NASA Observations in Support of Earth System Science

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** Talk prepared with assistance of numerous colleagues from NASA HQ and Field Centers!*

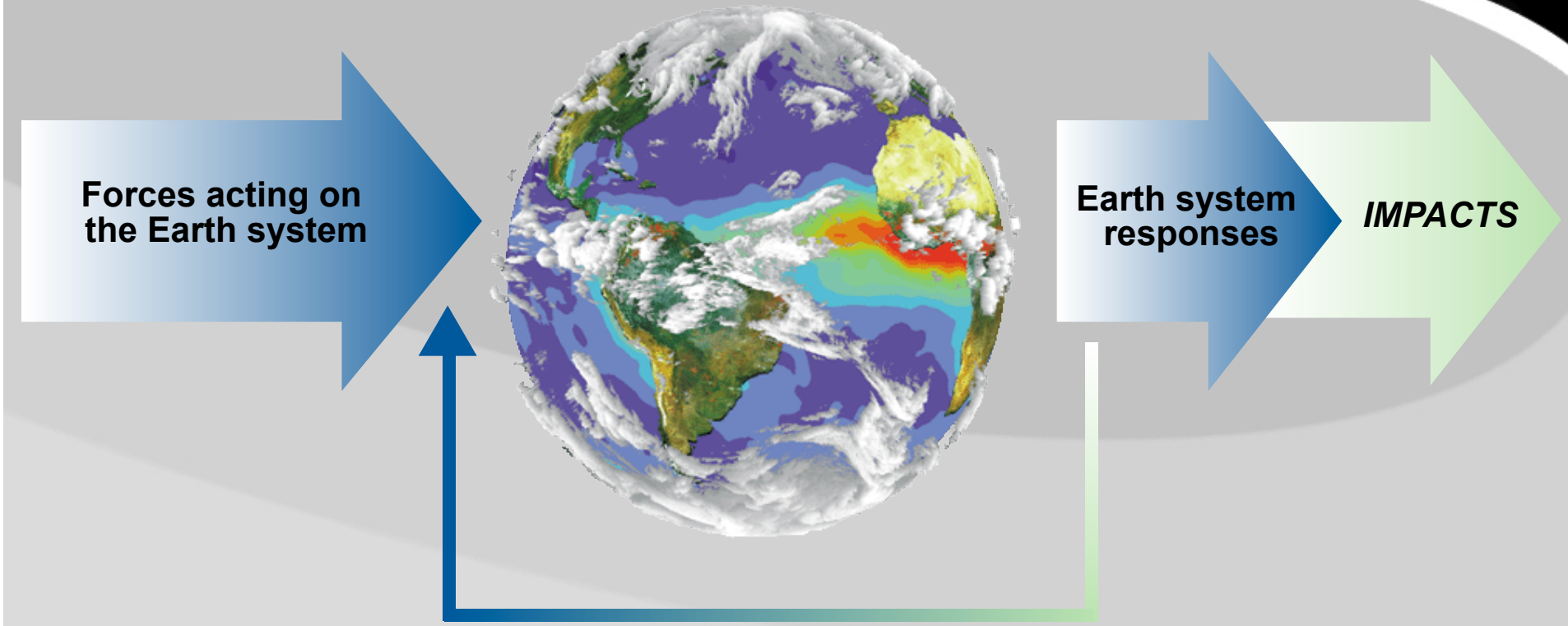
Overview of Talk

- Introduction – Earth System Science and NASA
- NASA's Contributions to Earth System Science
- Recent NASA Accomplishment
- Some Thoughts on the Future
- Summary

Some Noteworthy Elements of Earth System

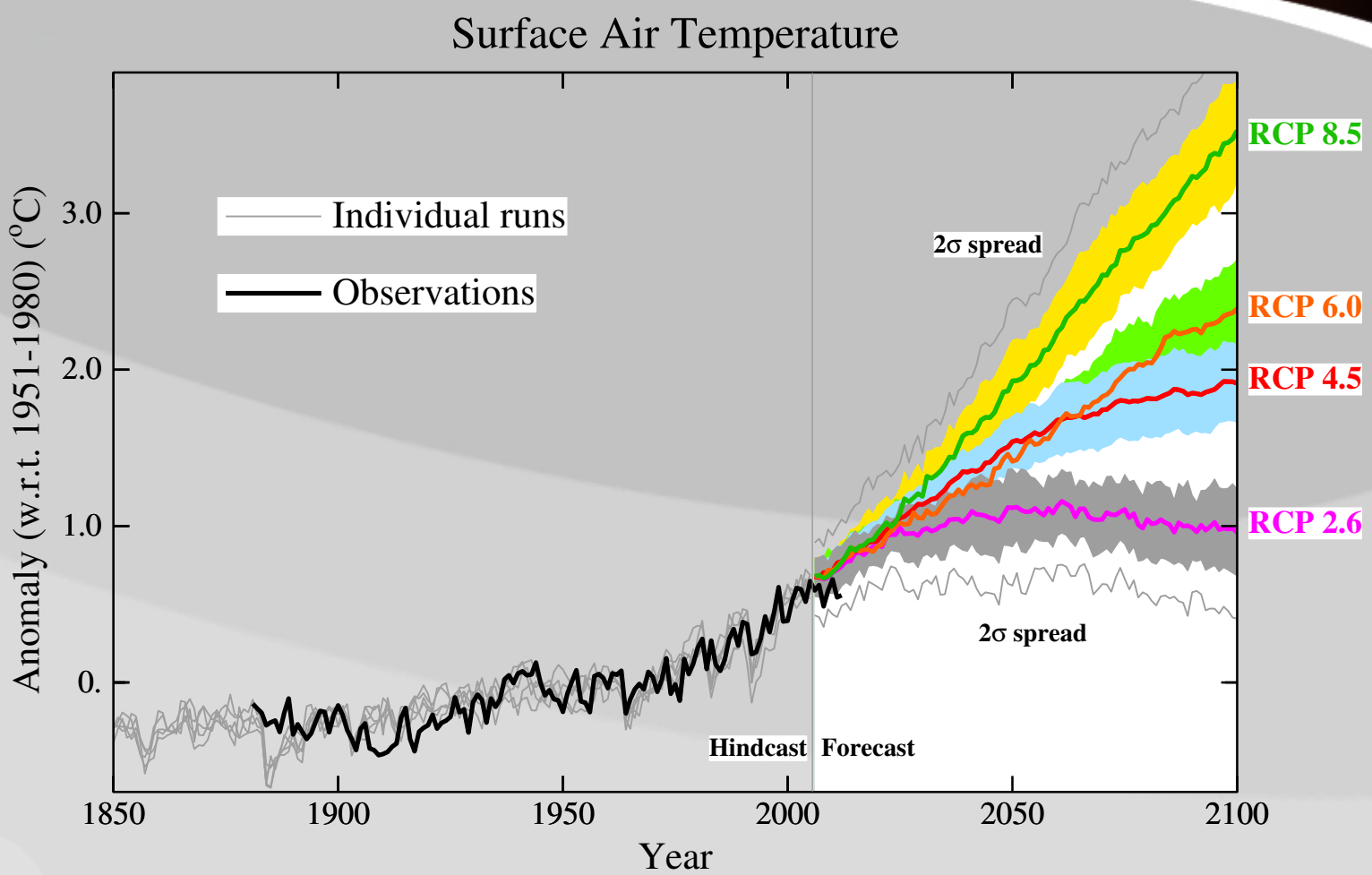
- Carbon-based life
- Oxidative/protective atmosphere (ozone!)
- Water in multiple, interacting phases
- Fluid atmosphere and ocean that absorb, emit, and/or redistribute heat/energy
- A well-defined surface (solid/liquid) that interacts with overlying atmosphere through biogeochemical cycles
- Externally-imposed and internally-generated variability
  - Externally-imposed – e.g., solar cycles (diurnal, seasonal, …), events
  - Internally-generated – e.g., short-term weather, multi-week/ month/year/decade …
- Us!
  - We CAN change the Earth system
  - We can recognize that we change the Earth system!
  - We can decide what, if anything, we choose to do with that knowledge.

Earth as a Dynamic System



Feedbacks

GISS-Projected Global Temperature Changes



GISS ModelE2 Global Mean Surface Air Temperature Forecasts through 2100 (CMIP5)

NASA Earth Science Products for the Nation and the World

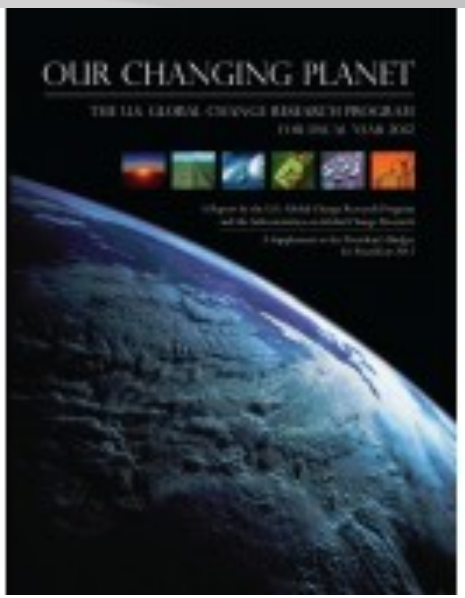
- Scientific Knowledge
  - Discovery
  - Process Knowledge
  - Trend Detection and Attribution
  - Forecasting Capability
- Applications to National and Global Needs
  - Environmental Policy
  - Resource Management
  - Forecasting and Assessment
  - Decision-Making by Public and Private Sectors
- Technical Capability for Space and Airborne Science
- Environmental Data for Public Use
- Trained Workforce for Science and Technology
- A Better-Informed and Inspired Public

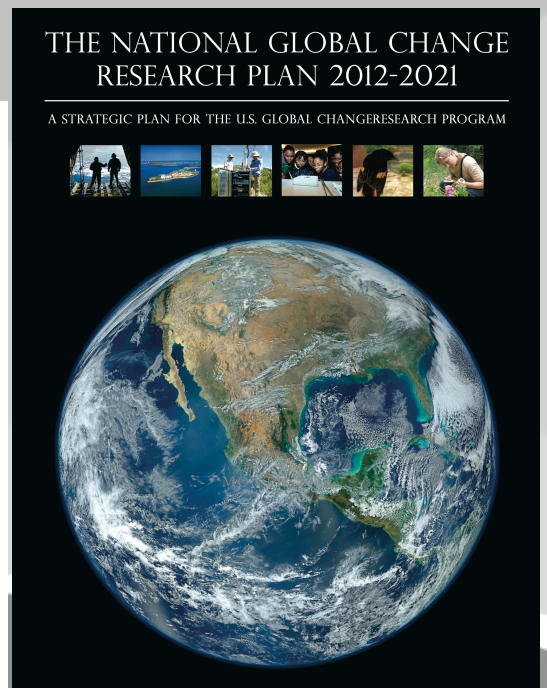
NASA Role in National Initiatives

NASA is the largest contributor to the US Global Change Research Program (USGCRP), which coordinates climate-related research of 13 Federal Agencies and publishes documents, including

- **Strategic Plan 2012-2021**
- **Annual *Our Changing Planet***
- **Global Climate Change Impacts in the United States**

NASA also contributes to Administration initiatives in Earth Observation, Oceans, and Arctic





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NASA Earth Observing
Satellite Fleet - 2012
Launch-CY2011
Launch-CY2012
Launch-CY2013
Aquarius
OSTM/Jason 2 (NOAA)
Jason
QuikSCAT*
TRMM
EO-1
Landsat-7 (USGS)
Aqua
ACRIMSAT
Terra
SORCE
LDCM
GRACE (2)
Aura
CALIPSO
CloudSat
Suomi-NPP

ESD Orbital Flight Portfolio – 2014-2022

- **GPM** (2/2014) – Global Precipitation mapping, w/JAXA
- **OCO-2** (7/2014) – Atmospheric CO_2 monitoring, recovery mission
- **SAGE-III/ISS** (8/2014) – Ozone, Temp, Humidity profiles, w/HEOMD, ESA
- **SMAP** (10/2014) – Soil Moisture and Freeze/Thaw cycling, w/CSA (minor)
- **ICESat-2** (late-2016) – Precision Ice Topography, Ecosystem monitoring
- ***CYGNSS [EV-Mission/1]*** *(late 2016)*
- **GRACE-FO** (8/2017) – Gravity/Ice Mass/Ground Water, w/GFZ & DLR
- ***OCO-3/ISS*** *(Fall 2017)* – CO2 continuity, from ISS, OCO-2 spares
- ***TEMPO [EV-Instrument/1]*** *(2017)*
- **SWOT** (2020) – Wide-swath ocean altimetry, land water, w/CNES
- ***PACE*** *(2020)* – Ocean Color, possibly Aerosols
- ***EV-Instrument/2 Venture-Class*** *(NLT 2020)*
- ***L-band SAR*** *(2021)* – Solid Earth, Cryosphere, Ecosystems, w/ISRO
- ***CLARREO*** *(2022?)* – Precise global radiation balance, possibly w/UK
- ***EV-Mission/2*** *(NLT 2022)*
- ***EV-Instrument/3*** *(NLT 2022)*
- Significant studies ongoing for all other Tier-2 Decadal Survey missions

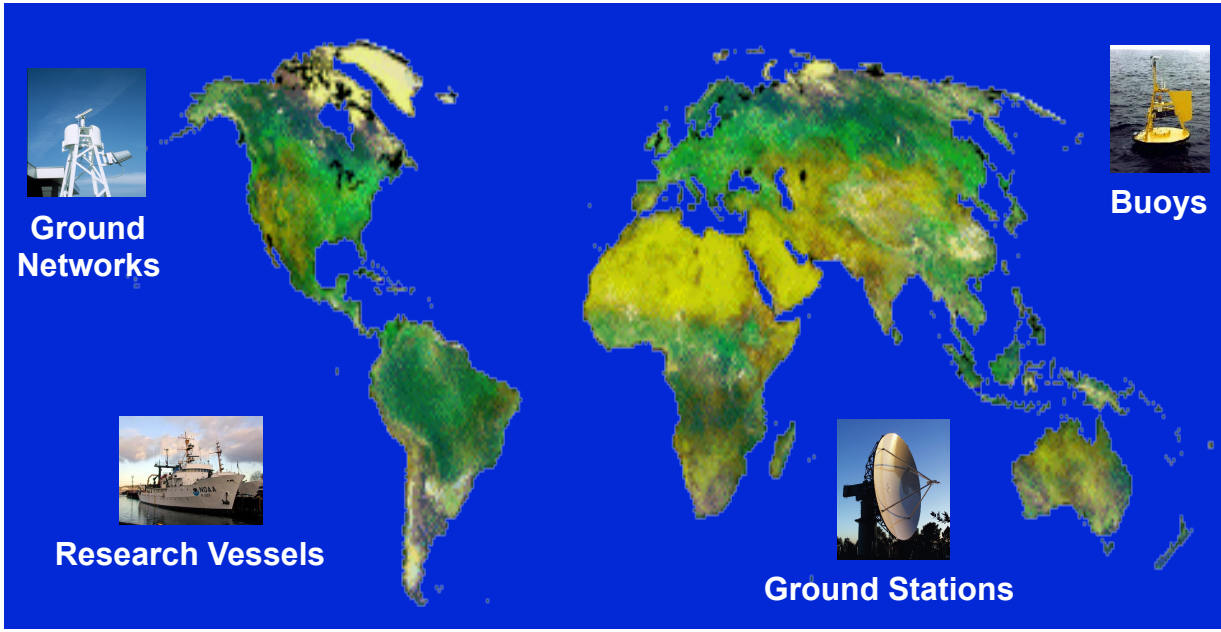
End-to-end Support in a Globally Integrated Program

Airborne Sensors

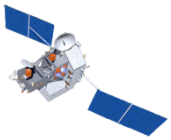
Research Balloons

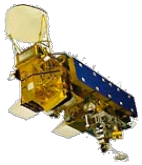
Uninhabited Aerial Vehicles

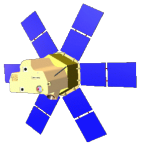
Field Campaigns

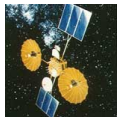


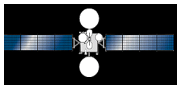
Space-based: Sensors & Data Relay

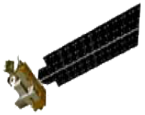


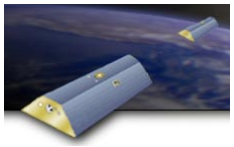












Ground Stations

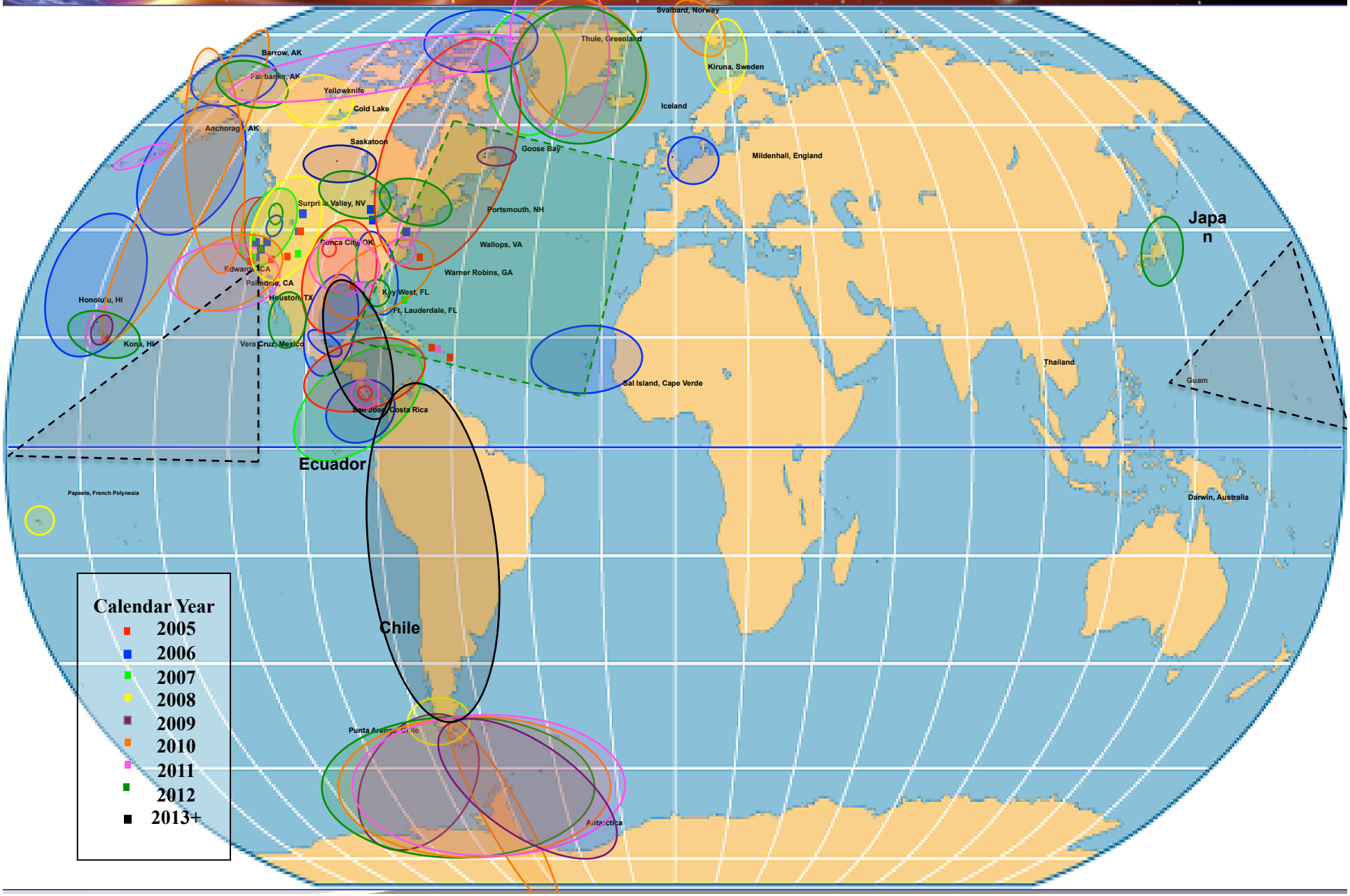
Research Balloons

NASA's & Partners' ground, sea, air and in-situ measurements augment space-based observations to validate science results and provide complimentary measurements

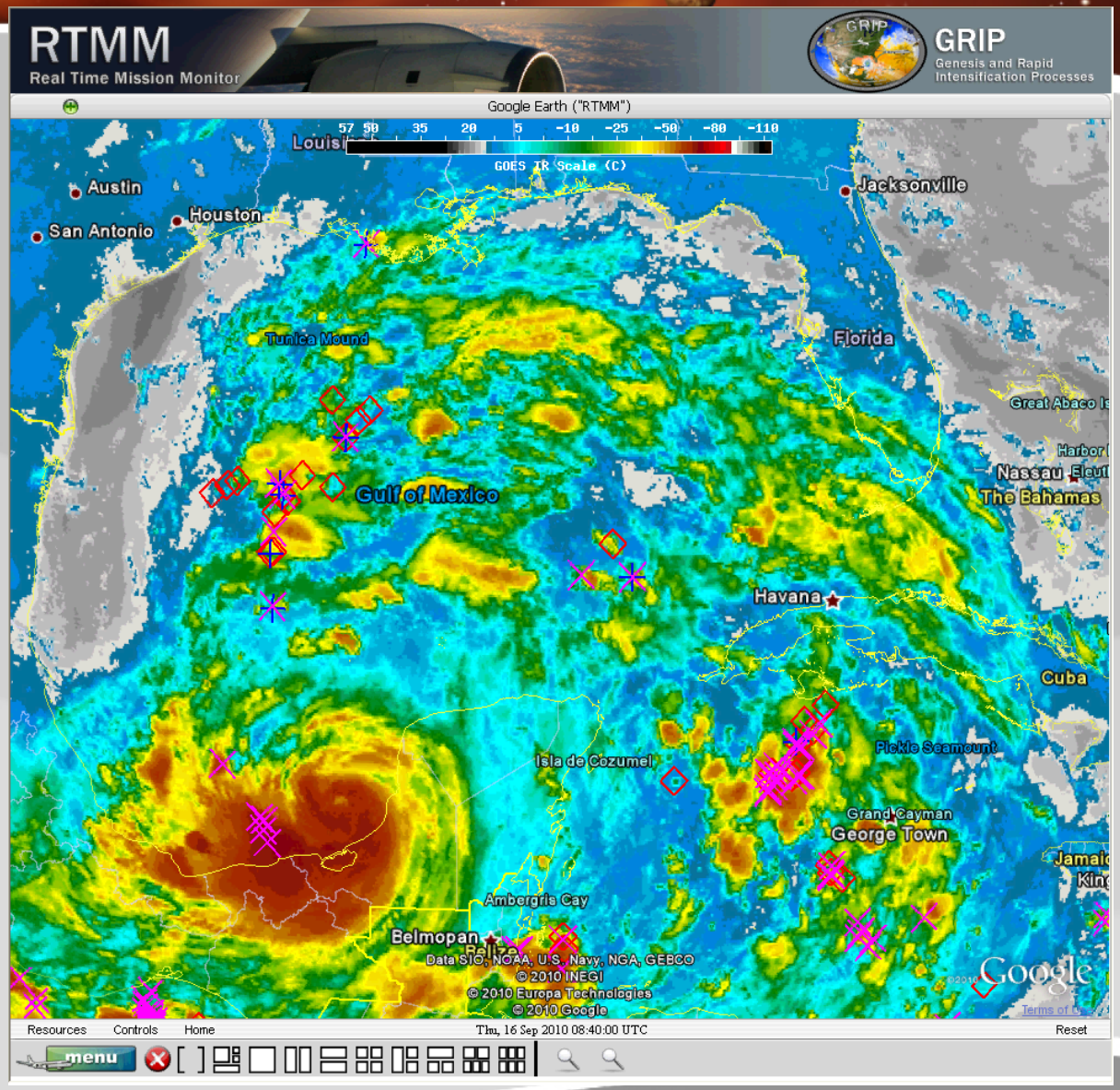
Suborbital (Airborne) Science by NASA/ESD

- What do we mean by suborbital science?
  - Usually mean airborne science, but could mean others
    - Balloon (usually discipline-specific, mainly middle atmosphere)
    - Sounding rocket (very limited use now, had more use earlier)
  - Usually does not mean surface-based measurements, although they are frequently incorporated into field work
- Why make use of suborbital platforms?
  - Process studies and environmental characterization
    - In situ
    - Remote sensing
  - Satellite calibration/validation
  - Platform for instrument/measurement technique test
- What's different about NASA's use of suborbital platforms from that of its interagency partners?
  - The platforms themselves
  - Integrated sensor/platform suites
  - Willingness/ability/staff to go where/when needed and do missions
  - The emphasis on making the connection to satellites

2005-2013 Airborne Campaigns



Integrated Airborne Observations of Hurricane Karl During GRIP



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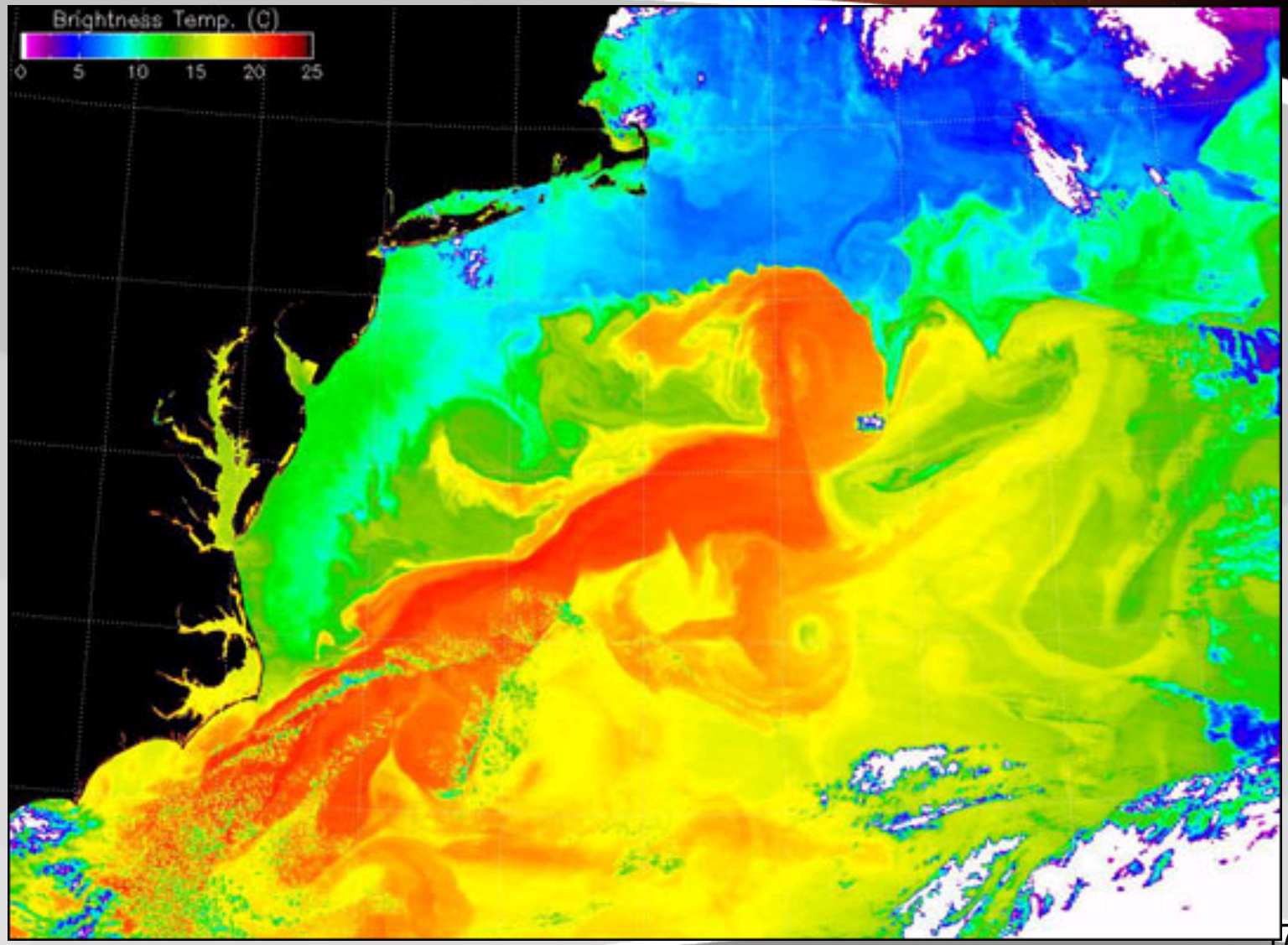
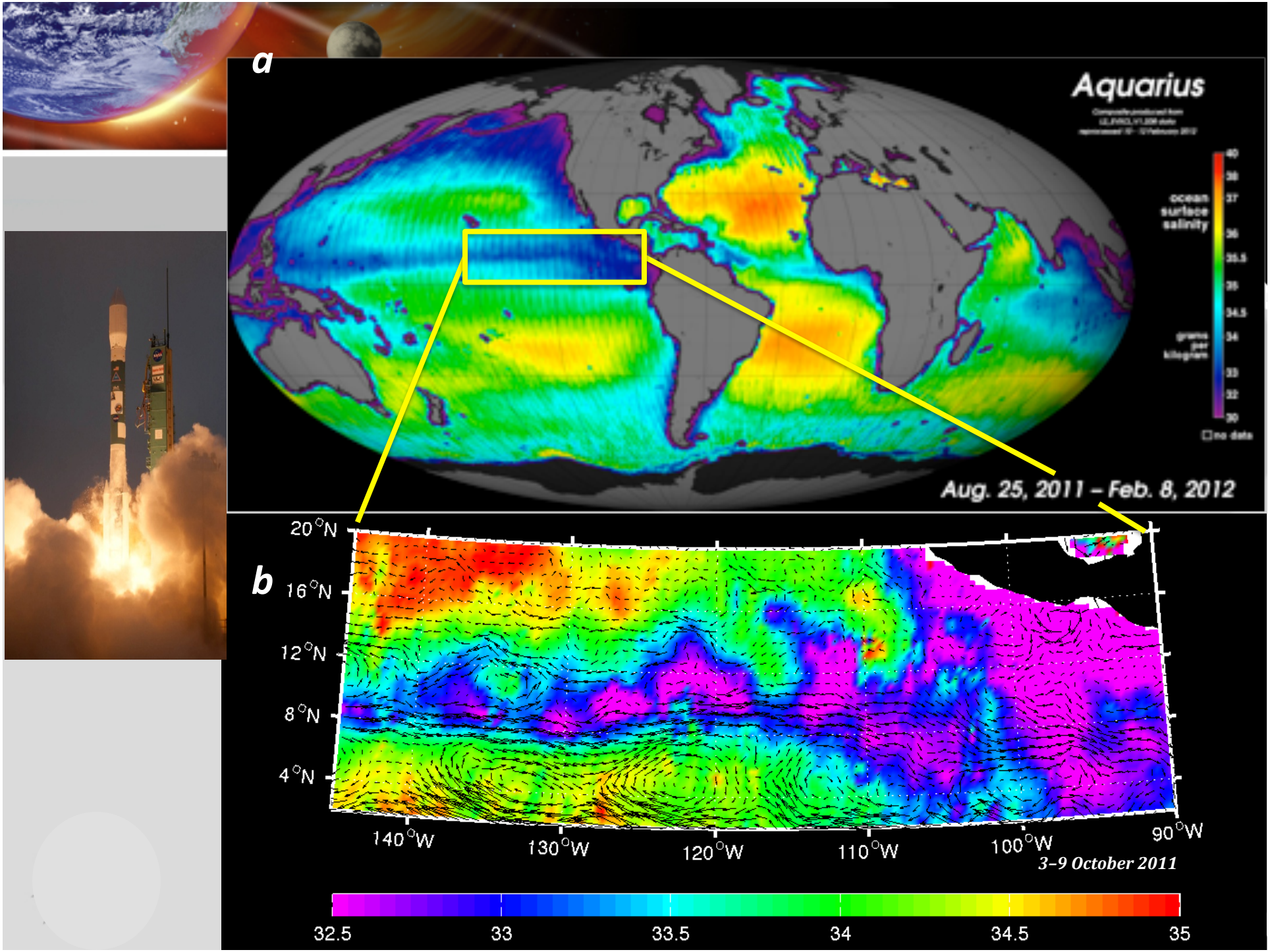
Examples of Scientific and Applications Accomplishments

Question Posed	What we Measure	Example Mission(s)	Scientific Accomplishment	Application Accomplishment
What is particulate distribution in Earth's atmosphere?	Atmospheric aerosol – presence, particle size, composition, height	Terra, Aqua, Aura, CALIPSO	Effect of particulates on global radiative forcing for climate change	PM 2.5 distributions that affect human health (with EPA)
What is distribution of ozone in Earth's stratosphere?	Column amounts and vertical profile of ozone	TOMS, UARS, SAGE, Aura, S-NPP	Documentation of Antarctic ozone hole, documenting impact of Montreal Protocol	Calculation of surface UV flux for human health studies (EPA, HHS)
What is distribution of precipitation in tropical oceans?	Rainfall rates over ocean	Tropical	Variability of tropical rainfall, role of tropical precipitation in global water cycle	Knowledge of hurricane structure and support for improved hurricane forecasting (NOAA)
What is distribution of sea ice in Arctic Antarctic oceans?	Sea ice extent	Aqua	Discovery of unexpectedly rapid decreases in 2007 and 2012	Information on ship trafficability in Arctic (DHS, DOD)
What are changes in ice mass in Greenland and Antarctic?	Ice sheet thickness, ice mass amounts	ICESat, GRACE	Documentation of changes in ice mass decreases in Greenland	Improved information for predicting sea level rise and associated coastal impacts (USGS)
What is distribution of biological activity in surface of Earth's oceans?	Surface concentrations of chlorophyll	SeaWifFS, Terra, Aqua	Documentation of role of oceans in carbon uptake/release	Identification and improved forecasting of harmful algal blooms (NOAA, EPA)

Sea Surface Temperature: MODIS

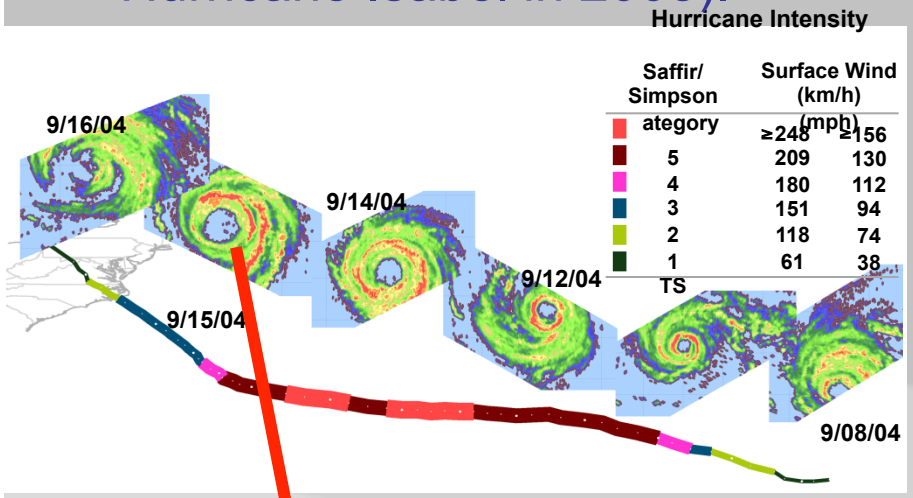


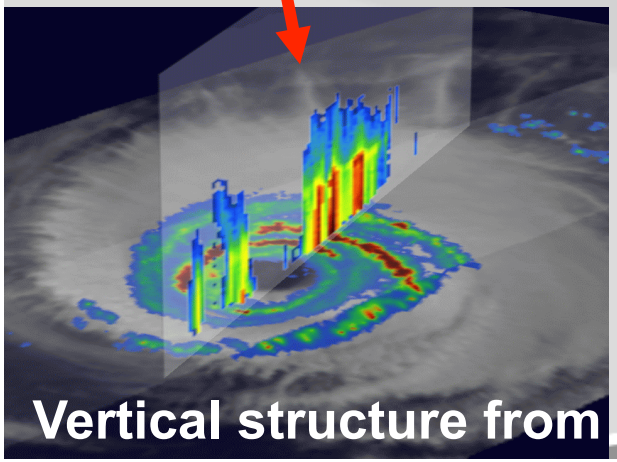
Terra/MODIS, May 2001


a
Aquarius
ocean surface salinity
grams per kilogram
no data
Aug. 25, 2011 – Feb. 8, 2012
b
20°N
16°N
12°N
8°N
4°N
140°W
130°W
120°W
110°W
100°W
90°W
3–9 October 2011
32.5
33
33.5
34
34.5
35

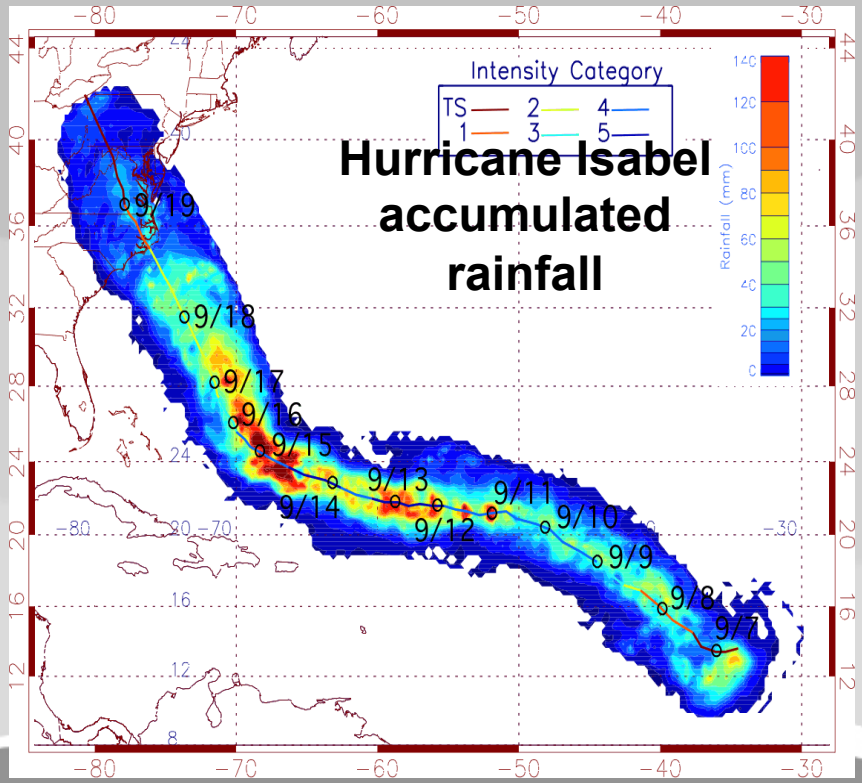
TRMM Tracks Changes In Rainfall Structure and Accumulation

- By itself, TRMM provides detailed views of hurricane structure and structure change (example here is Hurricane Isabel in 2003).

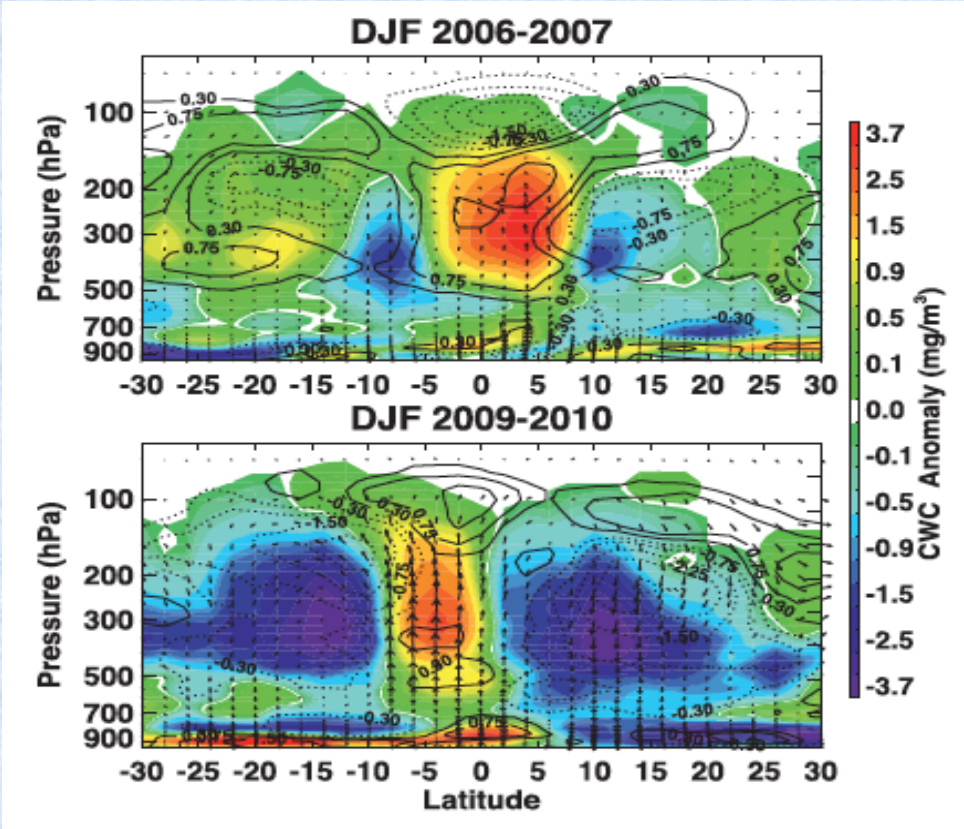




- Combined with other satellites, the TRMM multi-satellite precipitation analysis (3B42) helps map rainfall evolution in hurricanes.



Cloud Water Content During 2 Different El Niño Events

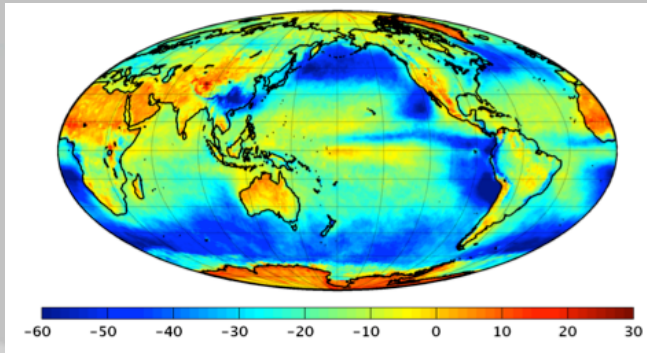


Latitude–height section of zonal mean cloud anomalies (cloud water content from CloudSat in shadings, cloud fraction from CloudSat in contours) during DJF 2006/07 and 2009/10, superimposed with ERA-Interim winds. The vertical pressure velocity (hPa/day) is enlarged 5000 times relative to the horizontal wind (m/s).

Su, H., and J. H. Jiang, 2013: Tropical Clouds and Circulation Changes During the 2006/07 and 2009/10 El Niños. *J. Climate*, 26, 399–413, doi: http://dx.doi.org/10.1175/JCLI-D-12-00152.1.

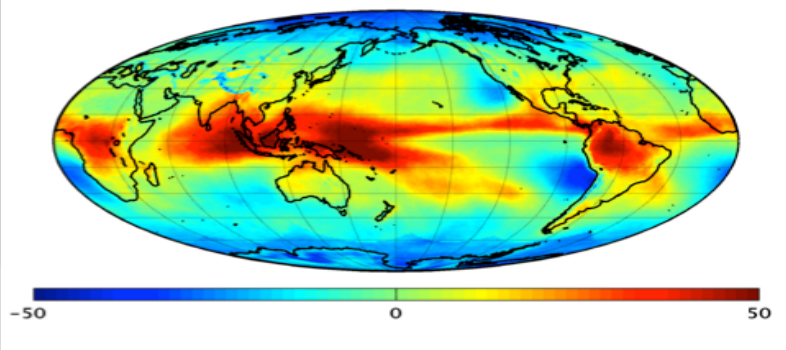
CERES Data Fusion: Net Radiative Effects of Clouds on Earth's Radiation Budget

Top-of-Atmosphere (-20.9 Wm^{-2})



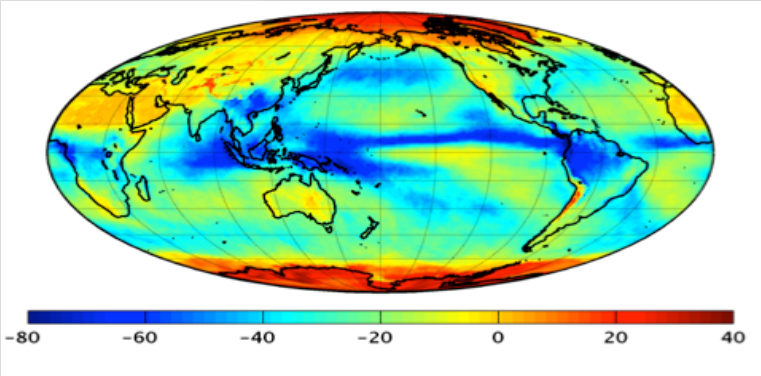
- SORCE-TIM: Solar Irradiance
- CERES: Reflected Solar, Emitted Thermal Flux
- MODIS: Cloud Detection & Properties
- 5 Geo Satellites: Diurnal Cycle

Within-Atmosphere (0.4 Wm^{-2})



- MODIS: Aerosol & Cloud Properties
- GMAO Reanalysis: Atmospheric State
- Aerosol Assimilation
- Constraints from: AIRS, CALIPSO, CloudSat

Surface (-21.3 Wm^{-2})



- MODIS: Surface albedo, emissivity & temperature
- NSIDC: Snow, sea-ice coverage

The extreme melt across the Greenland ice sheet in 2012

Data from three different satellite sensors – including the Oceansat-2 scatterometer, the Moderate-resolution Imaging Spectroradiometer (MODIS), and the Special Sensor Microwave Imager/Sounder – are combined to obtain composite melt maps, representing the most complete melt conditions detectable across the ice sheet.

Satellite observations reveal that melt occurred at or near the surface of the Greenland ice sheet across 98.6% of its entire extent on 12 July 2012, including the usually cold polar areas at high altitudes like Summit in the dry snow facies of the ice sheet. This melt event coincided with an anomalous ridge of warm air that became stagnant over Greenland.

Such a melt event is rare with the last significant one occurring in 1889 and the next previous one around seven centuries earlier in the Medieval Warm Period.

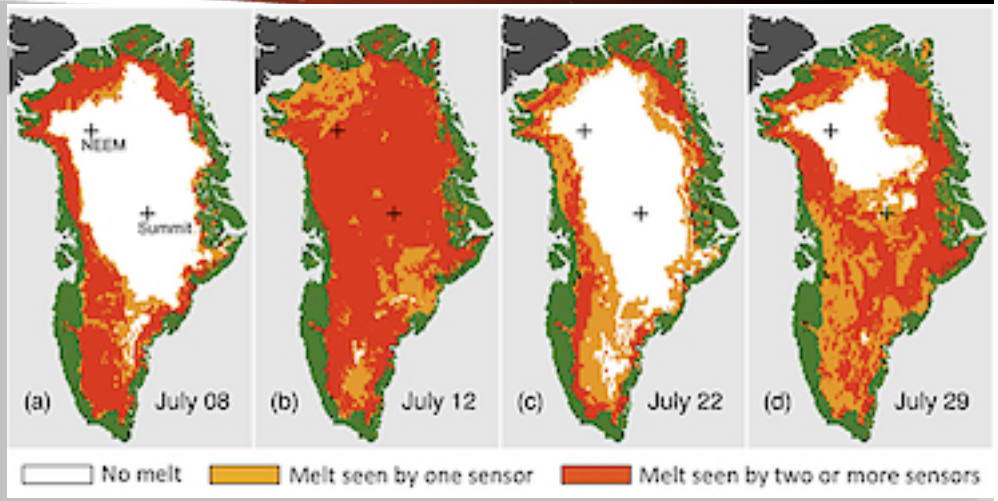
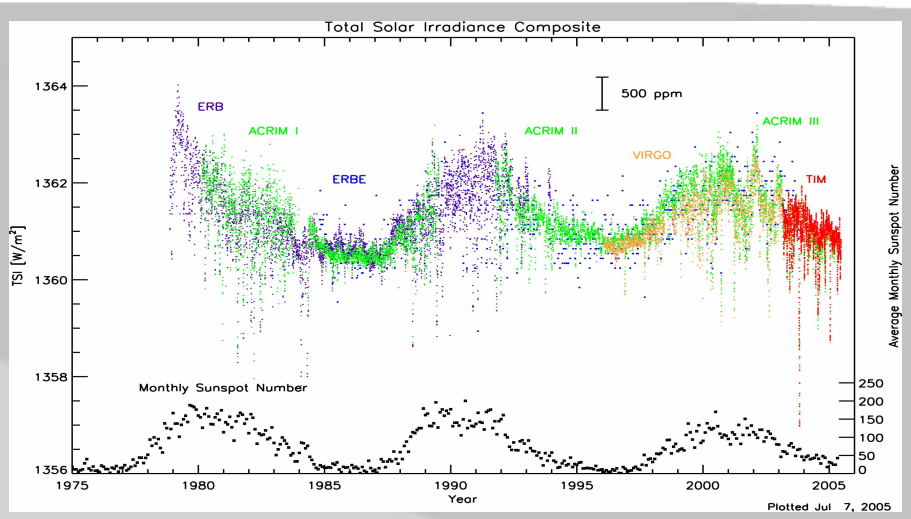


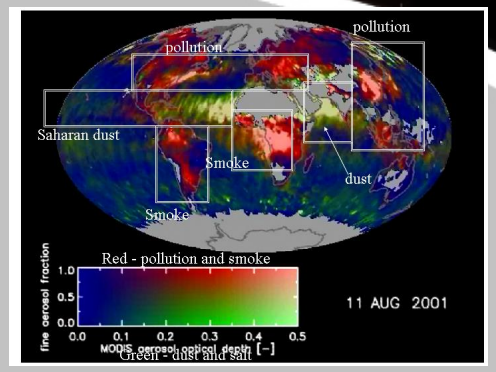
Figure Caption: Composite maps of melt extent from OS2, SSMIS, and MODIS satellite data for: (a) 8 July, (b) 12 July, (c) 22 July, and (d) 29 July 2012. In the red areas, two or more of the satellites detected melt while in the orange areas only one satellite detected melt. No melt was detected in the white areas, black indicates insufficient data, green and dark grey show land, and light grey represents ocean.

Nghiem, S. V., D. K. Hall, T. L. Mote, M. Tedesco, M. R. Albert, K. Keegan, C. A. Shuman, N. E. DiGirolamo, and G. Neumann (2012), GEOPHYSICAL RESEARCH LETTERS, VOL. 39, L20502, 6 PP., 2012, doi:10.1029/2012GL053611

Satellite-Enabled Accomplishment: Documentation of Climate Forcings

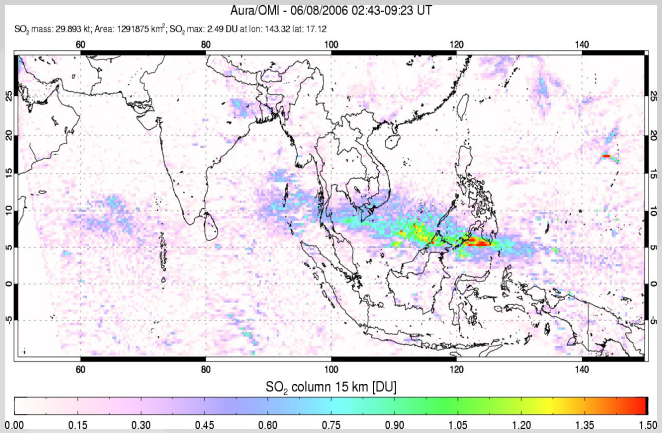


Satellite-measured total solar irradiance documents solar forcing of climate

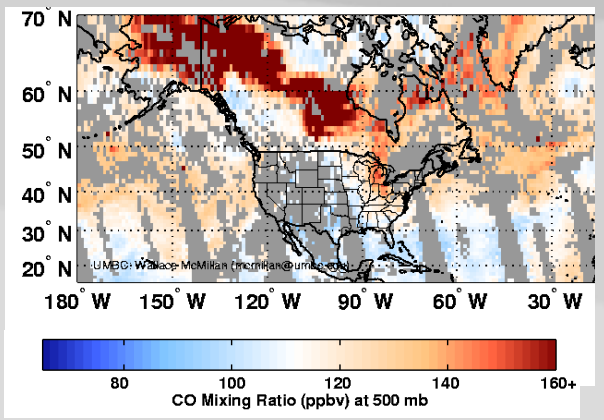


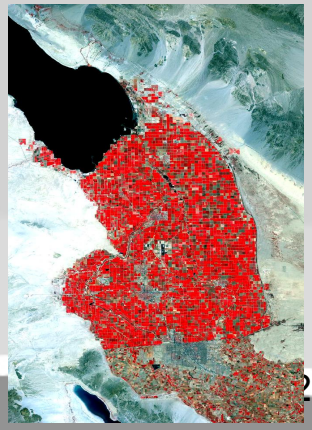
Aerosols provide major yet highly variable climate forcing

Land-cover change associated with human activity impacts biological and physical exchanges between surface and atmosphere



AIRS Carbon Monoxide

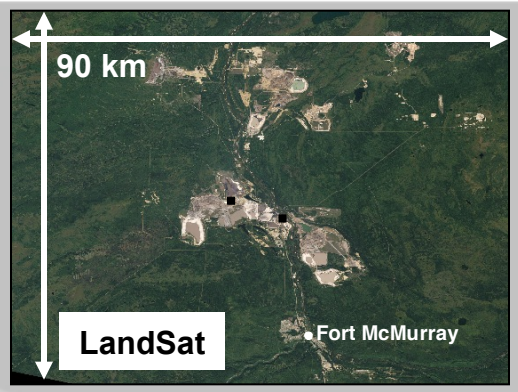




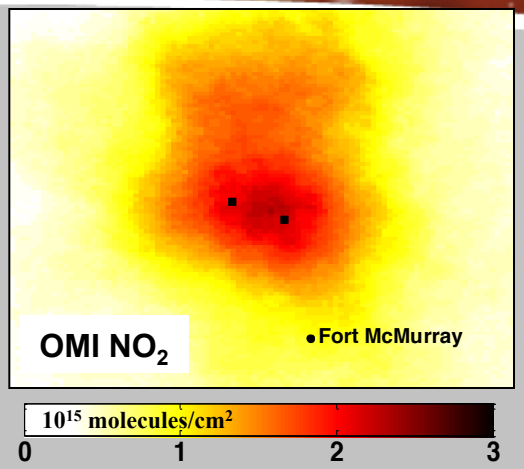
Volcanically-produced SO_2 can contribute to stratospheric aerosols

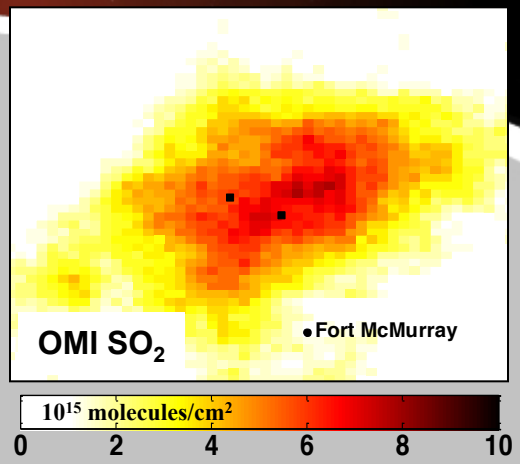
AIRS CO observations show large impacts of biomass burning

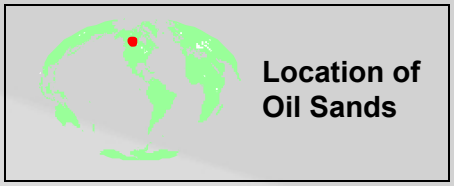
Aura/OMI measurements show distinct enhancements in NO_2 and SO_2 amounts over the Canadian oil sands

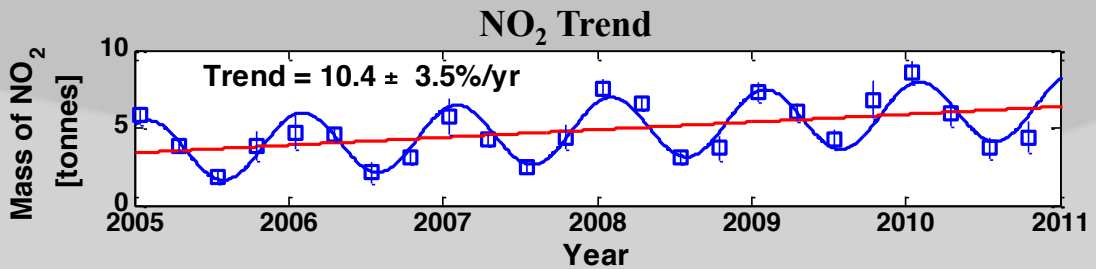


Landsat detects land use changes (deforestation) over the region of surface mining operations







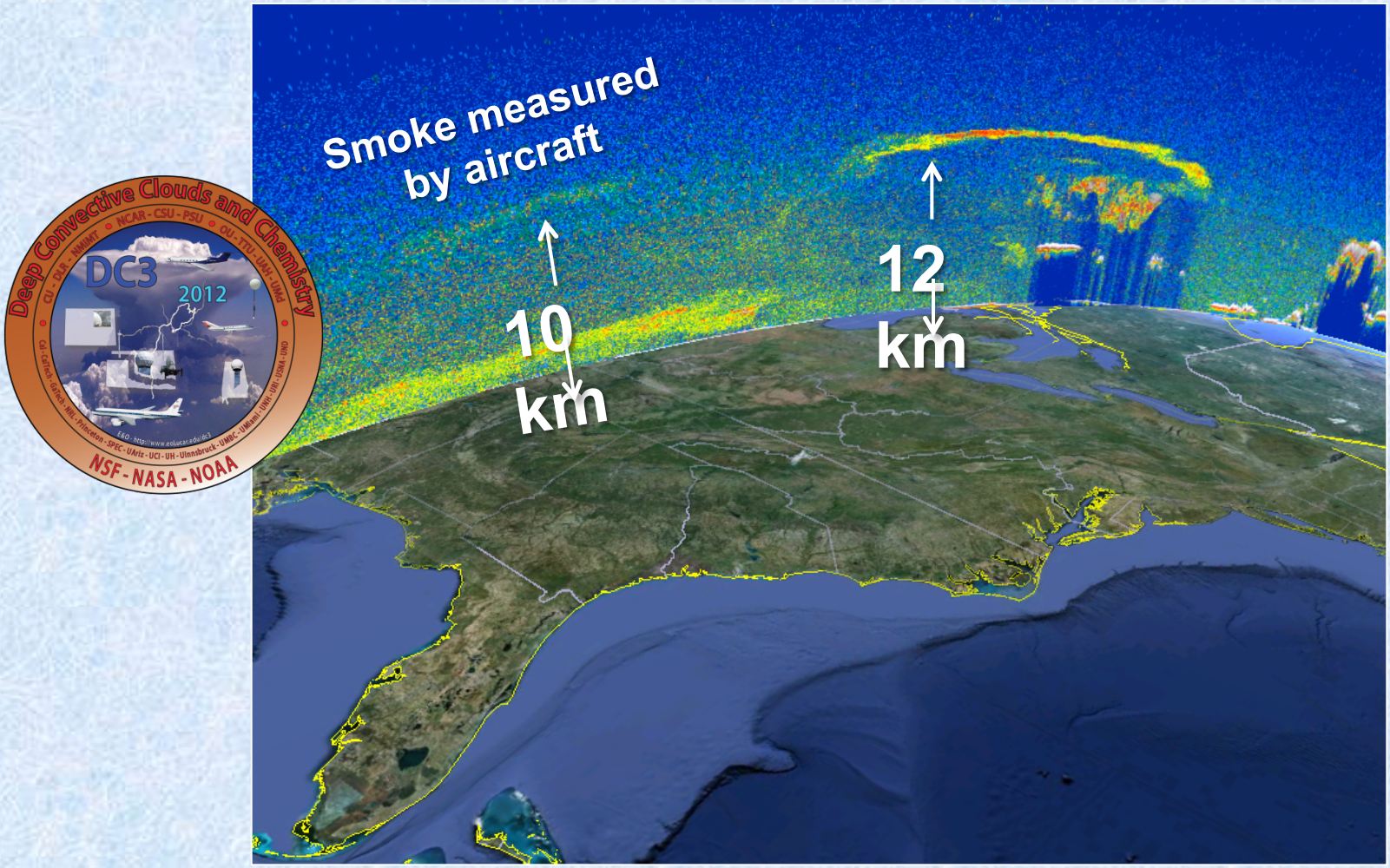


Data from the Ozone Monitoring Instrument (OMI) show distinct enhancements in the atmospheric pollutants nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) over a region of surface mining in the Canadian oil sands.

McLinden, C., et al., (2012), *Geophysical Research Letters*

CALIPSO Smoke Observations

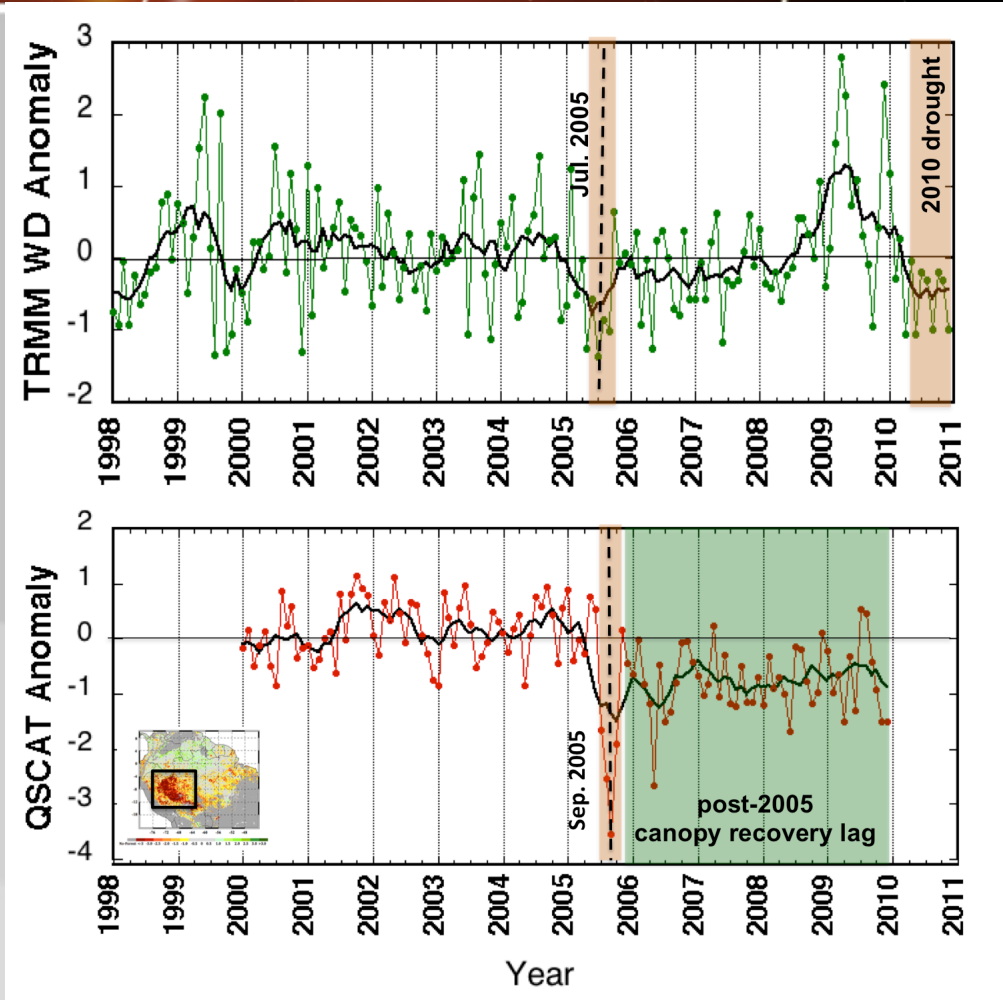
Smoke from Siberia over U.S. May 14th, 2012



jason.l.tackett

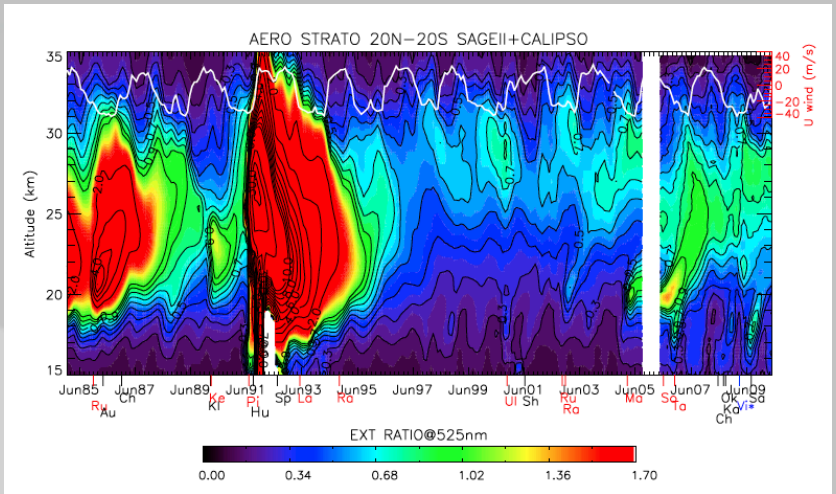
Post-drought increases in rainfall do not always result in canopy structure recovery

- The TRMM data show that the water deficit (WD) lessened in the years following 2005, until the 2010 drought (top)
- However, QSCAT data reveal that even >4 years after the drought, canopy structure had not returned to pre-drought levels (bottom).
- If droughts continue to occur at 5 – 10 y frequency, or increase in frequency, forest canopies may not ever recover, resulting in large-scale degradation of Amazonian rainforest from

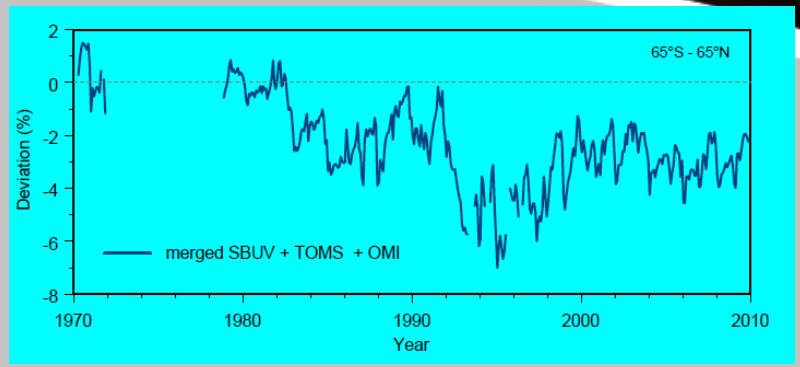


Above: Time series of TRMM (A) and QSCAT monthly anomaly over western Amazonia. Solid lines show the result of the auto-regressive moving average model of the order of 6 mo.

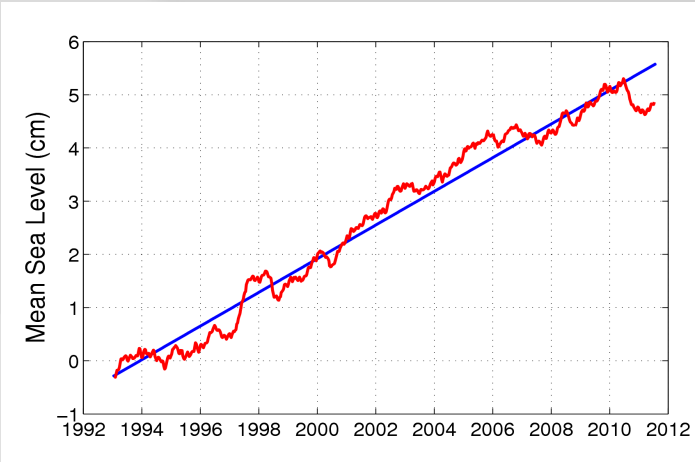
Long-Term Trends



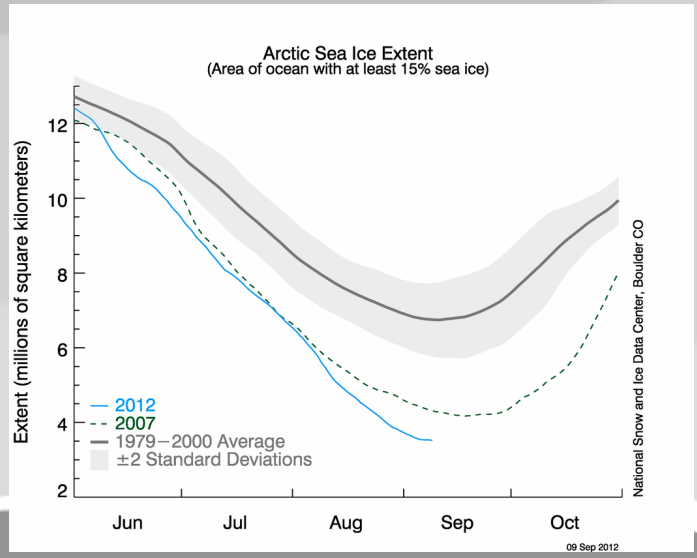
Long-Term Trends in Stratospheric Aerosols



Stratospheric Ozone Trends



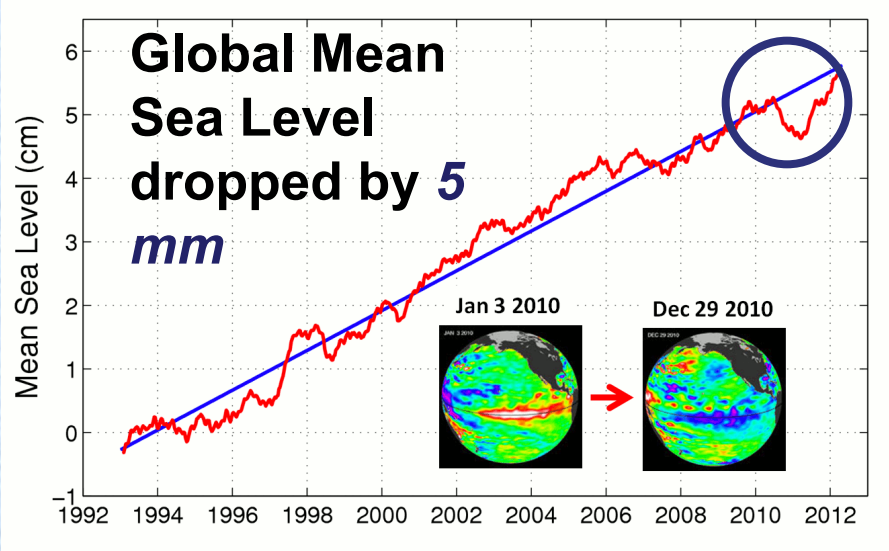
Global Sea Level Trend



Arctic Sea Ice Extent Changes

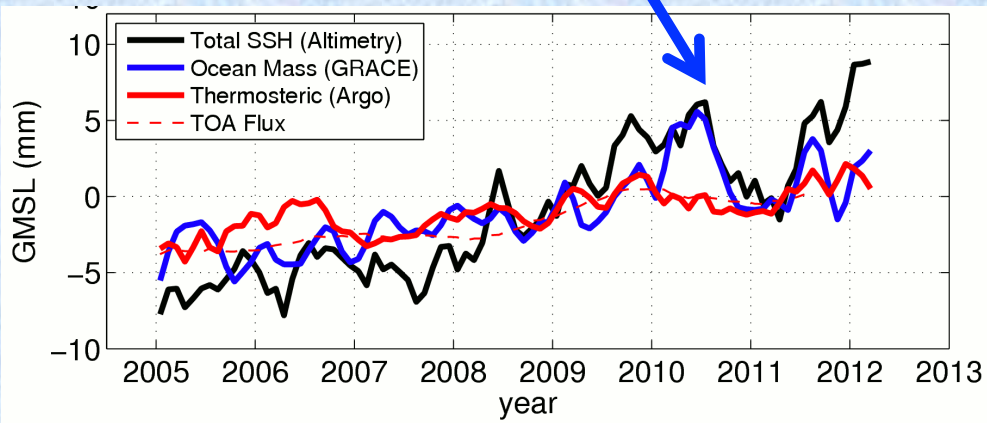
The 2011 La Niña: So Strong, the Oceans Fell

Boening et al., 2012a; (GRL).

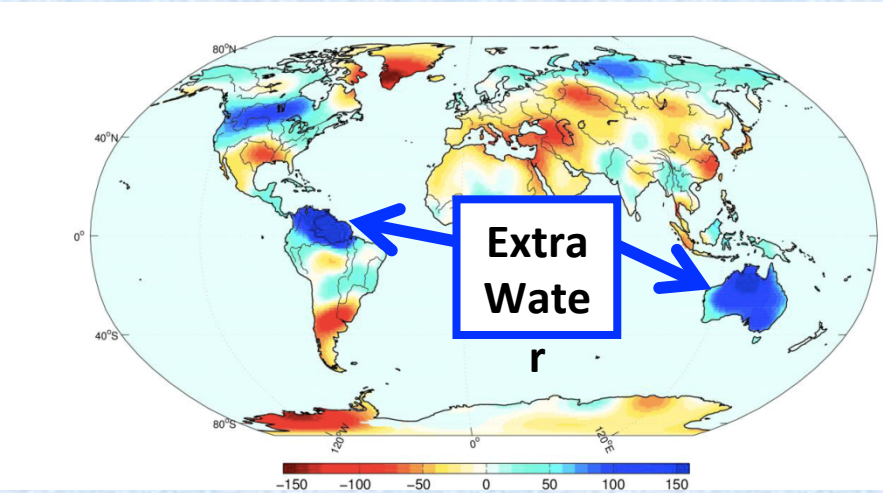


Explained by missing

ocean mass



GRACE shows change in land water storage from 2010 to 2011

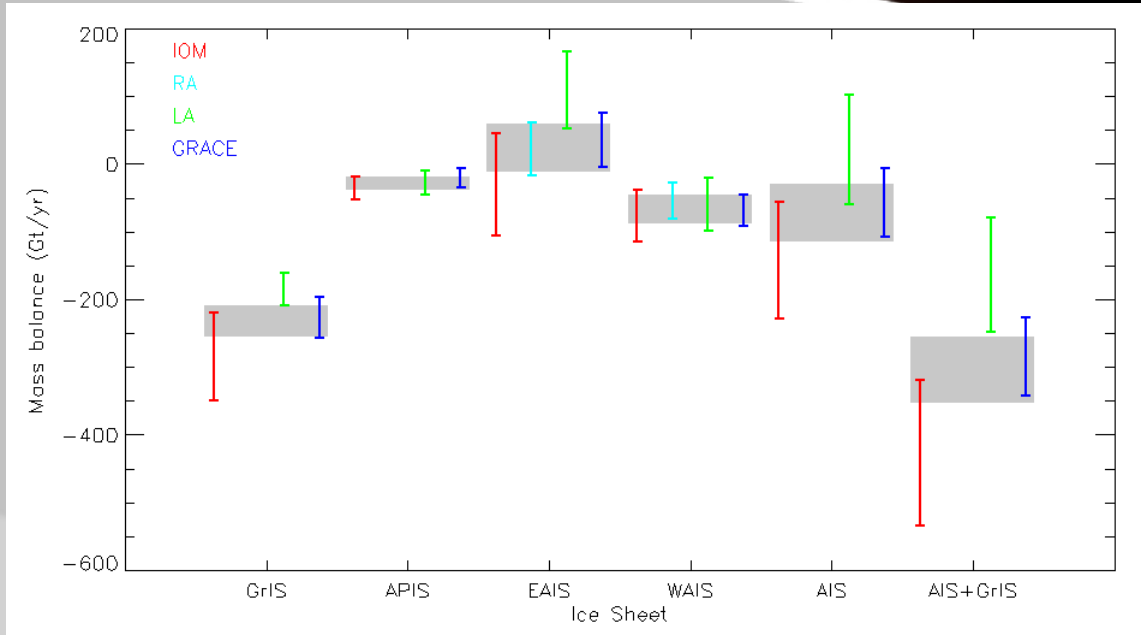


1) **The problem:** ***Projections*** **of how much the the GMSL will rise in the future** ***are highly uncertain*****.**
2) **What was done: Combination of GRACE data, satellite altimetry and ARGO data used to explain sources of** ***sea level drop in 2010/11***
3) **Main findings: GMSL drop was primarily caused by** ***freshwater exchange between ocean and land*****.**
4) **Next step: How do** ***water cycle*** **changes influence** ***sea level?***

Ice-Sheet Mass Balance Intercomparison Exercise (IMBIE)

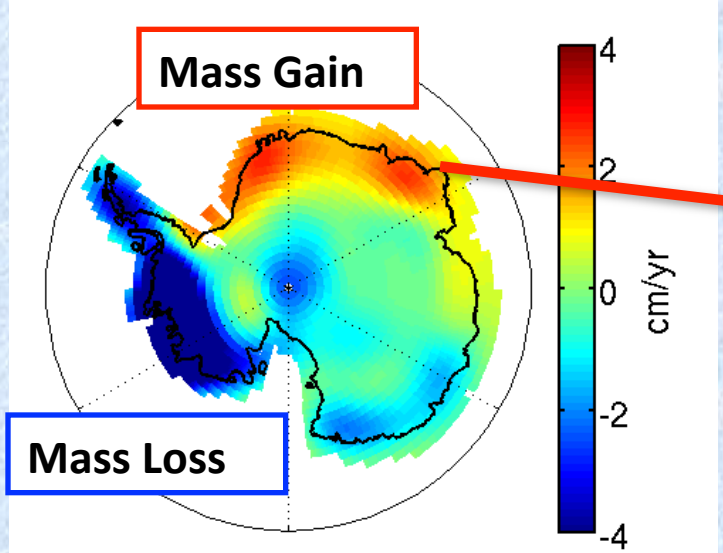
Shepherd, A., et al., *A Reconciled Estimate of Ice Sheet Mass Balance*, Science, 2012

- Joint NASA-ESA exercise to resolve discrepancies between estimates of Greenland and Antarctic ice sheet mass balance. Series of workshops held in the U.S. and the U.K. during the past year, bringing together experts in the various techniques used to measure ice sheet mass balance.
- The groups agreed to provide comparable estimates using commonly defined regional areas and time frames.
- The results confirm that both of the world's major ice sheets are losing ice, with nearly 2/3 of the total being produced by Greenland.

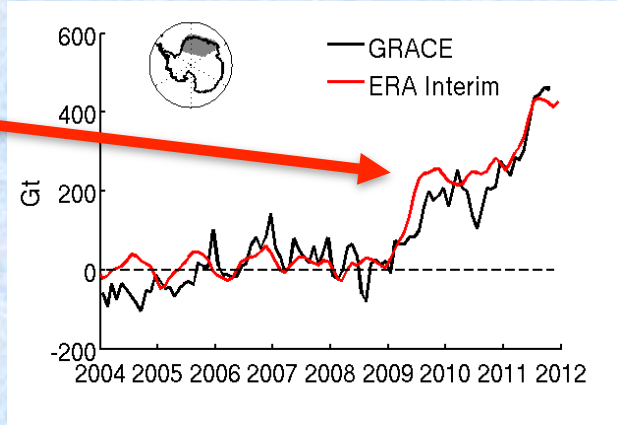


Intercomparisons of mass balance estimates using four independent geodetic techniques: Input-Output Method (IOM), red), Radar Altimetry (RA, cyan), Laser Altimetry (LA, green), and gravimetry (GRACE, blue). Four regional areas are considered: the Greenland Ice Sheet (GrIS), Antarctic Peninsula Ice Sheet (APIS), East Antarctic Ice Sheet (EAIS), West Antarctic Ice Sheet (WAIS), the combined Antarctic Ice Sheet (AIS), and the overall estimate for the AIS and GrIS. The grey areas constitute the reconciled estimates.

GRACE observes mass increase in Eastern Antarctica in 2009-11

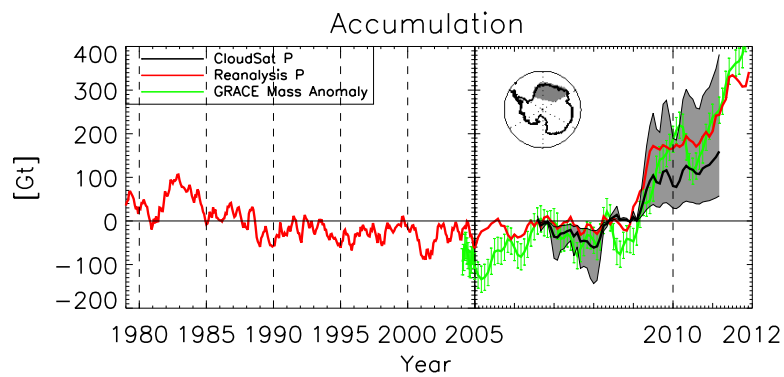


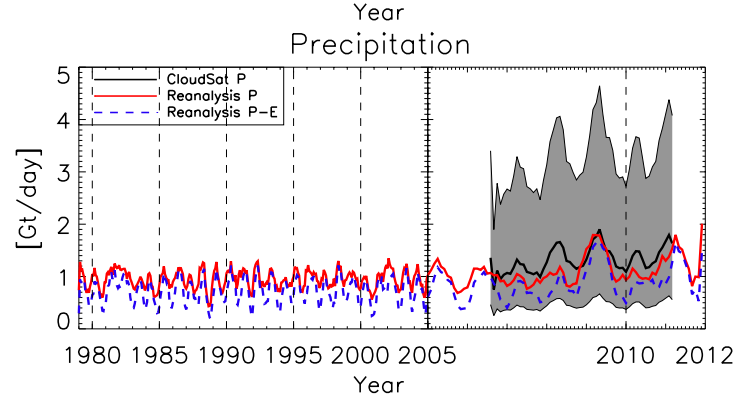
From Boening et al., 2012b (GRL)



CloudSat analysis by M. Lebsock, ERA Interim comparison F. Landerer

1) The problem: *Future Sea Level Rise* dependent on *ocean heat content* and balance between *ocean mass gain and terrestrial water storage*
2) What was done: *Mass gain in East Antarctica* observed by GRACE; CloudSat shows *high precipitation events* in 2009 and 2011
3) Main findings: Snow accumulation explains mass increase. *Unprecedented event in over 3 decades*
4) Next step: How does *balance* between *melting and P-E* affect *sea level?*





Overview of Talk

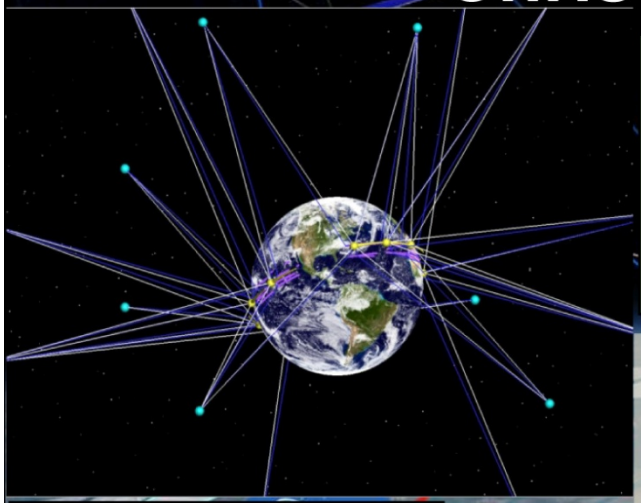
- Introduction – Earth System Science and NASA
- NASA's Contributions to Earth System Science
- Recent NASA Accomplishments
- Some Thoughts on the Future
- Summary

ESD Orbital Flight Portfolio – 2014-2022

- **GPM** (2/2014) – Global Precipitation mapping, w/JAXA
- **OCO-2** (7/2014) – Atmospheric CO_2 monitoring, recovery mission
- **SAGE-III/ISS** (8/2014) – Ozone, Temp, Humidity profiles, w/HEOMD, ESA
- **SMAP** (10/2014) – Soil Moisture and Freeze/Thaw cycling, w/CSA (minor)
- **ICESat-2** (late-2016) – Precision Ice Topography, Ecosystem monitoring
- ***CYGNSS [EV-Mission/1]*** *(late 2016)*
- **GRACE-FO** (8/2017) – Gravity/Ice Mass/Ground Water, w/GFZ & DLR
- ***OCO-3/ISS*** *(Fall 2017)* – CO2 continuity, from ISS, OCO-2 spares
- ***TEMPO [EV-Instrument/1]*** *(2017)*
- **SWOT** (2020) – Wide-swath ocean altimetry, land water, w/CNES
- ***PACE*** *(2020)* – Ocean Color, possibly Aerosols
- ***EV-Instrument/2 Venture-Class*** *(NLT 2020)*
- ***L-band SAR*** *(2021)* – Solid Earth, Cryosphere, Ecosystems, w/ISRO
- ***CLARREO*** *(2022?)* – Precise global radiation balance, possibly w/UK
- ***EV-Mission/2*** *(NLT 2022)*
- ***EV-Instrument/3*** *(NLT 2022)*
- Significant studies ongoing for all other Tier-2 Decadal Survey missions

CYclone Global Navigation Satellite System

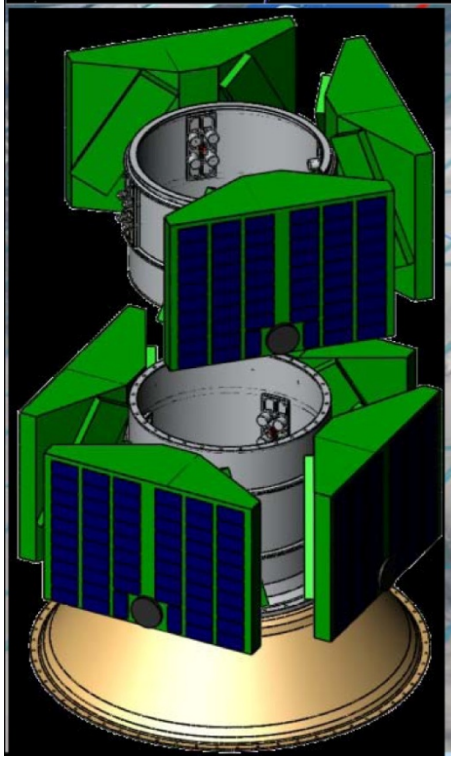
Chris Ruf, PI (U. Michigan)



CYGNSS is a constellation of 8 microsatellites that will use direct and reflected GPS signals to measure ocean surface wind speeds during most precipitation levels. This will increase the understanding of Tropical Cyclone genesis and intensification.

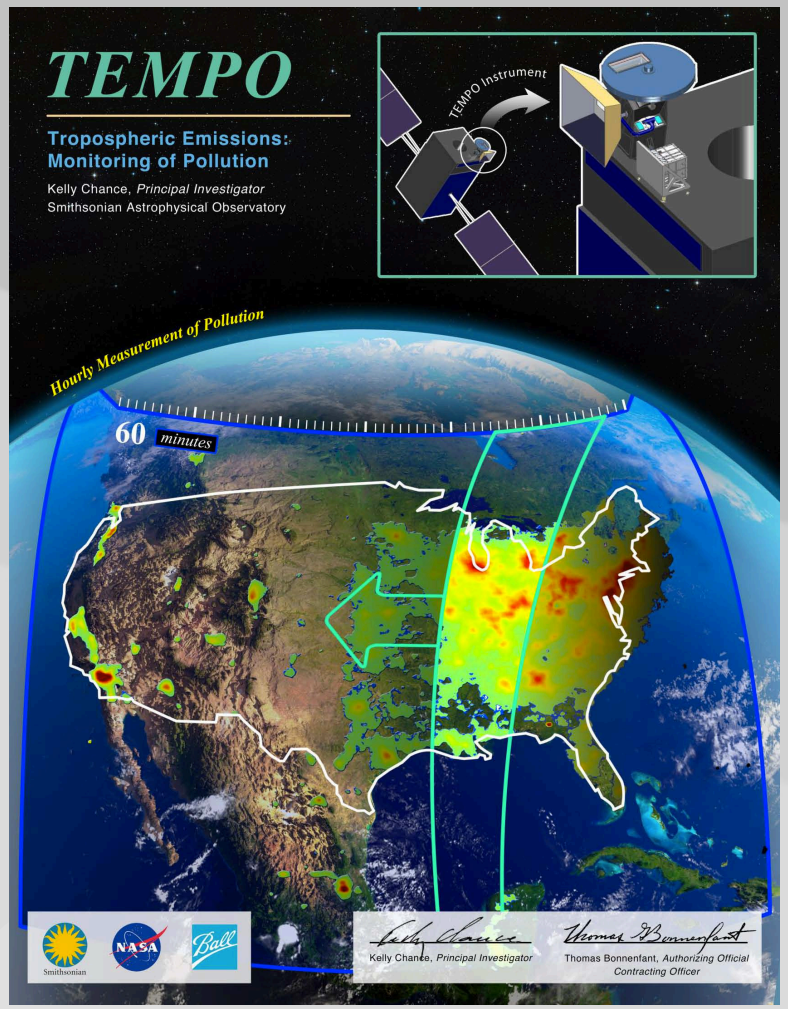
Primary Science Objectives

- **Measure ocean surface wind speed in almost all precipitating conditions including those in the Tropical Cyclone eyewall**
- **Measure ocean surface wind speed in the Tropical Cyclone inner core with sufficient frequency to resolve genesis and rapid intensification.**



Partners	Southwest Research Institute: Primary Observatory development Surrey Satellite Technology, U.S.: Delay Doppler Mapping Instrument NASA Ames Research Center: Deployment Module
Risk	7120.5D Category 3; 8705.4 Payload Risk Class D
LRD	Target date February 2016
Orbit	35 deg inclination, 500 km altitude
Duration	2 year
Payload	Delay Doppler Mapping Instrument
LCC	$151.7M (RY$)

Newly Selected EV-I Mission – TEMPO for Geostationary Atmospheric Composition Measurements



- Tropospheric pollution observations from Geostationary Orbit using a UV and Visible Offner Grating spectrometer
  - It will retrieve Ozone, NO_2, SO_2, aerosols, CH_2O, among others.
- TEMPO will be simultaneous with, and complements related EU/GEMS Sentinel 4 and Korean GEO AQ observations, forming a global AQ constellation in GEO.
- Operational agencies like EPA and NOAA are part of the science team.
- TEMPO will be a pathfinder to using hosted commercial payloads from GEO

The International Effort in Satellites and Global Observations for Climate

- Space-based perspective provides unequalled vantage point for observing entire Earth system
- Efforts of all countries are needed to provide needed breadth, resilience, and innovation
- Cooperation among nations, including data sharing calibration/validation, and assessment, enhances value of all nations' efforts
- Satellite data can support both long-term climate and near-term operational requirements, and be used to improve quality of life for all the world's citizens
- Numerous entities and mechanisms exist that are facilitating this coordination

CEOS Committee on Earth Observation Satellites

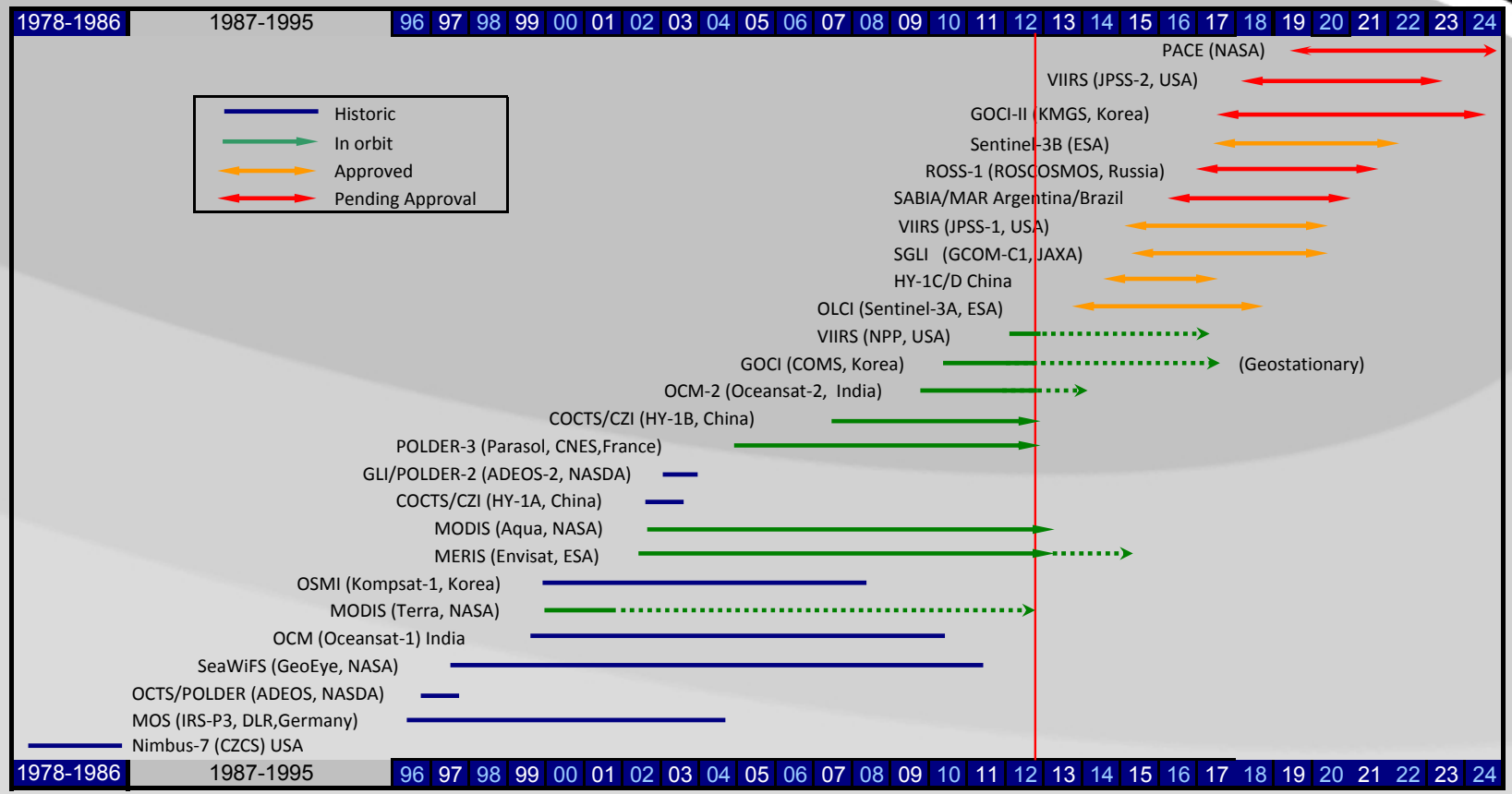
GEO GROUP ON EARTH OBSERVATIONS

GCOS GLOBAL CLIMATE OBSERVING SYSTEM

CGMS COORDINATION GROUP FOR METEOROLOGICAL SATELLITES

World Meteorological Organization
Working together in weather, climate and water

Timeline of Satellite Observations for Ocean Color



Evolution Towards Future Observing Fleet

- Enhanced temporal sampling (higher altitude orbits, constellations of small satellites)
- Enhanced use of active remote sensing techniques (especially radar), providing 3-D information and previously unavailable information
- Enhanced spatial resolution and revisit capabilities
- Enhanced absolute calibration to allow for non-continuous measurements where appropriate
- Reduced size (and costs) of sensors and associated platforms and needed launch vehicles
- Enhanced spectral range and resolution that will provide new and improved information (e.g., first ever global observations of selected environmental parameters)
- Enhanced data delivery through on-board processing, more frequent downlinks, and rapid surface distribution to partners/ users, including rapid targeting of observations by complementary methods and incorporation into forecasting systems

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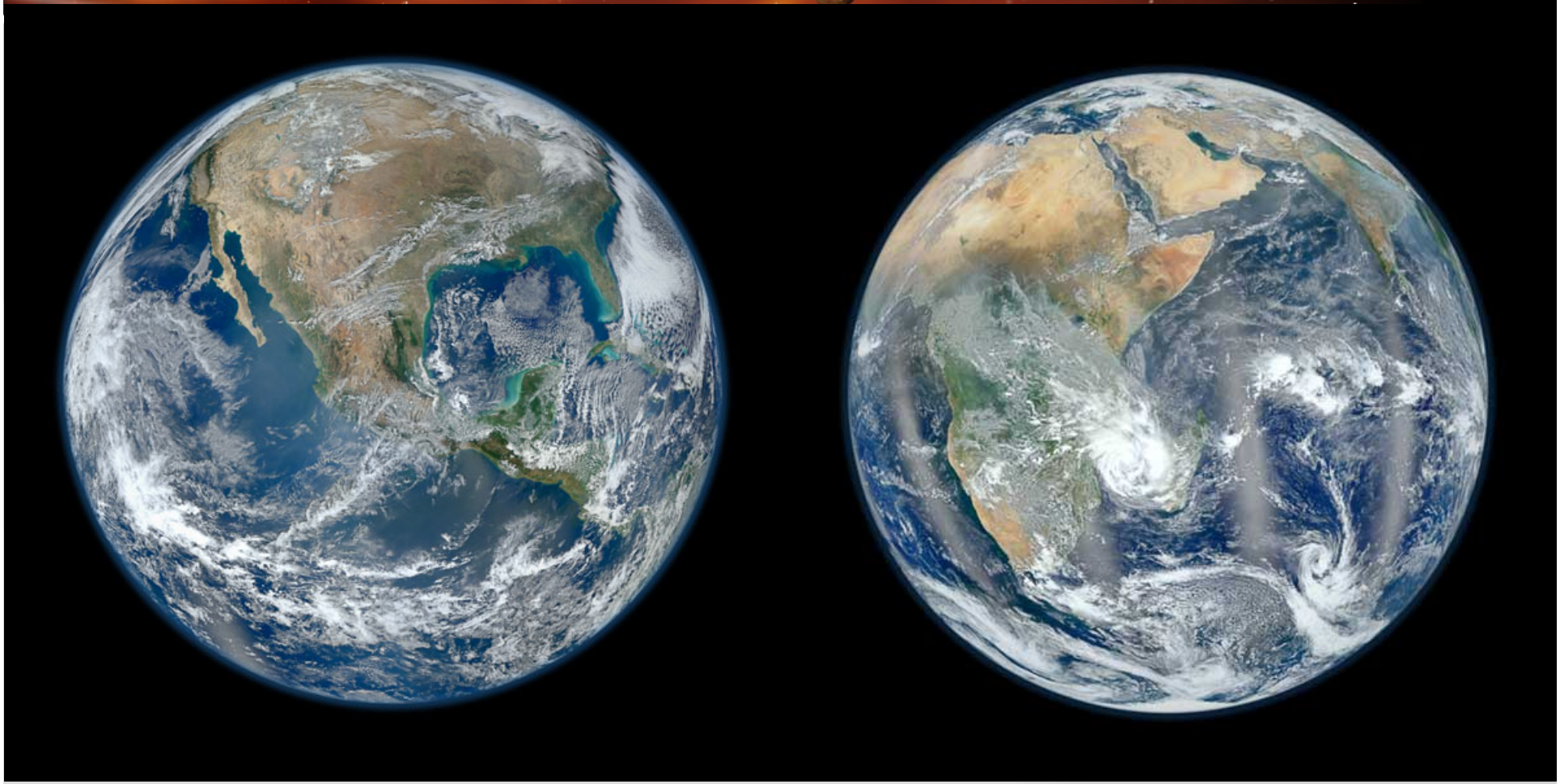
Concluding Messages

- NASA Observations of the Earth system have provided unique insight into the behavior of the Earth system, its evolution, and development of insight into its future.
- Satellite observations provide a marvelous way of looking at the Earth, and are complemented by surface-based and airborne measurements made by NASA and its partners.
- The information we obtain to help us learn about the Earth system also helps to address major societal issues with both short- and long-term implications
- Our ability to add to both our knowledge about our home planet and the usefulness of our knowledge for societal benefit will only increase in the future with advances in observational and information systems technology and increasing role of interagency and international partnerships

A new "Blue Marble"



Suomi-NPP Commissioning Complete
February 23, 2012