Basic physical equations

1904: Vilhelm Bjerknes identified the "primitive equations"

These capture the flow of mass and energy in the atmosphere;

Sets out a manifesto for practical forecasting

Zonal (East-West) Wind:

$$\frac{\partial u}{\partial t} = \eta v - \frac{\partial \Phi}{\partial x} - c_p \theta \frac{\partial \pi}{\partial x} - z \frac{\partial u}{\partial \sigma} - \frac{\partial (\frac{u^2+v^2}{2})}{\partial x}$$

Meridional (North-South) Wind:

$$\frac{\partial v}{\partial t} = -\eta \frac{u}{v} - \frac{\partial \Phi}{\partial y} - c_p \theta \frac{\partial \pi}{\partial y} - z \frac{\partial v}{\partial \sigma} - \frac{\partial (\frac{u^2+v^2}{2})}{\partial y}$$

Temperature:

$$\frac{\delta T}{\partial t} = \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z}$$

Precipitable Water:

$$\frac{\delta W}{\partial t} = u \frac{\partial W}{\partial x} + v \frac{\partial W}{\partial y} + w \frac{\partial W}{\partial z}$$

Air pressure:

$$\frac{\partial}{\partial t} \frac{\partial p}{\partial \sigma} = u \frac{\partial}{\partial x} x \frac{\partial p}{\partial \sigma} + v \frac{\partial}{\partial y} y \frac{\partial p}{\partial \sigma} + w \frac{\partial}{\partial z} z \frac{\partial p}{\partial \sigma}$$

Towards Numerical Forecasts

1910s: Lewis Fry Richardson performs the first numerical weather forecast, imagines a giant computer to do this regularly;

First plan for massively parallel computation

Image Source: Lynch, P. (2008). The origins of computer weather prediction and climate modeling.

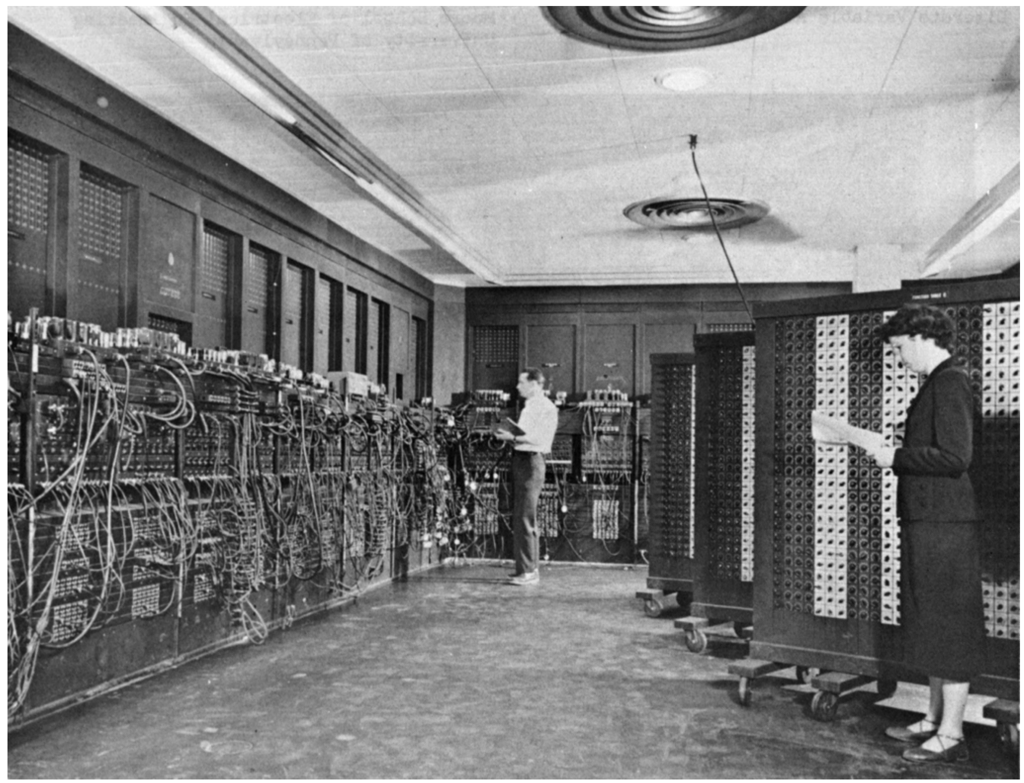
(What a forecast factory actually looks like)

The Yellowstone supercomputer at the NCAR Wyoming Supercomputing Center, Cheyenne

First Computer Model of Weather

1950s: John Von Neumann develops a killer app for the first programmable electronic computer ENIAC: weather forecasting

Imagines uses in weather control, geo-engineering, etc.



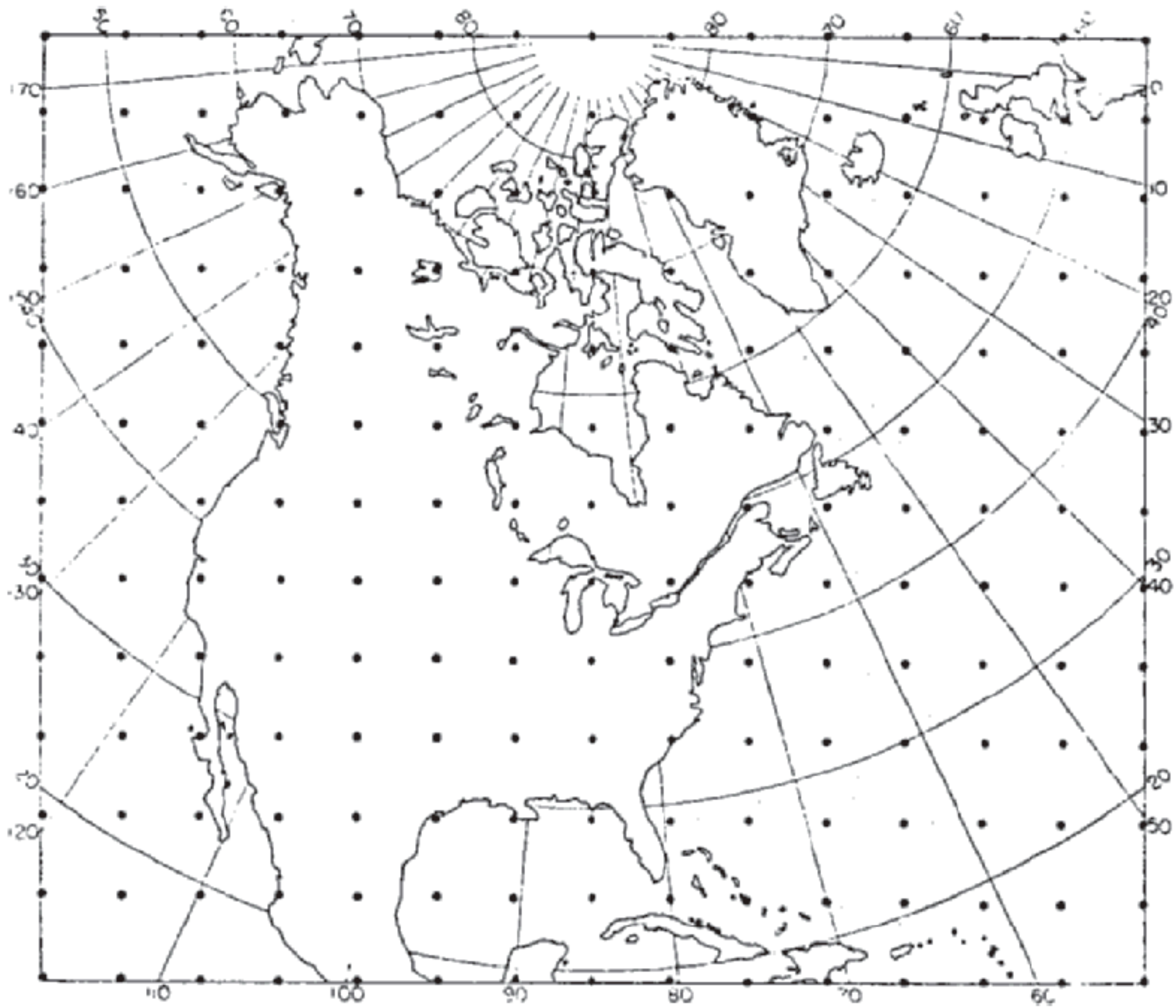
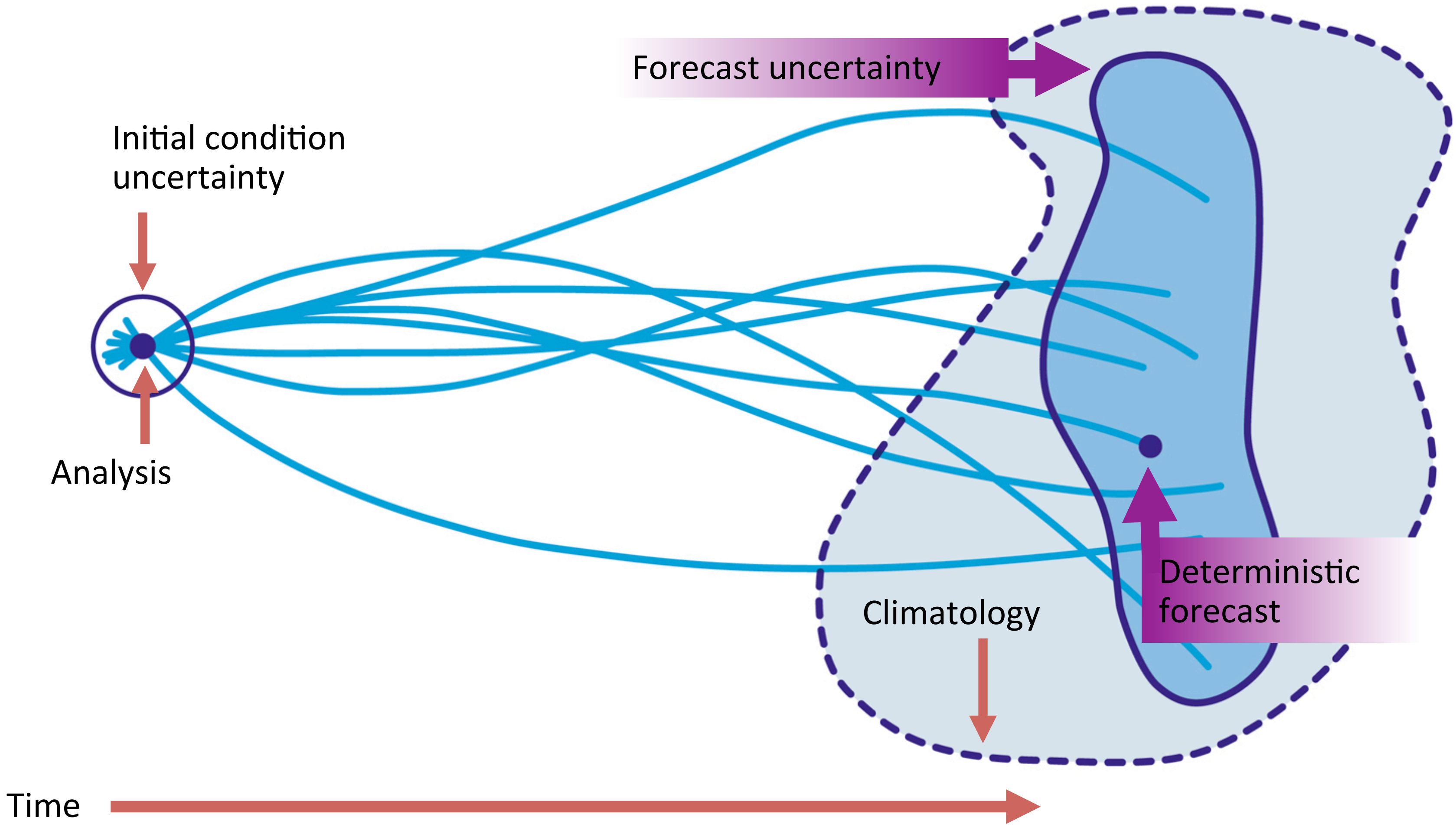
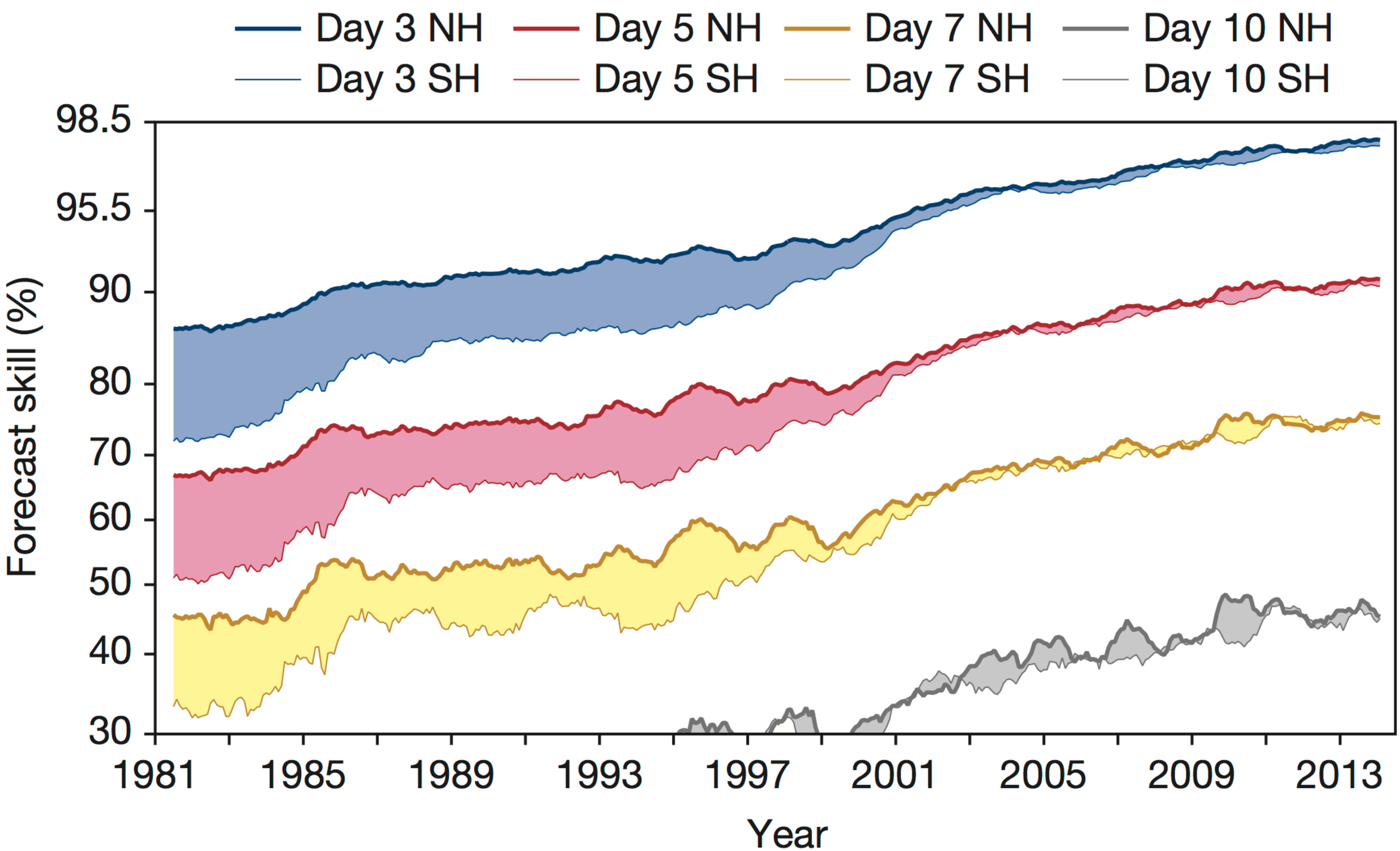


Image Source: Lynch, P. (2008). The ENIAC Forecasts: A Recreation. Bulletin of the American Meteorological Society

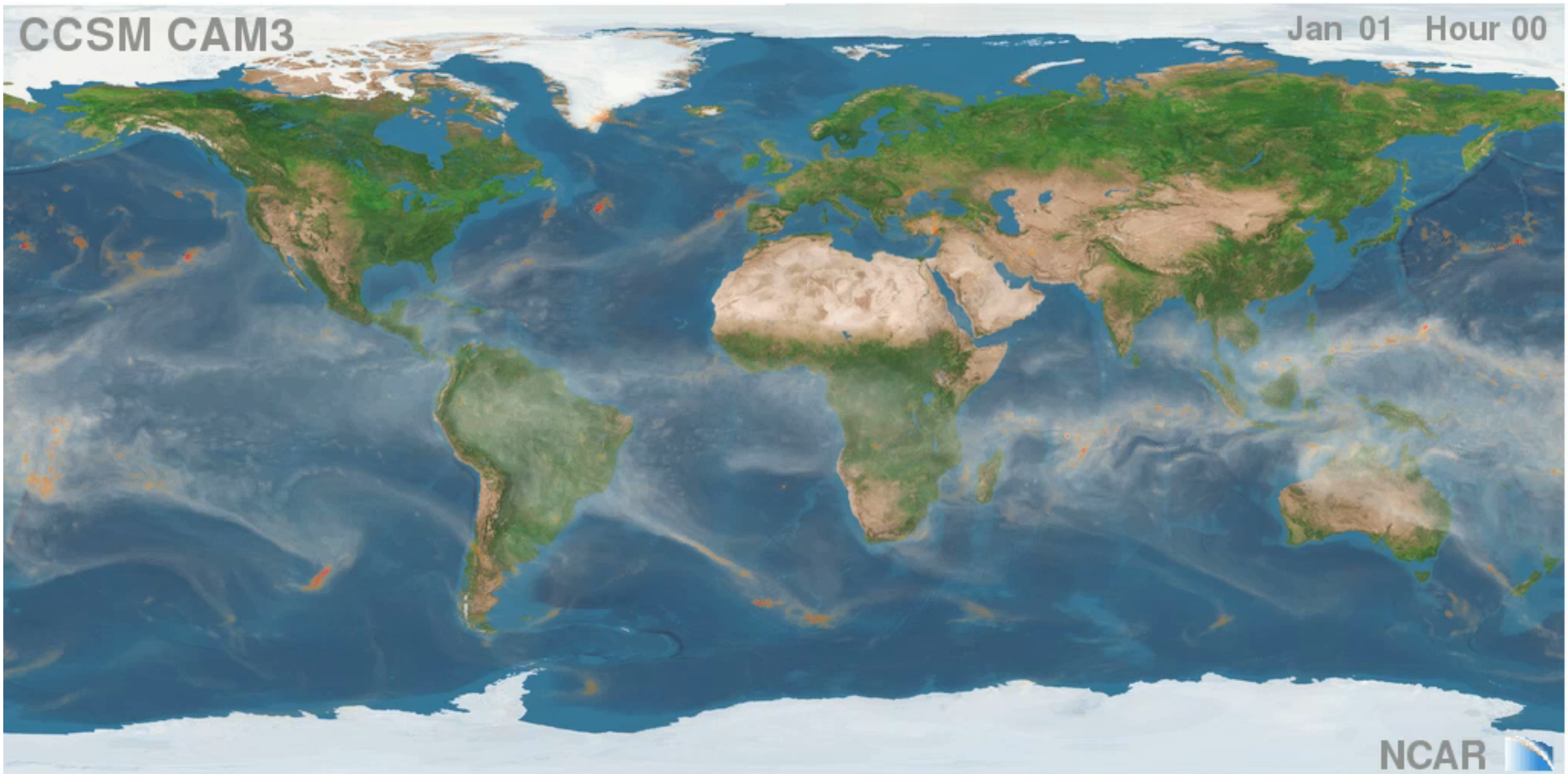
Forecasting Weather and Climate





Bauer, P., Thorpe, A., & Brunet, G. (2015). The quiet revolution of numerical weather prediction. Nature, 525(7567), 47–55.

Global Precipitation in CCSM CAM3

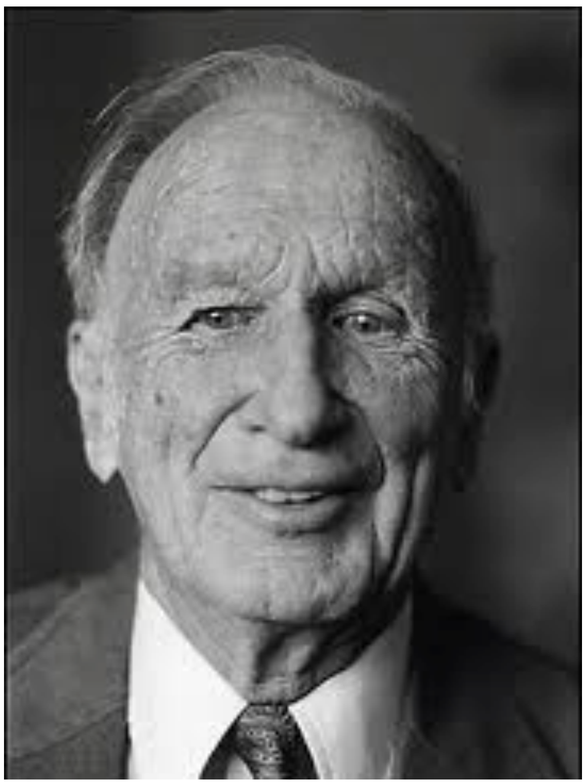


Source: http://www.vets.ucar.edu/vg/T341/index.shtml

The discovery of Chaos

•1950s: Edward Lorenz discovers non-linear effects in weather forecasting, develops Chaos Theory;

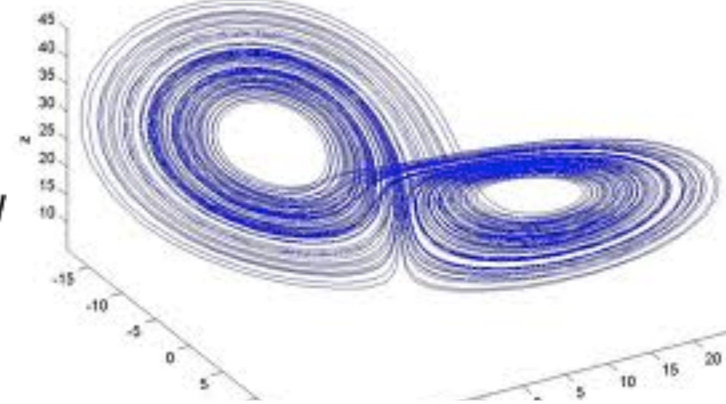
•Basis for understanding what is predictable and what isn't

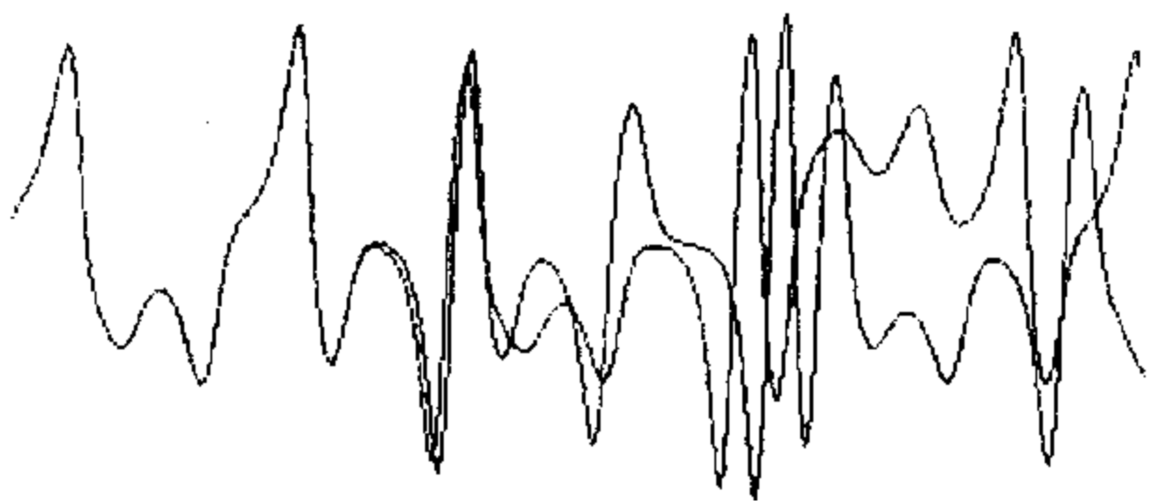


$$\frac{dx}{dt} = \sigma(y - x)$$

$$\frac{dy}{dt} = x(\rho - z) - y$$

$$\frac{dz}{dt} = xy - \beta z$$





Chaos Theory

- Chaos is not the same as randomness
- Simple rules can create chaotic patterns
- Chaos Game:

  https://trinket.io/python/7922fc9d9c
- Lorenz's Example:

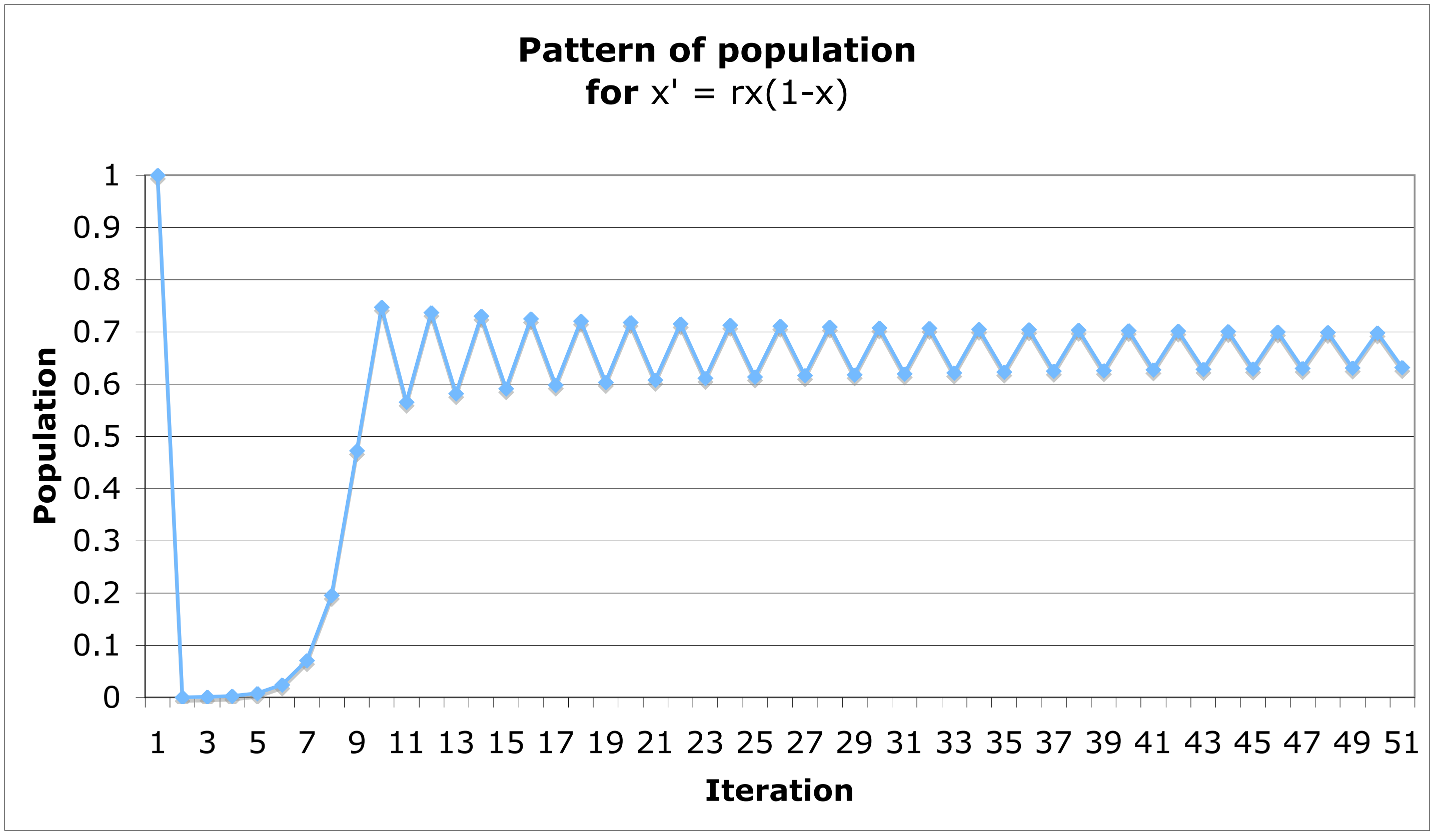
  $x' = x^2 - C$

  The logistic equation

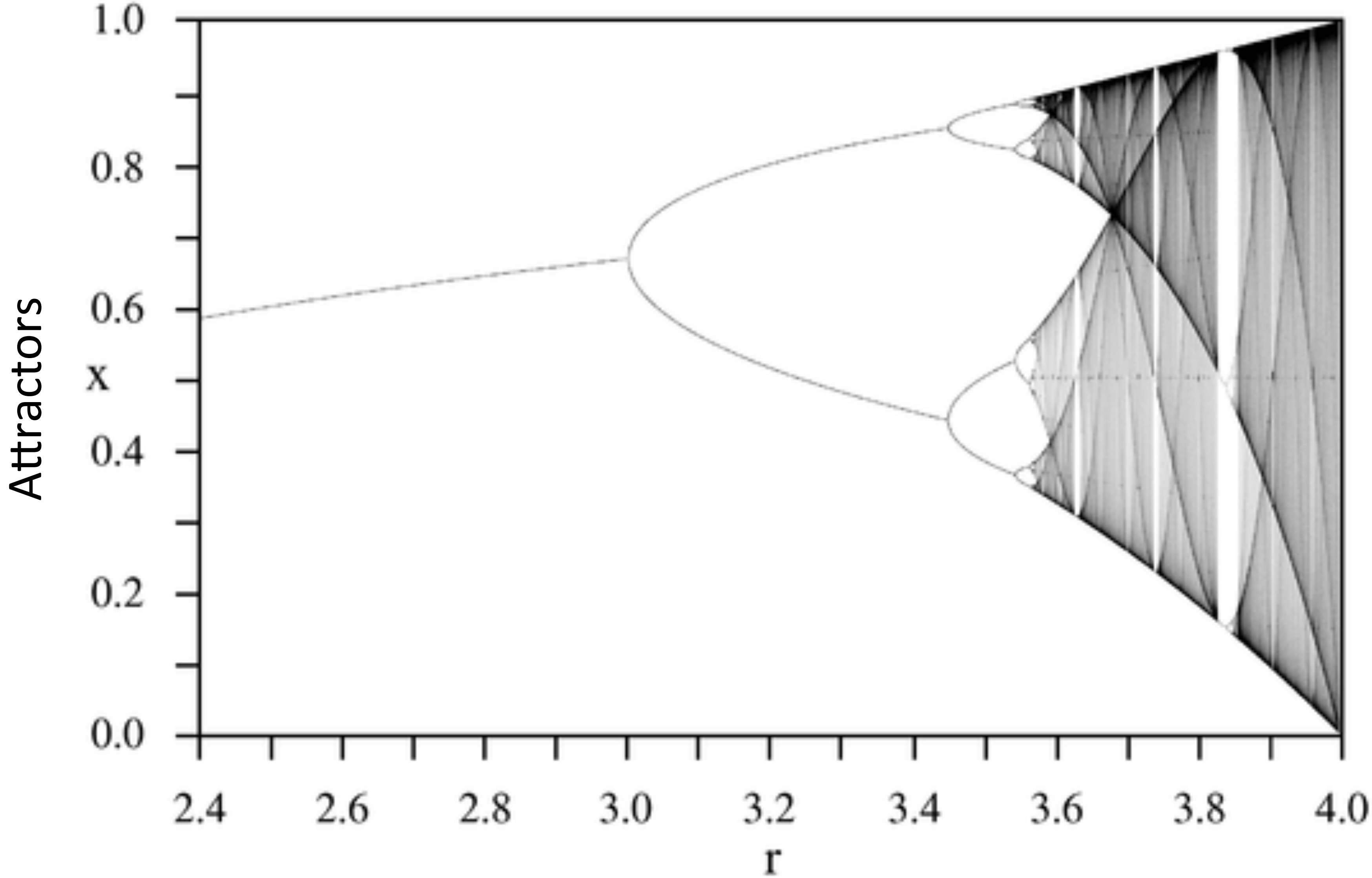
Key concepts

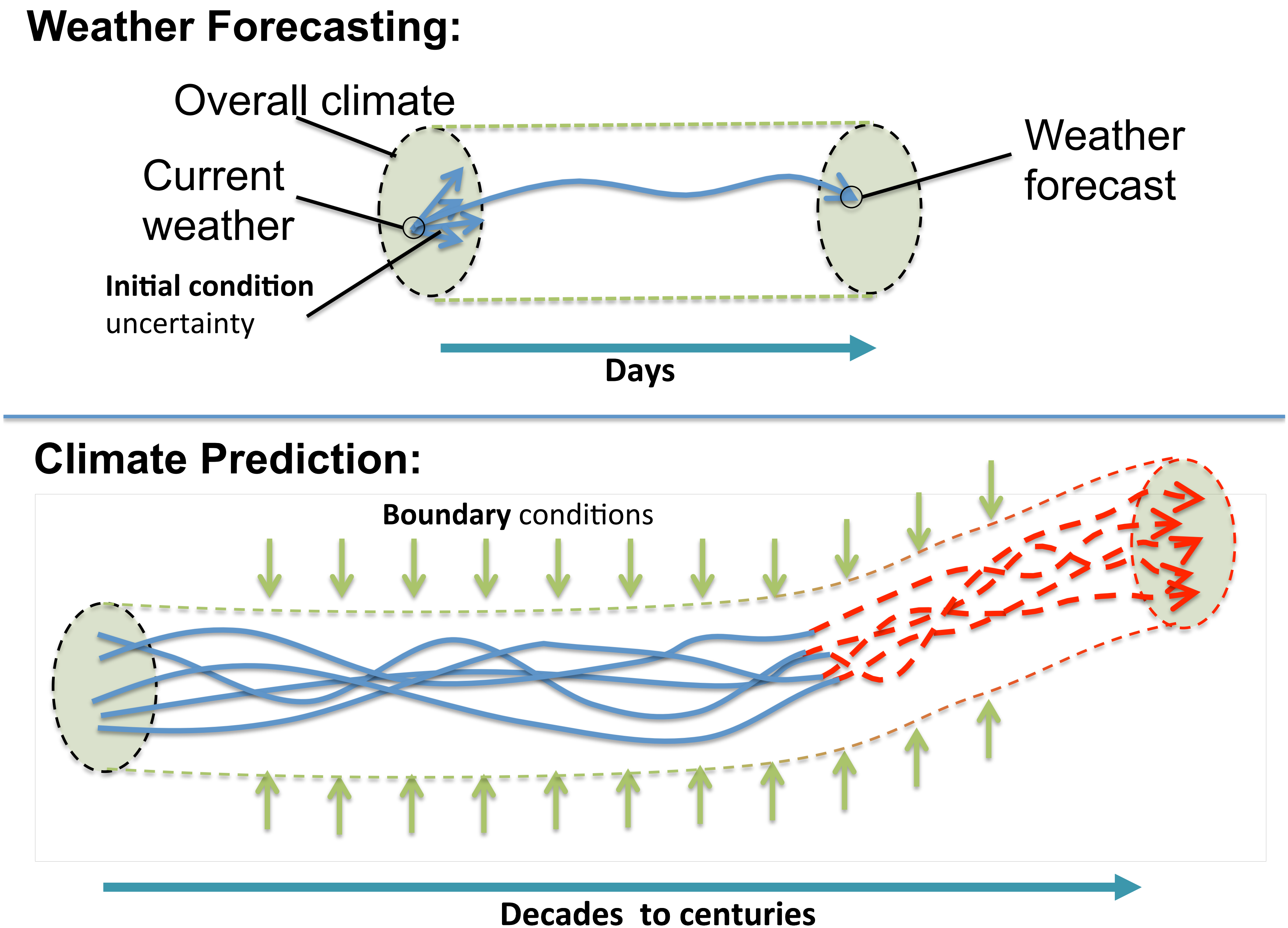
- Non-linear Dynamical Systems
  - Inputs are not proportional to outputs
  - Determinism: Can you work out future states?
- Sensitivity to Initial Conditions
  - The "butterfly effect"
  - E.g. The Lorenz Attractor
- Denseness
- Attractors (Simple and Strange)
- Criticality and Tipping Points
- Self-similarity and Fractals

Non-Linear Dynamical Systems



Bifurcation Diagram for x' = rx(1-x)





Weather Forecasting:
Overall climate
Current weather
Initial condition uncertainty
Weather forecast
Days
Climate Prediction:
Boundary conditions
Decades to centuries

For Next Week

- Draft of Assignment 1 is due
- Bring a paper copy of your draft to class
  - We'll do a peer review exercise
  - You get to re-submit within 1 week

- Read any 2 articles from Climate Central Blog
  - http://www.climatecentral.org/news
  - Think about how they're written