Spectral Signatures of Earth’s Climate Variability over 5 Years from IASI

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ABSTRACT

Interannual variability in spectrally resolved longwave radiances is quantified at a variety of spatial scales using 5 yr of IASI observations. Maximum variability is seen at the smallest scales investigated (10° zonal means) at northern and southern high latitudes across the center of the 15-μm CO₂ band. As the spatial scale increases, the overall magnitude of interannual variability is reduced across the spectrum and the spectral shape of the variability changes. In spectral regions sensitive to conditions in the upper troposphere, the effect of increasing spatial scale is relatively small and at the global scale these parts of the spectrum show the greatest year-to-year variability. Conversely, the atmospheric window (8–12 μm), which is sensitive to variations in surface temperature and cloud, shows a marked reduction in interannual variability with increasing spatial scale. Over the 5 yr studied, at global scales the standard deviation in annual mean brightness temperature is less than 0.17 K across the spectrum, dropping to less than 0.05 K across the window. Spectrally integrating the IASI measurements to create pseudobroadband and window channels indicates a variation about the mean that is higher for the broadband channel than for the window channel at the global and quasi-global scales and over the Southern Hemisphere. These findings are in agreement with observations from CERES Terra over the same period and imply that at the largest spatial scales, over the period considered here, fluctuations in mid- to upper-tropospheric temperatures and water vapor, and not cloud or surface temperature, play the dominant role in determining the level of interannual variability in all-sky outgoing longwave radiation.

1. Introduction

The potential for using measurements of spectrally resolved outgoing longwave radiation (OLR) directly to monitor the climatic state and detect and attribute change has been recognized for some time (e.g., Charlock 1984; Kiehl 1986; Goody et al. 1995; Iacono and Clough 1996; Slingo and Webb 1997; Harries et al. 2001). More recently, interest in the topic has been revived as a result of the prospect of a dedicated space mission, the Climate Absolute Radiance and Refractivity Observatory (CLARREO), which seeks to establish high absolute accuracy benchmark climate observations of spectrally resolved thermal infrared and reflected solar radiation, in combination with measurements of atmospheric refraction (Wielicki et al. 2013). Theoretical studies by members of the CLARREO science team have shown how distinct longwave spectral signals from different climate forcing and feedback mechanisms may be derived and, importantly, within the context of the temporal and spatial sampling strategy envisaged for CLARREO, appear to combine with a high degree of linearity (Leroy et al. 2008; Huang et al. 2010).

To date, attempts to evaluate changes in the forcing of climate and associated feedback processes by considering changes over time to spectrally resolved OLR observations of the earth have typically been restricted to clear-sky conditions (Harries et al. 2001; Griggs and Harries 2007). These studies demonstrated that sharp spectral features due to long-term increases in the concentration of individual molecules such as CO₂, CH₄, and CFCs can be identified. However, the detection of changes in the outgoing spectrum that might be due to water vapor and, in particular, cloud feedback processes are much more difficult to unambiguously discern (e.g., Brindley and Allan 2003). In particular, the high level of variability in the cloud field in space and time not only
has implications for the interpretation of spatially and temporally averaged radiances (e.g., Kato et al. 2011) but, crucially, makes disentangling responses to climate forcing from underlying climate variability a hugely challenging task. While there have been several studies on the impact that temporal and spatial sampling may have on the accuracy with which climate change signals can be detected in OLR observations (Brindley and Harries 2003a, b; Kirk-Davidoff et al. 2005), understanding the exact nature and level of background variability seen in observed all-sky spectra is an important question that has not yet been fully addressed.

Recognizing this challenge, the work presented here exploits the emerging radiance record available from the Infrared Atmospheric Sounding Interferometer (IASI) on the European Meteorological Operation (MetOp) satellite (Hilton et al. 2012) to investigate the interannual variability in average OLR spectra at different spatial scales. Results are placed in the context of broadband observations from the Clouds and the Earth’s Radiant Energy System (CERES) instruments (Wielicki et al. 1996) to assess both the consistency between the different records and the additional insights that can be gained from the higher spectral resolution available from IASI. Hence, in section 2 we briefly introduce IASI and CERES before focusing on the insights provided by the former instrument in section 3. Where appropriate, we also make reference to the results presented in Huang and Ramaswamy (2009), who, in their efforts to assess the time evolution of spectral OLR, evaluated the monthly and annual variability seen in global mean observations from the Atmospheric Infrared Sounder (AIRS; Chahine et al. 2006) over the period 2002–07. We show that the interannual variability manifested across the IASI spectra is less than 0.17 K in brightness temperature in the global annual mean, collapsing to a value of less than 0.05 K in the so-called atmospheric window (\(\sim 800–1250 \text{ cm}^{-1}\)), a remarkable result with implications for the variability of the cloud field and the land surface. In section 4 we use the observations from CERES to illustrate that these results are consistent with patterns of behavior seen in both broadband and window OLR fluxes and investigate issues related to instrument sampling. We discuss the potential implications of these results, as well as the caveats associated with our study, in section 5.

2. Observational tools

a. IASI

IASI is a Michelson interferometer, covering the spectral range from 645 to 2760 cm\(^{-1}\) in three separate wavenumber bands running from 645 to 1210, 1210 to 2000, and 2000 to 2760 cm\(^{-1}\) (Simeoni et al. 2004) with an apodized half-width of 0.5 cm\(^{-1}\). Since October 2006, this instrument has enabled high-resolution atmospheric sounding from the sun-synchronous MetOp-A platform, which has an equator crossing time of 0930 local time for the descending node. The instrument is a cross-track scanner, producing 30 “fields of regard” (FORs) per scan; each is an array of 2 \(\times\) 2 pixels with a 12-km diameter at nadir. Instrument noise levels are found to be within specification and stable over time except for wavenumbers below 680 cm\(^{-1}\) and in small band overlap regions where observations from different detectors are merged (Blumstein et al. 2007). In the spectral region of interest for this study, noise equivalent delta temperature (NE\(\Delta\)T) levels (expressed at 280 K) are always below 0.4 K (minimum wavenumber \(\sim 660 \text{ cm}^{-1}\)) and more typically less than 0.3 K. Comparisons with collocated observations from the Atmospheric Infrared Sounder indicate agreement between the two instruments to within \(+/−0.2\) K, while calibration-validation activities using aircraft-based interferometers give agreement to within \(+/−0.3\) K (Newman et al. 2008; Larar et al. 2010).

Here, we use only “nadir” IASI observations (in practice, within 5° of nadir) covering the spectral range 645–1600 cm\(^{-1}\) which, over the 5 yr from January 2008 to December 2012, yields \(\sim 160\) million spectra as input into the study. As neither high spatial nor spectral resolution is a priority, initial data reduction to the \(\sim 100\)-km spatial scale is made by averaging 16 IASI near-nadir spectra and the result is smoothed to a 2.8 cm\(^{-1}\) spectral resolution, with a view to facilitating comparisons with previous analyses which used data from the IRIS mission (Hanel et al. 1972) in future studies. The resulting IASI reduced resolution (hereafter IRR) spectra form the basic input to the averaging studies discussed in the following section and are comparable in spectral and spatial detail to those used in the work of Harries et al. (2001) and Grigges and Harries (2007). Figure 1 illustrates the global annual mean IRR spectrum for 2008–12, to place the variability plots shown in later sections in context. Principal spectral features are due to \(\text{CO}_2\) (\(\sim 650–800 \text{ cm}^{-1}\)), \(\text{O}_3\) (\(\sim 1000–1070 \text{ cm}^{-1}\)), \(\text{CH}_4\) (\(\sim 1200–1400 \text{ cm}^{-1}\), centered at 1303 cm\(^{-1}\)), and \(\text{H}_2\text{O}\) (\(\sim 1250–1600 \text{ cm}^{-1}\)), with other weaker bands also in evidence [e.g., CFCl\(_3\) (853 cm\(^{-1}\))].

In the large-scale annual averages presented in this study at least 1.6 million native resolution IASI spectra are used to obtain the final IRR results. If the source of the 0.4-K NE\(\Delta\)T error indicated above was purely random in nature, this would translate to a final uncertainty that is of the order \(3 \times 10^{-4} \text{ K}\) in zonal mean averages and a factor of \(\sim 4\) smaller in the global mean. In reality it is likely that there is a systematic component to the NE\(\Delta\)T that is not reduced by averaging and cannot be
estimated easily. However, since we are focused on diagnosing variability in this study, it is the stability of IASI that is paramount. Comparisons with AIRS show radiometric agreement between the two instruments that is within a few mK or better (Hilton et al. 2012 and references therein), suggesting excellent stability over time.

b. CERES

Since 2001, CERES has provided global measurements of the earth’s radiation budget from low-Earth orbit (Wielicki et al. 1996). Besides contributing to numerous important studies of the effects of different climate processes on the earth’s energy balance, the uncertainties associated with the measurements have also been rigorously assessed and documented (e.g., Loeb et al. 2009). In this study we make use of observations from the Terra and Aqua platforms over the same 2008–12 period considered for IASI. The CERES instrument measures the broadband shortwave radiation reflected at the top of the atmosphere (TOA) in conjunction with the total outgoing longwave radiation (OLR), the latter nominally covering the range 5–100 m.

In addition, observations are also made in a longwave window channel sensitive to radiation between approximately 8 and 12 μm. To make use of these window fluxes, we employ level 3 monthly mean files provided at 1° latitude–longitude resolution, derived from single-scanner footprints (so-called SSF1deg_Ed2.7). Note that these products are created from hourly data, which are obtained by using temporal interpolation assuming constant meteorology. Over non-snow-covered land, during the day a half-sine fit is used, with nighttime fluxes set to a constant value if the daytime flux is greater than the nighttime value. Over ocean and snow, linear interpolation is used between the CERES overpass times.

3. Interannual variability in IRR spectra

a. 10° zonal means

We begin by considering the interannual variation in IRR brightness temperature spectra at the 10° zonal scale, as this spatial scale is consistent with the type of averages expected to be produced by the CLARREO mission. The standard deviation across the 5 yr in the annual-mean brightness temperatures, \( \sigma_{TB} \), for 10° zonal bands in the Northern and Southern Hemispheres are shown in Figs. 2a and 2b, respectively. Maximum \( \sigma_{TB} \)’s occur across the 15-μm CO₂ band center (from \( \nu \approx 645 \) to 700 cm\(^{-1}\)) at northern and southern high latitudes, peaking at \( \approx 690 \) cm\(^{-1}\) in these zones. Noting the noise characteristics of IASI, we focus our discussions on observations in excess of 660 cm\(^{-1}\). Emission to space at the very center of the band at 667 cm\(^{-1}\) originates from the mid- to upper stratosphere. Moving away from the central peak, emission to space occurs from systematically lower levels in the stratosphere, until by \( \approx 680 \) cm\(^{-1}\) one is effectively sounding the tropopause. As wavenumber increases over the CO₂ band wing (\( \approx 700–760 \) cm\(^{-1}\)), emission to space occurs from systematically lower levels in the stratosphere, until by \( \approx 680 \) cm\(^{-1}\) one is effectively sounding the tropopause.

Distinct peaks in \( \sigma_{TB} \) are also seen in the center of the 1303 cm\(^{-1}\) CH\(_{4}\) band and within strong water vapor lines at wavenumbers > 1500 cm\(^{-1}\). These are largest within the 80°–90° zones but are still clearly apparent at lower latitudes, particularly in the Southern Hemisphere. In the Northern Hemisphere, variability within the atmospheric window region (\( \nu \approx 800–1250 \) cm\(^{-1}\)) is typically higher than that seen within the CO₂ band wing (from 720 to 760 cm\(^{-1}\)) and across the 6.3-μm water vapor vibration-rotation band (\( \nu > 1250 \) cm\(^{-1}\)). No consistent pattern with latitude is seen within the 9.6-μm O₃ band (\( \nu \approx 1000–1070 \) cm\(^{-1}\)), although for the majority of

![Fig. 1. Average 2008–12 global annual mean IRR brightness temperature spectrum. Vertical dashed lines at 700 and 1303 cm\(^{-1}\) are included to help orient the reader in the discussions concerning spectral features and variability contained in the main text.](http://journals.ametsoc.org/jcli/article-pdf/28/4/1649/4049529/jcli-d-14-00431_1.pdf)
zones the variability here is higher than across the atmospheric window as a whole. We note that the window region would be expected to be particularly sensitive to variations in surface temperature and cloud, with the changes in spectral shape we see here potentially reflecting variability in cloud microphysical properties (e.g., Strabala et al. 1994). In this study we make no attempt to separate out the different factors controlling this variability but anticipate that this will be an area for future investigation.

b. 30° zonal means

Moving to larger scales, Fig. 3 shows the interannual standard deviation in brightness temperature for 30° zones across both hemispheres. Here, 30° zonal mean radiances are constructed from the 10° zonal mean radiances employed in section 3a, applying equal weighting to each band, before converting to brightness temperature and calculating the associated standard deviation. The first point to note is that, as might be expected (e.g., Brindley and Harries 2003a,b; Kirk-Davidoff et al. 2005), the overall level of $\sigma_{TB}$ is decreased, falling to a maximum level of 0.9 K (compared to 1.15 K) across the CO$_2$ band center at Southern Hemisphere high latitudes (Fig. 3b). For both hemispheres the 60°–90° band shows the largest $\sigma_{TB}$ within the window region. While these values decline rather dramatically in the Southern Hemisphere within the lower-latitude bands, the reduction in the Northern Hemisphere is much less marked. Excepting the 9.6-μm O$_3$ band, within the 0°–30°S and 30°–60°S bands the variability across the window is lower than in other spectral regions (such as within the water vapor vibration-rotation band and 15-μm CO$_2$ band wing); behavior that is not exhibited in any of the other latitude bands.

Outside of the window the behavior within the highest-latitude zones is most striking. Consistent with the higher spatial resolution results, maximum $\sigma_{TB}$’s occur across the 15-μm CO$_2$ band center and at the peak of the 1303 cm$^{-1}$ CH$_4$ band, particularly in the Southern Hemisphere. The signatures of increased variability due to the strong water vapor lines at wavenumbers greater than 1500 cm$^{-1}$ are also still apparent within these zones.
c. Global mean

Focusing now on the largest spatial scale, Fig. 4a shows the differences from the mean spectrum shown in Fig. 1 for each year from 2008 to 2012. Immediately apparent is the degree of stability over the 5 yr sampled here, with year-to-year differences of less than 0.3 K across the spectral region covered (equivalent to radiance differences of \(0.3 \text{ mW m}^{-2} \text{ sr}^{-1}\)). This level of stability translates to the standard deviations in spectrally resolved global annual mean brightness temperature shown in Fig. 4b. Similar to section 3b, annual global mean radiance spectra were constructed from the \(10^\circ\) zonal means of section 3a, applying the appropriate area (cosine) weighting to each band, prior to their conversion to brightness temperature and calculation of standard deviation.

Across the entire spectral region the interannual global \(\sigma_{\text{TB}}\)’s are very small, at less than 0.17 K. While the reduction in overall variability with increasing spatial scale might be anticipated, the impact of global averaging is altered with spectral region, resulting in a distinct change in spectral shape. Figure 4b indicates that at the global scale, rather than peaking in the 15-\(\mu\)m CO\(_2\) band center, variability peaks within the CO\(_2\) band wing (700–740 cm\(^{-1}\)) and at the center of the 1303 cm\(^{-1}\) CH\(_4\) band. Note that because of the nonlinearity of the transformation from radiance to brightness temperature the impact of the variation on outgoing energy is larger in the former spectral region. Enhanced variability is also seen beyond 1350 cm\(^{-1}\) within the 6.3-\(\mu\)m H\(_2\)O vibration-rotation band with a further, secondary peak in \(\sigma_{\text{TB}}\) apparent across the 9.6-\(\mu\)m O\(_3\) band. Surprisingly, perhaps, within the context of Figs. 2 and 3, the lowest level of variability is seen within the atmospheric window (excluding the O\(_3\) band) at less than 0.05 K.

Returning to Fig. 4a, it is interesting to note that removing one year (2010) from the analysis can markedly affect the magnitude of the interannual variability in some spectral regions and hence the spectral shape. The early months of 2010 were associated with a strong El Niño [large positive multivariate El Niño–Southern Oscillation index (MEI) values] before transitioning to an even stronger La Niña in the summer. During El Niño conditions, one typically sees positive anomalies in OLR even at the global scale, with the converse being true for...
a La Niña phase (e.g., Loeb et al. 2012; Susskind et al. 2012). The positive brightness temperature differences seen during 2010 across the majority of the spectrum would suggest that enhanced planetary emission has in some sense “won” over the course of the year. What is particularly noteworthy is the peak seen across the 1303 cm$^{-1}$ CH$_4$ band and the somewhat enhanced positive difference in the CO$_2$ band wing. Both are indicative of anomalously warm mid- to upper-tropospheric temperatures. With 2010 removed, anomalies from the 4-yr (2008, 2009, 2011, and 2012) mean are significantly reduced (<0.15 K), with a peak associated standard deviation of less than 0.1 K (Fig. 4b). In this case, although the window region still shows minimum variation, the peak brightness temperature variability is no longer seen at 1303 cm$^{-1}$, but rather across the 6.3-μm H$_2$O vibration-rotation band at wavenumbers > 1400 cm$^{-1}$, within the 9.6-μm O$_3$ band, and both within the 15-μm CO$_2$ band wing and at the very center of the band. While the full 2008–12 period considered here does sample a relatively wide range of MEI values, these results indicate how the magnitude and spectral shape of estimates of variability are themselves critically dependent on the period sampled, particularly with respect to major global and regional events such as El Niño.

With this in mind, it is informative to compare Fig. 4b to the results shown in Fig. 3a of Huang and Ramaswamy (2009), who carried out a similar analysis using AIRS observations from 2002 to 2007. In their work the magnitude of global annual mean variability across the same spectral region as considered here does not exceed 0.16 K, but peaks in the center of the 15-μm CO$_2$ band. While a secondary peak is seen in the CO$_2$ band wing, the relative variability seen across the window and the 1250–1500 cm$^{-1}$ wavenumber range is of a different sense from that seen here, with larger variability in the former region compared to the latter. In addition, the variability across the window manifested in the AIRS measurements is also slightly larger than that seen here, reaching ~0.07 K. Results for smaller spatial scales are not presented by Huang and Ramaswamy but it is interesting to note that for the majority of the period they
considered the climate system was in an El Niño phase. Moreover, the range in MEI values was smaller than that seen over the 2008–12 period.

4. Comparison to broadband observations

a. Window, nonwindow, and broadband variability as a function of spatial scale

In this section we seek to investigate whether the spectrally resolved results seen in section 3 are consistent with spectrally integrated observations made over the same 5-yr period. To this end, we employ CERES Terra and Aqua broadband OLR and window fluxes. CERES window fluxes cover the range ~833–1250 cm\(^{-1}\), so by comparing them to the corresponding OLR measurements, we can assess whether a reduction in window relative to nonwindow interannual variability is seen as the spatial scale increases, as might be anticipated from the IRR results. In addition, by spectrally integrating the IRR data over the appropriate wavenumber range, we can perform a direct comparison with IRR window radiances. For completeness, a similar integration has also been performed over the full 660–1600 cm\(^{-1}\) range studied here to create “broadband” IRR radiances. However, these do not sample the energetically important far-infrared region (Sinha and Harries 1995; Harries et al. 2008), the majority of which is captured by the CERES OLR fluxes. Because of the different metrics being compared, the variability is presented in terms of the coefficient of variation (CV), which is simply the interannual standard deviation, \(\sigma\), divided by the 5-yr annual mean for each dataset, \(\mu\), expressed as a percentage:

\[
CV = 100 \frac{\sigma}{\mu}. \tag{1}
\]

In addition, it should be noted that

\[
\mu_{BB} = \mu_{win} + \mu_{nw} \quad \text{and} \quad \sigma_{BB} = \sqrt{\sigma_{win}^2 + \sigma_{nw}^2 + 2\text{cov}(win, nw)}, \tag{2}
\]

where the BB, win, and nw subscripts refer to the broadband, window, and nonwindow regions, respectively, and \(\text{cov}(win, nw)\) is the covariance between the window and nonwindow regions.

Figure 5a shows the interannual variability in CERES Terra and Aqua window channel fluxes as a function of latitude. Superimposed is the equivalent CV in IRR window radiances. It is clear that all three instruments show a very similar pattern of behavior, with minimum window variability in the Southern Hemisphere low and midlatitudes. It is also clear that the variability about the mean for all three datasets is very low, typically less than 1%. Peak variability is seen in the 70\(^\circ\)–90\(^\circ\) latitude bands with, in the Southern Hemisphere, larger variability being manifested in the CERES measurements. In the northern high latitudes the pattern switches such that IRR variability is typically higher. For a given latitude band, the difference between the CVs calculated for each instrument is generally less than 0.05%. However, three bands display noticeably higher discrepancies between the instruments: 70\(^\circ\)–80\(^\circ\)S and 0\(^\circ\)–10\(^\circ\)N, where the IRR CV is lower than that of the two CERES instruments, and 80\(^\circ\)–90\(^\circ\)N, where the opposite is true. Detailed analysis of these bands has not identified any obviously anomalous behavior for the two CERES instruments or for IASI and it should be noted that the latitudinal pattern is still consistent between the three instruments. Figure 5a thus gives confidence that, despite the differing overpass times and instrument characteristics of CERES Terra, Aqua, and IASI, the general pattern and level of interannual variability exhibited in window fluxes and radiances sampled by the three instruments over the 5 yr considered here is similar. Figure 5b shows how the relative level of variability in the different spectral ranges changes with scale. In section 3 the analysis of IRR spectra showed that as one moved from smaller to larger spatial scales the variation in the window region typically reduced more rapidly than in spectral regions outside of the window. Figure 5b confirms that this behavior is also captured in the spectrally integrated IRR data and for the two CERES instruments. While variability always reduces as the scale increases, at the 10\(^\circ\) and 30\(^\circ\) scale for all three instruments the mean window CV exceeds the equivalent nonwindow and broadband CVs by some margin. However, globally the nonwindow CV is either similar in value to or exceeds both the window and broadband CVs. This greater reduction in the window variability with spatial scale indicates that nonwindow variability becomes increasingly important and is most significant for the global average.

Furthermore, the influence of variability in spectral regions not sampled by the IRR broadband radiances (\(\nu < 660 \text{ cm}^{-1}\), \(\nu > 1600 \text{ cm}^{-1}\)) is more significant at the global scale. Recall that the CV is the interannual standard deviation divided by the 5-yr annual mean. At the 10\(^\circ\) and 30\(^\circ\) scales the larger spectral range of the CERES compared to the IRR broad band must lead to a greater increase in the mean for CERES when moving from the window to the broadband channel. The results show that this increase is not compensated sufficiently by the additional variability found at wavenumbers below 660 and above 1600 cm\(^{-1}\). Thus, the broadband CERES CVs are systematically smaller than the IRR.
cases. However, for the global average the broadband CVs are similar for all three instruments, indicating that at this scale the variability in the spectral regions not sampled by the IRR broad band is sufficient to compensate for their additive effect on the mean. This hints at an important role for the far-infrared region of the spectrum in determining all-sky OLR variability at the global scale.

b. Role of land–ocean sampling

In this section we provide an indication of the potential impact of spacecraft sampling patterns on the relative level of interannual variability seen between the window and broadband OLR. CERES Terra and Aqua are in sun-synchronous orbits with nominal ascending–descending local equator crossing times of 1030–22.30 and 1330–0130 LT, respectively. IASI is also in a sun-synchronous orbit, with a nominal local equator crossing time of 0930 LT (2130 LT). While the annual means created from IASI are representative purely of the conditions at the observation time, as noted in section 2b, the CERES means will contain the effects of temporal interpolation assuming constant meteorology between the instrument overpasses. We note however that using the Geostationary Enhanced “SYN1deg” CERES products does not markedly affect the results reported here, suggesting that a more explicit representation of the diurnal cycle, using the observations made by the individual CERES instruments as anchor points, does not influence OLR variability at the spatial and temporal scales considered here.

The ability of a sun-synchronous orbit to truly capture the annual mean brightness temperature and its variability from year to year will depend on its overpass time because of a susceptibility to the phase of the diurnal cycle. Effects of this type are discussed in detail by Kirk-Davidoff et al. (2005) within the context of smaller, 15° × 30° grid-box averages. They use 3-hourly 11-μm brightness temperatures (BT11s) from the Global Cloud Imagery project (Salby et al. 1991) to assess the effects of different sampling strategies on the associated sampling error. Most pertinent within the context of this study,
they show that, although a sun-synchronous orbit will never represent the optimal solution for capturing the true diurnal behavior, a 1000–2200 LT equator crossing time would be expected to minimize the error seen from this type of orbit and that the year-to-year bias errors are highly correlated. Nonetheless, they note that interannual variability in the diurnal cycle will introduce an additional component of variability into estimates of the mean made from sun-synchronous data. We might expect that these effects would be largest in locations where the magnitude of the diurnal cycle is largest. In addition, they should be manifested in spectral regions that are most sensitive to these variations.

Figure 6a shows the relative magnitude of the window and broadband CV for each instrument for a variety of spatial regions of intermediate scale. In the Northern Hemisphere, tropics and deep tropics, the ratios of window to broadband CV are very similar for the two CERES instruments and systematically smaller for IASI. This difference is consistent with the results presented in Fig. 5b and the associated discussion. However, over the Southern Hemisphere there is a marked discrepancy between Terra and Aqua, with the former showing a much reduced ratio relative to the latter. The equivalent IASI ratio is intermediate between the two values. Investigation of the contributing factors indicates that it is the window channel standard deviation that is responsible for this behavior, being approximately halved for Terra relative to Aqua when considering the Southern Hemisphere as a whole. Given the land–ocean distribution, we might expect any sensitivity to interannual variability in the diurnal cycle (and hence overpass time) to be more marked in the Northern Hemisphere so this result is rather surprising. What is more consistent with expectation is the reduction in window standard deviation seen between the Northern and Southern Hemispheres for all instruments, which is reflected in the lower CV ratios over the Southern Hemisphere.

This reduction in window to broadband CV ratio over the Southern Hemisphere, coupled with the very low window standard deviations seen in oceanic bands (e.g., 50°–60°S; Fig. 2b), does indicate that instrument sampling will influence the exact magnitude and spectral distribution of variability, even at the extended temporal and spatial scales considered here. Figure 6b is an attempt to illustrate this more clearly using the IRR observations. Here, the data have been subdivided into...
land, ocean, day, and night subcategories prior to averaging. For all regions the window relative to the broadband CV is enhanced when only land scenes are considered. The most spectacular ocean–land differences are seen for the Northern Hemisphere case, where a negative covariance between the window and non-window parts of the spectrum results in very low broadband standard deviations over land. More typically, the window and broadband standard deviations over land are both enhanced relative to those seen over ocean but the fractional increase relative to the mean is larger for the window channel. Restricting each region to ocean scenes only, the window CV is always comparable to, or smaller than, the equivalent broadband value.

5. Discussion and conclusions

In this study we have used 5 yr of IASI observations to assess the level of interannual variability seen within the earth’s outgoing longwave radiation spectrum (from 660 to 1600 cm\(^{-1}\)) at a variety of spatial scales ranging from 10° zonal means to global averages. Our results indicate that on these time scales, peak interannual variability at wavenumbers between 15- \(\mu\)m \(\mathrm{CO}_2\) band (660–690 cm\(^{-1}\)) at high latitudes. At the very center of the band (\(\sim\)667 cm\(^{-1}\)), this is likely a reflection of variation in planetary wave activity and, particularly in the Northern Hemisphere, the effects of sudden stratospheric warmings (e.g., Charlton and Polvani 2007). The variability at wavenumbers between \(\sim\)670 and 690 cm\(^{-1}\), sounding the tropopause, is consistent with the fact that the seasonal cycle in tropopause temperature peaks over Southern Hemisphere high latitudes with a secondary maximum over the Arctic, and can show significant interannual variability over both locations (e.g., Kishore et al. 2006).

As the spatial scale increases, the interannual variability is reduced across the spectrum, but this reduction occurs at a different rate for different spectral regions. While the interannual variability within the atmospheric window, most sensitive to surface temperature and cloud, diminishes relatively rapidly with scale, variability in areas of the spectrum sensitive to mid- to upper-tropospheric temperature and water vapor shows a slower reduction. As a consequence, at the global scale, interannual variability peaks in the wing of the 15-\(\mu\)m \(\mathrm{CO}_2\) band, across the 1303 cm\(^{-1}\) \(\mathrm{CH}_4\) band, and within the 6.3-\(\mu\)m water vapor vibration-rotation band at wavenumbers greater than 1400 cm\(^{-1}\). At this global scale, interannual variability across the entire spectrum is less than 0.17 K, declining to less than 0.05 K across the window. These values translate to equivalent radiance values of 0.17 and 0.05 mW m\(^{-2}\) cm\(^{-1}\) sr\(^{-1}\) and highlight the remarkable stability of longwave emission from our planet as a whole. Similar findings in terms of the magnitude of spectral variability were reported by Huang and Ramaswamy (2009) based on analysis of AIRS data from 2002 to 2007. However, in that work the spectral shape of the variability was different from what we obtain here from IASI. It is an open question as to whether this change in shape is a result of the different periods covered, the different overpass times of the satellites carrying AIRS and IASI, or a result of instrument performance. Nonetheless, results of this type put observationally based limits on how the earth’s spectral emission to space varies interannually on the global scale, an important constraint that can be used to test and improve climate models.

Using broadband and window fluxes from the CERES instruments on Terra and Aqua, we have shown that as the spatial scale increases, the OLR displays a similar reduction in interannual variability and is consistent with the spectral analysis in how this scaling behavior differs in different spectral regions. At the smallest scales, the percentage variation about the mean (the coefficient of variation, CV) is substantially larger for the window channel compared to the broadband channel. As the scale increases, the CV in each spectral regime becomes more equivalent until at the global scale, for CERES Terra at least, the broadband CV exceeds that seen in the window channel. This behavior arises because of the increasing importance of the variation from spectral regions outside of the window to the total broadband variance. Equivalent behavior is seen in suitably spectrally integrated IASI observations.

Previous work has illustrated a strong anticorrelation between cloud and surface temperature variations within the tropics, which may result in a compensation effect across the atmospheric window at the global scale (e.g., Huang and Ramaswamy 2008). While OLR across the remainder of the longwave spectrum would also be affected by the presence of cloud, the impact of low and midlevel cloud across much of the spectrum is strongly damped by overlying upper-tropospheric water vapor. It is feasible that high-level cloud and surface temperature variations compensate each other in such a way that there is a minimal signal across the window coupled with enhanced variability in the \(\mathrm{CO}_2\) band wing and water vapor vibration-rotation band. However, we have performed a set of realistic spectral simulations (to be reported upon in a follow-on study) that do not show this behavior. It also appears inconsistent with the findings of Huang and Ramaswamy (2009). There, much larger changes are seen across the window than within the water vapor bands or \(\mathrm{CO}_2\) band wing when comparing
all-sky to clear-sky conditions. Hence, at the global and quasi-global scales, we argue that our results imply that it is fluctuations in mid- to upper-tropospheric temperatures and water vapor, and not cloud or surface temperature, that play the dominant role in determining the level of interannual all-sky OLR variability, at least over the period we have considered here.

Given current interest in developing climate monitoring missions that will explicitly use spectrally resolved information, it is interesting to note the potential effects of sampling and record length on the robustness of our findings. A reliable estimate of background variability is a key tool for determining whether a particular spectral signal is indicative of a true change or simply a climate fluctuation, and to identify which spectral regions offer the most promise for rapid change detection (e.g., Goody et al. 1995). Hence, factors that can perturb both the magnitude and spectral shape of the background variability need to be understood and their effects quantified.

Decomposing the IASI results further has allowed us to provisionally probe the effects of sampling on our results. Splitting the data into land and ocean and day and night categories indicates that enhanced variability is seen over land scenes, manifested through the magnitude of, in particular, window channel interannual standard deviations. This effect means that, even at the global scale, IASI window radiances show a larger CV than their broadband counterparts when only land scenes are averaged. Conversely, when only ocean scenes are included in the spatial averaging, the window CV falls below that seen for the broadband CV for a number of regions including the deep tropics, tropics, and both hemispheres. These findings suggest that the precise satellite overpass time will affect both the magnitude and shape of any temporally and spatially averaged spectra that are produced. Similar conclusions can be drawn regarding the effects of record length on the variability exhibited within that record. While these results indicate the care that must be attached to interpreting the results from a given satellite record, previous work suggests that for instruments in sun-synchronous orbit, an early morning equator crossing time, similar to that of both IASI and CERES Terra, will minimize diurnal sampling errors (Kirk-Davidoff et al. 2005). When all scenes are included in this study, a smaller CV for the window compared to broadband is seen for IASI for both the Southern Hemisphere, quasi-global, and global mean cases, and this pattern of behavior is replicated by CERES Terra. Similarly, even when individual years are excluded from the period of study, minimum variability at the global scale is still seen across the atmospheric window.

It should be noted that in the analysis presented here there is no attempt to account for any trends, either real, or arising as a result of instrument performance, in the IRR data. There have certainly been real, monotonic increases in the annual mean concentrations of certain greenhouse gases (e.g., CO₂, CH₄) over the 2008–12 time period and these would be expected to enhance absorption in those regions of the OLR spectrum sensitive to their presence. Acting in isolation, this increased absorption would drive the OLR in a consistent direction with time; however, in reality any response will be modified by the temperature variability over the vertical levels where the absorption is taking place. Figure 4a suggests that no consistent linear trend in spectral OLR as measured by IASI exists with time across the wave-number range considered here, at least at the global annual mean scale. Turning to instrumental effects, while the absolute accuracy of the measurements cannot be quantified, studies have shown that the radiometric performances of IASI and AIRS agree to within a few mK or less as a function of time (Hilton et al. 2012), implying excellent temporal stability.

There is clearly a substantial amount of further information that can be extracted from the IASI data. In the short term, work is ongoing to establish whether the variability highlighted here is replicated in atmospheric reanalysis datasets and, if so, what processes drive this behavior. Plans are in place to perform a detailed comparison with measurements from the AIRS instrument spanning the same time period, and the IASI data will also allow a reevaluation of previous analyses comparing spectra measured in 1970 by the Infrared Interferometer Spectrometer (IRIS) on Nimbus-4 (Hanel et al. 1972) to assess whether it is possible to unambiguously identify 40+ yr change signals in all-sky data from the two instruments.

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