How much CO₂ can accumulate in the atmosphere before we cross 2°C warming?

- Global warming target of 2015 Paris Agreement: 2°C
- How much CO₂ can accumulate in the atmosphere before this threshold is crossed?
- No certain answer
- Answers vary from 400 ppm in 2030, to 600 ppm after 2060 (Schneider et al., 2017a).

- Estimated economic value of an accurate answer:
  -$10 trillion in savings (Hope, 2015).

**PARAMETRISATION SCHEMES**

- Typical GCM grid scale: 10 to 150 km.
- Cloud formation scales: ~2 km or less.
- Clouds cannot be resolved by current climate models.
- Clouds modeled by heuristically approximated parameterisation schemes.

**RELATED WORK**

- Learn cloud parameterisations from cloud resolving model simulation data using:
  - Single-layer feed-forward neural networks (Brenowitz et al., 2018; Brenowitz and Bretherton, 2018)
  - Ensemble Kalman inversion model (Schneider et al., 2017a)
  - Random forest model (Gorman and Dwyer, 2018)
  - Multi-layer feed-forward neural network (Brenowitz et al., 2018)

- But...

**OBJECTIVE**

Want:
- A climate model which can objectively zoom in on clouds.

Where does ML fit in?
- Can a deep learning model recover the parameters underlying a cloud parameterisation scheme?

**Objective:**
- Recover the parameters underlying the chaotic behavior of the Lorenz-96 model.

**Lorenz-96 Model**

Slow large-scale variables $x_i([1,2,...,L])$:

\[
\frac{dx_i}{dt} = -x_{i-1}(x_{i-1} - x_{i+1}) - x_i + F - bx_i^eta \\
\frac{d^2x_i}{dt^2} = \beta x_{i-1}(x_{i-1} - x_{i+1}) - x_i + \frac{F}{\beta}
\]

Fast small-scale variables $y_{ij}([1,2,...,L][1,2,...,L])$:

\[
\frac{dy_{ij}}{dt} = -b x_{ij}(y_{ij} - y_{ij-1}) - y_{ij} + \frac{F}{\beta}
\]

**Learning Models**

- Learning algorithms:
  - Fully connected with 3 layers
  - 1D convolutional with 2 layers (each with 32 filters of size 3) followed by 3 FC layers
  - 2D convolutional with 1 layer (32 filters of size 3x3) followed by 3 FC layers

**RESULTS**

| Test Mode | Model Train Loss Test Loss Train R² Test R² |
|-----------|-------------------------------------------|-----------------|-----------------|
| LR        | 1.7512                                   | 1.7600          | 0.7588          | 0.8578          |
| FC        | 0.6531                                   | 0.6714          | 0.9004          | 0.9074          |
| Conv1D    | 0.6682                                   | 0.6412          | 0.9079          | 0.9060          |
| Conv2D    | 0.6502                                   | 0.6461          | 0.9073          | 0.9054          |

**Lorenz-96 Phase Diagram of the First Three Densities $X$ and $Y$ Variables using the Observed Parameters**

Figure 7. Errors between the Lorenz-96 model with the FC model trained on the Y variables with test, mode set to Alert (top row) and using the Conv1D model trained on Y variables with test, mode set to True (bottom row).

**References**