



Diurnal variation of high-level clouds from the synergy of AIRS and IASI space-borne infrared sounders

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Abstract. Among the processes governing the energy balance of our planet, high-level clouds, due to their coverage of about 30%, play an important role. The net radiative effect (cooling or warming of the planet) of these clouds strongly depends on their emissivity. The combination of cloud data retrieved from two space-borne infrared sounders, the Atmospheric InfraRed Sounder, AIRS, and the Infrared Atmospheric Sounding Interferometer, IASI, which observe the Earth at four local times per

- 10 day, allows to investigate the diurnal variation of these high-level clouds, distinguishing between high opaque, cirrus, and thin cirrus clouds. We demonstrate that the diurnal phase and amplitude of high-level clouds can be estimated from these measurements with an uncertainty of 1.5 h and 20%, respectively. We have applied the developed methodology to AIRS and IASI observations and obtained monthly distributions of diurnal phase and amplitude for the period 0f 2008–2015. In agreement with other studies, the diurnal cycle is the largest over land in the tropics. At higher latitudes, the diurnal cycle is
- 15 the largest during the summer. For the regions of high diurnal activity over land, the diurnal amplitudes of cloud amount are about 7 % for high opaque clouds, 9 % for cirrus, and 7 % for thin cirrus clouds. Over ocean, these values are 2 to 3 times smaller. The diurnal cycle of tropical thin cirrus seems to be similar over land and over ocean, with a minimum in the morning (9h LT) and a maximum during night (1h LT). Tropical high opaque clouds have a maximum in the evening (21h LT over land), a few hours after the peak of convective rain. This lag is explained by the fact that this cloud type not only includes the
- 20 convective cores, but also part of the thicker anvils. Tropical cirrus (with an emissivity > 0.5 or visible optical depth > 1.4) show a maximum amount during night (1h LT over land). This lag indicates that they may be a part of the deep convective cloud systems. However, the peak local times also vary regionally. We are providing a global monthly database of detected diurnal cycle amplitude and phase for each cloud type.

1 Introduction

- 25 Clouds play an important role in the Earth's energy budget through a complex interaction with solar, atmospheric, and terrestrial radiation, air humidity, and aerosols. Optically thick clouds efficiently reflect the incoming solar radiation and, globally, clouds are responsible for about two thirds of the planetary albedo. Thin cirrus keep the planet warm because they are transparent in the shortwave (SW) and opaque in the long-wave (LW), allowing solar radiation to warm the surface and trapping the outgoing LW radiation, acting as a "greenhouse film". In addition to these counteracting processes, all clouds
- 30 emit thermal radiation in all directions in accordance with their temperature, and the radiation escaping the atmosphere cools





the planet. The algebraic sign of the net radiative effect of the cloud depends on its height, optical depth, vertical cloud layering, surface albedo and temperature, and local solar time.

Due to the importance of clouds for the Earth's energy budget, global satellite observations of cloud properties and their diurnal variations are essential for climate studies, for constraining climate models, and for evaluating cloud parameterizations.

- 5 Besides the mean amount of different cloud types, their diurnal variation also modulates the radiative cooling and heating of the atmosphere and of the surface. Both the clouds embedded in the planetary boundary layer and the clouds connected with the surface through deep convection exhibit systematic diurnal variations related to the daily cycle of surface solar heating. The first global analyses of diurnal cloud variations were based on the cloud products of the International Cloud Climatology Project (ISCCP), with a global, 3-hourly coverage (Cairns, 1995; Rossow and Cairns, 1995; Rossow and Schiffer, 1999). The
- 10 most notable features of the cloud diurnal cycle are significant differences between the phase of low-level cloud variations over ocean and land and between the phase of low-level and high-level cloud variations:
 - low-level clouds over ocean have a maximum amount early morning, while over land the maximum is in the early afternoon;
 - high-level clouds have a maximum amount early to late evening;
- 15 mid-level clouds have a maximum amount late at night or early morning.

As the combination of ISCCP two window channels, one IR and one visible, has low sensitivity to thin cirrus at night and when low-level clouds are underneath, a complementary study, using infrared (IR) sounder (TOVS Path-B) to identify high opaque clouds, cirrus and thin cirrus according to their emissivity, yielded the following conclusions (Stubenrauch et al., 2006):

- high opaque clouds over land in the tropics and midlatitude summertime have a maximum amount in the evening;
- 20 thin cirrus increase during the afternoon and persist during the night;
 - the varying proportions of thinner and thicker cirrus imply a gradual thickening of the cirrus clouds from late afternoon into the night time;
 - mid-level cloud amount exhibits a small increase during nighttime.

The high spectral resolution of the modern IR vertical sounders allows to select the spectral channels with the contribution

- 25 functions centred at different heights: the radiances measured near the centre of the 15µm CO₂ absorption band are sensitive to the upper atmospheric layers while the radiances in the absorption band wings are used to probe successively lower levels. Compared to other passive remote sensing instruments, IR sounders are sensitive to cirrus with emissivity as low as 0.1, day and night (Stubenrauch et al.2010, 2017; Menzel et al., 2016). As passive instruments determine in general the uppermost cloud layer in the case of multi-level cloud fields, the results on the lower cloud diurnal cycle will be inevitably modulated by the
- 30 clouds above. Therefore, we concentrate at the diurnal variation of high-level clouds.





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The CIRS (Cloud from Infrared Sounders) cloud climatologies established from AIRS (Chahine et al., 2006) and IASI (Hilton et al., 2012), now covering 15 and 10 years, respectively, have been presented by Stubenrauch et al.(2017). In this article, we use the synergy of these two instruments, observing each point of the Earth at least at four local times, to build a data base of amplitude and phase of the diurnal cycle of amount and emissivity of high-level clouds, which can further be used for regional and global climate studies and for climate model evaluation.

The structure of the article is as follows. In Section 2, we shortly describe the AIRS and IASI cloud data as well as the environmental data used for this study. Then we present the newly developed approach to estimate the diurnal cycle of cloud amount from a combination of AIRS and IASI observations. Section 3 discusses the diurnal variation of high opaque clouds, cirrus, and their atmospheric environment. In particular, we try to establish the links and temporal lags between

10 the different high-level cloud types, the surface temperature, and relative humidity. Conclusions are drawn in Section 4.

2 Datasets and Methods

2.1 Cloud properties from AIRS and IASI

Since 2002, the AIRS cross-track scanning instrument aboard the polar orbiting Aqua satellite has been providing very high spectral resolution measurements of atmospheric radiation in 2378 spectral bands in the thermal infrared $(3.74-15.40 \ \mu m)$, at

15 a spatial resolution of about 13.5 km × 21 km at nadir to 41 km × 21 km at the scan extremes (Chahine et al., 2006). Local observation times (LT) are 1:30 and 13:30 LT.

IASI aboard the polar orbiting Metop-A platform is a Fourier Transform Spectrometer based on a Michelson interferometer, which covers the IR spectral domain from 3.62 to $15.5 \,\mu$ m. As a cross-track scanner, the swath corresponds to 30 ground fields per scan, each of these measures a 2 × 2 array of footprints. The geometry of IASI observations is similar to that of the AIRS instrument: ±48.3° ground coverage, 12 km resolution at nadir, with observations at 9:30 and 21:30 LT, since 2007.

- 20 instrument: ±48.3° ground coverage, 12 km resolution at nadir, with observations at 9:30 and 21:30 LT, since 2007. The CIRS (Clouds from IR Sounders) cloud property retrieval package (Feofilov and Stubenrauch, 2017; Stubenrauch et al., 2017) is based on a weighted χ^2 method using eight channels along the 15 µm CO₂ absorption band (Stubenrauch et al., 1999). It provides cloud pressure (p_{cld}), cloud emissivity (ϵ_{cld}), cloud temperature (T_{cld}) and cloud height (z_{cld}), as well as their uncertainties. We define the cloud types according to p_{cld} and ϵ_{cld} : high-level clouds are the ones with p_{cld} < 440 hPa, and these
- are further divided into high opaque ($\epsilon_{cld} > 0.95$), cirrus ($0.95 > \epsilon_{cld} > 0.5$), and thin cirrus ($0.5 > \epsilon_{cld} > 0.1$). Ancillary data (surface temperature, atmospheric temperature and water vapour) are used in the radiative transfer calculations of the retrieval.While the sensitivity of the retrieved cloud properties to ancillary data is small for high-level clouds, the low-level cloud amount is sensitive to surface temperature used in the retrieval (Stubenrauch et al., 2017). To avoid potential problems associated with inconsistent retrievals of the ancillary data between AIRS and IASI, we have adopted the same ancillary dataset
- 30 for both, namely, the ERA-Interim meteorological reanalysis (Dee et al., 2011) by the European Centre for Medium-Range Weather Forecasts (ECMWF). For the cloud retrieval, the 6-hourly reanalysis data, given at universal time, have been





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transformed and interpolated towards values at 1:30, 9:30, 13:30, and 21:30 LT. In addition, sea surface temperatures have been slightly corrected for a lack of diurnal variation (Stubenrauch et al., 2017).

From Fig.1, presenting latitudinal distributions of high opaque, cirrus and thin cirrus amount for January and for July, averaged from 2008 to 2015, separately at 01:30, 09:30, 13:30, and 21:30 LT, we deduce that (i) in the tropics (30S–30N) high-level clouds are present more than in half of the observed scenes (the sum of the three cloud types reaches 60%), (ii) tropical high-level cloud amount maximum moves with season towards the summer hemisphere, while the amount of high-level clouds in the midlatitudes is larger in winter, and (iii) all cloud types demonstrate a diurnal variation, but its zonal amplitude is small compared to the zonal mean of the corresponding cloud amount. Fig.1 will serve as a reference when considering the diurnal amplitudes discussed below.



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Fig.1. Latitudinal distribution of high opaque, cirrus, and thin cirrus cloud amount estimated from AIRS (01:30 and 13:30 LT) and IASI (09:30 and 21:30 LT) by the CIRS retrieval: (a) January; (b) July. Climatological averages over 2008 to 2015.

2.2 Estimating the diurnal cycle amplitude and phase

In this section we develop an approach to identify both the amplitude and the phase (or the "peak time") of the diurnal variation of cloud amount, using a combination of AIRS and IASI cloud data, with four measurements per day. Both amplitude and

two harmonic functions of the following form:





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phase depend on the cloud type, region, and season (Cairns, 1995; Soden, 2000; Tian et al., 2004; Stubenrauch et al., 2006; Eastman and Warren, 2014, and references therein), so for each location they should be determined individually.

The Nyquist-Shannon-Kotelnikov sampling theorem says: "if a function x(t) contains no frequencies higher than B hertz, it is completely determined by giving its ordinates at a series of points spaced 1/(2B) seconds apart". In application to diurnal variation analysis this means that four measurements per day are just on the edge of the diurnal cycle detectability. In addition, the condition of the theorem is not completely fulfilled since cloud diurnal cycle contains on administration of a completely fulfilled since cloud diurnal cycle.

- the condition of the theorem is not completely fulfilled since cloud diurnal cycle contains an admixture of a semi-diurnal harmonic (e. g. Cairns, 1995), which is clearly beyond the detection limit. Moreover, the sampling of AIRS and IASI measurements is not equidistant in time with its 8 and 4 hour intervals. Correspondingly, one has to use an external source of information to ensure an unambiguous detection of the diurnal cycle and estimate its phase φ and amplitude *A*. We found this
- 10 missing piece of the puzzle in the function describing the general behaviour of the cloud amount variation as a mixture of two harmonics: diurnal and semi-diurnal, obtained from the analysis of ISCCP observations (Cairns, 1995). Cairns (1995) has shown that the diurnal cycles of high-, middle-, and low-level clouds are well represented by a mixture of

$$A(t) = A_{24} \cdot \sin\left(\frac{2\pi}{24}t + \varphi_{24}\right) + A_{12} \cdot \sin\left(\frac{2\pi}{12}t + \varphi_{24} + \Delta\varphi\right) = A_{24} \cdot \left[\sin\left(\frac{2\pi}{24}t + \varphi_{24}\right) + 0.28 \cdot \sin\left(\frac{2\pi}{12}t + \varphi_{24} + \Delta\varphi\right)\right] (1)$$

- 15 where the indices "24" and "12" correspond to diurnal and semi-diurnal harmonics, respectively, *t* is time in hours, $\Delta \varphi$ is the phase shift between semi-diurnal and diurnal harmonics, and the numeric parameters are estimated from Fig.1 of (Cairns 1995). It is interesting to note that a similar mixture of diurnal and semi-diurnal harmonics describes tropical precipitation (Bowman et al., 2005). Since the ratio of $A_{12}/A_{24} \approx 0.28$ obtained from (Cairns 1995) does not change much with the type of the cloud, we simplify the equation to a form shown in the second part of Eq. (1). The phase shift $\Delta \varphi$ was found to be equal to
- 20 -2 h for the low- and mid-level clouds and 0 h for high-level clouds. Below, we show that the shape given by Eq. (1) represents the diurnal cycle in clouds better than a simple harmonic fit, but prior to validation of the shape one has to introduce a general diurnal cycle estimation approach itself. The examples shown in Fig.2 utilize the A(t) given by Eq. (1), though the approach remains valid for any periodic function.
- Figure 2 explains the approach for estimating the diurnal variation phase and amplitude: let us imagine that a real variation for 25 a given type of cloud at a given location is defined by Eq. (1), with A_{24} , φ_{24} , and $\Delta \varphi$ known (black curve in Fig.2a). For this case, the red circles in Fig.2a correspond to the values obtained at the local observation times of AIRS and IASI, which are passed to the diurnal phase/amplitude estimation algorithm. To test the sensitivity of the approach to the uncertainties of the amplitudes related to uncertainties of AIRS and IASI cloud amounts, we also consider the case when a 20% random "noise" is added to the amplitudes at the sampled observation times.







Fig.2. Illustration of the approach to estimate the diurnal variation phase and amplitude from four measurements, taking advantage of a known form of the variation: a) "True" profile measured at four points and moving guess profiles; b) Pearson's correlation coefficient calculated for guess profiles for noise-free and noisy simulations; c) determination of the amplitude with the phase known.

5 This uncertainty was estimated from the most recent CIRS-AIRS and CIRS-IASI cloud products (Stubenrauch et al., 2017) which were compared with active lidar cloud measurements of the CALIPSO mission (Winker et al., 2009). The comparison





showed a hit rate for individual measurements in the tropics and midlatitudes of the order of 88% over oceans and of 82% over land.

The first step in the analysis is to build the function in accordance with Eq. (1), with $\Delta \varphi$ corresponding to the cloud type under consideration and an *arbitrary amplitude* A_{24} . Then the phase estimation procedure changes φ_{24} by fine increments, each time

- 5 calculating A(t) at the four local observation times of AIRS and IASI (blue circles on grey curves in Fig.2a). A set of obtained values is compared to a reference "measurement" (red circles), and a Pearson's correlation coefficient k_{corr} is calculated for each phase shift (Fig.2b, phase converted to peak time for the sake of visualization). In the noise-free self-consistency study the maximum of k_{corr} should exactly match the phase reproducing the original function. The tests show that even 20% random noise added to the "reference" points does not spoil the phase determination by more than half of an hour. Since the peak of
- 10 the k_{corr} curve is not sharp, we make a conservative estimate of the uncertainty of our method of phase (or peak local time) determination to be ±1.5 h.

With the phase known, we estimate the A_{24} amplitude (Fig.2c) as follows: we build an anomaly of the best guess profile and compare it with the anomaly of the Eq. (1) at the four observation times. The mean ratio of amplitudes at these points gives an amplitude, which should be substituted into Eq. (1). To avoid zero-over-zero type of errors, we pick up only the A(t) points

- 15 with the absolute value greater than 0.2 of the maximal |A(t)| value. Another way of estimating the amplitude is to compare the maximal spans of the reference profile sampled at four observation times and that of the measured one. We find these methods to be equivalent, but the one involving more points should be less noisy and, therefore, more reliable. The noise in the measured points affects the A_{24} retrieval uncertainty and our analysis shows that the 20% noise in the source data leads to about 20% uncertainty of the retrieved amplitude.
- 20 To justify the choice of the relationship in Eq. (1) for the fitting, we have performed the following numerical experiment: one year of CIRS-AIRS and CIRS-IASI cloud data has been processed using the approach outlined above for two fitting functions: a harmonic one with a 24-h period and the one following (Cairns, 1995) described by Eq. (1). For each case, we have built a histogram of the best correlation coefficient values, separately for high- and low-level cloud amount variation. We found that with Eq. (1) one achieves ~8% and ~18% higher correlation coefficients for the diurnal cycle of high- and low-level clouds,
- 25 respectively, than with a harmonic function fitting. This justifies using Eq. (1) for the analysis. Searching a better fitting shape of the diurnal variation is out of the scope of this study, but the approach to estimate phase and amplitude of the diurnal variation, under the assumption of a known and fixed shape of the diurnal variation, remains valid for any periodic function (e. g. see the surface temperature variation fitting in Appendix B).

Summarizing this section, the "sliding profile approach" allows to estimate the phase and amplitude of the diurnal variation from four measurements per day performed at arbitrary time with respect to peak time. The uncertainty of the estimated peak time for the combination of four AIRS and IASI monthly averages over 1° latitude × 1° longitude is ±1.5h while the diurnal cycle amplitude is retrieved with ~20% uncertainty.





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3 Diurnal phase and amplitude of high clouds and their surrounding

3.1. Zonal averages

We apply the diurnal cycle estimation algorithm to the amount of all high-level clouds and separately of high opaque, cirrus and thin cirrus clouds from the CIRS-AIRS and CIRS-IASI cloud climatologies. To demonstrate the capabilities of the algorithm and the feasibility of the approach, we first compare average diurnal variations of high-level cloud amount over beit divergence of the algorithm and the feasibility of the approach, we first compare average diurnal variations of high-level cloud amount over

- latitudinal bands, separately for ocean and land, to those presented by Noel et al.(2018), determined using cloud properties retrieved from CATS (Cloud-Aerosol Transport System) lidar measurements (Palm et al., 2016, Yorks et al., 2016) aboard the International Space Station (ISS). When looking at the comparisons, the reader should keep in mind that the latter dataset has a much smaller statistics, both temporal (from February 2015 through October 2017 vs 8 years of AIRS/IASI) and spatial
- 10 (passive instruments scan the atmosphere in the direction perpendicular to the orbit to whereas active measurements provide a series of measurements along the orbit). Fig.3 presents the average diurnal variation of high-level cloud amount over three latitudinal bands, separately over ocean and over land, during boreal summer for CATS and during both boreal summer and boreal winter for AIRS / IASI. We explain smoother curves for AIRS-IASI by larger statistics and the shape assumption in the diurnal cycle estimation. In agreement with earlier studies, the diurnal cycle amplitudes are smaller over the ocean than over
- 15 land. They are the largest in the tropics and they are close to zero in winter hemisphere (see also Fig. S1 for Southern hemisphere in the supplement).

For each latitudinal band, the agreement between CATS and AIRS/IASI cloud diurnal cycle is indicated by Pearson's linear correlation coefficient. The values are in general high, when the diurnal amplitudes are large, which is the case in the summer hemisphere and tropics over land. For comparison, the amplitudes are much smaller in boreal winter. The peak local times

20 (marked in red and blue) do also agree within uncertainty range. We explain the difference between the diurnal cycle amplitudes shown in Fig.3 by (i) differences in geographical coverage (AIRS/IASI combination provides daily snapshots of the whole globe, whereas CATS needs about a month to cover the same area) and (ii) differences in sensitivity to optically thin clouds.

Fig.4 presents the contributions of the different cloud types (high opaque, cirrus and thin cirrus) to the total diurnal variation

- of high clouds for boreal summer in the Northern hemisphere (Fig. S2 for austral summer in the Southern hemisphere). Both the amplitudes and phases of these cloud types differ. This helps to explain the differences between the diurnal peak times obtained from instruments with different sensitivity to thin cirrus. The diurnal cycle will be shifted in phase accordingly. The distinction between the cloud types also allows a deeper interpretation of the diurnal cycle: cirrus which are the most abundant in the tropics have the largest amplitude in the diurnal cycle, with a minimum around 1PM and a maximum around
- 30 1AM over land. High opaque clouds have a maximum at 9PM which is several hours later than convective precipitation in the afternoon. This can be explained by the fact that high opaque clouds include part of the thicker anvil which develop afterwards. After 9PM cirrus anvils continue to develop. Over ocean convection often occurs in the early morning (e. g. Zipser et al., 2006;





Wall et al., 2018), which is followed by a high opaque cloud maximum around noon. This cirrus have a similar diurnal cycle over ocean and over land which lets assume that part of these this cirrus are formed by in situ freezing.



5 Fig.3. Comparison of average diurnal cycles of high-level cloud amount over three latitudinal bands estimated from CATS lidar observations (Noel et al., 2018) and from AIRS/IASI. CATS statistics only includes June, July, and August (JJA, red curves) whereas AIRS/IASI results are shown both for boreal summer (JJA, blue curves) and boreal winter (December, January and February, DJF, green curves) in 2008–2015. The correlation coefficients between AIRS/IASI and CATS for JJA are marked in black; the peak local times for CATS are marked in red, and for AIRS/IASI in blue. a) 30N–60N, ocean; b) 30N–60N, land; c) 15N–30N, ocean;

10 d) 15N-30N, land; e) 15S-15N, ocean; f) 15S-15N, land.







Fig.4. Diurnal cycle of high opaque, cirrus, and thin cirrus amount in in NH midlatitudes, NH subtropics and tropics in boreal summer: a) 30N-60N, ocean; b) 30N-60N, land; c) 15N-30N, ocean; d) 15N-30N, land; e) 15S-15N, ocean; f) 15S-15N, land. The AIRS/IASI statistics is averaged for 2008-2015.

5 3.2. **Geographical distributions**

We first present geographical maps of phase and amplitude of the diurnal cycle of the high-level cloud types and then explore the links to their atmospheric environment. The latter includes surface temperature (T_{surf}) and upper tropospheric (UT) relative humidity (RH), the parameters, which are both linked to their formation and then affected by the clouds.

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- We apply the approach described in Section 2.2 to cloud statistics gathered at grid cells of 1° latitude x 1° longitude, separately for January and July. To present the geographical distributions of diurnal amplitude and phase, we adopted the vector representation of diurnal amplitude and phase suggested by Cairns (1995) and also utilized in (Soden, 2000; Tian et al., 2004), where the vector's length corresponds to the amplitude of the diurnal variation and the phase is converted to a local peak time, represented by the direction of the vector. Since different cloud types are characterized by different diurnal amplitudes, a unit vector is added to the lower right corner of each panel. We consider the diurnal cycle to be reliably detected at a given





latitude/longitude, if the Pearson's correlation coefficient for the corresponding time series (see Section 2.2) is greater than 0.85, an empirical threshold based on examining numerous diurnal cycle plots.

Whenever we average the diurnal cycle parameters, we calculate the mean phase (or the peak time) using the corresponding amplitudes as weights. To avoid the error caused by averaging the phases in the vicinity of 24-0h transition (for example, direct averaging of 23h and 01h returns noon instead of midnight), we apply a "resulting force" algorithm (Appendix A).

- 5 averaging of 23h and 01h returns noon instead of midnight), we apply a "resulting force" algorithm (Appendix A). Figures 5 to 7 present detected diurnal variations for high-level clouds and relative humidity, for January and July. A common feature of all these maps is that the amplitudes of the diurnal variations maximize over the tropical belt and in the summer hemisphere midlatitudes. This is an expected behaviour consistent with other observations (e. g. Wyley and Woolf, 2002; Tian et al., 2004; Hong et al., 2006; Stubenrauch et al., 2006). Compared to the Figs.5 and 6 of (Hong et al., 2006), the peak times
- 10 differ by 2 to 3 hours, but the direct comparison is hindered by the methodological (separating the clouds by brightness temperature selects only the coldest and relatively opaque ones compared to using the emissivity thresholds) and by spatio-temporal averaging differences. Another expected feature is the magnitude of diurnal change over land being generally larger than that over ocean: this can be explained by less strong convection (e. g. Tian et al., 2004; Zipser et al., 2006), as the ocean surface temperature has a much smaller diurnal cycle (Fig. B1 in the Appendix B).
- 15 The clouds identified by the CIRS retrieval as high opaque ones, for which a diurnal variation is detected, have an average diurnal amplitude of about 5%, but certain regions (Fig.6a, 7a) demonstrate amplitudes reaching 10%. The diurnal variation of cirrus clouds (Fig.6b, 7b) is larger than that of high opaque clouds: the average amplitude is ~8%, with some regions reaching the values of 12% and individual grid cells showing amplitudes of up to 20%. It is interesting to note that over some regions, for which the diurnal cycle in high opaque clouds was not detected, cirrus clouds show a clear signature of the diurnal
- 20 variation. This is explained by the much larger amount of the latter (Fig.1). The relatively small amount of high opaque clouds (about 5%) provides a "noisier" input. On the other hand, large "blank" areas in the winter hemisphere with no detected diurnal variation assure us that the algorithm is stable against false triggering provoked by noise.

In general T_{surf} over land is maximum between noon and 13h. High opaque clouds, often associated with deep convective cores in the tropics, have a large regional variability, which may be influenced by orography. Convection moves with the Intertropical

- 25 Convergence Zone (ITCZ) towards the summer hemisphere, with peak times between 18h and midnight. In July, there is a large contrast between oceanic peak times around noon and continental ones in the evening around 20h, in the Asian monsoon regions and in the Caribbean, while in January the peak time over Indonesia is during night. There is less contrast between land and ocean for the cirrus and thin cirrus peak times: with continental peak times between midnight and 2h and oceanic ones around 18h. Over land, a lag of about 3 hours can be identified for two thirds of the cases (see also Section 3.3.). It seems
- 30 to be more complicated to identify lags over ocean, with a maximum of cirrus in the evening. Thin cirrus have a maximum at midnight over ocean, lagging behind cirrus, which can be interpreted as the thinning of convective systems during night. Over land the situation is a bit more complicated, with a maximum after noon in large mountain areas (Rocky Mountains, South America, Africa and Asia) and some lagging behind cirrus, again to be interpreted as thinning of convective systems. UT





relative humidity seems to be maximum in the convective regions just a few hours after the maximum of cirrus and thin cirrus, as observed by (Horvath and Soden, 2008).



Fig.5. Diurnal variation of (a) high opaque clouds, (b) cirrus clouds, and (c) thin cirrus clouds estimated from AIRS/IASI for
January. Statistics is averaged over 2008 to 2015. Vector length is proportional to the amplitude and its orientation defines the local time of the peak: downwards for 0h, left for 6h, upwards for 12h, and right for 18h. For the sake of readability, the arrows are also coloured in tints of red for day 6h–18h and in tints of blue for night 18h–6h.







Fig.6. Diurnal variation of (a) high opaque clouds, (b) cirrus clouds, and (c) thin cirrus clouds estimated from AIRS/IASI for July. Statistics is averaged over 2008 to 2015. The vector representation is consistent with the caption of Fig.5.







Fig.7. Diurnal variation of average relative humidity in a layer 150 hPa below the tropopause, estimated from ERA-Interim reanalyses, a) for January and b) for July. The vector representation is consistent with the caption of Fig.5. The tropopause level was determined in accordance with (Reichler et al., 2003).

5 **3.3.** Specific regions

Since different geographical regions are characterized by different cloud regimes (e. g. Rossow et al., 2002), we define seven regions over land, presented in Fig.8, which we analyse more in detail. Regions 1, 3, 5 and 6 are in the Northern midlatitudes and subtropics / tropics, while regions 2, 4 and 7 are in the Southern subtropics / tropics. The regional amplitudes and peak times of cloud types, T_{surf} and UT relative humidity are summarized in Tables 1 and 2 and illustrated in Fig.9 which presents circular histograms of the peak amplitude local times, separately for January and July.

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The two regions in the Northern midlatitudes (1 and 6) show a large difference in the T_{surf} amplitude, with a larger one in summer. The regions which are affected by the ITCZ (2, 4 and 5) have a slightly larger T_{surf} amplitude in summer, while the two regions in the subtropics (3 and 7) show a a large T_{surf} amplitude both in January and in July. In general, a strong convective





activity is revealed by a very large diurnal cycle in the occurrence of high opaque clouds (more than 10%). This is the case for regions 2 and 4 in January and for regions 4 and 5 in July.



Fig.8. Regions selected for a more detailed analysis of the cloud diurnal cycle over land: 1 – North America, 2 – South America, 3 – 5 Northern Africa, 4 – South Africa, 5 – South Asia, 6 – North/East Asia, 7 – Australia.

The two regions in the Northern midlatitudes (1 and 6) show a large diurnal cycle in T_{surf} in summer (about 10 K), leading to some convective activity (diurnal cycle of high opaque clouds of about 7% and 5%, respectively) in the afternoon. However, multiple peak amplitude local times indicate effects of orography. The signals for cirrus and especially thin cirrus are more evident, with similar peak amplitudes and more concise peak amplitude local times in the early afternoon. The thin cirrus may

- 10 be orographic cirrus. UT relative humidity has two peaks, one in the early morning (5h) and one in the afternoon (17h), in both cases the afternoon peak lagging shortly behind cirrus and thin cirrus and the early morning peak lagging behind high opaque clouds during night. During winter, the diurnal T_{surf} amplitude is much smaller (about 5 K), and no diurnal cycle could be detected in high opaque clouds. The diurnal cycle in UT relative humidity has opposite peaks, again at 5h and 17h. Over North America, cirrus has multiple peaks while thin cirrus has a peak around 13h and a smaller one in the morning (7h), while over
- 15 North-East Asia there is one peak detected in cirrus around 14h. It is difficult to relate the UT humidity clearly to the cirrus during winter.

The two other regions in the Northern hemisphere are subtropical (3) and tropical (5). While the diurnal T_{surf} cycle is large both in January and in July (11 K) over North-West Africa, it is large (10 K) during the summer monsoon over the Indian subcontinent, while it is smaller (4 K) in January, when the ITCZ moves southwards. The diurnal behaviour of UT clouds is

20 quite different between these regions, whereas the peak amplitude times in UT relative humidity are similar (17h in winter and 5h in summer). In the subtropics, in summer there seems to be some convective activity with a peak time in the evening (21h - 24h), followed by the development of cirrus and thin cirrus during night (2h), whereas in winter no diurnal cycle of high opaque clouds could be detected, and cirrus and especially thin cirrus have multiple peak times. The summer monsoon over the Indian subcontinent leads to a peak amplitude time of high opaque clouds in the early evening, indicating convective





activity, followed by the development of cirrus anvils in the night and thin cirrus until noon. In January, the amplitude of the diurnal cycle of high opaque clouds is only half and later during night, while thin cirrus develop already in the morning, thickening towards cirrus in the afternoon.

			Januar	У		July					
variable zone	Tsurf	Conv.	Thick	RH	Thin	Tsurf	Conv.	Thick	RH	Thin	
N. America	8	N/D			•		,	7		0	
NE. Asia	J	N/D	1		N/D			9		9	
NW. Africa	8	N/D	8	~	2	0	*			8	
Indian cont.	0		1	~	-	8	-				
S. America	ð						7	-		2	
Africa	0						%			A	
Australia	ð	2	-				N/D	N/D	N/D	N/D	

5 Fig.9. Circular histograms of local time of peak amplitude for T_{surf} , high opaque clouds, thick cirrus, relative humidity (RH), and thin cirrus for average January and July. The convention for vector direction representation is consistent with that described in the caption of Fig.6 while the amplitude is proportional to normalized histogram count number. "N/D" marks the cases, for which the diurnal cycle could not be reliably detected.

Comparing the tropical regions in the Southern hemisphere, South America has a slightly smaller diurnal amplitude of T_{surf} than the African region (5 K compared to 7 K), as the latter also includes subtropical land and the former is part of the 'Amazonian green ocean'. In summer (January), maximum convective activity in South America seems to be from 15h on, with cirrus and thin cirrus during night. Thin cirrus also has another peak amplitude in parallel with high opaque cloud between noon and 18h. Over Africa the diurnal behaviour is similar. In winter (July), the peak amplitude times of high opaque clouds are again later, with cirrus during night and again thin cirrus at multiple times.





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For Australia, a diurnal cycle was only detectable in summer (January), with two peaks in high opaque clouds and in cirrus (19h and 1h) and a peak in thin cirrus in the early afternoon.

Table 1. Diurnal cycle amplitude and local time of the peak for T_{surf} , high opaque clouds, thick cirrus, thin cirrus, and relative humidity for average January. Long dash symbol (–) means that no reliable cycle was detected while a star symbol (*) corresponds to multiple peaks in the circular histogram (see Fig.9)

Variable	T _{surf}		High opaque		Cirrus		UT Relative humidity		Thin cirrus	
Geographic area	Ampl. [K]	Peak [h]	Ampl. [%]	Peak [h]	Ampl. [%]	Peak [h]	Ampl. [%]	Peak [h]	Ampl. [%]	Peak [h]
N. America	4.6	12.3	-	-	5.8	6-12	3.8	5; 17	5.2	7-13
N. E. Asia	6.3	14.0	-	-	7.4	15.1	3.3	5; 17	-	-
N. W. Africa	11.0	12.3	-	-	5.9	-	2.2	16.4	5.2	*
Indian cont.	9.7	12.0	5.7	22-2	5.3	15.2	1.8	17.9	4.8	9-15
S. America	4.9	12.5	7.5	16.1	12.8	23.3	5.2	5.0	7.3	13-19
Africa	6.9	12.7	7.9	17-22	12.2	1.3	4.4	4.8	7.8	*
Australia	11.3	12.1	7.5	20.3	8.2	19; 1	2.0	5.5	6.2	15.5

Table 2. Same as Table 1, but for average July.

Variable	T _{surf}		High opaque		Cirrus		UT Relative humidity		Thin cirrus	
Geographic area	Ampl. [K]	Peak [h]	Ampl. [%]	Peak [h]	Ampl. [%]	Peak [h]	Ampl. [%]	Peak [h]	Ampl. [%]	Peak [h]
N. America	10.5	11.8	7.2	14-2	7.7	16-24	2.9	5; 17	7.5	14.8
N. E. Asia	8.3	12.0	5.2	*	6.8	15.7	2.8	5; 17	6.4	15.9
N. W. Africa	11.0	12.5	6.9	22.7	8.1	1.4	2.7	4.9	7.3	2.3
Indian cont.	4.3	11.9	8.3	19.5	11.7	22.7	4	5.3	8.0	*
S. America	5.6	13.2	8.1	1.0	8.8	21.2	2.9	5.1	6.3	18.9
Africa	7.8	13.4	7.7	22.1	11.2	1.2	3.5	5; 17	7.0	*
Australia	8.5	12.6	_	_	_	_	1.5	5; 17	_	_

In general, UT relative humidity has a peak in the early morning for regions of convection, which may be explained by UT humidification from the dissipation of the anvils (e. g. Horvath and Soden, 2008). In winter, there seems to be a peak in UT relative humidity in the afternoon, often also just after the appearance of thin cirrus, which this time seems to be formed by in

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For the regions where diurnal variation was reliably detected both for high opaque clouds and for cirrus, the diurnal cycle amplitudes of these two cloud types are correlated with k_{corr} =0.75. This can be probably assigned to being part of the same cloud system. Even though peak times for cirrus clouds vary almost in the same limits as those of high opaque clouds do, an average lag of ~3 h can be identified for two thirds of the cases. We have to note that in certain cases the definition of the lag

5 becomes ambiguous due to possible 24 h phase shift, which is not detectable in our approach. For example, the 15 h peak in January histogram for thick clouds over South Asia (Fig.9) can be caused both by *in situ* formation of high clouds 4 hours after the peak of local insolation and by an outflow of the high opaque column with a characteristic time of ~16 h (the lag between high opaque and cirrus cloud peaks).

Another presumable element of the cloud system lifecycle is the dissipation of the anvil. This can be manifested both in the

- 10 RH change (Fig.8) and in thin cirrus variation (Fig.6c, 7c). The peak time of RH "release" from the cloud oscillates between late afternoon and early morning maxima (Kottayil et al., 2016) and its lag with respect to cirrus can be estimated as ~3.5 h. Finally, thin cirrus show good coupling with high opaque clouds and the cirrus, and the amplitudes of their diurnal cycle are comparable with those of the cirrus. The peak times for these clouds have broad distributions that makes it difficult to estimate the lags. We assign this to long characteristic times of anvil dissipation and to mixing the effects of *in situ* and convective
- 15 outflow cloud formation mechanisms: air parcels saturated with water vapour released in the process of anvil dissipation may travel to other areas and form clouds there. For the cases when the peak time distribution is narrow, the average lag with respect to anvil can be estimated as ~10 h, but the individual values vary from almost zero to 20 h.

These lags and correlations indicate that the convective cloud life cycle might be described as follows: (a) the convective cloud peak time precedes the cirrus anvil formation; (b) the cirrus anvil dissipates, releasing water vapour and turning to thin cirrus;

20 (c) both the cirrus anvil and thin cirrus are strongly coupled with the high opaque core; (d) relative humidity is strongly coupled with the cirrus.

4 Conclusions

Multi-spectral infrared sounders are advantageous for the retrieval of the high-level cloud properties. Their good spectral resolution allows a reliable cirrus identification down to an IR optical depth of 0.1, day and night. However, these instruments

25 are mostly onboard polar orbiting satellites, providing only observations twice per day. In this article, we present the synergy of AIRS and IASI observations, allowing to address the diurnal variation of high-level cloud cover, and separately for high opaque, cirrus, and thin cirrus clouds.

Based on previous studies (Stubenrauch et al., 2017), we needed to implement the same set of ancillary data (from meteorological reanalysis ERA-Interim) to extract a reliable diurnal cycle from the measurements performed by different

30 satellite instruments. We demonstrated the feasibility of determining the diurnal cycle amplitude and phase from just four measurements per day using the "sliding profile approach", which is based on the correlation of a measured variation with an assumed shape of the diurnal cycle. For the combination of AIRS and IASI, this approach allows estimating the diurnal





variation phase with an accuracy of ± 1.5 h while the amplitude is determined with ~20% accuracy. The zonally averaged diurnal cycle of high-level clouds retrieved from AIRS and IASI measurements compares relatively well with the one determined from CATS lidar observations, the latter of more limited statistics. Linear correlation coefficients reach 0.9 over land and 0.75 over ocean and the amplitudes are of the same order of magnitude. It is interesting to note that the local time of the minimum

5 moves from the summer hemisphere midlatitudes towards the tropics from 6h to noon and the one of the maximum from 17h to 1h. This means that the A-Train orbit captures the minimum and maximum cloud cover over tropical land.

Geographical maps of detected diurnal variation separately for high opaque, cirrus and thin cirrus often show a different behaviour, which indicates the importance to distinguish these different cloud types, also as they have different radiative effects. In general the amplitude of the diurnal cycle is larger over land than over ocean and largest in the tropics, followed by

10 summer midlatitudes, in agreement with other analyses.

A more detailed analysis of specific regions over land has shown that the largest diurnal cycle seems to prevail during summer monsoon over the Indian subcontinent with 8.3% for high opaque clouds, 11.7% for cirrus, and 8.0% for thin cirrus clouds. The local peak times vary with cloud type, season, and location. Lags and correlation coefficients between high opaque, cirrus, thin cirrus and UT relative humidity indicate a life cycle of continental tropical convective systems as: (a) the convective cloud

peak time precedes the cirrus anvil formation; (b) the cirrus anvil dissipates, releasing water vapour and turning to thin cirrus;(c) both the cirrus anvils and thin cirrus are strongly coupled with the high opaque core.

Author contribution

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Artem Feofilov performed the cloud property retrievals from AIRS and IASI observations, developed the methodology of diurnal variation retrieval from the combination of two infrared sounders, and analysed the data. Claudia Stubenrauch compared the retrieved diurnal variations with those retrieved from CATS lidar, performed the zonal analysis and established

Acknowledgements and Data

the links between the cloud system elements.

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25 clouds (high opaque, cirrus and thin cirrus), at a spatial resolution of 1° latitude x 1° longitude, from the AIRS-IASI synergy will be distributed by the French Data Centre AERIS.





Appendix A: Resulting force algorithm

To avoid error caused by averaging the phases in the vicinity of 24-0h transition (for example, direct averaging of 23h and 01h returns noon instead of midnight), we apply a "resulting force" algorithm, which is resembling the calculation of the tilt of a disk with masses on its edges (Fig. A1): the positions of the "masses" on the disk's perimeter correspond to phase values while

5 the masses themselves are proportional to the amplitudes. When everything is set up and the disk is "released", the direction of the tilt defines the average phase (arrow in Fig. A1b).



Fig. A1. Illustration of "resulting force" algorithm for calculating the average of phase values: a) diurnal cycle amplitudes are used as "weights" (black dots of different sizes), which are placed on the perimeter of the disk in accordance with the corresponding phase
 values; b) when "released", the disk tilts in the direction of the most frequent phases with the strongest amplitudes.







Appendix B: Diurnal variation of surface temperature

Fig. B1. Diurnal variation of surface temperatures, estimated from ERA-Interim reanalyses, in January (top) and in July (bottom). The vector representation is consistent with the caption of Fig.5.

5 We searched the parameters of diurnal variation of surface temperature using the shape provided by (Aires et al., 2004), which we approximate as follows:

$$A(t) = 0.95 \cdot \left[\frac{1}{t^2 + 15} + e^{-0.08 \cdot (t - 13.2)^2} + 0.04 \cdot t\right]$$
(B.1)

where the amplitude A(t) is in [K] and time t is in [h] and the coefficients come from the best fit approximation. As one can see (Fig. B1 and Tables 1 and 2), the amplitude of T_{surf} variation over land is large in tropical areas and in the summer

10 hemisphere, reaching 20 K in the deserts (the doubled amplitude corresponds to $max(T_{surf}) - min(T_{surf})$ temperature span) while the variation over ocean is mostly negligible. The absolute values of the T_{surf} variation agree with those reported in (Goetsche and Olesen, 2001; Pinker et al., 2007; Duan et al., 2014; Holmes et al., 2015; Ruzmaikin et al., 2017). The spreading of the diurnal cycle from coastal regions out to surrounding oceans has been noted already in (Yang and Slingo,





2000) who suggested a complex land-sea-breeze effects as an explanation. The local time of the peak is quite stable in all areas where the diurnal cycle was detected, both in January and July, and we estimate the interannual variability for the T_{surf} peak time for each zone to be ~0.5 h. Depending on the geographical area, T_{surf} peak time changes within 11.8–14.0h limits, and possible mechanisms of the lag with respect to peak of solar insulation are discussed in (Ait-Mesbach et al.2015).

According to their simulations, the soil thermal inertia "impacts directly the amplitude of T_{surf} variation with lower thermal 5 inertia inducing higher amplitude (and vice versa)". Their study shows that thermal inertia also impacts the turbulent heat fluxes.

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