# Challenges in large-eddy simulation of stratocumulus clouds

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The representation of low clouds in global circulation models is one of the largest sources of uncertainty in climate projections. The projection sensitivity stems from the large contribution of low-cloud shortwave reflectivity in the planetary energy balance, particularly of stratocumulus (Sc) cloud decks that form over the ocean. The lack of physical understanding of the factors controlling Sc cloudiness leads to poor prediction skill. Typically, large-eddy simulations (LES) are used to gain insight into boundary layer physics and to inform the development and evaluation of coarse-grained parameterizations used in weather and climate models. However, LES of Sc clouds has been challenging. The discussion focuses on physics-based modeling of the DYCOMS II RF01 observations. An LES model with an explicit turbulence parameterization, the buoyancy adjusted stretched vortex model, and a low numerical dissipation advection scheme is used. To investigate the effect of model error, simulations are carried out with variable grid resolution and physical processes, e.g., with and without radiation. Two main sources of model error are identified: (a) under-prediction of the amount of cloud liquid because of small (< 5%) errors in temperature and humidity in the cloud layer, and (b) a feedback between cloud-top radiative cooling and vertical turbulent fluxes. The sharp inversion does not lead to the degradation of model performance, with the exception of cloud liquid. Even though cloud-top radiative cooling is not significant in driving the turbulence in the boundary layer in the present case, it creates difficulties in the accurate prediction of the turbulent fluxes, which show significant sensitivity to grid resolution. Turbulence spectra are also discussed.

Keywords: Stratocumulus clouds, Large-eddy simulation, Model error, Grid convergence

# Effects of 3D Thermal Radiation on the Development of Shallow Cumulus Clouds: Parameterization and LES Application

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The development of clouds is highly influenced by radiative effects. In the first place, solar radiation heats the Earth’ s surface, thus causing updrafts of warm and moist air, which, while rising cools again and eventually forms a cloud. From the moment on that a cloud exists, radiation interacts with clouds and clouds interact with radiation. Clouds cause shadows at the surface, which in turn affect cloud formation by reducing solar insolation and thus forming updrafts. At the same time, solar radiation is absorbed by the clouds, causing heating at the illuminated cloud sides. Emission and absorption of thermal radiation lead to cooling at the cloud top and clouds sides and to modest warming at the cloud bottom. While the average cooling rate under cloudless sky conditions is only -1 to -2 K/d, heating rates can become orders of magnitude larger at the interface between cloud and air. The calculation of these heating and cooling rates of up to a few 100 K/d is a three-dimensional problem.
Although these 3D radiative effects are known and can be calculated with accurate radiative transfer models, their representation in cloud resolving models remains poor. With increasing resolution of today’ s cloud resolving models, these 3D effects become more and more important. Due to the high computational costs of accurate 3D radiative transfer models, 3D effects have been neglected in cloud model application. The so far used plane-parallel 1D approximations omit horizontal transport of radiation and thus neglect the cloud side heating and the shift of the cloud shadow (according to the solar zenith angle) in the solar spectral range, as well as cloud side cooling in the thermal spectral range. Recent development of fast 3D radiative transfer parameterizations allows now for the first time to account for the 3D effects and for systematical studies of the development of cloud fields under this more appropriate treatment of radiation.
In this talk, the focus will be on the effects of 3D thermal radiation on cloud development. The ’ Neighboring Column Approximation’ (NCA), a fast approach to account for 3D thermal heating rates in cloud resolving simulations will be introduced. The NCA can be efficiently parallelized since it only considers exchange of radiation with the neighboring column which turns out to be a good approximation. Computational costs of the NCA are a factor 1.5 –2 compared to a 1D radiation approximation. Results of the application of the NCA in cloud resolving models will be shown. A comparison of the results of the application of 1D and 3D thermal radiative effects shallow cumulus cloud fields and possible differences in cloud development both in terms of cloud dynamics and cloud microphysics will be outlined.

Keywords: 3D Thermal Radiation, Cloud Development, LES

# 3DCLOUD, a flexible three-dimensional cloud generator for radiative transfer

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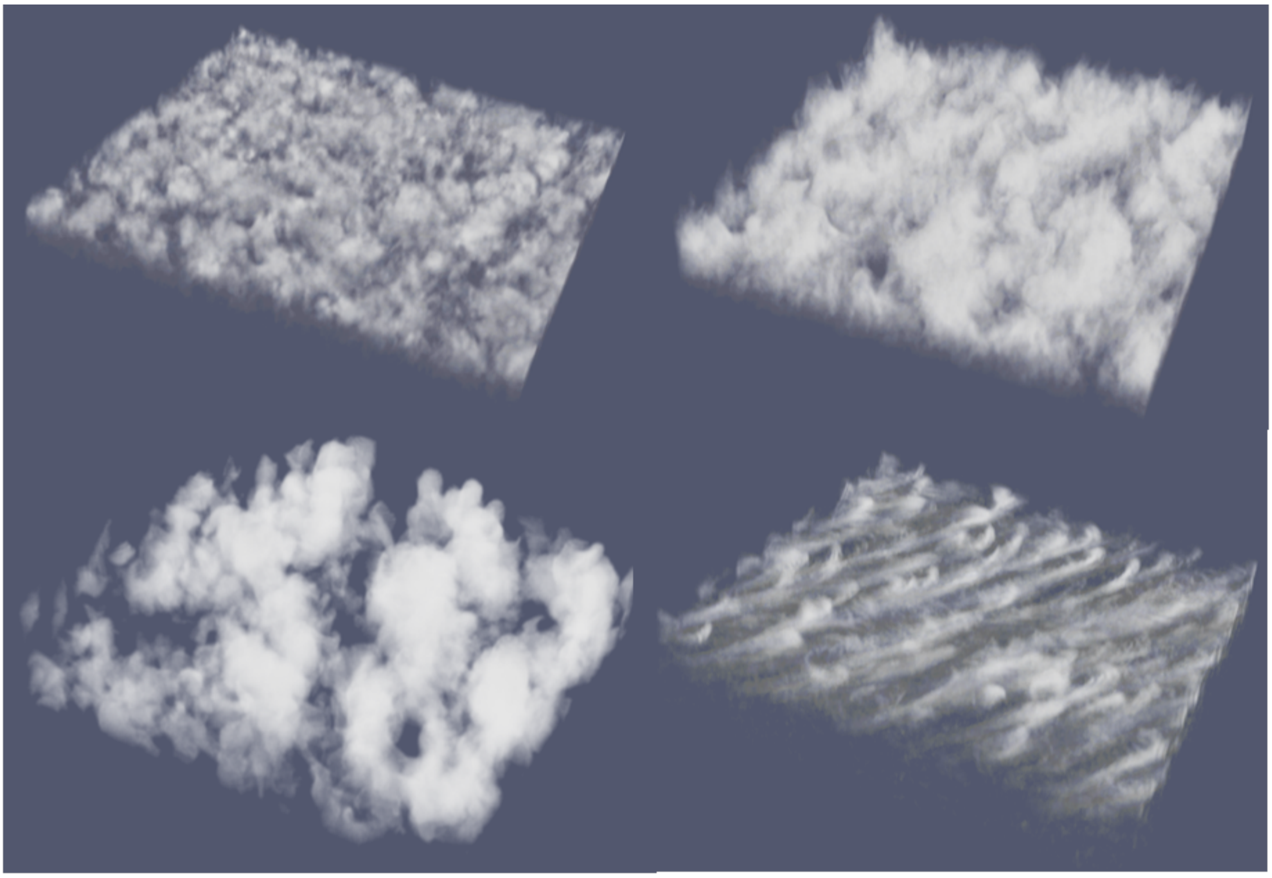
Determining the significance of the tridimensional (3D) inhomogeneity of clouds for climate and remote sensing applications requires the measurement and the simulation of the full range of actual cloud structure. The difficulty is to generate cloud property fields that are statistically representative of cloud fields in nature.

Cloud fields generated by dynamic cloud models, such as the large-eddy simulation model (LES), are very attractive, as they contain the state of the art of physical processes. Nevertheless, they are still very expensive to run in a 3-D domain. Stochastic models have the capability to simulate quickly realistic 2D and 3D cloud structures with just a few parameters. These stochastic models are often based on fractal or Fourier framework. The scale invariant properties observed in real clouds can be controlled. The power spectra of the logarithm of their optical properties typically exhibits a spectral slope of around −5/3 from small scale (a few meters) to the "integral scale" or the outer scale (few tenths of a kilometer to one-hundred kilometers), where the spectrum becomes flat (decorrelation occurs). The disadvantage of such models arises from the fact that effects of meteorological processes are not always considered and dominant scales of organization related to turbulent eddy due, for example, to wind shear, convection, and entrainment are not directly modelled. The aim of the 3DCLOUD (Szczap et al., 2014) is to reconcile these two approaches.

3DCLOUD is designed to generate cloud fields that share some statistical properties observed in real clouds such as the inhomogeneity parameter (standard deviation normalized by the mean of the studied quantity), the Fourier spectral slope (close to −5/3 between the smallest scale of the simulation to the outer scale). Firstly, 3DCLOUD assimilates meteorological profiles (humidity, pressure, temperature and wind velocity). The cloud coverage C, defined by the user, can also be assimilated. 3DCLOUD solves drastically simplified basic atmospheric equations, in order to simulate 3-D cloud structures of liquid or ice water content. Secondly, the Fourier filtering method is used to constrain independently the intensity of inhomogeneity parameter, of spectral slope, of outer scale and of mean of optical depth. Distribution of optical depth is assumed to be gamma.

3DCLOUD model was developed to run on a personal computer under Matlab environment with the Matlab statistics toolbox. 3DCLOUD is thirty times faster than the BRAMS model. We are developing 3DCLOUD_V2 code, an enhanced version of the 3DCLOUD model, where the wavelet framework is used instead of the Fourier framework in the second step. It is well known that wavelets are localized in both space and frequency whereas the standard Fourier transform is localized only in frequency. We show that new iterative wavelet method operating during the second step of 3DCLOUD_v2 algorithm can better control the spectral slope value while keeping spatially the cloud structure simulated during the second step of 3DCLOUD model.

Keywords: 3DCLOUD, radiative transfer, cloud generator



Volume rendering of stratocumulus, cumulus and cirrus fields generated by 3DCLOUD

# A two-dimensional demonstration of adjoint methods for atmospheric remote sensing

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Improved satellite observations of aerosols near clouds are needed to understand cloud-aerosol interactions. There is mounting evidence that we need to model three-dimensional (3D) effects to retrieve aerosols and clouds together in certain key regions, such as in broken cloud fields and near cloud edges. In previous work, we derived the adjoint method as a computationally efficient path to three-dimensional (3D) retrievals. This talk will show a synthetic retrieval study, in which we use a new two-dimensional (2D) radiative transfer solver (FSDOM) to retrieve cloud extinction and surface albedo from multi-angle reflectance measurements.

We generate multi-angle measurements with noise for several synthetic cloud fields and then retrieve the cloud extinction field as a 2D function of the horizontal and vertical coordinates. Our retrieval algorithm adjusts the cloud extinction field and surface albedo to minimize the measurement misfit function with a gradient-based, quasi-Newton approach. At each step we compute the value of the misfit function and its gradient with two calls to the solver FSDOM. First we solve the forward problem to compute the residual misfit with measurements, and second we solve the adjoint problem to compute the gradient of the misfit function with respect to all unknowns. In this way, the adjoint method allows us to make each adjustment to atmosphere and surface properties with only two radiative transfer calculations, regardless of the number of measurements and unknowns.

Our synthetic retrievals verify that adjoint methods are scalable to retrieval problems with many measurements and unknowns. In cases with moderately thick clouds, we can retrieve the vertically-integrated optical depth as a function of the horizontal coordinate. It is also possible to retrieve the vertical profile, i.e. the full 2D cloud field, for clouds that are separated by clear regions. The retrievals of the vertical profile improve for smaller cloud fractions. This leads to the interesting conclusion that cloud edges actually increase the amount of information that is available for the vertical profile. However, to exploit this information one must retrieve the horizontally heterogeneous cloud properties with a 2D (or 3D) model.

These synthetic retrievals show that adjoint methods can efficiently compute the gradient of the misfit function, and encourage our ongoing efforts to augment the existing 3D radiative transfer code SHDOM with derivative calculations based on the adjoint method.

Keywords: Adjoint methods, Inverse problems, Remote sensing, Cloud retrievals

 

# Assessment of 3D cloud radiative transfer effects using observed satellite data

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This study investigates SW and LW broadband radiative fluxes in the 3D cloud-laden atmospheres using a 3D radiative transfer (RT) model, *MCstar*, and satellite-observed cloud data. The 3D extinction coefficient fields are constructed by a newly devised Minimum cloud Information Deviation Profiling Method (MIDPM) that extrapolates CPR radar profiles at nadir into off-nadir regions within MODIS swath based on collocated information of MODIS-derived cloud properties and radar reflectivity profiles. The method is applied to low level maritime water clouds off California, for which the 3D radiative transfer simulations are performed.
The radiative fluxes thus simulated are compared to those obtained from CERES as a way to validate the MIDPM-constructed cloud fields and our 3D radiative transfer simulations. The results show that the simulated SW flux agrees with CERES values within 8 - 50 $Wm^{-2}$. The large bias is found to occur primarily in the case of large cloud fraction field including a number of thin clouds. A possible reason for the bias is likely to arise from the 1D retrieval error for such thin clouds, which tend to be affected by spatial heterogeneity and to overestimate the cloud optical thickness. Given that the uncertainty of instantaneous CERES TOA flux is around 9$Wm^{-2}$, the bias of 8-50$Wm^{-2}$ suggests that MIDPM captures a key aspect of the real 3D cloud field, though we need a future study of validation with more data in various conditions.
Such 3D-RT simulations also serve to address another objective of this study, i.e. to characterize the “observed” specific 3D-RT effects by the cloud morphology. The 3D-RT effects are characterized by errors of existing 1D approximations to 3D radiation field. The errors are investigated in terms of their dependence on solar zenith angle (SZA) for the satellite-constructed real cloud cases and are classified to three types corresponding to different simple morphologies, i.e. isolated cloud type, upper cloud-roughened type and lower cloud-roughened type. The error characteristics are further interpreted with the effective cloud fraction ($CF_e$) profile defined according to average cloud optical thickness and the standard deviation. It is confirmed that the $CF_e$ profile characteristics are consistent with classification of 3D-RT effect into the three types. Such a classification offers a novel insight into 3D-RT effect in a manner that relates to cloud morphology.

キーワード：3D radiative transfer、cloud radiative effect、observed cloud satellite data
Keywords: 3D radiative transfer, cloud radiative effect, observed cloud satellite data

# Application of the deterministic scheme for estimating cloud inhomogeneity effects in a high-resolution numerical model

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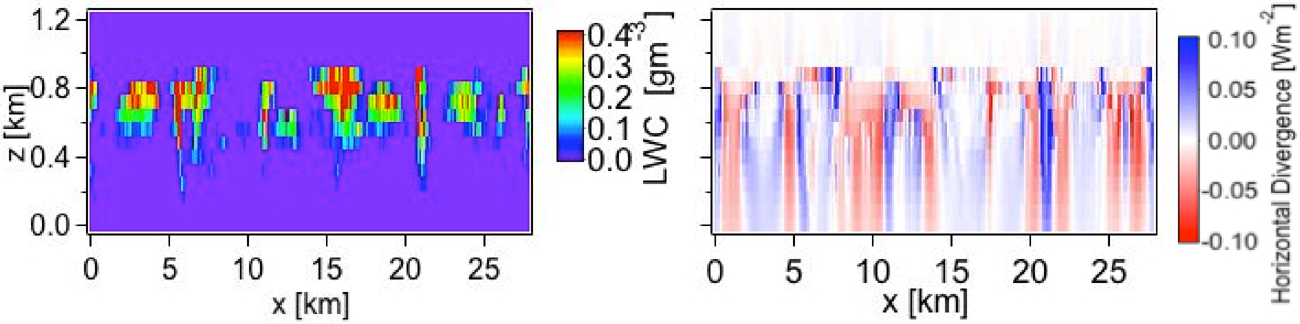
Three-dimensional (3D) radiative transfer effects of spatially inhomogeneous clouds in a very high-resolution numerical simulation are estimated by applying a 3D radiative transfer calculation method that incorporates the deterministic (explicit) scheme. The spatial inhomogeneity of clouds often complicates transport of radiation energy and heating/cooling in the atmosphere, influencing local and global radiation budgets. It is therefore significant to clarify the 3D radiative transfer effects not only for energy budget estimation but also for simulation of the cloud development process. However, there are some problems that hamper the investigation of the 3D radiative transfer effects. One is that the 3D radiative transfer calculation in spatially inhomogeneous clouds usually needs a large resource for computation compared to a plane-parallel approximation. Another is that it is difficult to obtain cloud fields appropriate to estimation of radiative transfer effects, especially in fine spatial scale. Recently, a Large Eddy Simulation (LES) model with a very high-resolution (with the order of 10 m in spatial grid) has been developed, making it possible to provide detailed cloud structure for investigation of cloud physics. In this study, results of the LES model, which deals with development and decay of shallow cumulus and stratocumulus, are used to estimation of the 3D radiative transfer effects. The 3D radiative transfer calculation method applied in this study explicitly solves the 3-D radiative transfer equation by iterative calculation. The 3-D radiative transfer equation is discretized by spherical harmonics expansion and the bidirectional upwind difference scheme for suppression of numerical oscillations. This method consistently satisfies the conservation of radiative energy within both every local grid and a whole domain, and thus is appropriate to calculation of radiation fluxes and their divergence/convergence. This method also has an advantage in calculation for a sequence of time evolution (i.e., the scene at a time is little different from that at the previous time step). Furthermore, this method can treat radiation with strong absorption, such as the infrared regions. For efficient computation, this method utilizes a correlated-k distribution method refined for efficient approximation of the wavelength integration. For a case study, infrared broadband radiation for a time variation of a broken cloud field is calculated, deriving the horizontal radiation transport, which is neglected in the plane-parallel approximation. The calculation result shows not only cloud top cooling but also an additional cooling at the boundaries of clouds and within optically thin clouds, which is caused by the horizontal divergences of infrared radiation. The radiative cooling at lateral boundaries of clouds may reduce infrared radiative heating in clouds as well as cooling at gaps of clouds (i.e., clear sky). The difference between the cooling/heating rates of 1D and 3D sometimes reaches the order of 10 K/day, which should not be ignored in the cloud development and dissipation process. It is suggested that incorporation of 3D radiative transfer into a high-resolution numerical model is helpful for the quantitative estimation of 3D effects.

Keywords: radiative transfer, cloud inhomogeneity effects, high-resolution numerical model, radiative energy flux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# Remote Sensing of 3D Cloud Microphysics via Radiative Transfer

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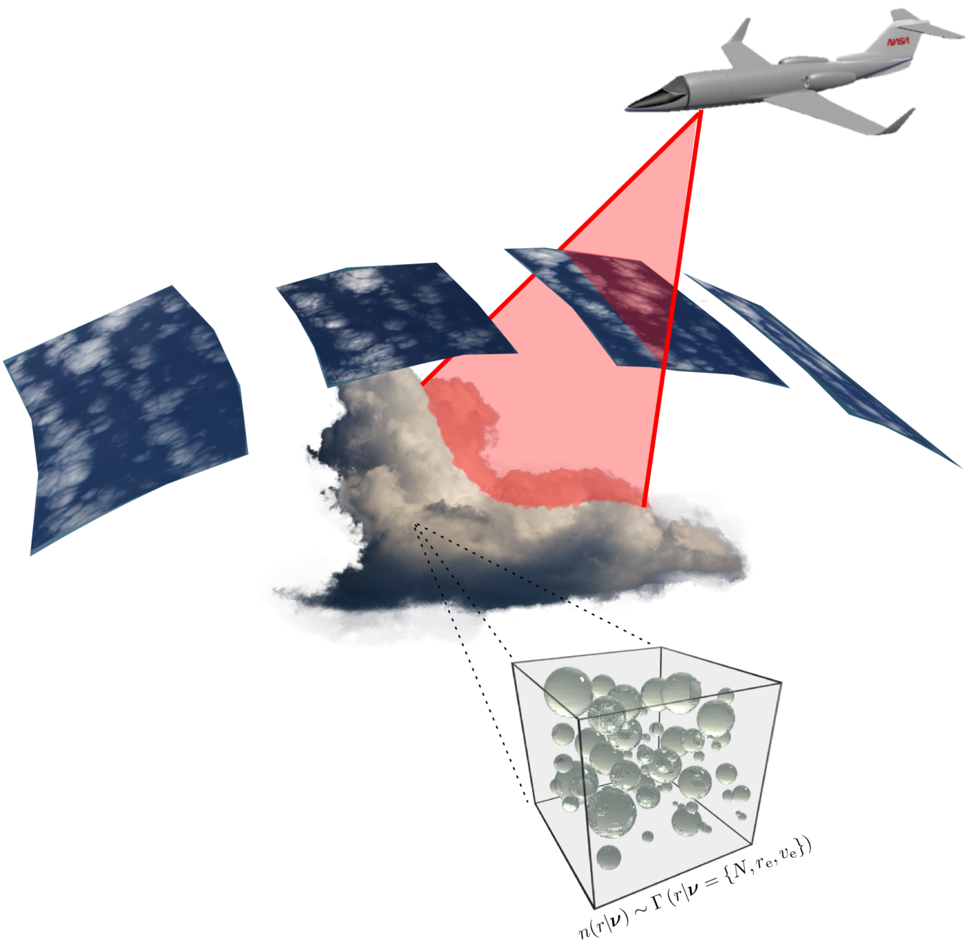
Recent advances in multi-view high-resolution instruments and computation power enable, in principle, 3D volumetric recovery of clouds. This is in contrast to current retrievals, which rely heavily on plane-parallel models and 1D radiative transfer. Plane-parallel models do not express the true 3D nature of the atmosphere, thus biasing retrievals. We pose and solve an inverse problem of passive atmospheric scatterer 3D tomography. The approach fits a microphysical 3D volumetric model of scatterers to multi-angular/multi-spectral images. The forward model is a numerical 3D radiative transfer solver. Model to data fit is posed as a high-dimensional optimization problem. The optimization is computationally tractable on large scales, thanks to an efficient algorithm, which we describe.

As a test-case, we apply the approach to cumulus clouds. Validation is done using a synthetic large-eddy simulation. A preliminary experimental demonstration is performed on data acquired by the Airborne Multi-angle Spectro-Polarimetric Imager (AirMSPI).

Keywords: 3360 Remote sensing, 6982 Tomography and imaging, 0629 Inverse scattering, 3311 Clouds and aerosols



# Retrieval of optical thickness and effective droplet radius of inhomogeneous clouds using a deep neural network

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Estimation of cloud properties such as the cloud optical thickness and effective droplet radius is usually based on the independent pixel approximation (IPA) assuming a plane-parallel, homogeneous cloud for each pixel of a satellite image. Prior studies have pointed out that horizontal and vertical inhomogeneities produce significant errors in the retrieved cloud properties. The observed reflectance at each pixel is influenced by the spatial arrangement of cloud water in adjacent pixels, which necessitates the consideration of the adjacent cloud effects when estimating the cloud properties at a target pixel. We study the feasibility of a multi-spectral, multi-pixel approach to estimate the cloud optical thickness and effective droplet radius using a deep neural network (DNN), which is a kind of machine-learning technique and has capabilities of multi-variable estimation, automatic characterization of data, and non-linear approximation. A Monte Carlo three-dimensional radiative transfer model is used to simulate the reflectances with a resolution of 280 m for large eddy simulation cloud fields in cases of boundary layer clouds. Two retrieval methods are constructed: 1) DNN-2r that correct IPA retrievals using the reflectances (from 3D simulations) at 0.86 and 2.13 μm and 2) DNN-4w that uses the so-called convolution layer and directly retrieve cloud properties from the reflectances at 0.86, 1.64, 2.13 and 3.75 μm. Both DNNs efficiently derive the spatial distribution of cloud properties at about 6×6 pixels all at once from reflectances at multiple pixels. Both DNNs outperform the IPA-based retrieval in estimating cloud optical thickness and effective droplet radius more accurately. The DNN-4w can robustly estimate cloud properties even for optically thick clouds, and the use of a convolution layer in the DNN seems adequate to represent three-dimensional radiative transfer effects.

キーワード：リモートセンシング、雲リトリーバル、ディープニューラルネット
Keywords: remote sensing, cloud retrieval, deep neural network

# Using polarimetry to retrieve the cloud coverage of Earth-like exoplanets

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Clouds in atmospheres of exoplanets play a key role in understanding their climate and radiative balance. They can also complicate the detection of chemical species in the atmosphere by flattening the spectra or by creating degeneracies between observables (Kitzmann et al. 2011, Line and Parmentier 2016)

Polarimetry promises to be a powerfull tool to detect and study exoplanets (Stam et al. 2004). The polarisation of the light scattered by the atmosphere of those planets contains a lot of information about the vertical structure of the atmosphere and about the composition of the clouds (Karalidi et al. 2012) and has already been very successful in the case of Venus (Rossi et al. 2015, 2016 in prep).

We used radiative transfer models based on the doubling-adding method to simulate the disk-integrated flux and polarization of light scattered by exoplanets with patchy, subsolar and polar water clouds. We show that the degree of polarization of the light scattered by an exoplanet can be used to discriminate between the different types of cloud coverage and to quantify the cloud coverage on the planetary scale. Use of both flux and polarization allows for a resolution of some ambiguities between cloud coverage and cloud top altitudes.

We then propose an observational strategy based on an iterative process using polarization phase curves in the wavelength range 300 to 900 nm that could help retrieve both orbital parameters and cloud coverage with minor ambiguities.

We intend to test this method using GCM outputs to simulate the cloud cover and the resulting flux and polarization of some exoplanets.

Keywords: polarimetry, atmospheres, exoplanets, clouds

 

# Radiative Transfer Modeling to Interpret Photopolarimetric Measurements of Brown Dwarf Emissions

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We present a novel radiative transfer scheme for computing the disc-resolved and disc-integrated polarized infrared emission of an oblate brown dwarf (BD) or planet. Using this capability, we model oblate cloud-bearing brown dwarfs at different orientations relative to the observer.

The dependence of the photo-polarimetric signal on cloud optical thickness and droplet size, stellar oblateness and inclination are examined qualitatively.

Knowledge of the oblateness and the projected inclination of the stellar axis in the viewing plane together allow the determination of the exact orientation in space of the stellar rotation axis, for both uniform and patchy brown dwarfs. Polarization measurements are most sensitive to the stellar limb, thus providing information complementary to photometric measurements which are susceptible to limb darkening. Information content analysis reveals that polarization can contribute significantly to the quality of the retrieval, especially when measurements can be made with high accuracy.

Keywords: Exoplanets, Brown dwarfs, Clouds, Oblateness, Temperature inhomogeneity