

Introduction to the Community Earth System Model (CESM)

William Collins
UC Berkeley and LBNL

thanks to

Gokhan Danabasoglu
CESM Chief Scientist, NCAR



12 FEBRUARY 2021



Outline

- Global Earth system models and CESM
- Coupled Model Intercomparison Project phase 6 (CMIP6) Efforts
- Updates on ongoing activities
- Towards CESM3

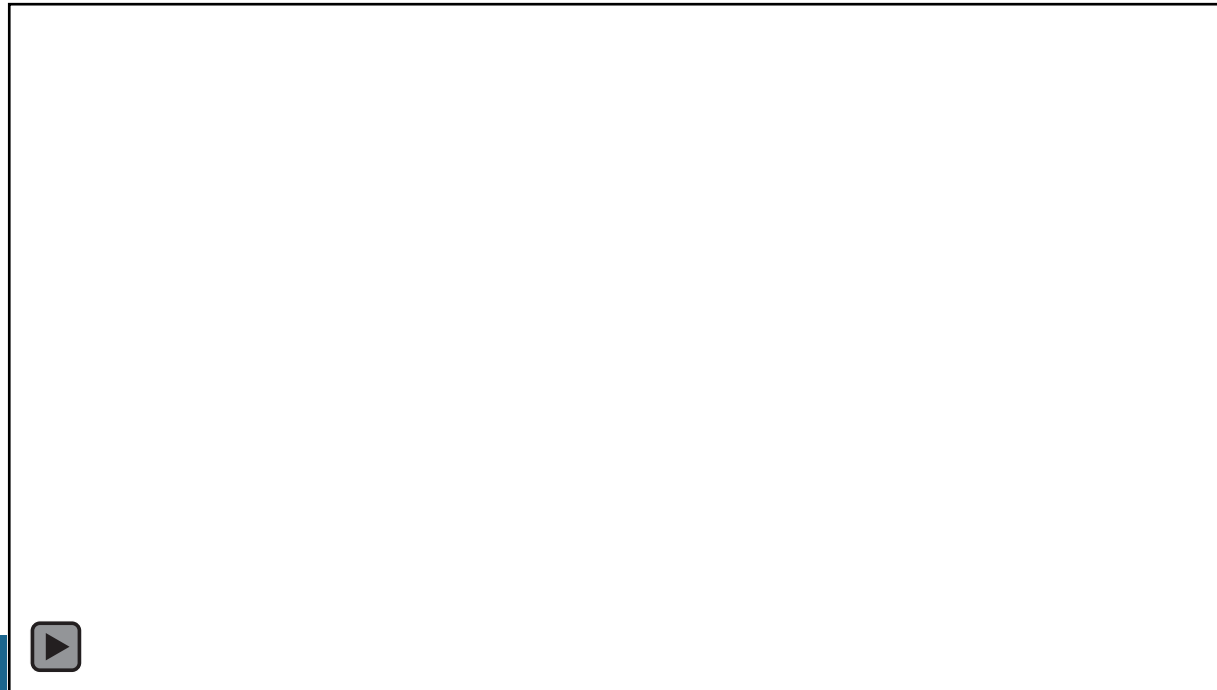
Global Earth System Models and CESM

Global Earth System Models

A virtual laboratory for experimentation

General purposes include:

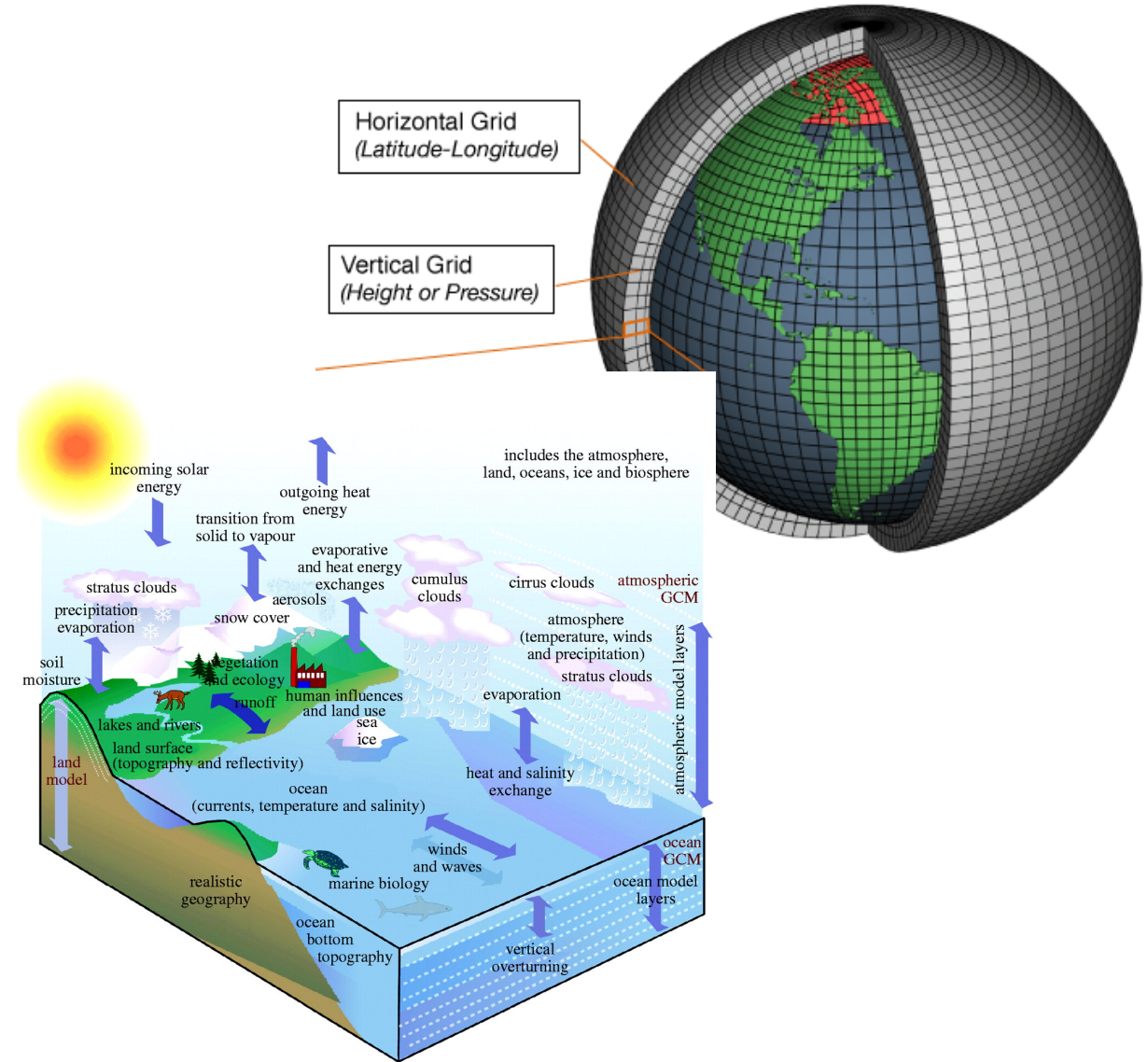
- To provide scientific understanding of observed events, climate change (historical, paleo), etc.,
- To simulate future climate change and its impacts,
- To make future predictions of weather and climate variability.



Long and Scheitlin

Global Earth System Models

- The models use physical equations to simulate key fields and processes in the atmosphere, ocean, land, sea-ice, land-ice, ...
- Processes that remain below the grid resolution need to be parameterized.
- Build on our understanding of processes from observations and highly-detailed models (e.g., process models, large eddy simulations).



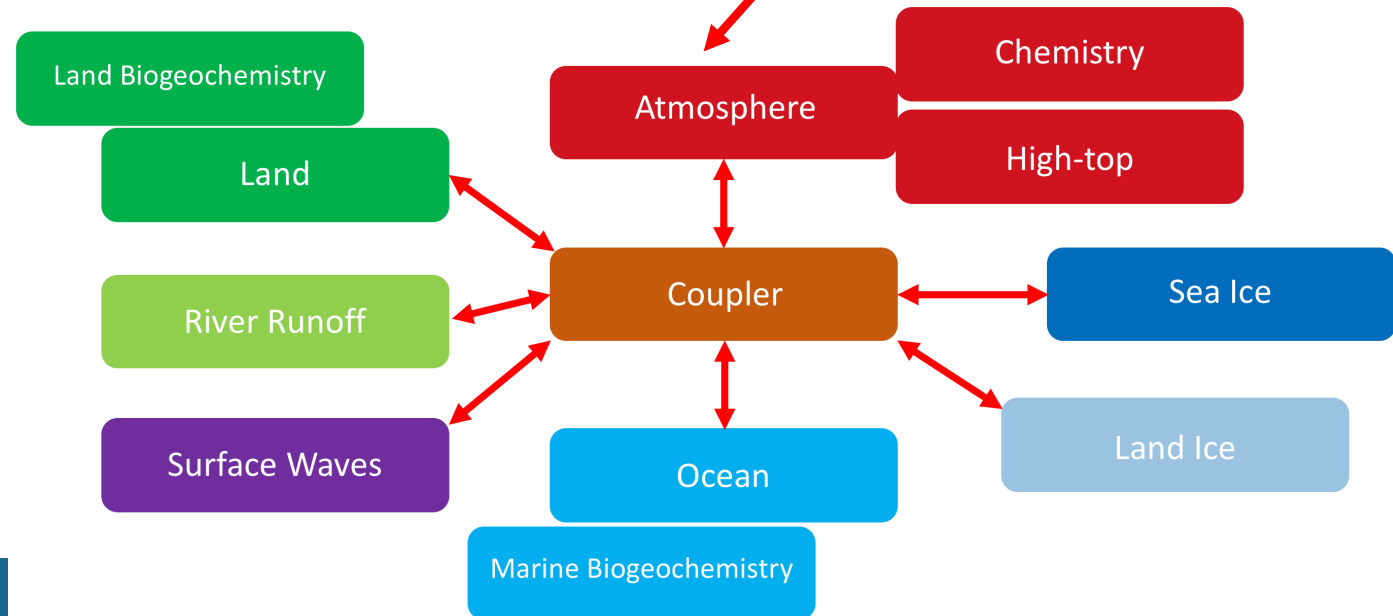
Global Earth System Models



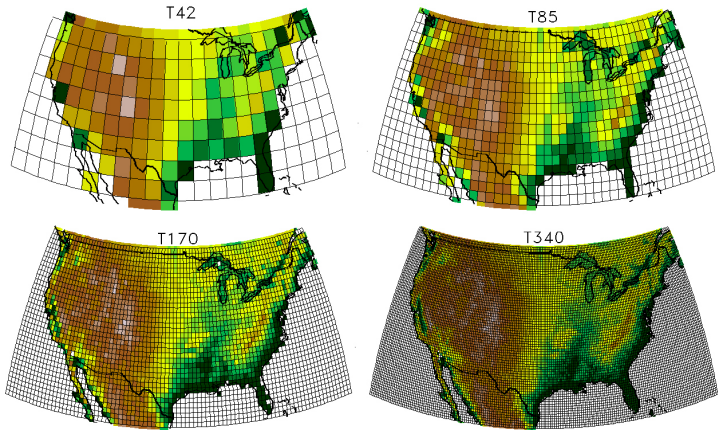
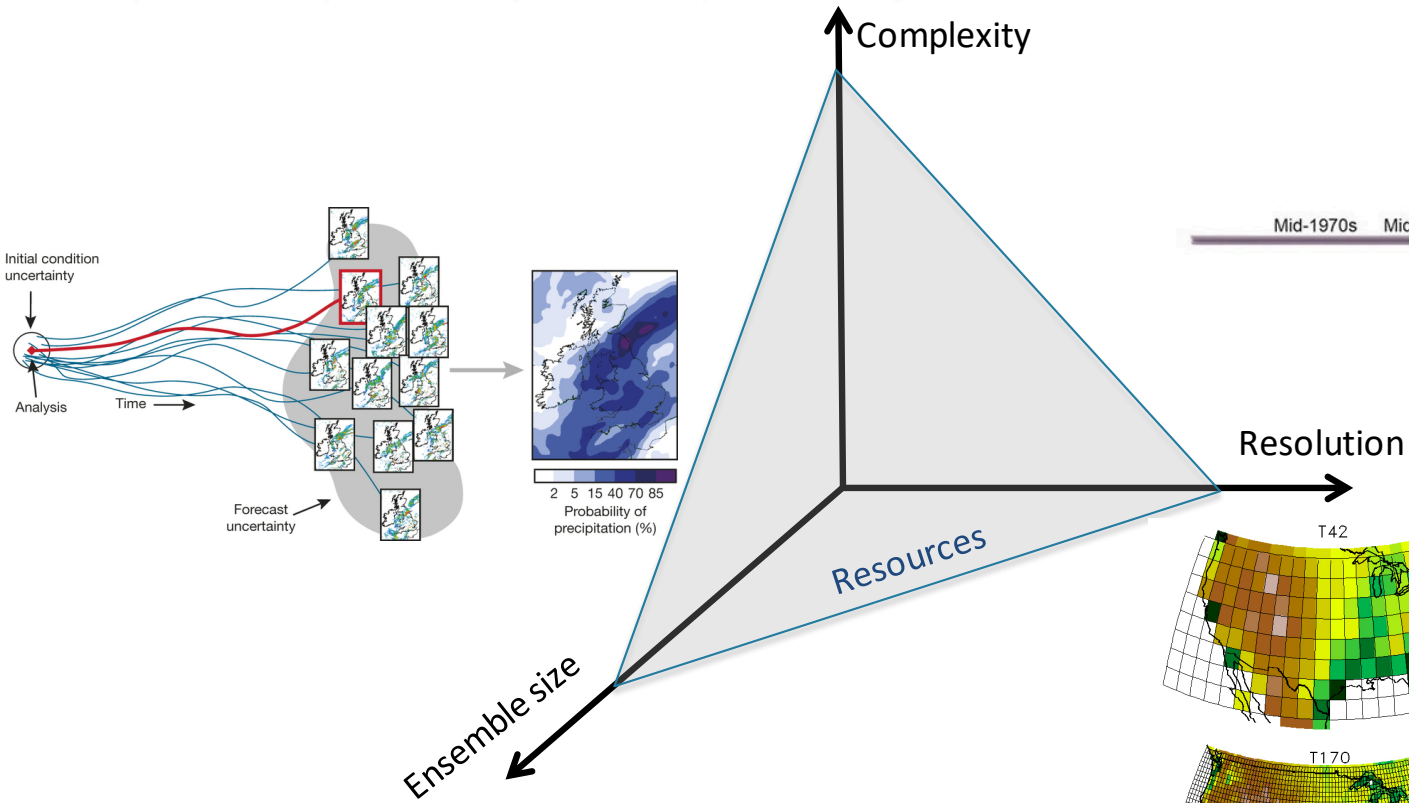
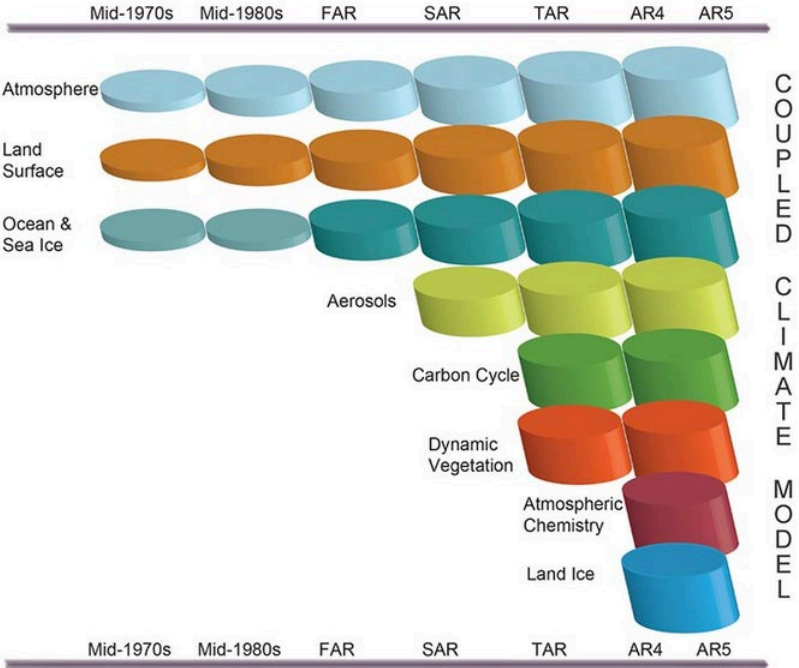
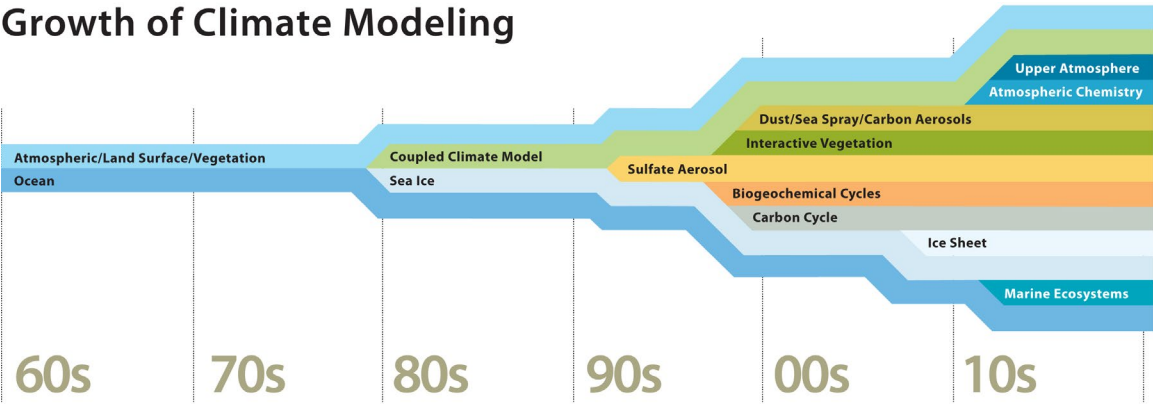
Forcings:

- Greenhouse gases
- Anthropogenic aerosols
- Volcanic eruptions
- Solar variability

Community Earth System Model



Growth of Climate Modeling



CESM Project

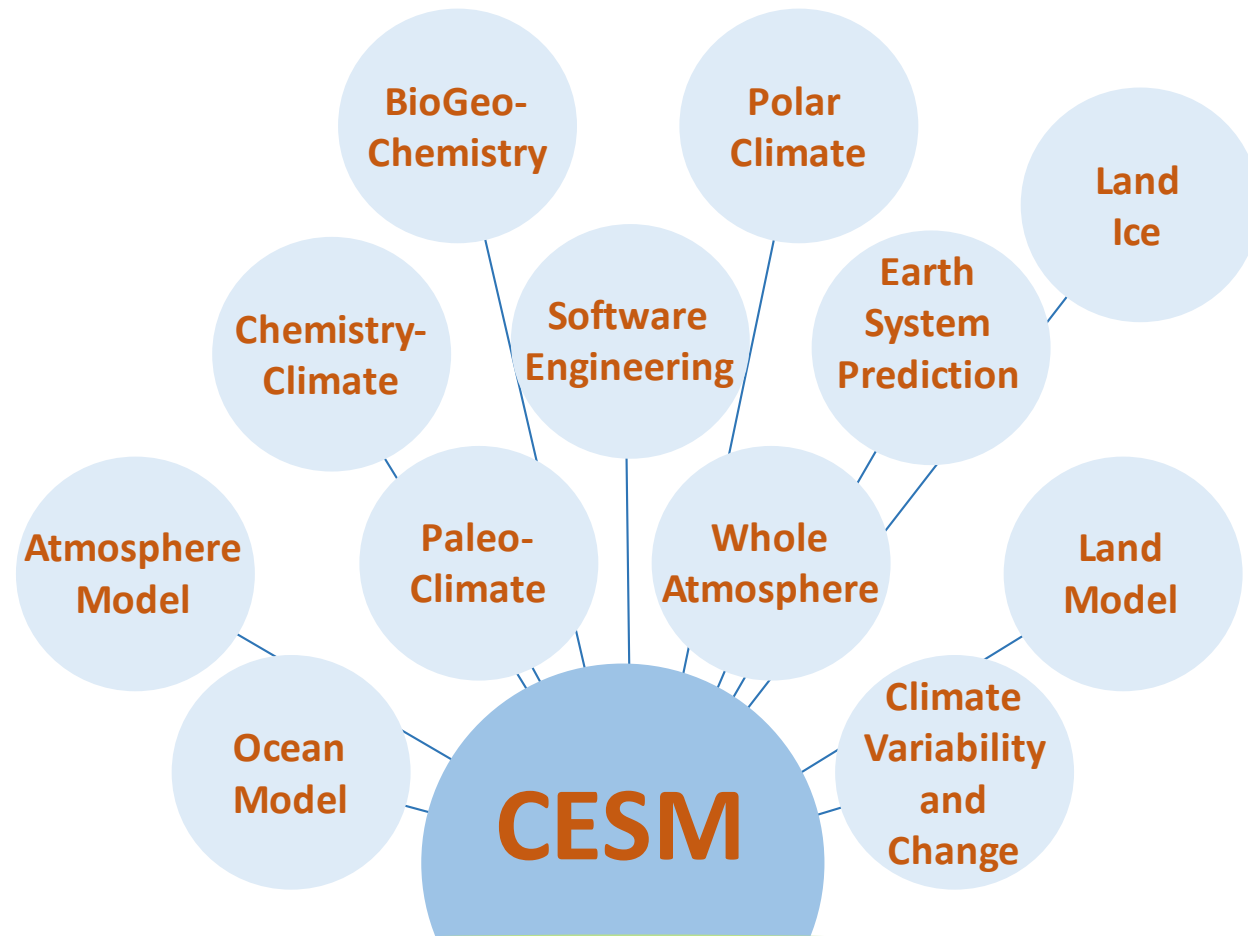
~25 years of model development and applications

Annual CESM Workshops are held in summers.

Most working groups have winter/spring meetings.

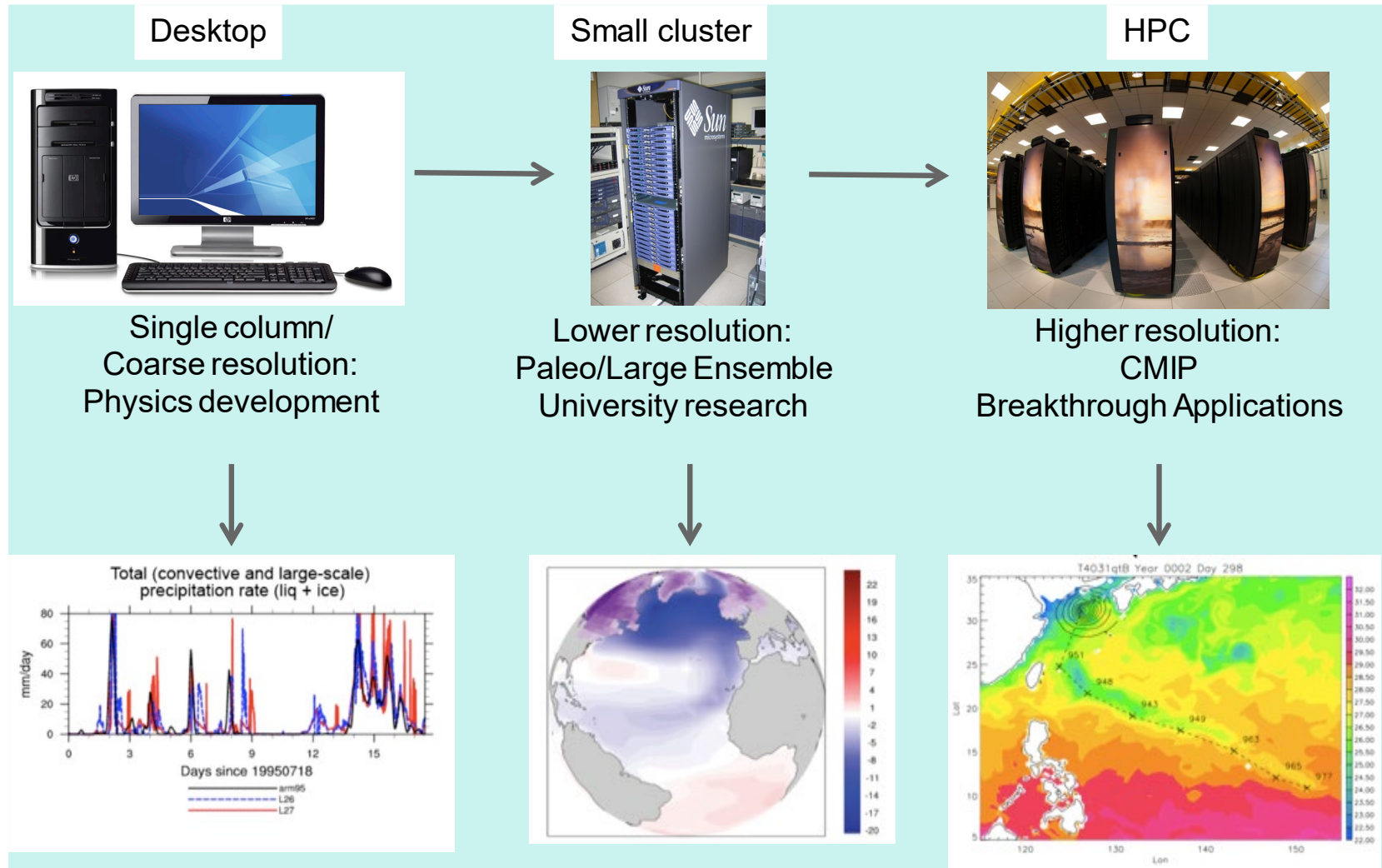
CESM Advisory Board

CESM Scientific Steering Committee



<http://www.cesm.ucar.edu/management>

CESM Supports a Range of Climate Science Goals Through a Single Model Code Base





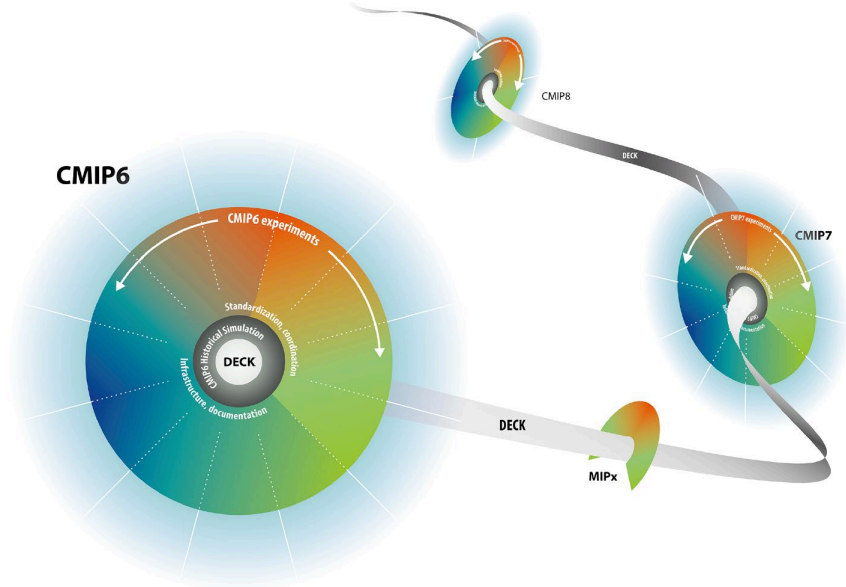
CESM Supports a Range of Climate Science Goals Through a Single Model Code Base

- All component models can be active.
- All component models can be replaced with “data models”:
Allowing, for example, ocean-only, ocean – sea-ice coupled, land-only, atmosphere-only, etc. configurations / experiments.
- Aqua planet, several atmospheric dynamical cores, and slab ocean model options are available.
- Numerous options are available within components.
- Increasing number of supported component sets / configurations are provided.

Coupled Model Intercomparison Project phase 6 (CMIP6) Efforts

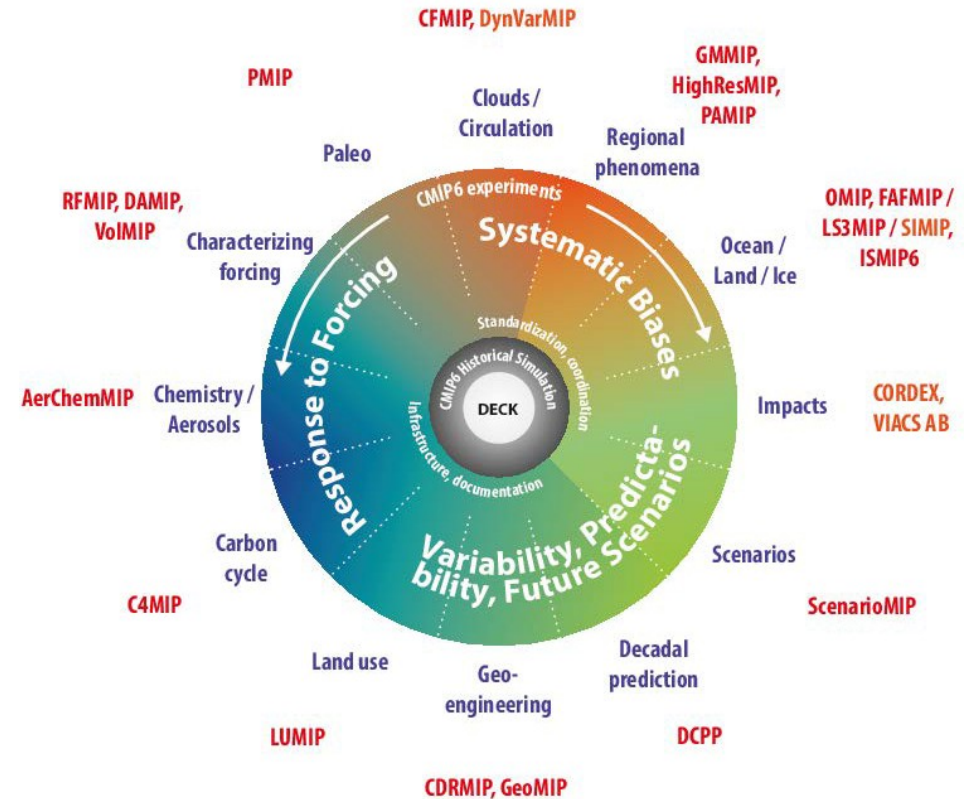
CESM2 Participation in CMIP6

Diagnostic, Evaluation, and Characterization of Klima (DECK)



- Pre-industrial control
- 1%CO2
- 4xCO2
- AMIP

Eyring et al. (2016, *GMD*)

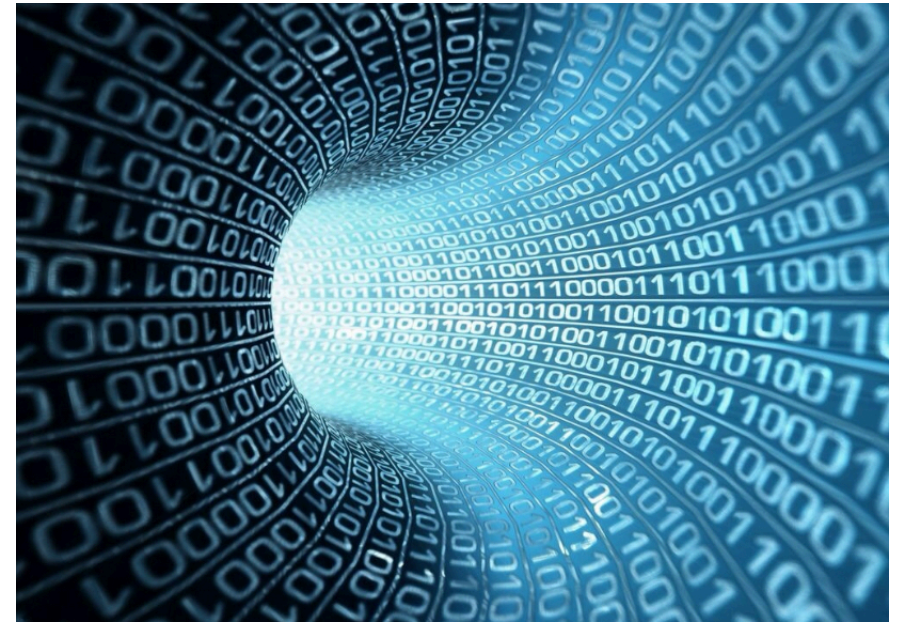


Set I: Two nominal 1° model versions w/ CAM6 and WACCM6 atmospheric model components

Set II: w/ 2° versions of CAM6 and WACCM6, but otherwise identical (primarily DECK)

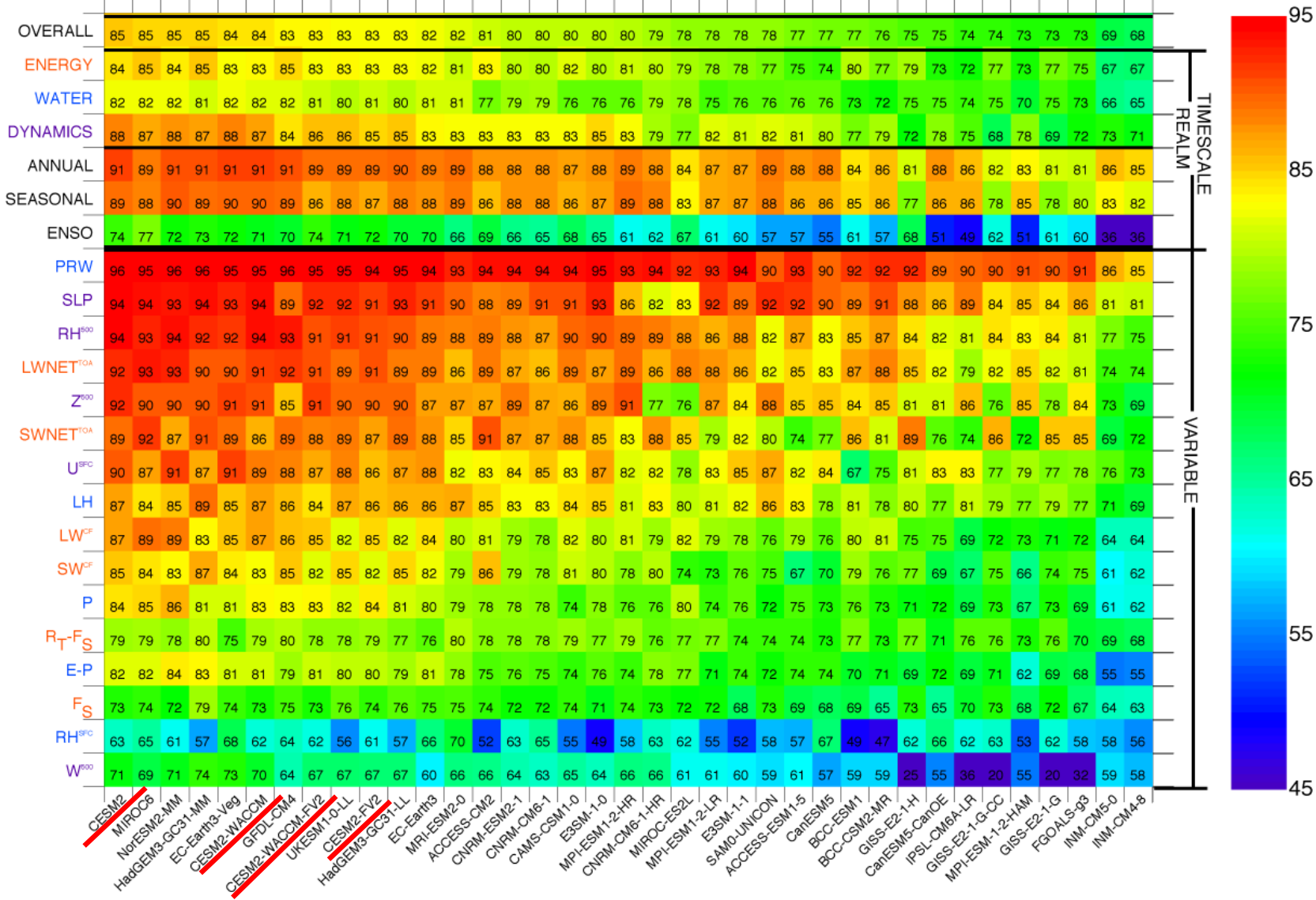
By the numbers

- ~1000 CESM2 simulations for CMIP6 have been run
- ~1.7 PB of compressed time series files have been generated
- ~600 TB of compressed CMIP6 files (>830K files) have been published on the ESGF
- This data volume is ~7x the total from CESM's CMIP5 contribution





A Model Performance Summary



CESM PUBLICATIONS

AGU CESM2 Virtual Special Issue

Below you can find a list of manuscripts that are published, in press, and submitted from the AGU CESM2 Virtual Special Issue, or view the [complete AGU CESM2 Virtual Special Issue](#)

To add or edit a publication to the special issue contact [webhelp@cgd.ucar.edu]

Show

10

entries

Search:

Citation

Bacmeister J. T., Hannay C., Medeiros B., Gettelman A., Neale R., Fredriksen H. B., Lipscomb W. H., Simpson I., Bailey D. A., Holland M., Lindsay K., Otto-Bliesner B. (2020). CO₂ increase experiments using the Community Earth System Model (CESM): Relationship to climate sensitivity and comparison of CESM1 to CESM2. *Manuscript submitted for publication to Journal of Advances in Modeling Earth Systems*.
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Bailey D. A., Holland M. M., DuVivier A. K., Hunke E. C., Turner A. K. (2020). Impact of a New Sea Ice Thermodynamic Formulation in the CESM2 sea ice component. *Manuscript submitted for publication to Journal of Advances in Modeling Earth Systems*.
[View PDF](#)

Bonan, G. B., Lombardozzi, D. L., Wieder, W. R., Oleson, K. W., Lawrence, D. M., Hoffman, F. M., & Collier, N. (2019). Model Structure and Climate Data Uncertainty in Historical Simulations of the Terrestrial Carbon Cycle (1850–2014). *Global Biogeochemical Cycles*, 33. <https://doi.org/10.1029/2019GB006175>

Capotondi, A., Deser, C., Phillips, A. S., Okumura, Y., Larson, S. M. (2019). ENSO and Pacific Decadal Variability in the Community Earth System Model Version 2. *Manuscript submitted for publication to Journal of Advances in Modeling Earth Systems*.
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Danabasoglu, G., Lamarque, J.-F., Bachmeister, J., Bailey, D. A., DuVivier, A. K., Edwards, J., Emmons, L. K., Fasullo, J., Garcia, R., Gettelman, A., Hannay, C., Holland, M. M., Large, W. G., Lawrence, D. M., Lenaerts, J. T. M., Lindsay, K., Lipscomb, W. H., Mills, M. J., Neale, R., Oleson, K. W., Otto-Bliesner, B., Phillips, A. S., Sacks, W., Tilmes, S., van Kampenhout, L., Vertenstein, M., Bertini, A., Dennis, J., Deser, C., Fischer, C., Fox-Kemper, B., Kay, J. E., Kinnison, D., Kushner, P. J., Long, M. C., Mickelson, S., Moore, J. K., Nienhouse, E., Polvani, L., Rasch, P. J., Strand, W. G. The Community Earth System Model version 2 (CESM2). *Journal of Advances in Modeling Earth Systems*, 12. <https://doi.org/10.1029/2019MS001916>

DeRepentigny, P., Jahn, A., Holland, M. M., Smith, A. (2020) Arctic Sea Ice in Two Configurations of the Community Earth System Model Version 2 (CESM2) During the 20th and 21st Centuries. *Manuscript submitted for publication to JGR: Oceans*
[View PDF](#) [View Supporting Information](#)

DuVivier, A. K., Holland, M. M., Kay, J. E., Tilmes, S., Gettelman, A., Bailey, D. A. (2019) Arctic and Antarctic sea ice state in the Community Earth System Model Version 2. *Manuscript submitted to JGR: Oceans*.
[View PDF](#)



JAMES | Journal of Advances in Modeling Earth Systems

RESEARCH ARTICLE
10.1029/2019MS001916

Special Section:
Community Earth System
Model version 2 (CESM2)
Special Collection

Key Points:
• Community Earth System Model
Version 2 includes many substantial
improvements

The Community Earth System Model Version 2 (CESM2)

G. Danabasoglu¹ , J.-F. Lamarque¹ , J. Bacmeister¹, D. A. Bailey¹ , A. K. DuVivier¹ , J. Edwards¹, L. K. Emmons² , J. Fasullo¹ , R. Garcia² , A. Gettelman^{1,2} , C. Hannay¹ , M. M. Holland¹ , W. G. Large¹, P. H. Lauritzen¹ , D. M. Lawrence¹ , J. T. M. Lenaerts³ , K. Lindsay¹, W. H. Lipscomb¹ , M. J. Mills² , R. Neale¹ , K. W. Oleson¹ , B. Otto-Bliesner¹ , A. S. Phillips¹ , W. Sacks¹, S. Tilmes² , L. van Kampenhout⁴, M. Vertenstein¹ , A. Bertini¹, J. Dennis⁵ , C. Deser¹ , C. Fischer¹, B. Fox-Kemper⁶ , J. E. Kay⁷ , D. Kinnison² , P. J. Kushner⁸ , V. E. Larson⁹ , M. C. Long¹ , S. Mickelson⁵ , J. K. Moore¹⁰, E. Nienhouse⁵, L. Polvani¹¹ , P. J. Rasch¹² , and W. G. Strand¹

45 already published or submitted

<http://www.cesm.ucar.edu/publications/>



Thank You!



BACKUP SLIDES

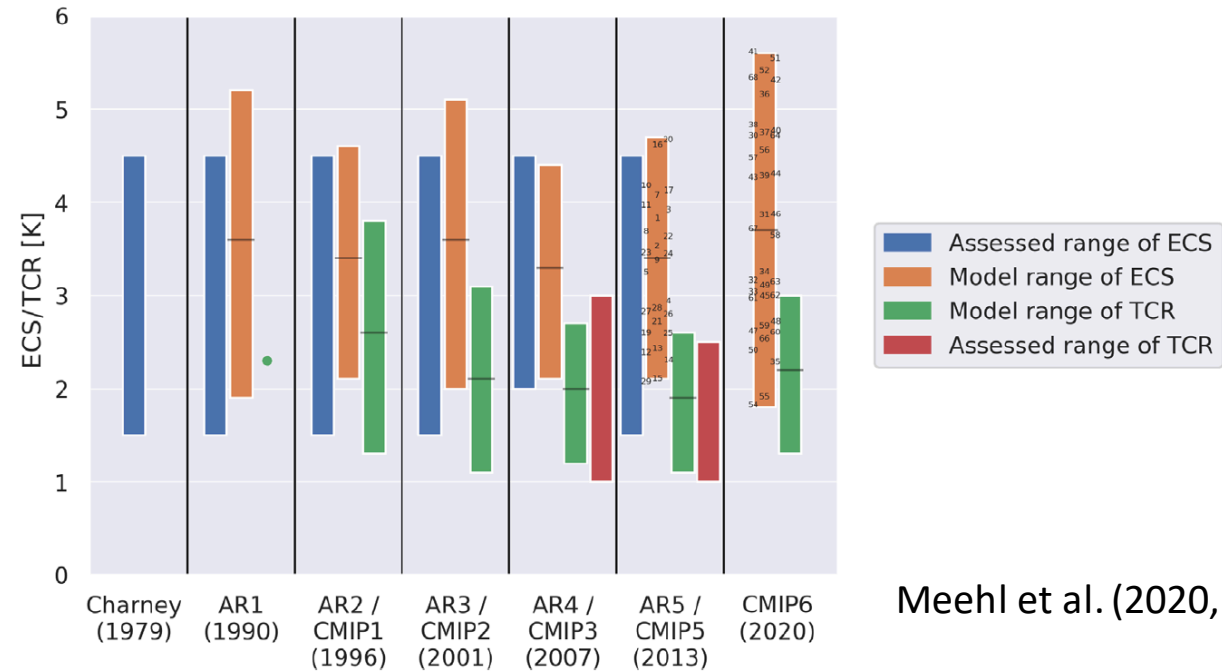
Equilibrium Climate Sensitivity (ECS) & Transient Climate Response (TCR)

CESM1(CAM5): 4.0-4.1°C

CESM2(CAM6): 5.3°C (SOM)
5.3°C (E_{ffCS})

CESM2(WACCM6): 5.1°C (SOM)
4.8°C (E_{ffCS})

Equilibrium climate sensitivity (gregory method) and transient climate response



Meehl et al. (2020, *Sci. Adv.*)

The increased ECS in CESM2 is due to a combination of relatively small changes to cloud microphysics and boundary layer parameters that were introduced during the development process (Gettelman et al. 2019; Bacmeister et al. 2020).

Cloud feedbacks particularly over the Southern Ocean latitudes are important.

Updates on Ongoing Activities

CESM2 Releases

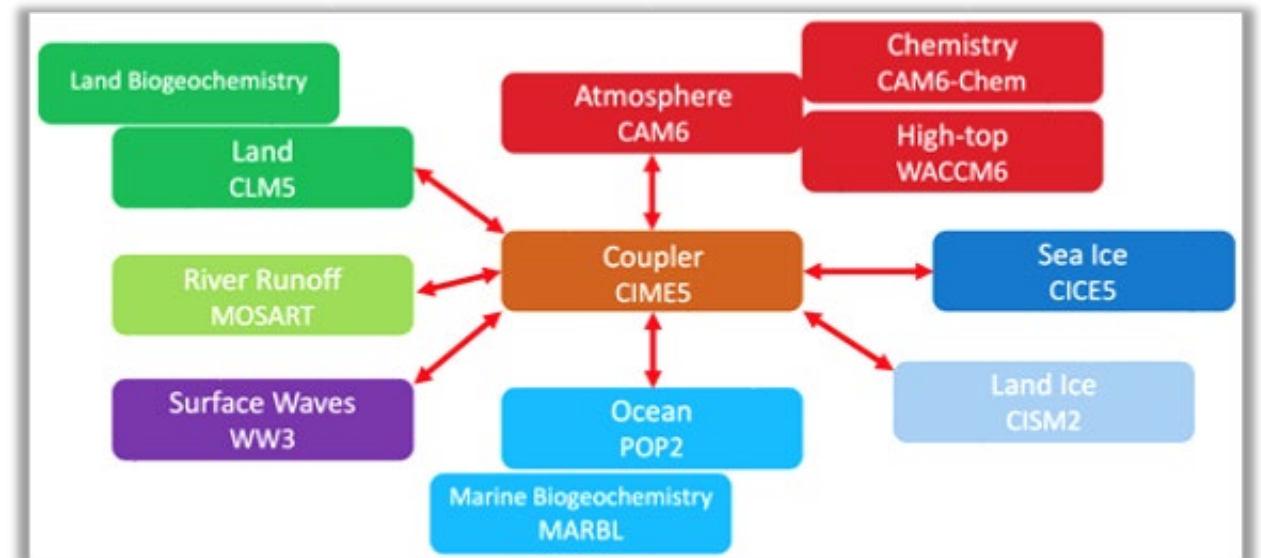
CESM2.1.0 (incremental) on 10 December 2018

CESM2.1.1 (incremental) on 10 June 2019

CESM2.1.2 (incremental) on 14 February 2020

CESM2.2 on 29 September 2020

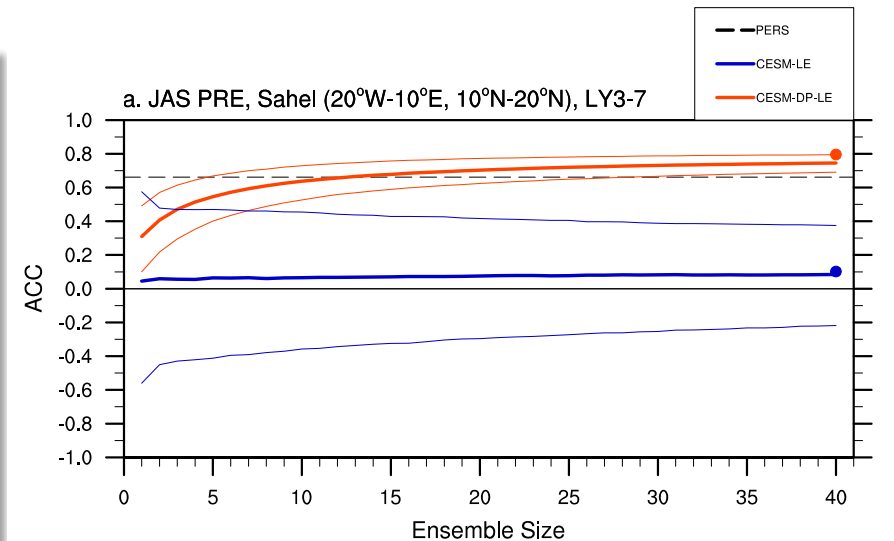
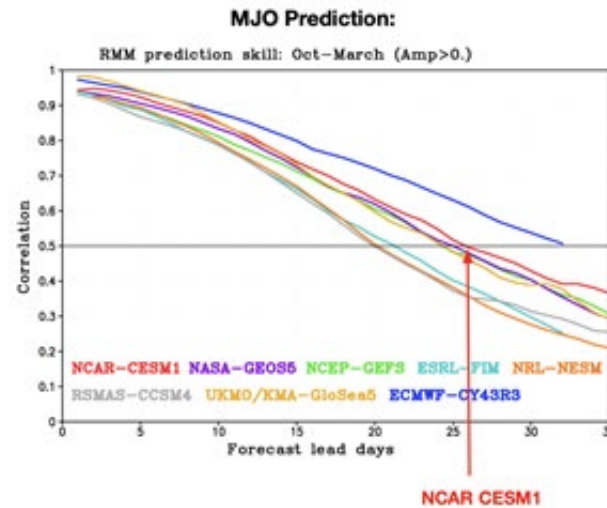
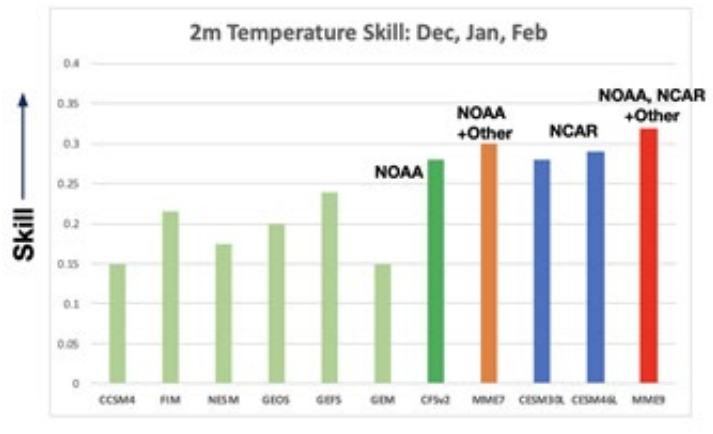
CESM2.1.x series are non-answer-changing and they further expand the available set of out-of-the-box configurations of CESM2 for readily performing the DECK, historical, and many MIP Tier 1 simulations for CMIP6.



Earth System Prediction Working Group (ESPWG)

Co-chairs: Kathy Pegion (GMU), Yaga Richter (NCAR), and Steve Yeager (NCAR)

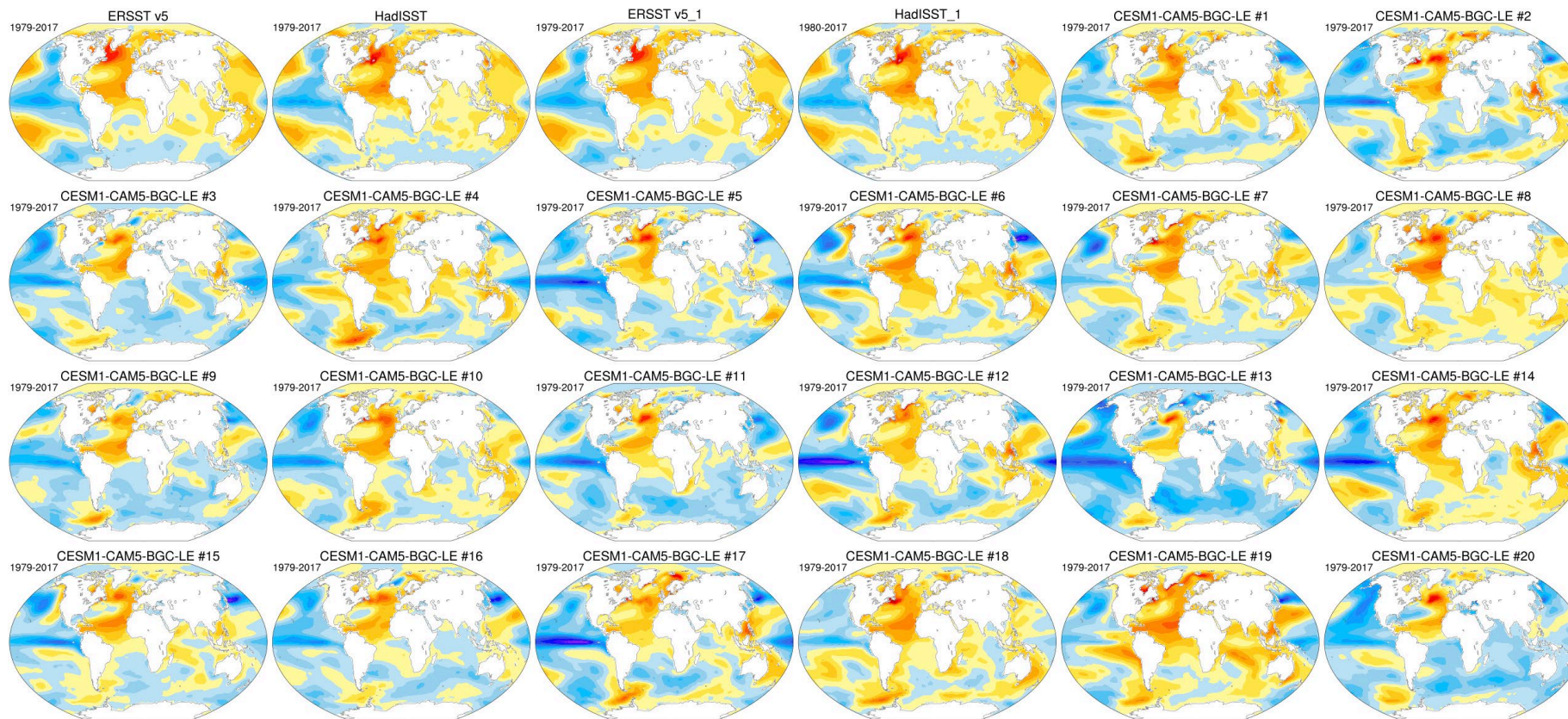
- ESPWG will serve the CESM and broader geoscience community by facilitating and coordinating fundamental research focused on understanding and advancing research on initialized Earth system predictions on timescales from subseasonal to multidecadal.
- A key aim is to facilitate ESP research through provision of large ensemble initialized hindcast/ forecast simulations that are too computationally burdensome for individual university researchers to undertake.



Richter, Yeager, et al.

CESM1 Large Ensemble Simulations

Atlantic Multi-Decadal Variability (AMV)



35+ members for the 1920-2080 period; same forcings; initial conditions differ only at round-off level in their atmospheric temperatures

Kay et al. (2015, *BAMS*)

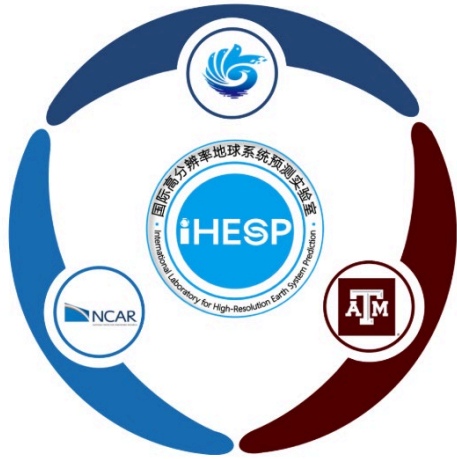
CESM2 Large Ensemble (CESM2-LENS)

A collaboration / partnership with the Institute for Basic Science (IBS) Center for Climate Physics (ICCP) in Busan, S. Korea

- A 100-member ensemble for the 1850-2100 period, using the SSP-3.70 scenario for the future extension;
- ~70 members have been completed;
- Anticipated completion date for the full ensemble is March / April 2021;
- Data are being transferred to NCAR and being CMORized; and will be available for use of the broader community via ESGF in early Summer 2021.



CESM High-Resolution (CESM-HR) Simulations



International Laboratory for High-Resolution Earth System Predictions (iHESP)

Qingdao National Laboratory for Marine Science and Technology (QNLM)

Texas A&M University (TAMU)

National Center for Atmospheric Research (NCAR)

CESM-HR: Atmosphere and land at 0.25°; ocean and sea-ice at nominal 0.1° resolution

The CESM (v1.3) code base used on the Sunway System is publicly available from the iHESP web site.

Geoscientific Model Development

An interactive open-access journal of the European Geosciences Union

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<https://doi.org/10.5194/gmd-2020-18>

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Submitted as: development and technical paper

Discussion papers

Abstract

Assets

Discussion

Metrics

21 Feb 2020

Review status

This preprint is currently under review for the journal GMD.

Optimizing High-Resolution Community Earth System Model on a Heterogeneous Many-Core Supercomputing Platform (CESM-HR_sw1.0)

Shaoqing Zhang^{1,4,5}, Haohuan Fu^{2,3,1}, Lixin Wu^{4,5}, Yuxuan Li⁶, Hong Wang^{1,4,5}, Yunhui Zeng⁷, Xiaohui Duan^{3,8}, Wubing Wan³, Li Wang⁷, Yuan Zhuang⁷, Hongsong Meng³, Kai Xu^{3,8}, Ping Xu^{3,6}, Lin Gan^{3,6}, Zhao Liu^{3,6}, Sihai Wu³, Yuhu Chen⁹, Haining Yu³, Shupeng Shi³, Lanning Wang^{3,10}, Shiming Xu^{10,2}, Wei Xue^{3,6}, Weiguo Liu^{3,8}, Qiang Guo⁷, Jie Zhang⁷, Guanghui Zhu⁷, Yang Tu⁷, Jim Edwards^{1,11}, Allison Baker^{1,11}, Jianlin Yong⁵, Man Yuan^{10,5}, Yangyang Yu⁵, Qiuying Zhang^{1,12}, Zedong Liu⁹, Minghui Li^{1,4,5}, Dongning Jia⁹, Guangwen Yang^{1,3,6}, Zhiqiang Wei⁹, Jingshan Pan⁷, Ping Chang^{1,12}, Gokhan Danabasoglu^{1,11}, Stephen Yeager^{1,11}, Nan Rosenbloom^{1,11}, and Ying Guo⁷

¹International Laboratory for High-Resolution Earth System Model and Prediction (iHESP), Qingdao, China

²Ministry of Education Key Lab. for Earth System Modeling, and Department of Earth System Science, Tsinghua University, Beijing, China

³National Supercomputing Center in Wuxi, Wuxi, China

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JAMES

Journal of Advances in Modeling Earth Systems

RESEARCH ARTICLE

10.1029/2020MS002298

Key Points:

- An unprecedented set of multi-century high-resolution Community Earth System Model (CESM) simulations is described
- High-resolution CESM simulations reveal a potential role of Southern Ocean polynyas in multidecadal climate variability
- High-resolution CESM exhibits significantly improved simulations of extreme events, such as tropical cyclones and atmospheric rivers

An Unprecedented Set of High-Resolution Earth System Simulations for Understanding Multiscale Interactions in Climate Variability and Change

Ping Chang^{1,2,3} , Shaoqing Zhang^{1,4,5} , Gokhan Danabasoglu^{1,6} , Stephen G. Yeager^{1,6} , Haohuan Fu^{1,7,8} , Hong Wang^{1,4,5} , Frederic S. Castruccio^{1,6} , Yuhu Chen⁹, James Edwards^{1,6} , Dan Fu^{1,2}, Yinglai Jia^{1,5}, Lucas C. Laurindo^{1,6} , Xue Liu^{1,2}, Nan Rosenbloom^{1,6} , R. Justin Small^{1,6}, Gaopeng Xu^{1,2}, Yunhui Zeng¹⁰, Qiuying Zhang^{1,2} , Julio Bacmeister^{1,6} , David A. Bailey^{1,6} , Xiaohui Duan^{8,11}, Alice K. DuVivier^{1,6} , Dapeng Li^{1,2} , Yuxuan Li¹¹, Richard Neale⁶ , Achim Stössel^{1,2} , Li Wang¹⁰, Yuan Zhuang¹⁰, Allison Baker^{1,6}, Susan Bates⁶, John Dennis⁶ , Xiliang Diao^{1,2}, Bolan Gan^{1,4,5} , Abishek Gopal^{1,2}, Dongning Jia⁹, Zhao Jing^{1,4,5}, Xiaohui Ma^{1,4,5} , R. Saravanan^{1,3}, Warren G. Strand⁶ , Jian Tao^{1,12} , Haiyuan Yang^{1,4,5} , Xiaoqi Wang^{1,2}, Zhiqiang Wei⁹, and Lixin Wu^{4,5}

CESM-HR Simulations

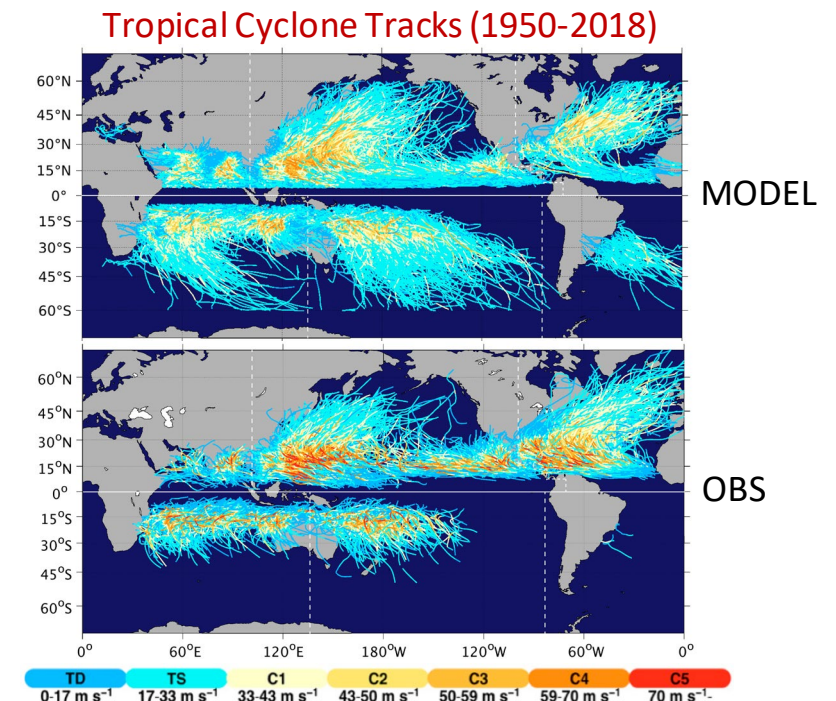
- 500-year pre-industrial (PI) control
- 1850-2100 transient simulation w/ RCP8.5
- 80-year 1%/year CO2 increase
- Ocean – sea-ice coupled simulation run for 4 cycles of JRA55-do for the 1958-2018 period

HighResMIP CESM Contributions

- 130-year 1950 control
- 1950-2050 transient simulation w/ RCP8.5
- 1950-2050 AMIP-style simulation

+ Low-resolution equivalents for all simulations

Data sets from coupled HighResMIP and the first 300 years of the PI control were released on 08 June 2020. The rest will be made available by the end of this year.



CESM2 Simulations with CMIP5 Forcings

Purpose of Simulations:

- Numerous studies have documented differences in CESM1-CMIP5 and CESM2-CMIP6 Simulations
- CESM2 has differences across all model components
- CESM1 vs CESM2 were run with different forcing during both the historical and future forcing periods

How do we disentangle the extent to which model structure and model forcing are responsible for simulation differences?

Simulations:

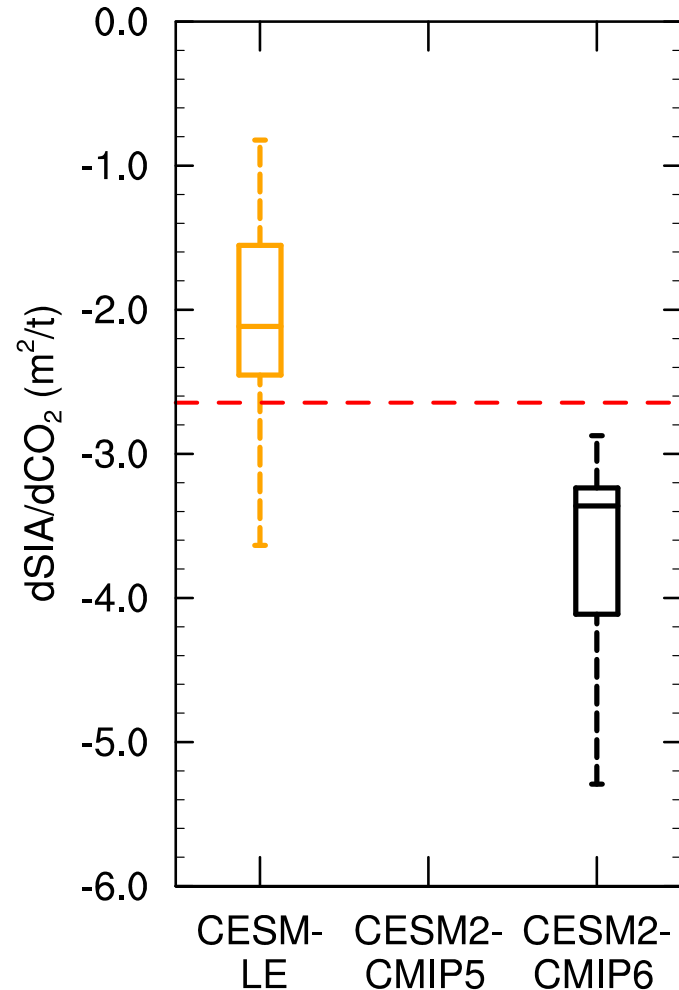
- 500-year pre-industrial control
- 7 member ensemble of 1850-2100 simulations
- Forcing for the simulations is largely based on the CESM1-CMIP5 simulations

Holland, Hannay, et al.

Disentangling forcing vs. model structure in CESM1 to CESM2 changes

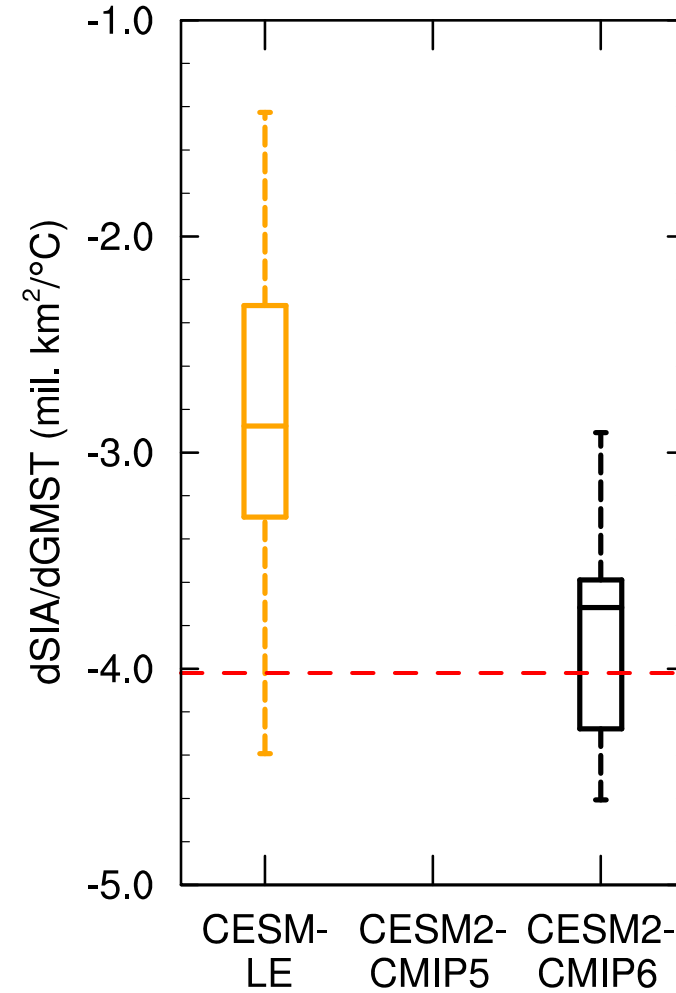
Example: Arctic Sea ice sensitivity 1979-2014

Figures courtesy of Patricia
DeRepentigny



Ice sensitivity to CO₂

- CESM2 has more ice loss per ton of accumulated CO₂ than CESM1 runs



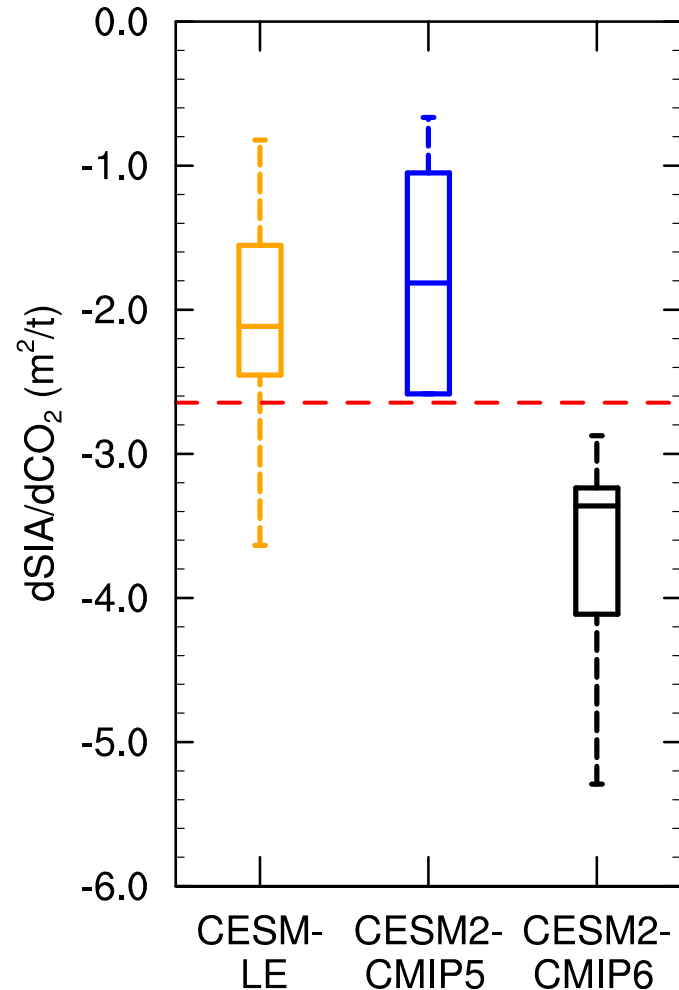
Ice sensitivity to GMST

- CESM2 has more ice loss per change in global temperature than CESM1 runs

Disentangling forcing vs. model structure in CESM1 to CESM2 changes

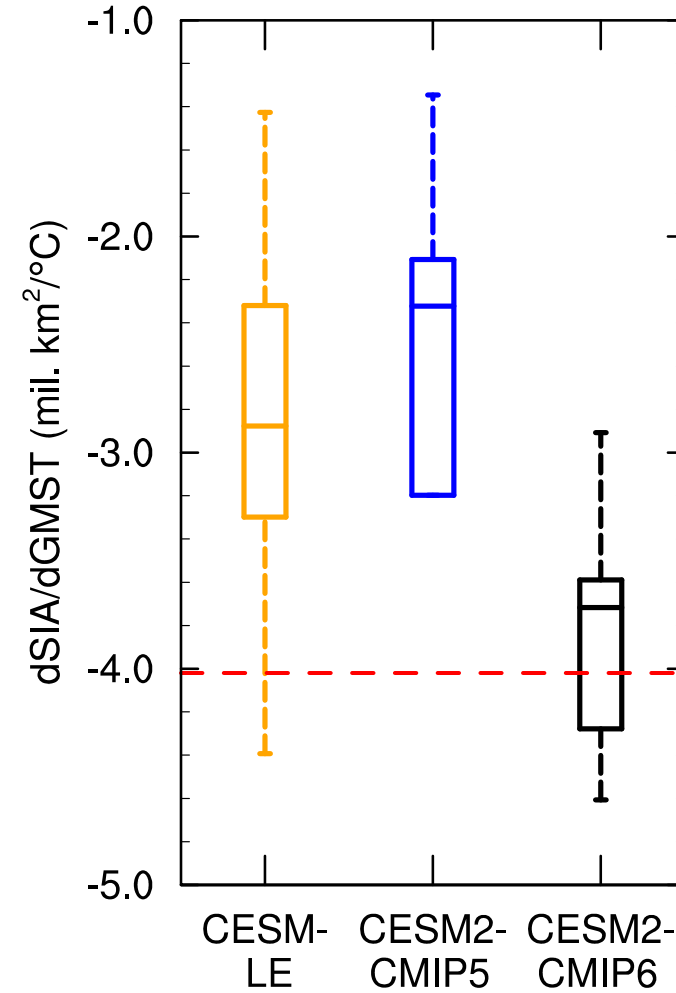
Example: Arctic Sea ice sensitivity 1979-2014

Figures courtesy of Patricia DeRepentigny



Ice sensitivity to CO2

- CESM2 has more ice loss per ton of accumulated CO2 than CESM1 runs
- CESM2-CMIP5 run comparison suggests that this is associated with forcing and not model differences



Ice sensitivity to GMST

- CESM2 has more ice loss per change in global temperature than CESM1 runs
- CESM2-CMIP5 run comparison suggests that this is associated with forcing and not model differences

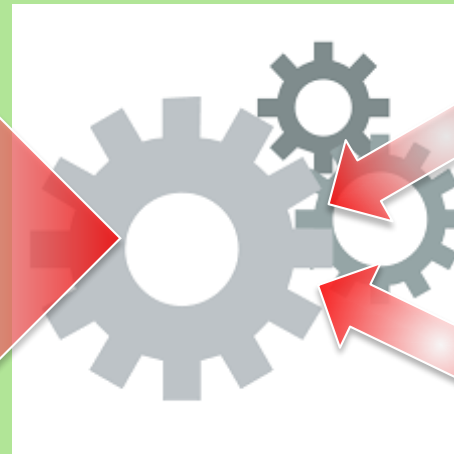
“Strongly” Coupled Data Assimilation: The Bleeding Edge

Observations of the climate system



Data Assimilation System

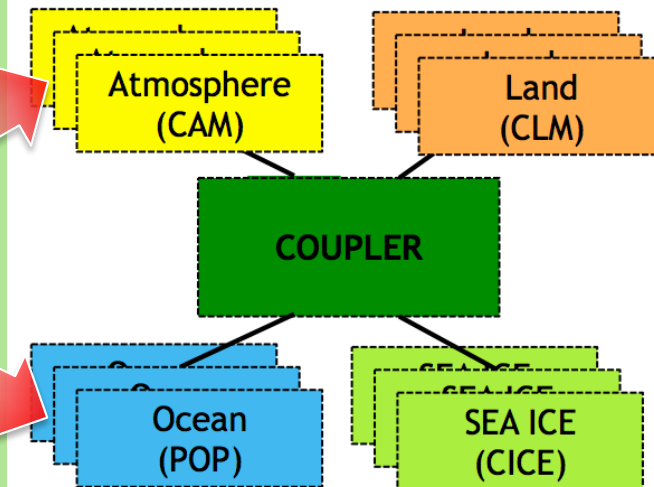
Data Assimilation Research Testbed (DART)



Ensemble Kalman Filter (EnKF)

Geophysical Model

Community Earth System Model

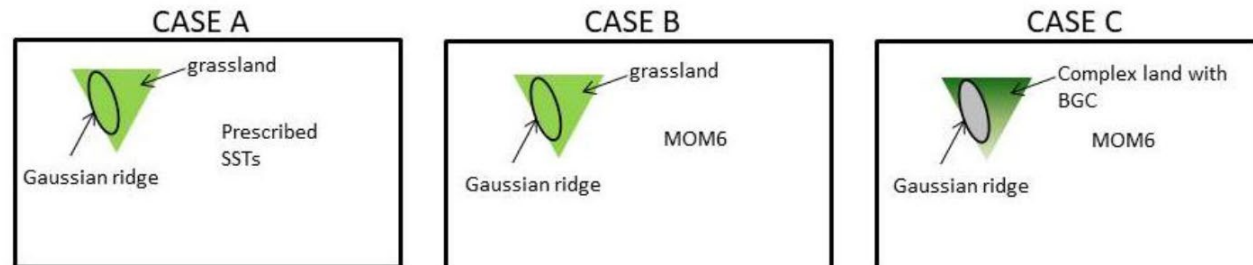


We have a prototype

Towards CESM3

Development of Coupled Idealized Modelling Toolkits

- Develop a Simpler Models query tool to allow users to easily understand which simpler model configurations are available and supported, their compatibilities, different options (e.g., physics packages);
- Develop infrastructure for customization of ocean basin and land geometries (overlaps with needs of the Paleoclimate community);
- Provide a toolchain for seamless model setup (components, grids, domain, physics) for coupled idealized configurations.



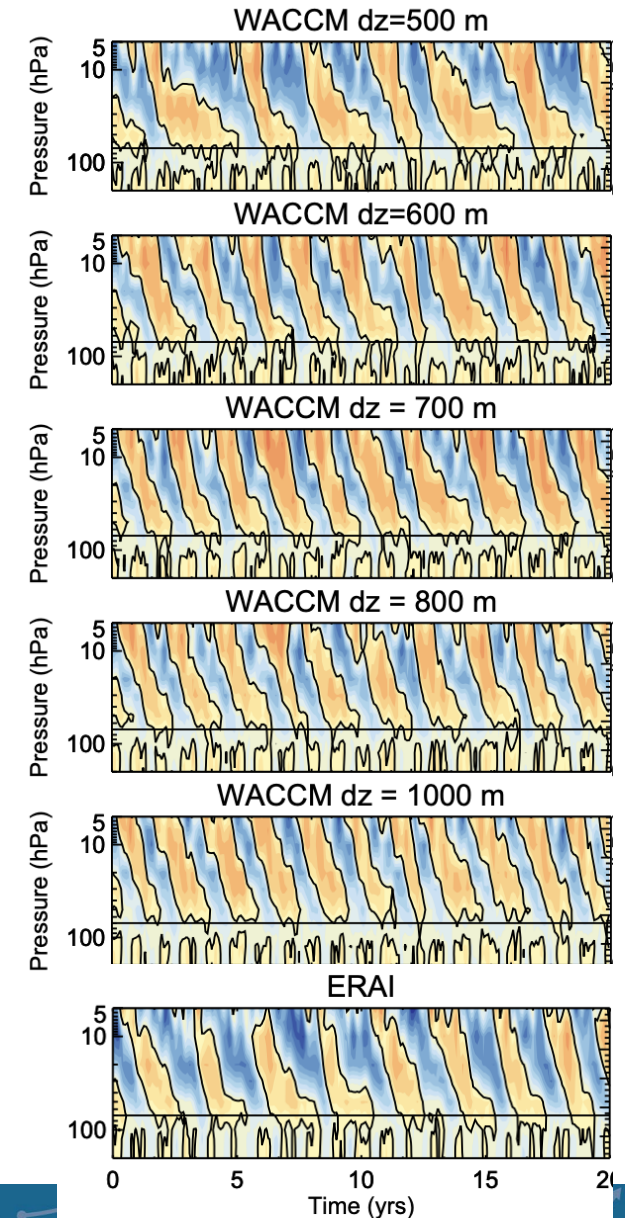
Isla Simpson et al.

Atmospheric Model Vertical Resolution and Top for the Next Workhorse Version of CESM

Investigate possible vertical grid configurations and model tops for the next generation, workhorse atmospheric model version of CESM.

This will be a model that does not extend as high as WACCM, but extends higher than CAM and has a grid structure with improvements in vertical resolution in the free troposphere and stratosphere and the boundary layer in order to capture features of interest.

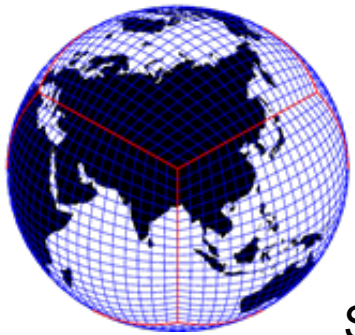
- Recommend a specific number of levels (expectation ~80), along with their spacing, with justification
- Recommend a specific top height with justification (expectation ~80 km)
- Recommend a "mid-level" height and resolution for cheaper simulation/tuning purposes. (secondary)



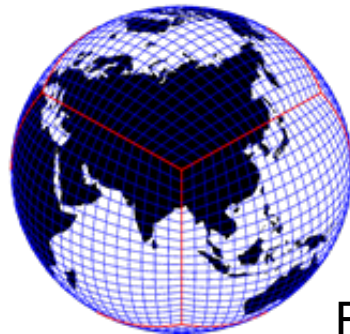
New Atmospheric Dynamical Cores in CESM

The following dynamical cores have been or are being integrated into the CESM:

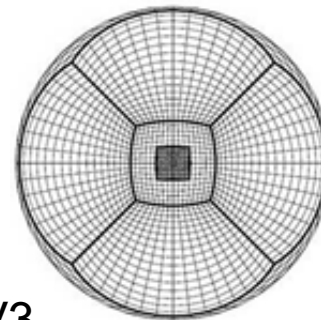
- **SE** dynamical core with option for accelerated transport scheme (**CSLAM**)
 - highly scalable hydrostatic dynamical core with flexible mesh-refinement options
 - capability of running physics on a separate (coarser) grid for uniform grid applications
- **FV3**: GFDL's dynamical core used by NCEP for global weather forecasting
 - scalable finite-volume dynamical core (currently using hydrostatic version; non-hydrostatic available)
- **MPAS**: NCAR's global weather forecast model
 - non-hydrostatic finite-volume dynamical core that also allows for flexible mesh-refinement



SE



FV3



MPAS



Peter Lauritzen

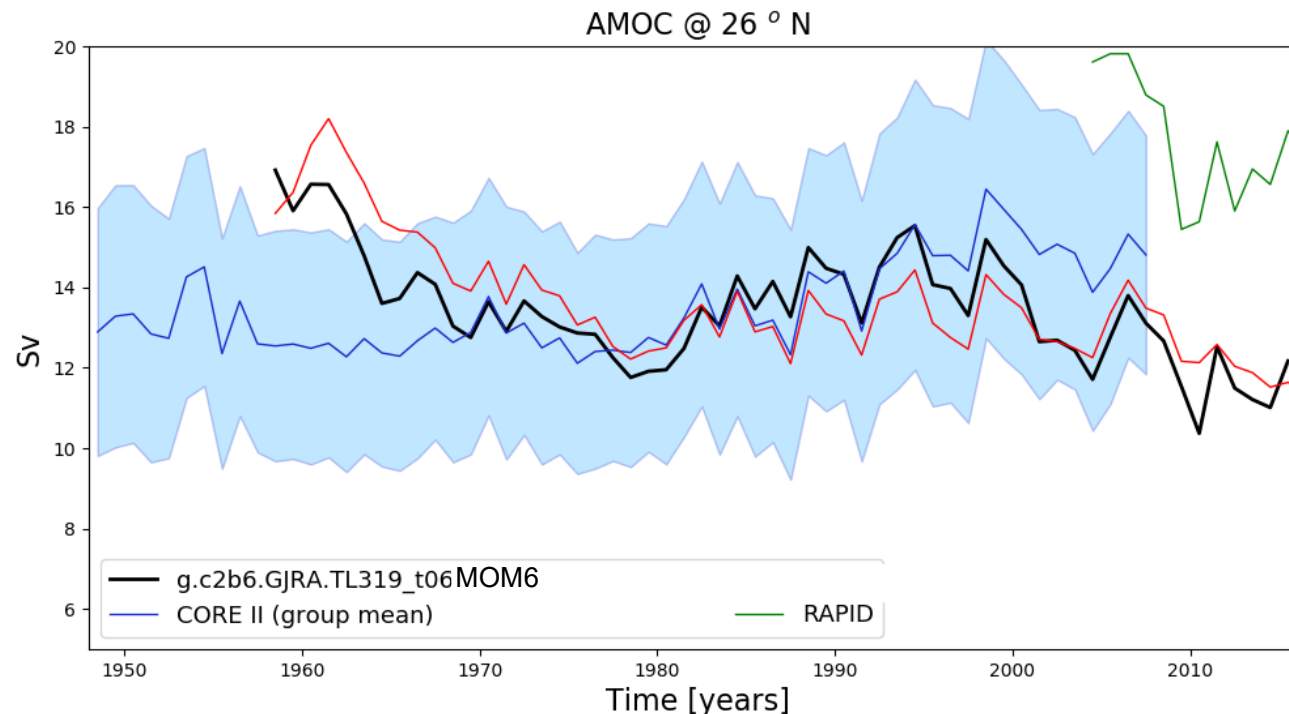
Modular Ocean Model version 6 (MOM6) in CESM3

A development prototype MOM6 version has been running within the CESM framework in ocean – sea-ice coupled and fully-coupled configurations;

The resolution is nominal $2/3^\circ$ in the horizontal (tripole grid with equatorial refinement) with 65 (z^*) levels in the vertical;

Conducting extensive simulations to gain experience and intuition for model sensitivities especially with the new approaches for mesoscale mixing parameter prescriptions

Atlantic Meridional
Overturning
Circulation at 26°N



Documentation and
Training Opportunities:
Webinars....algorithms,
practical, use cases

Early/friendly user
functional release of
MOM6 in CESM2.2