

Inferring Global Cloud Cover Properties and Trends with three decades of HIRS Data

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Abstract

A record of cloud occurrence in the upper troposphere has been extracted from NOAA/HIRS polar orbiting satellite data from 1995 to 2009. The HIRS sensor has flown on fifteen satellites from TIROS-N through NOAA-19 and Metop-A covering 30 years. A cloud record that used the CO₂ slicing method to infer cloud amount and height from 1979 to 2001 was published in Wylie et al (2005). This paper extends that record, making algorithm improvements and mitigating sensor to sensor calibration differences. Trends in cloud cover and high cloud frequency were found to be small but significant in these data.

1. Introduction

Determination of global cloud cover relies on a variety of sensors to contribute observations of different cloud types. The International Satellite Cloud Climatology Program (ISCCP) has collected the largest global cloud data set using visible and infrared measurements from the international suite of weather satellites. As a supplement for enhanced cirrus detection, multi-spectral infrared measurements from the NOAA polar orbiting High Resolution Infrared Radiometer Sounders (HIRS) have been used. Using regions of the infrared spectrum with differing sensitivity to atmospheric carbon dioxide, the HIRS measurements probe the atmosphere to different depths and reveal thin ice clouds high in the atmosphere. Cloud-top pressure (CTP) and cloud effective emissivity (CEE) (cloud fraction multiplied by cloud emissivity) are derived using the 15- μ m channels with the CO₂ slicing approach, proven to be effective for characterizing high-level transmissive ice clouds. Clouds are classified as high (CTP < 440 hPa), mid (440 < CTP < 680 hPa), and low (CTP > 680 hPa) as well as thin (CEE < 0.5), thick 0.5 < CEE < 0.95) and opaque (CEE > 0.95). Overall since 1979, HIRS measurements have found clouds most frequently in two locations: (1) the Inter-Tropical Convergence Zone (ITCZ) in the deep tropics where trade winds converge and (2) the middle to high latitude storm belts where low pressure systems and their fronts occur. In between are latitudes with fewer clouds called sub-tropical deserts over land and sub-tropical high pressure systems over oceans.

When cloud products from the HIRS/3 sensors (NOAA-15, -16, and -17) were found to be inconsistent with those from HIRS/2 sensors, an investigation of potential causes and mitigation strategies was undertaken. Sensor to sensor differences in the

evolution from HIRS/2 to HIRS/3 have introduced some spectral band differences; accurate determination of spectral response functions remains a major challenge that is being addressed more recently with inter-comparison to high spectral resolution sensors.

2. Reprocessing HIRS Data

HIRS data reprocessing is underway in order to mitigate several known issues affecting sensor to sensor radiance calibration and calculation of clear sky radiances. These include (a) comparing HIRS with high spectral resolution sensors (e.g. Advanced Infrared Sounder - AIRS, Infrared Atmospheric Sounding Interferometer - IASI) to create a consistent calibration back to 1995 and using HIRS simultaneous nadir overpasses before then, (b) implementing a 101 level radiative transfer model (Pressure Layer Fast Algorithm for Atmospheric Transmittances - PFAAST; Hannon et al 1996, Strow et al 2006) in the data reduction, and (c) refining radiance adjustments to mitigate calculated versus measured differences.

Based on the approach of Tobin et al. (2006), AIRS measurements were convolved to the HIRS spectral response functions and compared with collocated (within 10 minutes and 10 km) HIRS measurements. Differences were noted between HIRS on NOAA-14, -15, and -16 and AIRS in clear and cloudy scenes for CO₂ sensitive spectral bands 4 (704 cm⁻¹, 14.2 μm), 5 (715 cm⁻¹, 14.0 μm), 6 (732 cm⁻¹, 13.7 μm), and 7 (750 cm⁻¹, 13.3 μm); mitigation was accomplished with a modest shift of the HIRS spectral bands. For NOAA-14, based on 338 comparisons made with July 2003 measurements, spectral shifts of 2.0, 2.5, 3.0, and 1.5 cm⁻¹ to higher wavenumbers were suggested for bands 4, 5, 6, and 7 respectively (see Figure 1). No spectral shifts were found to be necessary for NOAA-15 and -16.

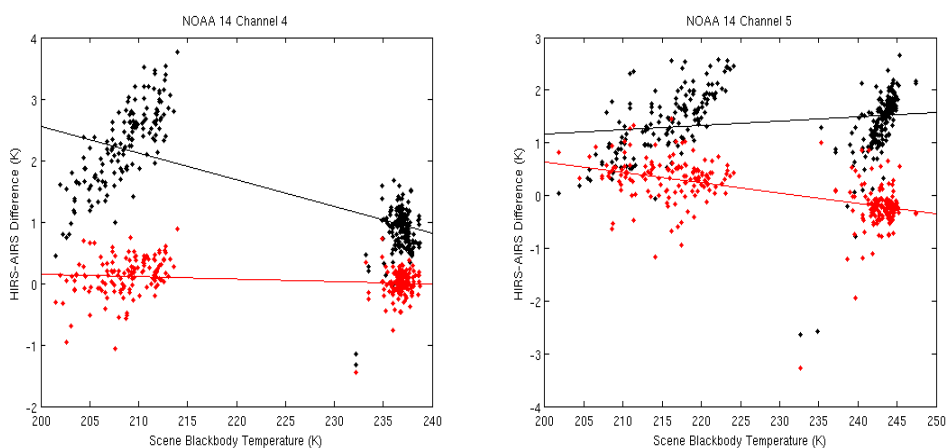


Figure 1. HIRS minus AIRS (convolved with HIRS spectral response functions, SRF) for the original (black) and shifted (red) SRF. Warm and cold scene differences are minimized for NOAA 14 HIRS CO₂ band 4 (5) at 704 cm⁻¹ (715 cm⁻¹) with a shift of 2.0 cm⁻¹ (2.5 cm⁻¹).

3. Cloud Algorithm Adjustments

Several additional adjustments to the cloud algorithm have been implemented after they were studied using the Moderate resolution Imaging Spectro-radiometer (MODIS) and the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) as a test bed (Menzel et al. 2008, Holz et al. 2008). These include (d) using CO₂ slicing for all ice and mixed phase clouds and infrared window determinations for all water clouds where cloud phase is indicated by split window considerations suggested by Heidinger and Pavolonis (2009), (e) modifying the CO₂ algorithm for top down application where the most opaque spectral band pair seeing cloud determines CTP, (f) lowering the "cloud signal" thresholds in CO₂ bands (change in radiance due to presence of cloud) to force more CO₂ slicing solutions for high thin clouds, (g) restricting CO₂ channel pair solutions to the appropriate portion of troposphere (determined by their weighting functions), (h) adjusting the ozone profile between 10 and 100 hPa to NCEP/NCAR Reanalysis (Kalnay et al. 1996) values (so that CO₂ radiances influenced by O₃ profiles are calculated more accurately), (i) using a sinusoidal varying CO₂ concentration that increases 1.5 ppm per year from 337.5 in January 1980 to 381 ppm in January 2009 with a seasonal amplitude change of ± 3 ppm, and (j) identifying stratospheric clouds when an opaque band (water vapor sensitive band 12 at 6.7 μm) is warmer than a less opaque band (window band 8 at 11 μm). All the improvements to the heritage cloud algorithm were tested on MODIS data where comparisons with CALIOP verified that the cloud product was improved.

A change in the cloud detection threshold ($[R_{\text{clear}} - R_{\text{cloud}}] > \text{NEDR threshold}$ from 1.0 to 0.5 $\text{mW m}^{-2} \text{ster}^{-1} \text{cm}$) resulted in a decrease of about 5% of low opaque clouds that are now correctly retrieved as thin high clouds.

The atmospheric CO₂ amount is adjusted daily in the radiative transfer calculations using the equation

$$\text{CO}_2(x) = [mx + a \cdot \sin(2\pi x/365)] + b$$

where $m = 1.5 \text{ ppmv} / 365$, $b = 337.5 \text{ ppmv}$, $a = 3 \text{ ppmv}$, and $x = \text{number of days since 1 January 1980}$.

Stratospheric cloud indications (when $\text{BT}_{6.7} > \text{BT}_{11}$) are located primarily in the Intertropical Convergence Zone; they are found in about 0.6 % of the HIRS observations. In this reprocessing, stratospheric clouds were added to the high opaque cloud category.

Figure 2 shows the percentage of stratospheric cloud observations for one month (July 1997) from 60 N to 60 S.

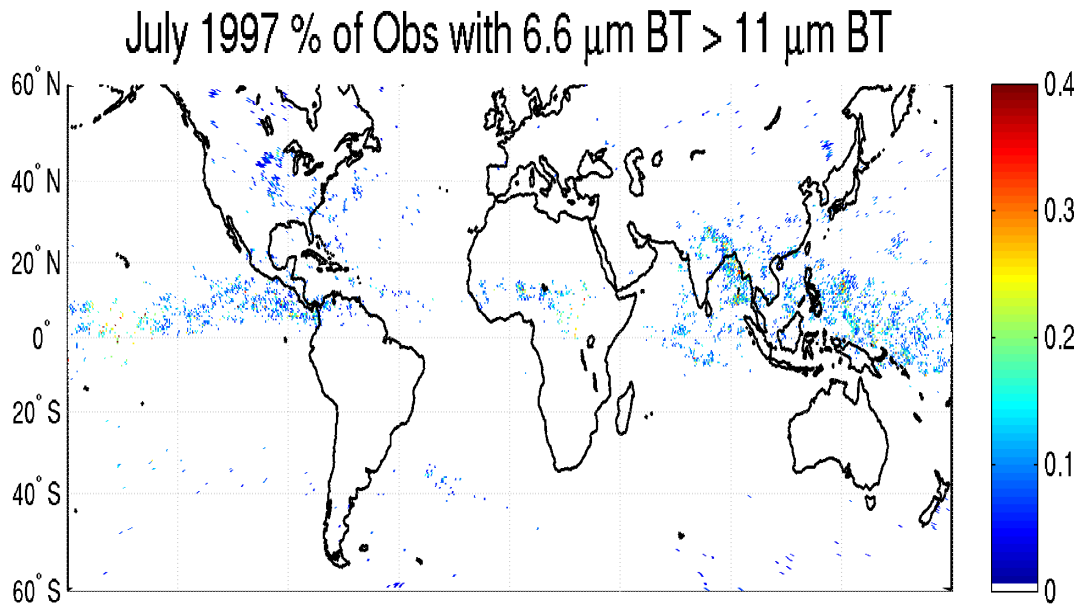


Figure 2. Percentage of HIRS observations from 60°N to 60°S in July 1997 that found the 6.6- μm spectral band warmer than the 11- μm spectral band (BT6.6 > BT11) suggesting a cloud in the stratosphere.

4. NOAA-14, -15, and -16 Cloud Observations

Cloud observations from NOAA-14 onwards were processed from 60°N to 60°S, including both ascending and descending orbits. HIRS view angles less than 32° from nadir were considered to mitigate cloud edge effects. The cloud mask was based on spatial and temporal variances of the IR window (at 11 μm) plus CO₂ screening of thin cirrus. Clear radiances were derived from forward radiance calculations with bias corrections interpolated from neighboring fields of view using the NCEP/NCAR Reanalysis. Figure 3 shows the baseline cloud trends from the work of Wylie et al. (2005), omitting their adjustments for orbit drift and CO₂ increase. The transition from HIRS/2 on NOAA-14 to HIRS/3 on NOAA-15 caused an unphysical increase in high cloud detection. The result of the algorithm changes (excluding the spectral shift) is shown in Figure 4; more high thin clouds, fewer clouds over land, and enhanced seasonal fluctuations are evident but the sensor to sensor differences have not been removed. The HIRS/2 to HIRS/3 cloud detection discontinuity was removed when the spectral band shifts for NOAA-14 HIRS/2 suggested by inter-calibration with AIRS were implemented. The result of the algorithm changes including NOAA-14 spectral shifts is shown in Figure 5; a consistent cloud trend is now evident.

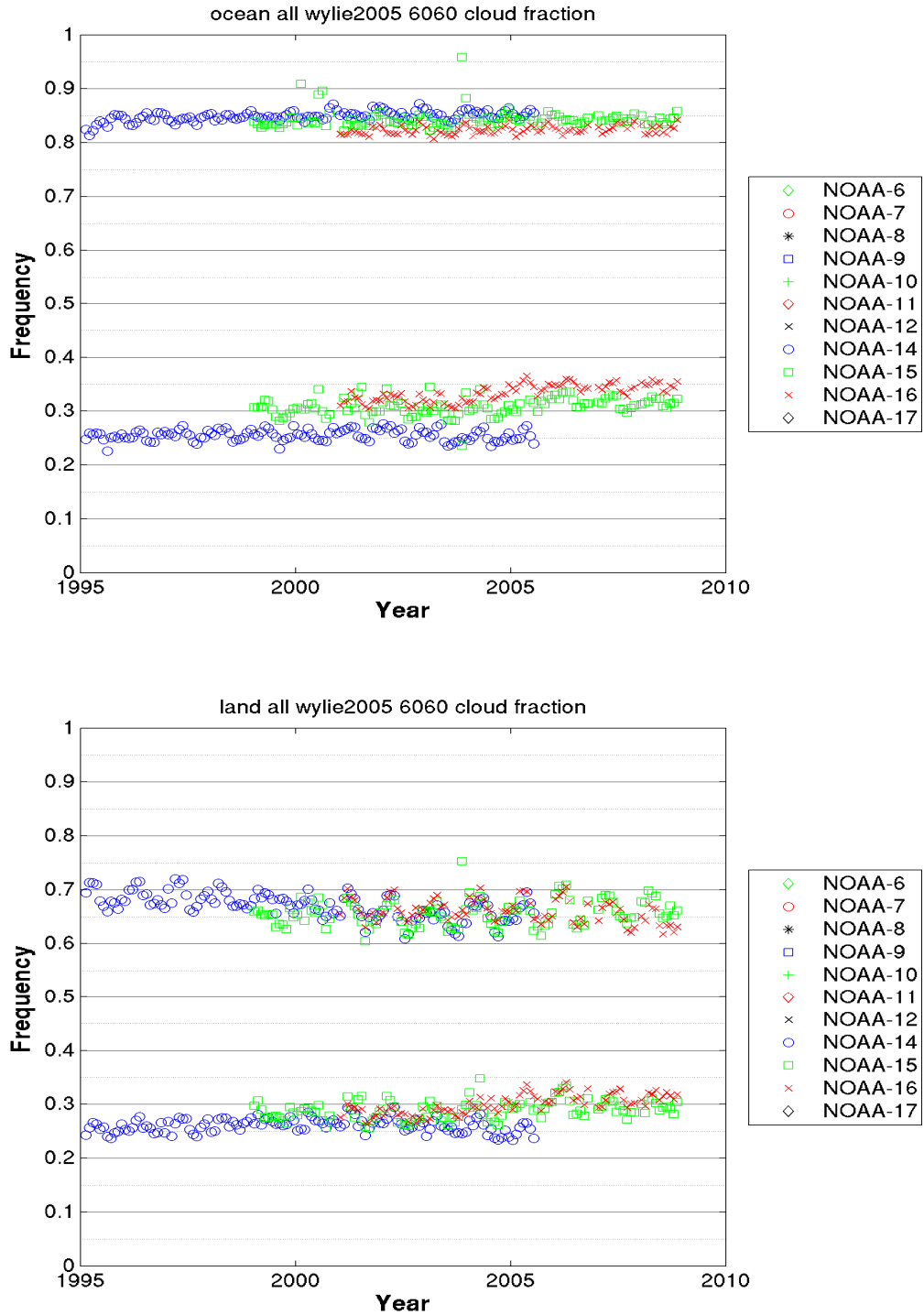


Figure 3. The percentage of HIRS observations that found “all” and “high” (CTP less than 440 hPa) clouds from 60 N to 60 S over oceans (top) and over land (bottom) since 1995 using the algorithm of Wylie et al (2005) omitting their adjustments for orbit drift and CO₂ increase.

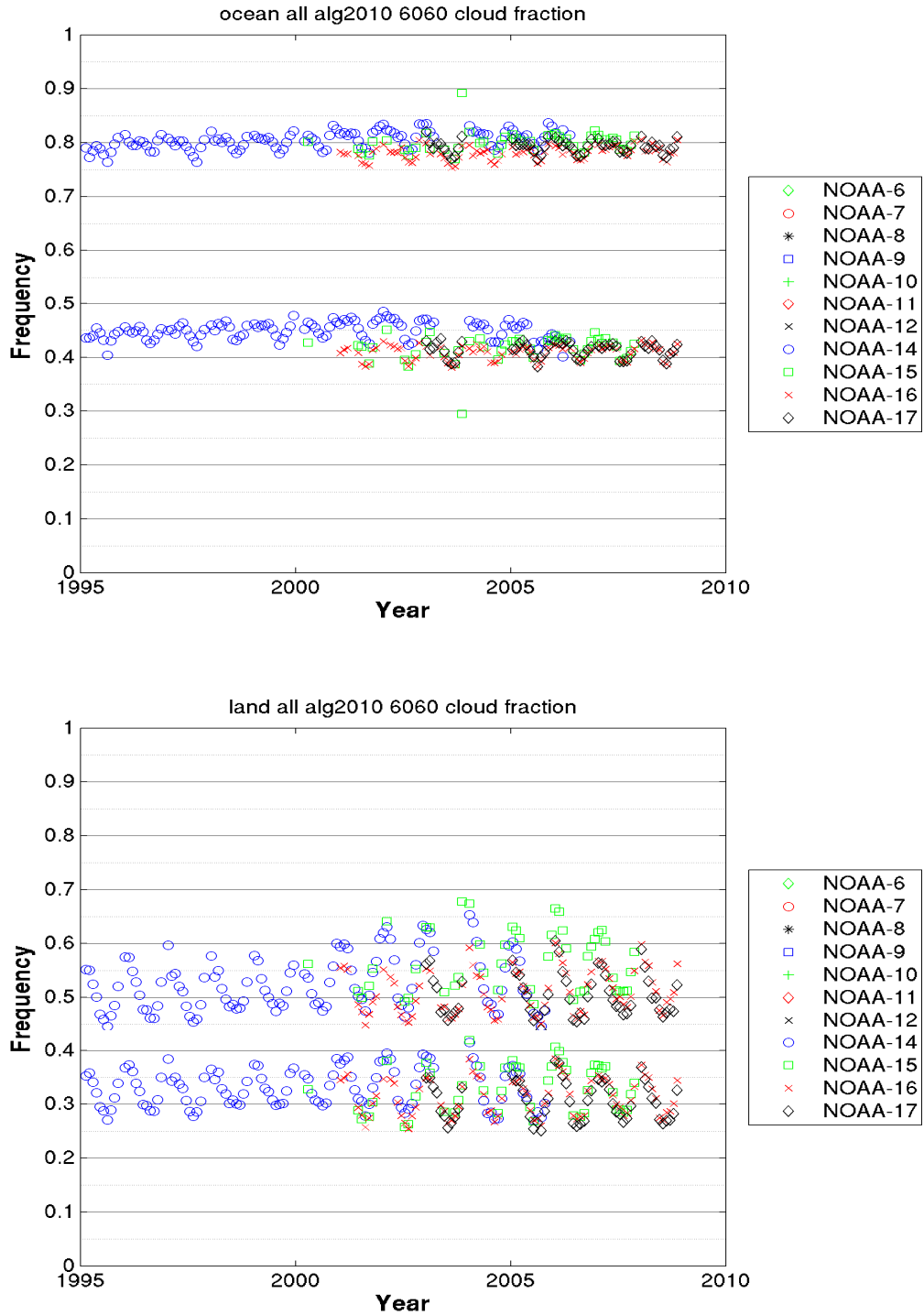


Figure 4. The percentage of HIRS observations that found “all” and “high” (CTP less than 440 hPa) clouds from 60 N to 60 S over oceans (top) and over land (bottom) since 1995 using the algorithm changes suggested by MODIS work but excluding the spectral shift.

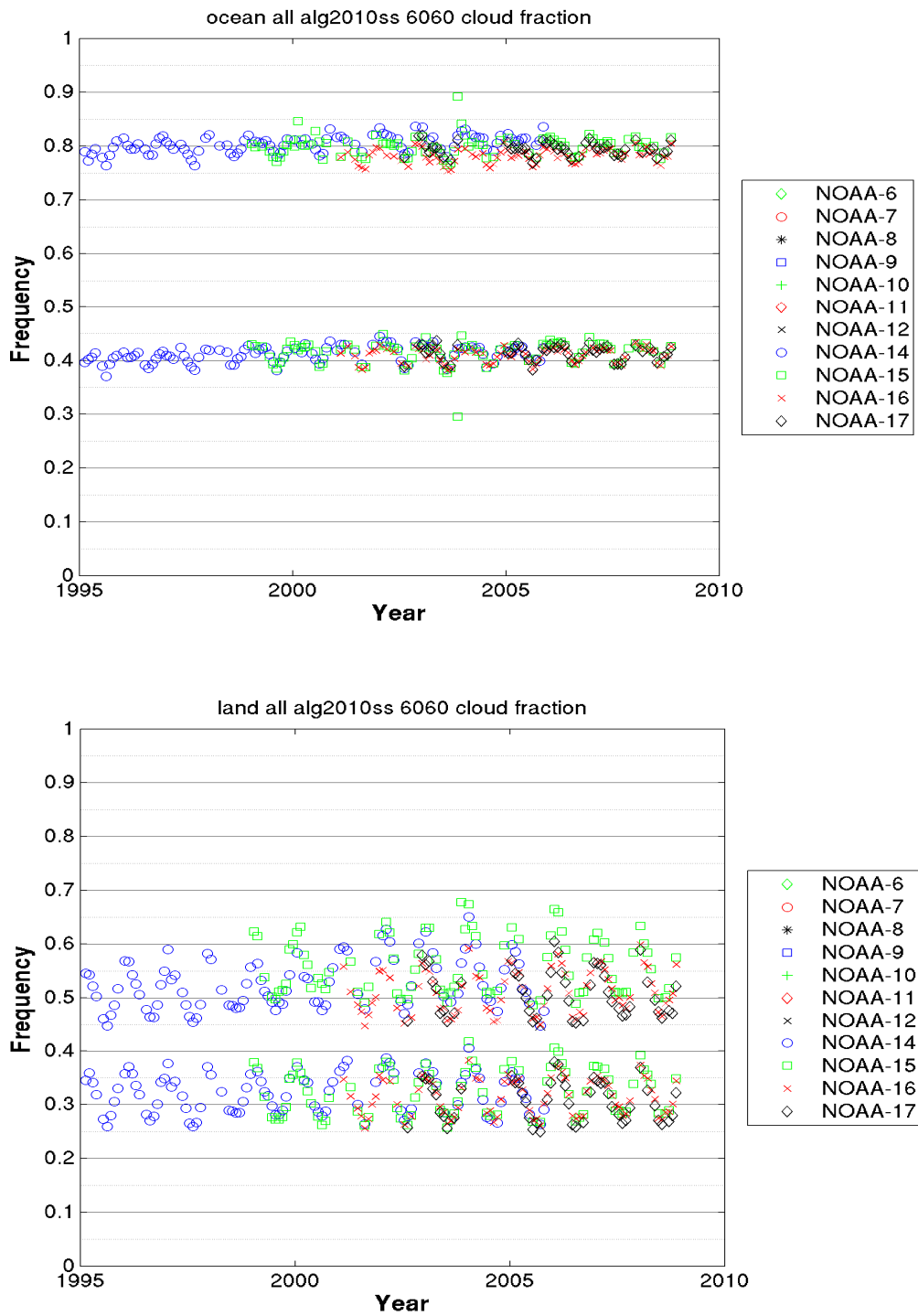


Figure 5. The percentage of HIRS observations that found “all” and “high” (CTP less than 440 hPa) clouds from 60 N to 60 S over oceans (top) and over land (bottom) since 1995 using the algorithm changes suggested by MODIS work and including the spectral shift.

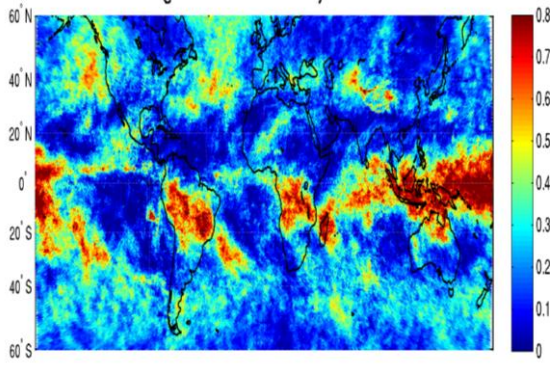
The geographical distribution of high clouds for January 2003 using the algorithm of Wylie et al. (2005) is compared to that using the adjusted algorithm including the

NOAA-14 spectral shift in Figure 6. The increased detection of high thin ice clouds in the current study is evident; this is primarily due to the reduction in the cloud signal threshold and the radiance bias adjustment incurred by the spectral shift. The major cloud patterns remain similar but there is a notable increase in southern hemisphere mid-latitude high clouds. The sensor to sensor consistency of the adjusted algorithm with spectral shift is also demonstrated in Figure 6 (bottom panel); histograms of the difference of high cloud observations from NOAA-14 to NOAA-15 show a bias for the Wylie et al. (2005) algorithm that has been removed in the adjusted algorithm with spectral shift.

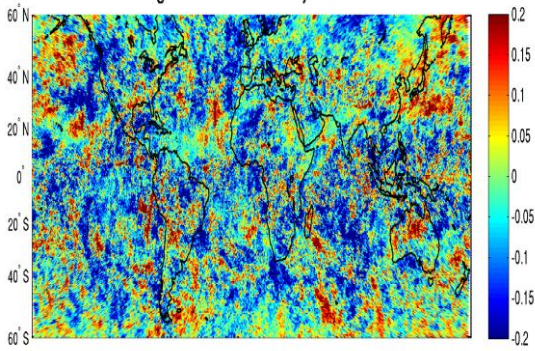
Figure 5 shows that the globally averaged frequency of cloud detection over ocean (excluding the poles where cloud detection is less certain) has stayed relatively constant at 80%; there are seasonal fluctuations of about 5% but no general trends. High clouds in the upper troposphere (above 440 hPa) are found over ocean in roughly two fifths of the HIRS measurements. A small increasing trend of ~ 0.5% per year is suggested in the winters (December-January-February - DJF) up until 2001 due in part from the orbital drift of NOAA-14; thereafter a decline by the same rate is indicated. Over land the all cloud detection is about 55%, with seasonal fluctuations of about 15%; high clouds are found in about one third of the observations with 10% seasonal fluctuations. A surprising feature of these data is that the globally averaged cloud cover has shown little change in spite of dramatic volcanic and El Nino events.

Figure 7 illustrates the change in high cloud (CTP less than 440 hPa) frequency during northern hemisphere winters (December, January, and February) from the 1990s (1995 through 1998 from NOAA-14 before it experienced considerable orbit drift) to the 2000s (2005 through 2008 from NOAA-15 and -16). There are some regions that change more than 10%. Increases are evident in the western Pacific (off the east coast of China), in the Atlantic corridor between Africa and South America, and in northern Canada. Decreases can be found in the mid Pacific, over the northern United States, off the eastern coast of Canada, over Spain, over eastern China (this has also been reported by Kaiser et al. (2009) as another effect of anthropogenic aerosol loading), and in the northern Pacific off the east coast of Russia.

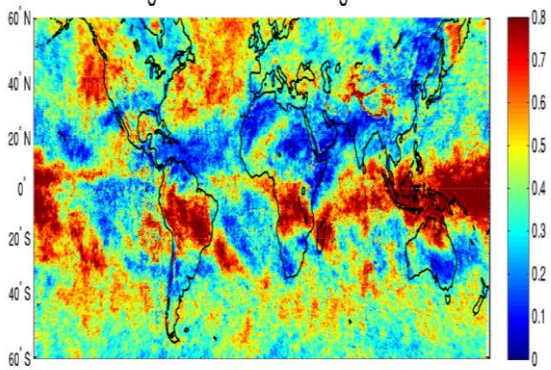
High Cloud Fraction Wylie2005



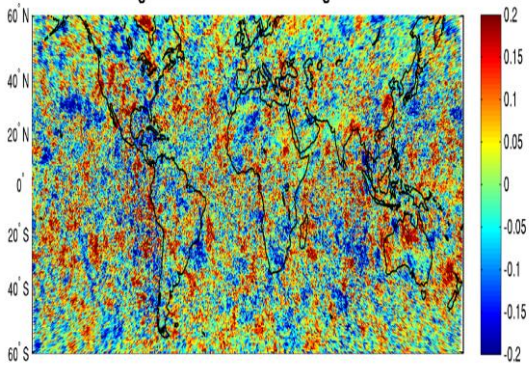
High Cloud Fraction Wylie2005



High Cloud Fraction 2010 Alg w SS



High Cloud Fraction 2010 Alg w SS



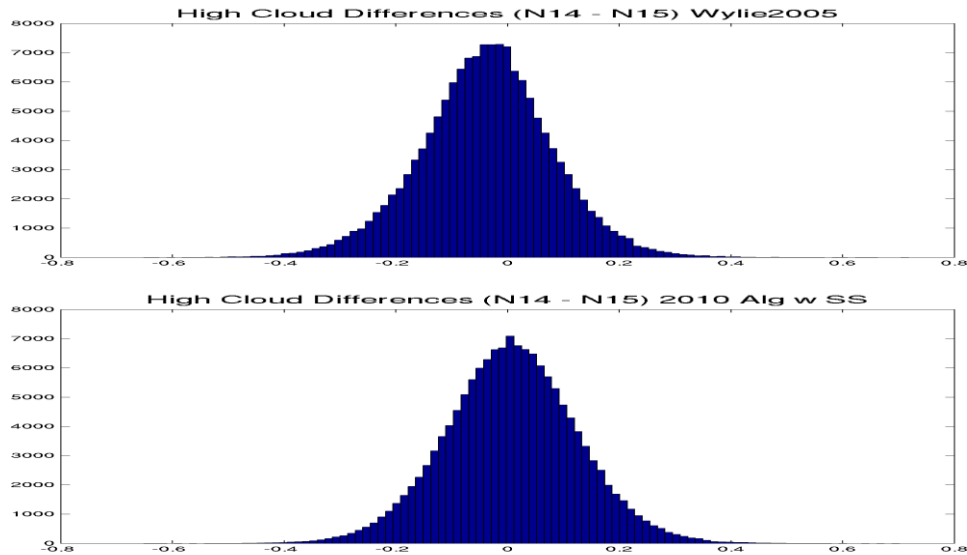


Figure 6: (Top) Frequency of high cloud detection and N14 minus N15 in January 2003 using the algorithm of Wylie et al (2005). (Middle) Same for the adjusted algorithm including N14 spectral shift; the increased detection of thin ice clouds and more uniform differences field are evident. (Bottom) Histograms of the difference of high cloud observations N14 minus N15 from January 2003 for the Wylie et al algorithm versus the adjusted algorithm with spectral shift.

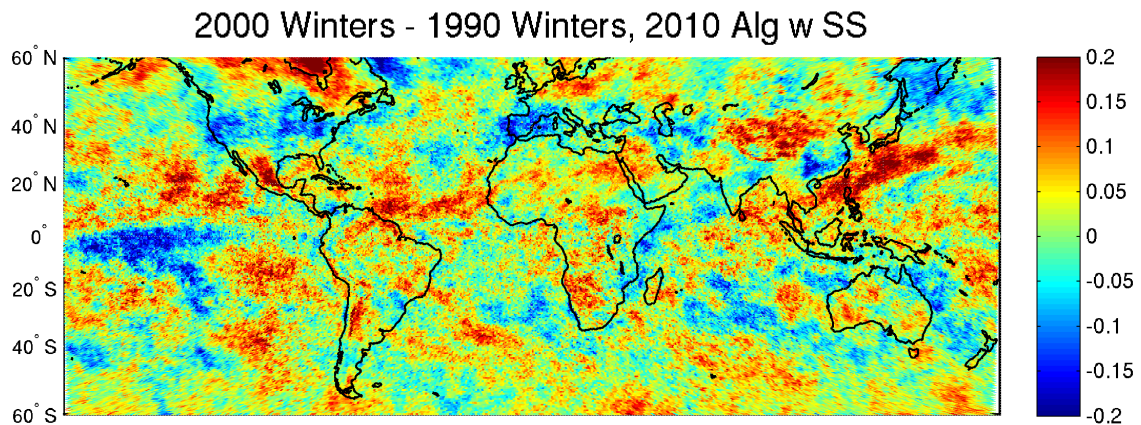


Figure 7: Ten year change in high cloud (CTP less than 440 hPa) frequency during northern hemisphere winters (December, January, and February) from the 1990s (1995 through 1998) to the 2000s (2005 through 2008).

5. Stratospheric Clouds

Stratospheric clouds usually occur as a result of convective intrusions from the troposphere into the stratosphere. Detection of stratospheric cloud patterns is often indicative of Walker circulation cells, which is caused by differences in heat distribution between ocean and land (Stubenrauch, 2006). Normally the tropical western Pacific is warm and wet with a low pressure system, and conversely the eastern Pacific is cool and dry under a high pressure system. This creates a pressure gradient from east to west and causes surface air to move east to west. The same thing happens in the Indian basin. Due to the pressure gradient between western Indian

Ocean and eastern Indian Ocean the surface air moves from west to east. When they meet over western Pacific, the air starts an upwelling motion, which results from a high pressure system in the northern hemisphere summer. This allows the air to reach the stratosphere where it can easily form clouds due to condensation of water vapor in the warmer temperatures in stratosphere. When El Nino occurs over eastern Pacific, the Walker circulation weakens or reverses, causing the ocean surface to be warmer than average, and stratospheric clouds are formed not over the western Pacific but the eastern Pacific.

Stratospheric clouds can be detected from satellite when a more opaque spectral band (such as those sensitive to CO₂ or H₂O in the atmosphere) produces a brightness temperature (BT) warmer than the less opaque spectral band (such as an infrared window) indicating measurements from the atmosphere where there is a positive lapse rate; the opposite occurs in the troposphere with a negative lapse rate. Schmetz et al (1997) using Meteosat data suggested that when the water vapor sensitive 6.7 μm band is warmer than the infrared window 11.0 μm by more than one degree Celsius ($BT_{6.7} > BT_{11} + 1 \text{ K}$), the measurements likely indicate a stratospheric cloud.

HIRS observations of the changes in the occurrence of stratospheric clouds have been compared with Sea Surface Temperature (SST) changes (Reynolds et al., 2002). Figure 8 shows that the ITCZ region increases (decreases) in stratospheric clouds (4b) are occurring during periods where the (4a) Niño 3.4 (4c) anomalies are colder (warmer) than the twenty-year (1990 - 2010) average. When stratospheric clouds dropped in 1997 during the El Niño event, the sea surface temperatures reached the peak anomaly above the average (2.9°C). After the El Niño year, stratospheric cloud occurrences show a straight line increasing trend until 2001 that correlates with the SST negative anomalies (shown in blue). After 2001 the decrease in stratospheric clouds correlates with positive SST anomalies (shown in red) until 2005.

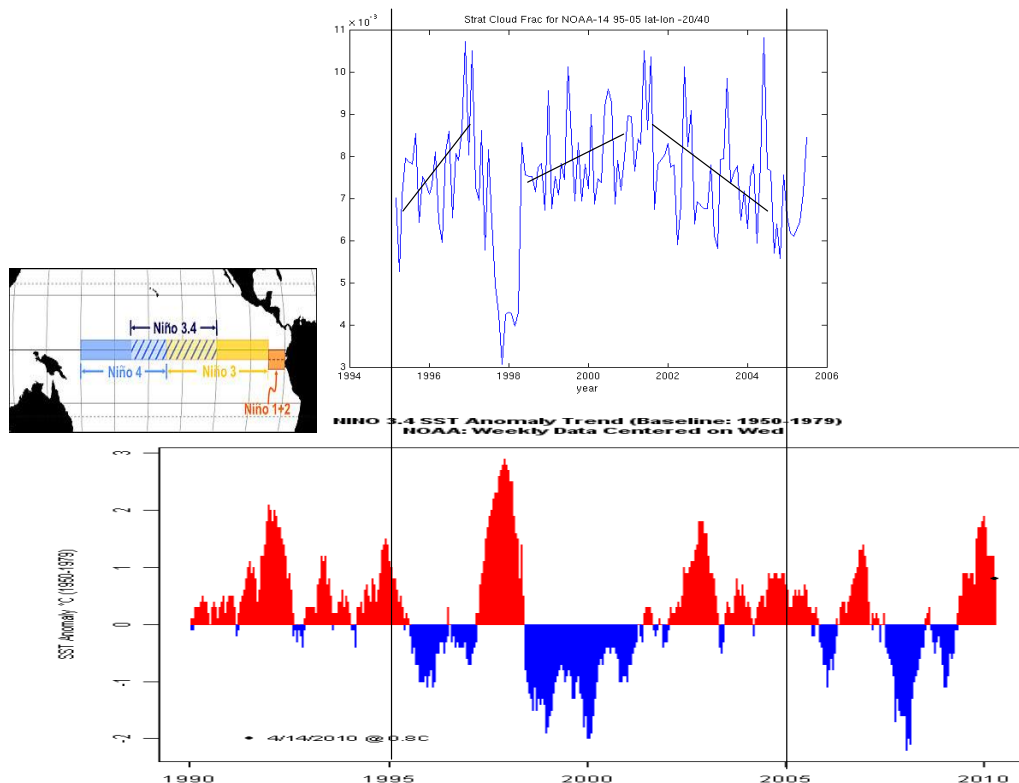


Figure 8. Fraction of all observations in the ITCZ (20S to 40N, 45W to 180W) finding stratospheric clouds (b) inferred from HIRS when $BT_{6.6} > BT_{11}$. A periodic seasonal cycle in the ITCZ is evident, peaking in the Northern Hemisphere summer. 1997 is anomalous due to El Niño occurrence. Weekly sea surface temperatures (SSTs) from 1990 to 2010 over the area illustrated in image (a) as Niño 3.4 tropical region (blue and yellow lines) is shown in the bottom image (c) (National Climate Data Center-NCDC).

6. Conclusions

Intercalibration of HIRS sensors with AIRS has suggested a spectral shift in the NOAA-14 HIRS CO_2 channels that removed a discontinuity in cloud property determinations between HIRS/2 on NOAA-14 and HIRS/3 on NOAA-15. High spectral resolution measurements provide a reliable calibration reference for the HIRS sensors from NOAA-14 onwards; intercalibration with AIRS (or IASI) enables removal of sensor to sensor calibration differences. For sensors prior to NOAA-14, the cloud property determinations reveal artifacts that can be attributed to sensor to sensor calibration differences; here, simultaneous nadir overpass (SNO) comparisons must be studied to stage a HIRS cloud data set that is useful for a long term cloud detection trend analysis. That data set must also include corrections for orbital drift.

Algorithm adjustments tested on MODIS and implemented on the HIRS resulted in more CO_2 slicing detection of thin ice clouds, clearer definition of a seasonal cycle in cloud cover especially over land, and detection of small but significant trends in high clouds.

Conclusions for this 1995 through 2009 HIRS cloud data set include: (a) clouds were found in ~80% (55%) of HIRS observations over ocean (land) since 1995 whereas high clouds were found in ~40% (33%) over ocean (land); (b) winter (DJF) clouds (all as well as high) over ocean suggest a small increase less than 0.5% per year from 1995 to 2003 and are decreasing thereafter; and (c) summer (JJA) clouds (all as well as high) remain constant 1995 to 2009.

The average cloud cover has not changed appreciably from the 1990s to the 2000s. Some changes are evident in high clouds during winters (DJF). Increases of more than 10% in high clouds occurred in the western Pacific (off the eastern coast of Asia) and in northern Canada. Decreases are found in the middle of the Pacific Ocean, the United States, Spain, and eastern China.

HIRS observations of stratospheric clouds are dominated by those occurring in the ITCZ and show distinctive trends from 1995 through 2005; increases are strongly correlated with decreases in SST.

Comparisons with CALIPSO (Holz et al. 2008) offer an opportunity to confirm HIRS detection of high and stratospheric clouds and improve HIRS thin cloud detection. These intercomparisons are ongoing and will be the topic of a future paper.

The ultimate goal is to contribute a near real-time compendium of monthly average global cloud properties that will be presented in the context of cloud trends and patterns from the past thirty years. This global climatology of cloud parameters will include cloud fraction, cloud-top pressure, and cloud emissivity; algorithm strengths, weaknesses, and inherent errors for each parameter will be clearly stated and documented. For example, detection of changes in cloud properties, either regionally or globally, would be identified and the magnitude of the change would be characterized whether it is outside the bounds inherent with the error sources of the data set.

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