Large Ensembles

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CESM Tutorial 2019
Learning goals

- What is an Ensemble? What is a *Large* Ensemble?
- What can Large Ensembles be used for?
- Large Ensemble resources
What is an Ensemble?

Ensemble:
What is an Ensemble?

**Ensemble**: a group of items viewed as a whole rather than individually
Ensemble: a group of items viewed as a whole rather than individually

CMIP5 multi-model ensemble

Global temperature anomaly [°C]

-0.5 0 0.5 1 1.5 2 2.5


Time [Year]

Observations
Historical
RCP2.6
RCP4.5
RCP6.0
RCP8.5

Projections
What is a Large Ensemble?
What is a Large Ensemble?

Large Ensemble

>10 runs
What is a Large Ensemble?

**Single Model**

- CESM2

**Large Ensemble**

- >10 runs
What is a Large Ensemble?

Single Model Initial-Condition Large Ensemble

CESM2

>10 runs
What is a Large Ensemble?

Single Model Initial-Condition Large Ensemble (SMILE)

CESM2

>10 runs
What is a Large Ensemble?

**Single Model Initial-Condition Large Ensemble (SMILE)**

- CESM2

>10 runs
What is a Large Ensemble?

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What is a Large Ensemble?

**Single Model Initial-Condition Large Ensemble (SMILE)**

- CESM2
- >10 runs

![Graph](image-url)
What is a Large Ensemble?

**Single Model Initial-Condition Large Ensemble (SMILE)**

Lorenz equations

\[
\frac{dx}{dt} = \sigma(y - x),
\]

\[
\frac{dy}{dt} = x(\rho - z) - y,
\]

\[
\frac{dz}{dt} = xy - \beta z.
\]
What is a Large Ensemble?

**Single Model Initial-Condition Large Ensemble (SMILE)**

Lorenz equations

\[
\begin{align*}
\frac{dx}{dt} &= \sigma(y - x), \\
\frac{dy}{dt} &= x(\rho - z) - y, \\
\frac{dz}{dt} &= xy - \beta z.
\end{align*}
\]
What is a Large Ensemble?

**Single Model Initial-Condition Large Ensemble (SMILE)**

Lorenz equations

\[
\frac{dx}{dt} = \sigma(y - x),
\]

\[
\frac{dy}{dt} = x(\rho - z) - y,
\]

\[
\frac{dz}{dt} = xy - \beta z.
\]

The Concept of Predictability

Temperature forecast for Boulder

Temperature measured in Boulder

Courtesy Falko Judt
What is a Large Ensemble?

**Single Model Initial-Condition Large Ensemble (SMILE)**

*CESM2*
What is a Large Ensemble?

Single Model Initial-Condition Large Ensemble (SMILE)

CESM2

Global Mean Surface Temperature Anomaly (K)

Kay et al. (2015)
What is a Large Ensemble?

**Single Model Initial-Condition Large Ensemble (SMILE)**
What is a Large Ensemble?

**Single Model Initial-Condition Large Ensemble (SMILE)**

- CESM2

![Graph showing global mean surface temperature anomaly](image)

- 1850 control
- member 1
- observations

- >10 runs

**Diagram**

- Global Mean Surface Temperature Anomaly (K)
- Y-axis: -1.0 to 5.0
- X-axis: 1850 to 2100

- CESM2
What is a Large Ensemble?

**Single Model Initial-Condition Large Ensemble (SMILE)**

Graph showing global mean surface temperature anomaly (K) from 1920 to 2100, with a trend towards increasing temperatures. The graph includes observations, a model run labeled "1er 1", and a time series from 1850 to 2000. The model used is CESM2.
What is a Large Ensemble?

Single Model Initial-Condition Large Ensemble (SMILE)

CESM2

Global Mean Surface Temperature Anomaly (K)

-1.0

0.0

1.0

2.0

3.0

4.0

5.0

1920 1950 2000

observations
What is a Large Ensemble?

**Single Model Initial-Condition Large Ensemble (SMILE)**

- CESM2
- >10 runs
- 1920: perturb initial conditions

**Graph**

- Global Mean Surface Temperature Anomaly (K)
- Observations
- 1850
- 1920
- 1950
- 2000
- 2100
What is a Large Ensemble?

Single Model Initial-Condition Large Ensemble (SMILE)

Global Mean Surface Temperature Anomaly (K)

-1.0  0.0  1.0  2.0  3.0  4.0  5.0

1850 control  member 1  observations

1850  1900  1920  1940  1960  1980  2000  2050  2100

>10 runs
What is a Large Ensemble?

**Single Model Initial-Condition Large Ensemble (SMILE)**

![Graph showing Global Mean Surface Temperature Anomaly](image)

- CESM2
- >10 runs
- Observations: members 2-30
- 1850 control, member 1

**Graph Details:**
- X-axis: Years from 1850 to 2100
- Y-axis: Global Mean Surface Temperature Anomaly (K)
- Light blue line: 1850 control
- Red line: member 1
- Grey shaded area: range of observations from members 2 to 30
What is a Large Ensemble?

**Single Model Initial-Condition Large Ensemble (SMILE)**

*After Deser et al. (2012)*
What is a Large Ensemble?

**Single Model Initial-Condition Large Ensemble (SMILE)**
What is a Large Ensemble?

**Single Model Initial-Condition Large Ensemble (SMILE)**

*CESM2*
What is a Large Ensemble?

**Single Model Initial-Condition Large Ensemble (SMILE)**

- **Average over all simulations**
- **Warmest simulation**
- **Coldest simulation**

**Maps**
- Global temperature trends
- USA temperature trends
- Seattle temperature trends

**Graphs**
- Observations vs. Projections
- Time series of temperature anomalies

*CESM2*
What can Large Ensembles be used for?
What can Large Ensembles be used for?

Interpret the observational record

Deser et al. (2016)
What can Large Ensembles be used for?

- Interpret the observational record
- Assess forced response and partition uncertainty

Interpret the observational record

Assess forced response and partition uncertainty

Deser et al. (2016)

Hawkins & Sutton (2009)
Deser et al. (2019)
What can Large Ensembles be used for?

Interpret the observational record

Assess forced response and partition uncertainty

Study internal variability

Deser et al. (2016)

Hawkins & Sutton (2009)
Deser et al. (2019)

Pendergrass et al. (2017)
What can Large Ensembles be used for?

**Interpret the observational record**

- [Image: Map showing temperature anomalies across the world.]
- **Deser et al. (2016)**

**Assess forced response and partition uncertainty**

- [Image: Graph showing fractional uncertainty (%) over time.]
- Hawkins & Sutton (2009)
- Deser et al. (2019)

**Study internal variability**

- [Image: Histograms showing precipitation trends in different seasons.]
- Pendergrass et al. (2017)

**Test new methods**

- [Image: Bar chart showing precipitation trend.]
- Lehner et al. (2018)
Large Ensemble resources

CESM1 Large Ensemble (CESM2 Large Ensemble with 100 ensemble members planned)
Large Ensemble resources

CESM1 Large Ensemble (CESM2 Large Ensemble with 100 ensemble members planned)

Multi-Model Large Ensemble Archive (MMLEA):

- Set of variables from different CMIP5-class LEs
- CMORized and made publicly available (CDG and Cheyenne)
- Includes Observational-LE for temperature and precipitation
- Goal of facilitating model comparison and evaluation - accelerating scientific discovery
- Idea for it to grow with community input (more variables, new LEs, new Observational-LEs, etc.)

www.cesm.ucar.edu/projects/community-projects/MMLEA/
Large Ensemble resources

**CESM1 Large Ensemble** (CESM2 Large Ensemble with 100 ensemble members planned)

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[Table of Modeling Centers, Model Versions, Model Resolution, Years, Initialization Method, Number of Members, and other details]

**SMILE email list:**
https://listserv.gwdg.de/mailman/listinfo/smile

[Website link for CESM1 Large Ensemble](www.cesm.ucar.edu/projects/community-projects/MMLEA/)
Large Ensemble resources

**CESM1 Large Ensemble** (CESM2 Large Ensemble with 100 ensemble members planned)

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[Table showing details of the Multi-Model Large Ensemble Archive]

**SMILE email list:**
https://listserv.gwdg.de/mailman/listinfo/smile

**Thanks!**
flehner@ucar.edu

[Link to CESM website]
What is a Large Ensemble?

Uncertainty in climate change projections: the role of internal variability

Clara Deser · Adam Phillips · Vincent Bourdette · Haiyan Teng

Communication of the role of natural variability in future North American climate

Clara Deser¹*, Reto Knutti¹, Susan Solomon² and Adam S. Phillips¹

As climate models improve, decision-makers' expectations for accurate climate variability, however, pose inherent limits to climate predictability and the related go illustrated here for North America. Other locations with low natural variability show pogenic forcing can be more readily identified, even on small scales. We call for a more modern and the public to improve communication and avoid raising expectations for
Limitations of a single LE

Model biases in decadal variability

“…indicating that the forced warming signal emerges earlier in observations than suggested by models.”

Lehner at al. (2017)

Model biases in 50-year trends, assessed using an observational LE

“…[it] is easier to detect the historical climate change signal in observations than in any given member of LENS.”

McKinnon at al. (2017)
Beyond a single LE

**US CLIVAR Working Group on Large Ensembles**

“Foster exchange of ideas relevant to LEs across disciplines (i.e., atmosphere, ocean, land, biogeochemistry)”

[usclivar.org/working-groups/large-ensemble-working-group](usclivar.org/working-groups/large-ensemble-working-group)

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**Creation of a Multi-Model Large Ensemble Archive (MMLEA):**

- Set of variables from different CMIP5-class LEs
- CMORized and made publicly available (CDG and Cheyenne)
- Includes Observational-LE (see Karen’s talk)
- Goal of facilitating model comparison and evaluation - accelerating scientific discovery
- Idea for it to grow with community input (more variables, new LEs, new Observational-Les, etc.)

Application #1: Interpretation of observational record

Temperature trend annual 1951-2010

Ensemble mean

(a) CESM1 EM (40) 1.02

(d) MPI EM (100) 1.52

(g) Observations 1.22

Temperature (°C 60yr⁻¹)

-3 -2.5 -2 -1.5 -1 -0.5 0 0.5 1 1.5 2 2.5 3
Application #1: Interpretation of observational record

Temperature trend annual 1951-2010

Ensemble mean

(a) CESM1 EM (40) 1.02
(b) CESM1 #22 1.61
(c) CESM1 #20 0.53

Strongest trend

(d) MPI EM (100) 1.52
(e) MPI #60 2.01

Weakest trend

(g) Observations 1.22

(f) MPI #48 0.96

Temperature (°C 60yr⁻¹)
Application #1: Interpretation of observational record

Temperature trend annual 1951-2010

Ensemble mean
- CESM1 EM (40)
- MPI EM (100)
- Observations

Strongest trend
- CESM1 #22
- MPI #60

Weakest trend
- CESM1 #20
- MPI #48

Deser at al. (submitted)
Application #1: Interpretation of observational record

Temperature trend annual 1951-2010

- Ensemble mean
  - CESM1 EM (40) 1.02
  - MPI EM (100) 1.52
  - Observations 1.22

- Strongest trend
  - CESM1 #22 1.61
  - MPI #60 2.01

- Weakest trend
  - CESM1 #20 0.53
  - MPI #48 0.96

→ All models consistent with observations, but that might be a low bar
Application #2: Evaluation of model variability

Temperature trend annual 1951-2010

Area with Signal-to-Noise > 2

Deser at al. (submitted)
Application #2: Evaluation of model variability

Temperature trend annual 1951-2010

Area with Signal-to-Noise > 2

Deser at al. (submitted)
Application #2: Evaluation of model variability

Temperature trend annual 1951-2010

- OBS-LE: estimate of real-world variability in trends

Deser at al. (submitted)
Application #2: Evaluation of model variability

Temperature trend annual 1951-2010

(a) CESM1
(b) MPI
(c) OBS-LE

Noise (σ_trends)

CESM1 σ_trends
57.1%

MPI σ_trends
41.5%

OBS-LE σ_trends

(d) CESM1 EM_trends
58.1%

(e) MPI EM_trends
97%

Signal-to-Noise (EM_trends/σ_trends)

Area with too much variability

Deser at al. (submitted)
Application #2: Evaluation of model variability

Temperature trend annual 1951-2010

Area with Signal-to-Noise > 2

Deser at al. (submitted)
Application #2: Evaluation of model variability

Temperature trend annual 1951-2010

(a) CESM1 $\sigma_{trends}$ 57.1%
(b) MPI $\sigma_{trends}$ 41.5%
(c) CanESM2 $\sigma_{trends}$ 36.8%
(d) OBS-LE $\sigma_{trends}$

(e) CSIRO-Mk3-6-0 $\sigma_{trends}$ 26.8%
(f) GFDL-CM3 $\sigma_{trends}$ 34%
(g) GFDL-ESM2M $\sigma_{trends}$ 52.5%
(h) EC-EARTH $\sigma_{trends}$ 39.3%
Application #3: Uncertainty partitioning

Didn’t have LEs, thus needed to make assumptions about the forced response of each model: 4th order polynomial fit to a single ensemble member.
Repeat H&S09 analysis with 7 LEs
Application #3: Uncertainty partitioning

(a) North America temperature (annual)

(c) Seattle precipitation (DJF)
Other applications and documentation of MMLE Archive

**Strength in Numbers: The Utility of Large Ensembles with Multiple Earth System Models**

US CLIVAR Working Group on Large Ensembles

Perspective submitted 21 June 2019 to *Nature Climate Change*

Feedback welcome on MMLE Archive
Contributions welcome
Updates and bug fixes planned later this summer