1. How do we obtain observations to constrain cloud feedback in climate models?

Motivation: Uncertainty in climate sensitivity remains a factor of 4 for 90% confidence bound (IPCC, 2007). This uncertainty is the major uncertainty in economic impacts of climate change (SCCM, 2010). Cloud feedback dominates this uncertainty (factor of 2.5 larger than water vapor/lapse rate feedback). Most of the uncertainty is from low clouds, high cloud feedback is positive in observations and models, model mechanisms need to be clarified.

Quantitative Goal: Cloud and radiation properties with sufficient interannual and decadal climate change accuracy to reduce cloud feedback uncertainty by at least a factor of 2.

Observations needed:

Basic quantities: TOA SW, LW, Net fluxes, Cloud fraction, height, temperature, optical depth, emissivity, particle phase, particle size. Environmental conditions: SST, atmospheric vertical structure. Monthly global, zonal, and regional sampling.

Derived quantities: TOA SW CRE, LW CRE, Net CRE

Really derived quantities (proxies):

Biggest Obstacles: Absolute accuracy and stability of satellite broadband radiation observations as well as passive cloud properties. Accuracy improvements needed are to 0.3% (95% confidence) in SW, 0.5% (95% confidence in LW, TBD for imager channel cloud properties. TBD on need for long-term lidar/radar observations. Passive cloud properties accuracy issues in polar regions, especially for polar night.

Present Data: CERES TOA radiative fluxes, MODIS cloud properties, A-train lidar/radar cloud vertical profiles, cloud fraction.

What work could be done now? Studies of MODIS cloud property vs lidar/radar cloud property anomalies (monthly zonal and monthly global) to test consistency for climate change. Determine accuracy needed for MODIS/VIIRS cloud properties as well as lidar/radar cloud properties. Determine orbital sampling requirements for this accuracy level of climate change.

Future observational strategies:
Satellite: Improved accuracy by factor of 6 in broadband SW (0.3% 95% confidence) and factor of 2 in broadband LW (0.5% 95% confidence), improved accuracy for VIIRS imager to X% in each spectral band used for cloud retrievals
Field Experiment: Do we need sustained polar aircraft campaigns to monitor polar cloud and radiation changes, i.e. IceBridge type approach for the polar component of cloud feedback. OSSEs to examine if this is feasible (sufficient sampling needed, is A-train sufficient?)

2. How do we obtain observations to characterize/constrain the anthropogenic aerosol forcing for direct, indirect and semi-direct effects?

Motivation: Anthropogenic radiative forcing uncertainty dominates the uncertainty of anthropogenic radiative forcing over the last several decades as well as the ability to use past warming observations to constrain climate sensitivity.

Quantitative Goal: Reduce uncertainty in anthropogenic radiative forcing to a level of 0.2 Wm^{-2}. Traceability matrix?

Observations needed: *Left for aerosol group to determine*

Basic quantities:
Derived quantities:
Really derived quantities (proxies):

Biggest Obstacles: Aerosol and cloud mixing cannot be discerned from space. Single-scattering albedo not known from space. Separating aerosol effects (second order) from cloud dynamics (first order). *Others left for aerosol group to determine*

Present Data: CERES TOA radiative fluxes, MODIS cloud and aerosol properties, A-train lidar/radar aerosol and cloud vertical profiles, cloud fraction. Passive microwave LWP.

What work could be done now? *Left for aerosol group to determine*

Future observational strategies: *Left for aerosol group to determine*
Satellite:
Field Experiment:

3. What is the TOA global net radiative balance, variability, and change over time, and their explanation? How is it related to the global warming hiatus??

Motivation: The warming hiatus has brought into focus the need for a rigorous understanding of global net radiative balance (90% ocean heat storage) but challenges remain in both satellite radiation and ocean in-situ observations. Global net radiation is currently constrained for decade average by ocean in-situ heat storage (ARGO), inter-annual variations from satellite radiation budget (CERES).

Quantitative Goal: Improve satellite absolute accuracy to 0.3 Wm^{-2} annual net radiation (1 sigma) and uncertainty in interannual variations to 0.1 Wm^{-2} (1 sigma). Traceability matrix?

Observations needed:

Basic quantities: Satellite TOA radiative fluxes (SW, LW, Net), Ocean temperature profiles (ARGO), surface temperature observations (land and ocean), Satellite Total Solar Irradiance (TSI)

Derived quantities: none

Really derived quantities (proxies): none

Biggest Obstacles: Absolute calibration for broadband satellite observations, improved absolute accuracy of TSI, obtaining deeper ocean sampling for ocean in-situ observations

Present Data: CERES TOA radiative fluxes, SORCE TSI, ARGO in-situ observations

What work could be done now? Modeling and observation studies to verify the absolute accuracy and interannual variation accuracy requirement. OSSEs to determine the ARGO improvements needed to verify ocean heat storage changes below the typical 1000m depth in the current observations. Study the need for higher accuracy of Spectral Solar Irradiance (TSIS) monitoring vs TSI only.

Future observational strategies:

Satellite: Improved absolute accuracy in satellite broadband SW radiances by a factor of 6 and LW radiances by a factor of 10. Improved accuracy of TSI (factor of 3) using TSIS observations

In-situ: Deeper ARGO temperature profiles (2000m? 3000m?)

4. How do we explain the 15 Wm^{-2} inconsistency in the global net surface/atmosphere energy balance?

Motivation: Attempts to reconcile the best estimates of surface radiative, sensible, and latent heat fluxes at the surface, or atmospheric column heating/cooling have failed to achieve consistency within better than 15 Wm^{-2}. This discrepancy represents roughly 20% of the global mean precipitation when expressed as latent heat.

Quantitative Goal: Reduce the total uncertainty in the surface and atmosphere net energy budget to less than 5 Wm^{-2} (goal needs more objective verification: 2? 1?). Traceability matrix?

Observations needed: Satellite precipitation, Satellite surface radiative fluxes, Satellite and/or 4-D assimilation surface latent heat fluxes, 4-D assimilation sensible heat fluxes, Satellite TOA fluxes (constrain atmosphere heating/cooling and SW surface fluxes), Cloud profiles and cloud properties to constrain in atmosphere heating/cooling rates, downward LW surface fluxes.

Basic quantities: Satellite TOA broadband radiative fluxes

Derived quantities: Satellite surface radiative fluxes, Satellite precipitation, Satellite and 4-D assimilation surface latent heat fluxes, 4-D assimilation surface sensible heat fluxes,

Really derived quantities (proxies):

Biggest Obstacles: Satellite precipitation algorithm dependence on rainfall drop size distribution, lack of open ocean high accuracy surface radiation observations to verify accuracy of satellite surface fluxes, accuracy of satellite and 4-D assimilation surface latent heat fluxes, verification of 4-D assimilation sensible heat fluxes. Satellite precipitation accuracy for drizzle and snowfall. TRMM radar/passive microwave precipitation limited to 35N to 35S. Most polar land BSRN sites are on coastlines, and ocean sites are on islands: questionable representativeness in radiation (e.g. island effect for clouds)

Present Data: CERES TOA and surface radiative fluxes, GPCP, TRMM and passive microwave precipitation, limited satellite surface latent heat fluxes (ocean only), 4-D assimilation surface latent and sensible heat fluxes, CALIPSO/CloudSat vertical cloud profiles, MODIS cloud properties.

What work could be done now? Studies of observation requirements to verify GPM Drop Size Distribution (DSD) assumptions to achieve stable pdfs as a function of precipitation type/meteorological state. Studies of utility and sampling requirements of long duration polar flights of ER-2 with multifrequency Doppler radar observations to estimate polar precipitation, drizzle, and snow. These studies might be accomplished with large domain CRM runs with multi-moment cloud and rainfall size distributions. Studies of the long term average (monthly and annual) accuracy of BSRN and ocean buoy surface radiative flux accuracy. Validation of current satellite surface fluxes limited by 5 Wm^{-2} BSRN absolute accuracy for land sites, and 10 Wm^{-2} (??) for open ocean buoys except 2 WHOI buoys.

Future observational strategies:
Satellite: Satellite GPM dual frequency precipitation observations,
Field Experiment: ER-2 multifrequency Doppler radar observations in extended duration flights (Ice Bridge like approach?)
In-Situ: Improved

5. How is the Arctic radiative environment changing?

Motivation: The rapid reduction of sea ice extent in the artic is changing the radiation environment so rapidly that TOA SW and LW flux trends are statistically significant after only 12 years of observations. Uncertain at this time if clouds are reducing or increasing the rapid warming in the arctic.

Quantitative Goal: TBD. Traceability matrix?

Observations needed: satellite sea ice extent, satellite TOA radiative fluxes and surface fluxes, satellite cloud properties (passive and active lidar/radar), 4-D assimilation temperature/humidity profiles, surface site (land and ocean) surface radiative fluxes, Aerosol properties including absorption and aerosol type.

Basic quantities: sea ice extent, TOA radiative fluxes, cloud fraction, optical depth, emissivity, multiple layering, cloud base/top height, cloud top temperature, particle phase/size

Derived quantities: SW, LW, and net cloud radiative effect, surface radiative fluxes, surface albedo

Really derived quantities (proxies):

Biggest Obstacles: Cloud property remote sensing over snow and ice surfaces require lidar/radar. Cloud base height below 1 km (radar) or for optical thickness above 3 (lidar), validation of surface fluxes over open ocean and sea ice, mixed phase clouds, accuracy of boundary layer temperature/humidity structure from 4-D assimilation. Obtaining aerosol properties and absorption. Large differences in sea ice extent change with season: spring, summer, fall, winter.

Present Data: CERES TOA radiative and surface fluxes, MODIS cloud and aerosol properties, A-train lidar/radar aerosol and cloud vertical profiles, cloud fraction. Passive microwave LWP and sea ice extent, 4-D assimilation T(z), q(z)

What work could be done now? Studies of current observations during the 8 years of A-train observations. Determine quantitative science question goals from observation and model studies. Field experiments to determine cloud and precipitation DSDs, and potentially to help validate surface fluxes. OSSEs to understand the amount of aircraft and surface site sampling required for field data. Ability to improve surface radiation validation data over land and ocean.

Future observational strategies:
Satellite: Improved accuracy of future cloud and aerosol vertical profiles, Far infrared spectra
Field Experiment: Use of IceBridge type regular aircraft flights and or high altitude (30km) long duration (month to year long) balloons or dirigibles.

6. Can we observe and confirm the water vapor greenhouse effect and feedback in the far-infrared?

Motivation: While we have tested the broadband water vapor greenhouse effect using CERES broadband observations, we have yet to verify this effect and the resulting water vapor feedback using spectrally resolved global spaceborne observations of the Far-Infrared (15 – 50 μm wavelengths). All of our current satellite infrared spectral observations are limited to 3.5 to 15 μm. As a result we have not spectrally observed half of the infrared radiation emitted to space. In the polar regions, 60 to 65% of the energy is emitted in the Far Infrared. Most of the water vapor greenhouse effect and water vapor feedback is in the Far Infrared. This observation would represent a key closure and verification of our radiative modeling understanding of 1/2 of the Earth's energy emitted to space.

Quantitative Goal: Observe the Far-Infrared spectrum at spectral resolution, coverage, and accuracy sufficient for verification of the water vapor greenhouse effect and water vapor feedback in climate models to an accuracy a factor of 2 better than the cloud feedback goal in question 1. Need to develop Traceability matrix.

Observations needed:

Basic quantities: Far infrared spectral radiances globally and zonally observed from at least 15 to 50 μm wavelength, with spectral resolution of TBD; cloud properties, especially clouds with temperatures < 250K. These properties include cloud fraction, height, temperature, emissivity, particle phase and size.

Derived quantities: Water vapor greenhouse effect

Observation/Model derived quantities: water vapor feedback

Biggest Obstacles: Far-Infrared spectra have been demonstrated in surface based (FIRST) and aircraft instruments (REFIR), but not in spaceborne observations. Instruments have been demonstrated in the laboratory that could meet the requirements and have achieved TRL-6 in the NASA ESTO IIP program.

Present Data: CERES TOA radiative fluxes (LW, 8-12 μm Window), 4-D assimilation temperature and humidity profiles, MODIS cloud properties (especially cirrus)

What work could be done now? Use OSSEs to determine traceability matrix for this study including orbital sampling, spectral resolution, and instrument accuracy/noise.

Future observational strategies:
Satellite: Far infrared spectrometer
Field Experiment: Not likely that field experiments could provide the global coverage to verify this question.

Radiation Cross-Cutting Recommendations

1. **Observing System Simulation Experiments (OSSEs) should be more widely used to improve the rigor of NASA observing system requirements, both for satellites as well as aircraft and field experiments.**
While OSSE approaches have been used in weather prediction for some time, very few climate observations have taken advantage of this approach to derive more objective observing requirements (e.g. accuracy, sampling). OSSEs can be applied to decadal climate change observations (using climate models and observation simulators), climate process observations (using GCM/CRM/LES models), as well as field experiments (using GCM/CRM/LES models). OSSEs provide an approach to requirements that is closer to a rigorous hypothesis test. Models represent our physical hypothesis about the climate system. While OSSEs are not justified if models are grossly unrealistic, in most cases they can be a key tool for improving the rigor of observation requirements. Close coordination is required between modeling and observation scientists.

2. **The NASA remote sensing community needs to rigorously determine the level of stability of biases in satellite retrieval algorithms that are used to determine decadal climate change**.
Current satellite retrieval algorithms focus entirely on random and bias errors for instantaneous retrievals appropriate to process or weather applications. These algorithms have not been evaluated for their ability to determine decadal climate change. A typical assumption is that they will perform without problem as long as the algorithm code remains constant. But most satellite retrievals have bias errors that greatly exceed the magnitude of decadal climate change. Studies need to be performed that these biases are sufficiently stable during climate change to avoid significant aliasing errors in deriving climate change from remote sensing algorithms.

3. **Science questions need to be based on quantitative specific goals**, **as opposed to qualitative general research areas of interest. This is critical for defining rigorous observing requirements.**
Science questions which are qualitative in nature are good for exploring totally unknown questions, but Earth science has been attacking such questions for over 30 years. It is time to move from qualitative to quantitative questions: in essence quantitative hypothesis tests, typically with observations testing model hypotheses.

4. **There is a need to determine not just what would make a significant improvement over current capabilities, but to also determine the final needed capability or uncertainty. Inotherwords, what is the quantitative "end game", or "how good is good enough".**

Given limited science resources, there is a critical need to prioritize. One aspect of prioritization is to quantify the point of diminishing returns. Infinite accuracy is not required, even though progress could be continually and objectively shown. Science questions need to determine quantitative final needed capabilities even if those change as our understanding of the science changes.

Overarching Issues

1. **Absolute accuracy remains a major issue**
   - Radiation accuracy: broadband and spectral, TOA and surface
   - Cloud property accuracy: passive and active
   - Aerosol property accuracy
   - Total and Spectral Solar Irradiance
   - Precipitation accuracy
   - Ocean heat storage accuracy
   - Missing Far Infrared spectra

2. **Sampling for Field Experiments**
   - Do we need more Ice Bridge like sampling for cloud and precipitation DSDs, aerosols, etc?