10-years of Computing and Atmospheric Research at NASA

1 day per day

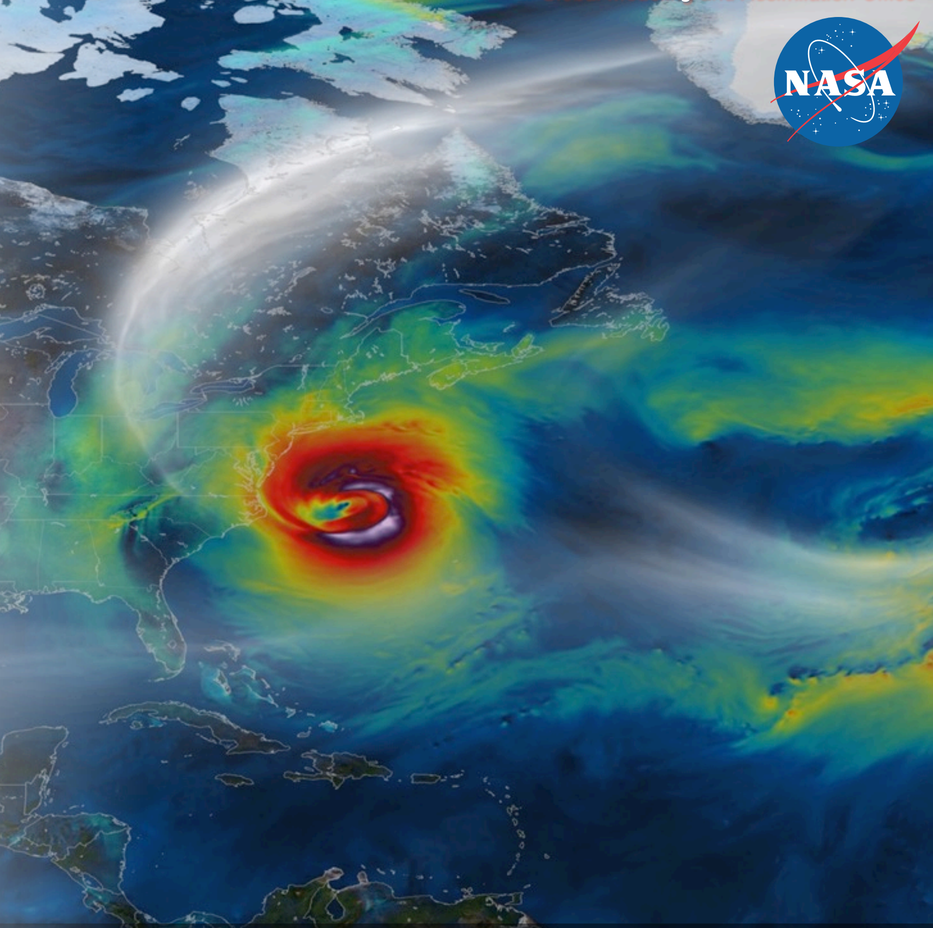
Bill Putman

Model development lead

Global Modeling and Assimilation Office

Outline

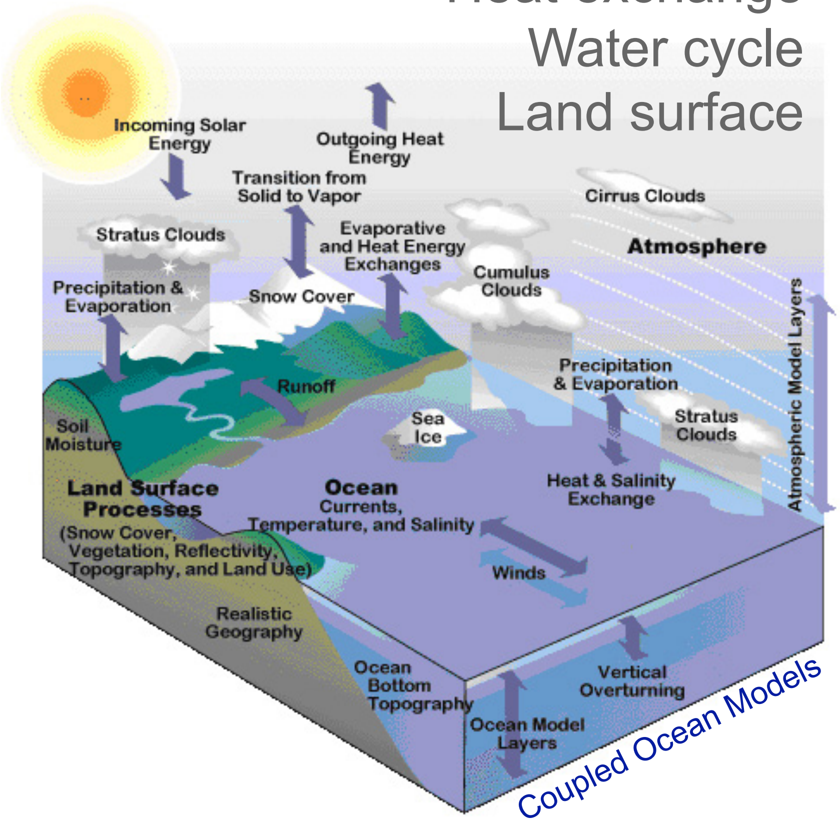
1. **Scheduling…**
2. **A brief history of weather/climate modeling**
   1. 1 day per day
3. **Evolution of modeling systems at Goddard**
   1. Computing
   2. Earth System Science
   3. Resolution
4. **Looking toward the future**
   1. Expanding capability
   2. Research systems
   3. Challenging the current hardware/system
5. **The pursuit of exascale**
   1. Future development
   2. Heterogeneous multi-core systems



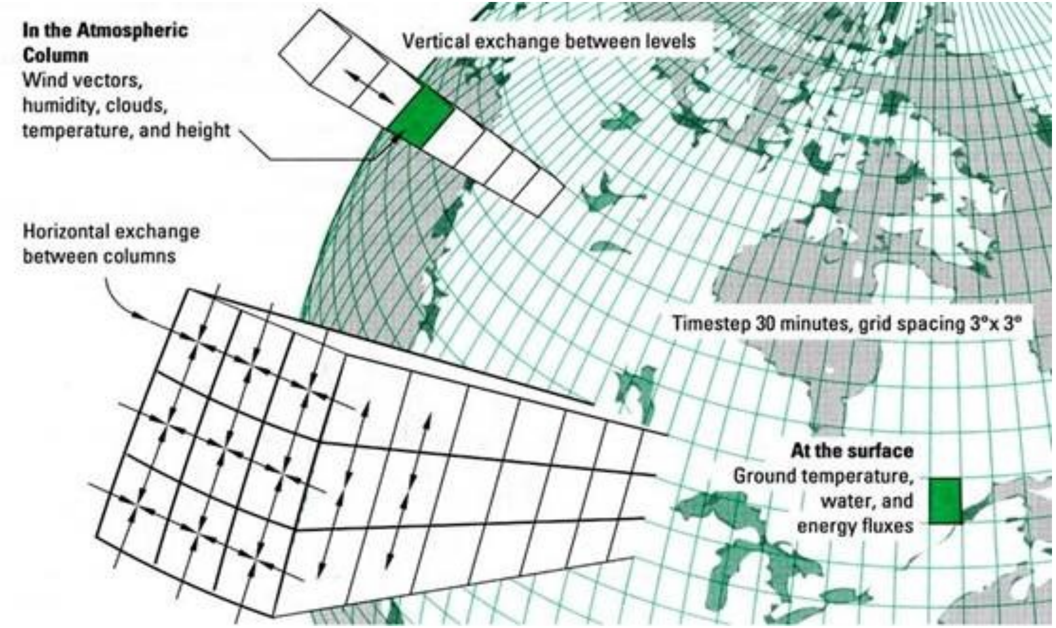
Hurricane Sandy
October 29, 2012
Surface Winds from 7-km GEOS-5 Forecast

Fundamentals of Weather/Climate Models

Physics: Radiative transfer
Heat exchange
Water cycle
Land surface



Dynamics: Grid decomposition
Momentum and heat fluxes
Moisture transport



1922, Lewis Fry Richardson Richardson's "Forecast Factory"

In 1922, Lewis Fry Richardson developed the first numerical weather prediction (NWP) system.

He divided the world into grid cells and applied finite difference solutions of differential equations.

His first attempt to calculate weather for a single eight-hour period took six weeks.

He proposed a "forecast-factory" of 64,000 people armed with mechanical calculators lead by a conductor to coordinate the forecast.

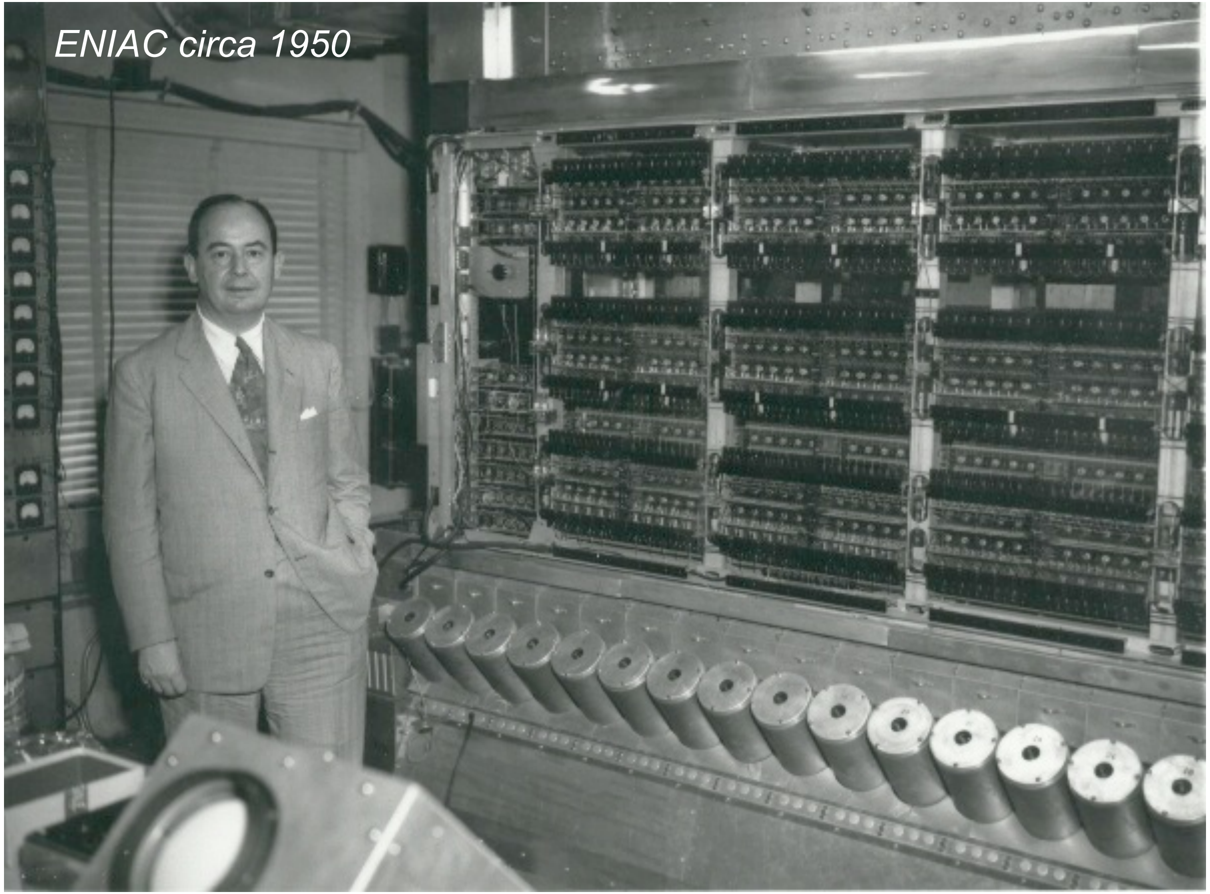
Yet even with this fanciful factory, Richardson would only be able to calculate weather about as fast as it actually happened.

[1-day per day]

http://celebrating200years.noaa.gov/foundations/numerical_wx_pred/theater.html

http://www.gfdl.noaa.gov/cms-filesystem-action/user_files/jrl/gcm/jrl_gcm_doc-history.pdf

1950, The First Numerical Weather Simulation



Jule Charney and John von Neumann completed a two-dimensional simulation on the ENIAC in 1950.

It covered North America with 270 points about 700 km apart. Starting with real weather data for a particular day, the computer solved all the equations for how the air should respond to the differences in conditions between each pair of adjacent cells.

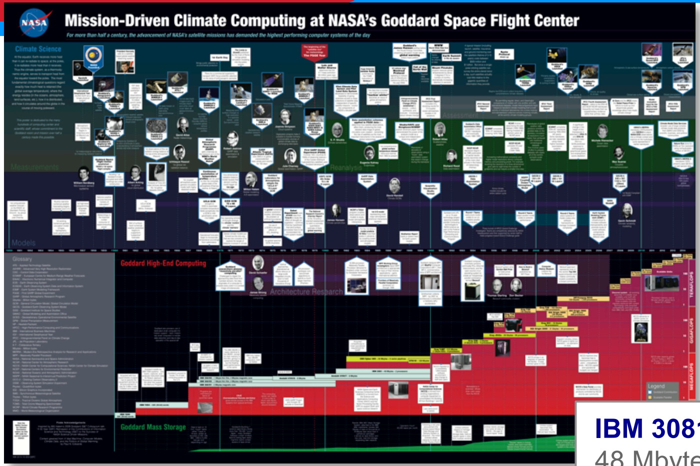
It took so long between each run to print and sort punched cards that "the calculation time for a 24-hour forecast was about 24 hours, that is, we were just able to keep pace with the weather."

[1-day per day]

http://www.whyy.org/tv12/franklinfacts/oct1601_6.jpg

https://www.aip.org/history/climate/GCM.htm

NASA Goddard Computing and Model Evolution



IBM 7090/7094
32K (36-bit) words

IBM 360/91 360/95
2/4 Mbytes magnetic core

Amdahl 470V/6 470V/7
8 Mbytes

IBM 3081
48 Mbytes 2-processors

Cray Y-MP
8-processors

Cray C98
6-processors

Cray J932s
96-processors

Cray T3D/T3E
32-130 Gbytes

SGI Origin 2000
64-processors

SGI Origin 3000
512-processors

SGI Origin 3800
608-processors

HP/Compaq SC45
1,400-processors
1 Tflop

Discover
Scalable Units 1-9
10 Tflops ➔ 1.7 Pflops

Atmospheric/Land Surface/Vegetation
Ocean
Coupled Climate Model
Sea Ice
Sulfate Aerosol
Interactive Vegetation
Dust/Sea Spray/Carbon Aerosols
Atmospheric Chemistry
Upper Atmosphere
Biogeochemical Cycles
Carbon Cycle
Ice Sheet
Marine Ecosystems

UCLA GCM
4x5-deg
2 levels

GISS GCM
4-deg
9 levels

GSFC GCM
4th Order
4-deg
9 levels

GEOS-1
Data Assimilation System (DAS)

GEOS-3
2-deg
48 levels

GEOS-4
1-deg
55 levels

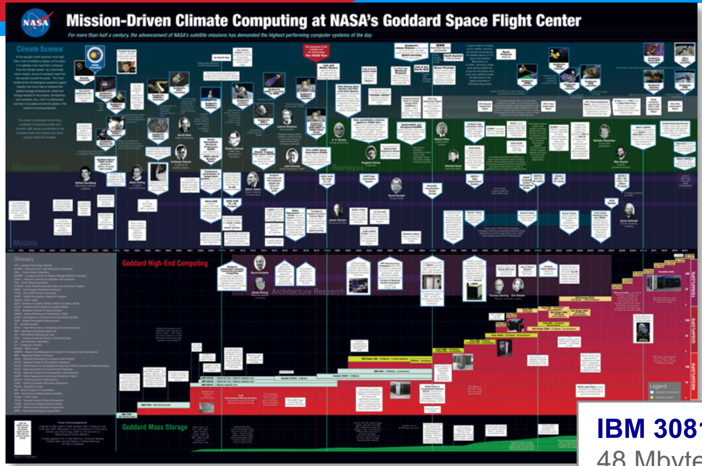
GEOS-5
1/2-deg DAS
1/4-deg GCM
72 levels

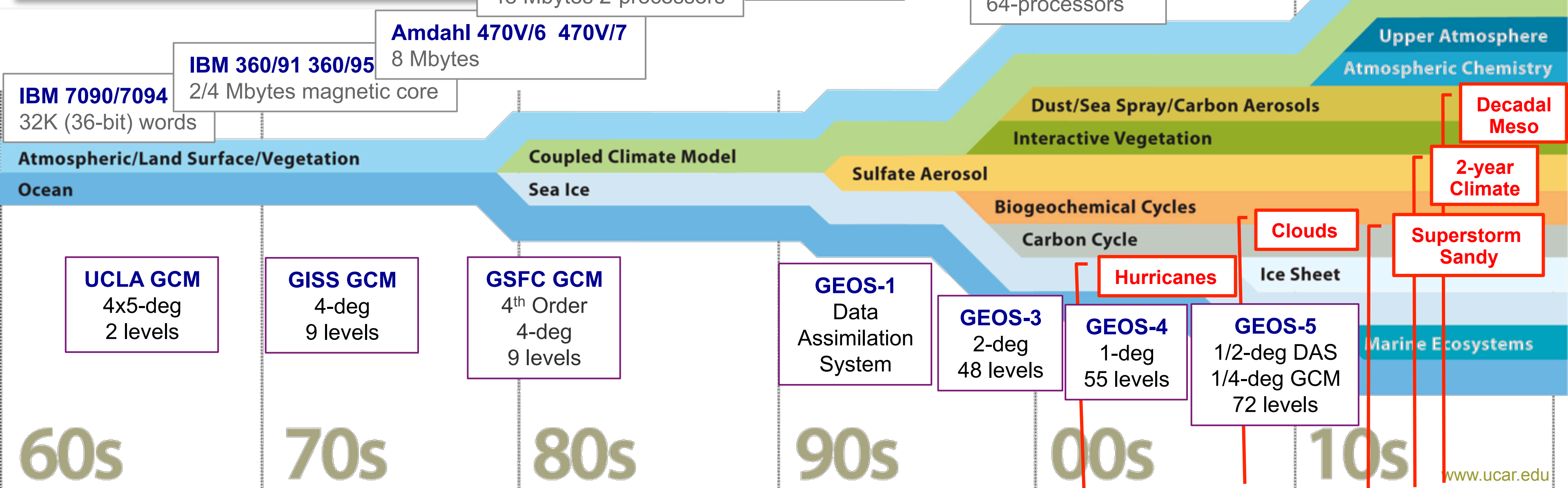
GEOS-5
Hybrid DAS
1/8-deg GCM
72 levels

60s 70s 80s 90s 00s 10s

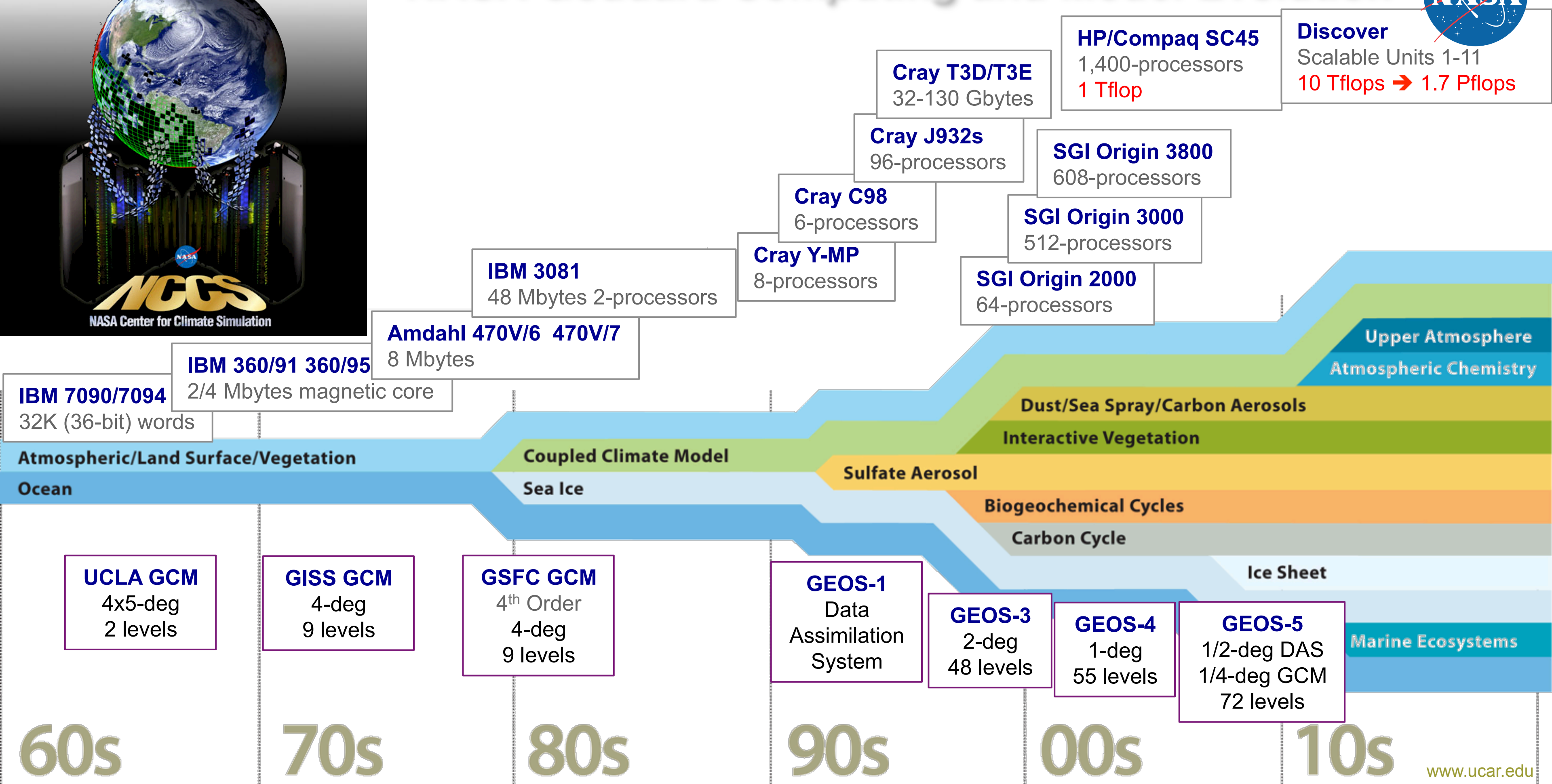
www.ucar.edu

NASA Goddard Computing and Model Evolution



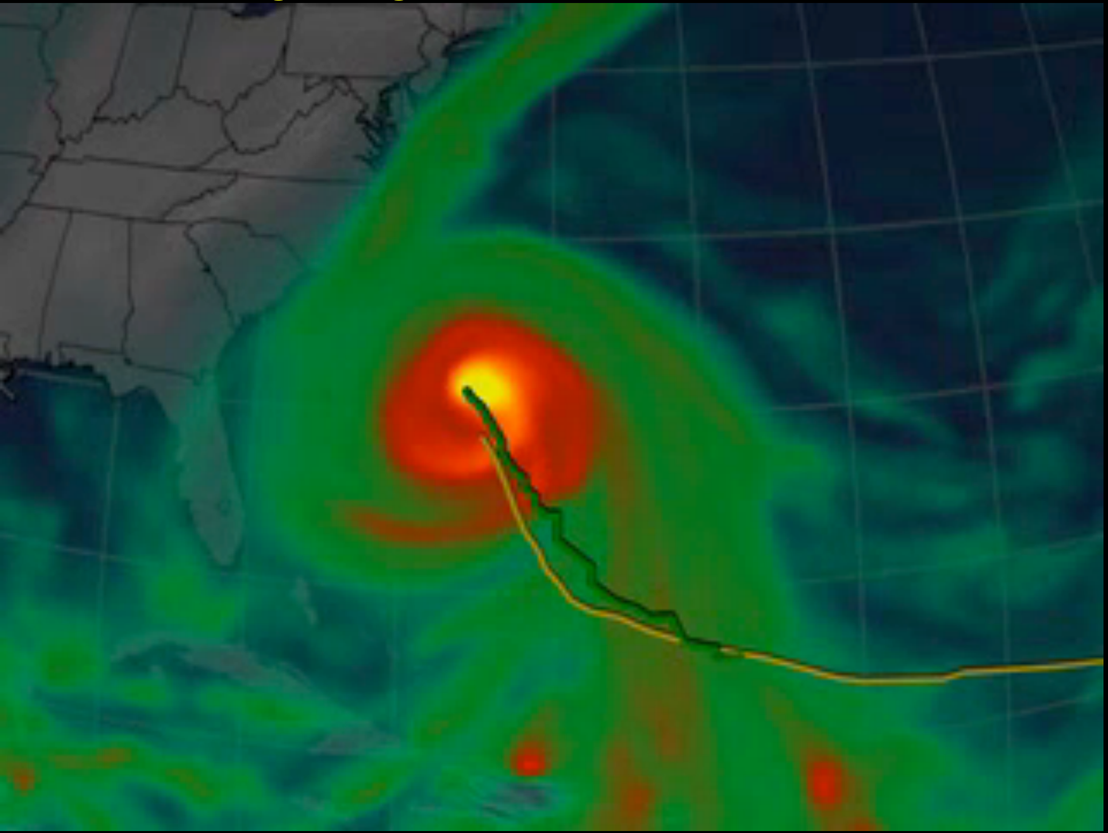


NASA Goddard Computing and Model Evolution



Hurricanes in Global Models *[circa 2003]*

Pioneering ¼-deg runs with the NASA fvGCM model



Hurricane Isabel, September 6-20 2003

¼-degree (25-km) resolution

256-processors of the SGI Origin at NCCS
512-processors of the SGI Altix “Columbia” at NAS

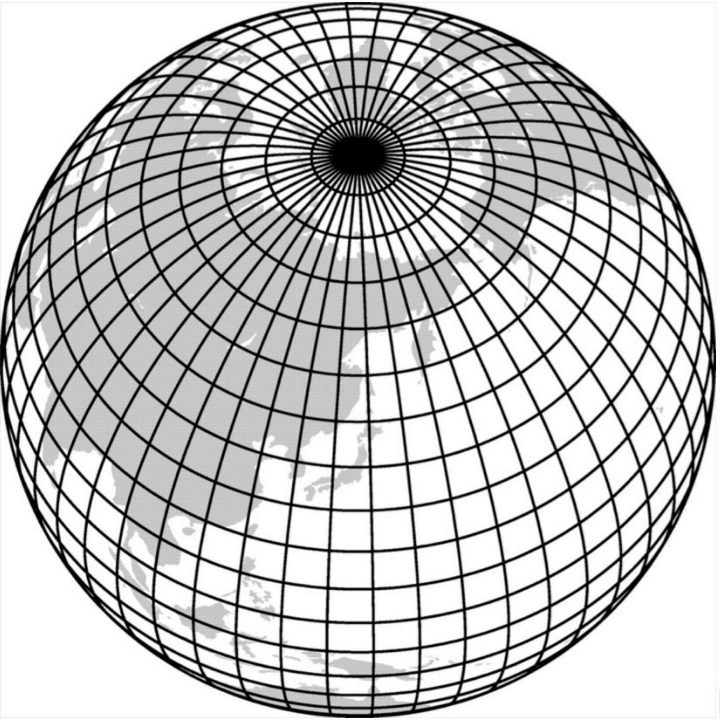
Hurricane Isabel appears as a large swirl of water vapor moving out of the tropics.

Global models in the mid-2000s were quickly becoming valuable tools for modeling tropical cyclone tracks.

Need higher resolution and more scalability to resolve realistic intensities.

Pursuing Higher Resolutions: *improving scalability*

A move away from Lat-Long Grids



Latitude-longitude grids

– Logically rectangular spherical grid

– Pole singularities

– Resolution converge at the poles

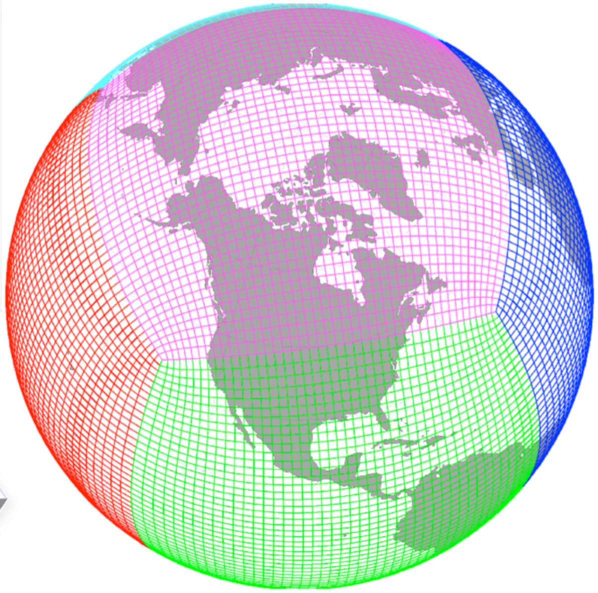
The Cubed-Sphere (hexahedron - quadrilaterals)

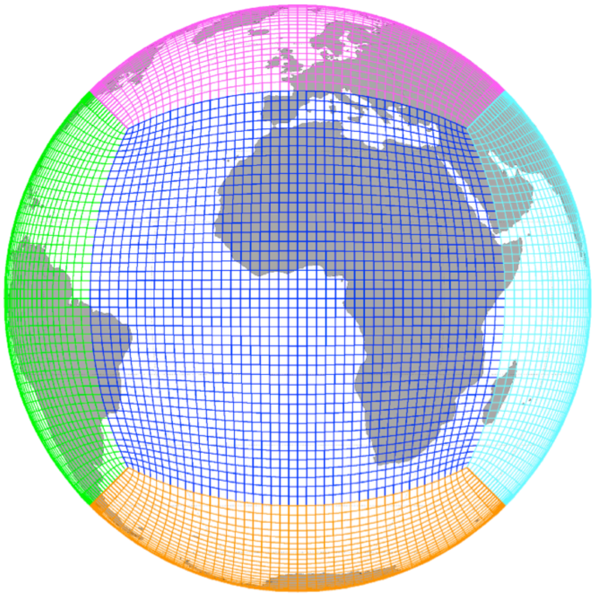
– Quasi-Uniform mapping of the cube to a sphere

– Quadrilateral shaped cells

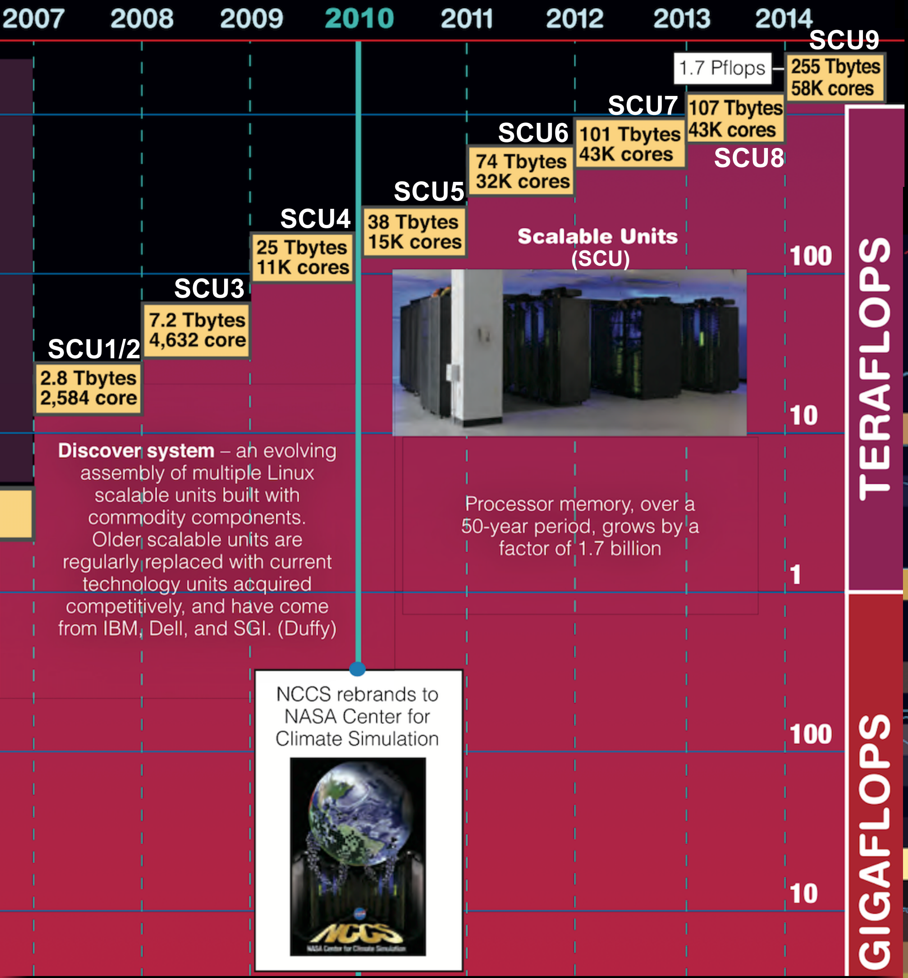
– Ideal for 2D X-Y Domain Decomposition (MPI parallelism)

– Suitable for adaptive mesh refinement



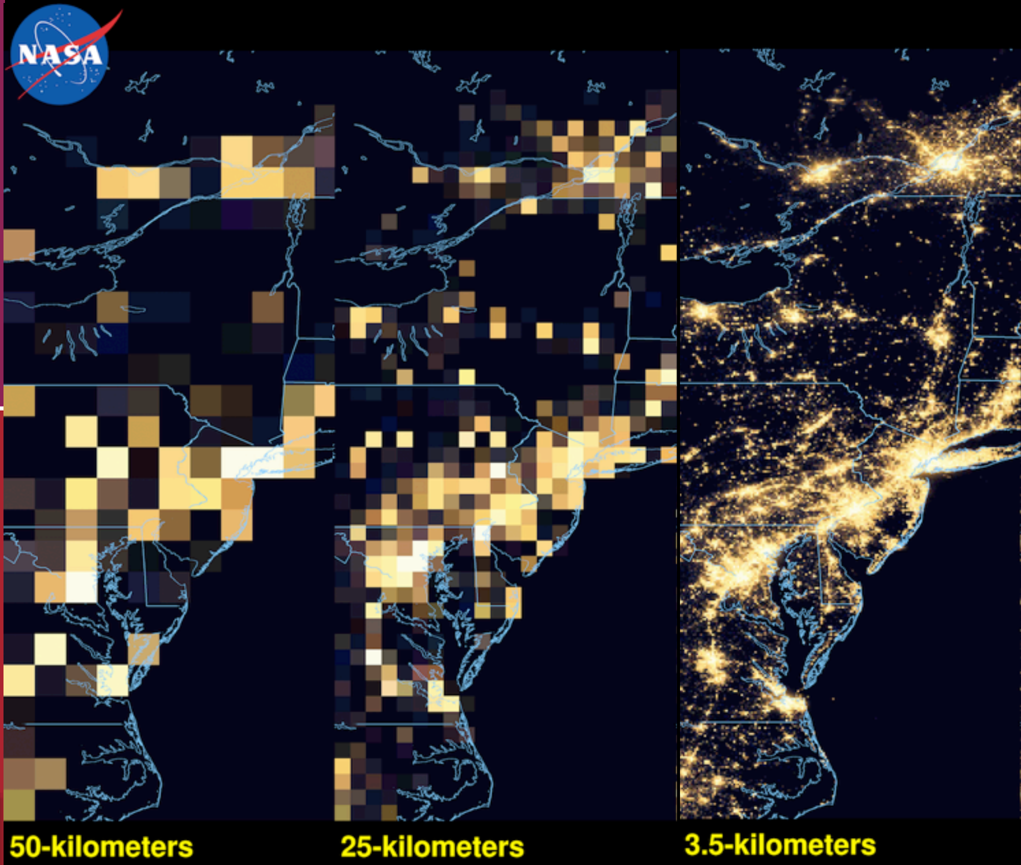


As Computing Power Rapidly Grows Models Push to Higher resolutions



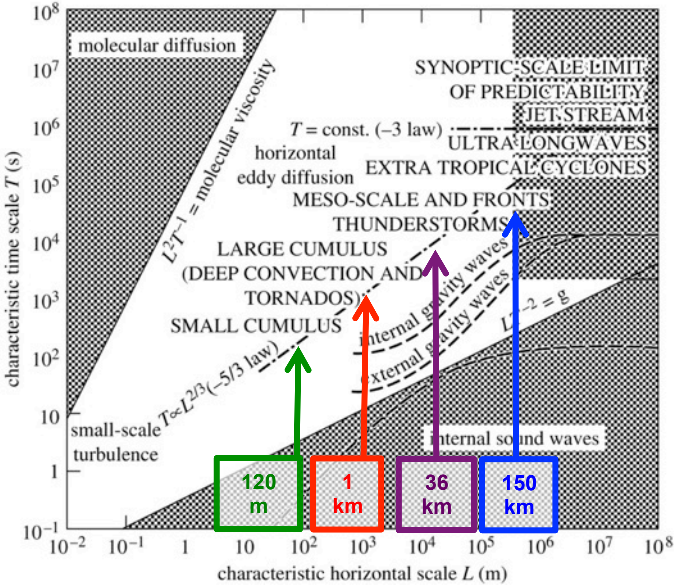
Discover takes us from Tflops ➔ Pflops

1,000 cores ➔ 70,000 cores

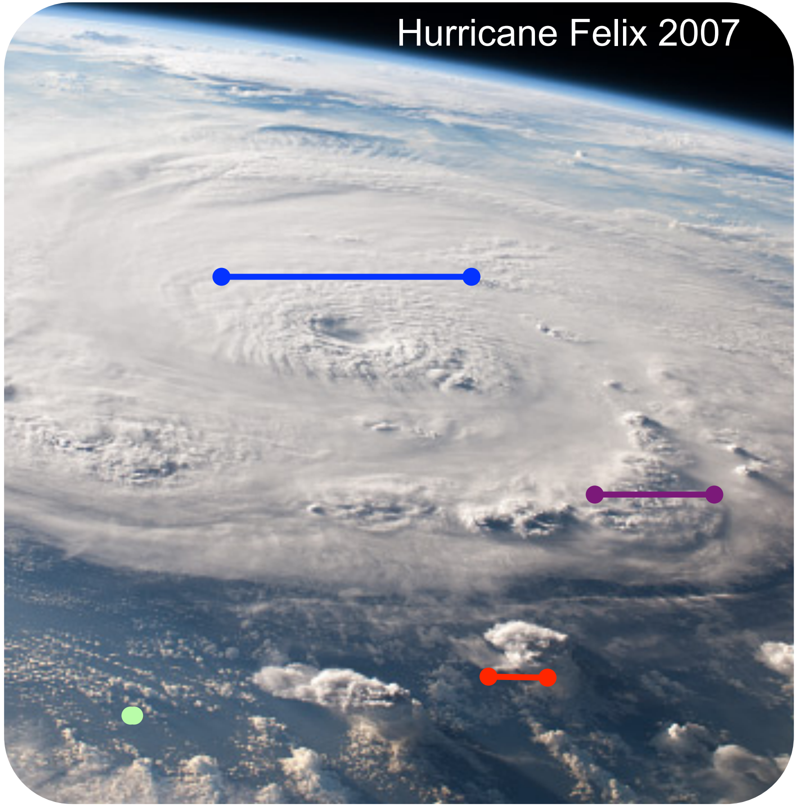


Night Lights 2012 using Suomi NPP VIIRS data at increasing horizontal resolution

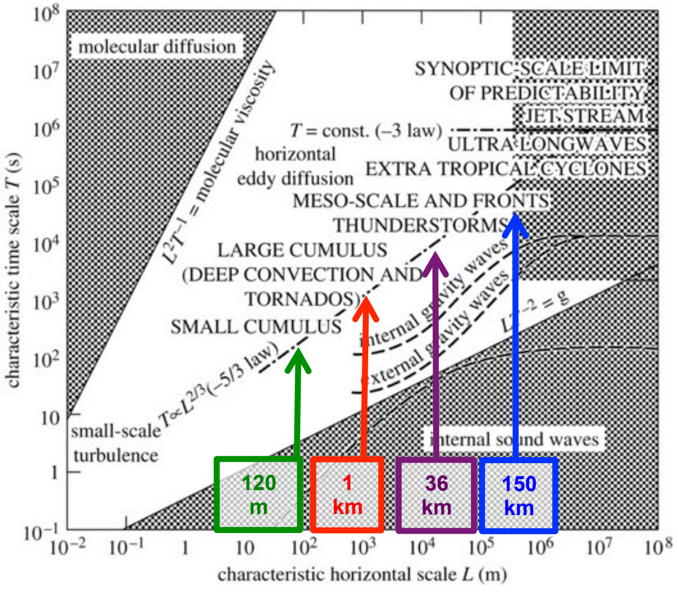
Science and Computing Required to Increase Resolvable Scales

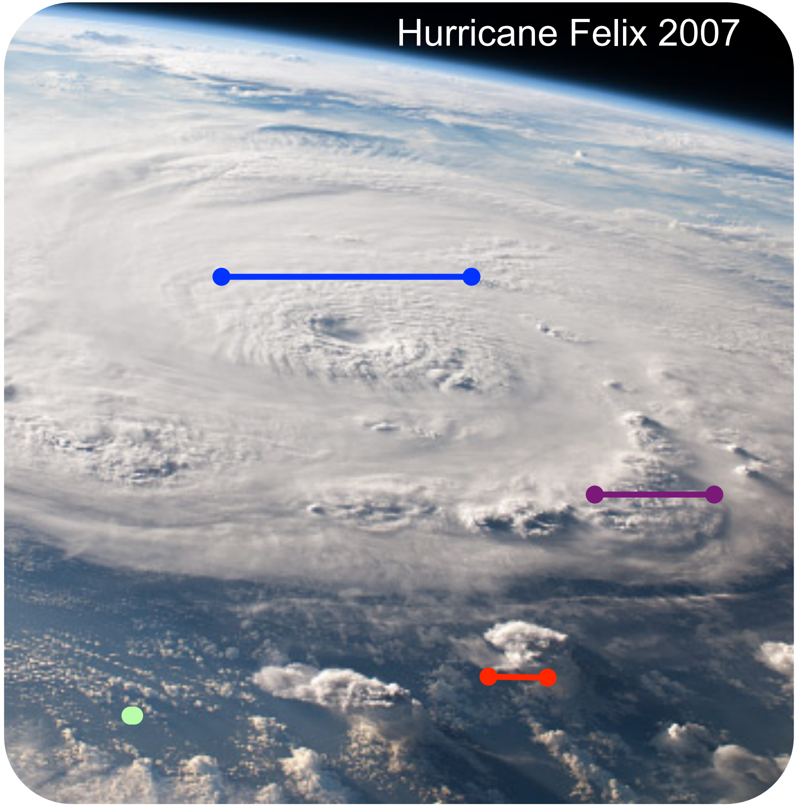


Resolution (km)	Resolvable ~12x (km)	Computing (Cores)
25.0	300	800
12.5	150	6,400
3.0	36	462,963
0.1	1.5	6,400,000,000
10 (m)	120 (m)	21,600,000,000,000,000



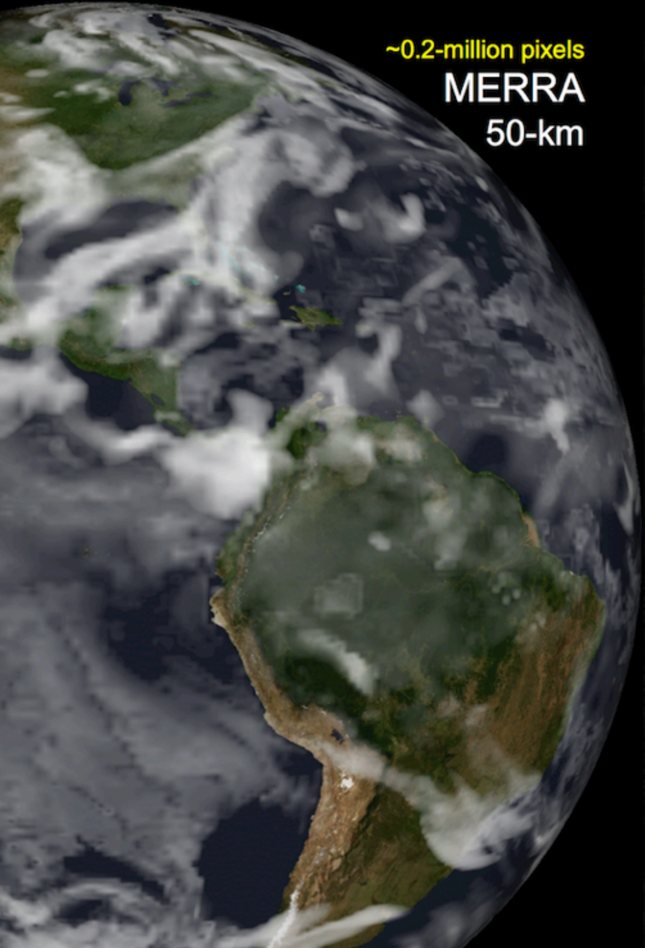
Science and Computing Required to Increase Resolvable Scales

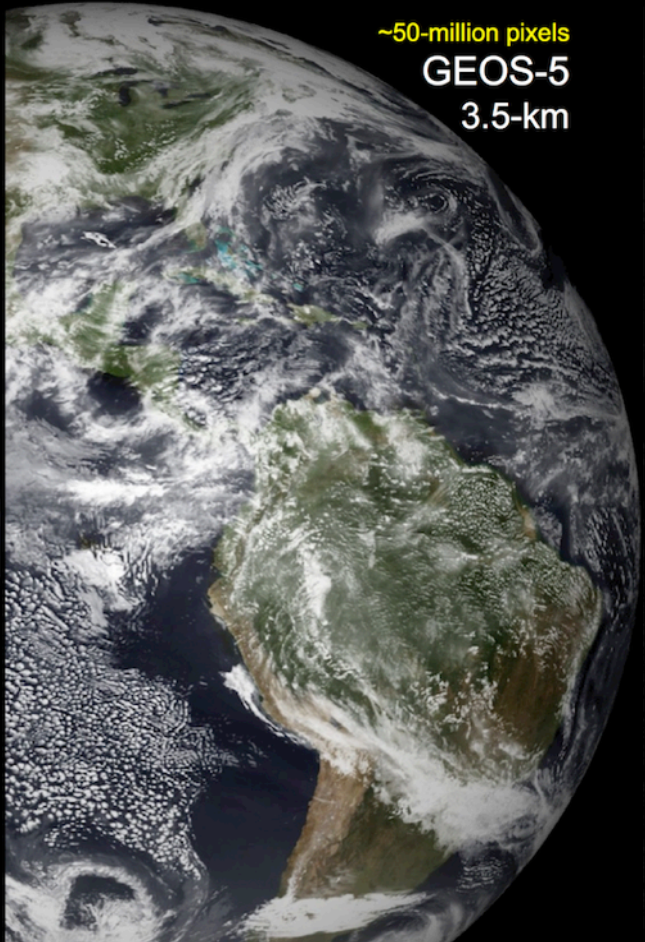


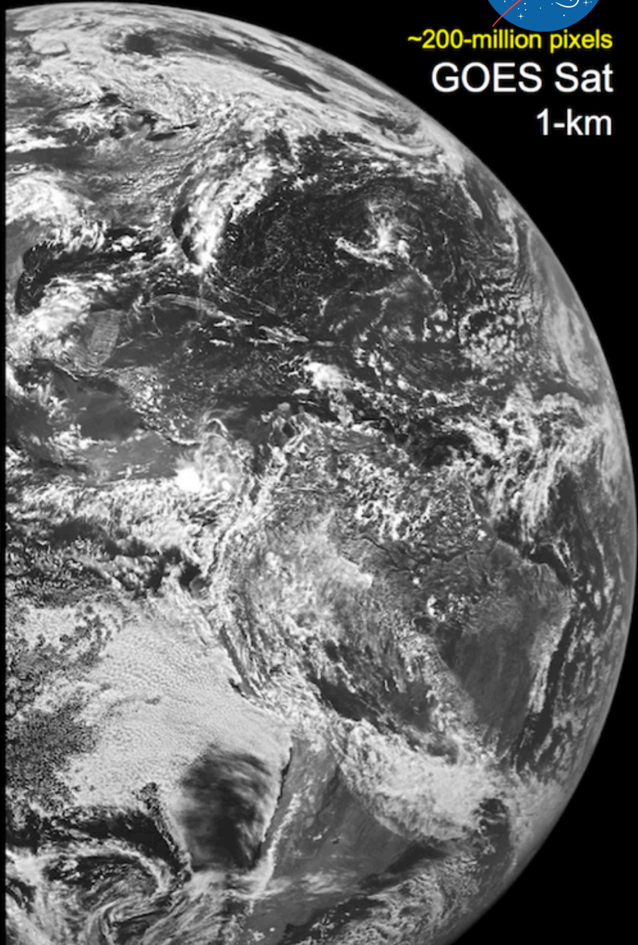


Resolution (km)	Resolvable ~12x (km)	Horz Factor	DT Factor	Computing (Cores)
25.0	300	1	1	800
12.5	150	4	2	6,400
6.0	72	17	4	57,870
3.0	36	69	8	462,963
1.0	12	625	25	12,500,000
0.1	1.5	40000	200	6,400,000,000
10 (m)	120 (m)	900000000	30000	21,600,000,000,000,000

Cloud-Permitting with GEOS-5

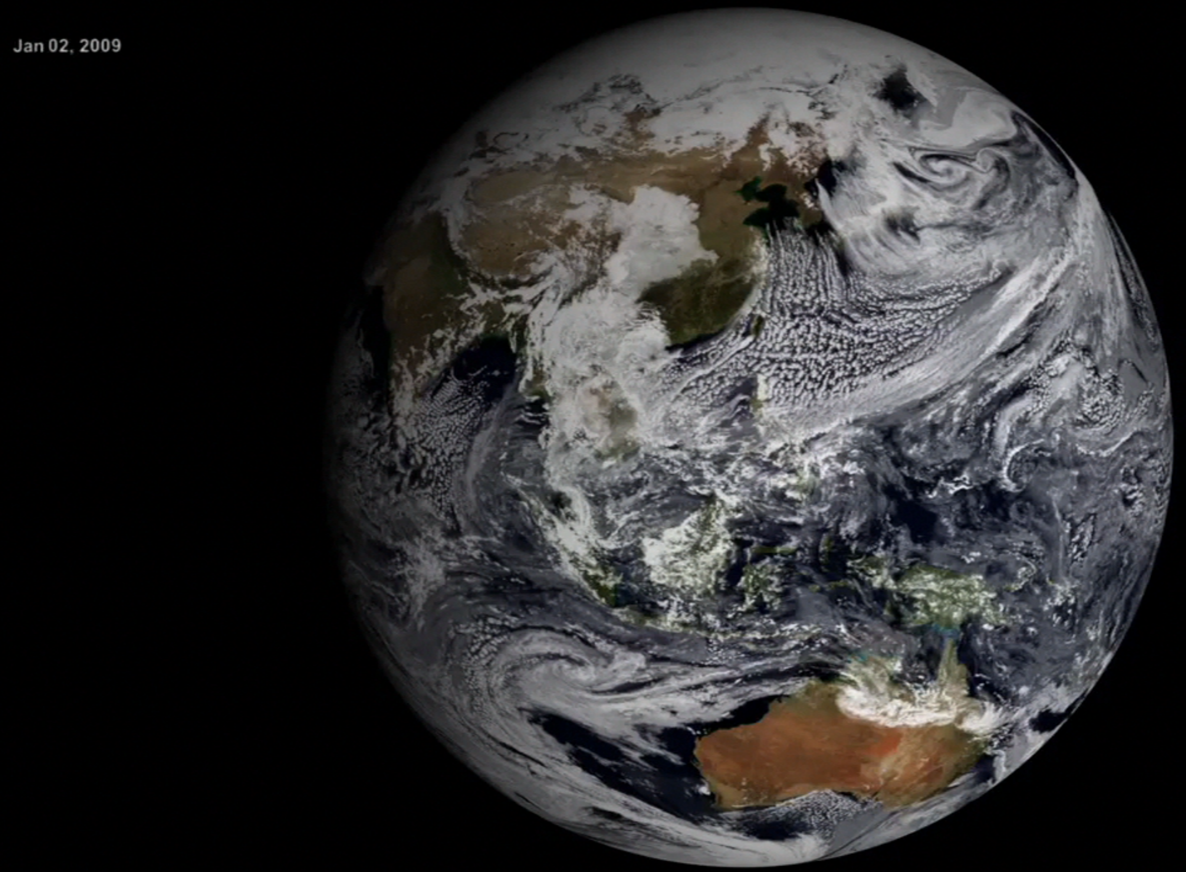






Cloud-Permitting with GEOS-5

Pioneering 3.5-km Global Cloud Permitting Run with GEOS-5 *[circa 2009]*



3.5-km Global Resolution
(50 million grid cells)

4,000-processors of Discover SCU3

The first global cloud permitting simulation with GEOS-5, and the highest resolution run of any global model at the time

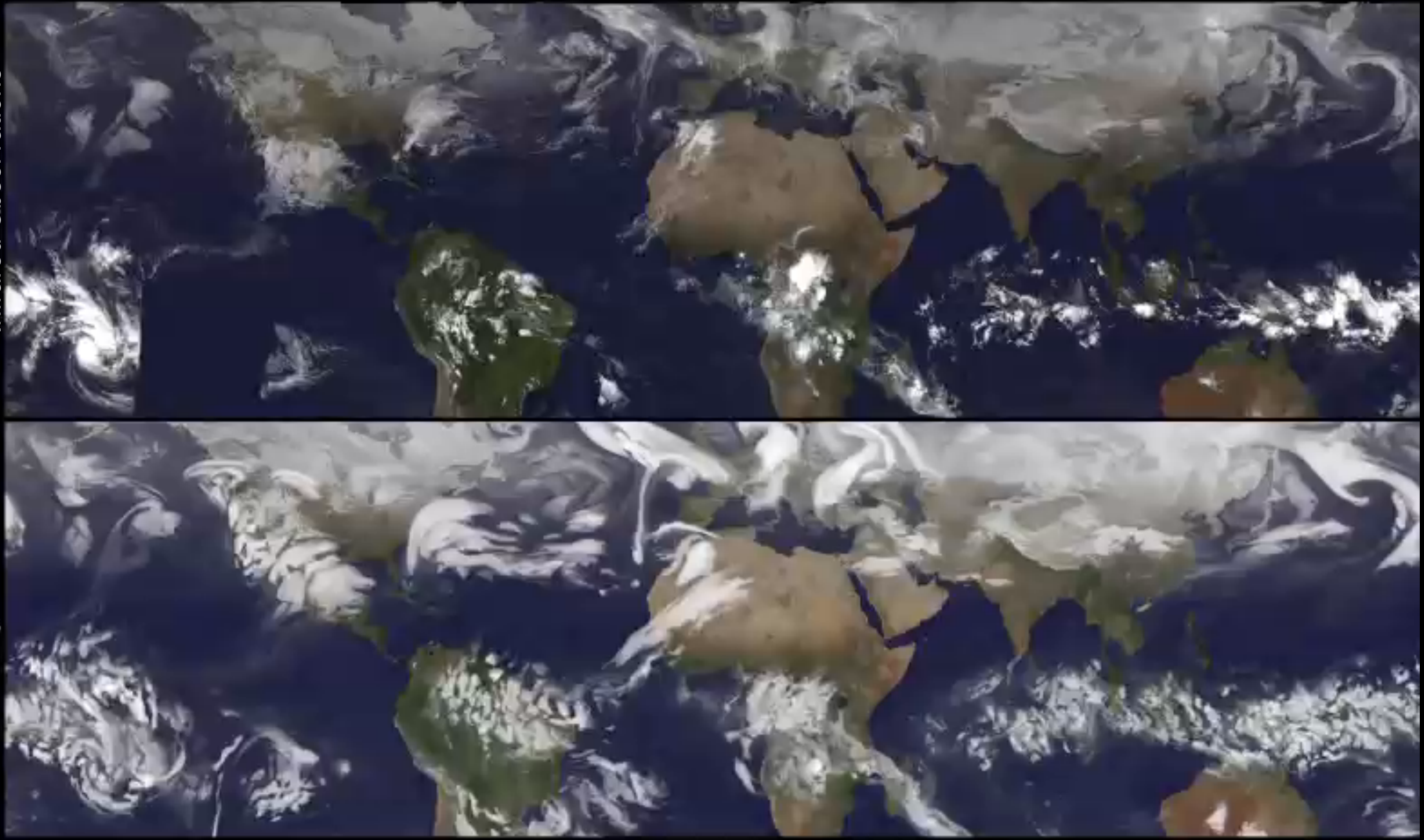
Throughput:
~1-day per day

Cloud-Permitting with GEOS-5

Pioneering 5-km Global Cloud Permitting Forecast with GEOS-5 *[circa 2010]*

Infrared Observations

GEOS-5 Model



5-km Global Resolution
(24 million grid cells)

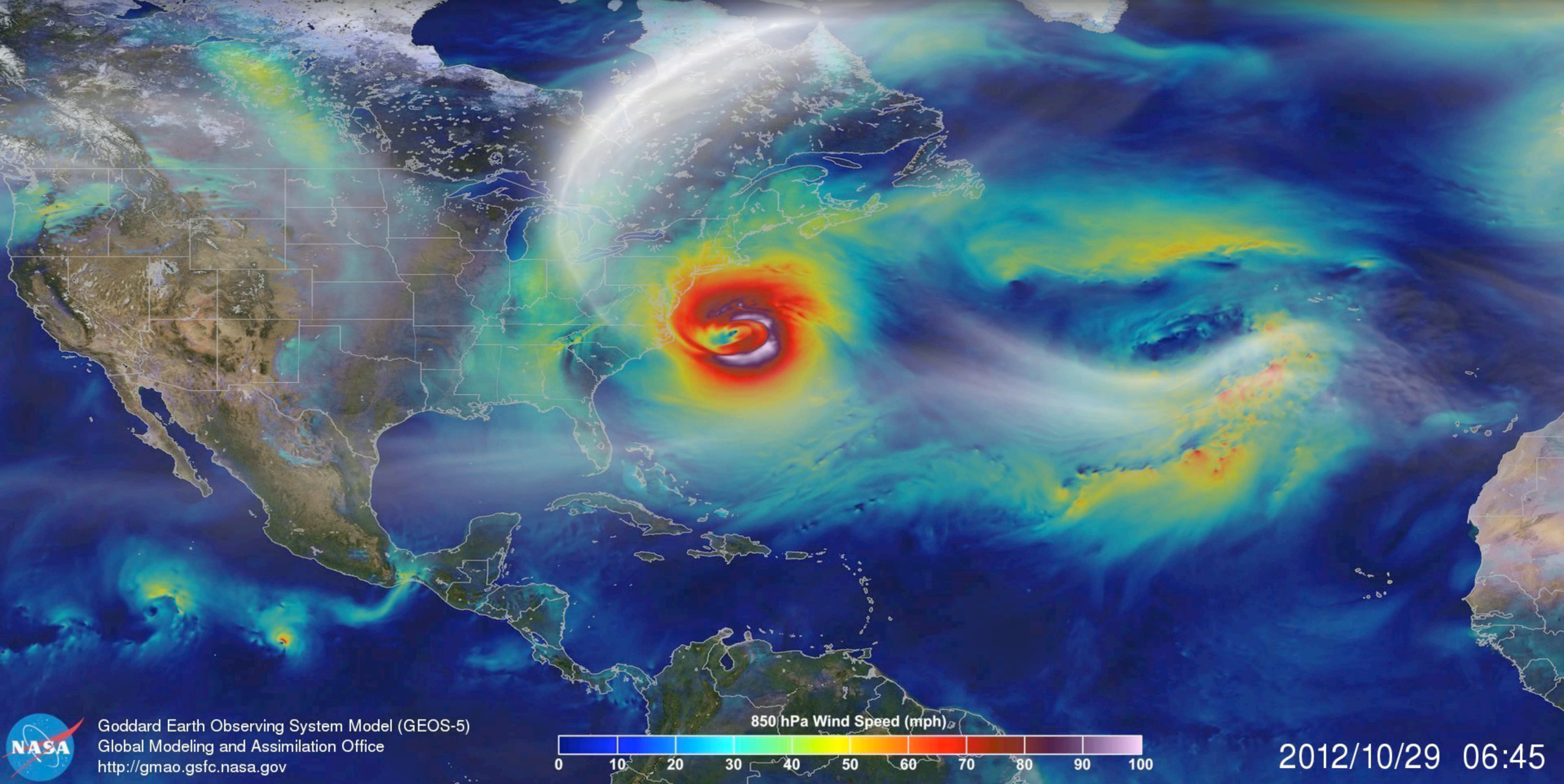
10,000-processors of Discover SCU4

Medium range weather forecasts at global cloud permitting resolutions with GEOS-5

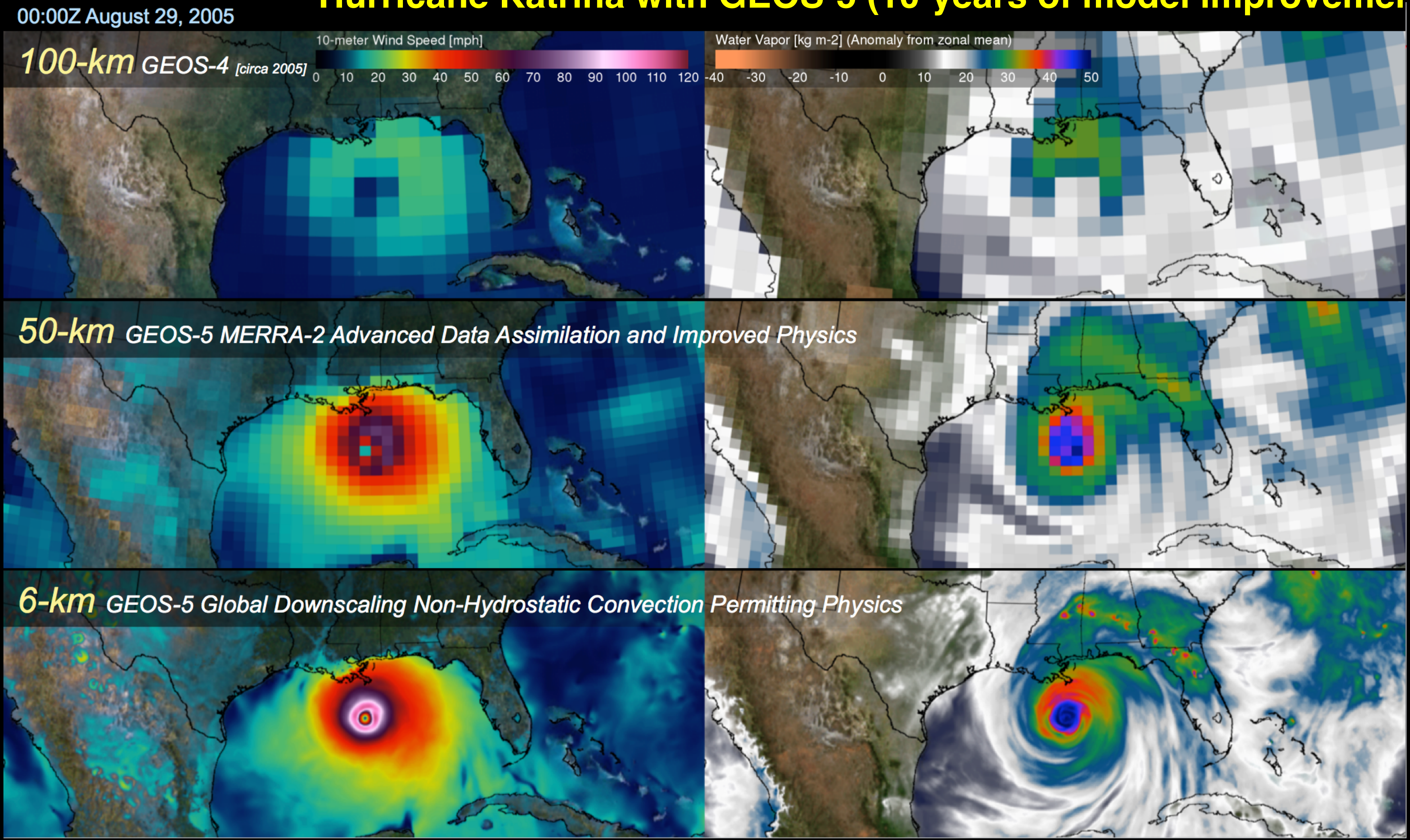
Throughput:
~5-days per day

2012 Hurricanes with 25-km DAS and Superstorm Sandy Forecast at 6-km

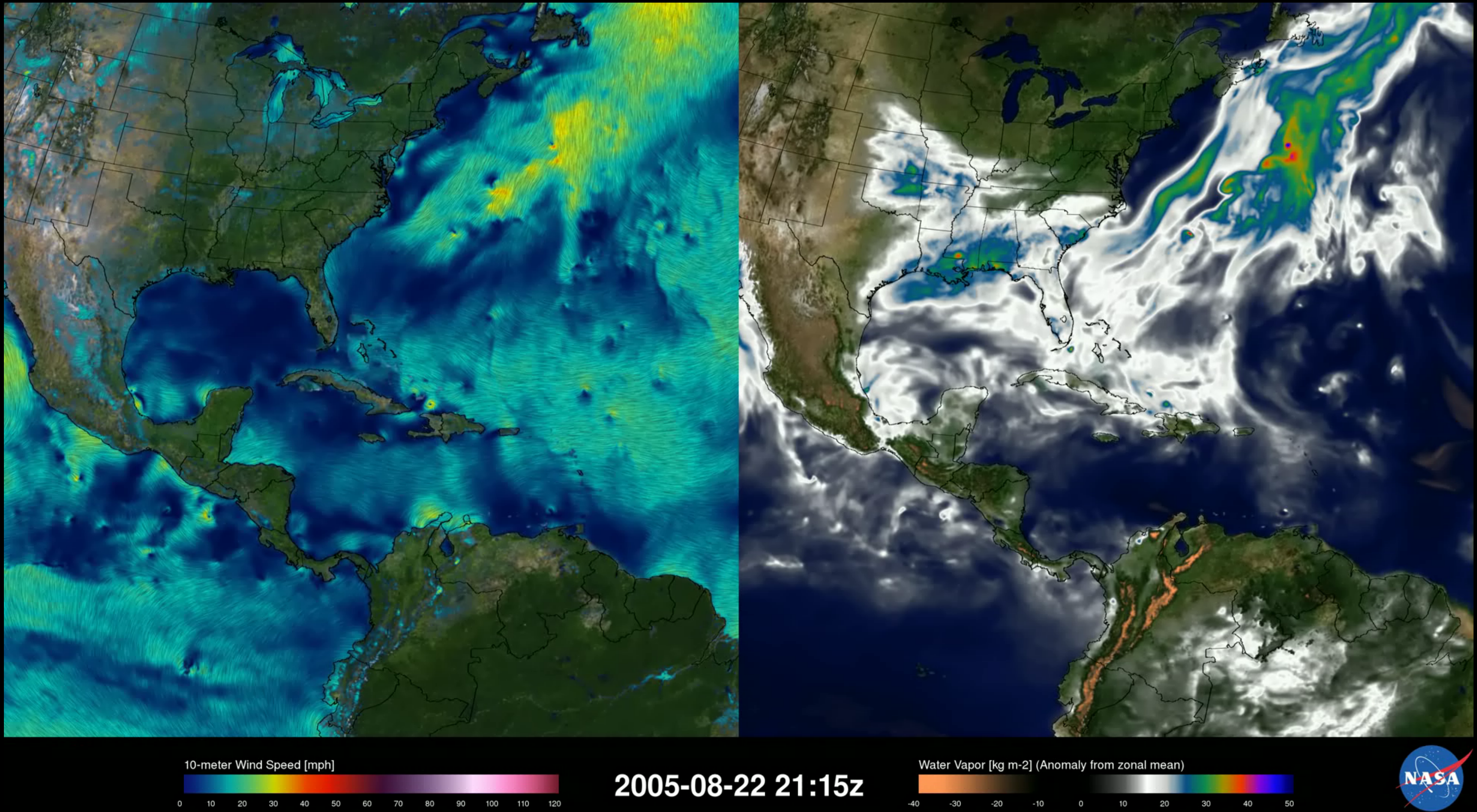
12,000 Cores of Discover SCU7 *[circa 2012]*



Hurricane Katrina with GEOS-5 (10-years of model improvements)



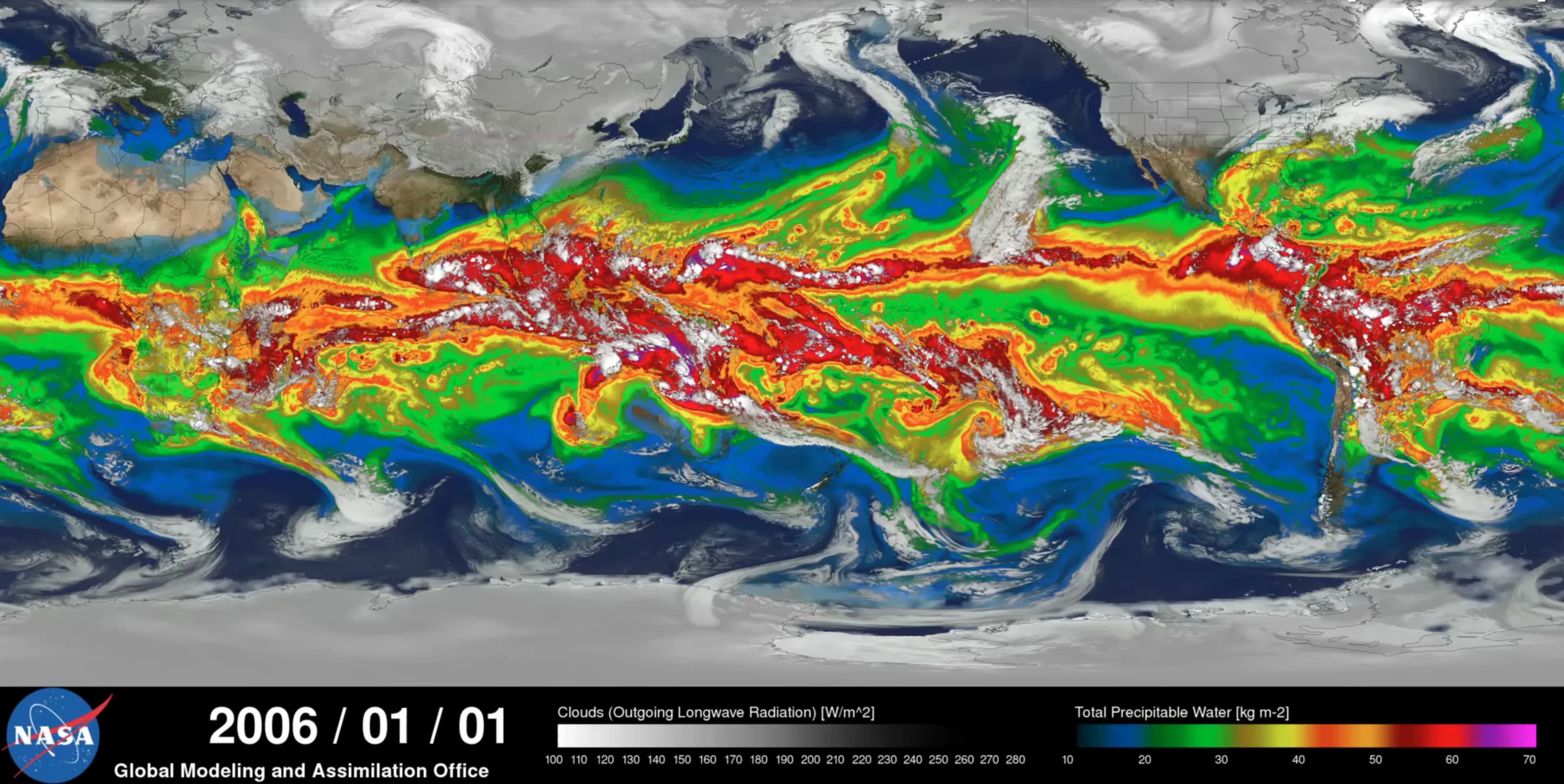
Hurricane Katrina with GEOS-5 (10-years of model improvements)



6-km GEOS-5 Global Downscaling Non-Hydrostatic Convection Permitting Physics

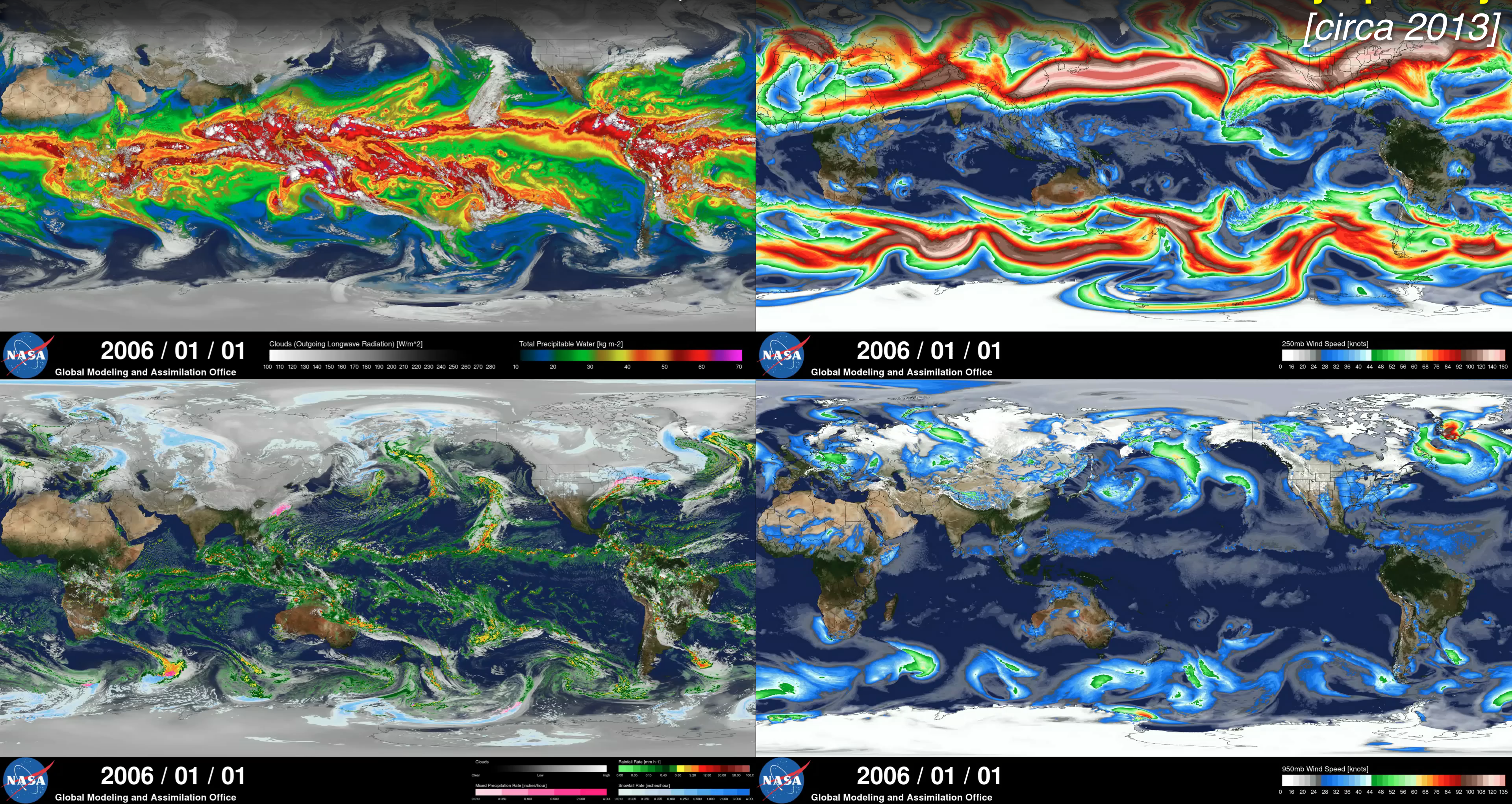
7-km Global 2-Year Simulation 7,000 Cores of Discover SCU9 **12 days per day**

[circa 2013]

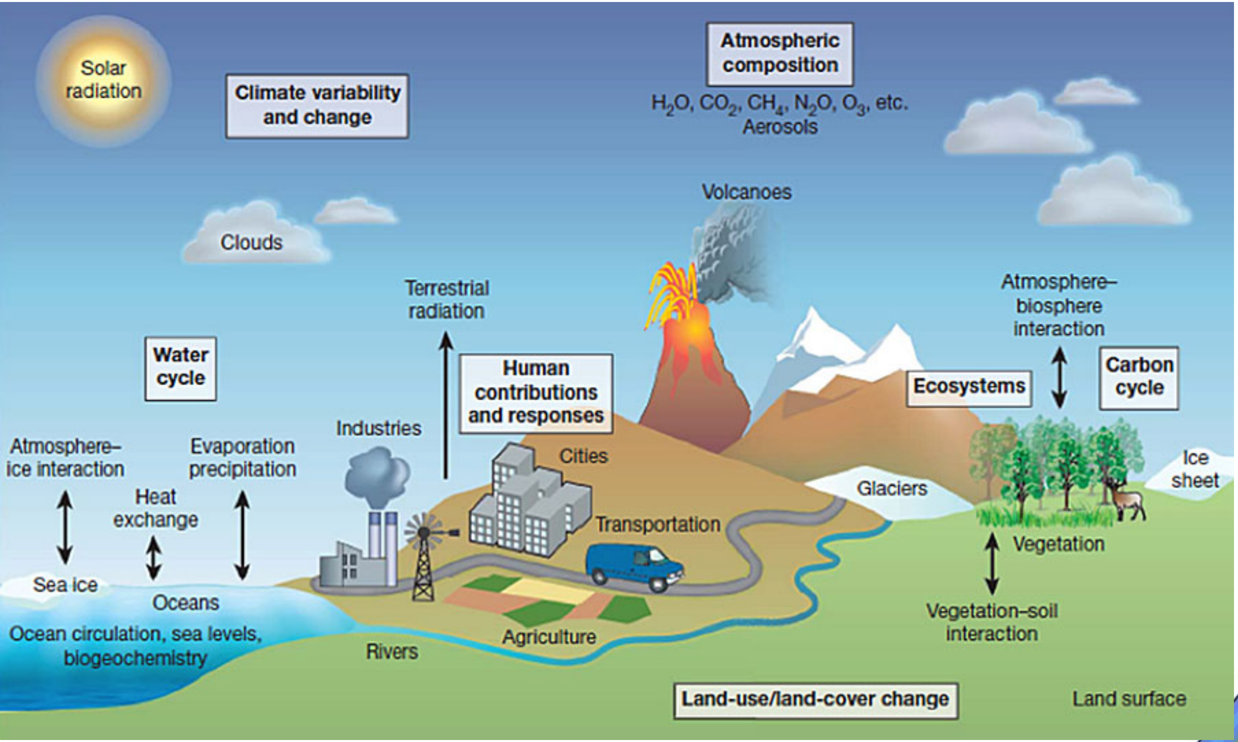


7-km Global 2-Year Simulation 7,000 Cores of Discover SCU9 **12 days per day**

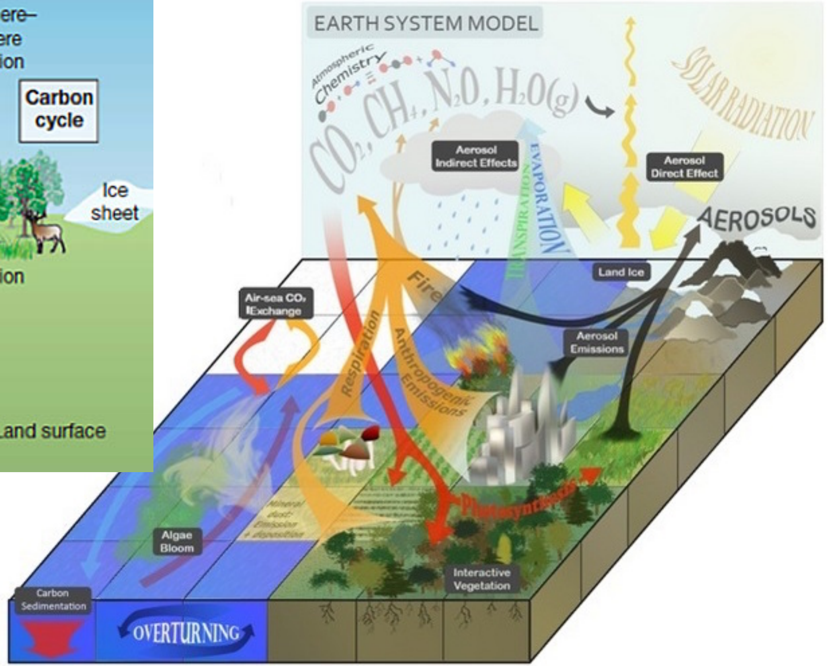
[circa 2013]



Adding Complexity to Global Models



Chemistry: Carbon Cycle
Gases
Aerosols
Indirect/Direct Effects



Surface Emissions: Volcanoes
Fires/Biomass Burning
Industrial Pollution

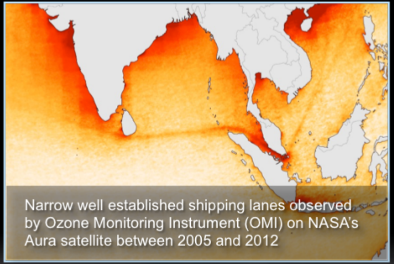
Adding Complexity to Global Models

Interactive Chemistry and Aerosols

Volcanoes

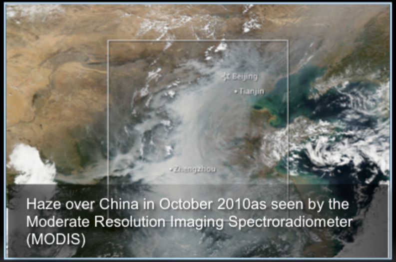
Photograph of ash plumes streaming from Mt Etna, Italy in 2001 taken by the Expedition 2 crew aboard the International Space Station

Ship Tracks



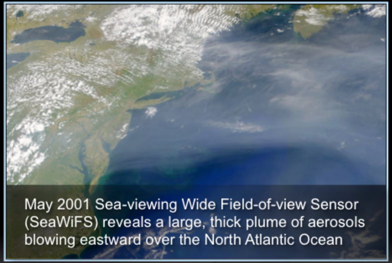
Narrow well established shipping lanes observed by Ozone Monitoring Instrument (OMI) on NASA's Aura satellite between 2005 and 2012

Smoke/Haze

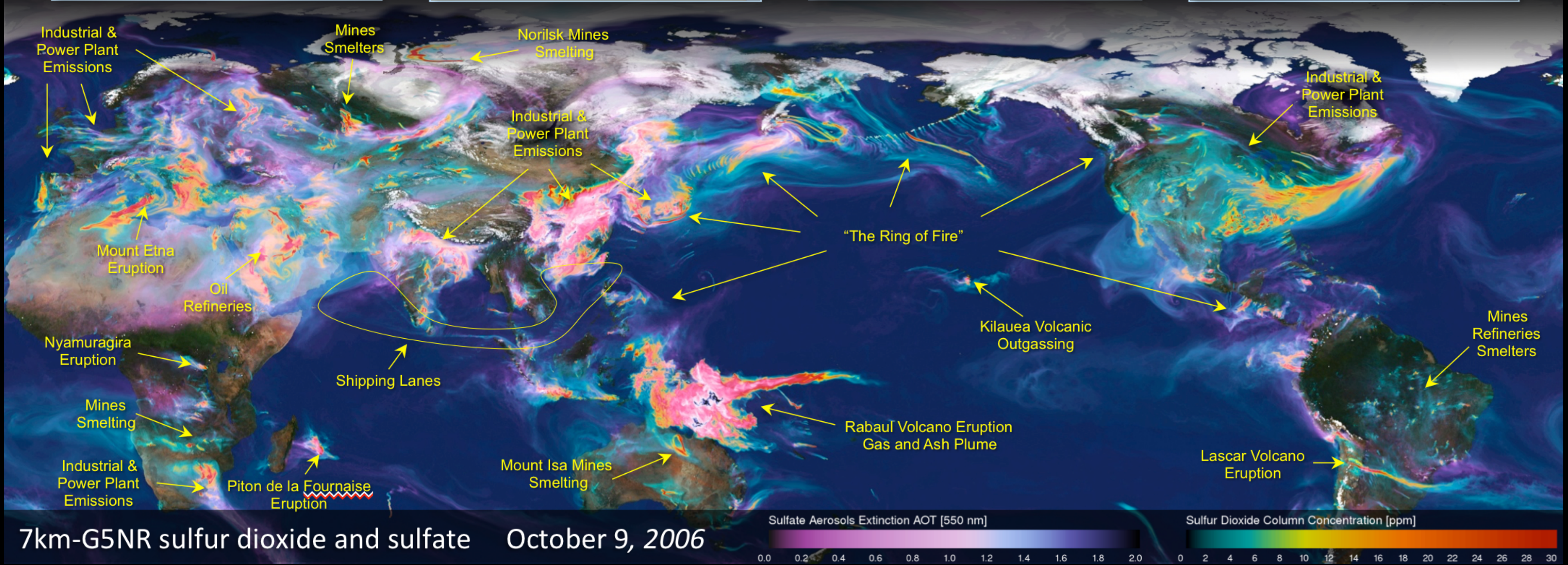


Haze over China in October 2010as seen by the Moderate Resolution Imaging Spectroradiometer (MODIS)

Dust



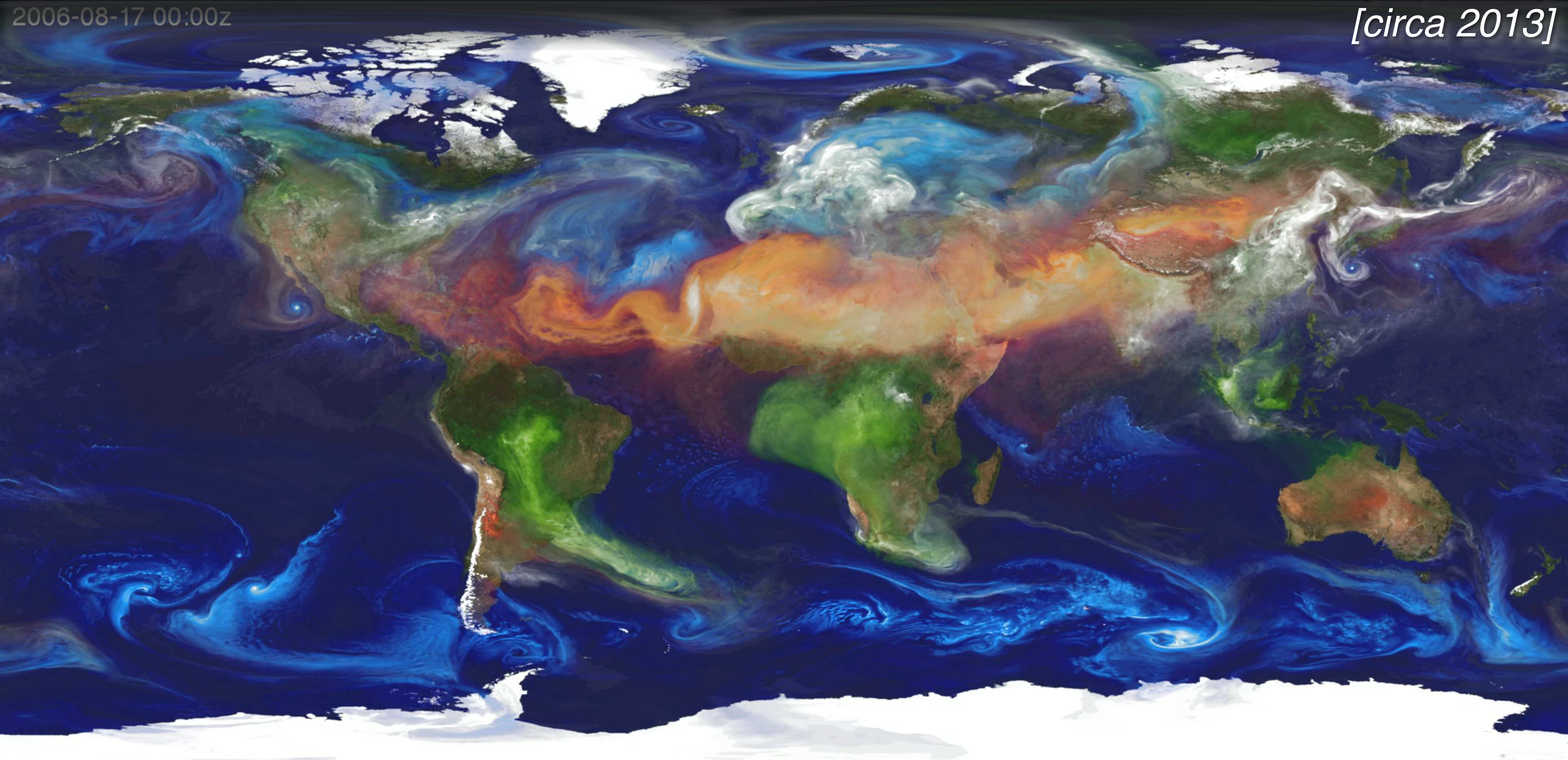
May 2001 Sea-viewing Wide Field-of-view Sensor (SeaWiFS) reveals a large, thick plume of aerosols blowing eastward over the North Atlantic Ocean



7km-G5NR sulfur dioxide and sulfate October 9, *2006*

7-km Global Aerosol Simulation 7,000 Cores of Discover SCU9 **12 days per day**

[circa 2013]

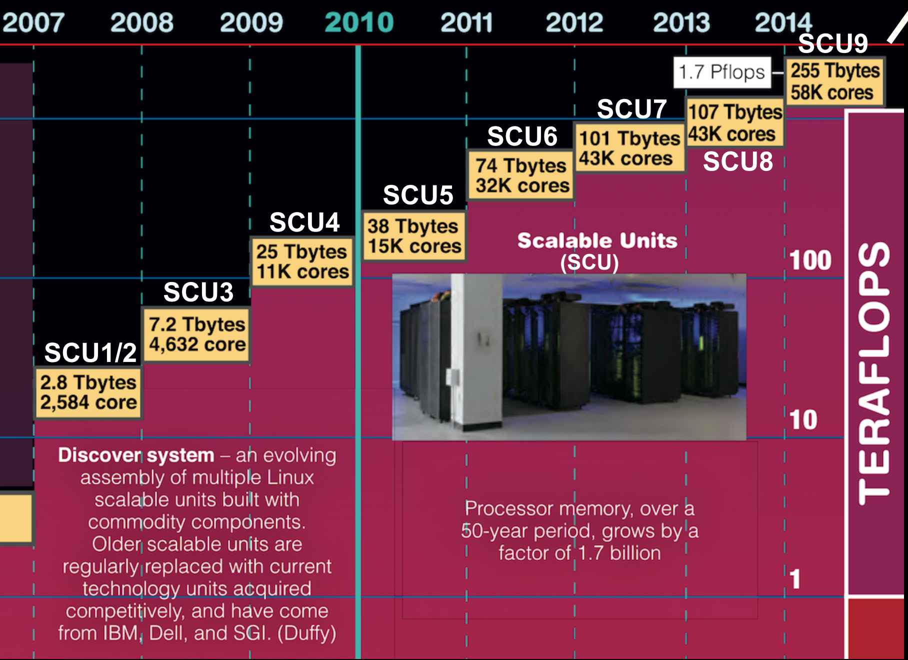


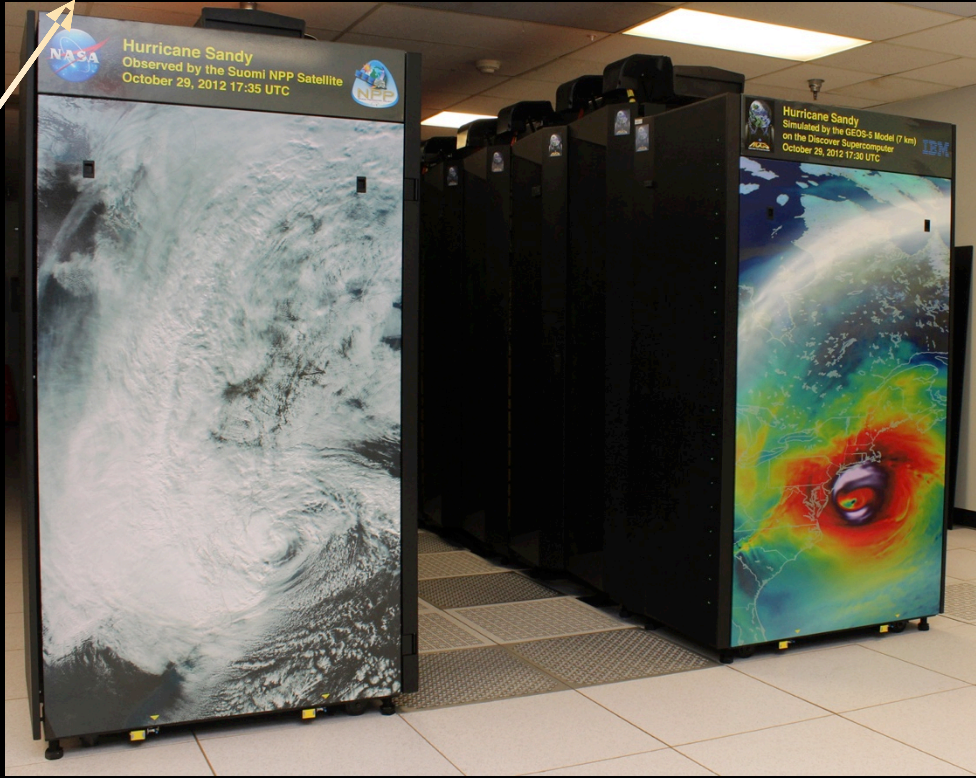
DUST CARBON SEASALT SULFATE

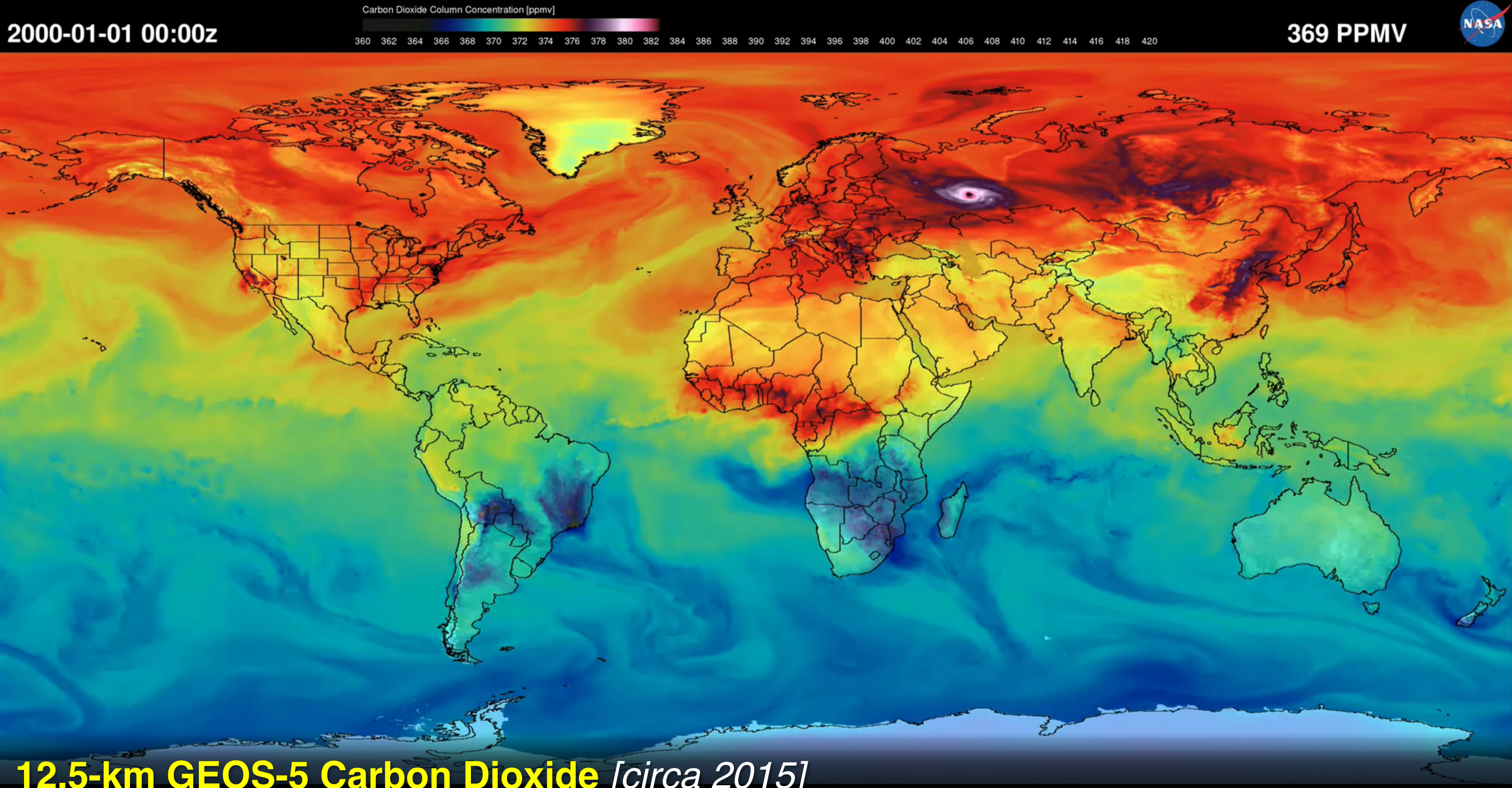
2015 Discover Expansion at NCCS

NASA's Center for Climate Simulation (NCCS) doubles the peak performance of the Discover supercomputer

2015	SCU10	SCU11	SCU12
3.3 Pflops	30,240 cores	16,800 cores	16,800 cores







12.5-km GEOS-5 Carbon Dioxide *[circa 2015]*

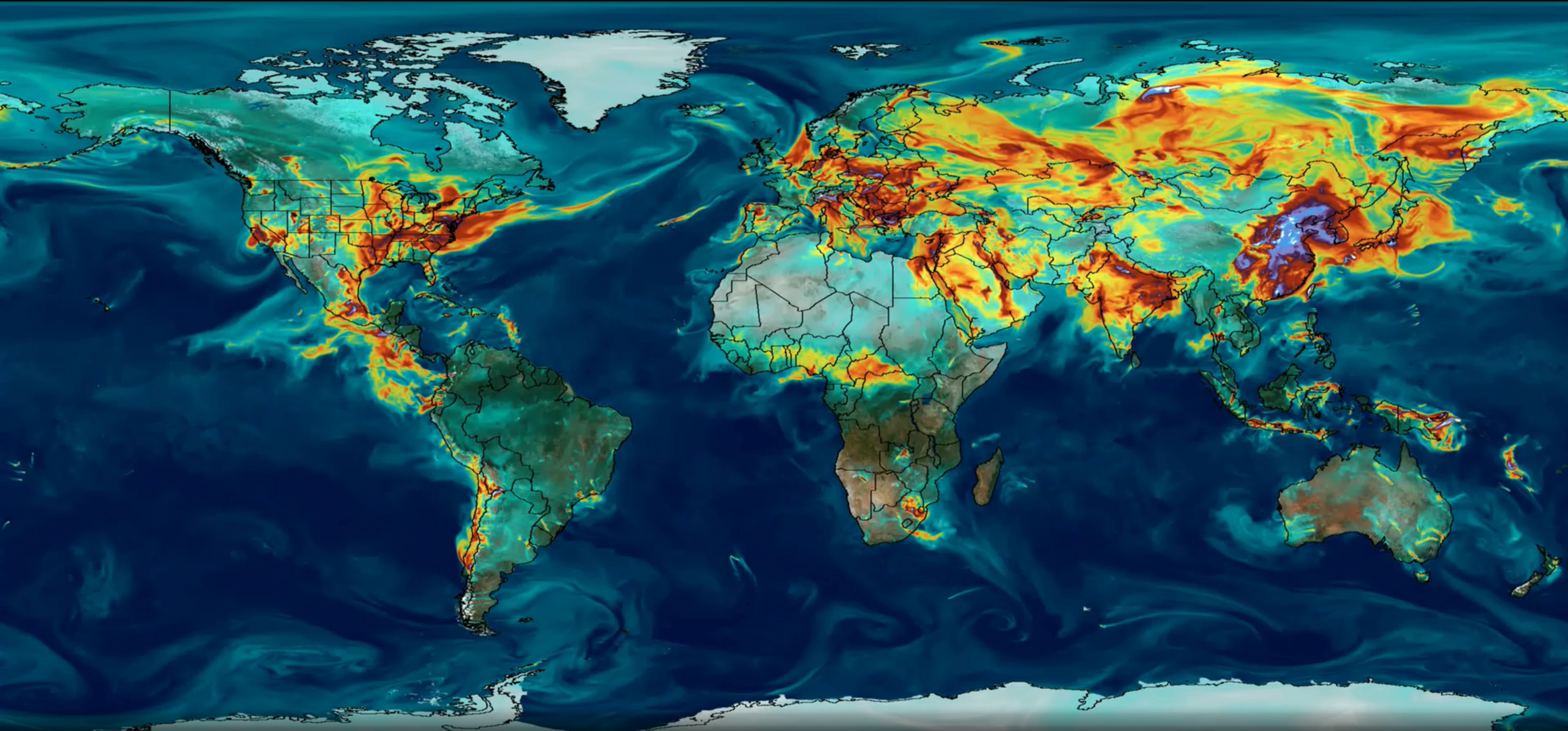
A decade of Simulation Data

7,000 Cores of Discover SC10 *~30 days per day*

2000-01-01 00:00z

Sulfur Dioxide Column Concentration [Dosbon Units]

0 2 4 6 8 10 12 14 16 18 20



12.5-km GEOS-5 Sulfur Dioxide *[circa 2015]*

A decade of Simulation Data

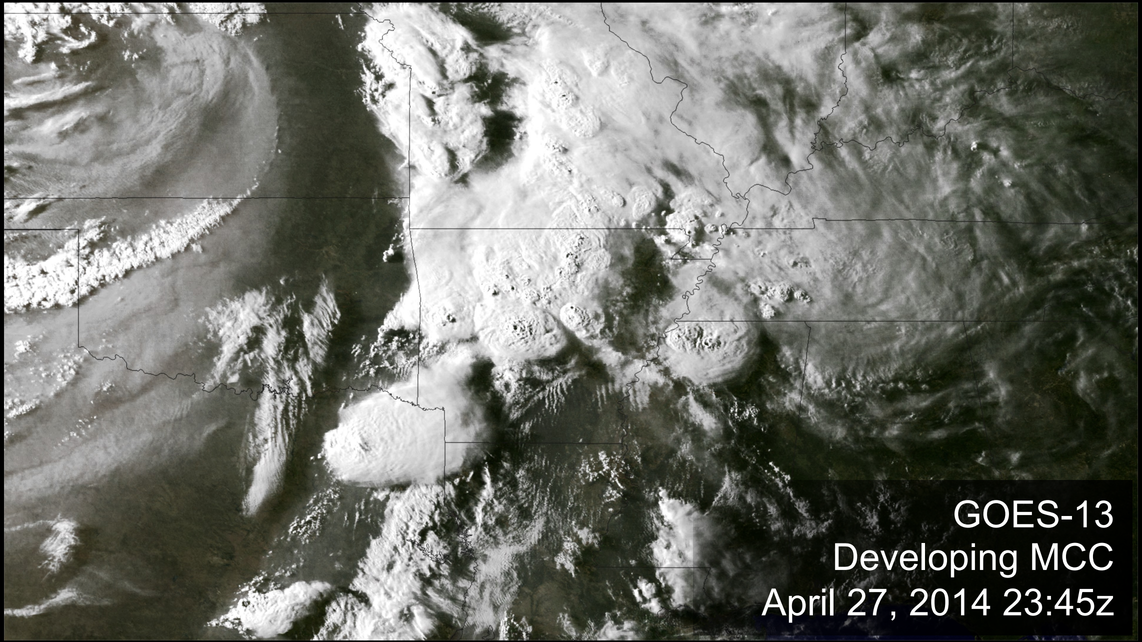
7,000 Cores of Discover SC10 *~30 days per day*

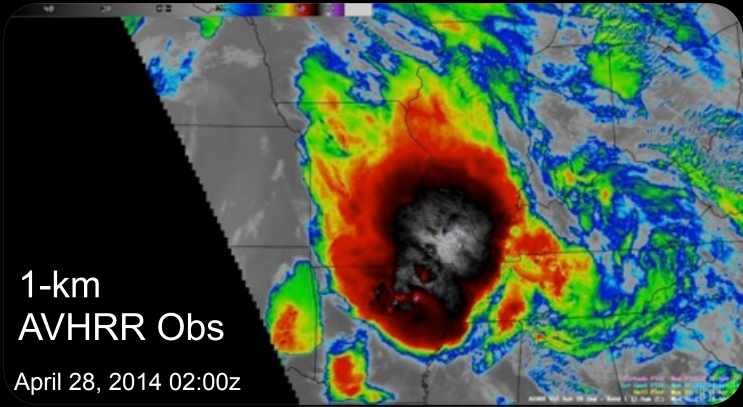
Looking Toward the Future

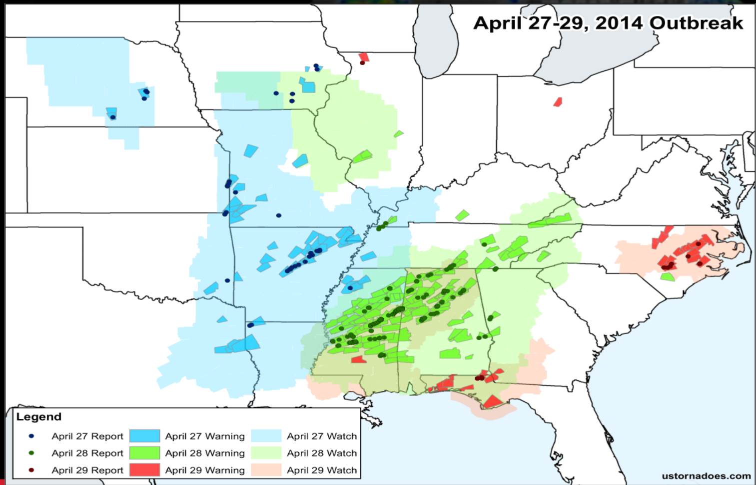
Mesoscale Convective Complex (MCC)

A mesoscale convective complex is a large thunderstorm

- Typical in spring over the Midwest US
- Progress over long distances
- Heavy rainfall, strong winds, frequent lighting, hail and often tornadoes.





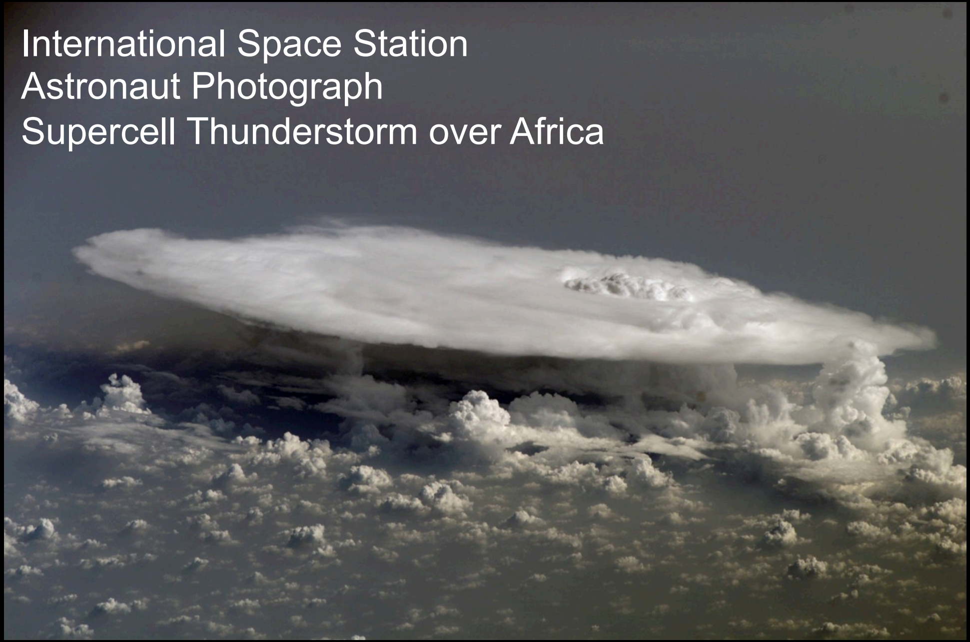


Looking Toward the Future

Supercell Thunderstorms

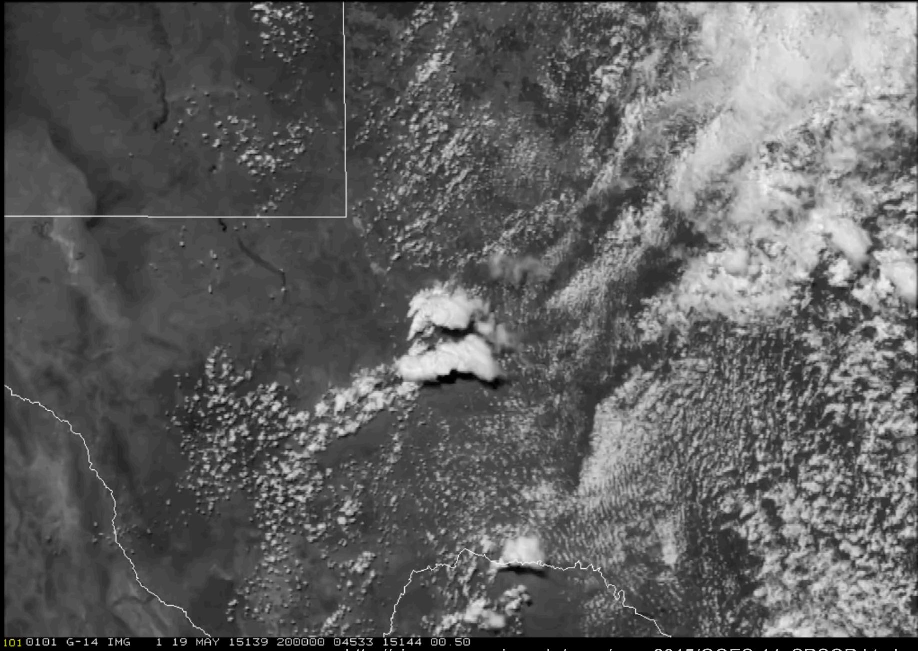
An isolated severe rotating thunderstorm

- Broad anvil cloud top
- Overshooting convective updrafts
- Damaging winds, large hail, tornadoes



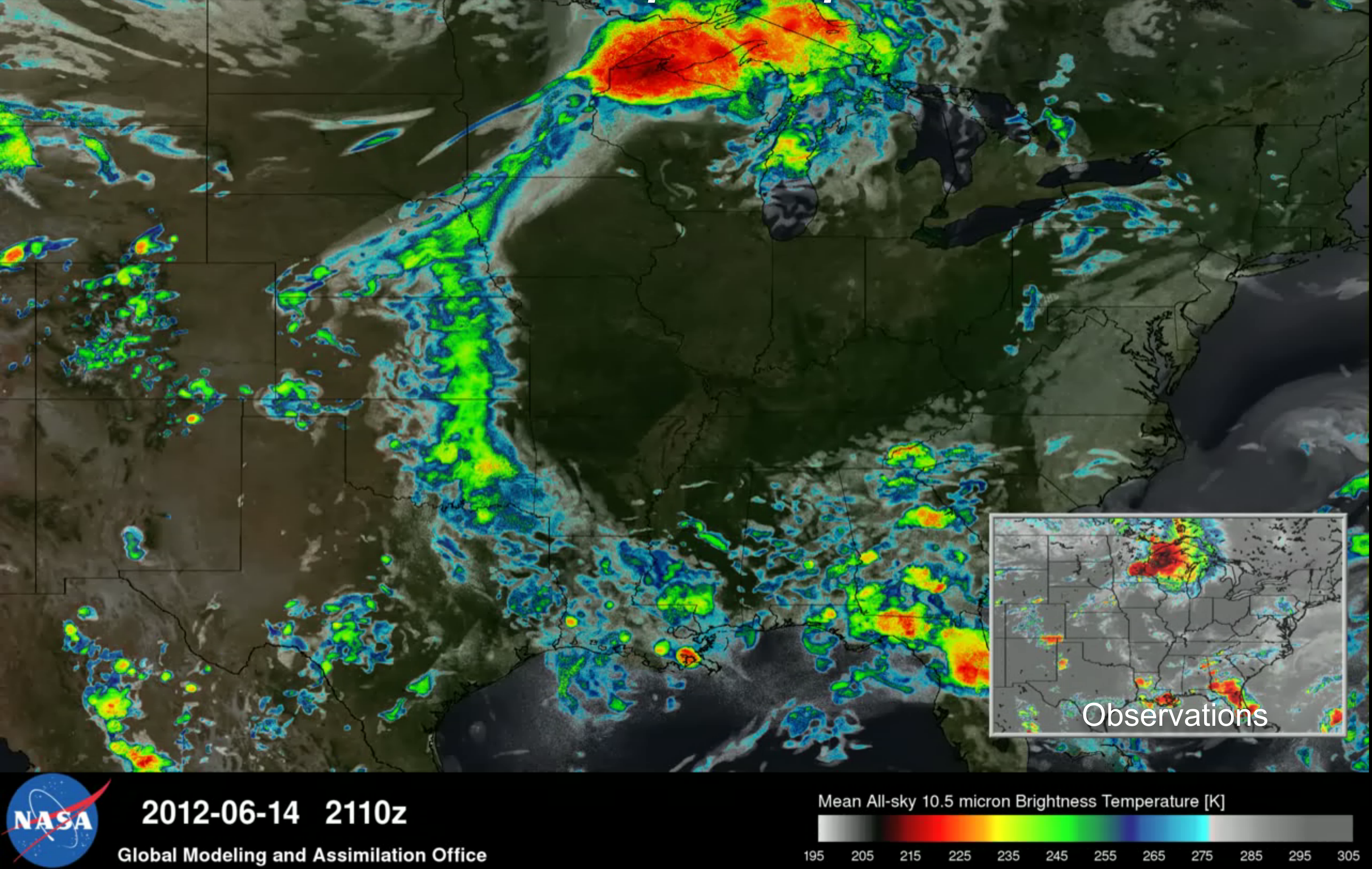
GOES-14 Satellite Observations

- 1-km Resolution
- 1-minute Super Rapid Scan Operations for GOES-R
- Thunderstorms over southwest Texas, 19 May 2015



http://cimss.ssec.wisc.edu/goes/srsor2015/GOES-14_SRSOR.html

GEOS-5 Clouds and Thunderstorms *[circa 2015]*



1.5-km Global Resolution (200 million grid cells)

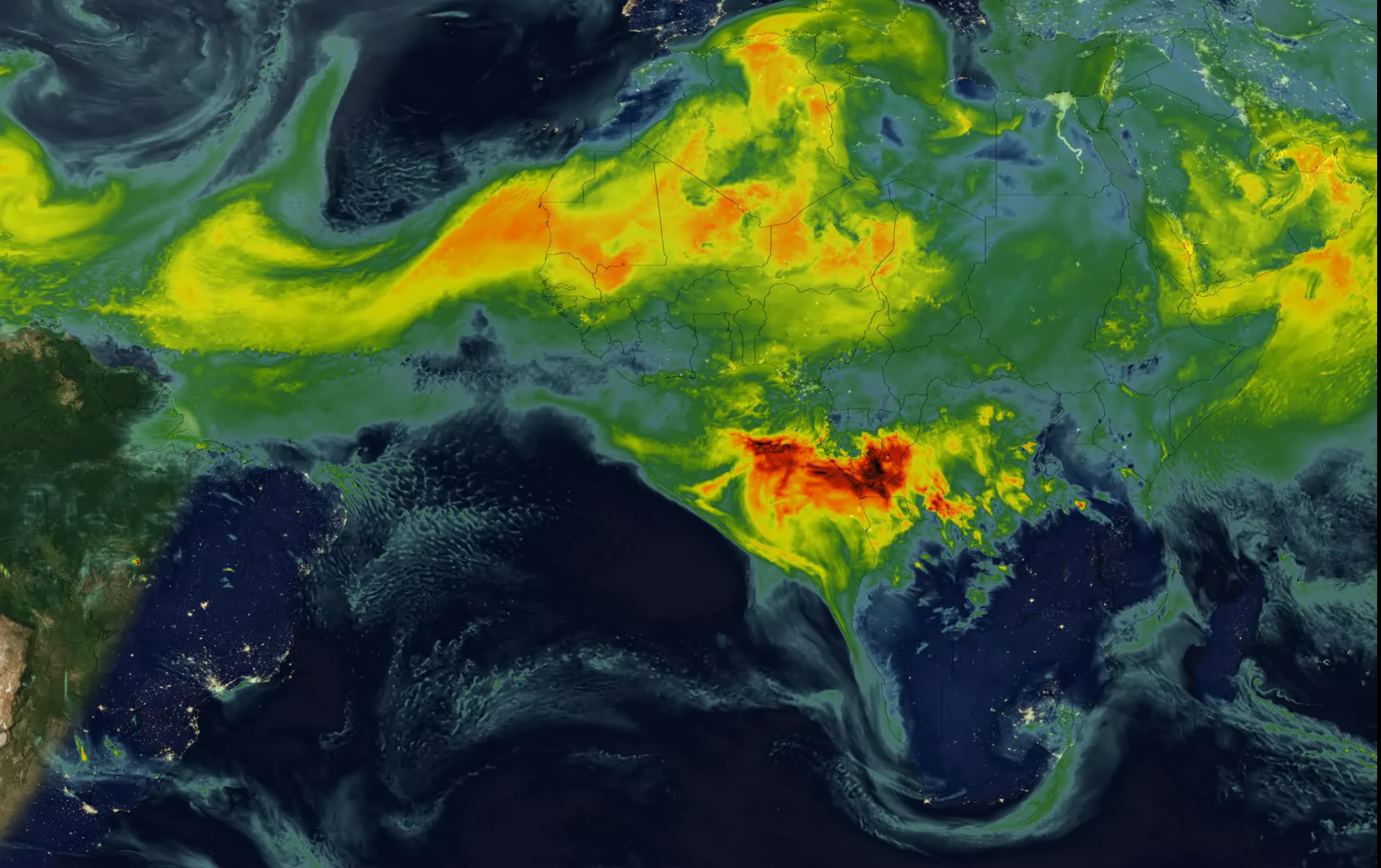
30,000-processors of Discover SCU10

The highest resolution global simulation to date, and the first ever to include interactive aerosols and carbon

Throughput:
~1-day per day

June 2012 Severe Weather Outbreaks

GEOS-5 Aerosol Optical Depth *[circa 2015]*



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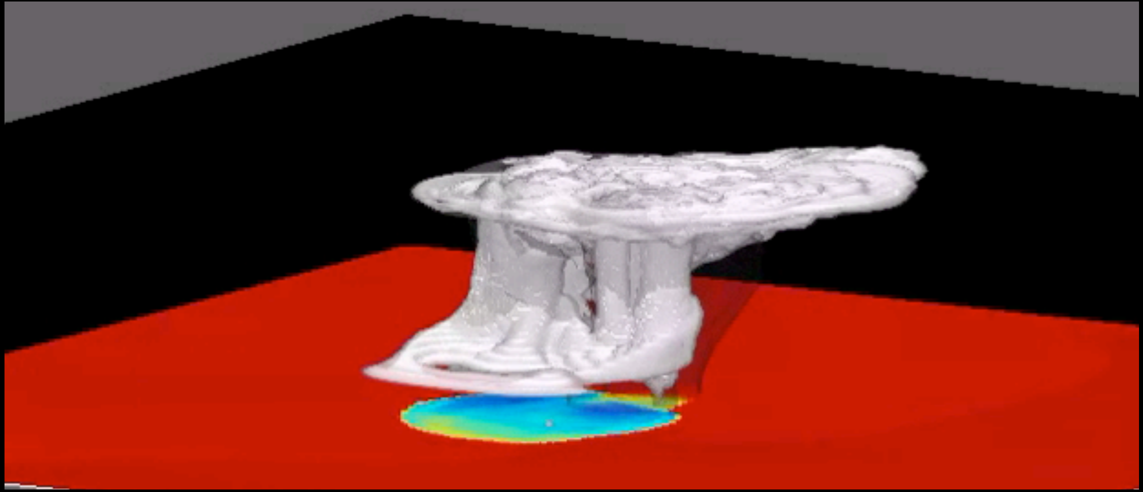
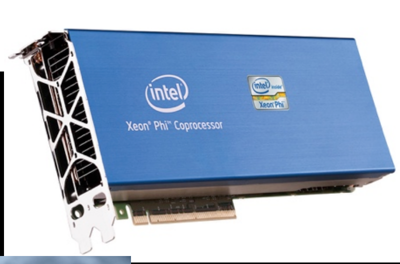
June 2012 Severe Weather Outbreaks

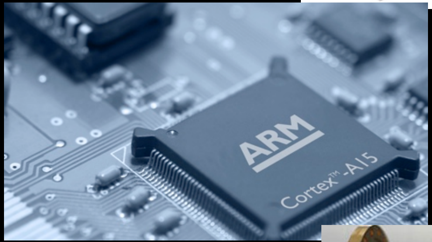
The Pursuit of Exascale

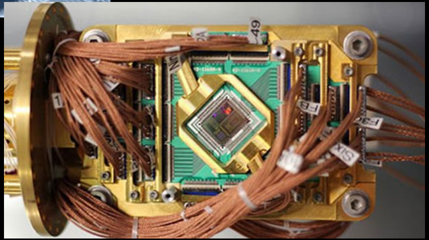
Resolution (km)	Resolvable ~12x (km)	Computing (Xeon Cores)
1.0	12	12,500,000
0.1	1.5	6,400,000,000
10 (m)	120 (m)	21,600,000,000,000,000

Tornado resolving global models 1-km FV3









http://www.gfdl.noaa.gov/visualizations-mesoscale-dynamics

GEOS-5 Global Clouds 1.5-km Resolution *[circa 2015]*