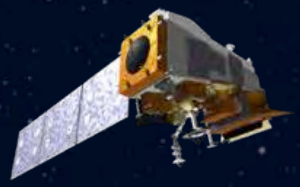
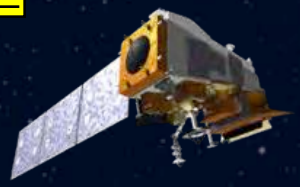


The Use of VIIRS for Environmental Intelligence

Mitch Goldberg, Program Scientist
Joint Polar Satellite System
National Environmental Satellite, Data, and Information Service
National Oceanic and Atmospheric Administration

2015 JACIE

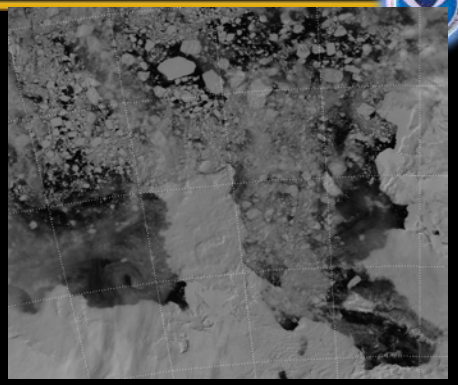


Why is NOAA interested in JACIE?

Why JACIE?

Quality image data is crucial to the Federal Government to aid in decision-making for global problems, such as climate change, food supply monitoring, and deforestation, and specific problems, such as the management of federal lands, defense and homeland security.

NOAA regularly uses NOAA provided imagery for environmental intelligence, and for significant events high spatial resolution and other technologies will be helpful.



Ice Monitoring

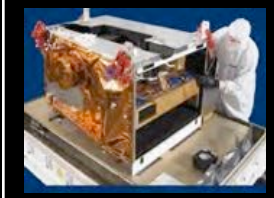
March 2012 – Harmful Algal Blooms Lake Erie

Fire detection

Upcoming Opportunities for Collaboration

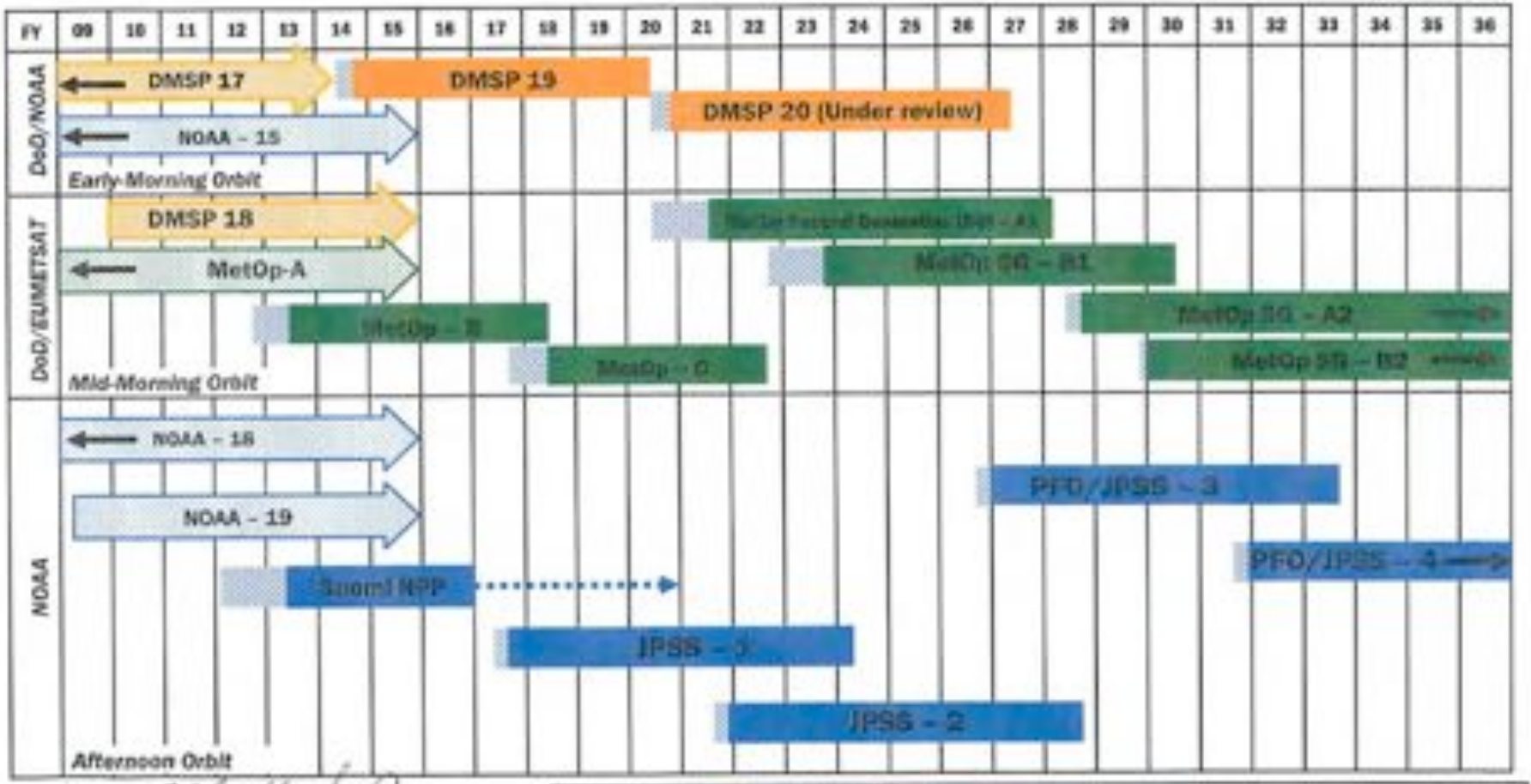
- More countries are joining the remote-sensing community
- Big Data / Cooperative Research And Development Agreement (CRADA)
  - DOC's big data project with Amazon Web Services, Google Cloud Platform, IBM, Microsoft Corp and the Open Cloud Consortium will explore ways of bringing the DOC closer to its goal of unleashing its vast resources of environmental data– transforming DOC data capabilities and supporting a data-driven economy.

JPSS is NOAA's next generation polar-orbiting satellite - JPSS-1 launch in March 2017

JPSS Instrument		Measurement
	**ATMS** - Advanced Technology Microwave Sounder	ATMS and CrIS together provide high vertical resolution **temperature** and **water vapor information needed to maintain and improve forecast skill** out to 5 to 7 days in advance for extreme weather events, including hurricanes and severe weather outbreaks
	**CrIS** - Cross-track Infrared Sounder	
	**VIIRS** – Visible Infrared Imaging Radiometer Suite	VIIRS provides many **critical imagery products** including snow/ice cover, clouds, fog, aerosols, fire, smoke plumes, vegetation health, phytoplankton abundance/chlorophyll
	**OMPS** - Ozone Mapping and Profiler Suite	Ozone spectrometers for **monitoring ozone** hole and recovery of stratospheric ozone and for UV index forecasts
	**CERES** - Clouds and the Earth's Radiant Energy System	Scanning radiometer which supports studies of Earth Radiation Budget

NOAA & Partner Polar Weather Satellite Programs
Continuity of Weather Observations

As of April 2015



Approved: Mark S. Paese
Assistant Administrator for Satellite and Information Services

Note: Extended operations are reflected through the current FY, based on current operating health.

DMSP: Defense Meteorological Satellite Program
JPSS: Joint Polar Satellite System Program
Suomi NPP: Suomi National Polar-orbiting Partnership

Note: DoD and EUMETSAT data provided for reference only

- Post Launch Test
- Operational based on design life
- Secondary
- Operational beyond FY 2036
- Extended mission life
- Launched before Oct 2008

VIIRS: Next Gen Operational Polar Orbiting Imaging Radiometer

- **22 spectral bands**
  - Visible to LWIR
  - Spatially registered
- **Better spatial resolution**
  - Reduced variation over scan
  - Higher resolution imaging bands
- **High radiometric accuracy**
  - NIST-traceable
  - Supported by on-board calibrators

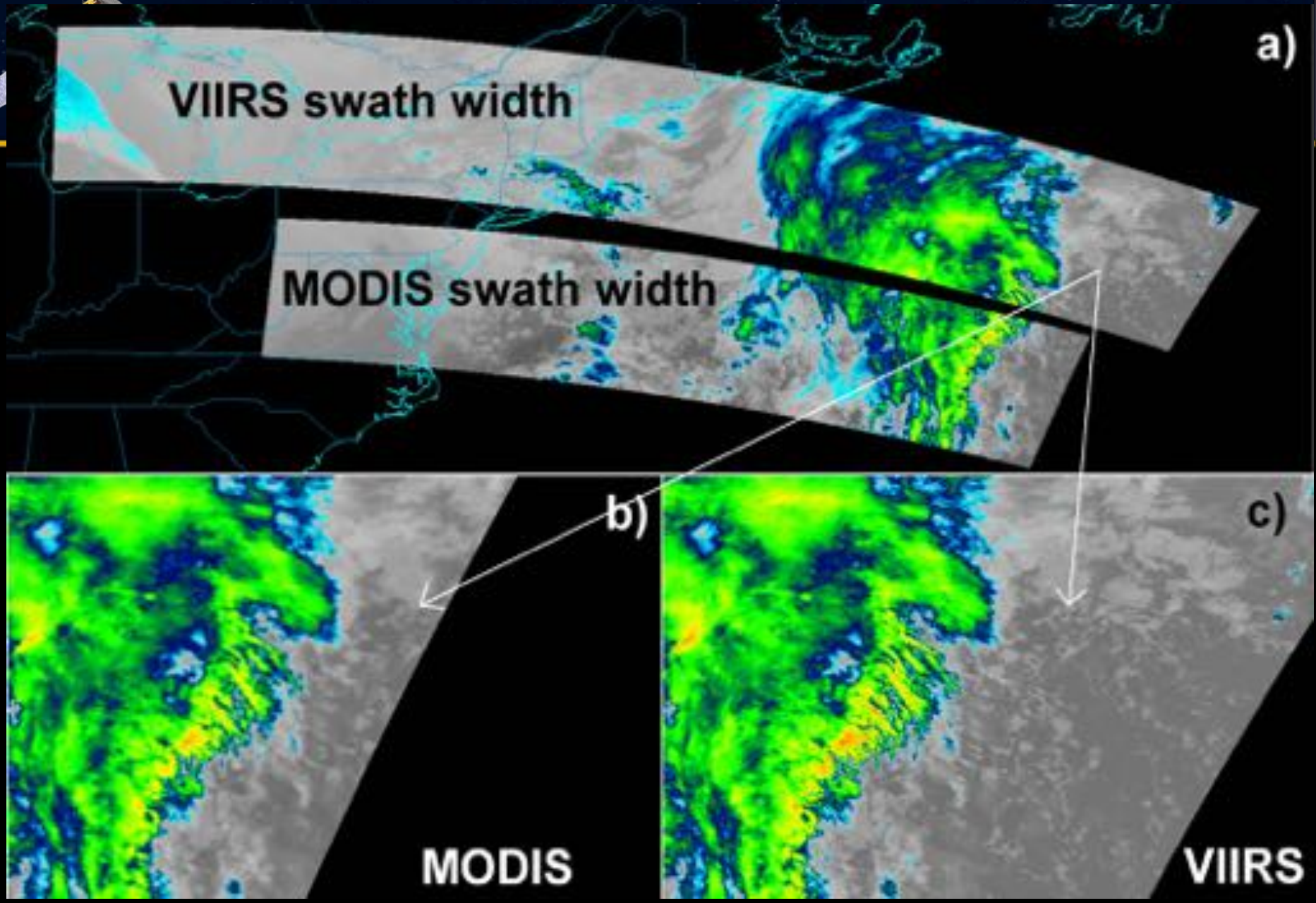
		Band No.	Wave-length (μm)	Horiz Sample Interval (km Downtrack x Crosstrack)		Driving EDRs
				Nadir	End of Scan	
VIS/NIR FPA	Silicon PIN Diodes	M1	0.412	0.742 x 0.259	1.60 x 1.58	Ocean Color Aerosols
		M2	0.445	0.742 x 0.259	1.60 x 1.58	Ocean Color Aerosols
		M3	0.488	0.742 x 0.259	1.60 x 1.58	Ocean Color Aerosols
		M4	0.555	0.742 x 0.259	1.60 x 1.58	Ocean Color Aerosols
		I1	0.640	0.371 x 0.387	0.80 x 0.789	Imagery
		M5	0.672	0.742 x 0.259	1.60 x 1.58	Ocean Color Aerosols
		M6	0.746	0.742 x 0.776	1.60 x 1.58	Atmospheric Corr'n
		I2	0.865	0.371 x 0.387	0.80 x 0.789	NDVI
		M7	0.865	0.742 x 0.259	1.60 x 1.58	Ocean Color Aerosols
CCD		DNB	0.7	0.742 x 0.742	0.742 x 0.742	Imagery
S/MWIR	PV HgCdTe (HCT)	M8	1.24	0.742 x 0.776	1.60 x 1.58	Cloud Particle Size
		M9	1.378	0.742 x 0.776	1.60 x 1.58	Cirrus/Cloud Cover
		I3	1.61	0.371 x 0.387	0.80 x 0.789	Binary Snow Map
		M10	1.61	0.742 x 0.776	1.60 x 1.58	Snow Fraction
		M11	2.25	0.742 x 0.776	1.60 x 1.58	Clouds
		I4	3.74	0.371 x 0.387	0.80 x 0.789	Imagery Clouds
		M12	3.70	0.742 x 0.776	1.60 x 1.58	SST
		M13	4.05	0.742 x 0.259	1.60 x 1.58	SST Fires
LWIR	PV HCT	M14	8.55	0.742 x 0.776	1.60 x 1.58	Cloud Top Properties
		M15	10.763	0.742 x 0.776	1.60 x 1.58	SST
		I5	11.450	0.371 x 0.387	0.80 x 0.789	Cloud Imagery
		M16	12.013	0.742 x 0.776	1.60 x 1.58	SST

VIIRS Improvements From AVHRR:

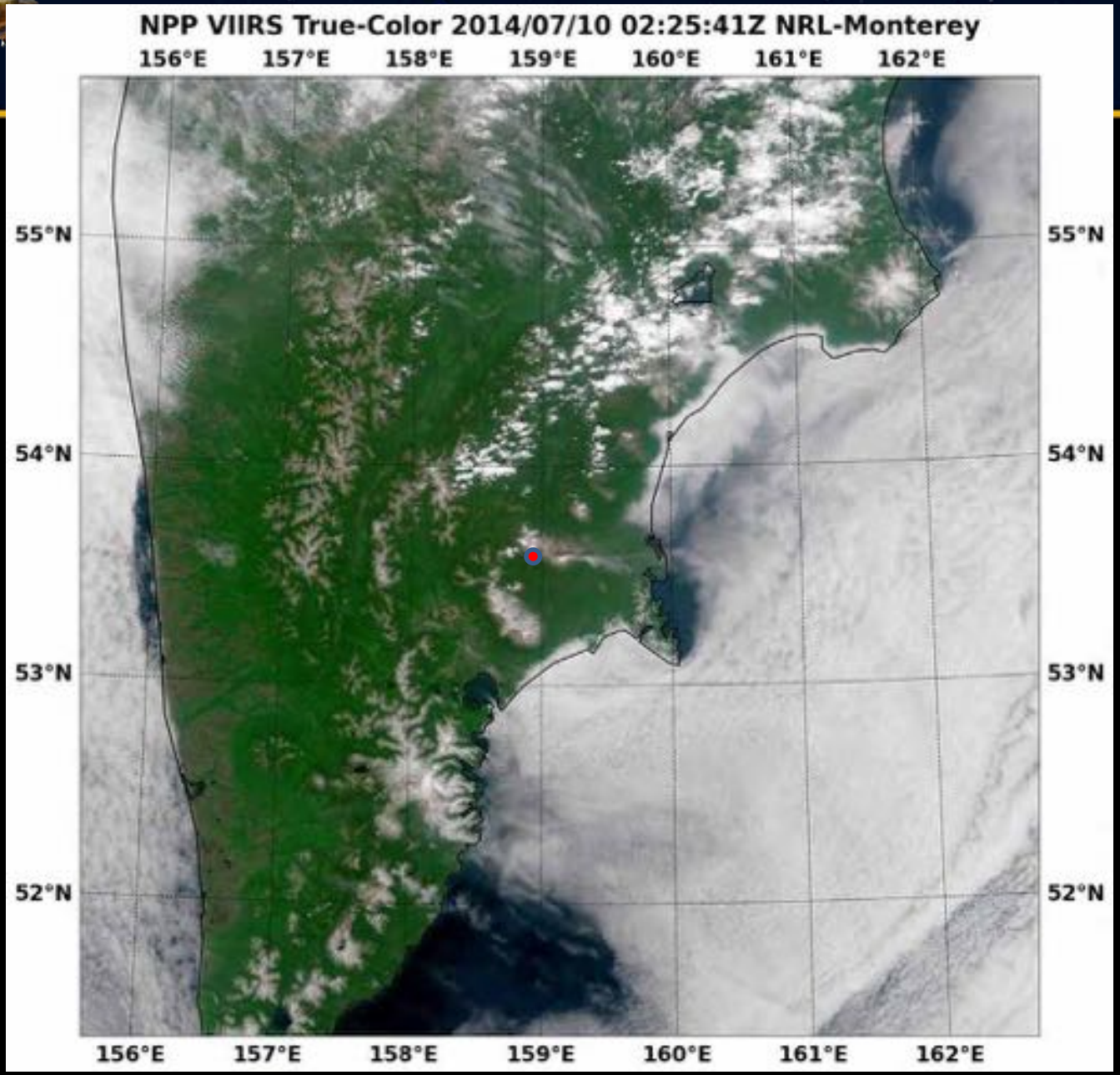
AVHRR does not have the spectral bands for: low light, ocean color, aerosol over land, discrimination of clouds from snow, sensitivity to thin cirrus, fire radiative power (intensity), and does not meet current user requirements

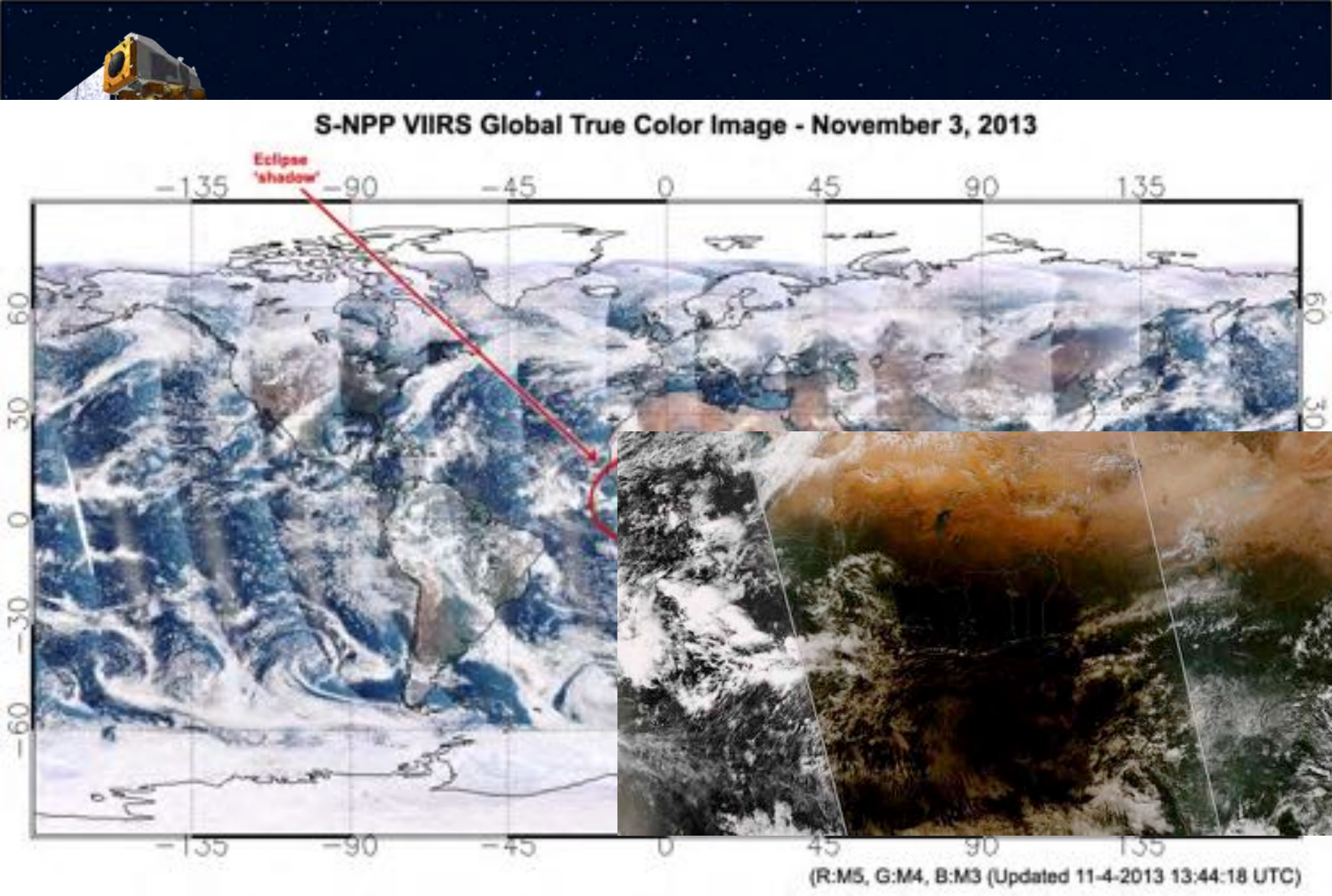
Greater spectral coverage with increased radiometric quality

VIIRS			MODIS Equivalent			AVHRR-3 Equivalent			OLS Equivalent		
Band	Range (um)	HSR (m)	Band	Range	HSR	Band	Range	HSR	Band	Range	HSR
DNB	0.500 - 0.900	750				Low light capabilities			HRD PMT	0.580 - 0.910 0.510 - 0.860	550 2700
M1	0.402 - 0.422	750	8	0.405 - 0.420	1000						
M2	0.436 - 0.454	750	9	0.438 - 0.448	1000						
M3	0.478 - 0.498	750	3 10	0.459 - 0.479 0.483 - 0.493	500 1000	Ocean Color, Aerosol					
M4	0.545 - 0.565	750	4 12	0.545 - 0.565 0.546 - 0.556	500 1000						
I1	0.600 - 0.680	375	1	0.620 - 0.670	250	1	0.572 - 0.703	1100			
M5	0.662 - 0.682	750	13 14	0.662 - 0.672 0.673 - 0.683	1000 1000	1	0.572 - 0.703	1100			
M6	0.739 - 0.754	750	15	0.743 - 0.753	1000	Atm Correction					
I2	0.846 - 0.885	375	2	0.841 - 0.876	250	2	0.720 - 1.000	1100			
M7	0.846 - 0.885	750	16	0.862 - 0.877	1000	2	0.720 - 1.000	1100			
M8	1.230 - 1.250	750	5	SAME	500	Cloud Particle Size					
M9	1.371 - 1.386	750	26	1.360 - 1.390	1000	Thin Cirrus					
I3	1.580 - 1.640	375	6	1.628 - 1.652	500	Snow Map					
M10	1.580 - 1.640	750	6	1.628 - 1.652	500	3a	SAME	1100			
M11	2.225 - 2.275	750	7	2.105 - 2.155	500	Cloud					
I4	3.550 - 3.930	375	20	3.660 - 3.840	1000	3b	SAME	1100			
M12	3.660 - 3.840	750	20	SAME	1000	3b	3.550 - 3.930	1100			
M13	3.973 - 4.128	750	21 22 23	3.929 - 3.989 3.929 - 3.989 4.020 - 4.080	1000 1000 1000	SST, Fire					
M14	8.400 - 8.700	750	29	SAME	1000	Cloud Top Propoerties					
M15	10.263 - 11.263	750	31	10.780 - 11.280	1000	4	10.300 - 11.300	1100			
I5	10.500 - 12.400	375	31 32	10.780 - 11.280 11.770 - 12.270	1000 1000	4 5	10.300 - 11.300 11.500 - 12.500	1100 1100	HRD	10.300 - 12.900	550
M16	11.538 - 12.488	750	32	11.770 - 12.270	1000	5	11.500 - 12.500	1100			

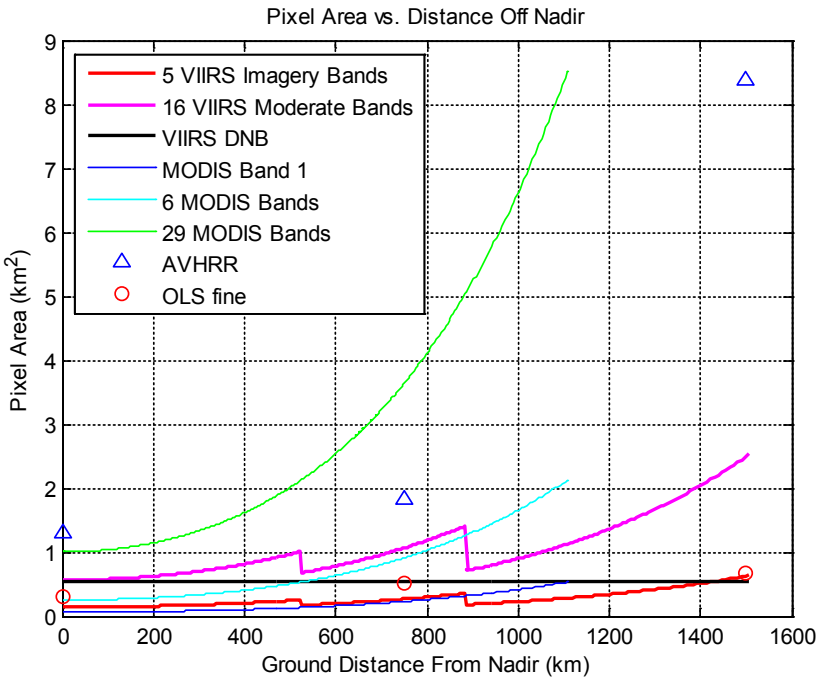

a)
VIIRS swath width
MODIS swath width
b)
c)
MODIS
VIIRS

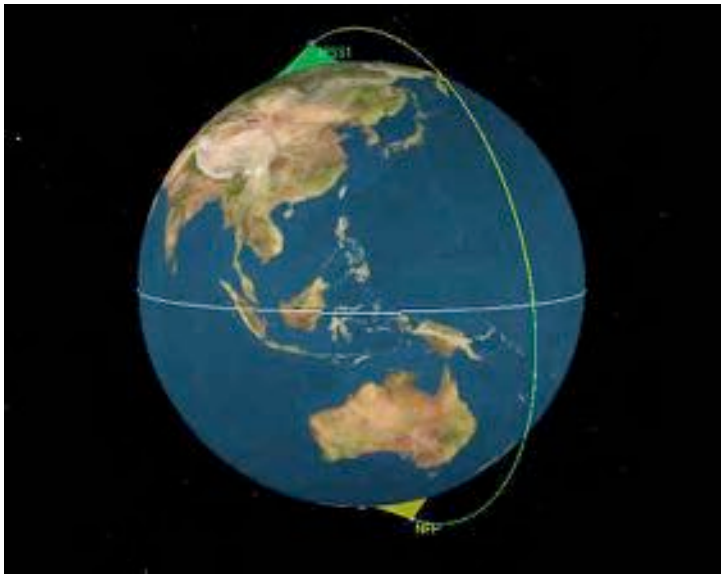
Comparing MODIS (250m) to VIIRS (375m) Edge of Scan

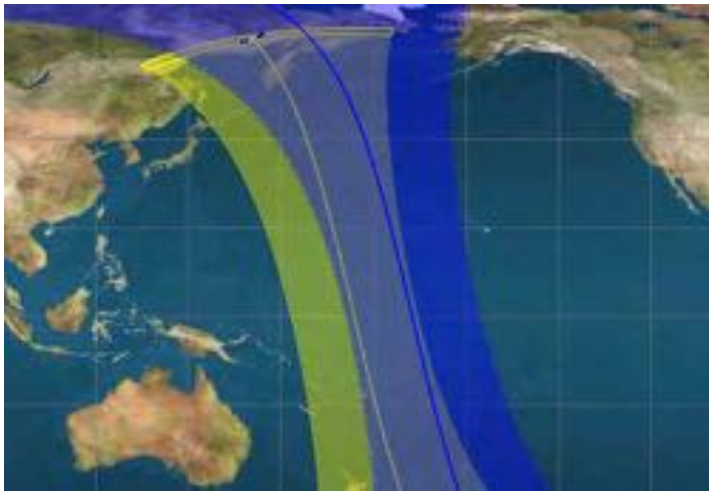



S-NPP VIIRS Global True Color Image - November 3, 2013
Eclipse 'shadow'
−135
−90
−45
0
45
90
135
60
30
0
−30
−60
(R:M5, G:M4, B:M3 (Updated 11-4-2013 13:44:18 UTC)

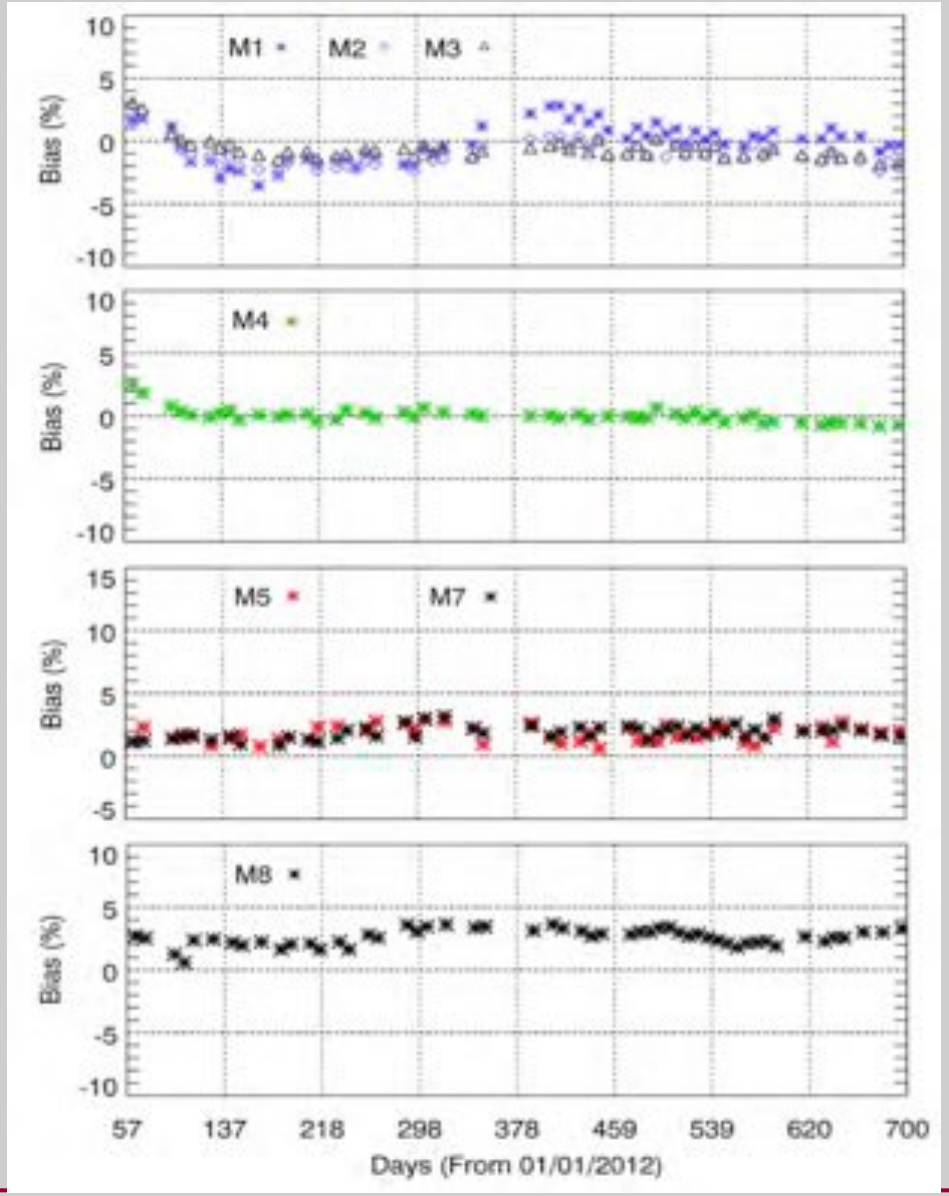
JPSS-1 satellites 50 minutes ahead of SNPP





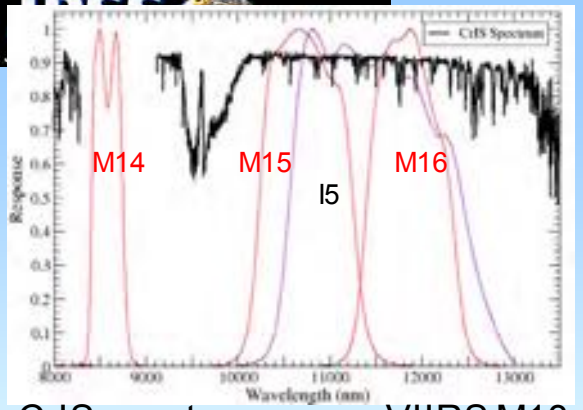


VIIRS and MODIR RSB Inter-comparison at SNO-x (over desert)

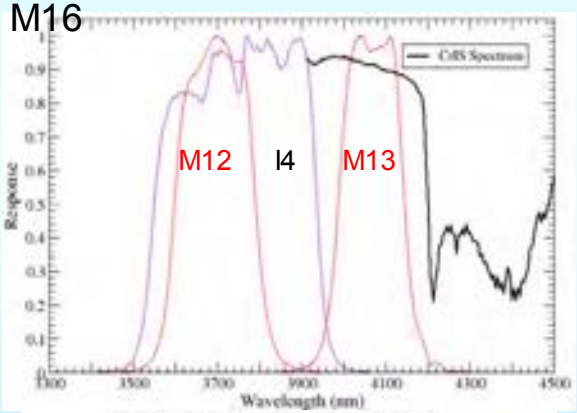


Cao

VIIRS-CrIS SDR Comparisons



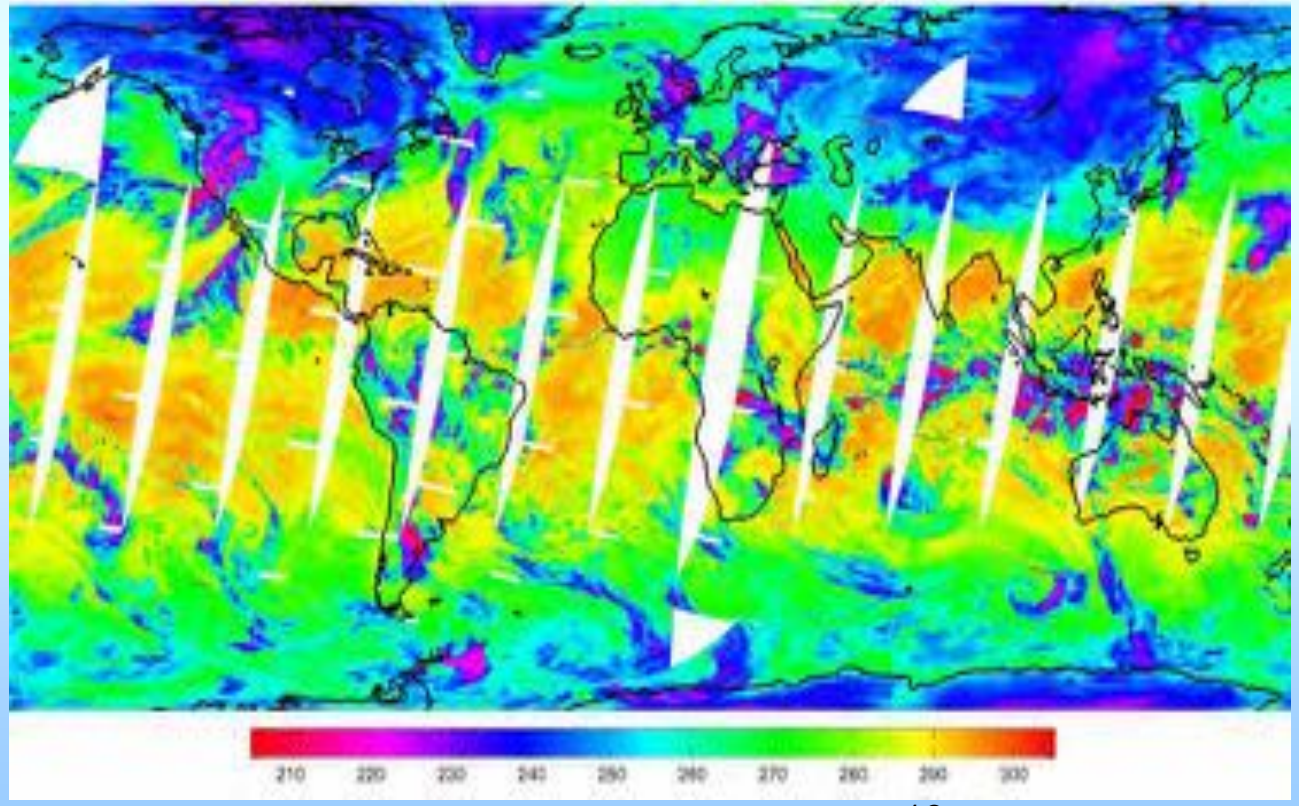
CrIS spectrum covers VIIRS M13, M15, M16, and I5 but does not include OOB response in M15 and M16

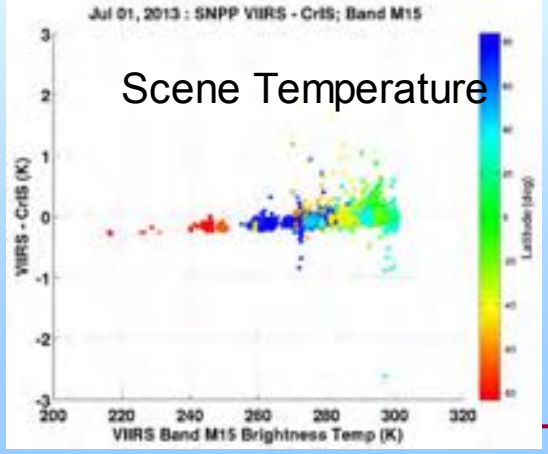


- VIIRS SDR accuracy/stability plus RVS performance
- Global; 2.9 million matchups daily from SNPP platform
- CrIS radiances anticipating Mx8.1
- In-band spectral radiance for M13, M15, M16 and I5
- Long term high quality data record to assess stability

CrIS convolved with VIIRS SRF

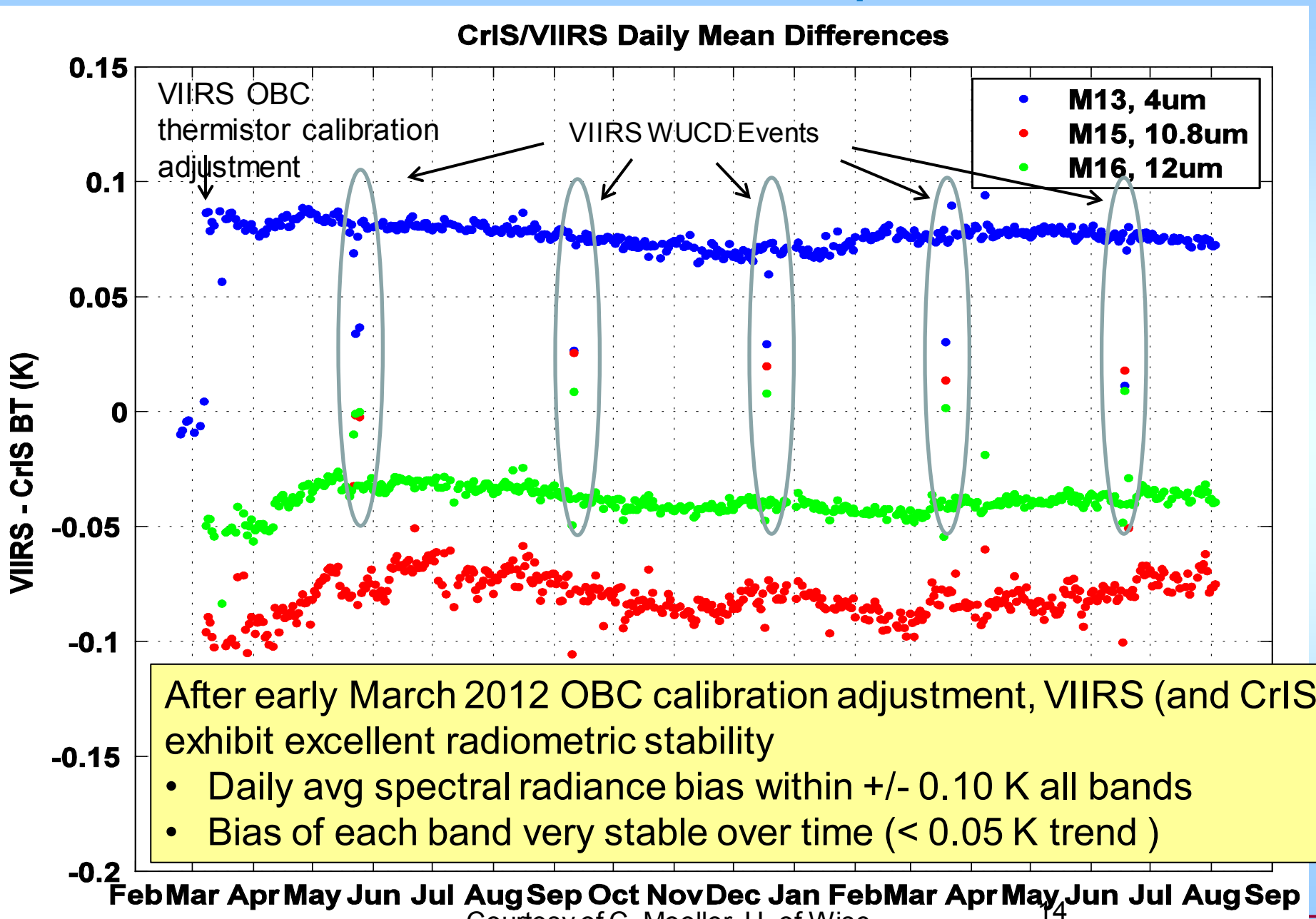
VIIRS mean within CrIS FOVs





Courtesy of C. Moeller, U. of

VIIRS-CrIS SDR Comparisons



After early March 2012 OBC calibration adjustment, VIIRS (and CrIS) exhibit excellent radiometric stability

- Daily avg spectral radiance bias within +/- 0.10 K all bands
- Bias of each band very stable over time (< 0.05 K trend)

Courtesy of C. Moeller, U. of Wisc.

NOAA operational forecasts/warnings competency drives the need of global imagery

VIIRS	Environmental Parameters	NOAA Operational Assessments and Forecasts/Warnings	Impacted Sectors
Provides daily high-resolution imagery and radiometry across the visible to long-wave infrared spectrum for a multitude of environmental assessments Provides significant improvements over AVHRR, much better spatial resolution and more spectral information (22 vs. 6 channels) New Day-Night-Band provides critical ice monitoring capabilities especially during the polar night and most accurate fog detection of any satellite sensor Provides the only continuity for NOAA AVHRR and NASA MODIS imagers, Only source of imagery with both high spatial resolution (~ 500 m) and large geographic coverage (3000 km wide) which provides global coverage with no gaps. Only source for Arctic regions (Alaska) where geostationary satellites are out of range. Only source of operational ocean color data	Cloud properties Fog	Cloud and fog data provide warnings needed for safe transport and commerce (land, ocean and air). Volcanic ash provides data for critical alerts needed for aviation safety. Fire and smoke information are critical for fire fighters and property owners. Smoke, dust, aerosols critical for air quality warnings	Public and Commercial Aviation, Insurance, Health, Home Owners, Energy, Tourism
	Volcanic Ash		
	Fire and Smoke		
	Dust and Aerosols		
	Vegetation properties and Land Surface Temperature	Vegetation properties and land surface temperature are used in agricultural, drought, fire risk assessments and provide data need to predict prolong periods of drought. Critical data for planners – water resources, food security.	Agriculture, Energy, Health, Water Management Tourism
	Snow and Ice Cover and Thickness	Snow pack information used in avalanche, water resources, river flood, transportation warnings. Ice data for Arctic Ocean navigation and winter maritime regions with ice conditions	Commerce, Water Management, Tourism
	Sea Surface Temperature (SST)	SST primary source of data for seasonal forecasts (El Nino, La Nina oscillations) and for predicting tropical storm intensification	Agriculture, Construction, Energy, Insurance
	Ocean Color - Phytoplankton Harmful Algal Blooms (HABs)	Phytoplankton concentration for monitoring health of aquatic life. Critical for fishing industry and conservation efforts. HAB data for monitoring health of coast ecosystems, alerting local community on poor water quality and to quarantine regions due to potential contamination of seafood	Fishing Industry, Local Coastal Economies, Health

Day Night Band May 20, 2012

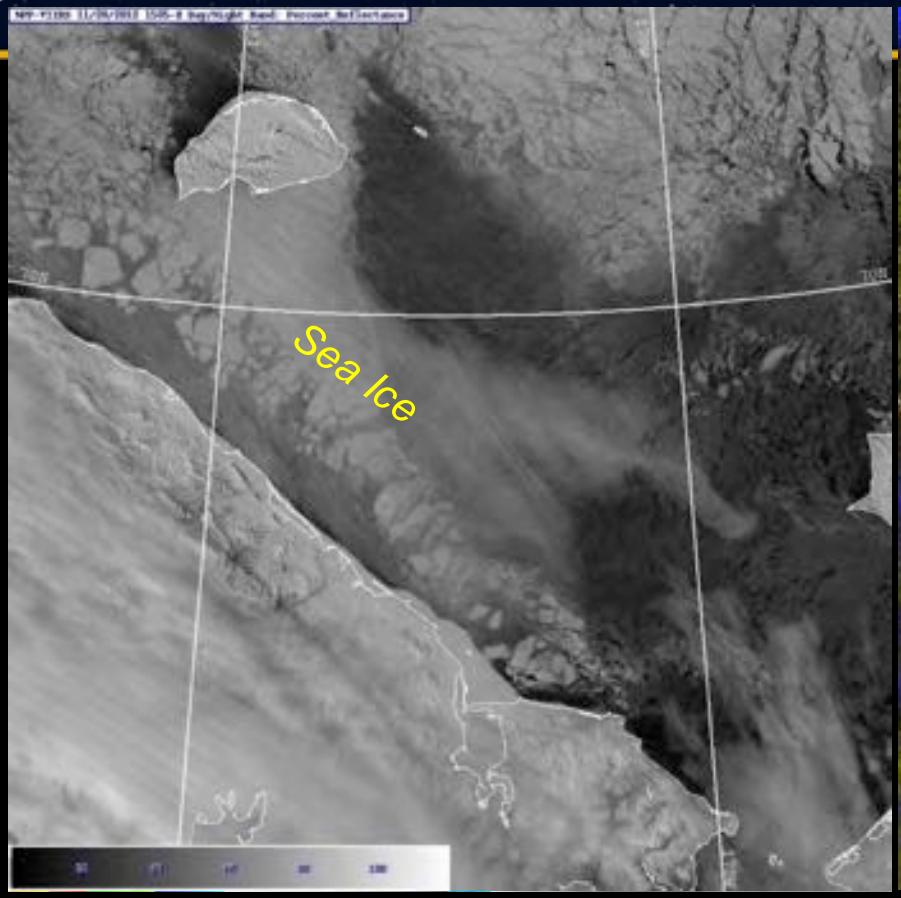
The Not-So-Dark Night…

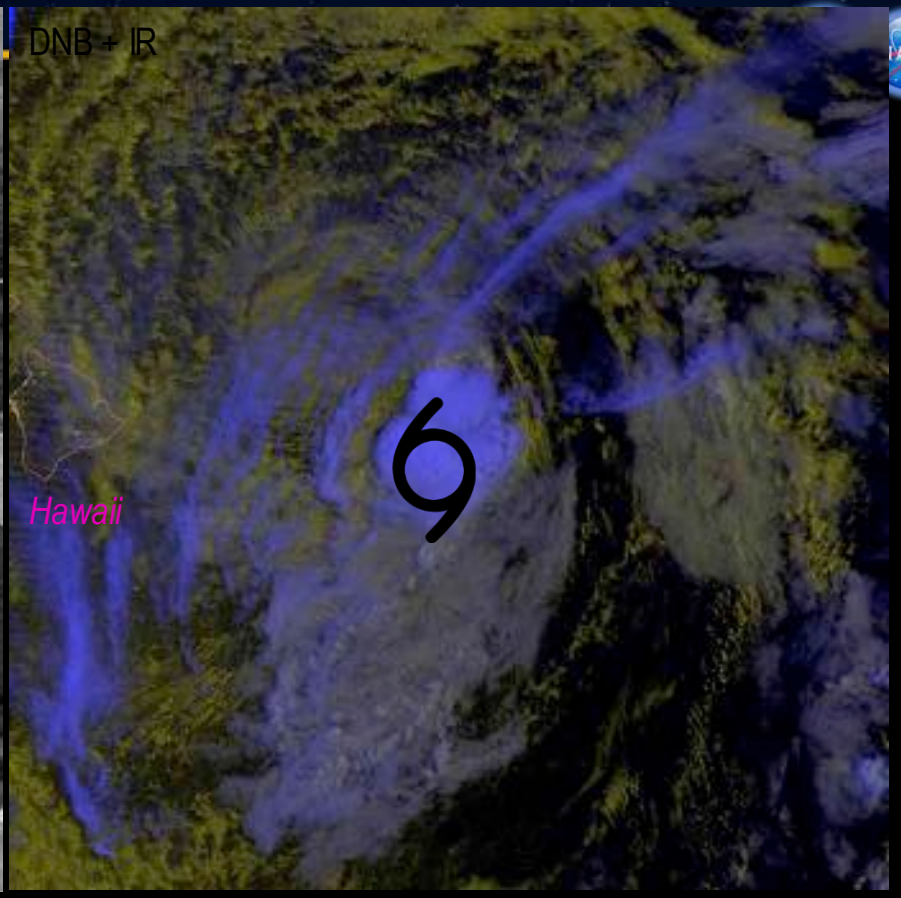
*Miller et al., Remote Sens. 2013, **5**, 6717-6766; doi:10.3390/rs5126717*

Day/Night Band (DNB) Attributes

- Spatial Resolution: 742 m (constant across swath via 64 aggregation modes)
- Sensitivity: 3.0 e-5 W m^{-2} μm^{-1} (L_{min}; signal to noise ratio ~10)
- Radiometric Calibration Accuracy ~ 13% (High Gain Stage)

The Benefits of Scattering





The ability of visible light to scatter through optically thin clouds (that are opaque at thermal infrared bands) enables the DNB to capture information

VIIRS Day Night Band Observation of the Power Outage – Washington DC/Baltimore Metro Area June 2012 Derecho

Nov 9, 2012

Super Storm Sandy

F/V Kiska Sea assist February 2013

DNB images from the previous night clearly showed the lights from F/V Kiska Sea and the ice pack around the vessel.

NWS Sea Ice personnel were able to assist the captain plot a track out of the ice pack, avoiding areas of thicker and higher concentration sea ice.

The timeliness of the DNB images provided an essential tool for this vessel assist.

7 Feb 2013 — Strong Northerly winds cause rapid advance of ice pack

10 Feb 2013 — 150+ F/V Kiska Sea crab pots were deemed in danger of being overrun by sea ice

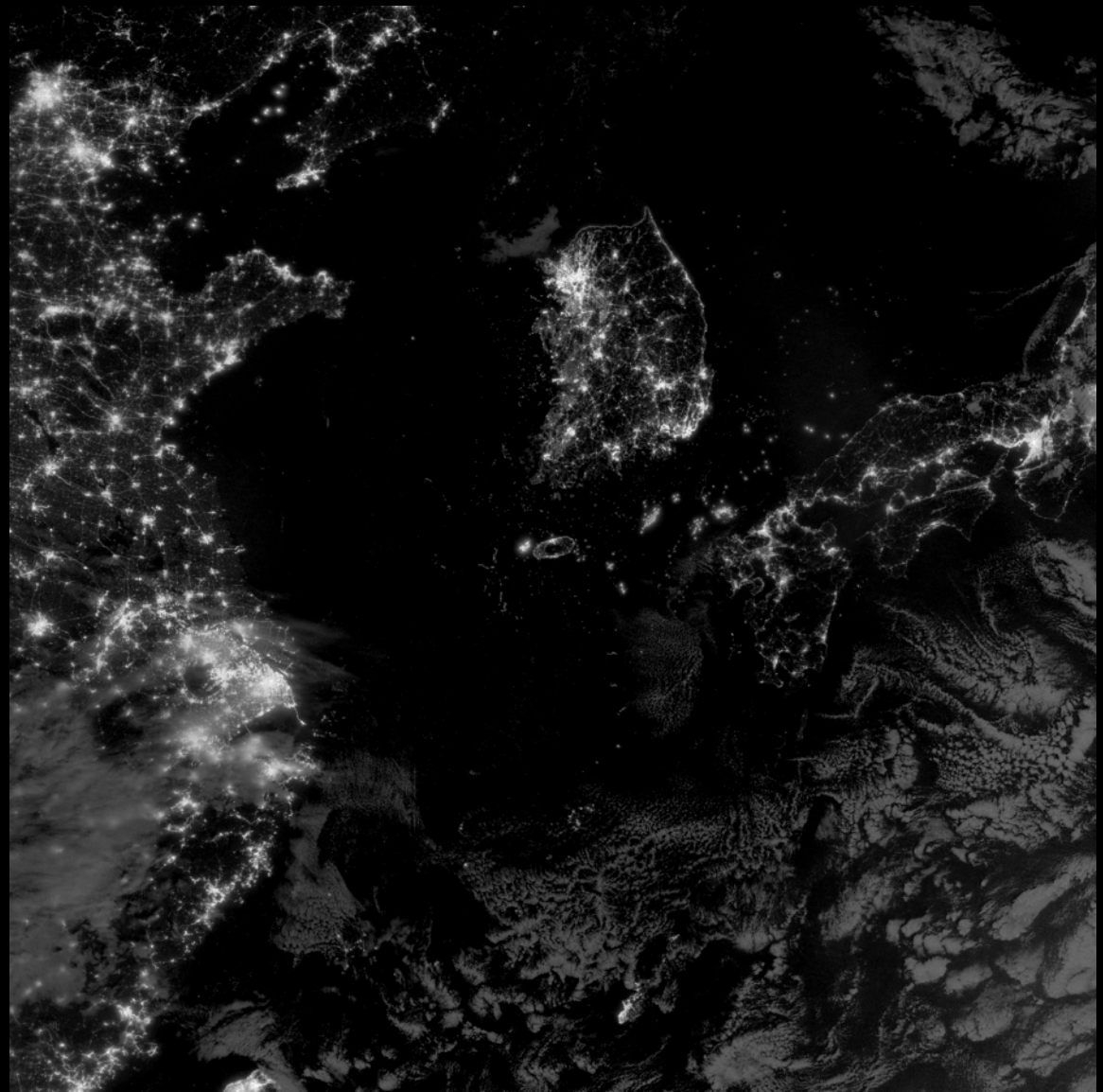
11 Feb 2013 — F/V Kiska Sea captain and NWS Sea Ice Desk worked together to get pots back and return to ice free waters

12 Feb 2013

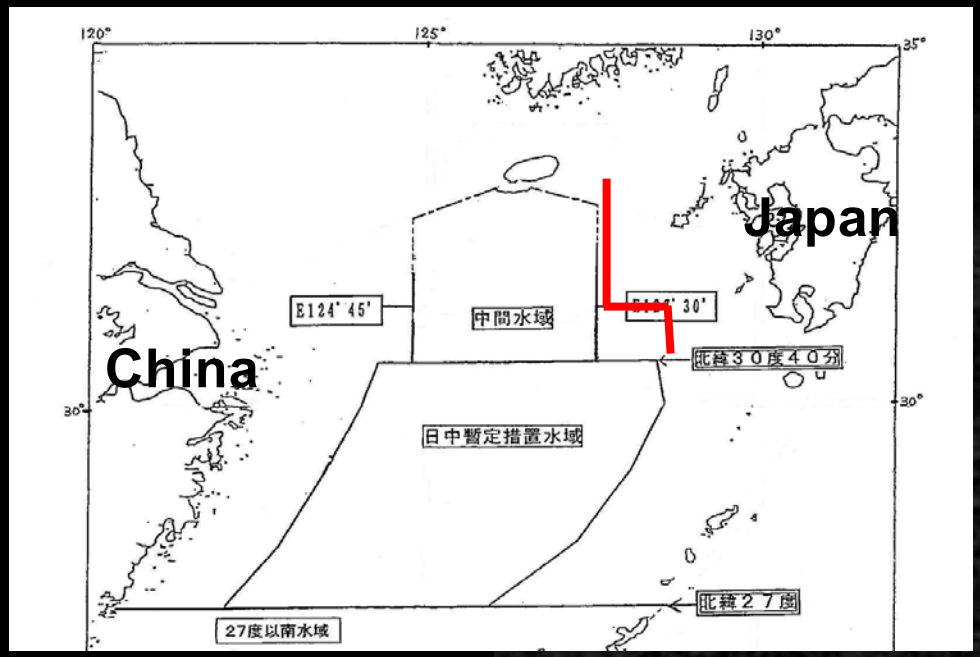
13 Feb 2013 — F/V Kiska Sea surrounded by sea ice, some >3 ft thick

15 Feb 2013

Fishing Example…



Fishing Example…



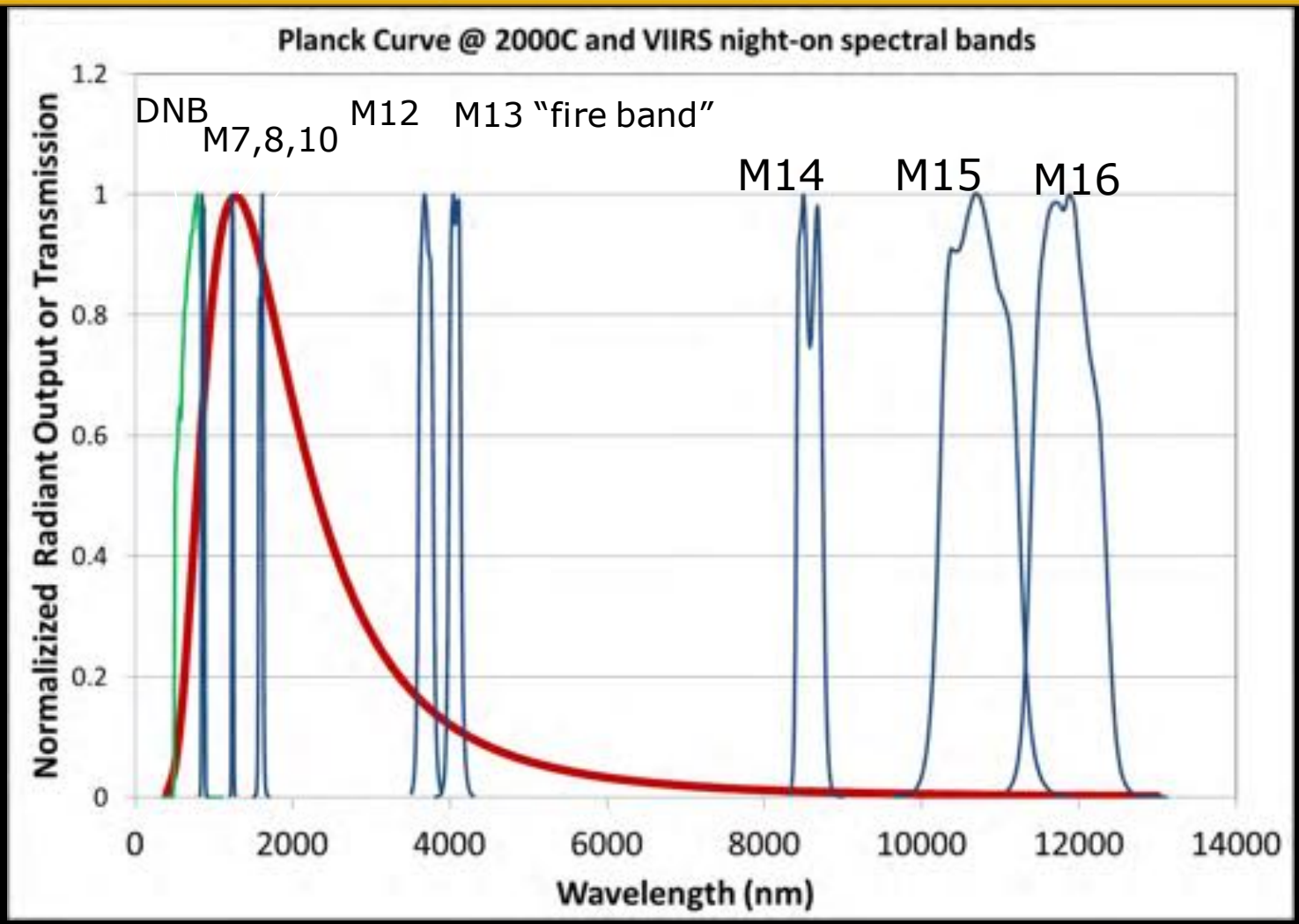
Courtesy: W. Straka, UW-CIMSS

Detection of Combustion Sources Basra, Iraq Region at Night

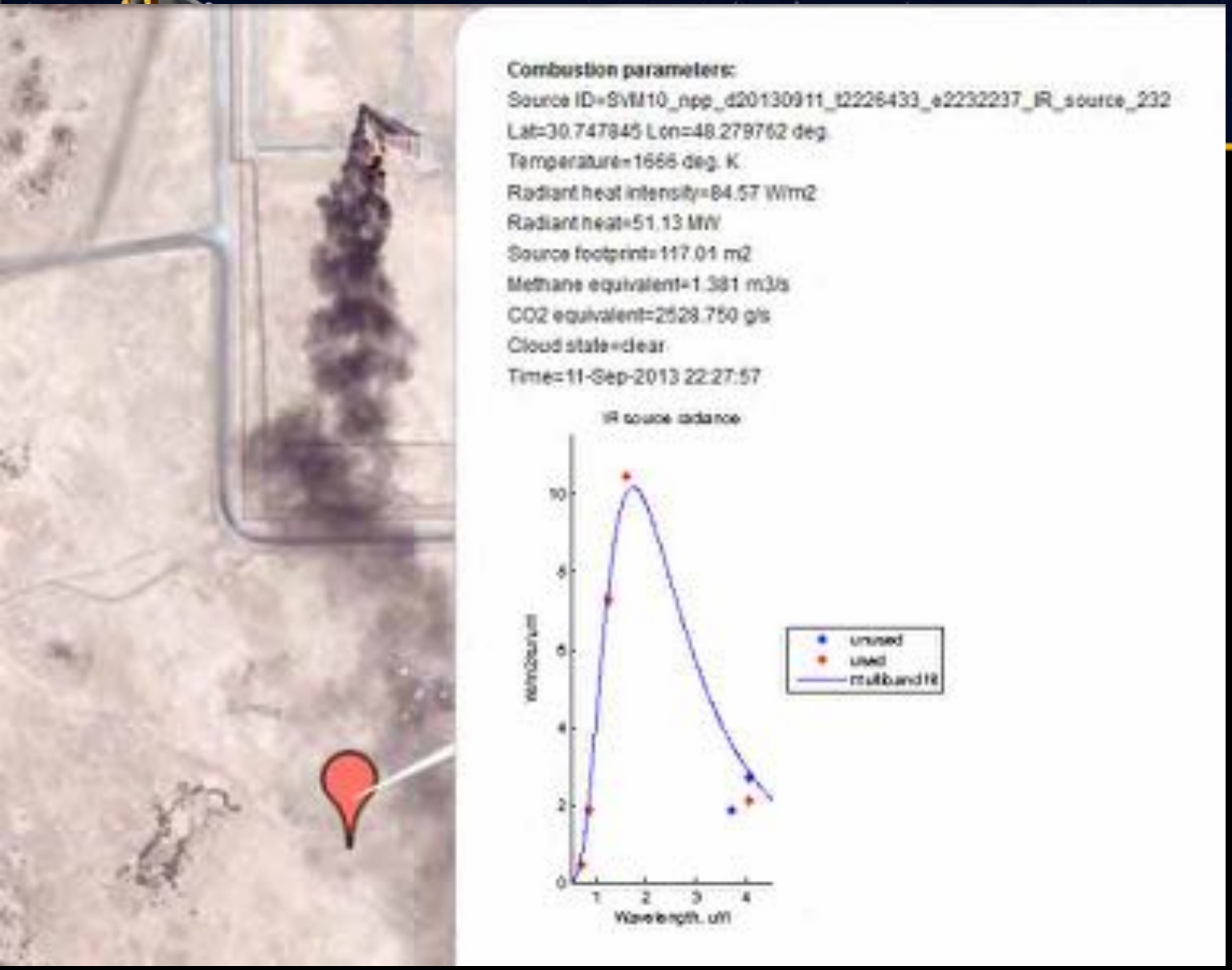
At night the VIIRS collects data in three daytime imaging bands: M7, M8, and M10.
The nighttime M10 data have an remarkable ability to detect combustion sources!

M10

What makes nighttime VIIRS data so great for gas flares?

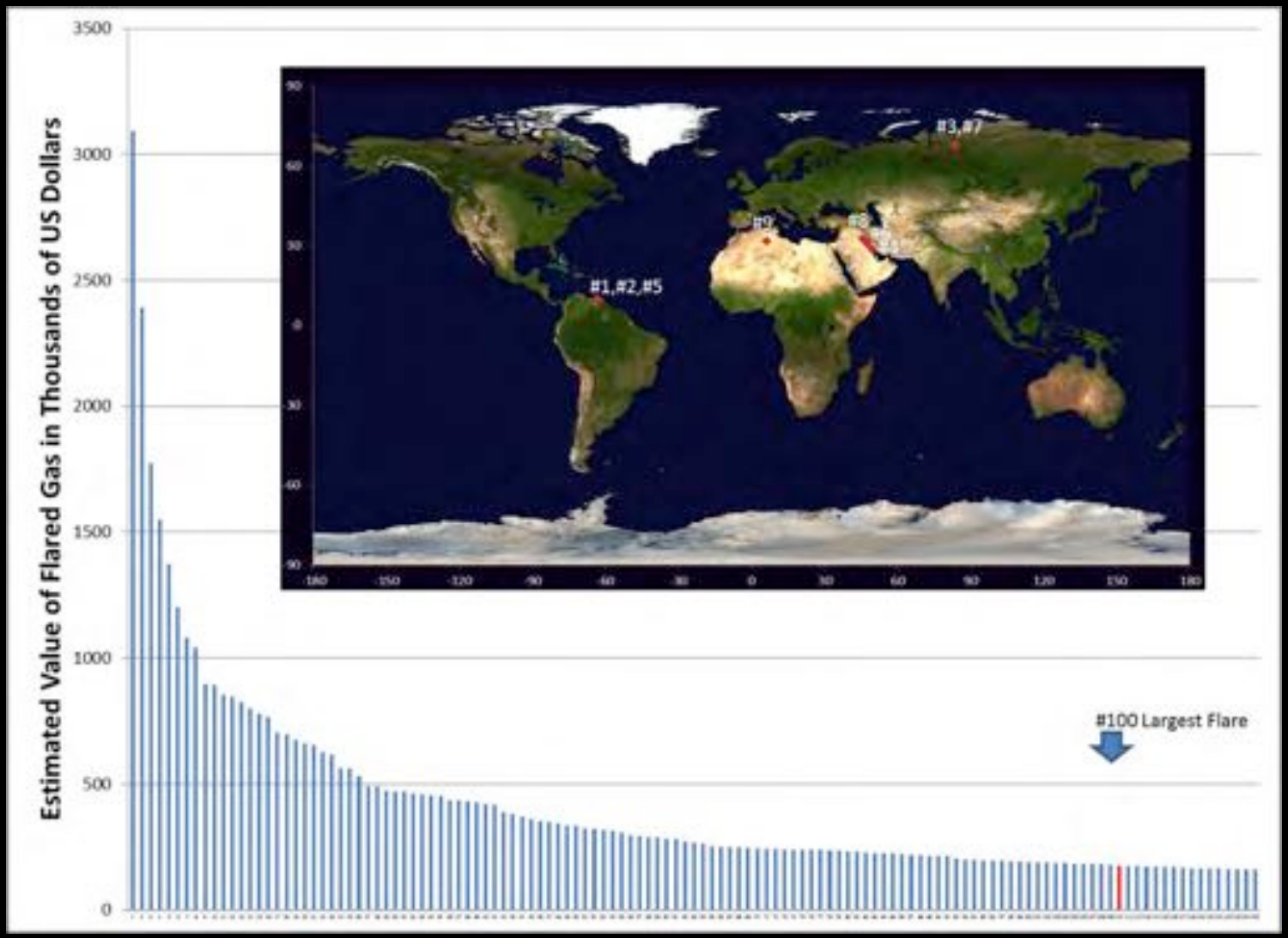


The M7,8,10 spectral bands are well placed to record the peak radiant emissions from flares. During daylight hours the signal is overwhelmed by sunlight. At night combustion sources stand out clearly against the noise background.

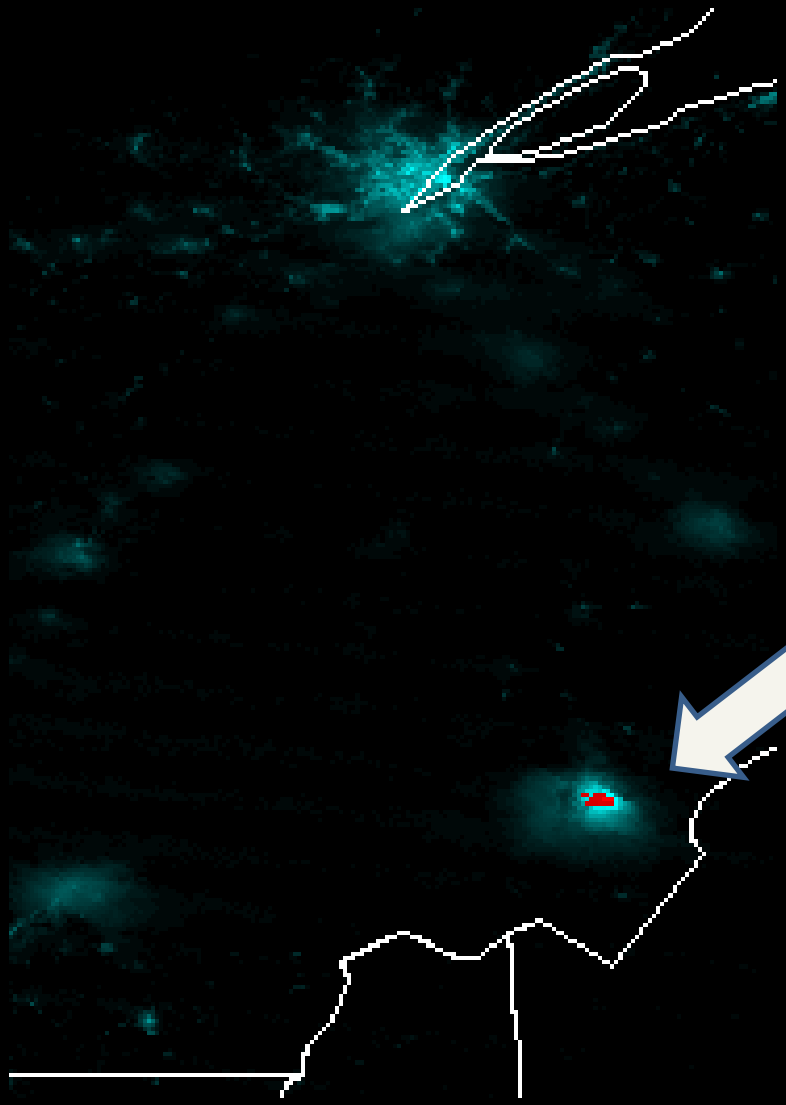


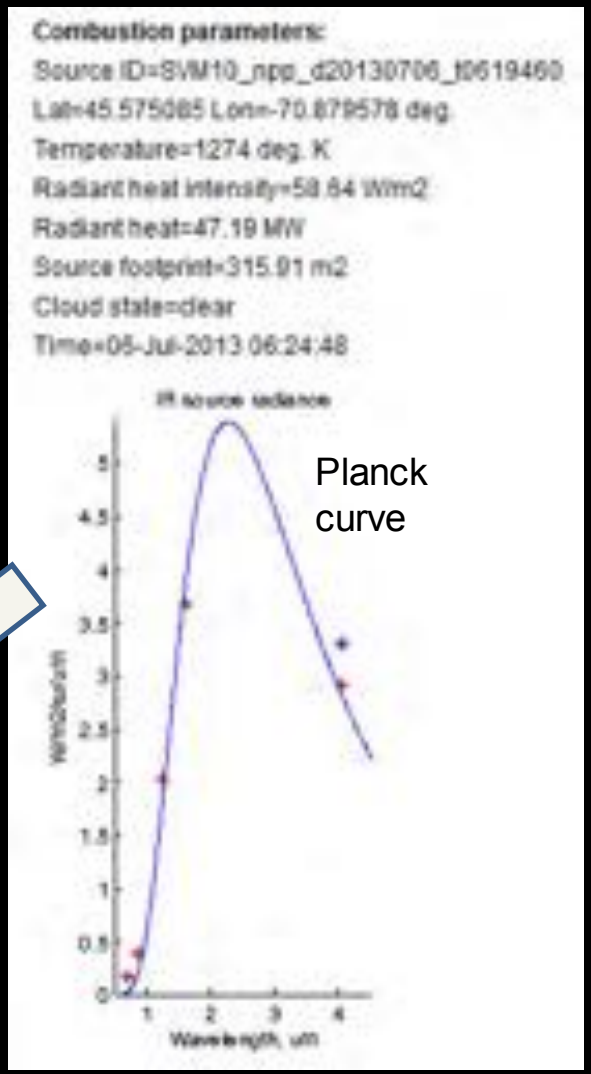
Iraq gas flare detection from September 11, 2013

Top 100 Gas Flares From January 2013



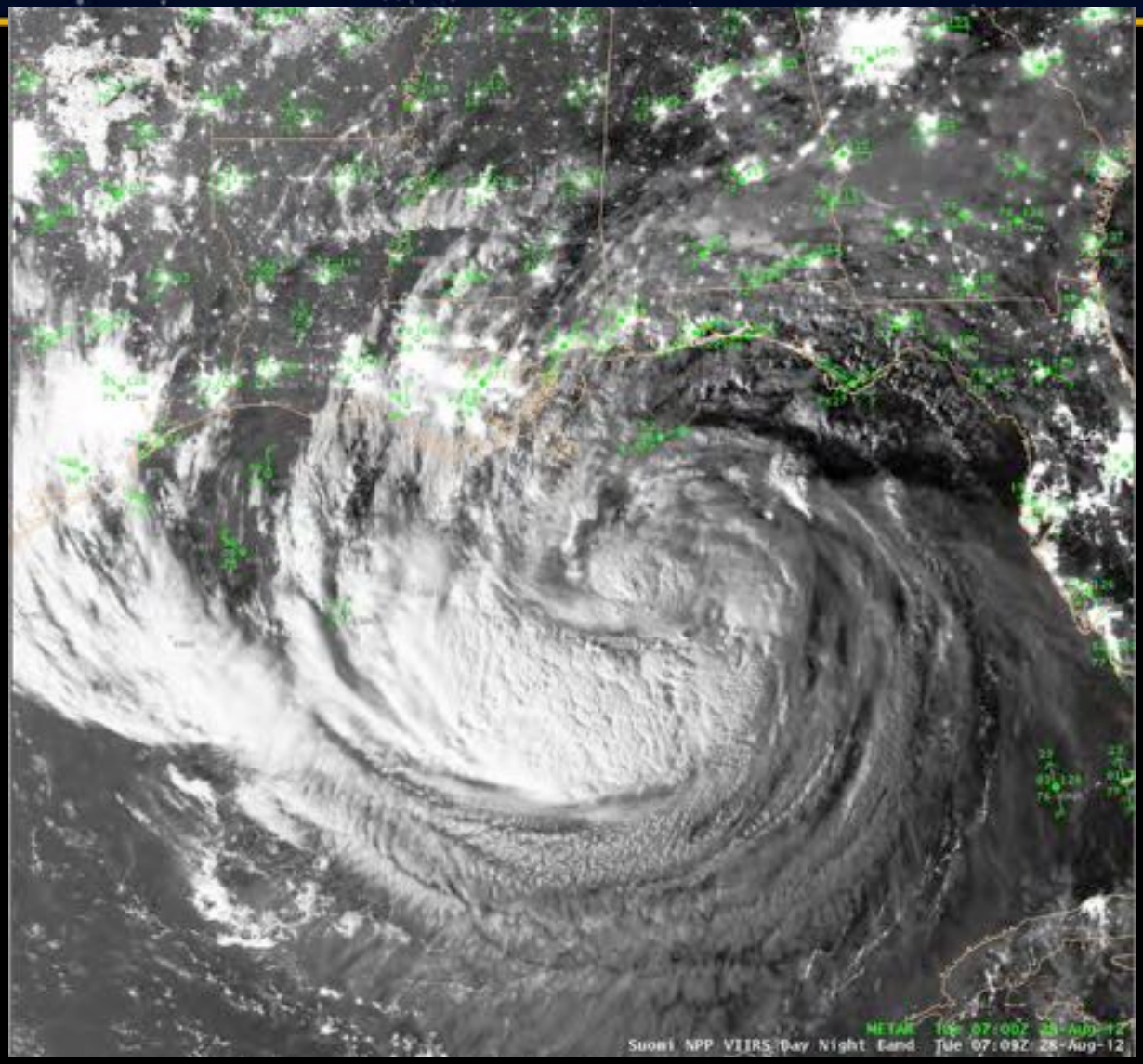
Lac-Megantic, Quebec Explosion Detected by VIIRS at Night



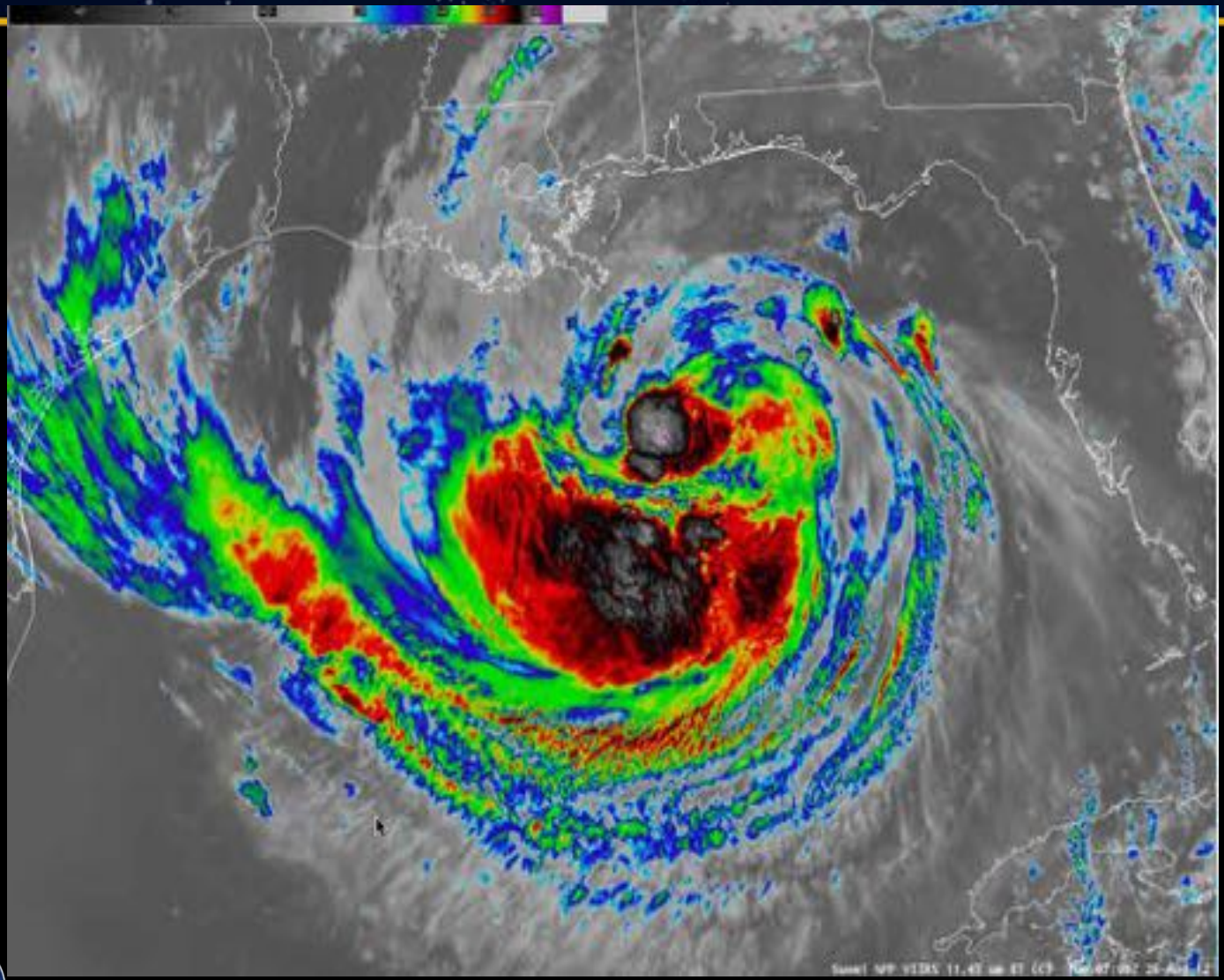


NGDC's VIIRS Nightfire product provides temperature, source size and radiant heat worldwide on a nightly basis

September 2012
VIIRS Day/Night Band
Tropical Storm Isaac in AWIPS

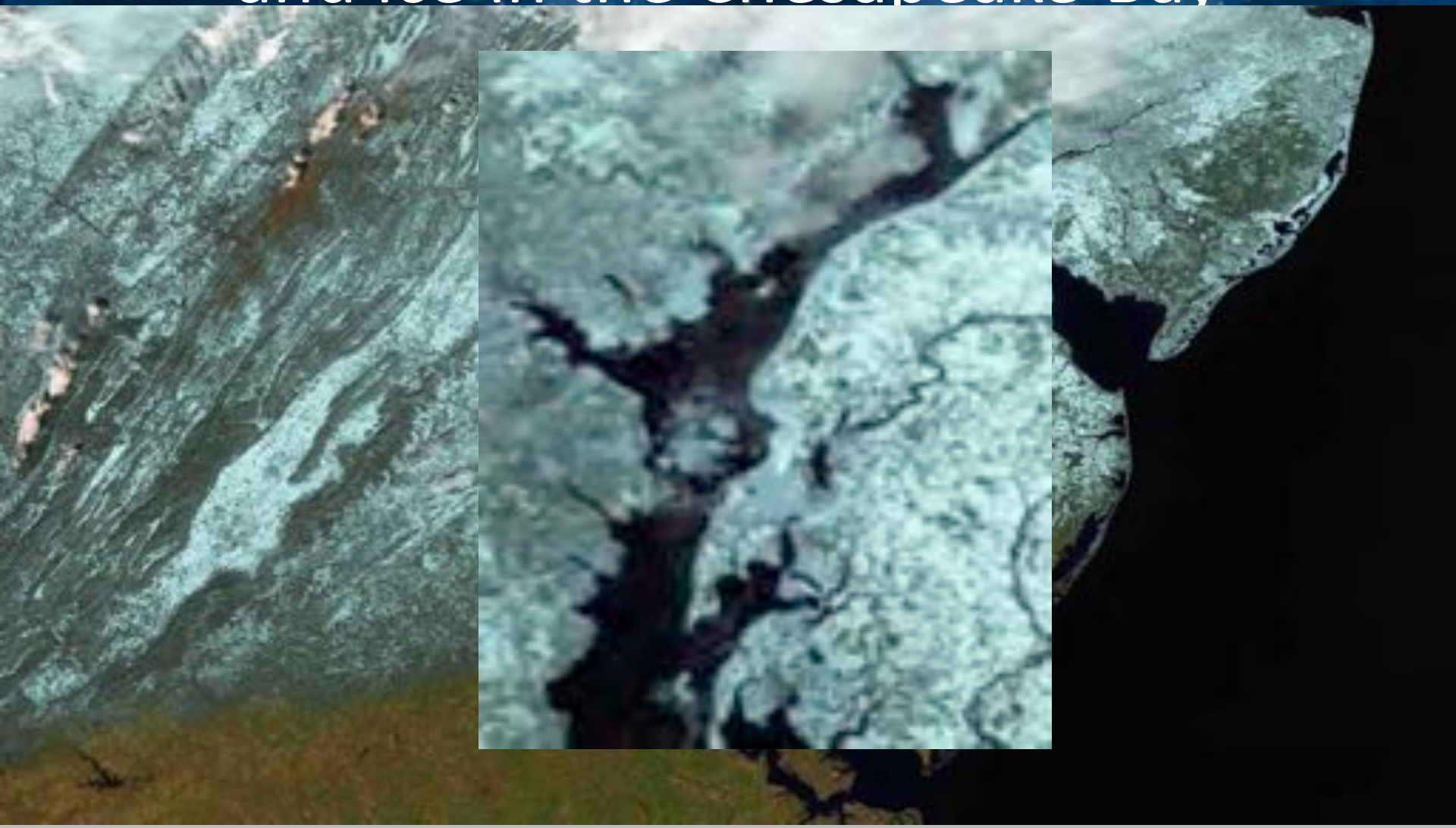


September 2012
VIIRS Day/Night Band
Tropical Storm Isaac in AWIPS

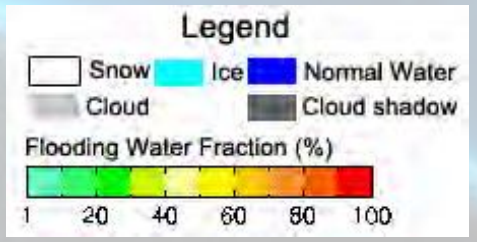


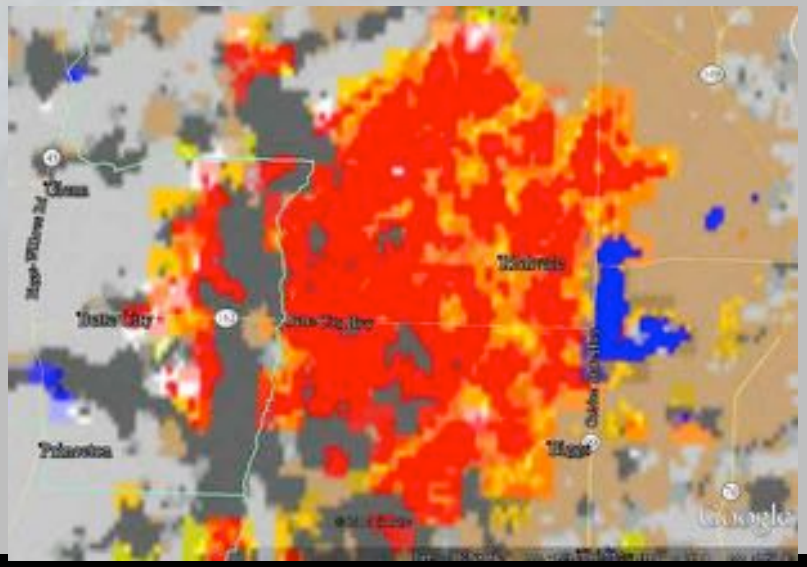
Great lakes ice imagery

March 7, 2014 - last snow of the season and ice in the Chesapeake Bay

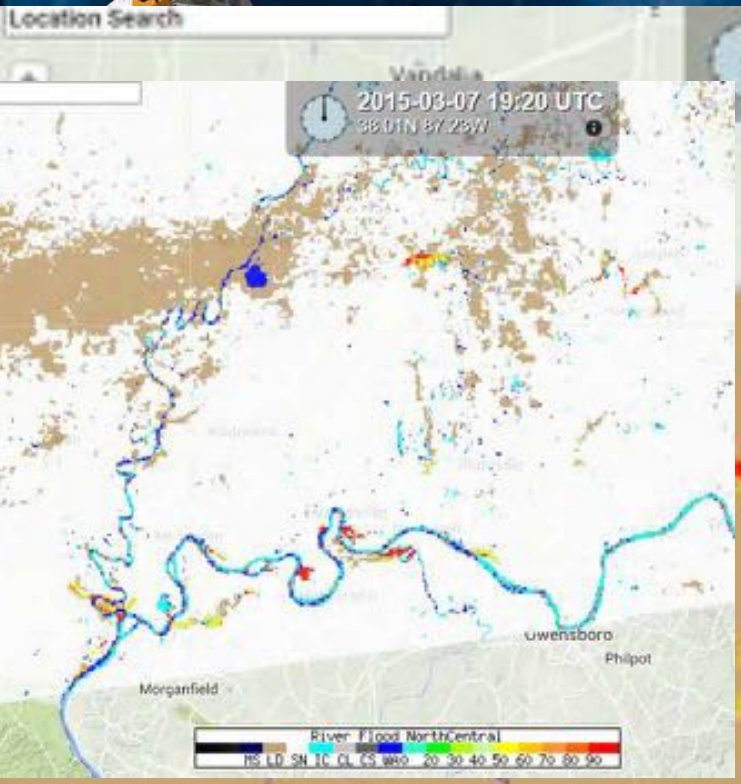


California Floods: Dec. 11-13, 2014





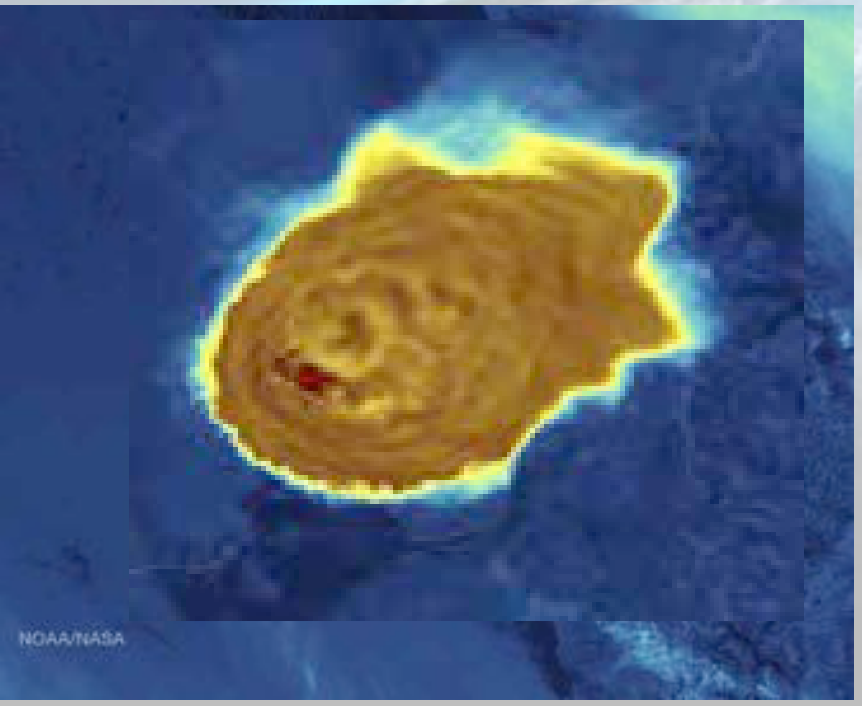
JPSS Proving Ground Delivering Experimental River Ice and Flood Products to NWS River Forecast Centers

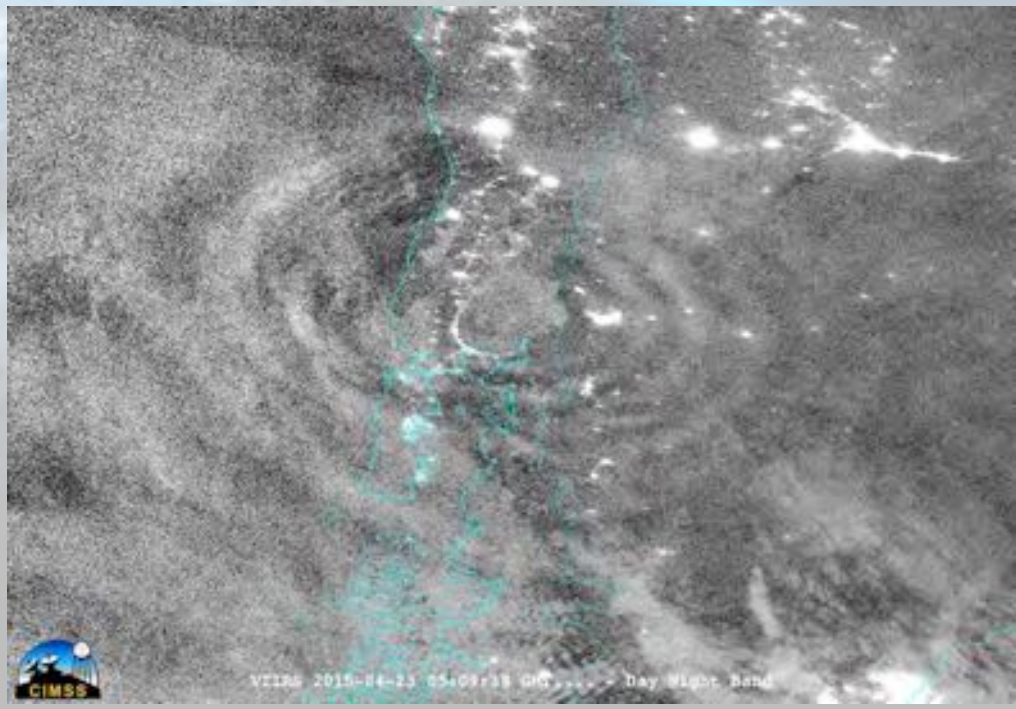


Evansville, In

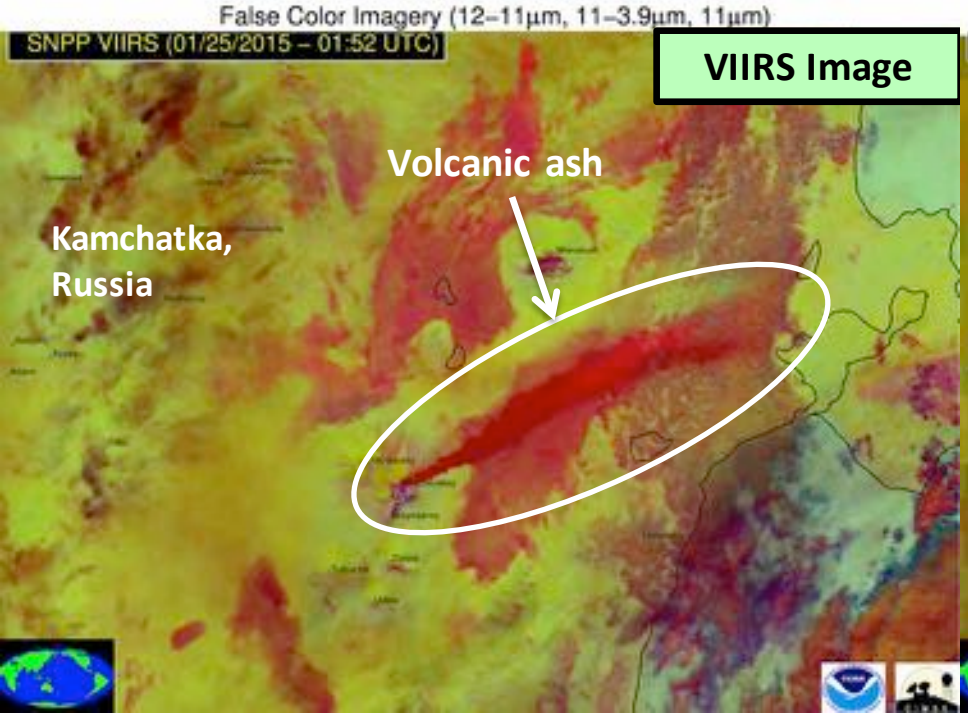
Calbuco Volcano

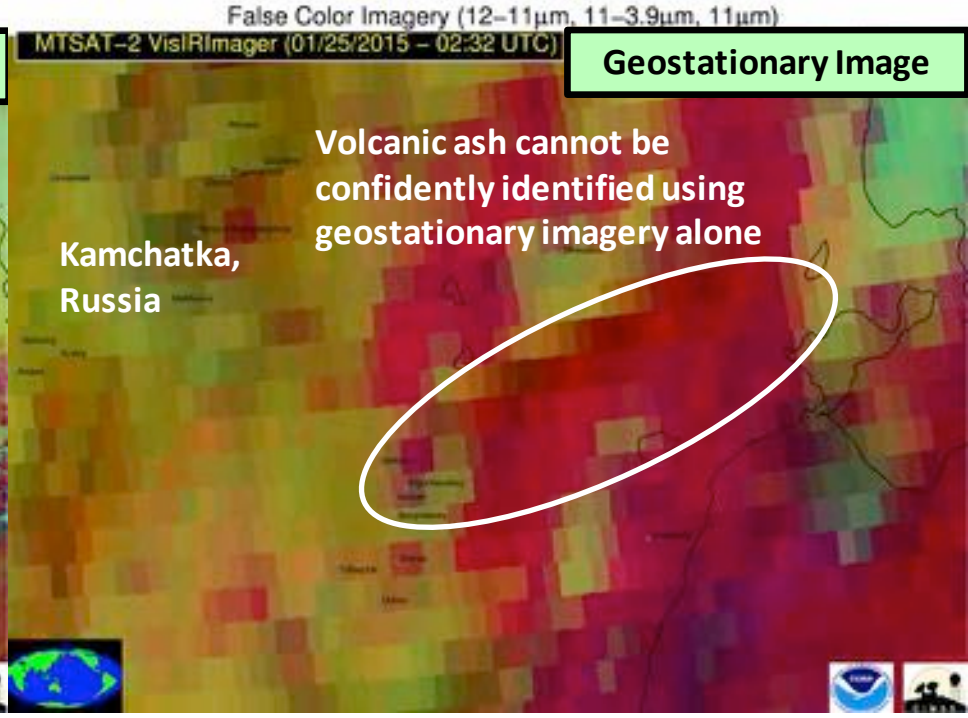
Calbuco Volcano in southern Chile has erupted for the first time since 1972, with the last major eruption occurring in 1961 that sent ash columns 12-15 kilometers high. This image was taken by the Suomi NPP satellite's VIIRS instrument color enhanced infrared and the Day Night Band at 0515Z on April 23, 2015





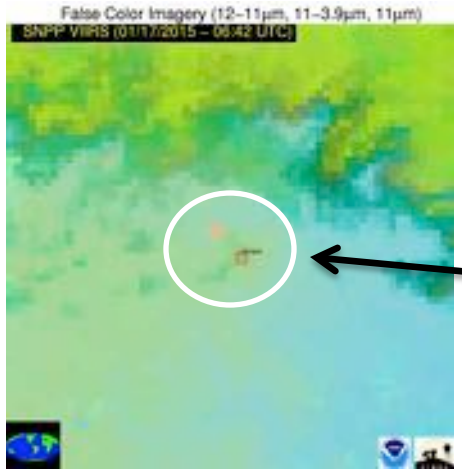
VIIRS is Critical for Mitigating Volcanic Related Aviation Hazards: Direct and indirect benefits





Direct Benefit: Nearly everyday VIIRS identifies volcanic activity that is not unambiguously identifiable using any other meteorological satellite sensor.

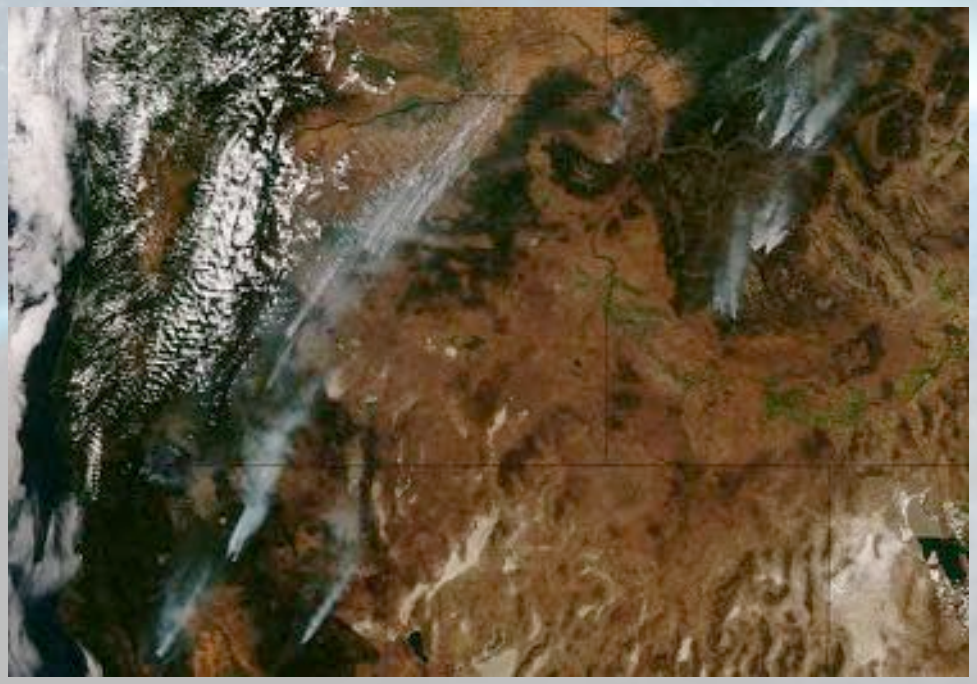
Indirect Benefit: The VIIRS images are used to identify subtle volcanic ash cloud features from geostationary imagery, thereby allowing the clouds to be tracked in time.



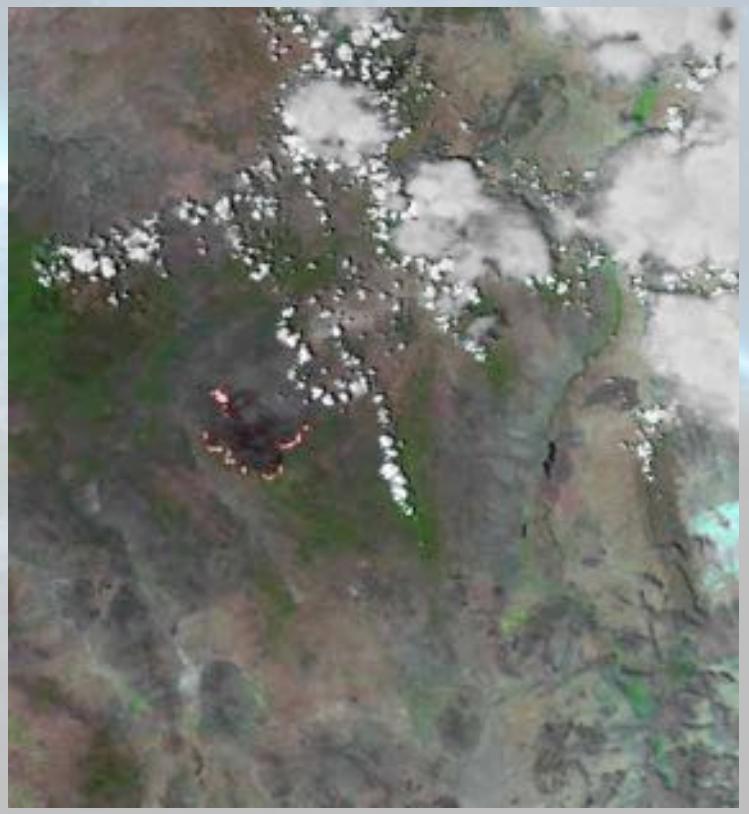
Recently, VIIRS was the first space sensor to detect renewed activity at Sangay Volcano in Ecuador (lava and ash emissions)

PI: Mike Pavolonis, NESDIS Center for SaTellite Applications and Research (STAR)

VIIRS Fire Imagery



2012 Pacific NW fires

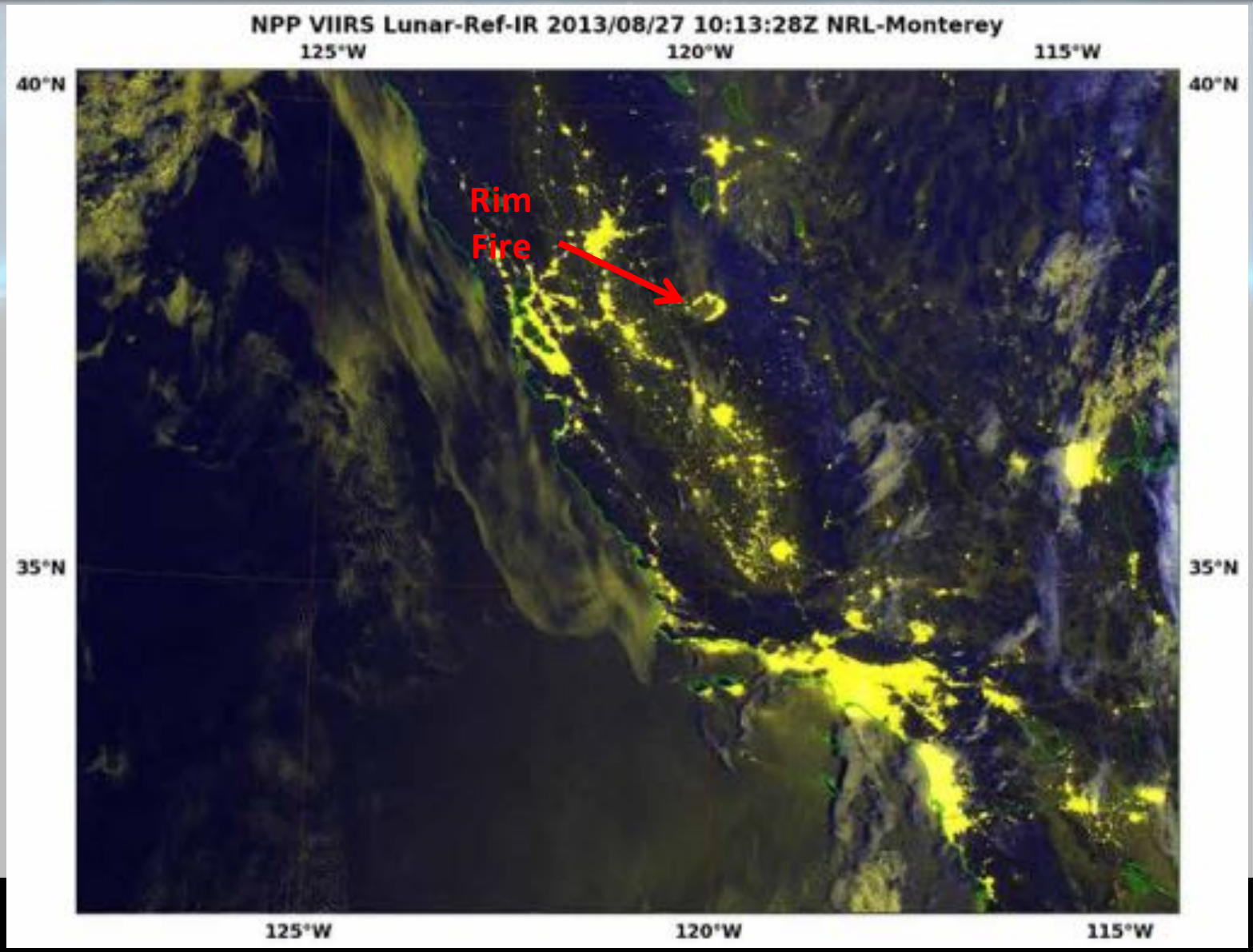


Whitewater-Baldy Complex fire, New Mexico is up to 259,025 acres burned. June 4, 2012.

Tracking the Rim Fire at Night

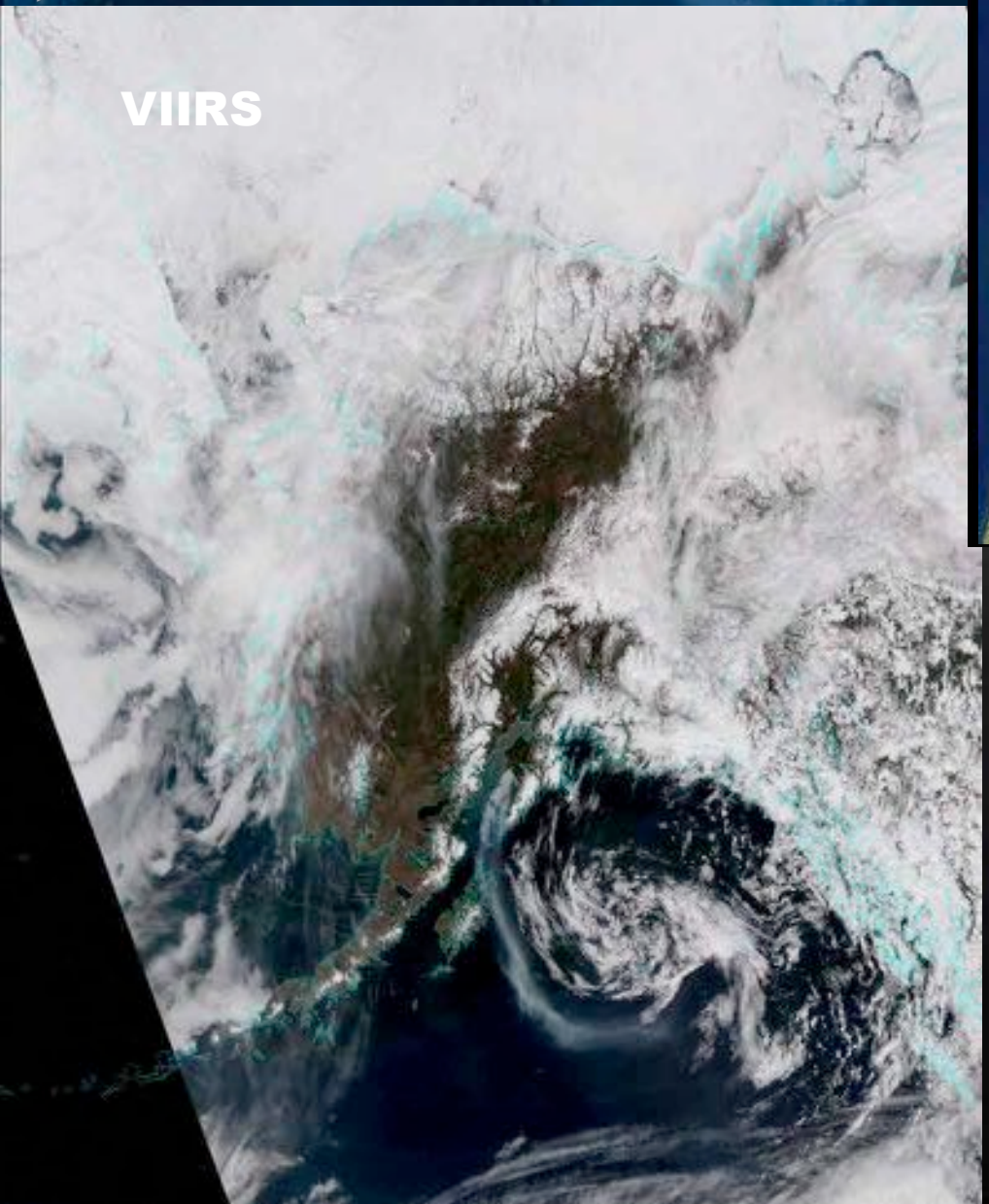
VIIRS DNB + IR enhanced with Lunar Irradiance Model

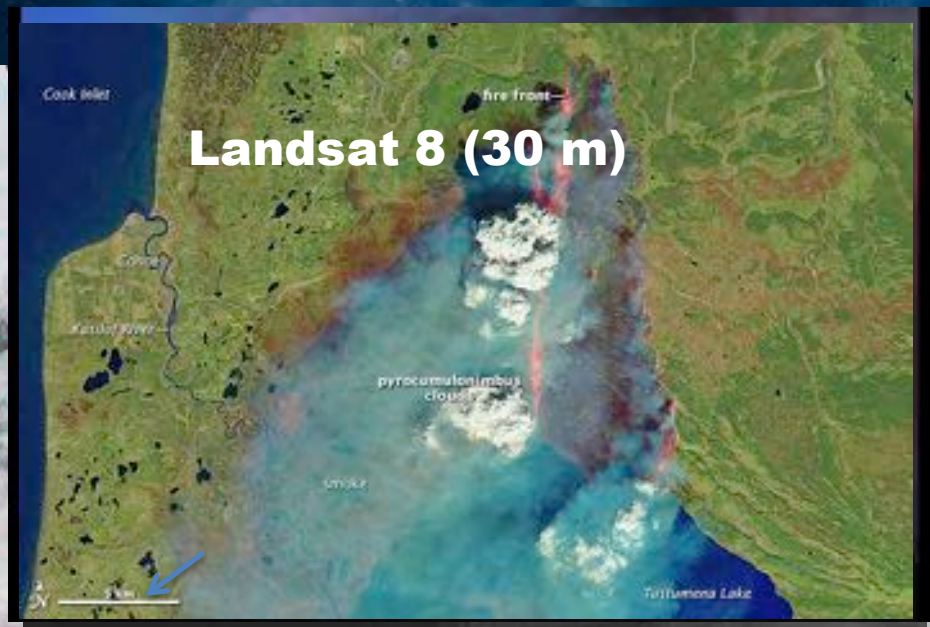
18 – 27 August

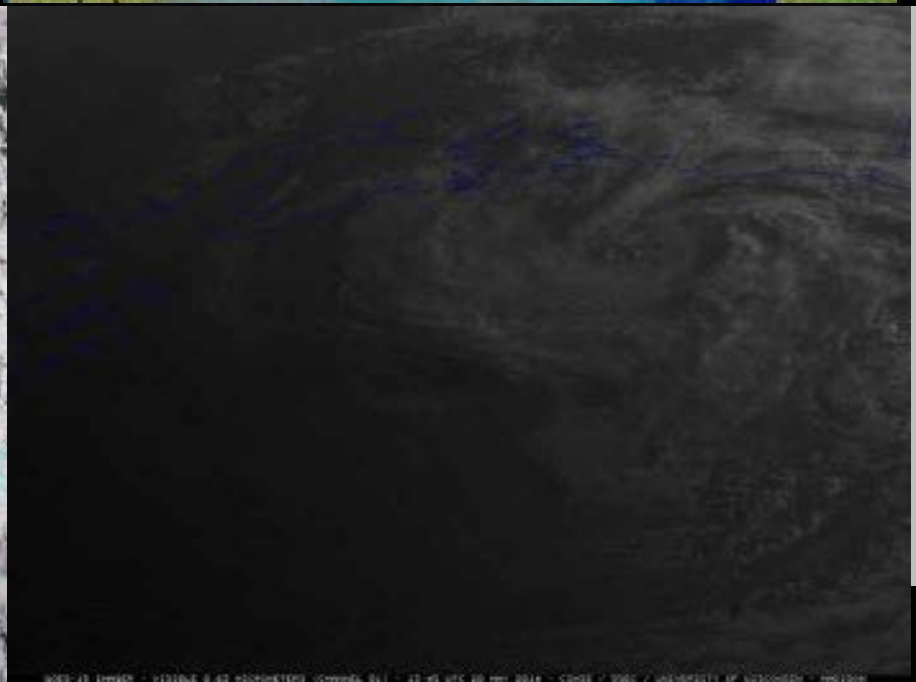


Integrating various satellite data is well recognized and emphasized

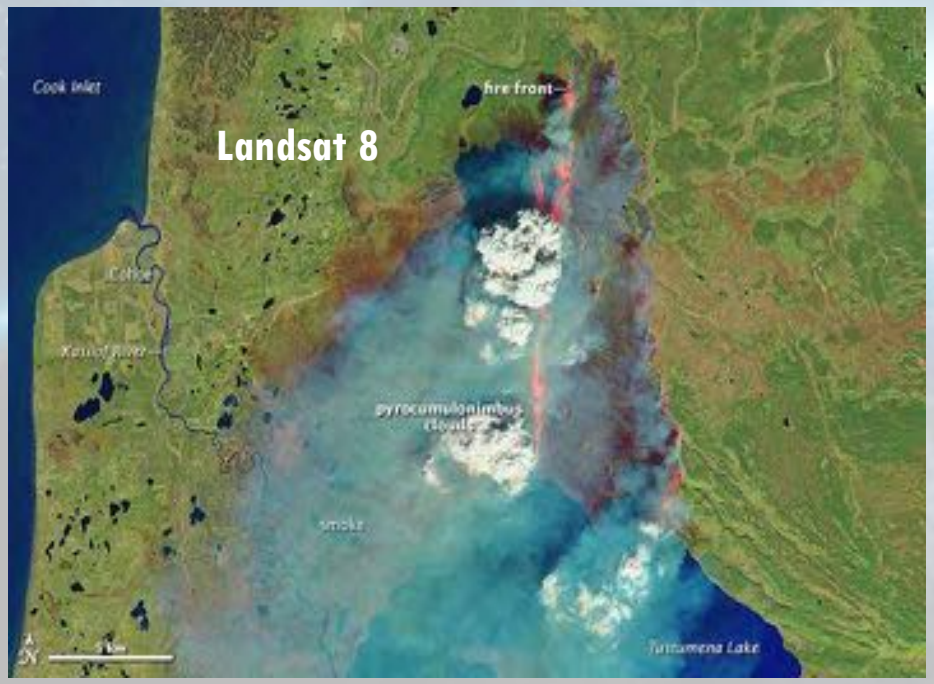
Funny River Fire – Alaska - May 20, 2014





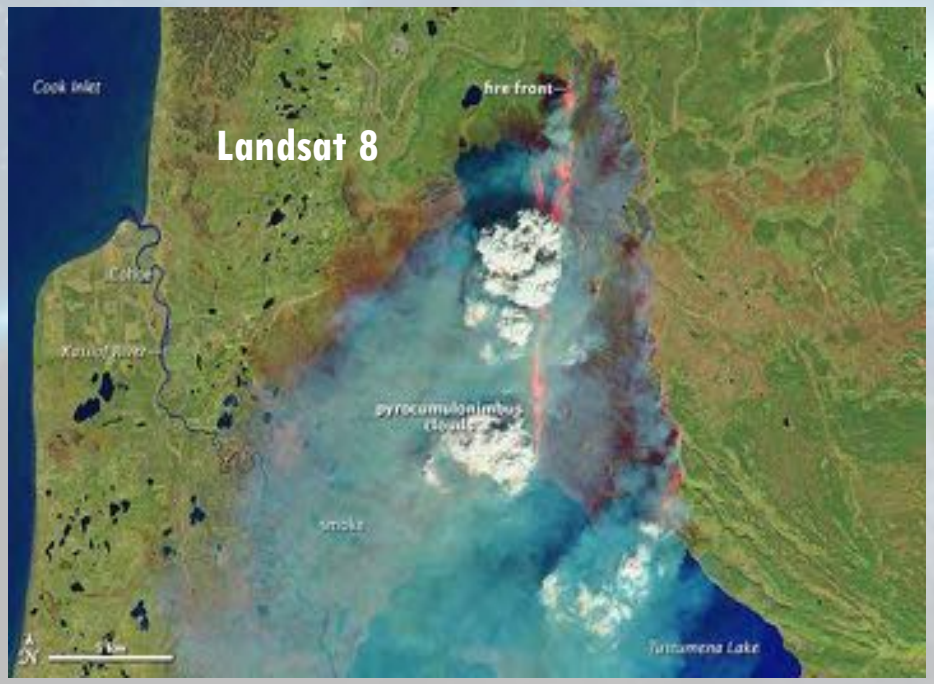


LANDSAT 8 (30 meter resolution vs VIIRS 375 meter resolution)



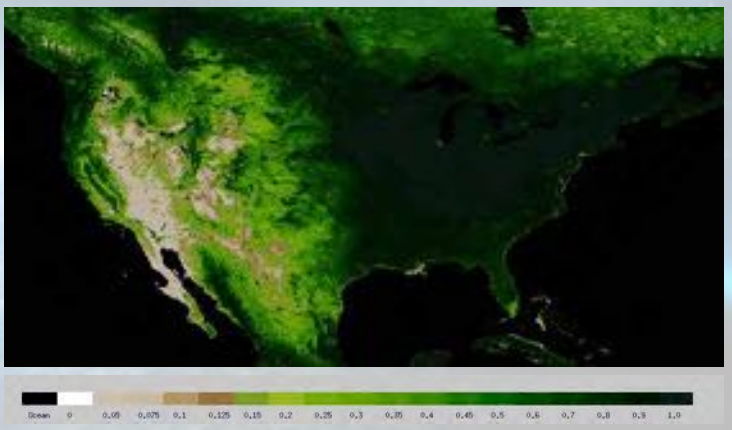
But Landsat has a 16 day repeat cycle –
it will not observe this location for another 16 days

LANDSAT 8 (30 meter resolution vs VIIRS (375 meter resolution)



Annual cycle of vegetation

Vegetation (August 2012 vs 2014)



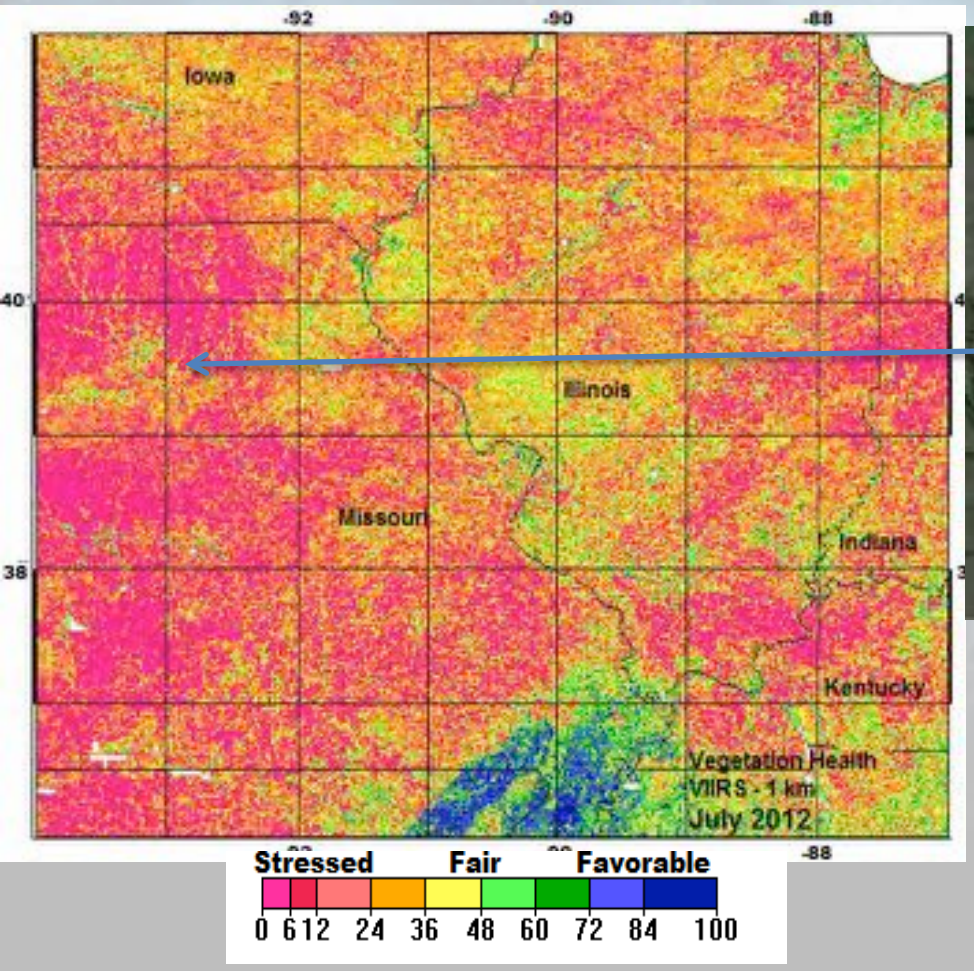
VIIRS GVF difference (15 Aug 2012 minus 15 Aug 2014)

USDA reported record corn production In 2014 - 629 million bushels vs 467 in 2004

Deep red has 30% less vegetation in 2012

Drought examples

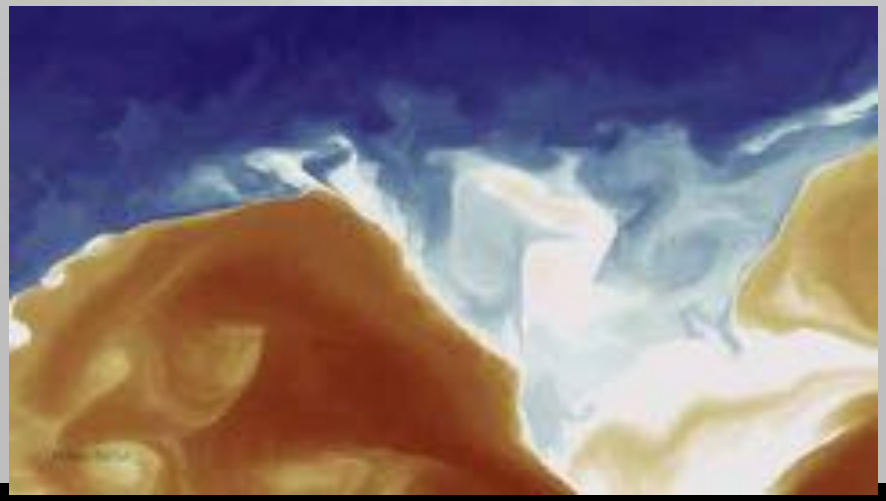
Vegetation health SNPP/VIIRS July 22, 2012

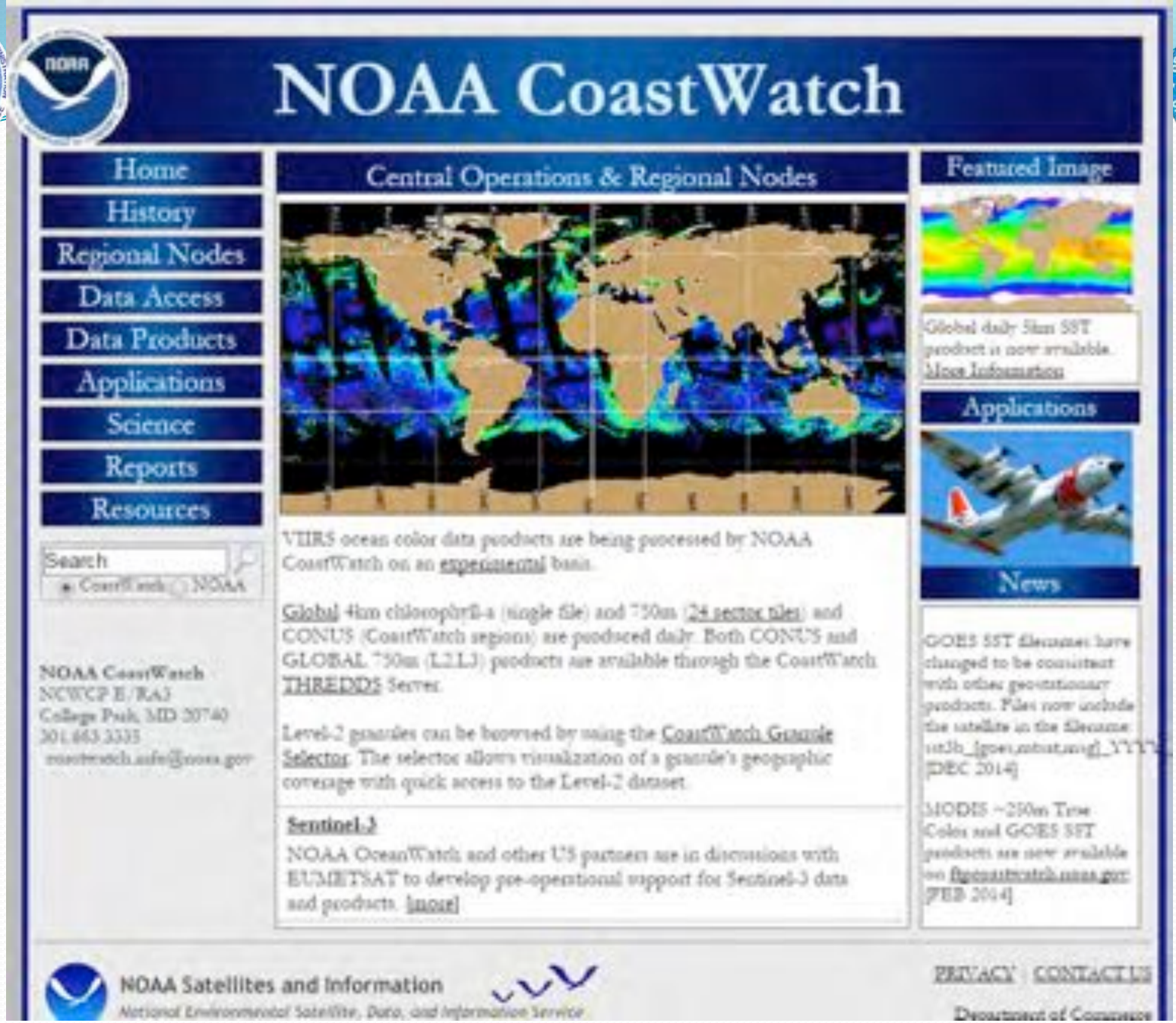


Detail imagery of ocean nutrients and sea surface temperature

Phytoplankton in the Baltic Sea

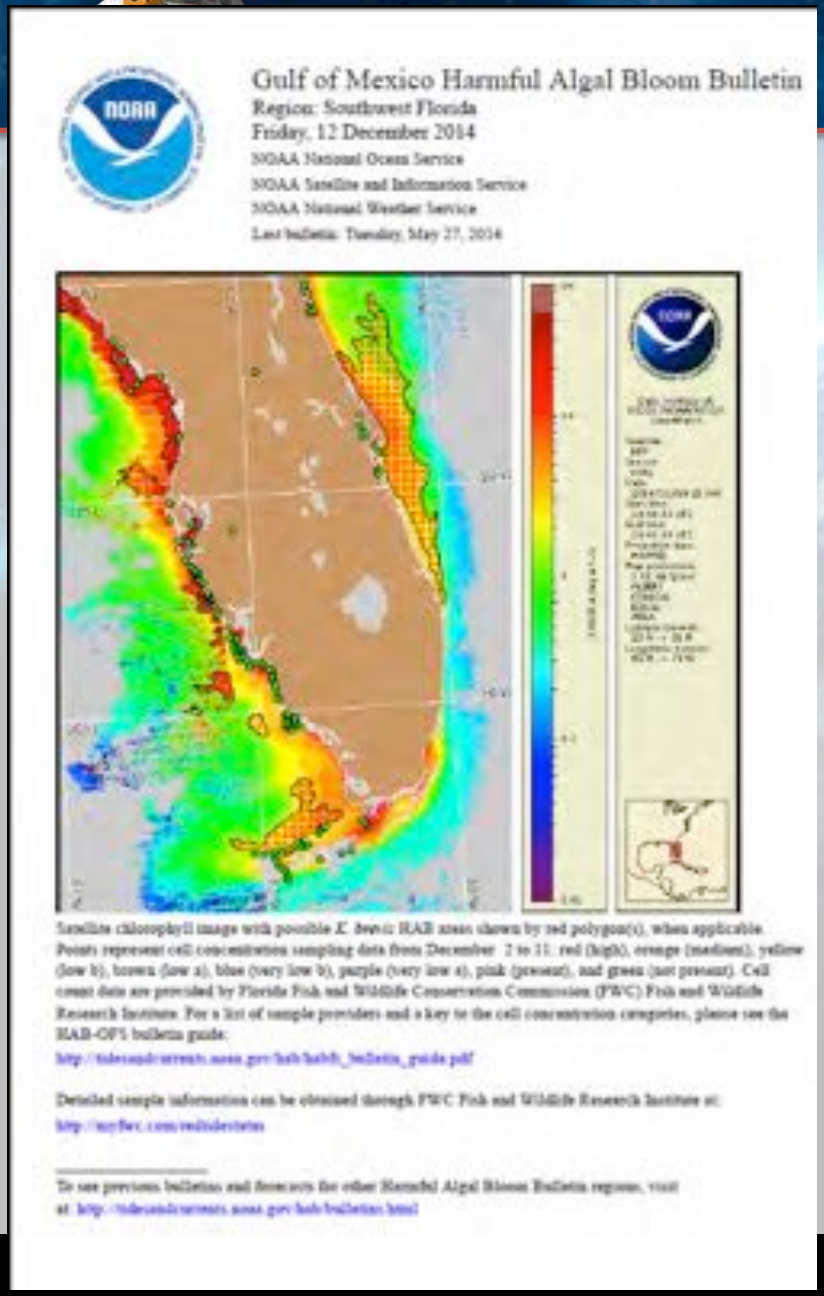
Sea surface temperature gradients south of Cape Cod





http://coastwatch.noaa.gov/

NOAA/NOS Harmful Algal Bloom Bulletins and Coral Reef Bulletins



Gulf of Mexico Harmful Algal Bloom Bulletin
Region: Southwest Florida
Friday, 12 December 2014
NOAA National Ocean Service
NOAA Satellite and Information Service
NOAA National Weather Service
Last bulletin: Tuesday, May 27, 2014

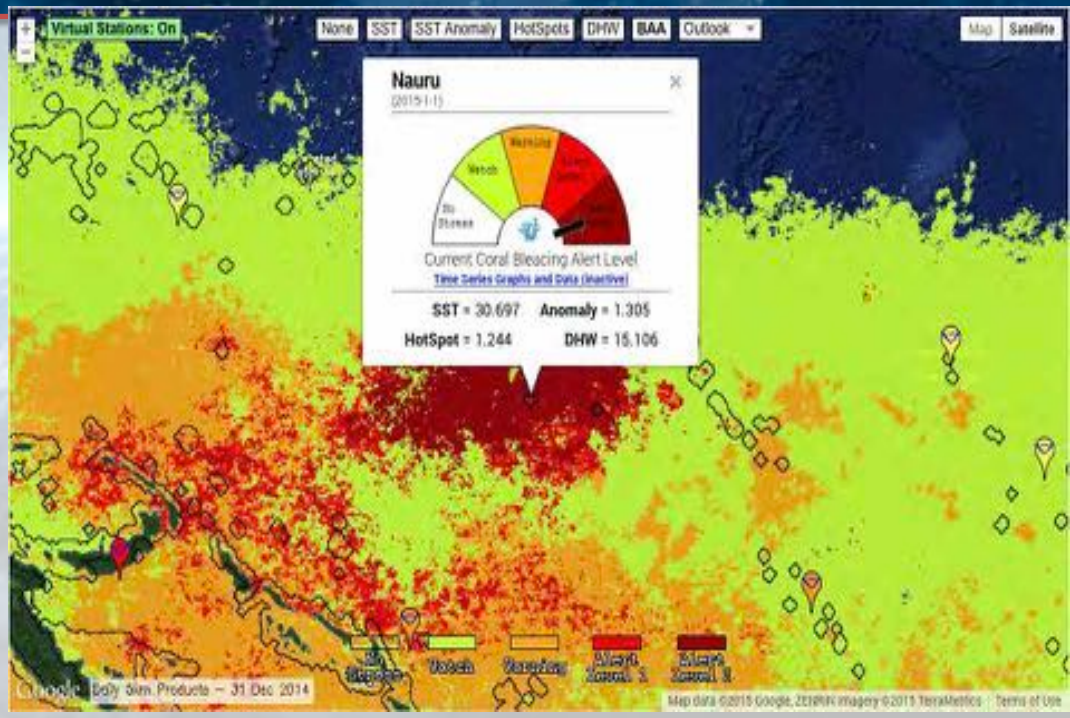
Satellite chlorophyll image with possible *K. brevis* HAB areas shown by red polygon(s), when applicable. Points represent cell concentration sampling data from December 2 to 11: red (high), orange (medium), yellow (low b), brown (low a), blue (very low b), purple (very low a), pink (present), and green (not present). Cell count data are provided by Florida Fish and Wildlife Conservation Commission (FWC) Fish and Wildlife Research Institute. For a list of sample providers and a key to the cell concentration categories, please see the HAB-OFS bulletin guide.

http://tidesandcurrents.noaa.gov/hab/habb_bulletin_guide.pdf

Detailed sample information can be obtained through FWC Fish and Wildlife Research Institute at:

http://myfwc.com/redtide/stats

To see previous bulletins and forecasts for other Harmful Algal Bloom Bulletin regions, visit at: http://tidesandcurrents.noaa.gov/hab/habbulletin.html



NOS/NMFS uses polar-orbiting data for

- Operational harmful algal bloom forecasts
- Response to other algal blooms
- Oil spill response
- Indirectly for boundary models for coastal hydrodynamic models

Oil Spill Mapping using VIIRS Imaging Channels

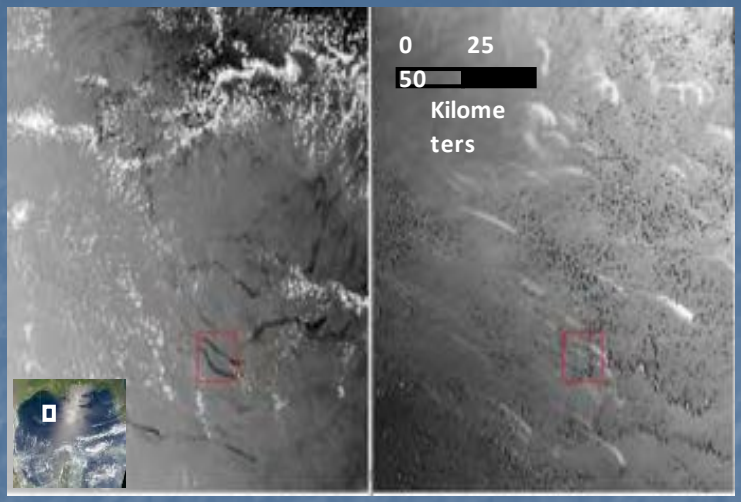


Fig. 2. VIIRS 865-nm images (imaging band #2) on (left) 15 and (right) 21 June 2013 from the same location in the northwest Gulf of Mexico (location shown in the inset figure) showing surface oil slicks due to natural seeps. Depending on the relative solar/viewing geometry (and therefore sun glint strength), the slicks can appear as both dark features (left) and bright features (right). Figure adapted from Hu et al. (2015, in press).

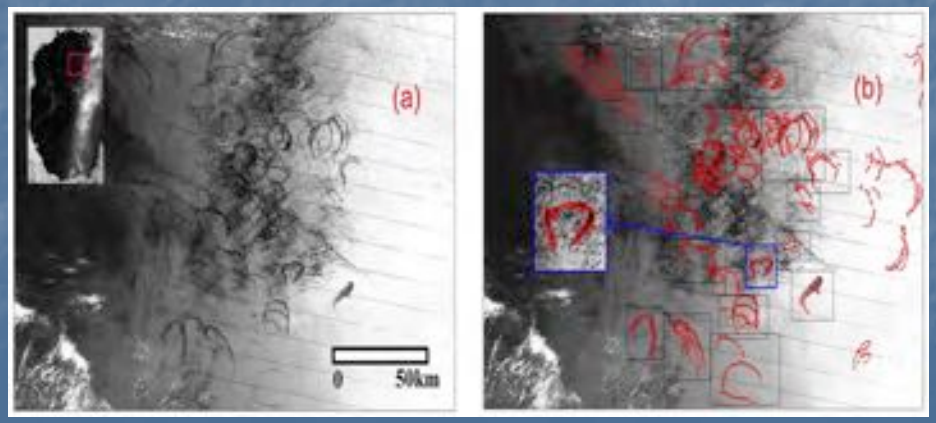


Fig. 4. Preliminary results of oil slick delineation from MODIS sun glint imagery on 2 June 2005. The parameters in the algorithm need to be fine tuned with VIIRS.


NOAA's Comprehensive L...
www.class.ncdc.noaa.gov/saa/products/welcome
» CLASS Home
» Login
» Register
» Help
» About CLASS
CLASS Help
All NOAA
» SEARCH
Please select a product to search
» GO
Around CLASS
» Home
» Search for Data
» Upload Search
» Search Results
» Shopping Cart
» Order Status
» Help
User Account
» User Profile
» User Preferences
Advanced Options
» Download Keys
Release Info
» Version 6.3.7.1
March 5, 2014
Other Links
» CLASS Home
» NODC
» NCDC
» NGDC
» NESDIS
» NOAA
» DOC
Image source: Suomi NPP VIIRS
CLASS
NEWS
Attention CORS users (06/23/14):
Starting January 1, 2014, the National Geodetic Survey's CORS data archived at CLASS now includes GPS+GLONASS data for stations with GNSS-capable equipment. The GLONASS broadcast navigation file (BRDC) is also available for users at the same starting date. (GLO navigation file name example: brdc1680.14g.gz)
CORS data collections include RINEX since 1994 and raw GPS from selected CORS sites since 2004. The original at-sampling rate was retained except where there was only the 30-second decimated rate data. For more info see the CORS CLASS search page.
Attention Suomi NPP Users:
The most recent global NPP operational products are now available in daily tar files for quick and easy downloads at: ftp://ftp-npp.class.ngdc.noaa.gov/. Please see the NPP help page for instructions. Up to the most recent 85 days of data will be available for direct online access.
Suomi NPP data access status (11/25/14):
The majority of S-NPP products are now available and can be ordered through CLASS. The ones available to the public will show the begin dates after the product name on the search page. Also, a "quick look" of which products are at which maturity stages can be easily viewed at the STAR Algorithm Product Maturity Matrix website. Details of high priority issues related to the data quality are contained in the Readme files provided by the S-NPP Project Scientist. Many of these have recently been updated. Please read these before ordering and using the data.
SEARCH FOR DATA
Environmental Data from Polar-orbiting Satellites
Environmental Data from Geostationary Satellites
Defense Meteorological Satellite Program (DMSP)
Suomi National Polar-orbiting Partnership (NPP)
Sea Surface Temperature data (SST)
RADARSAT
Altimetry / Sea Surface Height Data (JASON)
Global Navigation Satellite Systems (GNSS)
Other - Miscellaneous products in CLASS
SEARCH COLLECTION METADATA
» GO

www.nnvl.noaa.gov/sits-custom/VIIRSGallery.php

NOAA ENVIRONMENTAL VISUALIZATION LABORATORY

NOAA View explore. discover. learn.

Home

NOAA/NASA Suomi NPP VIIRS Gallery

Tropical Cyclone Quang in...

More

Calbuco Volcano Erupts in...

More

Satellite Imagery of Swir...

More

Satellites to be Used in ...

More

Sand Storm in the Rub Al ...

More

Super Typhoon Maysak on T...

More

Cyclone Nathan in the Cor...

More

Winter Storm Will Track S...

More

NOAA View Data Exploration

JPSS Science Seminars focus on emerging JPSS capabilities and how they can be quickly transitioned into support for NOAA operational missions.

Want to know more about our JPSS Science Seminars? Join the JPSS Science Seminars Email List

INTERACTIVE JPSS GALLERIES

VIDEO GALLERY

CLICK HERE TO VIEW

IMAGE GALLERY

CLICK HERE TO VIEW

Science Seminar Annual Digest

On behalf of the Joint Polar Satellite System (JPSS) Program Science, it is my pleasure to share with you our science digests, which are a collection of technical articles generated from a series of monthly science seminars. The digests capture the importance of the close collaborative efforts between product developers and key users to conceptualize and develop new products that help improve the use of JPSS data to enhance key services, such as forecasting of severe weather events and environmental monitoring of land, ocean and the cryosphere. I would like to thank our federal staff, private sector support staff, and university partners whose contributions and dedicated efforts have made JPSS a big success.

The JPSS program is committed to ensuring that its user community is prepared to utilize the satellite imagery and data available from JPSS – the United States' next generation polar-orbiting operational environmental satellite system. JPSS provides environmental observations which are used in a wide range of application areas that include severe weather, hazards, aviation, ocean, coastal, land, imagery and data assimilation.

2013

2014