Ensemble Predictions Systems and Probabilistic Forecasting

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Traditional Weather Forecasts

- What is a weather forecast?
  - Expected evolution of the atmosphere over the next few days.
  - Day-to-day changes not predictable beyond about a week.
- What do you expect from a weather forecast?
  - Chance or likelihood of Rainfall
  - Temperature (min/max)
  - Wind (speed/direction)
  - Cloud cover (cloudy, partly cloudy, clear skies, etc.)

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Traditional Weather Forecasts

- Why is it only possible within a couple of hours (~72 – 120 hrs)?
  - Numerically the Noise[1] is greater than signal[2]
  - Errors in initial conditions
- Up to ~3 days NWP models can *usually* forecast the general pattern of the weather quite accurately
- Beyond three days *chaos/non-linear characteristic of the atmosphere* becomes a major factor

  - *1: The small-scale, high-frequency solutions to the governing equations, which may obscure the solution required for forecasting.*
  - *2: Variations in the state of the atmosphere that have an identifiable and statistically discernible structure in time and/or space.*

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Deterministic NWP forecasts

GENERICALLY model output is produced in the following manner:

- 1. The initial state of the atmosphere is established using observational data
- 2. An atmospheric model simulates evolution from the established initial state
- 3. The model's output is processed and made available for use

INITIAL CONDITIONS ==> MODEL ==> OUTPUT

(http://www.hpc.ncep.noaa.gov/ensembletraining/)

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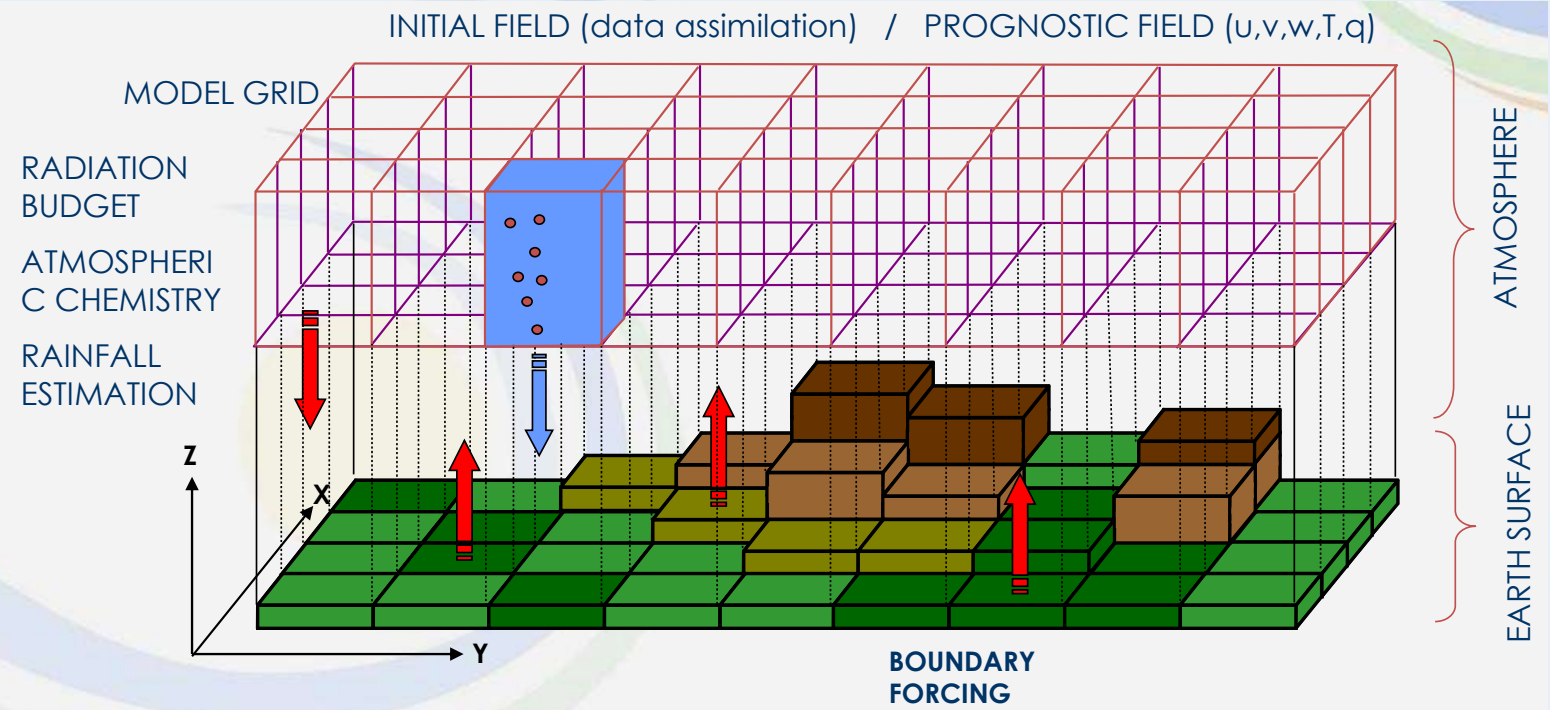
NWP forecast inherent errors

- Model equations do not fully capture ALL processes occurring in the atmosphere
  - With the solving of the dynamic equations, certain assumptions and simplifications are made due to:
    - Computer power capabilities
    - Human understanding
    - Resolution of the model (i.e. hydrostatic approximation)
- A model can not resolve atmospheric processes and features smaller than certain thresholds
  - Parameterizations schemes
  - Assumptions, simplifications and human understanding of processes
  - Horizontal resolution of models (implicit or explicit resolve of process)



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"Parameterization schemes by necessity distill only the essential aspects of the physical process they represent. Only a limited amount of complexity is possible within a parameterization since it is difficult enough to correctly reproduce the basic behaviours of the physical process for a variety of environmental conditions." Stensrud, 2011

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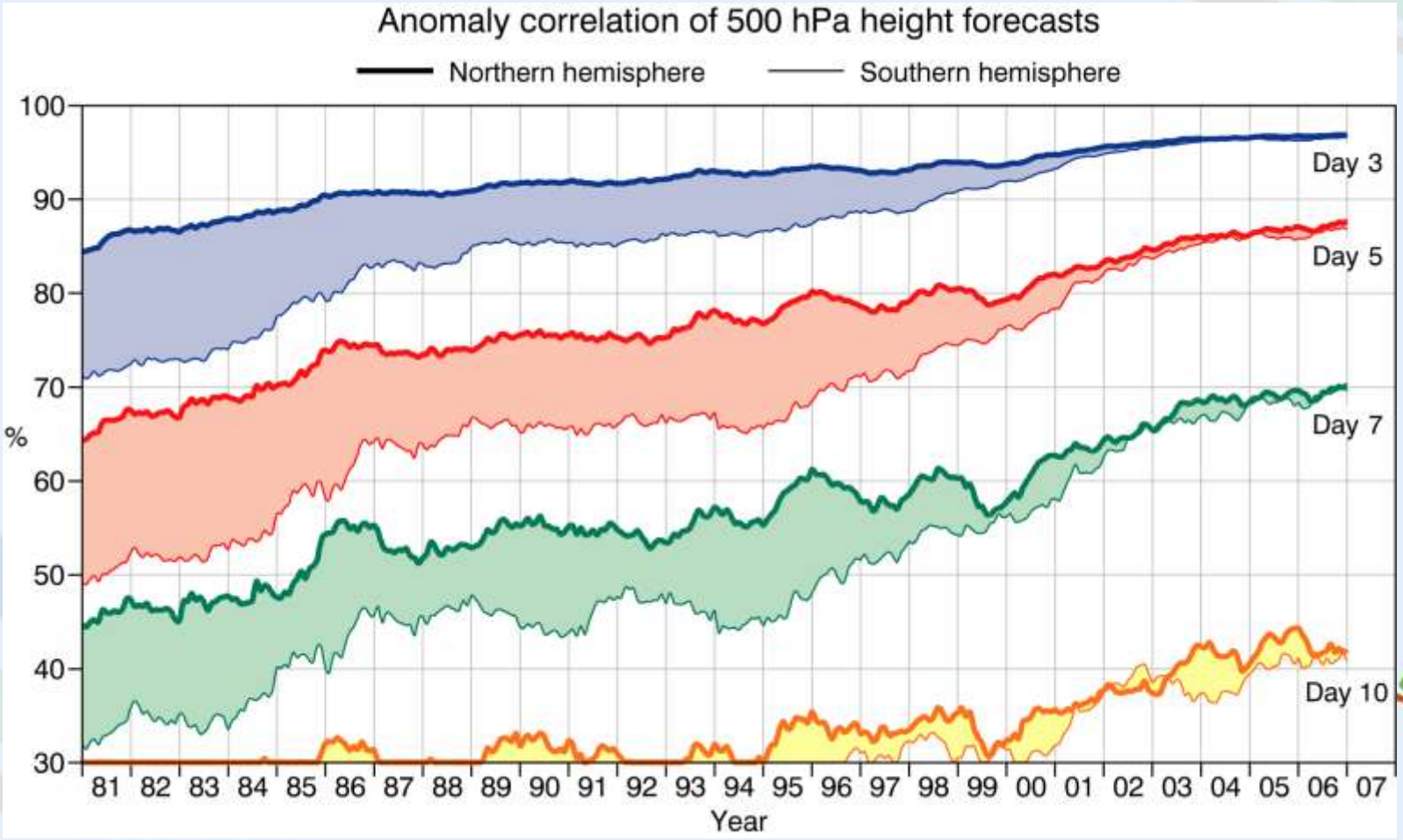
NWP forecast inherent errors

- Lack of comprehensive and quality observational data
  - Northern hemisphere has more in-situ measurements than southern hemisphere (land-ocean ratio)
  - Land coverage of in-situ measurements and upper-air observations
  - Contributes to errors in initial condition estimations



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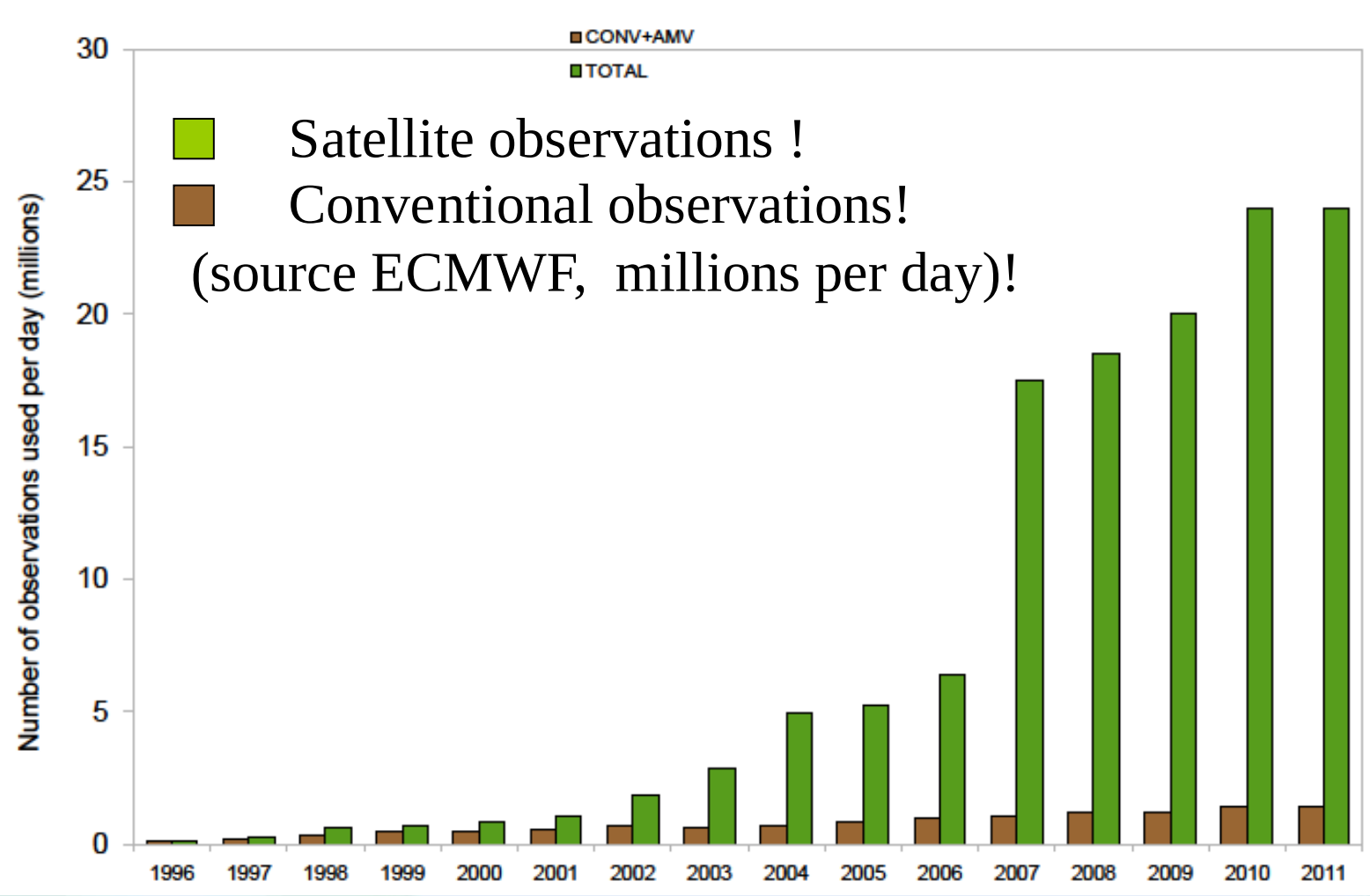
NWP forecast inherent errors



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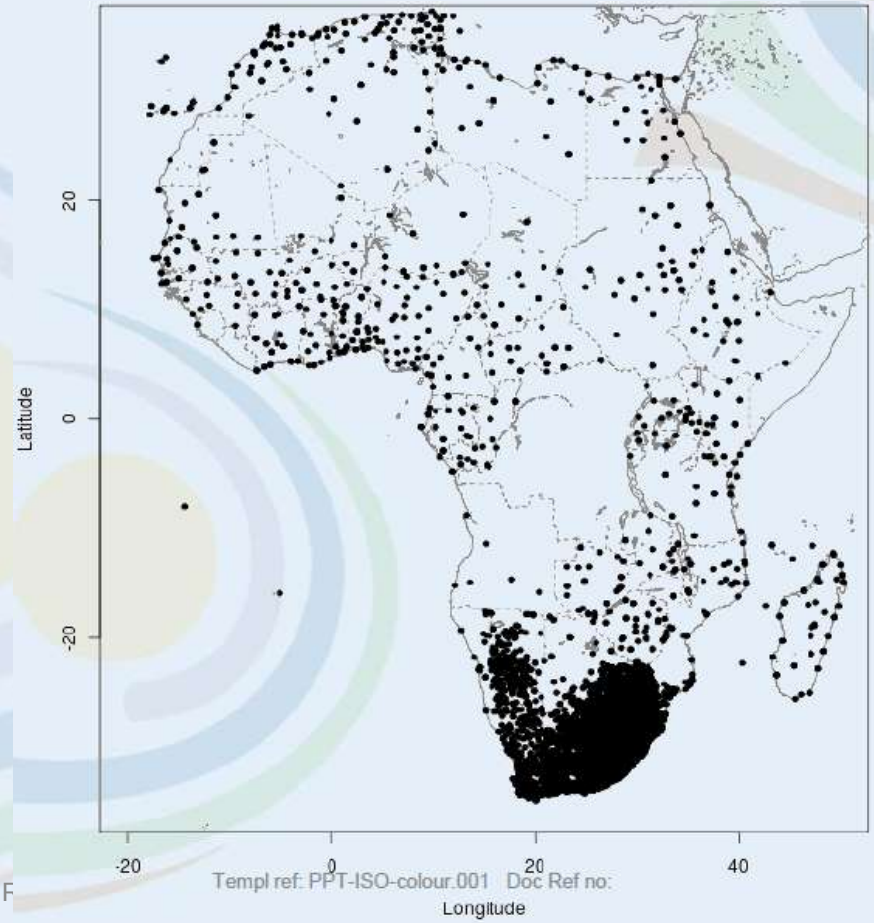

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Weather and Chaos

- “one flap of a sea-gull’s wing may forever change the future course of the weather” – Edward N. Lorenz (1969)
- Butterfly Effect
- Attractor is a set to which a dynamical system evolves after a long enough time
- Strange Attractors: same evolutionary equations, different initial conditions
- System is nonlinear, three-dimensional & deterministic – SAME AS ATMOSPHERE
- Lorenz map shows the state of dynamical system, evolves over time in a complex non-repeating system

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Weather and Chaos

- Even with a “perfect” model, there is a finite limit to the predictability of the atmosphere since we cannot observe the atmosphere perfectly – there are always sampling errors within the current estimation of the atmosphere
- Model simulations starting with different initial conditions diverge significantly with time and after about 5 days, have little relationship with each other

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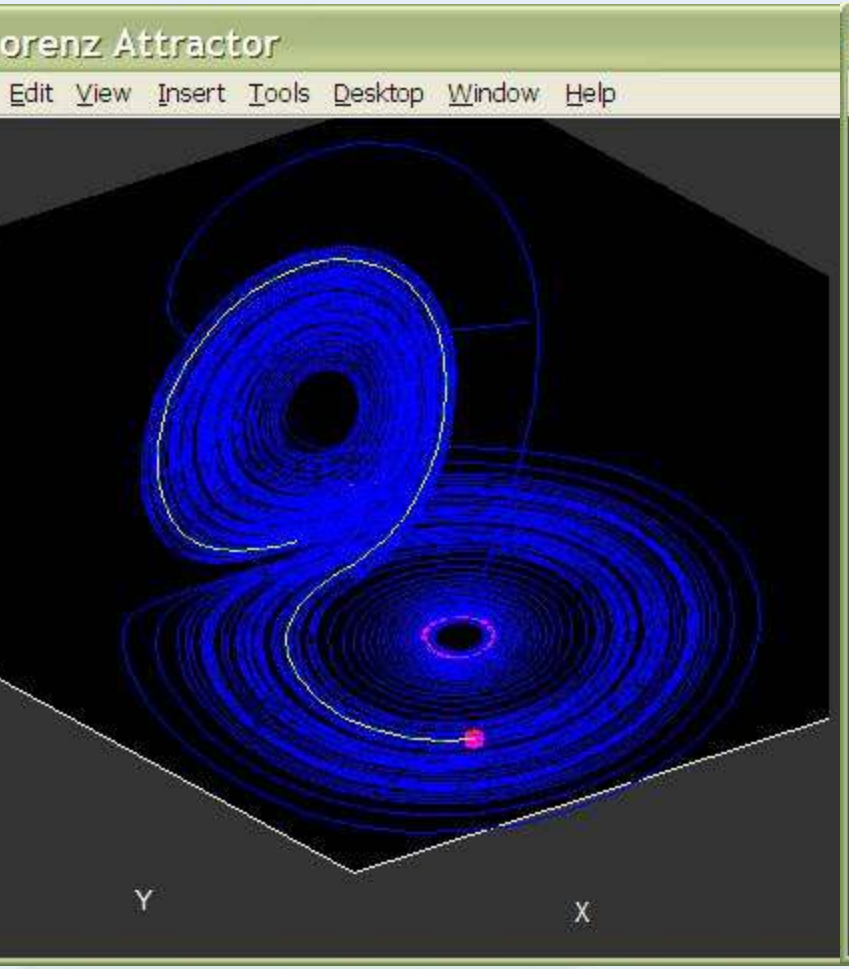
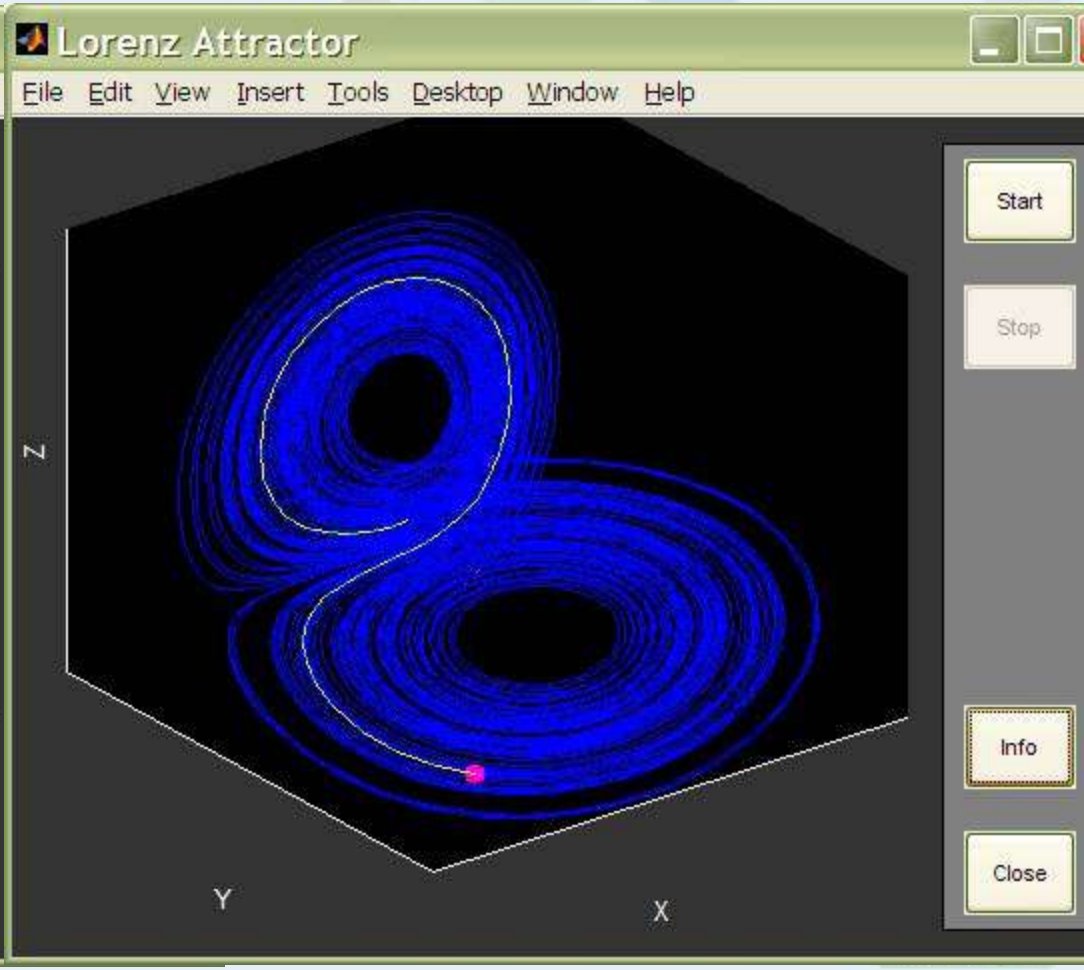
Weather and Chaos





Uncertainty of Forecasts

- Therefore, with a single deterministic forecasts there are always some uncertainty within the forecast caused by the non-linear characteristic of the atmosphere, estimations of initial conditions and inherent model errors
- However, a deterministic forecast does not indicate the level of uncertainty within the forecast
- Forecasting features with large societal impacts (i.e. thunderstorms) without uncertainty information hampers the best use of these forecasts (Stensrud, 2011)

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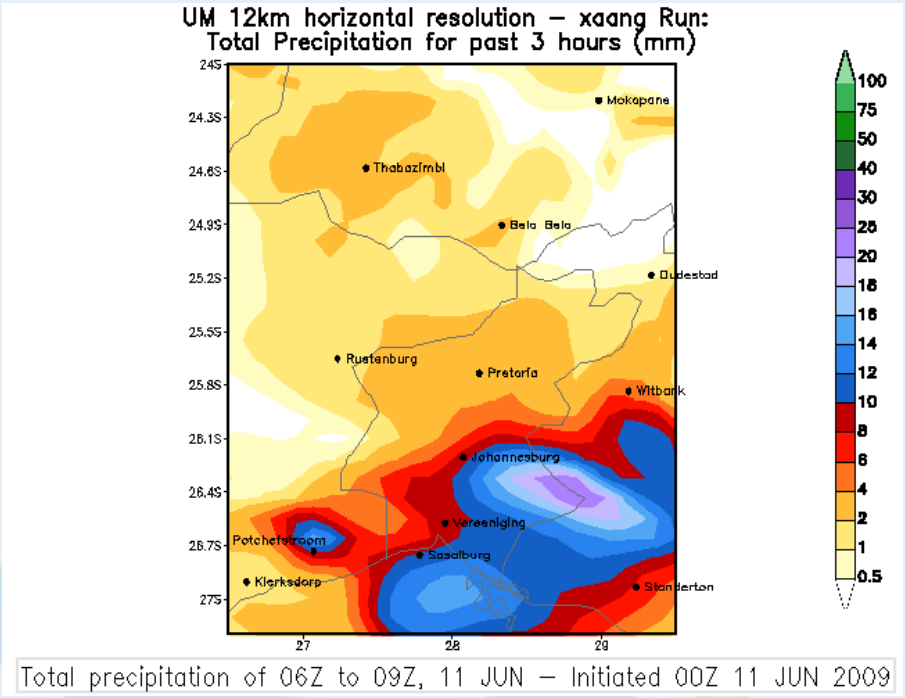
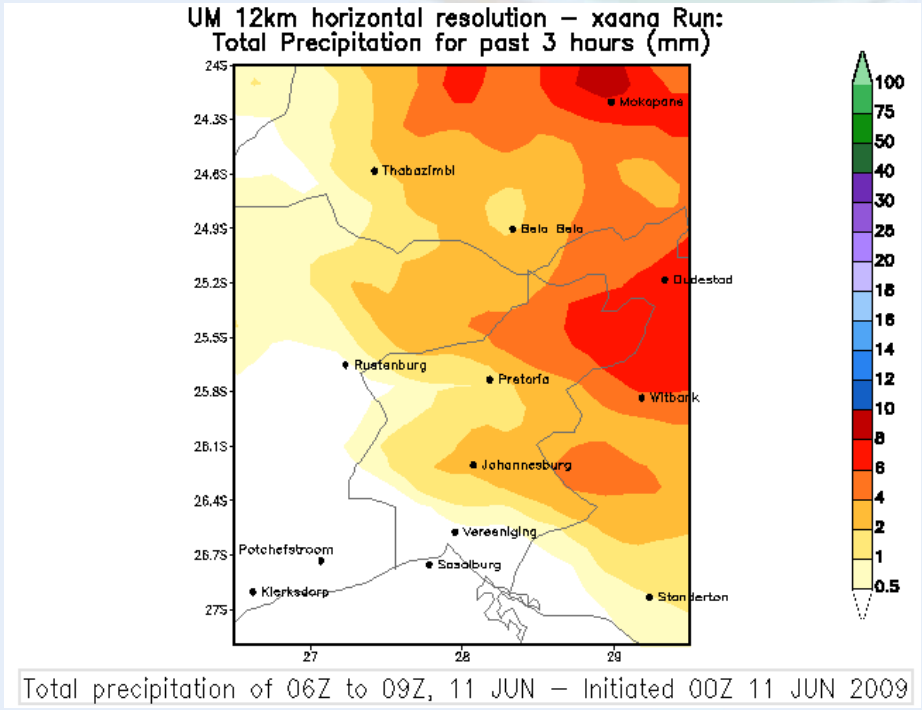
Uncertainty of Forecasts

11 June 2009Cut-off low over central SA





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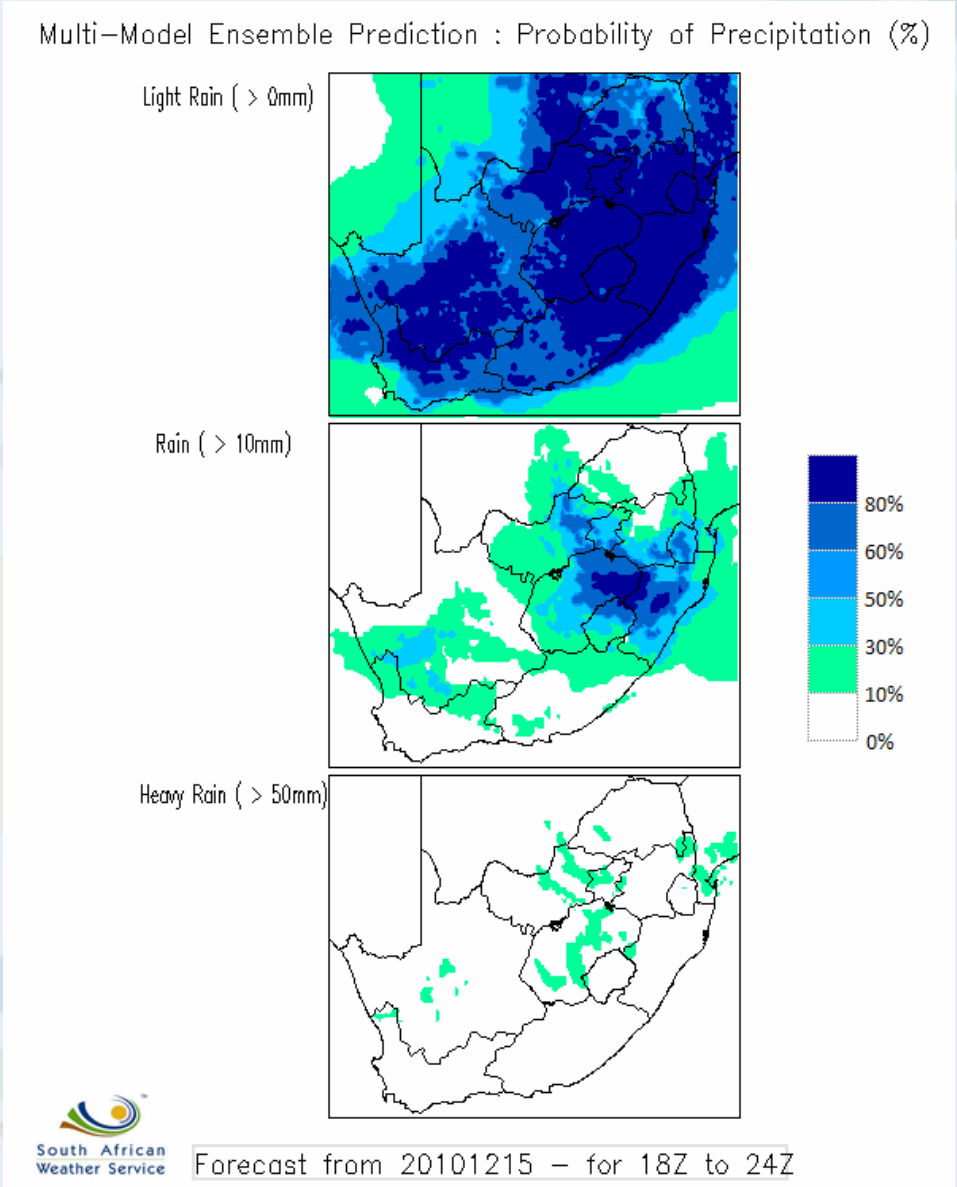
Uncertainty of Forecasts



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Longer Range Forecasts

- From 72hrs up to 14 days ahead…
- How is this done if weather predictability is at ~5 days?
- The detail of the forecast decreases over time
  - The predictability time limit becomes shorter as the scales of interest become smaller
  - ~ fine details (i.e. rainfall) have a shorter predictability
  - Orographically induced phenomenon is not forecast in detail (i.e. land/sea breezes)

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Ensemble Forecasts

Multiple numerical predictions are conducted using slightly different initial conditions that are all plausible given the past and current set of observations, or measurements. Sometimes the ensemble of forecasts may use different forecast models for different members, or different formulations of a forecast model.

An ensemble is a collection of forecasts that are valid for the exact time period.

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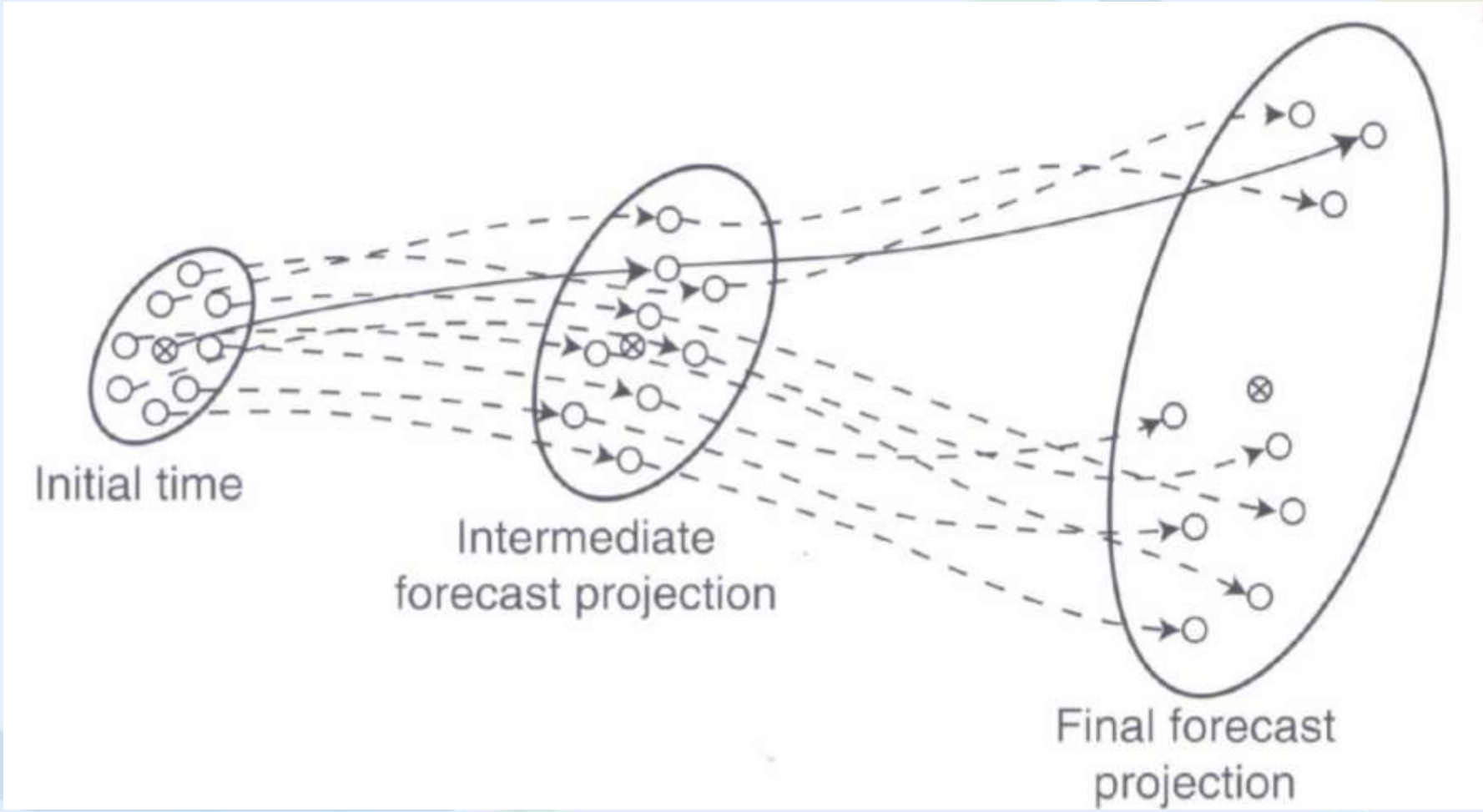
Ensemble Forecasts



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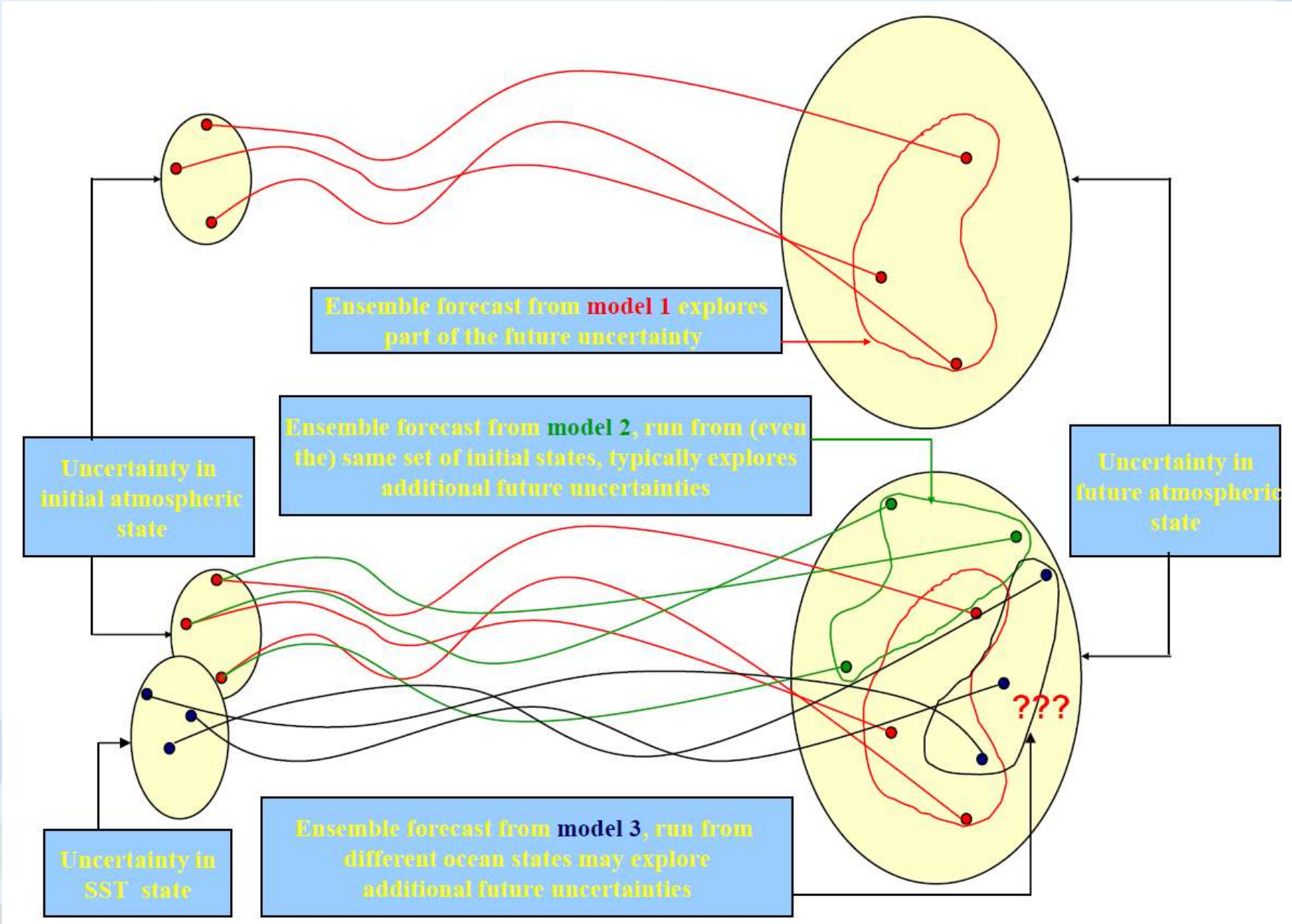
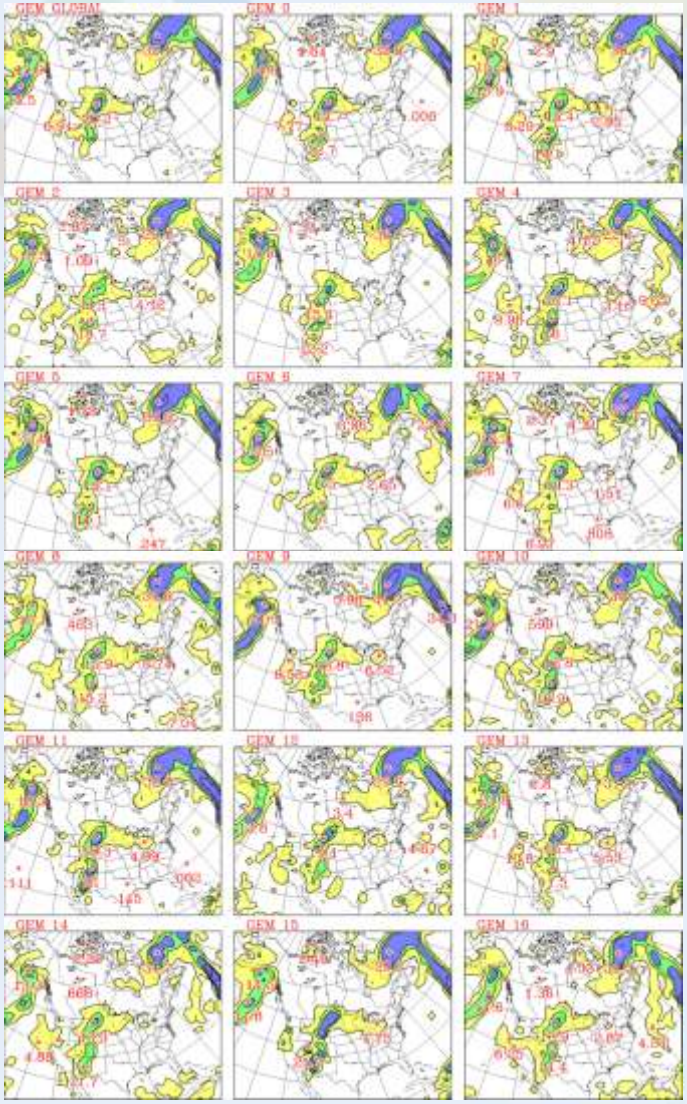
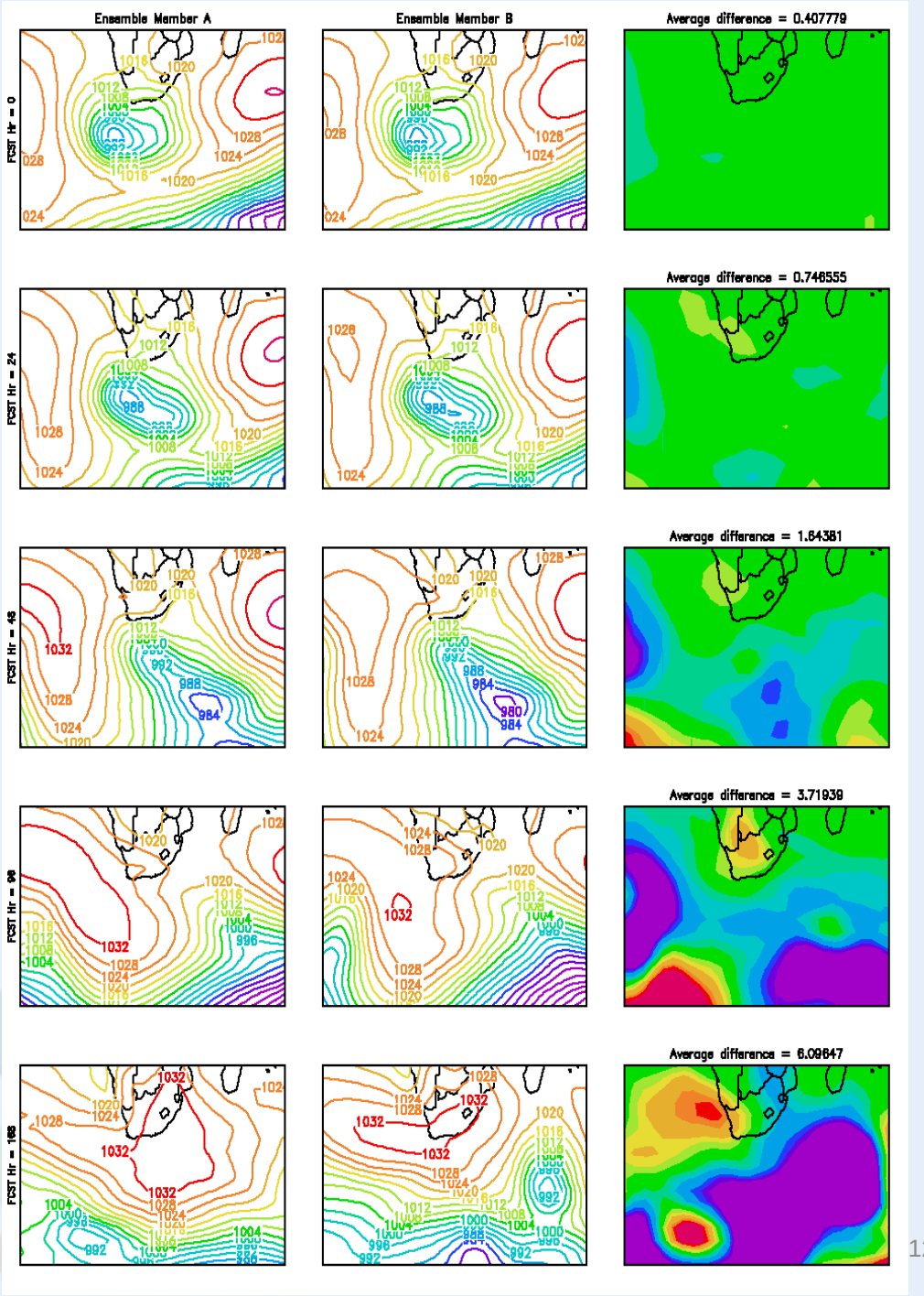

Ensemble forecast from model 1 explores part of the future uncertainty
Ensemble forecast from model 2, run from (even the) same set of initial states, typically explores additional future uncertainties
Uncertainty in initial atmospheric state
Uncertainty in future atmospheric state
???
Uncertainty in SST state
Ensemble forecast from model 3, run from different ocean states may explore additional future uncertainties

Ensemble Forecasts

- In an ensemble forecast the model runs many times from slightly different initial conditions
- This provides a range of more likely or less likely forecast solutions which allows forecasters to:
  - assess possible outcomes;
  - estimate risks
  - gauge confidence.



Canadian EPS (20 members – GEM model)
www.weatheroffice.gc.ca



To illustrate the effect of differences in initial conditions:

- Member A and Member B are initialised at the same time, but different perturbed IC's
- The difference between the two fields are shown in the right-hand column

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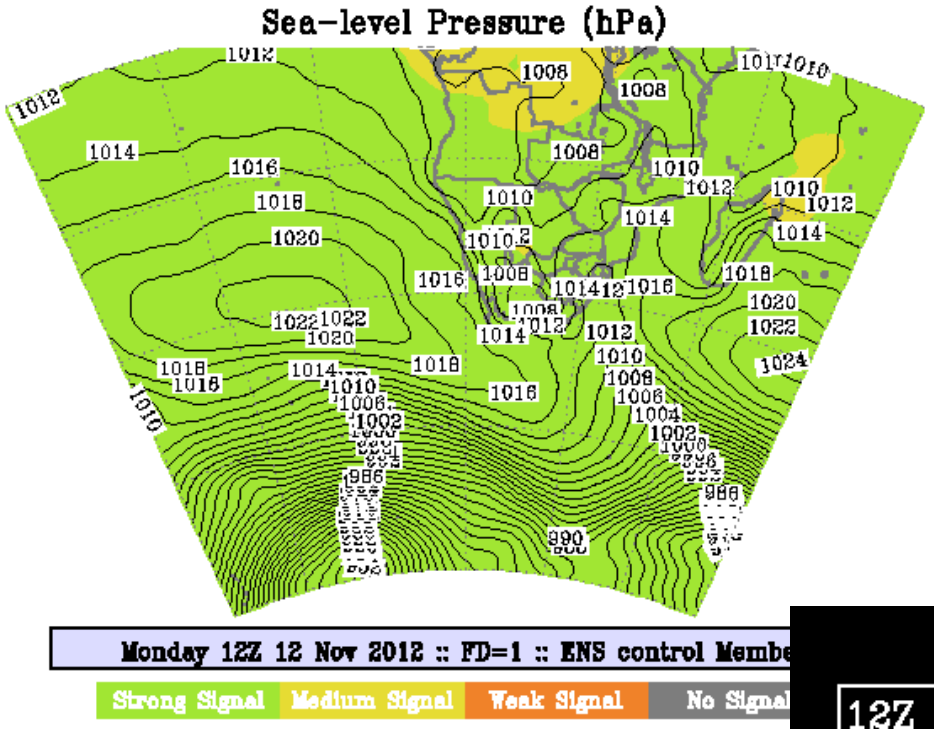
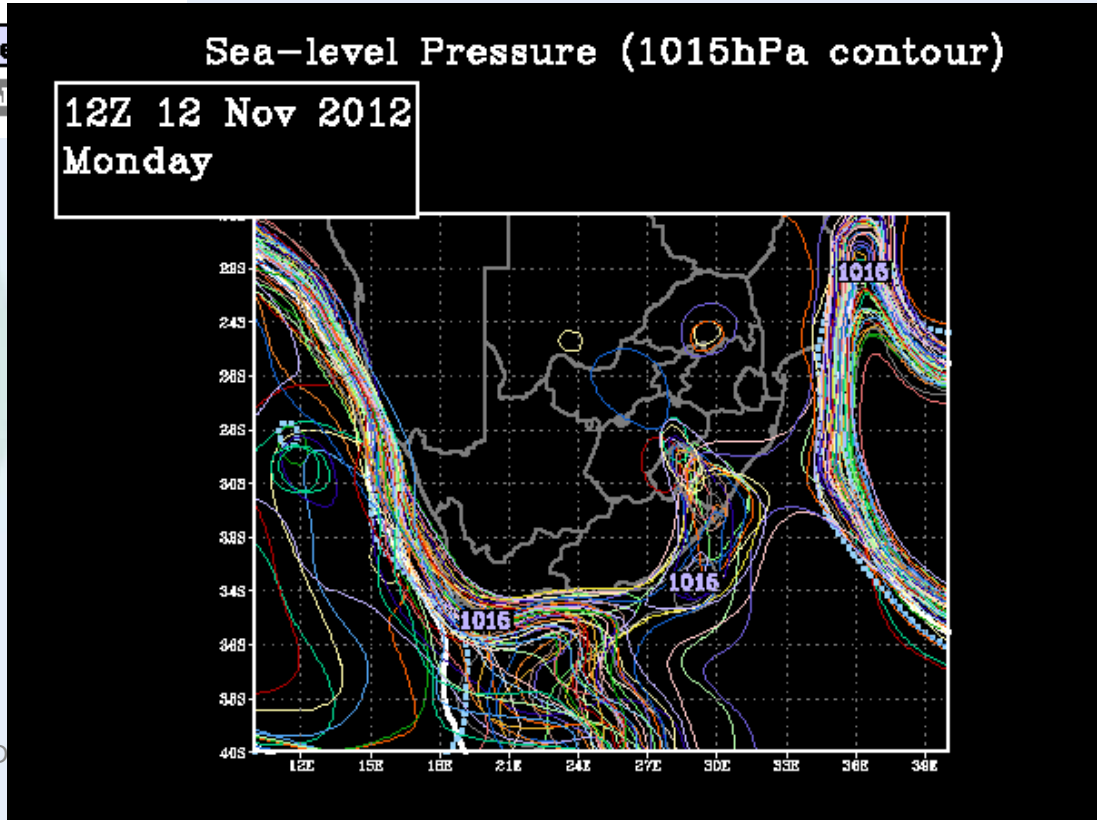
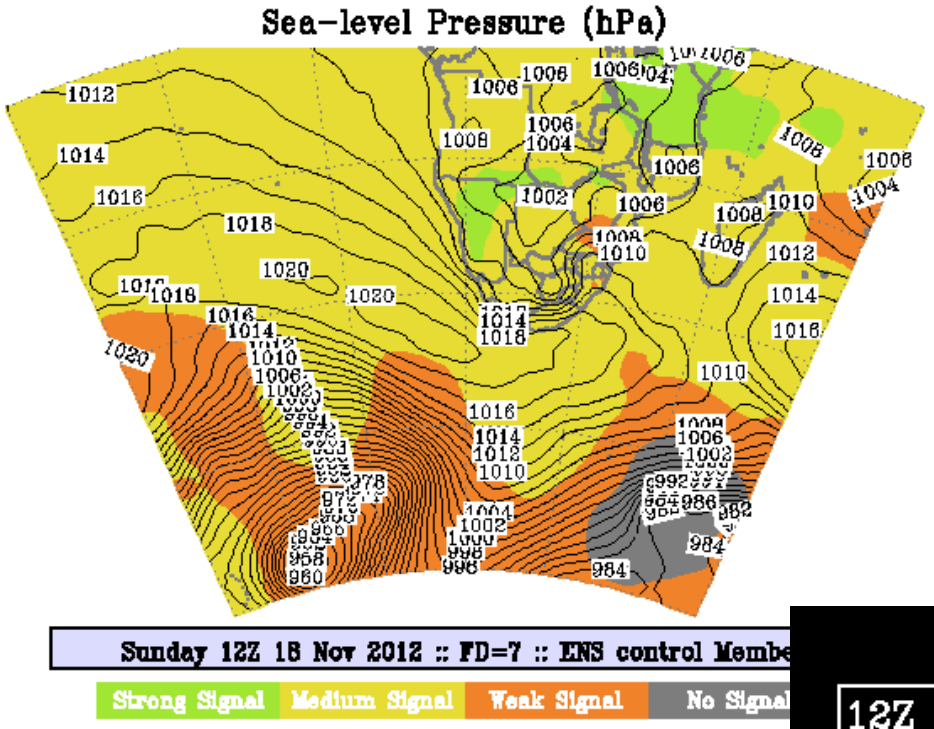
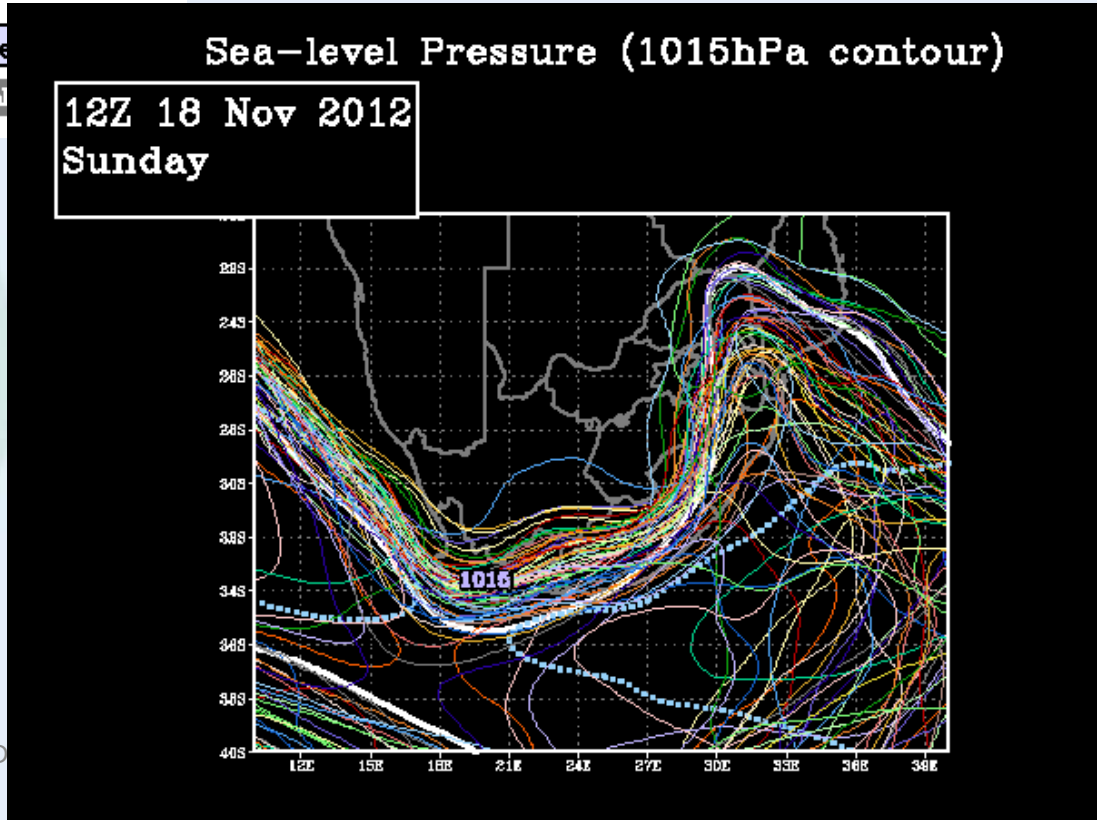
DAY 1


Sea-level Pressure (hPa)
Monday 12Z 12 Nov 2012 :: FD=1 :: ENS control Membe
Strong Signal
Medium Signal
Weak Signal
No Signal

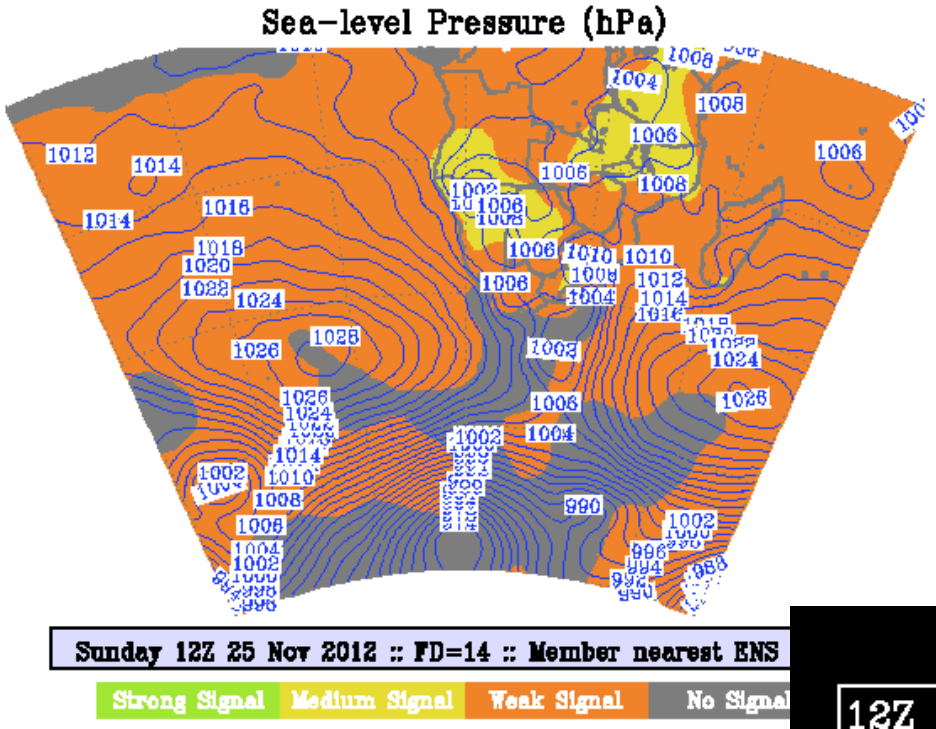

Sea-level Pressure (1015hPa contour)
12Z 12 Nov 2012
Monday
1016
1016
1016

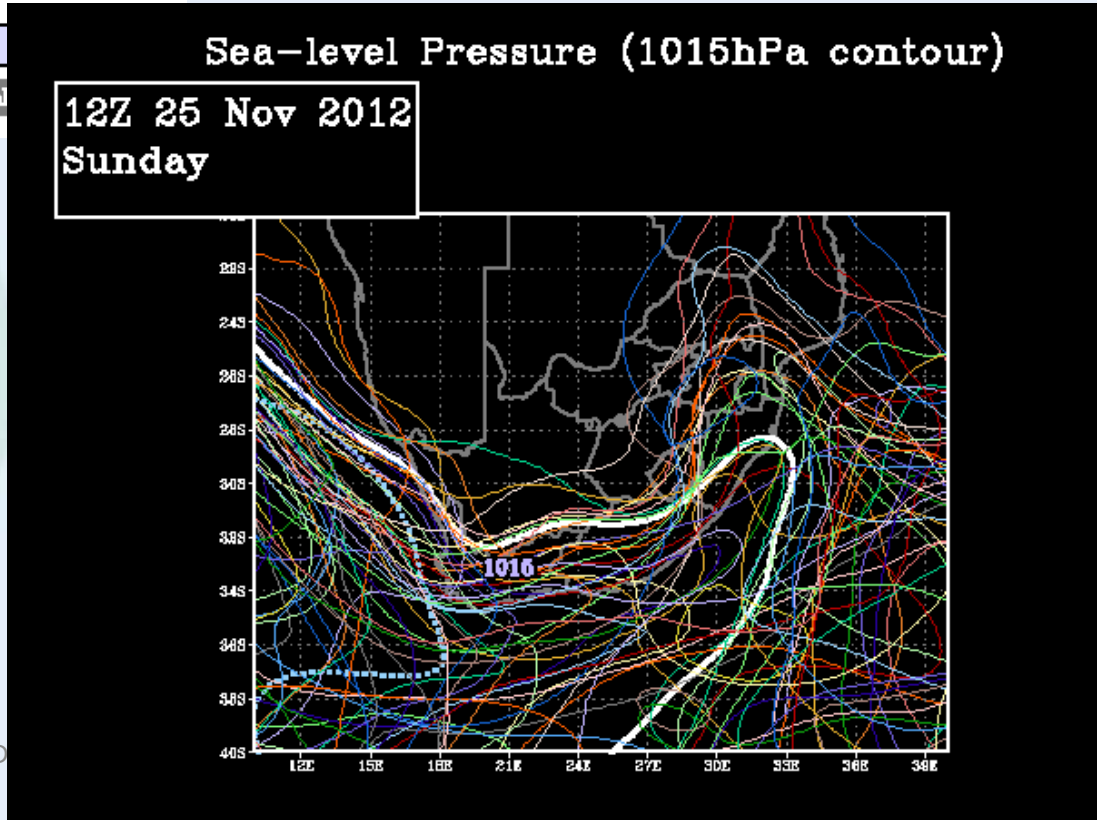
DAY 7


Sea–level Pressure (hPa)
Sunday 12Z 18 Nov 2012 :: FD=7 :: ENS control Membe
Strong Signal
Medium Signal
Weak Signal
No Signal


Sea–level Pressure (1015hPa contour)
12Z 18 Nov 2012
Sunday
1015

DAY 14


Sea–level Pressure (hPa)
Sunday 12Z 25 Nov 2012 :: FD=14 :: Member nearest ENS
Strong Signal
Medium Signal
Weak Signal
No Signal


Sea–level Pressure (1015hPa contour)
12Z 25 Nov 2012
Sunday
1016

Generating an Ensemble

- Collection of forecasts:
  - Same time
    - i.e.: same timescale, same forecast hour, same time-steps
  - Identity of each other
    - i.e.: same resolution, same domain

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Generating an Ensemble

- Ensemble consists of:
  - Different models (addresses model error)
  - Same model:
    - Initial conditions (perturbations)
    - Model configurations (physical schemes)
    - Initial times
    - Combination of above-mentioned
- Each of these “runs” are called an ensemble member

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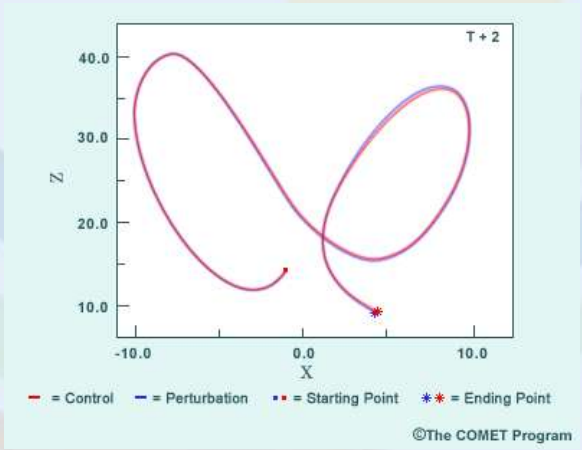
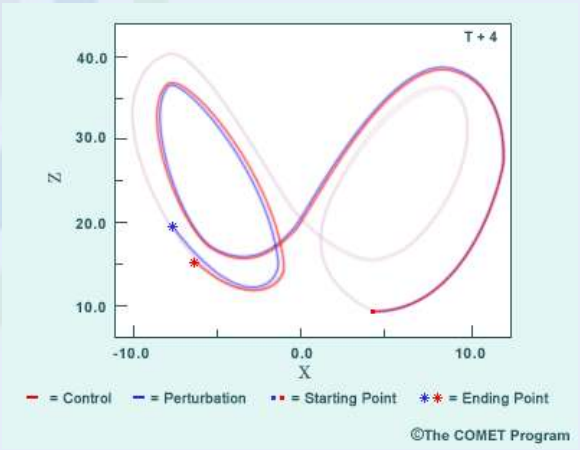
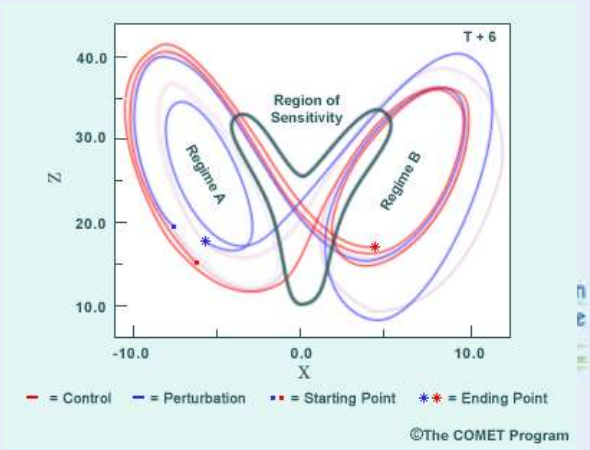
Methods for Generating an Ensemble

- **Monte Carlo:** change in initial conditions (+ and – random perturbations from analysis)
  - Perturbations: local deviation from the climatology
  - these numbers are not random at all -- they are strictly deterministic and reproduce-able







Methods for Generating an Ensemble

- **Lagged Average Forecasting:** different initial times (lags)
- Alternative to Monte Carlo
- Forecasts initialised at current initial time, t=0, as well as at previous times, t=-τ, -2τ, … , -(N-1)τ are combined to form an ensemble
- τ is typically 6, 12 or 24
- At short-range, skill decreases rapidly with lead-time
  - Thus: "older" forecasts reduces overall skill
  - Counteracted by weighting the forecasts

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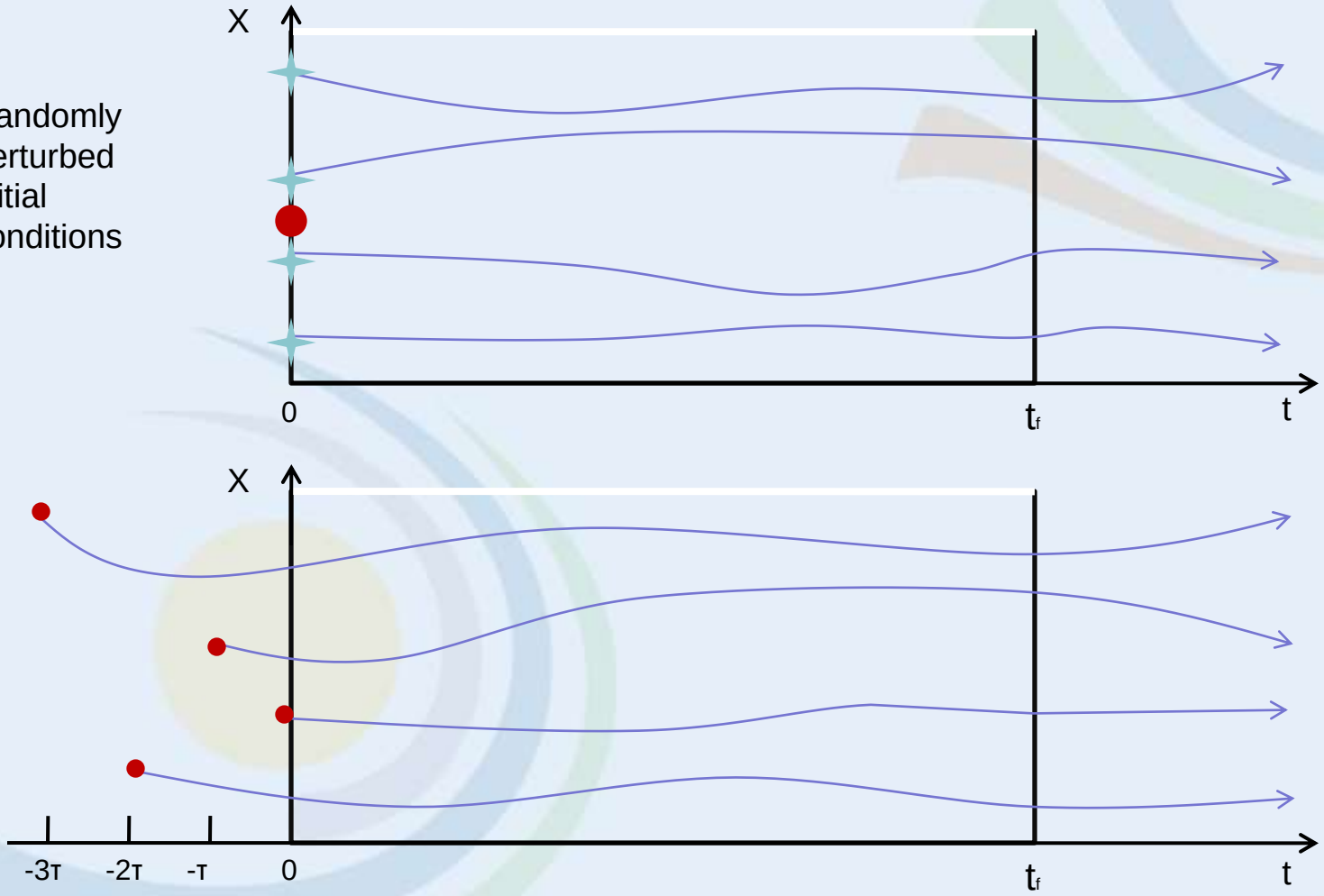
Monte Carlo *vs* Lagged Average Forecasts

Randomly perturbed initial conditions



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Methods for Generating an Ensemble

- Breeding of Growing Modes -
- Kalman filter – ensemble based data assimilation
- Singular vectors – optimal perturbations

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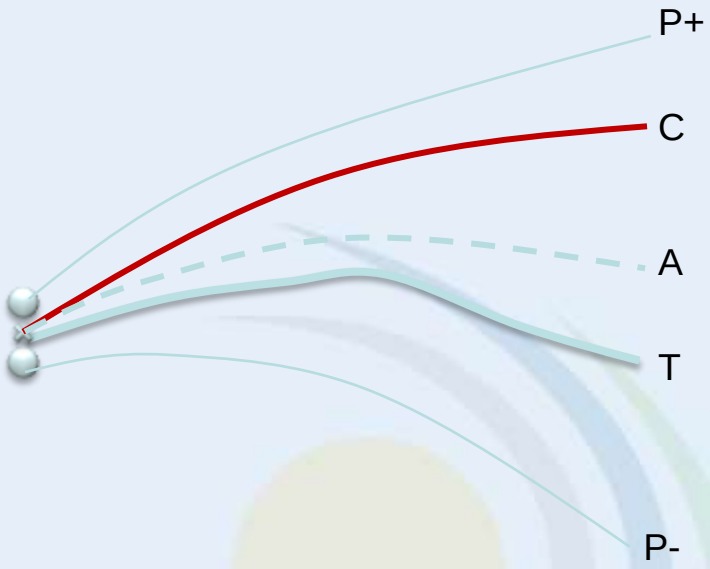
Methods for Generating an Ensemble



- Good ensemble (T member of ensemble)
- Average closer to T than C to T
    - Forecast errors dominated by system errors not initial condition

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Benefits of Ensemble Forecasting

- **Addressing uncertainty in atmospheric modelling:**
  - Errors in initial conditions are reduced by adding/subtracting perturbations to the analysis
  - Ensemble give a better representation of the possible future states of the atmosphere
    - Observed future state should fall within the forecast distribution
    - Forecast distribution should be as narrow as possible
    - Promotes confidence and increases skill in forecast

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Benefits of Ensemble Forecasting

- **Addressing uncertainty in atmospheric modelling:**
  - Internal model variability is determined through inter-ensemble member and signal-to-noise ratio
  - Ensembles of different models can utilize unique advantages of each model in providing a forecast that has more skill than any individual model
    - Weighted factors should be determined
    - Poor model can contaminate the ensemble

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Benefits of Ensemble Forecasting

- **Objective calculations of probability forecasts:**
  - Probability of an event is the percentage of ensemble members that forecast the event relative to the total number of members
  - Severe weather forecasts are improved with these probability calculations
  - Ensemble spread indicator of forecast skill
    - Indicators differ with season and geographical location

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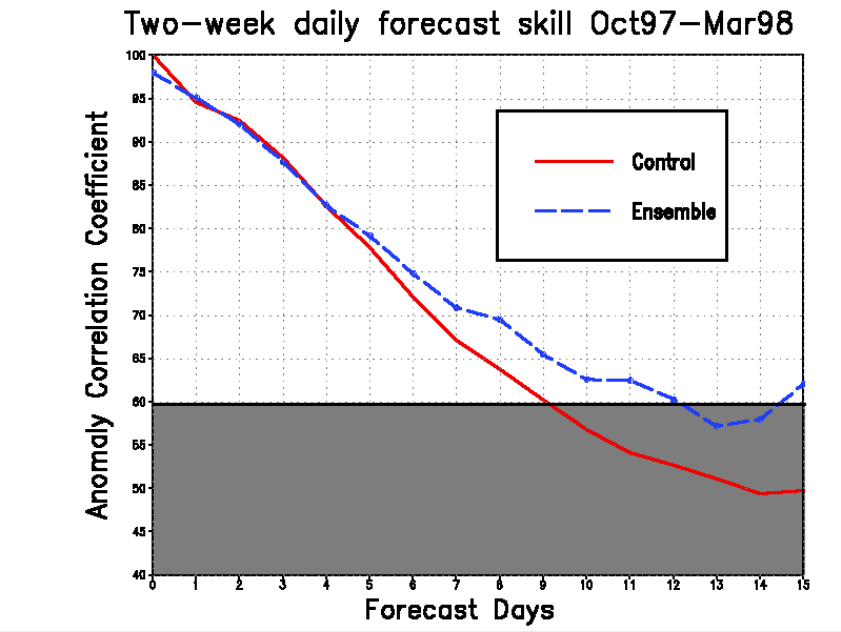
Benefits of Ensemble Forecasting

- **Overall improvement in forecast skill:**
  - The mean generally outperforms any member on most time-scales
    - Smoothing effect of averaging different forecasts
    - Producing a spread of forecasts whose mean is closest to the observed
  - Advantage of the improvement in skill is the extension of the predictability limit by a number of days



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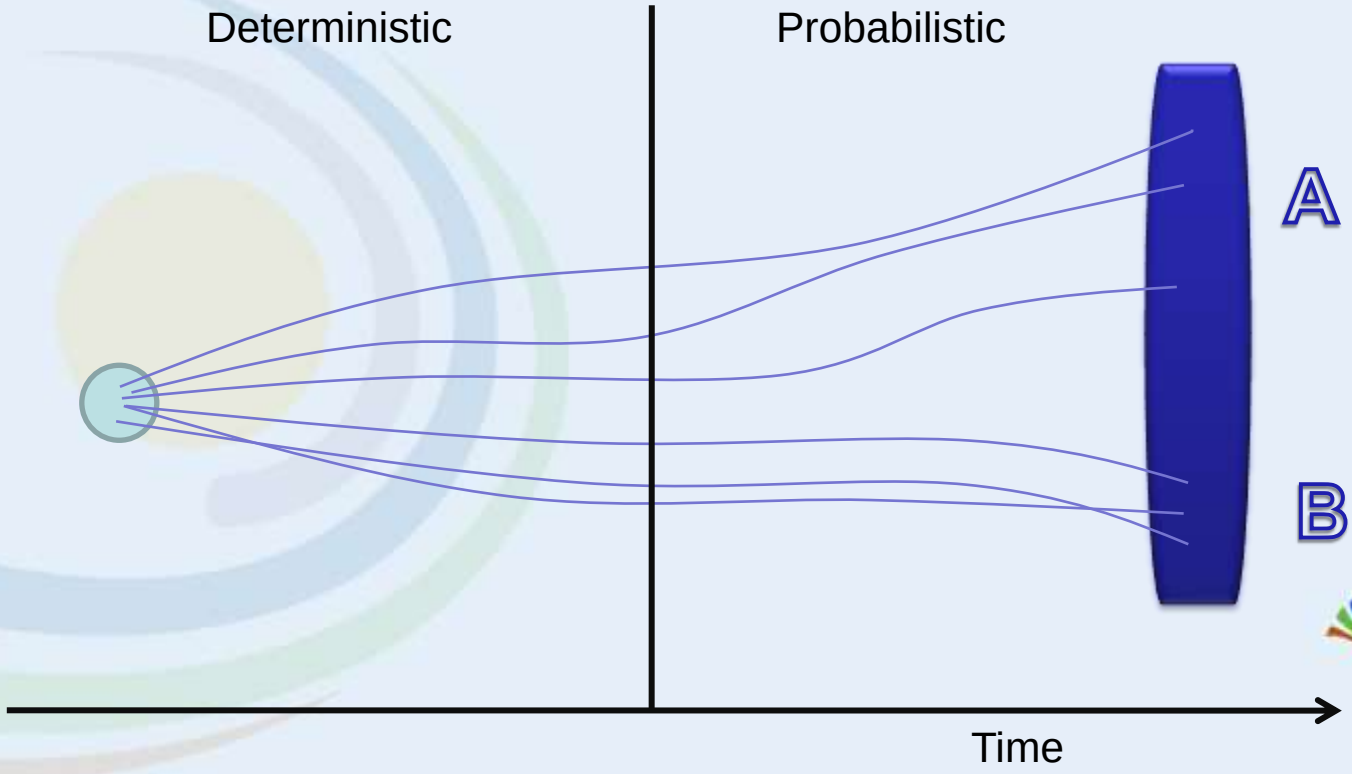
Benefits of Ensemble Forecasting

- **Clustering of Forecasts:**
  - Ensemble members begin to group into clusters/groups
  - Probability of groups occurring can be calculated from group population



Deterministic *vs.* Probabilistic

Deterministic

- Best, single forecast
- Finest resolution model
- Best data assimilation technique
  - Cloudy with rain-showers

Probabilistic

- Range of probabilities
- Forecast an event (precipitation) or category (below normal)
- Expressed as a percentage of probability of occurrence
  - Cloudy with 40% chance of rain
  - JFB: 30% chance of below normal and 70% of above normal rainfall

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