The Earth Climate Hyperspectral Observatory

Peter Pilewskie

University of Colorado

Laboratory for Atmospheric and Space Physics

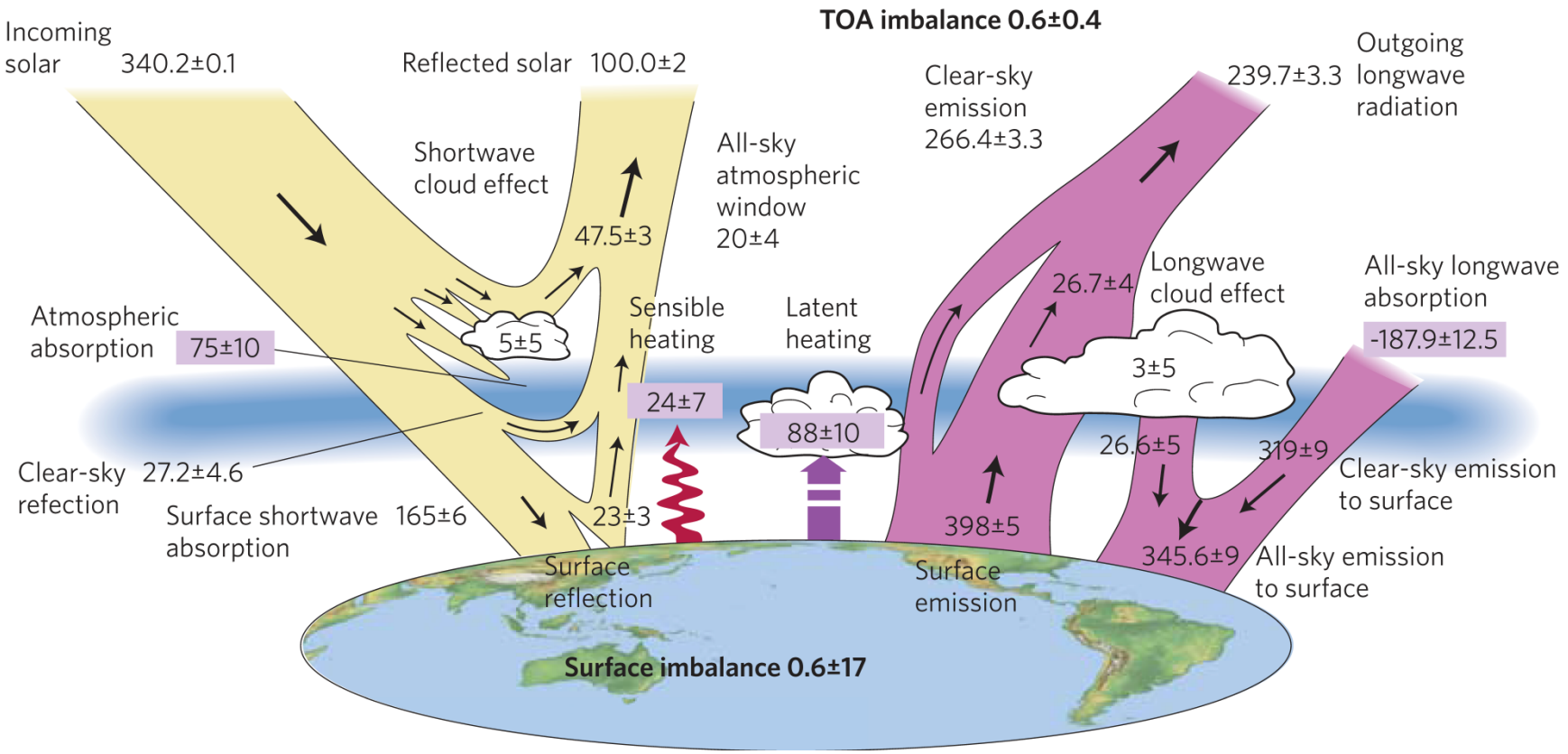
Department of Atmospheric and Oceanic Sciences

Summary

- Monitoring climate change in reflected shortwave radiation requires detecting trends of 0.5-1% per decade.
- Contiguous, spectrally resolved, high accuracy measurements over the entire shortwave spectrum are required for fast time-to-detection and requisite information content for attribution.
- Current observations and models are useful for testing new methods of *trend detection* and *attribution*.
- Earth Climate Hyperspectral Observatory (ECHO) Mission: high accuracy reflectance to monitor tends, link to atmospheric and surface characteristics, test atmospheric and climate models.

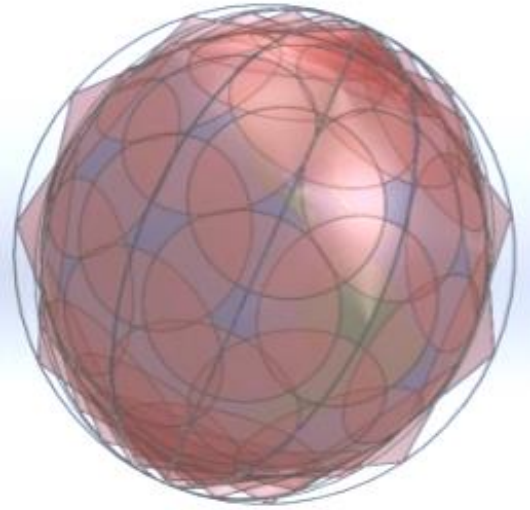
Global Energy Budget

Stephens et al., Nature Geo., 2012



Broadband Earth Energy Budget Experiment: Earth's Radiation Imbalance System (ERIS)

W. Wiscombe et al.



- Fly radiometers on Iridium constellation, hosted-payloads on 66 LEO platforms (780 km orbits)
- Measurements: Hourly shortwave (0.2-5 μm) and longwave (5-100 μm) irradiances from the Earth with 500-km resolution at TOA
- Uncertainty Goal : 0.1 W m^{-2}
- Observe annual 0.6 W m^{-2} imbalance?

Monitor an Annual TOA Imbalance?

- Incoming and total outgoing radiation are about 340 W m^{-2}, while the net imbalance is of order 0.5 Wm^{-2}, or 0.15% of the incoming or total outgoing radiation.
- Constraining a measurement of a net imbalance to 50% of its mean, 0.25 Wm^{-2}, is challenging.
  - Uncertainty in S_o alone is 0.12 W m^{-2}.
  - Outgoing irradiance needs to be known to 0.2 Wm^{-2} or 0.06% of the incoming/total outgoing radiation.
- To put these numbers in perspective: TSI from SORCE TIM is the most accurate (350 ppm; TSIS TIM ~ 100 ppm) and stable (10 ppm/yr) measurement of any component of the radiation budget yet it will account for a modest fraction of the error budget.

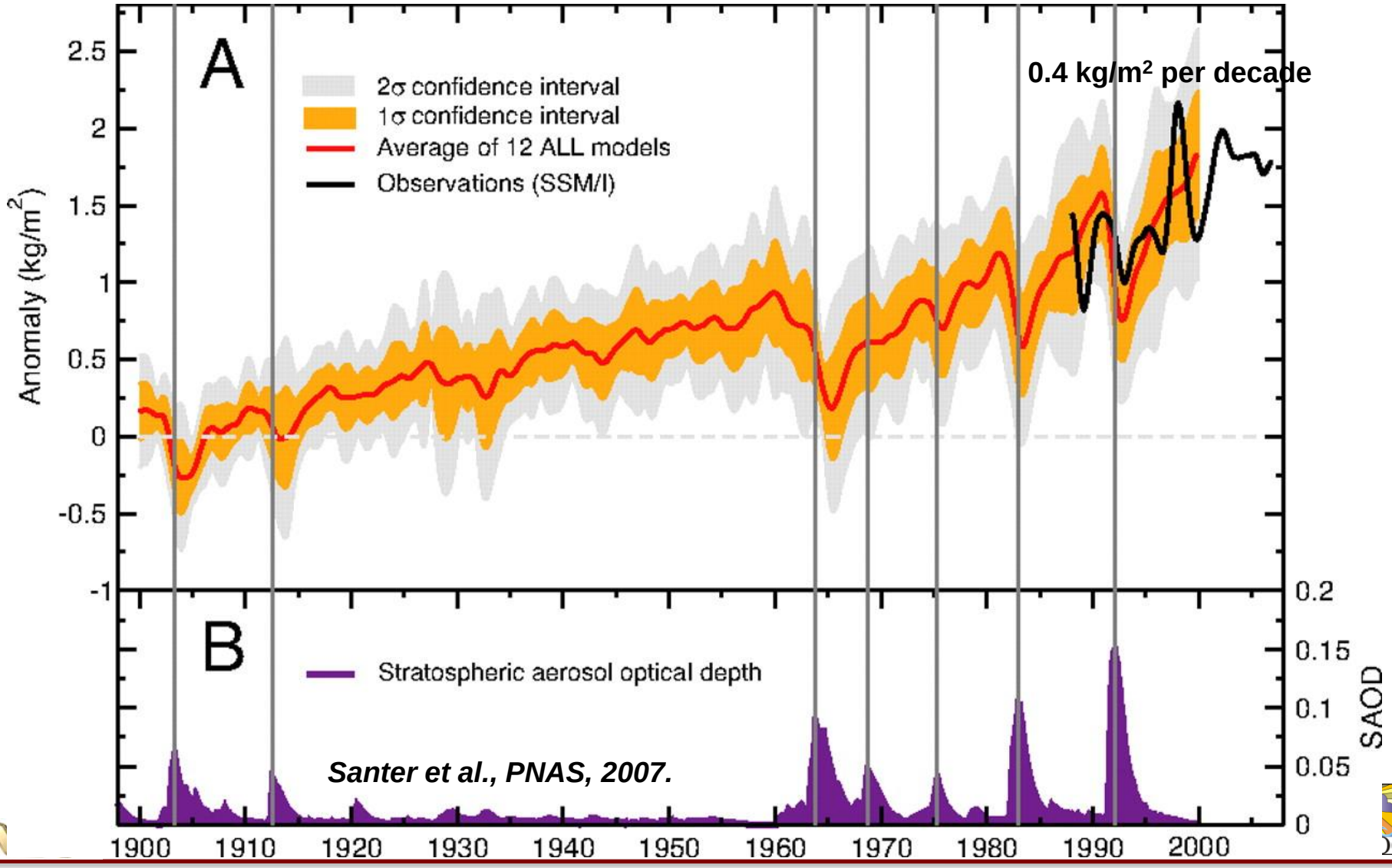
Outline & Questions

- How do we monitor top-of-atmosphere energy imbalance?
- How accurate do we need to be to detect a trend in shortwave radiation?
- Why make contiguous, spectrally resolved measurements? How much information is gained?
- What can we learn from current observations and models to determine what is required for a future climate observing system?
  - Trend detection
  - Attribution

Establishing a Shortwave Climate Benchmark

- A high accuracy record of climate change.
  - ➢ High accuracy, verified on-orbit.
  - ➢ Guarantees the consistency required for over long time periods.
  - ➢ It does not require a perfectly accurate retrieval algorithm.
- Must have high accuracy and information content necessary to detect long-term climate change trends and to test and climate predictions.
- Accuracy and sampling to assess and predict the impact of changes in the climate forcing variables on climate change.
- Benchmark variables are Direct Observables; reflected radiance or reflectance.

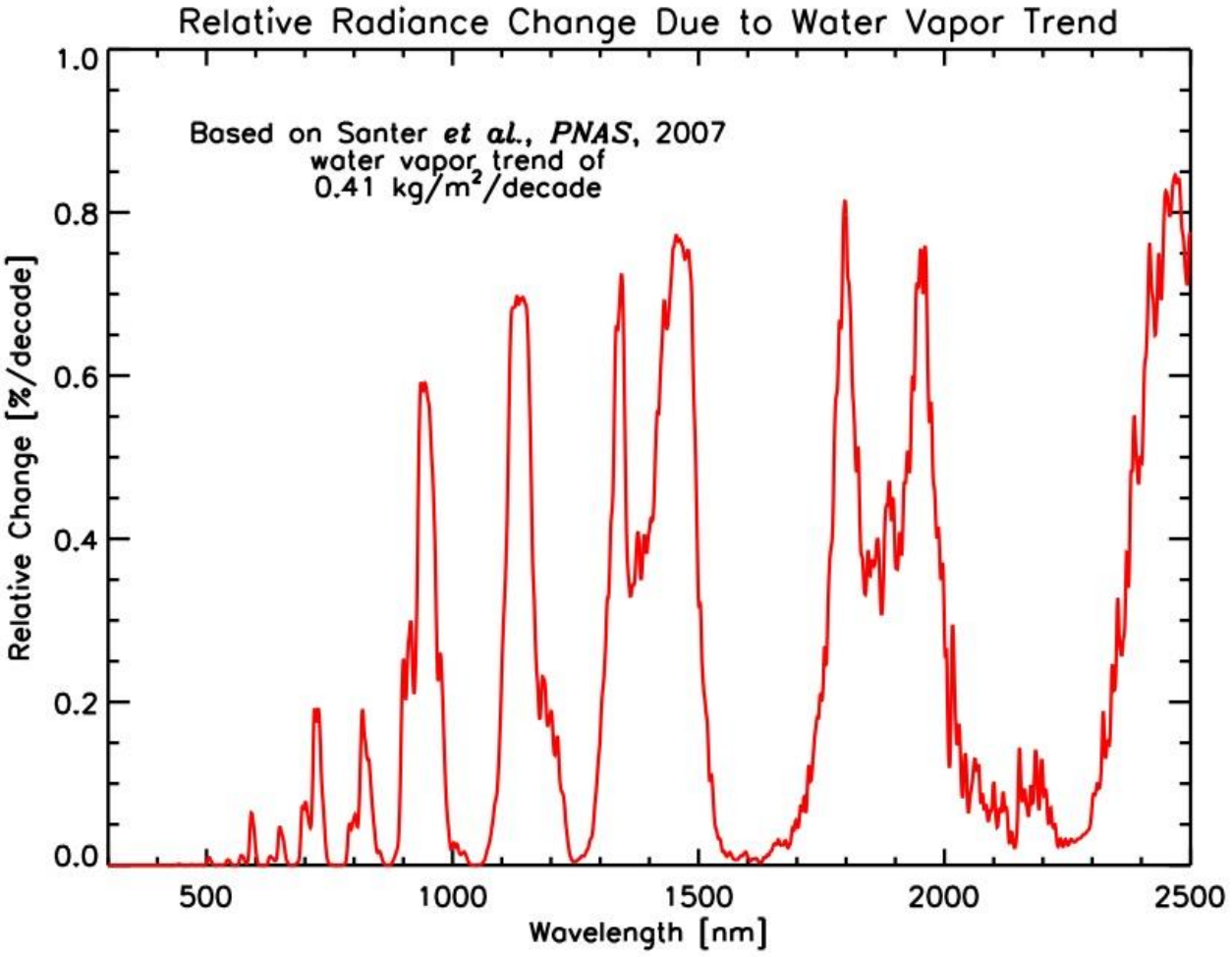
Water Vapor Trend



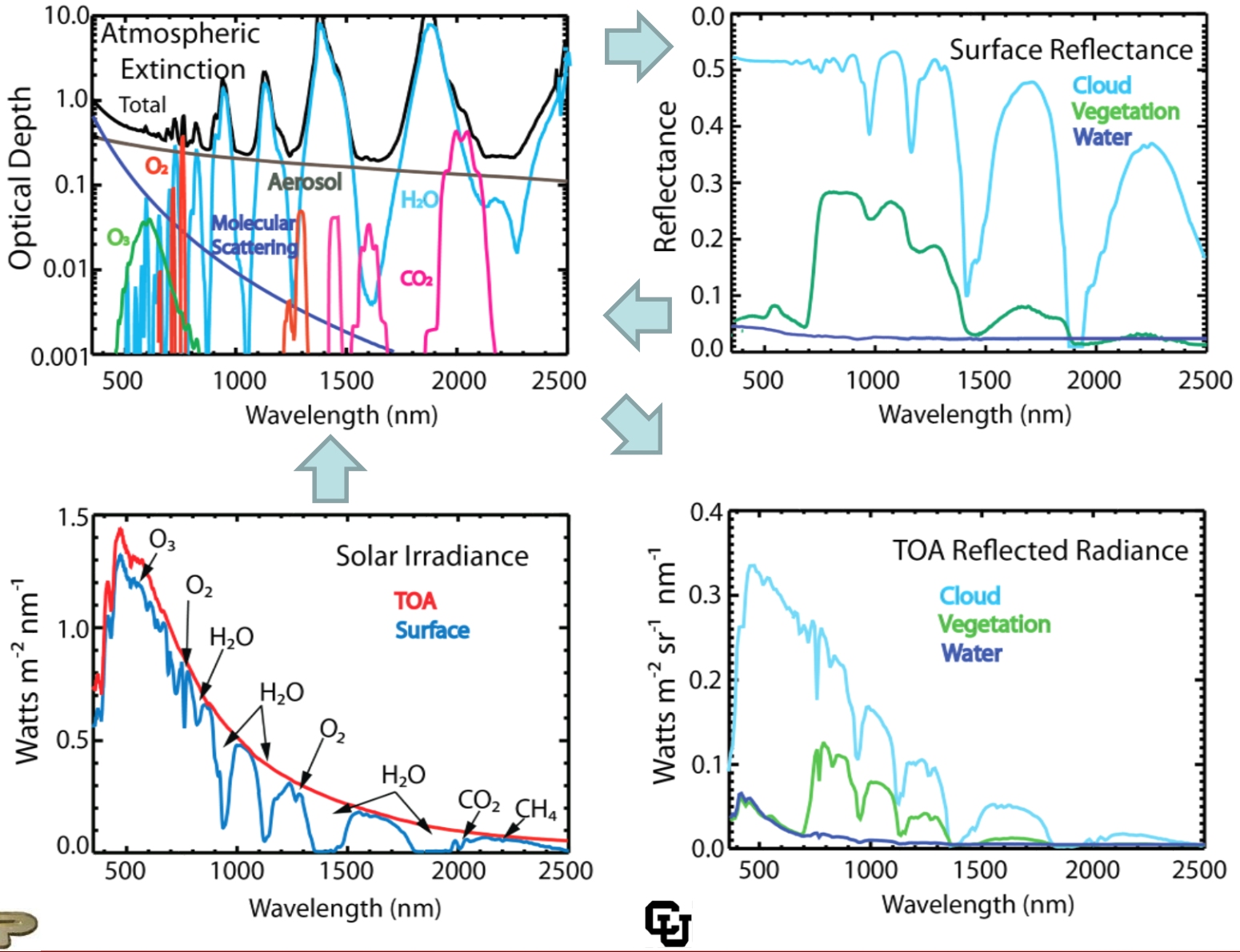
Santer et al., PNAS, 2007.

Sensitivity of Earth-Reflected Solar Radiance to Water Vapor

- Radiative transfer simulations used to derive changes in outgoing top-of-atmosphere spectral radiance due to 0.4 kg/m^2 per decade trend in water vapor.
- Largest absolute changes occur in the weak (sub-saturated) VNIR water band; largest fractional changes in the wings of the stronger SWIR bands.



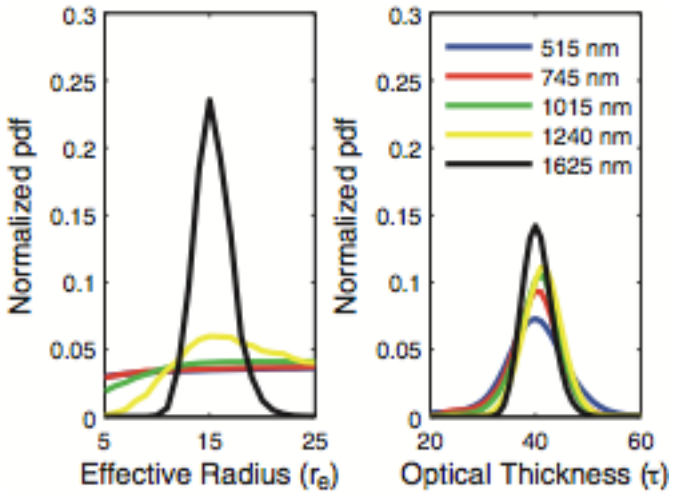
Attribution: Spectral *Un-mixing*



More Wavelengths Add Information

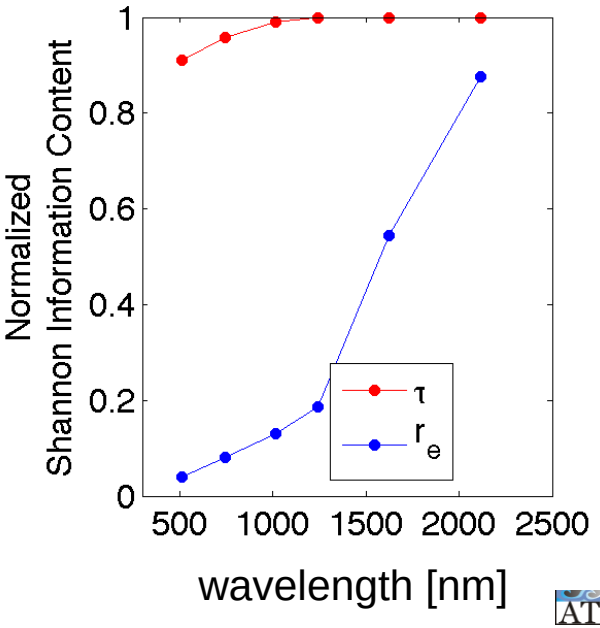
Shannon Information Content from Generalized Nonlinear Retrieval Analysis (GENRA)

- Use Bayes' theorem to *sequentially* update state vector ***x*** (set of cloud parameters we are interested in) with information from spectral channels [*Coddington et al.*, 2012].
- Gain in information from prior to posterior state vector is seen as narrowing of the probability density function of cloud-aerosol parameters ***x***, and the entropy ***S*** with respect to ***x*** is calculated at each step: $S(x) = -\sum p(x) \log_2 p(x)$
- The gain in information at each consecutive step is measured as $H = S_{prior} - S_{posterior}$

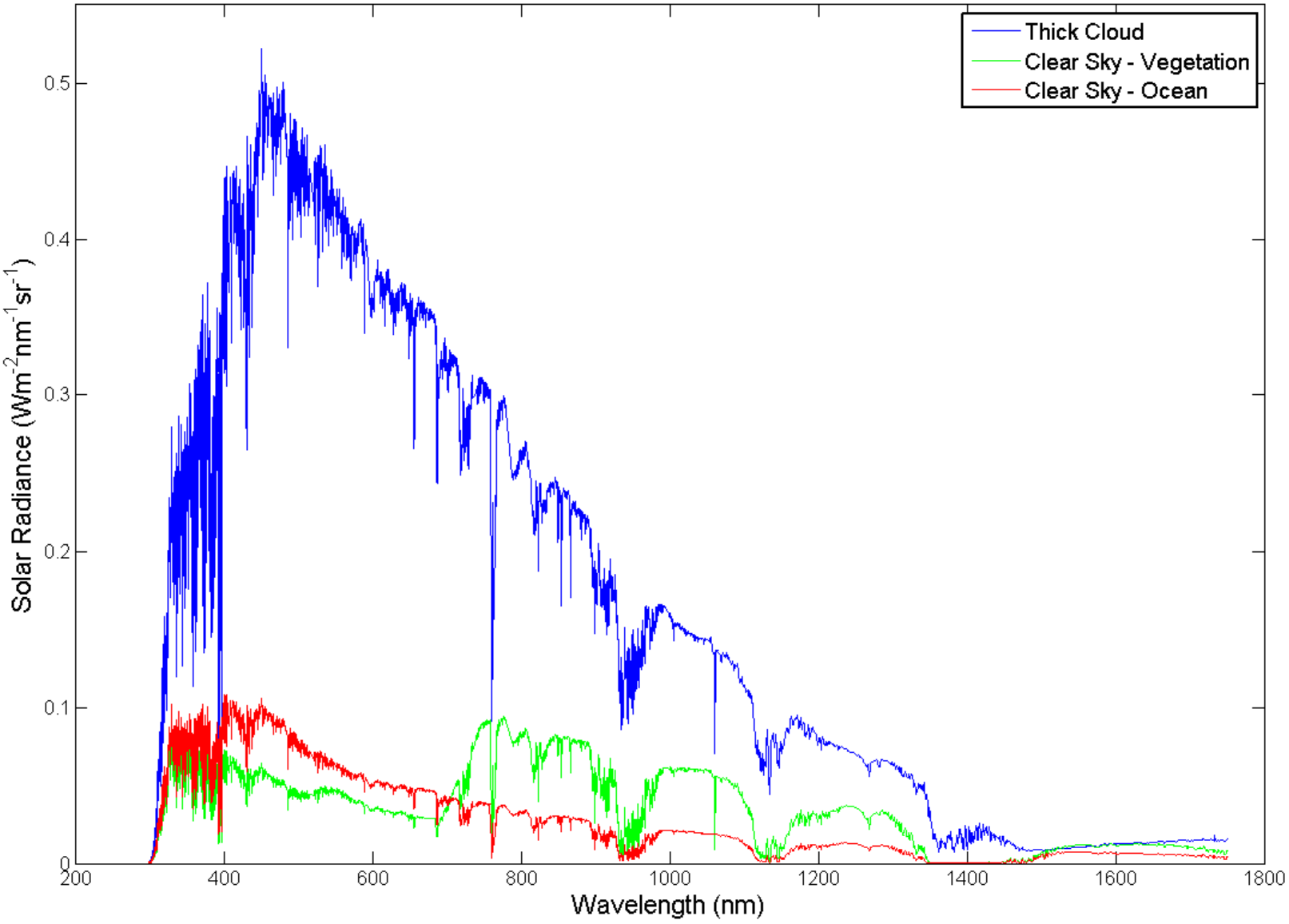


Adding information from six wavelengths consecutively narrows the PDFs of effective radius and optical thickness. At the same time, the Shannon information with respect to these parameters increases.

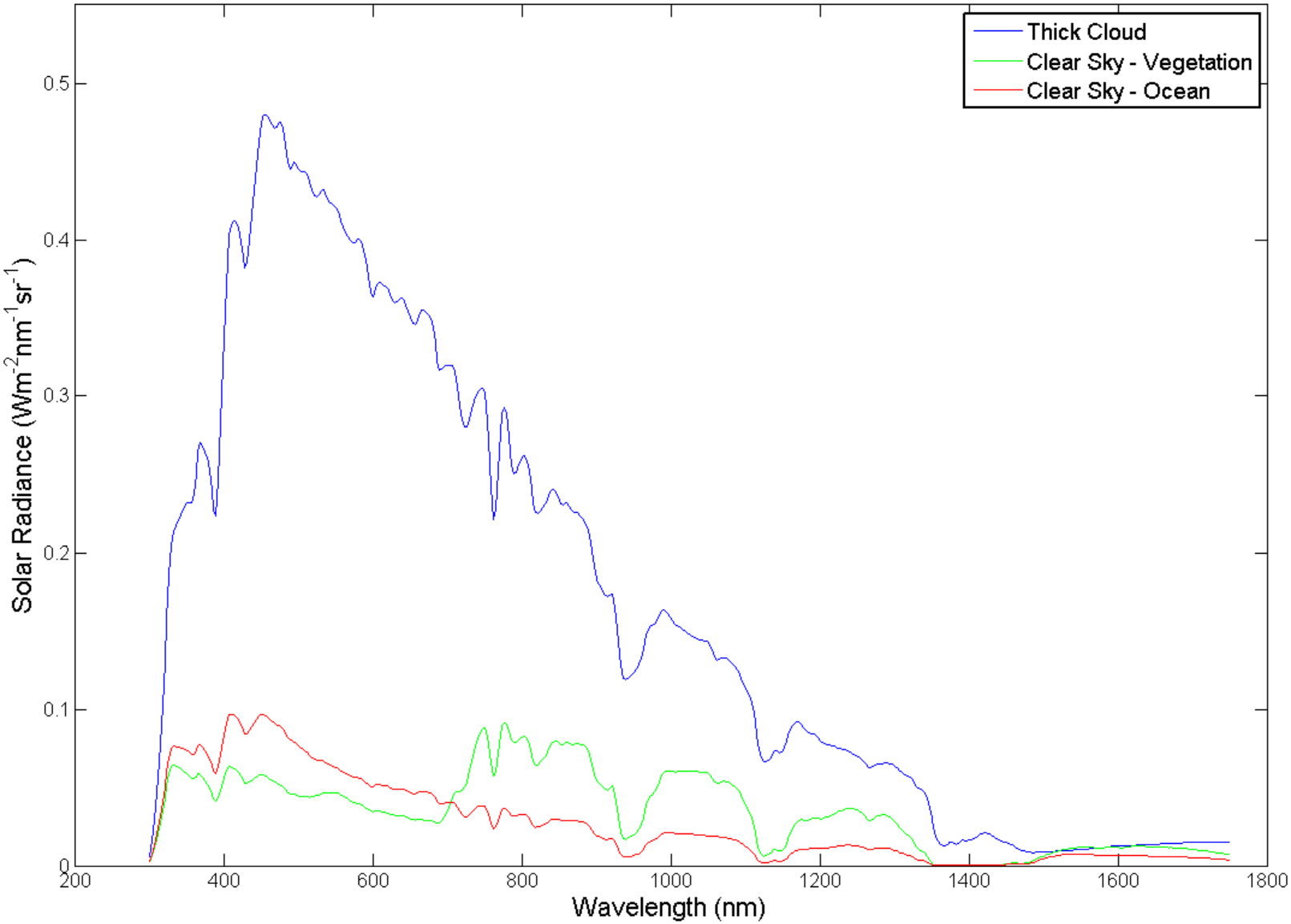
Coddington et al., 2012



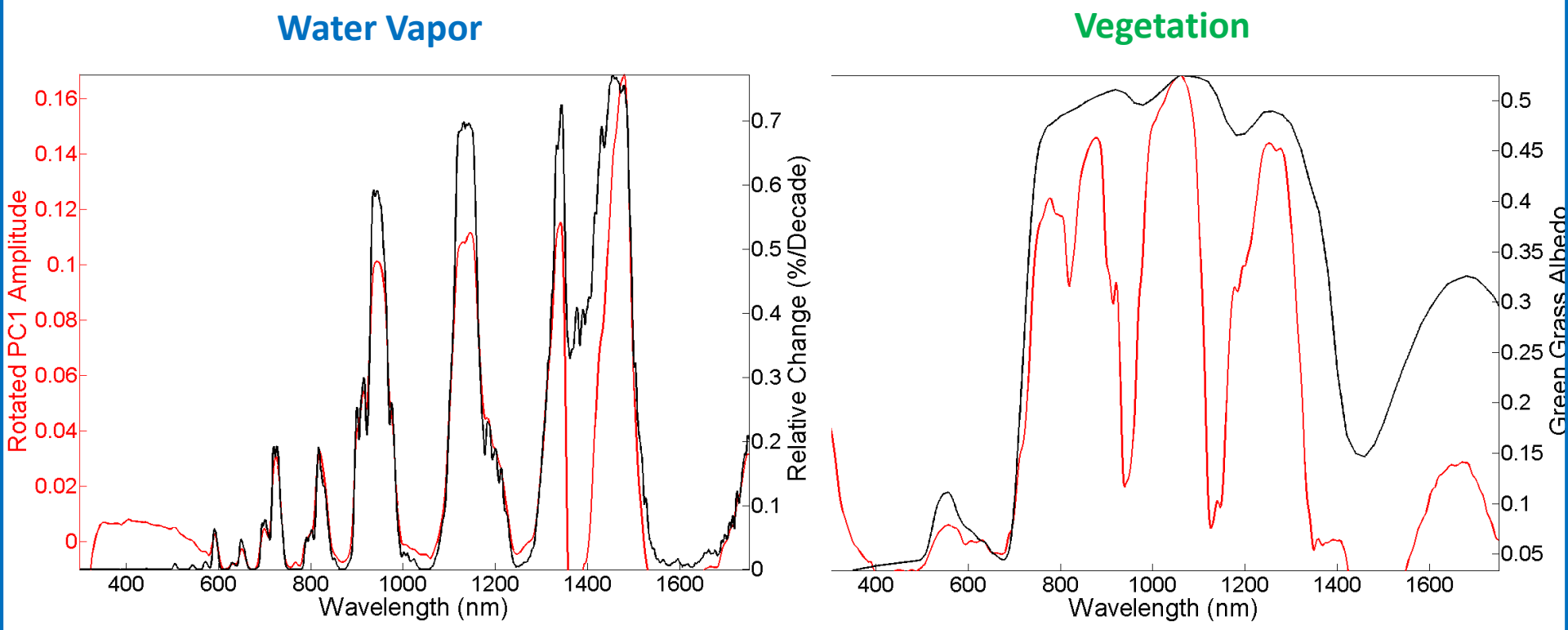
SCIAMACHY Native Resolution



SCIAMACHY Degraded to 10 nm



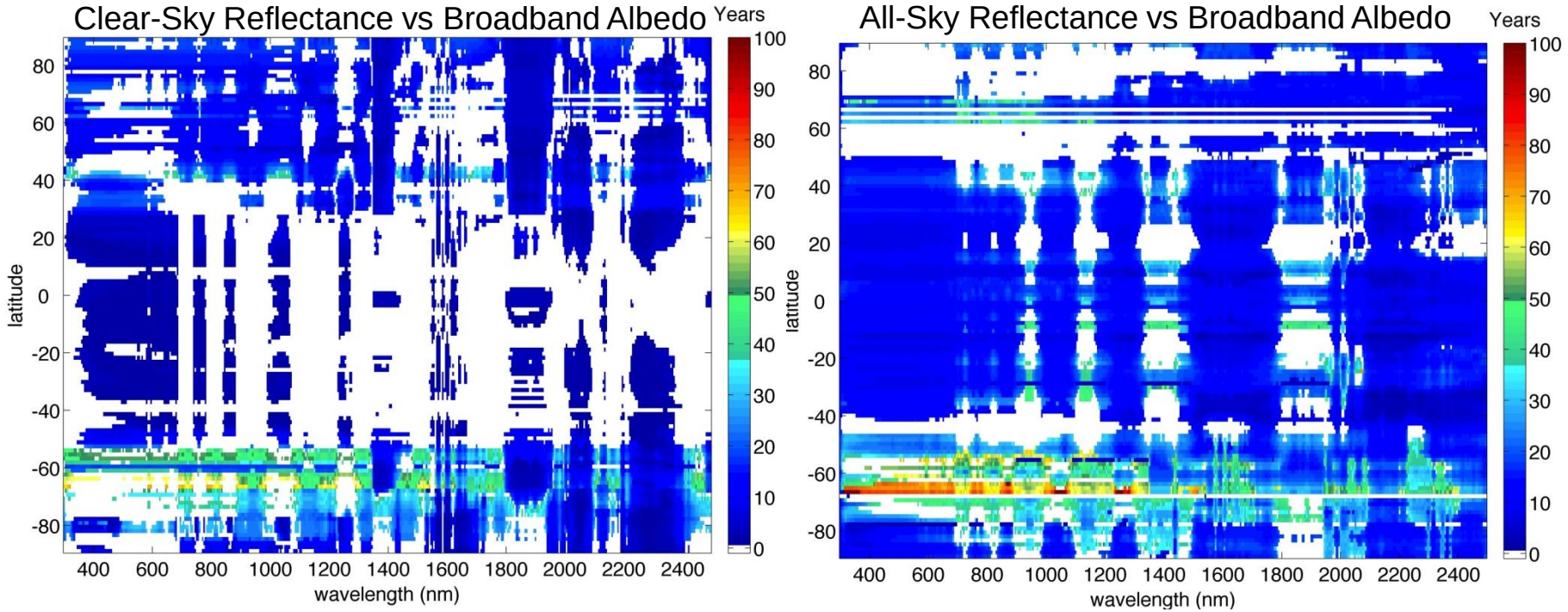
Attribution: Spectral Signatures



Roberts, Y. L., P. Pilewskie, and B. C. Kindel, J. Geophys. Res., 116, 2011

Change Detection Value Added From Spectrally Resolved Reflectance

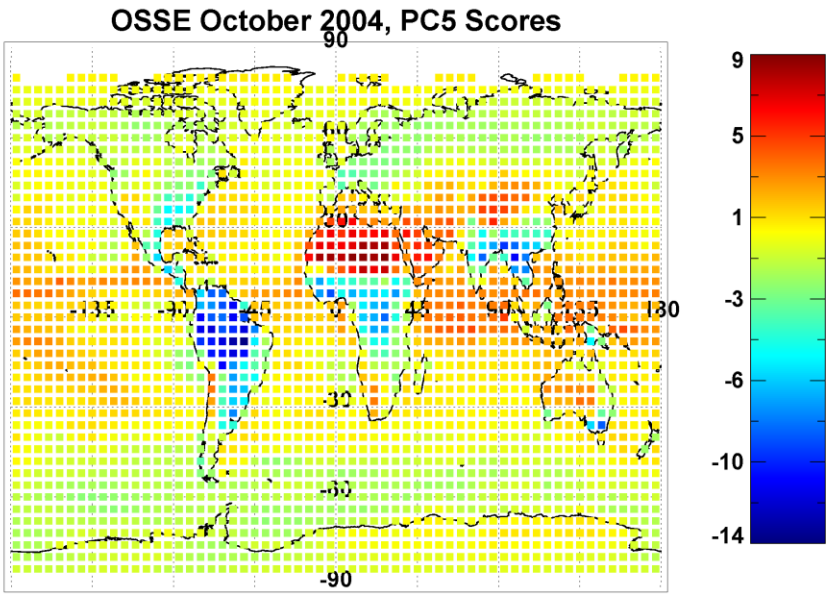
Observing System Simulation Experiments (OSSEs) of the 21st Century

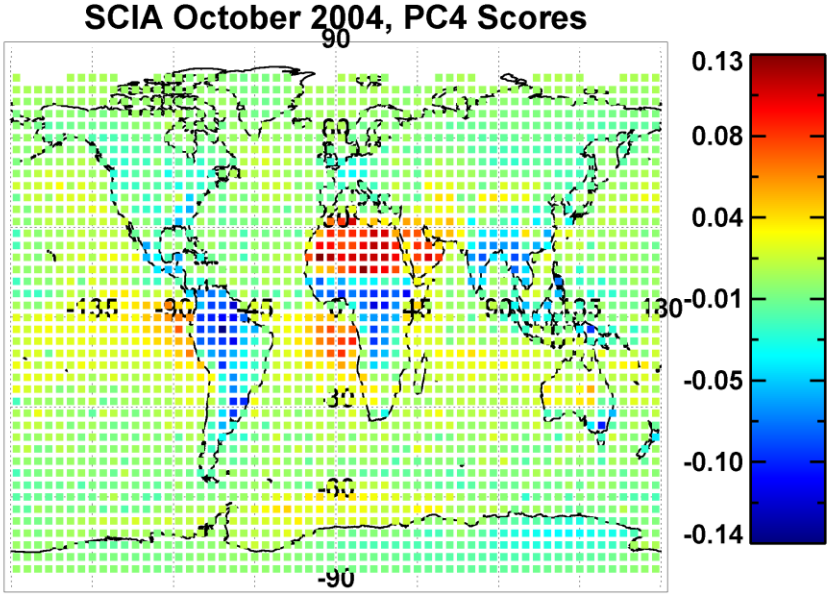


- Spectral albedo or radiance add value to change detection where plots are **NOT** shaded white.

Feldman, D., et al., JGR (2011)

SCIA and OSSE Vegetation Signals





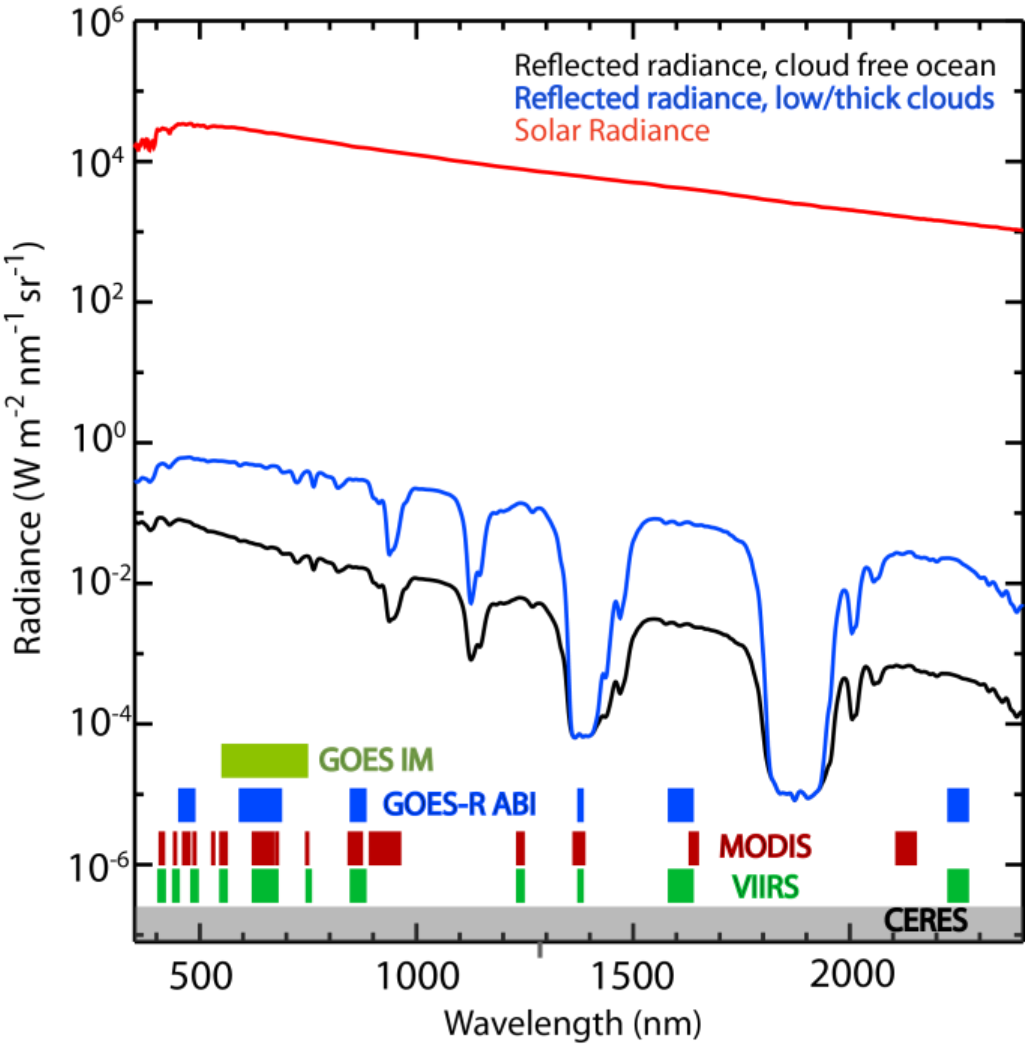
Roberts, Y. L.,et al., 2012

ECHO

Earth Climate Hyperspectral Observatory

Spectral Range	Spectral Resolution	Spatial Resolution	Swath Width	Polarization Sensitivity	Radiometric Uncertainty	Orbital Inclination	Repeat Cycle
350-2400 nm	6.4 nm	1 km	200 km	< 0.2%	0.2-0.4%	51.6°	30.06 days

Spectrum of Reflected Solar Radiation from Earth



Calibration by direct solar observations; method prototyped and validated in two NASA Incubator projects:

2007: *A Hyperspectral Imager to Meet CLARREO Goals of High Absolute Accuracy and On-Orbit SI Traceability.*

2010: *A HyperSpectral Imager for Climate Science*

HySICS IIP Development

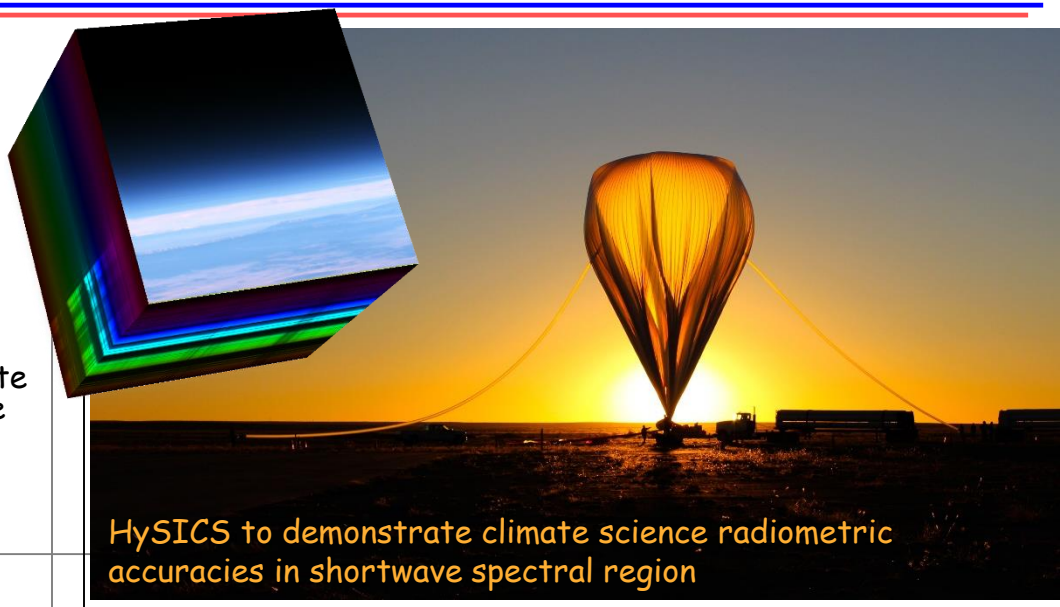
Objective

Build and flight test a hyperspectral imager with improved radiometric accuracies for climate science

- 350-2300 nm with single FPA to reduce cost & mass
- <0.2% (k=1) radiometric accuracy
- <8 nm spectral resolution
- 0.5 km (from LEO) IFOV and >100 km FOV
- <0.13% (k=1) instrumental polarization sensitivity

Perform two high-altitude balloon flights to demonstrate solar cross-calibration approach and to acquire sample Earth and lunar radiances

PI: Greg Kopp / LASP



Approach

Single HgCdTe FPA covers full shortwave spectral range with reduced mass, cost, volume, and complexity

Incorporate solar cross-calibration approaches demonstrated on prior IIP to provide on-orbit radiometric accuracy and stability tracking

Orthogonal configuration reduces polarization sensitivity

No-cost balloon flights from experienced team at NASA WFF demonstrate on-orbit capabilities

Key Milestones

• Instrument Design Complete	12/11
• Balloon Gondola and Interface Design Complete	08/12
• Gondola Assembly Complete	12/12
• Long Lead FPA, Grating, & Filter Procured	03/13
• Instrument Assembly Complete	03/13
• FPA Characterizations Complete	04/13
• Instrument Calibrations Complete	07/13
• Environmental Tests Complete	08/13
• Balloon Flight #1 Complete	09/13
• Balloon Flight #2 Complete	08/14

CoIs: Co-I – Peter Pilewskie / LASP
Balloon Flight Manager – David Stuchlik / WFF

ECHO Objectives

How does the Earth-reflected shortwave radiation vary over spectral, temporal, and spatial scales?

- Establish a benchmark of directly measured spectral reflected shortwave radiation.
- Improve the quality of ongoing climate records by transferring high accuracy radiometry to operational climate sensors.

What are the atmospheric and surface changes that dominate the variability in the observed reflected spectral shortwave record?

- Characterize the relevant physical parameters responsible for the observed variability in spectral reflected shortwave radiation.
- Advance the understanding of the processes controlling the observed variability in reflected shortwave radiation through data assimilation and model evaluation.

Downlink ALL data; users bring code to the data.

ECHO data products, heritage, and product level.

Product	Heritage – References
Calibrated geolocated reflectance (L1, L3)	HySICS
BRF/BRDF (L3)	MODIS(43B)/ASTER/MAIAC – *Liu et al.* [2009]; *Lyapustin et al.* [2011]
Cloud mask (L2, L3)	MODIS(35) – *Frey et al.* [2008]
Cloud top pressure (L2, L3)	POLDER (Oxygen-A) – *Buriez et al.* [1997]
Cloud thermodynamic phase (L2, L3)	SCIAMACHY – *Kokhanovsky et al.* [2006]; *Pilewskie and Twomey* [1987]
Cloud optical properties (L2, L3)	MODIS(06) – *Platnick et al.* [2003]
Aerosol parameters (L2, L3)	MODIS(04) – *Levy et al.* [2010]; *Hsu et al.* [2004; 2006] OMI(OMERUV/OMERO) – *Torres et al.* [2002; 2007]
Total precipitable water (L2, L3)	MODIS(05) (NIR) – *Gao and Kaufman* [2003]

Data Assimilation of ECHO Retrievals and Reflectances

The ECHO aerosol data assimilation strategy :

1) Consistent assimilation of independently retrieved products, make use of rigorous retrieval error characterization and averaging kernels.

2) Direct assimilation of reflectances, progressing from an interactive 1D-Var system towards a combined atmospheric-aerosol assimilation within a hybrid Ensemble/4D-Var system.

- Algorithms are currently in development at NOAA/NCEP, NASA/GMAO and NRL/Monterey.
- Participation in ICAP, ensure broad utilization of the ECHO data products, for both research and operational use.
- ECMWF, JMA, and NCEP provided letters of endorsement in support of ECHO to aid in the validation of aerosol analysis and enhancement of prediction skills in forecast models.

Summary

- Continuous near-full spectrum is required for shortwave climate benchmarking.
  - Energy arguments: 50% atmospheric absorption > 1400 nm
  - Increased information content over discrete band sampling
- Approximately 0.5-1%/decade change in reflectance based on various climate change predictions.
- For both a full-global case and a subset single SCIA orbit, 99% of the variance is explained by 5-6 components.
- Spectral resolution makes little difference in distributed variance in SCIA spectra.
  - Recommendation: 10 nm for cloud phase discrimination, surface characterization.

Summary

- Recommended spatial resolution based on cloud resolving arguments:
  - Tradeoff between IPA and PP assumptions.
- Trend detection in time series analysis.
  - Arctic PC2 is ice albedo and follows trend with sea ice extent.
  - SCIA observations/OSSE simulations share 7-dimensional subspace
  - PCs shows seasonal and annual trends
  - OSSE centennial variability evident in time series.
- Comparison between SCIA and model variability are similar (at 95% confidence kevel) over 6 dimensions.
- ECHO Mission: high accuracy reflectance to monitor tends, retrieve atmospheric and surface characteristics, test atmospheric and climate models, cross-calibrate other sensors.