Multi-year climatology of fog and low cloud occurrence in the Atacama Desert derived from satellite measurements

Böhm[1], C., J. Schween, U. Löhnert, S. Crewell[1]
[1] Institute of Geophysics and Meteorology, University of Cologne

Earth – Evolution at the dry limit
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1. Introduction

Within the German Science Foundation funded Collaborative Research Center "Earth – Evolution at the dry limit" our overarching goal is to understand the moisture supply to the Atacama Desert and the drivers of its variability.
- Quantifying fog water supply and its variability over longer time periods is essential in order to establish thresholds for growth and development of the local biota and for surface alterations.
- Scarce in-situ measurements → for long term means with high spatial coverage, satellite observations have to be considered.
- Utilizing MODIS observations and a newly installed network of weather stations, we investigate the following hypotheses:

(1) The MODIS cloud mask is able to indicate cloud contamination in case of fog.

(2) Spectral test provided with the MODIS cloud mask allow discrimination between higher clouds and ground fog.

(3) The warm season is characterized by more inland fog and less coastal fog compared the cold season

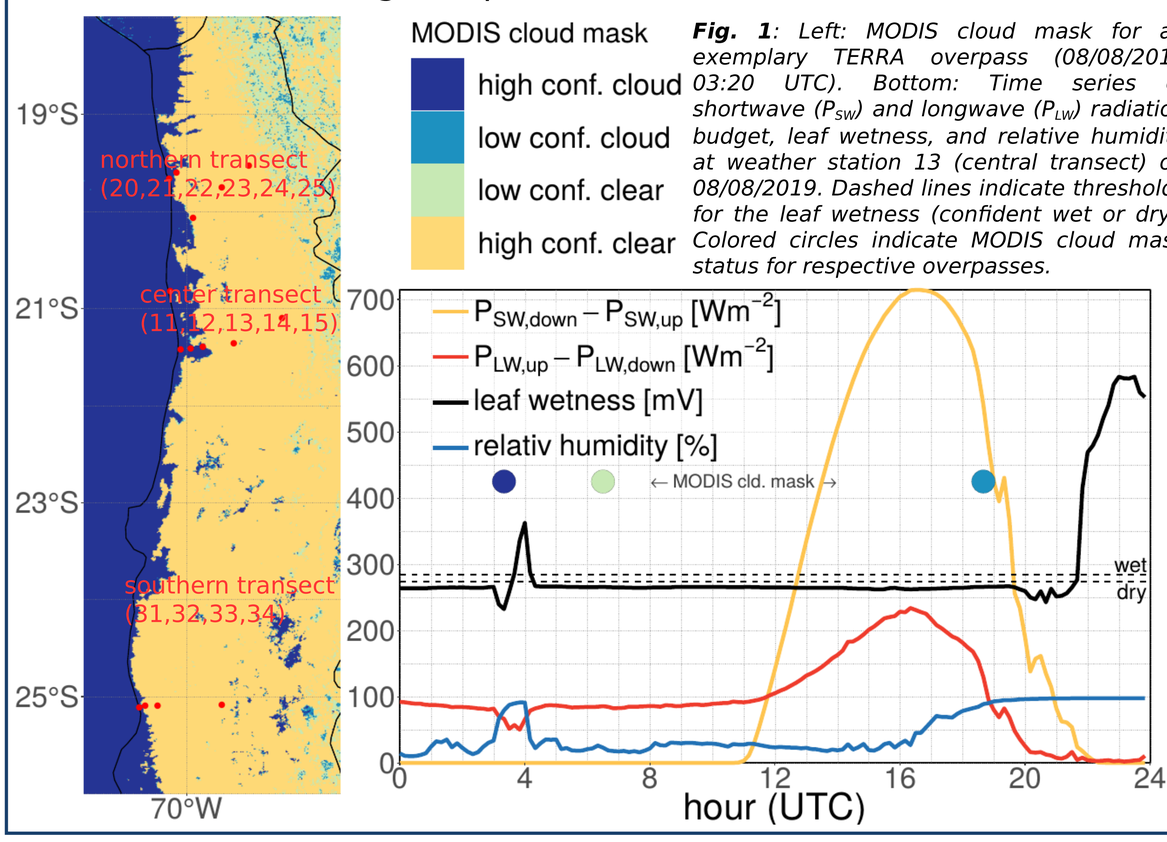


***Fig. 1**: Left: MODIS cloud mask for an exemplary TERRA overpass (08/08/2019 03:20 UTC). Bottom: Time series of shortwave (P_{SW}) and longwave (P_{LW}) radiation budget, leaf wetness, and relative humidity at weather station 13 (central transect) on 08/08/2019. Dashed lines indicate thresholds for the leaf wetness (confident wet or dry). Colored circles indicate MODIS cloud mask status for respective overpasses.*

2. MODIS data and ground "truth"

The MODIS cloud mask product (MOD35, MYD35; Ackerman, 2017) is derived via spectral threshold tests at various wavelengths. Scene characteristics (day, night, ocean, land, desert) determine the processing path. Data is available since 2000 at a horizontal resolution of 1km (nadir). Weather stations were deployed beginning in 2017. Fog is attributed when the leaf sensor indicates wetness (threshold see Fig. 1) and relHum>80%.

Bit	description	day	night
16	High Cloud Flag (1.38µm)	yes	--
17	High Cloud Flag (3.9-12 µm)	--	yes
18	Cloud Flag (IR Temperature Difference)	yes	yes
19	Cloud Flag (3.9-11 µm)	yes	yes
20	Cloud Flag (visible reflectance)	yes	--
21	Cloud Flag (visible ratio)	yes	--

***Tab. 1**: Description of selected threshold tests which are applied to determine the MODIS cloud mask. Two rightmost columns indicate whether the test is applied for day or night-time overpasses. Only a selection is summarized here. Details see Ackerman, 2010.*

***Tab. 2**: For each MODIS cloud mask category, the number N of coincidental station measurements is shown. N partitions into "fog free" and "fog" according to station measurements. Only night time retrievals are shown.*

MODIS cld. mask	N	Fog free	fog	Fog [%]
High conf. cloud	2206	1619	587	26.6
Low conf. cloud	677	578	99	14.6
Low conf. clear	158	138	20	12.7
High conf. clear	6815	6216	599	8.8

Highest relative fog occurrences fall into the "high conf. cloud" category. However, about half of the fog events are labeled clear. In such cases, the long wave radiation budget (Fig. 2) indicates a greater loss of energy.

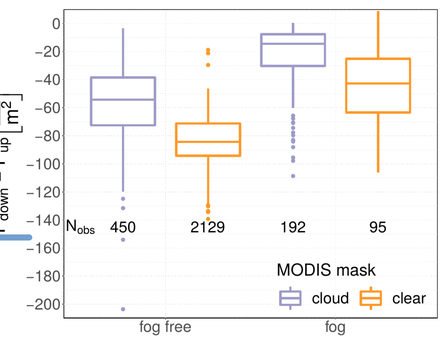
References:

Ackerman, S., P. Menzel, R. Frey, B.Baum, 2017: ***MODIS Atmosphere L2 Cloud Mask Product****. NASA MODIS Adaptive Processing System, Goddard Space Flight Center, [doi:10.5067/MODIS/MOD35_L2.061; doi:10.5067/MODIS/MYD35_L2.061]*

Ackerman, S., R. Frey, K. Strabala, Y. Liu, L. Gumley, B. Baum, P. Menzel, 2010: ***Discriminating clear-sky from cloud with MODIS Algorithm Theoretical Basis Document (MOD35)****, MODIS Cloud Mask Team, Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin.*

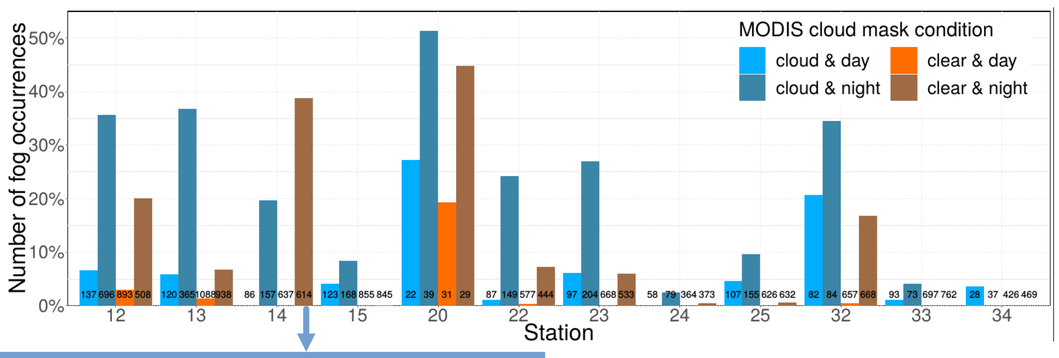
3. MODIS cloud mask assessment

***Fig. 2**: Longwave radiation budget grouped by discrimination of fog/fog free (ground-based) and cloud/clear (MODIS cloud mask, only high conf.). Longwave radiation is only available at the master stations (13, 23, 33). Statistics only include night time overpasses.*



MODIS cloud mask "clear" → higher energy loss → potentially thinner fog layer for "missed" fog events

***Fig. 3**: Number of fog occurrences at each station with concurrent MODIS obs. distinguished by day/night and cloud/clear (high conf.) Number of observations are indicated at the bottom of each bar.*



For station 14, almost 40% of the 614 observations at night with concurrent "ckear" sky indication by MODIS showed fog at the ground based sensor. This makes about 40% out of all fog events which were marked "clear" by MODIS.

Bits 17, 18, 19 show different configurations on average depending on whether fog was observed. → Potential for satellite based fog/cloud discrimination.

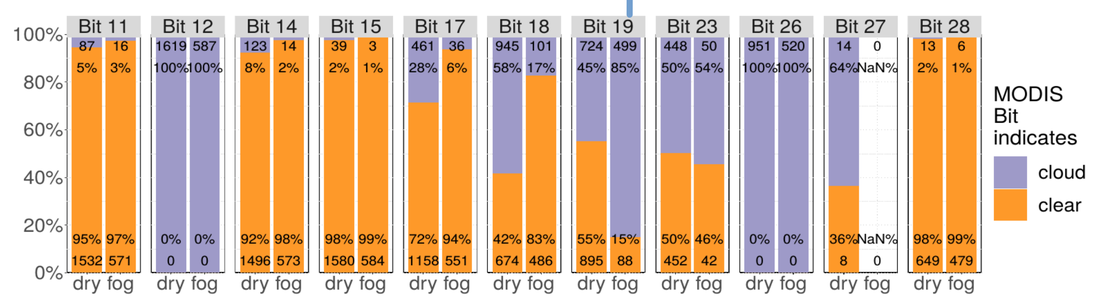


***Fig. 4**: Assessment of the individual MODIS cloud mask tests which are represented by the respective bits. Each bit reflects whether an individual test indicates cloudy or clear sky. Investigated are the bit configurations for all night time cases which resulted in "high conf. cloud" categorization. For each bit the total of 2206 coincidental observations partition into ground based "dry" or "fog" and the respective bit indicating "cloud" or "clear". Some tests are not always applied resulting in low numbers (e.g. Bit 27).*

5. Cloud cover climatology

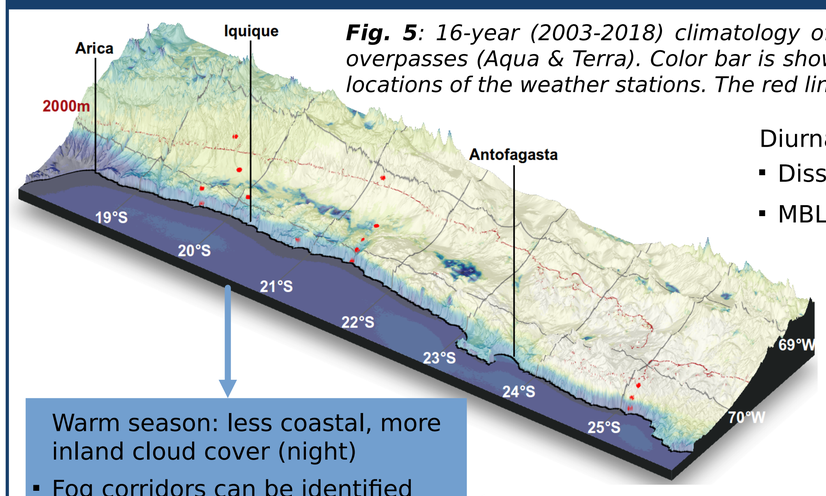


***Fig. 5**: 16-year (2003-2018) climatology of total cloud cover for night time overpasses (Aqua & Terra). Color bar is shown in Fig. 6. Red dots indicate the locations of the weather stations. The red line denotes the 2000m height line.*

Diurnal land surface heating:
- Dissipation of fog/low clouds
- MBL circulation drives stratus away

Nocturnal land surface cooling:
- possible radiation fog formation in the central depression
- MBL circulation drives stratus in

Warm season: less coastal, more inland cloud cover (night)
- Fog corridors can be identified
- Regions of high cloud cover in the central depression year-round

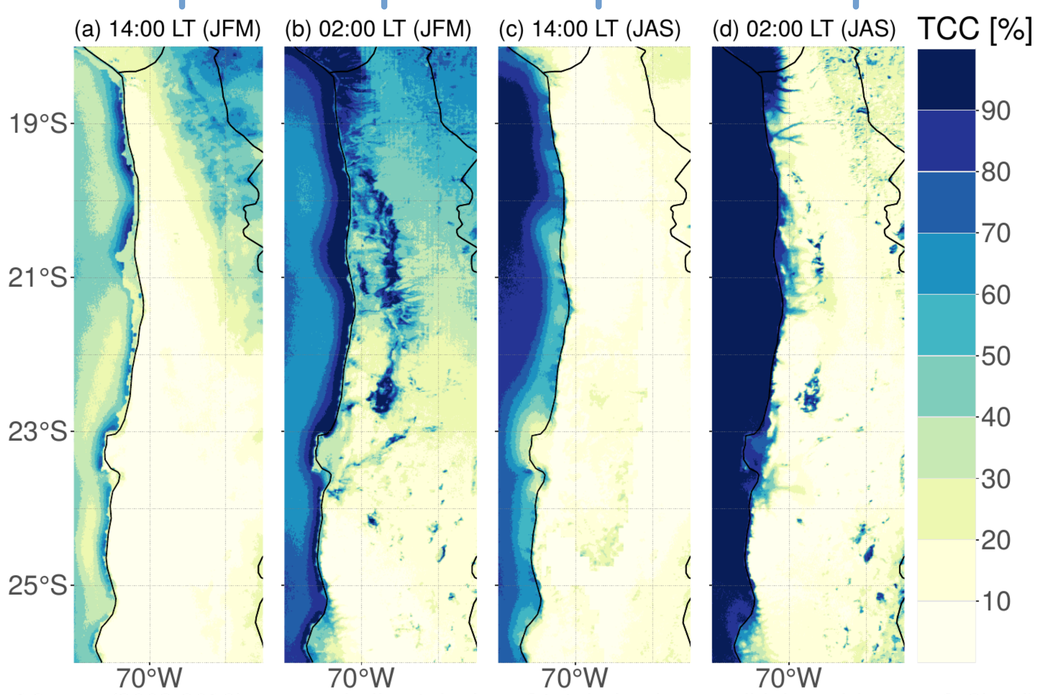


***Fig. 6**: 16-year (2003-2018) seasonal climatologies of total cloud cover (high and low conf. Cloud) for Aqua MODIS. Distinguished are day and night overpasses as well as summer (JFM) and winter (JAS) as indicated above figures.*

c.boehm@uni-koeln.de