AOSC 615
Advanced Methods in Data Assimilation

- Instructor: Kayo Ide
  - Contact: ide@umd.edu
  - Office& Hours: 3403 CSS & By app.
- Class:
  - Time: Tu.Th. 12:30-01:45
  - Room: 1164 PLS
  - URL: http://aosc.umd.edu/~ide

AOSC615: Advanced Data Assimilation

Class work

Lectures

1. Introduction
2. Mathematical Background
3. "3D" Methods
4. Uncertainty evolution
5. "4D" Methods
6. Advanced schemes
7. Special Topics

Projects

- Students will work on implementation of the data assimilation methods using the identical twin experiments

1. Introduction
   1. DA Overview
      a) Background
      b) Schematics
      c) Elements with Examples
      d) Challenges
   2. AOSC 615 Overview
      a) Objectives
      b) Project Description

- Project I

AOSC615: Advanced Data Assimilation

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What is Data Assimilation?

- Data assimilation is the problem of scientific estimation and prediction (not limited to geophysical or earth systems).

- Data assimilation is an iterative method that attempts to combine and make best use of
  - Model (computational) of the physical system
  - Observations

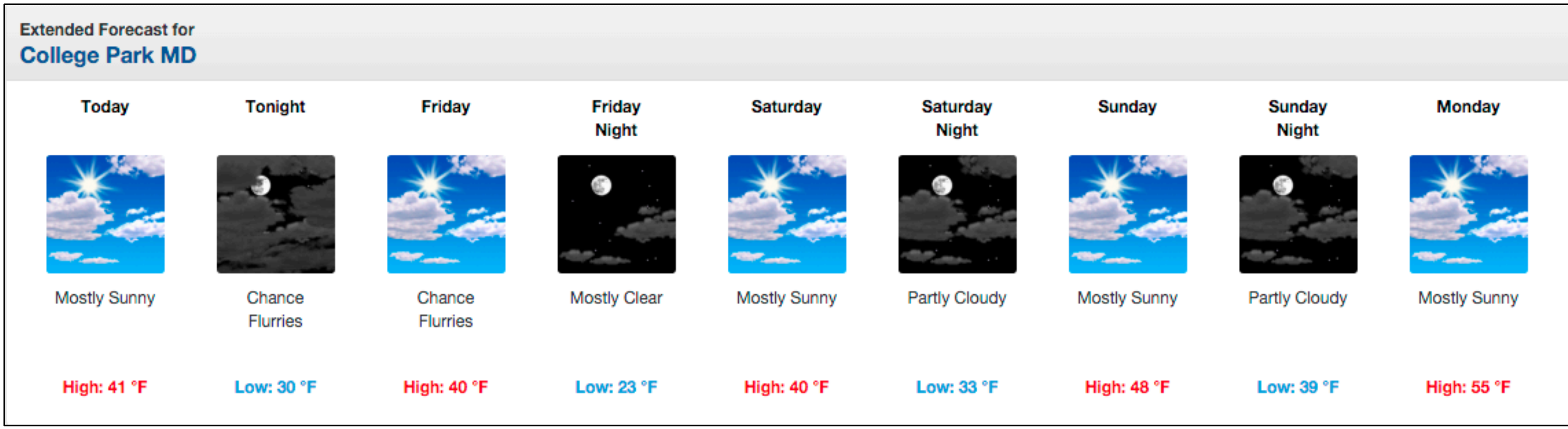
  to achieve the "goal".

- A familiar form is the Numerical Weather Prediction (NWP)

Data Assimilation

- Example: Weather forecast

weather.gov

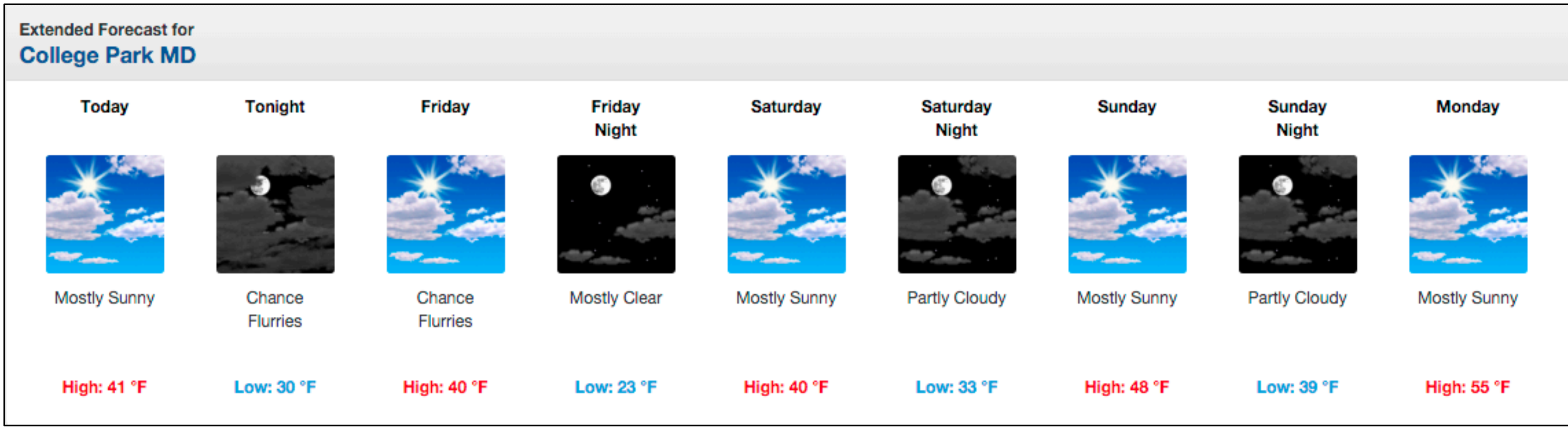


- How long do you trust?
- Why?
  - Nonlinear/complex nature of atmosphere
  - Imperfectness of the model & initial condition

→ **Uncertainty or likelihood needs to be taken into account**

Data Assimilation Example

- Most familiar form: Weather forecast



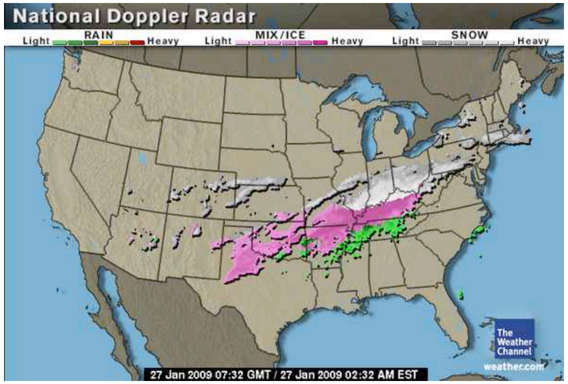
- Iterative method for initialization problem that attempts to combine
  - Model (computational) of the physical system
  - Observations

  by incorporating uncertainty for (re-analysis,) monitoring and forecasting

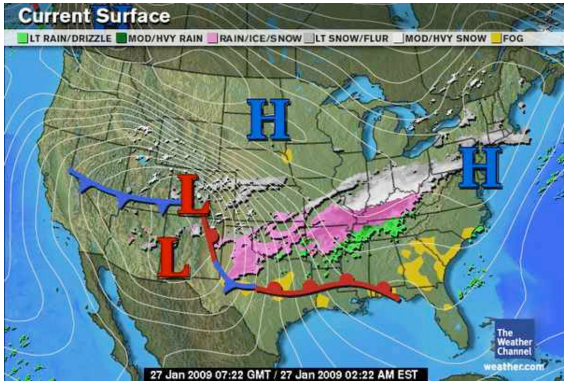
Forecasting

- Data assimilation attempts to estimate
  - States (current states, future states, or even past states)
  - Their likelihood (associated uncertainty)
- Forecast requirement
  - Current condition (initial condition)
  - Forecast model

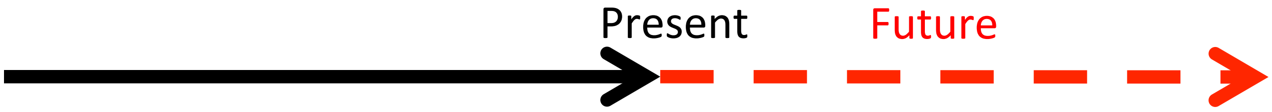
past conditions



current condition



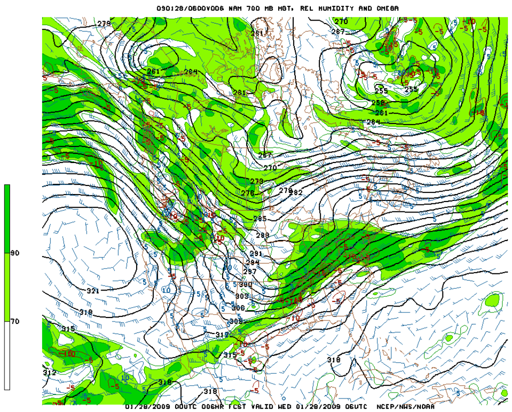
forecast



Forecasting

- Available:

model forecast from the past

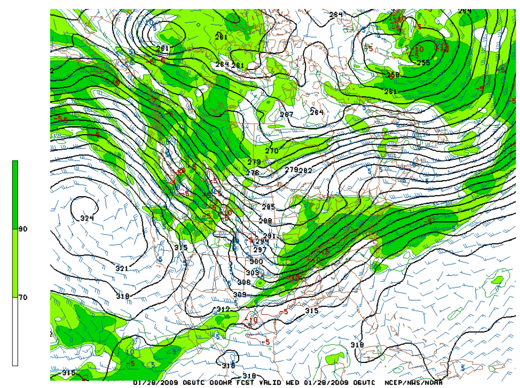


Insufficient representation of the complete current condition

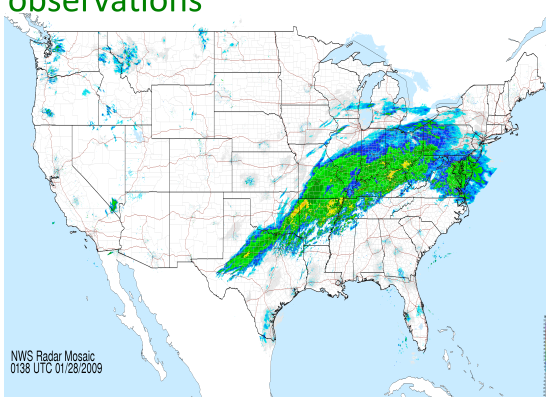
(=IC to the model forecast)

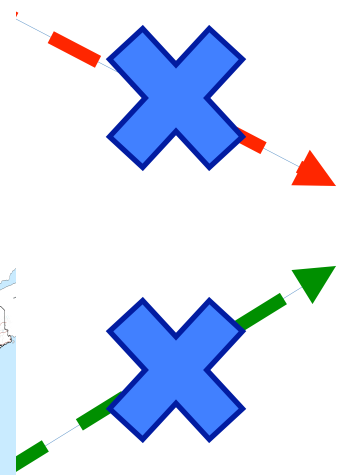
current condition

Analysis (700mb)



observations





Insufficient to provide with the complete current condition

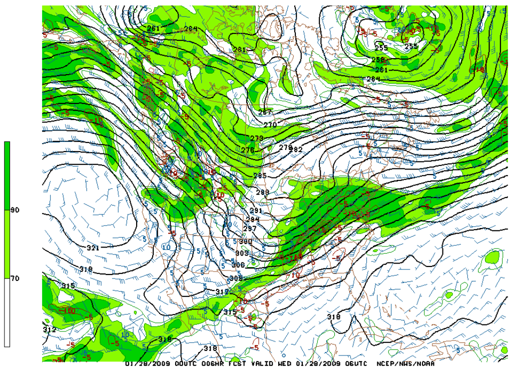
(=IC to the model forecast)

Schematics of Data Assimilation

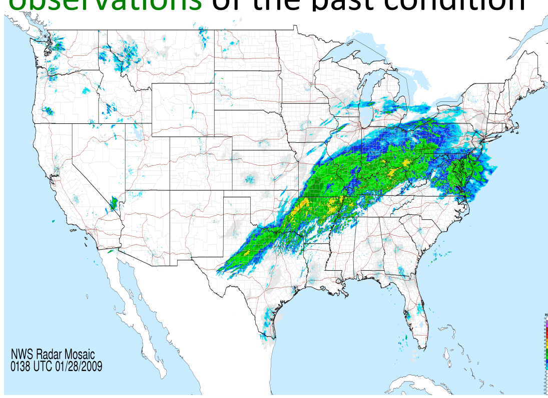
- Data assimilation is an iterative method that attempts to make best use of the model and the observations

model forecast from the past

6h forecast (700mb)



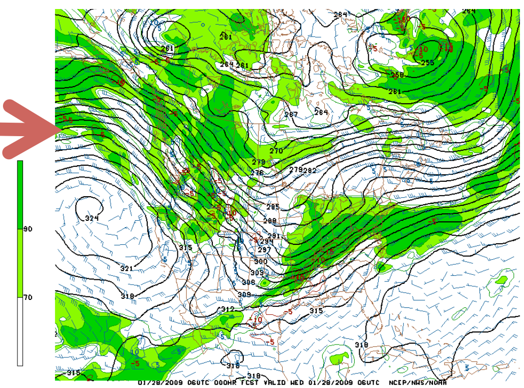
observations of the past condition



Assimilation of data into model forecast

current condition

Analysis (700mb)



Schematics of Data Assimilation

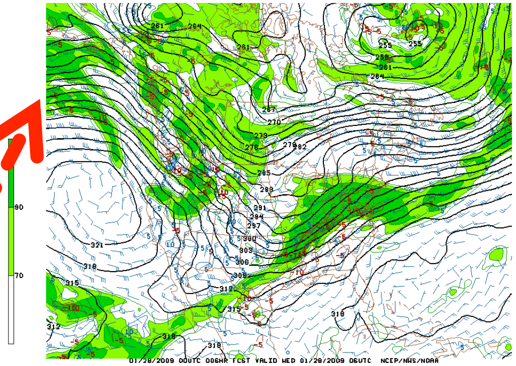
- Data assimilation is an iterative method

6hr Assimilation Window

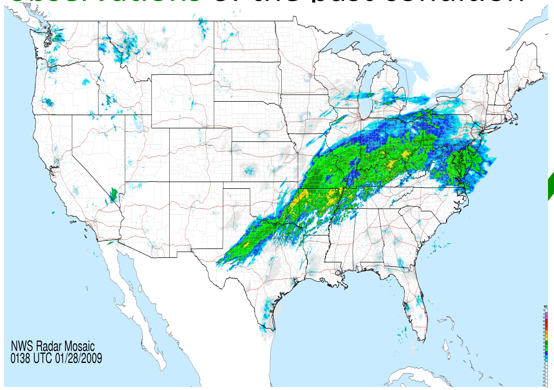
… imagine writing a data assimilation code…

model forecast from the past

6h forecast (700mb)



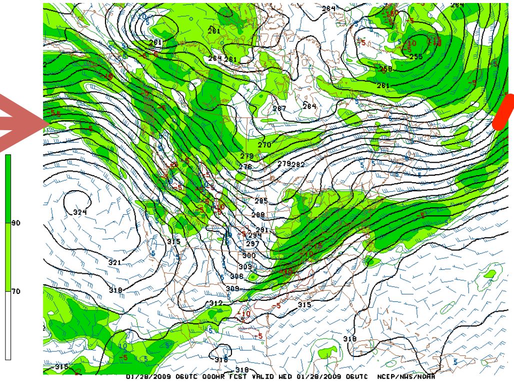
observations of the past condition



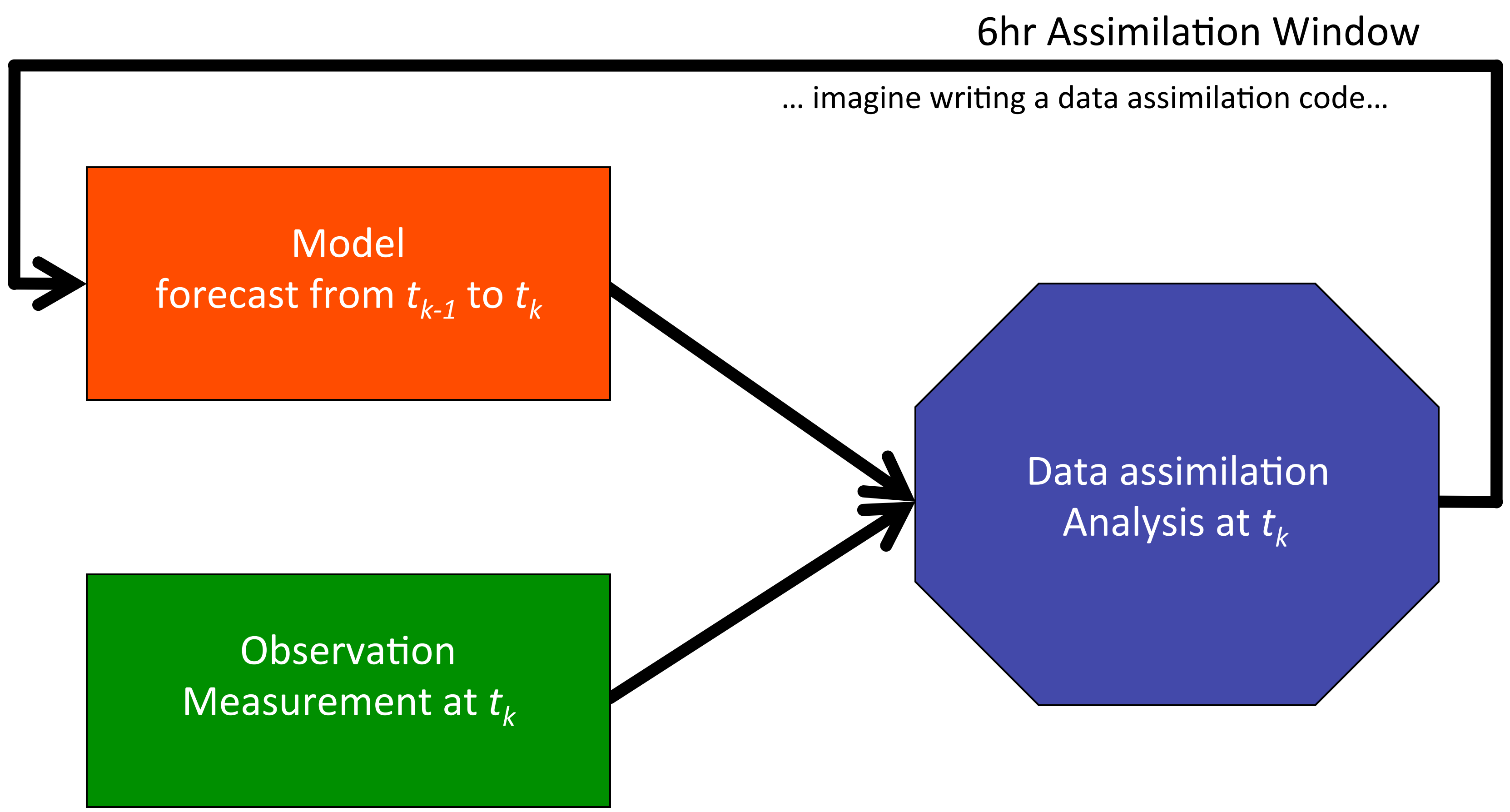
Assimilation of data into model forecast

current condition

Analysis (700mb)

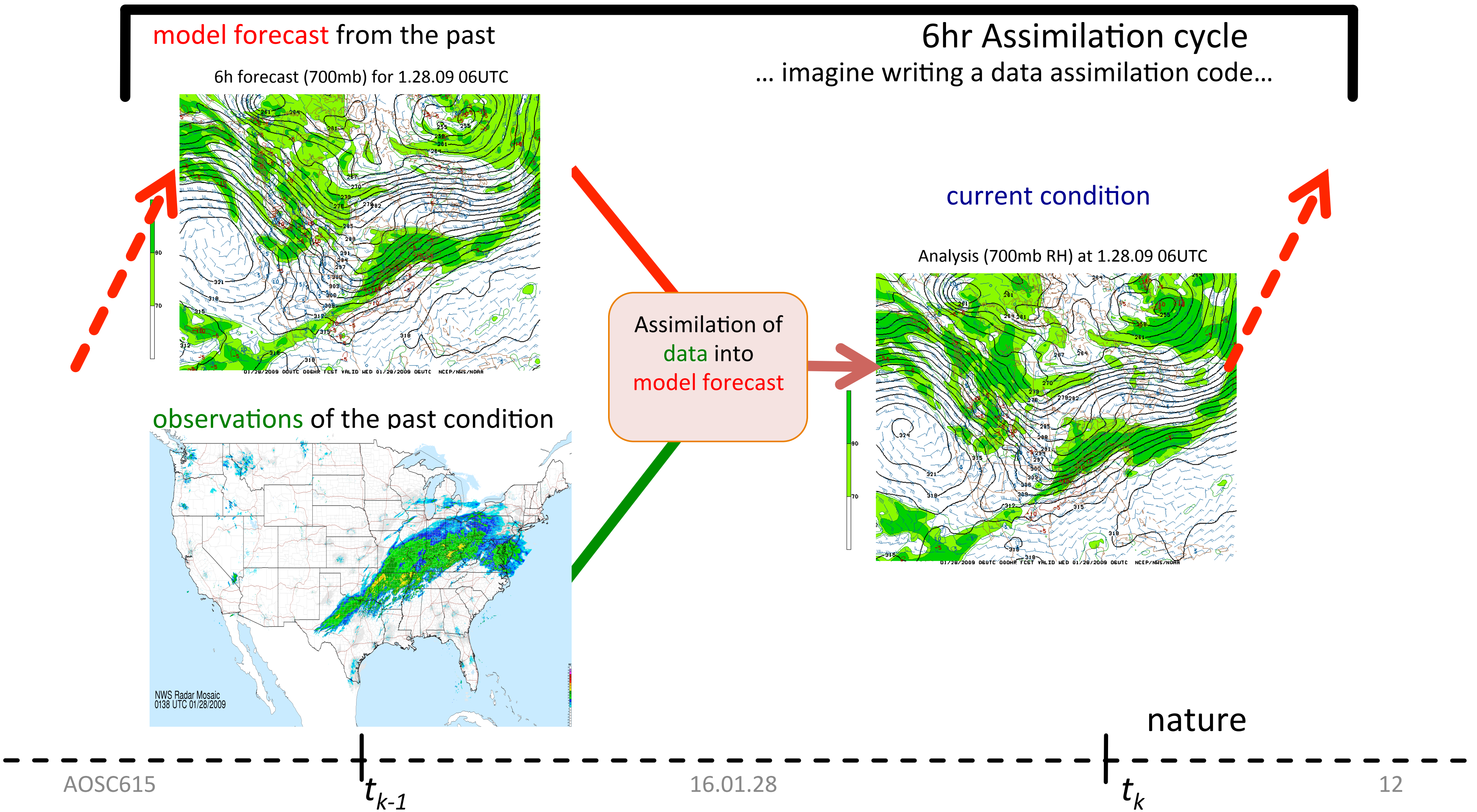


Data Assimilation Window



Schematic of Data Assimilation

- Data assimilation is an *iterative method for an initialization problem* to make best use of the model and the observations by incorporating uncertainties



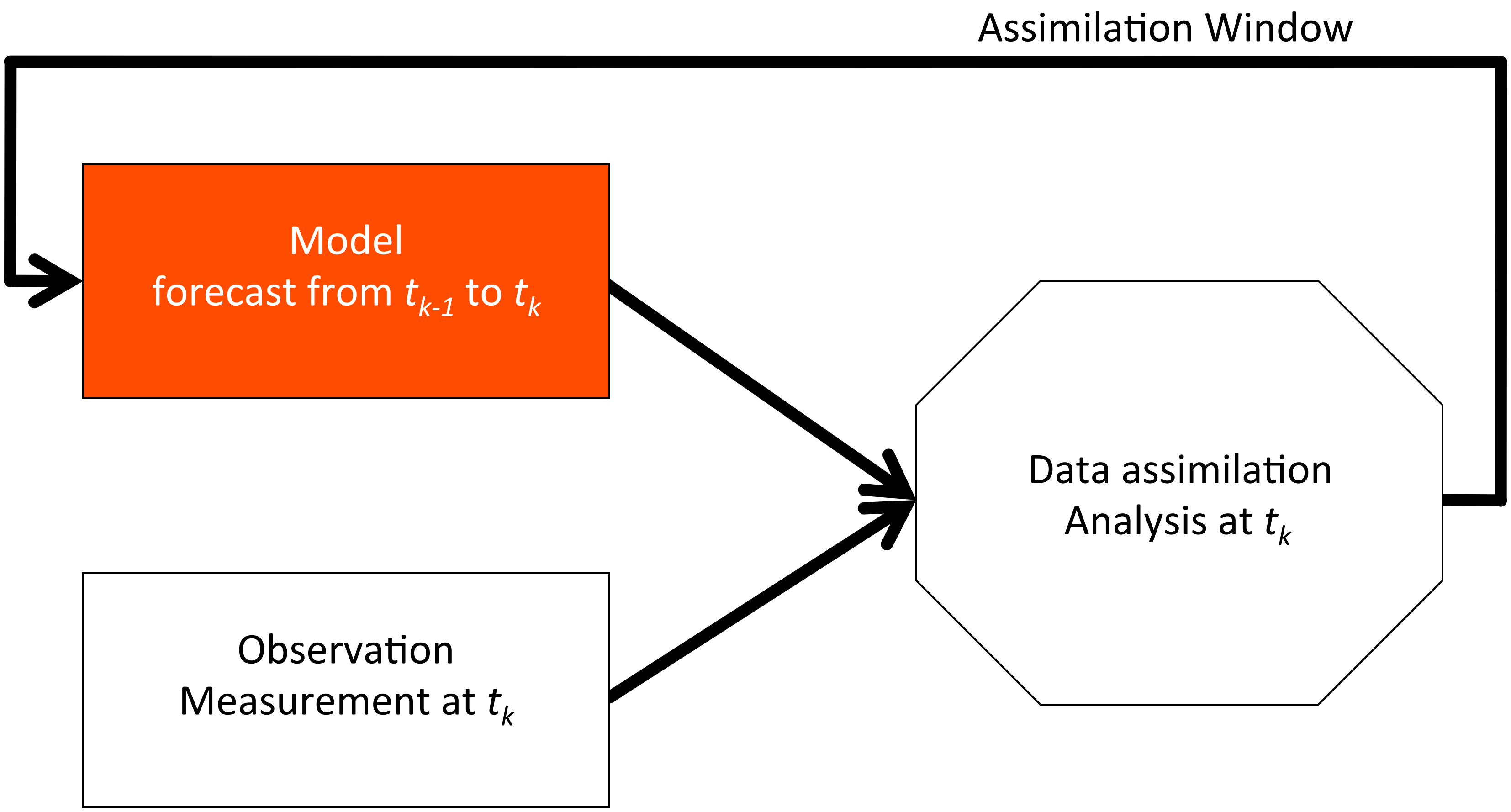
1. Introduction

- Data Assimilation Overview
  - Background
  - Schematics of Data Assimilation
  - **Elements of Data Assimilation & Basic Notation**
    - Model
    - Observations
    - Methods
    - Challenges

- AOSC 615 Overview

- Project Overview

Elements of Data Assimilation: Computational Model



Elements of Data Assimilation: Computational Model Atmosphere

- Physical Model equations: Primitive equations
  - Approximation & Parametrization
  - Topography & Boundary conditions

$$\frac{d}{dt}\mathbf{v} = -\frac{1}{\rho}\nabla p - \nabla\phi + \mathbf{f} - 2\Omega\times\mathbf{v}$$

$$\frac{\partial}{\partial t}\rho = -\nabla\cdot(\rho\mathbf{v})$$

$$p = \rho RT$$

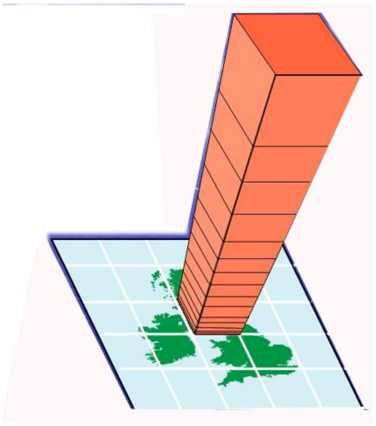
$$Q = C_p\frac{d}{dt}T - \frac{1}{\rho}\frac{d}{dt}p$$

$$\frac{\partial}{\partial t}\rho q = -\nabla\cdot(\rho\mathbf{v}q) + \rho(E-C)$$

- Computational Model
  - Each atmospheric variables are advanced at model grid points or by spectral coefficients
  - High resolution models are computationally expensive to run

Ex: $u_{ijl}(t_{k+1}) = u_{ijl}(t_k)$

$+\ \Delta t\bullet$discretized time tendency



Grid over England *http://www.climateprediction.net/*

Computational Model of Physical/Dynamical System

- Model variables: **x** is *N*-dimensional vector
  - Atmospheric model (spectral, gridded): $N \sim O(10^{6\text{-}7})$
- Model dynamics

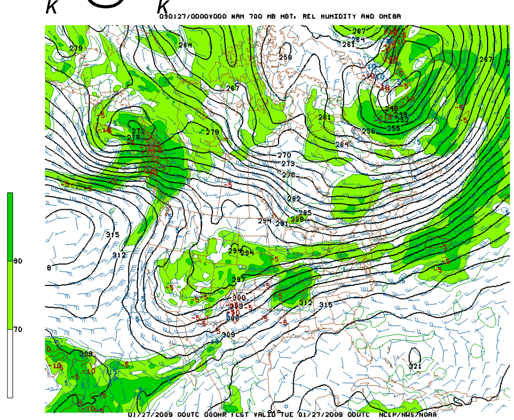
$$\mathbf{x} = \begin{pmatrix} \mathbf{T} \\ \mathbf{q} \\ \mathbf{D} \\ \mathbf{h} \\ \mathbf{p_s} \end{pmatrix} = \begin{pmatrix} \text{Temperature} \\ \text{moisture} \\ \text{divergence} \\ \text{vorticity} \\ \text{surface pressure} \end{pmatrix}$$

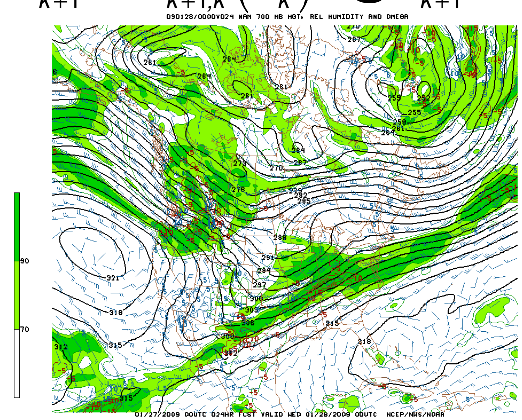
$$\mathbf{x}_{k+1} = \boldsymbol{m}_{k+1,k}\left(\mathbf{x}_k\right)$$

$\mathbf{x}_k$: model state vector at time t_k

$\boldsymbol{m}_{k+1,k}$: (forecast) model from time t_k to t_{k+1}

$\mathbf{x}_k$ @ $t_k = 01/27/09$ 0UTC ⟶ $\mathbf{x}_{k+1} = \boldsymbol{m}_{k+1,k}\left(\mathbf{x}_k\right)$ @ $t_{k+1} = t_k + 24h$





http://www.nco.ncep.noaa.gov/pmb/nwprod/analysis/

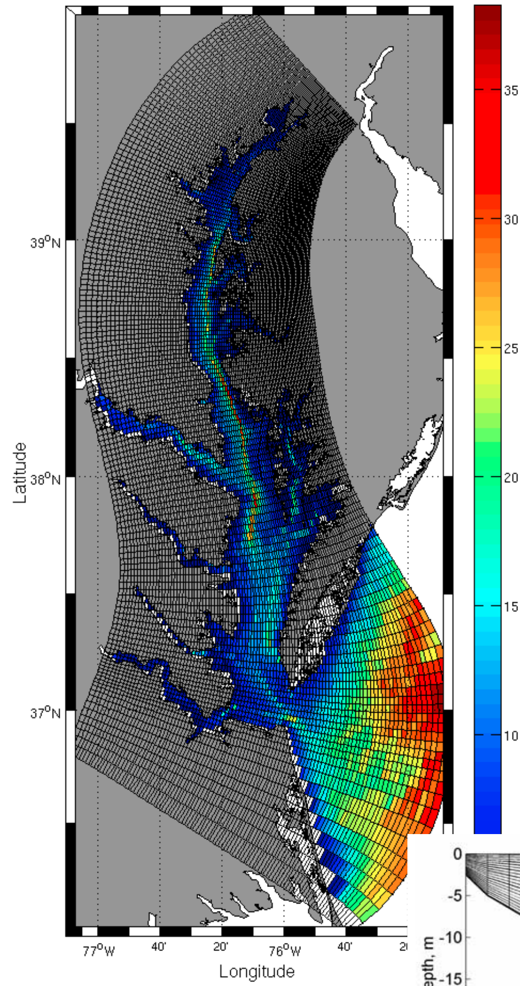
- To run a forecast, *N*-dimensional vector $\mathbf{x}_k$ must be determined accurately.

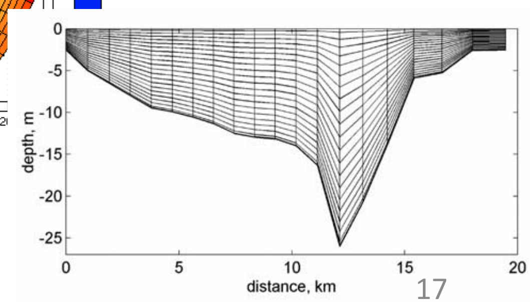
Elements of Data Assimilation: Computational Model Ocean

- Regional Ocean Modeling System
  - Primitive equation for

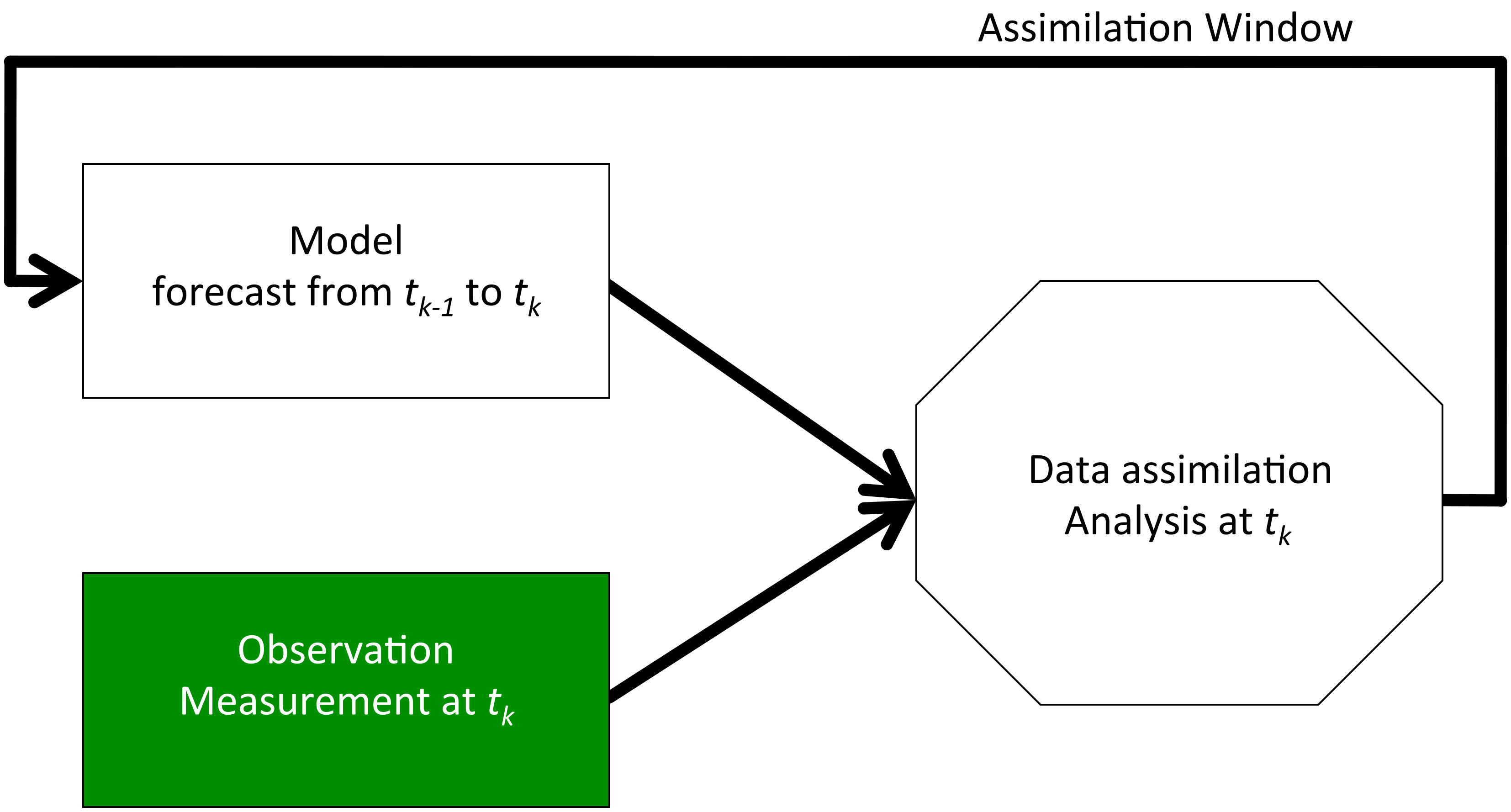
$$\mathbf{x} = \begin{pmatrix} \mathbf{u} \\ \mathbf{v} \\ \mathbf{T} \\ \mathbf{S} \\ \mathbf{\Phi} \end{pmatrix}_{\mathbf{r},t} \rightarrow \mathbf{x}_{k+1} = \boldsymbol{m}_{k+1,k}\left(\mathbf{x}_k\right)$$

  - Coordinate
    - Horizontal: Orthogonal curvilinear
    - Vertical: Stretched Sigma
  - Specification
    - Nested configuration
    - Boundary conditions
    - Atmospheric configuration





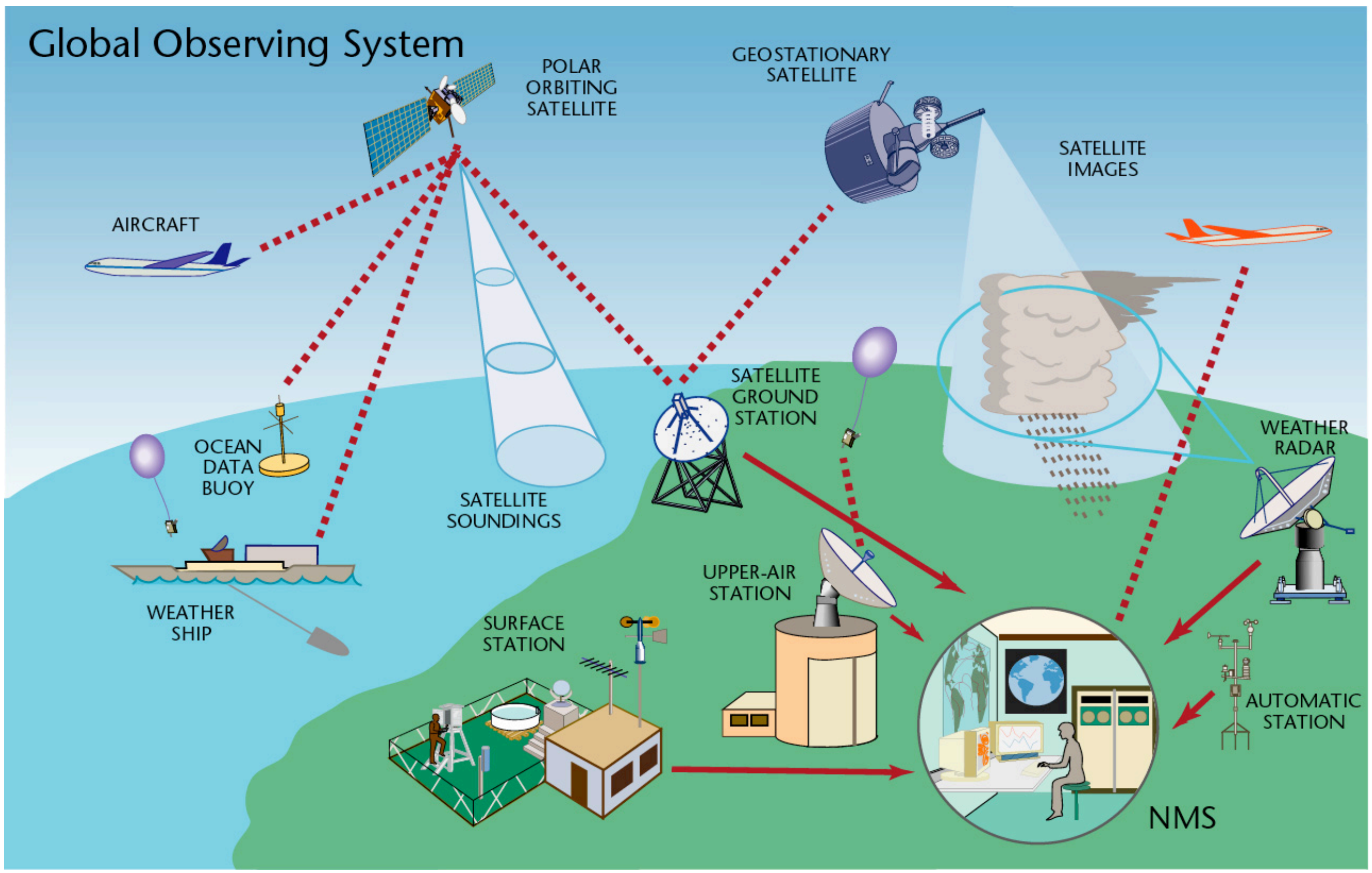
Elements of Data Assimilation: Observation



Observing System: Atmosphere

- Atmospheric Data Assimilation
  - Observations: Noisy heterogeneous sampling of the evolving state

<u>Instrument Type</u>



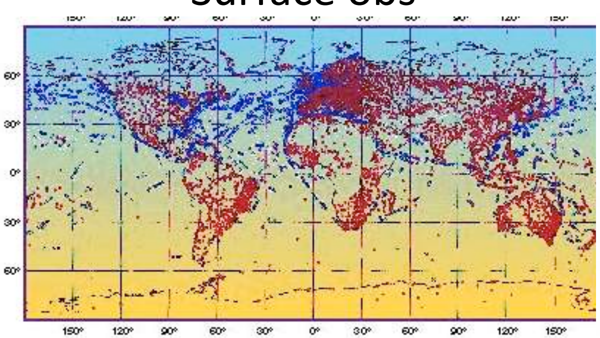
http://www.wmo.int/pages/prog/www/OSY/GOS.html

Example of Atmospheric Observation Operators : **y**=**h**(**x**) ("Forward Model")

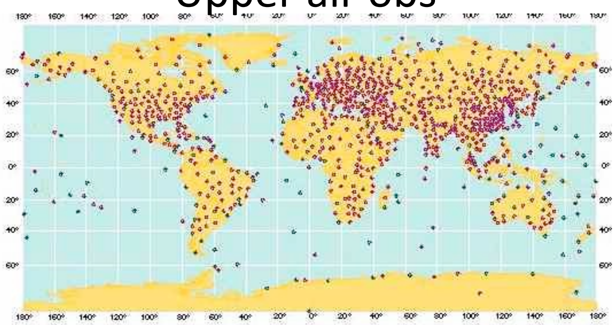
- Atmospheric Data Assimilation
  - Observations (**y**) in-situ or remote sensing
    - Noisy Heterogeneous sampling of the evolving state
    - Poor representation of forward model: **y** ←→ **x**

Coverage - Atmosphere

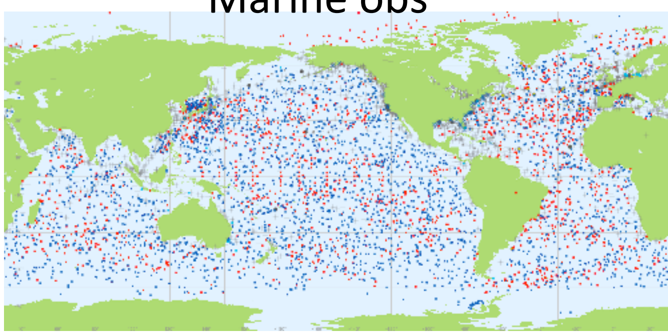
Surface obs



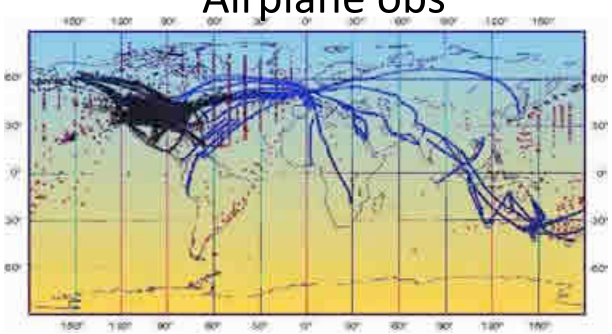
Upper air obs



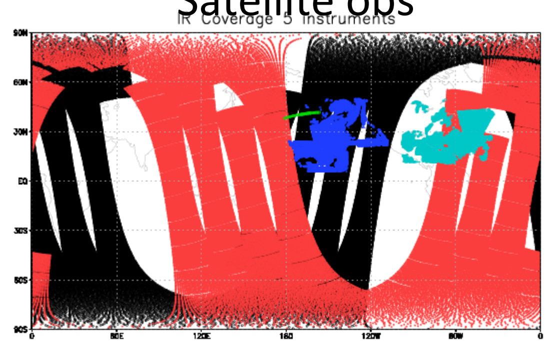
Marine obs

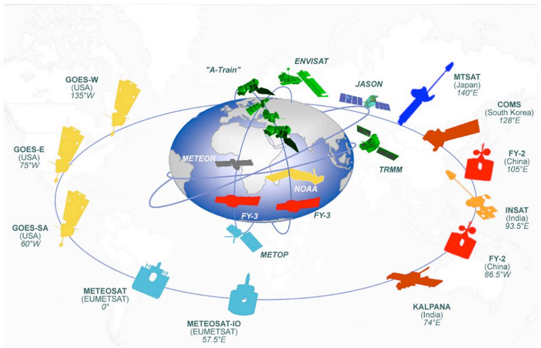


Airplane obs



Satellite obs

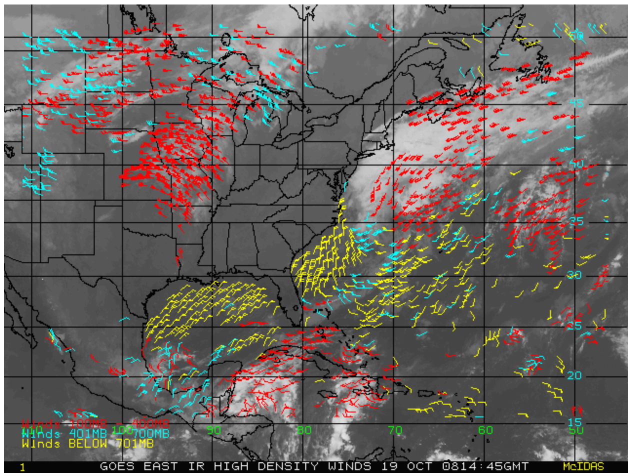


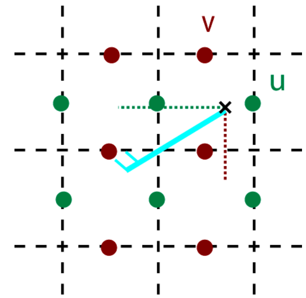


http://www.wmo.int/pages/prog/www/OSY/GOS.html

Example of Atmospheric Observation Operators : $\mathbf{y}=\mathbf{h}(\mathbf{x})$ ("Forward Model")

- Atmospheric Wind Vector



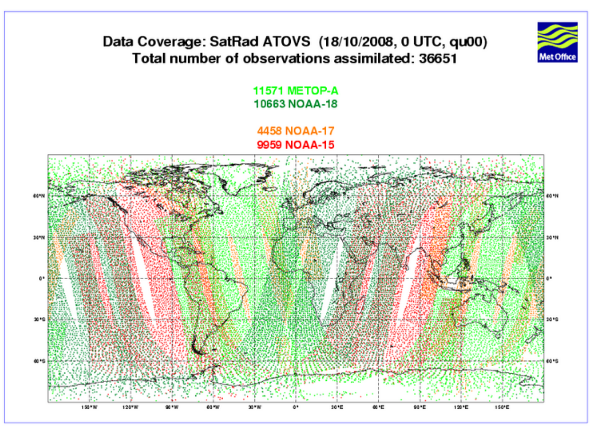


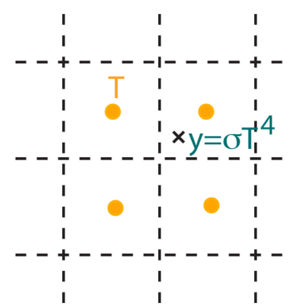
$$\mathbf{y}_{wind\ @\ \mathbf{r}_l} = \begin{pmatrix} u_{wind\ @\ \mathbf{r}_l} \\ v_{wind\ @\ \mathbf{r}_l} \end{pmatrix}$$

$$= \mathbf{H}_{wind\ @\ \mathbf{r}_l}\ \mathbf{x}$$

$\mathbf{H}_{wind\ @\ \mathbf{r}l}$: linear interpolation operator

- Radiance





$$\mathbf{y}_{radiance\ @\ \mathbf{r}_2} = \sigma T^4_{radiance\ @\ r_2}$$

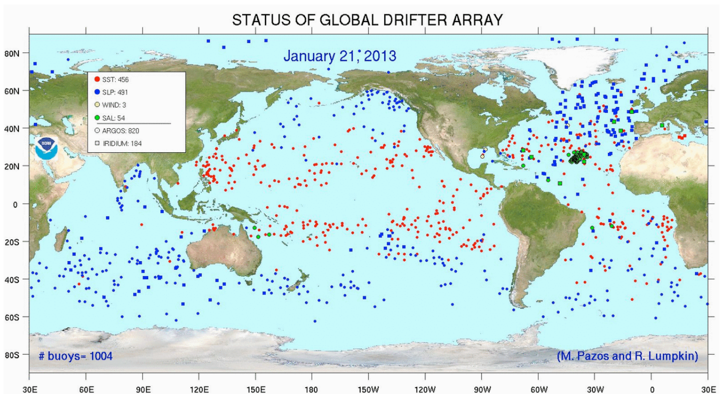
$$= \mathbf{h}_{radiance\ @\ r_2}(\mathbf{x})$$

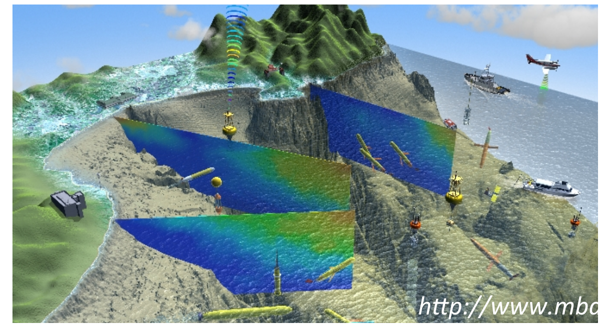
σ: Stefan-Boltzman constant

$\mathbf{h}_{radiance\ @\ \mathbf{r}2}$: nonlinear & interpolation operator

Observing Systems: Ocean

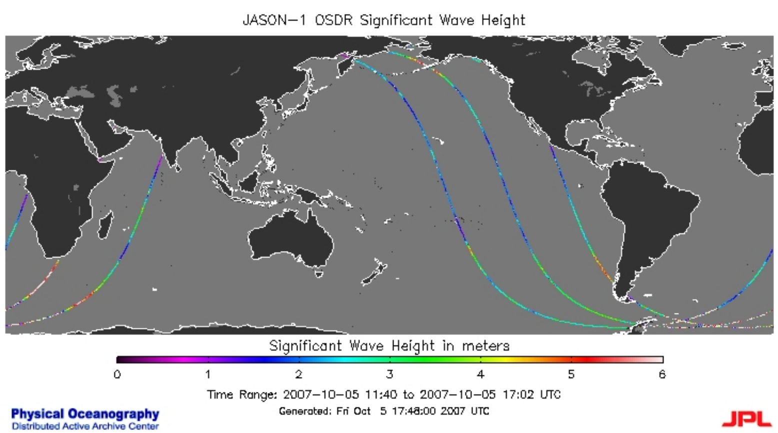
- In Situ

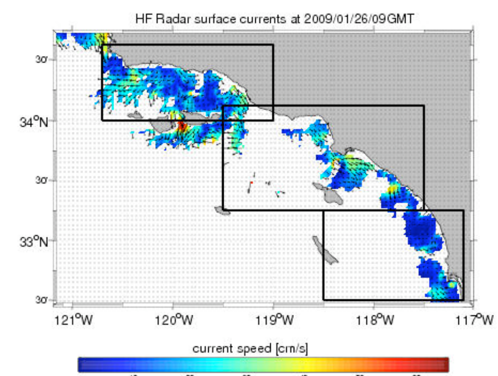




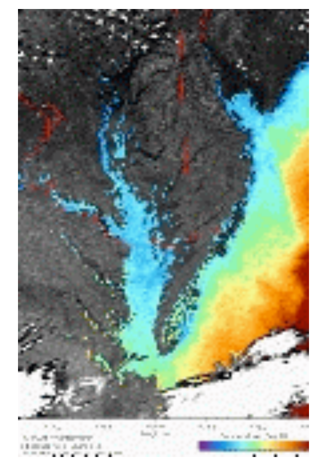
Monterey Bay

- Remote Sensing



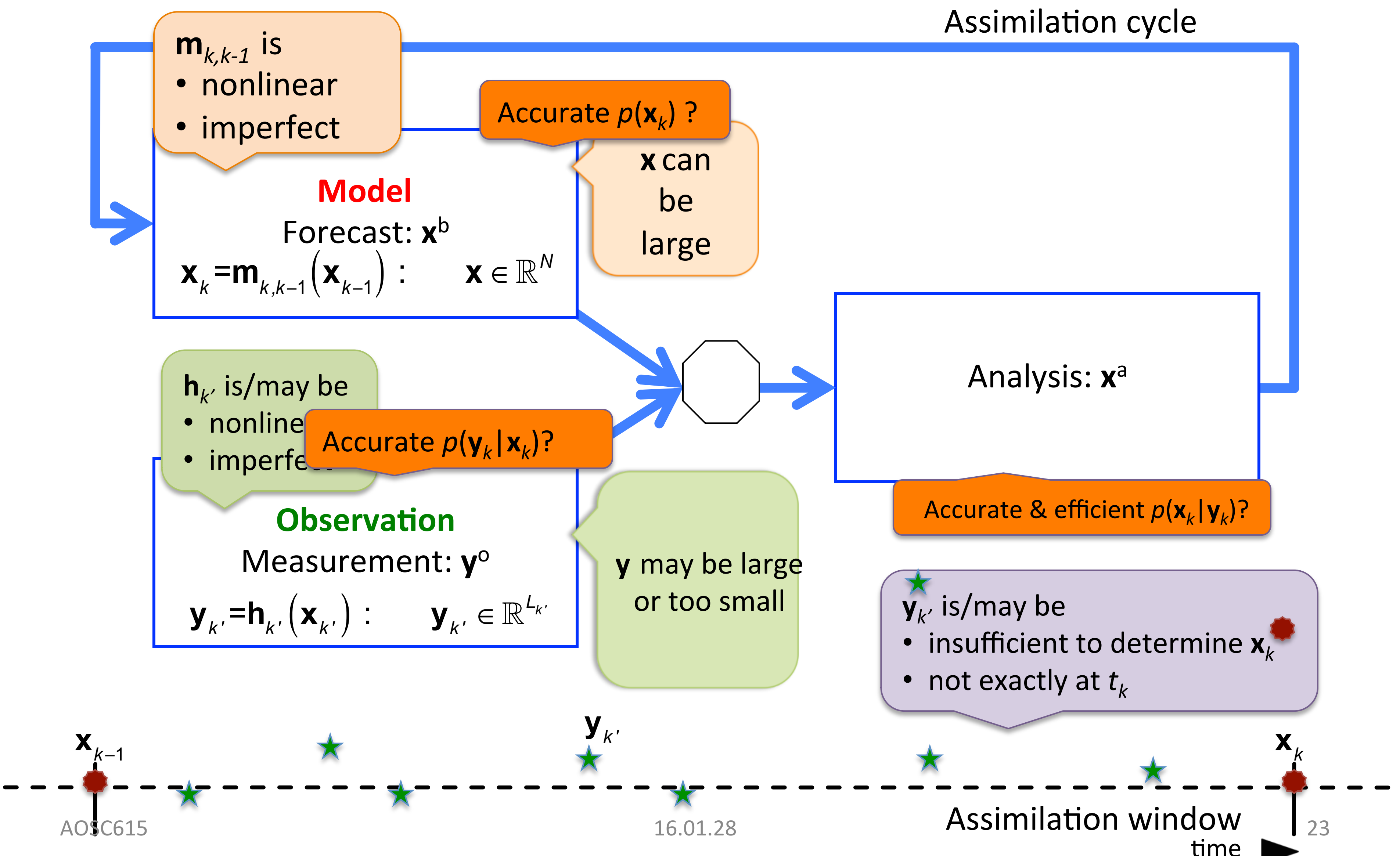


Southern CA Bight

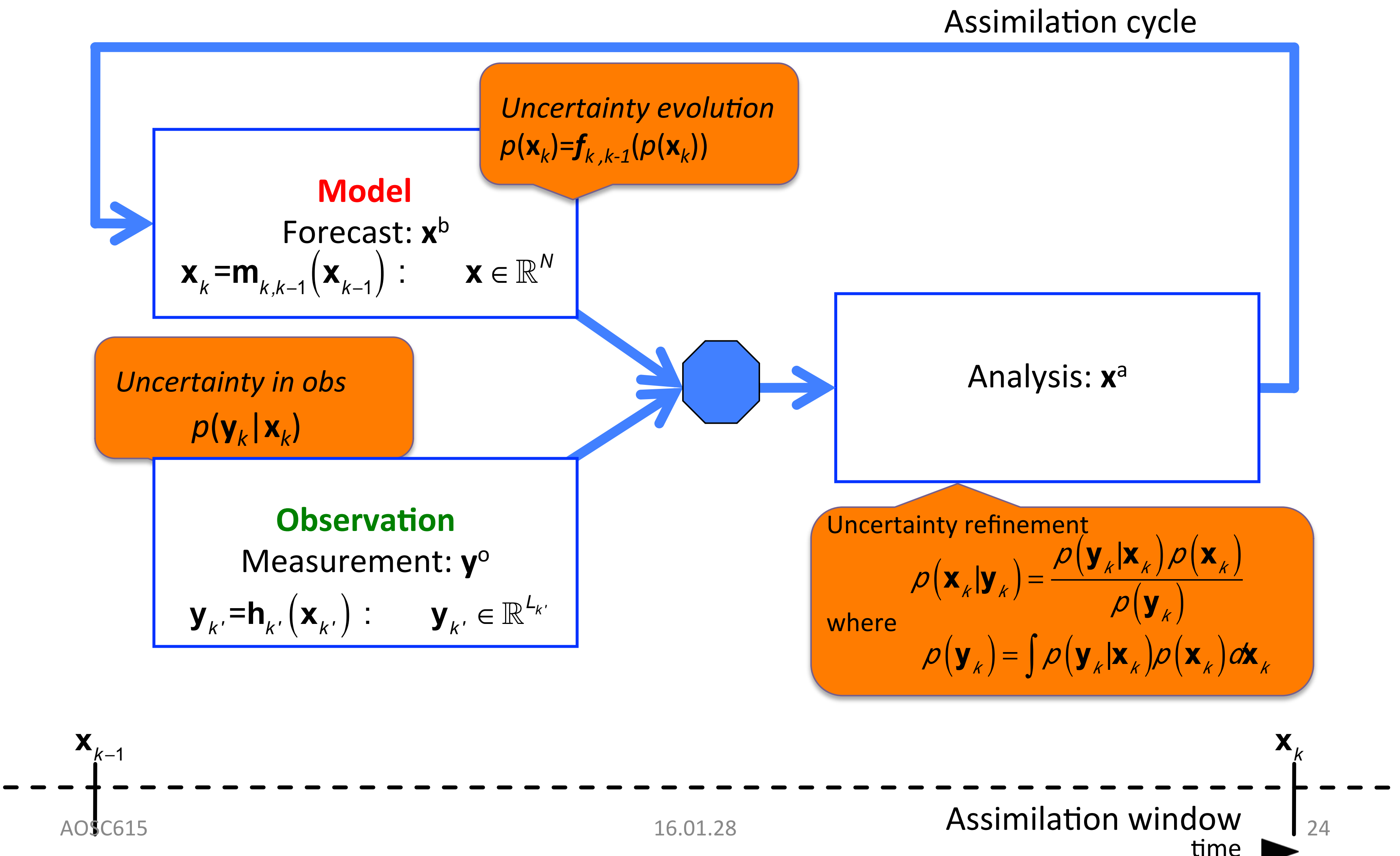


Chesapeake Bay SST

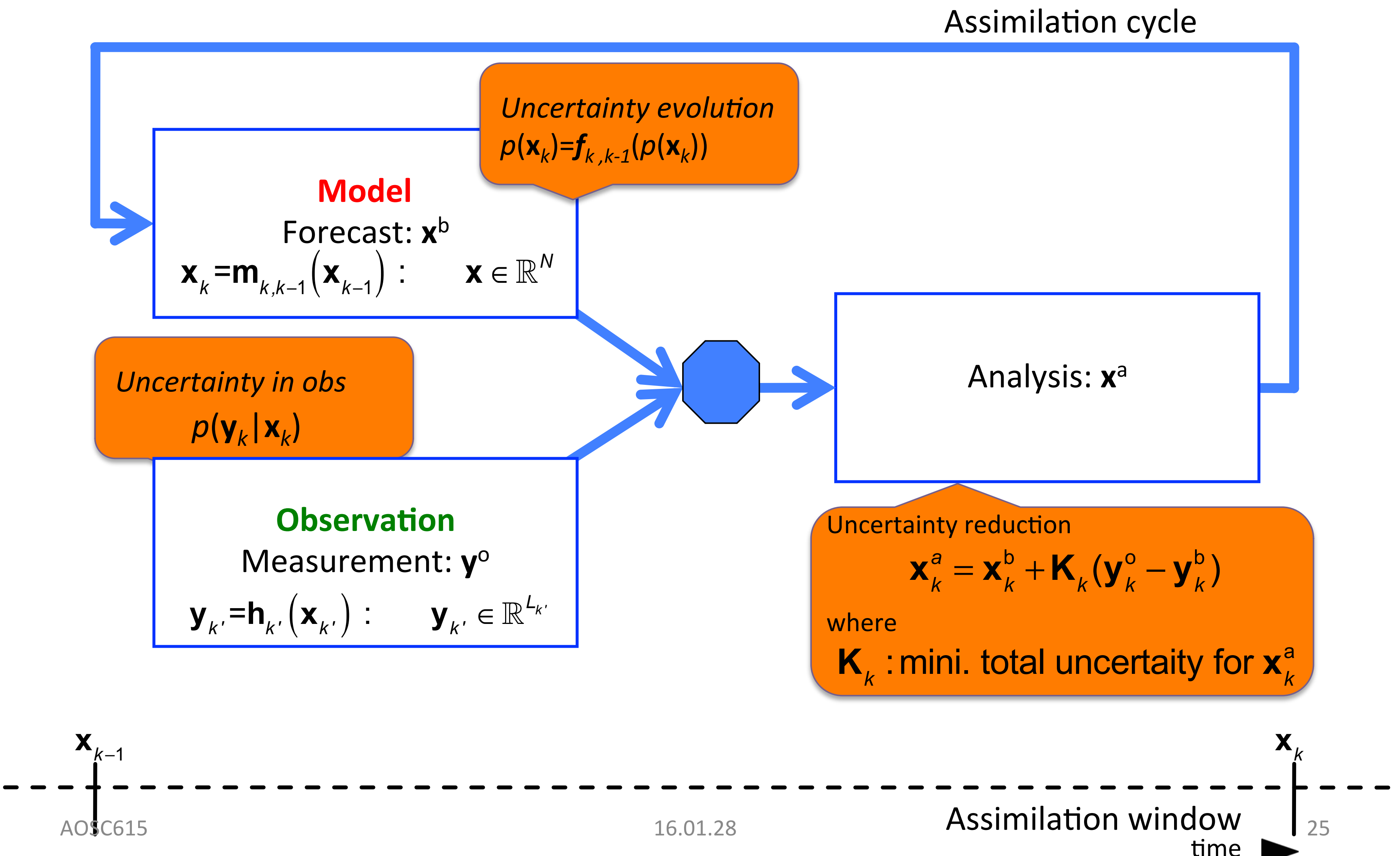
Challenges: Data Assimilation



Bayesian View Point to Data Assimilation



Risk-Reduction View Point to Data Assimilation



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01.06. Course Objectives

- Data assimilation integrates all available (and useful) sources of information concerning the underlying unknown nature.

This is generally not true

  - Primary information sources are (assumed to be correctly given):
    - Forecast by the model (dynamical/physical) obtained computationally by making forecast in forward time given the initial conditions
    - Observation that samples the nature

  - Resulting state is the analysis, which is
    - Best possible estimate of the state
    - Best possible initial condition for next forecast

Main focus of AOSC615

- Data assimilation is a scientific problem of
  - Estimation: as truthful as possible to the nature
  - Prediction: as informative as possible

  and not particularly limited to geophysical or earth systems.

Course Objectives

- AOSC 615 Objectives
  - Study fundamental concepts and ideas behind data assimilation
  - Learn major methods in data assimilation
  - Develop computer codes for the major methods
  - Foster ability to develop new data assimilation systems

AOSC 615 Format

- Class works
  - Lectures
    - Regular lectures
    - Special lectures by leading experts of data assimilation
  - Projects: Implementation of data assimilation methods
    - Using identical twin experiments
    - Based on the same model (=nature)

- Seminars
  - Students are highly encouraged to attend data assimilation seminars at AOSC, CSCAMM, & ESSIC
  - Announcement will be made as soon as possible
  - Some seminars will substitute regular lectures