Climate change observation accuracy: requirements and economic value

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Charney Report, 1979

Concerning Anthropogenic Climate Change:

“In order to address this question in its entirety, one would have to peer into the world of our grandchildren, the world of the twenty-first century.”

Foreword by Vern Suomi

Charney Report, 1979

Concerning Anthropogenic Climate Change:

"In order to address this question in its entirety, one would have to peer into the world of our grandchildren, ***the world of the twenty-first century****."*

Foreword by Vern Suomi

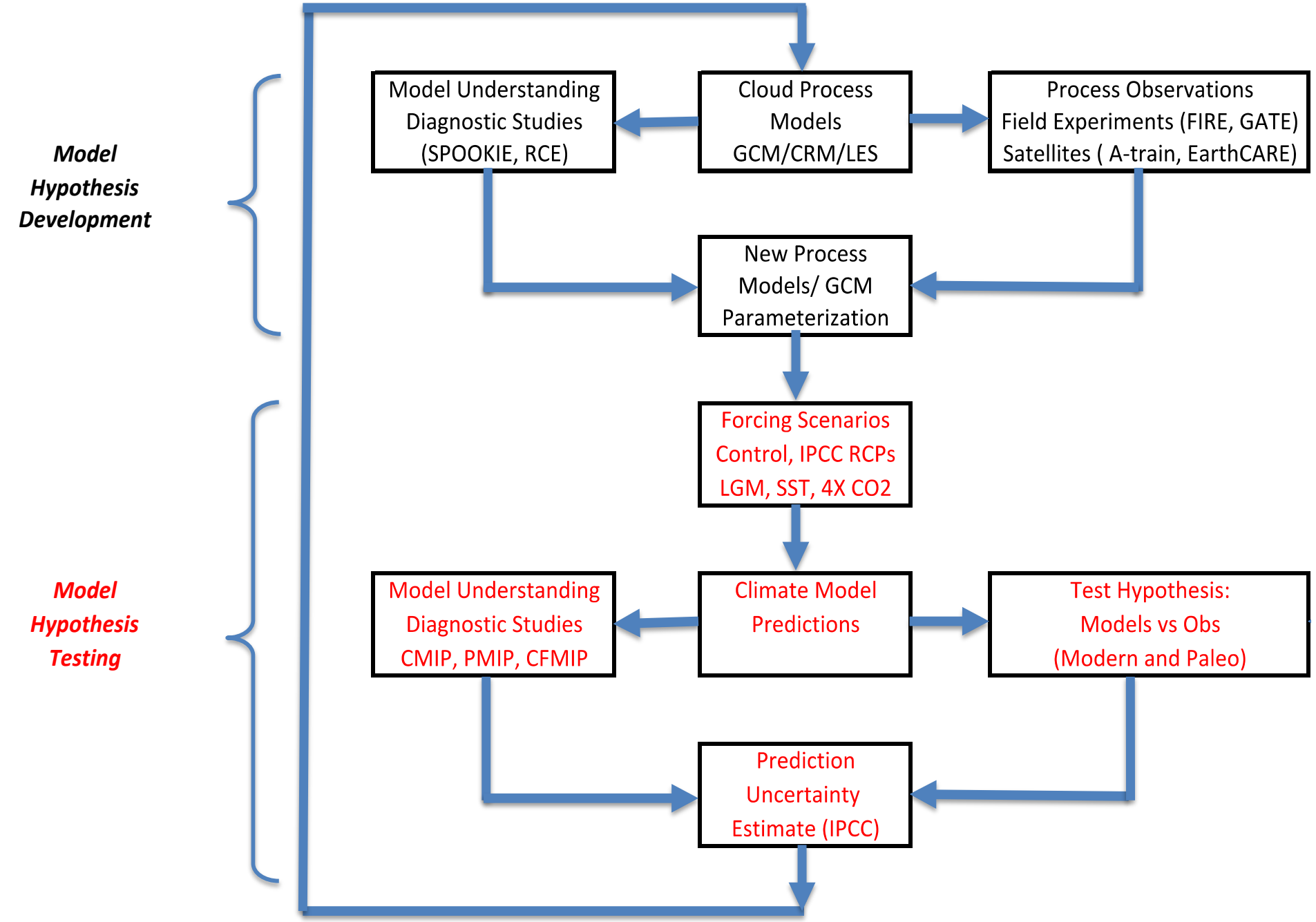
35 Years Later …

This drawing illustrates Diplo's approach to training and research on climate change.

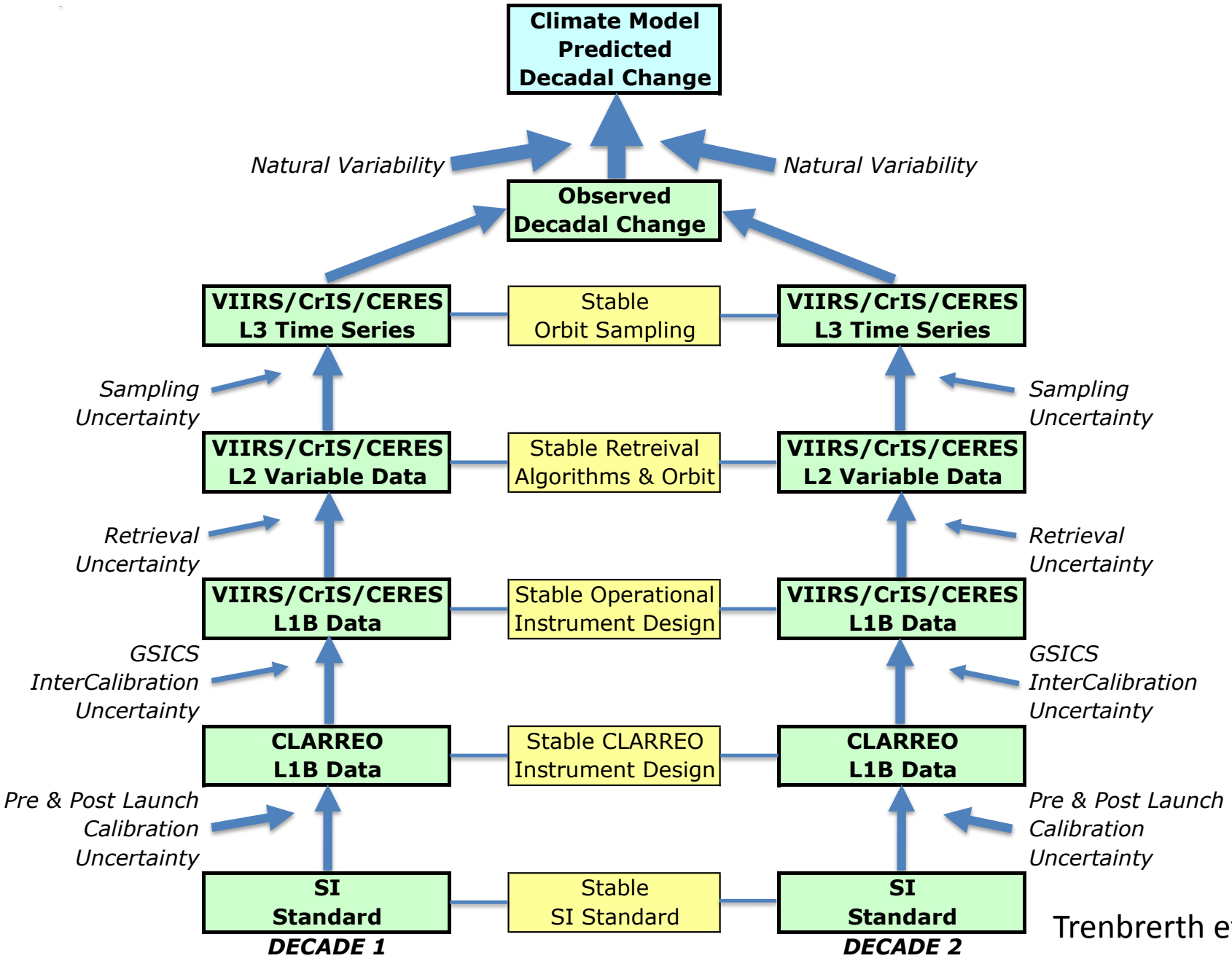
35 Years Later …

35 Years Later … More urgent, but …

- Lack of a climate observing system (vs. weather)
  - Climate is 10x the variables and 10x the accuracy of weather.
- Struggles to get sufficient resources for climate modeling
- Science questions typically qualitative not quantitative
  - Understand and explore vs rigorous hypothesis testing
  - Leads to intuitive “Seat of the Pants” requirements
  - After > 30 years of climate research: time to improve
- *What is the right amount to invest in climate science?*
  - Requires link of science to economics
  - Requires thinking outside narrow disciplines
  - Requires arguing for climate science, not our own science

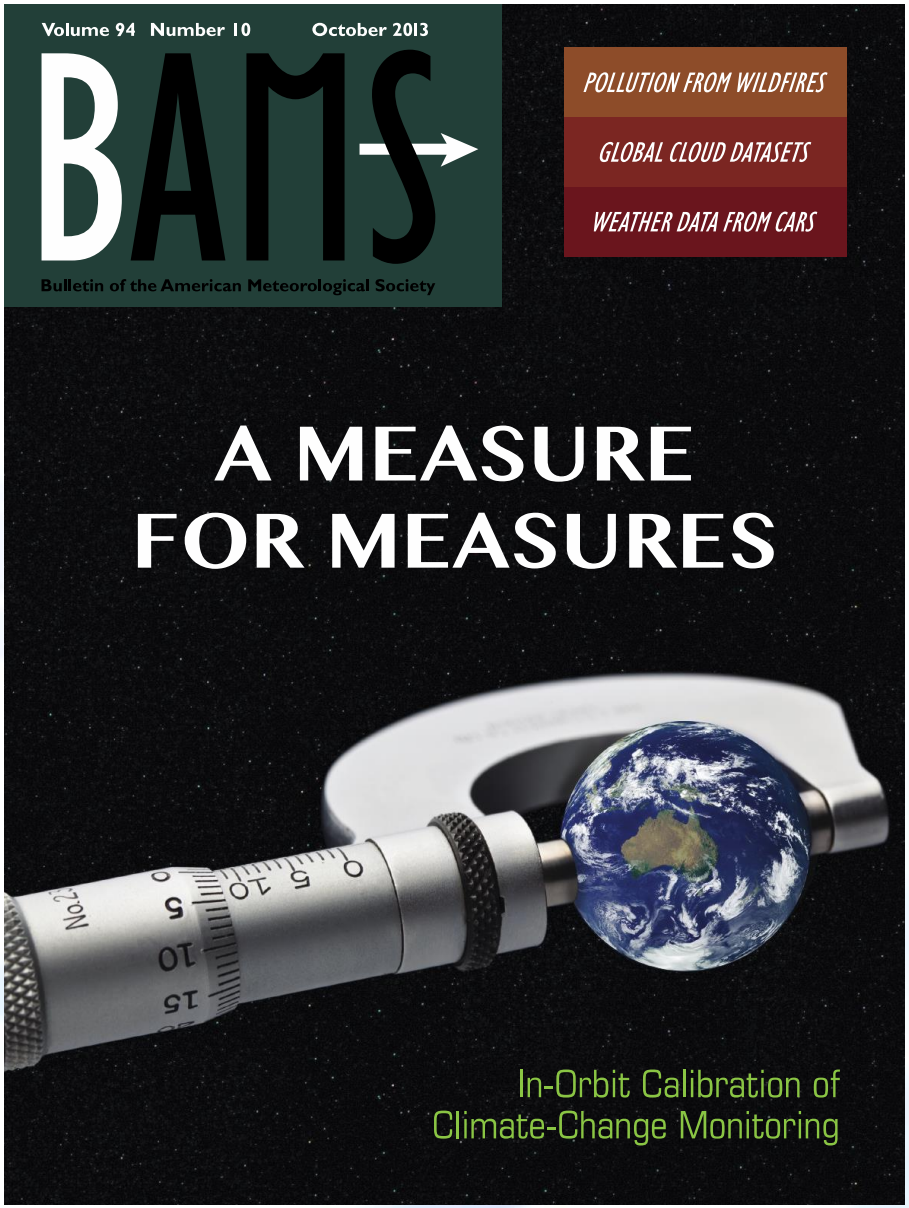

Model Hypothesis Development
Model Hypothesis Testing
Model Understanding Diagnostic Studies (SPOOKIE, RCE)
Cloud Process Models GCM/CRM/LES
Process Observations Field Experiments (FIRE, GATE) Satellites (A-train, EarthCARE)
New Process Models/ GCM Parameterization
Forcing Scenarios Control, IPCC RCPs LGM, SST, 4X CO2
Model Understanding Diagnostic Studies CMIP, PMIP, CFMIP
Climate Model Predictions
Test Hypothesis: Models vs Obs (Modern and Paleo)
Prediction Uncertainty Estimate (IPCC)

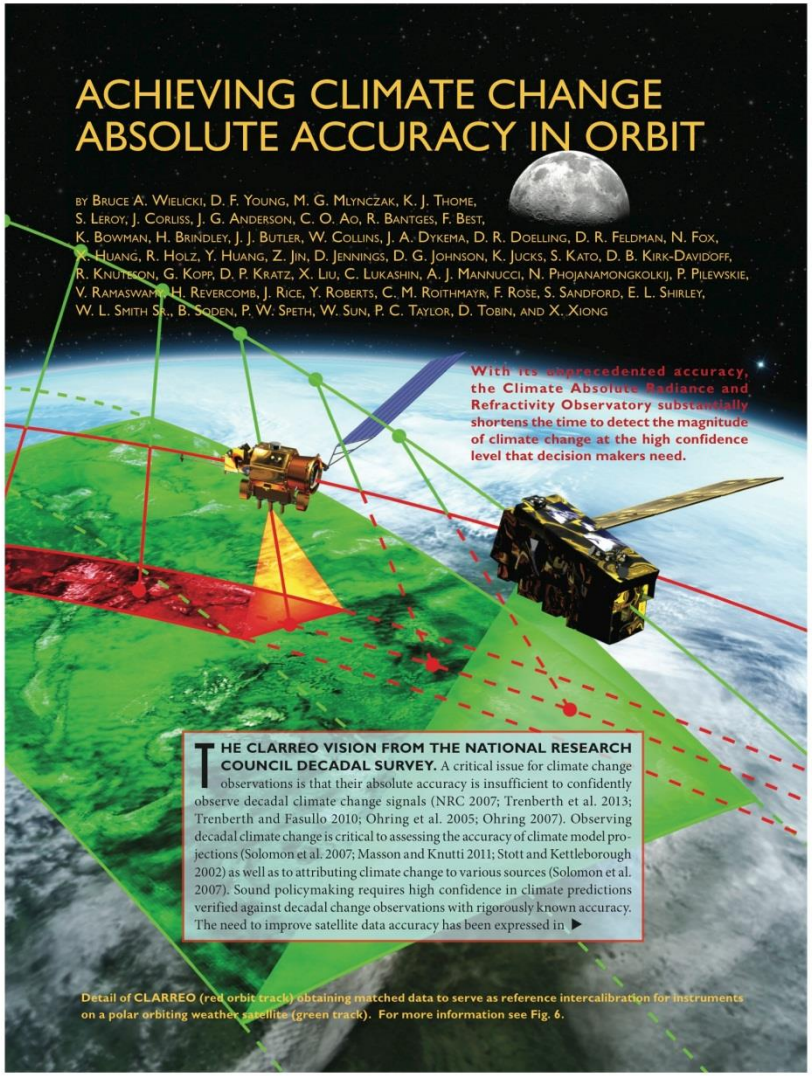
Accuracy of Climate Change Observations & Predictions



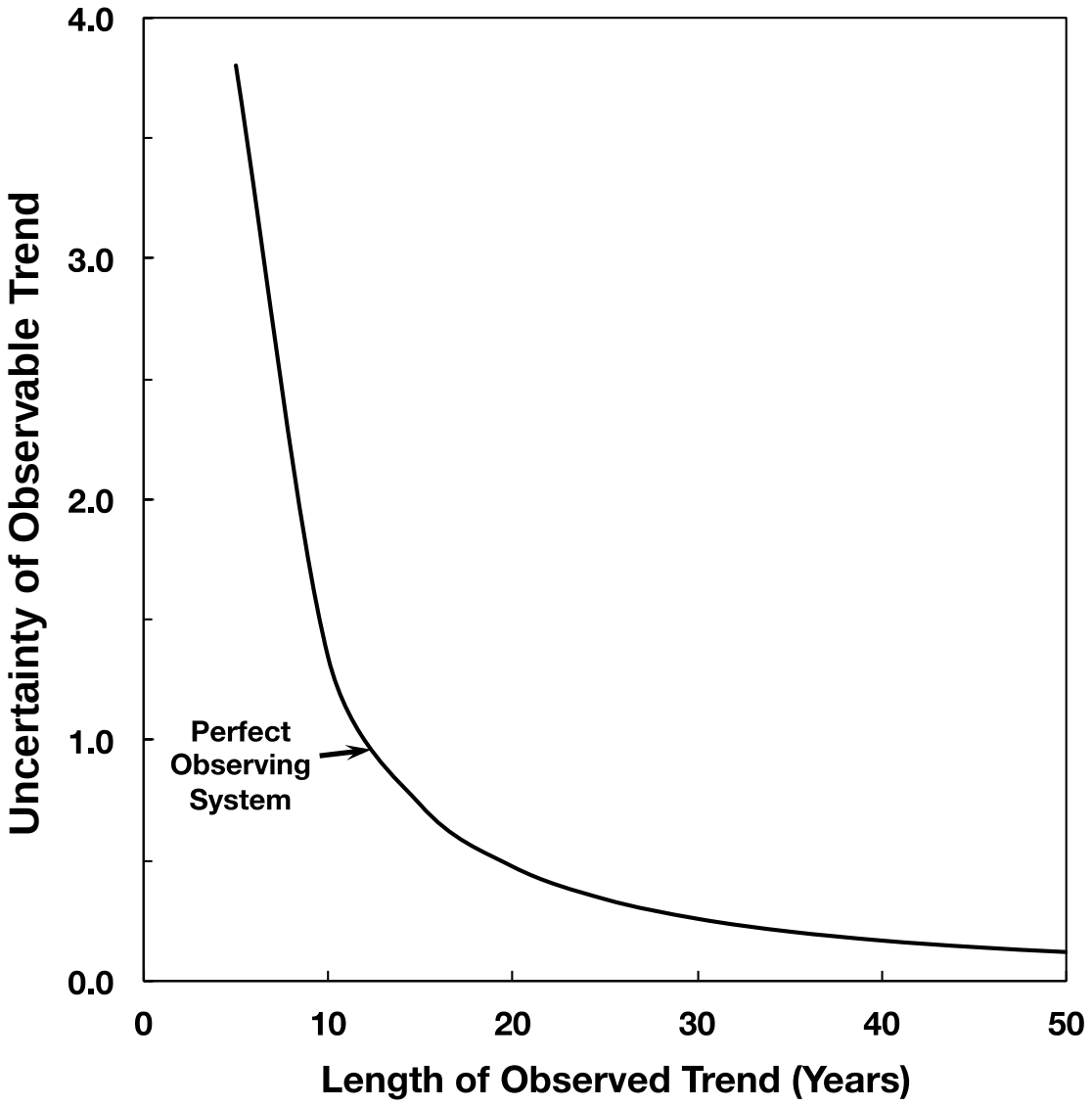
Trenbrerth et al. 2013

BAMS October, 2013





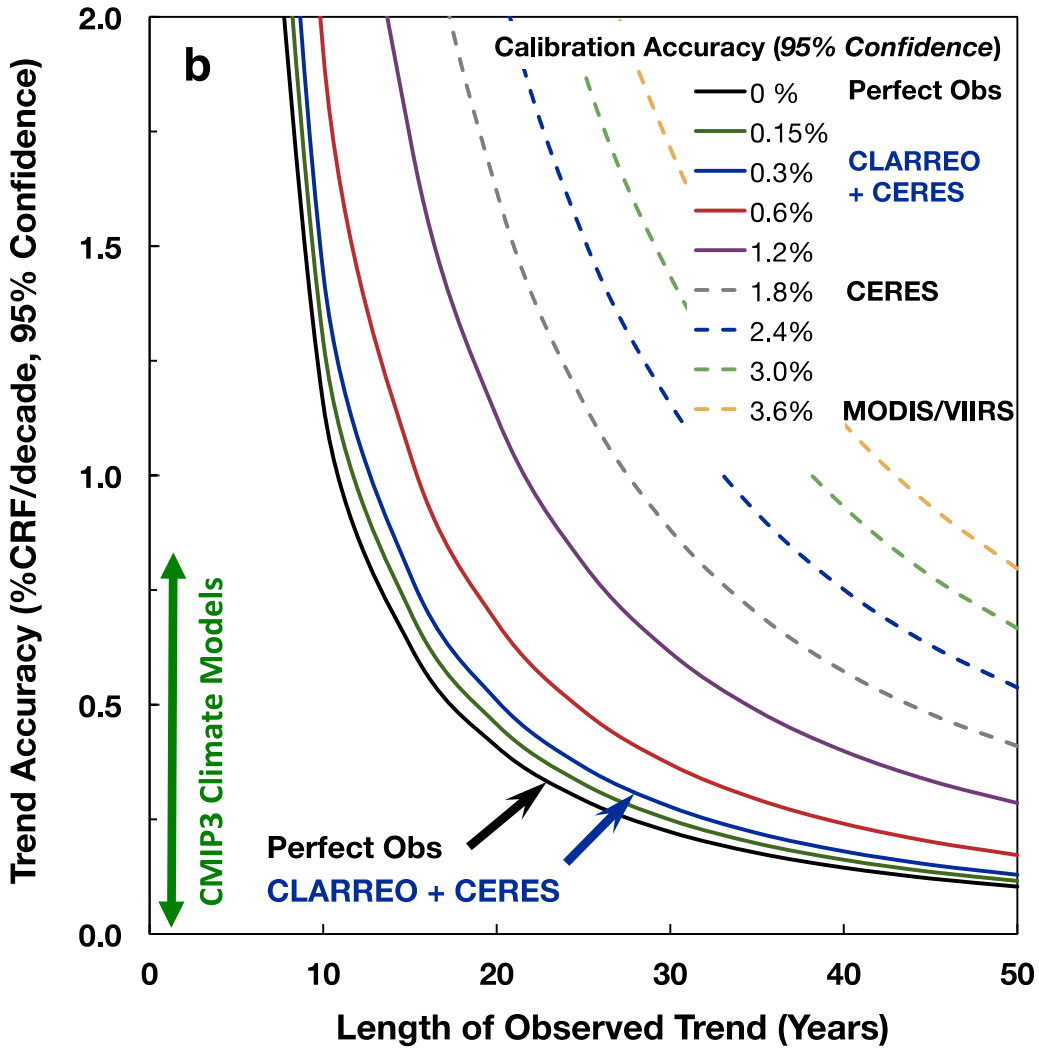
Accuracy Requirements of the Climate Observing System



The length of time required to detect a climate trend caused by human activities is determined by:

- *Natural variability*
- *The magnitude of human driven climate change*
- *The accuracy of the observing system*

Reflected Solar Accuracy and Climate Trends



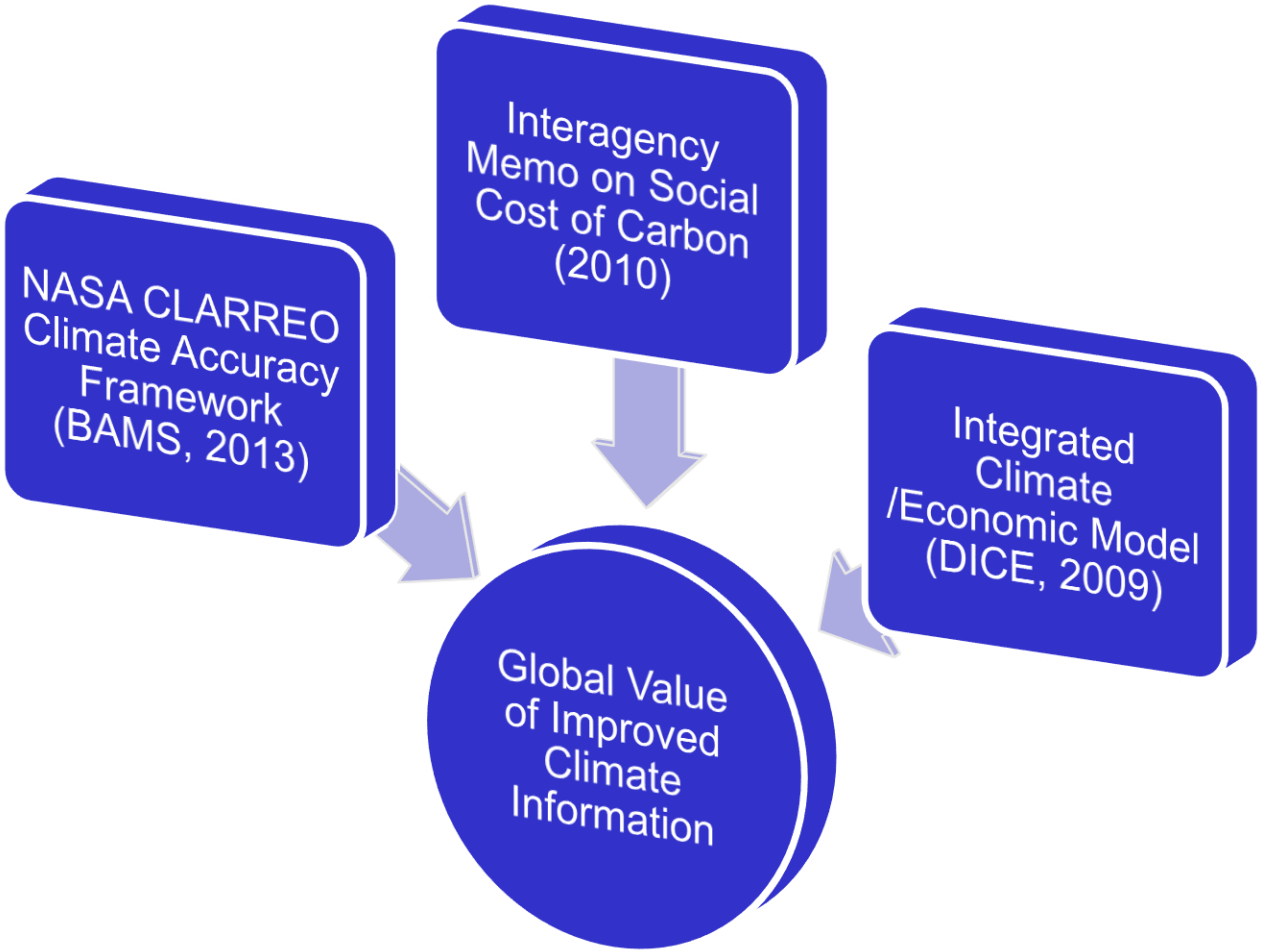
Climate Sensitivity Uncertainty is a factor of 4 (IPCC, 90% conf) which =*factor of 16 uncertainty in climate change economic impacts*

Climate Sensitivity Uncertainty = Cloud Feedback Uncertainty = Low Cloud Feedback = *Changes in SW CRF/decade (y-axis of figure)*

Higher Accuracy Observations = CLARREO reference intercal of CERES = *narrowed uncertainty 15 to 20 years earlier*

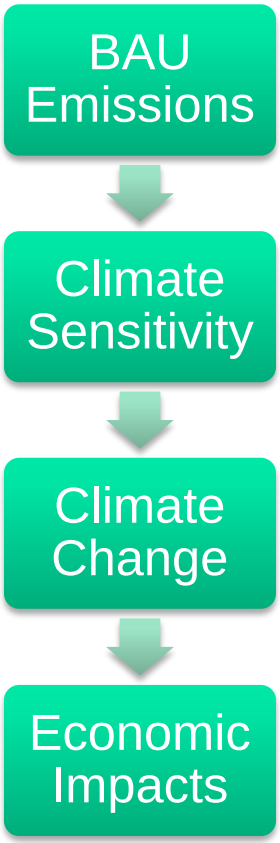
Wielicki et al. 2013, Bulletin of the American Meteorological Society

What is the right amount to invest in climate science?

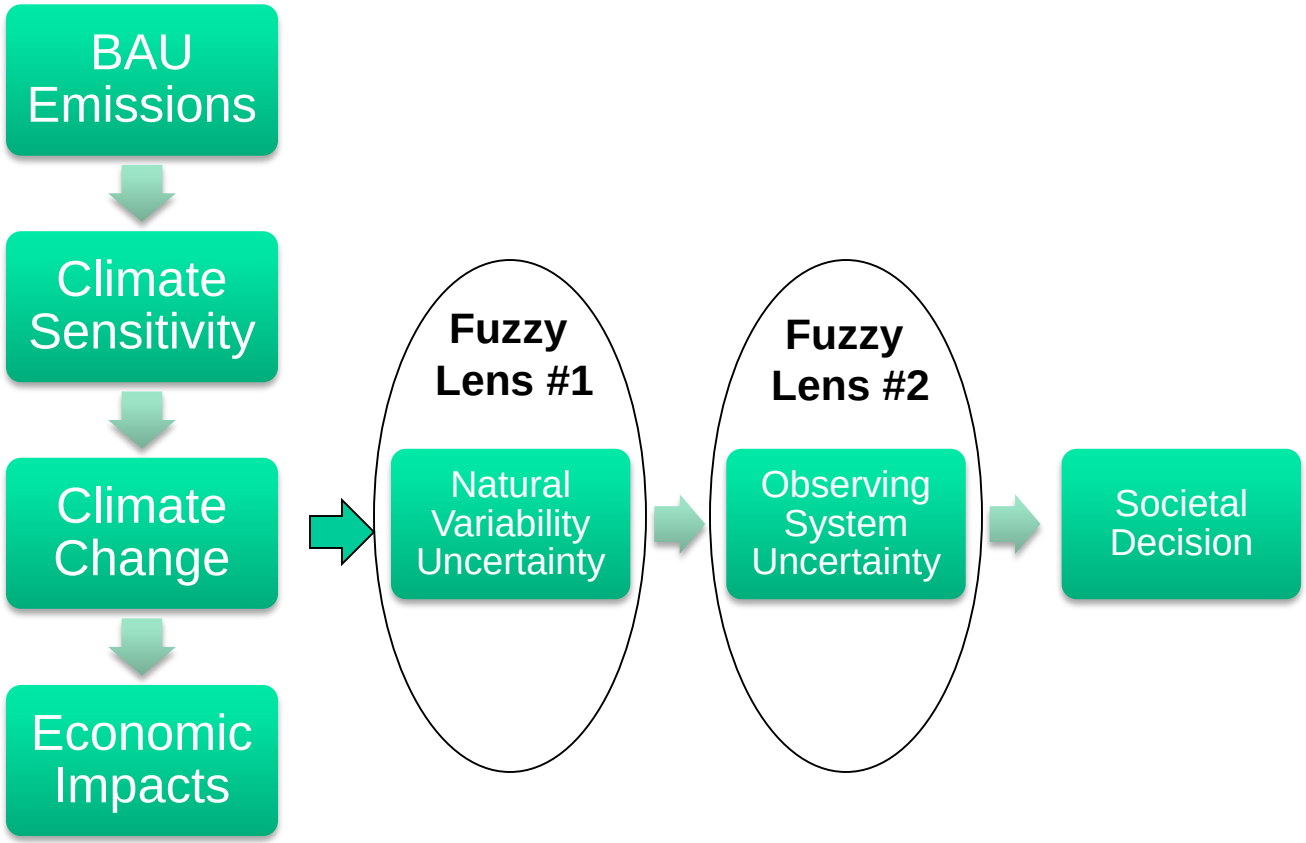


Cooke et al., Journal of Environment, Systems, and Decisions, 2014, paper has open and free distribution online: doi:10.1007/s10669-013-9451-8.
Cooke et al., Climate Policy, 2015, ISSN: 1469-3062

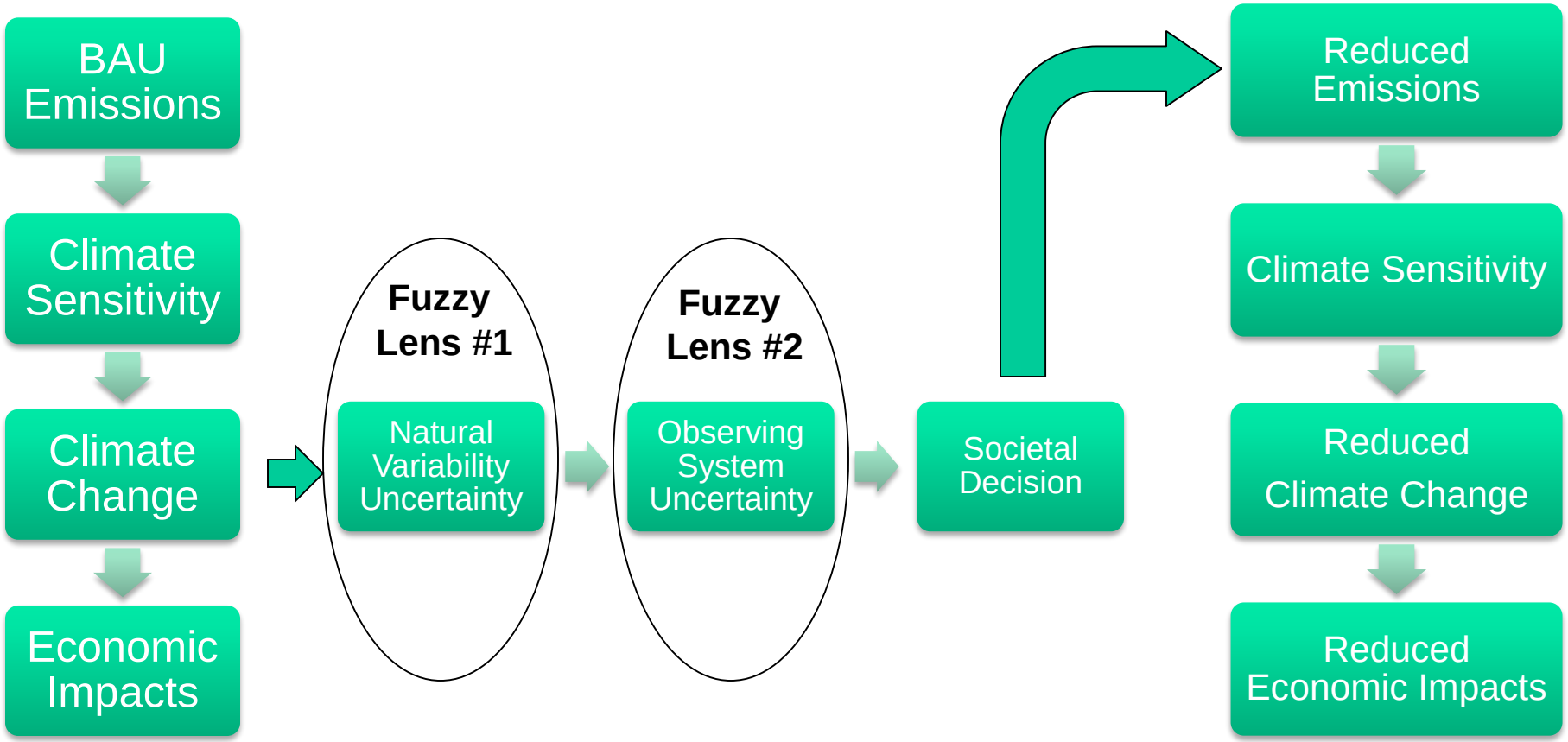
VOI Estimation Method



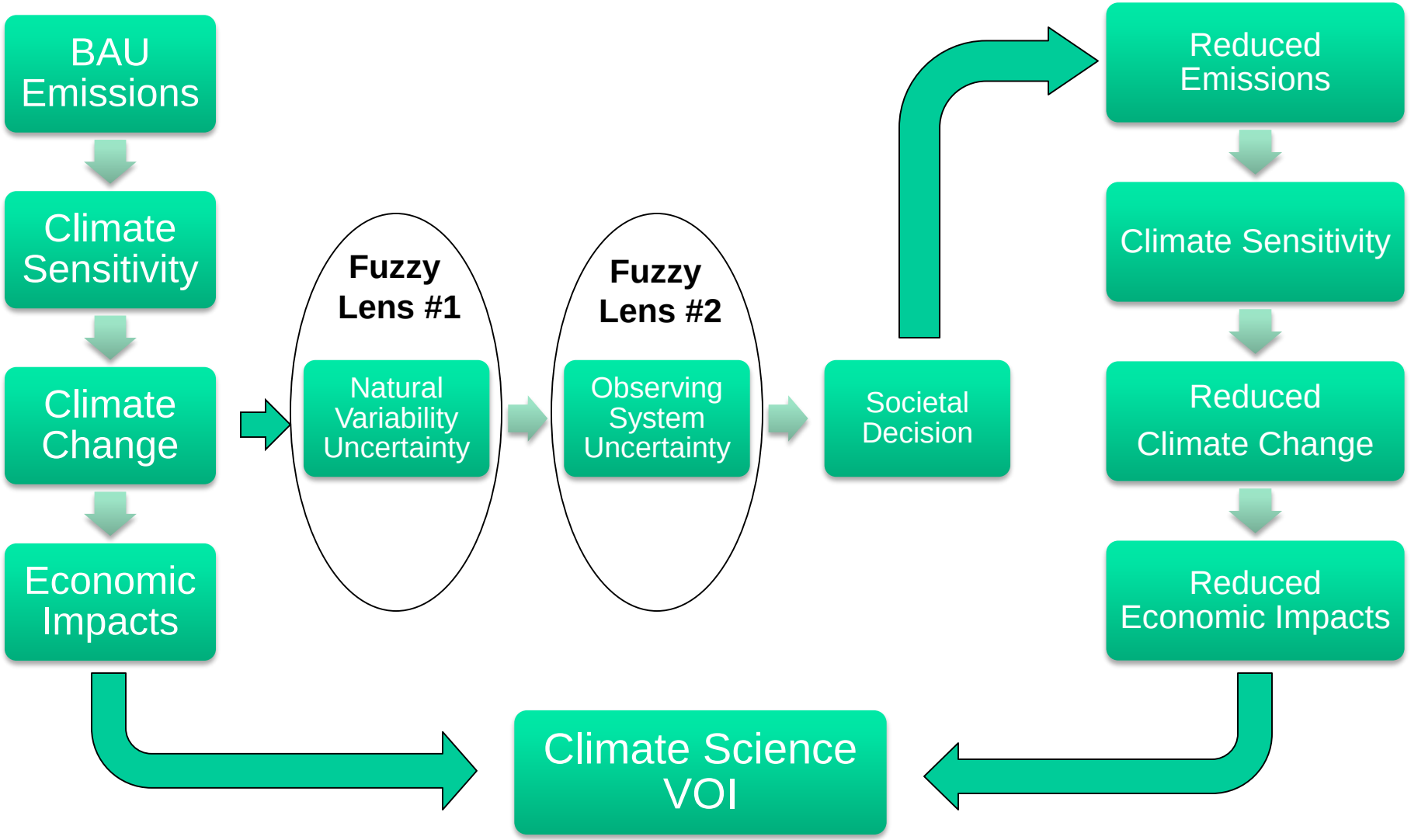
VOI Estimation Method



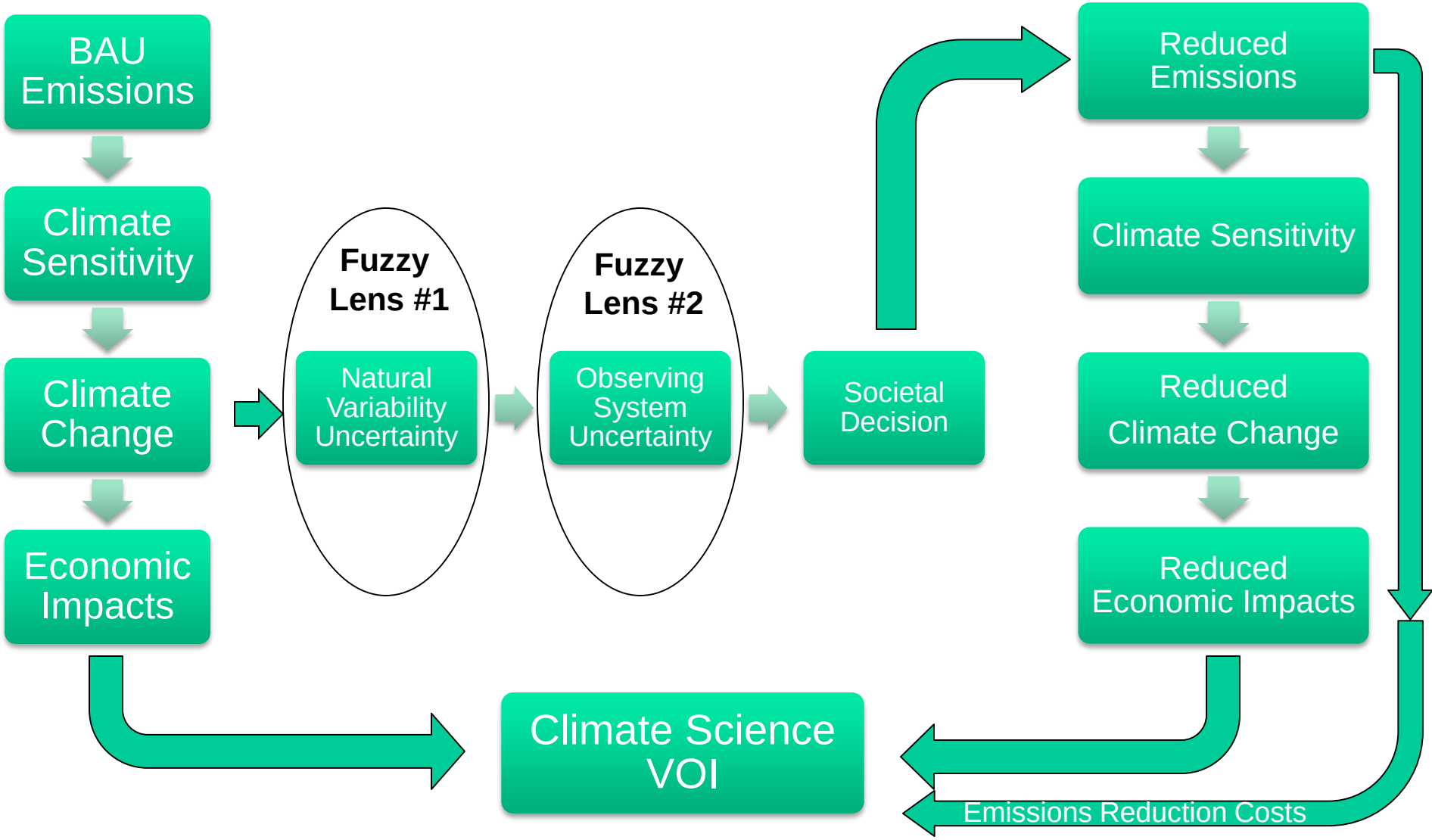
VOI Estimation Method



VOI Estimation Method



VOI Estimation Method



Economics: The Big Picture

- World GDP today ~ $70 Trillion US dollars

- Net Present Value (NPV)
  - compare a current investment to other investments that could have been made with the same resources

- Discount rate: 3%
  - 10 years: discount future value by factor of 1.3
  - 25 years: discount future value by factor of 2.1
  - 50 years: discount future value by factor of 4.4
  - 100 years: discount future value by factor of 21

- Business as usual climate damages in 2050 to 2100: 0.5% to 5% of GDP per year depending on climate sensitivity.

VOI vs. Discount Rate

Run 1000s of economic simulations and then average over the full IPCC distribution of possible climate sensitivity

Discount Rate	CLARREO/Improved Climate Observations VOI (US 2015 dollars, net present value)
2.5%	$17.6 T
3%	$11.7 T
5%	$3.1 T

Additional Cost of an advanced climate observing system:
~ $10B/yr worldwide
Cost for 30 years of such observations is ~ $200 to $250B (NPV)

Even at the highest discount rate, return on investment is very large

VOI vs. Discount Rate

Run 1000s of economic simulations and then average over the full IPCC distribution of possible climate sensitivity

Discount Rate	CLARREO/Improved Climate Observations VOI (US 2015 dollars, net present value)
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5%	$3.1 T

Advanced Climate Observing System:

Return on Investment: $50 per $1

Cost of Delay: $650B per year

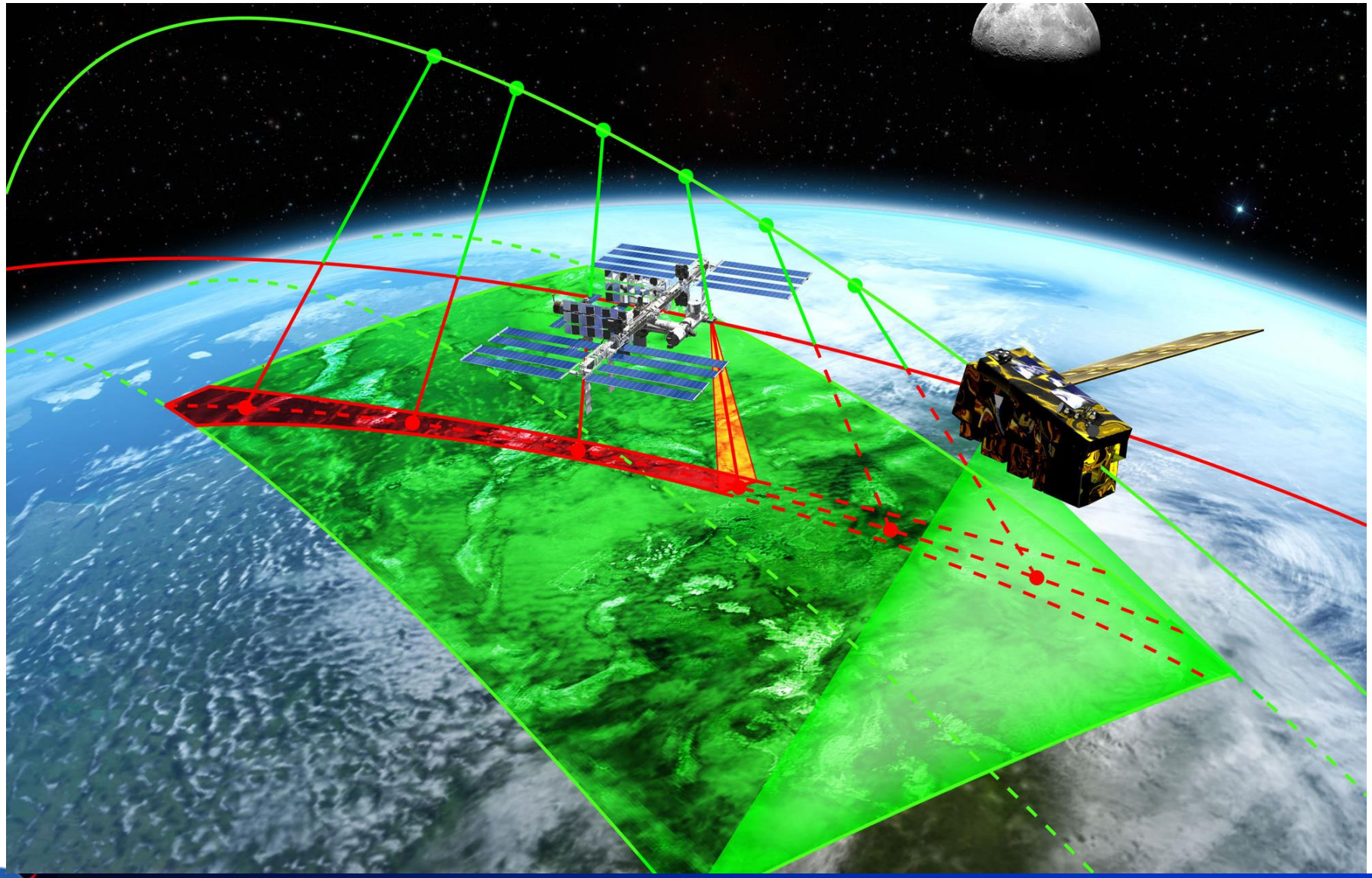
Even at the highest discount rate, return on investment is very large

Climate Observations: No Long Term Plan

- Global Satellite Observations without long term commitments
  - Radiation Budget (e.g. CERES)
  - Gravity (ice sheet mass) (e.g. GRACE)
  - Ice Sheet Elevation (e.g. ICESAT/Cryosat)
  - Sea Level Altimetry (e.g. JASON)
  - Sea surface Salinity (e.g. Aquarius)
  - Cloud and Aerosol Profiles (e.g. CALIPSO/Cloudsat, EarthCARE)
  - Precipitation (e.g. GPM, CloudSat/EarthCARE)
  - Soil Moisture (e.g. SMAP)
  - Ocean surface winds (e.g. QuickSCAT)
  - Carbon Source/Sinks (e.g. OCO)
  - Methane/Carbon Monoxide (MOPPIT)
  - In orbit Calibration References (e.g. CLARREO)
- Surface and In-situ observations have similar issues

An Exciting Next Step
Towards a Climate Observing System

CLARREO Pathfinder on ISS (2020)



CLARREO Pathfinder Begins in 2016!

CLARREO Pathfinder Mission Summary

- Demonstrate CLARREO calibration accuracy spectrometers (IR and RS) on International Space Station
- Nominal launch is in 2020, nominal operations 2 years
- At least one and potentially both spectrometers: final decision ~ mid-2016 (depends on final funding levels and international collaboration
- Class D low cost mission
  - Instrument design life 1 year at 85% probability, ~ 50% of achieving 4 yrs
- Demonstrate CLARREO level SI traceability in orbit
- Demonstrate CLARREO Reference Intercalibration for VIIRS, CERES, and CrIS instruments
- Take intercalibration observations for additional sensors (LEO, GEO) but Pathfinder budget only covers L0 processing for these orbit crossings
- If demonstrate success, then request funding to process full data stream and additional instrument intercalibration events, as well as nadir spectral benchmarking observations.

CLARREO Pathfinder on ISS

- Lessons learned from CLARREO Pathfinder will benefit a future CLARREO mission
  - Reduced risk
  - Demonstration of higher accuracy calibration approaches
  - Prove that high accuracy SI-traceability can be transferred to orbit
  - Show that high accuracy intercalibration is achievable
- CLARREO Pathfinder will demonstrate highest accuracy radiance and reflectance measurements from orbit
  - First on-orbit SI-traceable reflectance with uncertainty <0.5% (k=2)
  - First on-orbit SI-traceable temperature with uncertainty <0.1 K (k=3)
- Lessons learned from CLARREO Pathfinder will produce benefits across many NASA Earth Science Missions
  - Improved laboratory calibration approaches
  - Development and testing of innovative on-orbit SI-traceable methods
  - Transfer calibration to sensors in operation at time of CLARREO Pathfinder
  - Improved lunar irradiance standard

CLARREO Pathfinder will improve accuracy across Earth Sciences

Suggested Directions

- Quantitative Science Questions
  - Hypothesis Tests not “improve and explore”, think Higgs Boson
- Observing System Simulation Experiments (OSSEs)
  - Improve observing system requirements
  - Move from “base state” to “climate change” climate model tests
- Higher Accuracy Observations for Climate Change
  - See BAMS Oct 2013 paper for example: broadly applicable
- Economic Value of Improved Climate Observations and Models
  - See J. Env. Sys. Decisions paper for example: broadly applicable

Summary

Lack of accuracy = delayed knowledge

We lack a climate observing system capable of testing climate predictions with sufficient accuracy or completeness

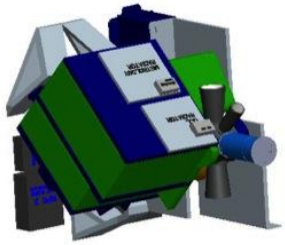
At our current pace, its seems unlikely that we will understand climate change even after another 35 years.

We cannot go back in time and measure what we failed to observe.

Its time to invest in an advanced climate observing system

Backup Slides

CLARREO: NIST in Orbit

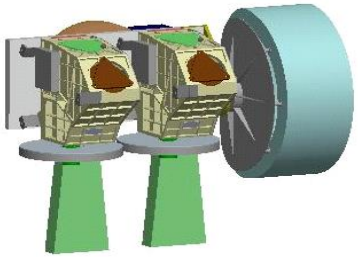


Infrared (IR) Instrument Suite

Fourier Transform Spectrometer

- Systematic error less than 0.1K (*k=3)*
- 200 – 2000 cm^{-1} contiguous spectral coverage
- 0.5 cm^{-1} unapodized spectral resolution
- 25 km nadir fov, 1 earth sample every 200 km

- *Mass: 76 Kg*
- *Power: 124 W*



Reflected Solar (RS) Instrument Suite

Two Grating Spectrometers Gimbal-mounted (1-axis)

- Systematic error less than 0.3% (*k=2*) of earth mean reflectance
- 320 – 2300 nm contiguous spectral coverage
- 4 nm sampling, 8 nm res
- 300 m fov, 100 km swath

- *Mass: 67 Kg*
- *Power: 96 W*
- *Power and Mass are total for both spectrometers*

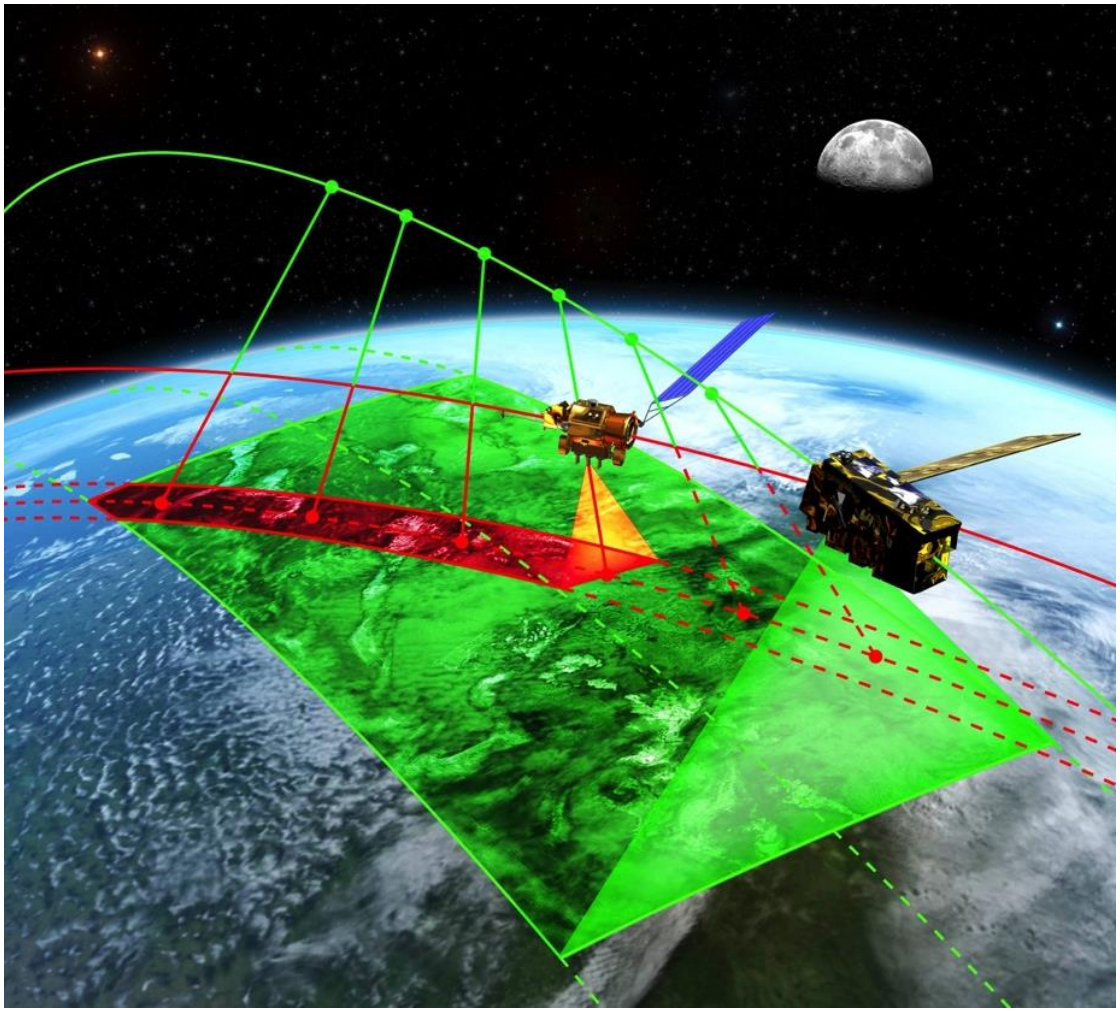
GNSS Radio Occultation Receiver

GNSS Receiver, POD Antenna, RO Antennae

- Refractivity uncertainty 0.03% (*k=1*) for 5 to 20 km altitude range. (Equivalent to 0.1K (*k=3*) for temperature
- 1000 occultations/day

- *Mass: 18 Kg*
- *Power: 35 W*

Calibration Reference Spectrometers (IR/RS) for Global Climate, Weather, Land, Ocean satellite instruments

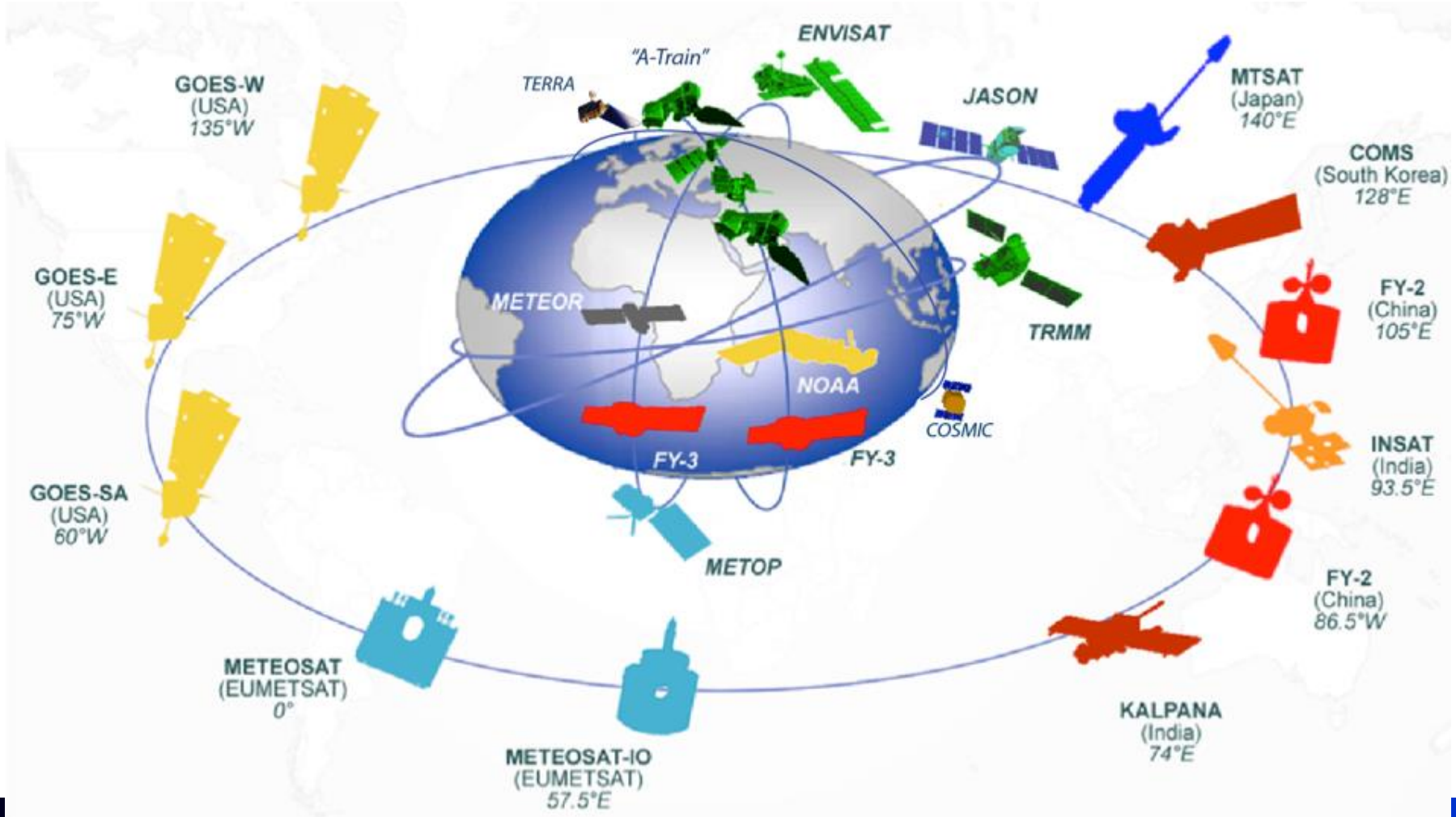


Provide spectral, angle, space, and time matched orbit crossing observations for all leo and geo orbits critical to support reference intercalibration

Endorsed by WMO & GSICS

Calibrate Leo and Geo instruments relevant to climate sensitivity:
- JPSS: VIIRS, CrIS, CERES
- METOP: IASI, AVHRR
- Geostationary imagers/ sounders

Global Satellite Observations (WMO)



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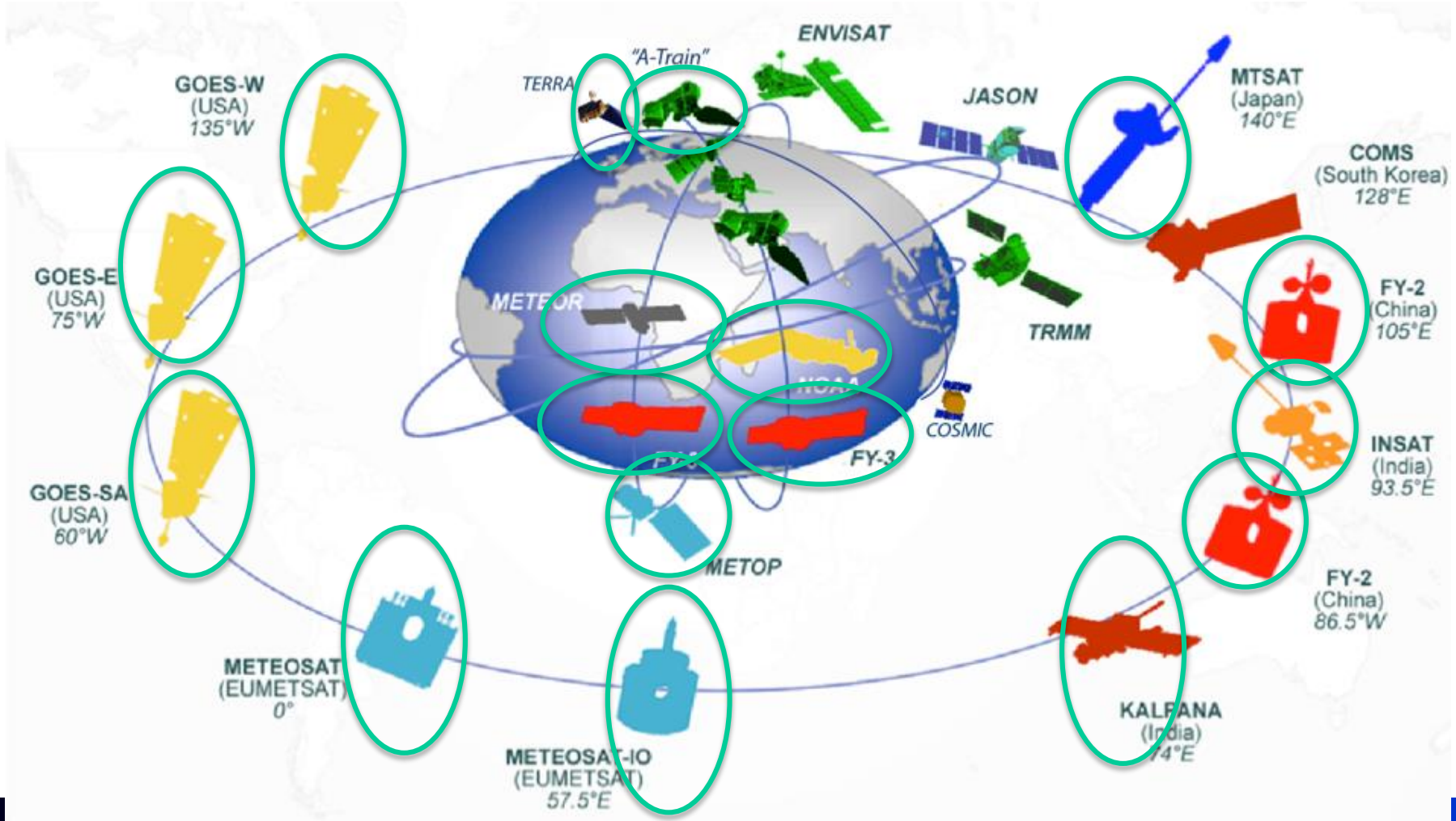


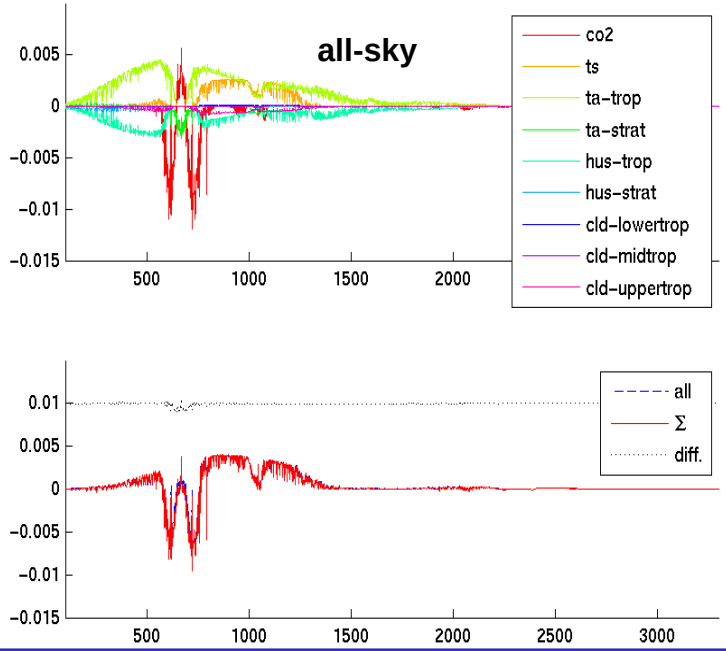
Climate OSSEs - Observing System Simulation Experiments

Climate modelers are the prime data users of high accuracy climate change observations

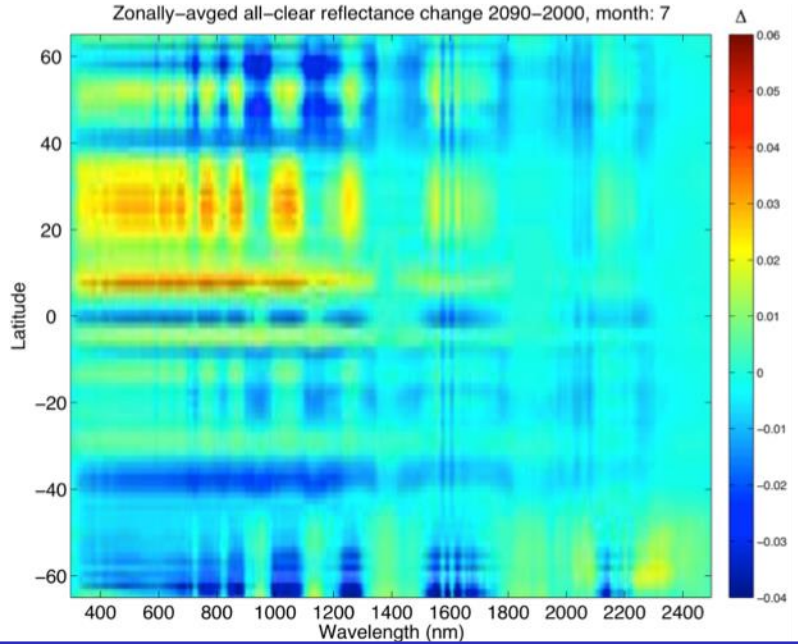
OSSEs have been run by several modeling groups for measurement requirements (UC-Berkeley, Univ. Michigan, GFDL)

Studies include climate change fingerprinting methods using time/space averaged spectral data to define spectral resolution (IR 0.5 cm^{-1} unapodized, RS 15 nm) & spectral coverage (IR 200 to 2000 cm^{-1}, RS 300 to 2500 nm). 10 journal papers to date.

- ***Studies by GFDL/ Harvard demonstrate the linearity of all-sky decadal change IR signals***
- ***Eliminates the requirement for global clear-sky observations (Huang and Leroy, 2009)***

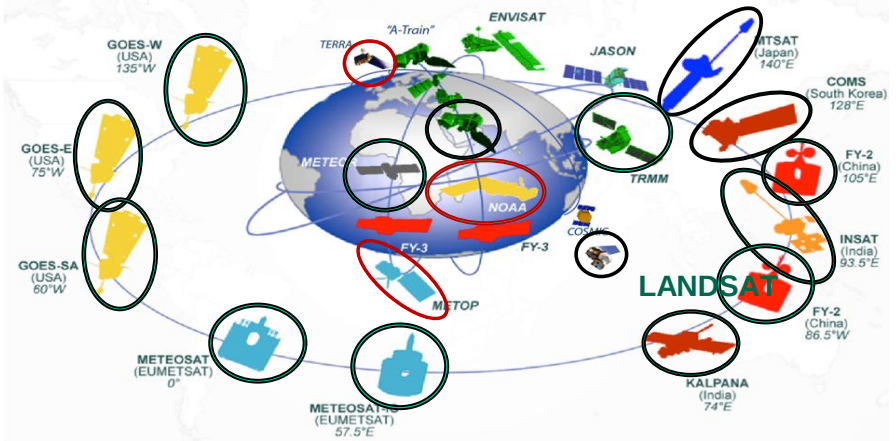


Studies by U-Cal Berkeley, LASP, and LaRC demonstrate the linearity and information content of the decadal change solar-reflected radiance signals. (Collins & Feldman, 2009, Feldman et al. 2010,2011)



Near-Term Impact (<1 year)

- Near-term (<1 year):
  - Provide ***first*** observed far-infrared (IR) spectra since Nimbus 4 IRIS in 1971 to enable studies of the Earth's water vapor greenhouse effect (50% in the far-IR), atmospheric cooling rate, and cirrus effects on the far-IR.
  - Provide a year of data on-orbit crossings with NPP, JPSS1, METOP, Terra, Aqua, and geostationary satellites (5 for global coverage). Demonstrate the use of IR and RS as reference instruments for intercalibration as part of GSICS (Global Space Based Inter-Calibration System).
  - Put the lunar spectral irradiance on an SI-traceable scale with 10 to 20 times the current accuracy of 5 to 10% (1 sigma).



Benefits and linkages to other missions

Mid-Term Impact (2-3 years)

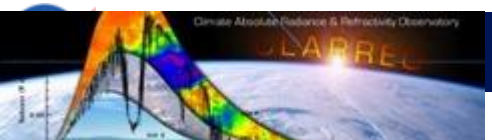
- Disclaimer: Assumes that the instruments are preforming well on orbit (i.e., achieving climate change accuracy, acceptable instrument noise, acceptable duty cycle) and the mission is extended beyond the initial year.

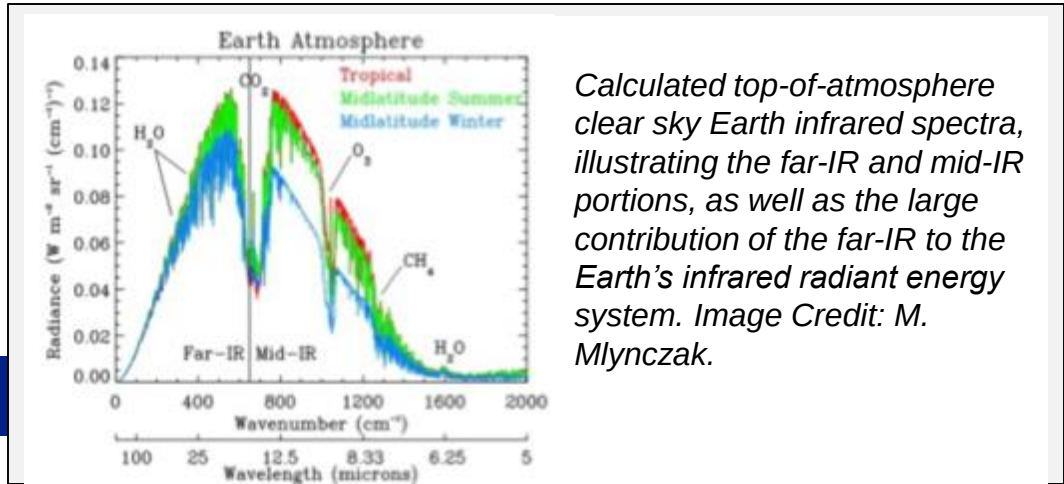
- During the 2nd and 3rd year of the technology demonstration, the following could be accomplished if funded as extensions:

– Quantify interannual variability of the far-IR greenhouse effect, atmospheric cooling rate, and cirrus effects on the IR

– Quantify interannual variability of both reflected solar and thermal infrared spectra: the first full spectra ever observed of the Earth.

– Ability to use the calibration reference instruments through monthly intercalibration over 3 years to detect trends in calibration change of operational instruments such as CrIS, IASI, VIIRS, HIRS, AVHRR, CERES, and geostationary satellite sounders and imagers.

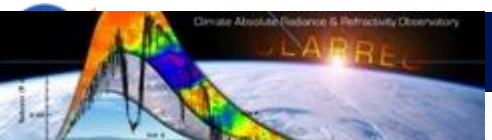




Calculated top-of-atmosphere clear sky Earth infrared spectra, illustrating the far-IR and mid-IR portions, as well as the large contribution of the far-IR to the Earth's infrared radiant energy system. Image Credit: M. Mlynczak.

Longer Term Impact (4-5 years)

- Disclaimer: Again, this assumes that the instruments are preforming well on orbit and the mission extended beyond year 3.
- During the 4th and 5th year of the technology demonstration, the following can be accomplished:
  - Provide an initial anchor for a climate record benchmark at levels of accuracy a factor of 5 to 10 beyond current instruments.
  - Extend the statistical reliability of the inter annual natural variability for Far Infrared science and for IR and RS Spectral fingerprints of climate change examined in years 2 and 3 by covering a full normal 5 year ENSO cycle (i.e. El Nino and La Nina phases).
  - Extend the ability to determine long term calibration drifts in a wide range of Earth sensors in LEO and GEO.
  - Extend the lunar irradiance spectral calibration to include many more lunar cycles and thereby verify the variations due to libration of the moon.
  - Verify the calibration capability of the instruments over the full nominal 5 year nominal instrument lifetime of future missions.
  - Incorporate any lessons learned into future instrument designs, further reducing risk.



What won't the CLARREO Pathfinder do?

- A low-cost pathfinder on ISS should not be expected to achieve the full complement of scientific goals of a full CLARREO mission (conducted on one or more specialized free-flyer spacecraft), however, it can certainly be expected to achieve the risk-reduction goals mentioned prior and to demonstrate the full performance of the calibration and verification systems.
- The short planned lifetime (1 to 2 years) of the CLARREO Pathfinder will likely result in a record shorter than the 5 years of observations needed to begin the CLARREO full mission spectral fingerprint benchmarks (L2 and L3 data products)
- The Pathfinder budget will support full Level 0 processing, but will not support complete Level 2 and 3 processing. Only observations sufficient to demonstrate the calibration accuracy and intercalibration capability will be processed to Level 1. No level 2 or 3 processing is planned. Only Level 4 processing sufficient to demonstrate intercalibration for CERES, VIIRS, and CrIS.
- If the Pathfinder is judged highly successful, HQ may decide at a later time to fund processing of the Pathfinder Level 0 observations to provide full CLARREO mission L1 through L4 data products.
- GNSS-RO observations are not obtained on ISS
- CLARREO full mission pre-formulation studies will continue in parallel with CLARREO Pathfinder

Demonstrating calibration accuracy and intercalibration capability
Key steps toward a full CLARREO mission

Collaborations

- ***International***
  - *UK NPL, Universities, UK Space Agency*
  - *Canada McGill University: Y. Huang*
  - *India: ISRO, Indian Institute of Tropical Meteorology (leads climate research)*
- ***Other U.S. Agencies***
  - NIST: calibration accuracy technologies, instrument calibration reviews (NIST $2M invested)
  - NOAA climate modeling
  - DOE climate modeling (LBNL, UC Berkeley): OSSEs: Collins and Feldman
- ***NASA***
  - NASA Radiation Sciences Program: Spectral Fingerprinting of climate change
  - Goddard Space Flight Center: RS Calibration Demonstration System development
  - JPL: Radio Occultation for climate applications (TRIG instrument and analysis methods)
  - NASA Langley engineering groups: IR Calibration Demonstration System development
- ***Universities***
  - University of Wisconsin: IR spectrometer IIP demonstration of TRL 6 at CLARREO accuracy, spectral fingerprinting, IR intercalibration: Revercomb, Smith, Tobin, Knuteson, Best
  - University of Colorado LASP: RS spectrometer IIP demonstration of TRL 6, 30km altitude balloon flight: Kopp, Pilewskie
  - Harvard University: QCL laser development, IR metrology, OSSEs, RO: Leroy, Dykema
  - Univ. Michigan: IR spectral fingerprinting and climate trends: X. Huang

Further Information

- Mission Overview: Wielicki et al. 2013, BAMS cover article
- Economic value of higher accuracy climate obs: Cooke et al., J. Environ. Systems and Decisions, 2014; Cooke et al. Climate Policy, 2015
- CLARREO Web site: http://clarreo.larc.nasa.gov
- CLARREO Science Team Report (~200 page summary of mission science, instruments, orbits, options, costs): http://clarreo.larc.nasa.gov
- CLARREO related/funded journal papers: 130 papers, 1100 citations, list can be found at: http://clarreo.larc.nasa.gov
- CLARREO Science Team Meeting Presentations: http://clarreo.larc.nasa.gov
  - 2 meetings per year
- CLARREO conference presentations: a wide range of venues, U.S. and international

Determining the Accuracy of Decadal Change Trends and Time to Detect Trends

- A perfect climate observing system is limited in trend accuracy only by climate system natural variability (e.g. ENSO) (Leroy et al, 2008).

- Degradation of accuracy of an actual climate observing system relative to a perfect one (fractional error in accuracy, where perfect is $U_a = 1.0$) is given by:

$$U_a = (1 + \Sigma f_i^2)^{1/2} \text{ , where } f_i^2 = \sigma_i^2 \tau_i / \sigma_{var}^2 \tau_{var}$$

  for linear trends where s is standard deviation, τ is autocorrelation time, σ_{var} is natural variability, and σ_i is one of the CLARREO error sources.

- Degradation of the time to detect climate trends relative to a perfect observing system (fractional error in detection time U_t) is similarly given by:

$$U_t = (1 + \Sigma f_i^2)^{1/3}$$

  Degradation in time to detect trends is only ⅔ of degradation in accuracy.

Decadal Change Trends

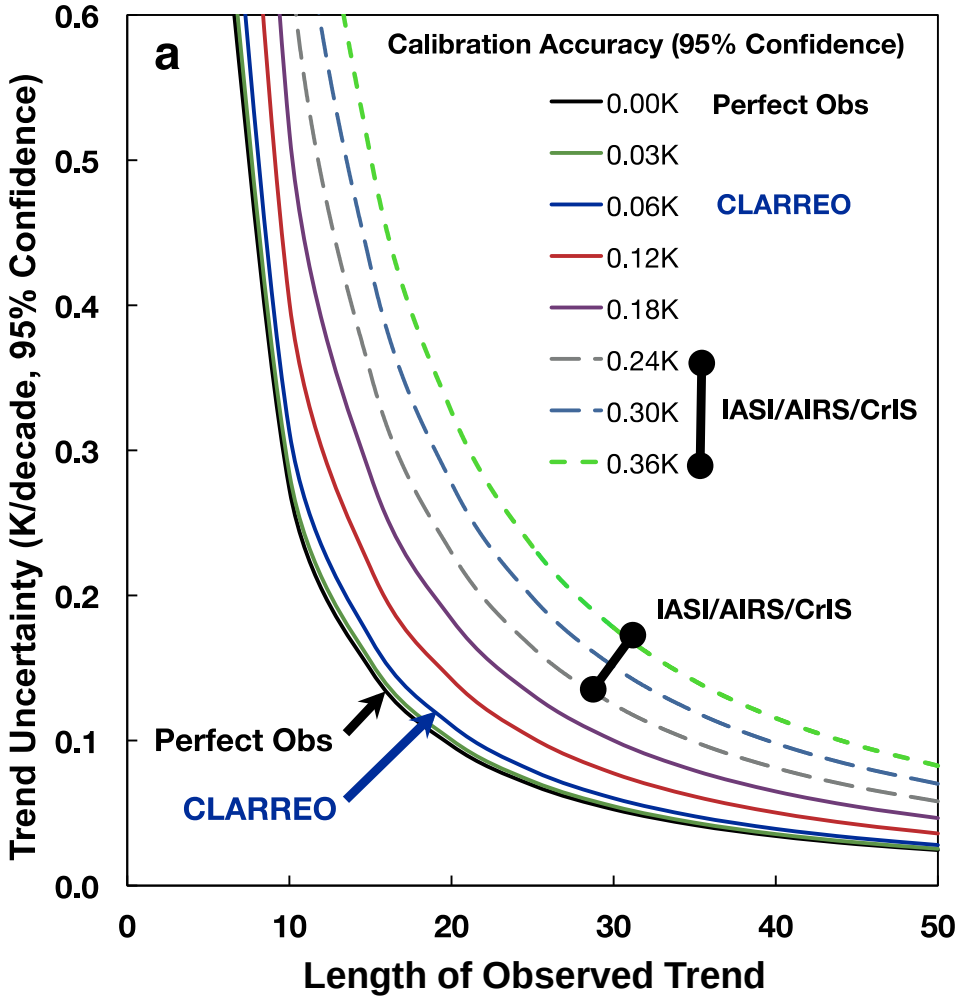
- The absolute accuracy of climate change observations is required *only at large time and space scales such as zonal annual, not at instantaneous field of view. Therefore all errors in climate change observation error budgets are determined over many 1000s of observations: never 1, or even a few.*

- Climate change requirements can be very different than a typical NASA Earth Science process mission interested in retrievals at instantaneous fields of view at high space/time resolution*, where instrument noise issues may dominate instantaneous retrievals*

- *So what accuracy relative to a perfect observing system is needed?*

Requirements focus on long term climate change

Infrared Accuracy and Climate Trends

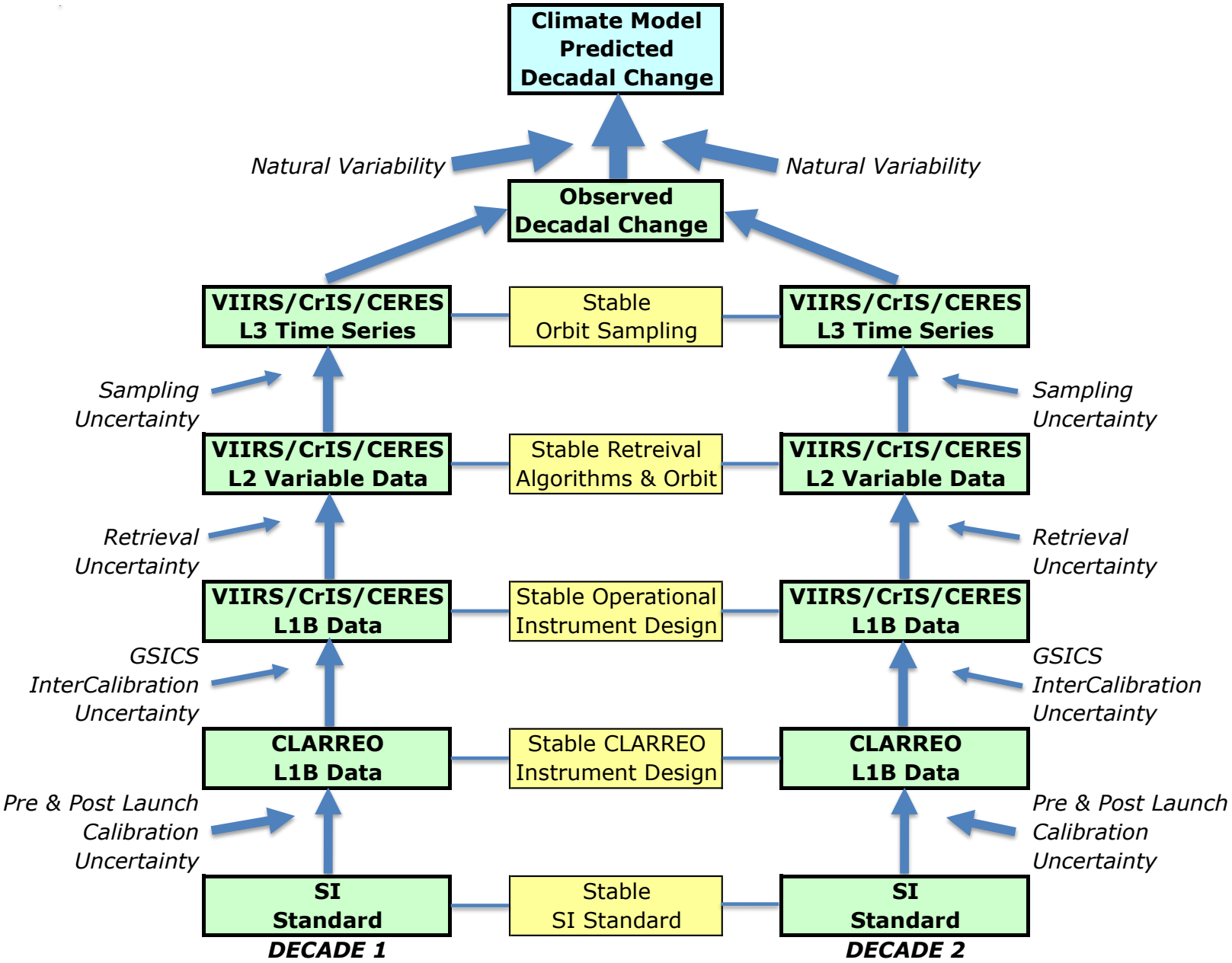


IPCC next few decades temperature trends: 0.16C to 0.34C varying with climate sensitivity

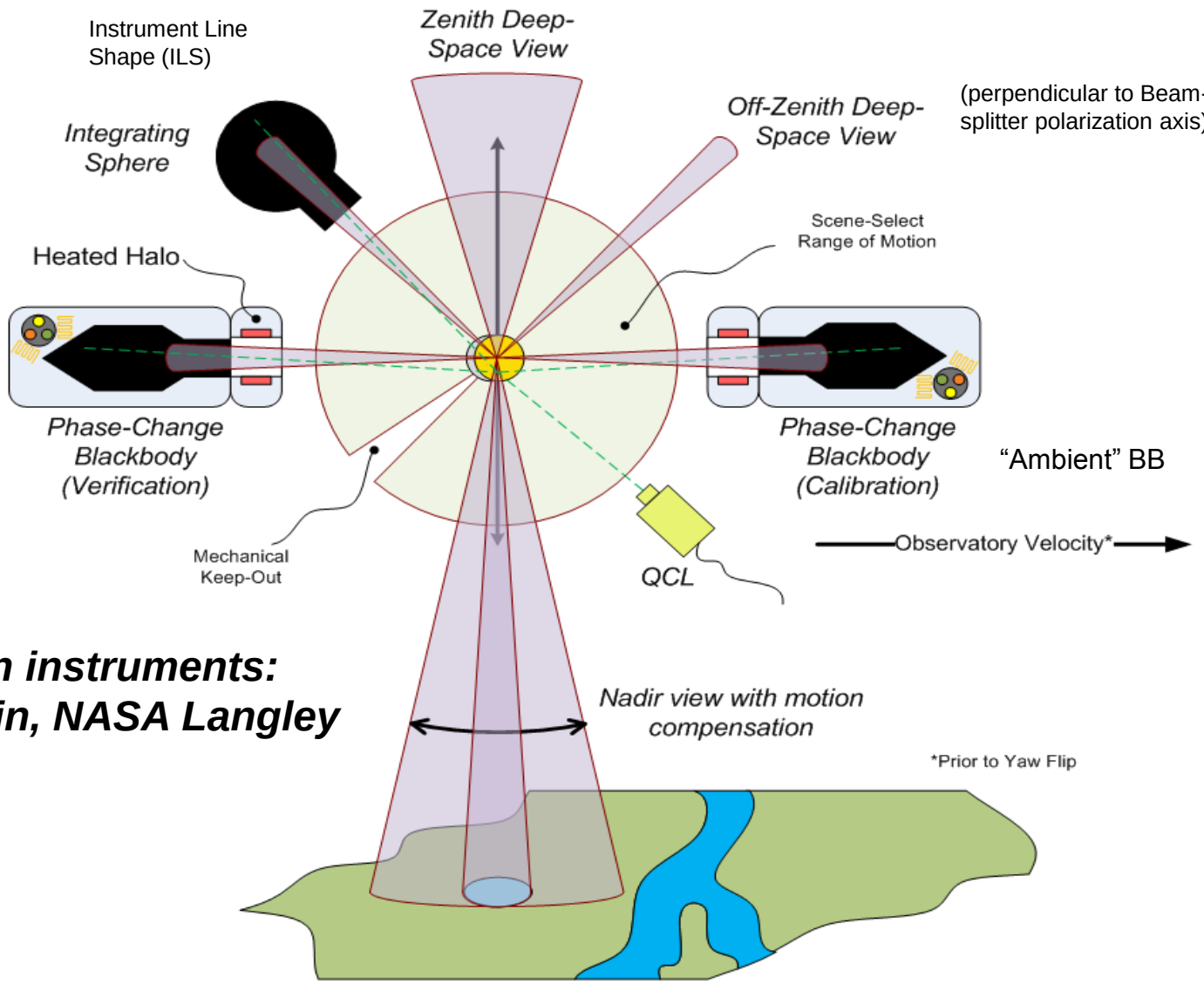
An uncertainty of half the magnitude of the trend is ~ 0.1C. Achieved 15 years earlier with CLARREO accuracy.

High accuracy is critical to more rapid understanding of climate change

Decadal Change Reference Intercalibration Tracing Mission Requirements



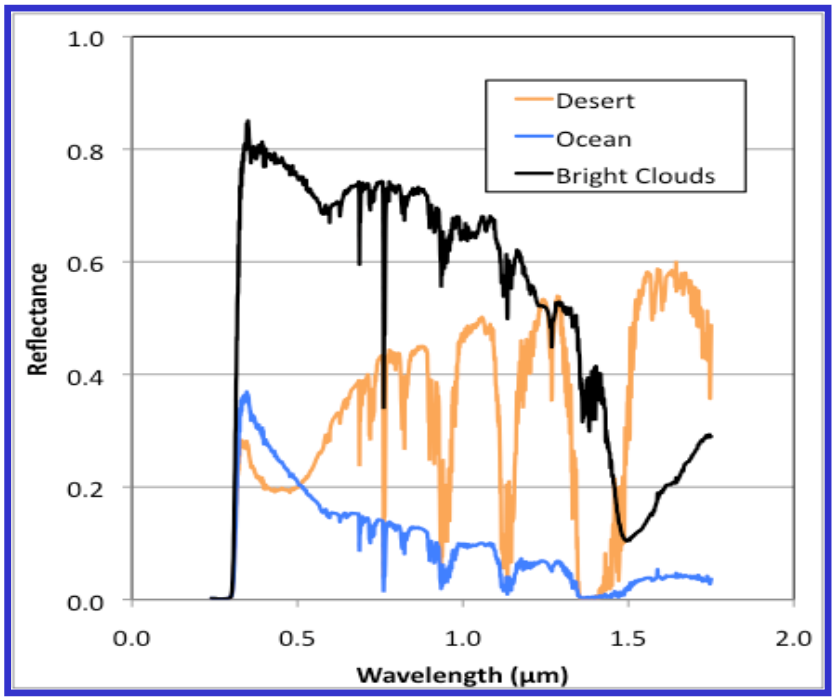
IR On-orbit Verification



Demonstration instruments:
Univ Wisconsin, NASA Langley

SI Traceable Accuracy 0.1K (*k*=3) all Earth Scene Temps (190 to 320K)

CLARREO Reflected Solar Measurements



– Calibration accuracy attained using the Sun as a calibration reference standard
– Attenuator verification relies on lunar views without attenuator
– Lunar/solar disks and stars used to verify stray light performance
– No scanning mirrors: observe the moon/sun with same optics path as Earth
– Provides reference intercalibration for operational sensors
– Spectral Range 320 – 2300 nm, 8 nm spectral resolution (4 nm sampling)
– CU LASP concept (Kopp/Pilewskie) demonstrated with IIP instrument. GSFC CDS
– 0.3% with 95% confidence (i.e. *k=2*)

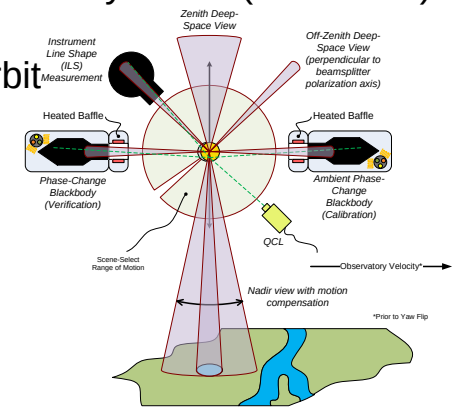
Climate Absolute Radiance & Refractivity Observatory (CLARREO)

Science Objectives:

- Enable more accurate observations of climate change (by factors of 5 to 10)
- Enable more rapid climate change observation (by 15 to 20 yrs) and narrow uncertainty in climate sensitivity through improved accuracy
- Provide the first spectral observation of the Earth's water vapor greenhouse effect and the first spectral fingerprints of climate change
- Provide the reference intercalibration benchmark for the WMO Global Space-based Inter-calibration System (GSICS) to tie 30 to 40 Earth viewing sensors in LEO and GEO orbits to higher accuracy standard on-orbit

Instruments/Mission:

- Full 320 – 2300 nm reflected solar spectrum with 4nm sampling, accuracy 0.3% (95% conf.)
- Full 200 – 2000 cm^{-1} infrared spectrum with 0.5 cm^{-1} sampling, accuracy 0.07K (95% conf.)
- Radio Occultation (TriG)
- 90° polar or 57° ISS orbit
- Accuracy of climate change trends within 20% and time to detect climate trends within 15% of a perfect observing system.



Project Approach:

- Tier 1 Decadal Survey Mission
- Passed Mission Concept Review in Nov 2010. Currently in pre-phase A.
- Advance measurement design maturity (all components now TRL 6) and incorporate NIST recent calibration advances
- Focus on lower cost, smaller instruments with ability to achieve required accuracy on-orbit
- Focus on alternative implementation options (e.g., ISS achieves 70% science @ 40% of cost).

Project Team:

- Langley: Project Management, Systems Engineering, Science Team Lead, Data Center, Infrared Spectrometer Lead
- NASA Goddard: Reflected Solar Spectrometer Lead
- JPL: GNSS Radio Occultation Lead
- Competitively selected Science Definition Team (7 Universities + NASA + International partners)
- Government Partners: NIST, NOAA
- UK NPL, Imperial College, NCEO, ISRO, IITM
- WMO GSICS

Why a Science Value Matrix?

- Science is a cost/value proposition with uncertainty in both *costs* and *value*
  - Cost can be determined with ~ 30% uncertainty and is always addressed
  - Science value or priority for mission elements of design are rarely addressed, but could be and often should be

- CLARREO has developed a new science value matrix concept to assist in:
  - Understanding cost/value
  - Understanding robustness of mission options
  - Understanding how one aspect of the mission (e.g. instrument accuracy) relates to others (science goals, climate record length, orbit sampling, instrument noise)
  - Understanding the impact of baseline vs threshold mission
  - Optimizing the mission design for cost/schedule/risk
  - Eliminating mission requirements "creep"
  - Communicating the mission design trades to NASA HQ
  - Moving the CLARREO science team discussions from "I feel" or "I think" or "I'm sure" to more quantitative basis on mission requirements
  - Improving and quantifying communication between scientists and engineers

A Science Value Matrix is a valuable tool to optimize mission design

Science Value Metrics

Science Value of a Science Objective =

*Science Impact * Trend Accuracy * (Record Length)$^{0.5}$ * Verification * Risk*

- Science Impact
  - Uniqueness of CLARREO contribution
  - Importance of science objective to reducing climate change uncertainties
- Accuracy
  - Accuracy in decadal change trends for a given record length
- Climate Record Length
  - Sqrt(record length) reduction in noise from natural variability
- Verification
  - SI traceable calibration verification
  - Independent instruments, analysis, observations (CCSP chapter 12, metrology)
- Risk
  - Technological, budget, schedule, flexibility of mission options

CLARREO MCR Mission: 2 IR/RO in 2018, 2 RS in 2020

CLARREO Decadal Change Science Objective	Related Decadal Change Climate Variable	Science Impact Factor*	CLARREO MCR: 2018: 2 IR/RO, 2020: 2 RS					
			Calibration Verification Factor	Climate Record Length$^{0.5}$ 70% Prob	1 IR FTS per S/C 1 S/C Trend Accuracy	1 Solar per S/C 1 S/C Trend Accuracy	1 GPS per S/C 1 S/C Trend Accuracy	Total Mission Science Value
Cloud Feedback SW	*Reflected SW flux, albedo*	2	1.9	2.2	0	1.05	0	***8.9***
	Solar Cloud Properties							
Cloud Feedback LW	*Earth Emitted LW flux*	1	1.8	2.2	1.03	0	0	***4.1***
	IR cloud properties							
Cloud Feedback Net	*Net Cloud Radiative Forcing*	5	1.8	1.6	1.03	1.05	0	***14.7***
Temperature Response & Lapse Rate Feedback	*Temperature Profile*	3	1.9	2.2	1.03	0	1.0	***12.9***
Water Vapor Response & Water Vapor Feedback	*Water Vapor Profile*	3	1.9	2.2	1.03	0	0.2	***15.7***
Aerosol Direct Radiative Forcing	Aerosol Radiative Forcing Aerosol Properties	1.5	1.9	2.2	0	1.0	0	***6.4***
Snow & Ice Albedo Feedback	*Reflected SW flux, albedo* *Snow/Ice Cover, Cloud Cover*	1.5	1.9	2.2	0	1.05	0	***6.7***
Land Albedo Change & Radiative Forcing	*Reflected SW flux, albedo*	0.5	2.0	2.2	0	1.05	0	***2.3***
Vegetation Index Change	*Vegetation Index*	1	2.0	2.2	0	1.05	0	***4.7***
Science Value of Individual Components (IR, RS, RO)					**23.8**	**29.0**	**8.9**	
Science Value of combined IR/RS science (net cloud feedback)						**14.7**		
Total Mission Science Value Metric								***76.5***
Percent of Mission Science Value of Individual Components (IR, RS, RO)					**31%**	**38%**	**12%**	
Percent of Mission Science Value of combined IR/RS science						**19%**		
Total Mission Science Value as Percent of Decadal Survey Reference Mission								***89%***

* *Science Impact Factor is common to all scenarios.*
Science Impact for Temperature is split evenly between GNSS-RO and IR
Technology risk is similar for all variations
All metrics are relative: higher is better. Only relative differences are relevant: absolute scale is arbitrary.

sanity check value sum	**76.5**
sanity check % sum	**100%**

CLARREO ISS Mission Class C Mission: 1 IR/RS

CLARREO Decadal Change Science Objective	Related Decadal Change Climate Variable	Science Impact Factor*	CLARREO Space Station Option: 1 IR, 1 RS, 0 RO						
			Reference Intercalibration & Spectral Fingerprint Capability	Calibration Verification Factor	Climate Record Length$^{0.5}$ 70% Prob	1 IR FTS Space Station Trend Accuracy	1 Solar Space Station Trend Accuracy	0 GPS Space Station Trend Accuracy	Total Mission Science Value
Cloud Feedback SW	*Reflected SW flux, albedo*	**2**	0.83	1.5	2.5	0	1.05	0	***6.5***
	Solar Cloud Properties								
Cloud Feedback LW	*Earth Emitted LW flux*	**1**	0.83	1.0	2.5	1.03	0	0	***2.1***
	IR cloud properties								
Cloud Feedback Net	*Net Cloud Radiative Forcing*	**5**	0.83	1.3	1.8	1.03	1.05	0	***9.8***
Temperature Response & Lapse Rate Feedback	*Temperature Profile*	**3**	0.83	1.5	2.5	1.03	0	0	***4.8***
Water Vapor Response & Water Vapor Feedback	*Water Vapor Profile*	**3**	0.83	1.5	2.5	1.03	0	0	***9.6***
Aerosol Direct Radiative Forcing	Aerosol Radiative Forcing Aerosol Properties	**1.5**	0.83	1.5	2.5	0	1.0	0	***4.7***
Snow & Ice Albedo Feedback	*Reflected SW flux, albedo* *Snow/Ice Cover, Cloud Cover*	**1.5**	0.83	1.5	2.5	0	1.05	0	***4.9***
Land Albedo Change & Radiative Forcing	*Reflected SW flux, albedo*	**0.5**	0.83	2.0	2.5	0	1.05	0	***2.2***
Vegetation Index Change	*Vegetation Index*	**1**	0.83	2.0	2.5	0	1.05	0	***4.4***
Science Value of Individual Components (IR, RS, RO)						**16.6**	**22.6**	**0.0**	
Science Value of combined IR/RS science (net cloud feedback)						**9.8**			
Total Mission Science Value Metric									***49.0***
Percent of Mission Science Value of Individual Components (IR, RS, RO)						**34%**	**46%**	**0%**	
Percent of Mission Science Value of combined IR/RS science						**20%**			
Total Mission Science Value as Percent of Decadal Survey Reference Mission									***57%***

* *Science Impact Factor is common to all scenarios.*
Science Impact for Temperature is split evenly between GNSS-RO and IR

check value sum **49.0**
check % sum **100%**