<u>Title</u> (150 character limit):
The Long-term Challenge of Detecting Unambiguous Trends in Stratospheric Temperature

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<u>White Paper Description</u> (350 character limit):
Accurate monitoring of stratospheric temperature is an important task for the scientific disentangling of natural variability and anthropogenic change. Satellite measurements in the stratosphere lack the needed SI traceability. Timely implementation of CLARREO will provide the reference inter-calibration needed to substantiate long-term trends.

<u>White Paper Description</u> (1500 character limit):

1. The Long-term Challenge of Detecting Unambiguous Trends in Stratospheric Temperature

Despite its importance for radiation budget, dynamics and chemistry, the rate and vertical structure of stratospheric temperature change remains poorly constrained (Stocker et al. 2013). Many stratospheric trace gas species, such as carbon dioxide, ozone, and water vapor, affect the radiation energy balance by interacting with the shortwave solar radiation and the longwave terrestrial radiation. Numerical experiments show that stratospheric contributions are critical for the climate system to maintain the balance of the top-of-the atmosphere radiation energy budget during transient climate change. For example, the magnitude of the overall time-varying stratospheric effect on the outgoing longwave radiation can be comparable to that of the overall longwave cloud feedback, and the intermodal spread is as large as that of the overall non-cloud tropospheric feedback (Huang 2013).

To highlight the importance and challenges related to stratospheric trend detection we quote from recent literature:

Temperature trends in the stratosphere are an important component of global change. These trends can provide evidence of the roles of natural and anthropogenic climate change mechanisms; the ‘‘fingerprint’’ of distinct tropospheric warming and stratospheric cooling provides information on the effects of these mechanisms. (Randel et al. 2009)

Atmospheric temperature trends through the depth of the atmosphere offer the possibility of separating the effects of multiple climate forcings, as climate model simulations indicate that each external forcing produces a different characteristic vertical and zonal pattern of temperature response. GHG forcing is expected to warm the troposphere and cool the stratosphere. Stratospheric ozone depletion cools the stratosphere, with the cooling being most pronounced in the polar regions. (Bindoff et al. IPCC 2013)

There is increasing agreement between various datasets over temperature change for the bulk of the troposphere and lower stratosphere, but appreciable uncertainty remains as to rates of change and variations with height. The upper stratosphere is more problematic still, as reliance has to be placed on satellite data alone for global monitoring, and instrumental changes make it difficult to construct a coherent record for the whole of the satellite era. (Simmons et al. 2014)

a. Summary of Current Satellite Capabilities

The U.S. POESS program built a series of infrared sensors called the Stratospheric Sounding Unit (SSU) for flight on the NOAA series of sun-synchronous polar orbiting satellites starting in 1979. These instruments used a broadband infrared detector, which viewed the atmosphere through a pressured gas cell containing CO_2. Unfortunately the CO_2 gas cells tended to leak, which caused the vertical peak for sensor response to change with time. This error combined with calibration differences among the seven SSU sensors, has caused spurious trends in upper stratospheric temperature, which are still being actively studied at NOAA NESDIS. Despite these issues a general cooling trend was observed from 1979 to 2005. Near the end of the SSU series, the passive microwave AMSU-A sensor was added to the NOAA satellite series with channels that peak in the lower, middle, and upper stratosphere similar to the SSU sensor. AMSU-A uses oxygen absorption bands/lines for atmospheric temperature sounding. A recent paper by Simmons et al. (2014) showed that when the ERA-Interim data assimilation switched from using SSU to AMSU-A in 1999, it introduced a discontinuity of 5 degrees (!) in the temperature time series at 1 hPa. This makes the use of ERA-Interim for trend detection problematic. No doubt the AMSU-A is a great improvement on the SSU with respect to stability. However, the absolute calibration of the AMSU-A sensor is less well understood. As quoted previously, Simmons et al. (2014) has identified the middle and upper stratosphere as a problematic region for construction of a coherent temperature record from existing conventional radiosonde and satellite data.

One of the recent additions to the space based observing system is the active GPS radio occultation (RO) measurement from the joint U.S./Taiwan COSMIC program. COSMIC is composed of NASA JPL designed radio receivers on a Taiwanese satellite constellation of six satellites measuring phase delays due to atmospheric bending of pulses emitted by the Global Positioning Satellite network. COSMIC has been producing global daily meteorological products since 2007. Almost immediately the GPS RO bending angles were adopted for inclusion in ECMWF data assimilation and treated as an anchor dataset, although only in a limited height region covering the upper troposphere and lower stratosphere. However, in altitudes above 30 hPa both the random and systematic error of the COSMIC and GRAS RO temperature information increases with height (Steiner et al. 2013). This currently limits the use of GPS RO to monitoring of the lower stratosphere where it complements the existing radiosonde observations by providing more uniform global spatial coverage. There is a need for a reference GPS RO measurement that extends the useful accuracy to the middle and upper stratosphere.

Spectrally resolved infrared spectra of the Earth (often referred to as hyperspectral infrared) were first collected in the 1970s. However, routine global hyperspectral infrared observations only began with the NASA AIRS sensor on the Aqua platform in September 2002 as input into operational numerical weather prediction models (NWP). AIRS has operated for more than 13 years collecting top of atmosphere infrared spectra with good radiometric accuracy. Narrow spectral channels near the 667.7 cm^{-1} CO_2 Q-branch peak in the middle and upper stratosphere. Pan et al. (2015) have recently shown that analysis of the AIRS high peaking channels gives a statistically significant cooling trend that increases with height in the stratosphere over the period 2003–2012. This is in apparent conflict with the AMSU-A oxygen channels observed during the same time period. The operational follow-on to the NASA AIRS sensor is the NOAA Cross-track Infrared Sounder (CrIS) currently operating on the Suomi-NPP satellite. While the AIRS results are intriguing, they justify the need for an on-orbit infrared calibration reference that can be used to tie operational satellites to international standards over the next several decades.

Inter-calibration of operational sensors is an element of the Climate Absolute Radiance and Refractivity Observatory (CLARREO) mission that was chosen as one of four Tier 1 missions in the 2007 Decadal Survey. Highlights include emission spectra that include the same stratospheric channels used by the operational infrared sounders, but using new technologies specifically developed under NASA Instrument Incubator Program (IIP) efforts to verify expected accuracy on-orbit. The CLARREO mission includes a reference GPS radio-occultation receiver to provide bending angle measurements that are expected to improve the understanding of the ionospheric corrections used in analysis of existing GPS RO observations. The authors recommend that the CLARREO mission be flown as an observatory or as separate flight elements depending on cost and schedule constraints. Details are available in Wielicki et al BAMS 2014.

b. Linking space-based observations with other observations

Interpretation of infrared radiance in the carbon dioxide bands at 15 and 4.3 microns requires estimates of CO_2 profiles such as from the NOAA Carbon Tracker program. Moreover, the infrared hyperspectral radiance and RO data will be used in conjunction with the GRUAN reference radiosonde and ozone-sonde network to provide global reference validation data.

c. The anticipated scientific and societal benefits

A changing Brewer-Dobson circulation has a significant role in the dynamical coupling between the stratosphere and troposphere with implications for surface climate and weather (Butchart 2014). The Value of Information for the proposed space-borne CLARREO system relative to current space-borne systems ranges from 2 to 30 trillion US dollars (Cooke et al. 2013).

d. The science communities that would be involved.

The NWP forecast, NWP re-analysis, Global Climate Model, and middle atmospheres composition communities will be involved.

2. Time to start a coherent record of stratospheric temperature change.

We are midway through the second decade of the 21st century and yet the science of decadal climate change requires accuracies significantly higher than current systems (Wielicki et al. BAMS 2014). A timely execution of the CLARREO mission will overlap with the operational JPSS series and METOP series to provide inter-calibration for programs that will last through 2040 and backward in time through 2003.

3. Space-based observations are indispensable.

The existing radiosonde network has adequate vertical resolution but does not routinely make global observations above (30 hPa) to characterize the middle and upper stratosphere (Seidel et al. 2011). Only global satellite observations have sufficient time and space sampling to characterize long-term zonal temperature trends in the stratosphere.

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