

1 **CloudViT: exploring cloud type classification with vision transformers**

2 **in global satellite data.**

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4 Julien Lenhardt ¹, Johannes Quaas ^{1,2}, Dino Sejdinovic ³, Daniel Klocke ⁴

5

6 ¹Leipzig Institute for Meteorology, Universität Leipzig, Leipzig, Germany

7 ²ScaDS.AI - Center for Scalable Data Analytics and Artificial Intelligence, Leipzig University, Humboldtstraße 25, 04105

8 Leipzig, Germany

9 ³School of Computer and Mathematical Sciences & Australian Institute for Machine Learning, University of Adelaide, Adelaide,

10 Australia

11 ⁴Max Planck Institute for Meteorology (MPI-M), Hamburg, Germany

12 *Correspondence to:* Julien Lenhardt (julien.lenhardt@uni-leipzig.de)

13 Abstract

14

15 Clouds constitute, through their interactions with incoming solar radiation and outgoing terrestrial radiation, a fundamental
16 element of the Earth's climate system. Different cloud types show a variety in cloud microphysical or optical properties, phase,
17 or vertical extent, and thus disparate radiative effects. Both in observational and model datasets, classifying clouds is important
18 since different cloud types respond differently to current and future anthropogenic climate change. Cloud types have traditionally
19 been defined using a simplified partition of cloud top pressure and optical thickness, but recently using deep learning. In this
20 study, we present a method called CloudViT (Cloud Vision Transformer) building on surface observations and spatial extracts of
21 cloud properties from the MODIS instrument to derive cloud types, leveraging spatial patterns with a vision transformer model.
22 The performance of the model is fair and hampered by the limited number of samples and the challenging matching between data
23 sources arising during the collocation process. The method is then evaluated through the distributions of cloud type properties and
24 global spatial patterns of cloud type occurrences. Potential improvements emerge in the reduction in mismatches between data
25 sources, the extension of the collocated dataset, and the refinement of the classification model. While the application of the
26 method in its current state comes with apparent uncertainties due to limited performance, it raises relevant challenges and
27 limitations, from which the community can benefit from discussing for the development of similar methods. To foster future
28 advancements, the dataset and model are available from Zenodo (Lenhardt et al., 2024b).

29

30 1 Introduction

31

32 Clouds form an essential component in the Earth's climate, by impacting the atmospheric energy budget and water cycle, and by
33 influencing the reflected solar radiation as well as the outgoing terrestrial radiation fluxes. Clouds are highly variable spatially
34 and temporally, and occur in a large variety of types (Howard, 1803; WMO, 2017). Typically, separating clouds between low and
35 high (WMO, 1975), and between stratiform and cumuliform (WMO, 1975, 2017), reveals different and complex cloud effects on
36 processes such as radiation and precipitation formation (Hartmann et al., 1992; Dhuria and Kyle, 1990). The high variability and
37 complexity of clouds are some of the causes for the uncertainties in estimates of their response to anthropogenic climate change
38 both currently and in the future (Boucher et al., 2013; Forster et al., 2021). These uncertainties manifest both in observational
39 datasets for which the aim is to constrain past and current effects, and in climate models where cloud representation is of utmost
40 importance to properly constrain future scenarios. Through the phase (liquid, ice or mixed), the droplet size distribution, the
41 vertical structure or other micro- and macro-physical properties, different cloud types can lead to drastically diverse radiative
42 effects making the cloud type a property of interest to help describe their involvement in the weather and climate system
43 (Ramanathan et al., 1989; Slingo, 1990; Oreopoulos et al., 2017; Luo et al., 2023). Unravelling and understanding trends in
44 clouds has become more tractable in recent decades due to the large amount of remote sensing data made available globally on a
45 daily basis. However, analysing such extensive datasets manually becomes challenging, especially with the goal of extracting
46 meaningful information about different cloud types based on their patterns, microphysical properties or radiative effects.
47 Algorithms have taken over this complex task but still struggle to provide objective groupings out of the intricate spatio-temporal
48 patterns observed in remote sensing data. At the same time, applying methods which are engineered on remote sensing data to
49 climate models could become more viable as new global climate models are bridging the gap in resolution by reaching km-scale
50 resolutions, though this transfer to climate model data comes with its own challenges.

51 Traditional cloud classification methods are built on simple characteristics. The standard classification developed as part of the
52 International Satellite Cloud Climatology Project (ISCCP) relies on three levels (low, medium, high) of cloud altitude using as
53 proxy the cloud top pressure (CTP) and three thresholds of cloud optical thickness (COT), defining overall nine cloud types
54 (Rossow et al., 1991). This classification is performed on scalar fields, setting aside any spatial pattern in the cloud field from
55 which information could be obtained to better inform the classification process. Relying on the same type of two-dimensional
56 histograms, recent methods have been developed aiming at refining the created clusters and partially relaxing the constraints on
57 the pre-defined thresholds (Tzallas et al., 2022). The reason to choose the two parameters is that such a classification lends itself
58 to the analysis of cloud radiative effects: the cloud radiative effect in the solar is a monotonic function of COT, the one in the
59 terrestrial spectrum, of CTP. However, one might be interested in sensitivities of cloud thickness or water content to different
60 drivers (e.g., aerosols) for given cloud types, which is hampered by using CTP and COT to define the types. Also, COT does not
61 map well onto the distinction between cumuliform and stratiform clouds. For such reasons, Unglaub et al. (2020) defined cloud
62 regimes from cloud base height and variability in cloud top height, hinting at the added value of some measure of spatial
63 variability and pattern. However, to leverage spatial structure and textures, cloud classification methods based on artificial
64 intelligence (AI) have opened new avenues of research built upon vast amounts of remote sensing data. For example, using
65 convolutional neural networks (CNNs; LeCun et al., 1989; LeCun et al., 1995), Zhang et al. (2018) use ground-based images and
66 human-labelled cloud types to develop a model for meteorological cloud classification and support weather prediction tasks.
67 Using a similar architecture, Rasp et al. (2020) classify clouds from expert-labelled satellite images of four different cloud
68 organisation patterns in the trades. This method further emphasises how expert knowledge to identify cloud patterns can be
69 learned by CNN models and allow to then better constrain radiative effects of mesoscale convection (Wood and Hartmann, 2006;
70 Bony et al., 2020; Stevens et al., 2020) which would prove to be too cumbersome manually. The application of deep learning to
71 the classification of mesoscale cloud patterns in particular (Muhlbauer et al., 2014; Yuan et al. 2020; McCoy et al., 2023)
72 additionally demonstrates how specific cloud organization patterns, observable by experts in satellite data, can be learned by
73 machine learning models, and allows a deeper analysis of their radiative effects and characteristics on longer time periods and
74 larger spatial scales. These studies rely on human observers to initially classify clouds or cloud patterns directly from images,
75 relying on visual aspects to distinguish clouds, and subsequently linking the identified cloud types to local meteorological
76 conditions. Kuma et al. (2023) also capitalize on ground-based observations but connect them to shortwave and longwave
77 radiation satellite retrievals at coarser spatial and temporal resolutions. The method relies on identifying patterns directly in
78 radiation retrievals to associate them to daily occurrence probabilities of cloud types. This method has the benefit of being able to
79 be used on outputs from large ensembles of global model simulations and reanalysis datasets which cover extended time-scales
80 compared to observational datasets. Relying on similar model architectures, Zantedeschi et al. (2019) and Kaps et al. (2023)
81 classify cloud types derived from active remote sensing labels. The study from Kaps et al. (2023) capitalizes on the model from

82 Zantedeschi et al. (2019) to extrapolate cloud type estimates using global passive remote sensing data, and jointly trains a model
83 on coarsened data with spatial resolution similar to current global climate models. Other methods have been developed without
84 the use of cloud type labels, drawing conclusions from clusters appearing in large remote sensing radiation retrievals (Kurihana
85 et al., 2022). In general, the developed methods rely on identifying characteristic patterns arising in images (related to visible
86 features of cloud types), radiation retrievals (related to radiative properties of cloud types), or cloud properties retrievals (related
87 to physical properties of cloud types). Each choice of cloud type labels introduces a certain level of subjectivity in the derived
88 cloud types. For example, there is less subjectivity in the expert-labelled images than in the produced cloud clusters, which
89 naturally introduces some subsequent biases. Choosing certain input quantities also physically constrains the variability of cloud
90 type properties which can hinder the interpretation of the derived cloud type estimates. However, the transferability to global
91 climate model outputs is a great advantage of some of these methods as they provide a crucial way to diagnose the representation
92 of clouds in climate models and push towards reducing uncertainties in representing future-climate clouds (Kuma et al. 2023;
93 Kaps et al. 2023).

94 In this study, we investigate the classification of clouds by merging surface observations of cloud types and passive satellite
95 retrievals of cloud properties, building a method called CloudViT (Cloud Vision Transformer). Following a similar methodology
96 from previous work (Lenhardt et al., 2024a), we define cloud scenes as tiles of 128x128 pixels which encompass cloud
97 microphysical and optical properties at a 1 km horizontal resolution. The employed cloud properties are from the MODerate
98 Resolution Imaging Spectroradiometer (MODIS, Platnick et al. (2017)), and more particularly the cloud top height (CTH), the
99 cloud optical thickness (COT) and the cloud water path (CWP), which are paired with surface network observations of cloud
100 types (cf. Table 1). To harness the spatial aspect of the cloud scene and extract relevant features from the input cloud properties,
101 we resort to computer vision models based on CNNs and transformers (Dosovitskiy et al., 2020). Firstly, a vision transformer
102 model is trained in a self-supervised setting to create a condensed latent representation of the input cloud field. Subsequently, a
103 simpler classification model is fitted to predict the cloud type corresponding to the cloud scene, learning from the labels of a
104 wide ground-based observation network. The formulated method has the goal to produce estimates of cloud types while
105 generalising from the local ground observations to global distributions, increasing both the temporal and spatial coverage. The
106 method relies partly on the assumption that the observed cloud types exist on scales similar to the extent of the tiles, and
107 additionally builds on the spatial patterns characteristic of different cloud types. Moreover, as the ground-based cloud type
108 observations provide consistent labels which are only available at sparse locations, we can leverage long-standing instruments
109 like MODIS to design an algorithm based on satellite retrievals suited to generalisation to global distributions.

110 Firstly, we introduce in section 2 the different datasets used in the study alongside the collocation process between the
111 ground-based and satellite datasets. Subsequently, the different components of the CloudViT method are presented in section 3,
112 supported by sensitivity studies about the generalisation skill of the models and the benefits of the spatial context. In section 4,
113 we evaluate the method and investigate the distribution of cloud properties following the predicted cloud types. The results in
114 section 5 focus on the extension to a global distribution of cloud types. Challenges, limitations, and lessons learned from
115 CloudViT’s development are highlighted in the following section 6, with the guiding idea of making cloud type classification
116 with vision transformers reliable, capable of achieving notable performance, and potentially applicable to high-resolution climate
117 model simulations. Eventually, we conclude over the presented method and challenges of cloud type classification.

118 **2 Data**

119

120 **2.1 Surface observations**

121

122 The cloud type observations used in this study come from two similar global observation datasets maintained by the UK Met
123 Office, one providing observations made at sea (Met Office, 2006) and the second providing observations made on land (Met
124 Office, 2008). These observations are performed from weather stations (land or sea) or ships, by trained observers following the
125 WMO code tables (WMO, 2019). Each cloud level (high, WMO code table 0509; medium, WMO code table 0515; low, WMO
126 code table 0513; see Table A.1) is separated in 9 different types describing in more detail the aspect and type of the observed
127 clouds. The labels thus provide a high level of detail regarding the observed cloud scene from the surface. Naturally, the case of
128 multilayer clouds poses a problem since the field of view and the visibility from the surface are limited, which is why we remove
129 the potential multilayered cases from the training dataset to focus only on single-layer observed cloud scenes. It induces potential
130 selection bias issues as some cloud types might more likely be observed in multilayered configurations. The relative amounts of
131 each cloud type before and after the filtering and collocation process are displayed in Figure 2. Similarly, uncertainty is greater for
132 medium and high clouds as their observation can be more challenging than for low clouds. Furthermore, the spatial distribution

133 of the labels (Fig. 1, Fig. A.1) can be problematic as the marine observations are distributed mainly along ship routes. On the
134 other hand, combining that with land observations provides a more complete representation of cloud types, especially for high
135 level ones, all the while introducing the influence of orography. Other studies like Kuma et al. (2023) and Lenhardt et al. (2024a)
136 have built estimates of cloud quantities based on these ground-based observation datasets, overcoming limitations pertaining to
137 incomplete field of view and disparate spatial distribution.

138 For simplifying the analysis but also the training of the classification model, we group the 27 reported WMO cloud types into 4
139 and 10 categories, similarly to Kuma et al. (2023). The first categorisation allows for broad classification by dividing the cloud
140 species into high, medium, cumuliform and stratiform types. The second categorisation provides a more detailed classification
141 while still limiting the subdivision of similar cloud types. This prevents a too pronounced unbalance in the cloud type labels
142 while possibly removing some of the subjective biases and uncertainty stemming from the human observers. The detailed
143 categories corresponding to the WMO codes are available in Table A.1 and shown in Figure 2.

144

145 2.2 Satellite retrievals

146

147 In addition to the surface observations, we use satellite retrievals from MODIS, in particular from the AQUA satellite. MODIS
148 retrievals offer a vast amount of data at kilometre-scale resolution with daily overpasses. Each of the supplied granule file
149 contains cloud microphysical and optical properties across a region with a span of around 2330 km x 2000 km. We make use of
150 the available CUMULO dataset (Zantedeschi et al., 2019) since it allows access to preprocessed MODIS level 2 satellite data,
151 with global coverage, and for two full years (2008 and 2016). Among the data variables available, we rely on two unified
152 products (cf. Table 1) describing either cloud properties (MODIS06 level 2 cloud product, hereafter MYD06; Platnick et al.,
153 2017) or the cloud cover (MODIS35 level 2 cloud flag mask, hereafter MYD35; Ackerman et al., 2017). The latter's main usage
154 is to help screen for cloud scenes with a minimum cloud coverage.

155 The MYD06 data product incorporates miscellaneous properties pertaining to the cloud top (temperature, pressure, height)
156 alongside some microphysical and optical properties (effective radius, water path, optical depth). As mentioned previously, our
157 method builds upon level 2 data which are typically obtained from calibrated radiances through methods described in Platnick et
158 al. (2017). More specifically, cloud top properties are retrieved using several radiance channels: harnessing the opacity of CO₂,
159 the CTP of high clouds is retrieved with wavelengths in the CO₂ absorption range, while infrared wavelengths combined with
160 simulated brightness temperatures are used for lower and thicker clouds. The related CTH retrieval can thus suffer from regional
161 biases as the brightness temperatures are based on vertical profiles from reanalysis using regional and monthly averaged lapse
162 rate data along with surface temperature (Baum et al., 2012). The method introduced here can thus incorporate said biases from
163 the input data into the learning process. The microphysical and optical properties of clouds - COT and cloud effective radius
164 (CER) - are retrieved concurrently from multispectral reflectances, CTP values, surface types and cloud masks. Lastly, the CWP
165 is also retrieved as part of the cloud optical properties algorithm detailed in Platnick et al. (2017). The additional input quantities
166 needed to derive and retrieve the mentioned cloud properties (e.g. water vapour and ozone vertical profiles from reanalysis;
167 Platnick et al., 2003; Baum et al., 2012) can result in subsequent uncertainties where only sparse observations like in remote
168 marine areas are available for the data assimilation. Eventually, from the entirety of available MYD06 retrievals, we select three
169 cloud properties in particular, namely the CTH, COT, and CWP.

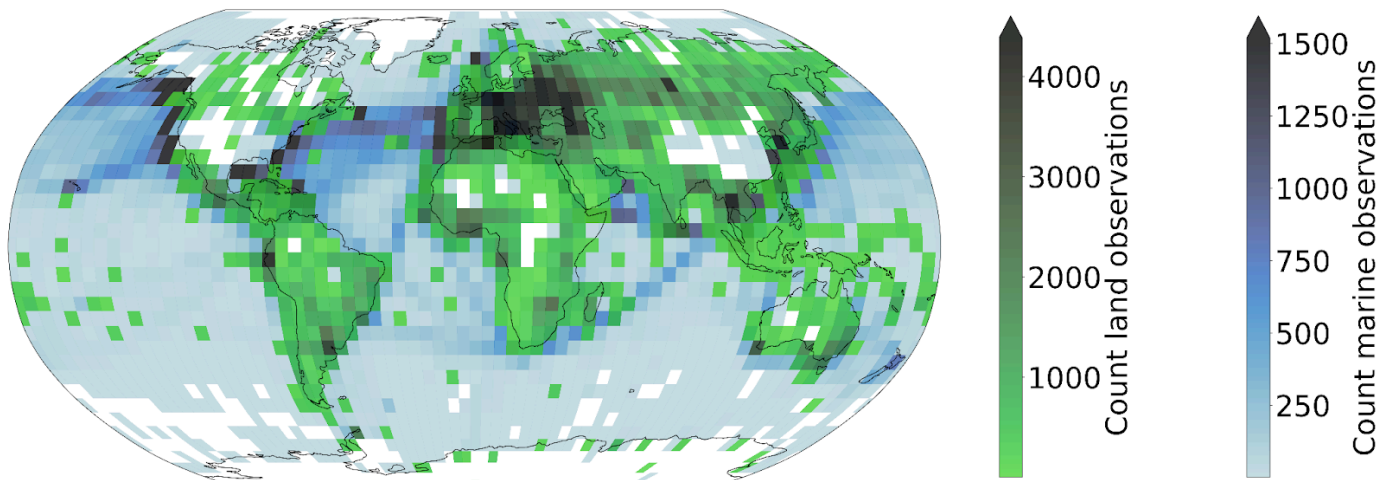
170 As a whole, the MYD06 product has the advantage that, building directly on cloud properties, we can design a classification
171 model from which the relationship between cloud type and other cloud properties can then be examined. Relying on calibrated
172 radiances which lie ahead in the retrieval process could offer a more neutral input but due to the large associated dimensionality,
173 extracting information about clouds might become more challenging. Additionally, basing the method on commonly used cloud
174 properties allows us to directly associate the results with other derived cloud classifications, making the comparison and
175 understanding of the predictions more straightforward. Nevertheless, the biases introduced by using level 2 data in comparison to
176 level 1 calibrated radiances and reflectances should be properly characterised and taken into account in the behaviour of the
177 statistical model.

178 Alongside the colocated dataset, we build a collection of randomly sampled tiles out of the satellite retrievals from the year 2008.
179 For each granule, a maximum of 20 tiles are sampled while ensuring the amount of missing data stays limited. This process leads
180 to the compilation of more than 1.3M single tiles of cloud properties. These tiles are then randomly split temporally into training
181 (70%), validation (10%) and test (20%) sets. This dataset is the basis for the self-supervised training procedure presented in the
182 following section.

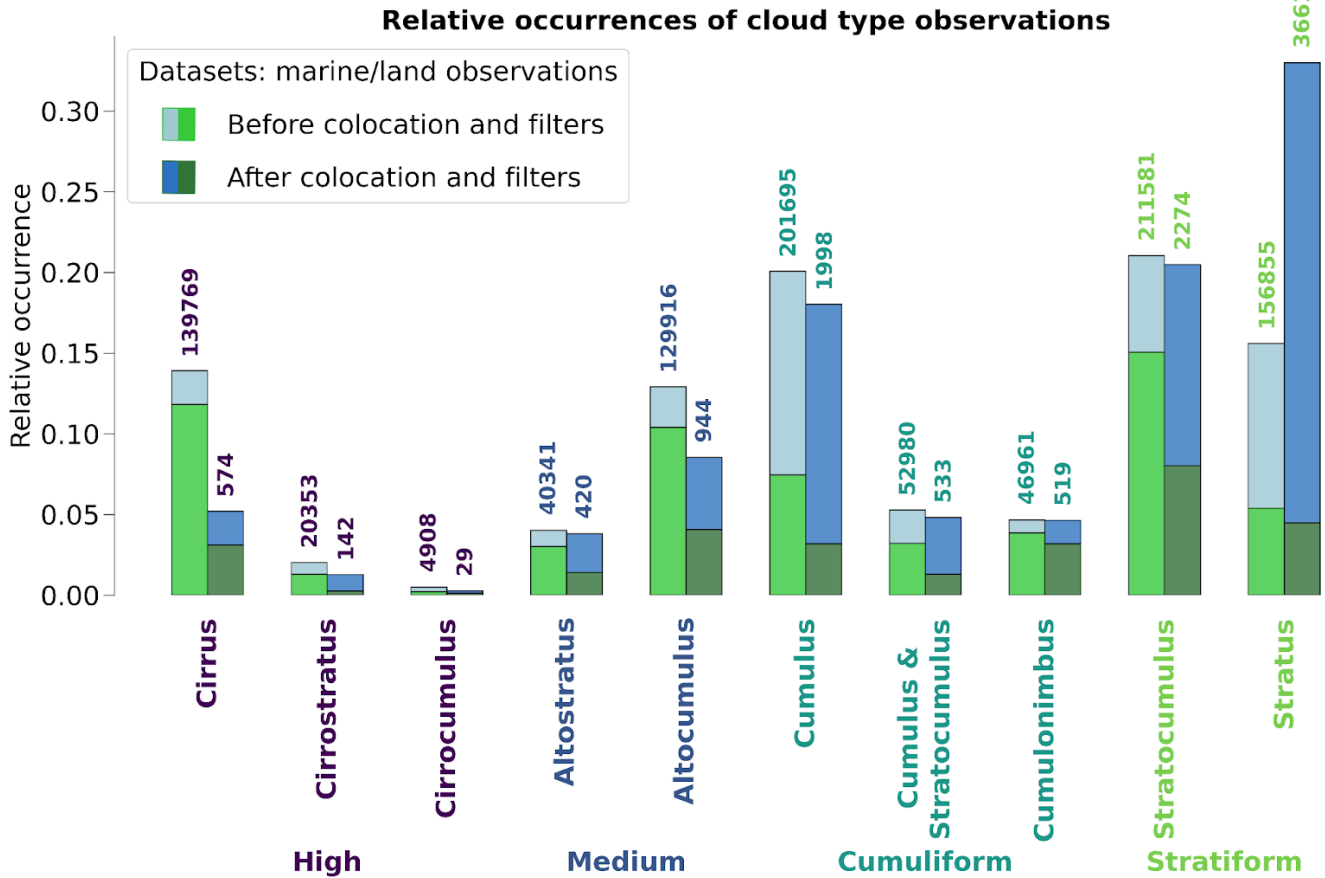
Data product	Description	Variables	Resolution	Usage
Global marine meteorological observations (Met Office, 2006)	Marine surface observations	Cloud type	Latitude/longitude coordinates 0.1° Hourly/daily observations	Labels
Land SYNOP reports (Met Office, 2008)	Land surface observations	Cloud type	Latitude/longitude coordinates 0.1° Hourly/daily observations	Labels
MODIS Atmosphere L2 Cloud Product (MYD06) (Platnick, 2017)	Cloud-top properties, cloud optical and microphysical properties	Cloud top height, CTH (m) Cloud optical thickness, COT (a.u.) Cloud water path, CWP (g.m ⁻²)	1-km pixel resolution Daily overpass	Input features
MODIS Atmosphere L2 Cloud Mask Product (MYD35) (Ackerman, 2017)	Cloud pixel flag	Cloud mask	1-km resolution Daily overpass	Used for cloud scene filtering

184 **Table 1 : Datasets description. The surface observations are provided by a worldwide station network available from the**
 185 **UK MetOffice (Met Office, 2006; Met Office, 2008; see section 2.1). The MODIS data are derived from the collection 6.1**
 186 **of the datasets (Ackerman, 2017; Platnick et al., 2017; see section 2.2).**
 187

Marine (2008, 2016) & land (2016) cloud type observations count



188 **Figure 1: Spatial distribution of cloud type observations for marine (years 2008 and 2016; Met Office, 2006) and land**
 189 **(year 2016; Met Office, 2008). The corresponding spatial distributions of cloud type observations are included in Figures**
 190 **A.1 and A.2, for before and after the colocation process, respectively.**
 191
 192



193
 194 **Figure 2: Relative occurrences of cloud types before and after the collocation and filtering process, indicated for both the**
 195 **marine (blue; Met Office, 2006) and land (green; Met Office, 2008) observational datasets. The x axis corresponds to the**
 196 **cloud types in the case of 4 and 10 categories. The corresponding numbers of collocated samples for each cloud type are**
 197 **detailed in Table A.1.**

198 **3 Method**

199

200 **3.1 Method outline**

201

202 Relying on computer vision models and their large number of trainable parameters usually requires adapting the training strategy,
 203 particularly when the training dataset is of modest size. In the presented study, the amount of labels available is greatly reduced
 204 during the collocation process (see Table A.1 for the number of samples per cloud type) but still contains useful and exploitable
 205 information about the observed cloud types. We thus introduce a self-supervised learning process which allows us to draw on the
 206 larger amount of satellite data available before addressing the more complex task of cloud classification. The larger purpose of
 207 this methodology is to be able to classify clouds on a global scale, outside of the areas where surface observations were made and
 208 outside of the typical coverage of human observation stations.

209 For the self-supervised task, we train two models to reconstruct 3D data cubes of cloud properties. The first model, which is used
 210 as a baseline, is a CNN backbone we previously presented in Lenhardt et al. (2024a) to handle satellite retrievals of cloud
 211 properties for cloud base height prediction. The second model we develop in this study is based on vision transformers
 212 (Dosovitskiy et al., 2020), a recent type of model compared to the more typical CNNs for computer vision applications. The
 213 spatial pattern of the cloud properties and their scale provide information about clouds, which can be leveraged to classify them
 214 for example into more stratiform and more cumuliform types. During the training phase of these models, the samples are images
 215 of size 128x128 pixels consisting of three different cloud properties: CTH, COT and CWP. We ensure that the models learn to
 216 distinguish cloud patterns and not to recognise specific geographical locations by extracting samples randomly across global
 217 satellite retrievals from the year 2008, without adding information about their location. In a second step, a classification model is
 218 trained on the collocated samples of cloud properties and surface observations. As mentioned in section 2.1, the number of types

219 reported in the observations for clouds is reduced to either 4 or 10 classes (Kuma et al. 2023). The training process follows a
 220 supervised learning framework, where the classification model outputs a single cloud type (among the 4 or 10 cloud types) for
 221 the whole extent of the input cloud scene of size 128x128 pixels. The benefit of the presented method using either a CNN or a
 222 vision transformer, which are models incorporating a certain level of spatial awareness, is that it is consistent with the cloud type
 223 identified by the human observer. Furthermore, in comparison to conventional methods like the ISCCP, the method benefits from
 224 a potential ability to distinguish cloud types without using predefined thresholds.

225

226 3.2 Vision transformer

227

228 Vision transformers were introduced by Dosovitskiy et al. (2020), building on the transformer architecture previously presented
 229 in Vaswani et al. (2017) which was mainly applied to natural language processing (NLP) tasks. The adaptation to images was
 230 made by splitting images into patches of a certain size, 16 pixels in the case of the seminal paper, and providing the sequence of
 231 embeddings of these patches to a transformer. The patches from the images are then treated as words would be in a NLP
 232 application. The transformer can then be trained in a supervised fashion to classify the input images. They have been shown to
 233 perform at the same level or even outperform classical computer vision models like ResNets on tasks like classification (e.g. see
 234 Section 4 of Dosovitskiy et al., 2020). However, as mentioned in section 3.1, this type of model, alongside CNNs, is data hungry
 235 and requires a large number of labelled samples to be trained from scratch in a supervised fashion. In this setting, self-supervised
 236 pretraining can lead to highly performant models while not requiring a larger training dataset. We train a vision transformer
 237 following the self-supervised pretraining methodology presented in Atito et al. (2023), named Self-supervised vision
 238 Transformer (SiT). This methodology allows to train vision transformers in a self-supervised fashion building on the concept of
 239 Group Masked Model Learning (GMML), additionally using the same autoencoder framework as with traditional CNNs like the
 240 commonly used U-Net (Ronneberger et al., 2015) or our baseline model from Lenhardt et al. (2024a). The SiT architecture used
 241 in this study is adapted from the seminal vision transformer architecture (Dosovitskiy et al., 2020) by setting the latent dimension
 242 to 256, similarly to the CNN architecture introduced in Lenhardt et al. (2024a).

243 One strength of the transformer architecture is the possibility to easily include several simultaneous learning tasks. We can use
 244 this ability to our advantage and incorporate two objectives for the self-supervised training process: input reconstruction
 245 following GMML and contrastive learning. The input reconstruction is achieved by adapting the transformer into an autoencoder
 246 architecture. Like with traditional CNN autoencoders, the task is for the model to reconstruct the provided input. We benefit
 247 further from another advantage of vision transformers as they showcase a reduced complexity compared to CNNs since they rely
 248 to a much lesser degree on convolution operations. The methodology of Atito et al. (2023) additionally uses recent results in
 249 GMML to further help in the self-supervised learning task. The framework of GMML is integrated in the reconstruction task by
 250 replacing random parts of the input image with noise. The overarching goal of this image modification is to train the model to
 251 learn semantic representations of the input data, allowing reconstruction of masked areas only with knowledge of some other
 252 patches in the input image. The objective for this reconstruction task hence takes the form of the l1-loss, a commonly used metric
 253 (Zhao et al., 2016) between the standardised input and the reconstructed output:

$$254 \quad L_r = \frac{1}{N} \sum_{i=1}^N \left\| x_i - D_{\theta}(E_{\theta}(x_i^c)) \right\| \quad (1)$$

255 where x_i is the input standardised image, x_i^c is the corrupted standardised image, $\|\cdot\|$ is the l1-loss, N is the batch size, D_{θ} and E_{θ}
 256 are namely the decoder and encoder parts of the model with θ designating their learnable parameters.

257 The second learning task included in the training process is based on contrastive learning. Since the presented self-supervised
 258 process does not rely on labels for the training data contrary to the vision transformer from Dosovitskiy et al. (2020), the learning
 259 task needs to be adapted. To this extent, several geometric transformations and perturbations are applied to the training samples
 260 for which the transformer should produce similar outputs. The synthetic pairs can then be used as matching pairs and a metric
 261 can be built measuring their similarity. The contrastive task is thus training the model to minimise the distance between matching
 262 pairs of sample and corresponding augmented sample, while maximising the distance between different samples in the batch.
 263 Atito et al. (2023) propose to use as a contrastive metric the arithmetic mean over the matching pairs in the batch of the cross
 264 entropy of their normalised similarities:

$$265 \quad L_c = -\frac{1}{N} \sum_{i=1}^N \log l_c(x_i, x_i^a, E_{\theta}, D_{\theta}) \quad (2)$$

266 where the similarity metric between a sample x_i and its augmented version x_i^a is the normalised temperature-scaled softmax
267 similarity (Chen et al., 2020). The actual process of the contrastive learning further requires the use of a momentum encoder to
268 generate different versions for the pairs of samples and their corresponding augmented samples.

269 The integral self-supervised training process consists in a combination of the two previously presented learning tasks. For each
270 batch of samples, we create augmented versions of the samples which together constitute matching pairs. GMMML corruptions are
271 applied to both samples and the model is subsequently trained to reconstruct the original inputs from these corrupted samples. At
272 the same time, the similarity between matching pairs of samples is maximised. The complete loss function thus takes the form of:

$$273 \quad L = \alpha \times L_r + L_c \quad (3)$$

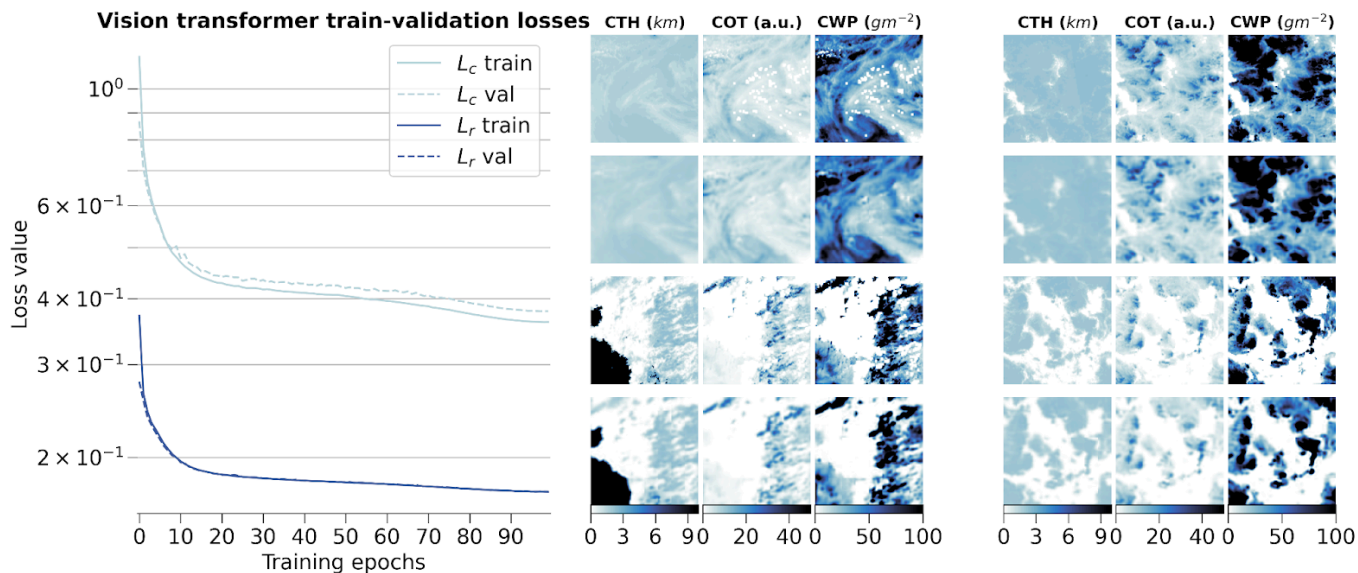
274 where α is a scaling factor between the two tasks. We follow the recommendation of Atito et al. (2023) to set $\alpha = 5$ in the case
275 of small-scale datasets so that the vision transformer can learn enough of the local inductive bias.

276 We set out to examine in further detail the ability of the vision transformer and of the self-supervised training methodology by
277 evaluating how different configurations of the input data and of the model architecture can impact the quality of the learnt
278 representations and the transfer to cloud classification. We mainly discuss in this section the reconstruction skill of the vision
279 transformer and the potential influence of contrastive learning. The transfer to the cloud classification task will be described in
280 the following section where fine-tuning to the downstream task or the use of external models are surveyed. Since training vision
281 transformers requires large computing resources, we limit ourselves for all the pretraining processes to only 10% of the initial
282 dataset mentioned in section 2.2, similar to what is done in Atito et al. (2023) regarding ablation studies.

283 To begin with, we investigate how the two architectures of vision transformers fare during the self-supervised training and how
284 the scaling factor between the contrastive loss and the reconstruction loss impacts the learning process. The two architectures
285 tested correspond to the small variant of the vision transformer from Atito et al. (2023) and the base variant from Dosovitskiy et
286 al. (2020). To offer an overview on each model’s complexity, their respective numbers of parameters are 21M and 86M, the main
287 difference originating from the number of heads in the self-attention layers, the size of the multi-layer perceptron (MLP) and the
288 hidden dimension. We additionally investigate the self-supervised training process by using pre-trained weights made available
289 in Atito et al. (2023) for which the pretraining was done on a computer vision task, the ImageNet-1K dataset (Deng et al., 2009).
290 However, the pretrained weights of the ImageNet-1K dataset are only made available for the small variant of the vision
291 transformer. An additional comparison is done with a model trained only on the colocated dataset using the small variant. The
292 contrastive and reconstruction losses for the different model setups are detailed in Figure B.1. Firstly, we notice that the model
293 trained solely on the colocated dataset would need more epochs to reach similar performance compared to all the other setups. As
294 the colocated dataset contains two orders of magnitude less samples than the training dataset, the model has also seen much less
295 data after 10 epochs, hindering the training process most notably for the contrastive loss. Even after further training the model on
296 the colocated dataset for 150 epochs, it is struggling to match the other models trained on the complete training dataset with best
297 contrastive and reconstruction losses of 0.95 and 0.23, respectively. On the other hand, the other setups reach similar
298 performance in both contrastive and reconstruction losses after 10 epochs. The model with pretrained weights displays better
299 performance right from the start of the training process but improves only marginally thereafter. This could be explained by the
300 fact that using the pretrained weights allows the model to capture already well the structure and patterns of the clouds in the
301 remote sensing data even though their modality is different from the one seen in the ImageNet-1K dataset. It thus shows the
302 strength of transfer learning in computer vision tasks. Nevertheless, we can observe that for the pretrained model both the
303 contrastive and reconstruction losses are reaching a plateau after only a few epochs while the other model setups display a
304 negative gradient indicating further learning capabilities. Focusing on the different variants trained with scaling factors of 1 or 5,
305 we notice that the choice of a larger scaling factor leads to better reconstruction skill while losing almost no performance with
306 respect to the contrastive loss.

307 Eventually, we decide to use as model the small variant of the vision transformer with a scaling factor α of 5, as it showcases
308 good performance in both tasks during the training while having a number of parameters four times smaller than the base variant.
309 Furthermore, the self-supervised training task on the large unlabelled dataset allows the model to have plenty of data to learn
310 from, the pre-trained model weights giving only marginal gain for a few epochs at the start. The small variant of the vision
311 transformer was shown to perform very well on a large variety of tasks as per the results from Atito et al. (2023). The results
312 across the training, validation and test datasets are shown in Figure 3 for the training process and some examples of reconstructed
313 samples belonging to all three splits, while Figure 4 highlights the spatial distribution of the reconstruction error per channel and
314 across splits. On the left panel of Figure 3, the losses show a consistent decreasing trend even at the end of the training epochs.
315 The training process was halted after 100 epochs due to computational limitations, but would gain to be extended as the vision
316 transformer’s performance seems to still be improvable. On the right panel of Figure 3, the reconstructions presented for some

317 random samples reveal where the model would benefit from an improved performance: the reconstructions appear realistic, but
 318 fail to reproduce the exact sharpness that is visible in the satellite retrievals. While this aspect would not guarantee a decisive
 319 improvement in the downstream task which only relies on the encodings, it would greatly help build more trust in the model. A
 320 related case that can lead to observed patterns of reconstruction errors in Figure 4 lies in the reconstruction of cloud scenes with
 321 convective cells. The invigorated core of the convective cell stands much higher and holds more water compared to its
 322 surroundings which can lead to steep gradients in the cloud quantities when observed from space. As the reconstructions are not
 323 able to reproduce these features, larger errors can arise from such cloud scenes. This could further propagate to the classification
 324 performance on the related classes, e.g. mesoscale convection clouds or cumulonimbus, whose intricate patterns are better
 325 assessed on their own directly (Bony et al., 2020; Rasp et al., 2020; Stevens et al., 2020; Yuan et al. 2020; McCoy et al., 2023).
 326 The additional patterns in the reconstruction error of Figure 4, in particular for COT, are visible in some consistent areas over
 327 land. A deeper analysis of the spatial generalisation skill of the model than the one presented in section 3.3.2 covering only the
 328 colocated dataset might help constrain the spatial generalisation performance of the vision transformer and infer potential
 329 performance caveats still remaining.
 330 Ultimately, we can compare the skill of the vision transformer to that of the baseline CNN autoencoder from Lenhardt et al.
 331 (2024a). The CNN autoencoder was trained using as reconstruction error the mean squared error (MSE) on similar MODIS data
 332 but only with MODIS granules over the ocean. It was shown to perform similarly with a slightly higher error over land when
 333 evaluated over a global dataset. The vision transformer model outperforms the CNN autoencoder on all metrics (MSE and
 334 l1-loss) across all data splits (training, validation and test), displaying consistently across data splits on average an MSE of 0.15
 335 and a l1-loss of 0.12 compared to 0.3 for both metrics for the CNN. Examples of reconstructed samples additionally show how
 336 the l1-loss helps produce sharper edges in the reconstruction, a well-known issue with the application of MSE as target metric in
 337 computer vision (Zhao et al., 2016). The contribution to the error comes mostly from the COT channel for both models and the
 338 error is concentrated in areas of higher variability for the respective channels. The metrics values are summarised in Table B.1.
 339 The spatial generalisation skill, alongside the sensitivity to the tile size and the impact of data augmentation on the performance
 340 on the cloud classification task are analysed in the following section.



341
 342 **Figure 3: (left) Training and validation losses during model optimization for the small variant of the vision transformer**
 343 **on the global training dataset. (right) Examples of tiles (first and third rows) with the corresponding reconstructions**
 344 **(second and fourth rows) for the different cloud property channels.**
 345

346 3.3 Cloud type classification

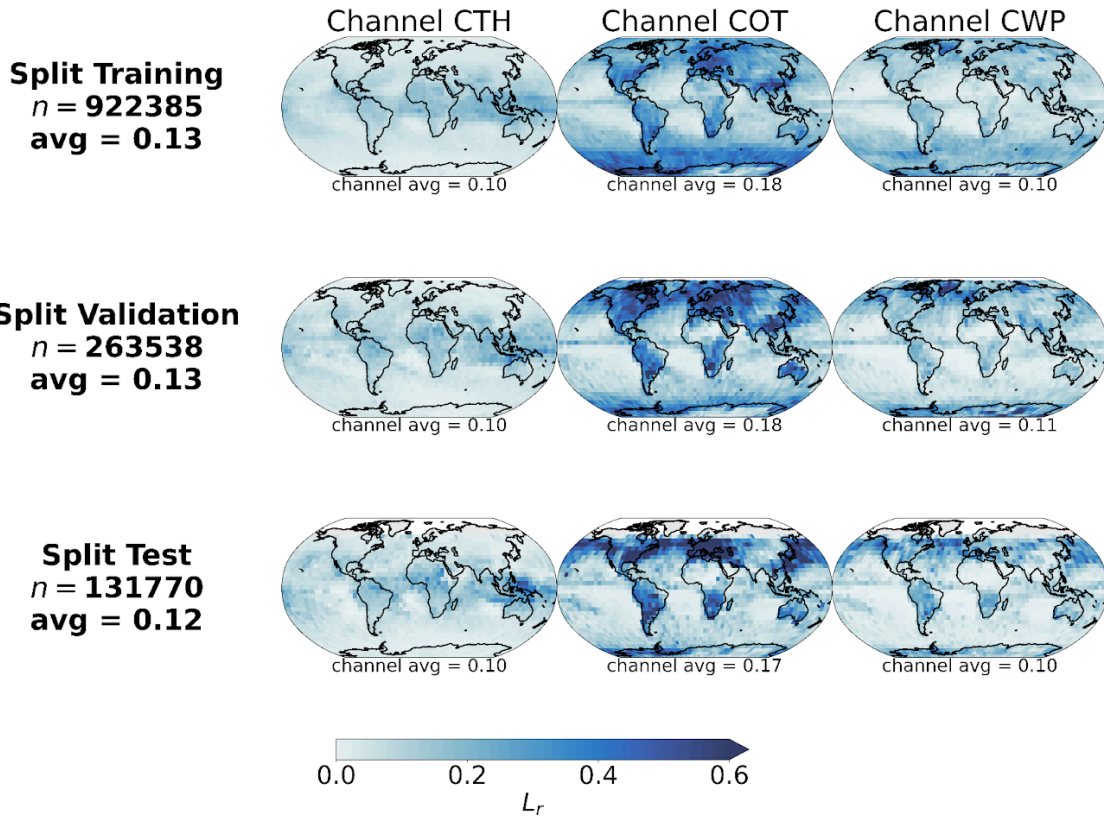
347
 348 The next task at hand is the cloud type classification, building on the colocated samples of satellite retrievals and surface
 349 observations. For the two years of MODIS AQUA data available, out of 104 823 colocated samples we retain only 11 094 for our
 350 training and testing datasets after filtering, among others, for missing data - typically 50% of the samples are discarded, mainly
 351 when the colocated observation lies on the edges of the satellite granule - and single layer cloud observations as reported by the
 352 observer - around 60% of the previously filtered samples are kept. A main caveat arising from colocating these two data sources
 353 is the potential mismatch between the actual clouds jointly depicted. Contrarily to methods like Zantedeschi et al. (2019) which

354 relies on joint retrievals of cloud properties and cloud type or Kuma et al. (2023) which aggregates observations at daily time
355 scales, the presented colocated dataset leaves room for misaligned surface observations and satellite retrievals. As it will be also
356 highlighted later on, this potential misalignment between data sources constitutes a hurdle in the development of the cloud
357 classification method. Indeed, if the model needs to learn from satellite data that actually does not visibly fit the surface
358 observation, then the learning process is hindered. Attempts to reduce this risk have not yielded satisfying results. For example,
359 decreasing the time-window described in section 2.2 did not ultimately yield improvements in the classification performance,
360 especially due to generalisation limitations from a lower number of samples. Furthermore, these attempts are mainly limited by
361 the amount of satellite data that would be necessary to build a substantial and consistent colocated dataset which would span a
362 larger timeframe than the two years used in this study. After the filtering of the colocated dataset, the cloud type observations are
363 then regrouped into 4 or 10 types as mentioned previously. The rest of the study will focus on these categories as targets. From
364 the latent space representations produced by the vision transformer or the CNN autoencoder, we build a classification model
365 either by attaching a classification head to the encoder network or by using a simpler classification model like a random forest
366 (RF; Breiman, 2001). To investigate the performance of the classification models on the two classification tasks at hand (4 and
367 10 cloud types), we use different metrics tailored to unbalanced classification setups as the cloud types are not equally
368 represented (see Figure 2 and Table A.1). A first method to assign similar weight to all classes regardless of the class' cardinality
369 is to use macro-averaged metrics. In this framework, the metric of interest is averaged over the samples of each class separately
370 before being averaged over the classes. This leads to a higher weight for minority classes for which the model might perform
371 differently, usually worse, compared to the majority classes providing different information over traditional averaging strategies
372 (micro-averaged for example) where the result will be dominated by the samples from the majority classes. We report several
373 metrics adapted to an unbalanced setting: the index balanced accuracy (IBA; Garcia et al., 2012) of the geometric mean, the
374 macro-averaged accuracy and the macro-averaged f1-score.

375 For the classification model we investigate two alternatives: a RF classification model (implementation from *Scikit-learn*
376 package, Pedregosa et al., 2011) and a MLP classification head (Hinton, 1989; implemented in *PyTorch*, Paszke et al., 2019).
377 However, a wider diversity of classification models could be implemented based on the backbone provided by the vision
378 transformer. The base model architecture and weights are made available on Zenodo (Lenhardt et al., 2024b) to foster a more
379 complete exploration of possibilities regarding the classification model, building on the backbone of the vision transformer. For
380 example, with a more extensive training dataset, more complex classification models could be explored. In the case of the
381 architecture presented here, the RF model provides simplicity in the implementation and the training process, while the MLP is
382 the typical architecture used for the downstream task following a network like a vision transformer or a CNN. The RF model has
383 10 or 25 trees, for the cases of 4 and 10 cloud types respectively, with a maximum depth of 5. Basic hyper-parameter
384 optimization showed that with the reduced amount of samples and the limited variety in cloud scenes for some categories (even
385 more with balanced classes, see section 3.3.3), models displaying limited complexity avoided overfitting and generalised better
386 on unseen data. The MLP consists of two fully-connected layers (hidden dimension 4096) with a Gaussian Error Linear Unit
387 (Hendrycks & Gimpel, 2016) in between and is trained using the cross-entropy loss. The sensitivity studies and experiments are
388 done only using RF models but the evaluation in the subsequent section will be done on both types of classification methods.
389 Various sensitivities could be explored in the presented setting but we here focus on the potential benefit of the spatial context,
390 the ability to generalise spatially to unseen locations and the impact of balancing the labelled dataset.

391

Spatial L_r mean per channel



392

393

Figure 4: Spatial distributions of mean channel reconstruction errors for CTH, COT and CWP, aggregated on a 5° regular grid for the training, validation and test datasets.

394

395

396 3.3.1 Spatial context and tile size

397 We look at the influence of the input size by training vision transformers (small variant) on different sizes of inputs namely
 398 128x128, 64x64, 32x32 and 16x16. We do not consider larger tile sizes as the cloud scene might then be less representative of the
 399 surface observation, especially since we only consider samples with single labels, and as the assumption that the observed cloud
 400 type occurs on such scales would likely not hold. The losses relative to the vision transformer models trained on the different
 401 input tile sizes are detailed in Figure B.2. Since these models were trained on a reduced dataset as mentioned previously, their
 402 skill cannot be directly compared to the one displayed in Figure 3. While the contrastive losses are similar across input tile sizes,
 403 the reconstruction losses differ. Since we kept the ratio between the patch size and the tile size constant when training the
 404 different models, the difference in reconstruction skill could be attributed to the dimensionality of each patch being much
 405 smaller, for example for a tile of size 16x16 a patch will be 2x2. The reconstruction head being a fairly shallow CNN, the
 406 reconstruction of the spatial patterns inside the patches showcases better skill for smaller input patches after a few epochs, while
 407 for larger patch sizes - and thus tile sizes - a longer training process would be needed as to improve the truthfulness of the
 408 reconstruction to the input. Examples of reconstructions depending on the input tile size are included in Figure B.3 and visually
 409 display how a larger field of view can help capture the larger cloud organisation or even individual sparse clouds. To further
 410 evaluate the potential benefit of the spatial context for the downstream classification task, we consider as an alternate input the
 411 flattened cloud properties of a 9x9 tile centred on the observation location. This yields an input of similar dimensionality
 412 compared to the latent space representation of both the CNN and the vision transformer (3 channels x 9 x 9 = 243). We then train
 413 the same RF classification model on each of the latent representations derived from the trained vision transformers and on the
 414 flattened cloud properties. From the classification metrics, we observe that the smaller the tile size the more prone the model is to
 415 overfitting towards the majority classes (high and stratiform cloud types in the case of 4 types) leading to a decreased
 416 performance on the validation set. For instance, choosing an input tile size of 16x16 results in a decrease of 20% across metrics
 417 from the training to the validation set (compared to around 10-15% across metrics for the larger input tile sizes), and leads to
 418 metrics on the validation set more than 10% lower than with larger input tile sizes. The predictions made using larger spatial
 419 context (tile size greater than 16x16) outperform the method with 9x9 flattened tile inputs across all considered metrics on the

420 validation set. With the input tile size 16x16, the reduced spatial context seems to be limiting for the performance but another
421 explanation could be a complex latent space compared to the input dimensionality. Overall, even with the vision transformer
422 backbones being trained only partially, the wider input tile size provides better classification skill and generalisation to unseen
423 data. In the rest of the study and experiments, if not mentioned specifically, the input tile size is chosen to be 128x128.

424

425 3.3.2 Spatial generalisation

426 To investigate the spatial generalisation skill of the cloud classification method, we split our colocated dataset into samples
427 located in the Northern or Southern hemispheres. Two vision transformer models are additionally trained on samples from only
428 the respective hemisphere and tested on the other one. The losses relative to the training and testing of both hemispherical
429 models are included in Figure B.4. Both hemispherical models display similar performance both on the training and testing
430 datasets, showing that even for a reduced number of training samples, epochs and spatial coverage the vision transformer
431 architecture generalises well to unseen data. Building on the two trained vision transformers, we set out to evaluate the skill on
432 the classification tasks. Splitting the labels between the two hemispheres yields 9246 samples for the Northern hemisphere and
433 1848 samples for the Southern hemisphere. Investigating the different classification metrics for training and testing on both
434 hemispheres, it is clear that the classification model trained on the Southern hemisphere struggles to generalise from such a low
435 number of labelled samples and probably overfits since the performance is worsened on the Northern hemisphere samples
436 (decrease of almost 50% across metrics from the training to the testing set). The classification model trained on the Northern
437 hemisphere generalises well in the case of the 4 cloud types with consistent metric values between hemispheres (marginal
438 decrease of around 15% across metrics from the training to the testing set). Overall, the model trained on samples from the
439 Northern hemisphere and for both cases of number of cloud types, the performance on the Southern hemisphere is similar to
440 models with larger tile sizes from the previous section, showing consistency across experiments even with limited datasets for
441 the training of the vision transformer.

442

443 3.3.3 Balanced training dataset

444 Balancing the number of samples among classes in the input dataset can be a way to leverage enough information from the
445 underrepresented classes. We compare here the performance skill of two classification models trained on the colocated dataset or
446 on a balanced equivalent. To this extent, we use a sampler implementation from the *imbalanced-learn* package (Lemaitre et al.,
447 2017), namely the Synthetic Minority Oversampling Technique (SMOTE; Chawla et al., 2002) to oversample the minority
448 classes. Doing so leads to improved classification skill with consistent increases across metrics on the validation set of 3-7% and
449 15-35% for the cases of 4 or 10 cloud types, respectively. The oversampling impacts mostly the cloud types from the high and
450 medium classes, and from the cirrocumulus and cirrostratus classes, in the case of 4 cloud types and 10 cloud types, respectively
451 (see Table A.1). The methods evaluated in the following section will thus include the same over-sampling strategy to overcome
452 the representation of the minority classes and improve the performance on the classification task.

453 4 Evaluation

454

455 4.1 Classification evaluation

456

457 In the following section, we detail the classification performance on the test set of the previously mentioned models. Two
458 baseline models are included, namely a classification model built on the CNN autoencoder from Lenhardt et al. (2024a) and a RF
459 model built on the flattened 9x9 input tiles as described in section 3.3.1. The method developed in this study is represented by
460 two models using the aforementioned vision transformer model (see section 3.2) as backbone complemented by either a RF
461 classifier or a MLP (see section 3.3). In the rest of the study, we denote the trained vision transformer model followed by the
462 classification model as CloudViT (Cloud Vision Transformer) in its two classification variants (RF or MLP). The classification
463 metrics on the test dataset for these four models are summarised in Table 2 for the case of the 4 cloud types and in Table C.1 for
464 the 10 cloud types. Since the number of samples is very limited, the performance of the models cannot be only considered as is
465 but is further evaluated in the subsequent sections through distributions of cloud properties and spatial occurrence distributions.
466 We emphasize here the need to perform an evaluation beyond the metrics to assess the skill of the model to represent
467 characteristics expected from different cloud types. These characteristics can relate to the distribution of their physical
468 parameters and their occurrences, both of which can be assessed thoroughly here only with a more extensive dataset. The
469 CloudViT/RF method performs the best across all of the three metrics included, despite showing still limited performance overall.
470 Firstly, the macro-averaged multi-class accuracy does not differ by a large margin between the different methods, but the

471 class-wise accuracies reveal several limitations. The baseline 9x9 RF model largely overfits towards the high and stratiform types
472 (train and test class accuracies of 0.84/0.81 and 0.63/0.62, respectively), performing poorly on the medium and cumuliform types
473 (train and test class accuracies of 0.31/0.21 and 0.19/0.15, respectively). The CloudViT/MLP model is biased towards stratiform
474 clouds (train and test class accuracy of 0.79/0.79) while struggling to identify the other three types (train and test accuracies all
475 falling between 0.10 and 0.40). The baseline CNN/RF and the CloudViT/RF models are performing quite similarly both on
476 aggregated and class-wise metrics. However, the CloudViT/RF model showcases improved performance on the stratiform class
477 (increase of 0.13 in the class accuracy both on the train and test datasets) and only a marginal decrease (0.03) on the class
478 accuracies for medium and cumuliform clouds. The performance on the high clouds is similar with slightly higher accuracies for
479 the CloudViT/RF model. Other metrics like the IBA of the geometric mean and the F1-score further emphasise that the
480 CloudViT/RF model outperforms the other methods while addressing the imbalance training data to generalise with satisfactory
481 skill on the unseen test dataset. Nevertheless, the performance detailed here across classes shows apparent limitations as scores
482 are not ideal. An obvious hurdle of the learning process resides in the overall limited number of samples and the noise present in
483 particular for cloud types with minimal numbers of samples. Building a dataset with more labels would improve the
484 classification performance by allowing the classification to more easily converge towards each cloud type’s mean state arising
485 from a larger number of samples. The simplicity of the classification models chosen here represents a constraint that could be
486 lifted if more training samples were available as overfitting and balance would then represent lesser issues. Furthermore, the
487 patterns in the class accuracies can be traced back to shortcomings in the observational dataset. Having only considered
488 single-layer cloud scenes in the colocated dataset, the high clouds are well predicted in accordance with the observations as a
489 surface observer would identify with certainty this type of cloud if no other lower cloud is blocking the field of view from the
490 surface. Stratiform clouds could be more challenging for the observers as they typically display high cloud fraction and high
491 optical thickness, limiting the ability of the surface observer to quantify with certainty the amount of clouds in other levels.
492 However, such characteristics can be well captured by computer vision models which build on patterns in the three-dimensional
493 input data which in particular the baseline 9x9 RF model lacks. This difference between models is in particular apparent for the
494 cumuliform class which is mostly composed of observations of cumulus. A cloud scene relative to a cumulus observation will
495 most likely display a lower cloud fraction as the individual clouds are sparsely distributed, extracting only the very near points
496 around the observation might then be too reductive and limit the accuracy of the classification model. It is confirmed by the
497 accuracy on this cloud type for which the baseline 9x9 RF model is largely outperformed by all three other models both on
498 training and test datasets (class accuracy increases between 150% up to 260% on the test dataset). Overall, the classification
499 model shows fair performance that could be probably improved by widening the scope of the cumbersome collocation process
500 which requires large amounts of remote sensing data, and by accordingly refining the RF or MLP architectures presented here.
501 Using the classification model developed here thus comes with apparent uncertainties across the different cloud types. Efforts
502 were made with the aim to classify all cloud types consistently from the limited training dataset available but to limited
503 outcomes. The extension of the training dataset appears as an obvious way to purposefully improve the classification
504 performance of the model. An extended colocated dataset would allow stricter filtering, mainly with respect to the collocation
505 time-window, which would help improve the representativeness of the samples. The analysis of the classification performance
506 shows here the limitations of a reduced-size dataset with potential underlying discrepancies between data sources during
507 collocation. Nonetheless, the evaluation of the predictions in the following section provides insights and reveals relevant features
508 in the predicted cloud types.

509

Method	Multi-class accuracy *	IBA geometric mean	F1-score *
Baseline 9x9 RF	0.45	0.32	0.35
Baseline CNN/RF	0.45	0.32	0.40
CloudViT/MLP	0.40	0.32	0.42
CloudViT/RF	0.46	0.36	0.43
CloudViT/RF (train)	0.55	0.41	0.49

510 **Table 2: Classification metrics on the test set in the case of 4 cloud types. The metrics noted with a * are referring to their**
511 **macro-averaged estimate. The method on which the rest of the study is based is highlighted in bold. The baseline**
512 **CNN/RF refers to the CNN backbone introduced in Lenhardt et al. (2024a).**

513

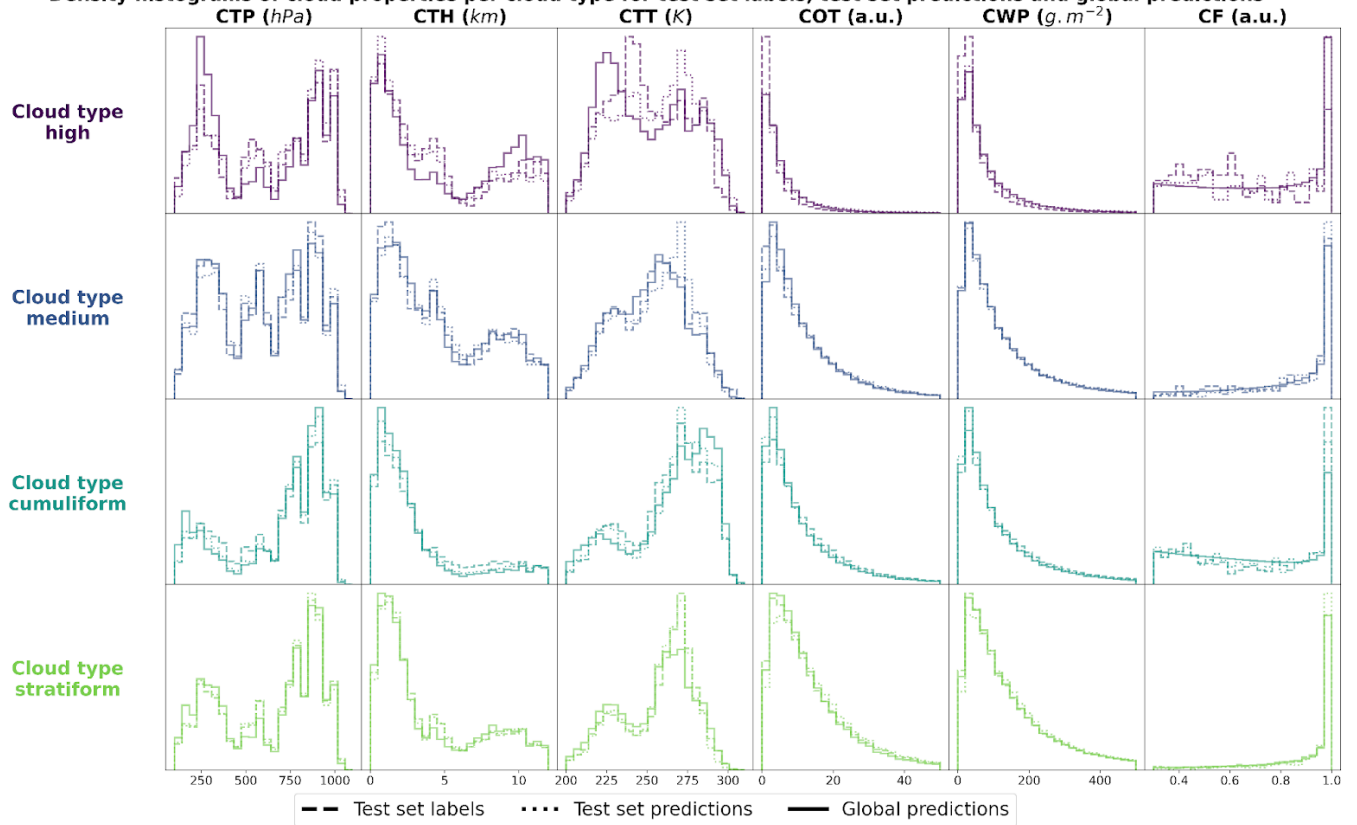
514 4.2 Histograms of cloud properties

515

516 In order to evaluate the physical soundness of the predictions made by the CloudViT model, we investigate the distribution of
517 several cloud properties with respect to the observed and predicted cloud types. In Figure 5, we summarise the distribution of
518 cloud top pressure (CTP), cloud top height (CTH), cloud top temperature (CTT), cloud optical thickness (COT), cloud water path
519 (CWP) and cloud fraction (CF) for the 4 cloud types (high, medium, cumuliform, stratiform) and for three different datasets: the
520 test set labels, the test set predictions and the dataset of global predictions. The latter is built on global MODIS AQUA granules
521 for the year 2016 - the year is chosen to avoid any overlap with cloud scenes seen during the training of the vision transformer on
522 data from 2008 - from which we regularly sample tiles in order to build a more comprehensive and global dataset of cloud types
523 to further evaluate the method. The spatial distribution of cloud types for this dataset is highlighted in the following section and
524 the global dataset is made available at Lenhardt et al. (2024b). The histograms are built by reporting the respective cloud
525 properties for all the cloudy pixels in each sampled tile from the dataset apart from the cloud fraction which is computed for the
526 whole tile from the cloud mask. As a consequence, unless the whole cloud field is composed of only a single cloud type, the
527 histograms will cover a large range of cloud properties due to multi-layer clouds or multi cloud types scenes (e.g. convective
528 cells with associated anvils or cumulus/stratocumulus transitions). Even though the trained model only produces fair evaluation
529 metrics on the test set, the histograms of cloud properties display interesting features consistent with expected characteristics of
530 the different cloud types. On Figure 5, the histograms pertaining to the test set labels and predictions have distributions close to
531 identical across cloud types showing a good agreement in the clouds depicted in both datasets while the global dataset histograms
532 provides a less noisy overview of the distribution of the cloud properties per cloud type. The high clouds are characterised by
533 low cloud water path and optical thickness, along with colder and higher cloud tops as well as more frequent cloud fractions
534 smaller than one. All of these aspects are emphasised in the global predictions compared to the limited test set samples, showing
535 the CloudViT model manages to extract the representative characteristics of the cloud type from the labels. The cumuliform
536 category encompasses mostly low warm clouds with reduced cloud fractions and moderate cloud water path and optical
537 thickness. Inside this class, the higher and colder cloud tops are concentrated in the cumulonimbus class, along with larger cloud
538 water path and cloud optical thickness (see Fig. C.1). The stratiform class includes thick cloud fields with high cloud water path
539 and almost full spatial coverage of the cloud scenes (cloud fraction close to 1 in most cases). A fraction of the clouds in this class
540 are slightly higher and colder and correspond to stratus/nimbostratus clouds which can also be seen in Figure C.1. The
541 distributions for medium clouds showcase similarities with several other types and are best evaluated in combination with their
542 spatial distribution (see Section 5). Examining in more detail the refined cloud types with the 10 cloud types (see Fig. C.1)
543 reveals slight differences inside broader cloud types. For example, the distinction between the three high cloud types (cirrus,
544 cirrostratus and cirrocumulus) appears through separations in cloud fraction, cloud optical thickness and cloud water path which
545 were not obvious from the limited amount of labelled samples. The differences between the three high cloud types further
546 manifest in distributions of cloud top quantities for which cirrus and cirrostratus display potential multilayered cloud scenes with
547 a combination of low/warm and high/cold cloud tops. Overall, the CloudViT model seems to generalise well from a few samples
548 (only around 10 for the cirrocumulus class) by exhibiting in parts physical consistency inside predicted types. Due to the large
549 cloud scenes considered as input for the classification, the distribution of the cloud properties might not be as representative of
550 single cloud types as an input tile of, for example, 16 pixels. The main caveat regarding performance on high and medium clouds
551 from our method is that the ground-based observer identifies these cloud types with higher uncertainty compared to that of low
552 clouds. Additionally, stratiform clouds with high cloud fraction can hinder the trustworthiness of the surface observation if the
553 whole field of view is cloudy. Even though the limitations of ground-based observations are evident, they still provide quality
554 observations on which a classification model can be trained. The collocation between these surface observations and the satellite
555 retrievals is thus of crucial importance and guides the performance of the later trained model. It partly contributes in the case of
556 CloudViT to a hurdle to achieve notable classification performance. The model, however, shows its ability to generalise from
557 limited samples to consistent and physically-relevant distributions of cloud properties among the predicted cloud types. By
558 refining the training dataset, the improvements can be expected to reflect directly on the classification performance. The
559 characteristics observed in the histograms across cloud types contribute to an increase in confidence in the ability of CloudViT to
560 discern various cloud types in large remote sensing datasets despite the method's limited ability described in the previous section.

561

Density histograms of cloud properties per cloud type for test set labels, test set predictions and global predictions



562

563 **Figure 5: Density histograms of cloud properties for each cloud type from high, medium, cumuliform and stratiform.**

564 **5 Global cloud type distributions in MODIS data**

565

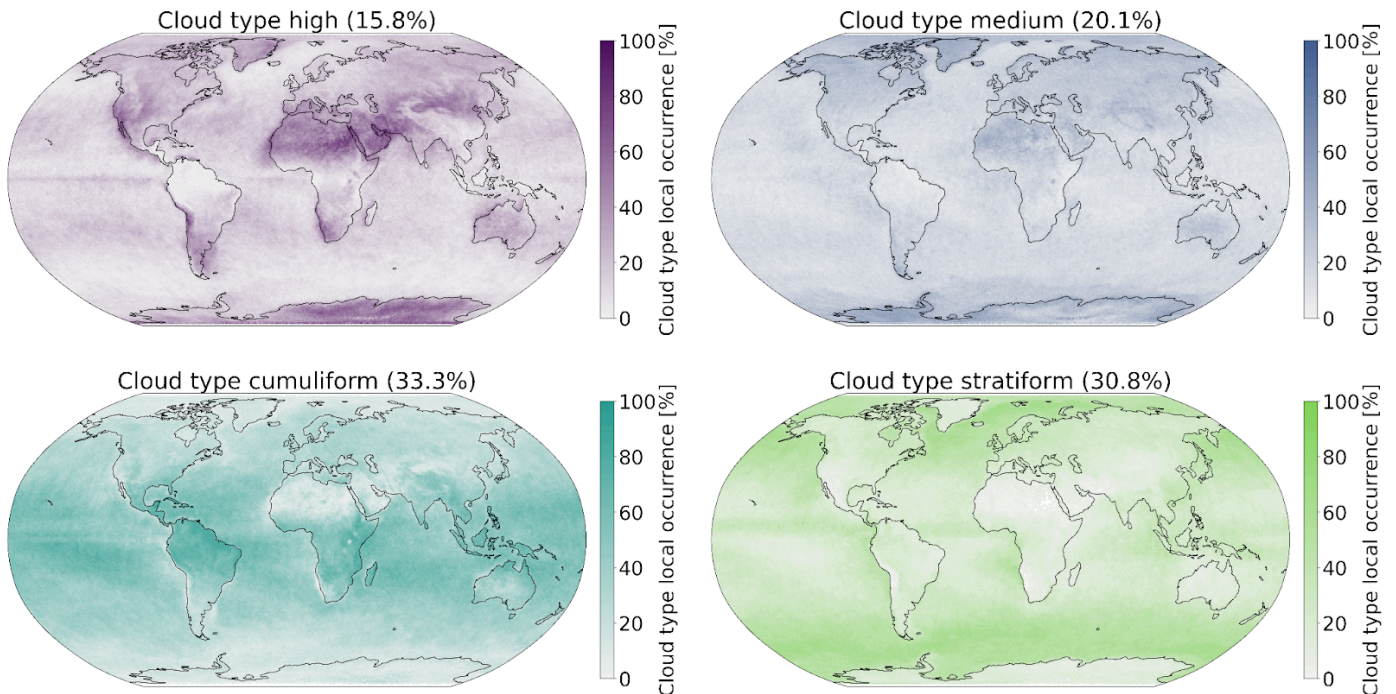
566

567 Additionally to the physical and microphysical characteristics of the different cloud types, their global spatial distribution can
 568 help us further understand in which regions they are more or less frequent and qualitatively assess the presented classification
 569 method compared to other remote sensing products. To this extent, as mentioned in the previous evaluation section (see Section
 570 4), we build an extensive cloud type dataset for the year 2016 from MODIS AQUA granules which are regularly sampled for
 571 tiles of 128x128 pixels. The sampling step (64) is chosen for computational efficiency and memory purposes to be not too small
 572 to avoid large overlap between neighbouring tiles but large enough to ensure representativeness in the later aggregated
 573 predictions of the MODIS granules. Furthermore, as the area covered by each tile is rather wide, the spatial distribution of cloud
 574 types might be less smooth than other products (e.g. Sassen et al., 2008) or other methods (Zantedeschi et al., 2020) which are
 575 providing cloud types for smaller cloud fields. Additionally, the dataset is built on single daily overpasses of the MODIS
 576 instrument and can thus be biased towards the local retrieval time (13:30 h, early afternoon for AQUA).

577 The spatial distributions of the predicted cloud types for the global dataset for the year 2016 are detailed in Figure 6 and Figure
 578 C.2 for 4 and 10 cloud types, respectively. Firstly, we note that CloudViT predictions capture large scale patterns which are in
 579 agreement with observational datasets (Sassen et al., 2008; Cesana et al., 2019; Wood, 2012; Pincus et al., 2023). Stratiform
 580 clouds, and in particular stratocumulus (see Fig C.2), are frequent in the high latitudes and along the western coasts of America
 581 and Africa. Cumuliform clouds are concentrated in the Tropics apart from the areas where stratocumulus clouds are dominant.
 582 Medium clouds are concentrated in the polar regions and over land in the higher latitudes. High clouds make up a large portion
 583 of clouds in the polar regions but also over land. The first notable difference is the low occurrence of high clouds in the Tropics
 584 which would be expected to be higher (Sassen et al., 2008; Pincus et al., 2023). An explanation could be the frequent occurrence
 585 of high clouds in multi-layer cloud scenes related to convection in the Tropics. Furthermore, in such cases the model probably
 586 identifies the cloud types with larger cloud fraction and thus discards potential high clouds in the scene. Incorporating more
 587 samples of high clouds in that region (see Fig. A.1) could potentially help the performance of the classification model in that
 588 regard. The presented spatial distributions may suffer from the somewhat limited performance of the classification model despite

589 the corresponding reasonable representation of cloud type characteristics showcased in section 4.2. Nevertheless, some
590 informative features are observed in Figures 6 and C.2 and point towards the good direction for further improving CloudViT.
591

Spatial distributions of CloudViT cloud type occurrences (year 2016)



592

593

594

595

Figure 6: Spatial distributions of the CloudViT cloud type occurrences (cloud types high, medium, cumuliform, stratiform) for MYD06 granules for the year 2016 aggregated on a 1° regular grid.

596 6 Challenges and limitations

597

598 The method and results presented offer a good foundation for further development and critical analysis, though they also have
599 notable limitations that should be addressed.. The following section aims to focus on several aspects that we feel are relevant for
600 the community when developing cloud type classification methods similar to the one presented here, namely on the benefits of
601 such methods, dataset curation and extension, and the potential application to climate model data.

602 Spatially-resolved cloud properties provide usable context for the CloudViT model to improve the cloud classification, as shown
603 in the comparison to the baseline method with limited spatial information. Introducing this new transformer model architecture
604 additionally improves the classification skill over the CNN backbone mentioned in Lenhardt et al. (2024a). While the
605 performance improvement between baseline CNN and CloudViT is apparent, the overall limited performance of the model stands
606 out, especially when comparing to metrics typically achieved by CNNs or ViTs alike in common classification tasks. Our
607 experiments suggest that the current architecture, while leveraging capabilities of transformers, does not yet fully exploit the
608 organizational and multi-scale spatial features critical for robust cloud type classification. The transformer's self-attention
609 mechanism may require stronger spatial priors (e.g. multi-resolution patch embeddings) to improve the attention of the model to
610 both fine- and coarse-scale features specific to cloud spatial organization. The self-supervised pre-training of CloudViT
611 circumvents this aspect of the ViT architecture to some extent and partly alleviates its data-hungry training process. However,
612 when tackling the targeted cloud classification problem, the limited size of the colocated dataset constitutes a hurdle for the
613 proper training and evaluation of the method on labelled samples. The classification model could also be refined by finding
614 better alternatives to the RF or MLP presented here. The overall finetuning process involving the vision transformer and the
615 MLP classification head proved to be cumbersome but holds great promise if the labels and training process are refined. Transfer
616 learning from a typical ImageNet-trained model did not yield a notable performance difference which shows the current need for
617 foundation models trained on remote sensing data. The main hurdle here remains the large diversity in instruments, quantities
618 and resolutions among remote sensing products which hinders the possibility of a unified model.

619 Additionally, the hypothesis as to why the model fails to achieve great performance in this study rests heavily on the colocation
620 process between surface observations and satellite data. The method would benefit from including further ground-based
621 observations through the colocation process, but then much larger storage and computational facilities would be needed as global
622 MODIS data represents thousands of granules each day. To further improve the output of the colocation process and the spatial
623 coverage of the CloudViT predictions, the direct application to granules from MODIS TERRA would technically not require
624 much more work as the instruments are similar and provide the same cloud properties. More training samples could
625 simultaneously solve performance issues by providing a clearer vision of the different cloud types for the classification model to
626 learn from. The improvements through a larger training dataset will yield relevant benefits only if the potential mismatches
627 occurring during the colocation process are tackled. Indeed, relaxing some spatial and time constraints during colocation would
628 allow more samples to be retrieved, but it would simultaneously decrease the likely representativeness of the satellite data with
629 respect to surface observation. On the contrary, improving the representativeness of the training samples combined with an
630 extended number of colocated samples could solve the performance issues faced by the model presented here, and potentially
631 achieve performance aligned with a wider usage of the method for cloud type analysis.

632 Another interesting aspect to discuss here is the application of cloud type classification methods to climate model data. However,
633 the presented method CloudViT would need further improvement on classification metrics before it can be considered to be used
634 on model data with the aim to gain detailed insights into cloud type representation. In general, the application to climate model
635 data can prove to be technically straightforward and can result in practical insights into how such methods can be transferred to
636 model data (see Appendix D). Generally, cloud type diagnostics could be a resourceful addition to the panel of existing
637 assessment methods for model data (Kuma et al., 2023; Kaps et al., 2023). A benefit of using quantities such as cloud top
638 variables or optical thickness as input for the classification method is that these necessary cloud quantities can be obtained from
639 common simulation outputs (cloud liquid water and ice contents, altitude, droplet number). However, some caveats can appear
640 when applying a cloud classification method to climate model data. As mentioned in more details in Appendix D, the input
641 scaling is crucial to ensure proper portability of a method to other data sources. The absence of nighttime retrievals in the
642 MODIS data also turns the evaluation of predictions on nighttime data points across the model data into a challenging issue.
643 However, clouds play a role in the climate system both during the day when they cool the surface by mostly reflecting incoming
644 solar radiation but also at night when they warm the surface by trapping outgoing terrestrial radiation. Shifts and changes in
645 cloud occurrence and distribution in the current climate but also in future projections could further influence global climate
646 change (Luo et al., 2024). Applying a cloud classification methodology to a limited high-resolution climate model simulation is
647 an encouraging direction, but considering more common and computationally less expensive global km-scale simulations
648 (horizontal resolution of 5 km for example) could be of greater interest to the community to study longer time scales. To this
649 extent, two conceivable approaches would consist in either retraining a method on coarser input cloud properties matching the
650 model data resolution - the MODIS Cloud product is also available at a 5 km resolution even though the 1 km equivalent is
651 recommended for use - or in using such a method as is but with the coarse input scaled to fit the resolution of the tiles on which it
652 was trained on. The first option could be more interesting as computer vision models are commonly trained on coarser
653 resolutions first to learn the broad specificity and patterns in the data before fine-tuning the model on finer resolution (Touvron et
654 al., 2019).

655 7 Conclusion

656
657 This study introduces a new method called CloudViT to classify cloud types from MODIS cloud properties, specifically CTH,
658 COT and CWP. CloudViT delivers estimates for either 4 (high, medium, cumuliform, stratiform) or 10 (cirrus, cirrostratus,
659 cirrocumulus, altostratus, altocumulus, cumulus, cumulus and stratocumulus, cumulonimbus, stratocumulus, stratus) cloud types
660 with fair performance. The classification model was built on ground-based observations of cloud types (Section 2.1) and
661 experiments about its generalisation skill and the benefits of spatial information were presented (Section 3). We evaluated the
662 classification model by examining distributions of cloud properties in Section 4 and the global spatial distribution of cloud types
663 in Section 5. Lastly, we pinned down some existing challenges, limitations, and lessons learned from the development of the
664 method for cloud type classification. The global dataset alongside the CloudViT code and weights are made available on Zenodo
665 (Lenhardt et al., 2024b) to encourage future developments.

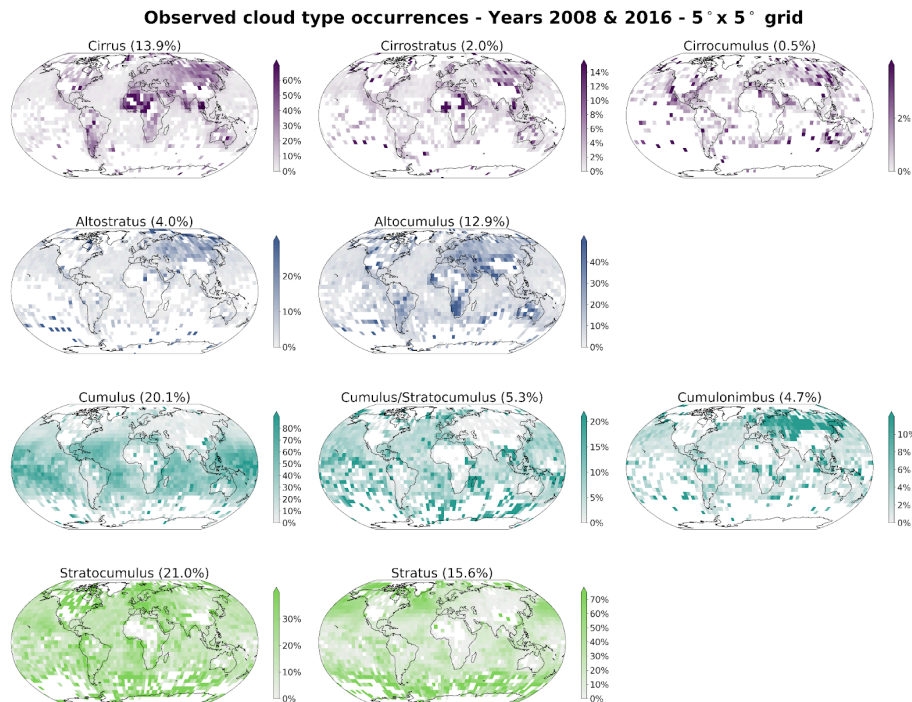
666
667 In conclusion, the method presented here showcases and highlights a wide array of potential applications in the study of cloud
668 types, their characteristics and evolution, and their past, current, and future effects on the Earth's climate: from the extension of
669 sparse surface observations to global yearly predictions, and existing challenges and limitations in the design of

670 vision-transformer-based models. Despite the relatively imbalanced performance assessment of the method which shows both
671 great promise in capturing large scale characteristics of cloud types distributions but struggles to capture precisely the features in
672 the training dataset, the design and development of CloudViT is an interesting study in the line of improving existing cloud
673 classification methodologies. Identified challenges and limitations in this particular case can be useful to the community, both in
674 terms of methodology development and caveat to be avoided. We recommend future advancements in cloud classification
675 methods like CloudViT being firstly focused on data curation and followingly on model tuning once the performance has been
676 raised to desirable levels. To this extent, the necessary datasets and model architecture code are made available on Zenodo
677 (Lenhardt et al., 2024b).

679 Appendix A: Cloud type observations

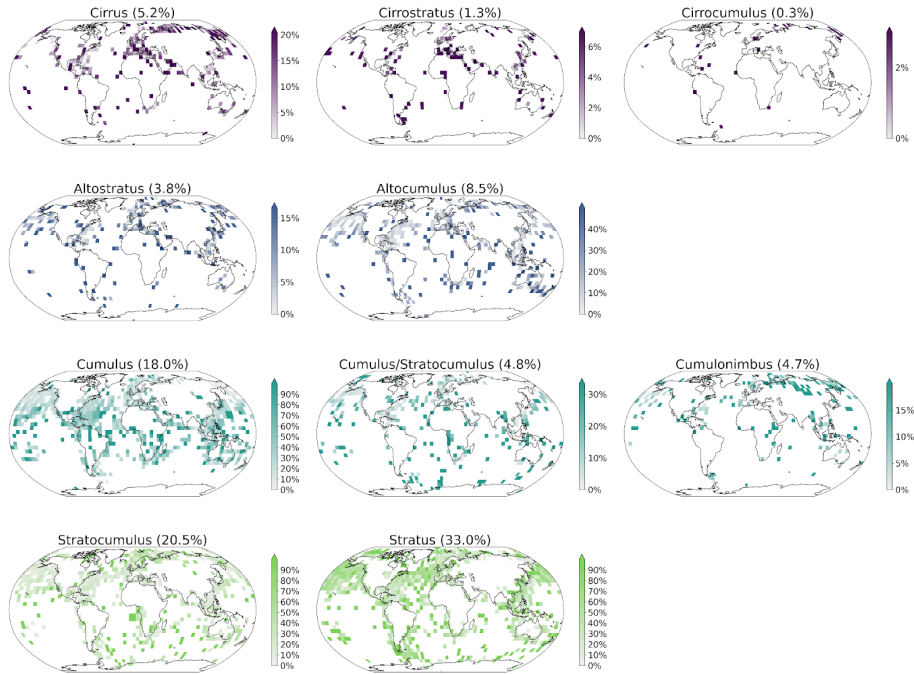
WMO codes	Cloud type: 4 groups	Cloud type: 10 groups	Colocated samples
High clouds 1-6	High	Cirrus	n = 574
High clouds 7-8		Cirrostratus	n = 142
High clouds 9		Cirrocumulus	n = 29
Medium clouds 1-2	Medium	Altostratus	n = 420
Medium clouds 3-9		Alto cumulus	n = 944
Low clouds 1-3	Cumuliform	Cumulus	n = 1998
Low clouds 8		Cumulus and stratocumulus	n = 533
Low clouds 9	Stratiform	Cumulonimbus	n = 519
Low clouds 4-5		Stratocumulus	n = 2274
Low clouds 6-7		Stratus	n = 3661
Total			n = 11 094

680 **Table A.1: Cloud types from the WMO observational datasets, their groups following Kuma et al. (2023) and the**
681 **corresponding number of samples in the colocated dataset. The WMO codes correspond to the 9 types for each level.**



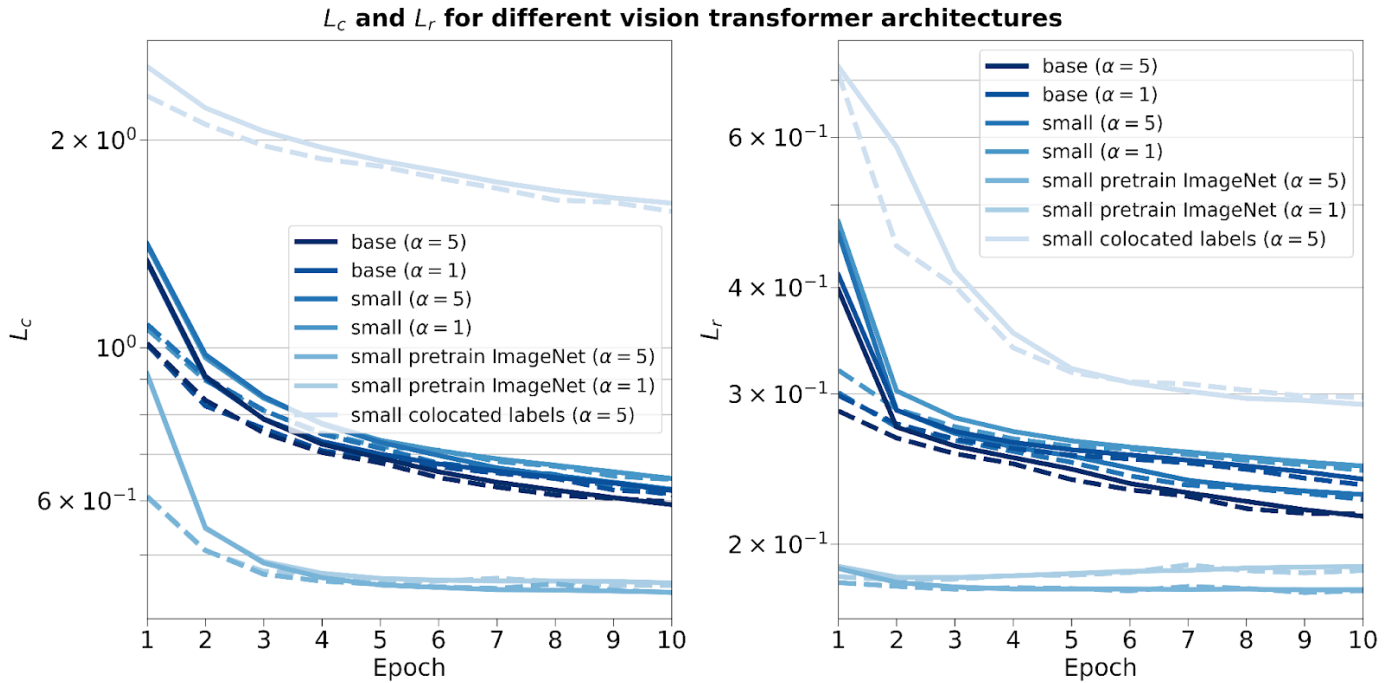
682 **Figure A.1: Spatial distributions of observed cloud types (cloud types cirrus, cirrostratus, cirrocumulus, altostratus,**
683 **alto cumulus, cumulus, cumulus and stratocumulus, cumulonimbus, stratocumulus, stratus) from the Met Office datasets**
684 **(Met Office, 2006; Met Office, 2008) for the years 2008 and 2016. Overall percentage of each label in the total dataset is**
685 **indicated in brackets.**
686
687

Observed cloud type occurrences - Colocated dataset - 5° x 5° grid



688

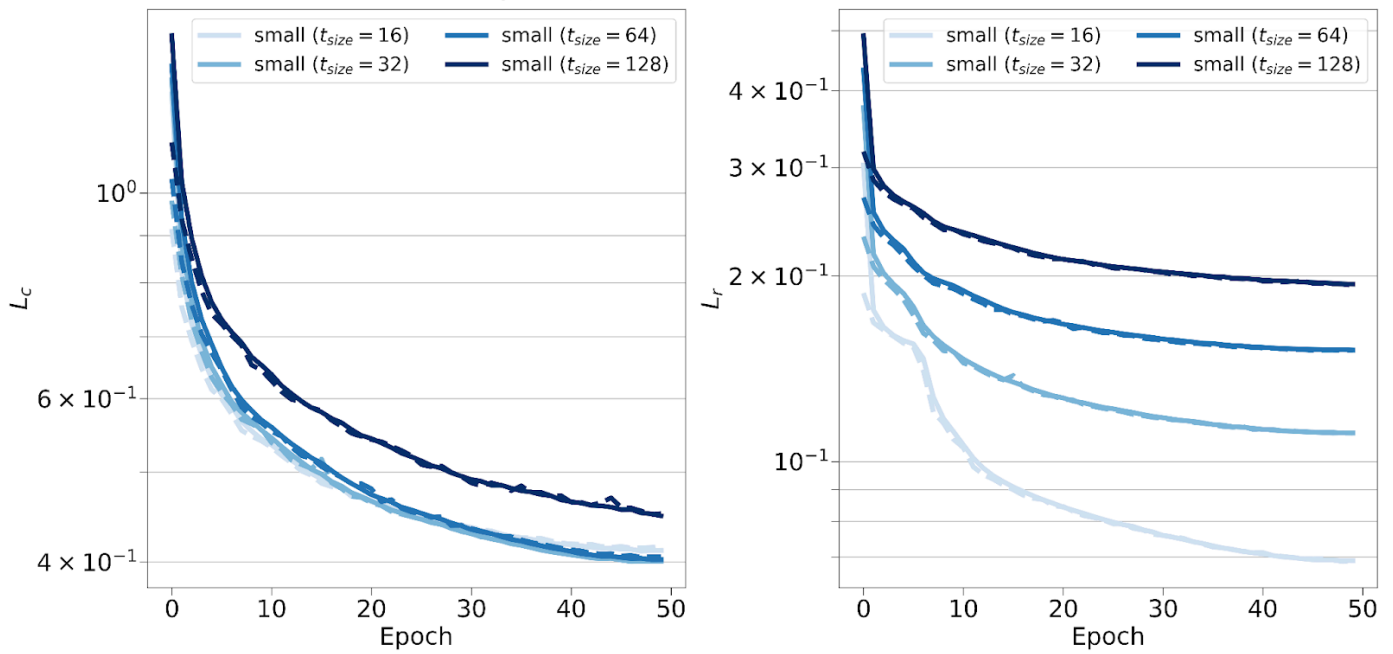
689 **Figure A.2: Spatial distributions of observed cloud types (cloud types cirrus, cirrostratus, cirrocumulus, altostratus,**
 690 **altocumulus, cumulus, cumulus and stratocumulus, cumulonimbus, stratocumulus, stratus) from the Met Office datasets**
 691 **(Met Office, 2006; Met Office, 2008) for the years 2008 and 2016 colocated with the satellite cloud retrievals (Platnick et**
 692 **al., 2017) used for training the classification model. Overall percentage of each label in the total dataset is indicated in**
 693 **brackets.**

699 **Figure B.1: Training and validation contrastive (left) and reconstruction (right) losses for different vision transformer**
700 **architectures, pretraining weights, training datasets and scaling factor α .**702 **B.2 Reconstruction errors for the CNN autoencoder and the vision transformer (small variant) on the test set**

Model type	Reconstruction error	CTH	COT	CWP
CNN autoencoder	MSE	0.27	0.39	0.25
	l1-loss	0.36	0.33	0.21
Vision transformer (small variant)	MSE	0.06	0.25	0.13
	l1-loss	0.10	0.17	0.10

704 **Table B.1: Reconstruction relative errors of the CNN (Lenhardt et al., 2024a) and the vision transformer models across**
705 **channels (CTH, COT and CWP) on the test dataset.**

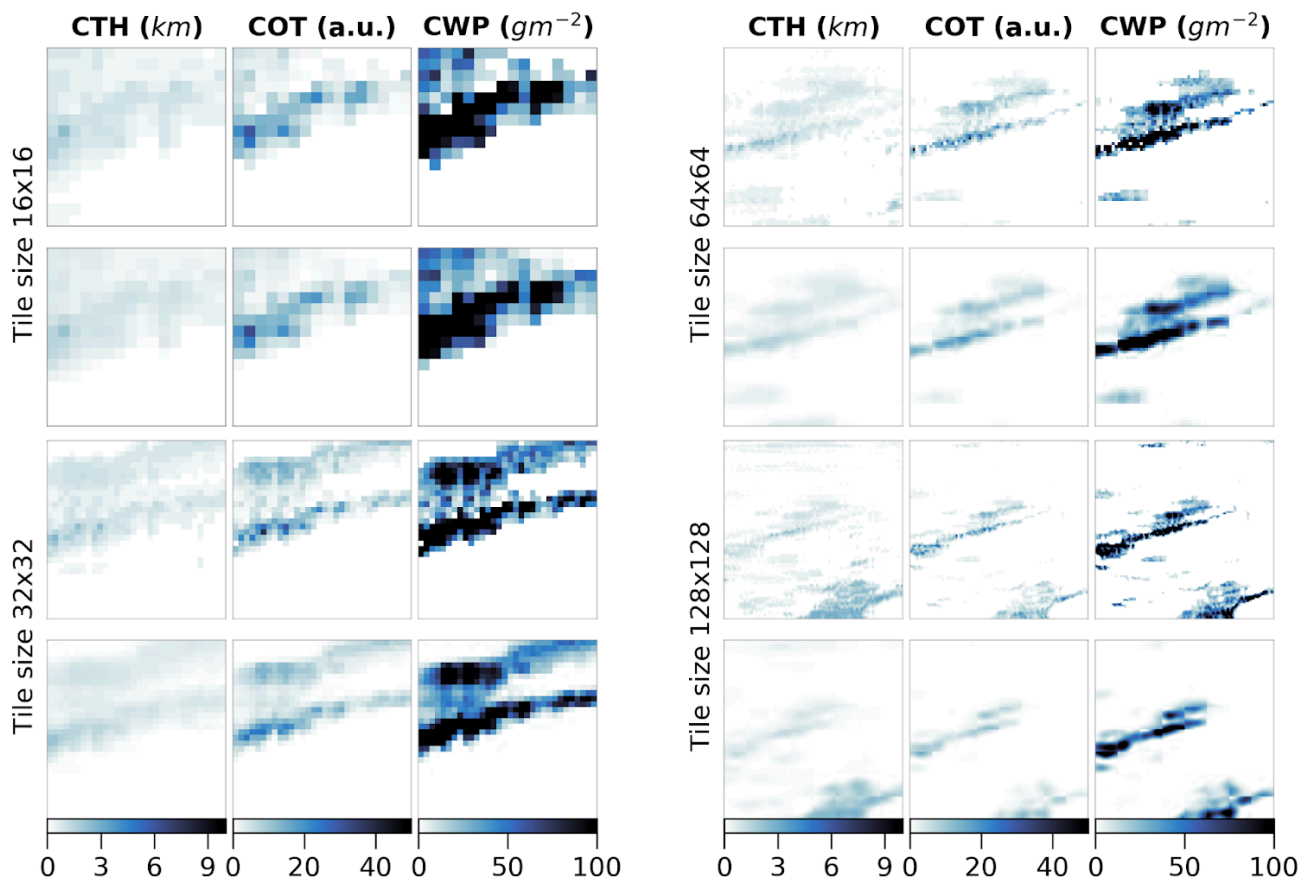
L_c and L_r for different tile sizes



708

709 Figure B.2: Training and validation contrastive (left) and reconstruction (right) losses for vision transformers trained on
710 different input tile sizes of 16, 32, 64 and 128.

711

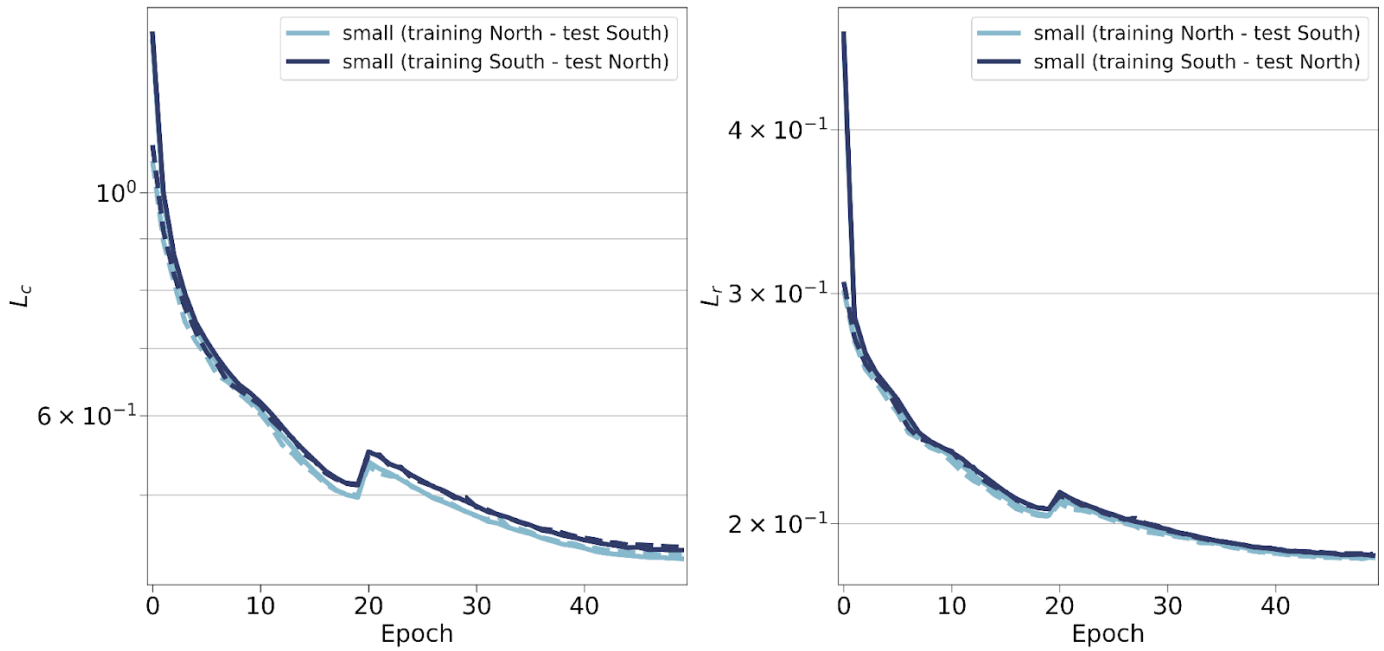


712

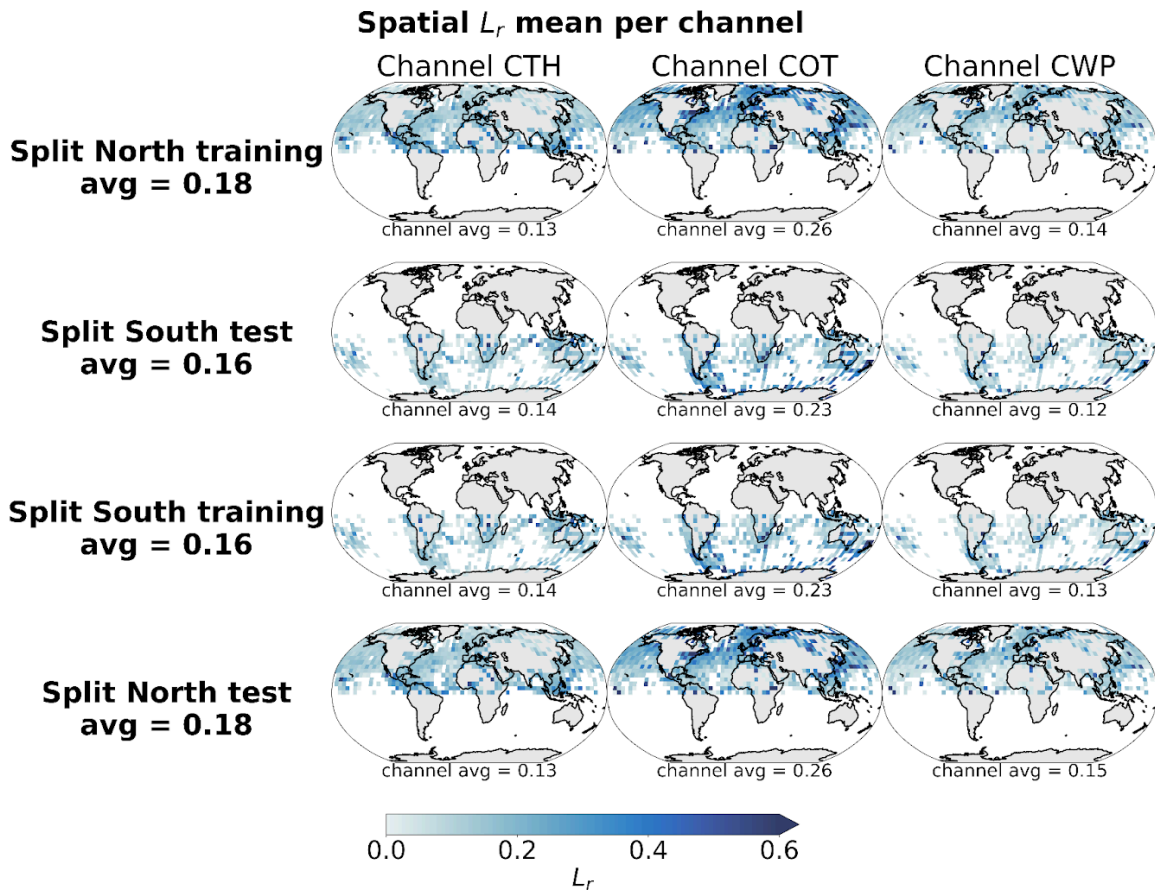
713 Figure B.3: Input tiles (first and third rows) and corresponding reconstructions (second and fourth rows) for vision
714 transformers trained on the relevant input tile sizes of 16, 32, 64 and 128.

715

L_c and L_r for different spatial splits



717
 718 **Figure B.4:** Training (full lines) and validation (dashed lines) metrics for the contrastive (left) and reconstruction (right)
 719 losses for vision transformers trained on samples from the Northern or Southern hemispheres.



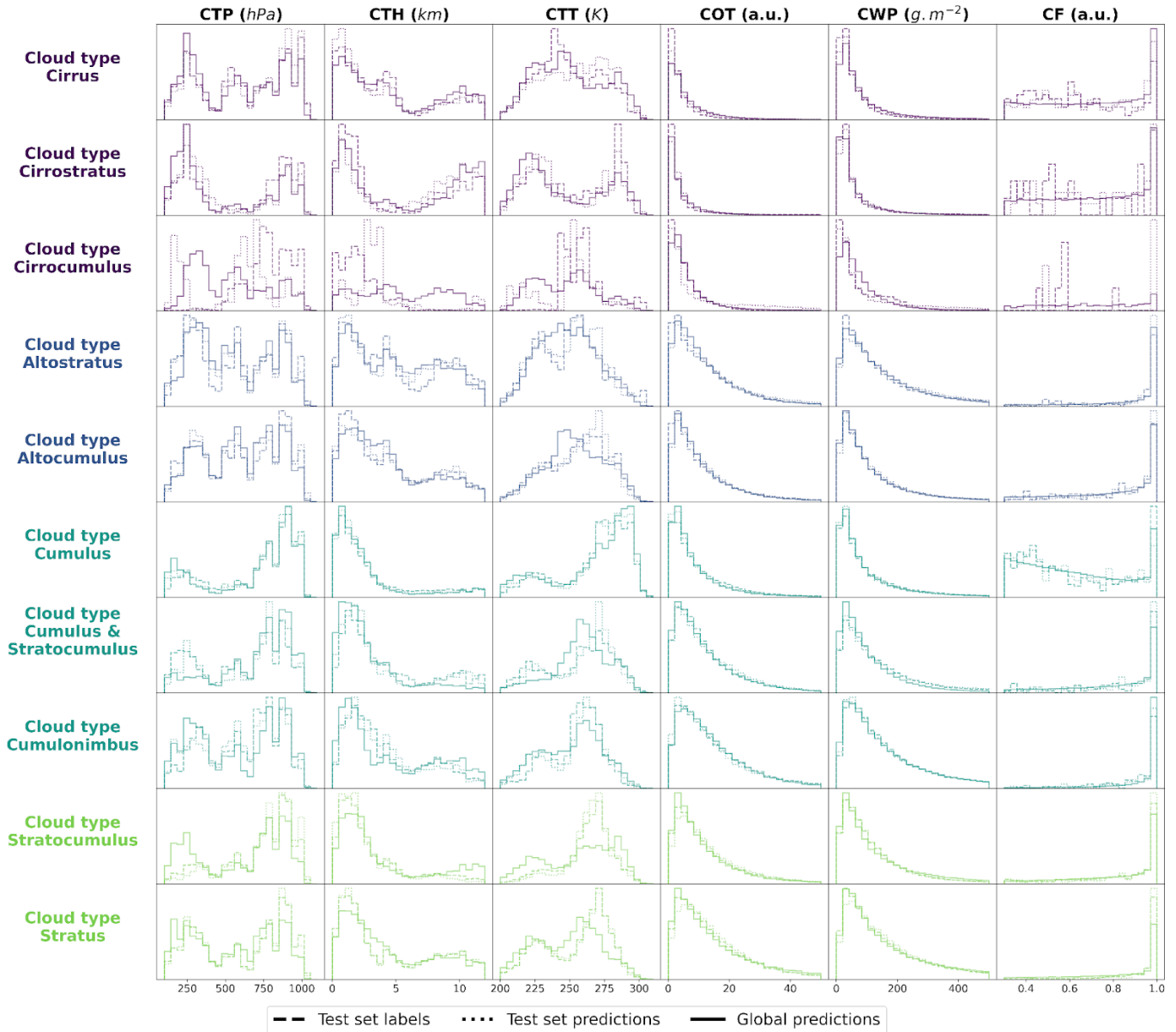
720
 721 **Figure B.5:** Spatial distributions of the mean channel reconstruction errors for the Northern and Southern hemispheres
 722 colocated samples. The first two rows correspond to the model trained on the samples from the Northern hemisphere and
 723 the last two rows to the model trained on the samples from the Southern hemisphere.

724 Appendix C: Cloud type classification for 10 types

Method	Multi-class accuracy *	IBA geometric mean	F1-score *
Baseline 9x9 RF	0.19	0.26	0.16
Baseline CNN/RF	0.22	0.18	0.17
CloudViT/MLP	0.22	0.20	0.16
CloudViT/RF	0.23	0.26	0.21

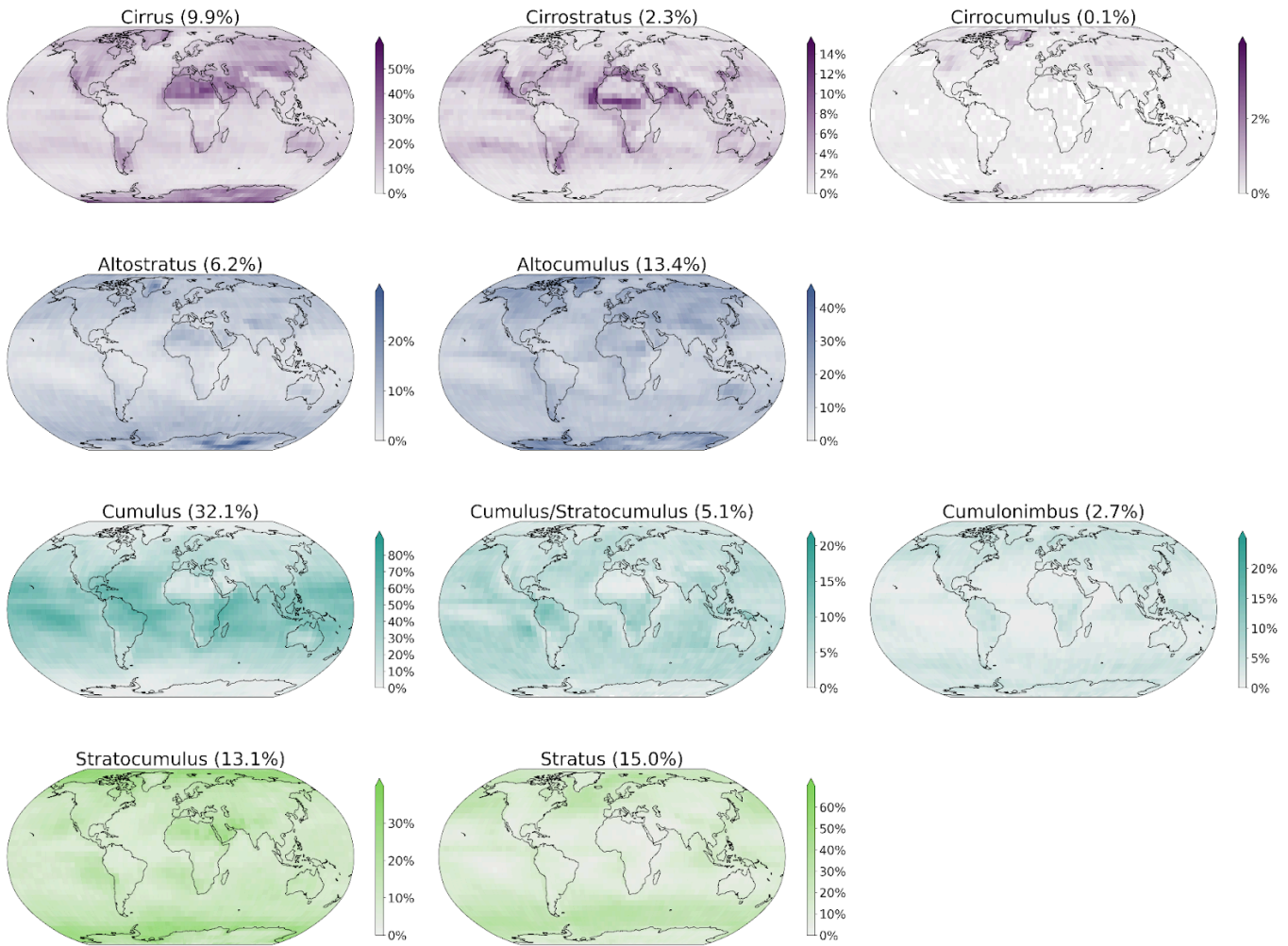
725 Table C.1: Classification metrics on the test set in the case of 10 cloud types. The metrics noted with a * are referring to
 726 their macro-averaged estimate. The baseline CNN/RF refers to the CNN backbone introduced in Lenhardt et al. (2024a).
 727

Density histograms of cloud properties per cloud class for test set labels, test set predictions and global predictions



728
 729 Figure C.1: Density histograms of cloud properties for each cloud type from cirrus, cirrostratus, cirrocumulus,
 730 altostratus, alto cumulus, cumulus, cumulus and stratocumulus, cumulonimbus, stratocumulus, stratus.
 731

Spatial distributions of CloudViT cloud type occurrences (year 2016)



732

733 **Figure C.2: Spatial distributions of the CloudViT cloud type occurrences (cloud types cirrus, cirrostratus, cirrocumulus,**

734 **altostratus, alto cumulus, cumulus, cumulus and stratocumulus, cumulonimbus, stratocumulus, stratus) for MYD06**

735 **granules for the year 2016 aggregated on a 1° regular grid.**

736 Appendix D: Exploring the technical feasibility of the application to a global storm-resolving model simulation

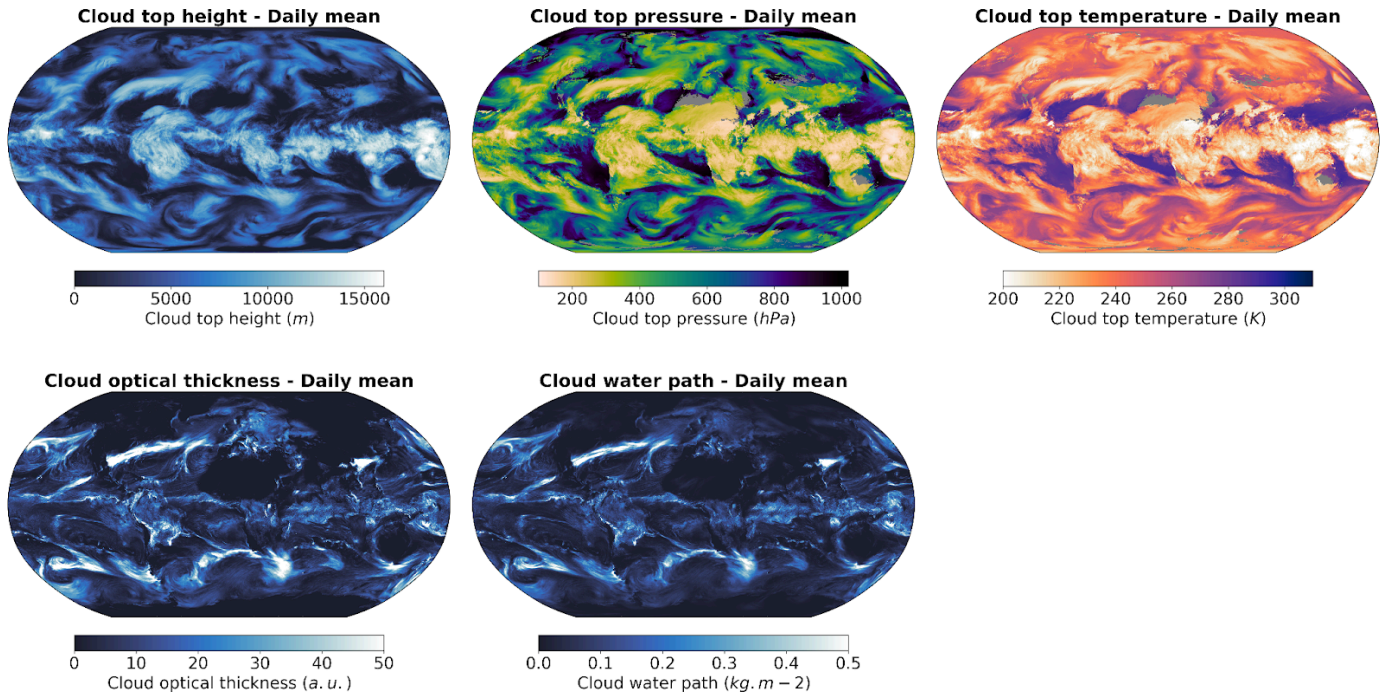
737

738 As a proof of concept and for probing the potential applicability of methods similar to CloudViT, we technically explore how to
 739 investigate the cloud type representation in general circulation model (GCM) outputs. We build on a new generation of GCMs at
 740 kilometre resolution, namely the ICON-Sapphire (Hohenegger et al., 2023). As the resolution of the simulation increases, some
 741 processes like deep convection can be directly resolved instead of parameterized. Hence, building diagnostics about cloud
 742 representation is of importance to help evaluate the simulations. In particular, we use the simulation run by the Max Planck
 743 Institute for Meteorology (MPI-M) for the period between the 5th and 12th of December 1972, aiming at recreating the Blue
 744 Marble picture made during the Apollo 17 mission on the 7th of December. Here we only use the complete outputs provided for
 745 the 11th of December. The grid used contains 335 544 320 grid points at each level in the atmosphere (R02B11 grid), and outputs
 746 are provided every 30 minutes during the simulation for the atmospheric quantities of interest, resulting in overall 48 time steps.
 747 As the effective horizontal resolution of the model simulation and the MODIS data are on similar scales, we can technically
 748 effectively apply CloudViT on the model outputs. From the model outputs, we derive the cloud properties necessary for the
 749 method introduced in this study.

750 In order to compute the different cloud properties used in our method (Table 1), we use the available atmospheric outputs from
 751 the model simulation. The simulation was made using the ICON-2.6.6-rc version in R02B11 grid resolution with 90 vertical
 752 levels in the atmosphere (335544320 grid points per level) and 128 vertical levels in the ocean (237102291 surface grid points).
 753 Observed aerosols and greenhouse gas concentrations of December 1972 were used for the atmosphere. The cloud top quantities
 754 are retrieved by defining the top-most level where the liquid water content (variable name clw) or the ice content (variable name
 755 cli) are above a predefined threshold of 1 mg.kg^{-1} . This threshold relates to particles of sizes of at least a few micrometres which
 756 is similar to what the sensors on the MODIS AQUA instrument are able to retrieve. Using 3D outputs of atmospheric quantities
 757 like temperature (variable name ta) and pressure (variable name $pfull$), we derive the cloud top properties also present in the
 758 MODIS MOD/MYD06 level 2 cloud properties product. The CTH is derived using the altitude in the corresponding vertical
 759 level in the grid. Secondly, the CWP is computed by summing the vertically integrated cloud liquid water path (variable name
 760 $cllvi$) and cloud ice path (variable name $clivi$) which are already provided as simulation outputs. Lastly, we computed the COT by
 761 vertically summing the layer-wise COT computed from the following equation, detailed in Carslaw (2022), equation 12.49
 762 (Chapter 12.3, page 515):

$$763 \quad \tau_c = \frac{9}{5} \left(\frac{4\pi}{3\sqrt{2}}\right)^{1/3} \rho_w^{-2/3} (kN_d)^{1/3} c_w^{-1/6} L^{5/6} = 0.2303 \text{ kg}^{-5/6} \text{ m}^{8/3} (kN_d)^{1/3} L^{5/6} \quad (\text{D.1})$$

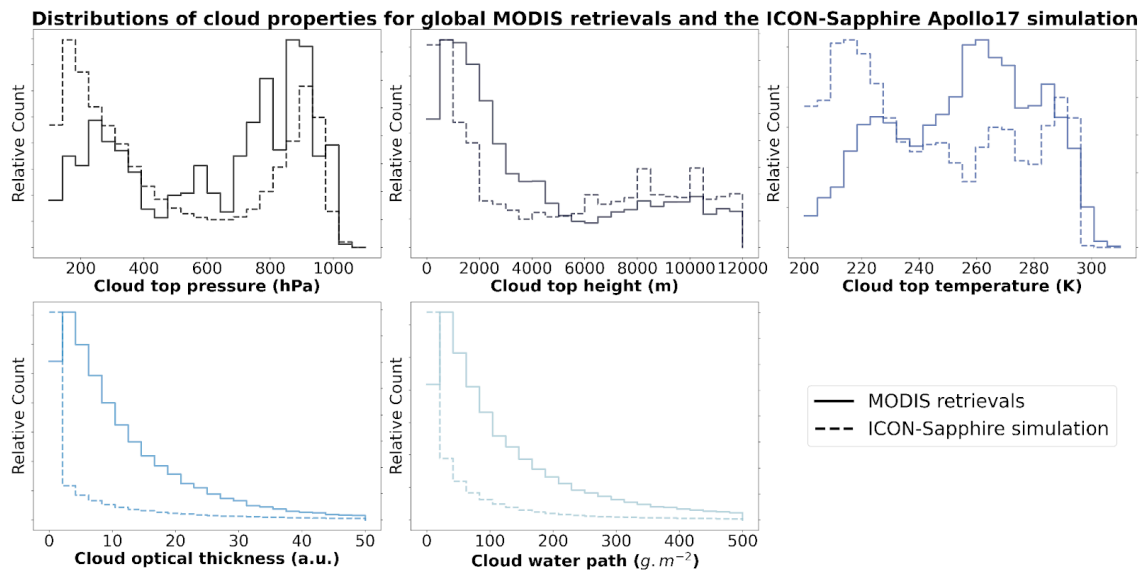
764 Where $L = clw * \rho_{air} * \delta z$ the layer liquid water path, $\rho_w = 1000 \text{ kg.m}^{-3}$ density of water, $k = 1$ a factor to account for
 765 the width of the droplet size distribution, $c_w = 2e^{-6} \text{ kg.m}^{-4}$ the adiabatic condensation rate and N_d the vertical droplet number
 766 defined in the simulation by the ECHAM6 parameterization (Equation 6; Stevens et al., 2013). However, the standardisation of
 767 the input cloud properties for the vision transformer model is still done based on statistics computed on MODIS data which could
 768 induce a bias in the latent representations and subsequently on the predictions. Extending the method to other datasets like this
 769 GCM simulation thus requires careful investigation that the cloud properties lie in the same range or display similar distributions.
 770 For each 30-minute time step, we proceed to sample tiles, regularly spaced, to reach global coverage of cloud type estimates.
 771 Figure D.3 displays the daily averaged occurrence of the cloud type predictions on a 1° regular grid for the 4 cloud types, the
 772 equivalent for 10 cloud types is presented in Figure D.4. However, due to the time period covered by the simulation, no global
 773 data record for cloud types can be used to evaluate the representation of cloud types by the ICON-Sapphire through the
 774 CloudViT method. A thorough analysis would be feasible for simulations covering a time period for which climate data records
 775 of cloud types are available, for example the ISCCP H-series climate data record (Young et al., 2018) which starts in 1983. The
 776 aim here is rather to present as a proof of concept the transfer of such a method to model data outputs. A large proportion of the
 777 predicted clouds belong to the high cloud type, hinting at the difference in sensitivity to clouds retrieved in the climate model
 778 data compared to the MODIS retrievals or the mismatch in the training process of CloudViT, high clouds being underrepresented
 779 and their corresponding classification metrics lower than for some other cloud types. However, increasing the cloud ice content
 780 threshold by an order of magnitude greatly decreases the amount of thin, high and cold clouds in the simulation dataset. This
 781 aspect would need further tuning through comparison with remote sensing retrievals which are not available for this particular
 782 simulated period. An important aspect to factor in is that the classification model was only trained on daytime satellite
 783 observations as the optical cloud properties necessary are only available then. Thus, results on nighttime cloud retrievals which is
 784 the case for some of the predictions produced from the presented simulation might need more meticulous evaluation. Even
 785 though it is a limiting factor in the case of the satellite dataset we are using, the simulation outputs provide us with the required
 786 variables across all timesteps.



788

789 **Figure D.1: Daily averages of cloud top height, cloud top pressure, cloud top temperature, cloud optical thickness and**
 790 **cloud water path for the 11th of December 1972 from the ICON-Sapphire Apollo 17 simulation.**

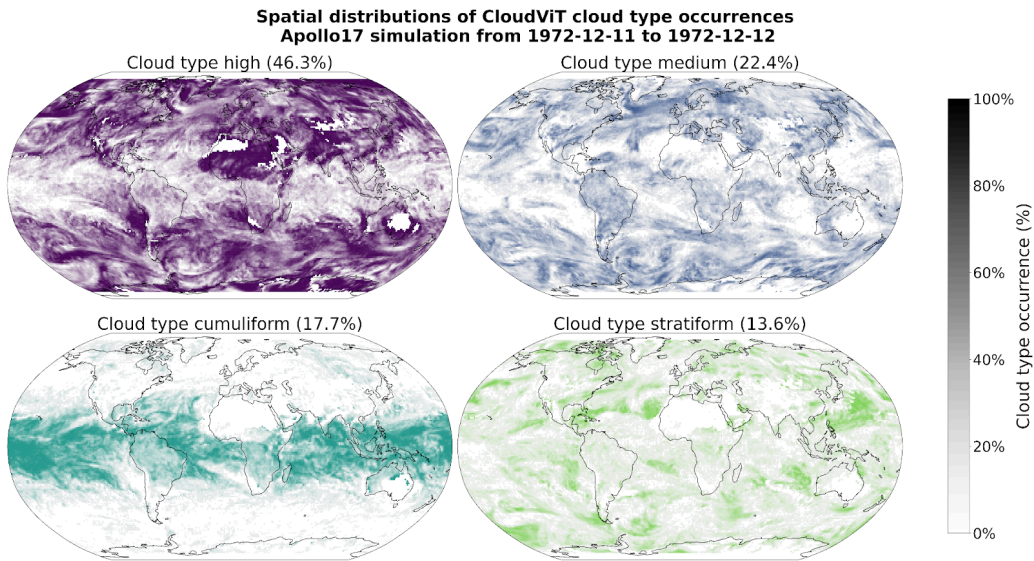
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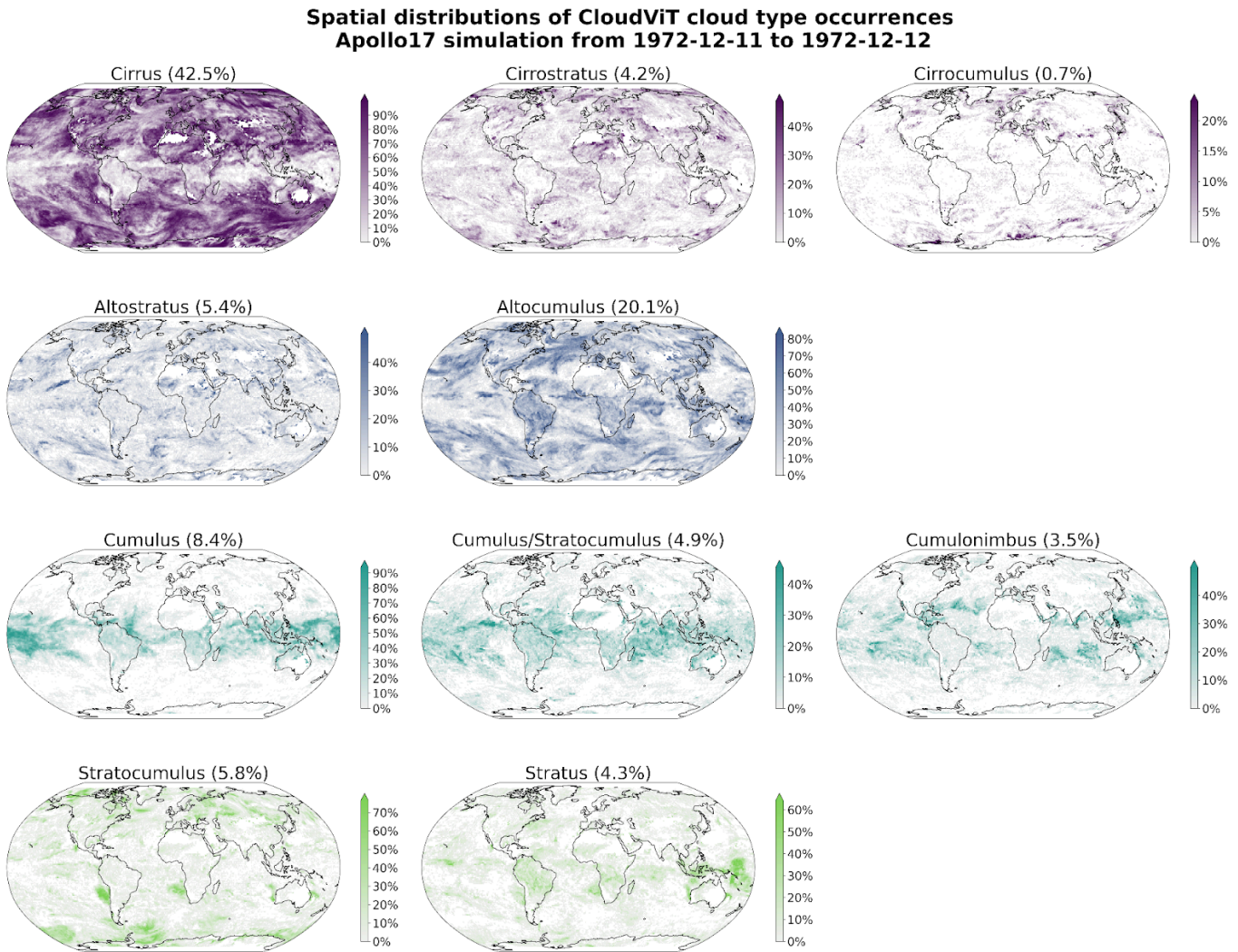
793 **Figure D.2: Distribution of cloud top pressure, cloud top height, cloud top temperature, cloud optical thickness and cloud**
 794 **water path for MODIS AQUA retrievals and the ICON-Sapphire Apollo 17 simulation.**

795



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Figure D.3: Spatial distributions of the CloudViT cloud type occurrences (cloud types high, medium, cumuliform, stratiform) for the ICON-Sapphire Apollo 17 simulation of December 11th 1972 aggregated on a 1° regular grid.



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Figure D.4: Spatial distribution of the CloudViT cloud type occurrences (cloud types cirrus, cirrostratus, cirrocumulus, altostratus, altostratus, altocumulus, cumulus, cumulus and stratocumulus, cumulonimbus, stratocumulus, stratus) for the ICON-Sapphire Apollo 17 simulation of December 11th 1972 aggregated on a 1° regular grid.

803 Code availability

804
805 The code used for the method and producing the plots is available on Zenodo (Lenhardt et al., 2024b).

806 Data availability

807
808 The global dataset of the cloud type predictions for the year 2016 is available on Zenodo (Lenhardt et al., 2024b). The dataset is
809 available as a csv file with corresponding coordinates, MODIS granule file, time of retrieval and predicted cloud type (4 and 10
810 groups) or in a netCDF file as daily aggregates on a regular grid with a resolution of 1 ° or 5 °. The meteorological observations
811 from the UK MetOffice (Met Office, 2006; Met Office 2008) are available through the CEDA archive at
812 <https://catalogue.ceda.ac.uk/uuid/77910bcec71c820d4c92f40d3ed3f249> and
813 <https://catalogue.ceda.ac.uk/uuid/9f80d42106ba708f92ada730ba321831> for ocean and land observations respectively. The files
814 from the CUMULO dataset (Zantedeschi et al., 2019) are available at
815 <https://www.dropbox.com/sh/i3s9q2v2jyjk2it/AACxXnXfMF5wuIqLXqH4NJOra?dl=0>. The simulation outputs are hosted by
816 the DKRZ (Deutsches Klimarechenzentrum).

817 Author contribution

818
819 JL, JQ, DS and DK designed the study. JL wrote the code. DK provided support regarding the climate model data. JL conducted
820 the analysis and JL, JQ and DS interpreted the results. JL prepared the manuscript, JQ, DS and DK reviewed the manuscript and
821 provided comments.

822 Competing interests

823
824 Some authors are members of the editorial board of journal ACP.

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826
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830 acknowledge the contributors of the CUMULO dataset (Zantedeschi et al., 2019) for providing access to the data files hosted at
831 <https://www.dropbox.com/sh/i3s9q2v2jyjk2it/AACxXnXfMF5wuIqLXqH4NJOra?dl=0>. Additionally, we acknowledge the
832 MODIS L2 Cloud product data set from the Level-1 and Atmosphere Archive and Distribution System (LAADS) Distributed
833 Active Archive Center (DAAC), located in the Goddard Space Flight Center in Greenbelt, Maryland
834 (https://ladsweb.modaps.eosdis.nasa.gov/archive/allData/61/MYD06_L2/). We would like to also acknowledge Monika Esch,
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