

Climate Change Detection and Attribution of Infrared Spectrum Measurements

Nipa Phojanamongkolkij, Peter Parker, and Marty Mlynczak

NASA Langley Research Center, Hampton, VA

Abstract

Climate change occurs when the Earth's energy budget changes due to natural or possibly anthropogenic forcings. These forcings cause the climate system to adjust resulting in a new climate state that is warmer or cooler than the original. The key question is how to detect and attribute climate change. The inference of infrared spectral signatures of climate change has been discussed in the literature for nearly 30 years. Pioneering work in the 1980s noted that distinct spectral signatures would be evident in changes in the infrared radiance emitted by the Earth and its atmosphere, and that these could be observed from orbiting satellites. Since then, a number of other studies have advanced the concepts of spectral signatures of climate change. Today the concept of using spectral signatures to identify and attribute atmospheric composition change is firmly accepted and is the foundation of the Climate Absolute Radiance and Refractivity Observatory (CLARREO) satellite mission being developed at NASA. In this work, we will present an overview of the current climate change detection concept using climate model calculations as surrogates for climate change. Any future research work improving the methodology to achieve this concept will be valuable to our society.

Background

The climate of the Earth's atmosphere is determined by the energy input from the Sun and the energy radiated from the Earth. Climate change occurs when the energy budget changes due to natural or possibly anthropogenic forcings. These forcings cause the climate system to adjust, sometimes engendering feedbacks that amplify or mitigate the forcings, resulting in a new climate state that is warmer or cooler than the original. The key question going forward is how to detect climate change. The measurement of infrared spectral signatures of climate change has been discussed in the literature relating to lower atmosphere (tropospheric) climate for nearly 30 years. Kiehl [1983] and Charlock [1984] noted that distinct spectral signatures would be evident in changes in the infrared radiance emitted by the Earth and its atmosphere, and that these could be observed from orbiting satellites.

Since the pioneering work of Kiehl and Charlock, a number of other studies have advanced the concepts of spectral signatures of climate change [e.g., Goody et al., 1995; Slingo and Webb, 1997]. Harries et al. [2001] showed convincingly the increase in the greenhouse effect due to methane using measurements of infrared radiance spectra taken 27 years apart from satellite spectrometers. More recently, Huang and Ramaswamy [2009] have shown that distinct infrared spectral signatures associated with specific aspects of atmospheric structure and composition change (e.g., cloud height, tropospheric water vapor, CO₂) can be uniquely determined. These signatures can be used to determine changes in atmospheric

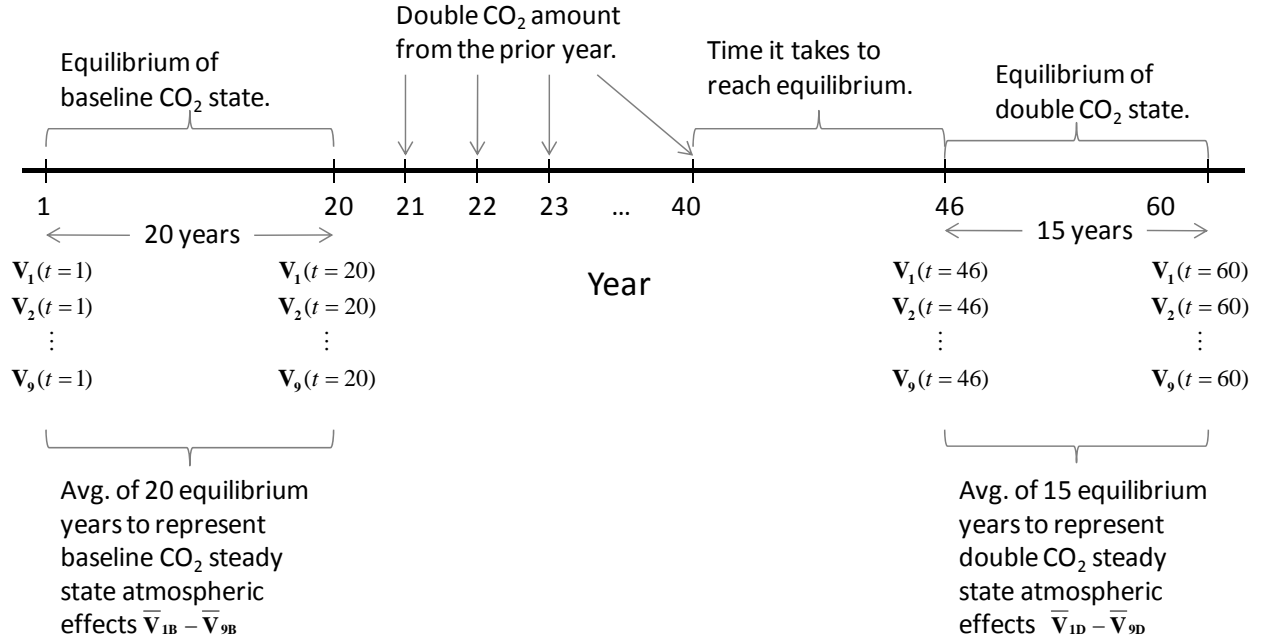
structure or composition can be monitored over decadal time scales. Today the concept of using spectral signatures to identify and attribute atmospheric composition change is the foundation of the Climate Absolute Radiance and Refractivity Observatory (CLARREO) satellite mission defined in the Earth Science Decadal Survey [National Research Council, 2007]. The CLARREO mission requires measurement of essentially the entire infrared emission spectrum of the Earth and its atmosphere, from 5 to 50 micrometers (200 to 2000 wavenumbers).

Current Challenge

The CLARREO is currently in the pre-formulation phase of the mission. There are at present no measured, complete infrared spectra to simulate CLARREO measurements and to evaluate the fingerprinting techniques. To demonstrate the climate change detection and attribution concept, climate model simulation runs of the Canadian Centre for Climate Modeling and Analysis (CCCMA) model from the Cloud Feedback Model Intercomparison Project (CFMIP) are used as surrogates for measured spectra from which to assess climate change. Figure 1 shows schematically the procedure of processing climate model data for this study. The CCCMA was initiated with CO₂ of 280 ppmv (baseline CO₂ scenario for pre-industrial conditions), after it equilibrated, it was run for 20 years. Then the CO₂ was gradually increased until it reached 580 ppmv (double CO₂ scenario), the model re-equilibrated and was run for additional 15 years. Outputs of the CCCMA model were 60-year time series of several responses. These responses were climate atmospheric effects (e.g., tropospheric water vapor, surface temperature, etc.) for all geographies that evolved over time. Only nine effects were determined to be the best-known major contributors to climate change, and therefore, they were considered in this study.

The mean steady-state effects for the baseline and double CO₂ scenarios were obtained from years 1-20 ($\bar{V}_{1B}, \bar{V}_{2B}, \dots, \bar{V}_{9B}$) and years 46-60 ($\bar{V}_{1D}, \bar{V}_{2D}, \dots, \bar{V}_{9D}$), respectively. Typical post-processing of the mean steady-state atmospheric effects was to calculate a corresponding spectral radiance by a moderate-resolution radiative transfer model (MODTRAN). The spectral radiance calculation was done twice, one for baseline and the other for double CO₂ scenario. The spectral radiance difference between the baseline and double CO₂ scenarios was then obtained. It is the radiance difference that is used for detecting and attributing climate change between two climate states. This process of generating radiance difference is shown in Figure 2.

Typically, the climate model resolves the globe into grid boxes and calculates atmospheric conditions for all grid boxes. The grid box size or resolution varies depending on climate models. Grid box of the CCCMA model has resolution of about 3.7 degree in latitude by 3.75 degree in longitude. Therefore, the model has 48 horizontal bands (180 degree/3.7 degree in latitude) and 96 vertical bands (360 degree/3.75 degree in longitude), resulting in a total of 4608 grid boxes. Procedures of processing climate model data, generating their associated spectral radiances, and calculating radiance differences described above were repeated 4608 times, one for each grid box.



where

$V_1(t)$ = a $(4608 \times t)$ matrix for lower tropospheric cloud effects at time t for 4608 grid boxes

$V_2(t)$ = a $(4608 \times t)$ matrix for middle tropospheric cloud effect at time t for 4608 grid boxes

$V_3(t)$ = a $(4608 \times t)$ matrix for upper tropospheric cloud effect at time t for 4608 grid boxes

$V_4(t)$ = a $(4608 \times t)$ matrix for CO₂ effect at time t for 4608 grid boxes

$V_5(t)$ = a $(4608 \times t)$ matrix for stratospheric water vapor effect at time t for 4608 grid boxes

$V_6(t)$ = a $(4608 \times t)$ matrix for tropospheric water vapor effect at time t for 4608 grid boxes

$V_7(t)$ = a $(4608 \times t)$ matrix for stratospheric temperature effect at time t for 4608 grid boxes

$V_8(t)$ = a $(4608 \times t)$ matrix for tropospheric temperature effect at time t for 4608 grid boxes

$V_9(t)$ = a $(4608 \times t)$ matrix for surface temperature effect at time t for 4608 grid boxes

$\bar{V}_{1B}, \bar{V}_{1D}$ = a (4608×1) vector for mean steady - state lower tropospheric cloud effect for baseline CO₂ and double CO₂ scenarios

$\bar{V}_{2B}, \bar{V}_{2D}$ = a (4608×1) vector for mean steady - state middle tropospheric cloud effect for baseline CO₂ and double CO₂ scenarios

$\bar{V}_{3B}, \bar{V}_{3D}$ = a (4608×1) vector for mean steady - state upper tropospheric cloud effect for baseline CO₂ and double CO₂ scenarios

$\bar{V}_{4B}, \bar{V}_{4D}$ = a (4608×1) vector for mean steady - state CO₂ effect for baseline CO₂ and double CO₂ scenarios

$\bar{V}_{5B}, \bar{V}_{5D}$ = a (4608×1) vector for mean steady - state stratospheric water vapor effect for baseline CO₂ and double CO₂ scenarios

$\bar{V}_{6B}, \bar{V}_{6D}$ = a (4608×1) vector for mean steady - state tropospheric water vapor effect for baseline CO₂ and double CO₂ scenarios

$\bar{V}_{7B}, \bar{V}_{7D}$ = a (4608×1) vector for mean steady - state stratospheric temperature effect for baseline CO₂ and double CO₂ scenarios

$\bar{V}_{8B}, \bar{V}_{8D}$ = a (4608×1) vector for mean steady - state tropospheric temperature effect for baseline CO₂ and double CO₂ scenarios

$\bar{V}_{9B}, \bar{V}_{9D}$ = a (4608×1) vector for mean steady - state surface temperature effect for baseline CO₂ and double CO₂ scenarios

Figure 1 Procedure of processing the CCCMA climate model data

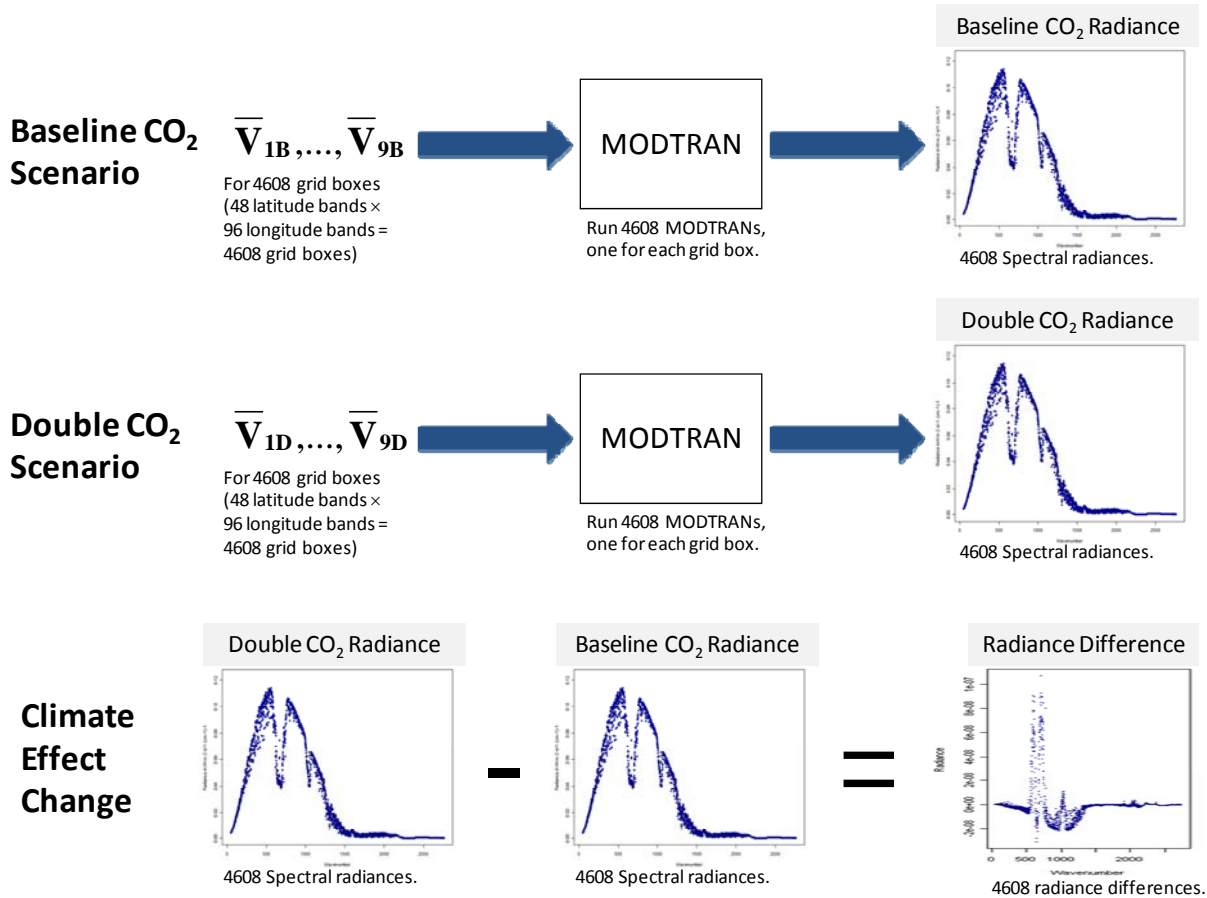


Figure 2 Procedure of generating radiance differences representing climate atmospheric effect change.

As discussed above, we are looking for changes in climate caused by changes in nine different effects (although there may be many more to consider with real data).

In order to quantify the contribution of each of the nine effects under study, nine one-effect-at-a-time suppression experiments were performed, assuming that the interaction effects are less likely to contribute to climate change. Table 1 lists all 9 suppression experiments. For example, Run 2 was an experiment that suppressed lower tropospheric cloud. The spectral radiance of the suppressed lower tropospheric cloud was calculated by inputting the mean steady-state of baseline CO₂ for lower tropospheric cloud while inputting the mean steady-states of double CO₂ for all other 8 effects into MODTRAN. This radiance was then subtracted from the double CO₂ radiance to get the signature of the contributing change due to the change in lower tropospheric cloud.

Table 1 Suppression experiments

Run ID	Description	Inputs to MODTRAN execution	Radiance difference obtained	Available radiance difference array size
Run 1	a. Experiment with baseline CO ₂ at 280 ppmv b. Experiment with double CO ₂ at 560 ppmv	a. $\bar{V}_{1B}, \dots, \bar{V}_{9B}$ b. $\bar{V}_{1D}, \dots, \bar{V}_{9D}$	$R(\bar{V}_{1D}, \dots, \bar{V}_{9D}) - R(\bar{V}_{1B}, \dots, \bar{V}_{9B})$	4608×1
Run 2	Suppression of lower tropospheric cloud effect V ₁	$\bar{V}_{1B}, \bar{V}_{2D}, \dots, \bar{V}_{9D}$	$R(\dots, \bar{V}_{1D}, \dots) - R(\dots, \bar{V}_{1B}, \dots)$	4608×1
Run 3	Suppression of middle tropospheric cloud effect V ₂	$\bar{V}_{1D}, \bar{V}_{2B}, \bar{V}_{3D}, \dots, \bar{V}_{9D}$	$R(\dots, \bar{V}_{2D}, \dots) - R(\dots, \bar{V}_{2B}, \dots)$	4608×1
Run 4	Suppression of upper tropospheric cloud effect V ₃	$\bar{V}_{1D}, \bar{V}_{2D}, \bar{V}_{3B}, \bar{V}_{4D}, \dots, \bar{V}_{9D}$	$R(\dots, \bar{V}_{3D}, \dots) - R(\dots, \bar{V}_{3B}, \dots)$	4608×1
Run 5	Suppression of CO ₂ effect V ₄	$\bar{V}_{1D}, \dots, \bar{V}_{3D}, \bar{V}_{4B}, \bar{V}_{5D}, \dots, \bar{V}_{9D}$	$R(\dots, \bar{V}_{4D}, \dots) - R(\dots, \bar{V}_{4B}, \dots)$	4608×1
Run 6	Suppression of stratospheric water vapor effect V ₅	$\bar{V}_{1D}, \dots, \bar{V}_{4D}, \bar{V}_{5B}, \bar{V}_{6D}, \dots, \bar{V}_{9D}$	$R(\dots, \bar{V}_{5D}, \dots) - R(\dots, \bar{V}_{5B}, \dots)$	4608×1
Run 7	Suppression of tropospheric water vapor effect V ₆	$\bar{V}_{1D}, \dots, \bar{V}_{5D}, \bar{V}_{6B}, \bar{V}_{7D}, \dots, \bar{V}_{9D}$	$R(\dots, \bar{V}_{6D}, \dots) - R(\dots, \bar{V}_{6B}, \dots)$	4608×1
Run 8	Suppression of stratospheric temperature effect V ₇	$\bar{V}_{1D}, \dots, \bar{V}_{6D}, \bar{V}_{7B}, \bar{V}_{8D}, \bar{V}_{9D}$	$R(\dots, \bar{V}_{7D}, \dots) - R(\dots, \bar{V}_{7B}, \dots)$	4608×1
Run 9	Suppression of tropospheric temperature effect V ₈	$\bar{V}_{1D}, \dots, \bar{V}_{7D}, \bar{V}_{8B}, \bar{V}_{9D}$	$R(\dots, \bar{V}_{8D}, \dots) - R(\dots, \bar{V}_{8B}, \dots)$	4608×1

Run 10	Suppression of surface temperature effect V_9	$\bar{V}_{1D}, \dots, \bar{V}_{8D}, \bar{V}_{9B}$	$R(\dots, \bar{V}_{9D}, \dots) - R(\dots, \bar{V}_{9B}, \dots)$	4608x1
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$R(\dots)$ is spectral radiance obtained from MODTRAN for a given climate mean steady-state effect inputs. $R(\dots, \bar{V}_{iD}, \dots)$ is a spectral radiance vector for all mean steady-state effects, including effect i , from the Double CO2 scenario. $R(\dots, \bar{V}_{iB}, \dots)$ is a spectral radiance vector for the mean steady-state effect i from the Baseline CO2 and all other mean steady-state effects from the Double CO2 scenario.

CLARREO is interested in detecting and attributing climate change globally and zonally. Typical zone is defined as a 10-degree latitude band. Figure 3 gives an example of the spectral signatures for a particular zone. Figure 3a represents a measurement of the change in atmospheric radiance due to the doubling of carbon dioxide in the atmosphere. This is the radiance difference obtained from Run 1. Figures 3b to 3j show the spectral signatures associated with changes in lower tropospheric cloud, middle tropospheric cloud, upper tropospheric cloud, CO₂, stratospheric water vapor, tropospheric water vapor, stratospheric temperature, tropospheric temperature, and surface temperature. These are the radiance differences obtained from Runs 2 to 10 respectively. They also aggregately explain the change in the infrared spectrum (Fig. 3a.) In practice, it is expected that the spectral changes (Fig. 3a) as a function of radiance vs. wavenumber (a reciprocal of wavelength) will be derived from the actual infrared satellite measurements. The spectral changes of all atmospheric effects (Fig. 3b-3j) will be derived either from the climate models under the control suppression experiments and from the existing satellites that were designed to measure specific atmospheric effects. Figure 4 shows the signature in each 10-degree latitude band varies across all 18 zones for two runs (Run 1 and Run 3).

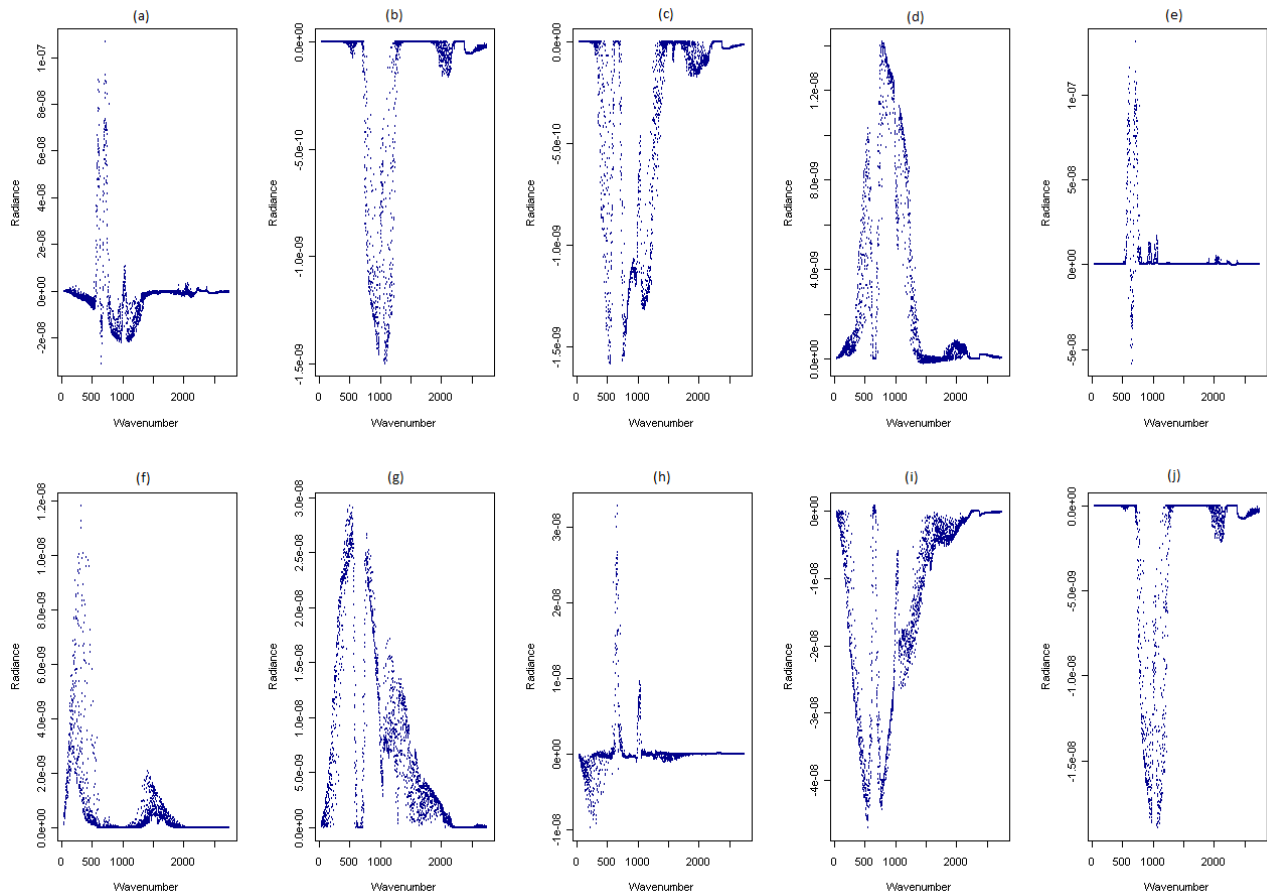
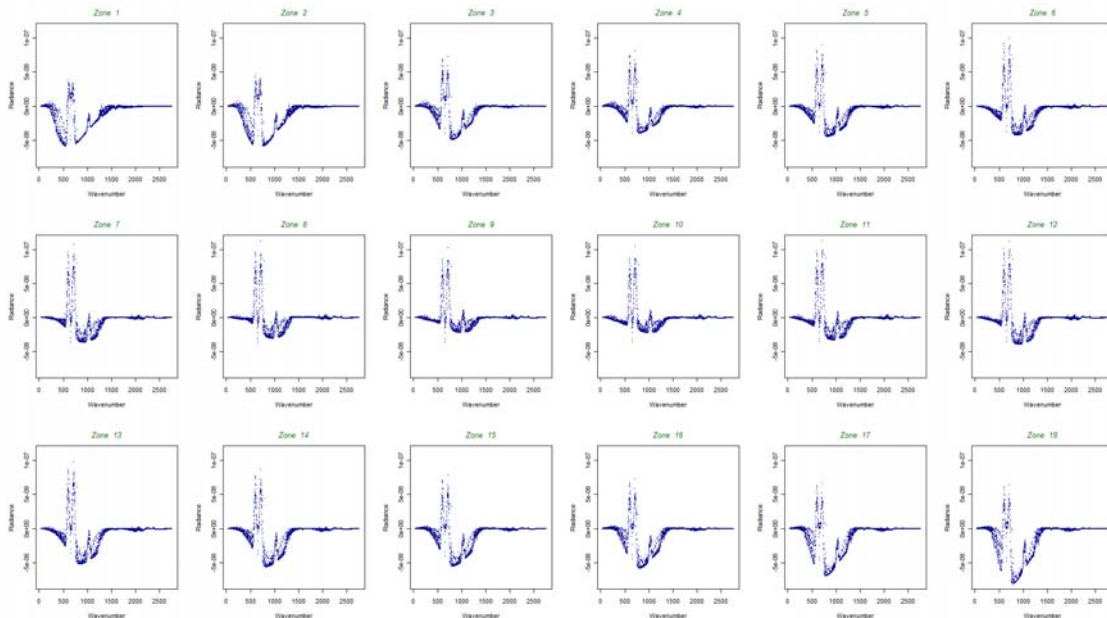
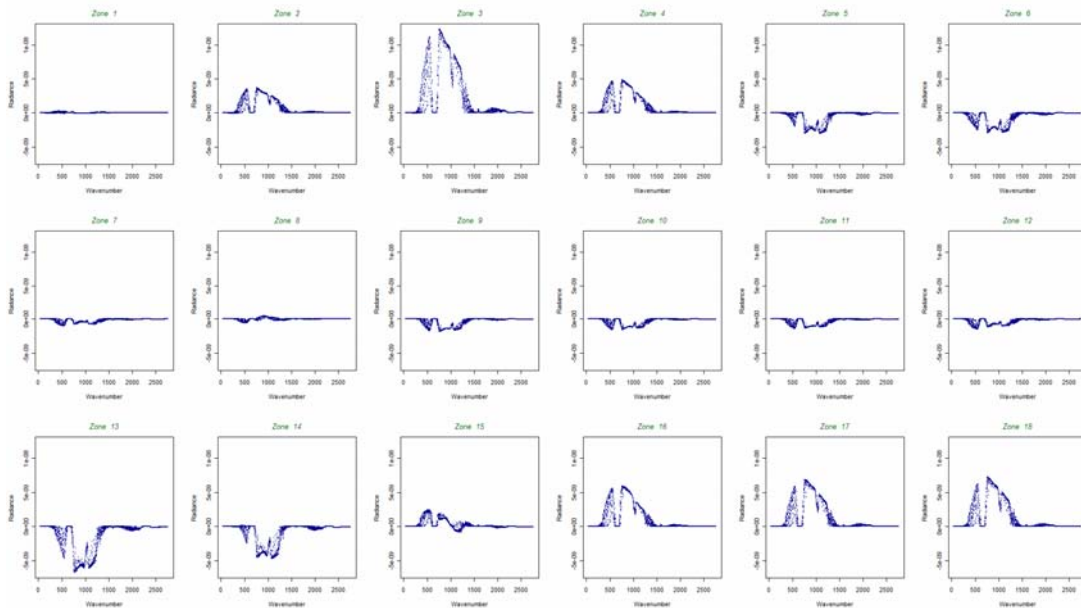


Figure 3 Example of the spectral signatures for a particular 10-degree latitude band (a) simulated change in infrared measurement. (b)-(j) spectral signatures due to changes in nine different atmospheric

parameters (e.g., water vapor, cloud height, temperature, etc.) aggregately explaining the change in the measure (a).



(a) Simulated changes in infrared spectra due to doubling of carbon dioxide in Earth's atmosphere as a function in 10 degree latitude bands (18 total zones).



(b) Middle Tropospheric Cloud

Figure 4 An example of (a) simulated changes in infrared spectral measurement (Run 1). (b) radiance changes associated with middle tropospheric cloud changes (Run 3).

There are two research objectives. The first objective is to identify globally and zonally which of the atmospheric effects change from the Baseline CO₂ to the Double CO₂ scenarios. The second is to quantify the magnitudes of all effects' changes. Achieving both objectives enables one to monitor atmospheric composition changes global and zonal over decadal time scales. The key challenge is how to achieve both objectives given many radiance difference spectral signatures are similar as shown in Figure 3.

Future Research Work

Future research focusing on exploring potential methodology is under way. The successful methodology will be able to detect globally and zonally which distinct infrared spectral signatures associated with specific atmospheric composition have changed. The accurate magnitude of change is also desired as this is an indication of which atmospheric component has changed. The current available data as described in Table 1 can be used to design and test potential methodologies. Future work to demonstrate this concept with the satellite spectral measurement is also planned. The proven successful methodology will be applied to the decadal time series of simulated-CLAREEO-like measurements to validate the utility of such measurements.

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