# Cloud base height retrieval from multi-angle satellite observations and its application to assess cloud heights over the southeast Pacific

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## 1. Introduction

The cloud base height ($z_{base}$) is an important parameter of a cloud, influencing the radiation energy budget, allowing the calculation of the cloud's subadiabaticity, and being the height at which the ambient aerosol concentration and the updraft speed determine the cloud's microphysical characteristics. Though one of the most difficult parameters to retrieve from satellite measurements, some attempts exist to determine $z_{base}$ from space. Lau et al. (2012) suggest an approach utilizing the Multi-angle Imaging SpectroRadiometer (MISR) on the Terra satellite. In a preliminary case study they investigated cloud top height ($z_{top}$) measurements along a horizontal profile. They compared the minimum $z_{top}$ along the profile with the $z_{base}$ from a collocated Lidar. For 12 scenes they found good agreement. To further investigate this approach, we developed a routine to retrieve $z_{base}$ from MISR $z_{top}$ measurements under the following assumptions:

(1) $z_{base}$ is homogeneous within a certain area of limited size.

(2) The $z_{top}$ distribution contains information on the $z_{base}$ for a limited area.

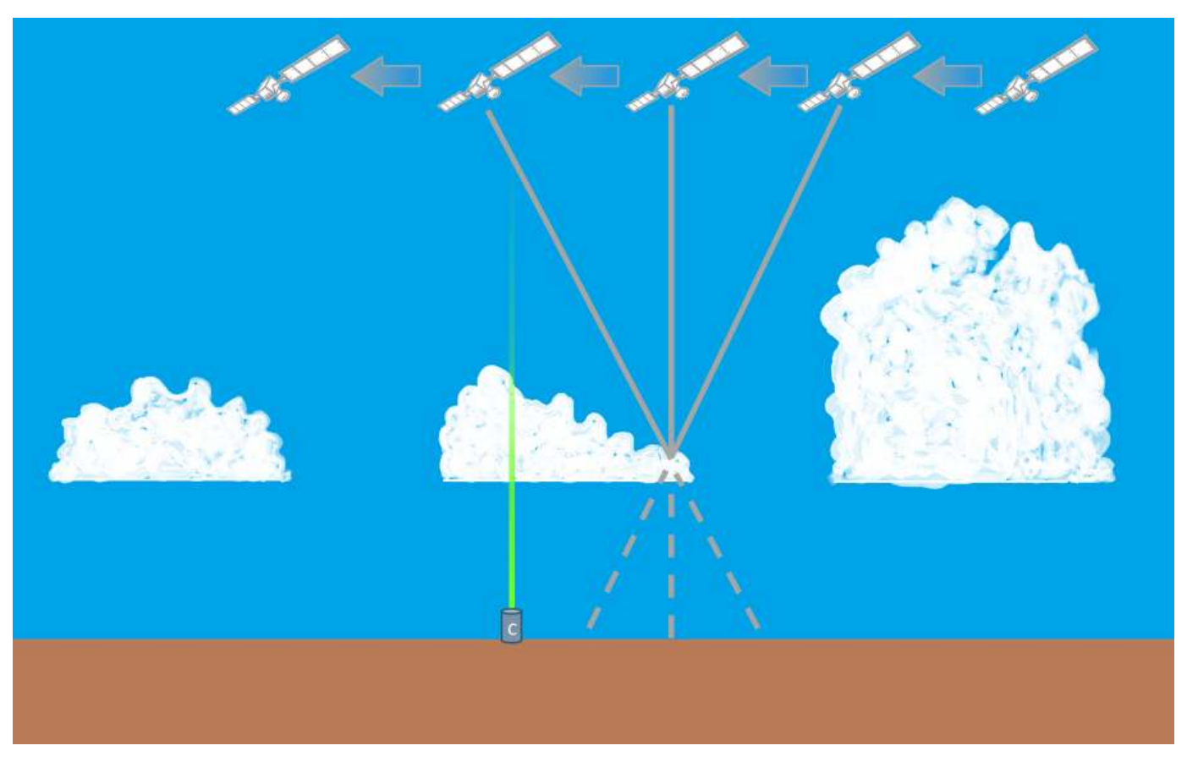

***Fig. 1**: Schematic depiction of a cloud field observed from different viewing angles during a satellite overpass. Ground based ceilometer measurements provide a reference to the cloud base height.*

We utilize the MISR Level 2TC Cloud Product (MIL2TCSP; Moroney and Mueller, 2012; Mueller et al., 2013) which we describe here very briefly:

- A cloud field is observed by different viewing angles.
- A pattern matching algorithm identifies equal cloud features from the different viewing angles and assigns the apparent ground position accordingly.
- Applying the geometric relationships between the measurements the cloud feature height and the motion vector are derived at a 70km resolution. Using the coarser resolved motion vectors $z_{top}$ is inferred on a finer resolution (1.1km).

Geometrically derived product is independent of auxiliary data or calibration.

## 2. Case Study

To illustrate the new approach, an individual $z_{base}$ retrieval is exemplified. In this case, the cloud scene from 21 August 2015 in the vicinity of the ceilometer station at Atlanta, Georgia, USA is investigated.

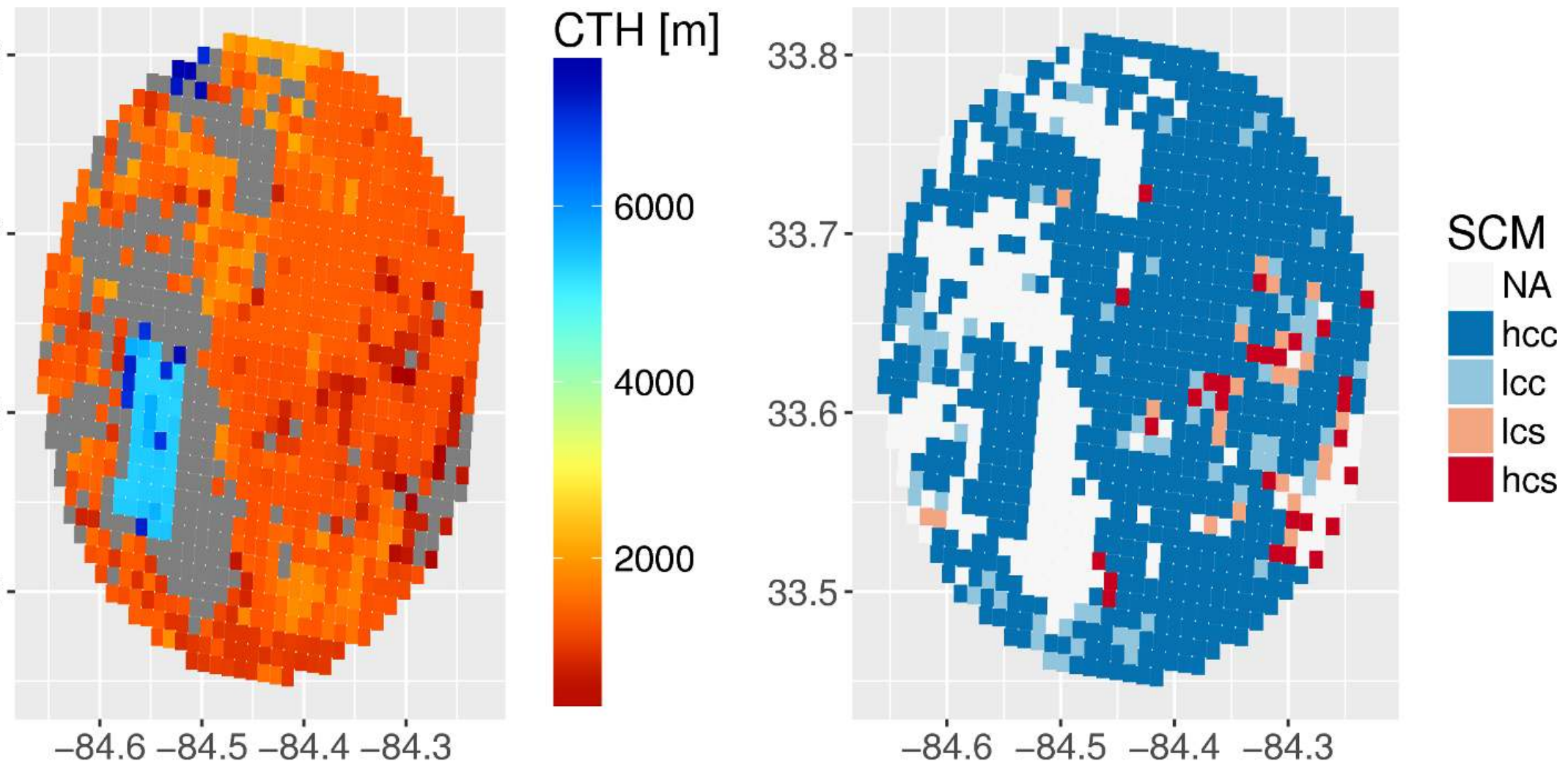

***Fig. 2**: MISR MIL2TCSP-product for a circular area with a 20 km radius from 21 August 2015. The scene is centered at the ceilometer station of the international airport of Atlanta, Georgia, USA. Left: Cloud top height (CTH). Right: Stereo derived cloud mask (SCM) with high confidence cloud (hcc), low confidence cloud (lcc), low confidence surface (lcs) and high confidence surface (hcs) classification.*

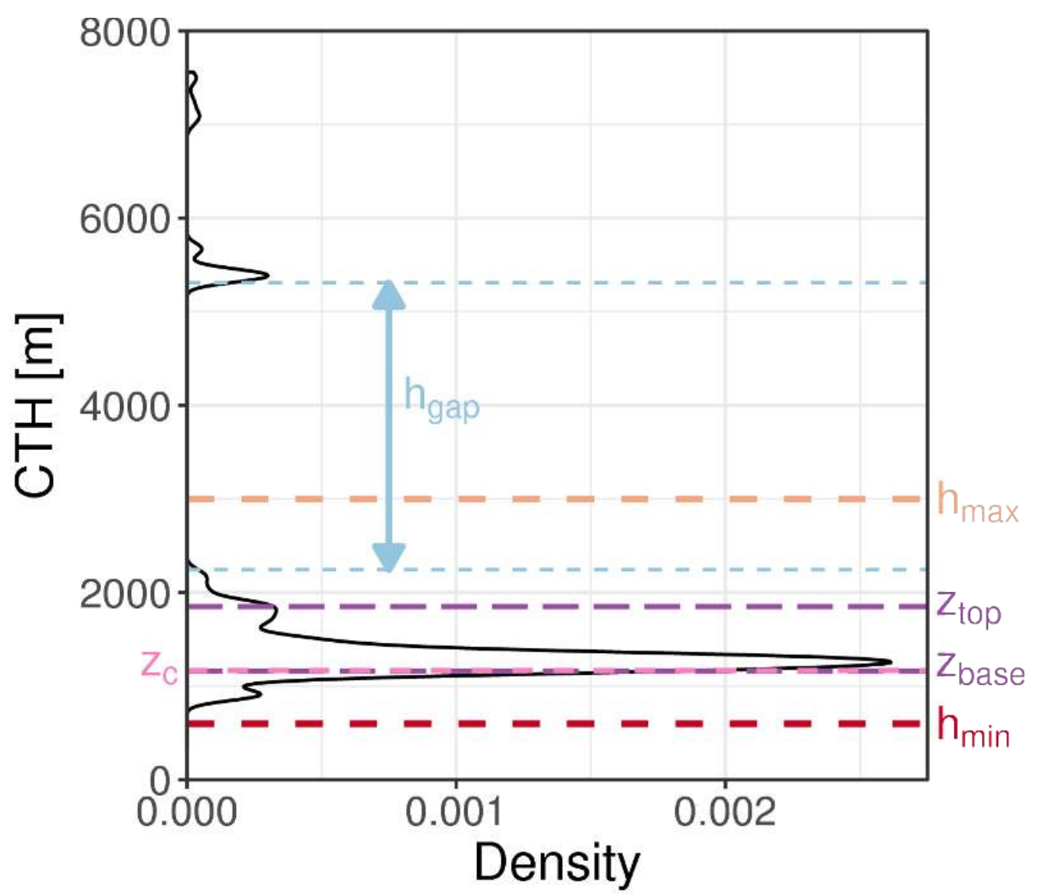

***Fig. 3**: Density of the CTH retrievals (hcc) enclosed within the specified area shown in Fig. 2.*

MISR $z_{base}$ (1160 m) and the ceilometer $z_c$ (1168 m) agree very well for this case.

MISR retrieval recipe:

- Consider high confident cloud pixel (hcc) only
- Cloud layer distinction distance: $h_{gap} = 500$ m
- Require a minimum number of valid pixel per layer of N = 10
- In multi layer case select bottom layer for further analysis
- MISR threshold height for distinction between surface and cloud:

$$h_{min} = 560\ \mathrm{m} + H_{terrain} + 2\sigma_{terrain}$$

- $z_{base}$ and $z_{top}$ are yielded by the 15th and 95th percentile of the MISR retrieval distribution, respectively.

***References:***

*Lau, M. W., Y. L. Yung, and D. L. Wu, 2012: **Determining Cloud Base and Thickness from Spaceborne Stereoscopic Imaging and Lidar Profiling Techniques**, Caltech Undergraduate Research Journal, Spring Issue.*

*Moroney, C, and K. Mueller, 2012: **Data Product Specification for the MISR Level 2 Cloud Product**, Tech. Rep. JPL D-72327.*

*Mueller, K., C. Moroney, V. Jovanovic, M. Garay, J.-P. Muller, L. Di Girolamo, and R. Davies, 2013: **MISR Level 2 Cloud Product Algorithm Theoretical Basis**, Tech. Rep. JPL D-73327.*

## 3. Parameter estimation and validation

Parameters for the retrieval algorithm which minimize the root mean square error (RMSE) and maximize the coefficient of determination ($r^2$) have been estimated using data from the year 2008. An independent validation has been carried out with data from the year 2007. See table for results of the comparison.

List of estimated parameters:

- Percentile p: 15th
- Minimum number of valid pixels per detected MISR layer: N = 10
- Radius of the field of view centered at the ceilometer station: $R_{fv}$ = 10 km

| data | slope | intercept [m] | r² | RMSE [m] | Bias [m] | n |
|---|---|---|---|---|---|---|
| 2008 | 0.61 | 413 | 0.43 | 404 | -79 | 5136 |
| 2007 | 0.60 | 425 | 0.43 | 386 | -64 | 6807 |

Similar statistical values for the validation period (2007). Estimated parameters guarantee a stable performance of the algorithm.

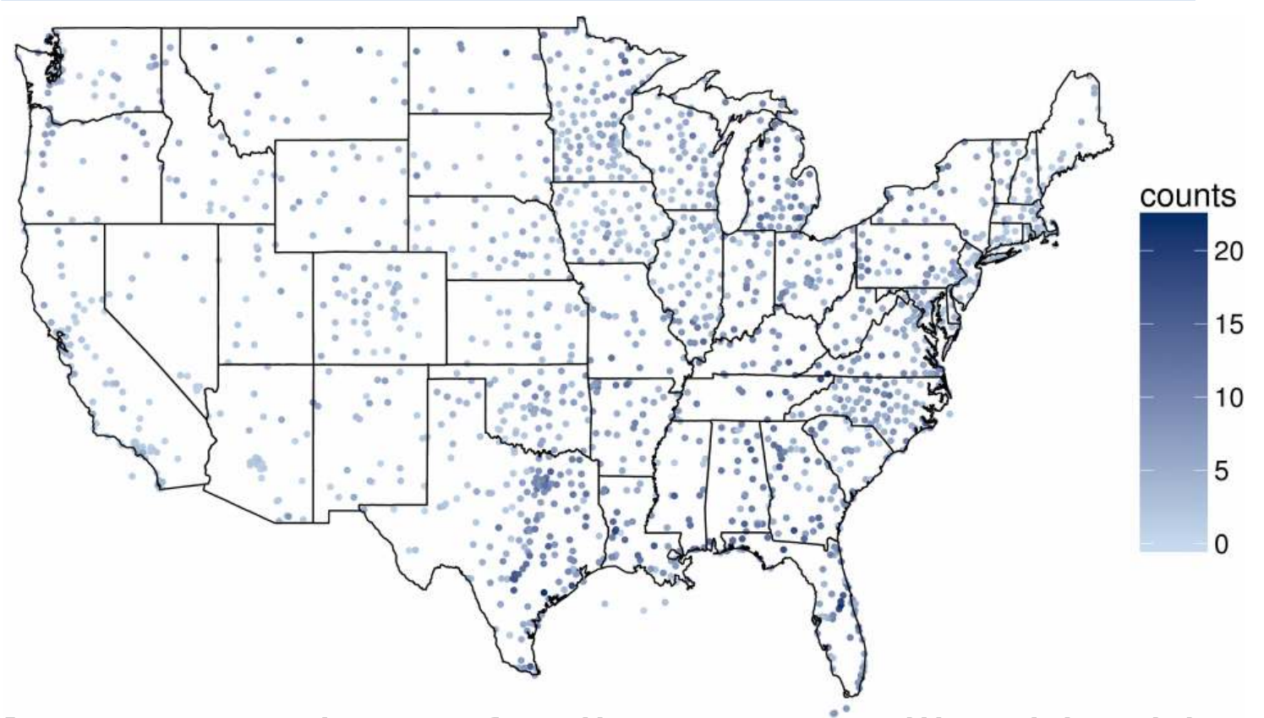

***Fig. 3**: Locations of ceilometers utilized in this study across the continental United States. Blue shading indicates the number of considered measurements to calibrate the $z_{base}$ retrieval algorithm.*

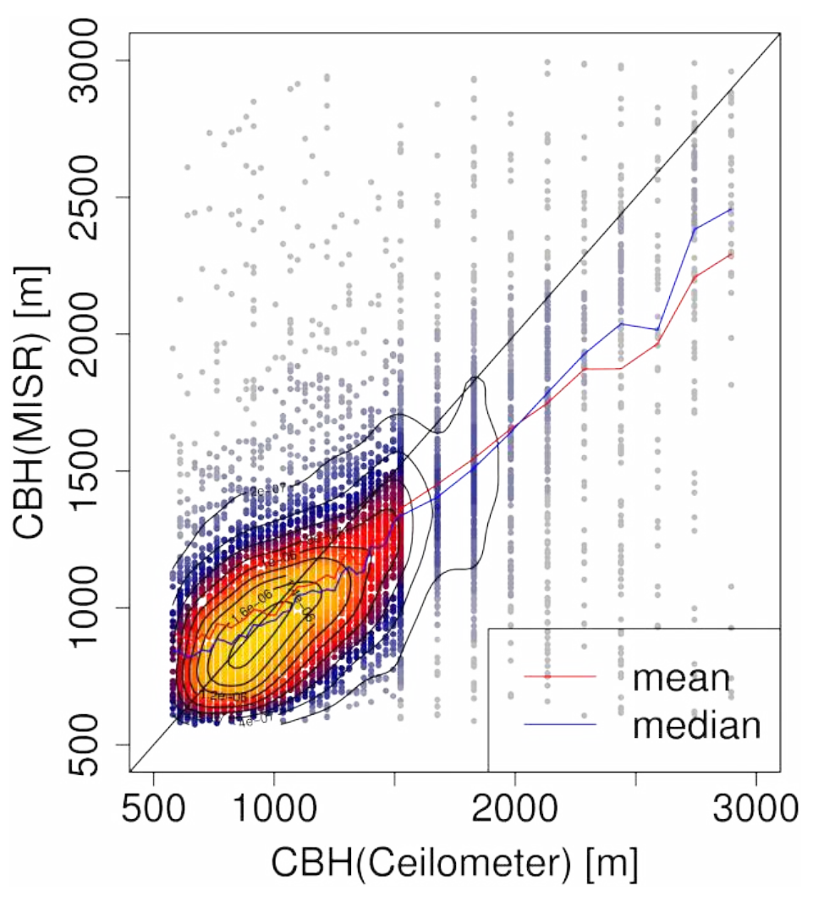

***Fig. 4**: Joint density of MISR and ceilometer $z_{base}$ for the year 2007. A map of the utilized ceilometer stations is shown in Fig. 3. For each ceilometer height bin, the mean (red) and the median (blue) of the MISR $z_{base}$ are shown.*

## 4. Global cloud base height climatology

The retrieval algorithm has been applied globally for a 3-year period (2007-2009) on a 0.25° x 0.25° grid. For each grid box the median $z_{base}$ has been calculated.

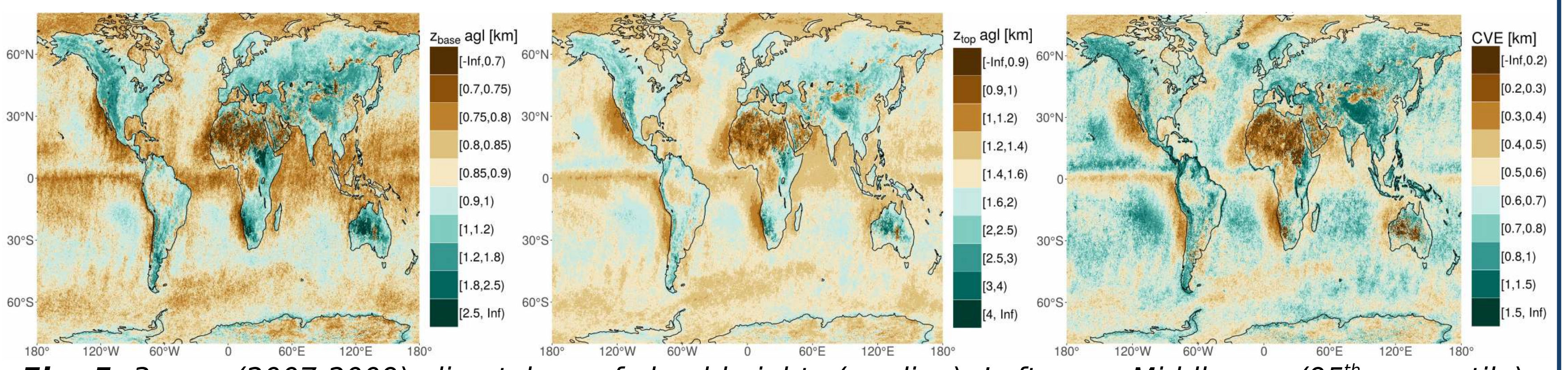

***Fig. 5**: 3-year (2007-2009) climatology of cloud heights (median). Left: $z_{base}$. Middle: $z_{top}$ ($95^{th}$ percentile). Right: Cloud Vertical Extent (CVE) derived as $z_{top}$-$z_{base}$ for each individual cloud scene.*

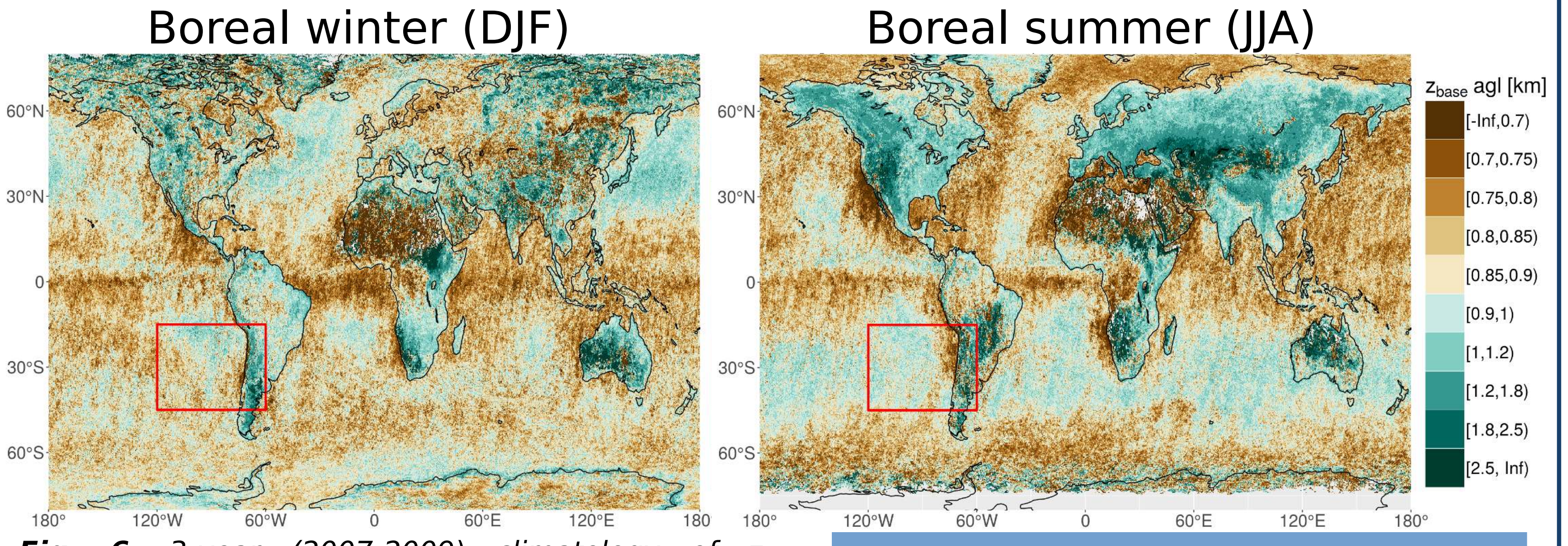
Boreal winter (DJF)
Boreal summer (JJA)

***Fig. 6**: 3-year (2007-2009) climatology of $z_{base}$ (median) for boreal winter (DJF) (left) and summer (JJA) (right). Red rectangle indicates the focus area for the regional cloud height study shown below.*

- Plausible spatial distribution of $z_{base}$
- Performs well on different kinds of terrain
- Seasonal patterns can be observed

## 5. Cloud base height over the southeast Pacific

Stratocumulus clouds, which are prevailing in the southeast Pacific area, are not well represented in climate models. These clouds constitute a major source of moisture to the coastal cliff of northern Chile by forming orographic fog.

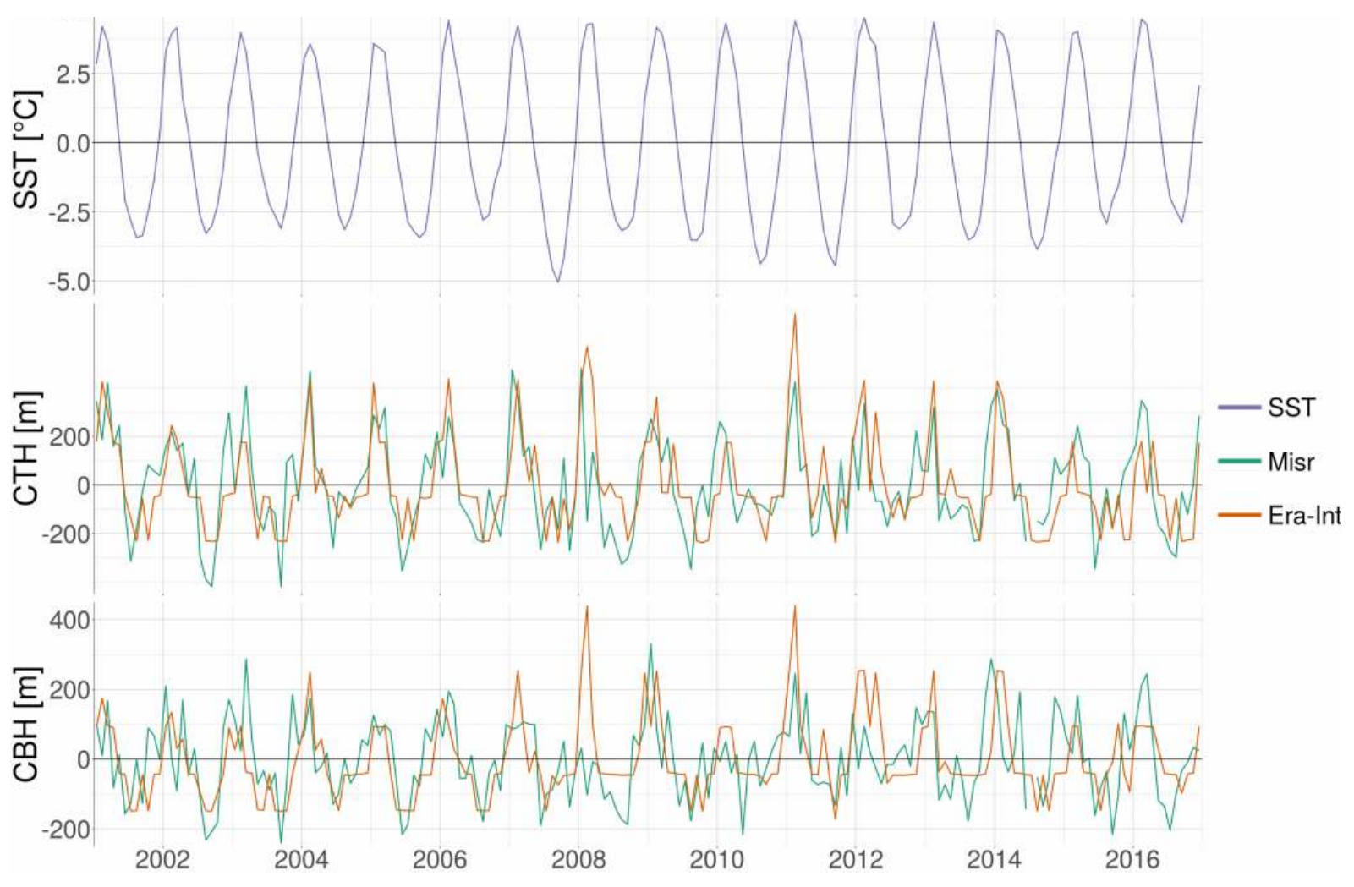

***Fig. 8**: Time series of Sea Surface Temperature (SST) (top), $z_{top}$ (middle), $z_{base}$ (bottom) anomalies. Cloud heights are derived from MISR (green) and ERA-Interim (orange). SST is derived from ERA-Interim. Shown are the deviations from the mean over the entire period from 2001 through 2016.*

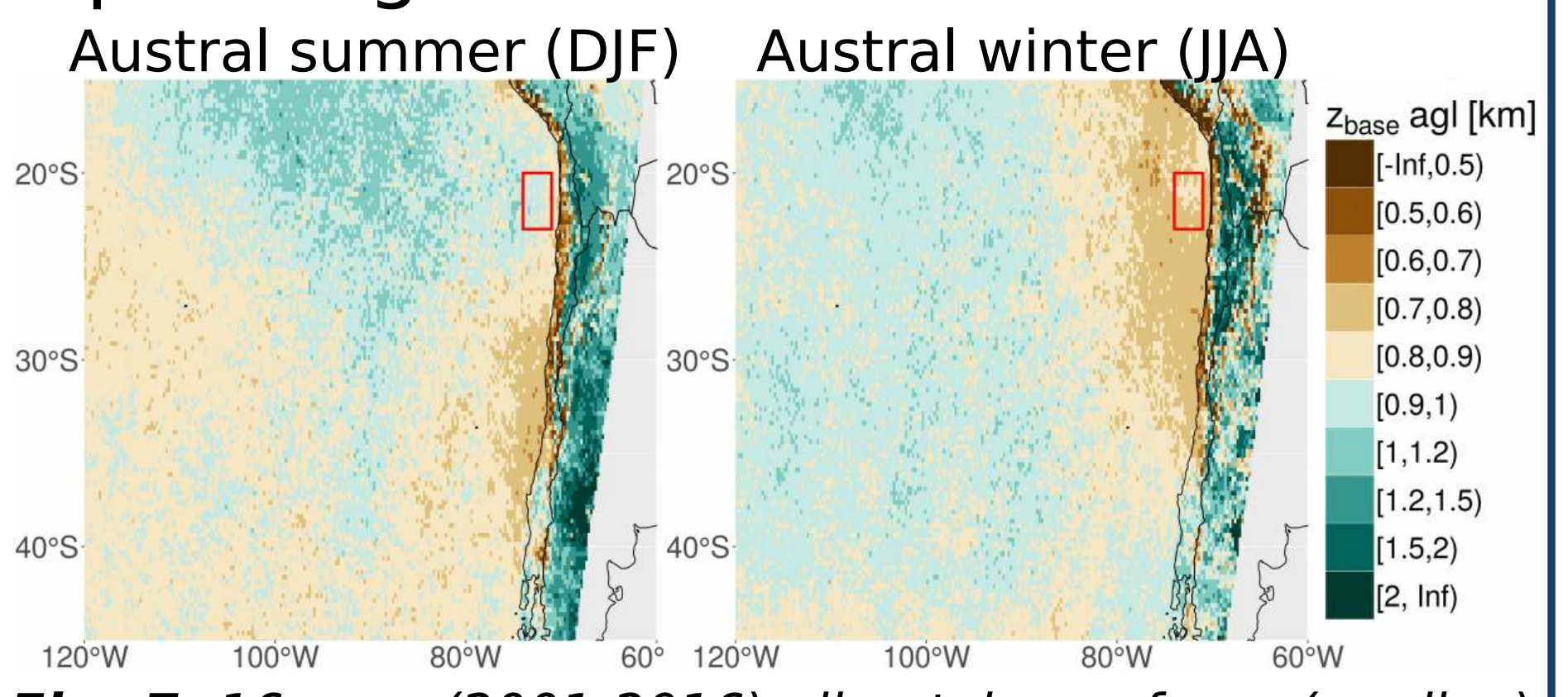
Austral summer (DJF)
Austral winter (JJA)

***Fig. 7**: 16-year (2001-2016) climatology of $z_{base}$ (median) for austral summer (DJF) (left) and winter (JJA) (right) over the southeast Pacific. Red rectangle indicates the focus area for the cloud height time series shown in Fig. 8.*

- Seasonality of cloud heights is captured similarly by MISR and ERA-Interim
- $z_{base}$ over the southeast Pacific ranges from ~600 m (near coast) to ~1200 m

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