Deep Learning on a Novel Ising Model to Study Arctic Sea Ice Dynamics

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Presentation Roadmap

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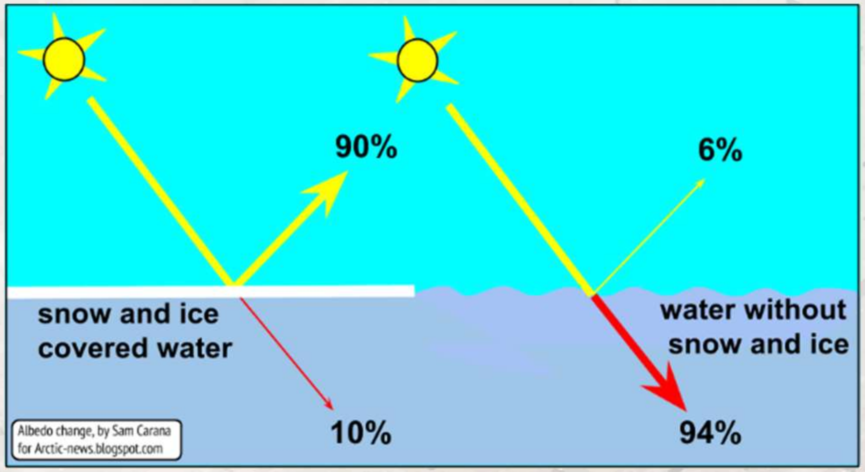
01

Significance

Why sea ice dynamics?

Sea Ice for climate change

- Ice coverage is widely acknowledged as a crucial indicator of global climate change
- Light-colored ice is essential to maintaining the cold temperature in the polar regions and subsequently the energy balance around the globe



Albedo, latent heat, insolation and more (2012)
https://arctic-news.blogspot.com/p/albedo.html

NASA Estimation

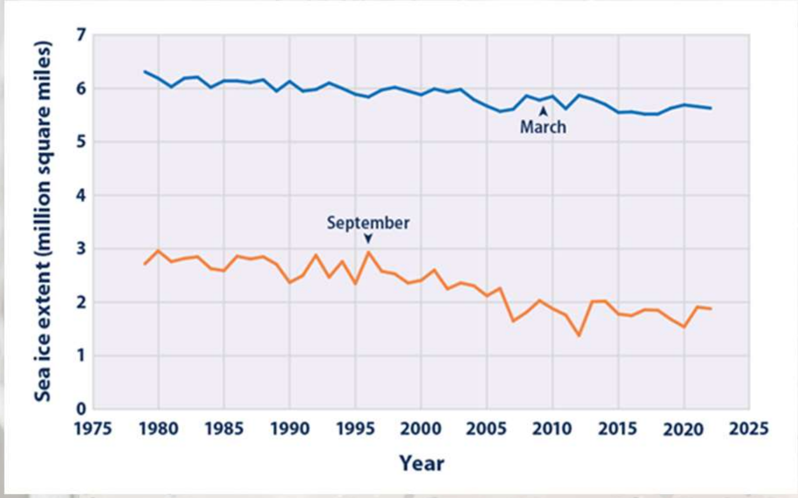
12.3%

September Arctic sea ice is now shrinking at a rate of 12.3% per decade

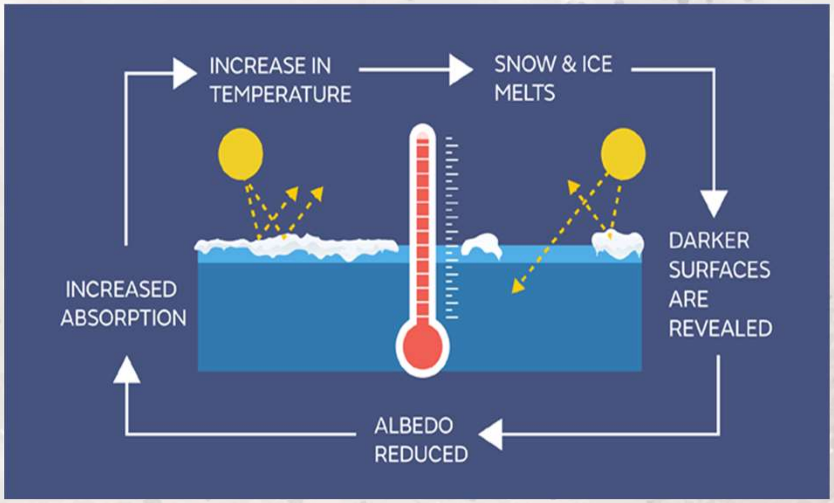
95%

Over the past 30 years, the oldest and thickest ice in the Arctic has declined by a stunning 95%.

- **Alarming sea ice loss has been detected in recent years**
- **The continued decline in ice coverage may lead to the feedback loop effect that furthers global warming and harms ecosystems**

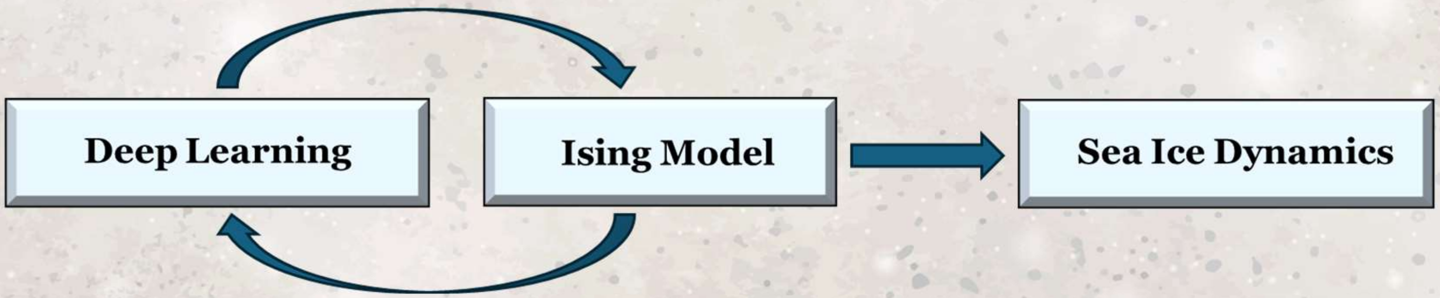


Climate change indicators: Arctic Sea Ice | US EPA. (n.d.) https://www.epa.gov/climate-indicators/climate-change-indicators-arctic-sea-ice



Sea ice in the climate system. Met Office. (n.d.). https://www.metoffice.gov.uk/research/climate/cryosphere-oceans/sea-ice/index

- Sea ice loss has been detected in recent years, a crucial indicator of global climate change; it is critically urgent to better model the sea ice dynamics.
- Many sea ice studies use machine learning without identifying the key physical principles underlying the dynamics.
- This pioneering research combines the classical Ising model in statistical physics with deep learning, unleashing their strong explanatory power of capturing the sea ice transition dynamics.
- Research framework as follows:



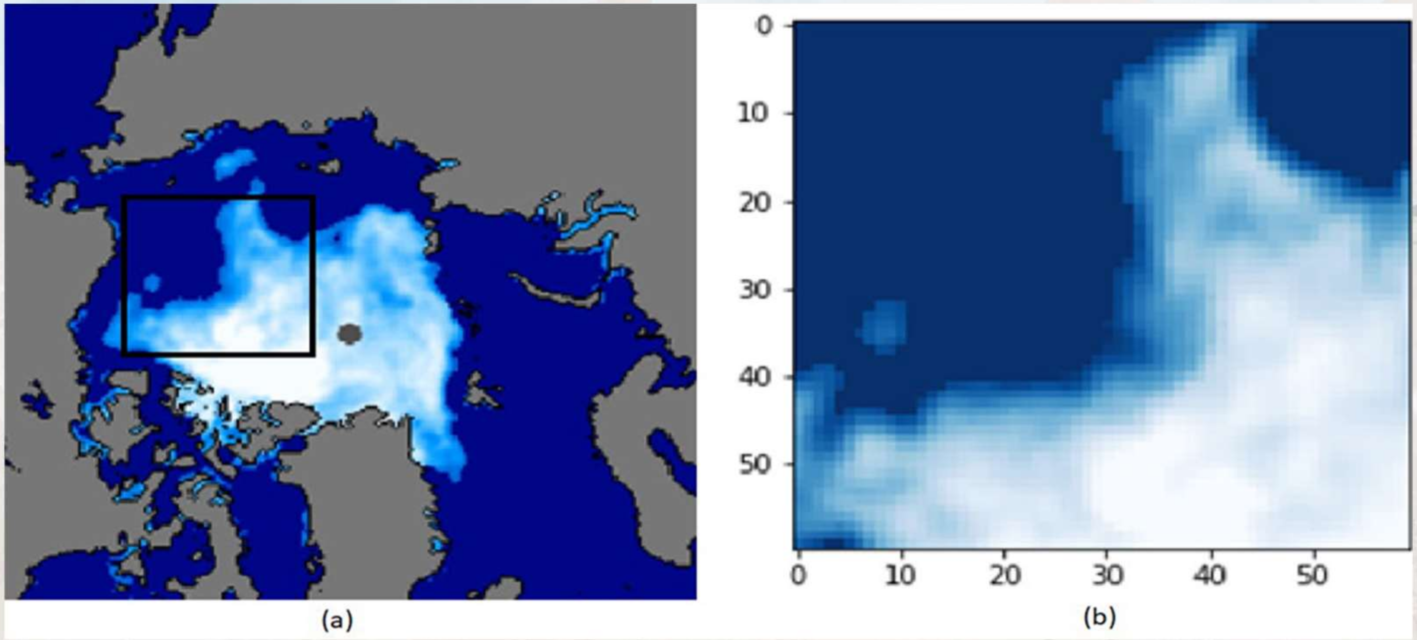
02

Data

Public dataset and the focus area for our study

Data

- Sea ice data has been diligently collected by *the National Snow and Ice Data Center (NSIDC).*
- Their publicly accessible data, called *"Near-Real-Time DMSP SSMIS Daily Polar Gridded Sea Ice Concentrations" (NRTSI)* records daily sea ice concentrations for both the Northern and Southern Hemispheres. These concentrations are generated based on the microwave brightness temperature detected by NASA's satellite sensor.
- Each NRTSI file contains a lattice of 448 rows by 304 columns, covering a large earth surface area with the north pole at the center. Each grid cell represents an area of approximately 25 kilometers by 25 kilometers, with an integer value from 0 to 250 that indicates the fractional ice coverage scaled by 250.



(a) Part of the NRTSI data on Sept 16th, 2022

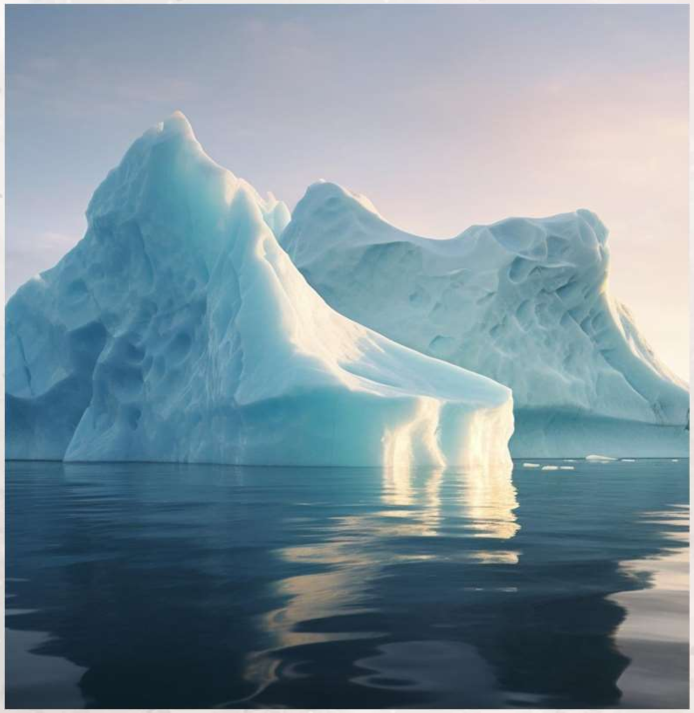
(b) The focus area for this study (black box), a 60x60 square lattice covering approximately 2.25 million square kilometers

03

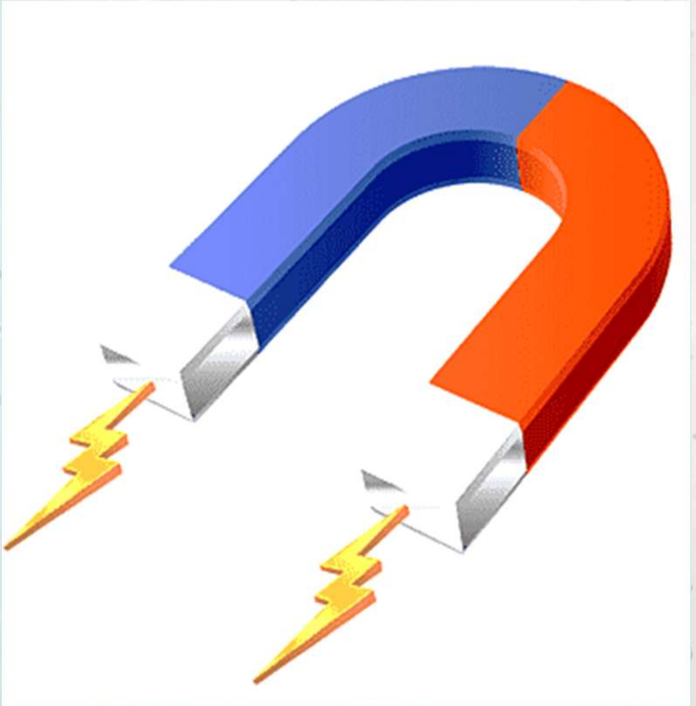
Physics Model

The classical Ising Model and new features

Ising Model



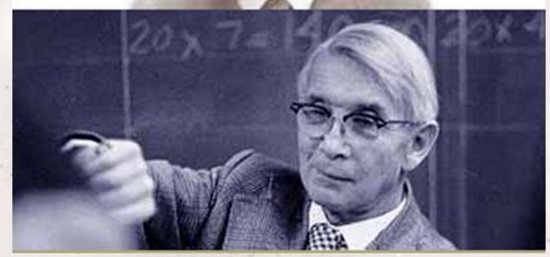
Can you see the similarity between ice-water transition and magnets?



Ising Model

- A brief history of Ising Model
  - Physicist Wilhelm Lenz proposed this whole idea of constructing a mathematical model to analyze the equilibrium and phase transition in magnetic systems.
  - Ising was able to solve the model in his 1924 Ph.D. thesis, but the 2-D version was only given an analytic description much later, by Lars Onsager (1944).
  - In recent years, Ising model has seen wide success in many fields outside of physics, including biology, environmental science, machine learning, social science etc.

- Ising Model proves to be an excellent model to investigate the ice/water evolution, given their reversible phase transitions year-round



Beitrag zur Theorie des
Ferro- und Paramagnetismus

1924

Dissertation

zur Erlangung der Doktorwürde
der Mathematisch-Naturwissenschaftlichen Fakultät
der Hamburgischen Universität
vorgelegt von

Ernst Ising
aus Bochum.

Hamburg
1924.

Ising Model: Theoretical Framework

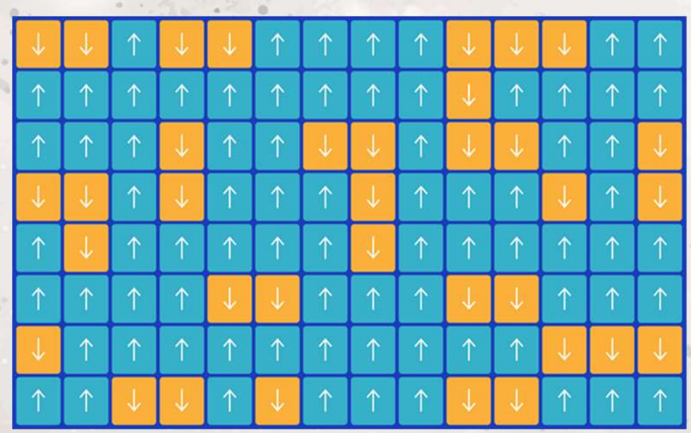
The Hamiltonian for the lattice σ in a standard IM is given as

$$H(\sigma) = -\sum_{<i,j>} J_{ij}\sigma_i\sigma_j - \sum_i B_i\sigma_i$$

The probability of any configuration follows

$$P_\beta(\sigma) = \frac{e^{-\beta H(\sigma)}}{Z_\beta},$$

where $Z_\beta = \sum_\sigma e^{-\beta\quad(\sigma)}$, $\beta = (k_B T)^{-1}$.



Quanta Magazine (2021, February 26) https://www.quantamagazine.org/the-cartoon-picture-of-magnets-that-has-transformed-science-20200624/

Ising Model: New Features

- The spin values in our study are allowed to be any real number between +1 (100% water) and -1 (100% ice).

- In this continuous Ising Model, the challenge to capture the random distribution of the post-flip spin value is addressed by introducing an innovative inertia factor *I*, which determines the probability of each flip as

$$P_{flip} = e^{-\beta(\underbrace{H_\nu - H_\mu}_{} + \underbrace{I\,|\sigma_i' - \sigma_i\,|}_{})}$$

The system Hamiltonian before and after the flip

The energy needed to overcome the inertia of the spin change, a term representing the natural resistance to state change, or the latent heat needed for the water/ice phase transition in classical thermodynamics.

04

Convolutional Neural Networks

Deep learning model to sovle the inverse Ising problem

Artificial Neural Networks

- Artificial neural networks (ANN) are a branch of artificial intelligence and machine learning inspired by the structure and functioning of the human brain.
- ANN consists of a collection of neurons that are interconnected
- Most modern deep learning models are based on multi-layered ANNs.

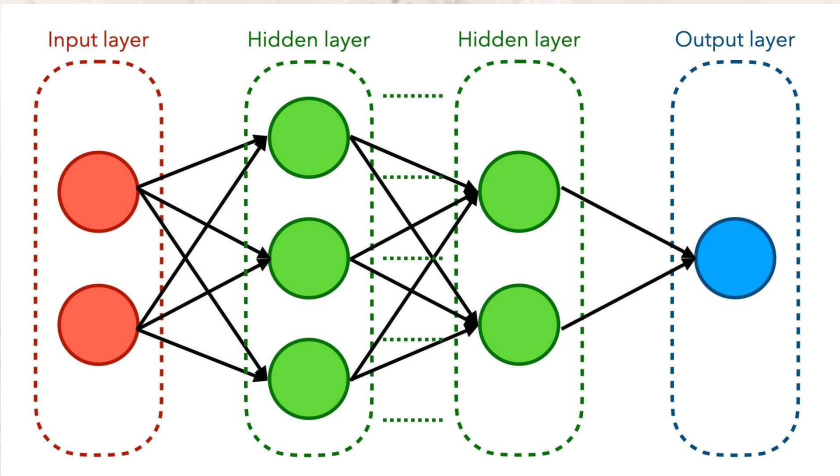


Illustration of multi-layered neural network
https://towardsdatascience.com/an-illustrated-guide-to-artificial-neural-networks-f149a549ba74

Convolutional Neural Networks

- Convolutional Neural Networks (CNN) are a type of ANN specialized to analyze data with grid-like topology
- CNN revolutionized computer vision in the 2010s
- The key of CNNs is convolutional layers, which employ a mathematical operation called convolution. A convolutional layer consists of kernels, or filters. The kernels slide along the input grid and compute the weighted sums, followed by an activation function to produce outputs.

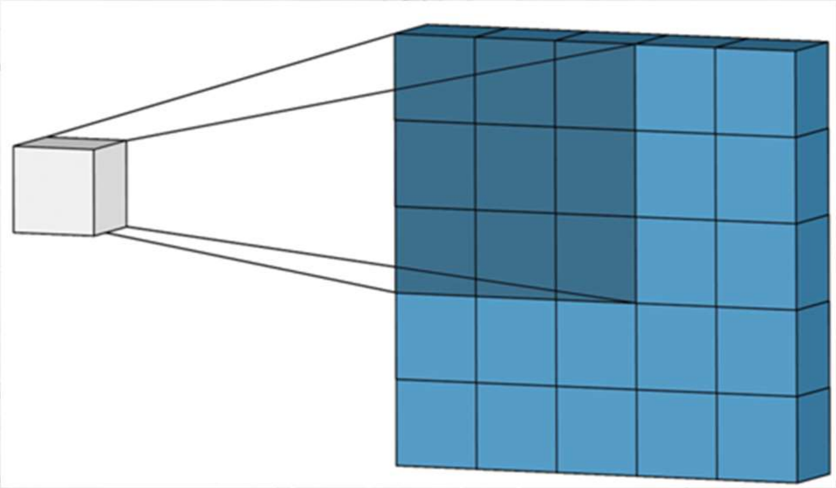
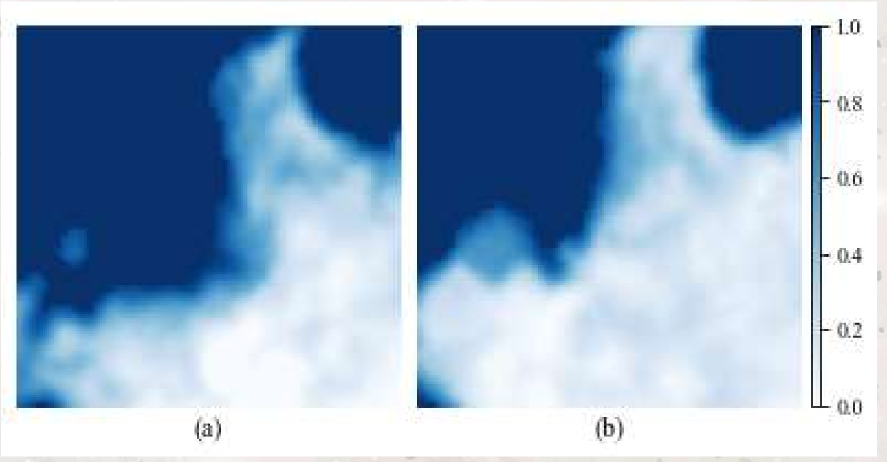


Illustration of convolution operation:
a (3x3) kernel applied to a (5x5) image
https://towardsdatascience.com/convolutional-neural-networks-explained-9cc5188c4939

CNN: Solve the Inverse Ising Problem



The initial and the final target states of an IM lattice simulation run, for instance , from (a) Sept 16th, 2022 to (b) Oct 1st, 2022

Can we train a deep learning model to recognize the differential of the initial and final state ice/water configurations, and to predict the Ising model parameters?

05

MCMC Simulation

The procedures and the programming pachakges

Simulation Setup

1

Prep

Conversion of NRTSI data into 60x60 Ising lattice

2

Period

Chosen to be consistenly half a month apart

3

Parameters

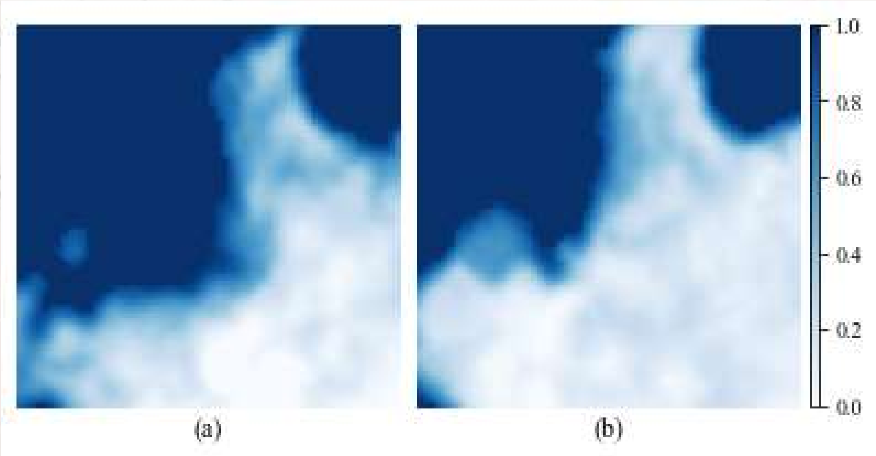
J_{ij}, I set to be constant each period

$\beta = 1$

$B_i = B_0 + B_x(x_i - x_0) + B_y(y_i - y_0)$

Ready!

Simulation Method: Metropolis MCMC



The initial and the final target states of an IM lattice simulation run, for instance , from (a) Sept 16th to (b) Oct 1st, 2022

- **Our goal is to find a set of Ising parameters *(J,* B_0, B_x, B_y *, I)* to match the observed final state lattice configuration as closely as possible upon the completion of the IM simulations**
- **Various Monte Carlo methods have been developed for the IM simulation. In this study, we follow the Metropolis-Hasting algorithm, a type of Markov Chain Monte Carlo (MCMC), for the simulation of the IM lattice evolution**

Simulation Steps

Repeat these MC steps 50,000 times for each semi-monthly simulation period

1 Select cell *i* at random from the 2-D lattice of the focus area. Let spin value of this cell be σ_i.

2 Generate another random variable σ'_i between -1 and +1.

3 Compute the energy change ΔH_i = $H_\nu - H_\mu$ from σ_i to σ'_i, the energy $I \mid \sigma'_i - \sigma_i \mid$ to overcome the inertia of changing spin value at *i*, and the total energy change ΔE = ΔHi + $I \mid \sigma'_i - \sigma_i \mid$

4

- If $\Delta E < 0$, the energy change is favorable since the energy is reduced. The spin value change is therefore accepted to σ'_i ;
- If $\Delta E > 0$, the probability of spin flip is determined by the Boltzmann distribution. In this case, another random variable *r* between 0 and 1 is generated. If *r* is less than $P = e^{-\beta \Delta E}$, the spin value change σ'_i is accepted; otherwise, the change is rejected and the spin value at *i* stays at σ_i.

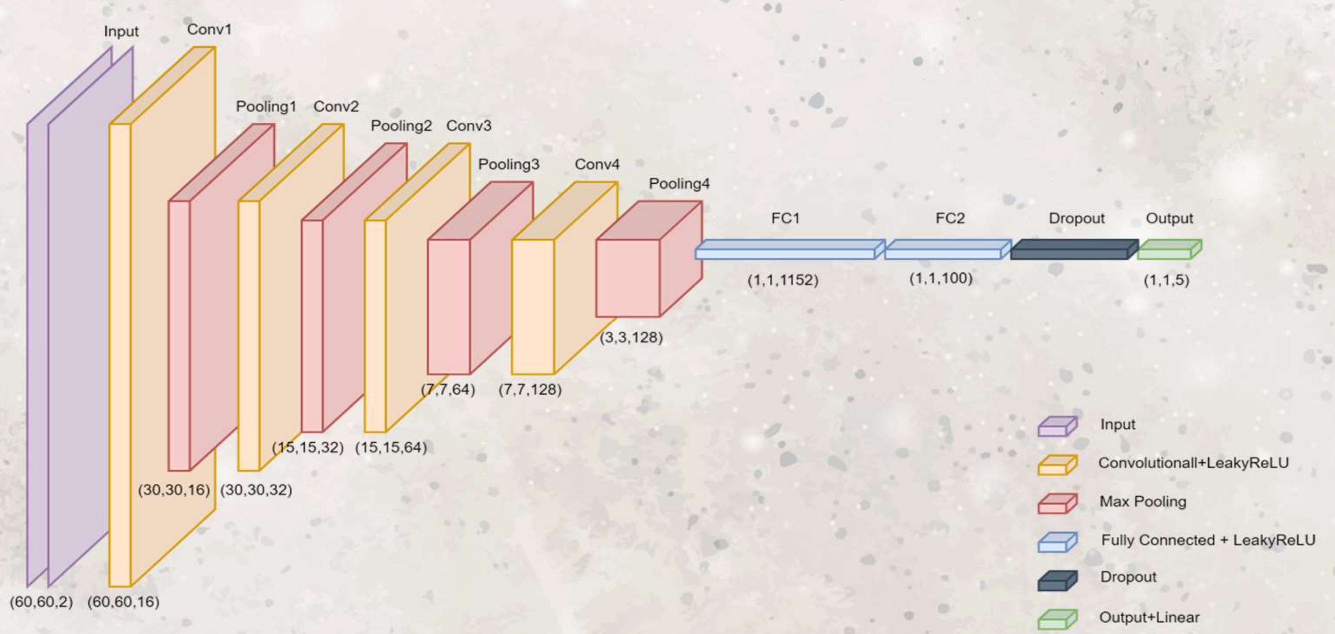
06

CNN Architecture

Neural Network architecture and training process

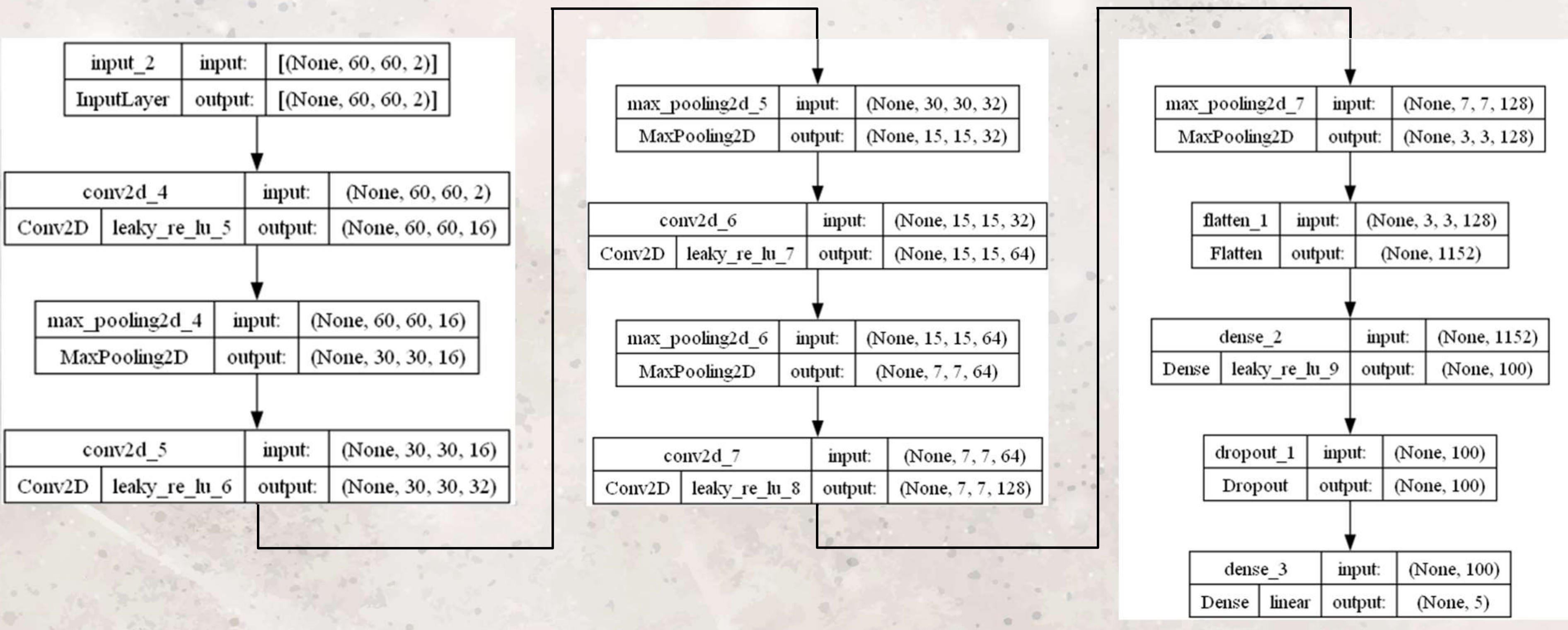
CNN Architecture

- We create a deep neural network with multiple convolutional layers to solve the inverse Ising problem.
- The inputs are 2 Ising configuration images of the initial and end states.
- The output is a vector of 5, corresponding to Ising parameters (J, B_0, B_x, B_y , I)
- Architecture diagram of our CNN as below:



CNN Architecture

- Architecture diagram of our CNN – plot from Keras/Tensorflow
- Total number of trainable parameters: 213,201

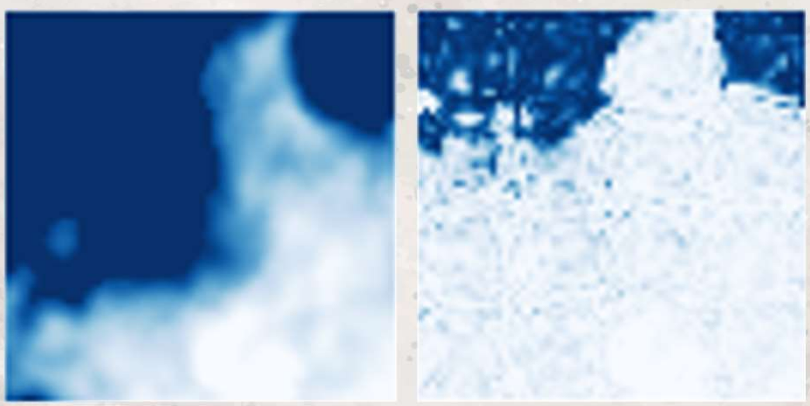


CNN Training Data

Training neural networks requires a substantial amount of data.
Where do we find enough data for CNN training?

Ising model itself offers infinite training data!

- **Start with the Ising lattice at the initial state of a simulation period**
- **Randomly select 10,000 set of parameters (J, B_0, B_x, B_y , I)**
- **For each set of parameters, run the Metropolis simulation steps.**
- **Generate 10,000 training samples corresponding to each of the initial states.**



(a) (b)

An example of the training samples corresponding to the initial state of the focus area on Sept 16th, 2022 and Ising parameters ($J = 2.31$, $B_0 = -14.5$, $B_x = -6.15$, $B_y = 0.07$, $I = 9.93$)

CNN Training and Prediction

- Inputs to CNN: training data generated from June 16th to Jan 1st
- Supervised learning process: the target set to be the corresponding Ising parameters (J, B_0, B_x, B_y , I).
- Optimizer: Adaptive Moment Estimation (ADAM)
- Loss function: Mean Square Error, a typical choice for regression models
- After the model is fully trained, estimating the best-fit Ising parameters for each of our study periods is straightforward
- Simply pass the observed initial and end state sea ice configuration images as inputs to the trained CNN
- Output of the trained CNN predicts the desired Ising parameters (J, B_0, B_x, B_y , I)

07

Results

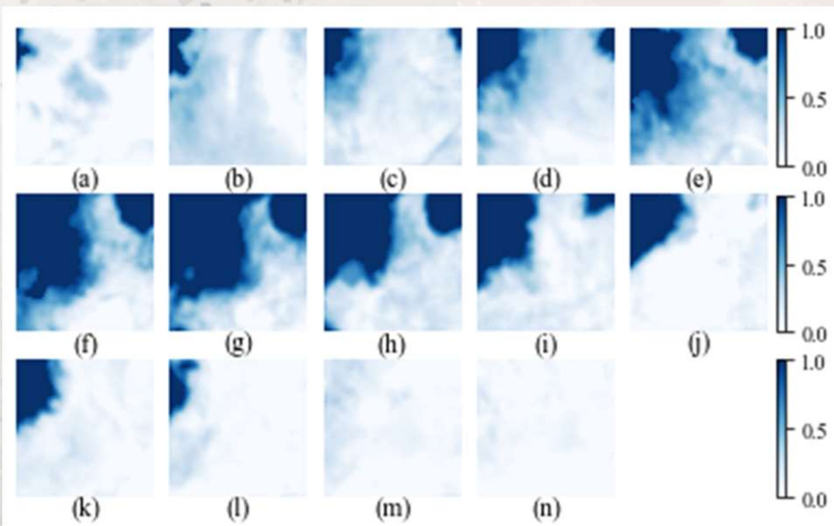
Simulation results and comparisons

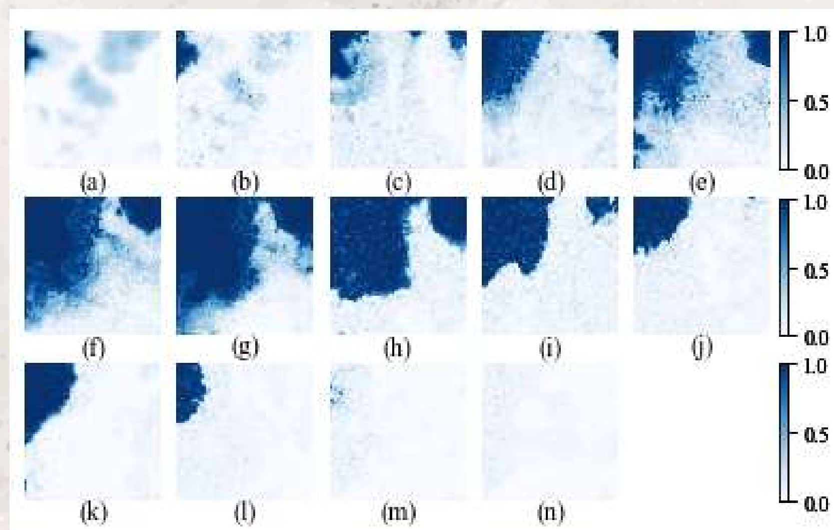
Simulation Results: 2022

	6/16 to 7/1	7/1 to 7/16	7/16 to 8/1	8/1 to 8/16	8/16 to 9/1	9/1 to 9/16	9/16 to 10/1	10/1 to 10/16	10/16 to 11/1	11/1 to 11/16	11/16 to 12/1	12/1 to 12/16	12/16 to 1/1/2023
J	2.1	2.6	2.9	2.6	2.5	2.5	2.3	2.4	3.5	2.1	2.6	2.3	2.8
B0	2.9	0.5	5.1	7.7	2.8	4.0	-7.1	-12.1	-30.0	-9.4	-18.6	-11.5	-28.0
Bx	3.5	-16.9	-14.9	2.7	-10.6	-7.6	-0.7	-4.1	-28.7	6.8	-1.9	-4.9	-4.3
By	-9.0	6.5	-4.7	3.4	-3.9	1.7	4.7	-6.2	-12.8	-34.5	-12.0	4.3	11.6
I	7.6	10.4	12.1	10.6	9.8	10.2	9.2	9.7	15.4	8.5	11.2	9.3	11.9

CNN Predicted Ising parameters of 2022 sea ice evolution

Simulation Results: 2022

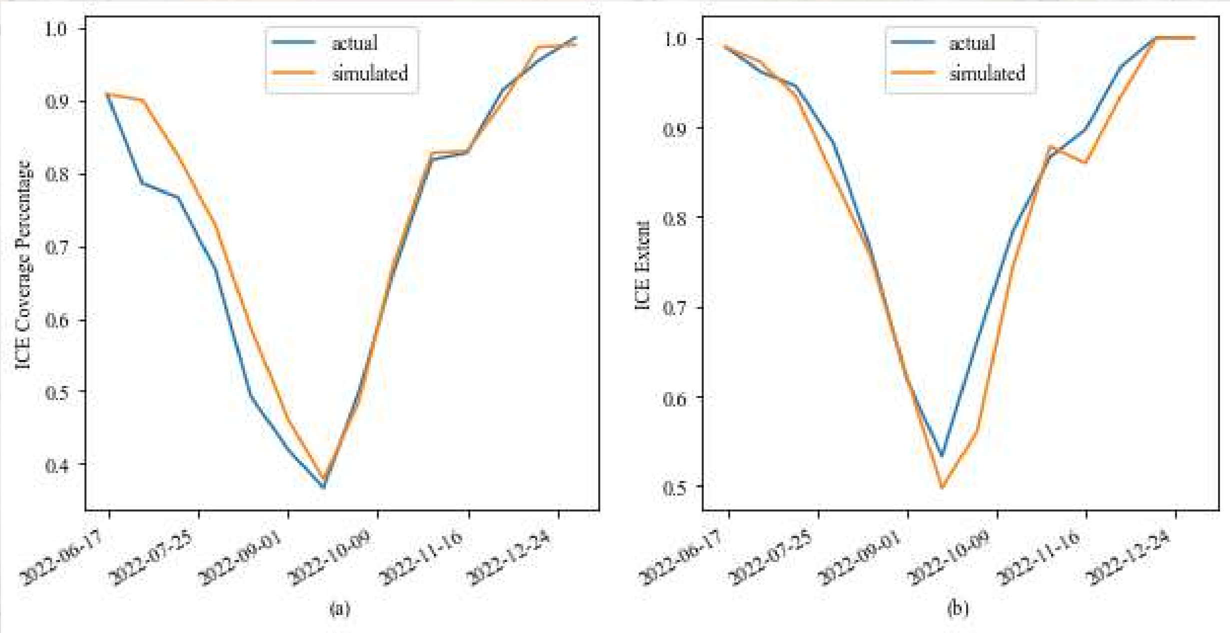




The actual (left) and the simulated (right) semi-monthly evolution of sea ice in our focus area in 2022: (a) June 16th, 2022, (b) July 1st, (c) July 16th, (d) Aug 1st, (e) Aug 16th, (f) Sept 1st, (g) Sept 16th, (h) Oct 1st, (i) Oct 16th, (j) Nov 1st, (k) Nov 16th, (l) Dec 1st, (m) Dec 16th, 2022, and (n) Jan 1st, 2023

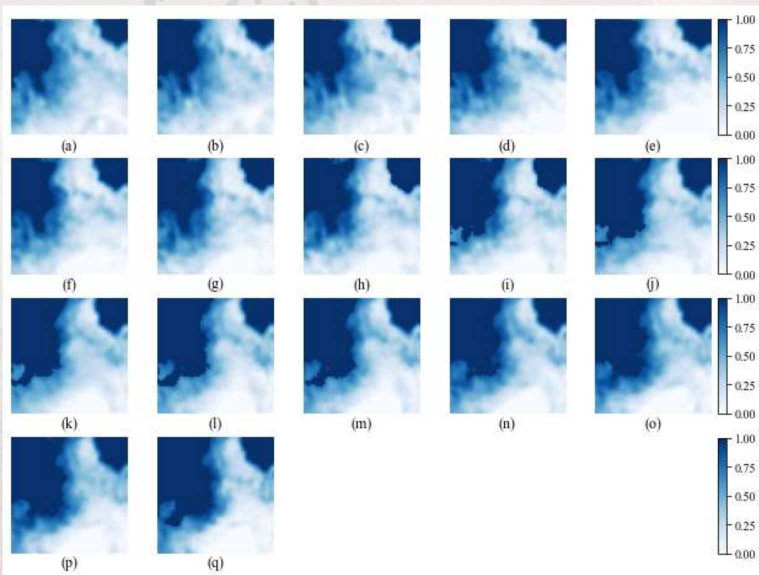
Simulation Results: 2022 Similarity

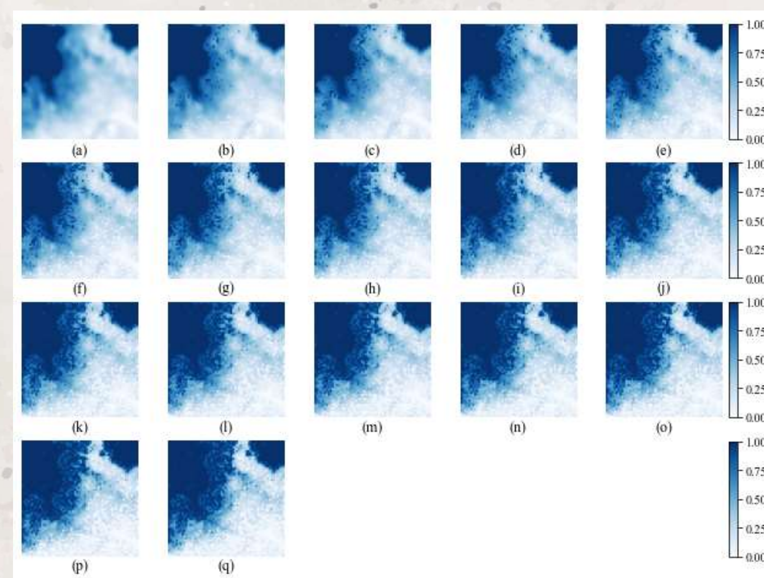
Ice Coverage Percentage = Arithmetic average of ice % over whole lattice
Ice Extent = Fraction of the lattice cells that is covered by at least 15% ice



The ice coverage percentage (a) and the sea ice extent (b) in our focus area from June 16th, 2022 to Jan 1st, 2023

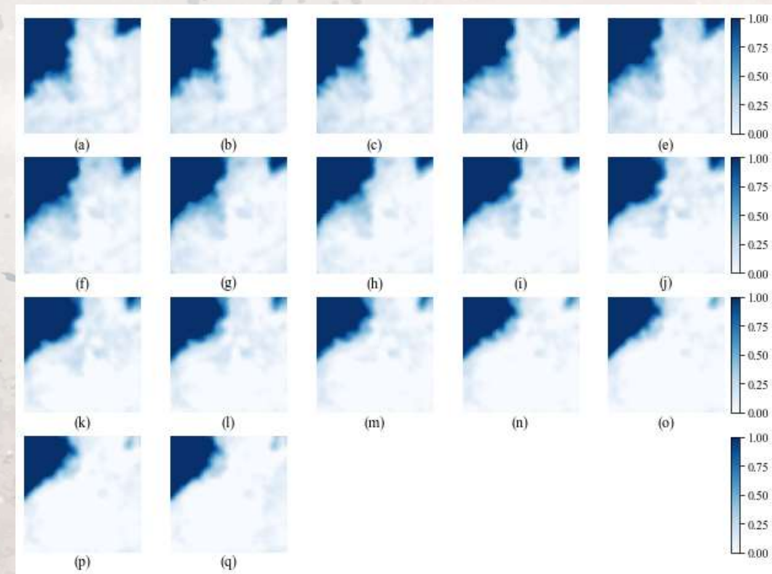
Simulation Results: 2022 Daily Dynamics

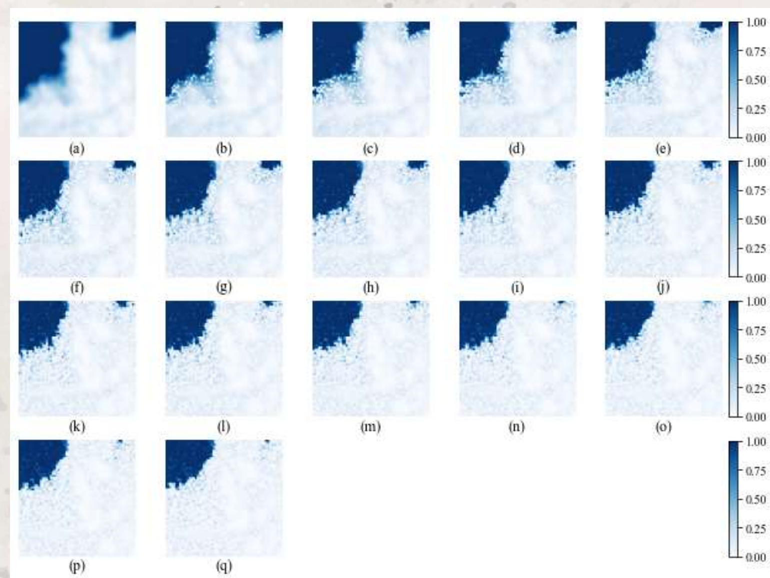




*The actual (left) and the simulated (right) daily evolution of sea ice in our focus area during **a melting cycle** from (a) Aug 16th, 2022 to (q) Sept 1st, 2022.*

Simulation Results: 2022 Daily Dynamics





*The actual (left) and the simulated (right) daily evolution of sea ice in our focus area during **a freezing cycle** from (a) Oct 16th, 2022 to (q) Nov 1st, 2022*

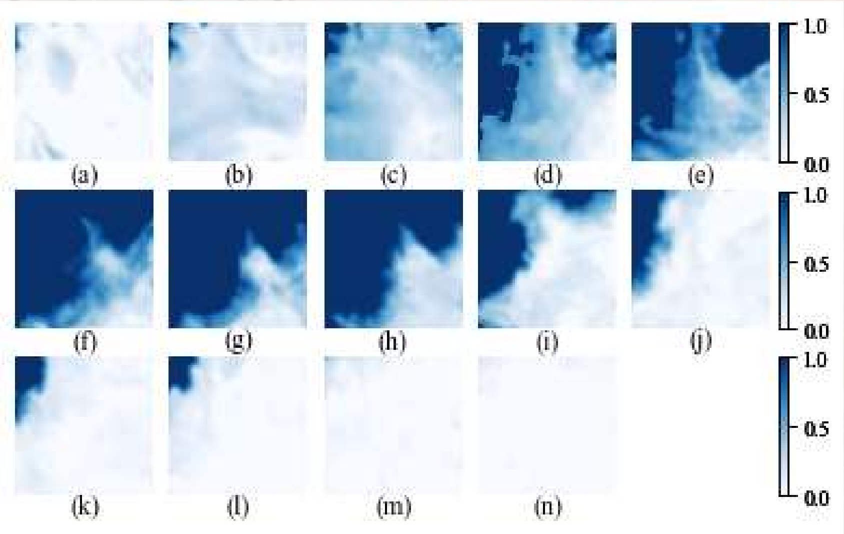
Simulation Results: 2023

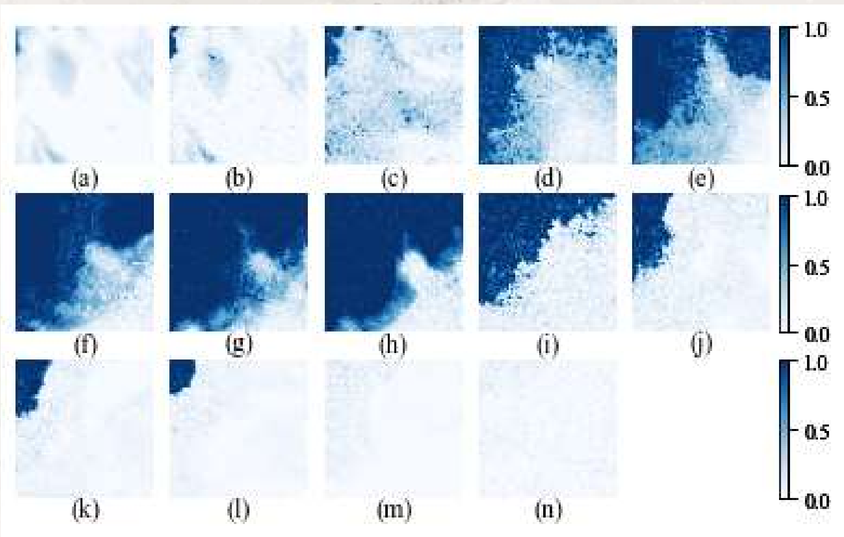
July 2023 has just been reported as the hottest month of the earth on record
2023 is the hottest year on record by a significant margin

	6/16 to 7/1	7/1 to 7/16	7/16 to 8/1	8/1 to 8/16	8/16 to 9/1	9/1 to 9/16	9/16 to 10/1	10/1 to 10/16	10/16 to 11/1	11/1 to 11/16	11/16 to 12/1	12/1 to 12/16	12/16 to 1/1
J	2.9	2.1	2.3	2.6	2.6	2.4	2.6	2.7	2.2	2.4	2.5	2.4	1.5
B0	9.2	4.7	6.1	5.6	4.5	0.8	-3.9	-14.6	-15.5	-14.2	-15.9	-16.4	-3.4
Bx	-0.9	-0.8	-5.1	-4.6	-14.3	-2.0	2.2	-6.2	-9.0	-16.7	-9.2	-3.3	-0.2
By	-5.3	-1.0	-6.3	3.3	-15.3	4.8	-2.2	-5.5	-11.4	1.1	-6.1	0.5	2.7
I	12.7	7.9	10.3	10.9	10.6	9.3	10.7	9.8	8.5	9.7	9.8	9.1	4.8

CNN predicted Ising Parameters of 2023 sea ice evolution

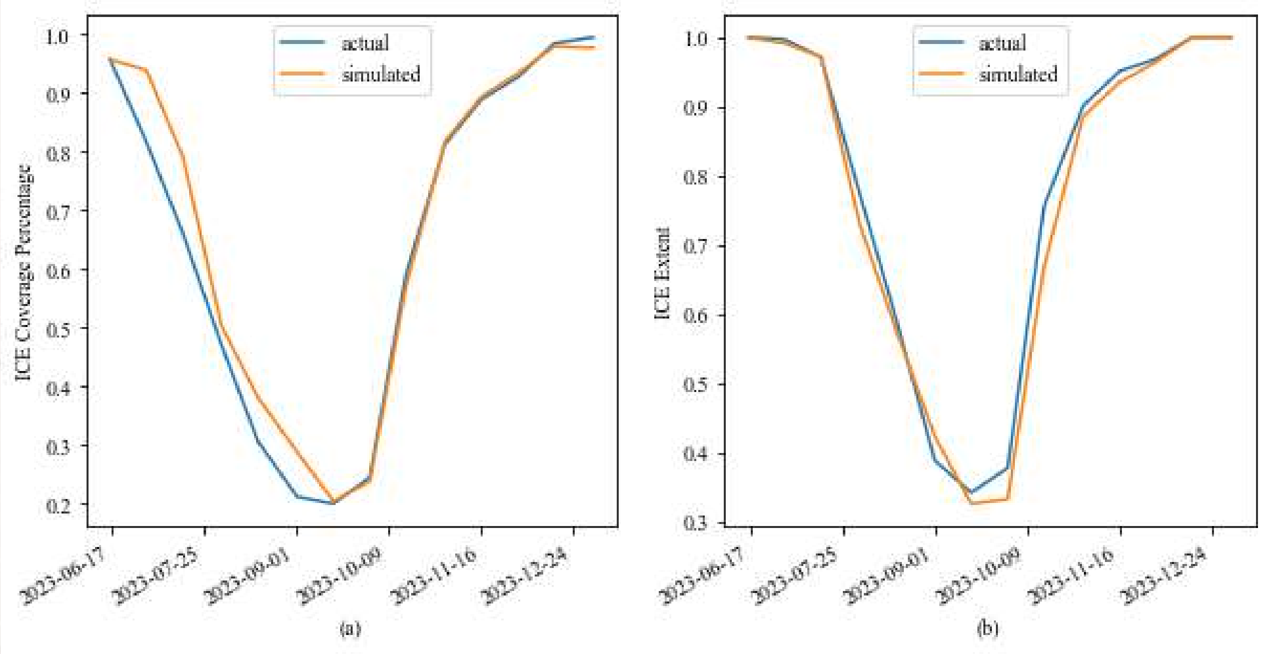
Simulation Results: 2023





The actual (left) and the simulated (right) semi-monthly evolution of sea ice in our focus area in 2023: (a) June 16th, 2023, (b) July 1st, (c) July 16th, (d) Aug 1st, (e) Aug 16th, (f) Sept 1st, (g) Sept 16th, (h) Oct 1st, (i) Oct 16th, (j) Nov 1st, (k) Nov 16th, (l) Dec 1st, (m) Dec 16th, 2023, and (n) Jan 1st, 2024

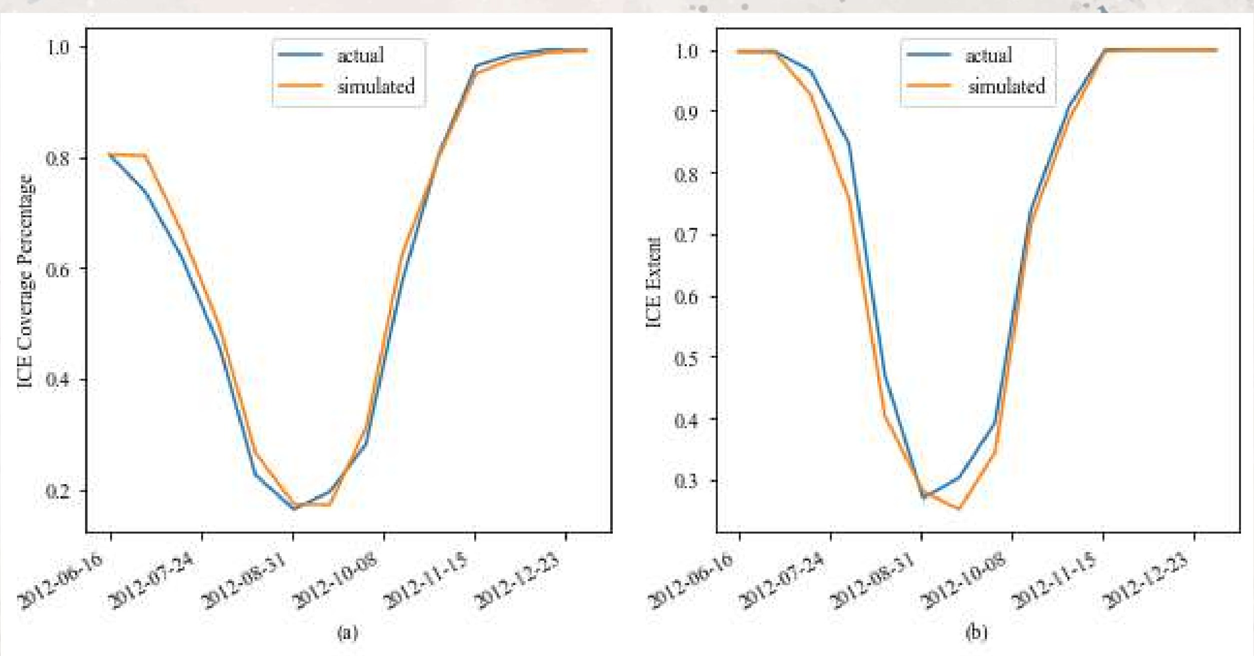
Simulation Results: 2023 Similarity



The ice coverage percentage (a) and the sea ice extent (b) in our focus area from June 16th, 2023 to Jan 1st, 2024

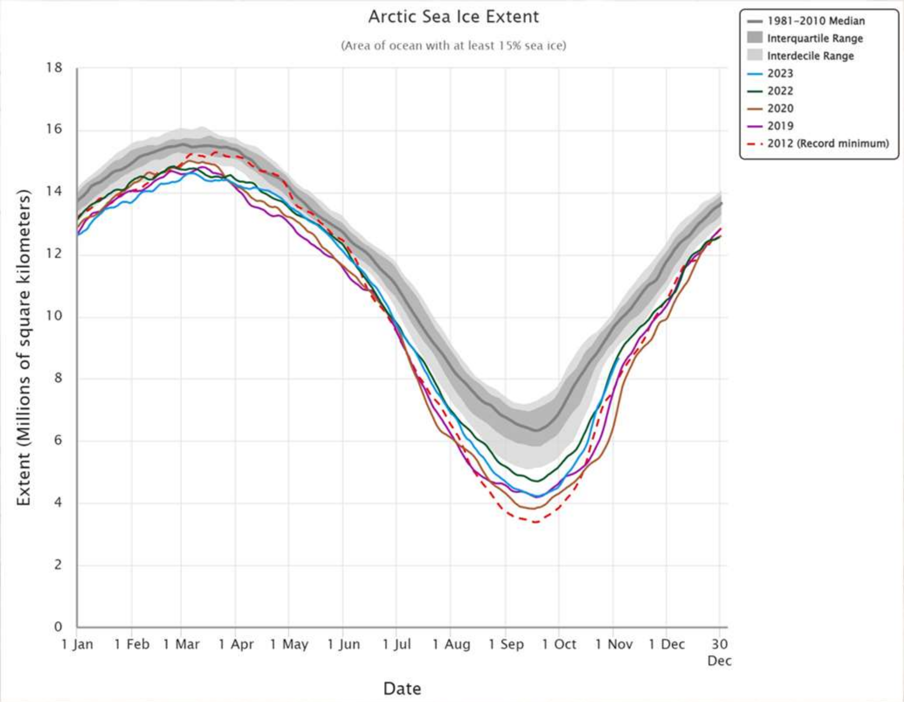
Simulation Results: 2012 Ice Extent

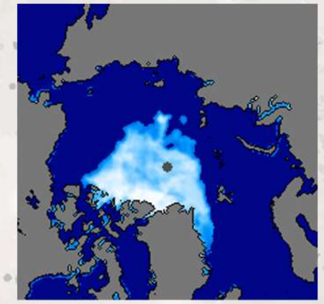
2012 recorded the lowest Arctic sea ice extent in recorded history



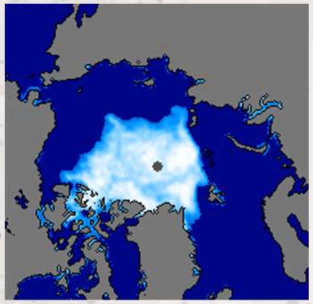
The ice coverage percentage (a) and the sea ice extent (b) in our focus area from June 16th, 2012 to Jan 1st, 2013

Official Arctic Sea Ice Extent History

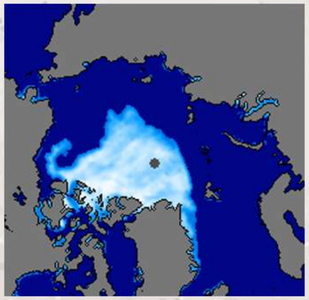




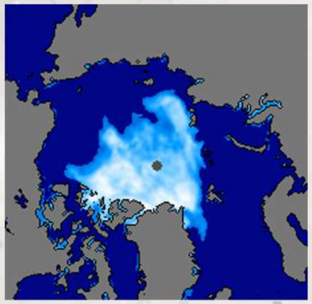
2012



2019



2020



2023

For the entire Arctic region in NRTSI data, Sept ice extent in 2023 was recorded to be the fourth lowest historically
https://nsidc.org/arcticseaicenews/

Comparison of sea ice extent btw 2023 & 2012

- 2023 is the hottest year on record
- 2023 did not break the record-low Arctic sea ice extent level set in 2012
- However, 2023 set the second lowest ice extent for our focus area (For the entire Arctic region not limited to our focus area, 2023 marks the 6th-lowest ice extent in history; all 6 minimums are well within small margins)
- 2023 not breaking ice extent record offers no reason for us to be optimistic about the future.
- In fact, in the 45-year-satellite record from 1979 to 2023, 17 of the lowest minimums have all occurred in the last 17 years
- Will the next decades see much higher temperature and much lower ice extent! ?
- Will we see an ice-free Arctic Ocean? If so, when?

08

Conclusions

Discussions and future work

Conclusions & Discussions

Physics Model

Continuous spin values and an innovative inertia factor introduced to a 2-D Ising Model.

MCMC Simulation

Metropolis-Hastings algorithm utilized to simulate the dynamics of the sea ice evolution in a focus area in the Arctic region.

Deep Learning

Train a deep convolutional neural network to learn the Ising interaction parameters

Results

Excellent similarity with the actual sea ice dynamics, based on the average ice coverage and the ice extent metrics.

Conclusions & Discussions

- When trained with CNN, the continuous-spin Ising model with the novel inertia factor proves to have extraordinary power to replicate and explain sea ice dynamics.
- The Ising parameters predicted by CNN reveal the substantial impact of the external forces in climate change research.
- The study presents ample possibilities to further enhance the physics modeling of the Arctic sea ice dynamics.
- This research validates the vast potential of coupling classical physics models with modern deep learning technology in environmental studies and other disciplines.

Discussion 1

Will the "Blue Ocean Event" happen, i.e., will we see an "ice-free" Arctic Ocean?

- Some research predicts that this can happen in the 2030s!

Discussion 2

Larger deep learning model

- A small CNN (~200,000 parameters only in this study) trained on the CPU of a PC demonstrates amazing power to solve for the Ising parameters and to explain the complex sea ice dynamics.
- Deeper and larger neural networks shall offer more power to learn enriched Ising parameters

Discussion 3

Explore Quantum Ising Model (QIM), a.k.a. Transverse Field Ising Model to harness the exponentially growing power of quantum computing?

Thanks!

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