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# Cloud Types and Properties Variability Over Poland (2003–2021)

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# Introduction: Clouds in the Global Climate

## Why Are Clouds Important?

### Regulating Earth's Radiation Budget

- Reflecting solar radiation (cooling effect)
- Absorbing infrared radiation (warming effect)
- Emitting radiation back into space (cooling effect)

### Contributing to the Water Cycle

- Transporting water vapor across the globe
- Condensing to form precipitation, which replenishes freshwater resources
- Releasing latent heat during condensation, driving atmospheric circulation

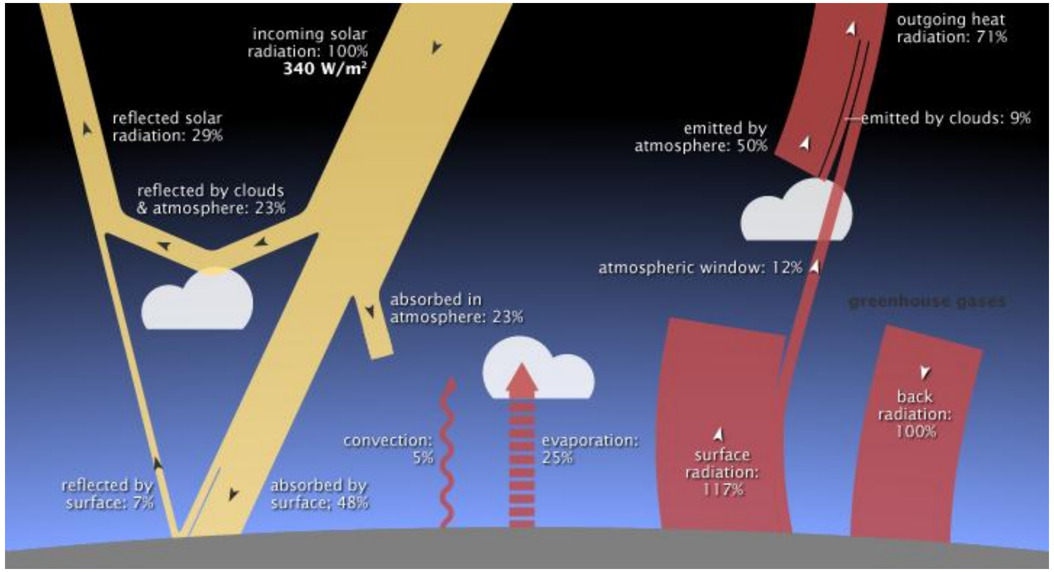



***Figure.*** *Radiative budget scheme.*

*Images Credits: NASA illustration by Robert Simmon, adapted from Trenberth et al. 2009, using CERES flux estimates provided by Norman Loeb.*

***Clouds are the main source of uncertainty in climate estimations***

# Introduction: Motivation

- To date, changes in cloud types over Poland have **only been studied with ground-based observations**.
- The most recent studies by Filipiak (2021) and Matuszko et al. (2022) reveal a **decreasing trend in *Stratus*, *Altostratus* and *Nimbostratus*** amounts **since the 1970s**. At the same time, the incidence of **convective and high clouds has increased**.
- Matuszko et al. (2022) suggests that the **increase in *Altocumulus* and high-level clouds is due to a decrease in low-level clouds** and, thus, a higher probability that human observers will detect mid- and high-level clouds.
- Kotarba (2018) noted that **ground-based observers** in Poland **are unable to determine** whether **mid- and high-level clouds** are present in up to **55%** and **64%** of cases, respectively.

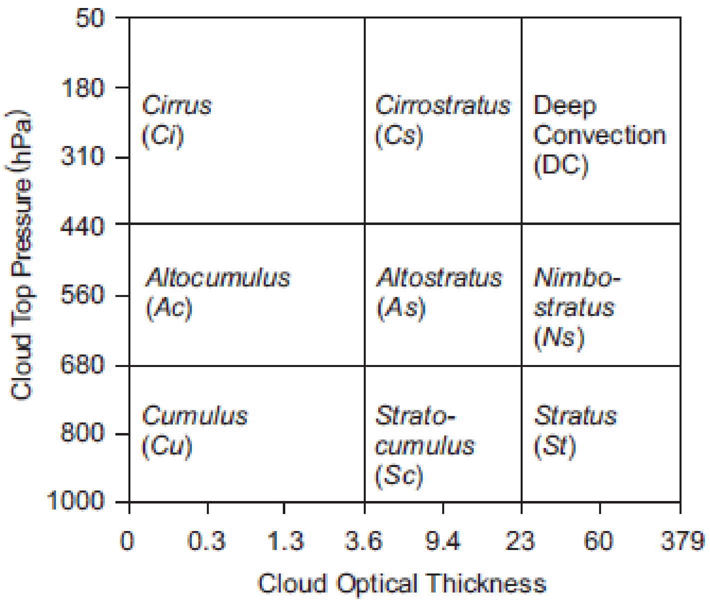

Filipiak, J. (2021) Change of cloudiness. In: Falarz, M. (Ed.). Cham: Springer International Publishing, pp. 217–274.

Kotarba, A.Z. (2018) Vertical profile of cloud amount over Poland: variability and uncertainty based on CloudSat–CALIPSO observations. International Journal of Climatology, 38(11), 4142–4154. Available from: https://doi.org/10.1002/joc.5558.

Matuszko, D., Bartoszek, K. & Soroka, J. (2022) Long-term variability of cloud cover in Poland (1971-2020). Atmospheric Research, 268, 106028. Available from: https://doi.org/10.1016/j.atmosres.2022.106028.

# Introduction: ISCCP Cloud Classification

## International Satellite Cloud Climatology Project (ISCCP) Cloud Classification




***Cloud Top Pressure***

*parameter representing the location of the top of the clouds*

***Cloud Optical Thickness***

*the degree to which the cloud prevents light from passing through it*

***Figure.*** *ISCCP cloud types classification.*

*Based on: Rossow W.B., Schiffer R.A., 1999, Advances in understanding clouds from ISCCP, Bulletin of the American Meteorological Society, Vol. 80, No. 11.*

**The differences between ISCCP and WMO approaches:**

- deep convective clouds – the class in the ISCCP classification contains SYNOP's *Cumulonimbus* clouds, but may include also some developed *Cumulus congestus* clouds;
- *Altostratus* and *Nimbostratus* clouds – these appear as separate classes in the ISCCP classification;
- *Cirrocumulus* clouds – this cloud type is not implemented in the ISCCP classification.

# Research Questions and Hypotesis

The **main aim** of this research is to examine the variability of **cloud type frequency, cloud type amount, and cloud properties** over Poland in the last two decades (2003–2021). This analysis is based on MODIS satellite data and SYNOP ground-based observations.

## Research questions

- How did **cloud types and properties vary** over Poland in the last two decades?
- Are **previously identified trends in high- and mid-level clouds** real, or are they a consequence of a decrease in lower-level clouds?
- How closely **does an ISCCP-based cloud typology agree with SYNOP**, WMO-defined cloud types?

## Hypotesis

MODIS data, classified with the ISCCP approach, confirms the changes in cloud type frequencies found in SYNOP observations.

# Materials and Methods: MODIS data

## Satellite observations of clouds

**Moderate Resolution Imaging Spectroradiometer (MODIS)**

offering the longest available cloud record from a stabilized polar orbit

- 2003–2021
- Terra and Aqua spacecrafts
- Level 2 data
- Collection 6.1
- Cloud Product: MOD06_L2 and MYD06_L2
- Spatial resolution: 1 km
- Daytime passes: 2 observations per day
- A total of 13,625 overpasses
- Missing data: 1.67%

**Analysed Cloud Properties:**

- cloud top pressure, CTP
- cloud optical thickness, COT
- cloud effective radius, CER
- cloud water path, CWP

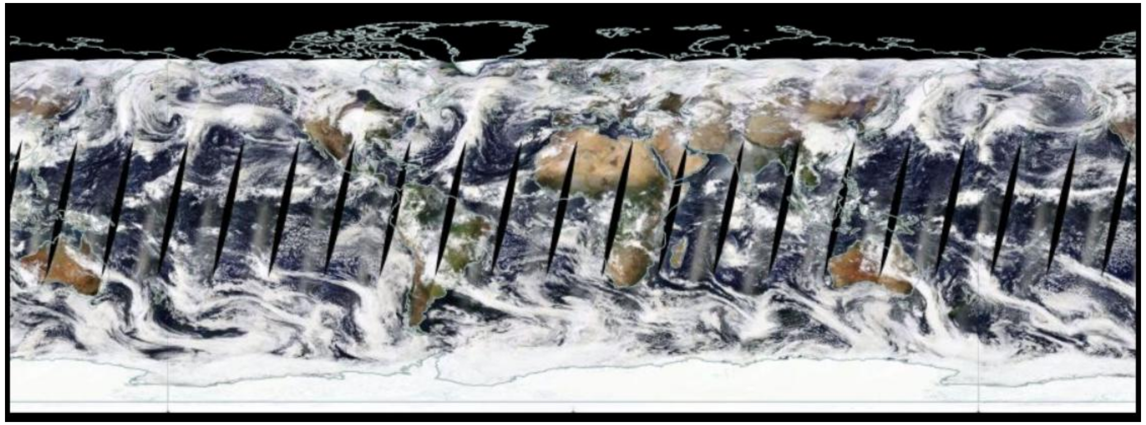


***Figure.*** *MODIS example data.*

*Image Credits: NASA, https://worldview.earthdata.nasa.gov.*

# Materials and Methods: SYNOP data

## Groud based observations of clouds

Cloud types (*genera*) from **SYNOP** reports (IMGW-PIB)

- Data from 27 stations in Poland
- No missing observations
- Group 8 of SYNOP reports ($8N_hC_LC_MC_H$)

| Genus of cloud | Code figure |
|---|---|
| *Cumulus (Cu)* | $C_L = 1, 2, 8$ |
| *Cumulonimbus (Cb)* | $C_L = 3, 9$ |
| *Stratus (St)* | $C_L = 6, 7$ |
| *Stratocumulus (Sc)* | $C_L = 4, 5, 8$ |
| *Altostratus + Nimbostratus (As + Ns)* | $C_M = 1, 2, 7$ |
| *Altocumulus (Ac)* | $C_M = 3, 4, 5, 6, 7, 8, 9$ |
| *Cirrus (Ci)* | $C_H = 1, 2, 3, 4, 5$ |
| *Cirrocumulus (Cc)* | $C_H = 9$ |
| *Cirrostratus (Cs)* | $C_H = 5, 6, 7, 8$ |

***Table.*** *The method used to decode Group $8N_hC_LC_MC_H$ of the SYNOP reports.*

*Based on Żmudzka (2007) and WMO (2019).*

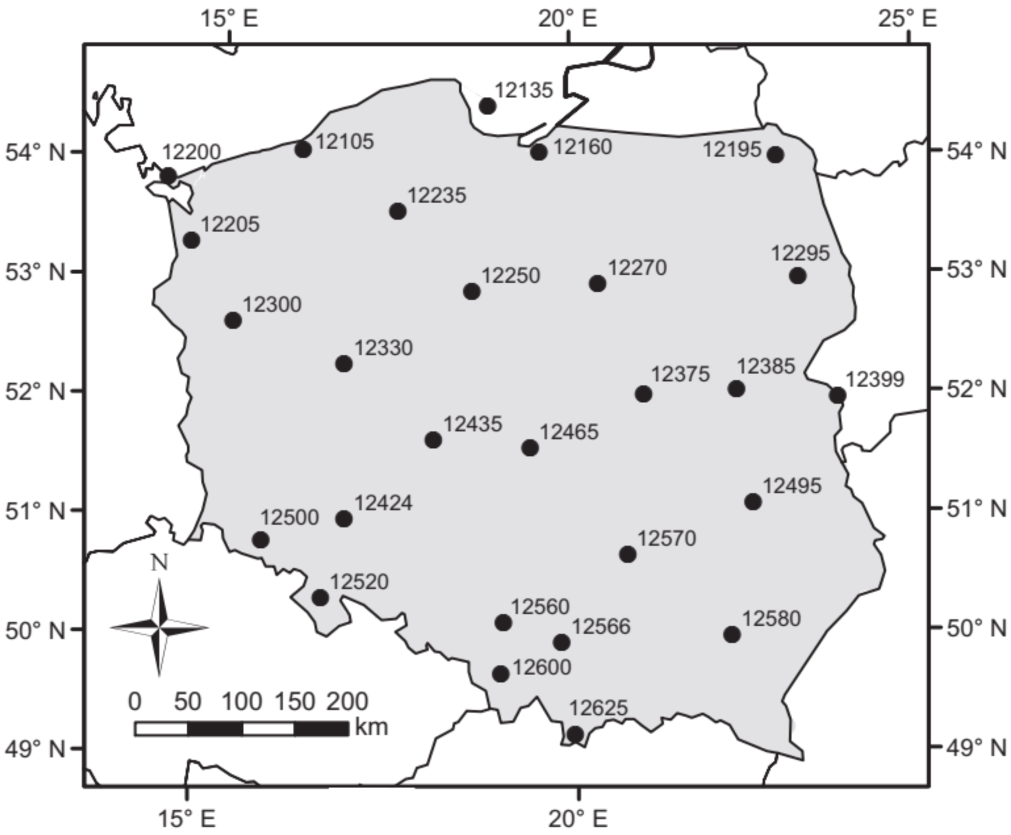



***Figure.*** *Location of SYNOP stations used in the study.*

# Materials and Methods: Matching MODIS and SYNOP data

**Temporal resolution**

- MODIS overpasses Poland between 8:58 and 12:35 UTC (from 8:58 to 10:48, and from 10:48 to 12:35 for Terra and Aqua, respectively) **=>** SYNOP observations from 9:00 and 12:00 UTC
- Any SYNOP data for which no MODIS data were available were deleted

**Spatial resolution**

- During a single pass, MODIS covers the whole of Poland (311,936 pixels), while SYNOP observations are limited to the vicinity of the 27 ground stations **=>** only MODIS data that were located no farther than 30 km from a SYNOP station (giving a total of 2821 pixels for each station) were considered
- The resulting subset of MODIS data (75,865 pixels) covered 24.3% of the territory of Poland

**Cloud type fraction and occurrence**

- **Cloud type fraction/ amount** – the fraction of the sky covered by clouds belonging to a specific type (0–100%)
- **Cloud type occurrence/ frequency of occurence** – reports the presence of a specific cloud type (binary)

MODIS: we assumed that a given cloud type had occurred if pixels classified as belonging to that type covered at least 1% of the 30 km area around a station

**Spatially-averaged mean monthly cloud type fraction and occurence**

# Results: MODIS and SYNOP Cloud Type Frequency

***Figure.*** *Frequency of occurence (%) of cloud types based on (MODIS) (a,c) and SYNOP (b) observations over Poland (2003-2021).*

- Both MODIS and SYNOP: *Cu* and *Sc* were the most frequent cloud types over Poland.
- MODIS data indicated that low-level clouds were approximately two times more frequent than SYNOP data, most of other cloud types – even more. Exception: *Ac.*
- MODIS: COT–CTP histogram made up of 49 sub-classes

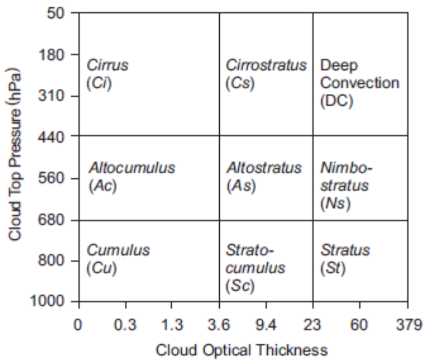
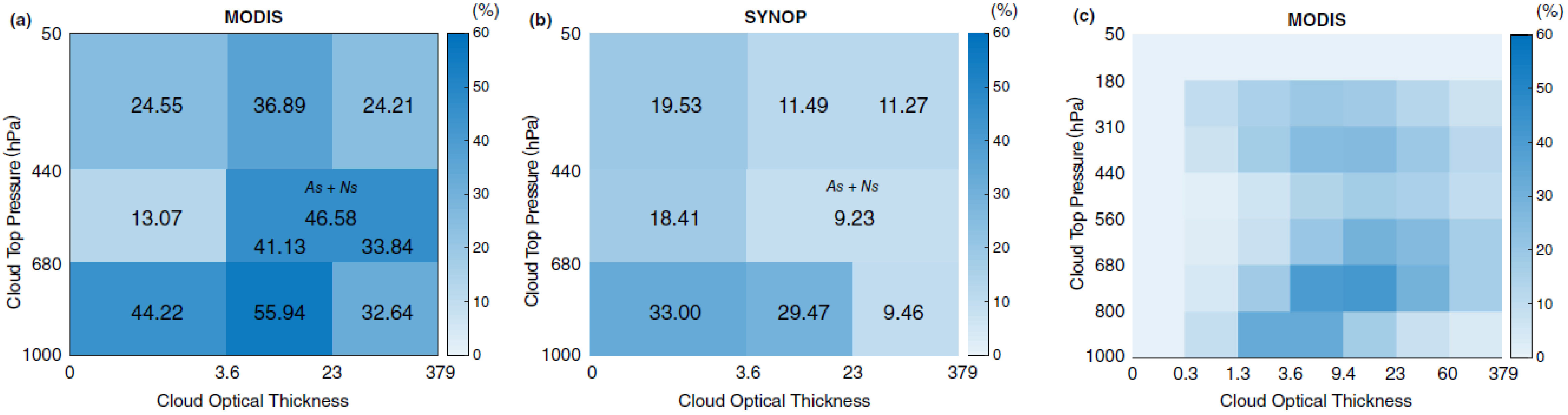
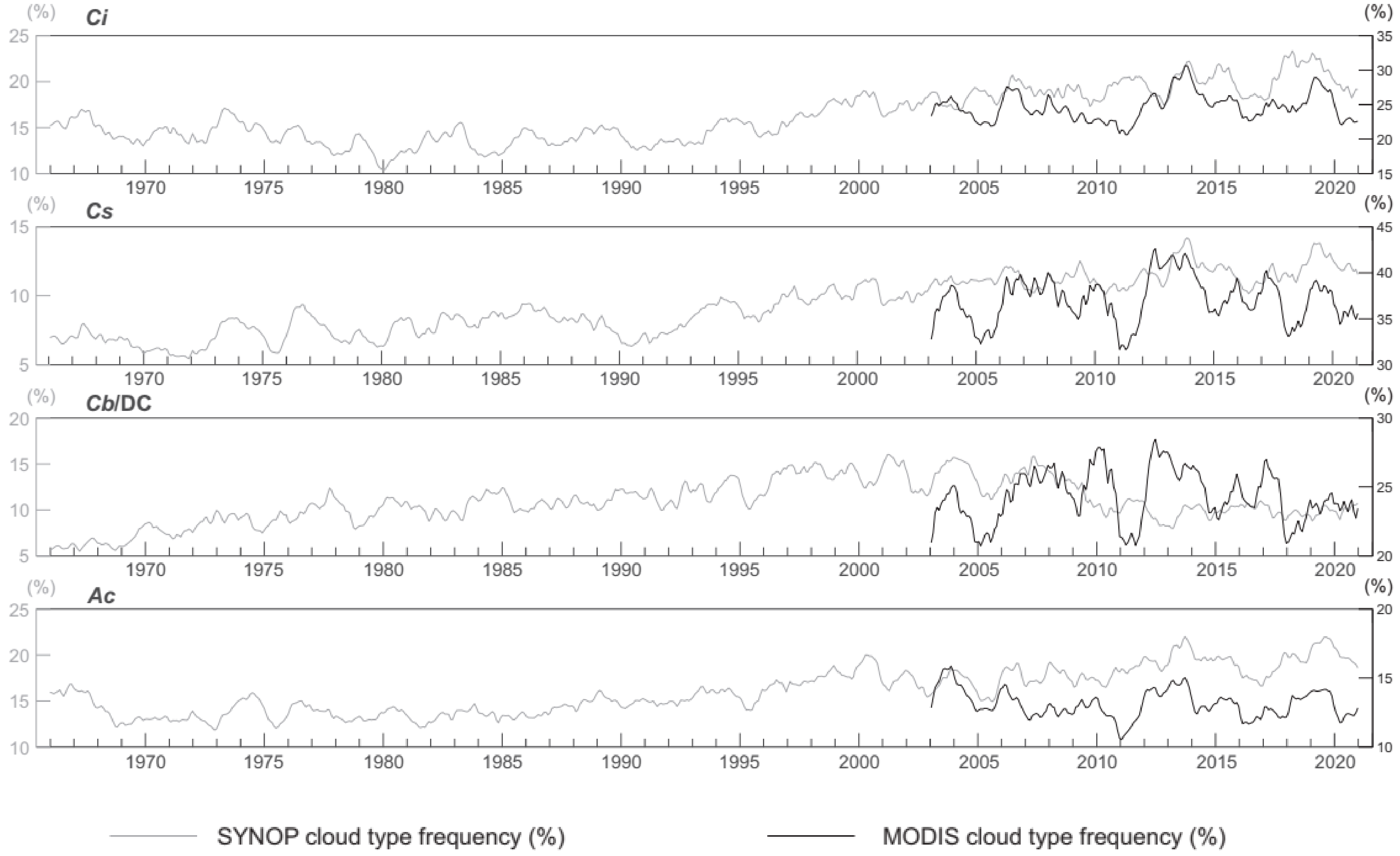



***Figure.*** *ISCCP classification (…)*



# Results: MODIS and SYNOP Cloud Type Frequency




- Temporal variability in mean monthly *St*, *Cu*, *As* + *Ns* cloud type frequency revealed only some similarities between MODIS and SYNOP estimations.

***Figure.** Temporal distribution of mean monthly cloud type frequency (%) over Poland based on MODIS (black line) and SYNOP (grey line) observations (2003-2021) (12-month average). For reference, SYNOP data are shown dating from 1966.*

# Results: MODIS and SYNOP Cloud Type Frequency

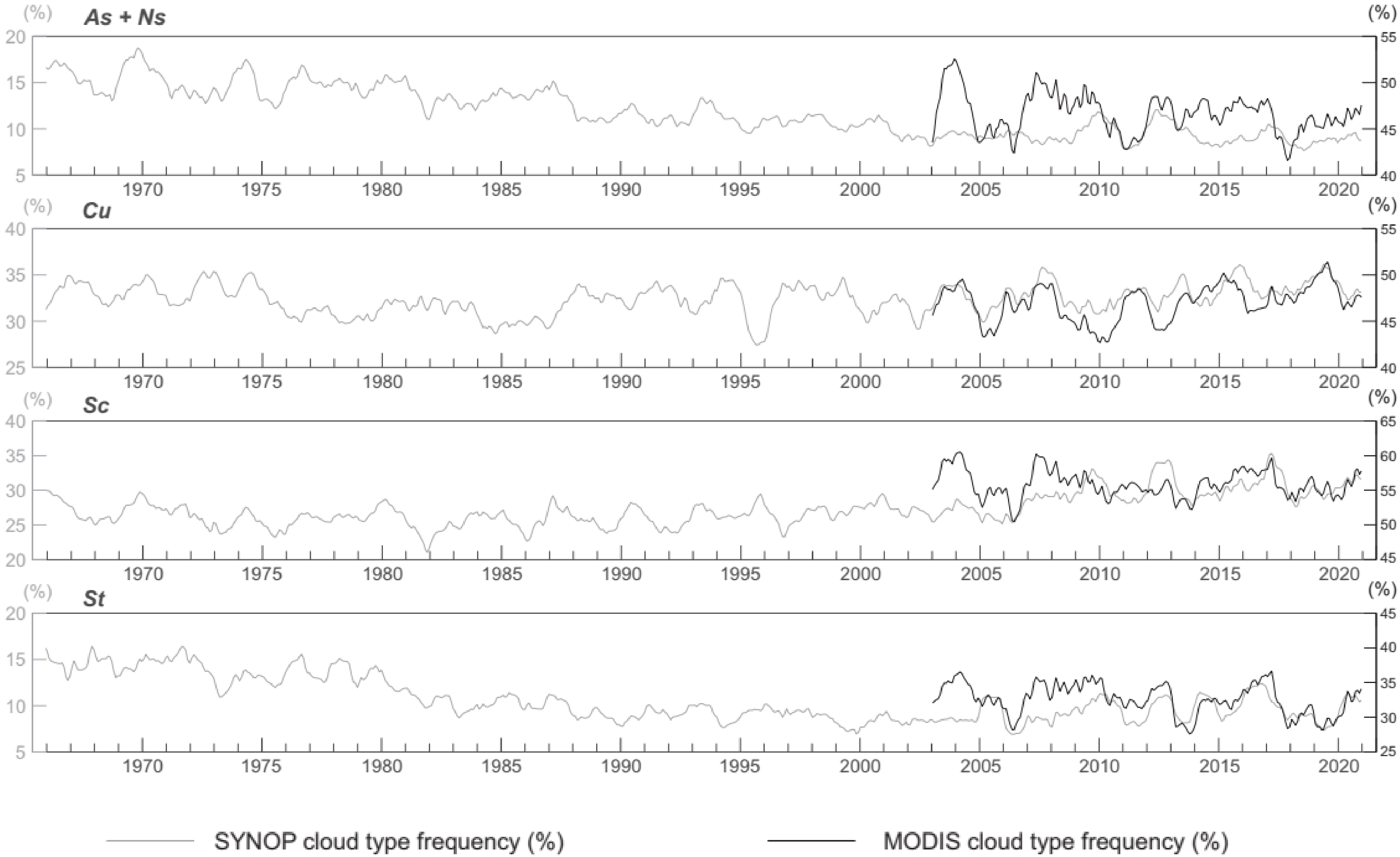



***Figure (continued).*** *Temporal distribution of mean monthly cloud type frequency (%) over Poland based on MODIS (black line) and SYNOP (grey line) observations (2003-2021) (12-month average). For reference, SYNOP data are shown dating from 1966.*

# Results: MODIS and SYNOP Cloud Type Frequency

- When expressed quantitatively with the Spearman rank correlation coefficient, the agreement between MODIS and SYNOP frequency observations was weak to moderate for most cloud types.
- The highest correlation was found for *St* (0.73).

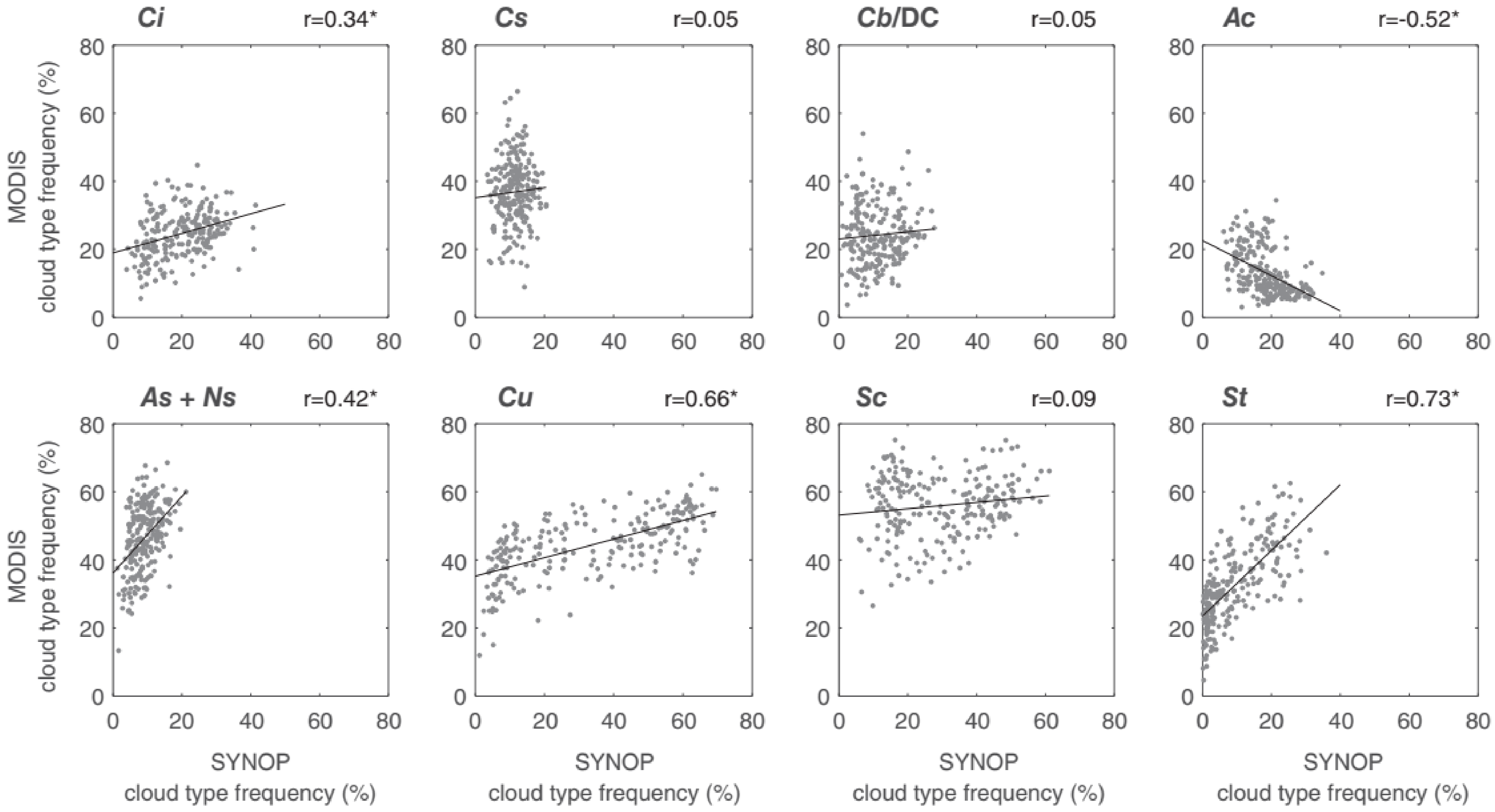



***Figure.*** *Spearman rank correlation coefficients for mean monthly SYNOP and MODIS cloud type frequencies over Poland (2003–2021). Asterisks indicate values that are statistically significant at α = 0.05.*

# Results: MODIS and SYNOP Cloud Type Frequency

***Figure.*** *Trends (% per decade) in the frequency of occurence of cloud types based on MODIS (a,c) and SYNOP (b) observations over Poland (2003-2021). Dots indicate values that are statistically significant at α = 0.05.*

- Trends in MODIS and SYNOP cloud type frequency differed not only with respect to individual values, but also their direction.
- MODIS 9-class: all trends remained statistically insignificant.
- MODIS 49-class: positive trend for high cloud frequency.

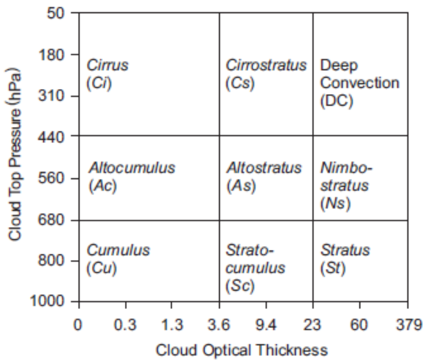
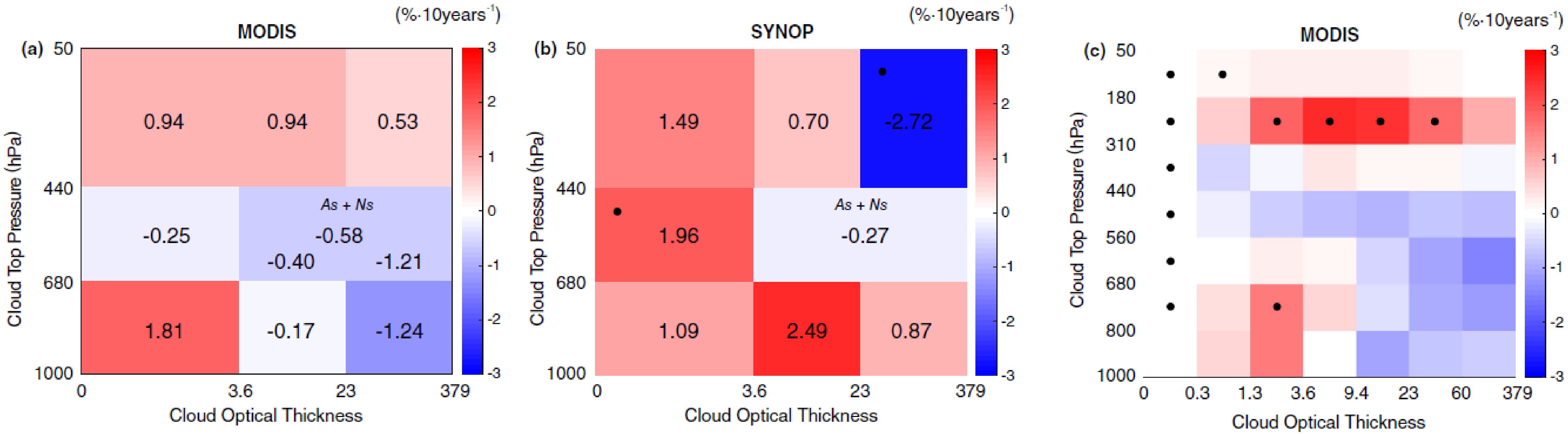



***Figure.*** *ISCCP classification (…)*



# Results: MODIS Cloud Type Amount

**Do trends in cloud type frequency over Poland follow trends in fraction?**

- *Sc* covered the largest part of the territory of Poland, followed by *Cs.*
- Even though the frequency of MODIS *Cu* clouds did not increase significantly during the period 2003–2021, there has been a positive, statistically significant increase (0.3% per decade) in *Cu* amount.
- High cloud fraction increased significantly.

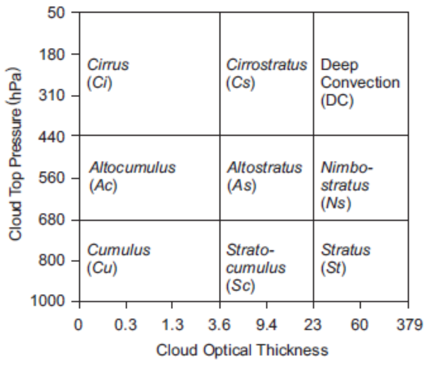
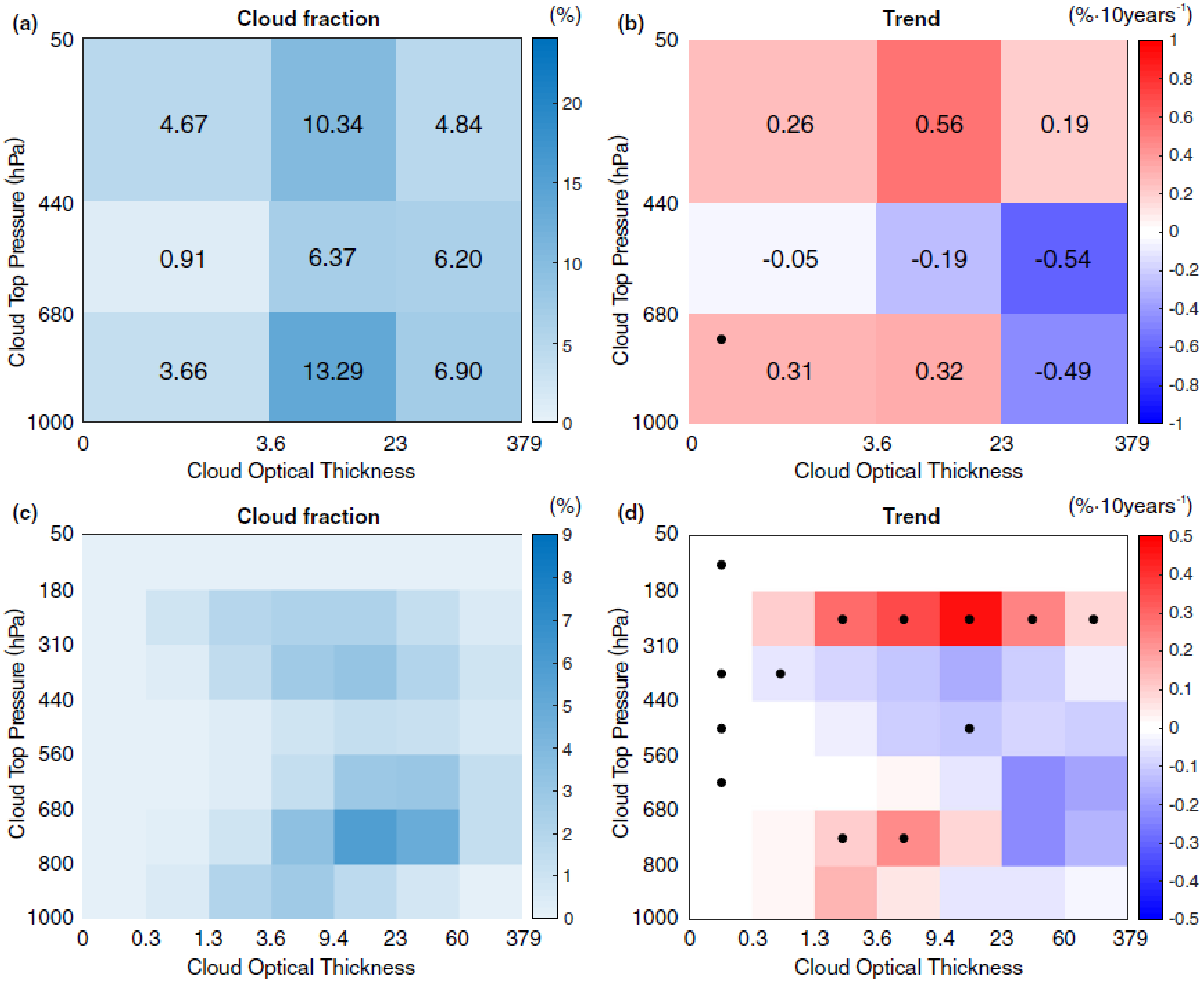



**Figure.** *ISCCP classification (…)*

***Figure [right].*** *Mean values (%) (a,b) and trends (% per decade) (c,d) in cloud type amount over Poland, based on MODIS observations (2003-2021). Dots indicate values that are statistically significant at α = 0.05.*



# Results: MODIS Cloud Type Amount

- The 9.4 > COT > 23, 180 < CTP < 310 hPa class (*Cs*): multiannual distribution of its mean monthly cloud amount was more similar to DC classes distribution rather than other *Cs* classes.
- Perhaps 9.4 > COT > 23, 180 < CTP < 310 hPa clouds should be classified as DC (and represent, for example, *Cb* anvil) rather than *Cs*?

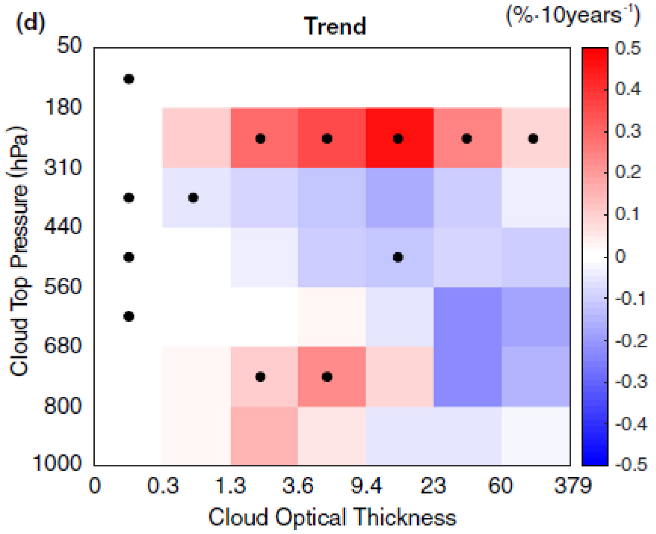
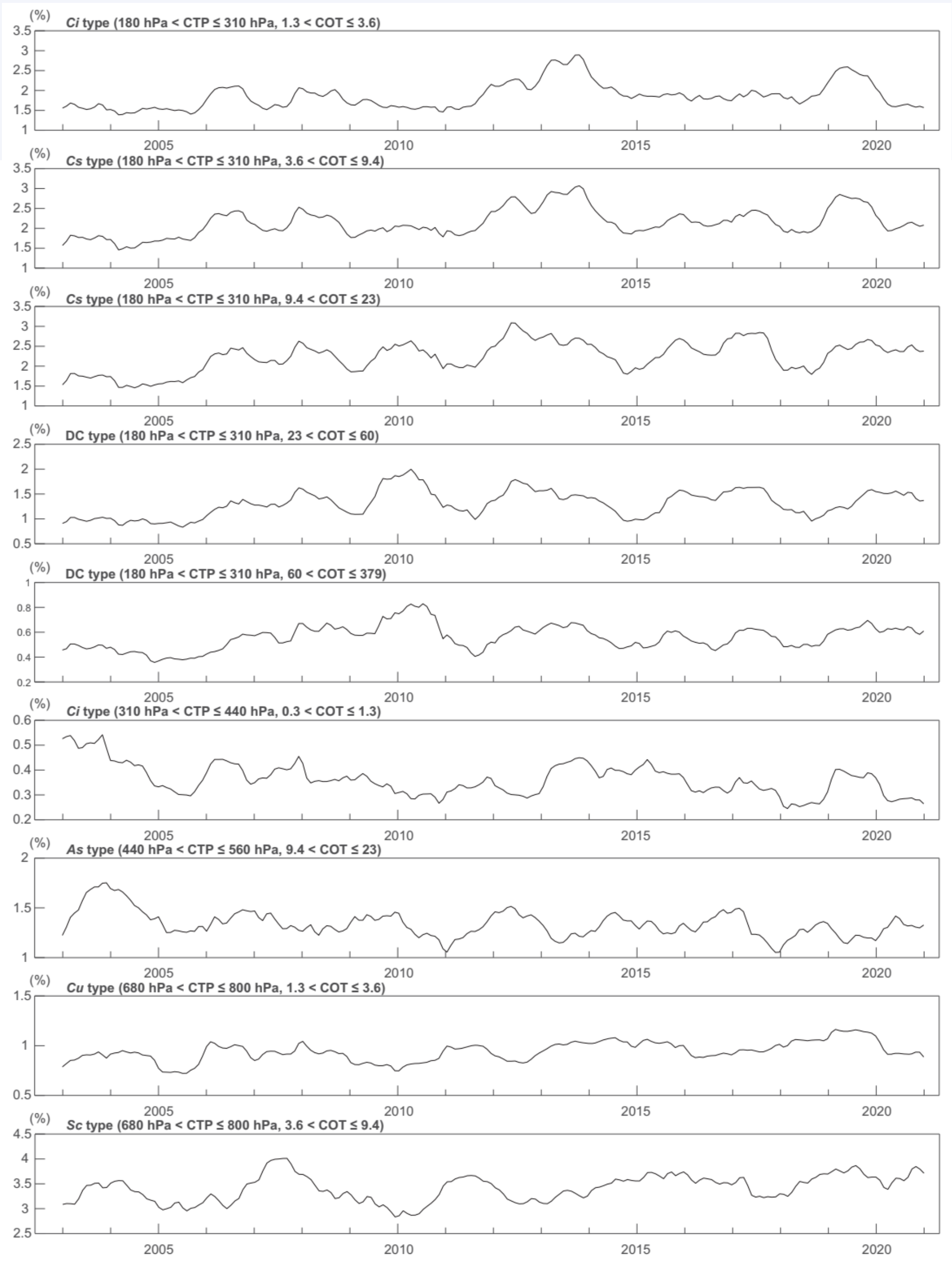



***Figure.*** *Trend in cloud type amount (…)*

***Figure [right].*** *Temporal distribution of mean monthly cloud type amount (%) over Poland, based on MODIS observations (2003–2021) (12-month average) for cloud types of COT greater than 0.3 where a statistically significant (α = 0.05) trend was identified (cases shown by dots in previous Figure, with COT > 0.3).*



# Results: MODIS Cloud Properties

- Values for both Terra and Aqua were similar.
- Values recorded during afternoon overpasses for CTP, COT and CWP were slightly lower than morning values: 632.3 versus 635.2 hPa (CTP), 22.7 versus 23.4 (COT), and 215.8 versus 219.6 g·m$^{-2}$ (CWP).

| Spacecraft | Terra | | | | Aqua | | | |
|---|---|---|---|---|---|---|---|---|
| Cloud property | CTP (hPa) | COT | CER (µm) | CWP (g·m$^{-2}$) | CTP (hPa) | COT | CER (µm) | CWP (g·m$^{-2}$) |
| Mean | 635.2 | 23.4 | 18.1 | 219.6 | 632.3 | 22.7 | 18.1 | 215.8 |
| CTP (hPa) sub-categories | | | | | | | | |
| ≥800 | 896.5 | 12.9 | 11.5 | 80.5 | 899.1 | 11.6 | 12.0 | 74.6 |
| [680, 800) | 730.7 | 25.7 | 11.6 | 176.2 | 729.8 | 24.8 | 11.7 | 168.4 |
| [560, 680) | 625.8 | 32.0 | 14.1 | 251.3 | 627.3 | 33.0 | 14.1 | 256.4 |
| [440, 560) | 499.2 | 32.0 | 21.2 | 327.9 | 505.1 | 32.7 | 21.0 | 337.1 |
| [310, 440) | 363.6 | 22.5 | 27.2 | 296.7 | 356.7 | 22.3 | 26.5 | 299.5 |
| <310 | 263.7 | 18.1 | 27.7 | 249.4 | 261.8 | 17.9 | 26.8 | 250.9 |
| COT sub-categories | | | | | | | | |
| <1.3 | 526.7 | 0.9 | 30.9 | 17.9 | 557.9 | 0.9 | 28.1 | 16.2 |
| [1.3, 3.6) | 585.3 | 2.4 | 24.6 | 36.4 | 568.5 | 2.4 | 24.0 | 35.8 |
| [3.6, 9.4) | 598.5 | 6.3 | 19.3 | 74.9 | 583.0 | 6.3 | 19.5 | 75.3 |
| [9.4, 23) | 571.4 | 15.3 | 17.0 | 161.5 | 571.4 | 15.2 | 17.0 | 160.6 |
| [23, 60) | 586.7 | 35.6 | 14.8 | 329.0 | 579.3 | 35.6 | 14.9 | 329.8 |
| ≥60 | 553.6 | 105.6 | 14.0 | 927.3 | 547.2 | 107.1 | 14.1 | 950.8 |

***Table.*** *Area-averaged mean values of cloud properties over Poland from MODIS Terra and Aqua spanning the period 2003-2021.*

# Results: MODIS Cloud Properties

- Clear seasonal variability
- CTP reached its highest value in spring, COT was highest (25–35) from November to February, CER values were highest in August (19.5–20.0 μm), and lowest in winter, The annual distribution for CWP was similar to COT.

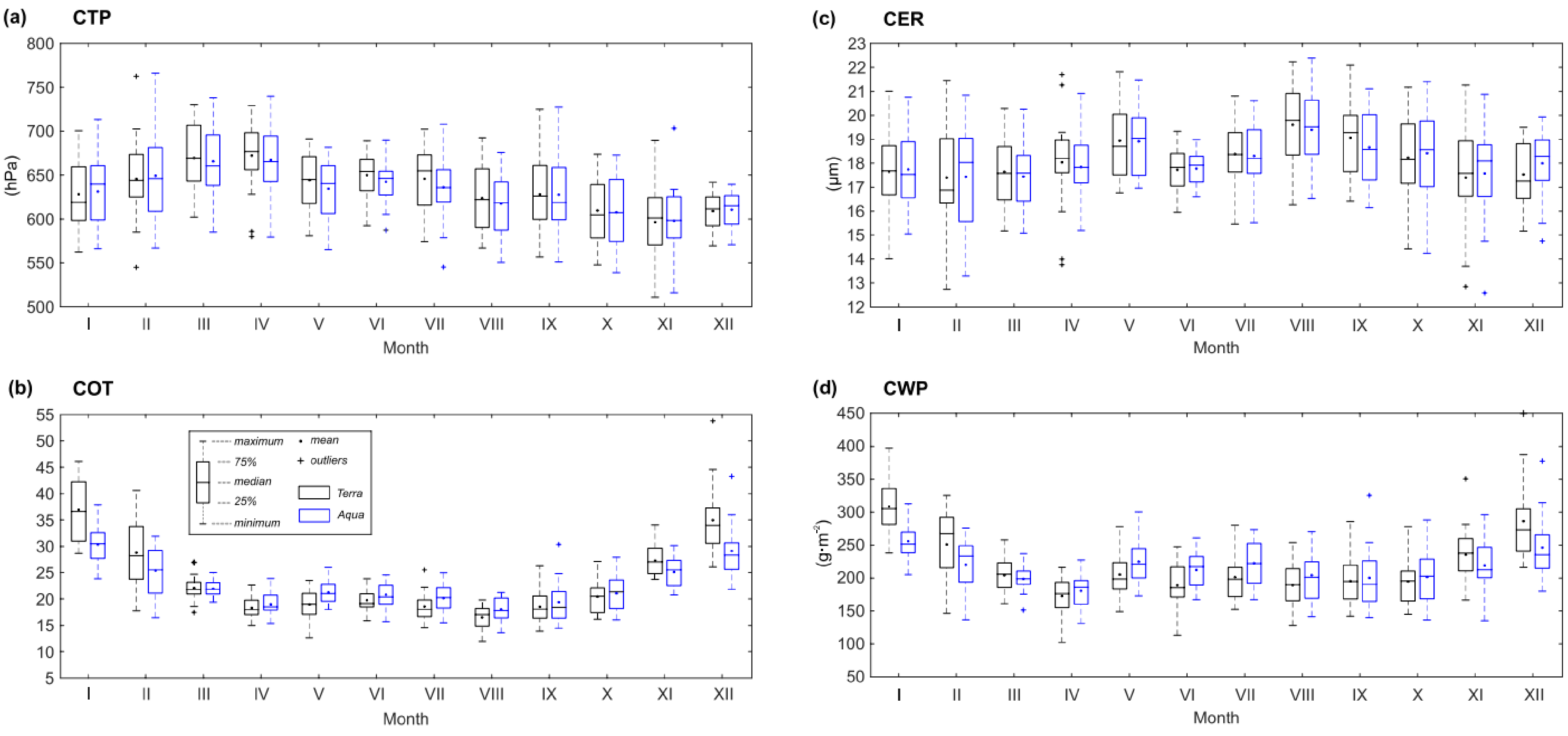
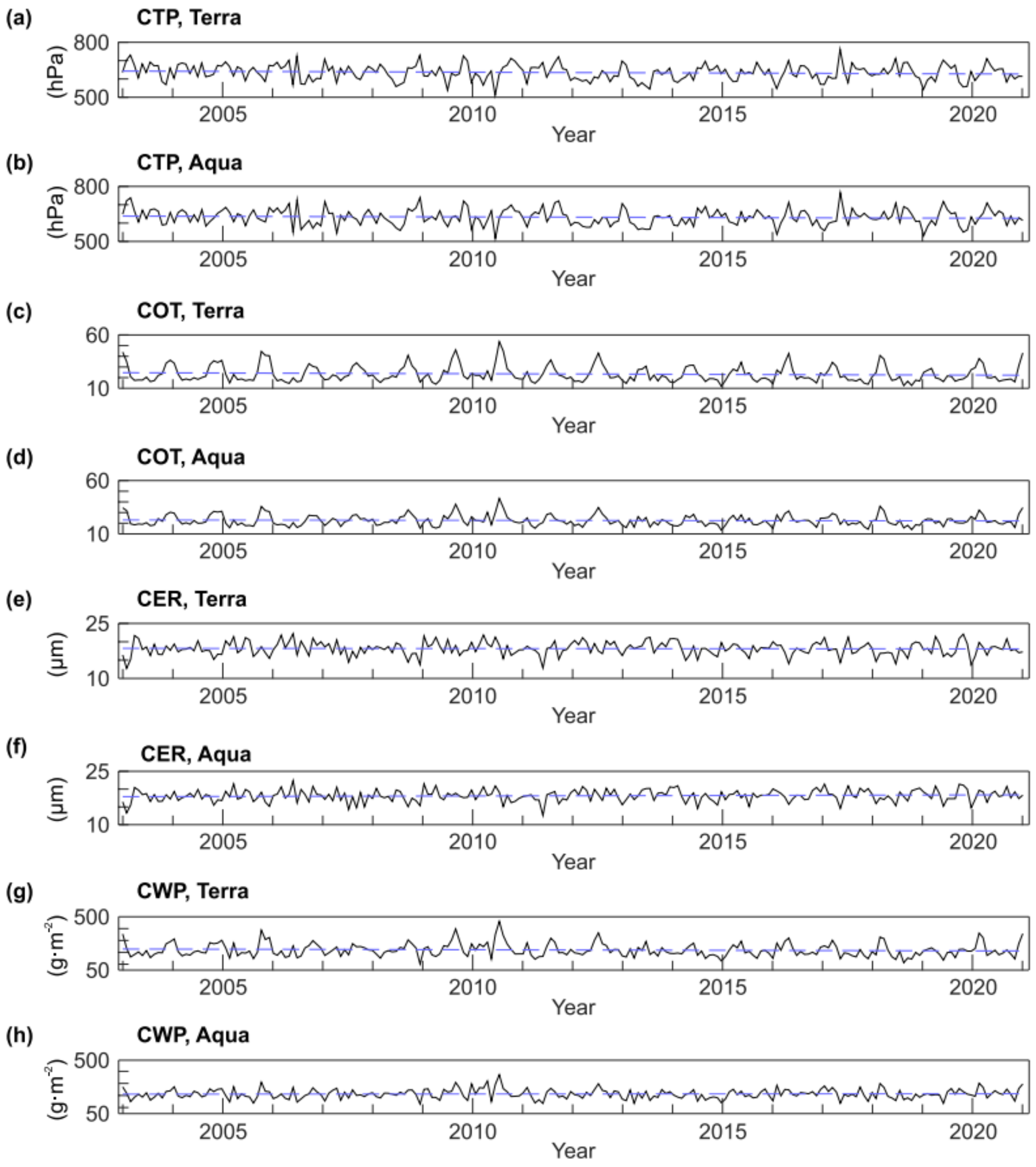



***Figure.*** *Monthly variability in cloud properties over Poland (2003–2021).*

# Results: MODIS Cloud Properties




- In general, temporal variability in cloud parameters did not follow a linear trend; instead, seasonal and other small-scale oscillations were observed.
- Nevertheless, for the period 2003–2021, CTP decreased significantly (by 9.7 hPa per decade) in morning passes.
- The multi-year distribution of COT shows clear, very regular seasonal variability, with higher peaks for Terra compared to Aqua.

***Figure.*** *Multi-annual distribution of mean monthly values of cloud properties over Poland (2003–2021) (continuous line), and the linear trend (dashed line).*

# Results: MODIS Cloud Properties

- A negative but statistically insignificant trend in CTP Aqua was also observed (−7.33 hPa per decade). No change was observed for all other analysed properties for area-averaged annual means.

| Spacecraft | Terra | | | | Aqua | | | |
|---|---|---|---|---|---|---|---|---|
| Cloud property | CTP (hPa) | COT | CER (μm) | CWP ($g \cdot m^{-2}$) | CTP (hPa) | COT | CER (μm) | CWP ($g \cdot m^{-2}$) |
| Mean | −9.66* | −1.43 | −0.09 | −10.35 | −7.33 | −0.64 | 0.32 | 2.25 |
| CTP (hPa) sub−categories | | | | | | | | |
| ≥800 | −2.83 | −0.92 | −0.10 | −3.82 | −2.88 | −0.33 | 0.17 | 0.52 |
| [680, 800) | 1.17 | −1.77* | 0.10 | −7.54 | 0.84 | −1.15 | 0.45* | −0.14 |
| [560, 680) | 0.59 | −2.25* | −0.41 | −19.01* | −0.36 | −1.68* | 0.13 | −7.83 |
| [440, 560) | 0.22 | −1.08 | −1.44* | −26.16* | 2.94* | 0.19 | −0.57 | −0.52 |
| [310, 440) | −2.08* | −0.28 | −0.85* | −12.89 | −2.39* | −0.13 | 0.02 | 2.06 |
| <310 | −2.57* | 0.29 | −0.06 | 9.43 | −2.31 | 0.68 | 0.52* | 21.20* |
| COT sub-categories | | | | | | | | |
| <1.3 | −0.07 | 0.01 | −0.93* | −0.41 | −1.90 | 0.01 | −0.22 | −0.06 |
| [1.3, 3.6) | −3.22 | −0.01 | −1.17* | −1.86* | −2.80 | 0.00 | −0.48 | 0.72 |
| [3.6, 9.4) | −6.03 | −0.02 | −0.70 | −2.67 | −1.99 | −0.02 | −0.21 | −0.94 |
| [9.4, 23) | −10.98 | −0.04 | −0.13 | −1.11 | −6.53 | −0.03 | 0.30 | 3.12 |
| [23, 60) | −11.76 | −0.19* | 0.19 | 2.93 | −7.87 | −0.11 | 0.63* | 13.06* |
| ≥60 | −17.38* | −0.90 | 0.18 | 2.99 | −13.8* | 0.64 | 0.60* | 46.13* |

***Table.*** *Ten-year trends in cloud properties over Poland based on MODIS Terra and Aqua data spanning the period 2003–2021. Asterisks indicate statistical significance at $\alpha = 0.05$.*

# Results: MODIS Cloud Properties

- Inter-annual cycles: **CTP primarily decreased in early spring and autumn**, whereas in May and July it increased.
- A significant and sizeable per decade decrease in COT was found in February.
- Minor changes were also found for per decade CER – a decrease in May and an increase in October.

***Table.*** *Ten-year monthly trends in cloud properties over Poland based on MODIS Terra and Aqua data spanning the period 2003–2021. Asterisks indicate statistical significance at α = 0.05.*

| | Terra | | | | Aqua | | | |
|---|---|---|---|---|---|---|---|---|
| Month | CTP (hPa) | COT | CER (μm) | CWP ($g{\cdot}m^{-2}$) | CTP (hPa) | COT | CER (μm) | CWP ($g{\cdot}m^{-2}$) |
| I | −1.79 | −2.46 | 0.24 | −7.61 | 0.89 | −1.54 | 0.44 | 0.00 |
| II | −10.08 | −7.15* | 1.00 | −43.67 | −12.43 | −5.72* | 1.29 | −29.98 |
| III | −20.20 | −1.82 | −0.18 | −16.36 | −17.20 | 0.30 | −0.04 | 7.08 |
| IV | −15.15 | 0.55 | −0.87 | −0.08 | −7.66 | 0.47 | −0.23 | 5.31 |
| V | 17.81 | 0.38 | −1.91* | −15.76 | 19.21 | 1.08 | −1.18 | −0.24 |
| VI | −0.92 | −0.52 | −0.46 | −4.01 | 7.16 | 0.35 | −0.20 | 12.77 |
| VII | 8.28 | −1.20 | −0.92 | −17.70 | 11.68 | −0.36 | −0.25 | −1.85 |
| VIII | −2.90 | −1.34 | 0.37 | −7.33 | 3.41 | −0.71 | 0.72 | 4.79 |
| IX | −45.96* | −0.64 | 0.96 | −2.44 | −41.76* | −0.12 | 1.29 | 9.53 |
| X | −34.24 | −0.21 | 1.33 | 11.97 | −29.62 | −0.11 | 1.63* | 16.96 |
| XI | 6.37 | −0.10 | −0.94 | −9.56 | 2.26 | 0.54 | −0.48 | 0.99 |
| XII | 1.51 | −1.91 | 0.14 | −6.86 | −5.36 | −1.39 | 0.67 | 2.51 |

# Results: MODIS Cloud Properties

- The spatial distribution of multi-annual mean values of cloud properties over Poland mirrors the country's primary topographical features.
- CTP clearly reflects both the river and lake network, as well as large forests.
- For most areas, there is a visible difference between Terra and Aqua.

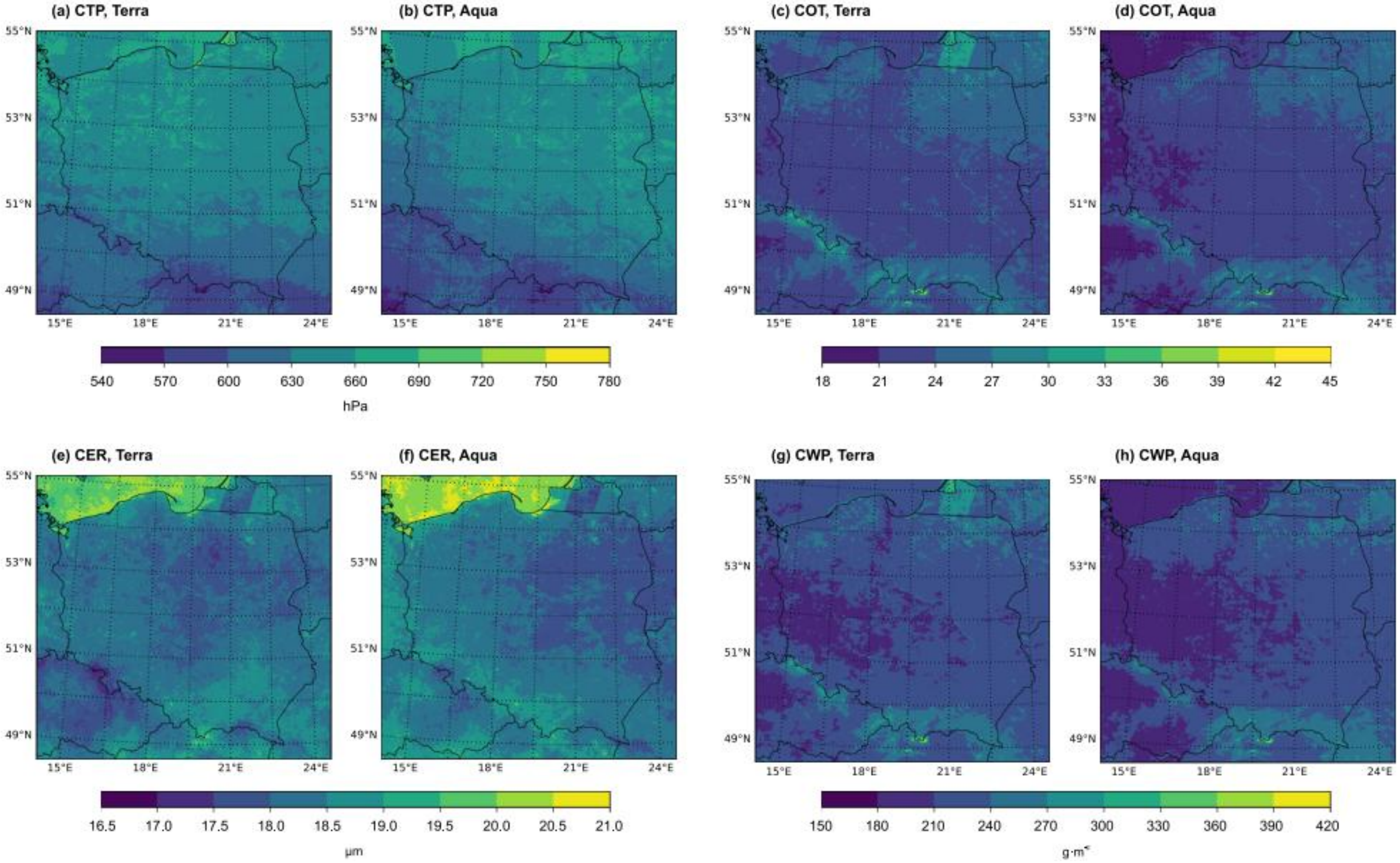



***Figure.*** *Spatial distribution of multi-annual mean CTP (hPa) (a, b), COT (c, d), CER (μm) (e, f) and CWP (g·m−2) (g, h) over Poland (2003–2021).*

# Results: MODIS Cloud Properties

- A linear trend calculated for each 1 km pixel
- A negative CTP trend was noted in northern Poland (for Terra) and in northwestern Poland (for Aqua)
- Decreases in COT and CWP were observed during morning overpasses
- CER: a negative trend occurred in central Poland for Terra, while a positive trend was observed in northwestern Poland for Aqua

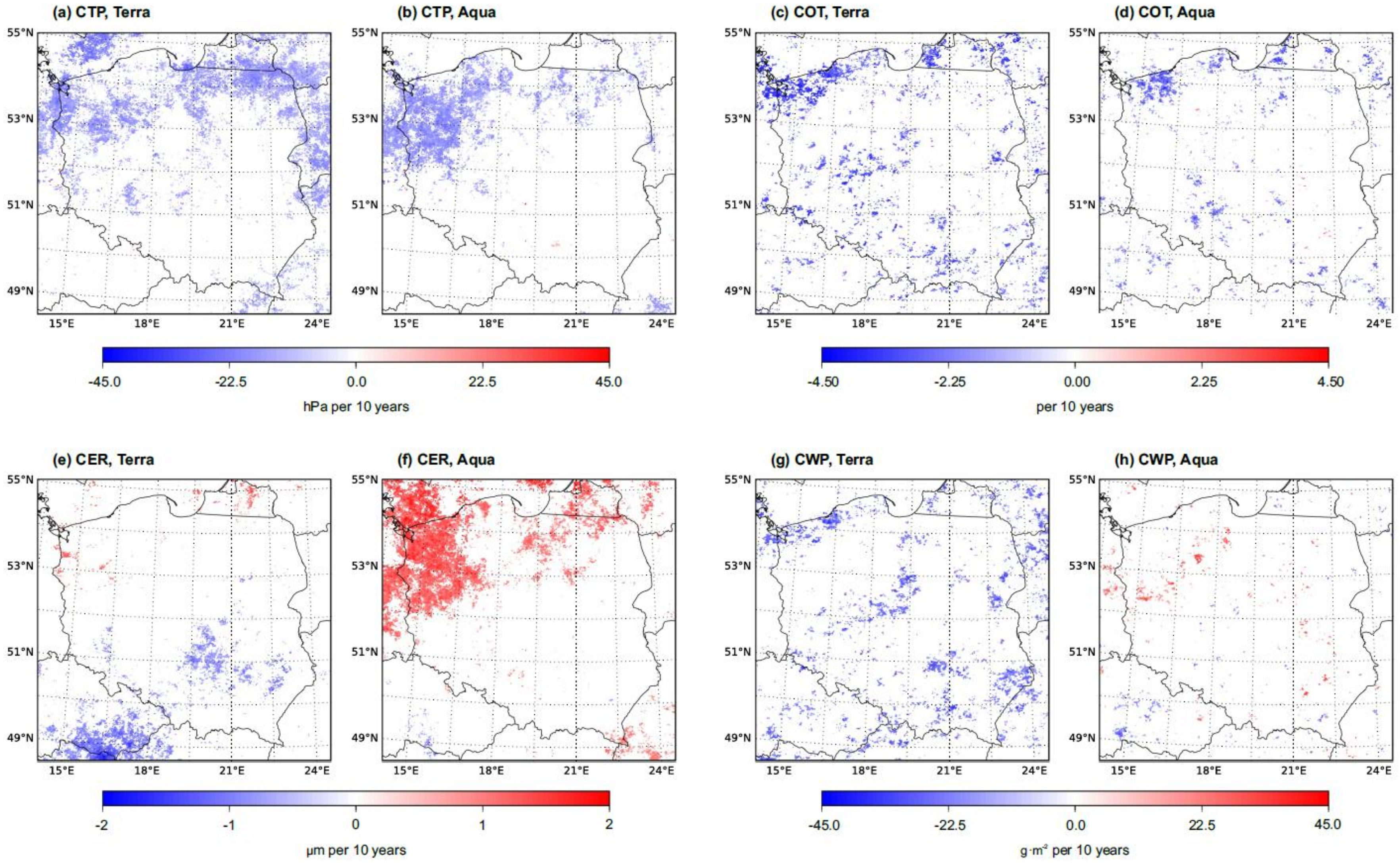



***Figure.*** *Spatial distribution of ten-year trends in CTP (hPa) (a–b), COT (c–d), CER (μm) (e–f) and CWP (g·m-2) (g–h) over Poland (2003–2021). Statistically significant values (α = 0.05) are shown in red (positive) or blue (negative).*

# Results: MODIS Cloud Properties

**Trends in Cloud at Different Altitudes and of a Different Optical Thickness**

- CTP sub-categories: positive or negative trend affected up to 40% of the area of Poland.
- A very evident decrease in CTP for high-level clouds (Terra and Aqua), covering 23%–35% of Poland.

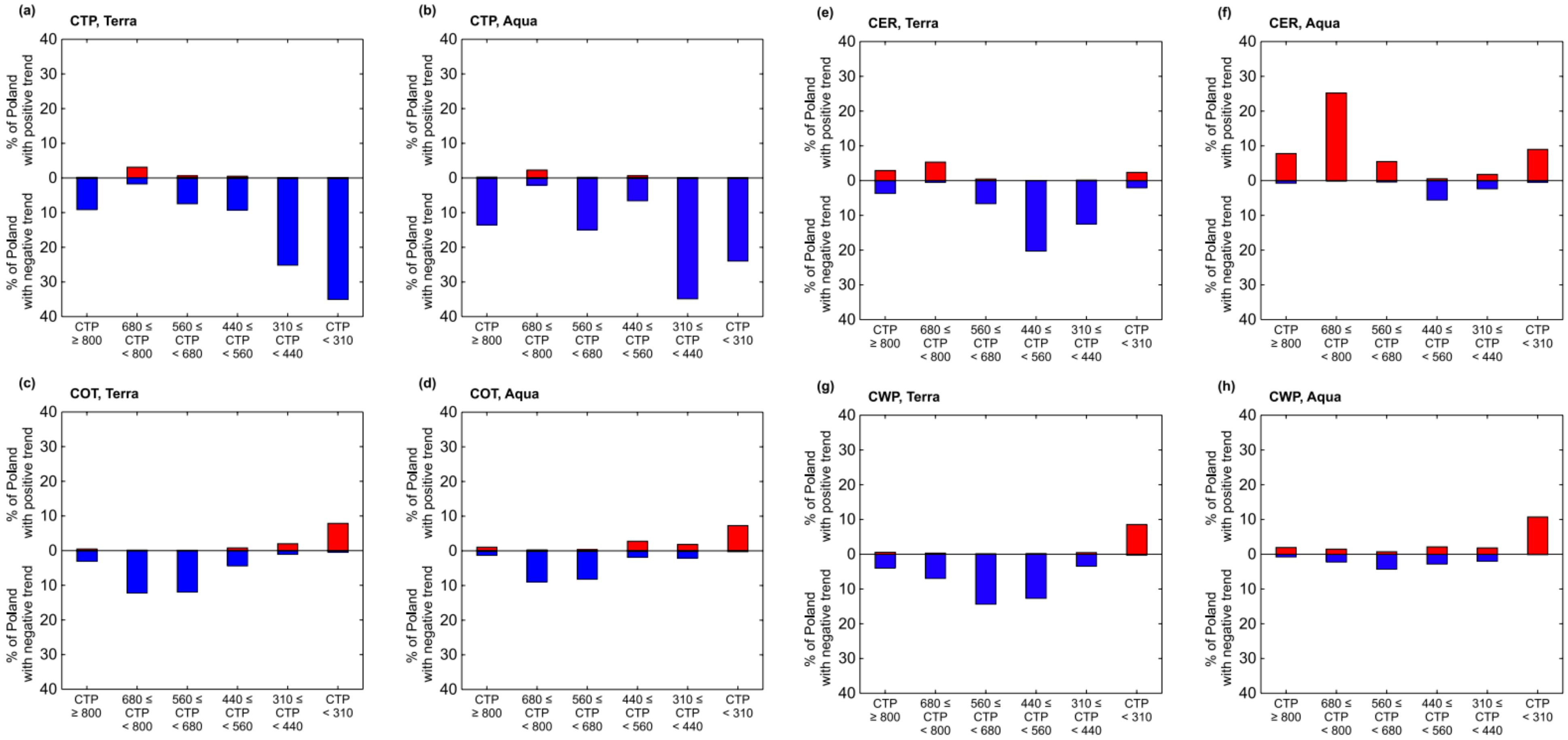



***Figure.*** *Percentage of the area of Poland with statistically significant (α = 0.05) positive (red) and negative (blue) ten-year trends in CTP (hPa) (a–b), COT (c–d), CER (µm) (e–f) and CWP (g·m-2) (g–h) for cloud of different CTP (2003–2021).*

# Results: MODIS Cloud Properties

**Trends in Cloud at Different Altitudes and of a Different Optical Thickness**

- COT sub-categories: positive or negative trend affected up to 20% of the area of Poland.

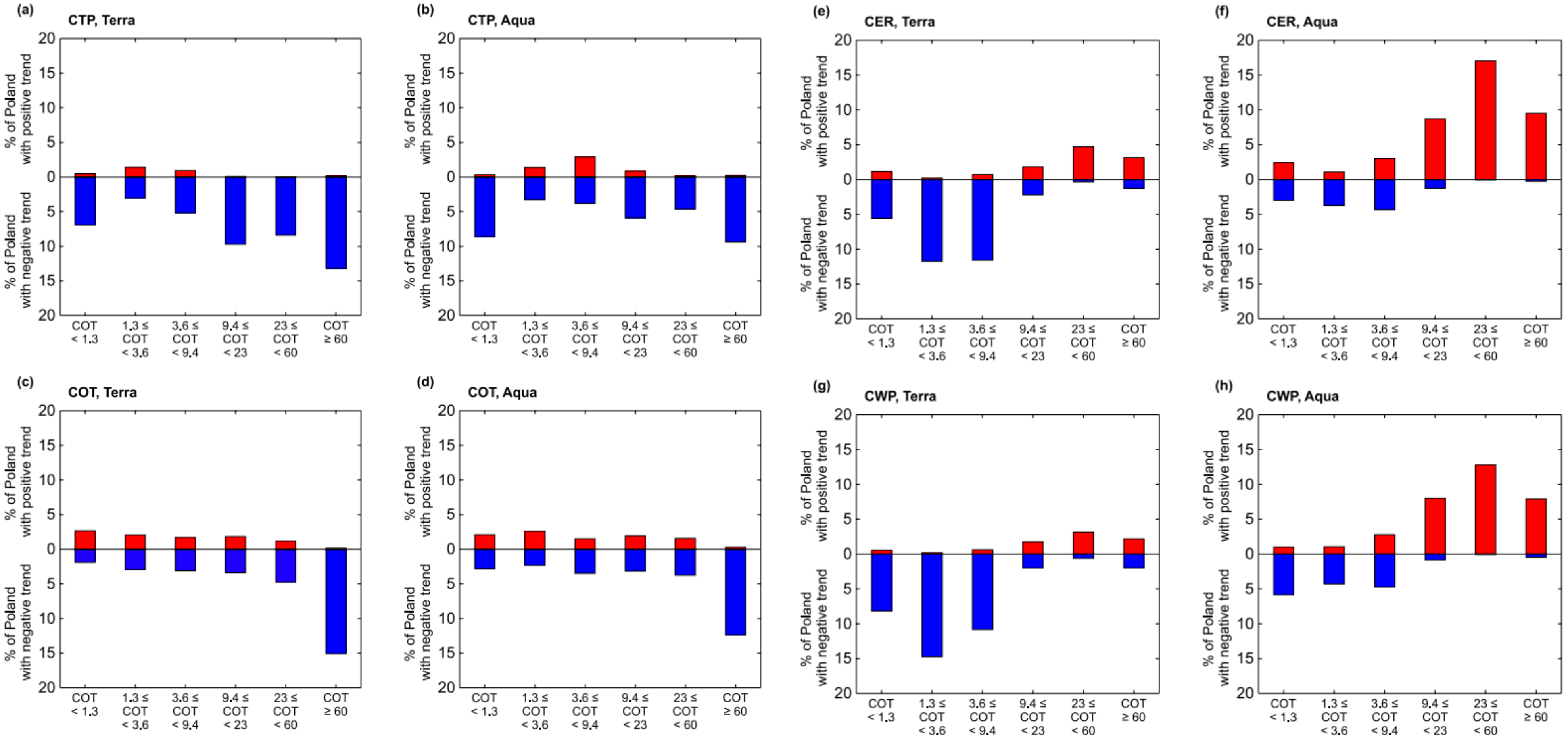



***Figure.** Percentage of the area of Poland with statistically significant (α = 0.05) positive (red) and negative (blue) ten-year trends in CTP (hPa) (a–b), COT (c–d), CER (μm) (e–f) and CWP (g·m-2) (g–h) for cloud of different COT (2003–2021).*

# Discussion

***Table.*** *Means (%) and trends (% per decade) in MODIS cloud type amounts over Poland (2003–2021) for radiuses of 15, 30 and 45 km around SYNOP stations and full swath MODIS data.*

| Radius | *Ci* | *Cs* | DC | *Ac* | *As* | *Ns* | *Cu* | *Sc* | *St* |
|---|---|---|---|---|---|---|---|---|---|
| Mean (%) | | | | | | | | | |
| 15 km | 4.66 | 10.33 | 4.85 | 0.92 | 6.39 | 6.25 | 3.66 | 13.29 | 6.84 |
| 30 km | 4.67 | 10.34 | 4.84 | 0.91 | 6.37 | 6.20 | 3.66 | 13.29 | 6.90 |
| 45 km | 4.66 | 10.33 | 4.83 | 0.91 | 6.36 | 6.18 | 3.69 | 13.34 | 6.93 |
| Full swath | 4.60 | 10.24 | 4.79 | 0.89 | 6.40 | 6.22 | 3.66 | 13.52 | 7.02 |
| Trend (% per decade) | | | | | | | | | |
| 15 km | 0.26 | 0.54 | 0.19 | −0.06 | −0.20 | −0.53 | **0.33** | 0.33 | −0.46 |
| 30 km | 0.26 | 0.56 | 0.19 | −0.05 | −0.19 | −0.54 | **0.31** | 0.32 | −0.49 |
| 45 km | 0.26 | 0.55 | 0.19 | −0.05 | −0.19 | −0.53 | **0.30** | 0.31 | −0.50 |
| Full swath | 0.27 | 0.55 | 0.21 | −0.06 | −0.25 | −0.60 | **0.29** | 0.32 | −0.46 |

*Note*: Statistically significant ($\alpha = 0.05$) values are shown in bold.

- The analysis of MODIS cloud type frequency and amount considered a 30-km radius around ground stations.
- This value was, however, established rather arbitrarily and different values might be more appropriate for individual locations, due to different landforms and weather conditions (notably, vertical visibility). Thus, we also calculated MODIS cloud type amounts for 15 and 45-km radiuses.
- As the results show, both cloud type amounts and their trends were almost identical for all cases.

# Discussion: Frequency Threshold

- In order to check if the choice of 1% (arbitrarily) was appropriate, we repeated the trend analysis and the Mann–Kendall test using MODIS cloud type frequencies for percentages running from 1 to 20 with a 1% increment (at 20, 20% of pixels around the station had to be classified as a specific cloud type in order to determine that it was present).
- The simulation showed that in only case of *Cu* the value of the threshold impacts the results of the analysis. In fact, a value of ≥3% led to the conclusion that MODIS *Cu* frequency significantly increased during the period 2003–2021, making it difficult to confirm the significance of the positive trend in the frequency of MODIS *Cu* over Poland.

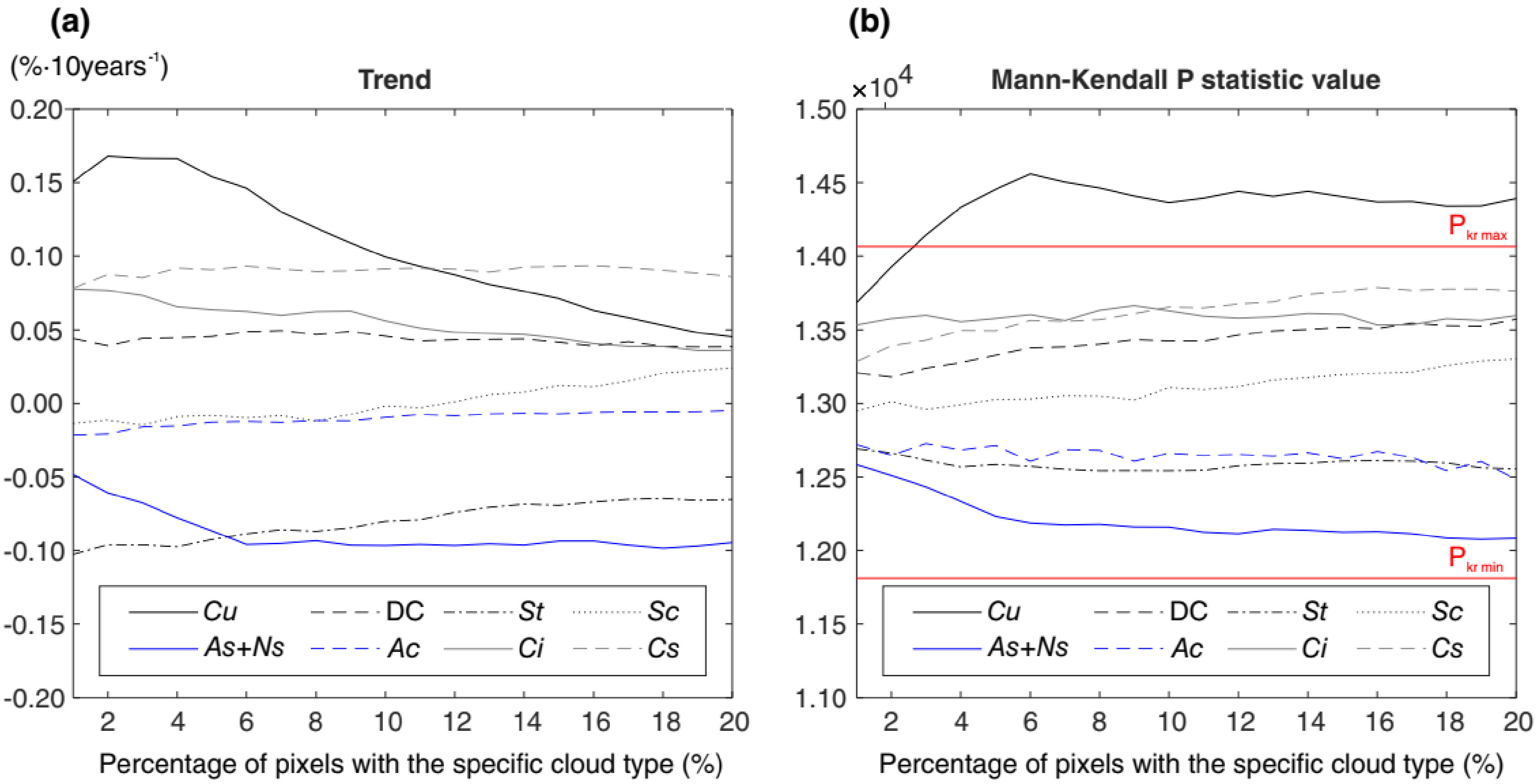



***Figure.*** *Trend per decade (a) and the Mann–Kendall statistic (b) for MODIS cloud type frequency, as a function of the percentage of pixels around a SYNOP station classified as each cloud type.*

# Discussion

***Table.*** *The difference (%) between full swath and 30 km radius MODIS cloud type amount over Poland (2003–2021).*

TABLE 3 The difference (%) between full swath and 30 km radius MODIS cloud type amounts over Poland (2003–2021).

| Cloud type | Mean value of MODIS cloud types amount (2003–2021): Full swath | Mean value of MODIS cloud types amount (2003–2021): SYNOP match (30 km) | Difference (%) ($\alpha = 0.05$) | *p*-value, Mann–Whitney *U*-test |
|---|---|---|---|---|
| *Ci* | 4.60 | 4.67 | 0.06 | 0.7151 |
| *Cs* | 10.24 | 10.34 | 0.09 | 0.7359 |
| DC | 4.79 | 4.84 | 0.05 | 0.7634 |
| *Ac* | 0.89 | 0.91 | 0.02 | 0.4984 |
| *As* | 6.40 | 6.37 | 0.03 | 0.8901 |
| *Ns* | 6.22 | 6.20 | 0.02 | 0.9165 |
| *Cu* | 3.66 | 3.66 | 0.01 | 0.8593 |
| *Sc* | 13.52 | 13.29 | 0.23 | 0.5025 |
| *St* | 7.02 | 6.90 | 0.13 | 0.7846 |

*Note*: All of the values of difference were statistically insignificant at $\alpha = 0.05$.

- Satellite observations offer a unique opportunity to check if the network of SYNOP stations (their density and number) in Poland is sufficient to provide a reliable cloud type climatology.
- MODIS cloud type amounts in the 30 km surrounding SYNOP stations comparing to the data for the whole area of Poland (MODIS full swath).
- No statistically significant difference between full swath and SYNOP-match data for cloud type fraction for any cloud type considered.

# Summary and Conclusions

- We explored the hypothesis that MODIS data classified with the ISCCP philosophy confirms changes in cloud type frequencies found in surface-based observations. The **hypothesis was only supported for *Ci*, *As* + *Ns* and *Cu* clouds**. In the case of *Cb*/DC, *Ac* and *Sc*, MODIS and SYNOP data were not correlated, nor were trends consistent. This suggests that the *Cb*/DC, *Ac* and *Sc* detection criteria used in the two sources are sufficiently different to make a comparison between surface and satellite cloud type climatologies impossible.

- **SYNOP & MODIS are not fully consistent**, and cannot substitute for each other in cloud type climatologies, at least for the area of Poland.

- The **increase in high-level cloud frequency over Poland**, which has been observed by other authors who based their research on synoptic data, is not due to a decrease in the frequency of low- and mid-level clouds, it is confirmed by satellite records.

- We identified a **strong positive trend for both the frequency and fraction of high cloud**.

- The use of a more-detailed, 49-class ISCCP cloud typology made it possible to detect statistically significant trends in high cloud, along with more subtle changes in low and midlevel clouds. These changes could not be observed using the coarser-resolution ISCCP classification (the standard nine classes).

# Summary and Conclusions

- In the 2003–2021 period, **CTP over Poland has consistently decreased by 7.3–9.7 hPa per decade**. This decline was apparent for both Terra and Aqua and primarily affected northern and north-western Poland, with local decreases reaching up to −40.0 hPa per decade. High clouds (CTP < 440 hPa) exhibited the most pronounced changes, with a statistically significant negative trend observed over 25%–35% of the country area.

- While area-averaged monthly means for cloud microphysical and optical characteristics did not change over the analysed period, a detailed investigation of clouds with different CTP or COT revealed additional phenomena. Specifically, COT declined by 1.15–2.25 every 10years for low-to-mid level clouds (CTP 560–800hPa), CER and CWP decreased in clouds with COT <9.4 during morning passes, and CER and CWP increased in clouds with COT ≥9.4 during afternoon passes.

- MODIS data examined at its native 1 km spatial resolution revealed local trends, as well as possible artefacts, but these did not significantly affect the overall temporal variability analysis.

# Takeaway Message

- Satellite records confirm the **increase in high-level cloud** frequency over Poland observed in ground-based synoptic data.
- Over the past two decades, cloud top pressure has consistently decreased, particularly for high clouds, indicating **a general rise in cloud top heights**.
- MODIS and SYNOP data **are not fully consistent** and therefore cannot replace each other in cloud type climatologies.

**Articles:**


**Wojciechowska, I.**, Kotarba, A. Z., & Żmudzka, E. (2023). Cloud type frequency over Poland (2003–2021) revealed by independent satellite-based (MODIS) and surface-based (SYNOP) observations. *International Journal of Climatology*, 43(11), 5208–5226. https://doi.org/10.1002/joc.8141.

**Wojciechowska, I.** (2025), The Temporal and Spatial Variability of Cloud Properties Over Poland Based on Satellite Data (2003–2021). *Int J Climatol* e8804. https://doi.org/10.1002/joc.8804.

# *Thank You!*

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