Use of Satellite Measurements in Data Assimilation:

Overview of NOAA efforts to improve the assimilation of satellite data in support of US Joint Center for Satellite Data Assimiation (JCSDA)

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NOAA/NESDIS/STAR & JCSDA

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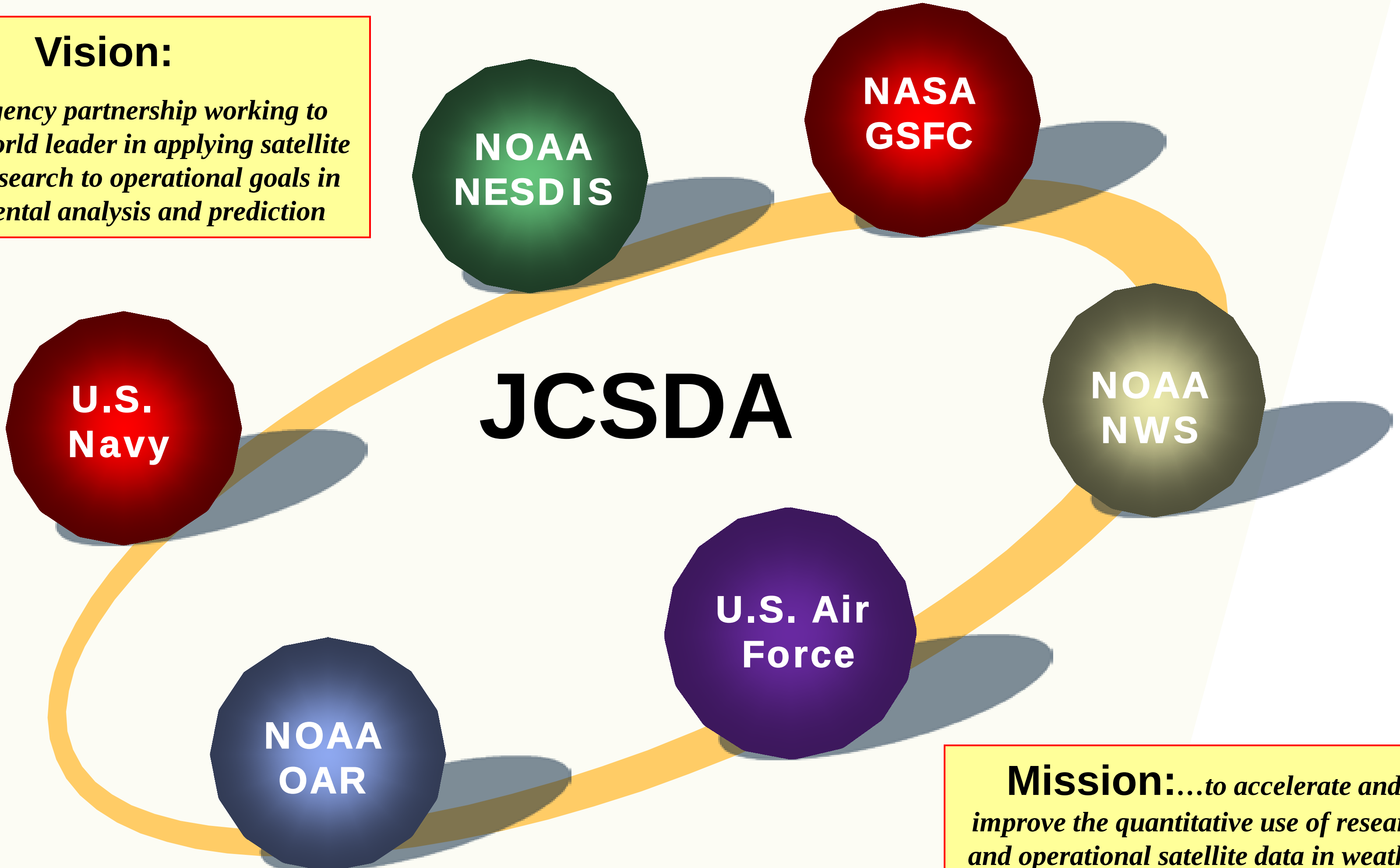
Contents

JCSDA

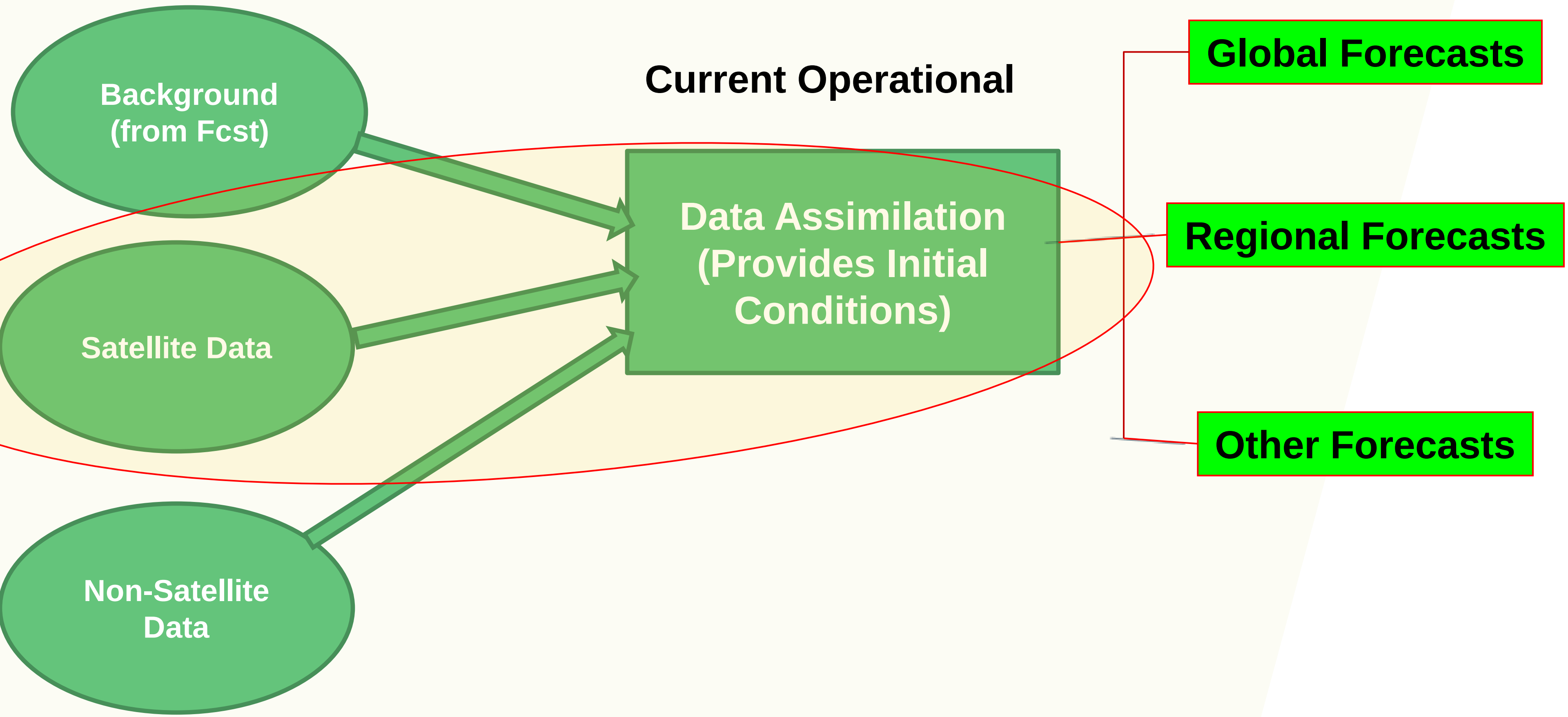
Vision:

An interagency partnership working to become a world leader in applying satellite data and research to operational goals in environmental analysis and prediction



Mission:*…to accelerate and improve the quantitative use of research and operational satellite data in weather, ocean, climate and environmental analysis and prediction models.*

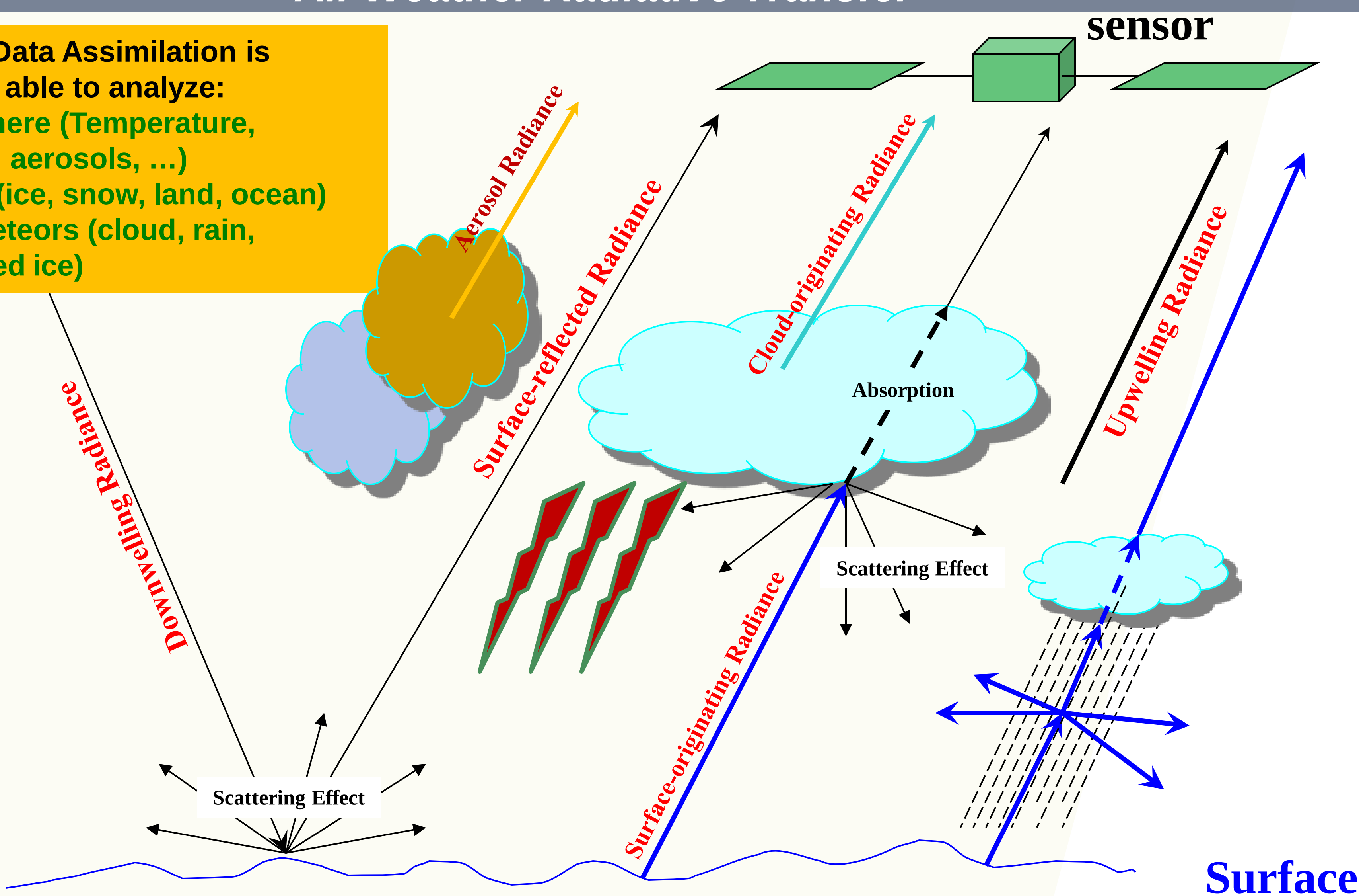
Satellite Data Assimilation



What do satellites measure?

All-Weather Radiative Transfer

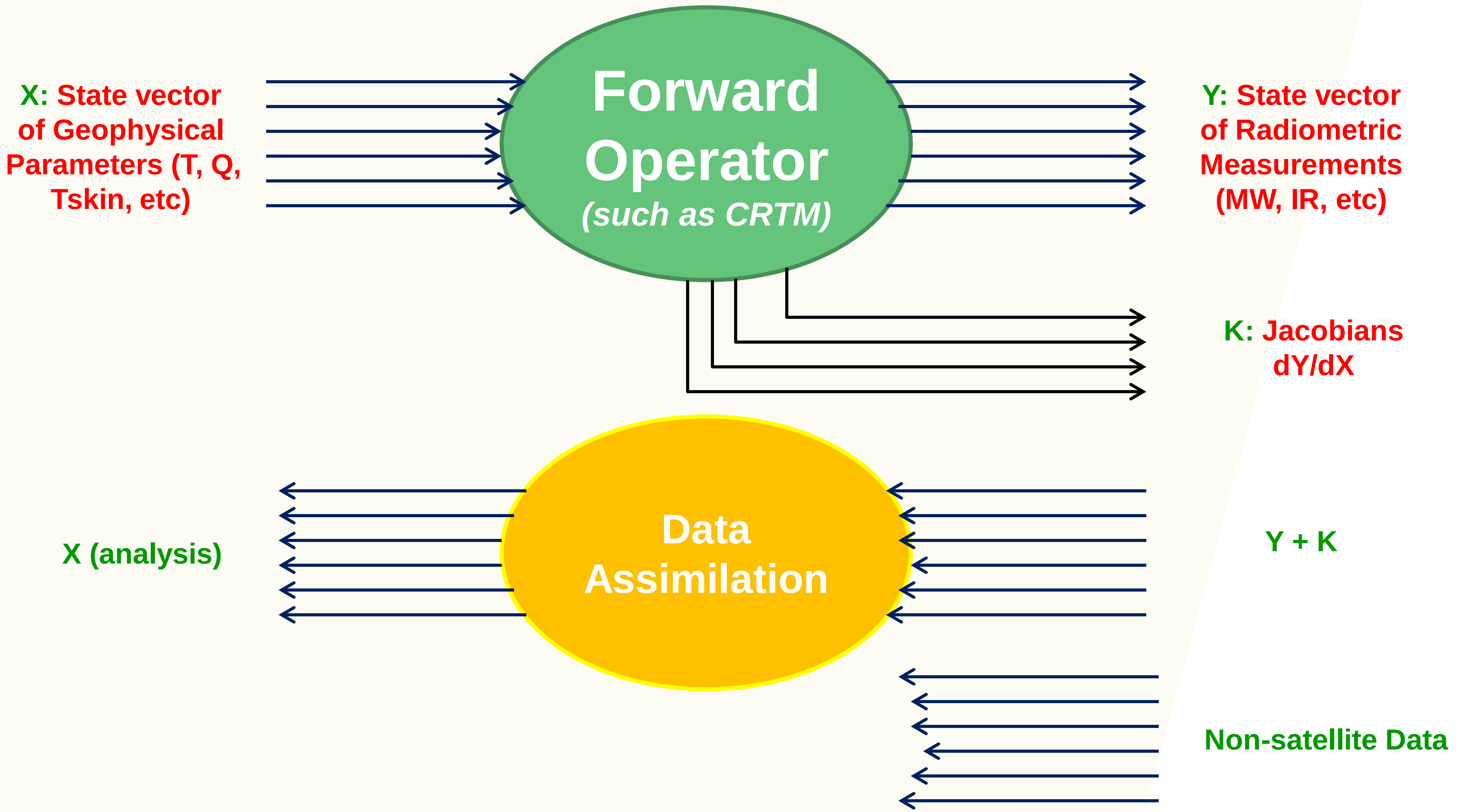
Satellite Data Assimilation is therefore able to analyze:
-Atmosphere (Temperature, moisture, aerosols, …)
-Surface (ice, snow, land, ocean)
-Hydrometeors (cloud, rain, suspended ice)



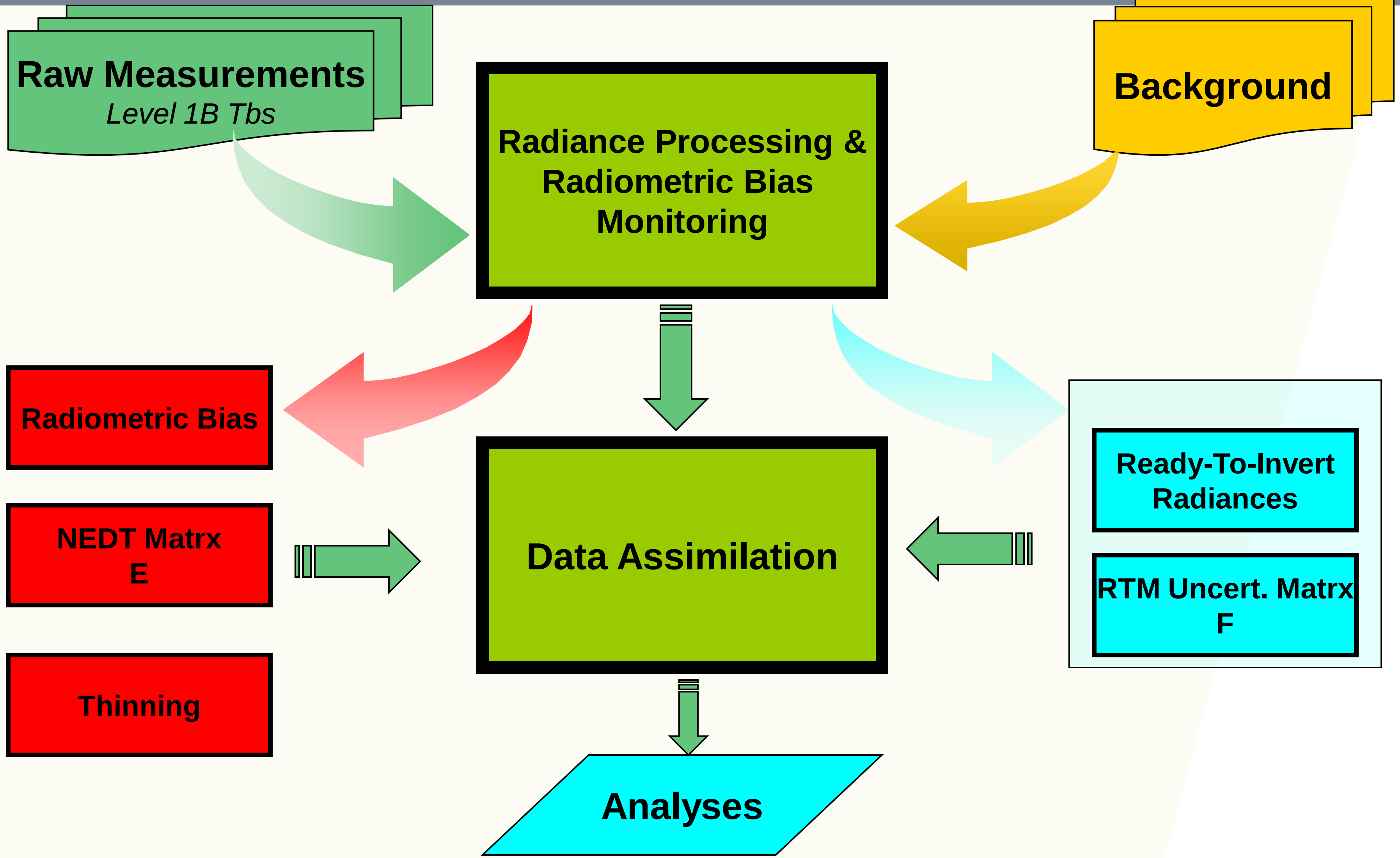
Sensors Types

- Depending on targeted phenomena, sensors would be (in order of importance for DA)
  - Microwave sounders (sounding of T, Q)
  - Hyperspectral Infrared sensors (sounding, trace gases, etc)
  - Radio Occultation sensors (temperature sounding)
  - Infrared Sensors from Geo platforms (AMVs, ..)
  - Active sensors (wind, wave height, etc)
  - Microwave Imagers (Precipitation, cloud, …)
  - Etc

Satellite Data Assimilation



Concept Diagram of Satellite Data Assimilation



Core Mathematical Basis

Bayes Theorem (of Joint probabilities)

$$P(X, Y) = P(Y \mid X) \times P(X) = P(X \mid Y) \times P(Y)$$

$$P(X \mid Y^m) = \frac{P(Y^m \mid X) \times P(X)}{P(Y^m)}$$

=1

Core Mathematical Basis

Maximizing $P(X \mid Y^m) =$

$$\left\{ \exp\left[-\frac{1}{2}\left(X - X_0\right)^T \times B^{-1} \times \left(X - X_0\right)\right] \times \exp\left[-\frac{1}{2}\left(Y^m - Y(X)\right)^T \times E^{-1} \times \left(Y^m - Y(X)\right)\right] \right\}$$

Is Equivalent to Minimizing

$$-\ln\left(P(X \mid Y^m)\right)$$

Which amounts to Minimizing J(X) –also called COST FUNCTION – Same cost Function used in 1DVAR Data Assimilation System

$$J(X) = \left[\frac{1}{2}\left(X - X_0\right)^T \times B^{-1} \times \left(X - X_0\right)\right] + \left[\frac{1}{2}\left(Y^m - Y(X)\right)^T \times E^{-1} \times \left(Y^m - Y(X)\right)\right]$$

Cost Function Minimization

- To find the optimal solution, solve for:

$$\frac{\partial J(X)}{\partial X} = J'(X) = 0$$

- Assuming Linearity $$y(x) = y(x_0) + K\left[x - x_0\right]$$

- This leads to iterative solution:

Preferred when nParams << nChan (IR)

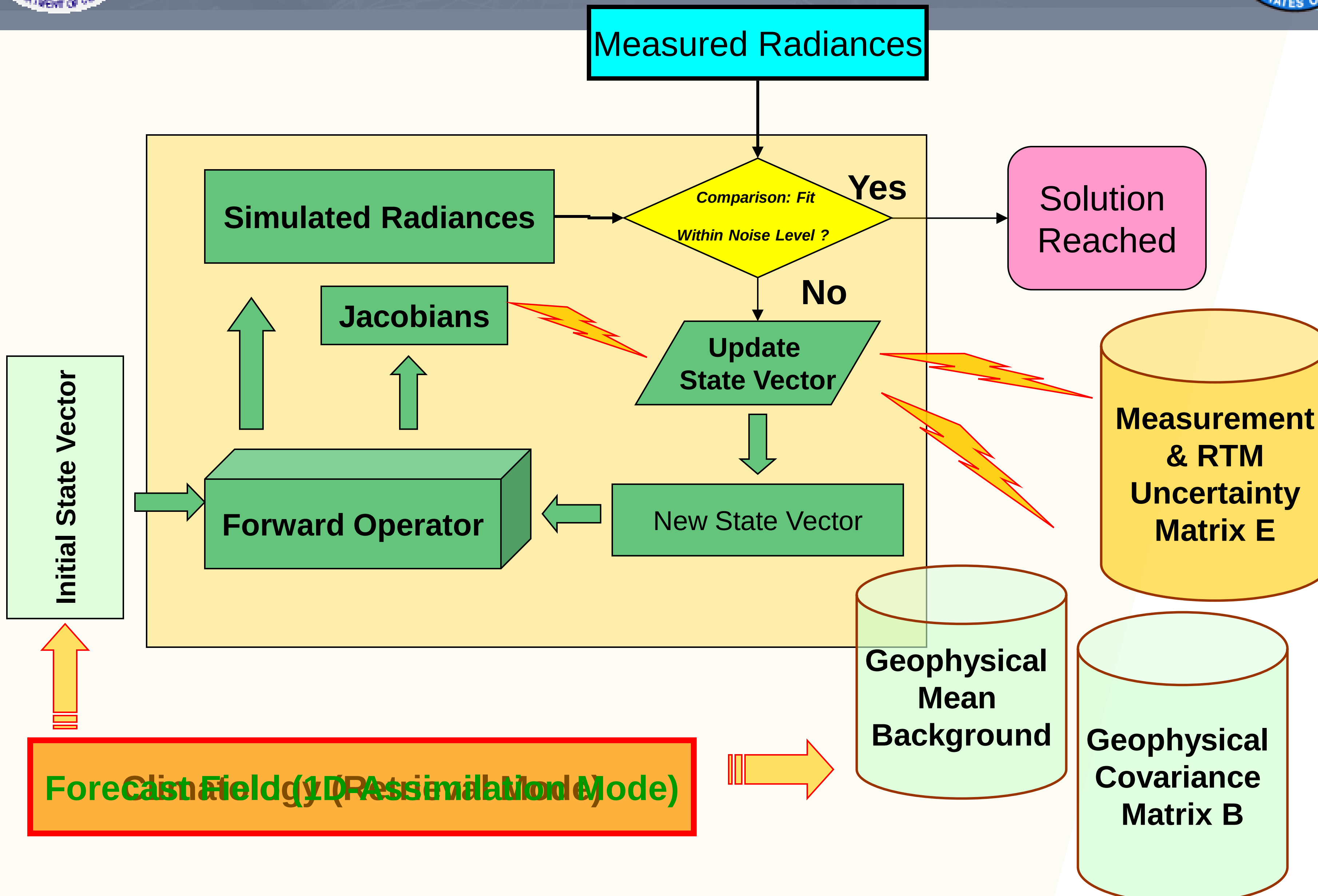
$$\Delta X_{n+1} = \left\{ \left(B^{-1} + K_n^T E^{-1} K_n \right)^{-1} K_n^T E^{-1} \right\} \left[\left(Y^m - Y(X_n) \right) + K_n \Delta X_n \right]$$

$$\Delta X_{n+1} = \left\{ B K_n^T \left(K_n B K_n^T + E \right)^{-1} \right\} \left[\left(Y^m - Y(X_n) \right) + K_n \Delta X_n \right]$$

More efficient (1 inversion)

Preferred when nChan << nParams (MW)

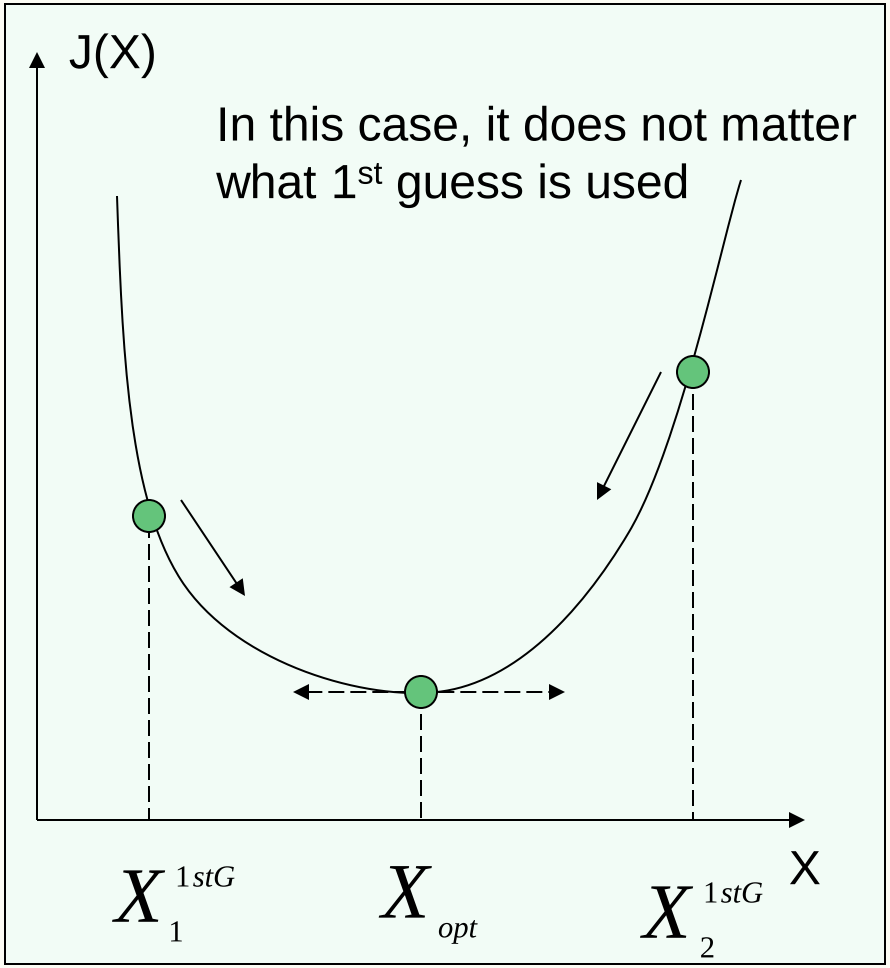
Variational Retrieval/Assimilation

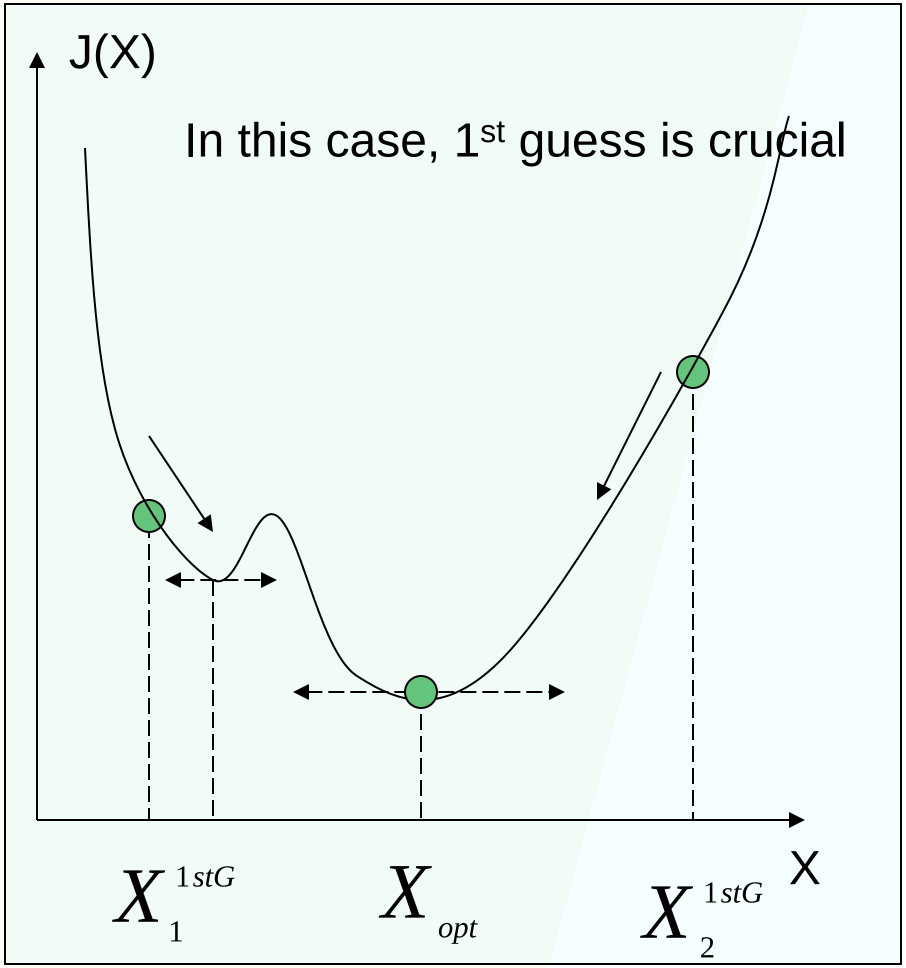


Most Important Assumptions Made in Solution Derivation

- Local linearity
- Gaussian Distribution of the Instrument/Model Errors
- Gaussian Distribution of the Background Error
- Independence between Instrument/Model errors and Background Errors

Multi-Dimensional Problem Leads to Higher chances of Local Minima



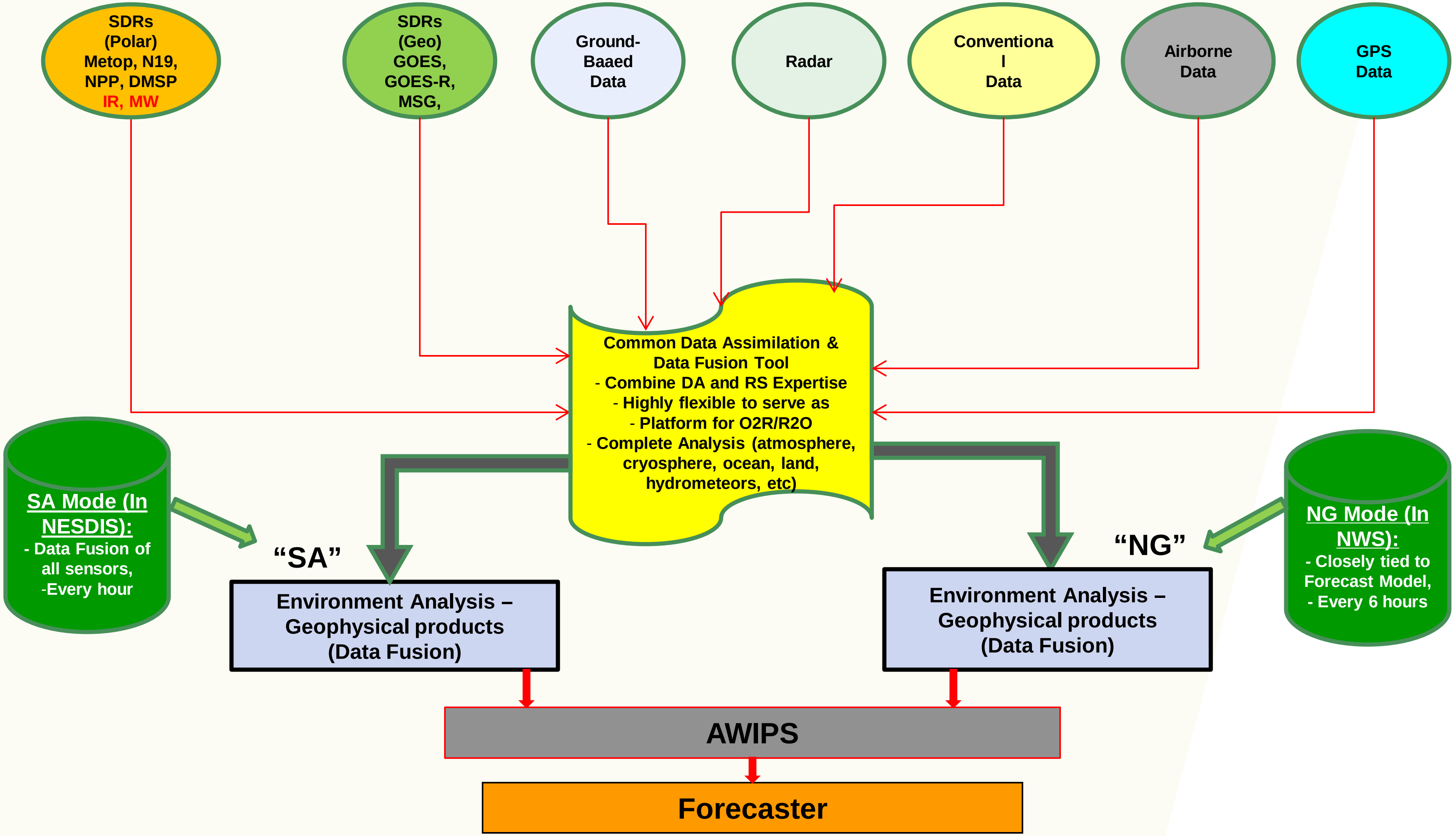


Importance of First Guess Background

Contents

Future Merged SA and NG Product Generation

"Provide what the forecasters need, when they need it…"



Contents

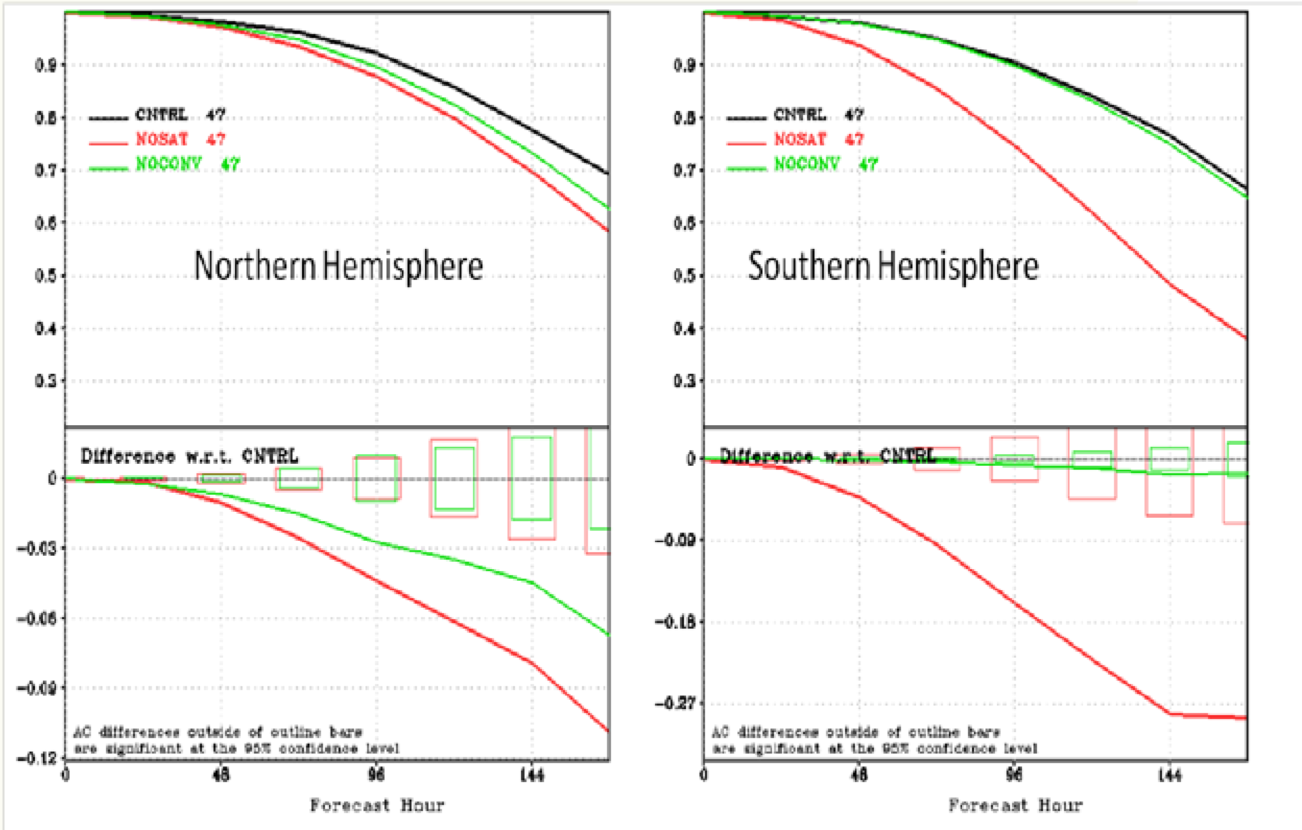
OSE Activities / Impact Assessment

- An extensive assessment of the global observing system impact on NOAA forecast system has been undertaken.
- The impact assessment was done wrt satellite data (collectively &individually: microwave AMSU, MHS, GPS, hyperspectral IR, AMVs, etc) as well as conventional data.
- Satellite data as a group, had a very significant impact which surpasses the conventional data impact (by a wide margin), especially in the southern hemisphere.

(1) No Satellite / (2) No Conventional Data

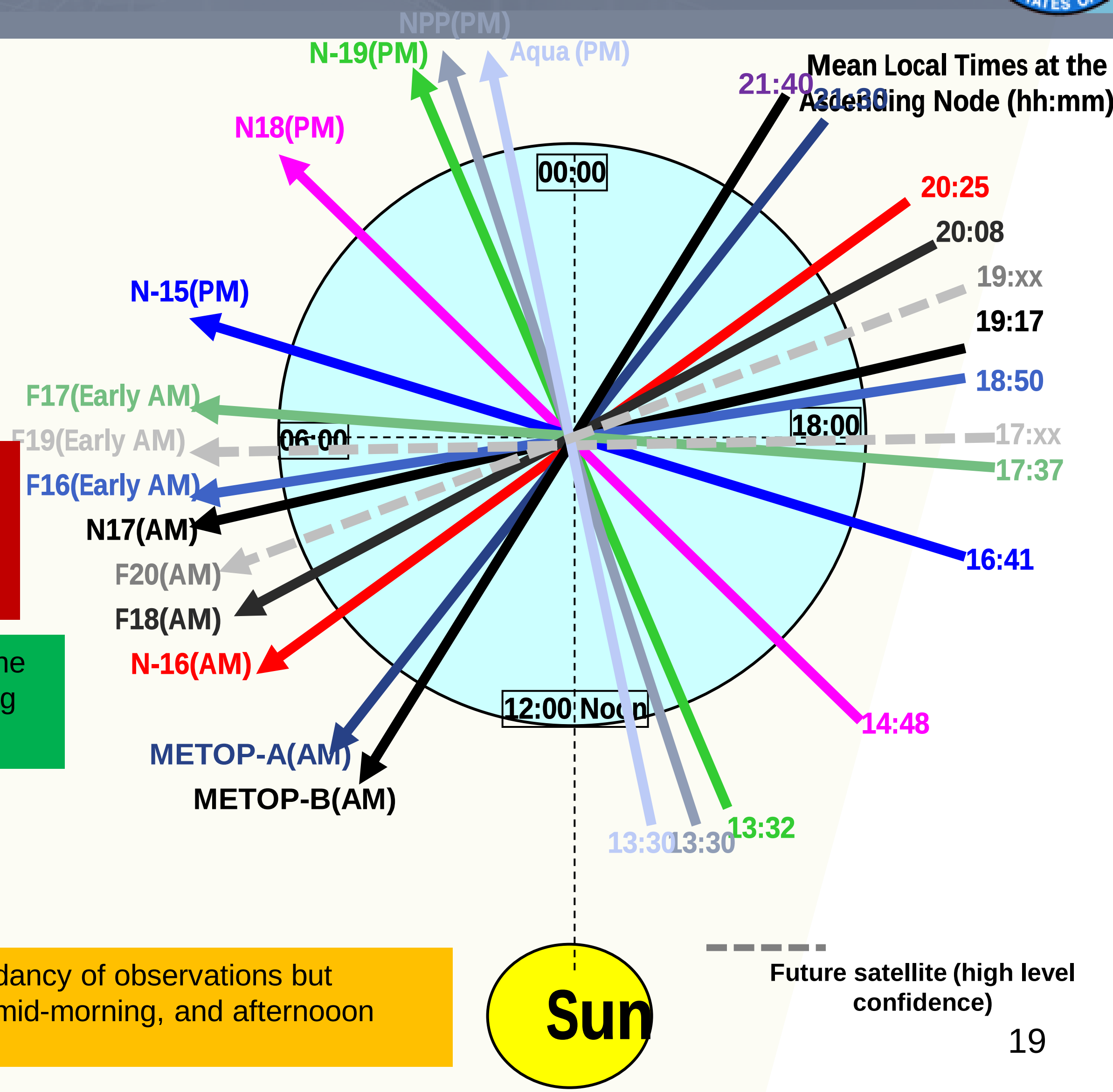
15 Aug – 30 Sep 2010

500 hPa Anomaly Correlations



Results from the extensive data denials experiments performed in the JCSDA, aimed at assessing the impact of the global Plots courtesy of J. Jung.

Impact Assessment of the Orbital Distribution



The "1polar" experiment removes the redundancy of observations plus both the early-morning and afternoon polar orbits (leaving only **mid-morning observations).**

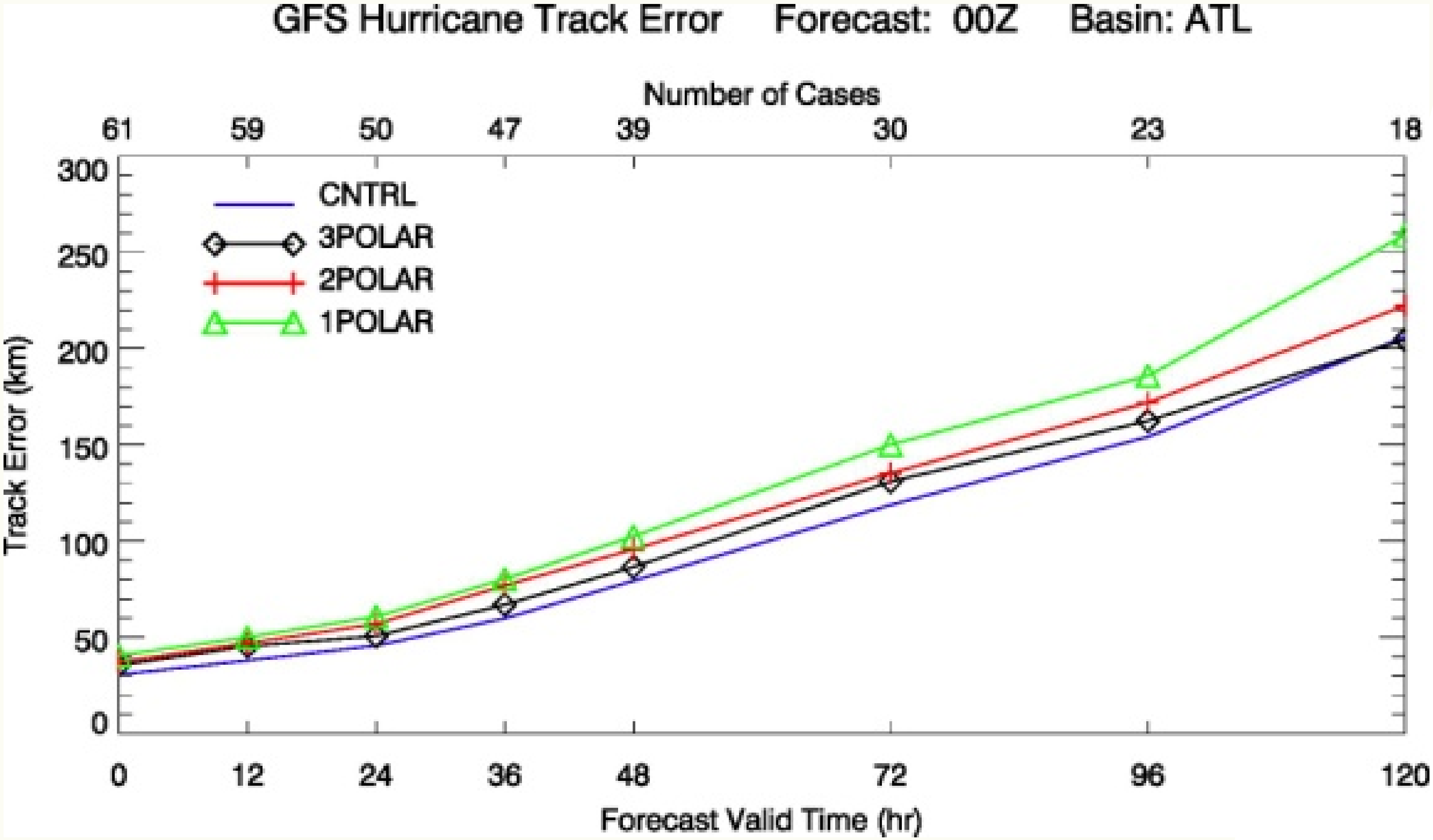
The "Control" experiment establishes baseline performance of the current satellite observing system capability.

The "2polar" experiment removes the redundancy of observations plus all platforms flying in the afternoon polar orbit (the data gap).

The "3polar" experiment removes the redundancy of observations but maintains platforms flying in early-morning, mid-morning, and afternooon polar orbits.

Constellation as of September 2012. Sources: NESDIS/OSO & CGMS/WMO pages

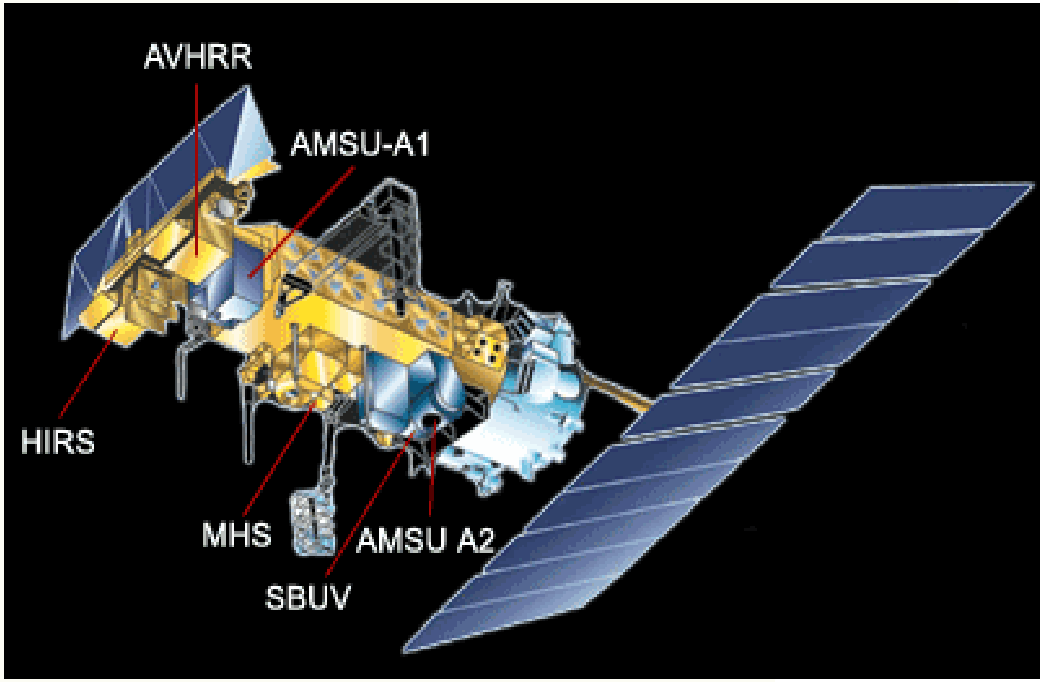
Importance of Orbital Coverage



Contents

AMSU and MHS

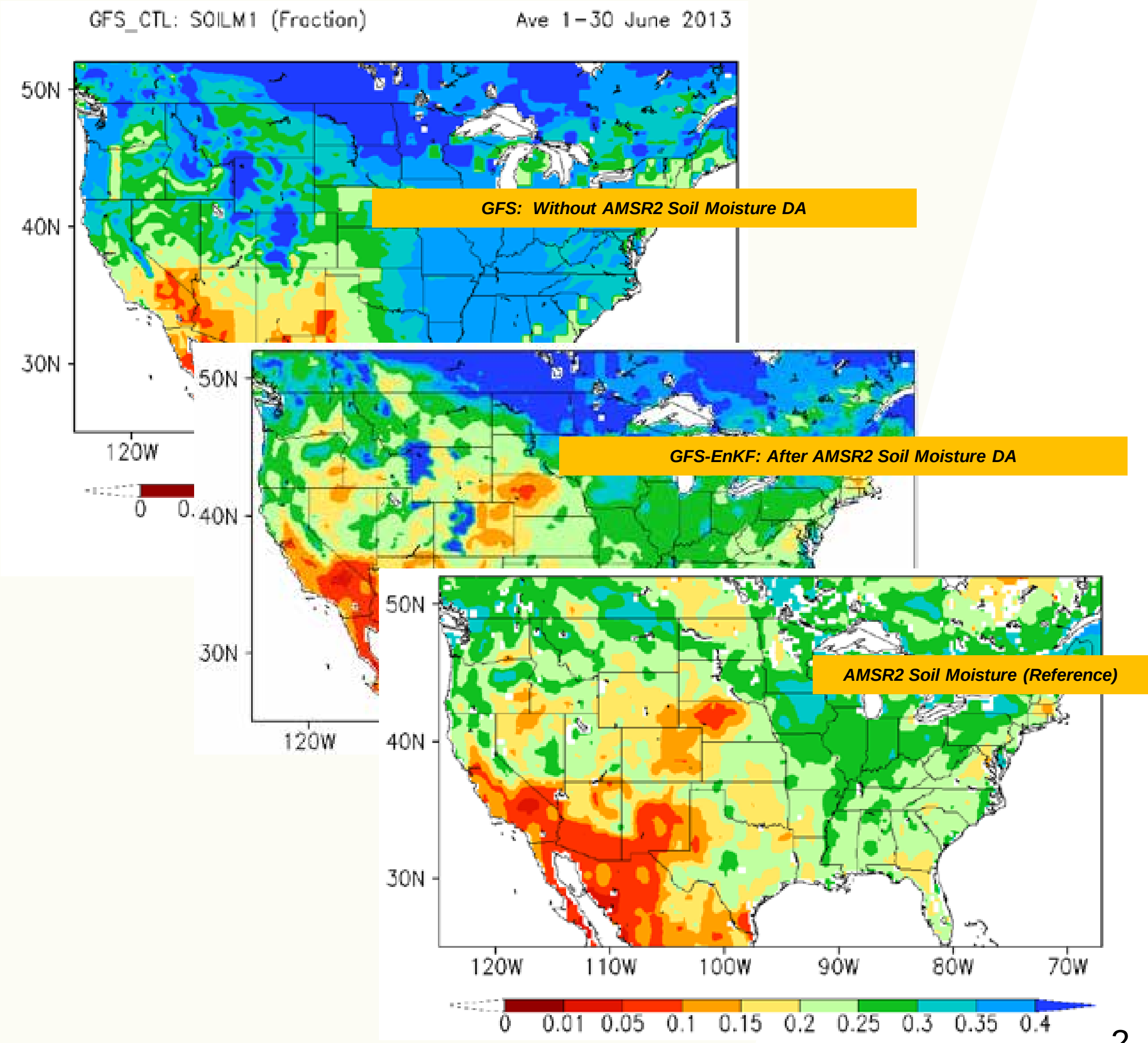
- Main purpose of the microwave sensors (AMSU and MHS) is the atmospheric sounding (T and WV)
- AMSU has two modules (A-1 and A-2) with channels ranging from 23.8 GHz to 89 GHz
- AMSU has 30 scan positions per scanline
- MHS probes at frequencies between 89 and 183 GHz
- MHS has a higher spatial resolution (90 scan positions per scanline)



AMSR-2 Data Assimilation

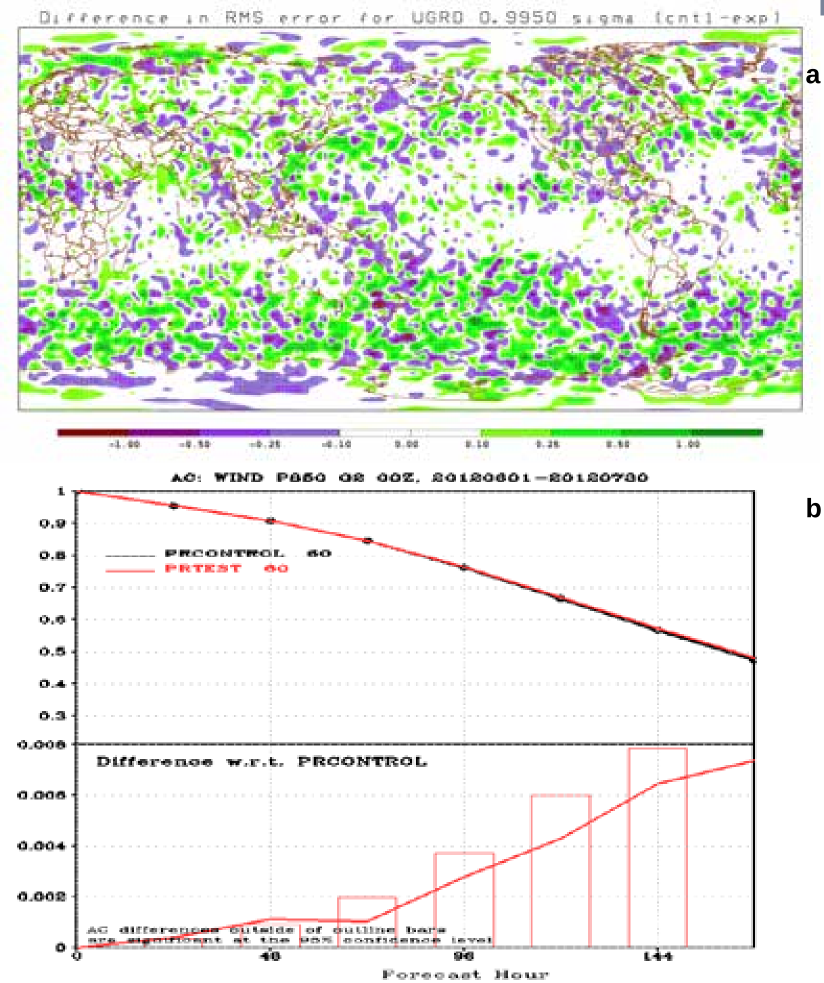
Assimilation of Satellite Soil Moisture Product from AMSR2 in Global Forecast System.

In this figure, the Noah LSM multiple year means and standard deviations are used to scale the surface layer soil moisture



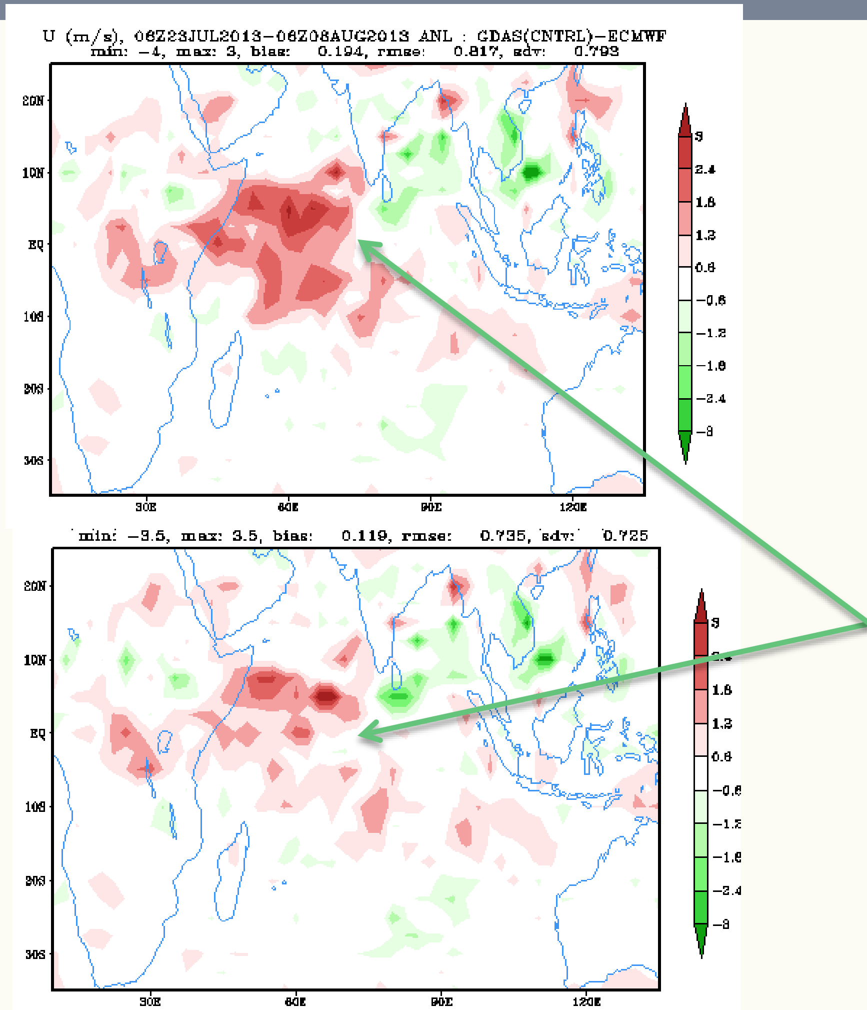
OSCAT Data Assimilation

- OSCAT DA was improved in the next version of the GDAS system
- Pre-assessment of data is necessary to optimize and characterize filtering, thinning, biases and observation error estimates
- Errors in wind direction has a bigger effect on A/C than intensity
- OSCAT has since died



Impact assessment of the OSCAT scatterometer data assimilation. These plots represent the forecast impact (b) and verification results (a) of OSCAT winds experiments. ***They represent the change in anomaly correlation and RMS (increase or decrease) of the surface wind speed at 0.995 sigma level. The impact, globally, at 48 hours lead time is mixed, but overall positive. Plot courtesy of Li Bi, Riverside Inc, JCSDA Active Sensors data assimilation scientist.***

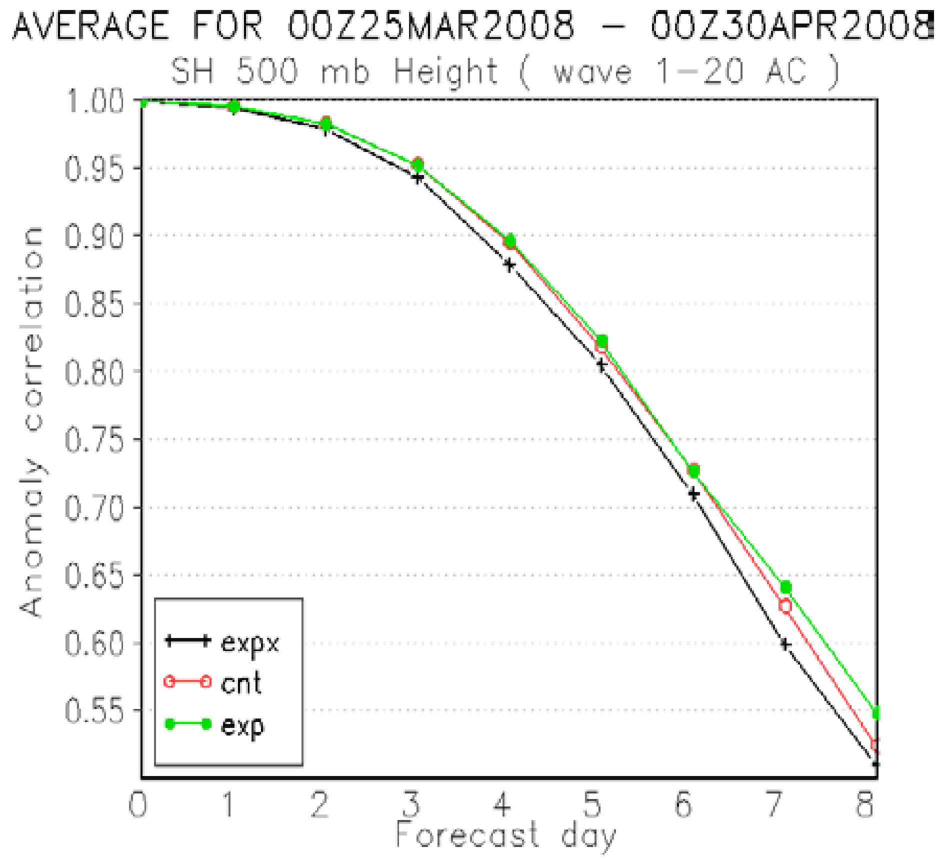
Assimilation of Atmospheric Motion Vector (AMV)



- Improvement of Wind analysis by optimizing the AMVs assimilation (from GOES sensors)
- U-wind component of the GDAS analysis is improved with respect to ECMWF analysis in the region of the Tropical Easterly Jet (TEJ).

GPS RO Assimilation

- AC scores (the higher the better) as a function of the forecast day for the 500 mb gph in Southern Hemisphere
- 40-day experiments:
  - **expx (NO COSMIC)**
  - **cnt (old RO assimilation code - with COSMIC)**
  - **exp (updated RO assimilation code - with COSMIC)**



COSMIC provides 8 hours of gain in model forecast skill starting at day 4

Plots courtesy of L. Cucurull. Internal JCSDA project.

Contents

1 Introduction & Concepts

2 Why users should be interested in Data Assimilation?

3 Why are satellites important for Assimilation/Forecasts?

4 Different Sensors for Different Applications

5 **What is Involved in Satellite Data Assimilation?**

6 Conclusions & Look into the future

Steps to transition a new sensor to operational data assimilation (1/2)

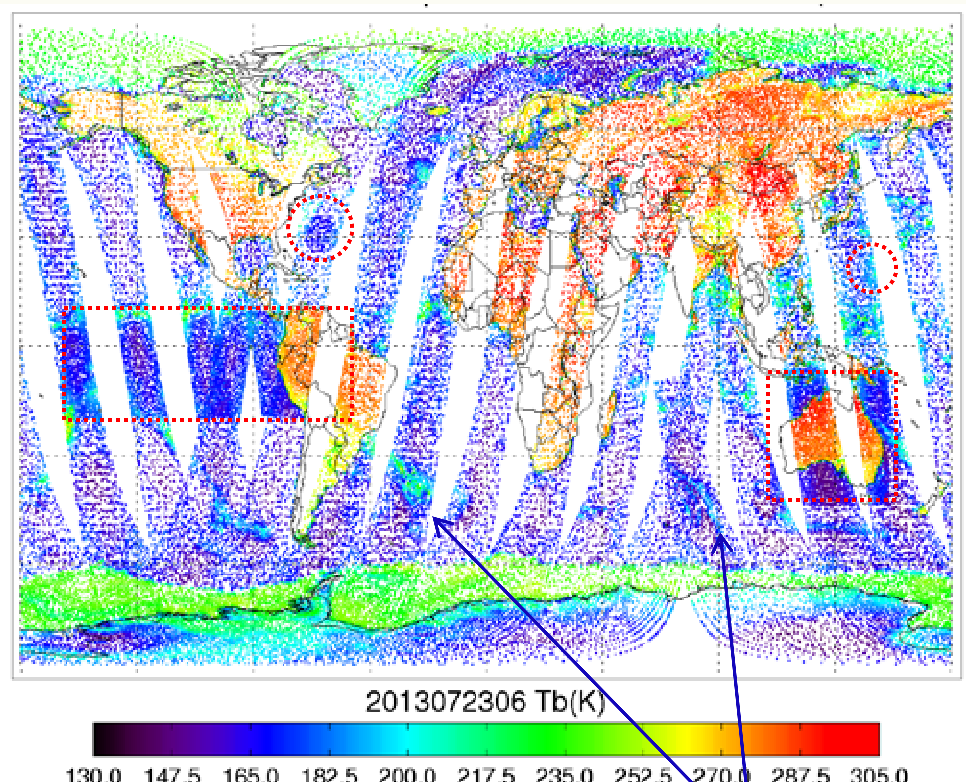
- **1- Pre-Launch phase:**
  - Forward model preparation
  - Covariance matrix preparation for all parameters in the assimilation control vector
  - Preparation of the tools for preprocessing data, QC/flagging the data.
  - Assess hardware and software requirements needed and plan accordingly
  - Assess footprint averaging, thinning methodologies that are appropriate, for the specific sensor. Thinning is understood as spatially and spectrally.
  - Obtain sample data
  - Obtain/generate decoding codes for the sample data
  - Initial estimates of instrument noise from data
  - Simulation of a full data assimilation exercise on simulated data (sample files)
  - Generation of a flow of simulated data, based on proxy real data (for example ATMS data based on AMSU data) with identical format as the expected real data
  - Set up the ingest system, assess potential bottlenecks and fix issues. Goal: simulate as much as possible the expected configuration after launch, before the launch.

Steps to transition a new sensor to operational data assimilation (2/2)

- **2- Post-Launch Phase:**
  - Monitor telemetry, noise NeDT, stability of gains, hot loads, cold loads, and other major parameters.
  - Assess quality of measurements (by comparing to simulation based on forecast/analysis fields) (OB-BK)
  - Assess geo-location quality of measurements
  - Assess QC/pre-processing tools (rain flag ice flag, convergence metric, etc)
  - Determine/monitor bias of measurements as well as RTM uncertainties
  - Test/Adjust footprint matching & thinning methodology
  - Perform parallel assimilation tests to determine impact on forecast skills
  - Full operational implementation if tests positive.
  - Continuous improvement/fine tuning of assimilation methodology, QC, bias adjustment, thinning, etc.

Satellite Data Thinning

Thinning of AMSU-A (N15+N19+Metop-A) Ch-2 Tb
(0006 UTC 23 July, 2013)



Specified

Two target regions

Two domain areas

Auto detected

Higher density in higher variation regions associated with cloudy, frontal system, moisture tongue.

∨ Objective of CSTROT:

Ø Develop a new thinning scheme to optimize satellite data usage in GSI data assimilation for both global and regional modeling systems.

∨ CSTROT Functions:

Ø Thinning options:

- using Standard Deviation
- using regression
- by skipping points

Ø Representation options:

- Random points
- Closest point
- Averaging

Ø Nested domain options:

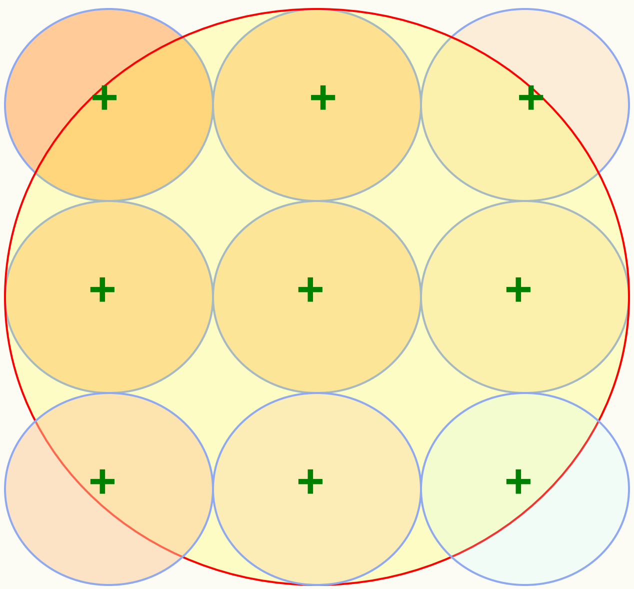
- by target regions
- by domain size

The tool will allow an optimal information content extraction while optimizing computation time

CSTROT is an "intelligent" thinning tool to optimize satellite data selection in DA.

Footprint Matching

(Case of AMSU/MHS)



- Footprint matching is very sensor-dependent
- Different Approaches for Footprint matching:
  - Simple averaging
  - Backus Gilbert

Let’s not forget about HPC

- Data assimilation is computer-intensive
- Supercomputers are thereforw very important for satellite data assimilation

Challenges in Satellite Data Assimilation

(From JCSDA)

- Difficult to ingest all satellite data due to a lack of computational resources and fast radiative transfer schemes

- Difficult to use satellite measurements that are affected by surface

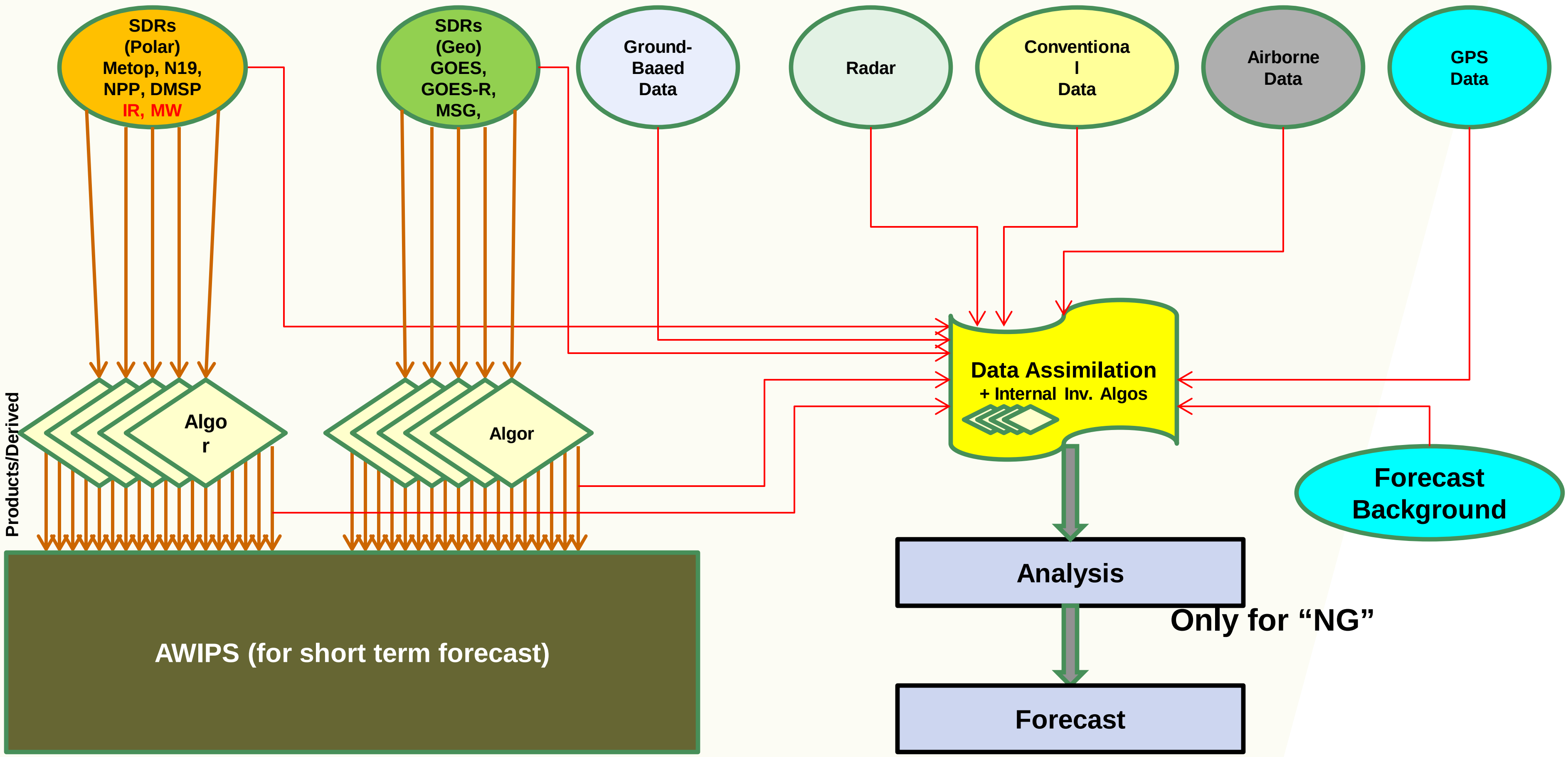
- Difficult to assimilate satellite radiances that are affected by aerosols and clouds

- There is a lot of work to be done still..

Contents

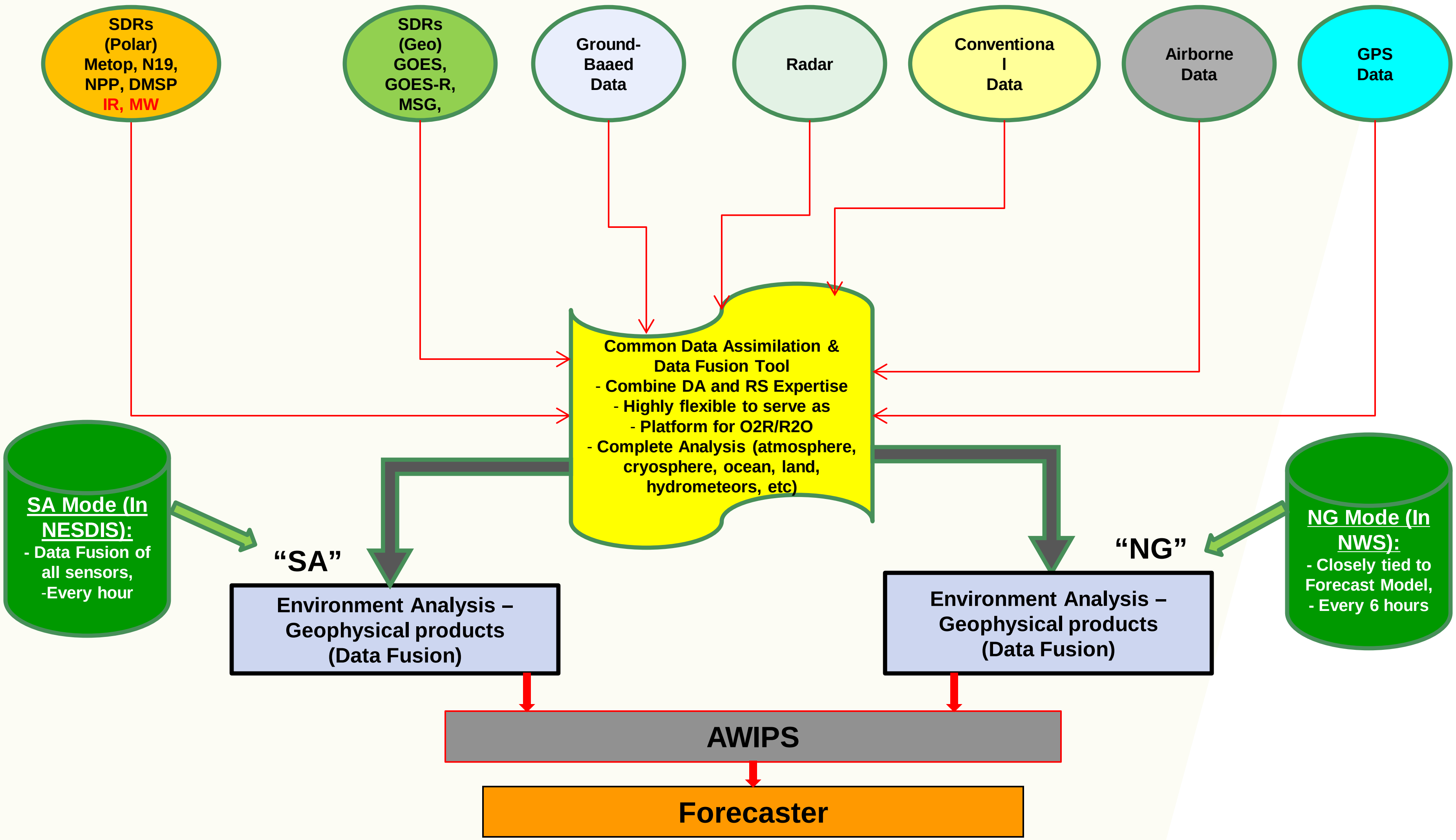
Current Use of Satellite Data

(Numerical Guidance and Situation Awareness)



Future Merged SA and NG Product Generation

“Provide what the forecasters need, when they need it…”



Increase Role of Assimilation in NWP and Climate Reanalysis (1/2)

- Satellite data is critically used in data assimilation system (traditionally for NWP)
- Satellite Measurements by nature are sensitive to all sorts of parameters (products). If it can retrieved, it can be ‘analyzed’.
- Efforts are ongoing to extend/improve the assimilation to all sensors (active/passive, RO, IR/MW, Lightning, etc), all situations (cloudy, rainy, ice-covered, ..)
- Coupled data assimilation is becoming a major focus: this will lead to using data assimilation analysis beyond NWP (to ocean, land, cryosphere, hydrometeors, etc)
- Increase in spatial resolution (~13kms) and temporal resolution (hourly analysis are becoming more and more common) will lead to usage of assimilation for situational awareness purposes (nowcasting and short term forecasting)

Increase Role of Assimilation in NWP and Climate Reanalysis (2/2)

- Satellite data is more and more frequently used in conjunction (or blended): MW and IR TPW, ground-based and satellite, Geo and Leo
- Data assimilation presents an excellent tool to perform this data 'fusion' of sort.
- Data assimilation is becoming the 'entry point' for the usage of satellite data for diverse types of users
- Cross-sensors intercalibration happens naturally inside the data assimilation: A unique analysis is produced out of the hundreds of measurements types.
- This lesser sensitivity to calibration errors is naturally extending the capability to climate applications (re-analysis)

JCSDA Activities in Training, Education & Outreach

- **Monthly Seminar Series on DA:** ***remote access available***
- **Summer colloquium in satellite data assimilation (3-year cycle).** ***Next one planned for summer 2015.*** ***Open for everyone***
- **JCSDA Annual symposium co-organized during the next AMS annual meeting in 215.**
- **Annual JCSDA workshop on satellite data assimilation.** ***Next one planned for May 2015)***
- **Joint Workshops with Other Programs and International Partners.** ***DTC-JCSDA joint workshop/tutorial, ECMWF-JCSDA workshop, etc***
- **JCSDA Newsletters (quarterly)**
  - Highlight achievements by JCSDA scientists (internal/external)
  - Disseminate results and promote collaboration
- **Active web site: jcsda.noaa.gov**

Thank You !

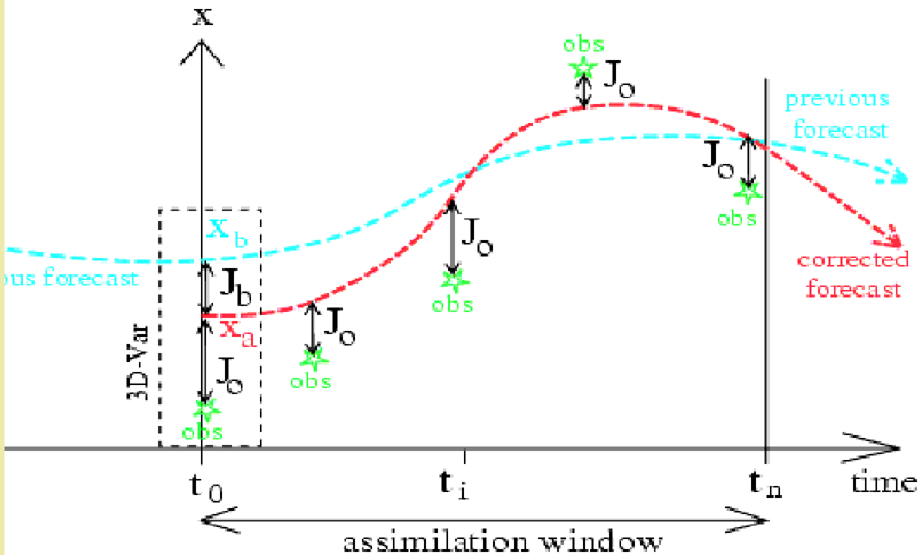
Questions?

BACKUP SLIDES

Four Dimension Variational Analysis (4DVAR)

- Within an assimilation window, recent measurements are accounted for to reduce the time-dependent cost-function and produce a new trajectory for subsequent forecast.

- Difficulties:
  - Adjoint in temporal domain can be non-linear
  - Huge computational requirements and storage



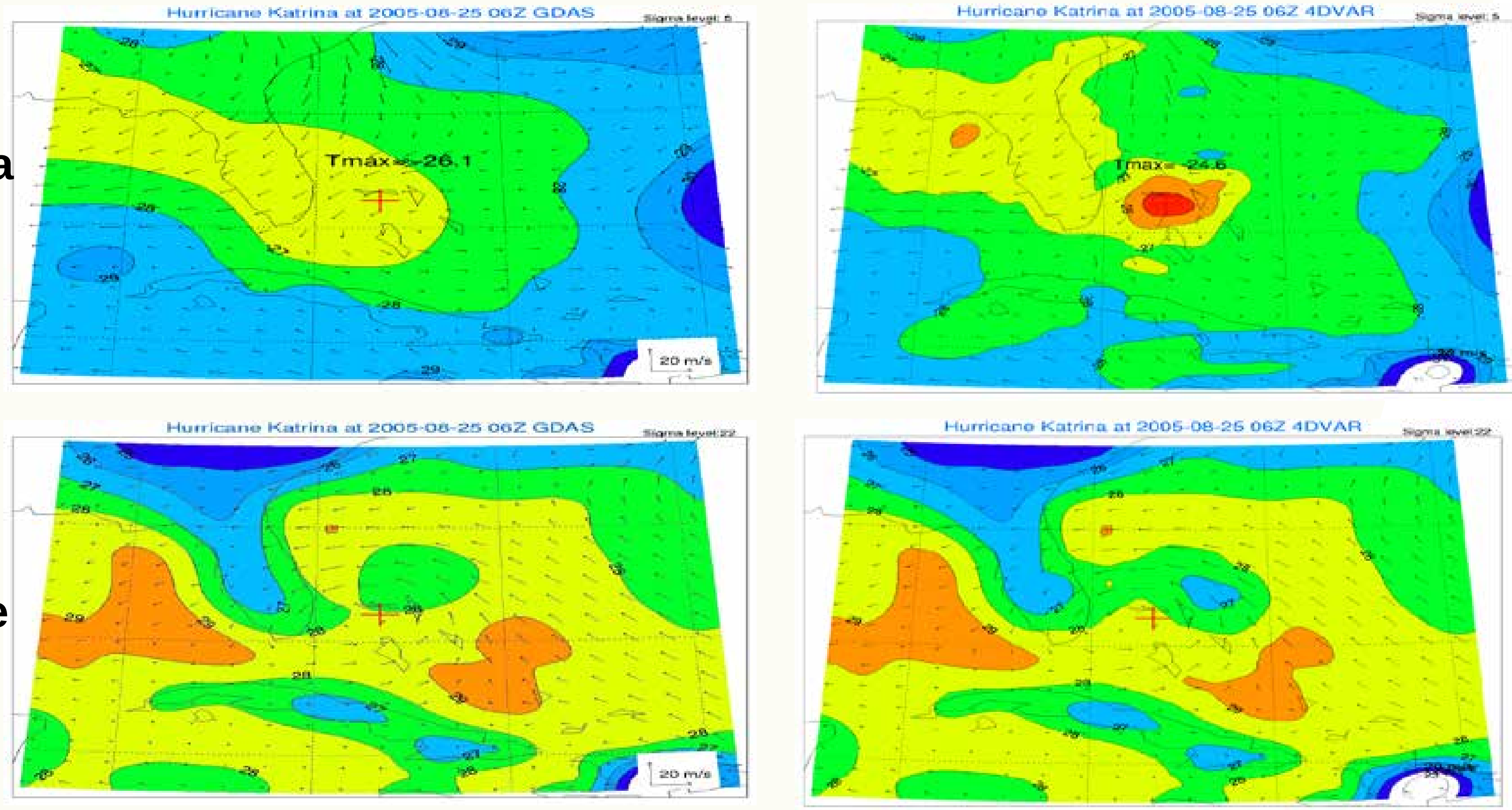
$$
\begin{aligned}
J(x) \quad = \quad & \frac{1}{2}(x - x_b)^T B^{-1} (x - x_b) + \\
& \frac{1}{2}\sum_i^n [y_i - H_i(x_i)]^T R_i^{-1} [y_i - H_i(x_i)]
\end{aligned}
$$

1DVAR+4DVAR: Katrina Analysis

GDAS | 4DVAR

250 hPa

Surface



Above figures compare GDAS analysis temperature fields near 250 hPa and surface with 1DVAR retrievals and 4DVAR analysis. The temperature field from analysis shows hurricane warm core is about 2 degree warmer than GDAS analysis. Uses of cloudy radiances under storm conditions dramatically improve warm core structure. At 0600 UTC August 25, 2005, Katrina was at tropical storm intensity, with the minimum central pressure of 1000 hPa.