AIBEDO MILESTONE REPORT 5

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Problem statement

- Clouds modulate the Earth's radiation budget. They impact atmospheric radiation, surface temperature, precipitation among many others.
- This makes clouds ideal for climate intervention such as '**Marine Cloud Brightening**'→ engineer the climate by changing low clouds using sea spray aerosol injections in the boundary layer
- Designing such intervention experiments are computationally expensive in conventional models (Earth System Models).

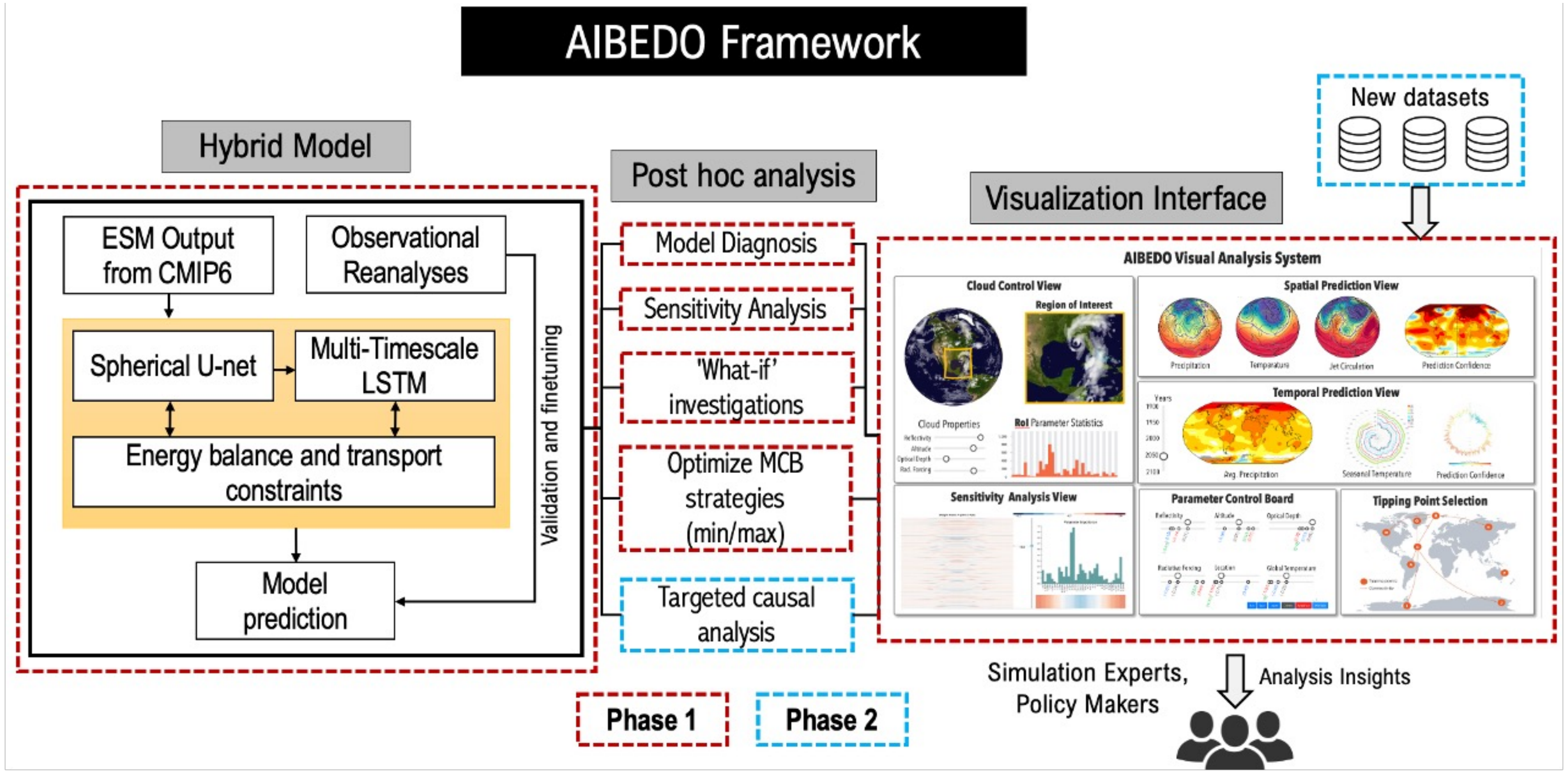
- **Goal**: Use AI to Construct a Clouds → Climate Response Function

$$\Omega(S): \quad \delta C(\vec{x}, h, \tau) \rightarrow \begin{cases} \delta\Psi_{atm}(\vec{x}) \\ \delta\Psi_{ocn}(\vec{x}) \\ \delta T_s(\vec{x}) \\ \delta P(\vec{x}) \end{cases}$$

A Perturbation in Low Clouds

Circulation and Surface Climate Response

We develop a physics-informed machine learning model to emulate the response function. This is an **order of magnitude faster** than conventional models making them ideal for scenario generation, search of large parameters, etc.



- AIBEDO is a hybrid AI model framework developed to resolve the weaknesses of Earth System Models by generating rapid and robust multi-decadal climate projections. We will demonstrate its utility using marine cloud brightening scenarios—to avoid climate tipping points, and consequences of ill-planned interventions.
- Our hybrid model consists of a Spherical U-Net (spatial), and Multi-timescale LSTM (temporal) module bolstered by physics constraints. Our model will be trained on 20 CMIP6 model ensemble data, and validated against observational reanalysis data.
- The interactive nature of AIBEDO with parameter controls provides a unique tool for policymakers and modelers alike to perform 'what-if' investigations, run climate related scenarios, or identify consequences of ill-planned, or rogue MCB experiments.

Overview of Milestone 5

- Objective:

  Identify potential datasets and providers for Phase 2 to address predictability of climate effects

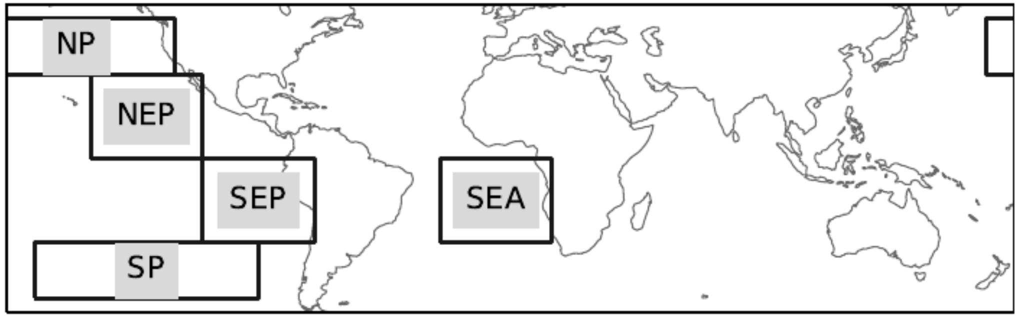
- Updates Overview:

  1. AIBEDO Marine Cloud Brightening Experiments
  2. Phase 2 data providers (datasets, experiments)
  3. Model development update—Temporal spherical U-net
  4. Physics constraints—denormalization, monthly vs. annual
  5. Comparison of AIBEDO prediction on different CMIP model ensembles
  6. Documentation update

Marine Cloud Brightening experiments using AIBEDO

- Targeted cloud perturbations in Earth System Models (ESM) is done by modifying a variable called CDNC (*Cloud Droplet Number Concentration*) within clouds
- This is a not a <u>direct</u> input variable to AIBEDO. However, CDNC can be mapped to AIBEDO input variables
- In Phase 2, we will generate datasets with targeted cloud perturbations with known CDNC. The output of ESMs for those experiments will consist of variables that can be provided to AIBEDO as input (Net Surface temperature, net clearsky radiation, etc.)
- We will then compare the ESM and AIBEDO runs to determine how well AIBEDO replicates the cloud perturbation runs.
- If AIBEDO performs well for these cloud perturbations, we will generate a mapping function between CDNC and AIBEDO input variables. This enables the modeler to direct perform MCB experiments using AIBEDO.

Phase 2 Data



- Provider: University of Washington (Dr. Phil Rasch and team)
- Datasets: Strategically perturbed Marine Cloud Brightening experiment runs in CESM2, E3SM and UKMO Earth System Models
- A targeted cooling will be established for five geographic regions with a total cooling that is intended to counteract some of the warming associated with doubling of CO_2.

- The project will first introduce perturbations in the cloud fields in the Earth System models in 5 regions of the planet (shown above).
- And then introduce similar changes in the AIBEDO model to see how accurate the AI model is reproducing or predicting the response of the GCM

Phase 2 Data (contd.)

- The specific science questions to be addressed by these experiments are:
  - What are the climatic consequences of increasing the albedo in regions of the planet known for persistent marine cloud distributions?
  - Are the climate effects linear with respect to the regions?
  - How do the climate responses scale with the amplitude of the forcing?
  - Is the response to MCB sensitive to the background state of the atmosphere? Interannual, decadal, longer?
  - Are consistent signatures seen across models? e.g. Amazon precipitation? Impacts on sea ice and polar climate?
  - What is the variability of the climate response?
  - Can one "optimize" the MCB to achieve particular climate goals, such as avoid tipping points?

Phase 2 Data (contd.)

- The AIBEDO team will participate in this inter-model comparison by contributing CESM2 simulations

ID	Simulation Name	Model Configuration	Description	Length (model years x ensemble members)
1	MCB Calibration R1 + R2 + R3	Fixed-SST	Short atmosphere-only experiments aimed at identifying CDNC values in NE Pac (R1), SE Pac (R2), and SE Atl (R3) required to achieve -1.8Wm-2 forcing	10 x 5
2	E3SM Control	Fully Coupled	Control SSP2-4.5 experiments	2015 to 2070 x 10
3	E3SM Control	Fully Coupled + CDNC Fixed R1	SSP2-4.5 experiments with CDNC forcing applied in the NE tropical Pacific	2015 to 2070 x 3
4	E3SM Control	Fully Coupled + CDNC Fixed R2	SSP2-4.5 experiments with CDNC forcing applied in the SE tropical Pacific	2015 to 2070 x 3
5	E3SM Control	Fully Coupled + CDNC Fixed R3	SSP2-4.5 experiments with CDNC forcing applied in the SE tropical Atlantic	2015 to 2070 x 3
6	E3SM Control	Fully Coupled + CDNC Fixed R1 + R2 + R3	SSP2-4.5 experiments with CDNC forcing applied in the NE Pac, SE Pac, and SE Atl	2015 to 2070 x 10

More details on Phase 2 Experiments can be found in the documentation website.

AIBEDO Model Development Update

- In our previous milestone, we had reported that we included a short-term lag response of 3 months to capture the effects of cloud perturbations
  - We augmented the Spherical U-net that does simultaneous predictions to a "Temporal Spherical U-Net" algorithm
  - We have included the code in the documentation page
- We are also exploring additional methodologies such as Spherical Convolutional LSTM model to capture this relationship
  - In the upcoming months, we will be developing several 'baseline' models such as Convolutional Neural Networks, 3D CNN, etc. to compare the performance of spherical U-Net

AIBEDO Model Development Update (Contd.)

- We removed a few input variables after consulting with MCB experts to facilitate easy tuning of AIBEDO for MCB experiments—the output variables remain the same (temperature, surface pressure, and precipitation)

lcloud - Low cloud amount
clwvi - Mass of cloud liquid water in a column
clivi - Mass of cloud ice water in a column
cres - TOA cloud radiative effect in shortwave
crel - TOA cloud radiative effect in longwave
cresSurf - Surface Cloud radiative effect in shortwave
crelSurf - Surface Cloud radiative effect in longwave
netTOAcs - Net clearsky TOA radiation
netSurfcs - Net clearsky Surface radiation
lsmask - Land Sea Mask

- The variables highlighted in orange are removed from the model.
- While these variables enhance the performance of AIBEDO to emulate the climate response of clouds, it is more difficult to engineer MCB experiments with those present.
- Our preprocessed datasets will however have those, which can be used by others for different applications.

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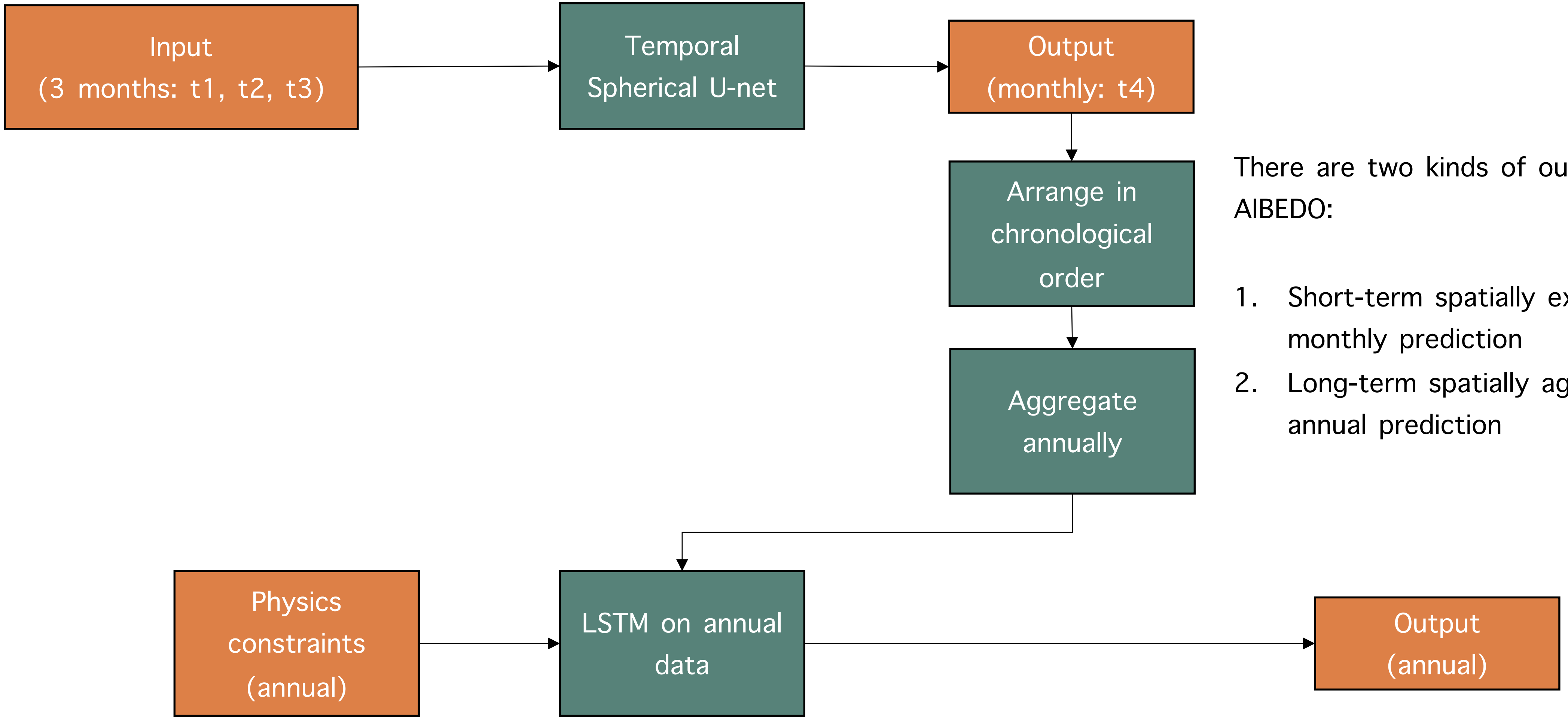
AIBEDO Model Development Update (Contd.)

- We proposed to include a multi-timescale component in AIBEDO—to capture short-term and long-term impacts
- Temporal Spherical U-net captures the 3-months lag response (short-term response) of cloud perturbations
- We developed an additional Long Short-Term Memory (LSTM) network based on model output from the Temporal Spherical U-net model to capture the decadal trends

AIBEDO Model Development Update (Contd.)

Schematic of Multi-Timescale LSTM feature of AIBEDO

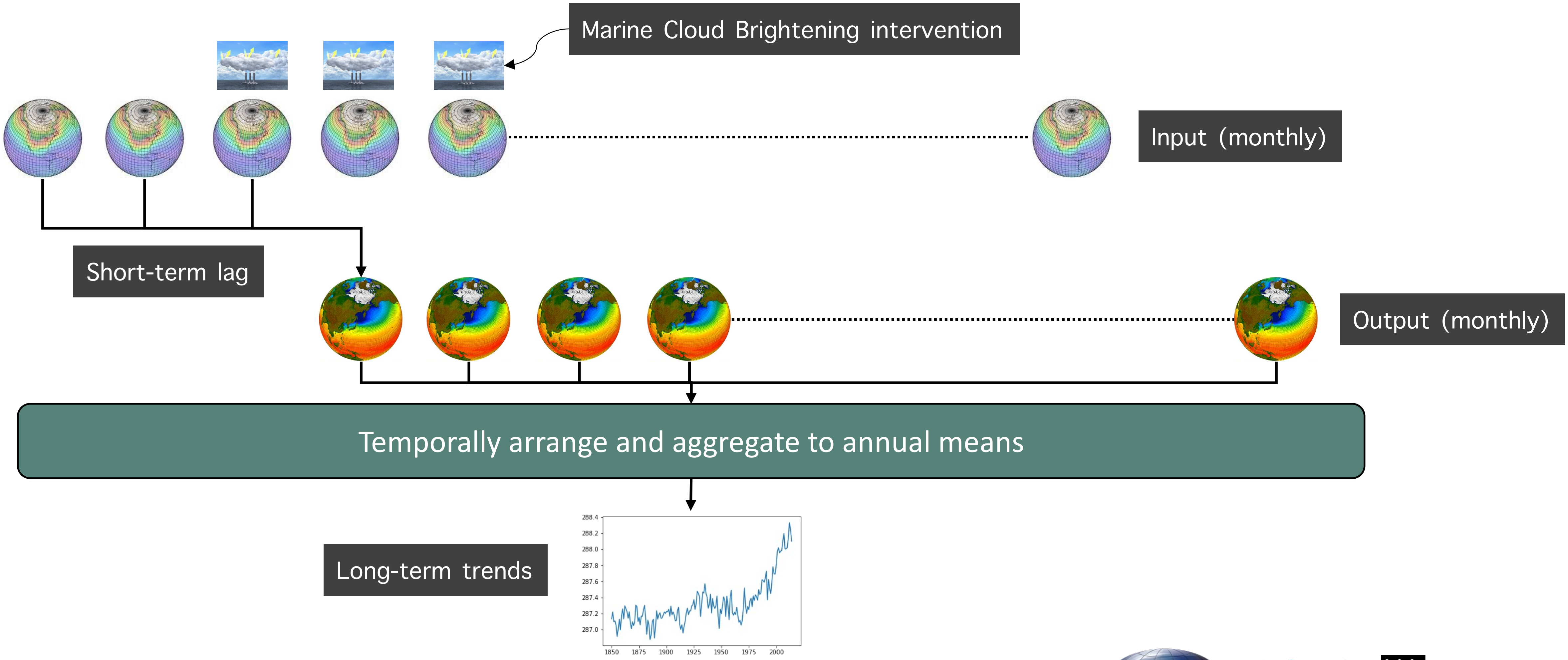


There are two kinds of output from AIBEDO:

1. Short-term spatially explicit monthly prediction
2. Long-term spatially aggregated annual prediction

AIBEDO Model Development Update (Contd.)

Schematic of AIBEDO during MCB experiments

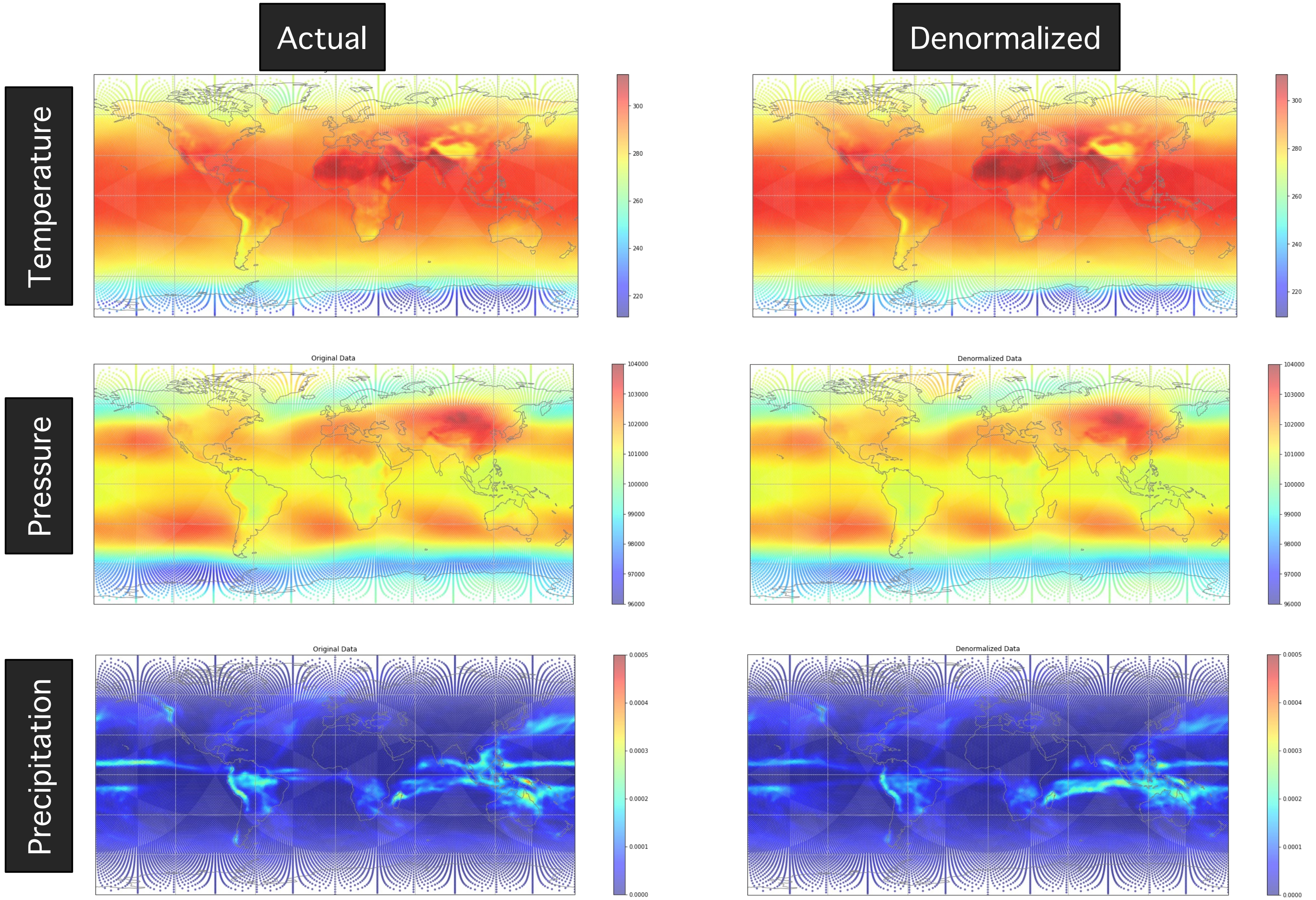


AIBEDO Model Development Update (Contd.)

- We reported in our previous report about how our preprocessing steps include ‘normalization’ of input and output variables
- This shifts the variables to a different space, hence to add physics constraints they had to be ‘denormalized’.
- We selected **CMIP6 multi-ESM ensemble average climatology and variability** for the denormalization
- We compared the actual and denormalized data to verify and confirmed that this method works well to map the data back and forth to normalized values

AIBEDO Model Development Update (Contd.)

Actual vs. Denormalized values from CMIP6 multi-ESM ensemble average climatology and variability



- The reconstruction of normalized data using the CMIP-6 multi—ESM ensemble average climatology and variability works best for surface pressure, followed by surface air temperature.
- Denormalization of precipitation performs the worst among the three, specifically in tropics.

AIBEDO Model Development Update (Contd.)

- Several of our physics constraints are annual conditions (e.g. mass conservation)
- While these can be directly included for the longer-term model (Annual LSTM), these need to be modified to appropriate monthly terms for the short-term Temporal Spherical U-Net model
- We are exploring methodologies to generate month-wise mean and standard deviation that can be used to apply these constraints in the short-term model.

Conference/Publications

- Kalai Ramea will be speaking at re:MARS about AIBEDO (June 22, 2022)
- Haruki Hirasawa will be presenting AIBEDO at Gordon Research Conference (June-July 2022)

Ongoing work

- We are incorporating physics constraints for both short-term and long-term models
- We are benchmarking AIBEDO trained on CMIP6 models against observational reanalysis data
  - These sub-selected datasets will be used for training AIBEDO
- We are comparing AIBEDO trained on one CMIP6 model ensemble against other CMIP6 (to understand deviations in variability)
- We are finetuning MCB experiments for Phase 2 dataset generation
- We have ongoing conversations with MCB experts to develop the visual analysis interface