Remote Sensing of Climate Change processes in the Earth system

Remote sensing involves the collection of information about the surface of the Earth and its atmosphere by detecting reflected or emitted electromagnetic radiation from sensors aboard airplanes and satellites.

Climate change results from imbalances in the Earth's energy budget, where heat inputs from the sun and Earth's interior are either greater or smaller than heat outputs radiated into space

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DIVISION C

Summary Slide 1

Remote Sensing of Climate Change Processes

2022 event rules

NC Science Olympiad Oct 2021-22 Coaches Institute

REMOTE SENSING

Science Olympiad

See General Rules, Eye Protection & other Policies on www.soinc.org as they apply to every event.

1. **DESCRIPTION**: Participants will use remote sensing imagery, data, and computational process skills to complete tasks related to climate change processes in the Earth system.

   A TEAM OF UP TO: 2 **APPROXIMATE TIME**: 50 minutes

2. **EVENT PARAMETERS**:
   a. Each team may bring four 8.5" x 11" sheets of paper that contain information on both sides in any form and from any source.
   b. Each participant may bring a metric ruler, a protractor, and a non-programmable, non-graphing calculator dedicated to computation.

3. **THE COMPETITION**:
   a. The event will consist of questions and activities testing concepts related to the collection and use of remote sensing data to observe and study climate change processes in the Earth system.
   b. The test should be divided equally, approximately 25 % on each, across the following topic areas:
      i. Remote sensing instrumentation and physics: active vs. passive sensors; optical and infrared imagers; radiometers; LiDAR; radar altimetry; precipitation radar; blackbody radiation; Planck function, Wein's Law; Stefan–Boltzmann Law; beam attenuation; absorption and scattering by aerosols; refraction and refractive indices; scattering, **gravity.**
      ii. Interpretation of remote sensing images and data sets from the following satellites: Atmospheric and sea-surface temperature (GOES–16, ATMS and CrIS on NPP); global mean temperature; energy flux (CERES on NPP); optical, infrared and Doppler radar imagery of clouds and precipitation (MODIS, CALIPSO, CloudSat); CO2 cycle (OCO-2); aerosol scattering, absorption and optical depth (MODIS); detection of trace gas concentrations by satellites (OCO-2, AURA); sea level rise and surface waves (radar altimeters, especially Topex-Poseidon, Jason-1 and Jason-3, **Grace**).
      iii. Climate processes and climate change: greenhouse gases (concentrations and distribution) and trace gas concentrations; clouds and radiation; aerosol forcing; carbon cycle; surface albedo; comparison of remote sensing data with climate model data
      iv. Using, applying, and interpreting the output of small-scale models of planetary energy balance

4. **SAMPLE QUESTIONS/TASKS**:
   a. Use a comparison of visible and IR satellite images of clouds to interpret relationships between clouds and outgoing radiation, and to explain how clouds influence the Earth's radiative balance.
   b. Given information characterizing the extinction coefficient of a layer of dust in the atmosphere and the observed reduction in outgoing radiation, calculate the thickness of the dust layer.
   c. Modify a simple energy balance model to include an idealized greenhouse gas response to these CO2 concentrations and show how this affects global atmospheric temperature.
   d. Interpret a pair of radar altimeter returns to look at differences in significant wave height.
   e. **Interpret signals of changes in groundwater storage from Grace gravity data.**

5. **SCORING**: High score wins. Points will be awarded for the quality and accuracy of responses. Selected questions may be used as tiebreakers.

Recommended Resources: The Science Olympiad Store (store.soinc.org) carries a varient of resources to purchase for this event; other resources are in the Event Page at soinc.org

This event is sponsored by Lockheed Martin

2022 rules additions: 3.b.i. remote sensing instrumentation and physics of GRAVITY, 3.b.ii. the GRACE satellite mission, 4.e. interpreting changes in groundwater storage from GRACE gravity data

Summary Slide 2

What do students need to be familiar with ?

1. Climate processes and climate change, including climate models related to the Earth's energy balance
(how the Earth system works and how scientists model it)

2. The basics of modern remote sensing (RS): electromagnetic radiation (EMR), physical interactions EMR in the atmosphere, RS instrumentation & platforms
(how RS information is collected)

3. NASA satellite missions that collect data on climate change processes in the Earth system: oceans, surface & atmosphere
(specific RS satellites & sensor systems for this event's focus)

4. Remote sensing instrumentation and physics
(the physics for the event-specific the satellites & sensors)

5. Remote sensing data & small-scale models of planetary energy balance
(how to interpret RS data & simple models of planetary energy balance)

Remote Sensing Of Climate Change processes in the Earth system

A study plan for students

Immerse yourself in remote sensing. Don't limit yourself to this year's event focus …

View the Earth Observatory (EO) Image of the Day EVERY DAY. For those images that address aspects of this year's CLIMATE CHANGE event; read the article, pay attention to the technical descriptions, follow the hotlinks (especially those to the **event-specific** sensors and satellites), download the image and bookmark all satellite and sensor webpages.

Read and understand the Fundamentals of Remote Sensing tutorial at the Canadian Center for Remote Sensing website (CCRS). This can be downloaded as a PDF.

Read and understand the Fundamentals of Remote Sensing webinar slides at NASA's Applied Remote Sensing Training website. This can be downloaded as a PDF

Download and study the "The role of satellite remote sensing in climate change studies (Nature of Climate Change review article" … (posted on NCSO event resources webpage for Remote Sensing).

Learn about the physics of the Earth system interactions (ocean, surface, atmosphere & EMR) that affect the Earth's energy balance …

Follow the Science Feature Articles link on he Earth Observatory website. Look through the archive for articles that relate to CLIMATE CHANGE and REMOTE SENSING. Read and download these. Follow hotlinks in the articles to learn more about aspects of climate change and sensor systems .

Make sure you focus on & understand the processes listed in paragraph 3b of the 2022 event sheet.

Learn all about the event-specific remote sensing satellites and sensor systems listed in the event sheet …

Go to each home page for the specified satellite missions (often NASA) and learn about the satellite orbital characteristics and each of the sensor systems collecting images or data on climate change related phenomenon. Follow hotlinks to the satellite and sensor system home pages (often NASA Labs or major contractors) and information from the NASA Earth Science Reference Handbook (see links from Summary Slides #10 and #11).

Learn about the **Giovanni** Data portal and become familiar with the simple energy balance models from U of Chicago

Access and become familiar with **scientific data products** from the satellite missions and sensor systems. These are frequently presented graphically as regional or world-wide maps of temperature, sea level, glacier surface elevations, atmospheric chemical constituents, gravitational anomalies, etc. Test questions may ask you to interpret data presented in similar formats.

Download and read all the resources available on the NCSO Remote Sensing Resources webpage. Most are referenced in this NCSO Coaches Institute Summary.

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1. Where to learn about climate processes, Earth's energy balance and models of the Earth system ?

Climate & Earth's energy budget_ an Earth Observatory Feature Article
http://earthobservatory.nasa.gov/Features/EnergyBalance/page1.php
Global Climate Change: Vital Signs of the Planet @ NASA Global Climate Change
http://climate.nasa.gov/
http://climate.nasa.gov/evidence/
The study of Earth as an integrated system @ NASA Global Climate Change
http://climate.nasa.gov/nasa_science/science/

The Habitable Planet_ Radiative balance & greenhouse effect @ Annenberg Learner
https://www.learner.org/courses/envsci/unit/text.php?unit=2&secNum=3
The Habitable Planet_ Feedbacks in the atmosphere @ Annenberg Learner
https://www.learner.org/courses/envsci/unit/text.php?unit=2&secNum=9
The Habitable Planet_ Tipping Earth's energy balance @ Annenberg Learner
https://www.learner.org/courses/envsci/unit/text.php?unit=12&secNum=2
The Habitable Planet_ Aerosols @ Annenberg Learner
https://www.learner.org/courses/envsci/unit/text.php?unit=11&secNum=5

The role of satellite remote sensing in climate change studies (Nature of Climate Change review article … (to be posted on NCSO event resources webpage for Remote Sensing)

1. In your study of the physics of electromagnetic radiation and Earth's energy balance , be sure to learn about the following EMR & atmospheric physics processes listed in paragraph 3b of the 2022 event sheet.

Greenhouse gases (concentrations & distribution)
Trace gas concentrations
Clouds & radiation
Aerosol forcing
Carbon cycle
Surface albedo

Blackbody radiation
Planck function
Wein's Law
Stefan-Boltzmann Law
Beam attenuation
Absorption & scattering by aerosols
Refraction & refractive indices
Scattering

Relationships between Earth's gravitational changes and groundwater storage (new for 2022)

2. Where to learn about the basics of modern remote sensing, how remote sensing data is collected, the physics of electromagnetic radiation, how a digital image is created, how gravitational anomalies can detect changes in groundwater storage (new for 2022)?

Fundamentals of Remote Sensing Tutorial @ Canadian Center for Remote Sensing website (CCRS).
http://www.nrcan.gc.ca/earth-sciences/geomatics/satellite-imagery-air-photos/satellite-imagery-products/educational-resources/9309

Remote Sensing Feature Article @ Earth Observatory
http://earthobservatory.nasa.gov/Features/RemoteSensing/

Fundamentals of remote sensing training webinar@ NASA Applied Remote Sensing Trainings
http://arset.gsfc.nasa.gov/webinars/fundamentals-remote-sensing
http://arset.gsfc.nasa.gov/sites/default/files/airquality/webinars/Fundamentals/Fundamentals%20of%20Remote%20Sensing%20-%20Session%201_final.pdf

Tour of the Electromagnetic Spectrum @ NASA Mission:Science …
http://missionscience.nasa.gov/ems/index.html

Research satellites for atmospheric sciences, from 1978 to 2001 @ Earth Observatory
http://earthobservatory.nasa.gov/Features/RemoteSensingAtmosphere/

Principles of Remote Sensing, an introductory textbook; ITC 2009.

a comprehensive introduction to satellite-based remote sensing and instruments.

… Chapter 14.3 references Gravity and magnetic anomaly mapping

(this .pdf will be posted on the NCSO Remote Sensing resources page)

2. Where to learn about the basics of modern remote sensing, … ? (continued)

Space-based observations of Earth_ Feature Article @ Earth Observatory
http://earthobservatory.nasa.gov/Features/Observing/

Catalog of Earth satellite orbits_ Feature Article @ Earth Observatory
http://earthobservatory.nasa.gov/Features/OrbitsCatalog/

Space-based observations of the Earth_ Feature Article @ Earth Observatory
http://earthobservatory.nasa.gov/Features/Observing/

How to interpret a satellite image? Feature Article @ Earth Observatory
http://earthobservatory.nasa.gov/Features/ColorImage/

How to interpret a false-color satellite image_ Feature Article @ Earth Observatory
http://earthobservatory.nasa.gov/Features/FalseColor/

How LANDSAT images are made_ NASA & USGS LANDSAT website
http://landsat.gsfc.nasa.gov/wp-content/uploads/2012/12/How2make.pdf

2. In your study of modern remote sensing methods, be sure to learn about the following remote sensing processes listed in paragraph 3b of the 2022 event sheet.

Active & passive sensors

Optical & infrared imagers

Radiometers

LiDAR

Radar altimetry

Precipitation radar

Gravitational Anomaly Sensing (new for 2022 event)

*3. Where to learn about the **event-specific** NASA satellite missions used in researching climate change processes?*

Event-Specific **... NASA Earth Sensing Satellites**

AURA http://aura.gsfc.nasa.gov/ http://atrain.nasa.gov/publications/Aura.pdf

CALIPSO http://www-calipso.larc.nasa.gov/ http://atrain.nasa.gov/publications/CALIPSO.pdf

CLOUDSAT /http://cloudsat.atmos.colostate.edu http://atrain.nasa.gov/publications/CloudSat.pdf

GOES-16 http://www.goes-r.gov/ http://www.goes-r.gov/spacesegment/abi.html

Jason-1 & -3, TOPEX-Poseidon https://sealevel.jpl.nasa.gov/missions/
https://www.nesdis.noaa.gov/jason-3/ https://sealevel.jpl.nasa.gov/files/ostm/tp-fact-sheet.pdf

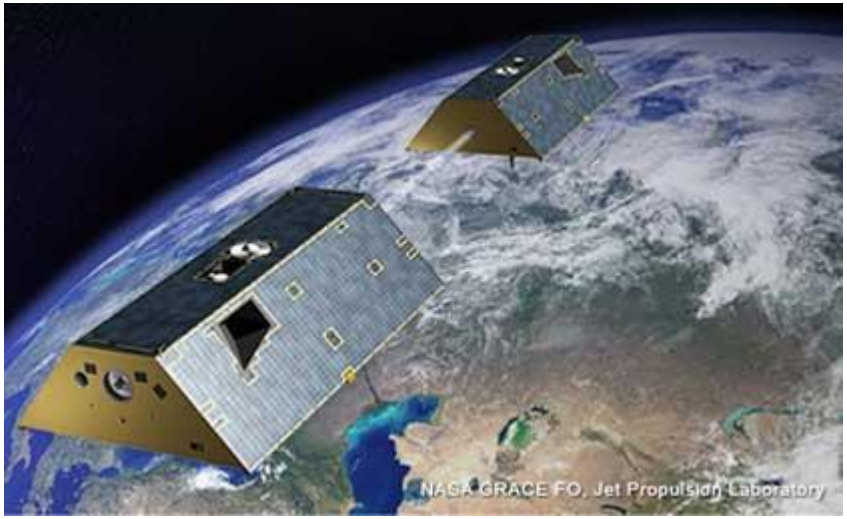
OCO-2 http://oco.jpl.nasa.gov/mission/html http://atrain.nasa.gov/publications/OCO.pdf

Suomi NPP https://jointmission.gsfc.nasa.gov/spacecraft.html
https://www.nasa.gov/mission_pages/NPP/main/index.html
https://www.nasa.gov/pdf/596329main_NPP_Brochure_ForWeb.pdf

GRACE & GRACE-FO

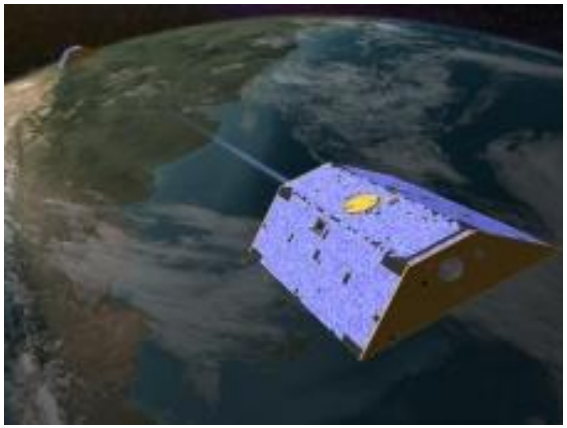
Event-Specific ... NASA Earth Sensing Satellites

GRACE ... Gravity Recovery and Climate Experiment
GRACE-FO (Follow-On)



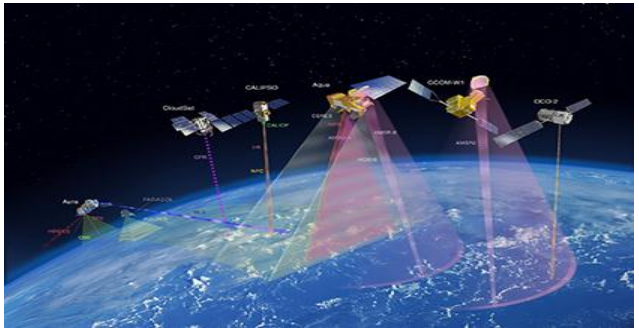
NASA GRACE Mission website
https://www.nasa.gov/mission_pages/Grace/index.html

JPL GRACE Mission website
https://grace.jpl.nasa.gov/
JPL GRACE-FO (Follow-On) Mission website
https://grace.jpl.nasa.gov/mission/grace-fo/
https://gracefo.jpl.nasa.gov/



U of Texas GRACE Mission website
http://www2.csr.utexas.edu/grace/

4. Where to learn about the **event-specific** sensors used aboard NASA satellite missions to research climate change ?



Event-specific … Satellite-based Sensor Systems

ABI (on GOES) http://www.goes-r.gov/spacesegment/abi.html

ATMS https://jointmission.gsfc.nasa.gov/atms.html

CERES http://ceres.larc.nasa.gov/

CrIS https://jointmission.gsfc.nasa.gov/cris.html

MODIS https://modis.gsfc.nasa.gov/about/ http://aqua.nasa.gov/modis

LiDAR http://www-calipso.larc.nasa.gov/

CLOUDSAT CPR http://cloudsat.atmos.colostate.edu/instrument

OCO-2 Spectrometers http/://oco.jpl.nasa.gov/observatory/instrument

OSTM/Poseidon Radar altimeters

https://sealevel.jpl.nasa.gov/technology/technologyinstrumentdescription/instrumentdescriptaltimeter/

https://www.nesdis.noaa.gov/jason-3/pdf/Jason-3%20Poseidon%203B%20Altimeter.pdf

VIIRS (on SuomiNPP) https://jointmission.gsfc.nasa.gov/viirs.html

https://www.youtube.com/watch?v=HAK7VxjT0h0

https://www.youtube.com/watch?v=l3rO41usObk

GRACE sensors

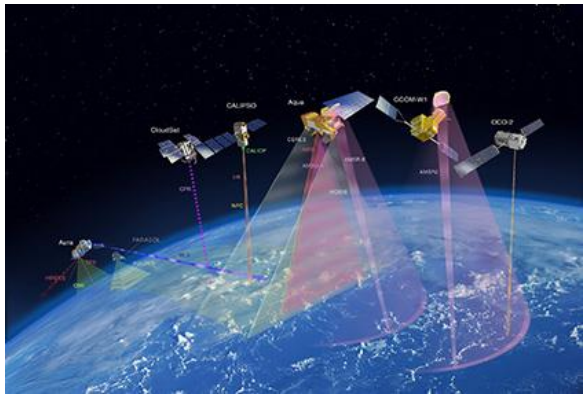
Event-specific … Satellite-based Sensor Systems

GRACE sensors … Gravity Recovery and Climate Experiment

JPL GRACE Mission website …
https://grace.jpl.nasa.gov/mission/grace/
https://grace.jpl.nasa.gov/system/internal_resources/details/original/97_GRACE_Fact_Sheet.pdf
https://grace.jpl.nasa.gov/mission/grace-fo/

U of Texas GRACE Mission website …
Science Instrument System (SIS)
http://www2.csr.utexas.edu/grace/spacecraft/sis.html

*4. Where to learn about the **event-specific** (instrumentation and) physics of climate change related data observed by the NASA Earth sensing missions?*



***Event-specific* ... EMR & physics phenomenon**

Atmospheric & sea-surface temperature ... **ATMS, CrIS**

Global mean temperature & energy flux ... **CERES**

Optical, infrared & Doppler radar imagery of clouds & precipitation ...
ABI, MODIS, VIIRS, CALIPSO LiDAR, CLOUD-SAT CPR

CO_2 Cycle ... **OCO-2 Spectrometers**

Aerosol scattering, absorption and optical depth ... **MODIS, VIIRS**

Detection of trace gas concentrations by satellites ... **OCO-2, AURA**

Sea level rise and surface waves ...
TOPEX-Poseidon, JASON-1 & 3 radar altimeters

Gravitational changes and groundwater storage ... **GRACE instrumentation**

Event-specific … EMR & physics phenomenon

Relationships between Gravitational anomaly changes and groundwater storage …

Gravity 101. Why study gravity to learn about water?
https://grace.jpl.nasa.gov/mission/gravity-101

Earth Observatory ARTICLE, March 2004. Gravity Recovery and Climate Experiment (GRACE) https://earthobservatory.nasa.gov/features/GRACE/page1.php

Earth Observatory ARTICLE, September 2012. The Gravity of Water
https://earthobservatory.nasa.gov/features/GRACEGroundwater

JPL News. Parched West Is Using Up Underground Water: NASA/UCI
https://www.jpl.nasa.gov/news/parched-west-is-using-up-underground-water-nasauci

JPL News. NASA Satellite Data Give Early Clues to Flood Danger
https://www.jpl.nasa.gov/news/nasa-satellite-data-give-early-clues-to-flood-danger

JPL News. NASA Helps Pinpoint Glaciers' Role in Sea Level Rise
https://www.jpl.nasa.gov/news/nasa-helps-pinpoint-glaciers-role-in-sea-level-rise

5. Where to learn how to access & interpret Remote sensing data sets & use simple models of planetary energy balance

Using ***Giovanni*** in education @ geo.mtu
http://www.geo.mtu.edu/~scarn/teaching/GE4250/lloyd_NASA_Giovanni.pdf
Using the ***Giovanni*** system @ NSF - Carleton College
http://serc.carleton.edu/eyesinthesky2/week4/using_giovanni.html
Giovanni data portal @ NASA Earthdata
http://giovanni.gsfc.nasa.gov/giovanni/
Giovanni - Access and Visualize Earth Science Data Online @ NASA Earthdata – YouTube
https://www.youtube.com/watch?v=Hc53UA9dv9A
Giovanni – Data access portal through Goddard Earth Sciences Data & Info Ctr
http://disc.sci.gsfc.nasa.gov/atdd/atdd/overview

MODTRAN_ modeling infrared light in the atmosphere @ Uchicago.edu
http://climatemodels.uchicago.edu/modtran/
RRTM_ modeling Earth's Energy Budget @ UChicago.edu
http://climatemodels.uchicago.edu/rrtm/rrtm.doc.html
Online course on energy balance modeling @ shodor.org
http://www.shodor.org/master/environmental/general/energy/index.html

5. Where to learn how to access & interpret Remote sensing data sets (continued)

Access and become familiar with **scientific data products** from the satellite missions and sensor systems. These are frequently presented graphically as regional or world-wide maps of temperature, sea level, glacier surface elevations, atmospheric chemical constituents, gravitational anomalies, etc. Test questions may ask you to interpret data presented in similar formats.

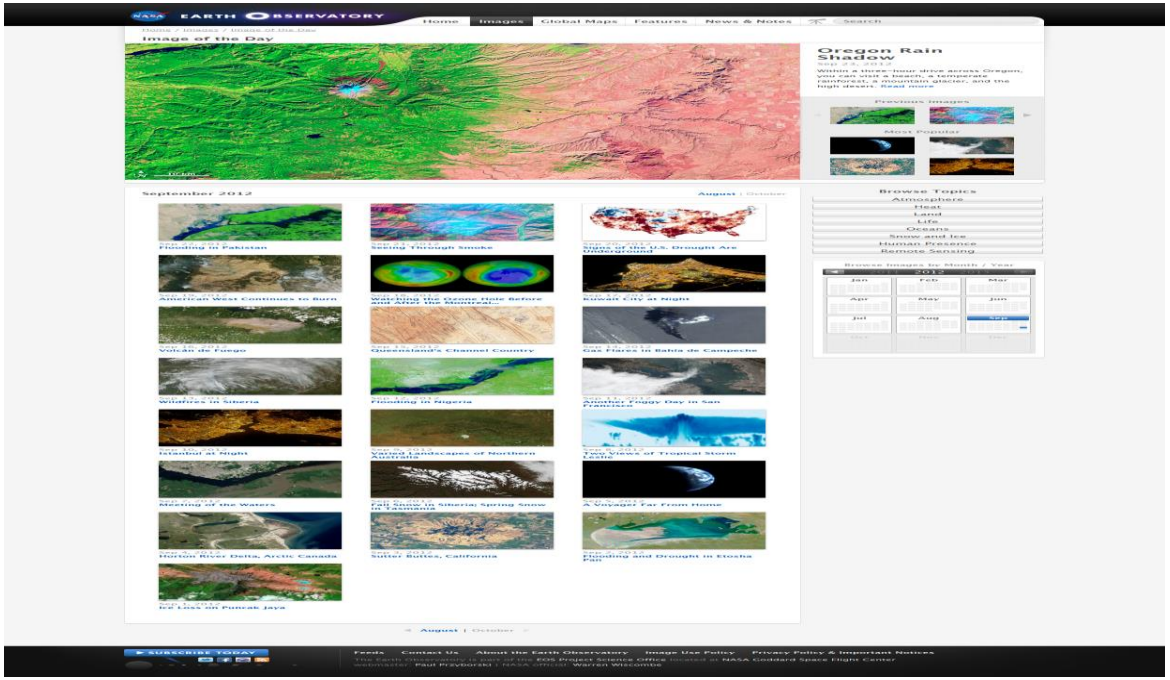
The following links access portals to scientific data products from the GRACE and GRACE Follow-On missions. Similar portals are available from websites for other NASA Earth sensing missions and instrumentation previously referenced in Slides #10.1 and #11.1.

JPL GRACE and GRACE-FO Mission websites …
https://grace.jpl.nasa.gov/data/get-data/
https://gracefo.jpl.nasa.gov/data/grace-fo-data/

U of Texas GRACE Mission website …
Science Instrument System (SIS)
http://www2.csr.utexas.edu/grace/science/

Earth Observatory Image of the Day

… http://earthobservatory.nasa.gov/IOTD/



Earth Observatory (EO) publishes a daily image of the Earth from space.

Each image is described, along with an explanation of the natural processes being observed, and the science that can be accomplished using the unique perspective gained from orbit.

An image archive database is readily available.

Many of the images used to create the NC Science Olympiad event tests come directly from the EO Image of the Day archive.

Remote Sensing Of Climate Change processes in the Earth system

Earth Observatory Image of the Day

... http://earthobservatory.nasa.gov/IOTD/

Earth Observatory (EO) Image of the Day.

A short article accompanies each Image of the Day.

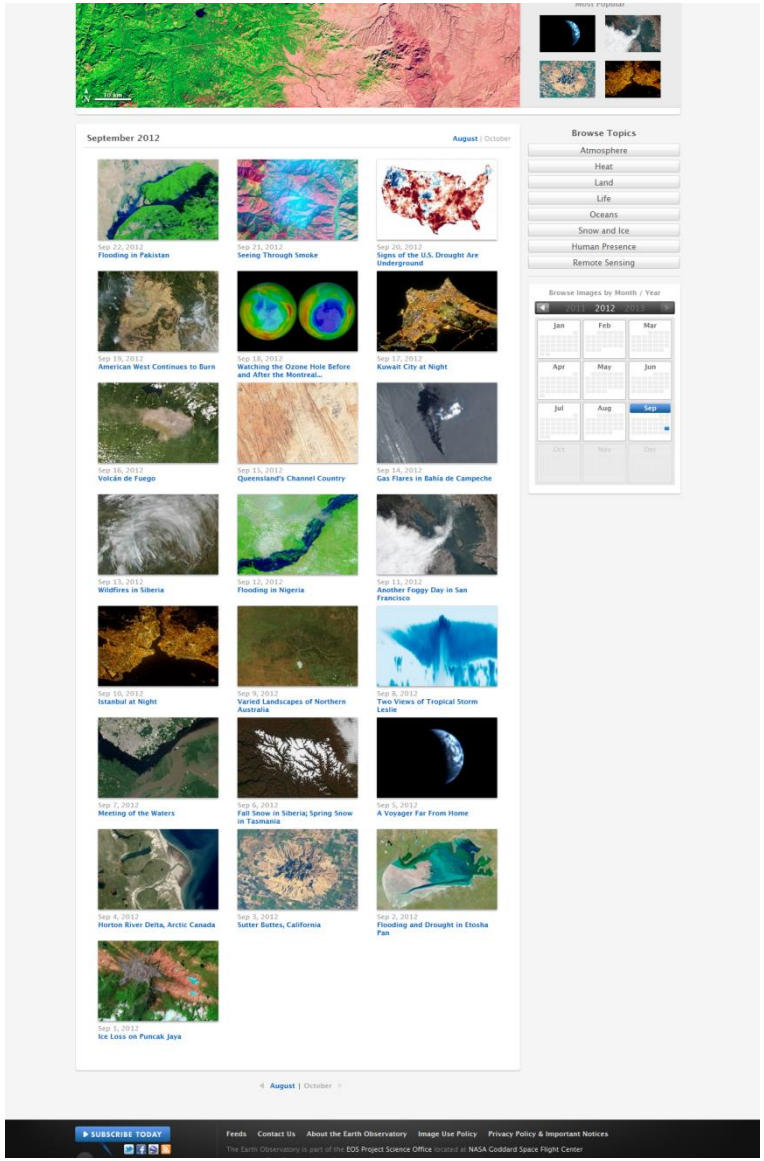
Most articles describe the date and location; interactions between geosphere, hydrosphere and biosphere; importance to society and ecosystems; and the satellite sensor system used to capture the image.

Time-lapsed comparison images are frequently shown.

Remote Sensing Of Climate Change processes in the Earth system

Earth Observatory Image of the Day

… http://earthobservatory.nasa.gov/IOTD/



Earth Observatory (EO) Image of the Day archive.

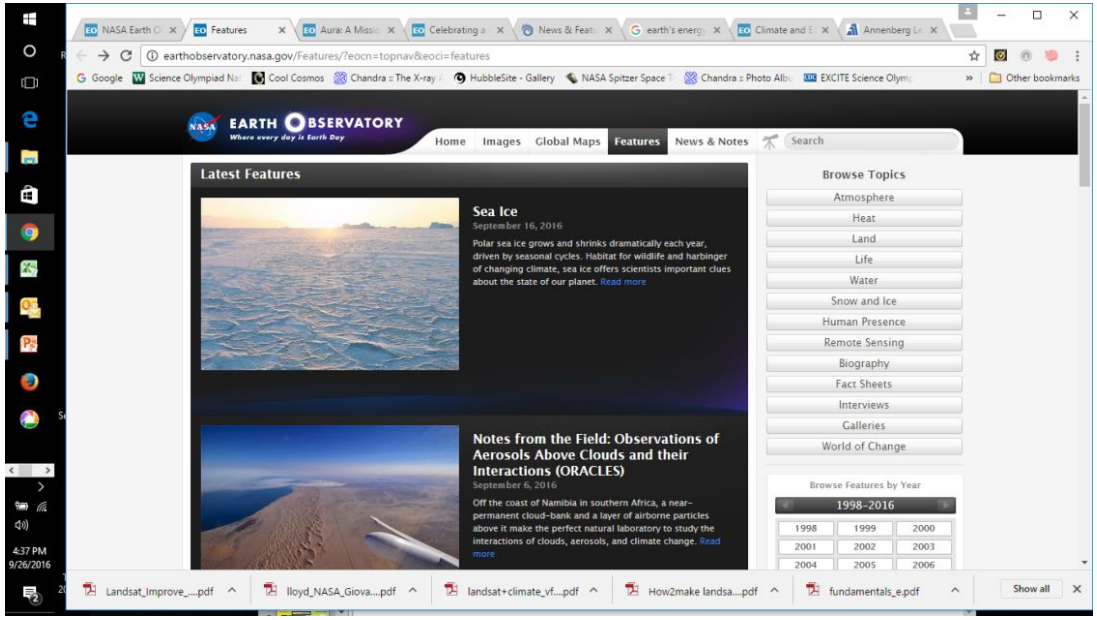
Monthly indexes of archived Images of the Day are accessible from the Image of the Day home page.

Many of the satellite images used to create the NC Science Olympiad event tests come directly from the EO Image of the Day archive. Reading the scientific descriptions for climate change-related images will help students prepare for the 2021-22 event.

Remote Sensing Of Climate Change processes in the Earth system

Earth Observatory Feature Articles

http://earthobservatory.nasa.gov/Features/?eocn=topnav&eoci=features



Earth Observatory (EO) Feature Articles.

Yearly and topical indexes of archived Feature Articles are accessible from the EO Features homepage. Topic indexes include Remote Sensing, Atmosphere, Water, etc.

Descriptions of climate processes and the remote-sensing approaches used to collect and analyze earth science data are discussed in depth. Reading the articles related to climate change will help students understand both the basic science of climate change, and the role of remote sensing in observing, evaluating, and understanding climate change.

Earth Observatory Feature Articles

http://earthobservatory.nasa.gov/Features/?eocn=topnav&eoci=features

Related Earth Observatory (EO) Feature Articles.

AURA- A mission dedicated to the Health of Earth's Atmosphere
http://earthobservatory.nasa.gov/Features/Aura/

An **AURA** of success
http://earthobservatory.nasa.gov/Features/Gallery/aura.php?all=y

Celebrating a Decade of **CLOUDSAT** and **CALIPSO**
http://earthobservatory.nasa.gov/Features/Gallery/cloudsat.php

Earth's temperature tracker
http://earthobservatory.nasa.gov/Features/GISSTemperature/

Teaching old data new tricks
http://earthobservatory.nasa.gov/Features/scatter/

CALIPSO: A global perspective of clouds & aerosols from space
http://earthobservatory.nasa.gov/Features/CALIPSO/

Research satellites for atmospheric sciences, from 1978 to 2001_CERES, MODIS
http://earthobservatory.nasa.gov/Features/RemoteSensingAtmosphere/

Aerosols: Tiny particles, big impact
http://earthobservatory.nasa.gov/Features/Aerosols/

Arctic Reflection: Clouds replace snow & ice as solar reflector
http://earthobservatory.nasa.gov/Features/ArcticReflector/

Double Vision: Monitoring Ocean Surface Topography
https://earthobservatory.nasa.gov/Features/jason/

GRACE …

Related Climate process and modeling webpages and activities

Clouds in the Balance_ Earth Observatory (EO) Feature Articles.
http://earthobservatory.nasa.gov/Features/CloudsInBalance/
Global Warming_ Earth Observatory (EO) Feature Articles.
http://earthobservatory.nasa.gov/Library/GlobalWarmingUpdate/
Volcanoes & Climate Change_ Earth Observatory (EO) Feature Articles.
http://earthobservatory.nasa.gov/Features/Volcano/

Tropical Atlantic Aerosols_ MY NASA data lesson
http://mynasadata.larc.nasa.gov/lesson-plans/my-nasa-data-lesson/?passid=56
What is the Future of Earth's Climate?
https://concord.org/stem-resources/what-future-earths-climate

NWS Jetstream educational topic matrix @ National Weather Service (NWS)
http://www.srh.noaa.gov/jetstream/matrix.html
NWS JetStream Remote Sensing @ NWS
http://www.srh.noaa.gov/jetstream/remote/remote_intro.html
NWS JetStream Energy Balance
http://www.srh.noaa.gov/jetstream/atmos/energy.html

NC SCIENCE OLYMPIAD OCT 2021-22 COACHES INSTITUTE

Remote Sensing Of Climate Change processes in the Earth system

nature climate change

REVIEW ARTICLE

PUBLISHED ONLINE: 15 SEPTEMBER 2013 | DOI: 10.1038/NCLIMATE1908

The role of satellite remote sensing in climate change studies

Jun Yang[1], Peng Gong[1,2,3]*, Rong Fu[4], Minghua Zhang[5], Jingming Chen[6,7], Shunlin Liang[8,9], Bing Xu[8,10], Jiancheng Shi[2] and Robert Dickinson[4]

Satellite remote sensing has provided major advances in understanding the climate system and its changes, by quantifying processes and spatio-temporal states of the atmosphere, land and oceans. In this Review, we highlight some important discoveries about the climate system that have not been detected by climate models and conventional observations; for example, the spatial pattern of sea-level rise and the cooling effects of increased stratospheric aerosols. New insights are made feasible by the unparalleled global- and fine-scale spatial coverage of satellite observations. Nevertheless, the short duration of observation series and their uncertainties still pose challenges for capturing the robust long-term trends of many climate variables. We point out the need for future work and future systems to make better use of remote sensing in climate change studies.

Observational data and model simulations are the foundations of our understanding of the climate system[1]. Satellite remote sensing (SRS) — which acquires information about the Earth's surface, subsurface and atmosphere remotely from sensors on board satellites (including geodetic satellites) — is an important component of climate system observations. Since the first space observation of solar irradiance and cloud reflection was made with radiometers onboard the Vanguard-2 satellite in 1959[2], SRS has gradually become a leading research method in climate change studies[3].

The use of satellites allows the observation of states and processes of the atmosphere, land and ocean at several spatio-temporal scales. For instance, it is one of the most efficient approaches for monitoring land cover and its changes through time over a variety of spatial scales[4,5]. Satellite data are frequently used with climate models to simulate the dynamics of the climate system and to improve climate projections[6]. Satellite data also contribute significantly to the improvement of meteorological reanalysis products that are widely used for climate change research, for example, the National Center for Environmental Prediction (NCEP) reanalysis[7]. The Global Climate Observing System (GCOS) has listed 26 out of 50 essential climate variables (ECVs) as significantly dependent on satellite observations[8]. Data from SRS is also widely used for developing prevention, mitigation and adaptation measures to cope with the impact of climate change[9].

Despite the aforementioned contributions of SRS, there are concerns about the suitability of satellite data for monitoring and understanding climate change[10]. Climate change studies require observations to be calibrated/validated and consistent, and to provide adequate temporal and spatial sampling over a long period of time[11]. However, satellite data often contain uncertainties caused by biases in sensors and retrieval algorithms, as well as inconsistencies between continuing satellite missions with the same sensors. The use of satellite observations in climate change studies requires a clear identification of such limitations.

In this Review we discuss the contribution of SRS to our understanding of climate change and the processes involved. We focus on SRS-enabled discoveries that have substantiated or challenged our fundamental knowledge of climate change. Our main goal is to reveal the unique contributions and major limitations of SRS as used in these studies. Technical details on instrumentation and retrieval methods can be found in a recent review[12].

Observations of the climate system

Conventional land-based observations are typically collected at fixed intervals with limited spatial coverage, whereas SRS allows for continual monitoring on the global scale. This has greatly enhanced our understanding of the climate system and its variations (Fig. 1).

Global warming. The warming trend of the Earth's mean surface temperature since the late nineteenth century has provided evidence for anthropogenic influences on global climate[13]. This trend was first identified by analysing anomalies in time series of near-surface air temperature over the land that were recorded by weather stations[14]. However, the existence of the trend was consistently challenged due to the biases in weather records[15] caused by such things as poor siting of the instrumentation and the influence of land-use/land-cover changes. Satellite data provides an independent way to investigate global temperature trends, particularly at the ocean surface and in the atmosphere.

The sea surface temperatures (SSTs) of the oceans — which are directly related to heat transfer between the atmosphere and oceans — serve as important indicators of the state of the climate system[16]. The Advanced Very High Resolution Radiometer on board the National Oceanic and Atmospheric Administration (NOAA) satellites allows us to monitor the SST worldwide. An increase in SST has been observed in all ocean basins since the 1970s, with an average estimated increase of 0.28 °C from 1984 to 2006[17]. This

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ERRATA … (changes in the October 2, 2021 Remote Sensing event Summary compared with previously posted .pdf files)

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2. Handout Slide #x