Response to Reviewer #1

We thank the Reviewer #1 for his/her positive assessment of the manuscript and for the corrections. Below, we provide point-by-point answers to each of the comments. We mark the reviewers' comments/questions and the authors comments/responses by "**RC:**" and "**AC:**", respectively. Where it was appropriate, we modified the text of the manuscript in accordance with the recommendations.

General comments

RC: The first two paragraphs of the introduction lack a few references.
AC: Following the recommendation of the second reviewer, we have removed the first paragraph.

RC: p. 3, l. 21: CIRS has already been described and Stubenrauch et al., 2017 already cited higher on the same page (l. 1 and 2, respectively), please fix
AC: Perhaps, the reviewer was misled by the same name, but CIRS cloud climatology described in the beginning of the page is not the same as the CIRS cloud property retrieval package discussed in this line and (Stubenrauch et al., 2017) refers to both of them, so the reference should remain.

RC: p. 5, l. 19: "the phase shift... was found": by who? Is this part of your results?
AC: Yes, we parameterized the curves of (Cairns, 1995). We changed the text to "By analysing the plots of (Cairns 1995) using least-square fitting of Eq. 1 we found that the phase shift $\Delta\varphi$ is equal to −2 h for the low- and mid level clouds and 0 h for high-level clouds"

RC: p. 5, l. 24: the "moving profile" approach is quite smart, did the authors invent it? If so please state it, otherwise provide a reference to previous use.
AC: We did not perform a search in literature for this approach and we cannot state that this is our "invention". We added a reference to (Goldberg et al., 2013) where a similar approach was used by one of the authors to find the period and phase of the interhemispheric coupling.

RC: p. 7, l. 25: "This justifies using Eq. (1) for the analysis." The experiment described between l. 20 and 25 justifies using Eq. (1) for the analysis *over the 24-h harmonic function selected by the authors*. It does not prove that Eq. (1) is the best function to use for the analysis. For instance, it would be possible to conjure many additional functions which might prove a worse fit than Eq. (1), but it would still not justify Eq. (1) as the best choice for the analysis. I understand the authors explain that searching for a better function is beyond the scope of the paper in the following sentence, and I'm fine with that, but the statement above is still incorrect. Unless I have misunderstood, please revisit the reasoning of this paragraph and make it more robust.
AC: We'd like to refer the Reviewer #1 to a plot we provided in the answers to the questions of Reviewer #1, Fig. R2-1a, which illustrates the aforementioned experiment performed using *real data*, and not for the *function selected by us* (the latter would give a perfect fit with all correlation coefficients equal to 1). As one can see, if the clouds exist (right-hand side of the plot), the "natural noise" related to uncertainties of the ancillary data and cloud retrieval methodology as well as to errors of parameterization given by Eq.1 leads to cases, for which the correlation coefficient is lower than 1. Still, the "semidiurnal fit" which corresponds to Eq. 1 gives higher correlation coefficients than a simple harmonic fit. The smoothness of the "tail" of the histogram and the general considerations regarding noise tell us that any other fitting function will not give a perfect fit, either and we are already close to good fitting.
To avoid the confusion, we rewrote the introductory sentence: "…we have performed the following numerical experiment using real data: one year of cloud data retrieved from AIRS and IASI with the help of CIRS has been processed…"

RC: section 3 : High clouds are identified unambiguously in CATS data by the altitude from which the lidar signal is backscattered to the instrument. This is not the case for the cloud detections documented in the AIRS/IASI dataset. Could you

comment on how the uncertainties in cloud altitude in the AIRS/IASI dataset might affect the retrieved diurnal cycle of high clouds in one way or another, and if these effects are consistent with the differences with CATS results?
AC: This is a good question and it requires several references to be answered. In Fig. 2 of (Feofilov and Stubenrauch, 2017) we provide the basics for the cloud pressure error estimate in chi2-retrievals. As one can see, for high clouds, due to larger contrast between the radiation of the cloud and that of clear sky scene, the chi2-curve is steep and the pressure error is small. Correspondingly, the emissivity error is small, too (emissivity curve is estimated in P±ΔP points). In Fig. S3 of (Stubenrauch et al., 2017), the cloud heights retrieved from AIRS are compared with those from CALIOP and they show quite a good agreement and stability over the whole range of cloud emissivity. Finally, in Fig. R1-1ab we show the emissivity error and pressure error distributions for high clouds. As one can see, both errors are small and therefore they should not affect high cloud determination accuracy to a significant degree.

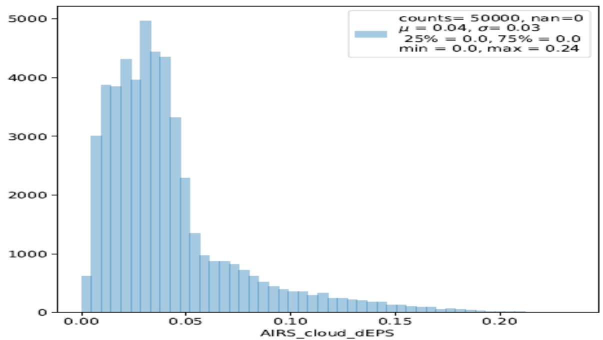


Fig. R1-1a. Emissivity error histogram for high clouds

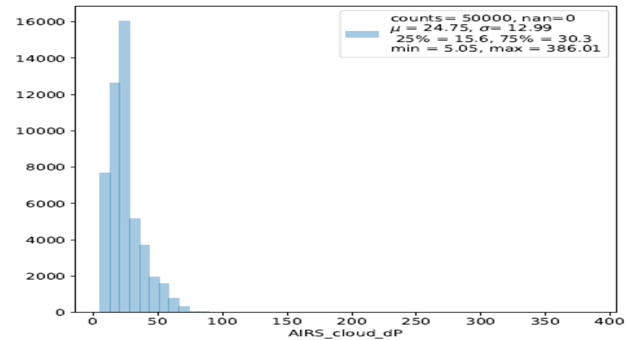


Fig. R1-1b. Pressure error histogram for high clouds

RC: section 3, figure 3: the comparison with CATS is interesting, but how do the AIRS/IASI cycles compare with the ISCCP daily cycles described by Rossow and Schiffer 1999? Their results are presented as part of the introduction, why not compare them to the AIRS/IASI results in addition to CATS in Fig. 3?
AC: We followed the advice and added the curves of (Rossow and Schiffer, 1999) to Fig. 3 and modified the text correspondingly. The behavior of all three curves over land is quite consistent whereas the ocean areas with their weak amplitudes show moderate agreement.

RC: p. 11, l.9: Wyley -> Wylie
AC: Fixed, thanks.

RC: Fig. 6: A more direct legend would be "Same as Fig. 5 for July"
AC: We have changed the legend following the advice.

RC: p. 18, l. 10: "(Fig. 8)" -> Fig. 9? (Fig. 8 shows the land regions)
AC: Actually, we meant Fig. 7, relative humidity, but anyway thanks for pointing out this inconsistency.

RC: p. 19, l.17: Maybe a dumb question, but who wrote the paper?
AC: Originally, the draft of the paper was written by the first author, but then the paper converged to its final form in the course of several iterations, so now it is difficult to assign this or that part of the text to this or that author.

RC: p. 19, l.26: Where were the CATS data shown in Fig. 3 obtained?
AC: We took the data directly from the plots of (Noel et al., 2018) by digitizing them with the help of freely distributed Tracer 2.01 software by Marcus Karolewski (https://sites.google.com/site/kalypsosimulation/Home/data-analysis-software-1). In manual mode, the accuracy of digitizing is one screen pixel that is about 0.1% of the full scale of the digitized value.

RC: p. 24, l.30: I tried getting the Wylie and Woolf paper by following the doi link but it does not work. Please fix it.

AC: The official doi copy-pasted from the journal's Web-site looks as follows: https://doi.org/10.1175/1520-0493(2002)130<0171:TDCOUT>2.0.CO;2 and if clicked it opens the page with the article (checked on the 25/08/19). Perhaps, a space or some other symbol spoiling the hyperlink was introduced on the author's or ACPD' side while formatting the file for online publishing. We believe, this will be checked and fixed by the production team when it comes to publication, but anyway, we've updated the link in the text.

Response to Reviewer #2

We thank the Reviewer #2 for his/her thorough analysis of the manuscript and for the corrections. Below, we provide point-by-point answers to each of the comments. We mark the reviewers' comments/questions and the authors comments/responses by "**RC:**" and "**AC:**", respectively. Where it was appropriate, we modified the text of the manuscript in accordance with the recommendations.

General comments

RC: 1) Description of fitting technique / section 2.2
Question 1A) Is delta_phi for all your high cloud analysis fixed to 0?
AC: Yes, it is. We added the sentence clarifying this in the text right after the Eq. 1.

RC: Is this value of 0 also based on Cairns 1995? (If yes please make this clear in the text, and otherwise explain how this value is determined)
AC: Yes, both values come from the figures of Cairns, 1995. We added an explanation to the text.

RC: Assuming the answer to 1A above is yes, I suggest you modify the text (starting somewhere around page 5 line 20) to read: "With the A12/A24 set to 0.28 and delta_phi set to 0, the diurnal "shape" of Eq. (1) is fixed (see the gray line in Fig. 2a) and the problem reduces to one of determining the amplitude A24 and phi_24. There are four total measurement (measurements at four times of the day) and the problem is therefore overdetermined. Thus we determine the best fit amplitude and phase using a "sliding profile approach", as depicted in Fig 2 and described below."
AC: Strictly mathematically, the problem of two variables and four measurement points is overdetermined. However, with the shape as in Fig. 2a and realistic measurement errors one can easily show that 2 measurements per day are not enough to retrieve the parameters of the diurnal cycle (e.g. one can fix the first and the third points at 0.5 and the positive and negative phases would give the same solution). The suggested phrase about the "overdetermined problem" can create a feeling that the information coming from the second satellite is redundant.
To avoid this, we modify the suggested text to "With the A_{12}/A_{24} set to 0.28 and $\Delta\varphi$ set to 0, the diurnal "shape" of Eq. (1) is fixed (see the grey line in Fig. 2a) and the problem reduces to one of determining the amplitude A_{24} and φ_{24}. Two satellite instruments provide us with measurements four times of the day, and we determine the best fit amplitude and phase using a minimization technique based on the "sliding profile" approach as depicted in Fig. 2 and described below." We believe that this text informs the reader about all necessary details.

RC: As regards the description of Figure 2 and the fitting process:
Page 7, line 13-15. I don't follow this description. Please rephrase. Why should a cloud fraction value of 0.2 yield a zero over zero? Does this mean the first red point in Fig 2c (near 1 UTC) is not used in the amplitude calculation?
AC: We have rephrased the text. As for the cloud fraction of 0.2 – the A(t) which is discussed here comes from Eq. 1 where the function changes sign and the amplitude is determined with respect to some virtual "zero line". Correspondingly, taking the values close to this line and building their ratios will lead to errors and therefore should be avoided.

RC: It is in no sense obvious to me that your sliding profile approach is any better than doing a least squares fit or any other minimization approach. Not that I think that it needs to be better, per se, but if you have a specific rationale for developing this approach rather than using established techniques for over determined problems it would be good to explain such
AC: This is a good point in the sense that the information content of the measured signal is always the same. However, the classical minimization approach applied here would operate in 2D space with the same weights for both variables giving less control over the retrieval. In our approach, we separate the variables and give the first priority to the phase because we believe that this is more important for understanding the mechanisms driving the cloud formation. In this case, the sensitivity of the problem to phase is directly visualized as the first fitting parameter and this makes it easier to explain as we can tell from our experience of presenting it to colleagues at different conferences. However, indeed, one should be able to retrieve close values using a different approach. We added an explanation to the text before the paragraph justifying the choice of the function.

RC: 2) Uncertainty in diurnal amplitude and phase due to ASSUME A12/A24 ratio and delta_phi. You assess the uncertainty in your results due to the impact of a 20% random uncertainty in the cloud fraction, the result of which is a 20% uncertainty in the amplitude (which is not surprising) and 1.5 hours uncertainty in the phase. This is a GOOD result! But what about the assumed values for A12/A24 and delta_phi? I can easily imagine that even a small change in either of these assumed values might have a large impact. In particular, I expect these values might have spatially coherent regional variations that might impact your later analysis.

AC: This is an absolutely valid question, the answer to which is partially given at the end of the section 2.2 where we discuss the harmonic fit. For the sake of simplicity we did not include in the manuscript the figure resulting from this numerical experiment, which we provide below (Fig. R2-1a). The numbers in this plot tell us that the real data can be better fitted with Eq. 1 than with a simple harmonic fit. To demonstrate the sensitivity of the retrieved amplitude and phase to the assumptions, we also performed a numerical experiment where we tried to fit the original function given by Eq. 1 using the simulated functions, for which we varied A_{12}/A_{24} in the limits from 0 to 0.5 and $\Delta\varphi$ from 0 to 24 hours.

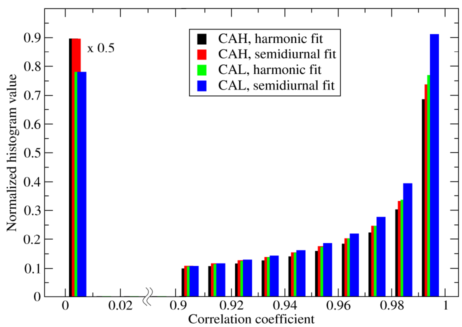


Fig. R2-1a: justifying the fitting function

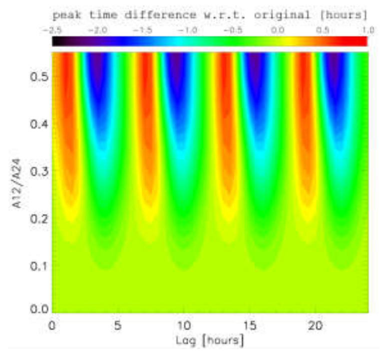


Fig. R2-1b: estimating the effects of A_{24} and $\Delta\varphi$ uncertainties on peak time definition

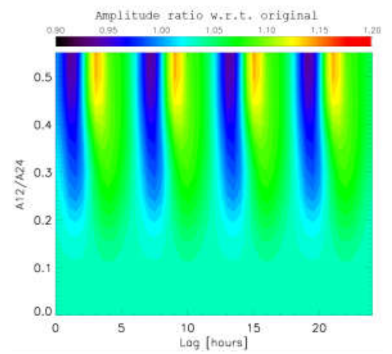


Fig. R2-1c: estimating the effects of A_{24} and $\Delta\varphi$ uncertainties on the retrieved amplitude

As one can see from Fig. R2-1bc, varying A_{12}/A_{24} up to 0.35 does not induce more than a 0.5 hour shift in the peak time definition for any of the $\Delta\varphi$ value. The most unfortunate combinations of A_{12}/A_{24} and $\Delta\varphi$ result in up to 2 hour shift, but there is no reason to believe that these combinations are realistic given that Eq. 1 provides a good quality fit (Fig. R2-1c). In the same way, the retrieved amplitude error rarely reaches 10%, so if we combine these values with the ones caused by the random uncertainty in the cloud fraction, this will not significantly change the uncertainty estimates given in the manuscript (20% uncertainty turns to 22% and 1.5 hour uncertainty turns to 1.6 hours). If the reviewer prefers to have this information in the methodological part, we can update these numbers and add an explanation. We can also add some or all of the panels of Fig. R2 to the Supplement.

RC: 3) Uncertainty due to sampling variability. I am very surprised to see that you do not discuss the sampling variability. Is the sampling variability small relative to the diurnal variations? For example, if you plotted the same result using any randomly chosen 5 or 8 years of data (rather than all 10 or 15 years) would all the results be so close together that I couldn't see any differences in any of the plots or values presented in Tables 1 and 2?

AC: We believe that one has to distinguish the methodological uncertainty, which is based on monthly data and which is discussed above, from the uncertainty caused by averaging the diurnal cycles over the years, which we do not discuss for the sake of simplicity. Of course, the averaged plots shown in Section 3.2 will slightly change if we remove some of the years, but their purpose is to give a general overview of what to expect from our data, which will be provided independently for each month.

RC: 4) What is new here? Do the results of the diurnal analysis differ from results of prior observational studies or extend our understanding of the diurnal cycle in some way? While reproducibility of results is an important aspect of science and having

some “new result” is not strictly necessary, I think the article would be more interesting if it does. In general, more concrete discussion on how the results are similar (or not) to other studies would make the analysis more valuable
AC: Indeed, there are no groundbreaking findings in this work, but we highlight the following features, which have not been done before: (i) retrieving a consistent cloud dataset from two instruments using the same principle, but different wavelengths, instrumental functions, footprints, etc. – this is not trivial because any issue in the cloud retrieval methodology will wash out any subtle effect like diurnal variation; (ii) the diurnal cycle retrieval approach from 4 measurements per day in the infrared is also new; (iii) the results confirm the observations made by other satellite instruments (we have added a discussion and modified some plots) and are free of different day vs night sensitivity issues (see the discussion of CATS and ISCCP); (iv) the results show the correlation and lags between the elements of the convective system. The suggested detailed comparison with other instruments is not straightforward because the sensitivity of different instruments to cloud thickness is not the same (see GEWEX report, Stubenrauch et al., 2012). On the other hand, we validate our results using the data from the active sounder (CALIOP lidar) that gives confidence for the clouds with the emissivity in the 0.1–0.95 range and we also compare the zonal averages with diurnal cycle retrieved from ISCCP observations. In addition, in the new Section 3.4 we relate the amplitudes of diurnal cycle to climate fluctuations.

Minor comments

RC: Introduction, first paragraph: I know this is well known material, but if you are going to start off a publication with such, you ought to support the material with appropriate references. Frankly, I think you might just drop this first paragraph and start the introduction with the second paragraph “Due to the importance of clouds … “ (line 3, page 2).
AC: We have re-written the introduction taking into account the recommendation.

RC: Page 2, line 5. Starting phrase is awkward, I suggest change to read simply, “The diurnal variation modulates …” .
AC: The phrase has been modified as suggested, thanks.

RC: Page 2, line 8. Perhaps change to "Many early global observational analyses ... ".
AC: This text has been re-written.

RC: Page 2. Line 10. Perhaps change “are significant” to “were found to be”.
AC: We have re-phrased this sentence.

RC: Page 2. Line 20-23. I think these three bullet points are also intended to apply to cloud over land in the tropics – and don’t for example apply to mid-latitude in the winter. Perhaps move the phrase “over land in the tropics” from the first bullet into line 18, or otherwise clarify.
AC: Thanks for noticing this inconsistency. The text has been modified.

RC: Page 4, line 1. What does “transformed” mean here?
AC: We have removed this word since it was related to technical processing, which does not explain much to the reader.

RC: Section 2.1. The spatial resolution of AIRS and IASI is coarse compared with most IR imagers. Perhaps it would be good to include some comments on how resolution impacts the cloud classes: high opaque (εcld > 0.95), cirrus (0.95 > εcld > 0.5), and thin cirrus (0.5 > εcld > 0.1).
AC: These concerns have been addressed in the articles we refer to in the manuscript, namely, Stubenrauch et al., 2010, 2017. Indeed, if the pixel is only partially covered with the cloud, the detected outgoing radiance represents a weighted sum of clear sky and cloud radiances, so we had to adjust the detection thresholds using nearly collocated CALIPSO and AIRS observations. With these adjustments, we obtained 85–95% hit rate for AIRS vs CALIOP cloud detection over land and oceans in the tropics and midlatitudes, which we consider to be a good result taking into account the difference in the footprint sizes of two instruments. In Fig. S3 of the supplement to Stubenrauch et al., 2017 we show the accuracy of cloud height detection versus the emissivity.

RC: Page 4, line 1. Also what does the correction to SST entail? If it is truly unimportant to the study results, then perhaps leave this line out. If it does matter, then you should probably explain a bit more.
AC: Again, this has been discussed in details in the article we are referring to (Stubenrauch et al., 2017), here we just remind the reader that we are not simply taking the surface temperature database with a known lack of diurnal variation. Even though it is more important for low level cloud retrievals and for the diurnal cycle of these clouds, which is not within the scope of current work, we do take care of these details. If the reviewer prefers, we can leave this line out, but in our opinion it makes sense to keep it.

RC: Page 4, line 5. Perhaps use "pixels" or "fields of view" rather than "scenes". To me "scene" implies a collection of pixels on some scale, for example a 60 km scene. As such a scene might have high-cloud even if only a fraction of the pixels contain clouds.
AC: We see the point, but we do not use the term "pixel" as it is linked with the imagers. The AIRS terminology names a bunch of measurements taken simultaneously a "golf ball", which consists of nine "spots", and we perform an individual retrieval for each of the spots, but to avoid the confusion we opted to generalize to "observations".

RC: Page 5, line 6. The word "admixture" seems a bit archaic to me and in general the idea of the diurnal cycle being a mixture of semi-diurnal cycles seems odd. Perhaps change to "... since variations in cloud amounts are known to include variations on both diurnal and semi-diurnal time scales."
AC: We agree with the suggestion, thanks.

RC: Page 7, line 1. What do you mean by "hit rate"? How does this translate into a 20% random noise?
AC: "Hit rate of X %" means that in X % of the collocated cases the cloud detected (or not detected) by AIRS was detected (or not detected) by CALIOP (hit rate is determined as a ratio of {(AIRS_CLOUD;CALIPSO_CLOUD)+(AIRS_CLEAR;CALIPSO_CLEAR)}/total_N). Correspondingly, if we take a pessimistic estimate of the probability of a wrong detection (100% minus the numbers of Stubenrauch et al., 2017), it should not exceed 20%. We added a brief explanation to the end of the paragraph.

RC: Page 7, line 3. Perhaps change "build the function" to "solve for A23 and phi_24". Also as far as I can see, you are only looking at high clouds in this study, so delta_phi is simply 0.
AC: We have added the comment regarding the delta_phi=0, but the suggested modification at the beginning the sentence does not match the algorithm: we build the function and then the solution is found in two steps. First, we move the function looking for the best phase shift and then we estimate the amplitude.

RC: Page 7, line 4. Perhaps change to "Having solved for phi_24, …"
AC: We modified the sentence to "Then we numerically solve the system for phi_24" to continue the algorithm and to specify that we are solving for two parameters.

RC: Page 7, line 13-15. I don't follow this description. Please rephrase. Why should a cloud fraction value of 0.2 yield a zero over zero?
AC: Please, see the answer to the same question in General comments. We have updated the text to make it clearer.

RC: Page 8, line 3. Change "… separately of high opaque …" to "… for high opaque …"
AC: We have changed the text.

RC: Figure 3. What is being "averaged" in Figure 3? Are the data being spatially averaged (if so what was the starting spatial scale)? Or temporally averaged (what time period)? For example do you first calculate the diurnal amplitude and peak time for each 1x1 latitude region (for each cloud type) using all years of data and then average spatially, or using 1 year of data and average in space and time ?
AC: For each zone, we first take the phase and amplitude value for a 1 lat x 1 lon monthly box already found and stored in our database, build the functions in accordance with Eq. 1 over 24 h with fine step, and average them. The resulting curve,

therefore, represents both temporal and spatial average. We have added a brief description of the averaging procedure to the text.

RC: Page 8, line 14. Early studies. Please provide specific references.
AC: We have added several references.

RC: Page 8, line 20. I presume you mean with the estimate 1.5 hours uncertainty. Perhaps clarify. (As a very minor point I note that 0 h to 22 h is a 2 hour difference, so perhaps just say, they agree to within 2 hours).
AC: Both statements are correct, so we have modified the text accordingly.

RC: Top of Page 9. What does "In situ Freezing" mean?
AC: By using this term we tried to distinguish the ice formation due to cooling of the upwelling humid air from the freezing of already existing water vapor due to local temperature decrease. To avoid the confusion, we changed the text to "some of these thin cirrus are formed locally having no relation to the convective systems."

RC: Page 8 / figure 4 Discussion. A) What about mid-latitudes? Don't they deserve some discussion? In particular, (A1) Over land, why are cirrus and thin cirrus cloud in phase and LEAD opaque cloud? This is very different than tropical/subtropical land. (A2) Over midlatitude land, diurnal variation of thin cirrus is larger than cirrus while the opposite is true for subtropics and tropics (where cirrus larger than thin cirrus). This is worth a comment, I think. (C3) Over mid-latitude ocean, are the relatively small variations real (larger than uncertainty)? If yes, does this mean that cirrus form more prominently overnight and thin during the day or might this be a retrieval artifact or ??
AC: This is a good point, but we don't think that one should compare the phases of the contribution curves and make the conclusions using only them. We provide these curves mostly to show the amplitude components of the total high cloud amount which we compare with the values retrieved from CATS and ISCCP whereas averaging the phase is a more subtle thing. Below in the text of the manuscript, we show that even for smaller areas the phase/amplitude diagrams (Fig. 9) are sometimes washed out and the phases of individual 1°×1° spots vary within several hours. When it comes to phases, we put more confidence in the individual 1°×1° values we show in Fig. 5-7 and in zonal averages calculated using a "resulting force" algorithm. In the present version of the manuscript we also have an updated discussion of Fig. 3 and Fig. 4.

RC: B) Subtropics ocean is similar to tropical ocean and subtropical land is similar to tropical land for boreal summer. This doesn't seem too surprising. What about boreal winter? Are subtropics similar to tropics in boreal winter? Similar to midlatitudes? Or differ from both? (Perhaps put NH winter and SH winter plots in supplementary material).
AC: Sorry, we didn't get this question – Fig. S1 of the supplement already shows the zones in the winter hemisphere and we mention this in the original text of the manuscript saying that the "amplitudes are close to zero in winter hemisphere". As one can see both from these plots and from Fig. 5 and 6, there's almost no material for the discussion for these zones.

RC: C) In general, is there anything here that is new or different from previous studies?
AC: The idea of building the CATS-like plots was twofold: (a) to validate our joint cloud retrieval + diurnal cycle retrieval methodology using the data from the active sounder and (b) to take advantage of the analysis performed by (Noel et al., 2018), who compared the diurnal cycle retrieved from the CATS observations with geostationary and ground-based observations. Basically, we show the consistency of our data with those of CATS and assume that we can extend the conclusions of (Noel et al., 2018) to our work. We also discuss and explain the similarities and differences between our results, CATS, and ISCCP diurnal cycles in this section.

RC: Page 11, line 2. 0.85 seems an arbitrary choice. I presume your results are NOT sensitive to this choice, meaning if you choose 0.7 it has little impact ? Please comment.
AC: The results cannot be insensitive to the choice because it is related to the goodness-of-fit and fitting 4 points with Eq. 1 and realistic noise resulting in k_corr equal to, let's say, 0.3 will never be equal to the fitting with 0.9. In the latter case, we have much more confidence that the retrieved diurnal cycle is not just a random function barely fitting the noise. Of course, k_corr=0.3 is an exaggeration and indeed the threshold of 0.7 still filters out pure noise, but the figures like, e.g. Fig. 5 become

more cluttered. So, we have chosen a threshold, which guarantees the presence of all main features and at the same time keeps the image “tidy”. We understand that this is a subjective criterion, that’s why we provide A24, phi24, and k_corr in the database, so that the researcher could make his/her own filtering, if needed.

RC: Page 11, line 10. Are the differences with Hong … Random? Systematic is some regions? Earlier or later?
AC: We have updated the comparison of AIRS/IASI diurnal cycle with Hong et al., 2006.

RC: Page 11, line 22. On stability. I agree that there are many fewer points with a retrieved diurnal cycle in the winter hemisphere but there are some signals that perhaps deserve some comments. In Figure 5a, is the feature in the (A) Atlantic off the US East Coast, (B) the Central Pacific, and (C) that Himalayas real? (Do other climatologies show these features? Any idea what is going on here?). Likewise, I wonder if the diurnal cycle observed of the Southern Ocean is real.
AC: Since we used a uniform filtering on k_corr (see the answer to the “Page 11, line 2” question) and the areas under consideration are quite large we should consider the detected diurnal variation in these regions as real as in the other ones. Similar features have been reported by e.g. Soden et al., 2000 or by Eastman and Warren, 2014, but taking into account smaller diurnal cycle amplitudes over the ocean, we would abstain from the discussion of these features on a $1^{o}\times1^{o}$ scale. Perhaps, a finer tuning of the detection threshold is needed for their analysis, but we wanted to use a uniform set of rules for the whole globe. As for Himalayas, the features are similar to those reported in Eastman and Warren, 2014 for the convective clouds (see their Fig. 8). We have added a short discussion on the detection of diurnal cycle over the oceans at the end of this paragraph.

RC: Page 11, line 26. Perhaps change to “In July, there is a large contrast between continental opaque clouds and nearby oceanic regions. Over the continents, the peak typically often occurs in the evening around 20h as compared with oceanic areas near the continents with peaks closer to noon. Nonetheless, in some other ocean locations opaque clouds also peak in the evening or overnight (e.g. tropical longitudes -115 to -135).”
AC: We added the suggested fragment, thanks.

RC: Page 11, line 27. As regards Indonesia, I think the Maritime continent has a complex land/sea breeze interactions that I don’t think the 1 degree data can capture well. I suggest it might be better to simply note this (and perhaps cite appropriate references) rather than trying to make any conclusions for this region.
AC: We have rewritten this part of the text.

RC: Figure 8. I suggest changing the numbering scheme used in Figure 8 and the discussion to match the order of the regions shown in Figure 9 and tables #1 and #2 from top to bottom. This will make the text easier to follow.
AC: We followed the suggestion and renumbered the regions in Fig. 8 and in the text.

RC: Section 3.3. What guided the selection of regions analyzed here? In particular, why are no oceanic regions selected for analysis? Also, the North America region that is highlighted includes the west coast and Rockies but misses most of the central U.S. and Eastern U.S. Was the intent to avoid Mesoscale Convective Systems (MCSs) that strongly influence the diurnal phase and amplitude in the Central/Southern US? I note that Figure 6a shows the Central and Eastern US is notably different from the western US.
AC: The selection was a tradeoff between the areas of observed strong variability with a stable phase in winter and summer for all (or at least for few) cloud types. The idea was to use the same regions to compare winter and summer diurnal cycles thus reducing the number of elements in the tables. As for the oceans, there was no region which would satisfy the aforementioned criteria and the phase/amplitude diagrams built for ocean areas did not allow to make a sound conclusion, so we decided to exclude these regions. Averaging over a large ocean zone (Fig. 3) improves the statistics and allows tracking some features, but the size of the region is considerably larger than any of the land regions. As for the Western/Central US, the choice was primarily driven by the features seen in Fig. 5-7b,c and B1. Increasing the size of the region would lead to mixing up several areas with different phases and make the phase/amplitude diagrams unusable.

RC: Page 15, line 8. I agree that multiple peaks could be explained by orographic effects, however, I also think that MCSs likely play some role here. In general, what leads you to make this statement? Is the intent that this statement is a conclusion Or are you speculating?
AC: It's true, there is no bullet-proof evidence of the mechanism responsible for these effects, and this is just one of possible explanations, so we toned this statement down to: "multiple peak amplitude local times may indicate effects of orography".

RC: Figure 9. Suggest change column header "Conv." To "Opq" in keeping with the figure caption, and to be consistent with the point that Opaque is not perfectly synonymous with convection.
AC: Thanks for noticing this. This has been fixed.

RC: Page 17, line 10. As with earlier comment, I do not know what "in situ freezing" means.
AC: Please, see the comment to "Top of Page 9" question. We have updated the text on p.17.

RC: Page 18, line 3. I am not clear on what "in the same limits" means here. Please rephrase.
AC: We have rephrased it to "Even though peak times for cirrus clouds and for high opaque clouds vary almost in the same range, an average lag of ~3 h can be identified for two thirds of the cases".

RC: Page 19, line 4-6. You write, "It is interesting to note that the local time of the minimum moves from the summer hemisphere midlatitudes towards the tropics from 6h to noon and the one of the maximum from 17h to 1h." I am confused, what is moving, the total amount of upper level cloud? What does "one of the maximum" mean? Perhaps expand and/or rephrase this remark.
AC: It is the local time of the minimum and maximum cloud amount that moves, but we decided to remove this sentence because it confuses the reader and contradicts with the methodology used in the study, according to which these times can be relatively well determined even if the local times of the observations do not match the maximum or the minimum. We rephrased this sentence to "AIRS alone with its observations at 1h30 and 13h30 LT is closer to capturing the maximum and minimum of cloud cover over tropical land than IASI observing the atmosphere at 9h30 and 21h30 LT."

RC: Page 19, line 10. What other analyses? Suggest references. Is there anything in the present work which adds to OR departs from the "other analysis?
AC: Please, see the answer to the general question #4, to the question to page 11, line 10, and the discussion around Fig. 3 and 4. Since we have added more references and updated the discussion above (e.g. see the corresponding references in Section 3.2.) we do not include them here to keep the flow of this section uninterrupted.

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

Artem G. Feofilov and Claudia J. Stubenrauch

LMD/IPSL, Sorbonne Université, UPMC Univ Paris 06, CNRS, École polytechnique, Palaiseau, 91128, France

Correspondence to: A. G. Feofilov (artem. feofilov@lmd. polytechnique. fr)

Abstract. ~~Among the processes governing the energy balance of our planet~~By covering about 30% of the Earth and by exerting a strong greenhouse effect, high-level clouds~~, due to their coverage of about 30%,~~ play an important role~~. The net radiative effect (cooling or~~ in the energy balance of our planet. Their warming ~~of~~and cooling effects within the ~~planet) of these clouds~~atmosphere strongly ~~depends~~depend 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 day, allows us to investigate the diurnal variation of these high-level clouds~~,~~ by 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~~By applying the developed methodology to AIRS and IASI cloud observations ~~and~~for the period of 2008−2015, we obtained monthly geographical distributions of diurnal phase and amplitude ~~for the period 0f 2008−2015.~~at a spatial resolution of 1° latitude x 1° longitude. In agreement with other studies, the diurnal cycle of high-level clouds is the largest over land in the tropics. At higher latitudes, ~~the~~their diurnal cycle is the largest during the summer. For ~~the~~selected continental regions ~~of high diurnal activity over land, the~~we found diurnal amplitudes of cloud amount ~~are~~of about 7 % for high opaque clouds~~, 9 % for cirrus,~~ and ~~7 %~~ for thin cirrus~~ clouds~~, and 9 % for cirrus. 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~~can be explained by the fact that this cloud type not only includes the 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~~are 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 of these three high-level cloud ~~type~~types.

1 Introduction

~~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 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. ~~Besides the mean amount of different cloud types, their~~The diurnal variation ~~also~~of clouds 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~~

The International Satellite Cloud Climatology Project (ISCCP, Rossow and Schiffer, 1999) uses multi-spectral imager data from a combination of polar orbiting and geostationary weather satellites to for a globally complete long-term cloud data record at spatial and temporal scales consistent with cloud dynamical processes (approximately 3 hr, 25 km). Although many regional studies were done earlier, the first global analyses of diurnal cloud variations were based on the ~~cloud~~ISCCP 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~~). Based on these results, the most notable features of the cloud diurnal cycle are significant differences between the phase of diurnal low-level cloud variations over ocean and land and between the phase of diurnal 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;
- mid-level clouds have a maximum amount late at night or early morning.

~~As~~However, the combination of ~~ISCCP~~maximal two atmospheric window channels, one IR and one visible, ~~has~~ (the latter not working during night) leads to a low sensitivity of ISCCP 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~~ By contrast, the ~~tropics and midlatitude summertime have a maximum amount in the evening;~~

~~• 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 used in this study allows to select the spectral channels with the contribution functions centred at different heights: the radiances measured near the centre of the 15μm CO_2 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). TIROS-N Operational Vertical Sounder (TOVS) data (TOVS Path-B, Scott et al. 1999) have been used by Stubenrauch et al. (2006) to identify high opaque clouds, cirrus, and thin cirrus according to their emissivity, and by exploiting the time drifting of the afternoon polar orbiting NOAA satellites, in combination with the non-drifting morning orbits, concluded over land in the tropics and midlatitude summertime:

- high opaque clouds have a maximum amount in the evening;
- 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 night time.

As passive instruments are only able to provide information on~~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 clouds above. Therefore, we concentrate ~~at~~on the diurnal variation of high-level clouds.

The CIRS (Cloud from Infrared Sounders) cloud climatologies established from the Atmospheric InfraRed Sounder (AIRS ~~(~~, Chahine et al., 2006) and the Infrared Atmospheric Sounding Interferometer (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~~ first presents a comparison of the diurnal variation of high-level cloud amount from our method with results from other datasets (3.1). Then we introduce the diurnal variation separately of high opaque ~~clouds~~cloud, cirrus, and thin cirrus~~, and their atmospheric environment. In particular~~ amount. For specific land regions, we try to establish the links and temporal lags between the different high-level cloud types, the surface temperature, and relative humidity~~.~~ (Section 3.3). Section 3.4 presents another application: as the combined dataset covers a period of eight years we analyse the geographical patterns of amplitude change as function of the global surface temperature change. 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 µm), at 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 *µ*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.

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 CO_2 absorption band (Stubenrauch et al., ~~1999~~1999b). 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 ($\varepsilon_{cld} > 0.95$), cirrus ($0.95 > \varepsilon_{cld} > 0.5$), and thin cirrus ($0.5 > \varepsilon_{cld} > 0.1$). 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 retrieval problems associated with inconsistent ~~retrievals of the~~ ancillary data between AIRS and IASI, we have adopted the same ancillary dataset for both, namely, the ERA-Interim meteorological reanalysis (Dee et al., 2011) by the European Centre for Medium-Range Weather Forecasts (ECMWF~~).~~), given 6-hourly at universal time. For the cloud retrieval, the ~~6-hourly reanalysis data, given at universal time,~~ERA-Interim surface temperature and pressure as well as atmospheric temperature and water vapour profiles have been ~~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~~the local observation times of ~~diurnal variation (~~AIRS and IASI.~~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~~observations (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, due to storm tracks, 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.~~It is the largest around the peak of the InterTropical Convergence Zone (ITCZ), with about 5% for cirrus. Fig. 1 will serve as a reference when considering the diurnal amplitudes discussed below.

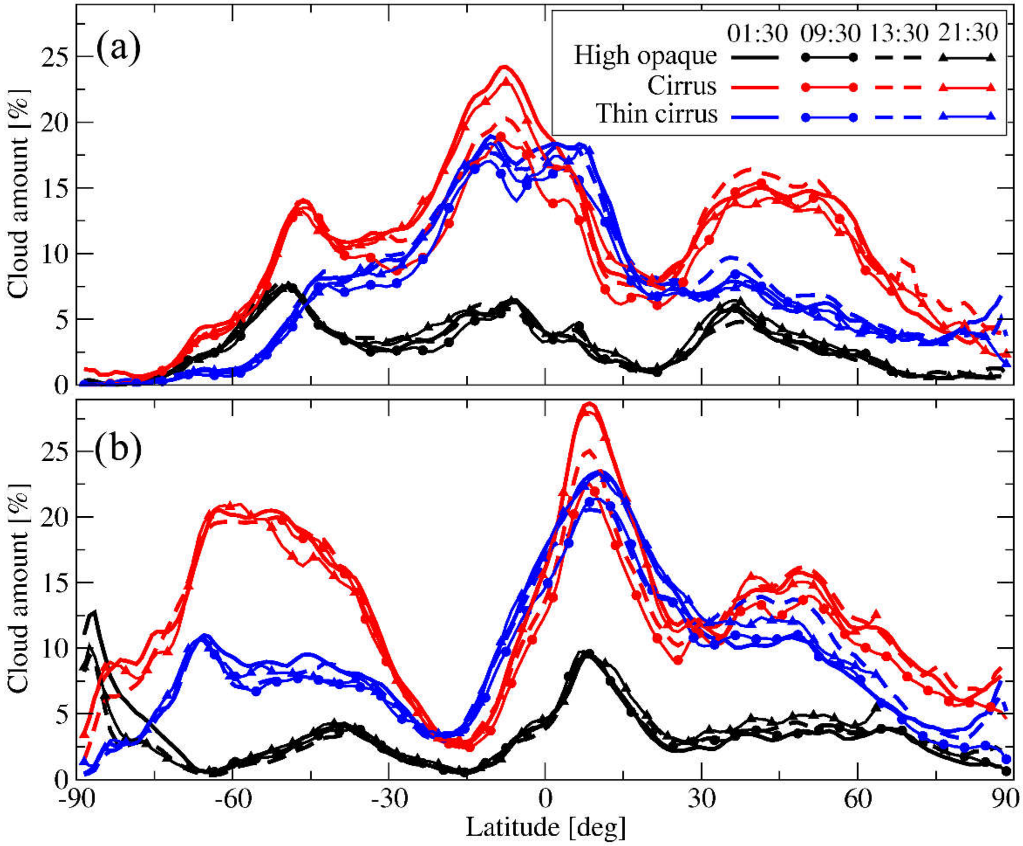


Fig. 1. Latitudinal distribution of high opaque, cirrus, and thin cirrus cloud amount estimated from AIRS (01:30 and 13:30 LT) and IASI (09:30 and 21:30 LT) by the CIRS retrieval: (a) January; (b) July. Climatological averages over 2008 to 2015.

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 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~~variations in cloud amounts are known to include variations on both diurnal ~~cycle contains an admixture of a~~and semi-diurnal ~~harmonic~~time scales (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 missing piece of the puzzle in the function describing the general behaviour of the diurnal cloud amount variation as a mixture of two harmonics~~:~~, diurnal and semi-diurnal, ~~obtained from~~as demonstrated by the analysis of ISCCP observations (Cairns, 1995).

~~Cairns (1995) has shown that~~Accordingly the diurnal cycles of high-, middle-, and low-level clouds are well represented by a mixture of two harmonic functions of the following form:

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

where the indices “24” and “12” correspond to diurnal and semi-diurnal harmonics, respectively, *t* is time in hours, $\cancel{\Delta\varphi}$ $\Delta\varphi$ 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 $\cancel{A_{12}/A_{24} \approx 0.28}$ $A_{12}/A_{24} \approx 0.28$ 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~~ $\cancel{\Delta\varphi}$ ~~was found to be equal to −2 h for the low- and mid-level clouds and 0 h for high-level clouds. Below, we~~(1) and use this ratio throughout the analysis assuming that it is A_{24}, which dominates the diurnal variation. By analysing Fig. 1 of (Cairns, 1995) using least-square fitting of Eq. 1 we found that the phase shift $\Delta\varphi$ is equal to −2 h for the low- and mid-level clouds and to 0 h for high-level clouds. With the A_{12}/A_{24} set to 0.28 and $\Delta\varphi$ set to 0, the diurnal “shape” of Eq. (1) is fixed (see the grey line in Fig. 2a) and the problem reduces to one of determining the amplitude A_{24} and φ_{24}. Two satellite instruments provide us with measurements four times of the day, and we determine the best fit amplitude and phase using a minimization technique based on the “sliding profile” approach as depicted in Fig. 2 and described below. This approach is similar to the one used in (Goldberg et al., 2013) where it was applied to determine the phase and period of interhemispheric coupling. Later in the text we will 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~~will remain valid for any periodic function.

Figure 2 explains the approach for estimating the diurnal variation phase and amplitude: let us imagine that a real diurnal variation for a given type of cloud at a given location is defined by Eq. (1), with $\cancel{A_{24}, \varphi_{24},}$ A_{24} and $\cancel{\Delta\varphi}$ φ_{24} 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.

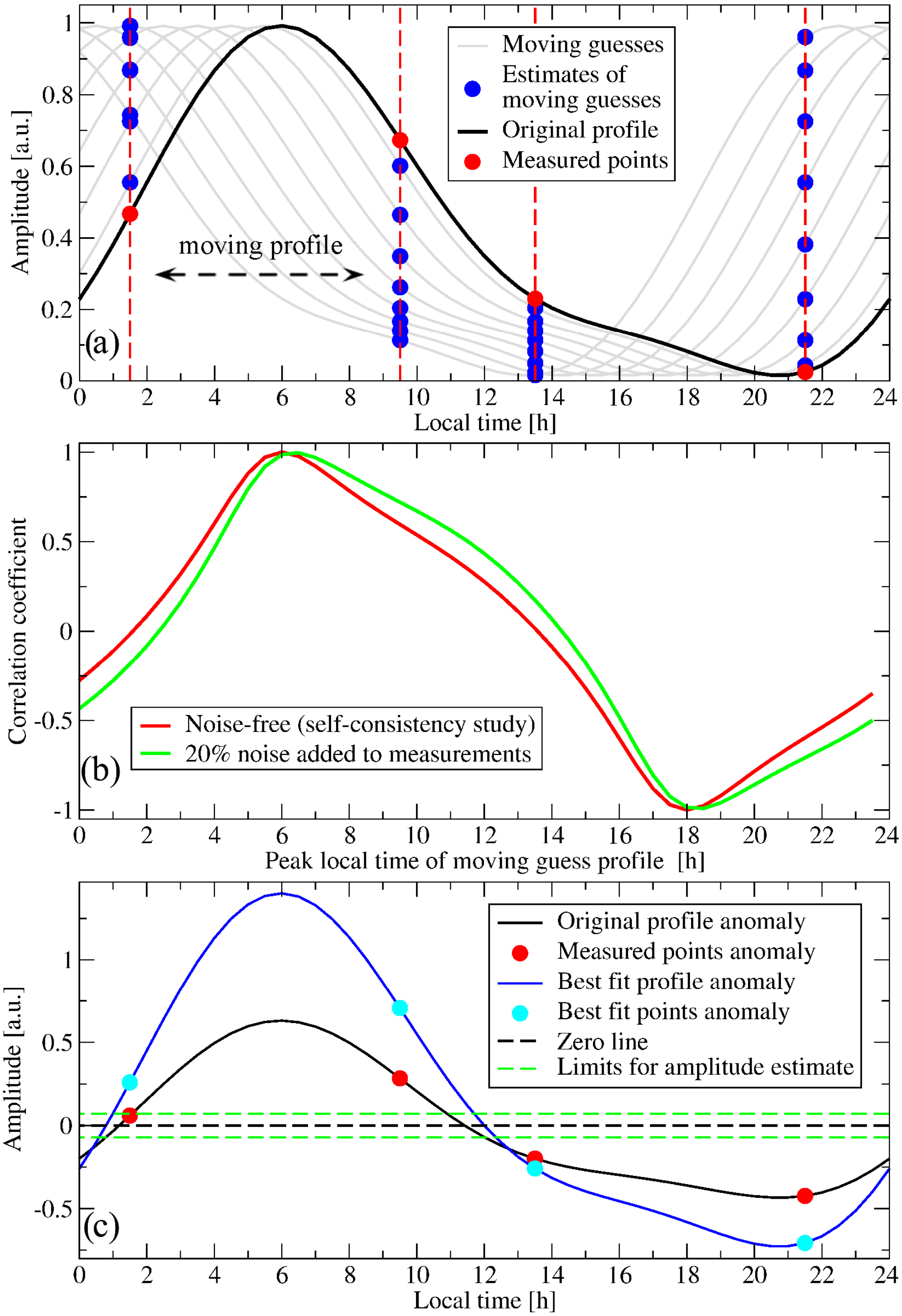


Fig. 2. Illustration of the approach to estimate the diurnal variation phase and amplitude from four measurements, taking advantage of a known form of the variation: a) “True” profile measured at four points and moving guess profiles; b) Pearson’s correlation coefficient calculated for guess profiles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

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~~.~~ (hit rate stands for the ratio of number of cases, for which AIRS cloud detection agrees with CALIOP, to the total number of cases).

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}.~~ A_{24}. Then ~~the phase estimation procedure changes~~we numerically solve the system for φ_{24} as follows. The ~~φ_{24} by~~ φ_{24} is changed in fine increments, each time 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 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}~~ A_{24} amplitude (Fig. 2c) as follows: we ~~build an anomaly~~ draw a virtual “zero line” at the level corresponding to a mean of ~~the best guess profile~~ all four points and calculate the magnitudes at these points with respect to this “zero line”. Then we compare ~~it~~the obtained values with ~~the anomaly of~~those estimated from the Eq. (1) ~~at the four observation times.~~ in the same way (dashed black line in Fig. 2c represents a zero line of Eq. 1). The mean ratio of amplitudes ~~at these points~~ gives ~~an amplitude, which should be substituted into Eq. (1). To avoid~~ A_{24}. Since using the values close to “zero line” might lead to zero-over-zero type of errors and to an increase of the A_{24} uncertainty, we pick up only the *A(t)* points with the ~~absolute value~~amplitude greater than 0.2 of the maximal | *A(t)* | value~~.~~ (the threshold is marked by green dashed lines in Fig. 2c). Another way of estimating ~~the amplitude~~ A_{24} 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~~on A_{24}, with 20% noise in the source data ~~leads~~leading to about 20% uncertainty ~~of~~in the ~~retrieved~~estimated amplitude.

To justify the choice of the relationship in Eq. (1) for the fitting, we have performed the following numerical experiment using real data: one year of ~~CIRS-~~AIRS and ~~CIRS-~~IASI cloud data ~~has been processed~~ using the ~~approach~~methodology outlined above for two different hypotheses on the fitting functions: a simple harmonic one with a 24-h period and ~~the one following (Cairns, 1995)~~a mixture of diurnal and semi-diurnal described by Eq. (1). For each ~~case~~tested hypothesis, we have built a histogram of the best correlation coefficient values, separately for high- and low-level cloud amount diurnal variation. We found that ~~with~~using Eq. (1) for the fitting of real-life observations one achieves ~8% and ~18% higher correlation coefficients for the diurnal cycle of high- and low-level clouds, respectively, than with a simple 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~~estimated with ~20% uncertainty.

3 Diurnal phase and amplitude of high clouds and their surrounding

3.1. Zonal averages

We apply the diurnal cycle estimation algorithm ~~to~~on the amount of all high-level clouds and separately ~~of~~on high opaque, cirrus, and thin cirrus ~~clouds~~cloud amount from the CIRS-AIRS and CIRS-IASI cloud climatologies. For the following analyses we determined A_{24} and φ_{24} for each month and each 1º latitude ×1º longitude grid box, calculated *A(t)* in accordance with Eq. 1, and averaged the resulting shapes for a given latitude band or region.

To demonstrate the ~~capabilities of the algorithm and the~~ feasibility of ~~the approach~~our methodology, we~~ first~~ compare ~~average~~ diurnal variations of high-level cloud amount averaged over three latitudinal bands, separately for ocean and land, to those presented by Noel et al.(2018), ~~determined using cloud properties retrieved from CATS (~~obtained from new lidar measurements of the Cloud-Aerosol Transport System~~) lidar measurements (~~ (CATS, 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 (~~), and to those from ISCCP presented by Rossow and Schiffer (1999). While lidar observations are more sensitive to thin cirrus than IR sounders, ISCCP is less sensitive to thin cirrus (e. g. Stubenrauch et al., ~~February 2015 through October 2017 vs 8~~ 2013). The much larger statistics of several years of global AIRS/IASI~~) and spatial (passive instruments scan the atmosphere in the direction perpendicular to the orbit to whereas active measurements provide a series~~ and ISCCP data compared to only nadir track statistics of ~~measurements along the orbit). Fig.3 presents the average~~ three years of CATS leads to a smoother behaviour of the diurnal ~~variation of high-level cloud amount over three latitudinal bands, separately over ocean and over land, during~~ variations presented in Fig. 3 for 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~~ . The shape assumption in the diurnal cycle estimation~~. In~~ used for AIRS/IASI also contributes to a smoother behaviour and is well compensating for the better temporal resolution of ISCCP. All three datasets show larger diurnal cycle amplitudes over land than over ocean, in agreement with ~~earlier~~many other studies~~, the diurnal cycle amplitudes~~

~~are smaller over the ocean than over land.~~ (e. g. Soden, 2000; Tian et al., 2004; Stubenrauch et al., 2006; Zhang et al. 2008). They are the largest in the tropics, and towards higher latitudes they ~~are close to zero~~decrease in winter ~~hemisphere~~ (see also Fig.~~-~~ S1 for Southern hemisphere in the supplement~~).~~), as shown for AIRS/IASI.

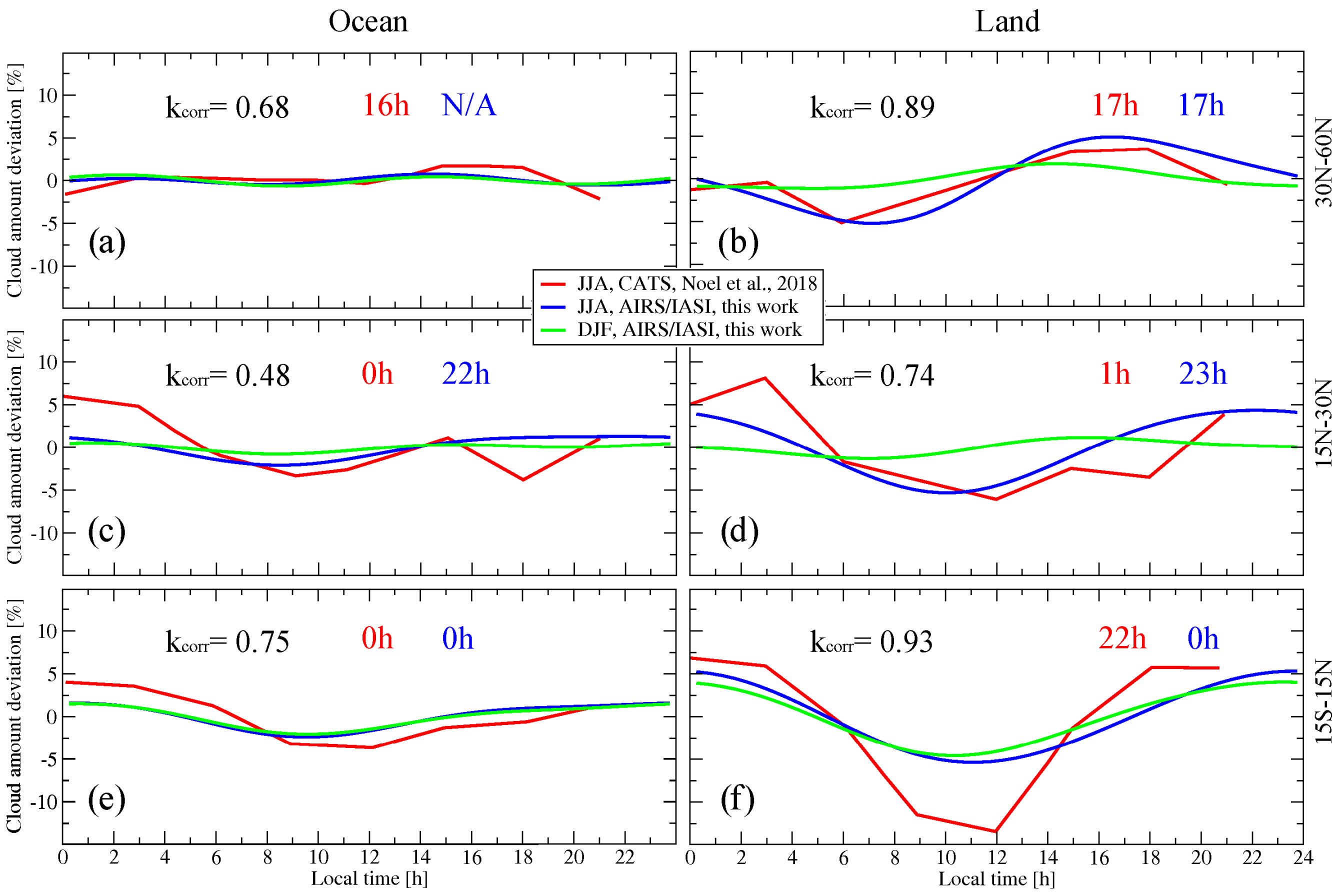
~~For each latitudinal band, the agreement between CATS and AIRS/IASI cloud~~ Differences in the amplitudes between AIRS/IASI and CATS may be mostly explained by the small sampling of CATS, as only a few regions per latitude band are sampled each time. With increasing sampling towards higher latitudes (to be checked in the CATS paper), the agreement increases: over midlatitude land, both curves agree very well. ISCCP agrees in general also well with AIRS/IASI, in particular in the tropics and the subtropics, except during night where the high-level cloud amount is slightly underestimated by ISCCP due to misidentification of thin cirrus as midlevel cloud (Stubenrauch et al., 1999a). Over summer midlatitude land, the lower sensitivity of ISCCP to thin cirrus also leads to a slight diurnal ~~cycle~~amplitude underestimation and in addition to a slight phase shift (see also Fig. 4).

Concerning the phase, the agreement between AIRS/IASI and CATS and between AIRS/IASI and ISCCP is indicated in Fig. 3 by Pearson's linear correlation ~~coefficient.~~coefficients, together with the local peak times. The values are in general high, when the diurnal amplitudes are large~~,~~ (above noise), which is the case in the summer hemisphere and tropics over land. ~~For comparison, the amplitudes are much smaller in boreal winter. The~~ The peak local times (marked in red and blue) of AIRS/IASI and CATS do ~~also~~ agree to within 2 hours that is comparable to the estimated 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~~ of 1.5 h. Concerning ISCCP, the local peak time in the tropics and subtropics has been systematically determined earlier, because of the slight underestimation of high-level cloud amount during night, while over summer midlatitude land the local peak time is estimated there hours later as by AIRS/IASI and CATS, because of missing thin cirrus during daytime. The latter are responsible for the local peak time at 17h LT, as seen in Fig. 4 which presents the contributions of the different cloud types (high opaque, cirrus and thin cirrus) to the total diurnal variation of high clouds for the same latitude bands as in Fig. 3, during boreal summer in the Northern hemisphere (Fig.~~-~~ S2 for austral summer in the Southern hemisphere). ~~Both~~Again, amplitudes are larger over land than over ocean, and in general the amplitudes ~~and~~ of the individual cloud types are larger than of all high-level clouds mixed together, as the 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 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. Thin cirrus have a similar diurnal cycle over ocean and over land which lets assume that part of these thin cirrus are formed by in situ freezing.~~. The diurnal cycle over tropical land, which is already largest for all high-level clouds together, as illustrated in Fig. 3, can be mainly understood as the diurnal cycle of deep convective cloud systems, with a peak of precipitation around 18h (Tian et al., 2004; Zhang et al. 2008), followed by high opaque cloud amount, including convective cores as well as part of thick anvil cirrus, with a peak around 21h and developing cirrus anvil amount with a maximum around 1h LT. The diurnal cycle of thin cirrus is smaller than the one of cirrus, because part of the thin cirrus corresponds to dissipating convective cloud systems and part to cirrus formed *in situ* by large-scale forcing (e. g. Luo and Rossow, 2004; Riihimaki et al., 2012). While the phase of cirrus and thin cirrus is lagged in the tropics, with a minimum of thin cirrus in the morning and a minimum of cirrus around 13h LT, their phase gets more similar towards higher latitudes. This can be probably explained by the fact that *in situ* freezing TTL cirrus do not exist at higher latitudes. In the midlatitudes cirrus and thin cirrus have a maximum in the afternoon and are most probably linked to synoptic situations of fronts. Some cirrus may be orographic, generated by ascent of air within large amplitude vertically propagating waves over mountains and even over hills (e. g. Queney, 1948; Ludlam, 1952).When comparing tropical land with tropical ocean, we observe a difference of about 11 hours for the high opaque clouds, with a broader maximum amount occurring in midmorning, again a few hours later than convection and precipitation of early morning (e. g. Tian et al., 2004; Zipser et al., 2006; Zhang et al., 2008). Cirrus and thin cirrus follow with maxima in the evening and during night. Their minima are again shifted, with the minimum of cirrus just before the maximum of high opaque clouds, as over land. The minimum of thin cirrus occurs in midmorning, similar to the minimum over land. The similar diurnal cycle of thin cirrus over ocean and over land is another indication that some of these thin cirrus are formed *in situ*, having no direct relation to the convective systems. The difference in phase of convection between ocean and land and the much broader peak of convection over ocean has been associated with differences in the vertical structure of land and ocean convection by Soden (2000). In contrary to land, over open ocean the thermal properties of the ocean surface undergo a relatively weak diurnal cycle. Chen and Houze (1997) have shown that the life-cycle of convective cloud systems also plays a role in affecting the diurnal cycle of cloudiness. The formation of longer lived oceanic convective cloud systems may introduce a bi-diurnal cycle, with large systems occurring at the same location only every other day.



Ocean
Land
Cloud amount deviation [%]
kcorr= 0.68
16h
N/A
(a)
kcorr= 0.89
17h
17h
(b)
30N-60N
JJA, CATS, Noel et al., 2018
JJA, AIRS/IASI, this work
DJF, AIRS/IASI, this work
kcorr= 0.48
0h
22h
(c)
kcorr= 0.74
1h
23h
(d)
15N-30N
kcorr= 0.75
0h
0h
(e)
kcorr= 0.93
22h
0h
(f)
15S-15N
Local time [h]
Local time [h]

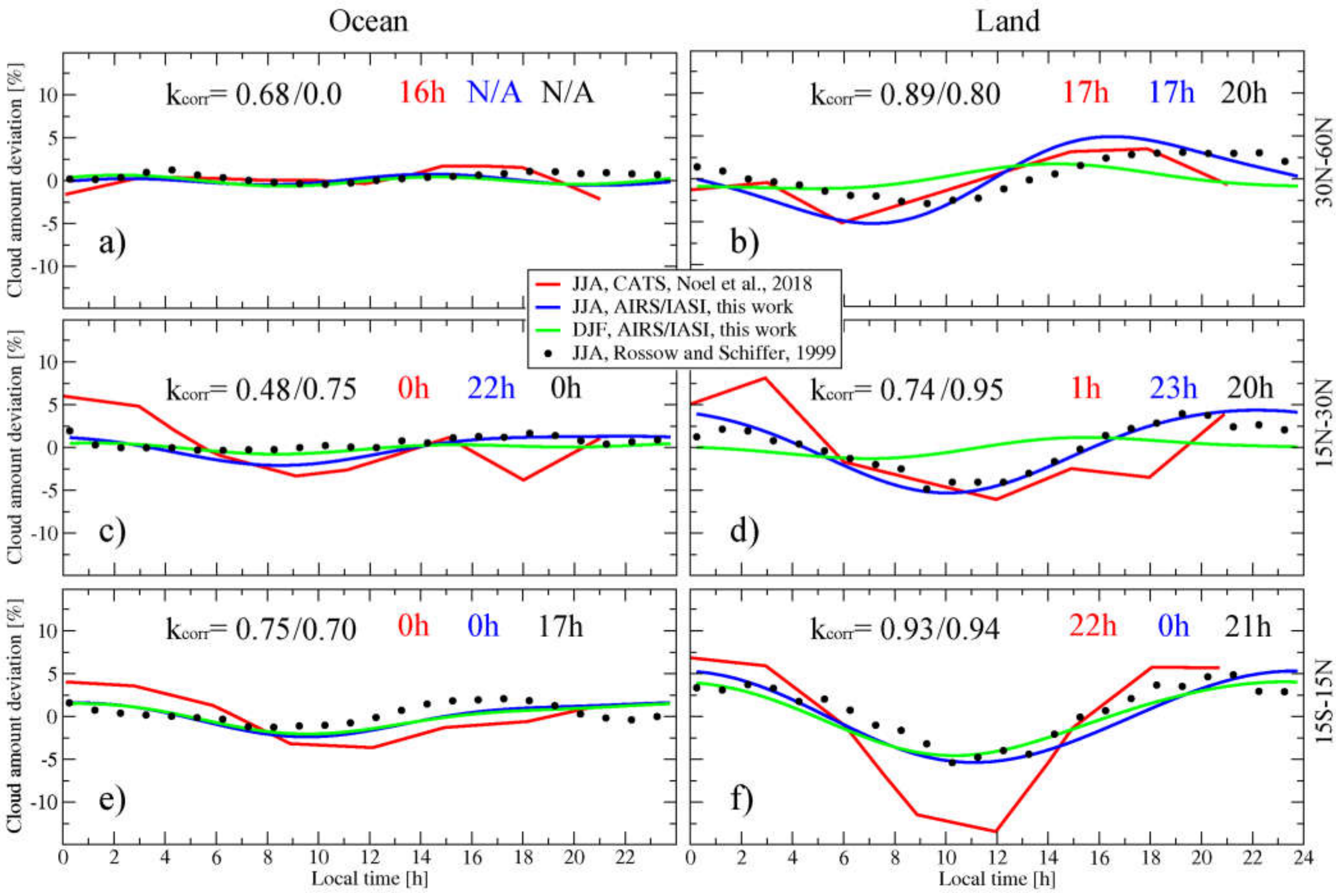


Fig. 3. Comparison of average diurnal cycles of high-level cloud amount over three latitudinal bands estimated from CATS lidar observations (Noel et al., 2018~~)~~), from AIRS/IASI (this work), and from ~~AIRS/IASI.~~ISCCP (Rossow and Schiffer, 1999). CATS statistics only includes June, July, and August (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 ISCCP JJA data cover the period of 1989–1991. The correlation coefficients ~~between~~ are given for AIRS/IASI ~~and~~vs CATS and AIRS/IASI vs ISCCP sequences for JJA ~~are marked~~ in ~~black~~the upper left part of each panel; the peak local times for CATS are marked in red, ~~and~~ for AIRS/IASI in blue, and for ISCCP in black in the upper right part of each panel. a) 30N−60N, ocean; b) 30N−60N, land; c) 15N−30N, ocean; d) 15N−30N, land; e) 15S−15N, ocean; f) 15S−15N, land.

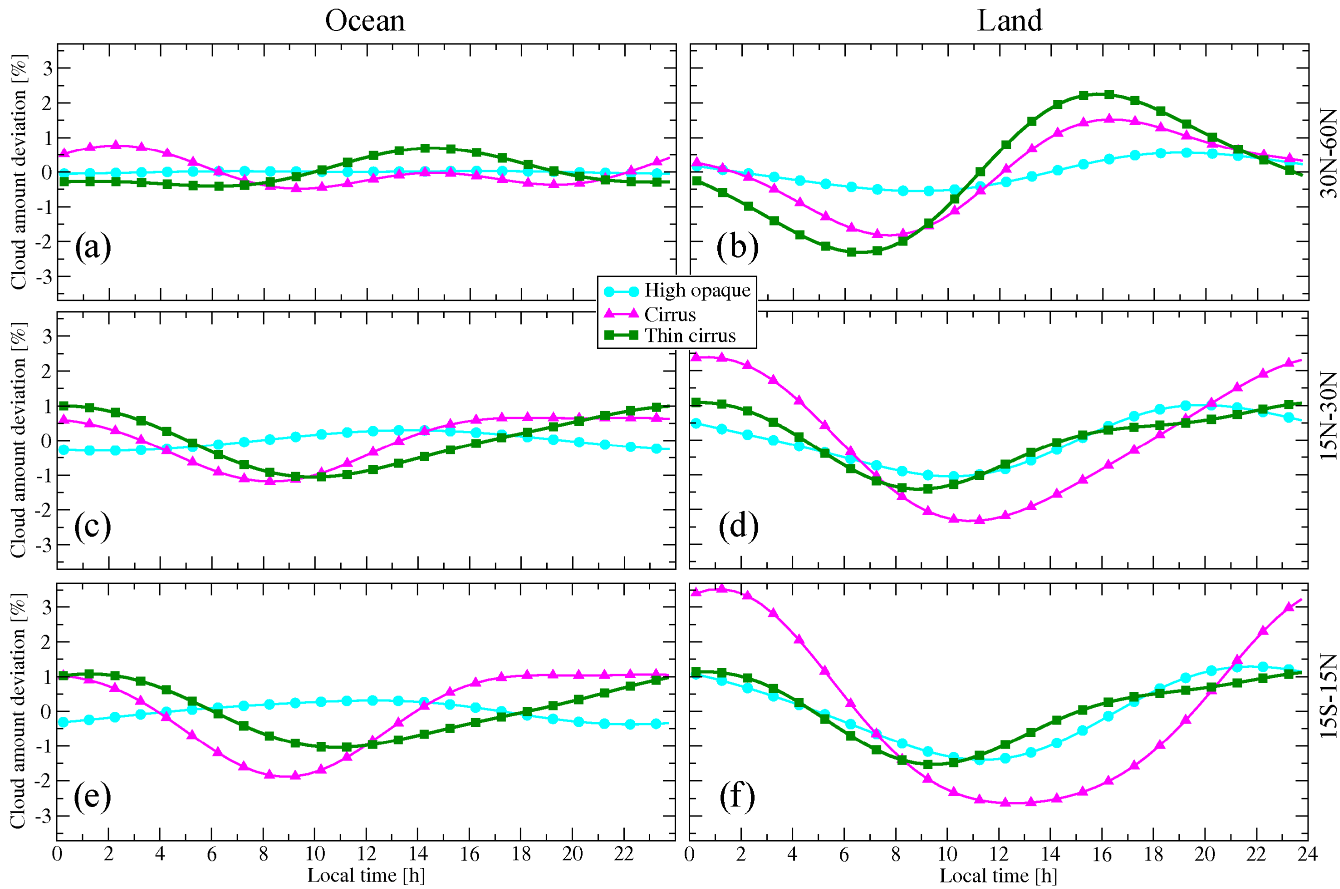


Fig. 4. Diurnal cycle of high opaque, cirrus, and thin cirrus amount in in NH midlatitudes, NH subtropics and tropics in boreal summer: a) 30N−60N, ocean; b) 30N−60N, land; c) 15N−30N, ocean; d) 15N−30N, land; e) 15S−15N, ocean; f) 15S−15N, land. The AIRS/IASI statistics is averaged for 2008−2015.

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.

We apply the ~~approach~~methodology described in Section 2.2 to cloud type amount statistics gathered ~~at~~over grid cells of 1° latitude x 1° longitude for the period 2008 - 2015, separately for January and July. ~~To present the geographical distributions of~~Average diurnal amplitude and phase~~, we adopted the vector representation of diurnal amplitude and phase~~ are represented by vectors as 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~~given as 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~~diurnal curves (see Section 2.2) is greater than 0.85, an empirical threshold based on examining numerous diurnal ~~cycle plots~~variation curves.

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~~errors 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).

Figures 5 ~~to 7~~and 6 present detected diurnal variations for the three different high-level ~~clouds and relative humidity~~cloud type amounts, for January and July, respectively. 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~~Rossow and Schiffer, 1999; Wylie 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~~) present peak times ~~differ by 2 to 3 hours, but the direct comparison is hindered by the methodological (separating the clouds by~~of precipitation, of very cold cloud amount (IR brightness temperature ~~selects only the coldest and relatively~~$T_B^{IR} < 210$ K) and of cold cloud amount ($T_B^{IR} < 235$ K) for different tropical regions, with lags between the three, corresponding to the development of deep convective systems. Compared to these results, our results are consistent when associating high opaque ~~ones compared to using the emissivity thresholds) and by spatio-temporal averaging differences~~clouds with very cold clouds and cirrus with the warmer clouds. 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).

In general, the high opaque cloud amount with about 5% is much smaller than the cirrus and thin cirrus amount (Fig. 1). 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 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.~~ 5a, 6a) demonstrate amplitudes reaching 10%. High opaque clouds, often associated with deep convective cores in the tropics, have a large regional variability, which may be influenced by orography. ~~Convection~~Maximum high opaque cloud amount moves with the ~~Intertropical 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.~~ continental opaque clouds and nearby oceanic regions. Over the continents, the peak typically often occurs in the evening around 20h as compared with oceanic areas near the continents with peaks closer to noon. Nonetheless, in some other ocean locations opaque clouds also peak in the evening or overnight (e.g. tropical longitudes –115 to –135). The diurnal variation of cirrus clouds (Fig. 5b, 6b) 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%. 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 to be more complicated to identify the 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, presented in Fig. 7, 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). While relatively small cloud amounts (like the one of high opaque clouds) or relatively cloud similar amounts during the day (like over ocean) provide a “noisier” input for the diurnal cycle estimation, 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, and the diurnal cycle of cirrus clouds detected over the tropical ocean in July (Fig. 6b) is very close to that reported in (Soden, 2000) for their averaged June-August, 1987 (10%, 18h). This allows to say that larger ocean zones, which demonstrate a consistent diurnal cycle, deserve attention. However, the global maps have been established with one single detection threshold using Pearson’s correlation coefficient of 0.85, so if one wants to focus on specific ocean regions one might want to refine the threshold on the correlation coefficient.

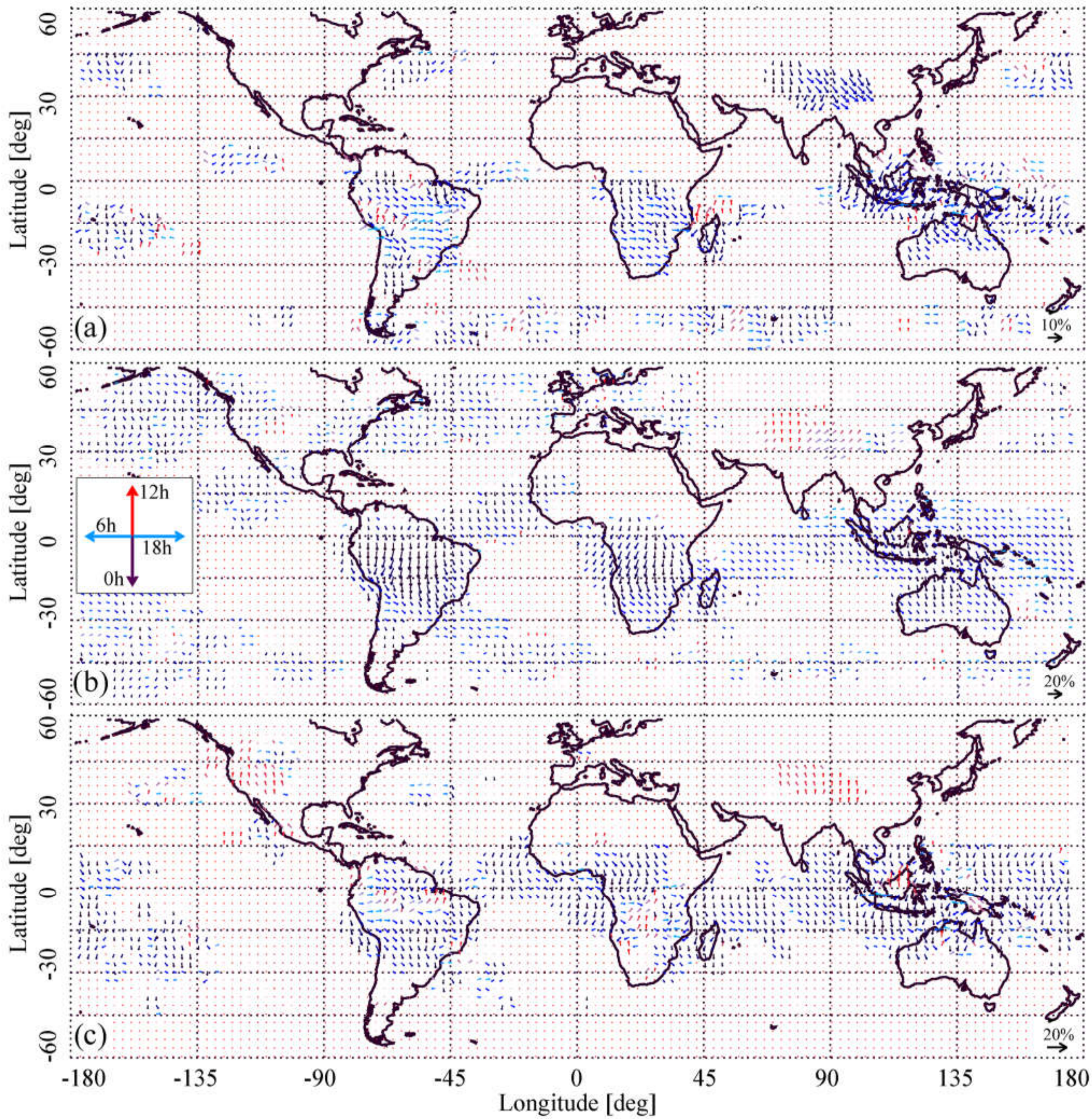


Fig. 5. Diurnal variation of (a) high opaque clouds, (b) cirrus clouds, and (c) thin cirrus clouds estimated from AIRS/IASI for January. Statistics is averaged over the period of 2008 ~~to~~ –2015. Vector length is proportional to the amplitude and its orientation defines the local time of the peak: 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.

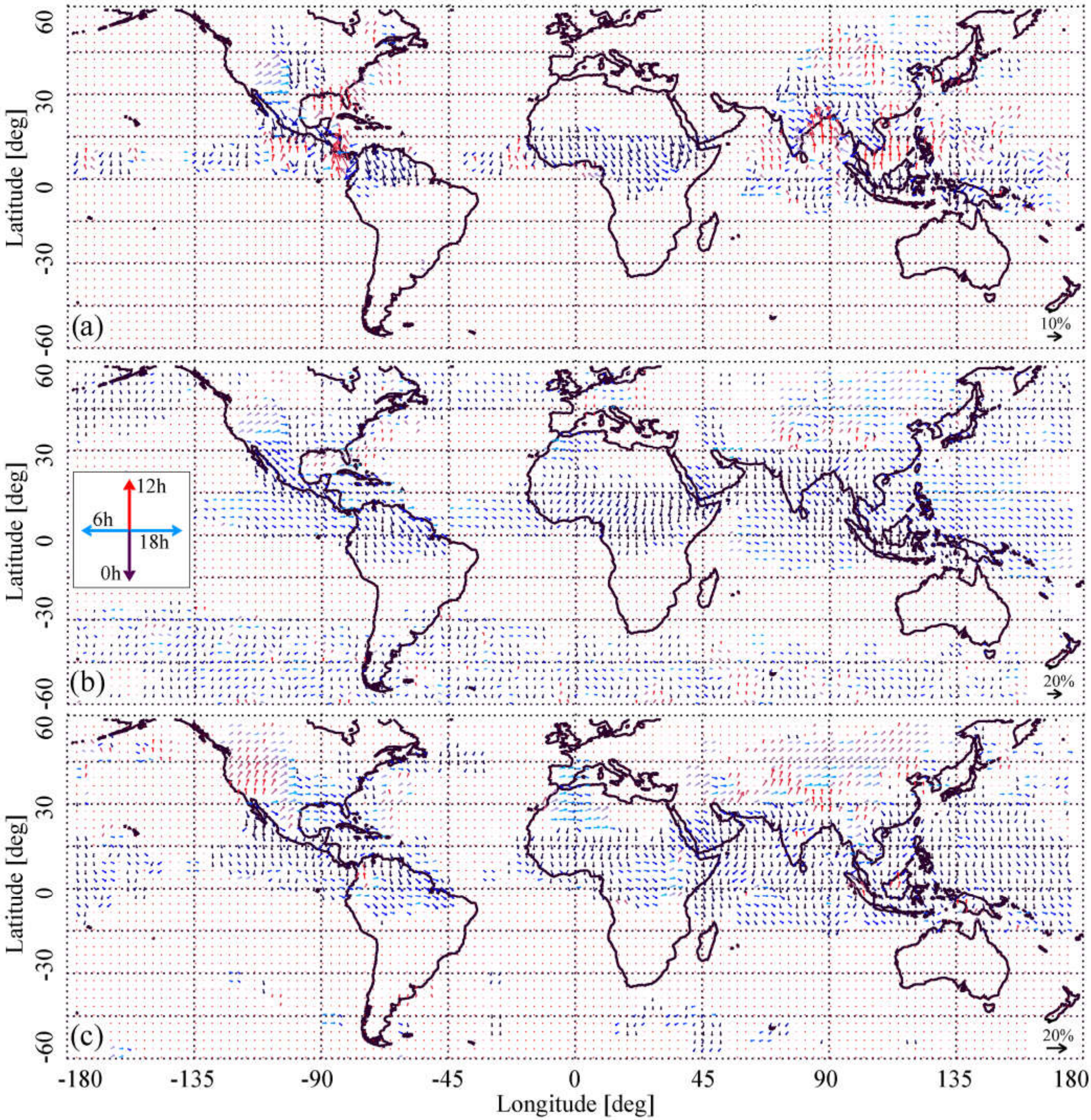


Fig.~~6. Diurnal variation of (a) high opaque clouds, (b) cirrus clouds, and (c) thin cirrus clouds estimated from AIRS/IASI for July. Statistics is averaged over 2008 to 2015. The vector representation is consistent with the caption of Fig.5.~~ 6. Same as Fig. 5, but for averaged July (2008 through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

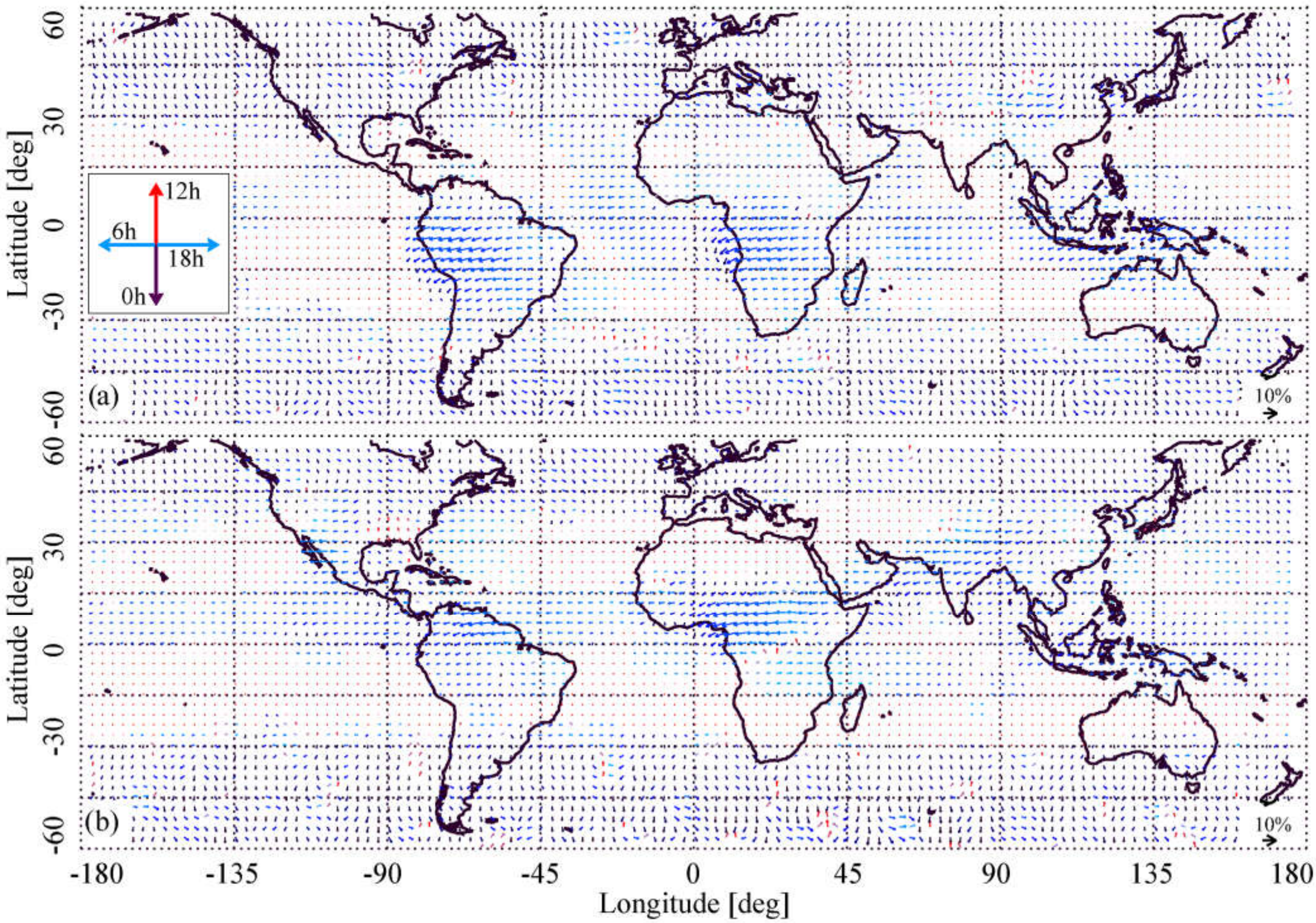


Fig. 7. Diurnal variation of average relative humidity in a layer 150 hPa below the tropopause, estimated from ERA-Interim reanalyses, a) for January and b) for July. The vector representation is consistent with the caption of Fig. 5. The tropopause level was determined in accordance with (Reichler et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

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, 2, 3~~, 5~~ and ~~6~~4 are in the Northern midlatitudes and subtropics / tropics, while regions ~~2, 4~~5, 6 and 7 are in the Southern subtropics / tropics. The regional amplitudes and peak times of cloud ~~types~~type amount, 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.

~~The~~ From these tables we deduce that the two regions in the Northern midlatitudes (1 and ~~6~~2) 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, 5 and ~~5~~6) 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~~6 and ~~4~~7 in January and for regions ~~4~~3 and ~~5~~4 in July.

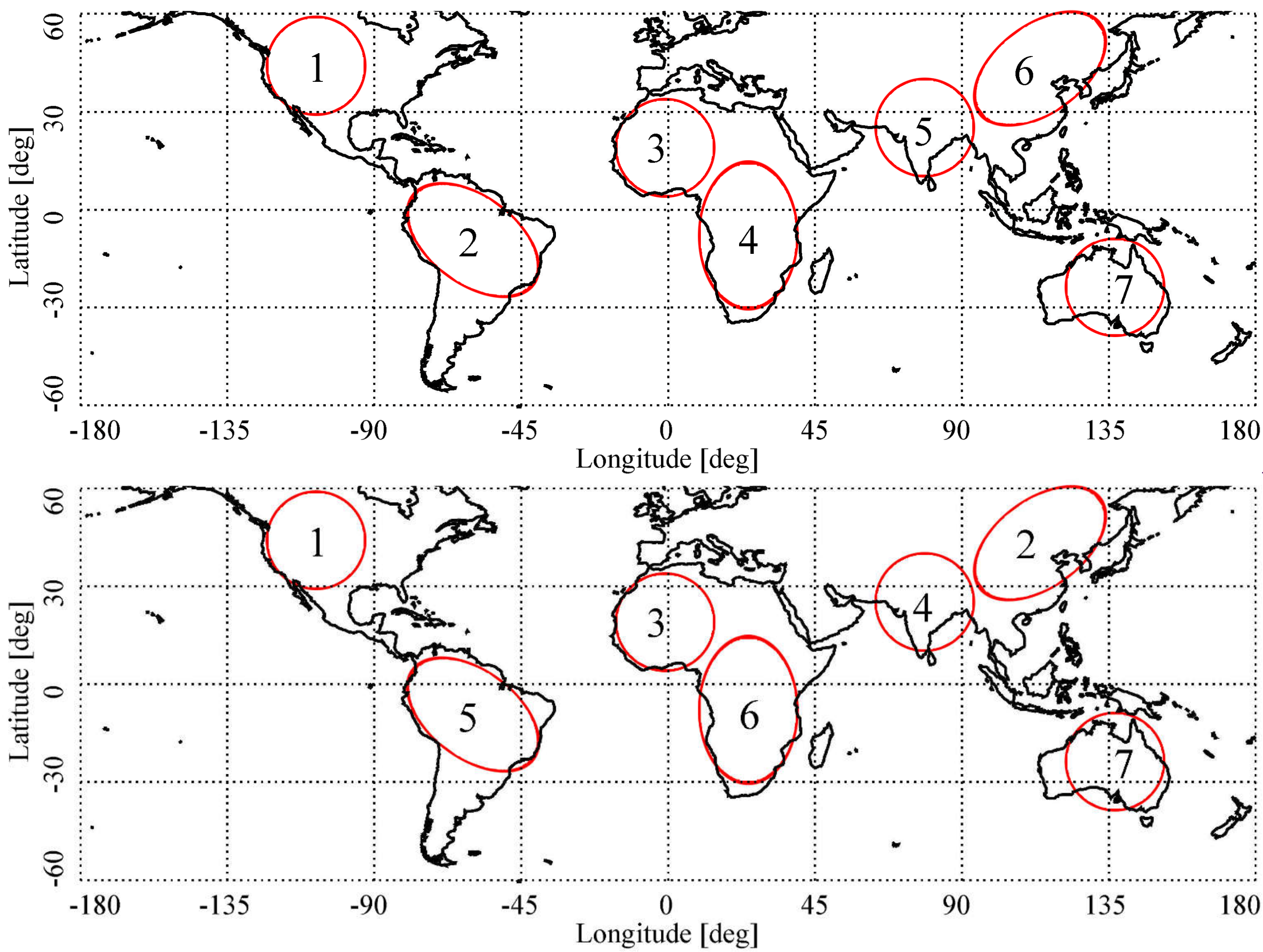
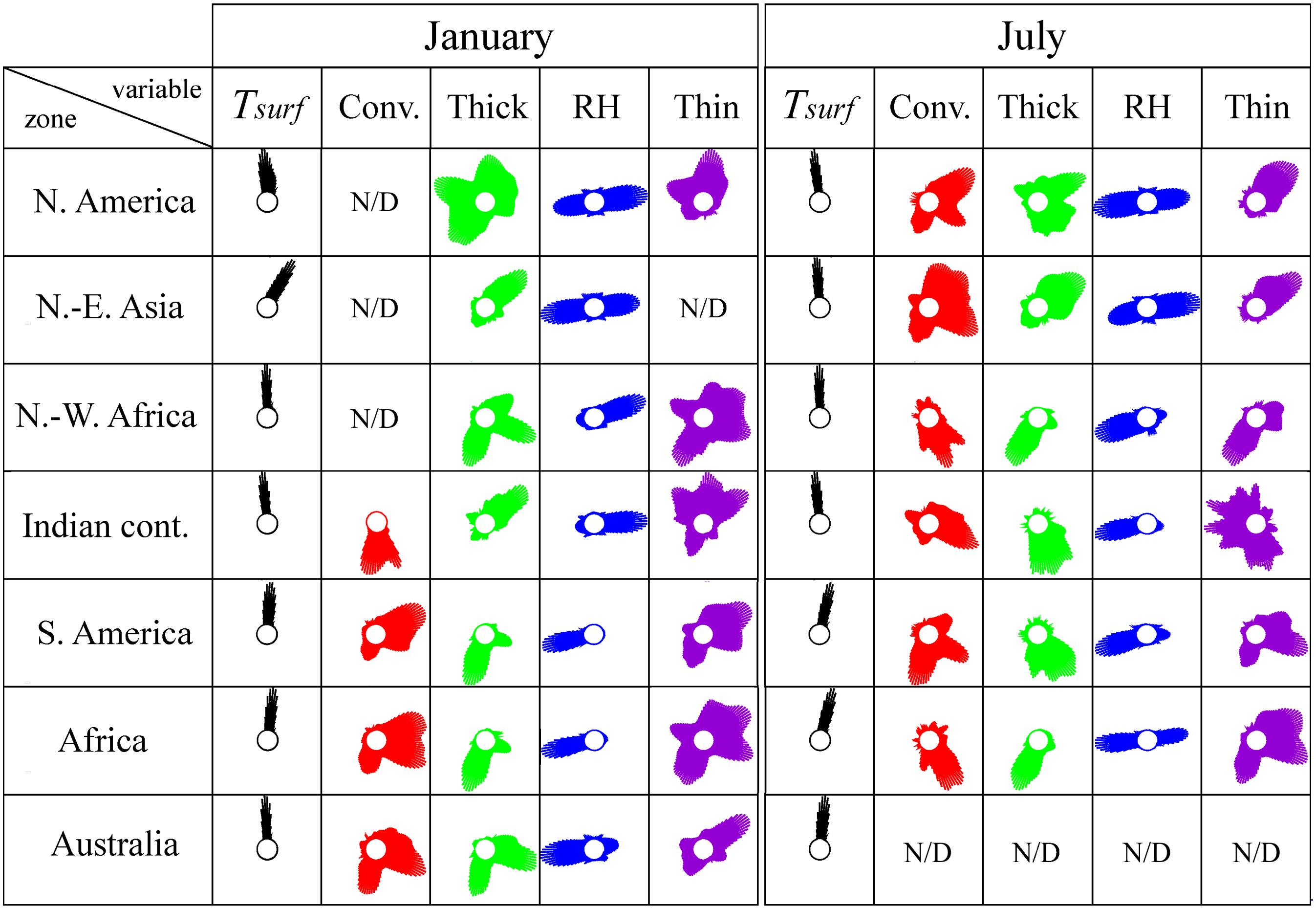


Fig. 8. Regions selected for a more detailed analysis of the cloud diurnal cycle over land: 1~~—~~ – North America, 2~~— South America,~~ – North/East Asia, 3~~—~~ – Northern Africa, 4~~—~~ – Indian continent, 5 – South America, 6 – South Africa, ~~5 — South Asia, 6 — North/East Asia,~~ 7~~—~~ – Australia.

~~The two regions in the Northern midlatitudes (1 and 6) show a~~ The large diurnal cycle in T_{surf} in summer (about 10 K~~), leading~~) of the two regions in the Northern midlatitudes (1 and 2) leads 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 may 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 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 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~~4). 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 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.


January
July
variable
zone
Tsurf
Conv.
Thick
RH
Thin
N. America
N.-E. Asia
N.-W. Africa
Indian cont.
S. America
Africa
Australia
N/D

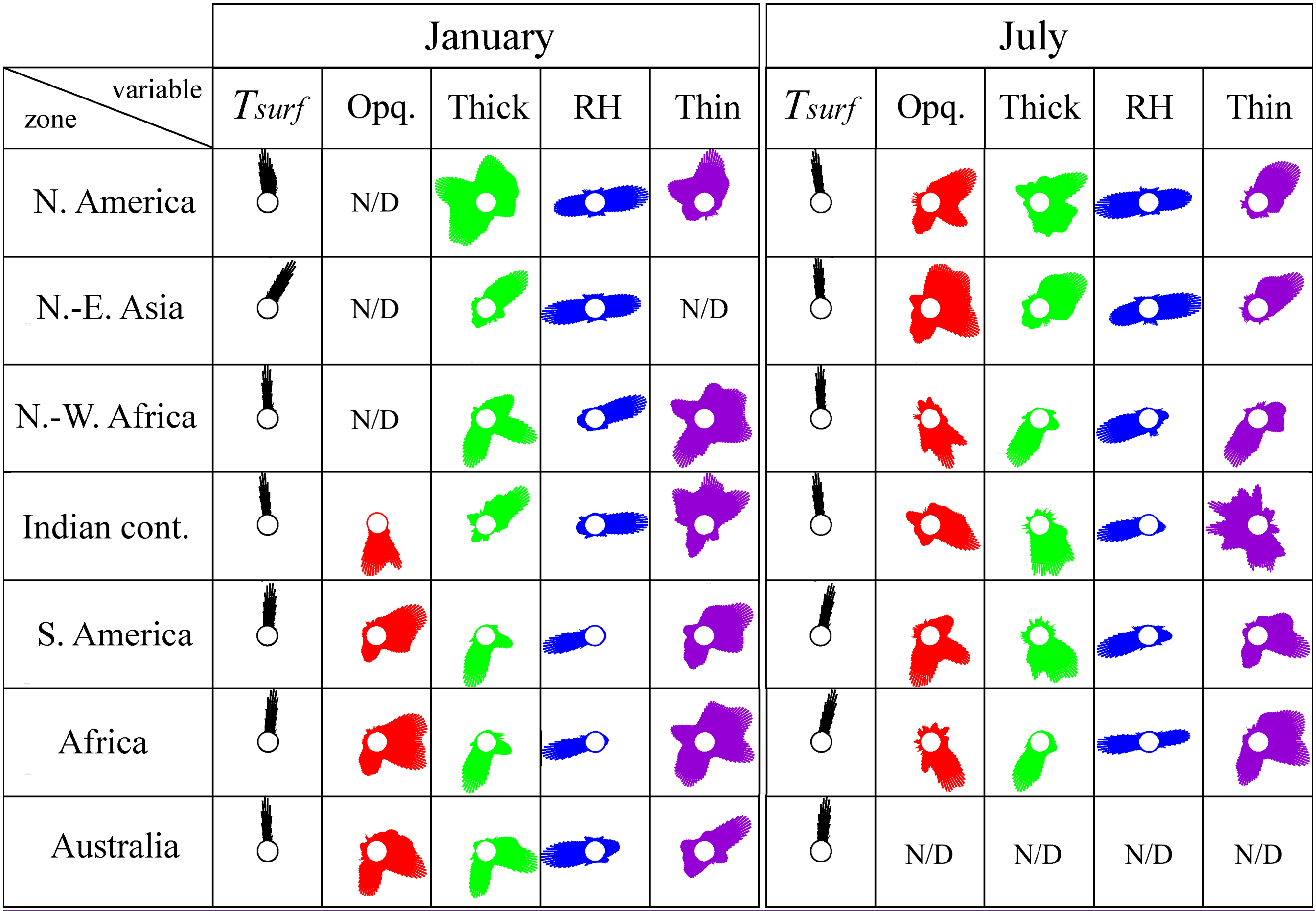


Fig. 9. Circular histograms of local time of peak amplitude for T_{surf}, high opaque clouds, thick cirrus, relative humidity (RH), and thin cirrus for average January and July. The convention for vector direction representation is consistent with that described in the caption of Fig. 6 while the amplitude 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.

~~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	−	−

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.

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~~seem to be formed ~~by~~ *in situ* ~~freezing.~~ , and not being offspring of a convective system.

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 and for high opaque clouds vary almost in the same ~~limits as those of high opaque clouds do~~range, 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 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 RH change (Fig.~~8~~ 7) and in thin cirrus variation (Fig. 5c, 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 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; (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~~.~~, lagging behind which may be associated with upper tropospheric humidification by cirrus outflow.

43.4. Relating diurnal amplitudes to climate fluctuations

As the period of eight years of combined AIRS and IASI observations is too short to directly study long-term variability of diurnal phases of the different cloud type amounts, we present in this section geographical patterns of diurnal amplitude variability in relation to climate variability, given by de-seasonalized monthly mean global surface temperature, T_{surf}, anomalies. Within this short time period, changes in global T_{surf} (or tropical, as both are strongly correlated) reflect the El Niño Southern Oscillation (ENSO). ENSO is the most dominant mode of interannual variability in the Earth's climate system, and has been often used to study cloud feedbacks (e. g. Lloyd et al., 2012; Liu et al., 2017; Stephens et al., 2018). In general, a positive global T_{surf} anomaly corresponds to El Niño, with maximum convection over the Central Pacific and a negative T_{surf} anomaly to La Niña, with maximum convection over the West Pacific. Stubenrauch et al. (2017) have shown with 15 years of AIRS-CIRS cloud data that changes in relative amount of tropical high opaque and thin cirrus with respect to increasing global mean T_{surf} have different geographical patterns (see their Fig. 12): while the high opaque clouds, often linked to strong precipitation (Protopapadaki et al., 2017), relative to all clouds, increase in a narrow band in the tropics, there is a large increase in relative thin cirrus amount around these regions.

By applying the same technique, namely by determining a change in diurnal amplitude of cloud type amount as a function of change in global mean T_{surf} by a linear regression of their monthly time anomalies, at a spatial resolution of 1°latitude x 1°longitude, we have obtained the spatial patterns presented in Fig. 10. Indeed, we observe also an ENSO pattern for the change in diurnal amplitude, with an increasing amplitude in regions of deep convection (the band near the equator, in the Central Pacific for El Niño and for the West Pacific and South America for La Niña). The strongest changes are observed for high opaque and cirrus cloud amount, but one can distinguish them also for the thin cirrus which seem to be directly linked to convective cloud systems. Considering the relative errors of the determined slopes, presented also as geographical maps in the supplement (Fig. S3), though in general quite noisy, we see nevertheless that the strongest signal over the Central Pacific has the smallest error (of about 30%). With this analysis we have shown yet in another way that high-level clouds linked to deep convective systems have the largest diurnal amplitudes. To study the change in phase is more delicate, already due to possible misinterpretation of peak amplitude around midnight and also as other factors such as winds may play a role.

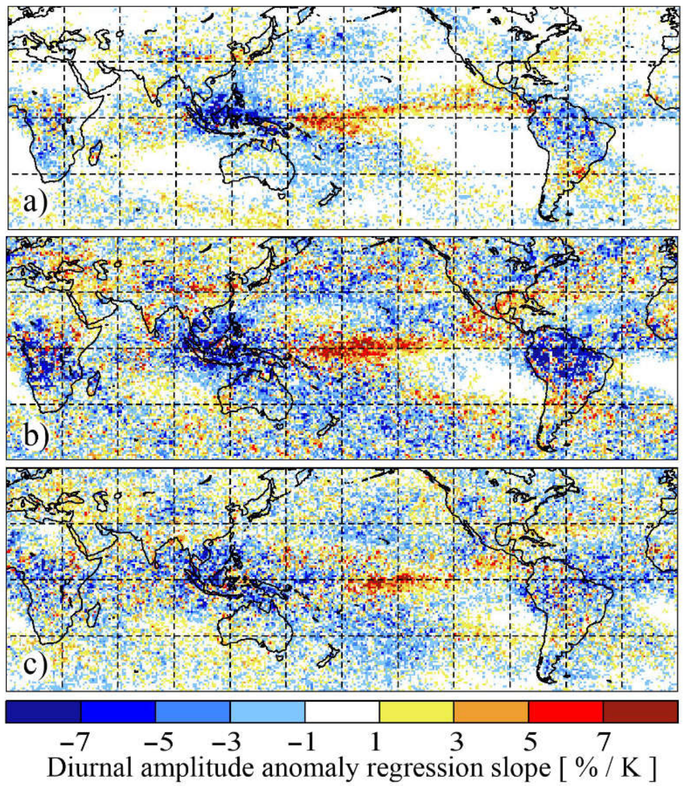


Fig. 10. Geographical maps of linear regression slopes for the period of 2008–2015 estimated from the ratio of de-seasonalized monthly mean diurnal amplitude anomalies determined from combined AIRS-CIRS and IASI-CIRS cloud data, and global mean T_{surf} anomalies, from ERA-Interim for (a) high opaque cloud amount, (b) cirrus, and (c) thin 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 are mostly ~~onboard~~aboard polar orbiting satellites, providing only observations twice per day. In this article, we ~~present~~presented a methodology to use the synergy of AIRS and IASI cloud observations~~, allowing~~ to address the diurnal variation not only of total high-level cloud ~~cover, and~~amount, but also 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 surface and atmospheric ancillary data (from meteorological reanalysis ERA-Interim) to extract a reliable diurnal cycle from the ~~measurements~~cloud retrievals performed ~~by~~on different satellite ~~instruments.~~instrument measurements. We demonstrated the feasibility ~~of determining~~to determine 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 ±1.5h 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 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~~The zonally averaged diurnal ~~variation~~cycle of high-level cloud amount estimated from AIRS and IASI cloud data compares relatively well with other datasets, such as the one determined from CATS lidar observations and the one from ISCCP multispectral imager observations. Slight differences can be understood by much more limited statistics of CATS, in particular in the tropics, and misidentification of thin cirrus by ISCCP.

Considering diurnal variations separately ~~for~~of high opaque, cirrus and thin cirrus ~~often show a different behaviour, which indicates the importance~~amount leads to ~~distinguish these~~a better understanding, as one can also study the lags between the different cloud types, which 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 summer midlatitudes, in agreement with other analyses. By using the time series of the eight years of combined AIRS-CIRS and IASI-CIRS data, we could relate diurnal amplitude changes to climate fluctuations, given by de-seasonalized global T_{surf} anomalies from ERA-Interim, and found that largest diurnal amplitudes of high-level cloud amount are linked to deep convective systems.

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~~.~~, but in general AIRS alone with its observations at 1h30 and 13h30 LT is closer to capturing the maximum and minimum of cloud cover over tropical land than IASI observing the atmosphere at 9h30 and 21h30 LT. 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

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 the links between the cloud system elements.

Acknowledgements and Data

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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 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).

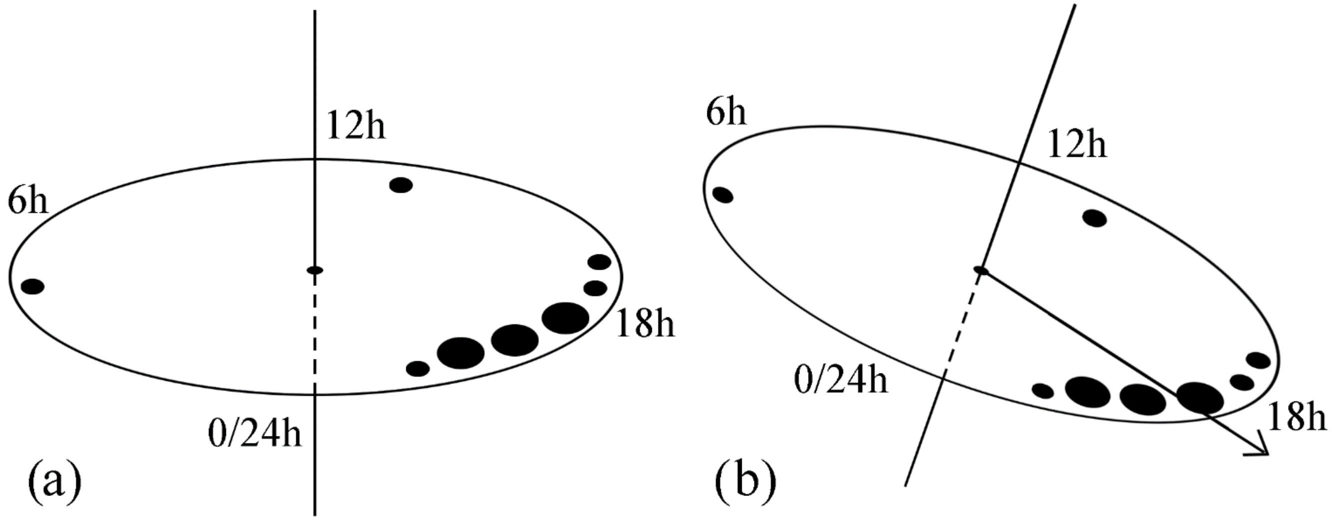

Fig. A1. Illustration of "resulting force" algorithm for calculating the average of phase values: a) diurnal cycle amplitudes are used as "weights" (black dots of different sizes), which are placed on the perimeter of the disk in accordance with the corresponding phase values; b) when "released", the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

Appendix B: Diurnal variation of surface temperature

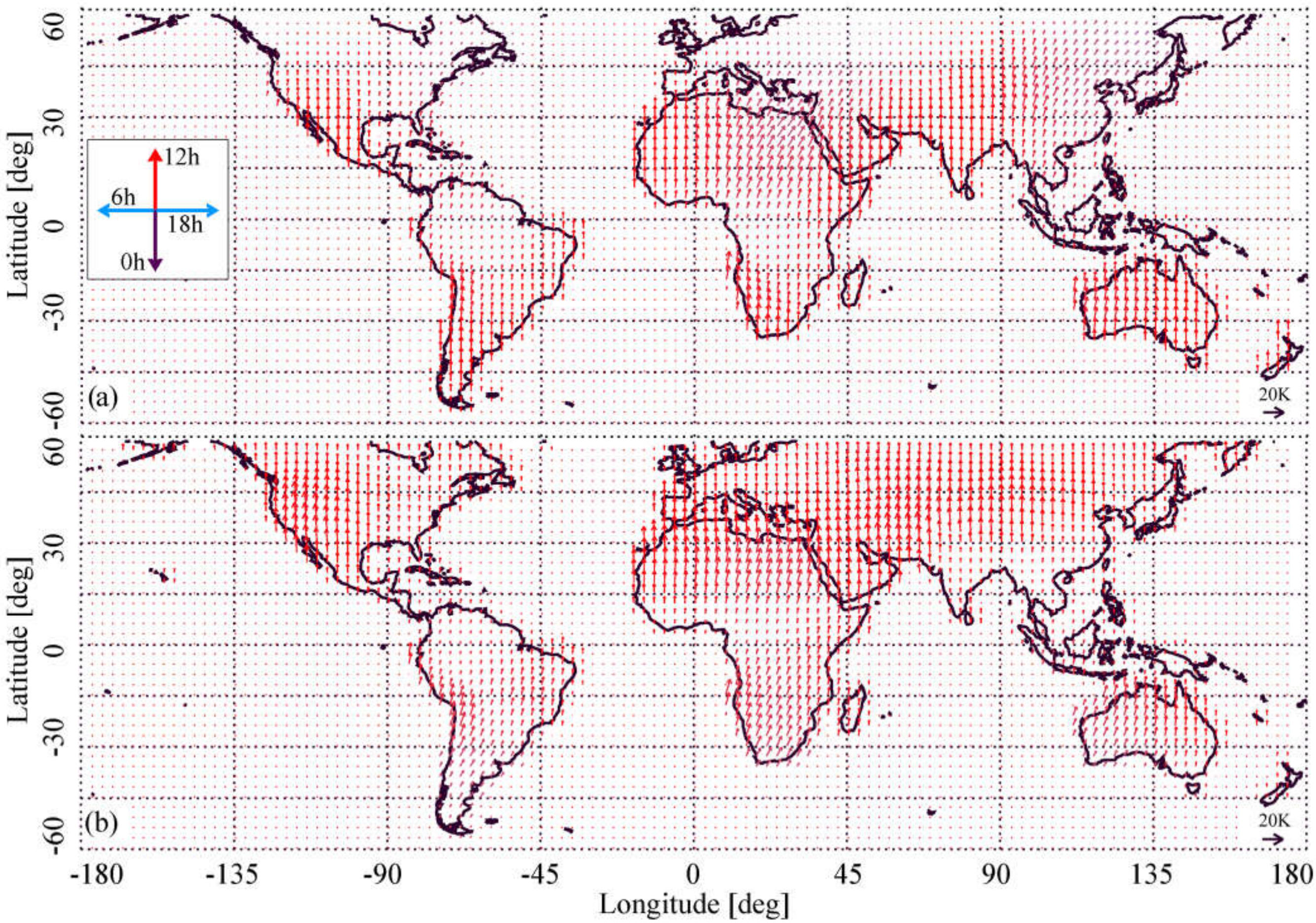

Fig. B1. Diurnal variation of surface temperatures, estimated from ERA-Interim reanalyses, in January (top) and in July (bottom). The vector representation is consistent with the caption of Fig. 5.

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

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

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 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 inertia inducing higher amplitude (and vice versa)”. Their study shows that thermal inertia also impacts the turbulent heat fluxes.

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