Clouds are considered one of the largest uncertainties in global climate models. In particular, two situations must be taken into account: (1) the impact of clouds on the incoming shortwave radiation from the sun, and (2) the impact of clouds on the longwave outgoing radiation emitted to space by the surface and atmosphere. The net result of these two events determines the warming or cooling impact that clouds will have on the planet. This research aims to look primarily at optical depth to assess the impact that high altitude, optically thin “subvisual” cirrus clouds (SVC) have on both the incoming solar radiation and the outgoing infrared radiation. In this study, the Aqua train satellite AIRS, CALIPSO, and MODIS instruments, provide the spectral radiance values, cloud height and cloud mask data, respectively, that can be used to determine the optical characteristics of clouds. CALIPSO and MODIS are used to identify clear versus cloudy fields of view, then radiance values along with atmospheric temperature profiles can be used in the radiative transfer equation to determine spectral values for emissivity, transmissivity and optical depth. The technique for determining the existence and optical properties of SVC is presented here. An example of its application is also shown.

**Introduction**

Clouds are considered one of the largest uncertainties in global climate models. The question is not just how many clouds are in the sky, but their composition and location that determine what impact clouds have on climate. It has been reported that climate models can vary by a factor of three, depending on how clouds are represented in the model. It has been estimated that the planet would be on average 20°F warmer if clouds were not present on Earth. Clearly clouds are an important factor to consider. In particular, two situations must be taken into account: (1) the impact of clouds on the incoming shortwave radiation from the sun, and (2) the impact of clouds on the longwave outgoing radiation emitted into space by the surface and atmosphere. In general clouds block incoming solar radiation, reflecting it back out to space, causing a net cooling of the Earth. On the other hand, these clouds also absorb the outgoing longwave radiation, which results in the Earth’s inability to release absorbed energy into space, causing a net warming effect. The net result of these two events determines the warming or cooling impact that clouds will have on the planet. The optical thickness, altitude, phase, and composition of the cloud all play a crucial role in determining its effectiveness at reflecting shortwave or trapping longwave radiation. While there are many factors that contribute to a cloud’s influence on the global energy budget, this paper aims to look primarily at optical depth to assess the impact that high altitude, optically thin “subvisual” cirrus clouds have on upwelling infrared radiation using a new multi-satellite collocation technique.

Before further examining subvisual cirrus clouds, a definition must be applied to clarify the ambiguous term “subvisual.” This term must not simply mean that it is not visible to the naked eye since many factors contribute to the ability to observe the cloud. These factors include viewing angle, illumination, color, contrast and molecular scattering to either grant or eliminate the ability to perceive the cloud. Subvisual cirrus clouds are defined as having an optical depth of 0.03 or smaller in the visual portion of the spectrum. For thin cirrus, optical values fall between 0.03 and 0.3, while opaque cirrostratus clouds have optical depth values reaching 3.0 within the visible spectrum. This does not necessarily mean that subvisual cirrus clouds are geometrically thin, Sassen and Cho (1992) observed subvisual and
“threshold-visible” cirrus clouds as thick as 4 kilometers. They can also have a spatial scale of a few hundred kilometers.

Subvisual cirrus clouds can form naturally either by outflow from a cumulonimbus cloud or through nucleation. Cumulonimbus clouds bring warm moist air into the upper troposphere where liquid droplets freeze into ice crystals. Wind shear can cause a top layer of clouds to travel outward from the center of a cumulonimbus anvil. The farther away the cloud ventures from the center, the thinner the clouds becomes, eventually leading to a subvisual cirrus cloud. During this process, ice crystals with a radius greater than 10-20 µm, will precipitate out of the cloud within a few hours. The thickness of the cloud has been estimated to decrease by an order of magnitude per day. Sometimes subvisual cirrus clouds are not associated with large convective anvils, these clouds can develop from nucleation, in which a humid layer rises up through “slow, synoptic-scale uplift or shear-driven turbulent mixing” into the cold upper troposphere region, causing ice crystals to form. Uplifting can be caused by continental scale bulges, larger scale convective systems, or through elevating above “stratiform regions of mesoscale convective systems.”

Part of the subvisual family, is aircraft contrails. Contrails are formed from aircraft that expel exhaust fumes with high relative humidity values into the upper tropopause. Thin clouds develop when the humid fumes cause the ambient air to reach or exceed liquid saturation levels. Water droplets form on the soot and sulfuric acid particles found within the exhaust and then freeze almost immediately into ice particles, due to the cold temperatures in this region. As a result, contrails are often called “seeds” for the formation of subvisual cirrus clouds. When comparing and contrasting anthropogenic subvisual cirrus clouds formed from contrails versus natural methods, it has been noted that both have similar particle size distribution, however, natural subvisual cirrus clouds have a higher concentration of particles. The spacing of particles can also differ; natural subvisual cirrus clouds have a more homogenous distribution, while contrails have a cluster type distribution, showing a lack of mixing with the surrounding environment. Particle distribution and concentration would alter the radiative properties of these two distinctive formation processes. It is not definitively clear how these variations in particle characteristics affect the radiative properties of these anthropogenic cirrus clouds.

Subvisual cirrus clouds dissipate at different rates depending on ice precipitation, and how absorbed energy is utilized within the cloud. Clearly if ice crystal precipitation dominates, the cloud will dissipate; however, if the ice crystals have a radius of 10µm or less, then the crystals will remain suspended and the cloud may persist for several days. If radiative energy is added, vertical mixing or a local temperature change can occur. If the energy absorbed results in heating variations, vertical mixing can occur, and the cloud becomes unstable; as a result, the cloud might cease to exist within a few hours. Since subvisual cirrus clouds are extremely thin it is likely that the properties of the clouds are uniform and therefore the heating rate should be constant. On the other hand the added energy may cause a local uniform temperature change, since warm air rises, the altitude of the cloud will increase. Increasing temperatures would melt ice crystals, increase molecular collisions and cause instability in the cloud. Another heat source capable of affecting the persistence of subvisual cirrus clouds comes from the energy carried by planetary and gravity waves as they travel through the atmosphere. In the absence of heat sources, cirrus clouds are capable of persisting for days in the cold tropopause region until they are advected out of the region and heated by subsidence.

Subvisual cirrus clouds are observed in the upper troposphere, usually in the top 2-km, where temperatures range between –60 and –70°C near the tropopause. These clouds are found most often in the tropics due to the exceptionally low temperature in the upper troposphere. In the tropics, water vapor concentrations are high, resulting in the formation of a substantial number of ice crystals. Due to the low temperatures, the droplets freeze quickly preventing continual droplet growth. In the tropics, ice nucleation occurs when super saturation values reach only 8%, allowing crystals to form sooner than in the midlatitude region. The end result reveals an abundance of ice crystals; however, they are minute in size, preventing precipitation, causing more persistent clouds. Subvisual cirrus clouds can also be found in the mid-latitudes; however, environmental circumstances are not ideal. Here, water vapor concentrations are lower, upper troposphere temperatures are warmer, and super saturation values are higher, 21% for nucleation. If conditions allow ice crystals to form, water vapor will aggregate quickly. Since temperatures are warmer the crystals take longer to form allowing
the droplets to reach larger sizes before freezing. These larger ice crystals will precipitate and the cloud will dissipate. These clouds have a tendency to vanish around midday. \(^6\) Given these conditions it seems logical that subvisual cirrus clouds are found more often in the tropics. The tropics have the cold upper troposphere temperatures, high quantities of ice formation and ideal conditions that prevents quick dissipation.

The greatest frequency of cirrus clouds is found in the Western Pacific during the winter months when the upper troposphere temperatures reach their lowest point. \(^7\) Two other areas of maximum cirrus frequency are Africa and South America. \(^1,3\) Variations in placement between studies have occurred depending on the time period of collection and the instrument employed. Subvisual cirrus have been estimated at greater than 40\% by Wang (1996) using SAGE, a solar occultation instrument, to 4-12\% in the morning and evening respectively by Dessler (2006) using a laser altimeter, GLAS. \(^3,16\) Within Dessler’s (2006) investigation, he examines the outgoing longwave radiation (OLR) in Wm\(^{-2}\) on a global basis in connection with NOAA’s Interpolated OLR data set. Low OLR values suggest a high rate of convective activity. The minimum OLR values are witnessed in Africa and South America where significant “continental convection” occurs, and there is also a broad minimum OLR value over the Western Pacific, site of “oceanic convection.” As OLR values decrease, there is a general upward trend for tropopause-level thin cirrus, at a constant temperature; thereby, enforcing the connection that convective activity plays a role in these upper troposphere clouds. Reasons form around convection causing temperature perturbations from gravity waves or the direct insertion of ice into the upper atmosphere. \(^3\) Despite small variations in position, the highest frequency of subvisual cirrus clouds appears to be constant.

When examining the effects that optical thickness, altitude, and composition, have on the absorption and scattering of radiation; it may be easier to examine the difference between how low-level water clouds and high-level ice clouds each impact radiation separately to better understand the outcome of the global energy budget as a whole. Let’s first examine the effects that solar and terrestrial radiation experience when encountering a low altitude cloud. These clouds are composed of water droplets, since droplets are fairly uniform in size and shape, the effect that these clouds have on radiation is reasonably understood. The higher the cloud optical depth, the more efficient they are at reflecting solar radiation back out to space, increasing the planet’s albedo. \(^6\) Optical depths are generally larger for clouds at lower altitudes, most likely due to the high quantities of water vapor and particles lower in the atmosphere. \(^10\) Because clouds at a low altitude possess temperatures close to the Earth’s surface temperature, they re-radiate the absorbed surface energy at nearly the same magnitudes as the surface emission and therefore have little impact on the greenhouse effect. They are inefficient at absorbing the upwelling surface radiation and so do not significantly contribute to a greenhouse effect. The end result is that low-level clouds work to cool the Earth. When looking at high altitude ice clouds, many complicating factors allow these clouds to either cool or warm the planet depending on a variety of issues. Uncertainty in this area comes from questions concerning the scattering properties of ice clouds, due to the variety of shapes and sizes of ice crystals that make up cirrus clouds. \(^8\) Large ice crystals have a tendency to scatter light in the forward direction while smaller ice crystals scatter light more equally in all directions. These clouds do not cause substantial disruption to incoming shortwave radiation. \(^10\) However, cirrus clouds have a strong greenhouse effect since the small ice particles have been shown to exhibit strong absorption features in the 8-12 µm window, which is characteristic to the longwave radiation leaving the earth. \(^11\) One study revealed that they could absorb up to fifty-percent of the upwelling longwave radiation. High altitude clouds are much colder than the Earth’s surface; as a result, the energy re-radiated from the cloud is at a much lower temperature compared to the surface or low clouds. \(^15\) Longwave absorption, in many cases can outweigh the albedo effect, causing a warming effect on the planetary temperatures. \(^8\)

Studies conducted on subvisual cirrus clouds have been mainly examined in the “warm pool” region, the region located in the western Pacific. The impact of these clouds has been seen to be largely dependent on optical depth. The main guideline appears to be: the thinner the cloud the less impact on the radiative energy. However, it seems to be agreed that the effects should not be disregarded. Iwasaki (2004) found that the radiative impact of SVC has been estimated at about 1 Wm\(^{-2}\). \(^6\) Jensen estimated that these clouds can cause heating rates of a few Kelvins per day. \(^7\) Results reveal radiative impact values as high as 4-5 Wm\(^{-2}\) for subvisual cirrus. \(^10\)
More specifically Heymsfield stated that “thin” cirrus absorbed 11 Wm\(^{-2}\) of long wave radiation and reflect 6 Wm\(^{-2}\) of short-wave radiation in the Tropics, resulting in an effect of 5 Wm\(^{-2}\).

**Methodology**

There have been numerous studies over the last few decades that look at subvisual cirrus clouds, each using different methods of technology. Instruments utilized have included MODIS Airborne Simulator (MAS), Geoscience Laser Altimeter (GLAS), High Resolution Interferometer Sounder (HIS) and Cloud and aerosol LIDAR system (CLS), just to name a few. With advancements in technology our ability to analyze clouds has enhanced. In April 1998, an article was published in Geophysical Research Letters entitled, “Infrared Spectral Absorption of Nearly Invisible Cirrus Clouds” by W.L Smith, S. Ackerman and associates that focused specifically at subvisual cirrus clouds, to examine their radiative properties formed from both natural and anthropogenic causes. This study used MAS, HIS, and CLS to illustrate the impact that these nearly invisible cirrus clouds can have on upwelling radiation absorption. The HIS Spectra results demonstrated that a nearly invisible layer of ice, located within the tropopause, exhibits strong spectral characteristics between 10 and 12 µm, the region that contributes greatest to the earth’s surface radiative cooling to space. The amount of infrared absorption was then calculated through a series of radiative transfer equations given the properties of the cloud from CLS. The study concluded that the subvisual layer of ice crystals that make up these cirrus clouds have little effect on incoming solar radiation but have a considerable impact on the long-wave absorption of terrestrial radiation. This result suggests that a strong ‘greenhouse warming’ effect could occur as small ice crystals accumulate near the tropopause from both natural and anthropogenic causes.

This study takes another look at the Smith (1998) using updated remote sensing capabilities. Since subvisual cirrus clouds have an extensive spectral variation of infrared absorption across the 8-12 micron window, broadband satellite radiometers have had difficulty detecting these clouds. For this study a hyper-spectral sounding instrument, AIRS (Atmospheric Infrared Sounder), with 2378 spectral channels, is to be used to detect the impact of the infrared absorption. To aid in the identification of the subvisual cirrus cloud, CALIPSO, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation, satellite combines an active lidar and a passive infrared and visible imager, which allows illustrations of aerosols and clouds vertically within the atmosphere. Since CALIPSO only observes along the sub-orbital track, MODIS, Moderate resolution Imaging Spectroradiometer, cloud mask product is advantageous when examining field of views surrounding the CALIPSO track, verifying that the clear radiance values are not being influenced by a cloud or cloudy radiance values are truly cloudy surrounding the orbit track. AIRS, CALIPSO and MODIS are part of the A-train, a series of five polar orbiting satellites that travel in a line at 705 km above the Earth to gather sun-synchronous data to achieve a complete picture of the atmosphere and cloud properties CALIPSO flies less than two minutes behind AIRS and MODIS, which are both located on the Aqua satellite. Each satellite in the A-train completes 14.55 orbits per day, and is separated by 24.7 degrees latitude at a speed of over 15,000 miles an hour. They have a repeat cycle every 16 days. These three instruments will allow information to be collected on the frequency of subvisual cirrus clouds as a function of geographical location. A new technique will be applied to identify the subvisual cirrus clouds and determine the effect that they have on upwelling infrared radiation. Spectral distributions can be made for emissivity, transmissivity, and optical depth in order to assess radiative impact of subvisual cirrus clouds.

The first task involved in this new technique for identifying subvisual cirrus clouds is to gather collocated data between the three satellites, AIRS, CALIPSO, and MODIS. To accomplish this crucial task, two FORTRAN programs written by Fred Nagle and Bob Holz from the University of Wisconsin-Madison are...
utilized to identify CALIPSO and MODIS points located within each AIRS field of view (FOV). Both programs use AIRS as the core footprint, since it has the lowest resolution. The footprint is broken down into 90 FOV across the longitudinal track and 135 FOV along the latitudinal track. The first program is the CALIPSO-AIRS collocation program, which identifies the CALIPSO shots located within each AIRS FOV. There can be up to 128 CALIPSO shots within each FOV; however, the real number lies less than 80 shots per FOV. Since CALIPSO measures along a sub-orbital track every latitudinal track is utilized; however, the longitudinal track only varies between about two of ninety longitudinal FOV, usually located within the low 30s. The second program is the MODIS-AIRS collocation program, which identifies the collocated MODIS shot numbers within the AIRS footprint. In this case there can be up to 300 MODIS shots within each AIRS FOV. This program only identifies those MODIS shots with a weight of one, meaning the MODIS shot lies 100% within the AIRS FOV. The MODIS and CALIPSO shots are now identified within each AIRS FOV; these points now correspond to data, which is representative of the other instruments. Figure 1, on the previous page, shows a summary of data placement for each instrument in the collocation program. Figures 2 and 3 illustrate the AIRS brightness temperature image and CALIPSO attenuated backscatter image respectively, for the February 23, 2007, case that will be used in this analysis of the new technique. Brightness temperature is a measure of radiation in terms of temperature that a black body would emit at that wavelength. The arrow in Figure 2, represents the approximate position of the CALIPSO track as it passes through the AIRS data set.

When examining the results of the CALIPSO-AIRS collocation program, it is noted that there are numerous CALIPSO values corresponding to each shot number for only one set of AIRS values. As a result, CALIPSO data must be averaged to correspond to the overall image that AIRS is observing. CALIPSO values for latitude, longitude, time in UTC (Universal Time Coordinated), and each of ten cloud height layers are averaged for each AIRS FOV. In this study cloud height refers to the CALIPSO cloud top height, which is used in the identification of cirrus clouds.

The next step in the process involves the identification of the cloudy FOV. For this study the minimum CALIPSO cloud height average for an AIRS FOV is 15 kilometers. Due to the possibilities of up to ten cloud layers, limitations are imposed to exclude multilevel cloud layers, especially those containing midlevel water clouds, which can greatly influence the infrared radiance values. Cases are only applied if the first cloud layer is above 15 kilometers, the second layer is either absent of is less than 3 kilometers and...
middle cloud layers are absent. If a case does not fall within these criteria, then it is rejected and omitted from the analysis.

Since CALIPSO measures using a lidar that cuts through the AIRS FOV, there is uncertainty about the clear and cloudy conditions within the AIRS FOV but not along the CALIPSO track. MODIS cloud mask data is acquired to verify a cloudy scene. From the MODIS-AIRS collocation program, the MODIS shots located within the AIRS FOV are known; as a result, the cloud mask product is simple to utilize. After averaging the cloud mask values, a solution can be obtained for the percent cloudy and the percent clear for each FOV. Since subvisual cirrus clouds are so thin, this study examines FOV with a probability of cloudy greater than or equal to 10%. Figure 4 on the previous page shows the cloud mask product for one AIRS FOV. These results produce a picture of the scene that is being viewed by AIRS and incorporated into the radiance values.

In order to compare clear and cloudy FOV, the next step involves locating the clear FOV. First is an examination of AIRS FOV in a 13x13 block of FOVs surrounding the cloudy FOV. The MODIS cloud mask is utilized again, being applied to this box surrounding the cloudy FOV. The surrounding FOV is labeled as clear if the probability of cloudy is less than 10%. After gathering all of the clear FOV within the 13x13 box, radiance values are inverse distance from the cloudy FOV weighted averaged to obtain representative clear sky radiance for the region possessing the cloudy FOV. If a clear FOV is not found within the 13 x 13 surrounding AIRS FOVs, the cloudy FOV is discarded for the cloud optical property determination

After identifying cloudy and clear FOV, infrared spectra radiance values can be obtained from AIRS. Due to the fact that atmospheric absorption above the cloud is not accounted for here in the cloud property determination process, only radiance values void of above cloud atmospheric contributions as observed within the atmospheric windows between 800 and 1000 cm\(^{-1}\) and between 1100 and 1130 cm\(^{-1}\) are considered here. Measurement noise also exists within the AIRS spectrum; as a result, a three point filtering system is employed. The filter involves comparing the differences from three consecutive spectral radiance points \((A\rightarrow B, B\rightarrow C, A\rightarrow C)\). The minimum of these three values is identified as \(\text{Crit}\). It was decided that acceptable values would be within three times the minimum value, defined as \(\text{Crit}\). If two spectral differences are greater than the \(\text{Crit}\) value then the common point between then is considered a “bad” point and eliminated from the data. The equations below describe the filtering process used:

\[
\begin{align*}
X_1 &= |\varepsilon(i)-\varepsilon(i-1)| \\
X_2 &= |\varepsilon(i)-\varepsilon(i+1)| \\
X_3 &= |\varepsilon(i+1)-\varepsilon(i-1)| \\
\text{Crit}\ &= \text{minimum} (X_1, X_2, X_3) \\
\text{Crit}\ &= 3(\text{Crit}) \\
\text{IF} \ (X_1>\text{Crit} \text{ and } X_2>\text{Crit}) \text{ Then } \varepsilon(i)=\text{BAD} \\
\text{IF} \ (X_2>\text{Crit} \text{ and } X_3>\text{Crit}) \text{ Then } \varepsilon(i+1)=\text{BAD} \\
\text{IF} \ (X_3>\text{Crit} \text{ and } X_1>\text{Crit}) \text{ Then } \varepsilon(i-1)=\text{BAD}
\end{align*}
\]

This filtering process eliminates the majority of outliers within the radiance measurement data set.

The last piece of information needed to determine emissivity is the “blackbody” cloud radiance defined using Planck’s law. The Planck equation can be written:

\[
B(\nu, T_{cl}) = \frac{c_1 \nu^3}{e^{c_2 \nu T_{cl}} - 1}
\]

\[
c_1 = 1.191066 \times 10^{-5}\ (\text{mW/m}^2/\text{ster/cm}^4)
\]

\[
c_2 = 1.438833\ (\text{cm deg K})
\]

Where \(\nu\) is the frequency (i.e., wavenumber) of the AIRS radiance measurements and \(T_{cl}\) is the temperature of the cloud. Atmospheric temperature-pressure profile data is acquired using constant pressure level analyses performed by the National Centers for Environmental Prediction (NCEP), which performs these analyses every six hours. A series of interpolations are needed to acquire the cloud temperature for each given case. Bi-linear interpolation with respect to latitude and longitude, followed by linear interpolations with respect to time and altitude are performed. In order to perform the linear interpolation with respect to altitude, the hypsometric equation must be used to define the
geopotential height of the pressure levels used for the atmospheric temperature analyses. The hypsometric equation is:

\[ Z = \text{const} \times \sum \left[ 0.5 \times (T(i+1)+T(i)) \times [\ln(P(i+1))-\ln(P(i))] \right] \]

where the sum is taken from \( i=1,N_{\text{levels}}-1 \), \( T \) is temperature in Kelvins, \( P \) is pressure in millibars and \( Z \) is the altitude in meters. From the altitude versus pressure relationship, a linear interpolation of atmospheric temperature can be performed to find the temperature of the atmosphere at the height of the cloud defined from the CALIPSO observations.

\[ T(z_{\text{cld}}) = \frac{T(Z_u)x(Z_{\text{cld}}-Z_l)+T(Z_l)x(Z_{\text{cld}}-Z_u)}{(2Z_{\text{cld}}-Z_u-Z_l)}. \]

Finally the temperature of the cloud has been found so that it can be entered into Planck’s equation, which describes the spectral radiance emitted by a black body at a given temperature and frequency.

Finally there is enough information to calculate effective spectral cloud emissivity values using the equations:

\[ R_{\text{meas}} = \varepsilon^* \text{cld} R_{\text{BOVC}} + (1- \varepsilon^* \text{cld}) R_{\text{clr}} \]

\[ R_{\text{BOVC}} = B_{\nu}(T_{\text{cld}}) \]

\[ \varepsilon^* \text{cld}(\nu) = \frac{[R_{\text{meas}}(\nu)-R_{\text{clr}}(\nu)]/[B_{\nu}(T_{\text{cld}})-R_{\text{clr}}(\nu)]}{B_{\nu}(T_{\text{cld}})} \]

where the effective cloud emissivity is the product of the true emissivity of the cloud and the fractional cloud cover, \( N \) (i.e., \( \varepsilon^* = N \varepsilon \)). In the above equations \( R_{\text{meas}} \) and \( R_{\text{clr}} \) are the spectral radiance values that correspond to the cloudy and clear FOV respectively, and \( B_{\nu}(T_{\text{cld}}) \) is the Planck radiance corresponding to the cloud temperature. This equation now fulfills the definition for emissivity, the ratio of radiance emitted by a cloud at a temperature to the radiance emitted by a blackbody obeying Planck’s law. These values will now describe the clouds ability to absorb and radiate energy. This information will lead to solutions for effective transmissivity (\( \tau^* \)) and optical depth \( \delta(\nu) \) through the equations:

\[ \tau^* = 1-\varepsilon^* = e^{-\delta} \]

\[ \delta(\nu) = \ln \tau(\nu) = \ln[1-\varepsilon^*(\nu)] \]

The effective transmissivity is the fraction relating the total radiance exiting the cloud layer, minus the radiance emitted by the cloud, relative to the radiance entering the cloud layer. Finally optical depth describes the cumulative attenuation of radiation as it passed thorough the cloud layer. The definition of subvisual cirrus clouds is a visible optical depth of less than 0.03. A visible optical depth of 0.03 generally corresponds to an infrared optical depth at the 10 \( \mu \)m wavelength (i.e., \( \nu = 1000 \text{ cm}^{-1} \)) optical depth close to a value of 0.1. In any case, daytime MODIS visible optical depth

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{spectral_emissivity.png}
\caption{Spectral Emissivity}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{spectral_transmissivity.png}
\caption{Spectral Transmissivity}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{optical_depth.png}
\caption{Optical Depth}
\end{figure}

Figures 5-7: Show the spectral solutions for effective emissivity, transmissivity and optical depth respectively for the given case study.
estimates will be used to classify the AIRS FOVs, which possess subvisual cirrus clouds as opposed to visible high-level cirrus clouds.

Results and Conclusions

The goal of this research is to develop a new technique for identifying subvisual cirrus clouds and produce spectral values for emissivity, transmissivity and optical depth to assess the impact that these cloud have on upwelling infrared radiation. Preliminary results, for one example AIRS granule, are shown plotted for the two atmospheric windows, located between 800 and 1000 cm\(^{-1}\) and between 1100 and 1130 cm\(^{-1}\). Figure 5-7 illustrate the results of the spectral, emissivity, transmissivity and optical depth respectively. The optical depth values all fall within the 0 and 0.1 values expected for subvisual cirrus clouds at the infrared wavelength of 10 $\mu$m. Figure 1, shows that in this case the cloud is absorbing less than ten-percent of the upwelling infrared radiation within the AIRS cloudy FOV, while transmitting the remaining radiation to space. This result is contrary to the case shown by Smith et al.,\(^{15}\) which showed a large increase in infrared cloud emissivity between 10 $\mu$m (i.e., 1000 cm\(^{-1}\)) and 12 $\mu$m (830 cm\(^{-1}\)). However, this is only a single example. The statistics for a large number of cloud situations over the entire globe, and covering all seasons, must be obtained to define the role of subvisual cirrus clouds on the Earth’s heat budget.

Future Work

The goal of this paper is to describe a new technique for determining how subvisual cirrus clouds absorb and transmit upwelling infrared radiation. The next step involves the application of this technique on a global scale to identify the frequency of subvisual cirrus clouds and their role on the global heat budget. In order to determine the role of subvisual cirrus clouds on the global heat budget, the infrared optical depth spectra determined by the technique outlined here, will be classified with respect to different visible optical depth categories. The visible optical depth will be defined from daytime AIRS co-located MODIS observations. The subvisual category, defined as visual optical depth values of less than 0.03, will represent the frequency of subvisual cirrus clouds. Once a global frequency of subvisual cirrus clouds can be determined, work can commence on an analysis of the infrared spectral optical depth determinations to define the impact of these clouds have of the global energy budget.

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