CLIMATE 589: The Art of Climate Modeling (Winter 2024)

Course number:	CLIMATE 589
Title:	The Art of Climate Modeling
Credit hours:	4
Meeting time:	Winter 2024 (starting on January/10/2024) MoWeFr 3:30-5:20pm (sometimes 4:50pm) in 1012 EECS (class typically meets twice a week, sometimes 3 times per week to make up some lost time (travel, some shorter Wed lectures)
Instructor:	Prof. Christiane Jablonowski (cjablono@umich.edu), University of Michigan, Department of Climate and Space Sciences and Engineering

Short catalogue description:
The course introduces the newest climate modeling techniques by surveying the design decisions in atmospheric General Circulation Models (GCMs), the trends in GCM and dynamical core modeling, and how GCMs are coupled. It is built upon hands-on GCM modeling and data projects, journal paper discussions, lectures, shared cyberinfrastructure and computational tools.

Long description:
1) Synopsis:
The course trains graduate students in the newest climate modeling techniques. It surveys the many design decisions in atmospheric General Circulation Models (GCMs), the trends in GCM and dynamical core modeling and how GCMs are coupled to land, ocean and ice components in Earth System Models (ESM). Furthermore, next-generation ESMs will require greater computing capabilities, transparent software designs with exchangeable model components, self-explanatory (metadata) descriptions of data and models, online gateways and portals for data exchanges, cloud computing capabilities, and shared online workspaces for science collaborations. The course will review and utilize a variety of climate and weather model (like the Community Earth System Model (CESM) or the Model for Prediction Across Scales (MPAS) developed by the National Center for Atmospheric Research (NCAR), the Department of Energy (DoE) Energy Exascale Earth System Model (E3SM), or NOAA's Unified Forecast System (UFS)) and survey computational tools. The students will learn how to work effectively with modern software infrastructure and high-performance computing systems (like NCAR's Derecho system) for the climate and weather sciences.

2) Overarching goals of the course:
After the completion of this course a GCM will no longer be a black box. The students will be enabled to make informed decisions on how to use GCMs in their research and what the limitations of GCMs are. The students will be exposed to real world GCMs, and software practices in atmospheric science, and will have an understanding of the GCM design literature and model documentations.

3) Scientific focus of the course

The main science focus of the course addresses the so-called dynamical cores of GCMs that describe the fluid dynamics component of weather and climate models. The design decisions for building dynamical cores of GCMs incorporate the choice of the equation set, numerical methods, computational grids, grid staggering options, accuracy, conservation properties, diffusion mechanisms and computational efficiency. The course will review the broad range of choices and provide an in-depth look at their pros and cons. In addition, the design decisions for building Earth System Models incorporate much more, such as the coupling strategy between the dynamical core and the subgrid-scale physical parameterizations. The course will review the design of selected physical parameterizations, as well as the coupling strategy to other components of the climate system such as the land, ocean and ice. The course will also discuss computational aspects such as the use of parallel hardware architectures.

Climate models and their individual components are typically compared to other models in international model intercomparsion projects and observations to assess their performance. The latter aspects demand the efficient use of computational tools and shared online workspaces. The course will review and utilize a selection of cyberinfrastructure tools.

4) Class format

This hands-on project-driven class is based on lectures, in-class journal paper discussions, GCM modeling projects, model data analyses, and the exploration of software tools in the climate modeling community. No exams are given. Grades are determined based on the GCM modeling projects and journal paper discussions.

Some of the modeling projects are 'homework-like', e.g. shorter projects or paper reviews that will take 1-2 weeks to finish. In addition, the students will be asked to pick a more comprehensive modeling project as a term project. The latter should ideally be relevant to both the course and the student's research area (if applicable). There will also be a list of suggested class projects.

The students will mostly utilize the most recent version of the Community Earth System Model (CESM2.X) developed at the National Center for Atmospheric Research (NCAR). In particular, the class will download the most recent development version of CESM's Community Atmosphere Model for most hands-on projects. Other models are also an option such as the Department of Energy's Energy Exascale Earth System Model (E3SM) or the Model for Predictions Across Scales (MPAS) as a stand-alone configuration. The class will get access to NCAR's high-performance computing platform (Cheyenne and Casper) and the data portal 'Earth System Grid Federation'.

Some class projects have common themes, such as the intercomparison of the dynamical cores in CAM or the design/modification of test cases for dynamical cores. The class will utilize a shared Wiki-driven online workspace to share and discuss results and create a collaborative spirit.

5) Grading policy

The course grade is based on 7 building blocks:

a) 12%: Modeling project 1 (due in week 3)
b) 12%: Modeling project 2 (due in week 5)
c) 12%: Modeling project 3 (due in week 7)
d) 12%: Modeling project 4 (due in week 9)
e) 12%: Modeling project 5 (due in week 11)
f) 10%: Journal paper discussions
g) 30%: Term project: individual modeling project with presentation

6) Student preparation (recommended prerequisites): Graduate standing or approved by instructor.
The enrolled student should have a basic understanding of

- atmospheric dynamics and the general circulation of the atmosphere
- Unix computing environment
- at least one higher-level programming language (like C/C++ or Fortran (preferred))
- numerical methods
- visualization techniques

There is no strict enforcement of these prerequisites, but knowledge of these areas will be helpful. The course will cover the principles of atmospheric dynamics and numerical methods to a certain degree, but with a strong focus on the practical model design decision in atmospheric General Circulation Models.

7) Expected learning outcomes:

After taking this course the students understand the general characteristics of climate and weather models (the big picture), and will be able to describe and judge the design choices for the dynamical cores of GCMs. In addition, the students will know how to configure, modify, run, and analyze climate and weather models on high-performance computing platforms with a particular focus on NCAR's climate model CESM.

General characteristics: Big Picture

- Know the history of weather and climate modeling
- Be able to explain the general characteristics and components of an atmospheric General Circulation Model (GCM), the differences between weather and climate (Earth-system) models, and the components of the climate system
- Be able to describe atmospheric model hierarchies, how models are tested and assessed, and judge their strengths and weaknesses
- Be able to review the components of a physical parameterization suite for a GCM and the general design principles behind parameterizations. Physics-dynamics coupling and time step considerations
- Be able to explain how and why climate models are tuned
- Be able to describe how a GCM is coupled to other components of the climate system like ocean, ice and land models (time steps, grids, coupling frequency, exchange processes)
- Understand the concepts behind predictability, uncertainty quantification, ensemble simulations, and ensemble spread

- Be able to use computational, data analysis, and visualization tools to extract scientific information
- Know how to locate existing climate and reanalysis data
- Be able to configure, modify, run, and analyze climate and weather models
- Understand how model intercomparisons are conducted

Design choices for the dynamical cores of GCMs
Be able to describe and judge the pros-and-cons of

- the differences between hydrostatic/nonhydrostatic and shallow-atmosphere/deep-atmosphere equation sets, and the selection criteria for the dry equation sets
- the advective and flux-form of the transport (advection) equation and desirable physical properties of numerical schemes for advection: monotonicity and positive-definiteness
- various horizontal grids such as latitude-longitude, cubed-sphere, icosahedral, hexagonal, variable-resolution grids
- horizontal grid staggering options like the Arakawa A, B, C, D, E grids, and the Z grid
- the choice of the vertical coordinate in GCMs: height-based, pressure-based, potential-temperature-based, or hybrid coordinates. Incorporation of orography.
- vertical grid staggering options like the Lorenz and Charney-Philips grid
- general characteristics of numerical schemes for the spatial discretization: spectral transform, finite element, finite volume and finite difference schemes
- general characteristics of numerical schemes for the temporal discretization: implicit versus explicit, semi-Lagrangian, one-step methods, multi-step methods
- accuracy and stability of numerical methods: what does accuracy and stability mean physically, how can these be determined for finite-difference-based discretizations, explain the CFL condition
- typical diffusion mechanisms in GCMs: explicit versus implicit diffusion, specific diffusion examples such as 2^{nd}-order versus high-order diffusion, monotonicity constraints, divergence damping, spatial and time filters. Why is diffusion needed and what are the effects of diffusion on kinetic energy spectra?
- Inclusion of moisture in dynamical cores

Class Wiki page:

https://sites.google.com/umich.edu/climate589wn24

8) Schedule (Winter 2024)

Week 1

1.) Wednesday 1/10 3:30-4:50pm
Overview and logistics of the course: Fluid flow in the atmosphere and oceans, basic characteristics. What is a General Circulation Model (GCM), weather model, climate model? Example predictions/projections. Components of the climate system.

To-do list: install X-terminal application on your laptop, watch Unix training, set up the NCAR account on Derecho, review Unix commands.

2.) Friday 1/12 3:30-5:20pm
Complexity of weather and climate models, importance of model intercomparisons. History of weather and climate modeling. Application areas for climate and weather models (paleo, decadal/centuries, S2S, medium-range weather, limited-area short-range weather & nowcasting). Model initialization. Overview of the Google Site class page (Wiki).
Journal paper 1 out: Complexity of Climate Models (including a brief review of the history)

Week 2

3.) Wednesday 1/17 3:30-5:20pm
Hands-on introduction to CESM, netcdf data formats, visualization aspects (ncview, ncvis, NCL, Panoply, GeoCAT/Python).
Modeling project 1 out.

4.) Friday 1/19 3:30-5:20pm
More hands-on CESM training. CESM Bulletin Board. NetCDF tools (NCO). Postprocessing steps (interpolation to pressure or height levels, anomalies, detrending, deseasonalizing, temporal and spatial averaging, weighted averages, column-integrated quantities). Pointers to existing repositories: climate model data (ESGF), reanalysis, observations. Version control (github).
Journal paper 1 discussion: Complexity of weather and climate models
Journal paper 2 out.

Week 3

5.) Monday 1/22 3:30-5:20pm
Overview of the CESM model and its 'Simpler Models' framework. CESM compsets. Ocean model hierarchy (fixed SST, slab ocean, pencil ocean, full-complexity ocean). Active model components versus data models.

6.) Wednesday 1/24 3:30-4:50pm
Strategies for evaluating dynamical cores and Earth System Models (model hierarchy). AMIP, CMIP and other MIP activities. Large Ensembles.

7.) Friday 1/26 3:30-5:20pm
Discussion of modeling project 1: Baroclinic waves
Continued discussion: Strategies for evaluating dynamical cores and Earth System Models (model hierarchy). CMIP and other MIP activities.
Modeling project 2 out.

Week 4

8.) Friday 2/2 3:30-5:20pm
Journal paper 2 discussion: Model hierarchy/CMIP
Overview of the design choices in GCMs and their dynamical cores, equation sets and prognostic variables in dynamical cores.

Week 5

9.) Monday 2/5 3:30-5:20pm
Model initializations.
Dynamical core / idealized model testing hierarchy.

10.) Wednesday 2/7 3:30-4:50pm
Computational grids and grid staggering options.

11.) Friday 2/9 3:30-5:20pm
Discussion of modeling project 2: Impact of topography and rain.
First look at the numerical make-up of the Community Atmosphere Mode (CAM).
Horizontal discretizations: Finite differences, finite volume, spectral element, spectral transform methods.
Modeling project 3 out.

Week 6

travel (no class during the week 2/12-2/16): watch 2 CESM Tutorial videos

CESM2 tutorial lectures from 2023, tutorial agenda is posted here:
https://www.cesm.ucar.edu/events/250/agenda
Watch the dynamical core lecture by Peter Lauritzen, youtube video (jump to 1h:16min)
https://www.youtube.com/watch?v=kWl7ss8XsJs&list=PLsqhY3nFckOEX41g8ZUnhGT2c--5kUZ1V&index=9
and one (or more) lectures of interest, from the 2023 CESM tutorial, available on youtube:
https://www.youtube.com/playlist?list=PLsqhY3nFckOEX41g8ZUnhGT2c--5kUZ1V

Agenda of previous CESM tutorials (with videos):
2022: https://www.cesm.ucar.edu/events/164/agenda
videos: https://www.youtube.com/playlist?list=PLsqhY3nFckOE9a6tHliDdeEKIXb78lqSk
2021: https://www.cesm.ucar.edu/events/tutorials/2021/
videos: https://www.youtube.com/playlist?list=PLsqhY3nFckOFfLVM2O7az_JgRq12W3u0q
2020: https://www.cesm.ucar.edu/events/tutorials/2020/coursework.html (with videos)
2019: https://www.cesm.ucar.edu/events/tutorials/2019/coursework.html (with videos)

Week 7

12.) Wednesday 2/21 3:30-4:50pm
Horizontal discretizations. Taylor series expansion, truncation error

13.) Friday 2/23 3:30-5:20pm
Horizontal discretizations. Treatment of advection.
Discussion of modeling project 3: Advection
Modeling project 4 out.
Journal paper 3 out.

Spring Break (2/26-3/1), no class

Week 8

14.) Monday 3/4 3:30-5:20pm
Characteristics of the advection equation (stability, accuracy, monotonicity, positive-definiteness, conservation).

15.) Wednesday 3/6 3:30-4:50pm
Aliasing, stability and kinetic energy spectra. Diffusion and filtering mechanisms in GCMs.

16.) Friday 3/8 3:30-5:20pm
Continued discussion of diffusion and filtering mechanisms in GCMs.
Journal paper 3 discussion: Dynamical Cores
Paper 4 out.

Week 9

17.) Monday 3/11 3:30-5:20pm
Lateral and upper/lower boundary conditions. Sponge layer mechanisms.

18.) Wednesday 3/13 3:30-5:20pm
Temporal discretizations: semi-Lagrangian techniques, explicit versus (semi-) implicit time stepping.

19.) Friday 3/15 3:30-5:20pm
Discussion of modeling project 4: Dissipation
Continued discussion: Temporal discretizations: semi-Lagrangian techniques, explicit versus (semi-) implicit time stepping.
Discuss ideas for term projects.
Modeling project 5 out.

Week 10

20.) Monday 3/18 3:30-5:20pm
Time steps for the equations of motion, tracer advection and physics, subcycling, coupling. Introduction to vertical discretizations, vertical resolution, and the position of the model top.

21.) Wednesday 3/20 3:30-4:50pm
Vertical discretizations and mapped coordinates, vertical staggering, inclusion of topography, smoothing of topography.

22.) Friday 3/22 3:30-5:20pm
Journal paper 4 discussion: Numerical methods/conservation.
Inclusion of moisture in dynamical cores. Introduction of a simplified physics framework and the Kessler-type warm-rain scheme.
Discuss ideas for term projects.
Journal paper 5 out.

Week 11

23.) Wednesday 3/27 3:30-5:20pm
Physics-dynamics coupling, calling sequence.
Overview of physical parameterizations and their design principles (Reynolds

averaging). Interoperable physics components: Common Community Physics Package (CCPP).

24.) Friday 3/29 3:30-5:20pm
Discussion of modeling project 5: Climate studies with intermediate-complexity model configurations.
Continued discussion of physical parameterizations (surface processes, boundary layer turbulence).
Finalize selection of term projects.

Week 12

25.) Wednesday 4/3 3:30-4:50pm
Journal paper 5 discussion: Physical parameterizations & tuning
Continued discussion of physical parameterizations (deep convection and cloud schemes, radiation, gravity wave drag schemes).
Paper 6 out.

26.) Friday 4/5 3:30-5:20pm
Uncertainty quantification and sensitivity studies, ensemble methods (perturbed parameter, perturbed and time-lagged initial state, uncertain lateral boundary conditions, physical-process or model component uncertainty, multi-model ensembles), ensemble spread for weather and climate assessments.

Week 13

27.) Wednesday 4/10 3:30-5:20pm
Validation & verification, predictability, tuning of GCM simulations.

28.) Friday 4/12 3:30-5:20pm
Journal paper 6 discussion: Ensembles
Land, ocean, ice models and their coupling strategies, surface energy balance.
Discussion of spatial and temporal coupling strategies in ESMs. Earth System Modeling Framework (ESMF).

Week 14

29.) Wednesday 4/17 3:30-4:50pm
Modeling trends: seamless dynamical downscaling approaches (variable-resolution modeling, nesting, stretched grids, adaptive meshes), superparameterizations, cloud-permitting resolutions, non-hydrostatic and deep-atmosphere modeling.
Overview of the international modeling community.

30.) Friday 4/19 3:30-5:20pm
Model diagnostics packages, overview of reanalyses products and how to get them, reanalysis intercomparison project, debugging of scientific codes, cloud computing. High-performance and parallel computing concepts. Machine Learning

Week 15

31.) Monday 4/22 3:30-5:20pm
Term project presentations

8) Class resources:
There is no single textbook that covers all aspects of the course. A variety of online sources will be utilized such as

- Dave Randall, Colorado State University:
  An Introduction to Atmospheric Modeling
  http://hogback.atmos.colostate.edu/group/dave/at604.html
  Free online resource. Very comprehensive discussion about the numerical methods for the dynamical cores of GCMs. Some prior knowledge of numerical methods is helpful. Mostly focuses on finite-difference methods.
- UK Met Office Model Documentation, written by A. Staniforth and A. White and N. Wood and J. Thuburn and M. Zerroukat and E. Cordero and T. Davies and M. Diamantakis:
  Joy of U.M. 6.3 - Model Formulation
  The very comprehensive and detailed documentation of the UK Met Office dynamical core (available online via Google search).
- Springer book by P. Lauritzen, C. Jablonowski, M. Taylor, R, Nair (Eds.)
  Numerical Techniques for Global Atmospheric Models
  The book is available as a free ebook via the UM library page. Comprehensive review of dynamical core modeling. Lots of practical examples and advice.
- NCAR CAM model documentation:
  https://www.cesm.ucar.edu/models/cesm2/
  https://www.cesm.ucar.edu/models/cesm2/atmosphere/
  Official documentation of the NCAR CESM dynamical cores and physical parameterizations.

Other recommended resources are

- Thomas Tomkins Warner
  Numerical Weather and Climate Prediction
  Cambridge University Press, 2011
  The book provides a comprehensive overview of weather and climate prediction, and surveys the strength and weaknesses of atmospheric models.
- David J. Stensrud
  Parameterization Scheme: Keys to Understanding Numerical Weather Prediction Models
  Cambridge University Press, 2007
  The book introduces the design principles of the most commonly used subgrid-scale physical parameterization schemes for weather and climate models. Freely available as an ebook via the UM library page.
- Dale Durran
  Numerical Methods for Wave Equations in Geophysical Fluid Dynamics
  2nd edition, Springer, 2010, or 1st edition (1999),
  The book focuses on the numerical techniques for the fluid flow component of climate models. The discussion is broad and comprehensive, most examples are

shown for Cartesian geometry. Freely available as a Springer ebook via the UM library page.

- Warren M. Washington and Claire L. Parkinson
  An Introduction to Three-Dimensional Climate Modeling
  2nd edition, University Science Books, 2005
  A good textbook at the graduate level, provides an overview of climate modeling. Not very technical.
- Eugenia Kalnay
  Atmospheric modeling, data assimilation and predictability
  Cambridge University Press, 2003
  Very nice overview of the numerical techniques in climate models, second half of the book discusses data assimilation.
- David Randall (Ed.)
  General Circulation Model Development
  Academic Press, 2000
  Collection that reviews the history of GCM modeling and surveys its status in 2000. Ebook (by Elsevier) available online via the UM library page
- Masaki Satoh
  Atmospheric Circulation Dynamics and General Circulation Models
  Springer (Praxis), 2004
  The book discusses both atmospheric dynamics and GCM modeling with an applied focus. Very thorough and detailed. Great resource for advanced readers. Freely available as a Springer ebook via the UM library page.
- Kevin Hamilton and Wataru Ohfuchi (Eds.)
  High Resolution Numerical Modelling of the Atmosphere and Ocean
  Springer (2008), available online as a Springer ebook via the UM library page.
  Collection of book chapters by different authors that focus on high-resolution aspects of atmospheric and oceanic modeling
- Mark Z. Jacobson
  Fundamentals of atmospheric modeling
  2nd Edition, Cambridge University Press, 2005
- Goosse H., P.Y. Barriat, W. Lefebvre, M.F. Loutre and V. Zunz.
  Introduction to Climate Dynamics and Climate Modeling
  Free Online Textbook. Very basic but efficiently fills in gaps.
- Philip Mote and Alan O'Neill (Eds.)
  Numerical Modeling of the Global Atmosphere in the Climate System,
  NATO Science Series, Vol. 550, 2000
- Kendal McGuffie, Ann Henderson-Sellers
  Climate Modeling Primer
  3rd edition, Wiley (2005). Easy to read, freely available online:
  https://onlinelibrary.wiley.com/doi/book/10.1002/0470857617
  4th edition (2014) also available online via UM library
- Andrew Gettelman and Richard B. Rood,
  Demystifying Climate Models, A Users Guide to Earth System Models
  Springer book in the Series 'Earth Systems Data and Models' Volume 2, 2016
  freely available online as an open access book:

https://link.springer.com/book/10.1007/978-3-662-48959-8
Provides a guide to climate simulation and prediction for the non-specialist. Offers non-technical explanations for how climate models are constructed, why they are uncertain, and what level of confidence we should place in them.

Reviews of atmospheric dynamics and the general circulation of the atmosphere:

- James Holton and Gregory Hakim
  An introduction to dynamic meteorology
  5th edition, Academic Press, 2012
  Available as a free ebook via the UM library page. 4th edition also works.
- B. Cushman-Roisin and J.-M. Beckers
  Introduction to Geophysical Fluid Dynamics: Physical and Numerical Aspects
  2nd edition, Elsevier, 2011
  Available as a free ebook via the UM library page.
- David Randall, Colorado State University:
  Lecture notes (graduate level):
  An Introduction to the General Circulation of the Atmosphere