The reply to the anonymous referee #2 (RC2)

We are grateful to the referee for the remarks. We took them into account while revising our paper. However, we do not agree with several suggestions made by the esteemed referee and below we present our argumentation for that.

Below, the actual comments of the referee are given in **bold courier font and blue colour**. The text added to the revised version of the manuscript is marked by red colour.

This manuscript focuses on the variability of the LWP gradient by seasons and by the horizontal scale of lakes.

To our opinion, the esteemed referee's view on the problem considerably differs from our view. We selected the first statement of the referee as the key which can help to understand and explain the reason for that. The statement presented above is correct, but we should not forget about the origin of experimental data taken for analysis. Actually, the origin of data and the reliability of data are very important issues which should be kept in mind before making any analysis.

We confess that may be it was our fault not to make proper emphasis on the fact that the LWP data derived from the space-borne observations by the SEVIRI instrument over water are still not validated and therefore may contain errors. Therefore, the analysis of the variability of the LWP land-sea contrast had the aim not only to reveal specific seasonal and diurnal features, but also to identify possible artefacts in measurements. It is obvious, that assessment of the self consistency of data should be of higher priority with respect to analysis of possible physical reasons of detected seasonal and diurnal features of the quantity under consideration (the LWP land-sea contrast in our case).

We guess that the referee assumes that our goal is to find explanations for the observed variability of the LWP contrast. It is true, but this goal stands in the relatively long perspective. The task of higher priority is to identify the main features of the LWP land-sea contrast and to eliminate possible measurement errors and artefacts. Fulfilling this task has appeared to be a separate large study which we presented in our manuscript. Therefore, in order to clarify our view on the problem and explicitly declare the goals and novelty of our study, we added the subsections "1.2 Motivation" and "1.3 Novelty" in the Introduction.

Obviously, the variability depends on the dynamic and thermodynamic states around the lakes (oceans). It is impossible to avoid the analysis of the boundary layer structure and comparison of the characteristic length-scale of the circulation and the scale of lakes. Linear theory will support you to explain the observed phenomena. However, the authors did not mention the dynamical aspect of the meso-scale circulation in the introduction section at all and slightly looked at the ICON simulations.

We have carefully studied the referee's comment containing a strong proposal to include in the analysis of the observed phenomena the "dynamical aspect of the meso-scale circulation". We agree that the introduction section and discussion of the identified land-ocean contrasts lacks a mention of the sea breeze mechanism. Indeed, strong sea breeze fronts initiate vertical currents that are often marked by the development of cumulus clouds. In response to this referee's remark, in the revised version we mention the sea breeze mechanism in the Subsection 1.2. We are grateful to the referee for providing links to relevant studies, which we reviewed in detail. However, our attention was drawn to another, later work by Miller et al. (2003) which provides a comprehensive review of see breeze research dating back 2500 years and focuses on recent studies. Therefore, we decided to refer specifically to this article in the revised version of our paper rather than to the papers suggested by the esteemed referee. And we emphasize, that modeling and applying the sea breeze mechanism to our results is definitely beyond the scope of our present study.

Explanation of the motivation for our study and mentioning the sea breeze mechanism have been included in the revised version as follows:

1.2 Motivation

Primarily, the motivation for our efforts to investigate the LWP land-sea difference originated from our previous studies (Kostsov et al. 2018, 2019) which were devoted to the problem of validation of space-borne remote observations of cloud parameters by means of ground-based passive microwave remote sounding. In these studies microwave measurements were conducted over land but in a coastal area. It should be emphasized that ground-based microwave remote measurements of LWP are the most reliable and widely used tool for validation of observations of LWP from space, in particular by the instruments SEVIRI and AVHRR which measure reflected solar radiation (Roebeling et al., 2008ab; Greuell and Roebeling 2009). However, to the best of our knowledge, there were no validations of space-borne measurements over water areas and over water bodies covered by ice/snow. The importance of such validations arises from the fact that retrieval algorithms use a land-sea mask, and also they use a sea-ice and a snow mask. A misclassification in a mask can cause errors which propagate to higher-level products of the satellite observations. Such situation can occur in winter and during off-season. In winter, the LWP retrieval over highly reflective surfaces (snow and ice) becomes even more complicated problem (Musial et al., 2014), and, as a consequence, the retrieval errors can increase. The mechanism of the error amplification is described by Han et al. (1999) and Platnick et al. (2001): (1) multiple reflections occur between a cloud and underlying surface; (2) the increase in reflectance contributed by a cloud is relatively smaller in case of highly reflective underlying surface. The problem becomes more complicated due to the variability of the ice/snow properties. It has been noted by Platnick et al. (2001) that, as shown in a number of studies, the albedo of the sea ice is dependent on several factors, for example on the presence of air bubbles. Besides, if ice is covered with a snow layer greater than several centimetres the overall reflectance is dominated by this snow layer. Also, the melting process can cause the decreases in reflectance. The complexity of the problem of space-borne remote sensing of cloud parameters over different surfaces stimulated us to conceive the study in which the general features of the LWP land-sea contrast derived from satellite measurements could be summarised and analysed. In our opinion, the joint comprehensive analysis of the large LWP data sets derived from space-borne observations over various surfaces can be valuable for development of validation algorithms.

The importance of studying the LWP land-sea difference rather than the LWP values over land and water separately arises from the fact that inconsistency of data can be detected more easily in this way. The vivid example of detecting inconsistency in data by means of looking at the land-sea contrast of atmospheric parameter is an artefact in ozone column measurements by the TOMS (Total Ozone Mapping Spectrometer) instrument (Cuevas, 2001). Persistent year-to-year differences in total ozone between continents and oceans were found in the mean global ozone data which were averaged in time. This feature has been named GHOST (Global Hidden Ozone Structures from TOMS). Part of these differences appeared to be caused by truncation of the lower tropospheric column due to the topography and by permanent differences in tropopause height distribution. The remaining part (66%) has found to be an artefact of the retrieval algorithm: the effects of the presence of UV-absorbing aerosols might have been accounted for not correctly. For examining the effect of each possible contribution to the observed difference, Cuevas (2001) selected the Iberian Peninsula region for a case study. The study by Cuevas (2001) was an encouraging example for us and additional stimulus to investigate common features of the LWP land-sea differences in Northern Europe with the aim to identify the natural effects and possible artefacts in measurements.

The second reason for making the present study was the lack of information on the LWP land-sea differences. Except the above mentioned works by Karlsson there were no special studies focused on the analysis of the LWP values over surfaces of various types in Northern Europe, in particular over land and water areas. Obviously, taking into account the diversity of properties of water bodies and the diversity of the features of local climate, we can expect that the LWP land-sea differences are highly variable in space and time. So far, not enough attention was paid to this interesting issue. In our view, this issue is important for development of regional weather and climate models from the perspective of more accurate simulations over water bodies and in neighbouring areas. As an example, the ICON model can be mentioned which has a special option for weather and climate simulations over lakes (ICON, 2021; ICON Tutorial, 2021).

The third motive to initiate the present study was the fact that so far not much attention was paid to the investigation of physical mechanisms which drive the LWP land-sea differences in Northern Europe. The reason for the differences in spring and summer has been suggested by Karlsson (2003): the inflow of cold water from melting snow and ice is cooling the near-surface atmospheric layer over the water bodies. As a result, in contrast to the land surface, this layer over the water bodies becomes very stable preventing the formation of clouds. This mechanism, however, does not explain the existence of the LWP land-sea difference during cold season when both land and water surfaces are covered with snow and ice. We would like to mention one more mechanism which has been suggested by an expert during an open discussion of the preprint of the present article (https://doi.org/10.5194/acp-2021-387-RC1, last access 29 March 2022):

‘In addition, during winter/spring, (dark) forest areas can absorb considerably more solar radiation than surrounding snow-covered ground or ice-covered water surfaces. This can also lead to updrafts and eventually cloud formation.’

The sea breeze mechanism should be mentioned also. Indeed, strong sea breeze fronts initiate vertical currents that are usually marked by the development of cumulus clouds. The detailed review of recent studies of the sea breeze features can be found in the paper by Miller et al. (2003). However the sea breeze mechanism is not able to fully explain the diversity of land-ocean contrasts presented in our work. Indeed, the sea breeze can be the reason for the development of convective cloudiness in the frontal zone, with an inland penetration up to several tens of kilometers. But the results presented in our work demonstrate the systematic suppression of cloudiness over water bodies, with a relatively uniform distribution of cloudiness over the land surface, regardless of the distance from the coastline (see the map in Fig. 2, for example). The sea breeze phenomena certainly can complement another physical mechanism proposed by Karlsson (2003) and already mentioned above. However, both of these mechanisms – the sea breeze circulation and the influx of melt water – cannot explain the existence of the land-ocean contrasts during the cold season, when both land and water surfaces are covered with snow and ice.

In our opinion, the necessary prerequisite for identifying the prevailing physical mechanisms which drive the LWP land-sea differences in Northern Europe is the special detailed statistical analysis of the LWP data provided by the satellite instruments over various water bodies and over land near these water bodies during different seasons. In the present work we make a kind of such analysis.

Added references:

Cuevas, E., Gil, M., Rodriguez, J., Navarro, M., and Hoinka, K.P.: Sea-land total ozone differences from TOMS: GHOST effect, Journal of Geophysical Research, 106 (D21), 27745-27755, https://doi.org/10.1029/2001JD900246, 2001.

Miller, S.T.K., Keim, B.D., Talbot, R.W., Mao, H.: Sea breeze: Structure, forecasting, and impacts, Reviews of Geophysics, 41(3), https://doi.org/10.1029/2003RG000124, 2003.

Since the corresponding author already documented several papers about the land-ocean contrast, and hence, it is about time to analyze dynamics in addition to the statistical analyses. Therefore, my recommendation is reject.

We would like to make some clarification. So far, we published three papers:

Kostsov, V. S., Kniffka, A., and Ionov, D. V.: Cloud liquid water path in the sub-Arctic region of Europe as derived from ground-based and space-borne remote observations, Atmos. Meas. Tech., 11, 5439-5460, doi:10.5194/amt-11-5439-2018, 2018.

Kostsov, V. S., Kniffka, A., Stengel, M., and Ionov, D. V.: Cross-comparison of cloud liquid water path derived from observations by two space-borne and one ground-based instrument in northern Europe, Atmos. Meas. Tech., 12, 5927–5946, https://doi.org/10.5194/amt-12-5927-2019, 2019.

Kostsov, V. S., Ionov, D. V., and Kniffka, A.: Detection of the cloud liquid water path horizontal inhomogeneity in a coastline area by means of ground-based microwave observations: feasibility study, Atmos. Meas. Tech., 13, 4565–4587, https://doi.org/10.5194/amt-13-4565-2020, 2020.

In the first two papers the problem of the assessment of the LWP land-sea contrast was just shortly mentioned. These papers were sharply focused on the comparison of the space-borne and ground-based measurements of LWP. So, up to now we made only one study completely focused on the LWP land-sea contrast (Kostsov et al., 2020) but this study was devoted to the problem of the LWP contrast detection only from ground-based observations at only one location. One can see that our present work is just the second specialized study of the LWP land-sea contrast and the very first study of its spatial and temporal features. Therefore, we do not agree with the referee's statement that the time has come to perform the analysis of dynamic processes. We also would like to mention that actually we started such analysis but using the ICON model. In our opinion, it is the matter of authors choice what tool and what way to use for investigations. We decided to follow the way of using modern state-of-the-art weather and climate models which are able to simulate a bunch of different processes and at the same time to account for local orography. The above mentioned progress of the present work in comparison to our previous studies is summarized in the revised version in Section 1.3:

1.3 Novelty

In the present study, the focus is made on the temporal and spatial variations of LWP in coastal areas at different scales. The goal of the present study is to analyse the phenomenon of the LWP horizontal inhomogeneities in the vicinity of a number of water bodies in Northern Europe which differ significantly in their geomorphology (shape, area, volume, etc.): Gulf of Finland, Gulf of Riga, the Neva River bay, Lake Ladoga, Lake Onega, Lake Peipus, Lake Pihkva, Lake Ilmen, and Lake Saimaa. The study is based on LWP data over Northern Europe obtained from seven years (2011-2017) of the space-borne measurements by the SEVIRI instrument. Initially, our aim was to answer the following main questions:

- What are the statistical distributions of the LWP land-sea difference during different seasons at different water bodies?
- Does the LWP land-sea contrast always exist during warm and cold season at water bodies with different properties, and what is its magnitude for large and small water bodies?
- How strong is the inter-annual variability of the LWP land-sea contrast and are there any long-term trends?
- Are there any characteristic features in the diurnal variations of the LWP land-sea contrast (for the day time when space-borne measurements by SEVIRI are available)?
- Is there any correlation between the ice/snow cover period and the magnitude of the LWP contrast?
- Can we distinguish artefacts in the LWP contrast data provided by SEVIRI and, if yes, when and how often do these artefacts appear?

In addition, for several specific cases, atmospheric parameters over the mesoscale domain comprising Gulf of Finland and several lakes have been simulated with the numerical model ICON in limited area and weather prediction mode. The goal of these simulations was to assess how modern state-of-the-art weather-climate model which account for a variety of processes and produce self-consistent data can be used for studying the problem of formation of the LWP land-sea contrast.

The authors can easily find some past researches on the meso-scale circulation related to the land-ocean contrast as follows. Please review in detail.
Hadi et al., (2000) Tropical Sea-breeze Circulation and Related Atmospheric Phenomena Observed with L-band Boundary Layer Radar in Indonesia, https://www.jstage.jst.go.jp/article/jmsj1965/78/2/78_2_123/_article

Niino (1987)The Linear Theory of Land and Sea Breeze Circulation, https://www.jstage.jst.go.jp/article/jmsj1965/65/6/65_6_901/_article/-char/en

Yan and Anthes (1987) The Effect of Latitude on the Sea Breeze https://doi.org/10.1175/1520-0493(1987)115<0936:TEOLOT>2.0.CO;2

We are grateful to the referee for providing these references. We have carefully read these papers which will certainly help us in future specialised research after the LWP contrast data will be validated and possible artefacts will be removed. To our opinion, making focus on sea breezes can be misleading at the present step of investigations.

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corresponding author