**Detecting atmospheric temperature, humidity, and cloud property changes by average-then-retrieve approach**

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**1. Introduction**

Atmospheric temperature, specific humidity, and cloud properties are expected to change due to radiative perturbations caused by increasing the concentration of carbon dioxide. Understanding how clouds and atmospheric properties change with time under radiative forcing is necessary to understand feedback (e.g. Knutti and Hegerl 2008). Because changes are small compared to natural variability of these properties (i.e. Wielicki et al. 2013), detecting changes is extremely challenging. Even though these properties are currently retrieved globally from satellite-based instruments, the uncertainty in the calibration of instruments usually makes it difficult to detect such changes within the lifetime of the instruments or even the duration of the missions. In this document, therefore, we briefly discuss needs for an alternative approach suitable for climate change signal detection but complementary to approaches currently used in retrieving temperature, humidity, and cloud properties.

Generally, global cloud and atmospheric properties are retrieved from satellite-based instruments using their instantaneous observations. Subsequently, retrieved values from an instrument’s field-of-view are averaged and the time rate of change of cloud or atmospheric properties can be inferred from averaged properties (retrieve-then-average approach). This is simple in concept but identifying artifacts of the retrieval is difficult in practice. Even if the same algorithm is used for the retrieval throughout the period, instrument calibration shifts and changes in inputs used for the retrieval (e.g. source of temperature or water vapor profiles), cause artifacts. In addition, the complexity of retrieval algorithms makes tracing error propagations and the error estimate in retrieved properties difficult, especially if the error is time-dependent. An alternative way to derive a trend of cloud and atmospheric properties is to tie their property change directly to the observed radiance change. This average-then-retrieve approach carries observed radiances as far as possible and retrieved values are directly tied to instrument stability (i.e. repeatability and reproducibility, Taylor and Kuyatt 1994). However, it requires separating cloud and atmospheric property changes contributing to the highly spatial- and temporally-averaged observed radiance change. In addition, the average-then-retrieve approach can retrieve anomalies or changes in cloud and atmospheric properties occurring over a region and a time period directly. Although mean values are not derived, there is an advantage in deriving anomalies directly. If the error is time-dependent (e.g. aliasing seasonal temperature or water vapor variability), the error in mean values affecting anomalies is difficult to eliminate. Because anomalies are much smaller than means, a small time-dependent error affects anomalies significantly. In addition, although unknown bias errors in the calibration affect both approaches, once observed radiances are averaged, both instrument noise and natural variability are reduced, with the larger the time and space averaging, the larger the reduction.

Some basic studies had been performed to investigate the possibility of the average-then-retrieve approach for climate applications. Earlier results are summarized in the next section. However, more work is required for the average-to-retrieve approach to be actually used in the future. Some of key challenges in developing the average-then-retrieve approach are also summarized in the next section.

**2. Average-then-retrieve approach**

The average-then-retrieve approach uses highly spatial- and temporally averaged spectral radiances. The spatial resolution used in the retrieval is typically a coarse grid resolution (e.g 10°× 10°) or zonal (e.g. 10°). The temporal resolution is monthly or seasonal. The approach relies on spectral information to separate changes in temperature, humidity, and cloud properties as a function of height. The concept to detect subtle changes in these properties using spectral information is not new and discussed by Goody et al. (1998), Leroy (1998), and Anderson et al. (2004).

Some basic studies to investigate the possibility of average-then-retrieve approach have been done by the Climate Absolute Radiance and Reflectivity Observatory (CLARREO) science definition team. Results using longwave spectral radiances show that clear-sky atmospheric property changes, such as temperature and water vapor amount, can be retrieved from highly-averaged spectral radiance change (Leroy et al. 2008a). However, a larger error occurs in retrieving cloud property (e.g. fraction, height, optical thickness, particle size) changes (Kato et al. 2011). Necessary conditions for the average-then-retrieve approach to work include: 1) Top-of-Atmosphere (TOA) spectral radiance change can be expressed as a linear combination of spectral radiance changes caused by cloud and atmospheric properties, 2) the magnitude of spectral radiance changes linearly corresponding to a small perturbation of cloud or atmospheric property, at least in the relevant parts of the spectrum, and 3) changes of cloud and atmospheric properties provide unique spectral radiances that can be separated by a linear regression approach. These assumptions are tested in an earlier study (Kato et al. 2011) and proved to be valid assumptions at least for annual and monthly and 10° zonal scales. 1) and 3) are also shown to be valid at an annual scale also by Leroy et al. (2008a) for clear-sky and by Huang et al. (2010a) for all-sky. Their results also imply that 2) is valid. Similar studies had been done for shortwave spectral radiances by Feldman et al. (2011), Jin et al. (2011), Roberts et al. (2011).

One challenge in developing the average-then-retrieve approach is to understand the magnitude and characteristic of retrieval errors. Because temperature, humidity, and cloud property changes are derived from the averaged spectral irradiances, errors in individual properties are not independent. Even if the error in separating the change of cloud properties contribution is large, however, when property changes are retrieved a sufficient number of times, the trend of property changes can be correctly inferred from retrieved properties (Kato et al. 2014). In addition, studies by Weatherhead et al. (1998), Leroy et al. (2008b), and Wielicki et al. (2013) indicate that the requirements for retrieving a trend are: 1) any retrieval bias error must be stable at a level much smaller than that of the trend of interest, and 2) any random error must be sufficiently small with sufficient independent samples to allow accurate detection of the trend. The average-then-retrieve approach can be designed specifically for trend detections but further studies are needed understand the error in order to meet these requirements. In addition, errors are expected to depend on temporal and spatial resolutions. Investigating an optimum resolution is required.

The average-then-retrieve approach requires stable instrument calibrations because calibration drifts directly affect averaged spectral radiances. This is true for retrieve-then-average approaches. However, the average-then-retrieve approach also depends on other conditions in which observations are taken. For example, subtle orbit drifts (e.g. overpass time change for a given location) and viewing zenith angle changes also affect averaged spectral radiances, hence, the result of the average-then-retrieve approach in a more direct way than the result of retrieve-then-average approaches. Therefore, the average-then-retrieve algorithm needs to be developed closely with a team determining instrument requirement of future missions.

Application of the average-then-retrieve approach is not limited to future observations. It can be applied to Atmospheric Infrared Sounder (AIRS), Cross-track Infrared Sounder (CrIS), or Moderate Resolution Imaging Spectroradiometer (MODIS). However, the characteristic of retrieval errors depends on instrument and need to be examined instrument by instrument. Because of this potential broader application of the approach, results of basic research on the average-then-retrieve approach conducted in the future will benefit remote sensing of atmosphere and climate change research communities.

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