PREDICTABILITY OF WEATHER & CLIMATE:

PREDICTIVE SIGNAL & NOISE IN SUB-SEASONAL TO DECADAL FORECASTS

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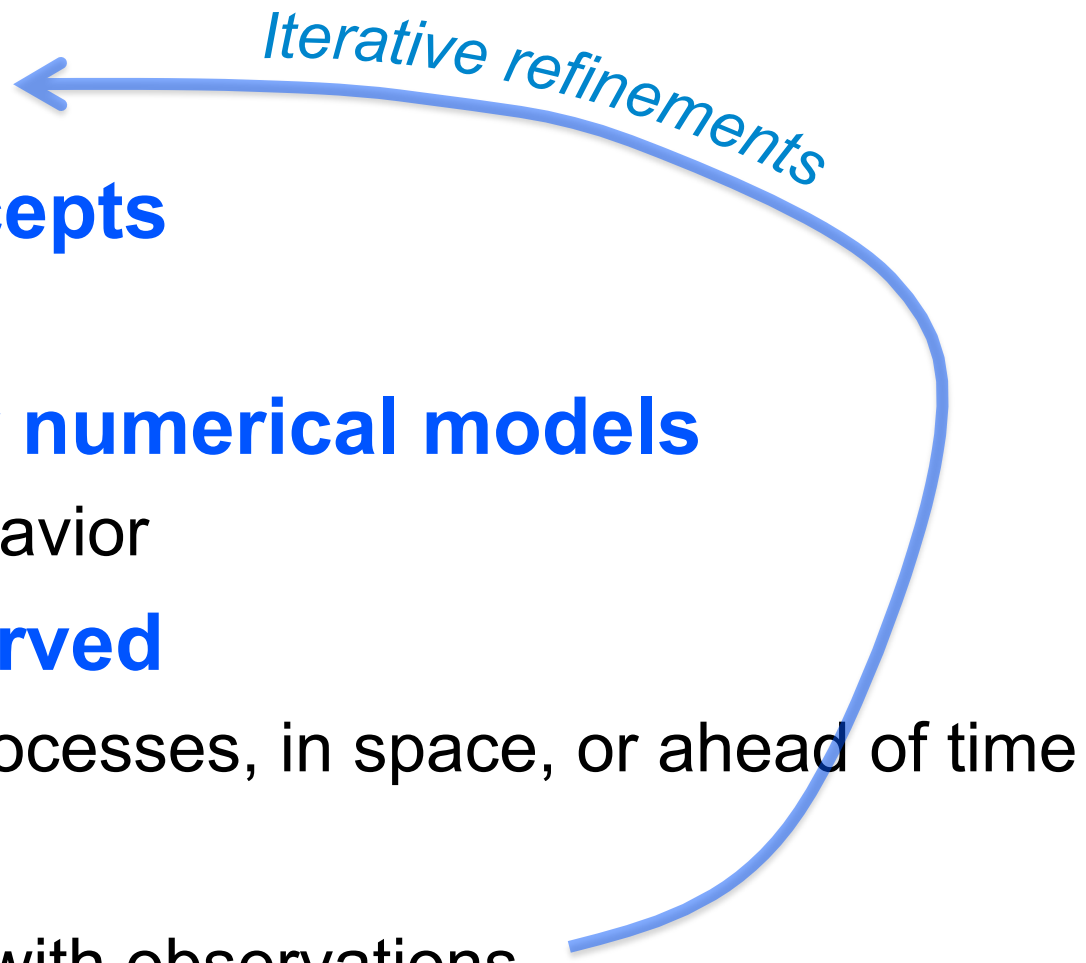
OUTLINE

- **Prediction** – Based on determinism
- **Loss of skill/info** – Due to sensitive dependence on initial condition
- **What is ”weather” & “climate”?**
- **Separate definitions of predictability?**
- **Predictable** weather & climate **phenomena**

PREDICTION IN BROAD SENSE

A BASIC TENET OF SCIENCE



- **Observe** nature
- Create **mental concepts**
  - Pictures, theories
- Build **conceptual or numerical models**
  - Describe natural behavior
- **Predict the unobserved**
  - Across variables / processes, in space, or ahead of time
- **Verify**
  - Compare prediction with observations

PREDICTION *– Centerpiece of scientific endeavor*

PREDICTION IN NARROW SENSE

- **Significance**
  - Time dependent systems evolve in time
    - Great societal interest in changing environmental conditions
- **Definition**
  - Retain information about state of system in time
    - Foresee time evolution of system - Chronology
- **Procedure**
  - Assess initial state of system
    - Incomplete knowledge
  - Project estimate of initial state into future
    - Approximate numerical models
- **Weather forecasts**
  - Short time horizon – Lots of cases & feedback
- **Longer range (S2D) forecasts**
  - Based on same principle – Fewer cases
    - Scarce verification data

BASIS & LIMITATIONS OF FORECASTING

- **Dependence** on initial condition
  - Apparent determinism on macro scales
  - Perfect prediction possible with
    - Perfect initial condition & perfect model
- **Sensitive dependence** on initial condition
  - Small initial changes amplify in forecast
- Same **instabilities** drive
  - Emergence of *phenomena from "basic flow"* &
  - Divergence of *forecast from reality*
- Determinism + instabilities = **Chaos**
  - Atmosphere, Atm-Ocean-Land-Cryosphere (ALOC) coupled sys.
- **Perfect prediction** possible **only with**
  - Perfect initial condition & perfect model

Predictions limited by initial & model errors

PREDICTABILITY

Study of what can or cannot be predicted

- **Affected by**
  - Initial error variance
  - Model imperfections
  - Position on attractor
- At **current level of initial & model errors**
  - Predictability = Forecast skill
- **Explore effect of reduced initial & model error, or changes in position on attractor** on
  - Forecast error variance
- **Measured** by
  - Host of verification metrics
    - Error variance wrt climatic variance, lead time that error reaches thresholds, etc
- **Practical implications**
  - Optimal user response to forecast depends on expected error
  - Allocation of R&D resources depends on expected reduction in fcst error

PREDICTION PREDICAMENT

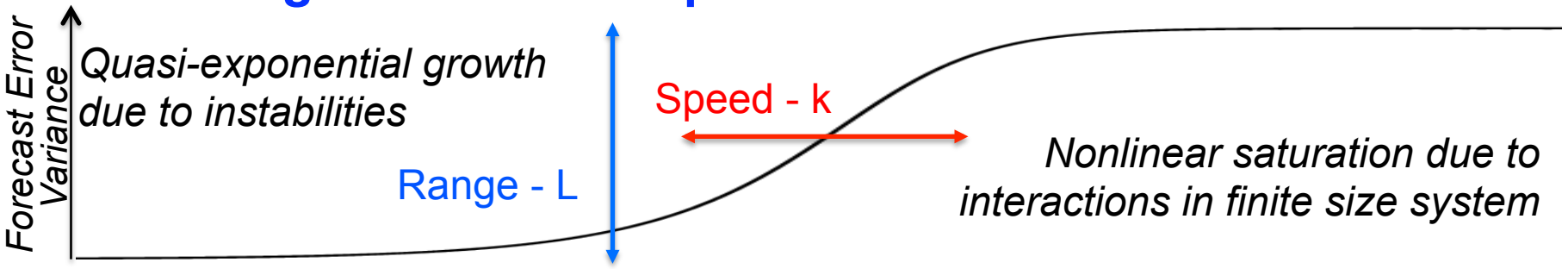
In the presence of chaos

- **Assume a perfect model**
  - Model related errors would further compound situation
- **Imperfect estimate of initial state** due to
  - Scarce/incomplete/erroneous observations
  - Suboptimal data assimilation procedures
- **Projection** of erroneous initial state into future
  - Initial errors amplified by instabilities

Nature of error growth?

CHAOTIC ERROR GROWTH

- Definition of **true error**
  - Difference btw forecast & truth interpolated onto model grid
- Behavior in complex systems
  - Initial exponential growth modulated by nonlinearities =>
    - **Logistic relationship** – *VERY GENERAL*



The *standard logistic function* is the logistic function with parameters ($k = 1$, $x_0 = 0$, $L = 1$) which yields

$$f(x) = \frac{1}{1 + e^{-x}}$$

$$f(x) = \frac{L}{1 + e^{-k(x - x_0)}}$$

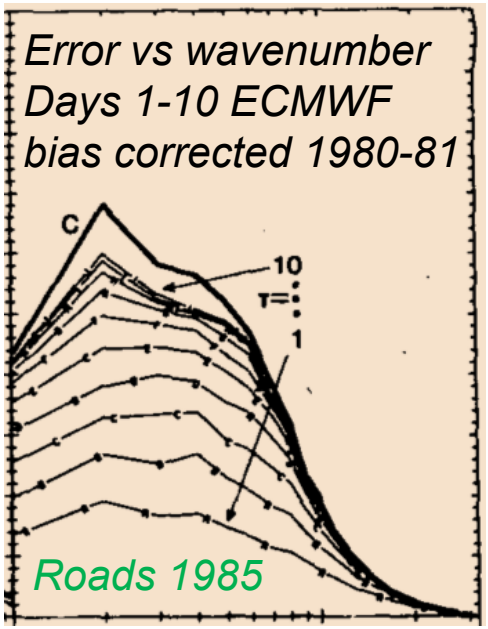
where

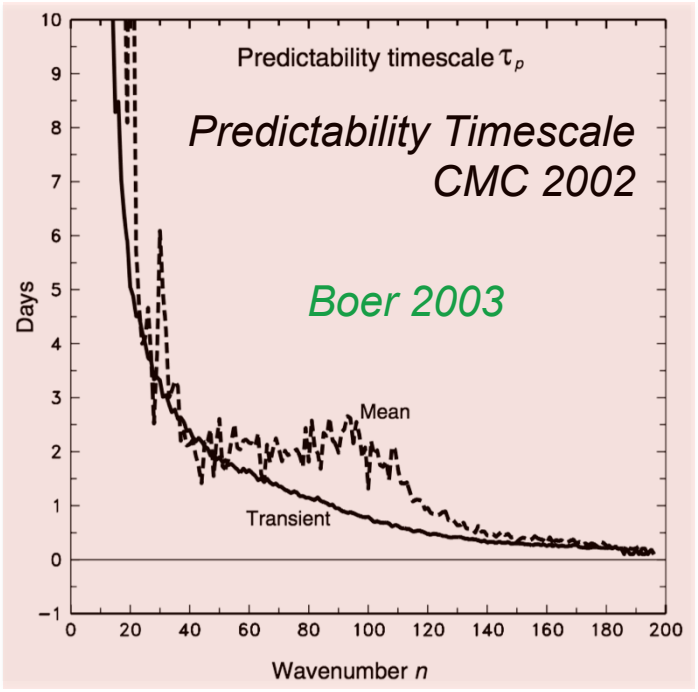
- e = the natural logarithm base (also known as Euler's number),
- x_0 = the x-value of the sigmoid's midpoint,
- L = the curve's maximum value, and
- k = the steepness of the curve.[1]

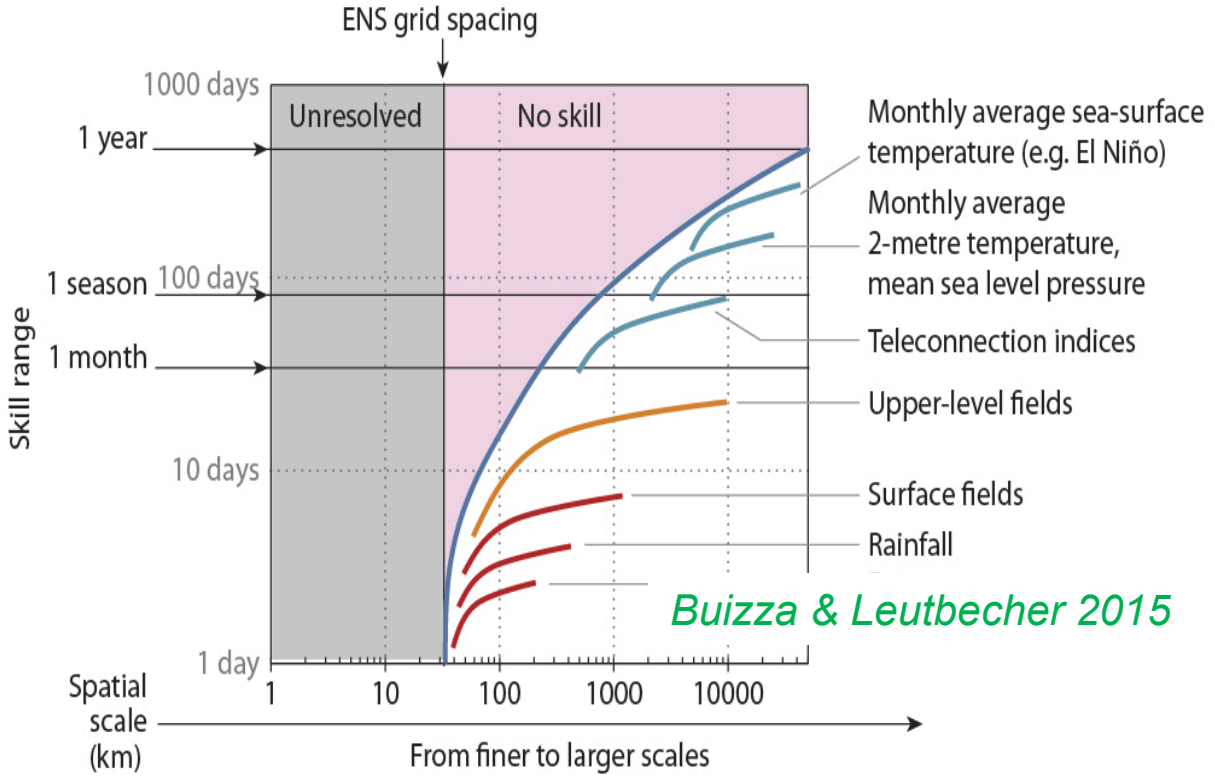
- **Range** (L) – function of size of attractor
  - Twice climatological variance (Var_{clim})
- **Speed** (k) – function of strength of instabilities

Lorenz 1982

SCALE DEPENDENT ERROR GROWTH







- Smaller scale errors saturate first
- Skill on large scales extends further
- Extends to coupled system phenomena

Overwhelming evidence for influence of scales on predictability

ROLE OF SIZE IN ERROR GROWTH

- **Fundamental role of size** in organization of systems
  - Inorganic matter, living organisms, cities, companies, etc
- Size in terms of both
  - Physical extent
  - Amount of material

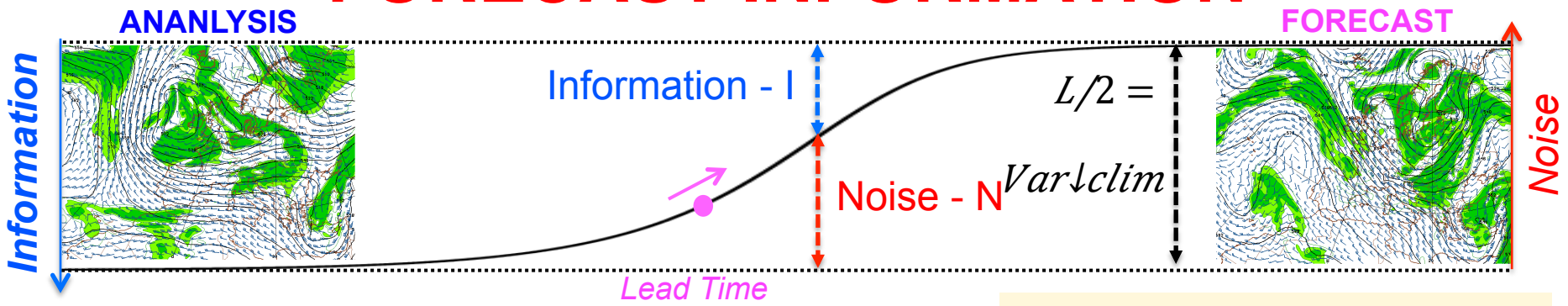
Geoffrey West 2017

AXIOMES

- **Complex systems organized from smaller components**
  - Each component has its own characteristic time for changes
- **Parent system necessarily larger than its components**
  - Its time scale cannot exceed that of its building blocks
- **Larger mass takes more time to change**
  - Ocean vs atmosphere

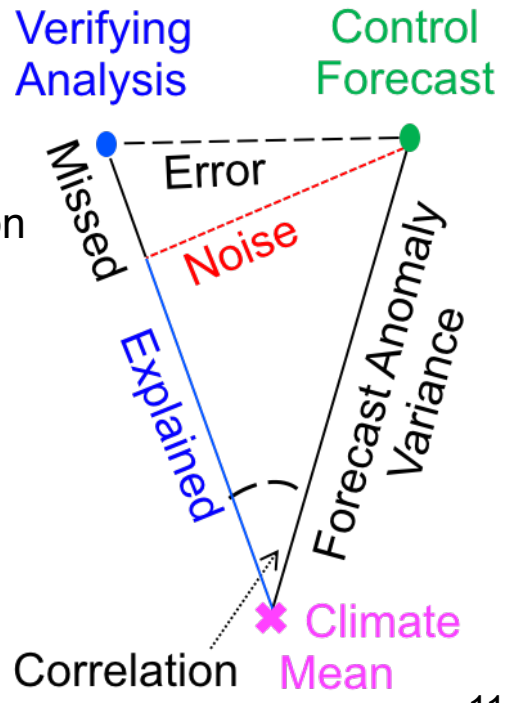
Larger / heavier phenomena & associated error evolve slower

FORECAST INFORMATION



- **Definition** - Information about state of system $Var\downarrow forecast = Var\downarrow climatol$
- **Measure** - Explained variance in verifying analysis, normalized $Var\downarrow forecast = Var\downarrow explained + Va$
  - Equals square of anomaly correlation
    - 1 / 0 = Perfect / Random forecast
- **Prediction**
  - Info captured about system by DA at initial time
  - Initial info propagated by model – Nothing added after initialization
- **Info in forecast converted to noise** w lead time
  - Integration called forecast until all info lost; noise generation thereafter
    - Intention does not count
- **How do we separate info from noise** variance as forecast progresses?
  - Temporal, spatial, ensemble filtering

$$\mathbf{I} = \frac{\mathbf{Var\downarrow explained}}{\mathbf{Var\downarrow climatology}}$$



TERMINOLOGY

Lorenz 1975

- **Weather**
  - "Complete state of the atmosphere at a particular instant"
    - Refers to an instantaneous state - ***Observable***, *exists in nature*
- **Weather predictability**
  - Whether chronological sequence of individual weather events predictable
  - Measured by correlation
- **Climate**
  - "Set of statistics of… many different states of the atmosphere"
    - Population statistics, directly not observable - ***Abstraction***
- **Climatic predictability**
  - Are changes in climatic statistics predictable?
    - Initial condition sensitivity, w/o known external forcing - *1st KIND*
      - Narrow definition of predictability, interest here
    - Equilibrium response to known external forcing – *2ND KIND*
      - E.g., hypothetical CO_2, solar insolation, land mass, orography, etc scenarios
      - "Prediction" in broad (not initial value) sense – Need plenty of numerical integrations
  - Measured by population statistics

DUALITY OF WEATHER & CLIMATE?

- **Weather** (instant state) & **climate** (statistics of states)
  - Useful terminology
- Tendency we may **associate two words** with
  - Two distinct entities
- Then we talk about **two distinct types of predictability**
  - For two "separate entities", weather & climate
- Yet both "weather" (directly) & "climate" (indirectly) refer to **same single reality**
  - ALOC with processes on **continuum of scales**

UNIFIED CONCEPT OF PREDICTABILITY

- **Narrow definition of prediction**
  - Projection of initial info into future
- **2nd kind of "climatic predictability"**
  - Climate mean in changing world - Not initial value problem
- **"Weather" & 1st kind of "climatic predictability"**
  - Study conversion of info into noise by chaotic divergence
- **Weather & climate relate to same reality**
  - Must avoid artificial demarcation across scales/systems
- **Common definition of predictability**
  - How long info from initial state retained
- **Predictable phenomena comprise of all scales**
  - Large scales more predictable
  - Corresponding finer scales lost deterministic connection w initial state

PREDICTABLE PHENOMENA

- All scales possess predictability
  - Commensurate to level of instabilities / growth rate
- **Large scales** (w slower growth) **more predictable**
  - Phenomena conveniently named after them
- Corresponding **finer scales unpredictable**
  - Their phase & amplitude unrelated to initial value
- **Phenomena = specific symbioses of all scales**
  - Fine scales organized in connection w large (predictable) scales
    - Provide stochastic forcing to large scales *AND/OR*
    - Respond to large scale forcing
  - Population statistics
    - Like molecules in Brownian motion – Individual phase / amplitude do not matter
- **Forecast implication**
  - Large scale predictable signal can be produced w a SINGLE fcst
  - Alternative noise realizations can be produced statistically

EXAMPLES

- **Convective clouds** – nowcasting
  - Convective instabilities in atmosphere, 100 m / 30 mins
- **Midlatitude cyclones** – weather forecasting
  - Baroclinic instabilities in atmosphere, 500 km / days
- **MJO** – S2S
  - Organized convection in atmosphere, 1,000s km / 30 days
- **ENSO** – Seasonal
  - Latent heat / organ. convection in ALOC, 10,000 km / 2 yrs
- **Atlantic meridional overturning circulation** – Decadal
  - Meridional imbalance in *ocean* heating, 10,000 km / decades

CONCLUSIONS

- **Prediction** – Based on determinism
  - Projection of incomplete info on initial state into future
- **Loss of skill/info** - Due to sensitivity in chaotic media
  - Same dynamical instabilities that give rise to phenomena
- **"Weather" & "climate"** refer to same single reality
  - Coupled Atmosphere-Land-Ocean-Cryosphere system
- **Common concept of predictability,** linked w initial info
  - How long info about system maintained in forecast
- **Info on small scales lost first**
  - No predictive info – Population statistics w/o multiple fcsts?

BACKGROUND

REFERENCES

- J. Roads, 1985: Forecasts of time averages with a numerical weather prediction model. JAS