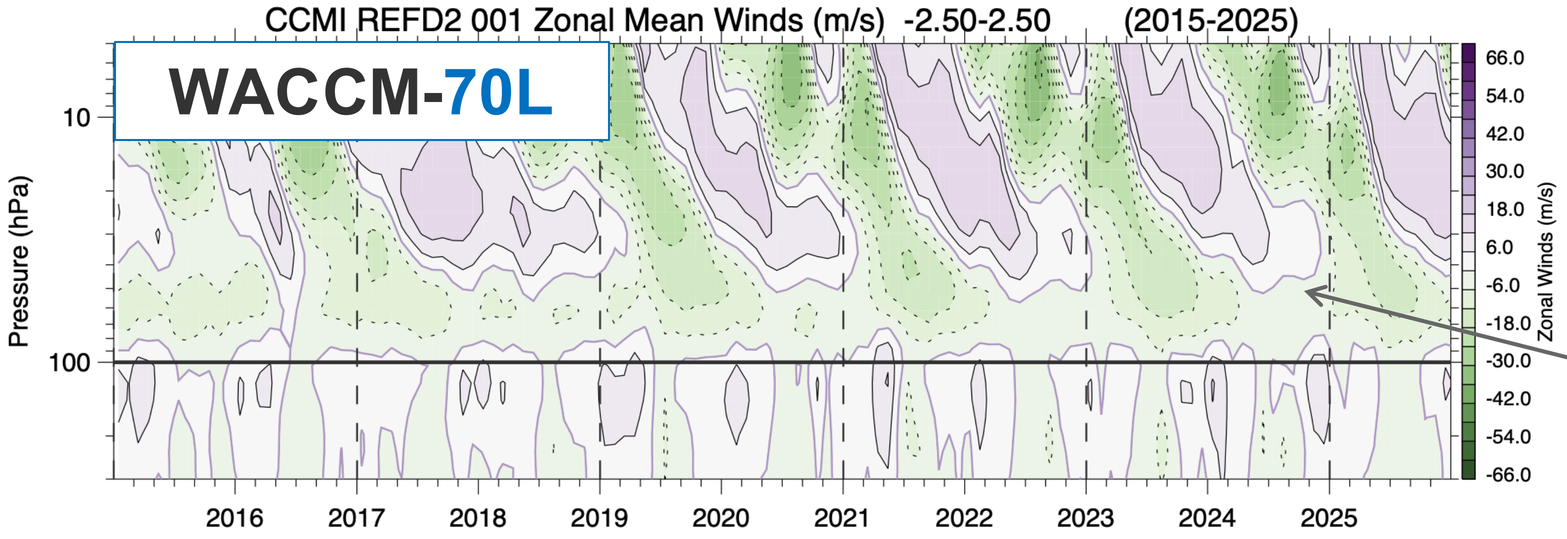
https://ncar.github.io/CAM

Stratospheric Quasi-Biennial Oscillation (QBO)



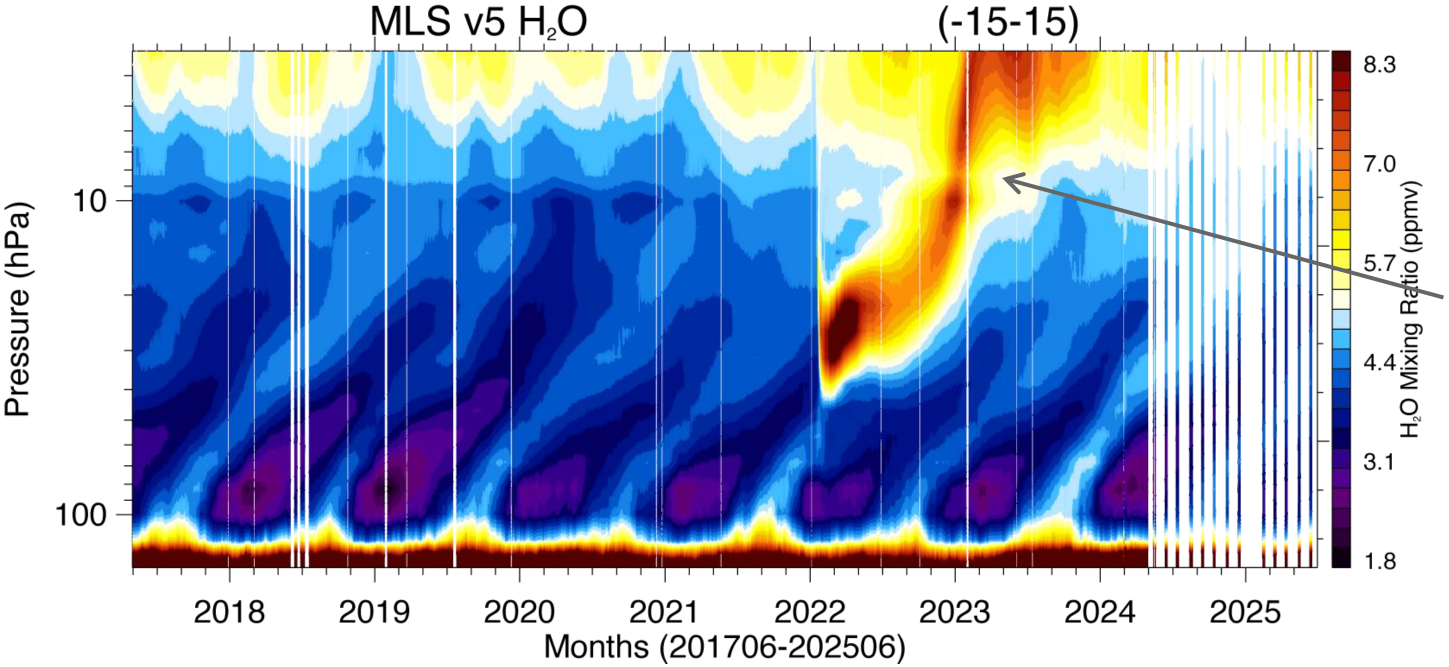
Successful simulation of the QBO

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

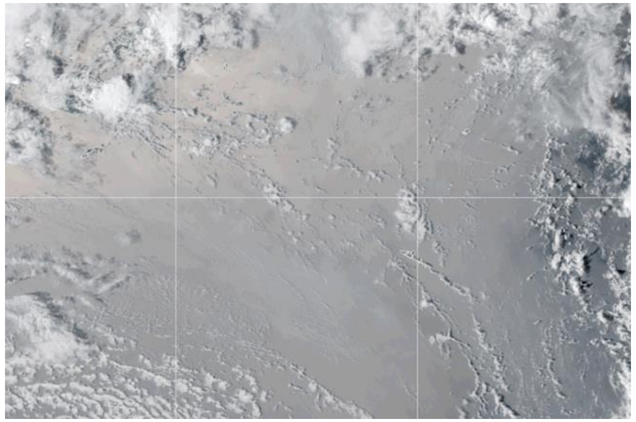


The QBO westerly does not come down to lower altitudes.

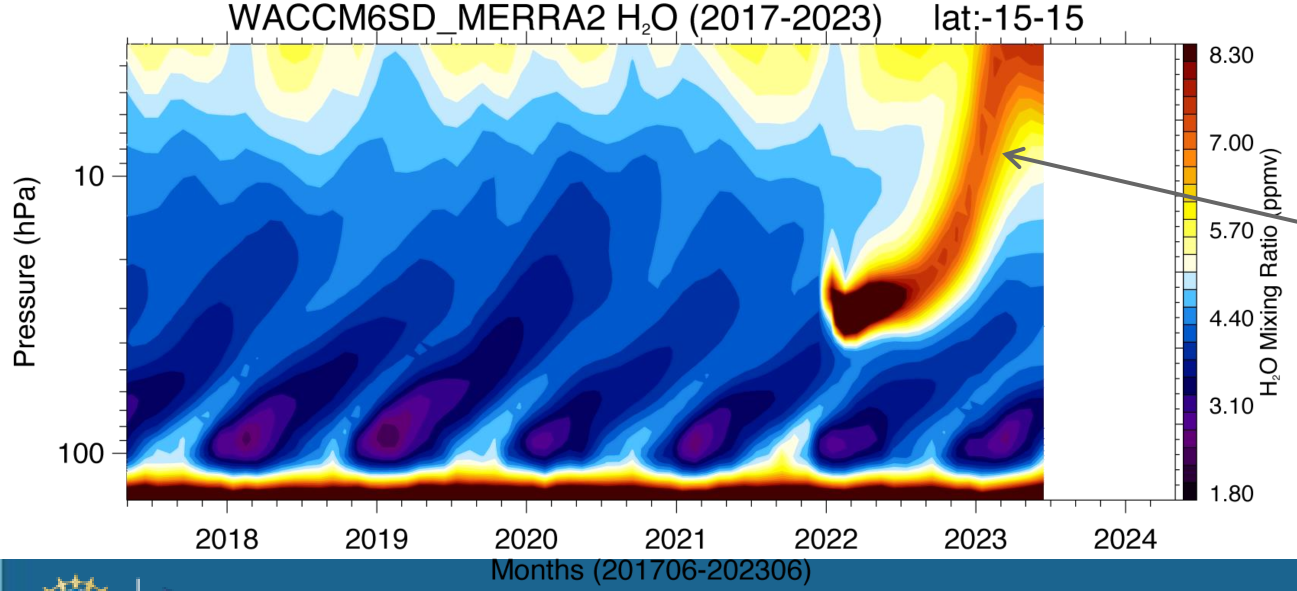
Stratospheric Water Vapor – Hunga Tonga Eruption



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 H_2O increase due to the Hunga Tonga volcanic eruption.

Credit: WACCM simulations (Jun Zhang)

Eos

SUPPORT *EOS*

How Sudden Stratospheric Warming Affects the Whole Atmosphere

Pedatella et al. (2018)

High above Earth's surface, air temperatu[…] and telecommunications.

By **N. M. Pedatella, J. L. Chau, H. Schmidt, L. P. Goncharenko**

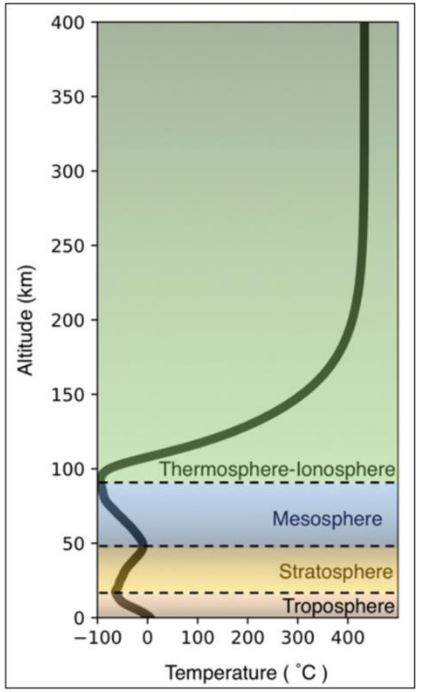


Fig. 2. Vertical profile of atmospheric temperature indicating the different layers of the atmosphere.

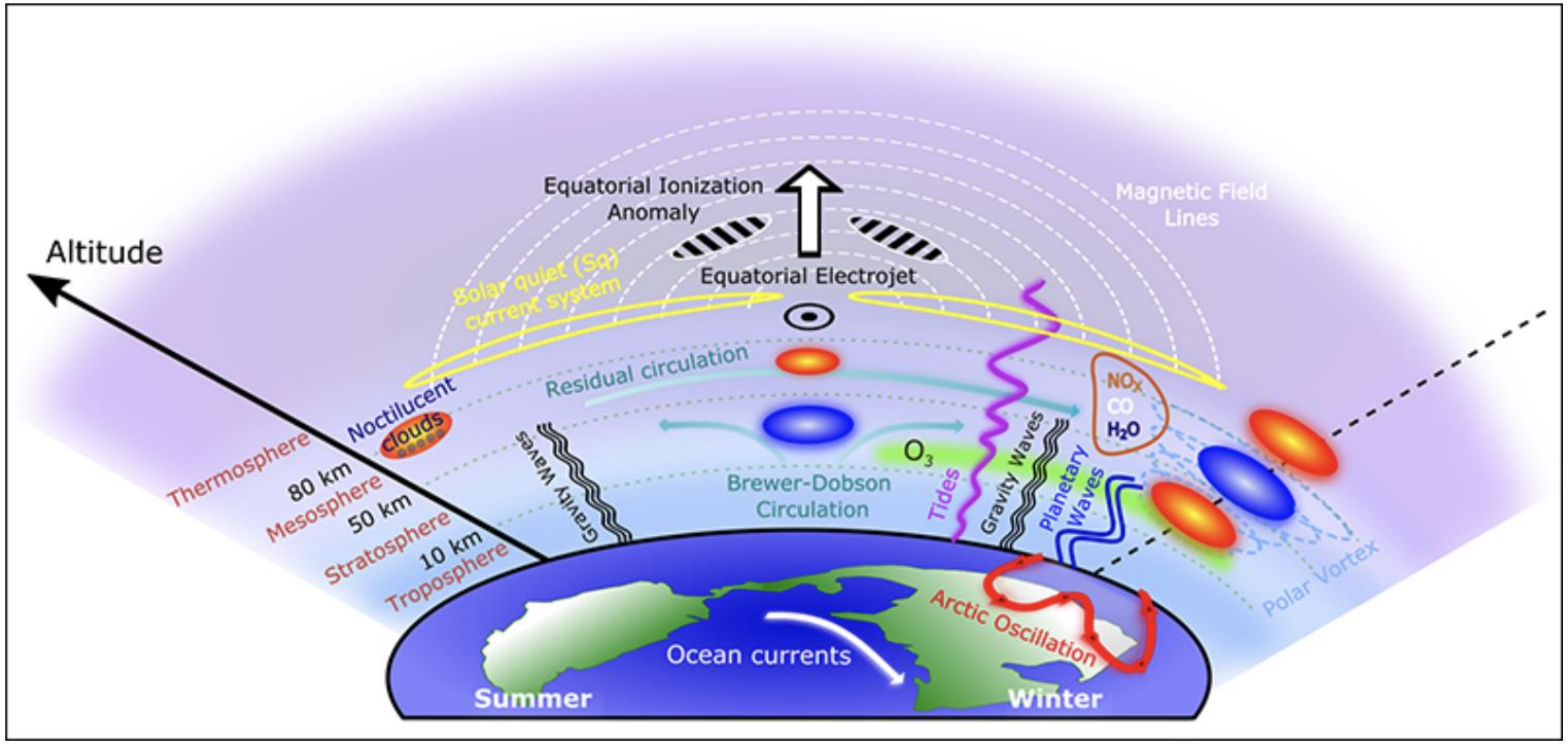


Fig. 1. Schematic of the coupling processes and atmospheric variability that occur during sudden stratospheric warming events. Red and blue circles denote regions of warming and cooling, respectively.

Pedatella, N. M., et al. (2018), How sudden stratospheric warming affects the whole atmosphere, *Eos*, *99*, https://doi.org/10.1029/2018EO092441

JGR Atmospheres

RESEARCH ARTICLE

10.1029/2024JD042412

Recent Lower Stratospheric Ozone Trends in CCMI-2022 Models: Role of Natural Variability and Transport

Samuel Benito-Barca[1,2], Marta Abalos[1], Natalia Calvo[1], Hella Garny[3], Thomas Birner[4], Nathan Luke Abraham[5,6], Hideharu Akiyoshi[7], Fraser Dennison[8,9], Patrick Jöckel[3], Bèatrice Josse[10], James Keeble[11], Doug Kinnison[12], Marion Marchand[13], Olaf Morgenstern[14,15,16], David Plummer[17], Eugene Rozanov[18], Sarah Strode[19,20], Timofei Sukhodolov[18], Shingo Watanabe[21], and Yousuke Yamashita[7]

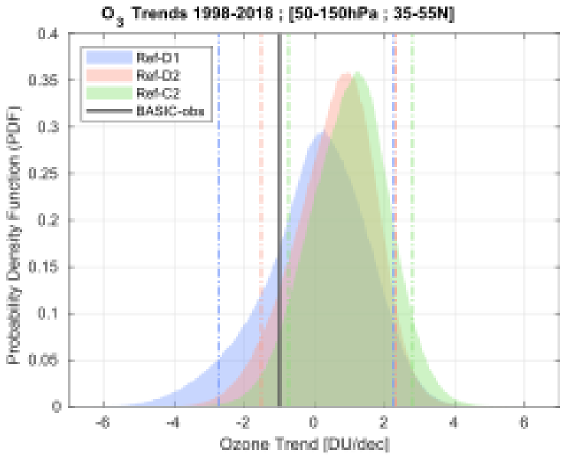
Key Points:

- Chemistry-climate models with observed sea surface temperatures can capture the recent decline in mid-latitude lower stratospheric ozone
- Trends over 1998–2018 are due to internal variability and not a linear response to the main climate variability modes or external forcings
- Large intermodel differences are due to different representations of ozone transport processes and their internal variability

Abstract Lower stratospheric ozone between 60°S and 60°N has continued to decline since 1998, despite the reduction of ozone-depleting substances following the Montreal Protocol. Previous studies have shown that, while chemistry-climate models reproduce the negative ozone trend in the tropical lower stratosphere as a response to increased upwelling, they fail to capture the ozone decline in northern midlatitudes. This study revisits recent lower stratospheric ozone trends over the period 1998–2018 using two types of simulations from the new Chemistry Climate Model Initiative 2022 (CCMI-2022): REF-D1, with observed sea surface temperatures, and REF-D2, with simulated ocean. The observed negative trend in midlatitudes falls within the range of model trends, especially when considering simulations with observed boundary conditions. There is a large spread in the simulated midlatitudes ozone trends, with some simulations showing positive and others negative trends. A multiple linear regression analysis shows that the spread in the trends is not explained by the different linear response to external forcings (solar cycle, global warming, and ozone-depleting substances) or to the main variability modes (El Niño-Southern Oscillation and the quasi-biennial oscillation) but is instead attributed to internal atmospheric variability. Moreover, the fact that some models show very different trends across members, while other models show similar trends in all members, suggests fundamental differences in the representation of the internal variability of ozone transport across models. Indeed, we report substantial intermodel differences in the ozone-transport connection on interannual timescales and we find that ozone trends are closely coupled to transport trends.

Citation:

Benito-Barca, S., Abalos, M., Calvo, N., Garny, H., Birner, T., Abraham, N. L., et al. (2025). Recent lower stratospheric ozone trends in CCMI-2022 models: Role of natural variability and transport. *Journal of Geophysical Research: Atmospheres*, *130*, e2024JD042412. https://doi.org/10.1029/2024JD042412



Benito-Barca et al. (2025)

JGR Atmospheres

RESEARCH ARTICLE

10.1029/2024JD041780

On the Timescales of the Response of the Brewer-Dobson Circulation to an Abrupt Quadrupling of CO_2

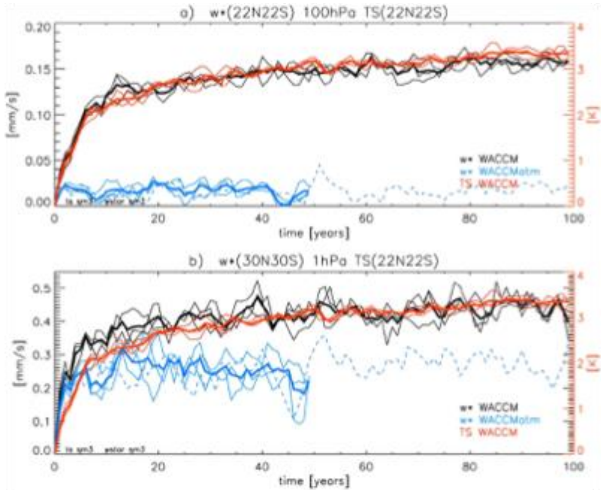
N. Calvo[1*], R. R. Garcia[2], G. Chiodo[3,4], D. R. Marsh[5], and L. M. Polvani[6,7,8]

*Affiliate Scientist at Atmospheric Chemistry, Observations, and Modeling Lab, National Center for Atmospheric Research, Boulder, CO, USA.

Key Points:

- Most of the response of tropical upwelling to an abrupt quadrupling of CO2 occurs on fast timescales (first 2-3 decades after the forcing)
- The tropical upwelling fast response in the shallow branch is driven mainly by changes in the SSTs from the well mixed shallow ocean
- In the deep branch, at 1 hPa, 70% of the fast response in tropical upwelling is due to radiative cooling and 30% to warmer SSTs

Abstract Changes in the Brewer-Dobson circulation (BDC) in response to increasing CO_2 concentrations can arise from the direct effect of radiative cooling in the stratosphere or the indirect effects induced by warmer sea surface temperatures (SSTs). This study aims to disentangle these two contributions in the Whole Atmosphere Community Climate Model (WACCM) by analyzing the timescales of the tropical upwelling response to an abrupt quadrupling of CO_2. Transient atmosphere-ocean climate model simulations of 100 years under $4xCO_2$ conditions are compared to preindustrial control simulations and to simulations with an atmosphere-only version of WACCM that uses preindustrial SSTs. We find that most of the response in both shallow and deep branches of the BDC occurs on fast timescales (first 2-3 decades). In the shallow branch of the BDC, the response is mainly driven by changes in SSTs in the well-mixed shallow ocean, which cause tropospheric warming and an intensification and upward displacement of the subtropical jets, and alter wave forcing in their vicinity. The contribution from stratospheric radiative cooling is almost negligible. In the upper stratosphere, the response of tropical upwelling begins earlier and develops faster than in the shallow branch, owing to the larger contribution from the rapid adjustments. At 1 hPa, 70% of the fast response relates to stratospheric radiative cooling and 30% to warmer SSTs. The modulation of the filtering of non-orographic gravity waves (mainly of frontal origin) in the subtropics explain most of the response in tropical upwelling in the deep branch, on both fast and slow timescales.



Citation:

Calvo, N., Garcia, R. R., Chiodo, G., Marsh, D. R., & Polvani, L. M. (2025). On the timescales of the response of the Brewer-Dobson circulation to an abrupt quadrupling of CO_2. *Journal of Geophysical Research: Atmospheres, 130*, e2024JD041780. https://doi.org/10.1029/2024JD041780

Calvo et al. (2025)

JGR Space Physics

RESEARCH ARTICLE

10.1029/2024JA032855

Key Points:

- The impact of migrating tides on the seasonal variations in the ionosphere and thermosphere is investigated using a whole atmosphere model
- Migrating diurnal and semidiurnal tides reduce the amplitude of the annual variation in thermosphere composition at middle to high latitudes
- Migrating diurnal and semidiurnal tides also reduce the semiannual variation in low latitude total electron content

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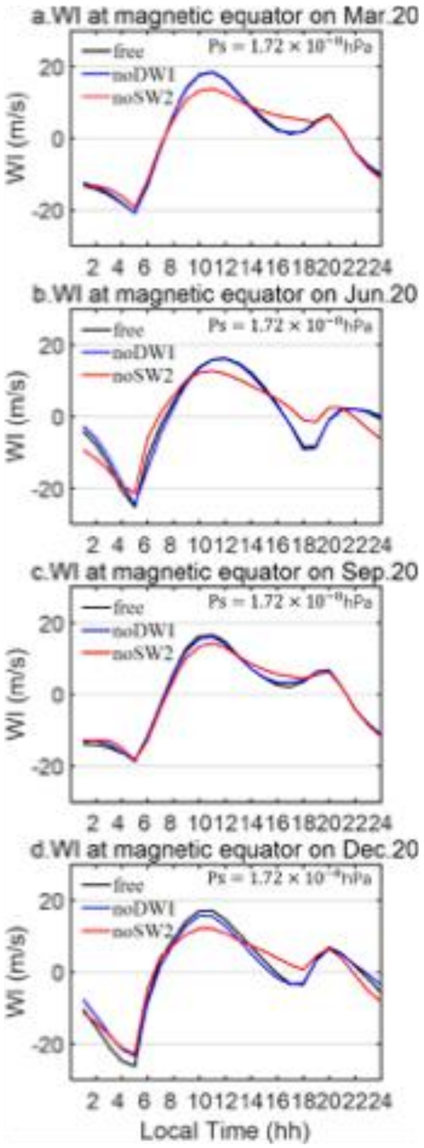
Citation:

Pedatella, N. M., Wu, K., Qian, L., & Gan, Q. (2024). Impact of upward propagating migrating diurnal and semidiurnal tides on the ionosphere-thermosphere seasonal variation. *Journal of Geophysical Research: Space Physics, 129*, e2024JA032855. https://doi.org/10.1029/2024JA032855

Impact of Upward Propagating Migrating Diurnal and Semidiurnal Tides on the Ionosphere-Thermosphere Seasonal Variation

N. M. Pedatella[1,2], K. Wu[1], L. Qian[1], and Q. Gan[3]

Abstract The Whole Atmosphere Community Climate Model with thermosphere-ionosphere eXtension (WACCM-X) is used to investigate the impact of the upward propagating migrating diurnal (DW1) and semidiurnal (SW2) tides on the seasonal variability in the ionosphere and thermosphere. In the lower thermosphere, the tides induce a westward acceleration that obtains maximum values of 10–20 ms^{-1} around solstice. The tidal dissipation also changes the meridional circulation and leads to a ~5 K cooling of the lower thermosphere. These changes result in a decrease in atomic oxygen in the lower thermosphere that maximizes during local winter. In the lower thermosphere, the DW1 has a greater impact around December solstice, while the SW2 has a greater impact around June solstice. The DW1 and SW2 induced changes in the lower thermosphere composition lead to changes in the thermosphere column integrated atomic oxygen to molecular nitrogen ratio (O/N_2). This leads to a reduction in the thermosphere annual variation at middle to high latitudes. The DW1 and SW2 also reduce the thermosphere neutral mass density. In the ionosphere, the DW1 and SW2 decrease the zonal and diurnal mean total electron content by ~20% globally, which is primarily attributed to the reduction in thermosphere O/N_2. The SW2 is found to have a greater influence on the low latitude ionosphere compared to the DW1 due to the SW2 having a greater impact on the equatorial electrodynamics. The results demonstrate that the upward propagating DW1 and SW2 both have significant effects on the ionosphere and thermosphere, including influencing the seasonal variability.



Pedatella et al. (2024)

Geophysical Research Letters

RESEARCH LETTER

10.1029/2024GL114265

Special Collection:
Chemistry and Climate Impacts of the Asian Summer Monsoon

Sources and Regional Attributions to Upper Troposphere Nitrogen Oxides During the Asian Summer Monsoon 2022

Jun Zhang[1], Douglas Kinnison[1], Louisa Emmons[1], Shawn Honomichl[1], Warren P. Smith[1], Simone Tilmes[1], Xinyue Wang[2], Alessandro Franchin[1], Frank Flocke[1], and Laura L. Pan[1]

Key Points:

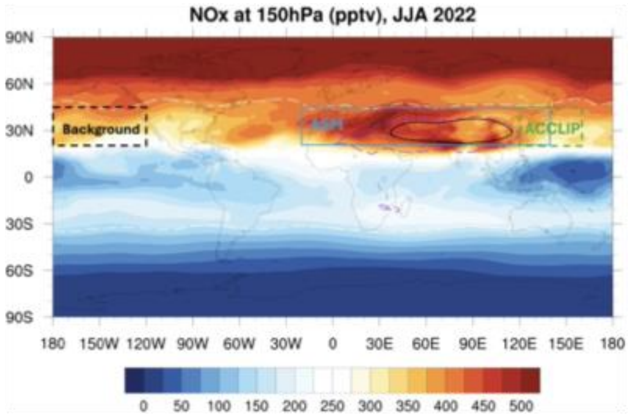
- A chemistry-climate model with a nitrogen oxides (NOx) tagging mechanism is used to examine upper troposphere/upper tropospheric (UT) NO_x origins
- Both South Asia and East Asia (EA) sources are significant UT NO_x contributors within the Asian Summer Monsoon (ASM) anticyclone
- For the observed NO_x during the 2022 Asian Summer Monsoon Chemical and Climate Impact Project campaign, EA contributions are prominent and especially from anthropogenic sources

Citation:

Zhang, J., Kinnison, D., Emmons, L., Honomichl, S., Smith, W. P., Tilmes, S., et al. (2025). Sources and regional attributions to upper troposphere nitrogen oxides during the Asian Summer Monsoon 2022. *Geophysical Research Letters*, *52*, e2024GL114265. https://doi.org/10.1029/2024GL114265

Abstract This study investigates the sources and regional attributions of nitrogen oxides (NO_x) in the upper troposphere/upper tropospheric (UT) during the Asian Summer Monsoon (ASM). The importance of South Asia (SA) and East Asia (EA) contributions is the subject of main interest. Using artificial tracers in a chemistry-climate model, simulations with tracers from surface anthropogenic and lightning sources in SA and EA are conducted. Model results are validated with airborne observations from the Asian Summer Monsoon Chemical and Climate Impact Project (ACCLIP) campaign in 2022 over the West Pacific. Good agreement between modeled and observed NO_x is found in the UT. The results indicate that within the ASM anticyclone, both SA and EA sources significantly contribute to the UT NOx, with contributions of 41% and 36%, respectively. While in the ACCLIP region during 2022, EA sources play a more important role, accounting for 50% compared to 19% from SA sources.

Plain Language Summary Nitrogen oxides (NO_x) in the upper troposphere (UT) are involved in various processes that are important for the greenhouse gas budget, with both cooling and warming effects. NO_x is also a significant component that produces ozone through chemical smog processes. The ASM is associated with an enhancement of NO_x in the UT, as it is an efficient pathway to transport the surface NO_x emission upward along with strong lightning NO_x production from deep convection. However, the specific contributions from various sources and regions to UT NO_x remain unclear. Our study employs model simulations to elucidate the origins of NO_x, particularly within the ASM and its eastward shedding region. We find that within the ASM anticyclone, both South Asia and East Asia sources are significant contributors to the UT NO_x, with 47% from anthropogenic and 30% from lightning sources, respectively. In the Asian Summer Monsoon Chemical and Climate Impact Project region, EA sources become prominent, accounting for 50% of the contribution, with anthropogenic sources outweighing lightning by approximately 30% in UT NO_x contribution.



Zhang et al. (2024)

Recent Work using WACCM

JGR Space Physics

RESEARCH ARTICLE
10.1029/2024JA032562

Impact of Arctic and Antarctic Sudden Stratospheric Warmings on Thermospheric Composition

Jiarong Zhang[1,2], Jens Oberheide[1], Nicholas M. Pedatella[3], and Guiping Liu[4]

Key Points:

- ~10% $\sum O/N_2$ depletion at low to mid latitudes is observed by GOLD and GUVI, as well as simulated in WACCM-X during the Arctic SSWs
- The variations of $\sum O/N_2$ during the 2019 Antarctic SSW are less pronounced, likely due to the event being a minor warming
- $\sum O/N_2$ variations during SSWs are driven by the reversals of MMC in the lower thermosphere, induced by westward-traveling planetary waves

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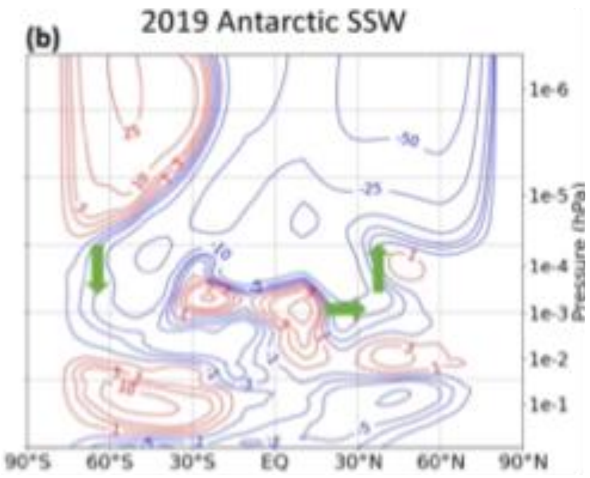
Citation:
Zhang, J., Oberheide, J., Pedatella, N. M., & Liu, G. (2025). Impact of Arctic and Antarctic sudden stratospheric warmings on thermospheric composition. *Journal of Geophysical Research: Space Physics*, *130*, e2024JA032562. https://doi.org/10.1029/2024JA032562

Abstract Using the Global-scale Observations of the Limb and Disk (GOLD) and the Global Ultraviolet Imager (GUVI), we examine the impact of sudden stratospheric warmings (SSWs) on the changes of thermospheric composition during the 2018–2019 and 2020–2021 Arctic SSWs and the 2019 Antarctic SSW. Contributions of planetary waves, gravity waves, and migrating tides are assessed by performing numerical experiments with the NSF National Center for Atmospheric Research (NCAR) vertically extended version of the Whole Atmosphere Community Climate Model (WACCM-X). The variations in the column integrated O and N_2 density ratio ($\sum O/N_2$) are generally similar among WACCM-X, GOLD, and GUVI observations though some differences exist. Following the onset of the Arctic SSWs, $\sum O/N_2$ is reduced by ~10% at low to mid latitudes. The variations during the 2019 Antarctic SSW are less pronounced, likely due to the event being a minor warming. WACCM-X simulations, with the Kp index and F10.7 cm solar flux kept at fixed low levels, confirm that the variability of $\sum O/N_2$ at low to mid latitudes is primarily induced by SSWs. The $\sum O/N_2$ changes are associated with the reversals of the mean meridional circulation (MMC) in the lower thermosphere, mainly driven by westward-traveling planetary waves. The results highlight that planetary wave activity during SSWs can significantly impact the mean state of the thermosphere.



Zhang et al. (2025)

What do you want to do?

- WACCM is one of the most advanced configurations of CESM, because it resolves
  - a greater vertical extent of the atmosphere (~140 km)
  - comprehensive chemistry and aerosols
  - middle and upper atmosphere dynamics and 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

Noctilucent clouds over Finland. *Jarvis, 2001*

QUESTIONS?

mijeong@ucar.edu (WACCM Liaison)
DiscussCESM (https://bb.cgd.ucar.edu/)