A satellite view of Earth from space, showing the Western Hemisphere. The Americas are visible, with North America in the upper right and South America in the lower right. The Pacific Ocean is on the left. The Earth's atmosphere and cloud cover are clearly visible.

# *Earth System Analysis and 100 Day Prediction*

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**Director, Earth System Research Lab**  
**President, American Meteorological Society**

**NOAA**  
**Earth System Research Laboratory**

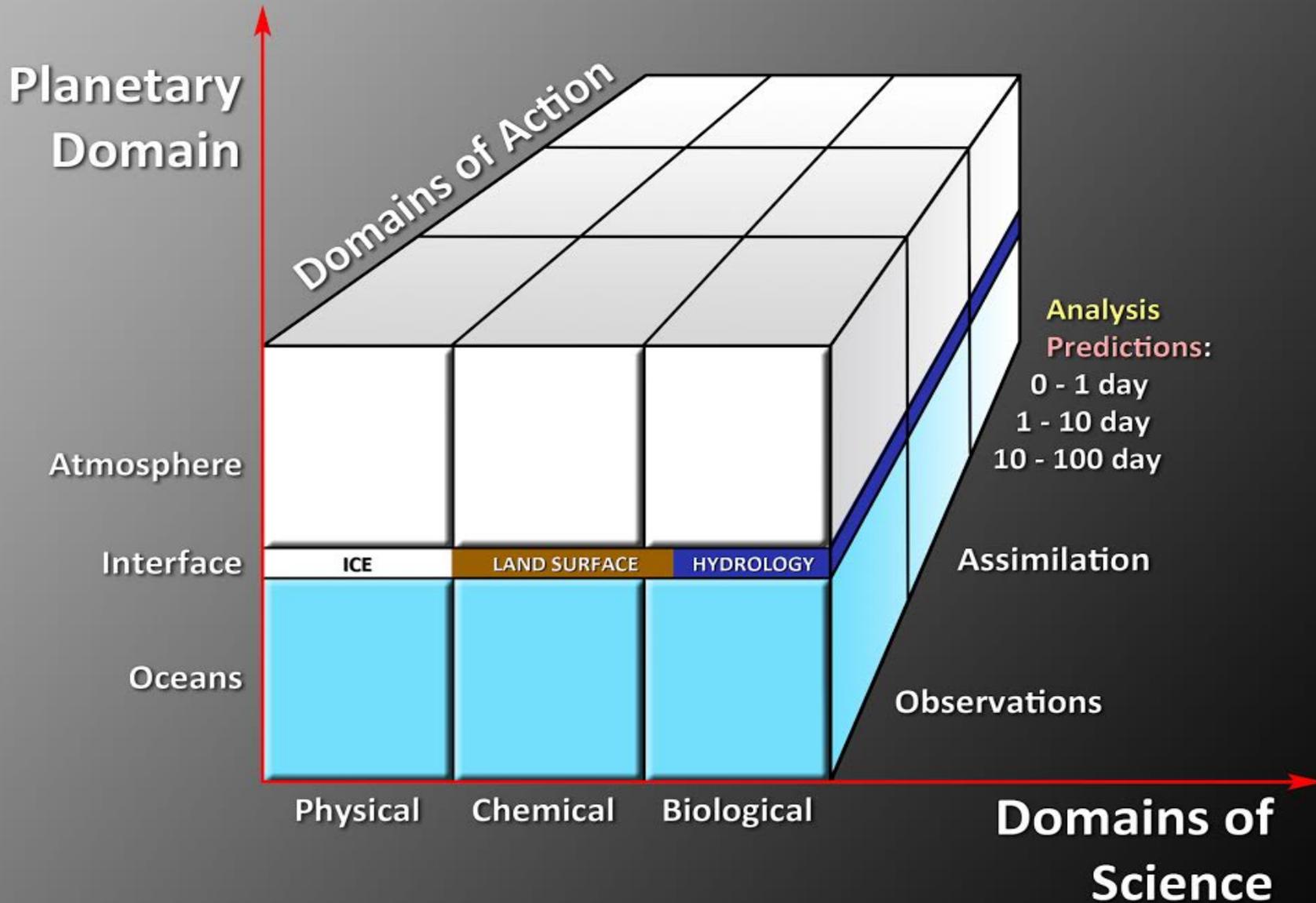
# *Earth System Analysis and 100 Day Prediction*

A proposal to use all available geophysical data, satellite and in situ, to continuously diagnose the full Earth system . . .

This system is needed for:

- Improved weather prediction.
- Observational constraints on climate forcings (e.g. aerosols, ice-albedo etc.)
- Required for 21<sup>st</sup> century emergencies.

# Earth System Analyzer: Components



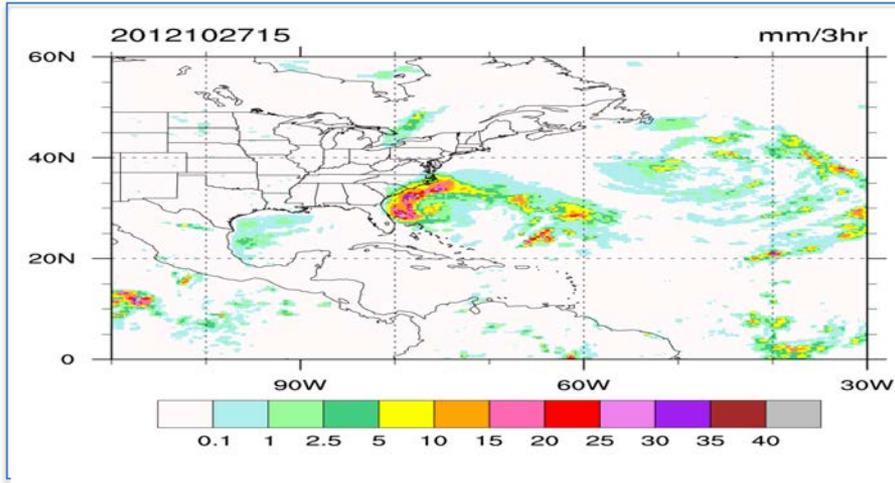
**ESRL FIM model prediction compared to actual satellite data over many days.**



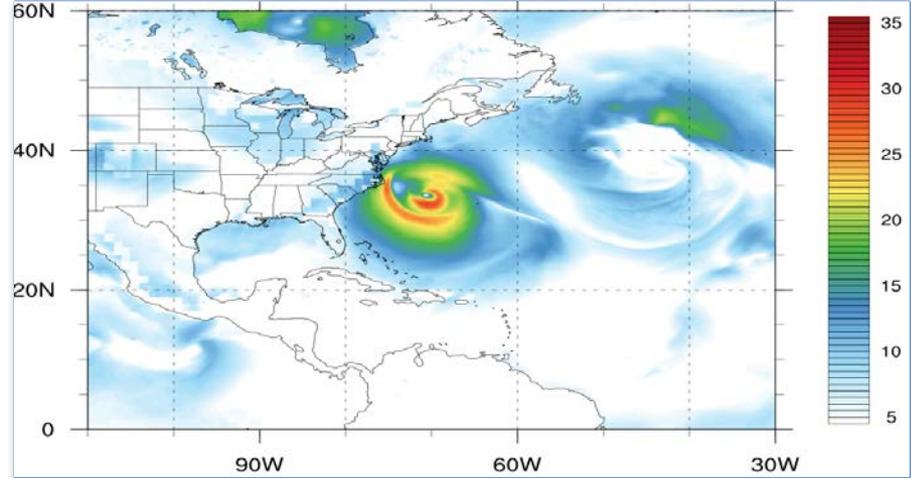
# NIM: ESRL/GSD global non-hydrostatic model at 3 km resolution

## Hurricane Sandy prediction – 72 hours

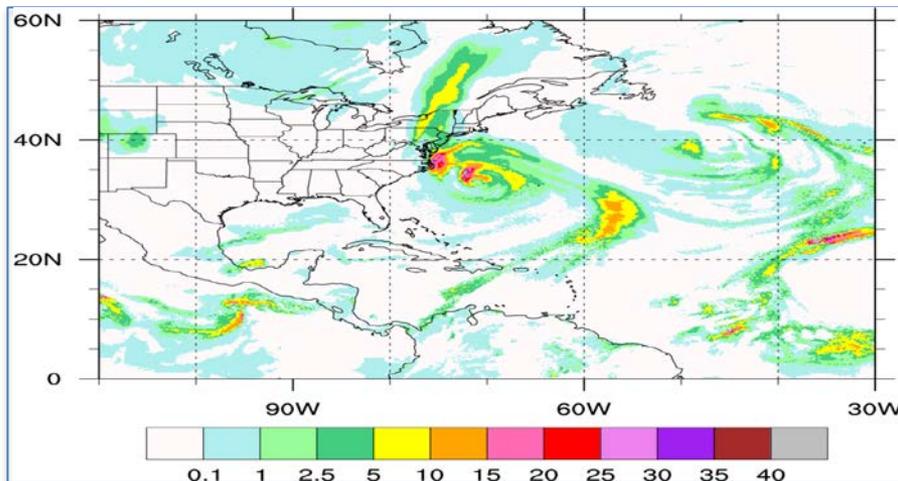
CMORPH obs 3hr precip



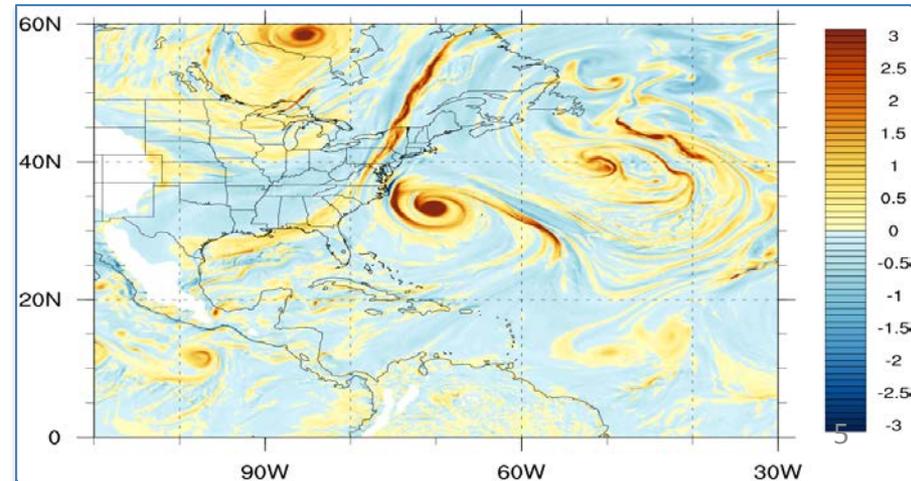
10m wndspd (m/s)



model 3hr precip (mm/3hr)

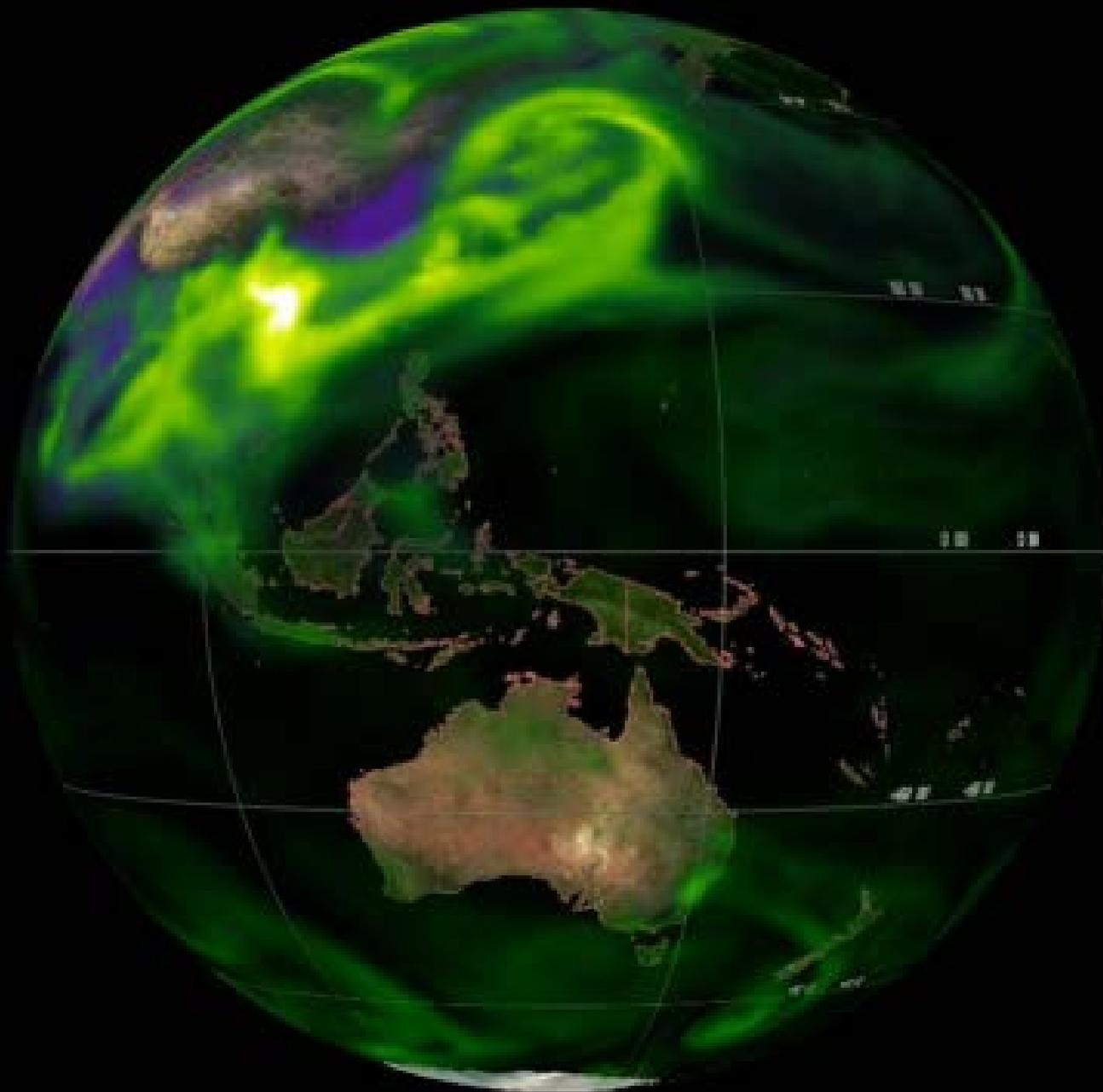


850 mb vorticity ( $\times 10^{-4} / \text{s}$ )



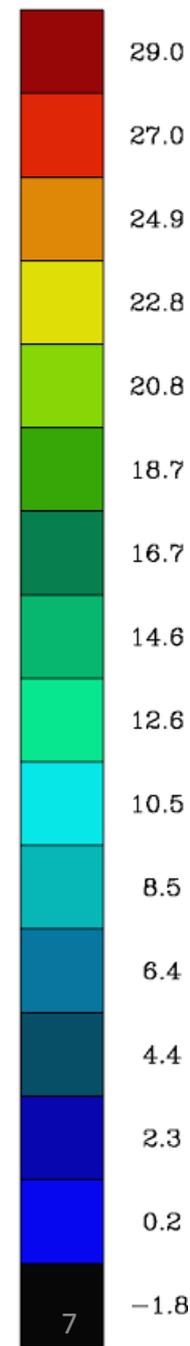
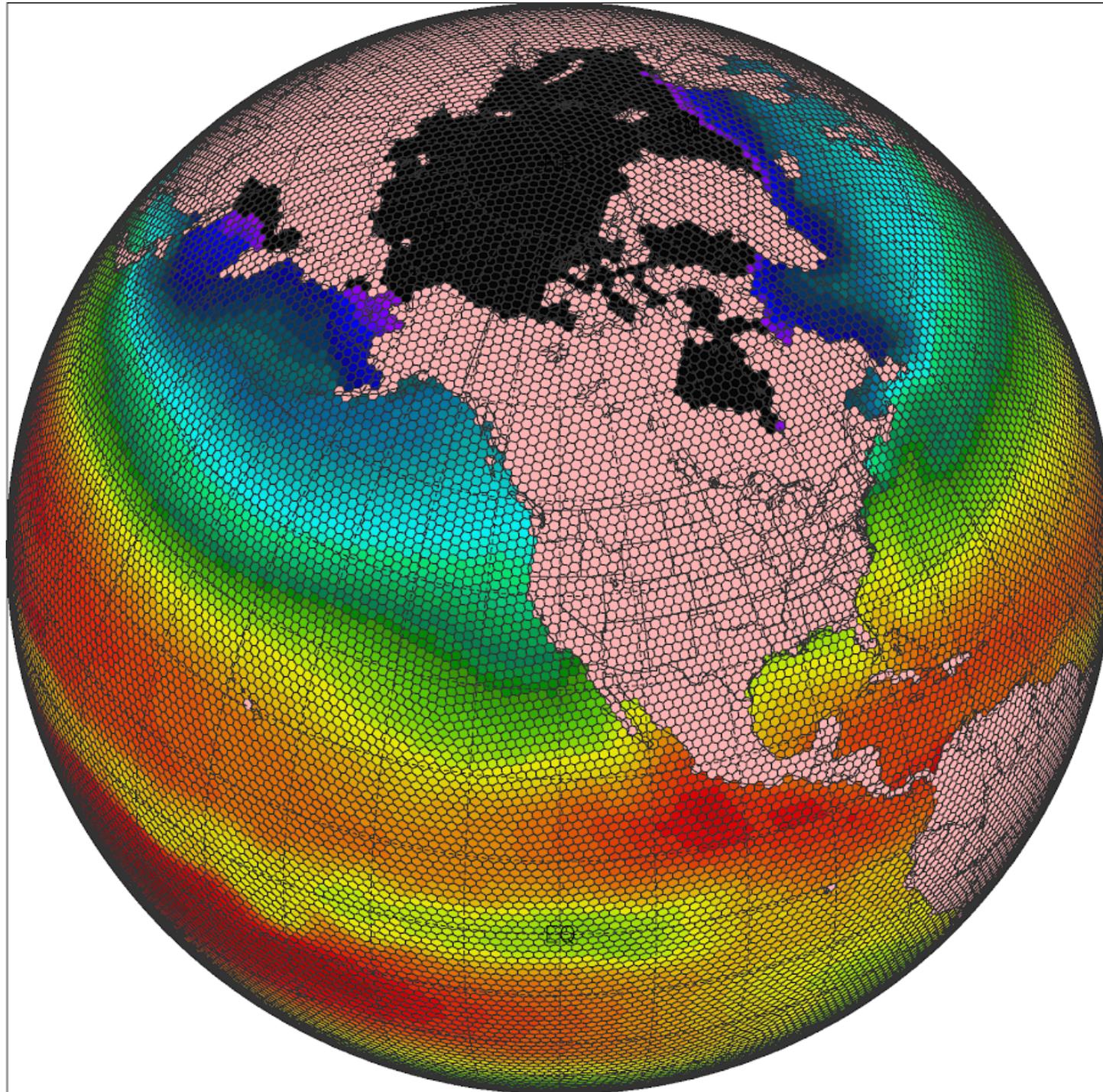
## Chemistry:

**There are several hundred atmospheric constituents that need to be tracked.**



ESRL/GSD  
iHYCOM

Global  
ocean  
model

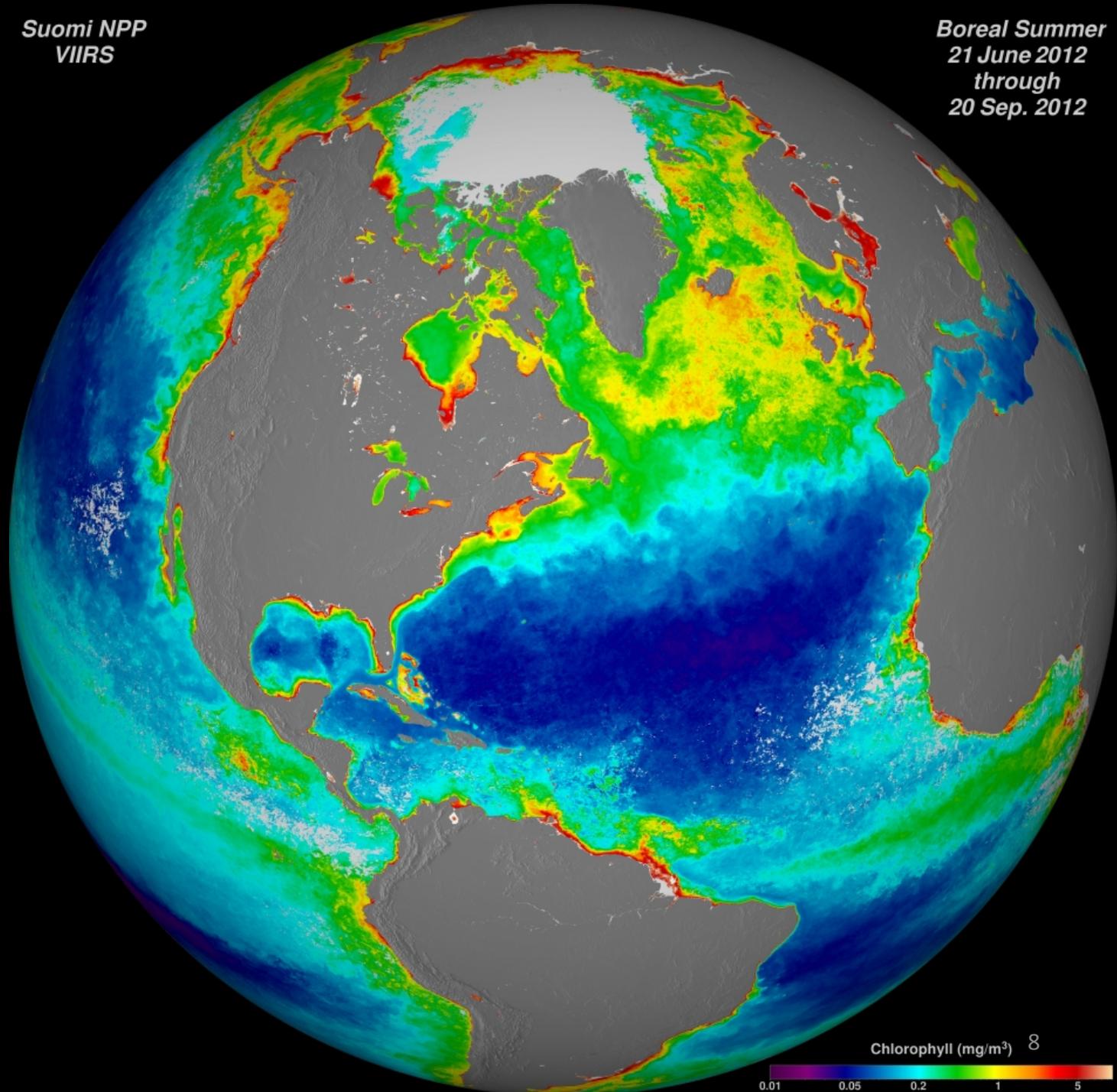


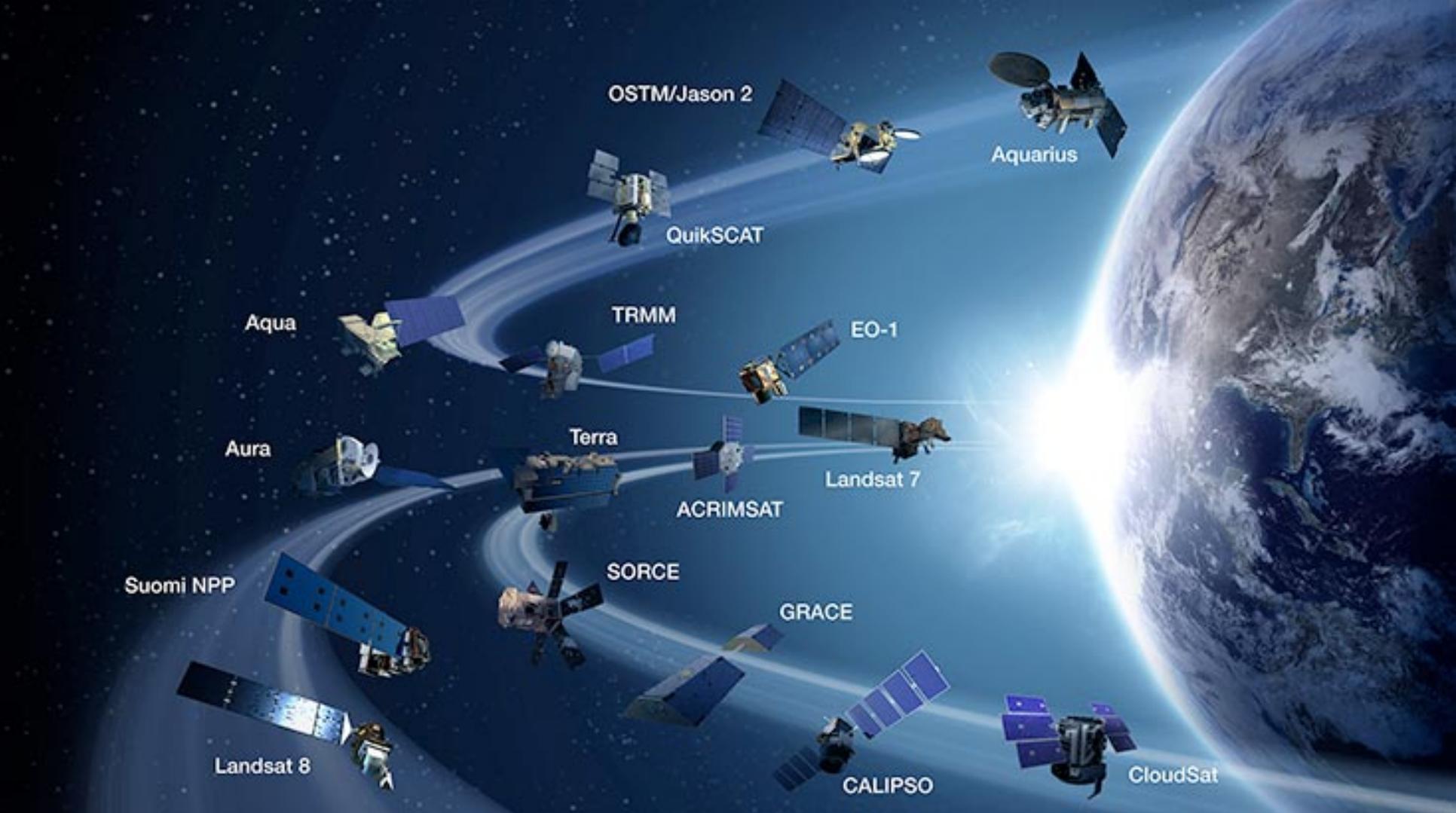
Suomi NPP  
VIIRS

Boreal Summer  
21 June 2012  
through  
20 Sep. 2012

Biology:

The most  
complex  
part of the  
Earth  
System.





## Initial Value Based Prediction is **DATA DOMINATED**:

- Use every instrument on every available satellite.
- Use all of the in situ data.
- Use advanced assimilation for all fields.

Use every  
sensor,

On every  
satellite,

And develop  
forward models  
for

Appropriate  
geophysical  
variables.

record with T/P and Jason; Improve the measure of the time-averaged ocean circulation; Improve the measure of global sea-level change; Improve open ocean tide models.

<https://sealevel.jpl.nasa.gov/missions/ostmjason2/>

**Kalpana-1 - Metsat-1** - meteorological services had been combined with telecommunication and television services in the INSAT series. carries a Very High Resolution Radiometer (VHRR) capable of imaging the Earth in the visible, thermal infrared and water vapour bands. It also carries a Data Relay Transponder (DRT) for collecting data from unattended meteorological platforms.

<https://directory.eoportal.org/web/eoportal/satellite-missions/k/kalpana-1>

**Kanopus-V N1 - Kanopus-V Environmental Satellite N1** - objective is to monitor Earth's surface, the atmosphere, ionosphere, and magnetosphere to detect and study the probability of strong earthquake occurrence. The requirements call for: Monitoring of man-made and natural emergencies including natural disasters and hydrometeorological phenomena; Mapping; Detection of forest fire seats, large environmental pollutant emissions; Recording of abnormal phenomena to study the possibility of earthquake prediction; Monitoring of agriculture, water and coastal resources; Land use; Highly operational observation of specified regions of the Earth's surface.

<https://directory.eoportal.org/web/eoportal/satellite-missions/k/kanopus-v-1>

**Kompsat-2 - Arirang 2, Korean planned Multipurpose Satellite-2** - provide high-resolution images, produced by the Multi-Spectral Camera (MSC), of the Korean peninsula for the production of maps and digital elevation models, applications for which include land use planning and disaster and risk management. <http://www.globalsecurity.org/space/world/rok/kompsat.htm>

**Kompsat-3 - Arirang 3, Korean Multipurpose Satellite-3** - The objective is to provide observation continuity from the KOMPSAT-1 and KOMPSAT-2 missions to meet the nation's needs for high-resolution optical imagery required for GIS (Geographical Information Systems) and other environmental, agricultural and oceanographic monitoring applications.

<https://directory.eoportal.org/web/eoportal/satellite-missions/k/kompsat-3>

**Kompsat-5 - Arirang 5, Korean Multipurpose Satellite-5** - mission objective is to develop, launch and operate an Earth observation SAR (Synthetic Aperture Radar) satellite system to provide imagery for geographic information applications and to monitor environmental disasters. provide high resolution mode SAR images of 1 meter resolution, standard mode SAR images of 3 meter resolution.

<https://directory.eoportal.org/web/eoportal/satellite-missions/k/kompsat-5>

**Kuaizhou-1 - KZ-1** - It will be used to monitor natural disasters and provide disaster-relief information.

<http://www.globalsecurity.org/space/world/china/kz-1.htm>

**Landsat 7** - The overall mission objective is to extend and improve upon the long-term record of medium-resolution multispectral imagery of the Earth's continental surfaces provided by the earlier Landsat satellites. mission performed flawlessly until May 2003, when a component of the ETM+ optical scanning system (called the scan line corrector or "SLC") failed, leaving wedge-shaped spaces of missing data on either side of the images. Six weeks later the ETM+ resumed its global land survey mission,

Lat:Lon 82.89988 : -236.25000



Satellite and in situ observations are like gasoline and oil for an engine: **YOU ALWAYS NEED BOTH.** ([ESRL/GMD Carbon network.](#))<sub>1</sub>

# Advanced geophysical assimilation

## From Bayes theorem to 4DVar and the (Ensemble) Kalman Filter

$$p(\mathbf{x}|\mathbf{y}) \propto \exp \left( -(\mathbf{x} - \mathbf{x}_b)^T \mathbf{P}^b{}^{-1} (\mathbf{x} - \mathbf{x}_b) - (\mathbf{y} - \mathbf{H}\mathbf{x})^T \mathbf{R}^{-1} (\mathbf{y} - \mathbf{H}\mathbf{x}) \right)$$

Variational methods maximize the posterior PDF to find the state trajectory  $\mathbf{x}$  that best fits the obs  $\mathbf{y}$  in a least-squares sense. In practice, this is done by minimizing a cost function, which is what's inside the *exp*:

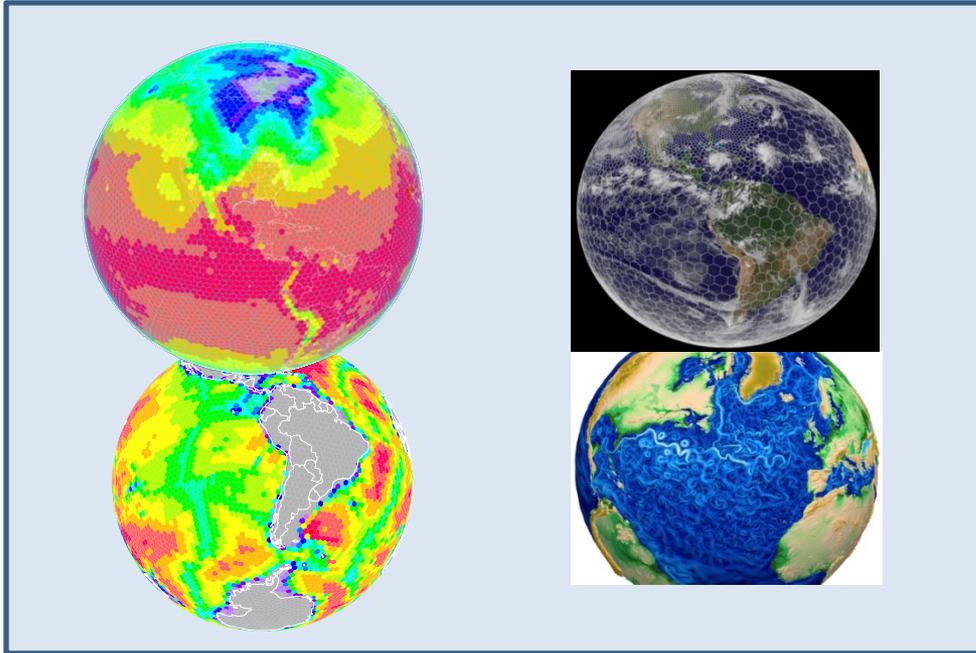
$$J(\mathbf{x}) \propto (\mathbf{x} - \mathbf{x}_b)^T \mathbf{P}^b{}^{-1} (\mathbf{x} - \mathbf{x}_b) + (\mathbf{y} - \mathbf{H}\mathbf{x})^T \mathbf{R}^{-1} (\mathbf{y} - \mathbf{H}\mathbf{x})$$

The minimum can be found analytically if  $\mathbf{H}$  is linear (see Lorenc 1986 *QJRMS* for the algebra). This gives the equations for the Kalman Filter

$$\begin{aligned} \mathbf{x}_a &= \mathbf{x}_b + \mathbf{K} (\mathbf{y} - \mathbf{H}\mathbf{x}_b), \quad \mathbf{P}^a = (\mathbf{I} - \mathbf{K}\mathbf{H}) \mathbf{P}^b \\ \mathbf{K} &= \mathbf{P}^b \mathbf{H}^T (\mathbf{H}\mathbf{P}^b \mathbf{H}^T + \mathbf{R})^{-1} \end{aligned}$$

- Matrix  $\mathbf{P}^b$  is too big for any computer, covariance update step impractical.
- Instead, represent PDFs of  $\mathbf{x}$  and  $\mathbf{y}$  by an ensemble, compute sample estimate of  $\mathbf{P}^b$ . Evolve the sample, not the full covariance. **EnKF** gives same result as full KF if ensemble size becomes infinite.

# NOAA Earth System Analyzer Components

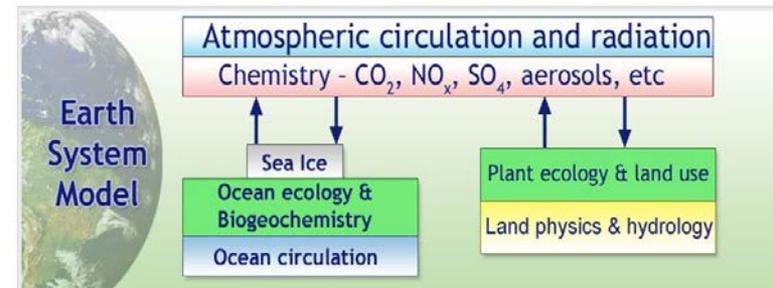


1. Multiple dynamics and physics assimilation for the major system components (air, ocean, land surface et.).

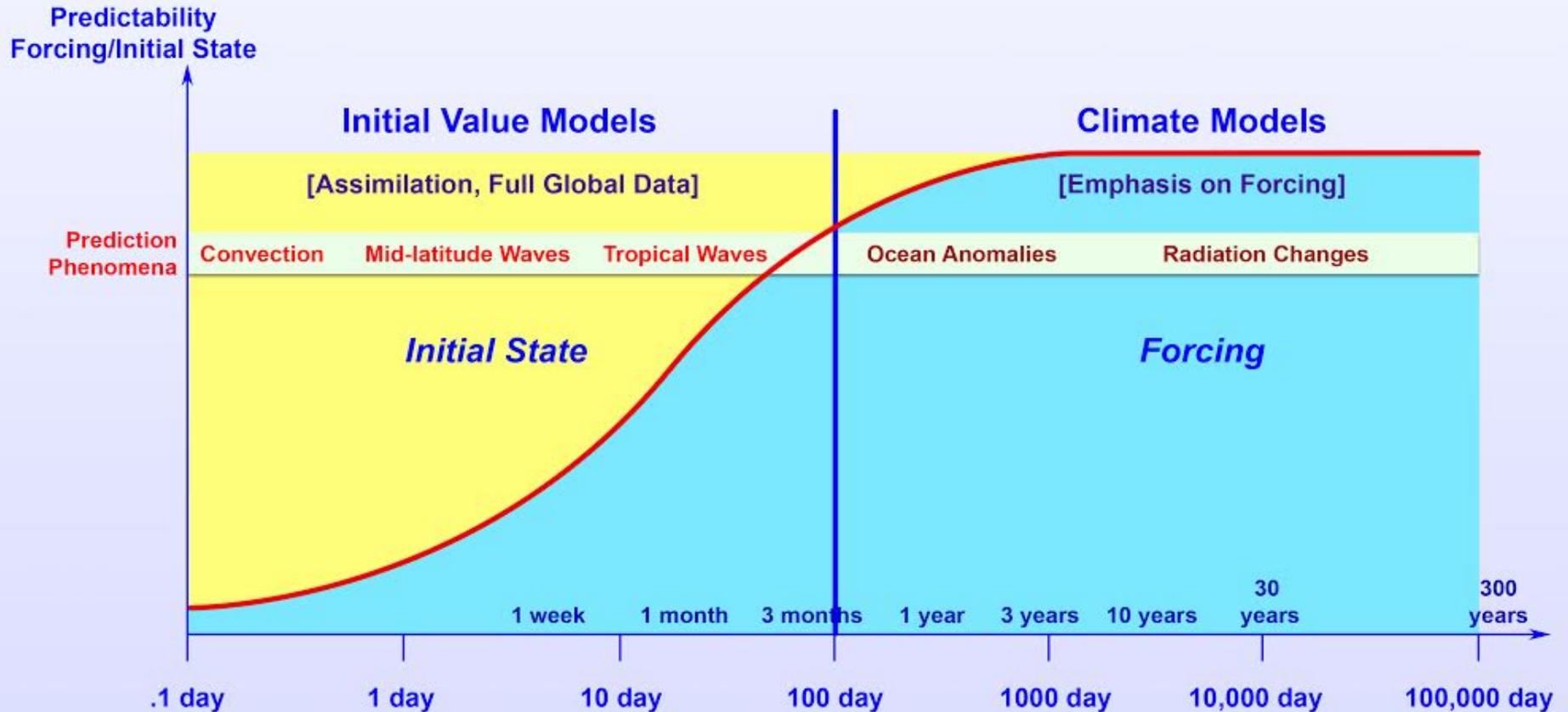
2. Continuous real time analysis.



3. Modeling **frameworks**.



# Sources of Geophysical Predictability



# *Earth System Analyzer*

“ A **framework** to continuously analyze the entire Earth system.”

**Physical Earth:** 100 vertical levels, 3 km resolution, every hour, 100 variables.

**Chemical Earth:** 100 vertical levels, 3 km resolution, every hour, 100 variables.

**Biological Earth:** 3 km resolution, daily, 10,000 variables.

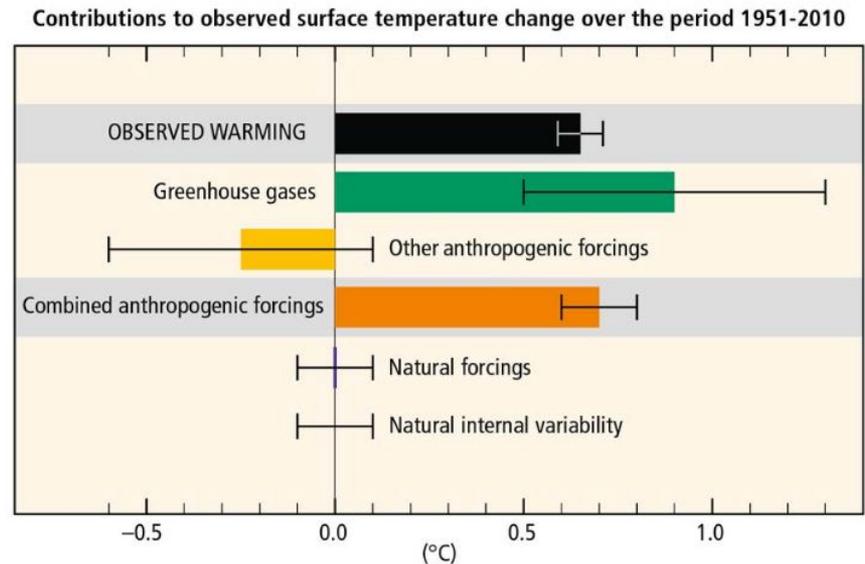
**Data Volume:** 10 terabytes per day

## Ben Santer:

"The recent slow-down in observed surface and tropospheric warming is a fascinating detective story," Santer said. "There is not a single culprit, as some scientists have claimed. Multiple factors are implicated. One is the temporary cooling effect of **internal climate noise**. Other factors are the external cooling influences of 21st century **volcanic activity**, an unusually low and long **minimum in the last solar cycle**, and an uptick in **Chinese emissions of sulfur dioxide**.

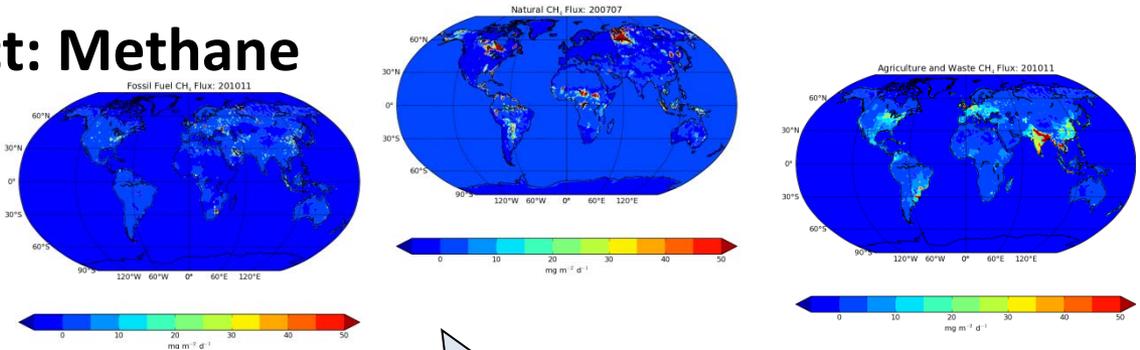
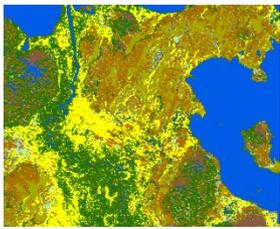
"The real scientific challenge is to obtain hard **quantitative estimates of the contributions** of each of these factors to the slow-down."

**Integrated , holistic observation based Earth system analysis :  
the only way to sort out the component contributions.**

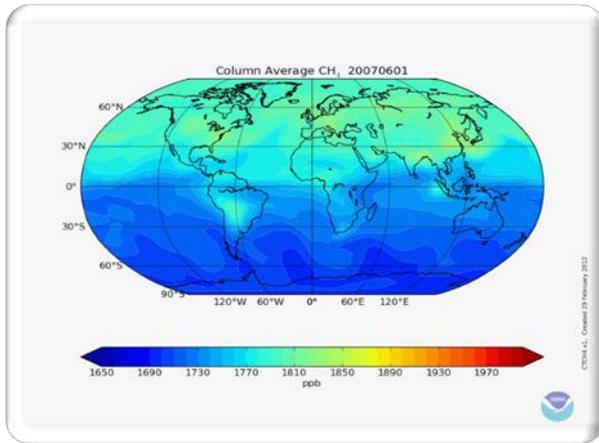


# ESRL Pilot Project: Methane

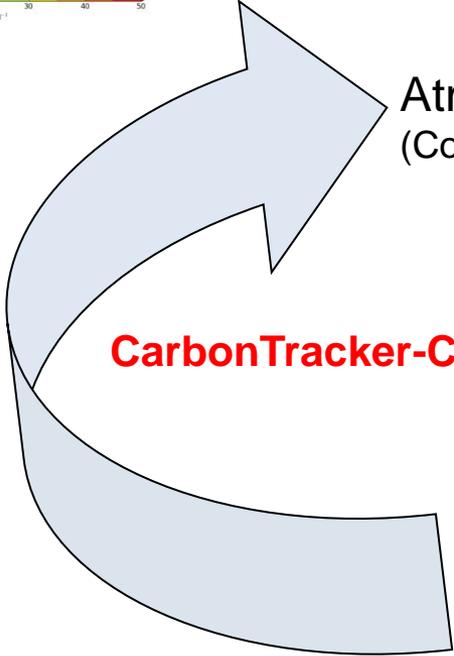
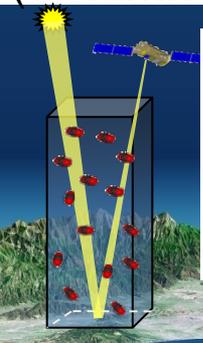
Remotely Sensed Ecological Data



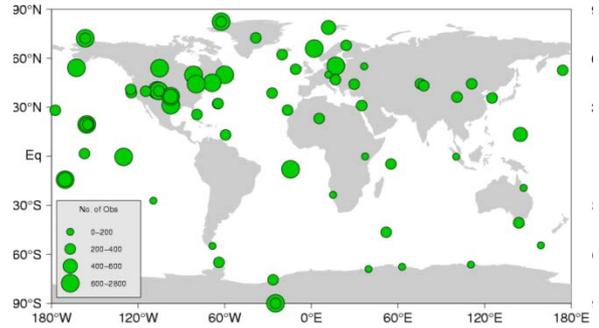
Atmospheric State  
(Concentration and Emissions)



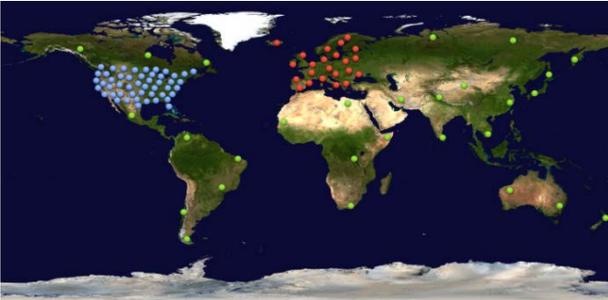
Satellites, TCCON  
(Column Data)



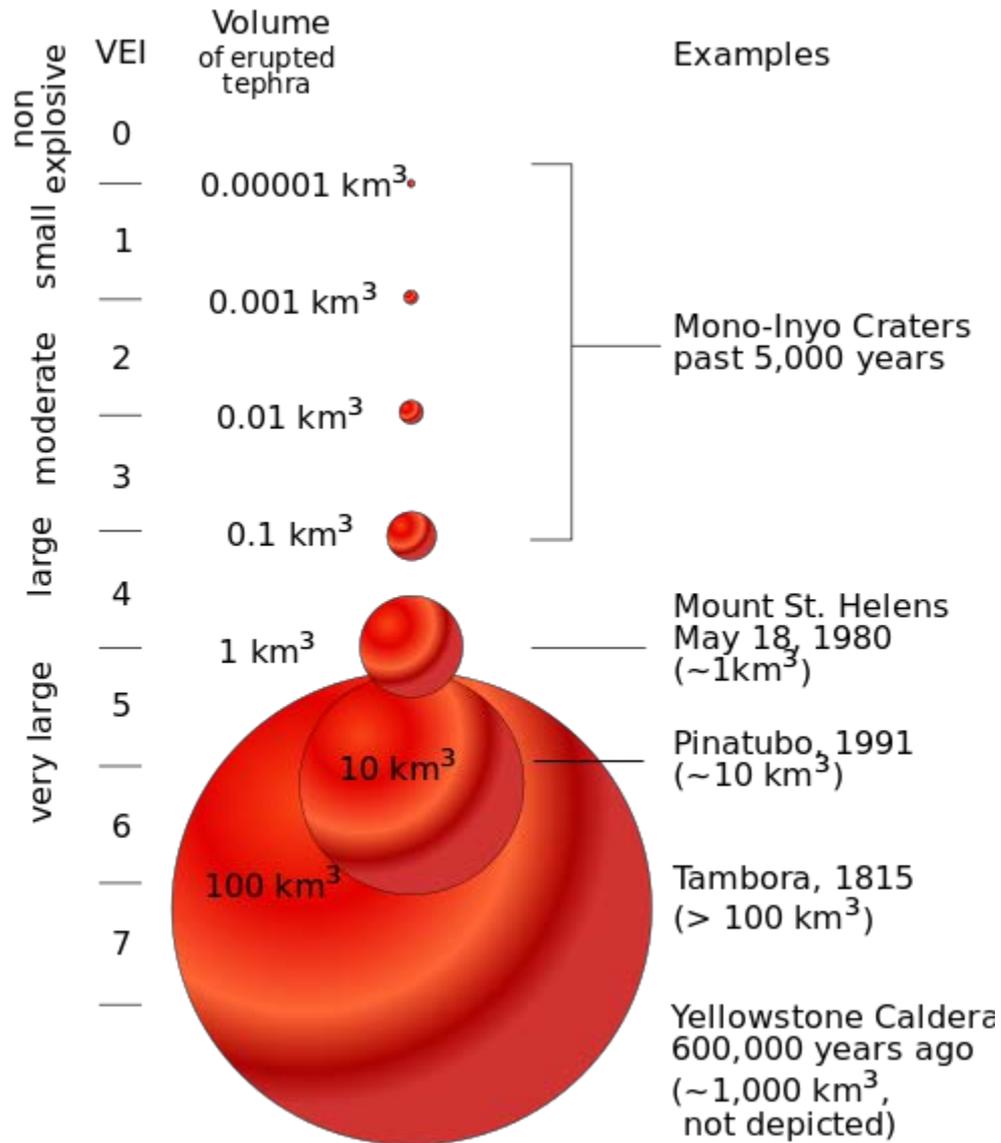
Current Surface Network



Earth Networks  
(Planned)



# Volcano Explosive Index



A volcano could kill a billion people if we were not **ready to act with good information**.<sup>18</sup>

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