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# General Circulation Model (GCM) Perfomance

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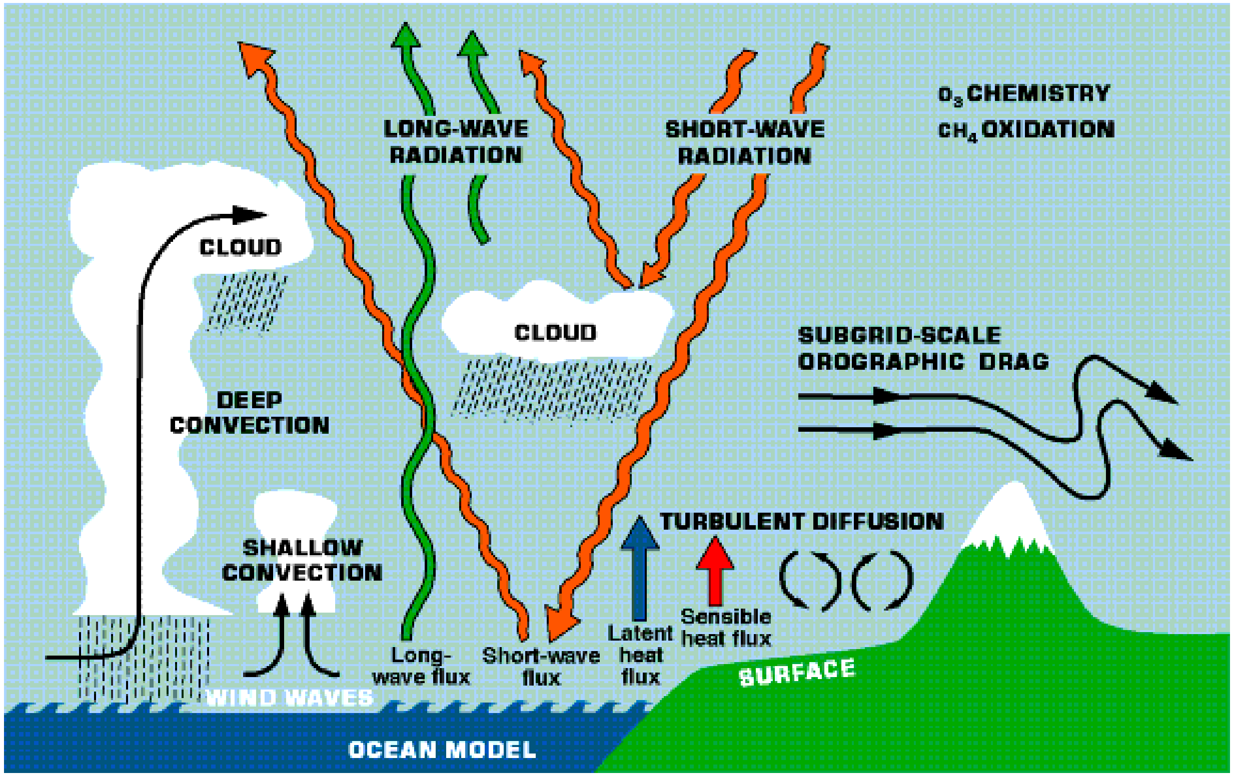
Kumasi, Ghana

# Agenda

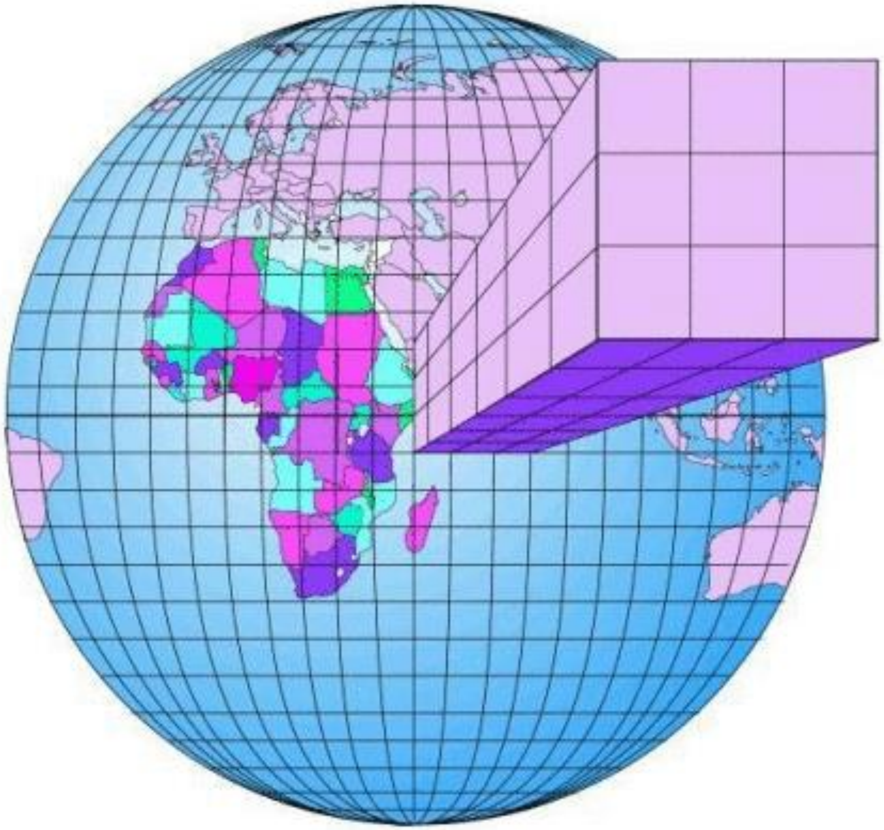
1. Very general few remarks on General Circulation Models
2. The representation of moist convection in models
3. The low confidence in climate projections over Africa and their causes
4. The representation of low level clouds in West Africa
5. Causes of poor representation of low clouds in West Africa
6. Impacts of poor representation of low clouds in models with explicit and parameterized convection
7. Impact on weather prediction and ways forward

# Processes in GCMs

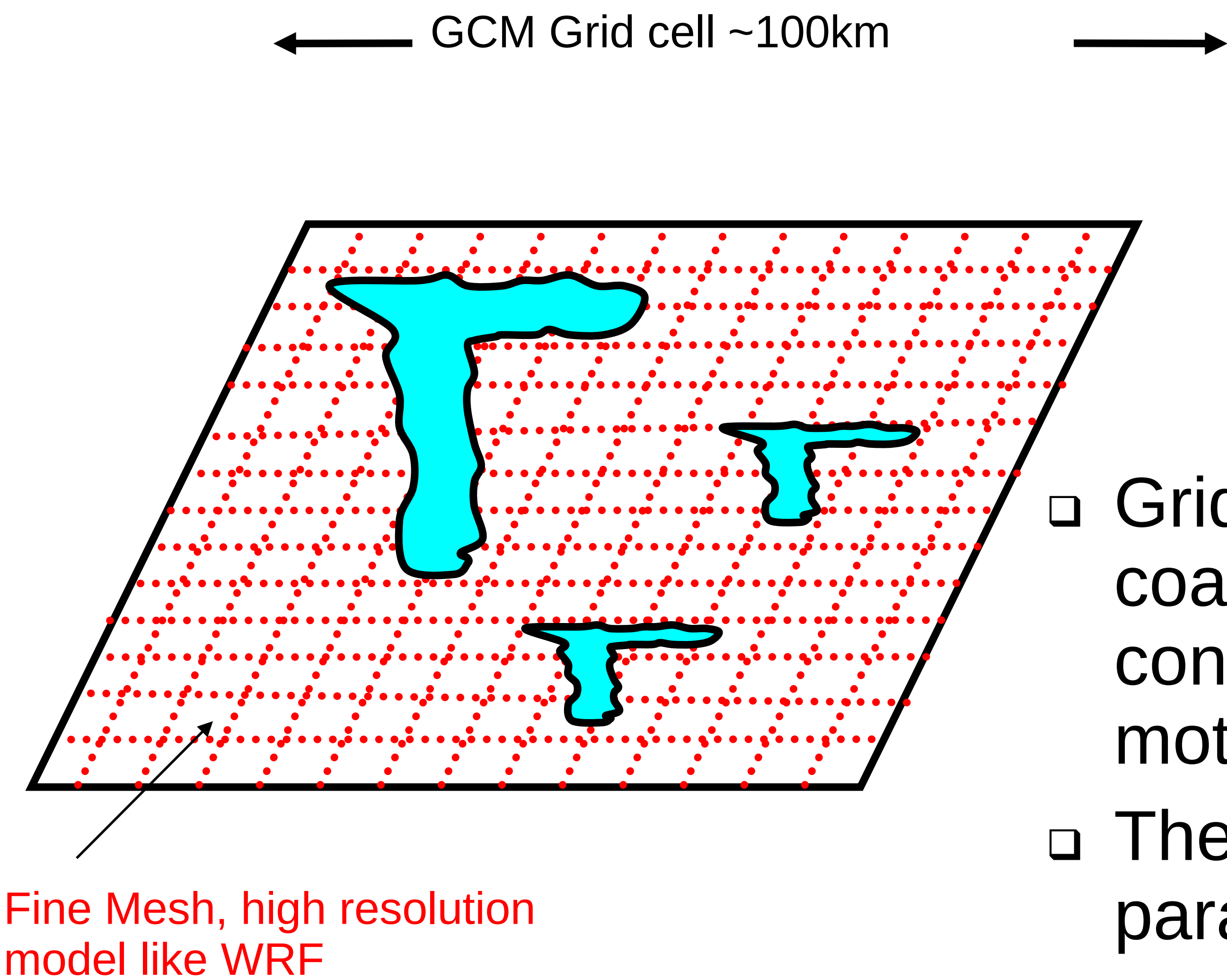



- Processes represented in global models are similar to high resolution models

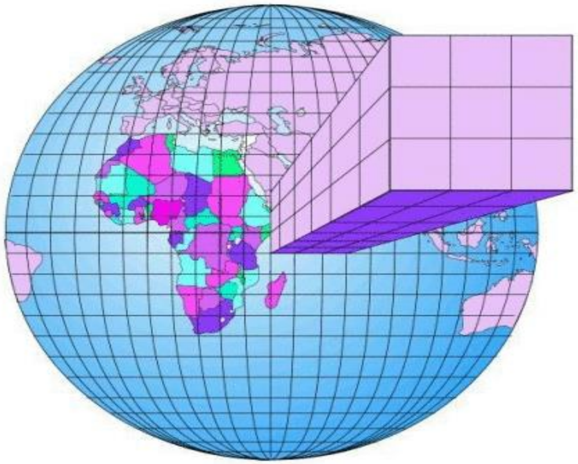
# Global Circulation Models (GCM)



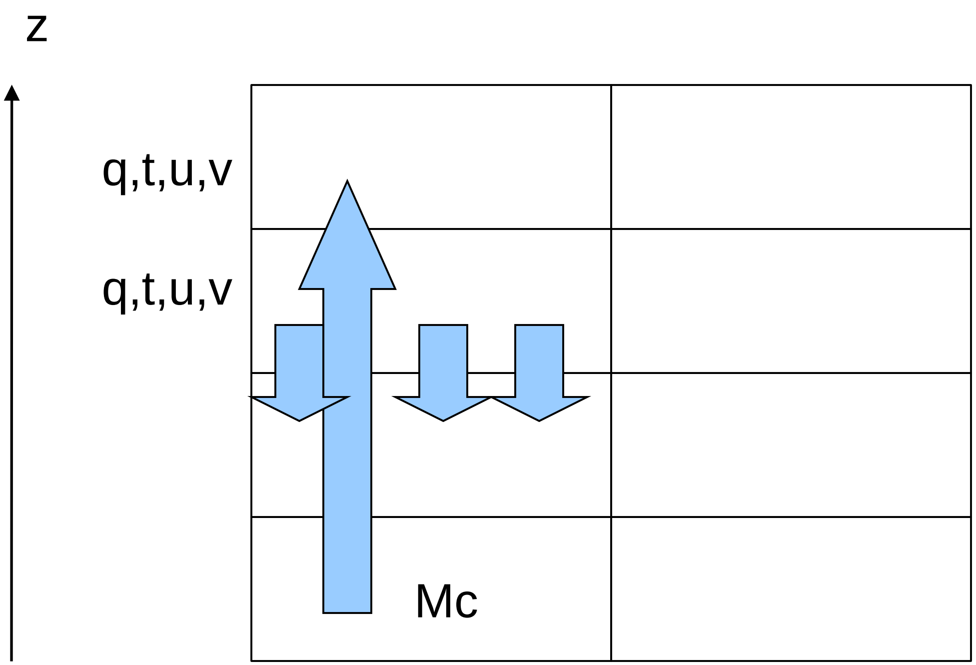
- Nowadays: seamless model approach
- Errors in GCMs are often errors in numerical weather forecasting models
- Errors develop after a few hours to days after start of integrations

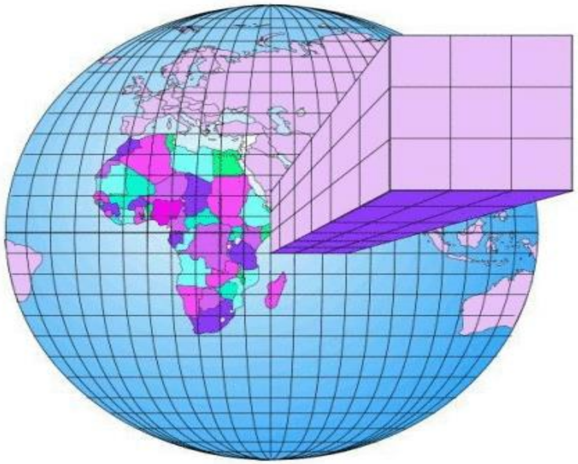



- Grid scale too coarse to present convective-scale motions
- They must be parametrized



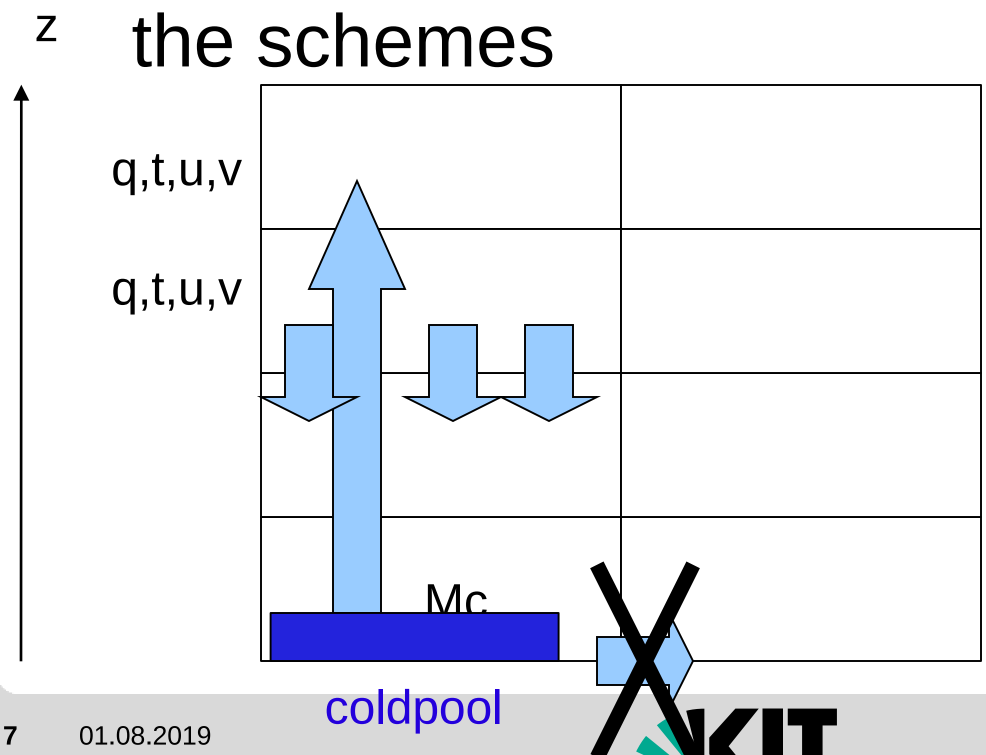
culations (convective mass flux Mc)
n the column profiles of the
large-scale model





culations (convective mass flux Mc)
n the column profiles of the
large-scale model

- There is no communication between columns in the schemes



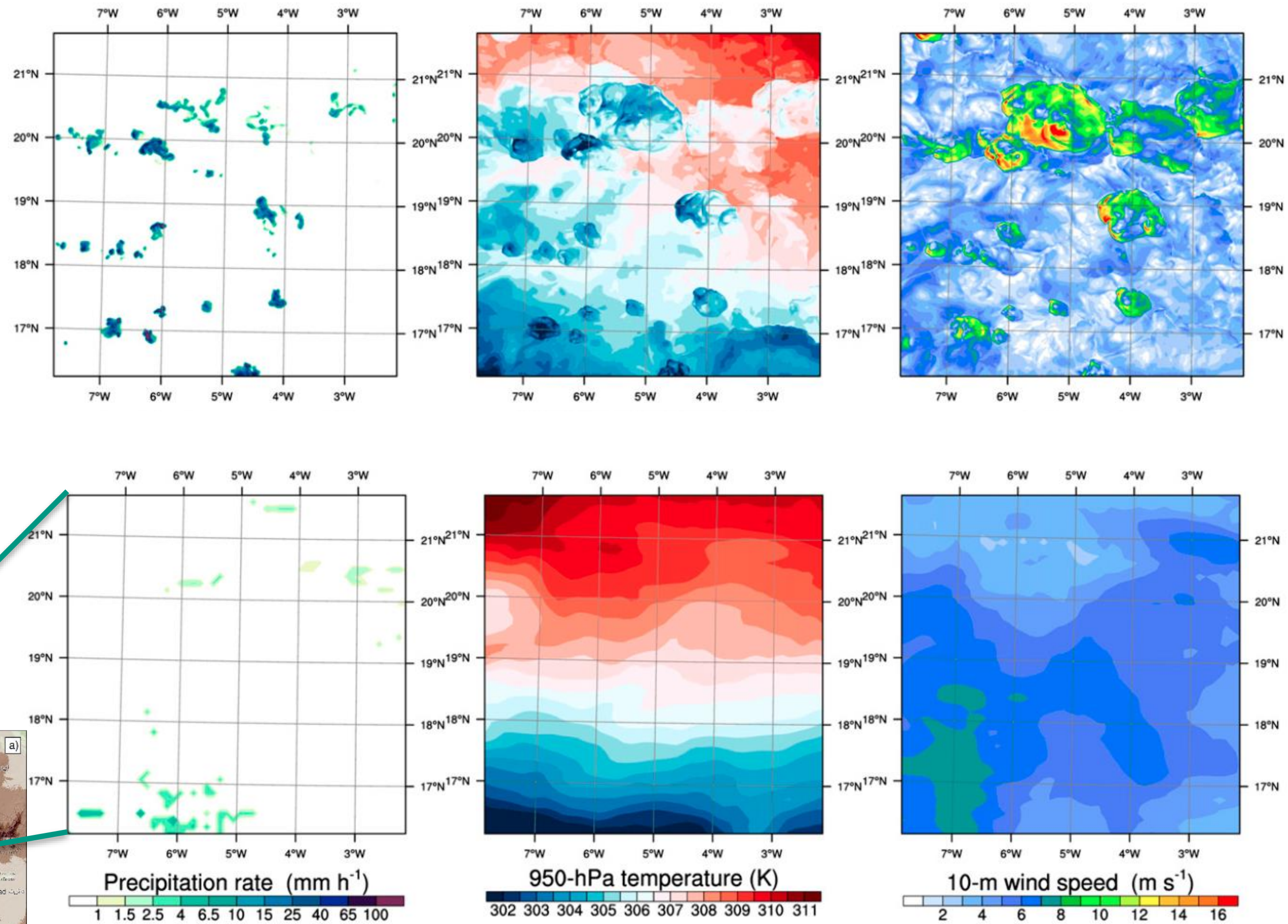
# High-resolution models do a better job

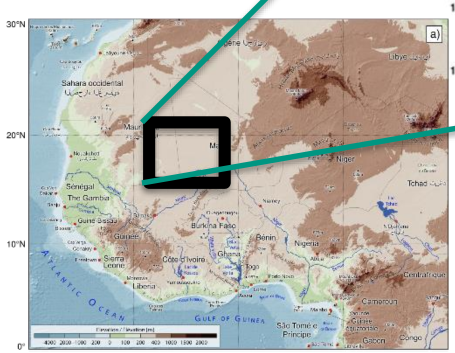
Rainfall | Temperature at 700 m | Wind at 10m

High resolution
= 1.5 x 1.5 km

**Simulated Day:**
**31. July 2006**

Resolution =
12.5 x 12.5 km

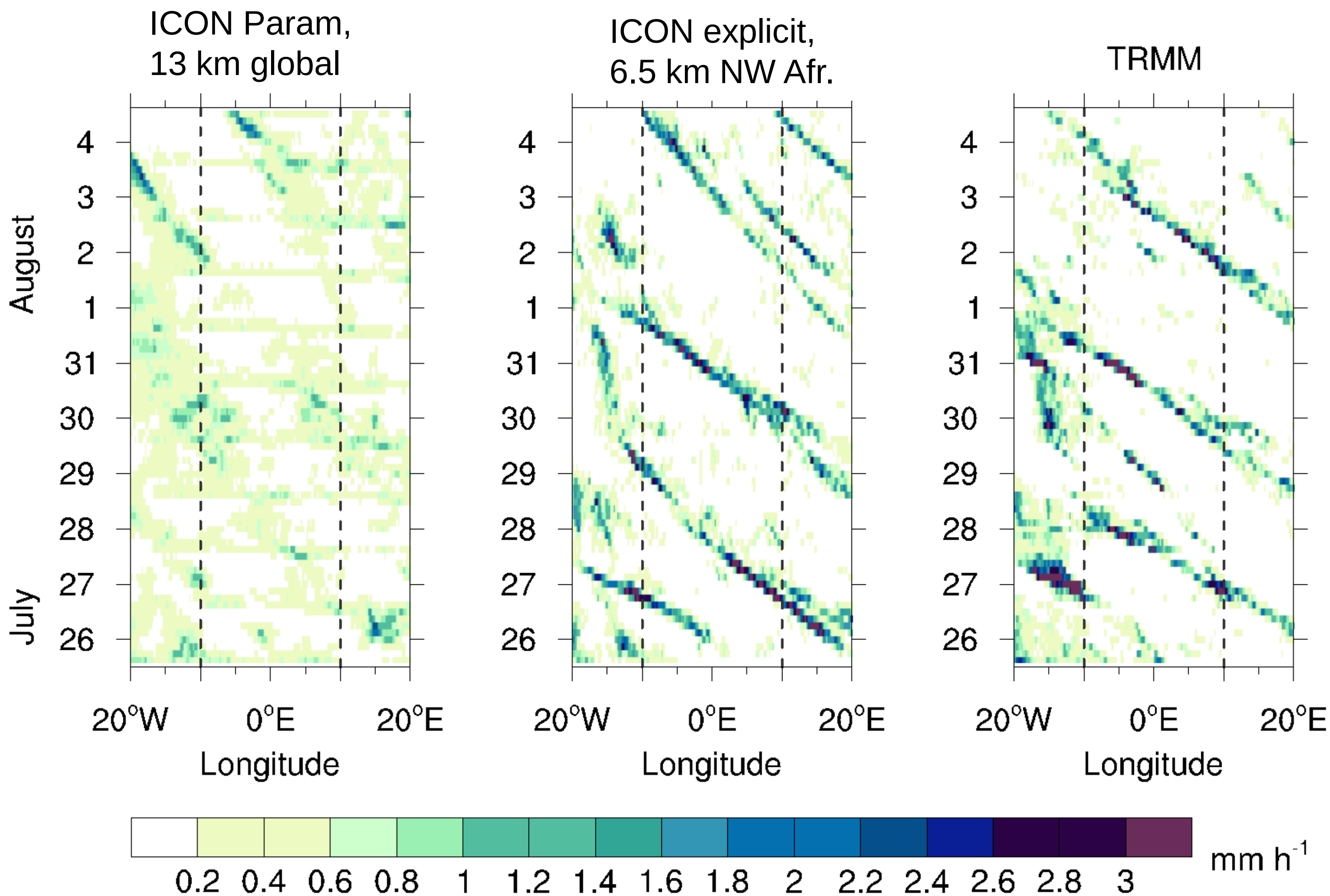


Source: Pantillon et al. (2015, MWR)

# High-resolution models do a better job

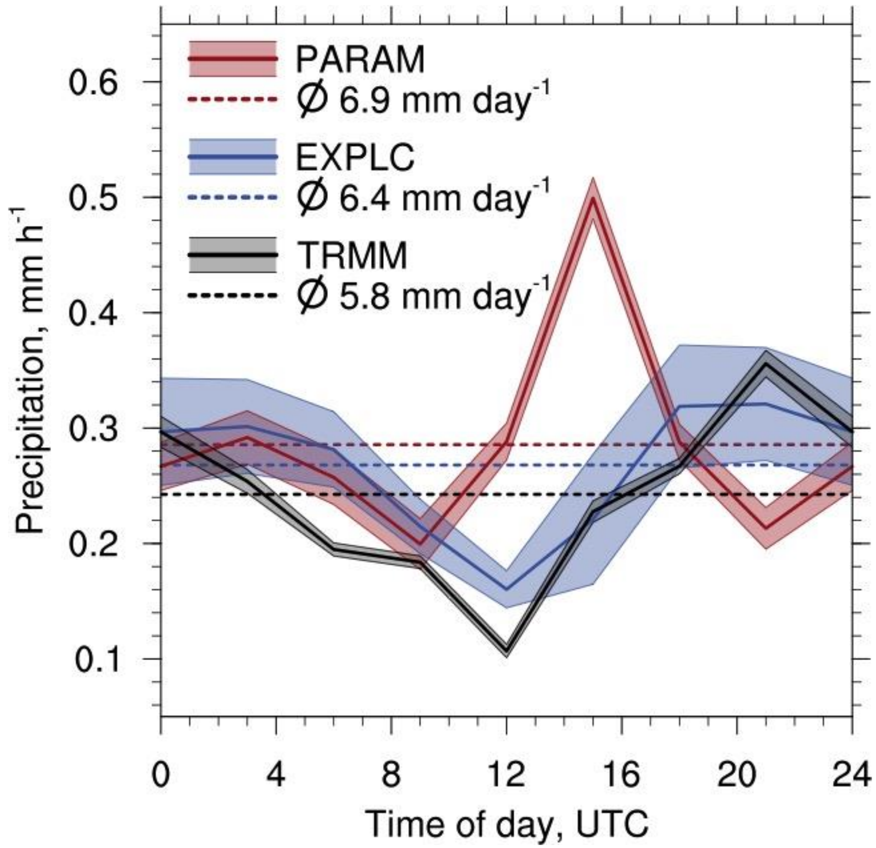
3-hourly precipitation averaged from 8-18°N, 25 July – 04 August 2016




Source: Pante and Knippertz (2019, Nat. Comm.)

# High-resolution models do a better job

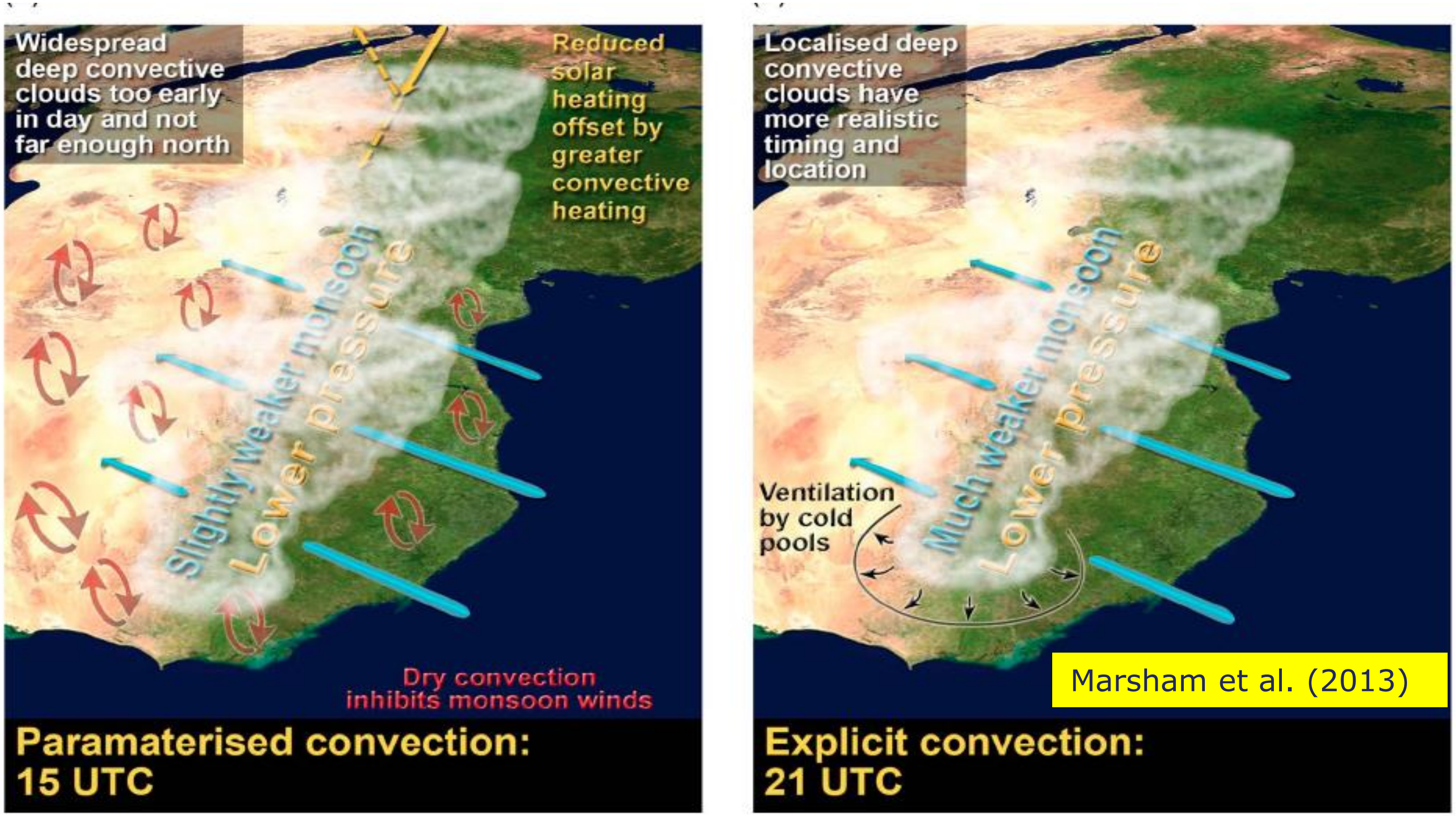
West Africa (8-18°N, 10°W-10°E)




Models with parameterized have a too early rainfall peak

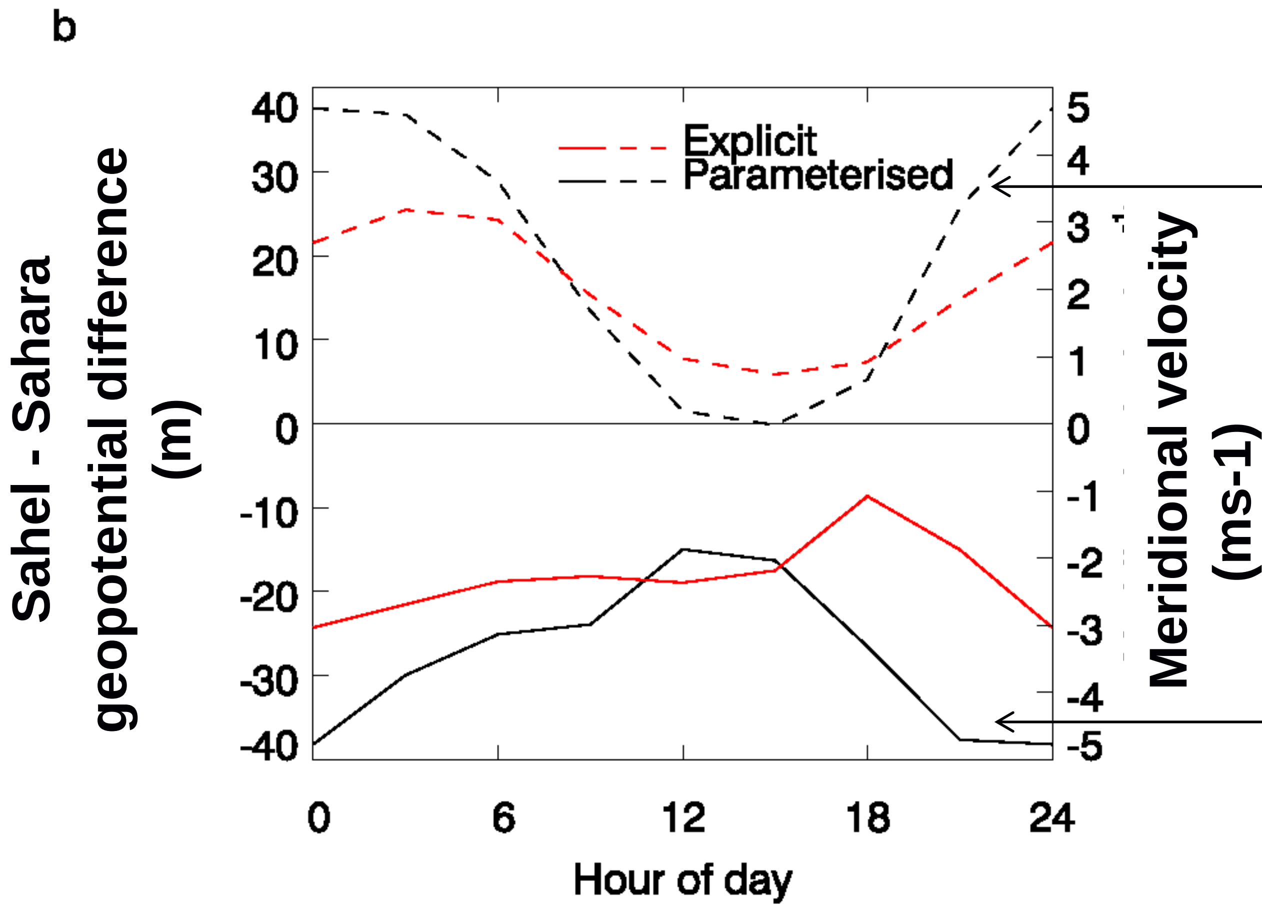
Source: Pante and Knippertz (2019, Nat. Comm.)

# Mean rainfall: comparison with observations




- **Parameterised** gives rain too early in the day
- **Explicit** gives timing close to observations

# Impact on the diurnal cycle of the WAM



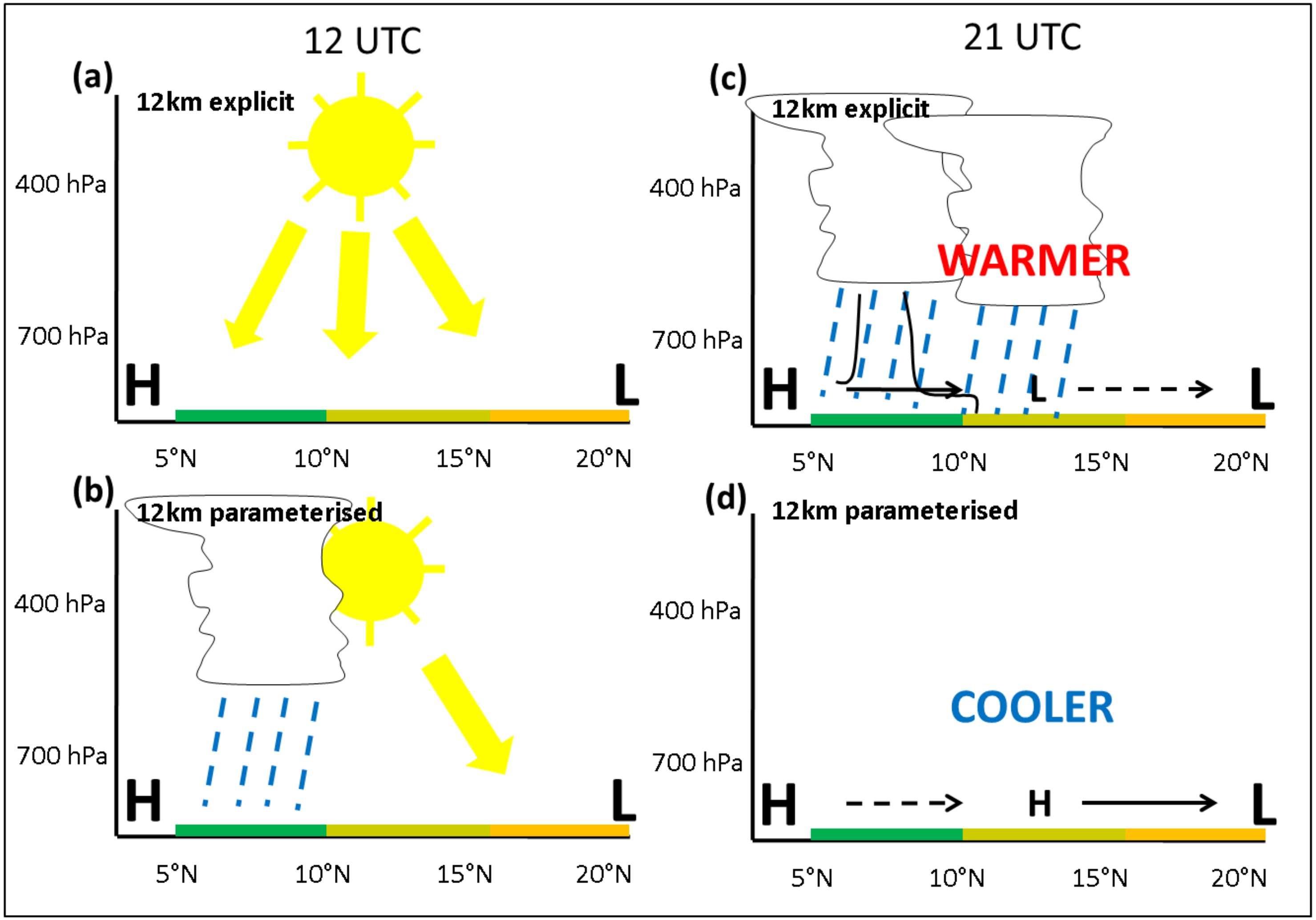

Parameterised model has stronger meridional winds at night.

Parameterised model has stronger pressure gradient at night due to lack of convective heating in Sahel.

Marsham et al. (2013)

- Diurnal cycle in pressure gradient consistent with diurnal cycle in rain.
- Later rainfall in explicit run gives later minimum in Sahel-Sahara pressure gradient.
- Stronger pressure gradient leads to stronger nocturnal monsoon winds in parameterised model.

# Differences in mean state: 12km runs



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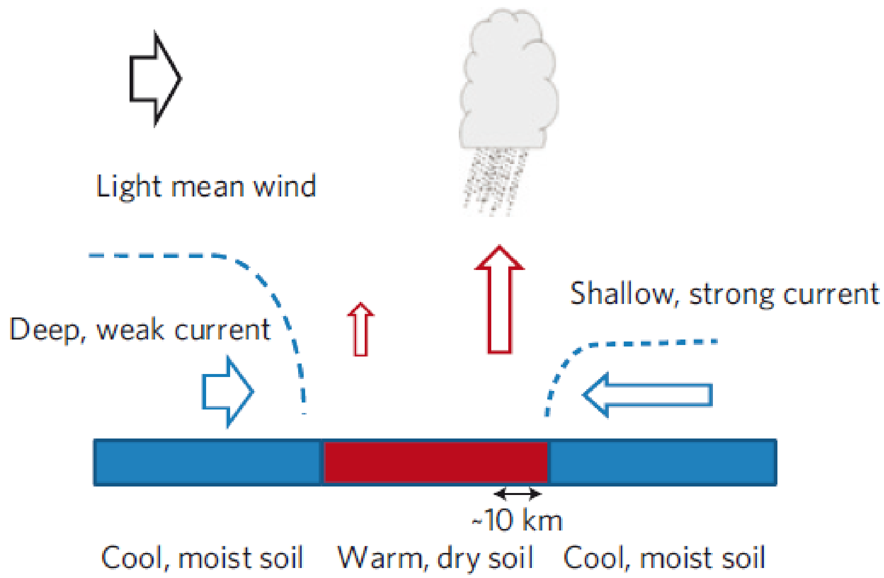
Schematic explaining Marsham et al. (2013)

# Proof of role of 10km soil moisture features for WAM via MCS upscaling effect




Taylor et al. (2011)

- Mesoscale (~ 10 km) soil moisture features in the Sahel impact on generation of Mesoscale Convective Systems (MCSs)
- Convections tends to occur over drier soils in the Sahel (Taylor et al. 2012)
- **MCS upscale the mesoscale effects – this is not resolved by climate models, nor is the preponderance of convection to occur over dry soil**s

# Problems in GCMs for (West) Africa

- No realistic representation of convection (diurnal cycle, organization, cold pools, initiation)
- For West Africa, this impacts on the rersentation (the diurnal cycle of) the whole monsoon system
- Other problems of GCMs in West Africa:

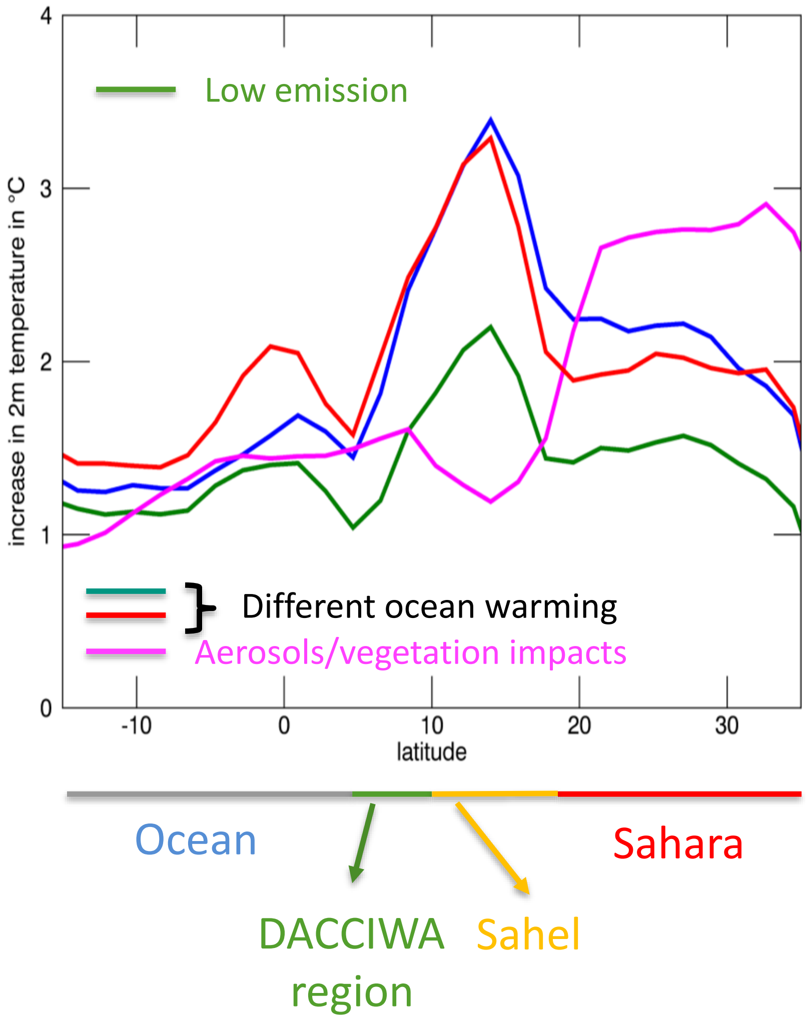
  warm bias of sea surface temperatures in the eastern tropical Atlantic

  Problems to represent dust lifting and transport

  Absence of low-level clouds in southern West Africa (see later)

→ Causes unreliable climate projections in West Africa, especially with respect to rainfall

# Long-term projections for southern West Africa: Temperature

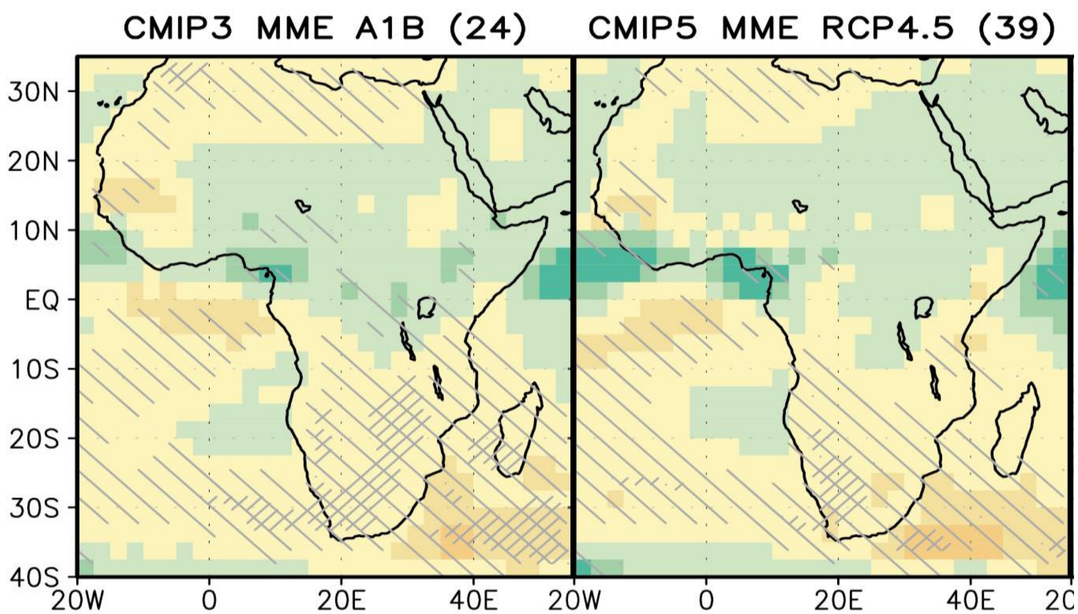



DACCIWA modelling results:

- Increase of near-surface temperature between 1–3°C until 2050 depending on scenario.
- Proximity to ocean will damp warming to 1–1.5°C.
- Warming is impacted by vegetation changes and interactions between clouds and aerosols.

Source: DACCIWA Policy Brief

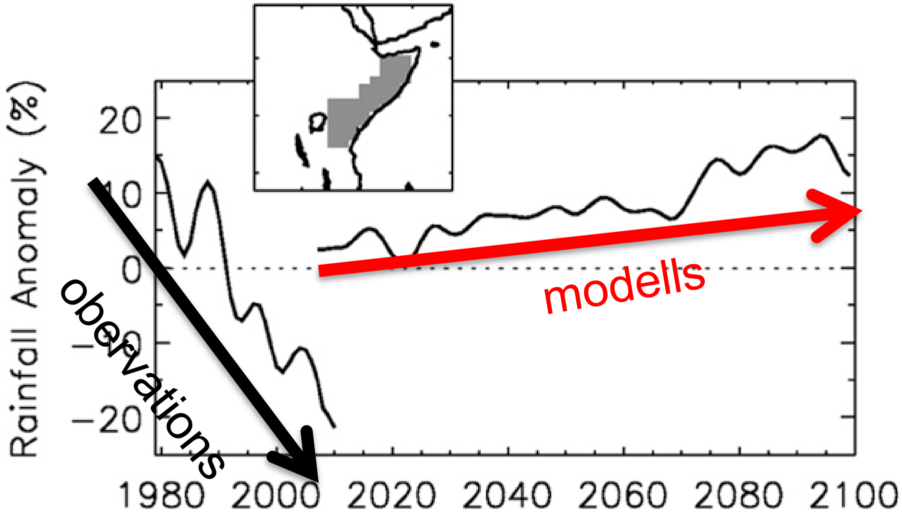
# Long-term outlook for southern West Africa: Precipitation




Source: IPCC, 2013

- Results from last two IPCC reports show low confidence in changes of rainfall.
- DACCIWA model projections confirm large sensitivities, showing that our understanding of future precipitation in the region remains poor.

# The East African Climate Paradox



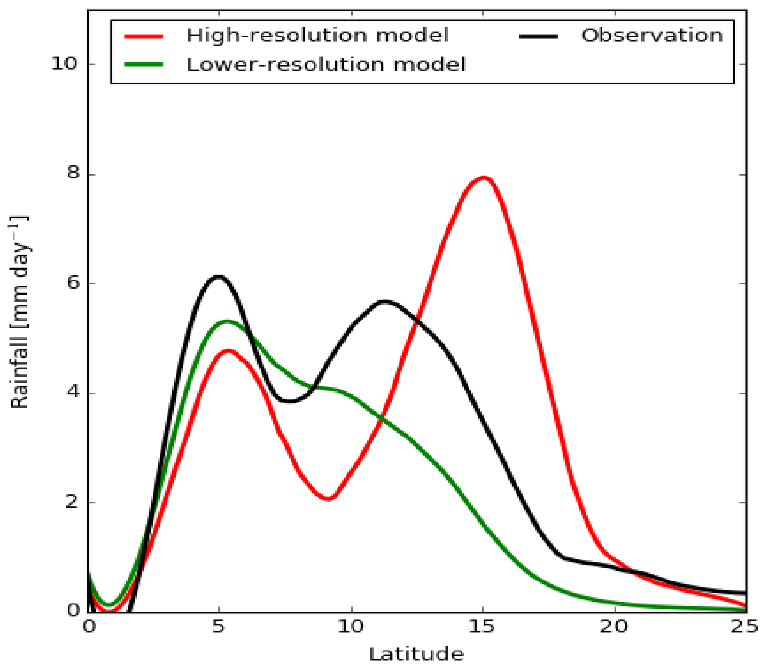

Source: Yang et al. (2014)

Observed rainfall trends in at the Greater Horn of Africa are at odds with climate projection

Various reasons are discussed, oceanic, aerosols, but errors in (organized) convection may also cause wrong vertical heating that forces, for example, the Walker circulation

-> see great work that is currently done in Reading and Leeds

# Models struggle to represent the complex atmosphere in West Africa




Source: DACCIWA Policy Brief

- DACCIWA has shown that even high-resolution, state-of-the-art weather forecasting models cannot reproduce the south-north distribution of rainfall (Kniffka et al. 2019, ACP)

# Problems in GCMs for (West) Africa

- Climate models struggle to realistically represent the West African monsoon (WAM).

  ➔ no reliable future projections and adequate adaption measures

- Low-level clouds over southern West Africa during July–September affect surface energy balance and precipitation.

  ➔ integral part of the WAM

- First study to systematically investigate reasons for biases in low clouds in IPCC climate models.



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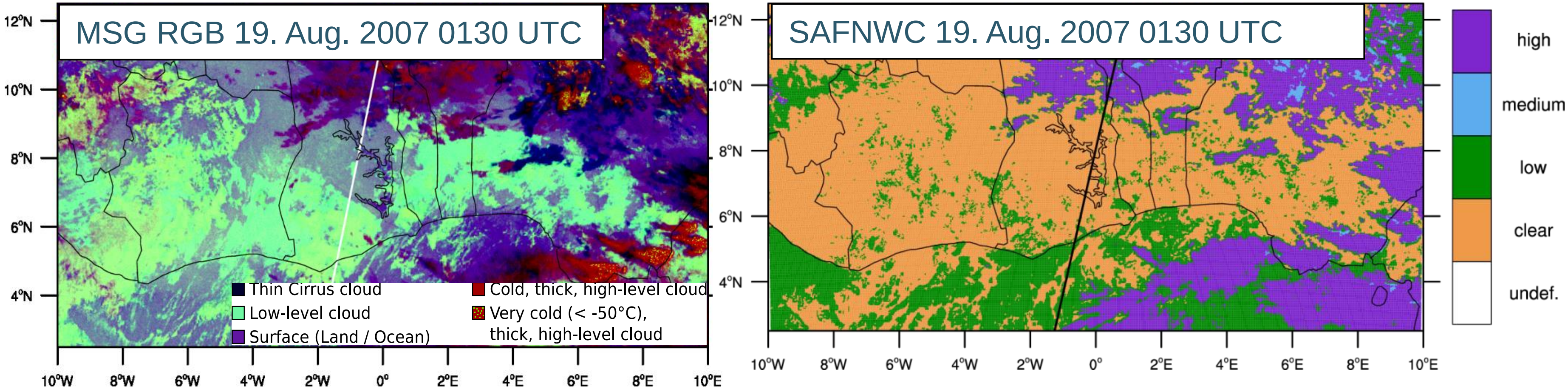
# Misrepresentation of low clouds in satellite products



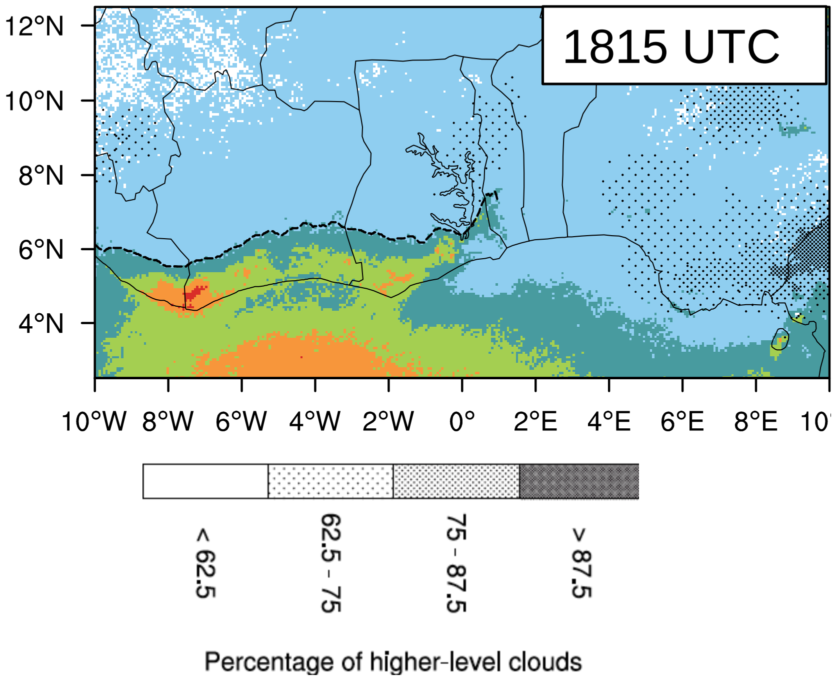

after van der Linden et al. (2015, JGR), modified

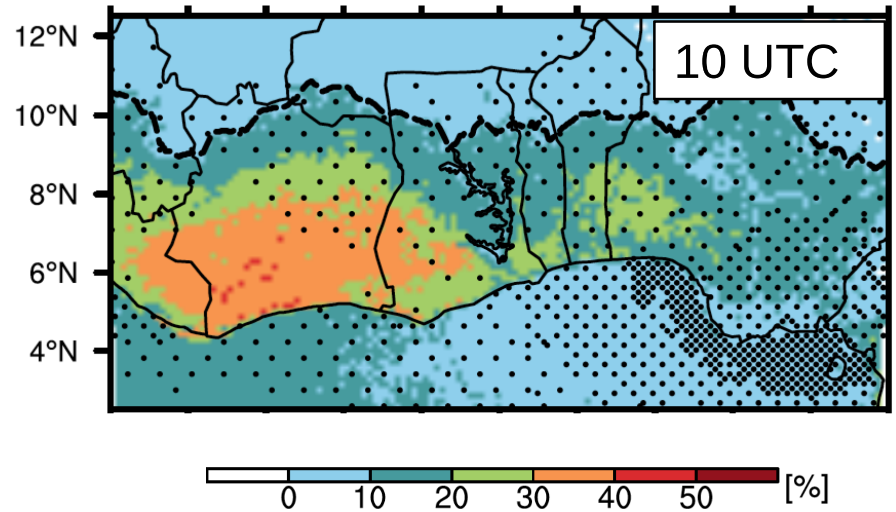
- Low thermal contrast to surface and frequent presence of obscuring higher clouds make detection challenging.

  ➔ overlooked in many studies

# The monsoon stratus is frequent and widespread

## Stratus Occurrence Frequency, Jul.-Sept. 2007-2011

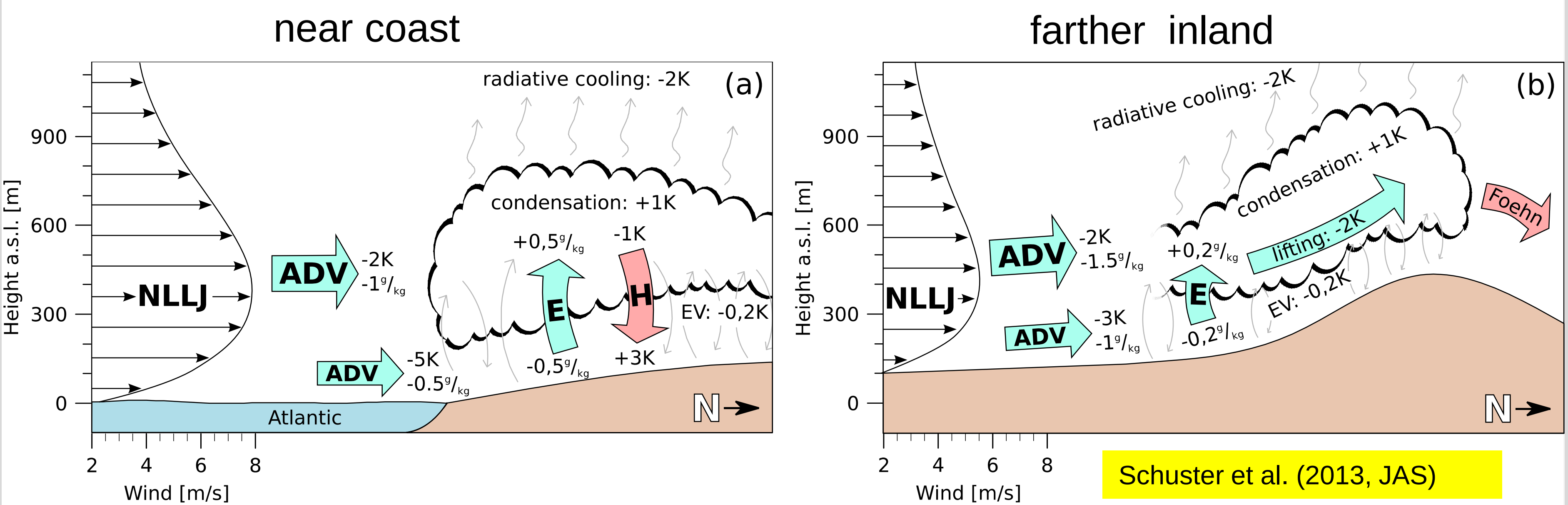



van der Linden et al. (2015, JGR)

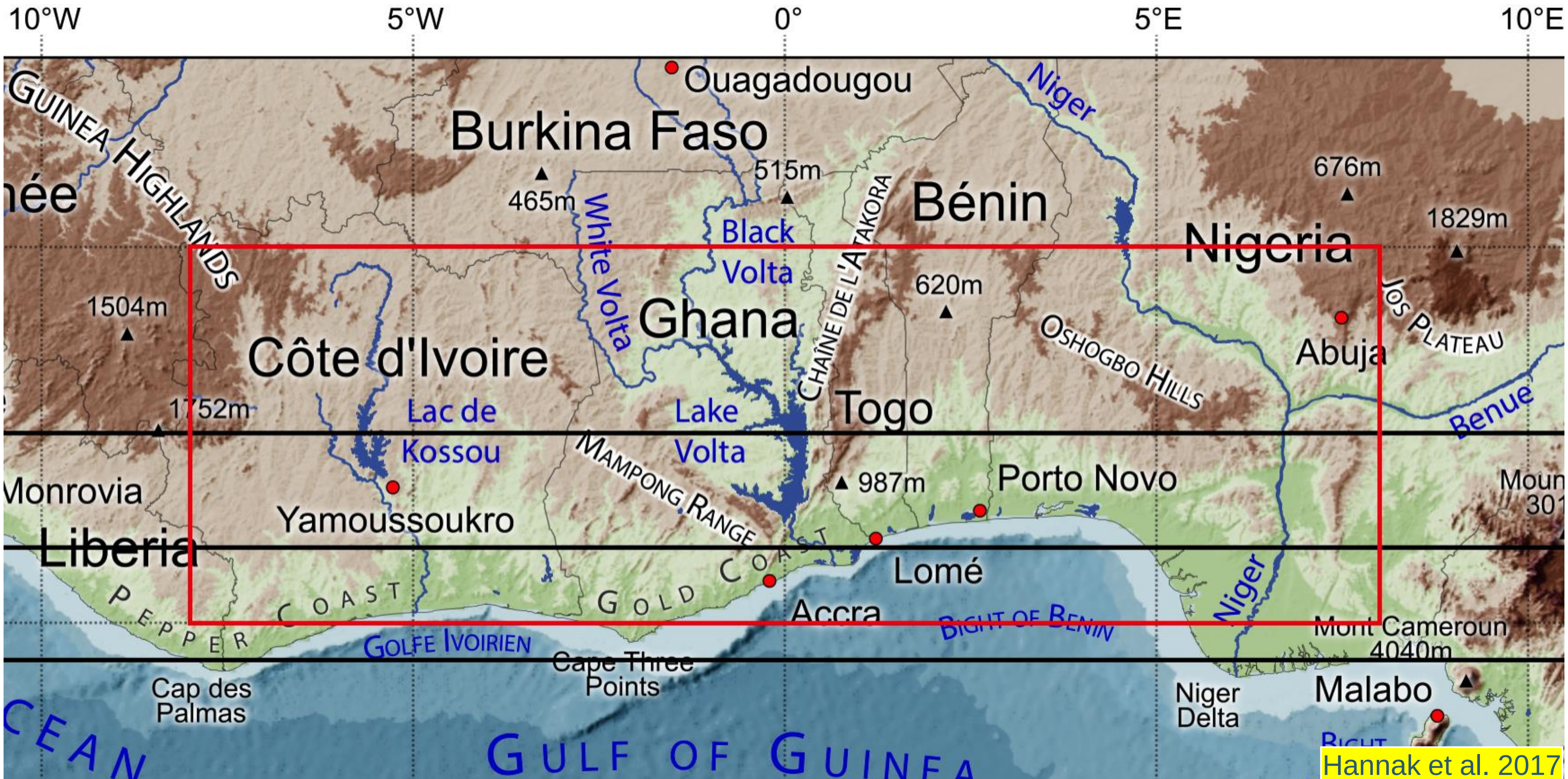
- Occurrence minimum in late afternoon / early evening
- Maximum thickness and extent around 10 UTC (~LT)
- Break up and rise to 850 hPa in course of day

# How are ultra-low clouds related to the NLLJ?




- Formation near level of nocturnal low-level jet (NLLJ, ~950 hPa)
- Processes involved in stratogenesis:
  - Cold air advection from the ocean
  - Cooling by orographic lifting
  - Turbulent mixing
  - Radiative Cooling (early night at surface, after cloud formation at cloud top)
- DACCIWA results for Savè (Benin) emphasize the role of the cold air advection from the ocean (Maritime Inflow) over turbulence (Lohou et al. 2019, ACPD)

# The DACCIWA study region




- DACCIWA region: 5-10°N, 8°W-8°E (red rectangle).
- Black lines used to calculate meridional 925-hPa geopotential height gradients (will not be shown).



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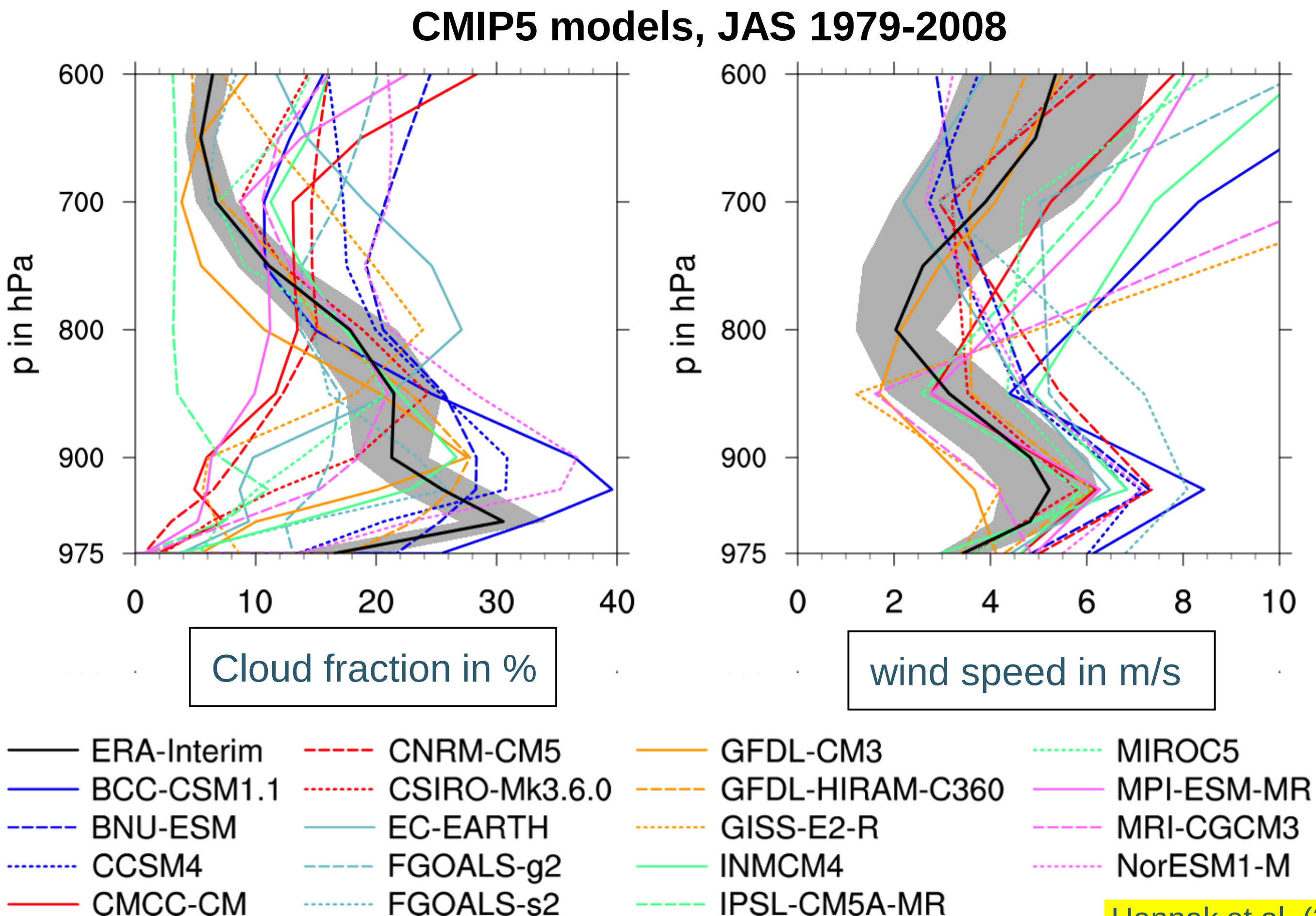
# Model evaluation

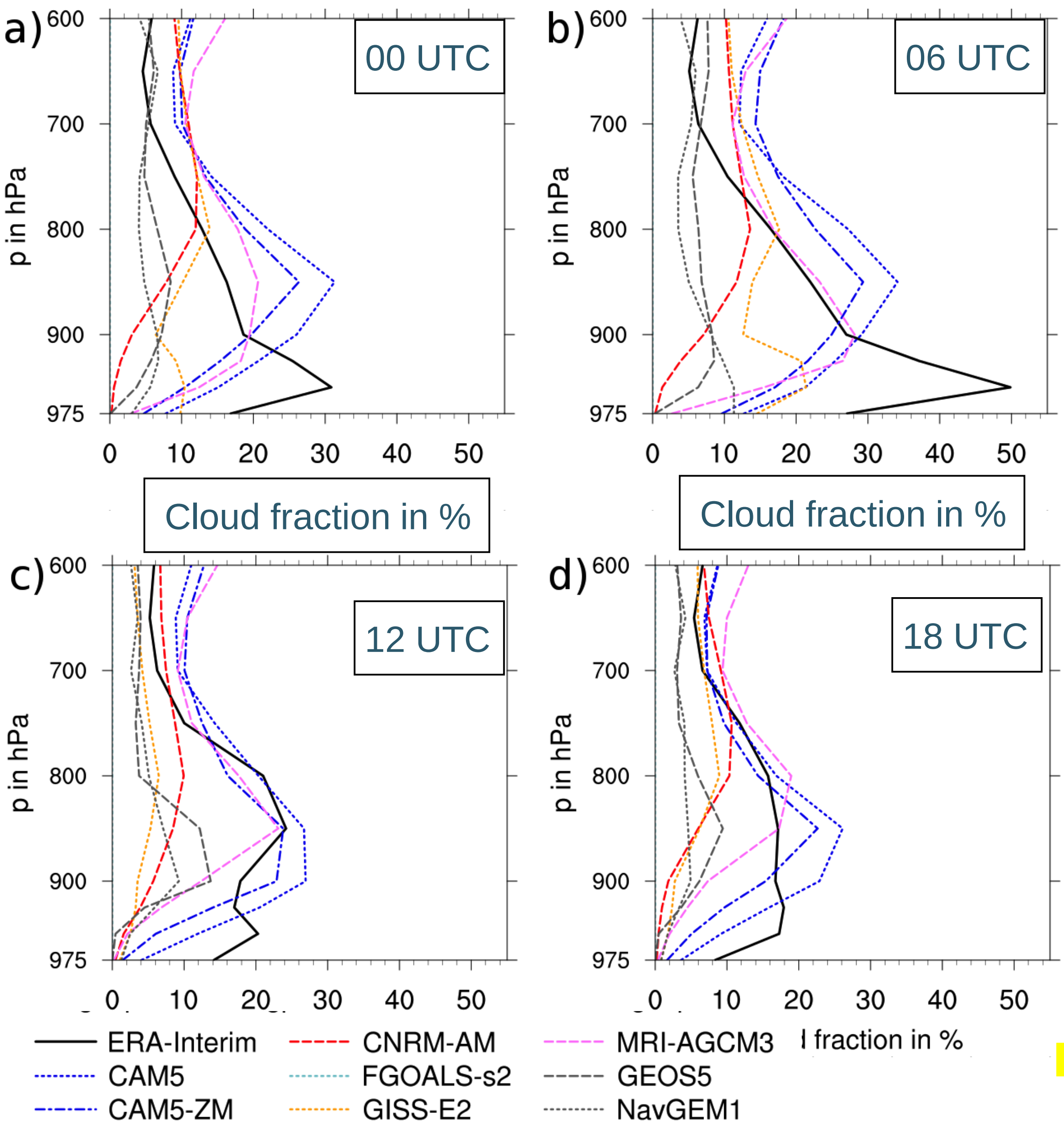



Hannak et al. (2017, J. Clim.)

- ERA-Interim agrees with surface observations (not shown).
- CMIP5 models have large biases in low-level cloud fraction & height.
- CMIP5 models overestimate the Low Level Jet (LLJ).

# Model evaluation

**YOTC models, JAS 1991-2010**




YOTC models:

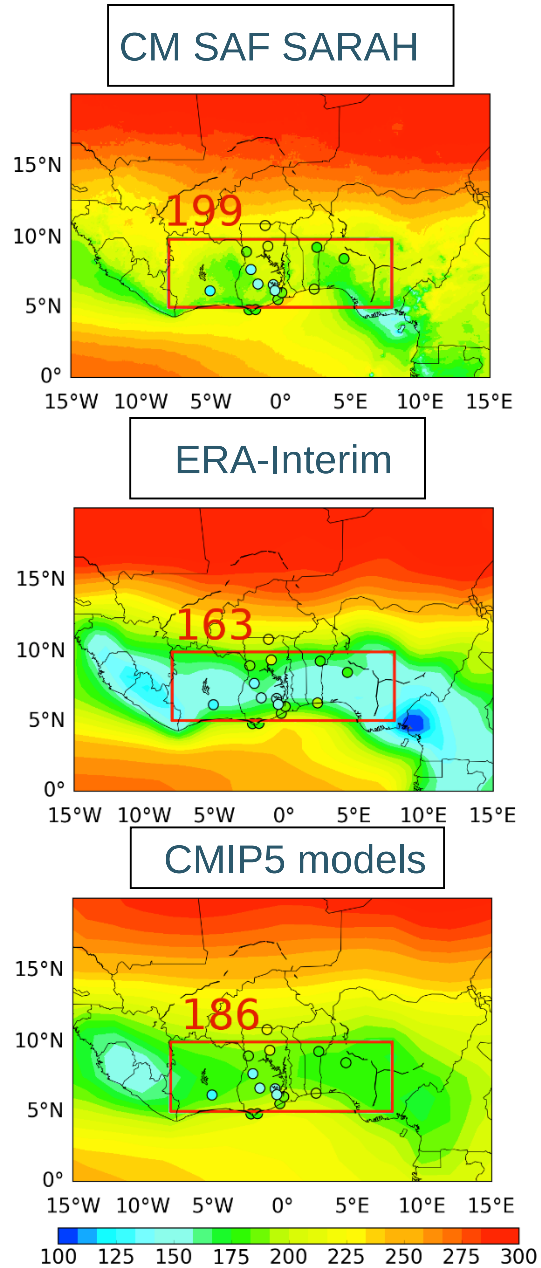
- Too few clouds
- too high
- To weak diurnal cycle
- to strong nighttime low-level jet (not shown)

Note:
6 out of the 8 YOTC models were used in CMIP5 though with coarser horizontal and vertical resolutions.

Hannak et al. (2017, J. Clim.)

# Model evaluation

**CMIP5 models, JAS 1991-2010**




- Validation of model downwelling solar radiation is a challenge in the WAM region.
- Yet, surface station measurements support the notion that too few clouds in CMIP5 models cause too much surface  downwelling shortwave radiation.

Hannak et al. (2017, J. Clim.)

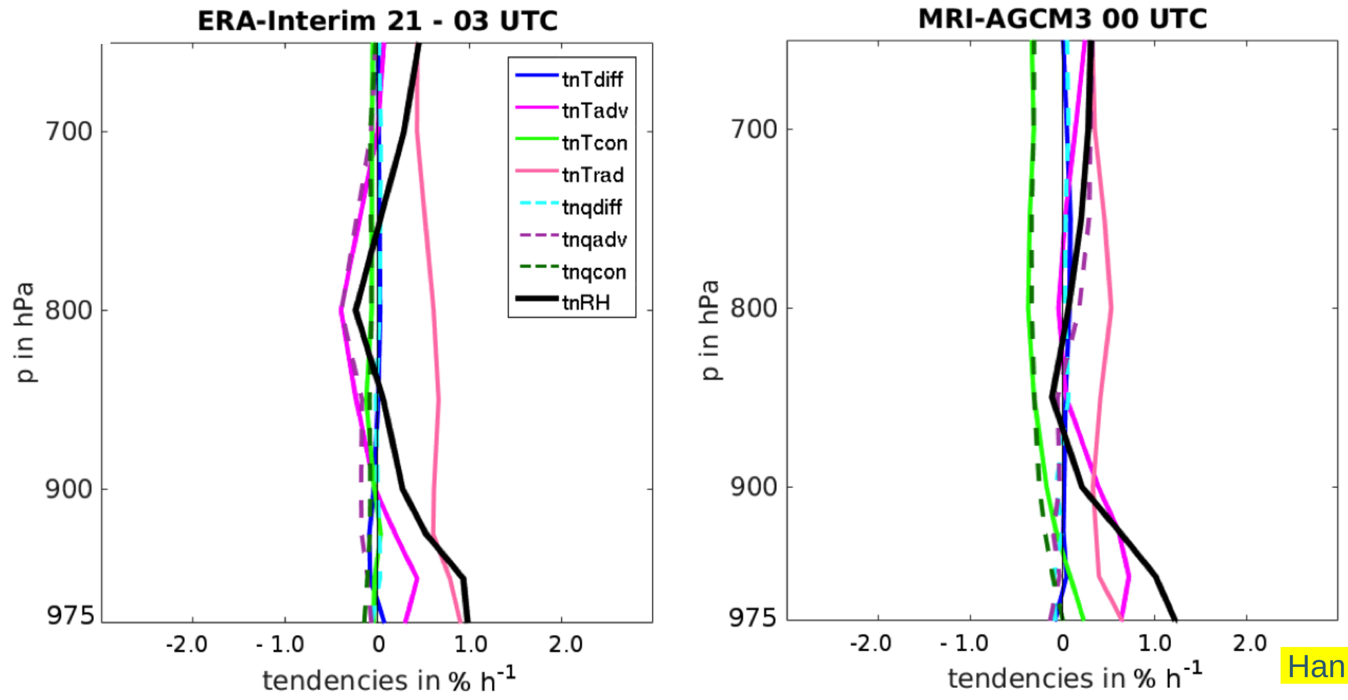
# Tendencies of relative humidity (RH)

$$\frac{\partial \mathrm{RH}}{\partial t} = \frac{p}{E}\left[\frac{0.622}{(0.378q + 0.622)^2}\frac{\partial q}{\partial t} - \frac{qL}{(0.378q + 0.622)R_v T^2}\frac{\partial T}{\partial t}\right]$$

Hannak et al. (2017, J. Clim.)

- Grid-point RH tendencies at pressure levels can be related to tendencies of q (specific humidity) and T (temperature).
- From ECMWF YOTC (2008-2009 only) and YOTC model output, contributions to the latter two tendencies by grid and sub-grid scale processes can be retrieved.

# Analysis of YOTC tendencies: Night




Hannak et al. (2017, J. Clim.)

- Longwave cooling & cold advection dominate nighttime RH tendencies.
- Reasonable agreement between ERA-I & MRI AGCM in RH and RH tendencies.
- Still, MRI underestimates the near-surface cloud layer.
  ➔ subgrid cloud schemes?



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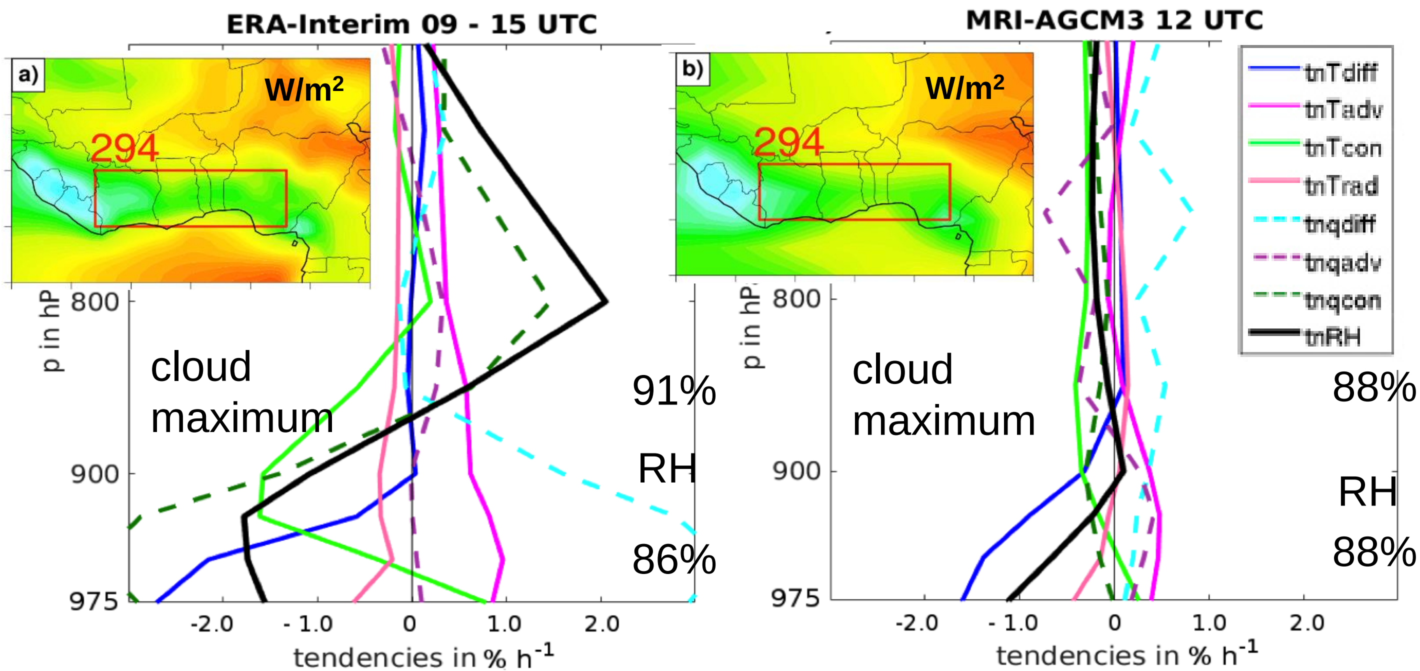
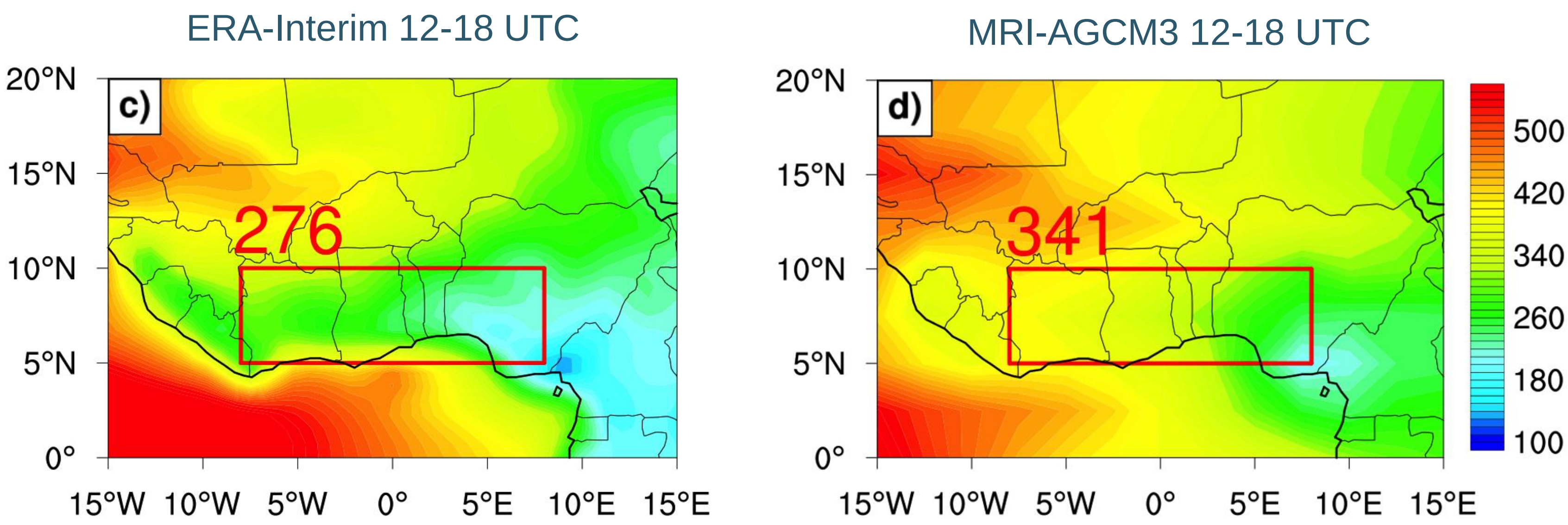
# Analysis of YOTC tendencies: Midday




Hannak et al. 2017

- Large differences in RH tendencies, e.g. due to shallow convection.
- ECMWF slightly more effective in upward transport of moisture and cloud generation.
- Yet, surface net shortwave radiation 6–12 UTC (inset) very similar between the two models.

# Analysis of YOTC tendencies: Afternoon




Hannak et al. 2017

- Too little moistening at 850 hPa in MRI (see 12 UTC)
  - ➔ less afternoon cloud
  - ➔ more surface net radiation
  - ➔ delayed evening transition compared to observations
  - ➔ too low RH in the evening
  - ➔ bad starting conditions for nighttime low-cloud formation

# Conclusions

- Low clouds over southern West Africa important.
- Hard to observe, but some promising new results.
- Climate models show large biases in low clouds and winds (often too high and diurnal cycle weak).
- Reasons include subgrid cloud scheme and daytime vertical transport of heat and moisture, leading to errors in cloud cover and surface solar radiation.

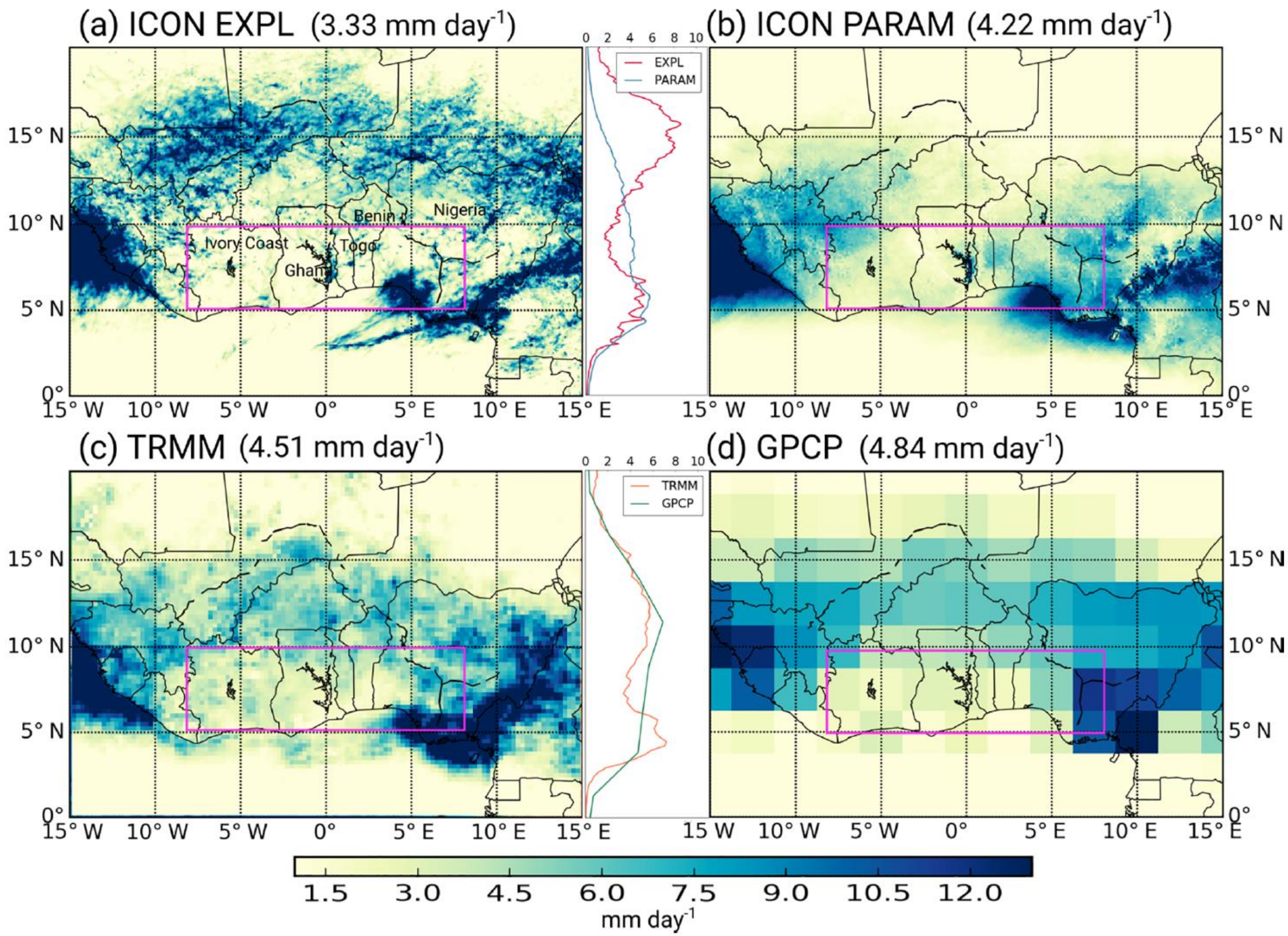
# Research questions

Q1: How important are the low clouds for the energy balance and rainfall in southern West Africa?

Q2: Do the low clouds affect neighbouring regions?

Q3: Does the sensitivity to low clouds depend on convective parametrization?

# Model evaluation – rainfall

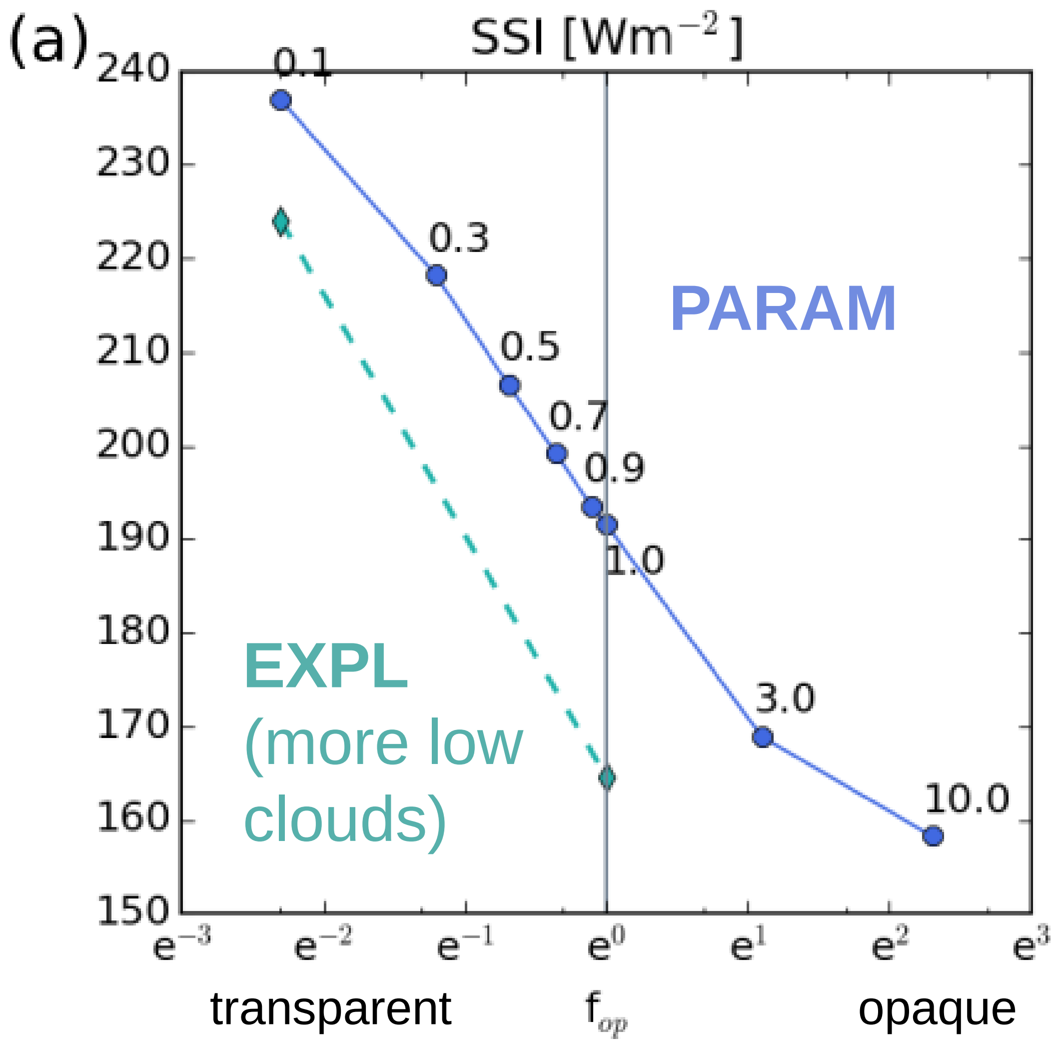



Source: Kniffka et al. (2019, ACP)

Q1: How important are the low clouds for the energy balance and rainfall in southern West Africa?

# Sensitivity – surface radiation

- Surface solar irradiance (SSI)
- Mean over DACCIWA box
- Day mean
- Varying opacity factor $f_{op}$

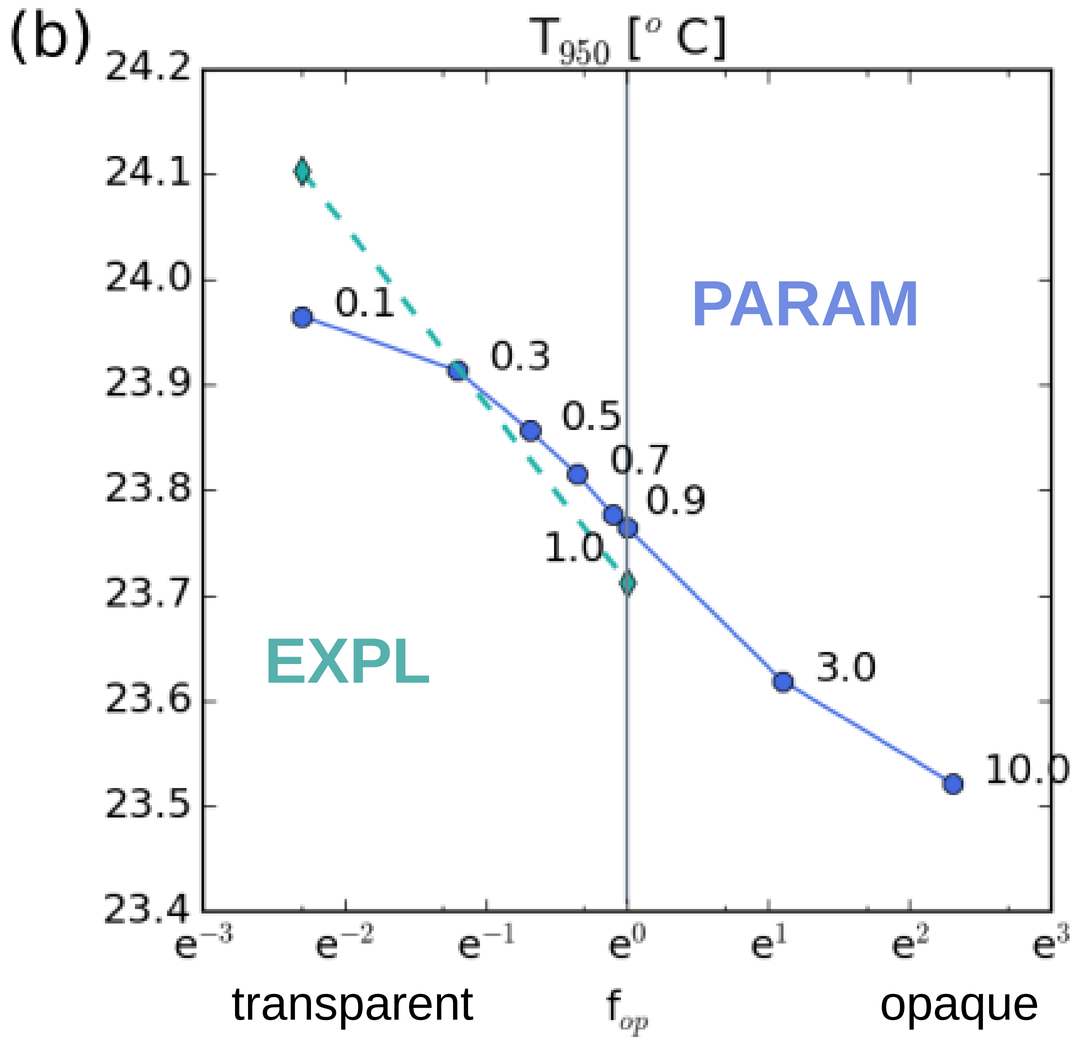



Source: Kniffka et al. (2019, ACP)

# Sensitivity – temperature

- Temperature at 950 hPa
- Mean over DACCIWA box
- Day mean
- Varying opacity factor $f_{op}$

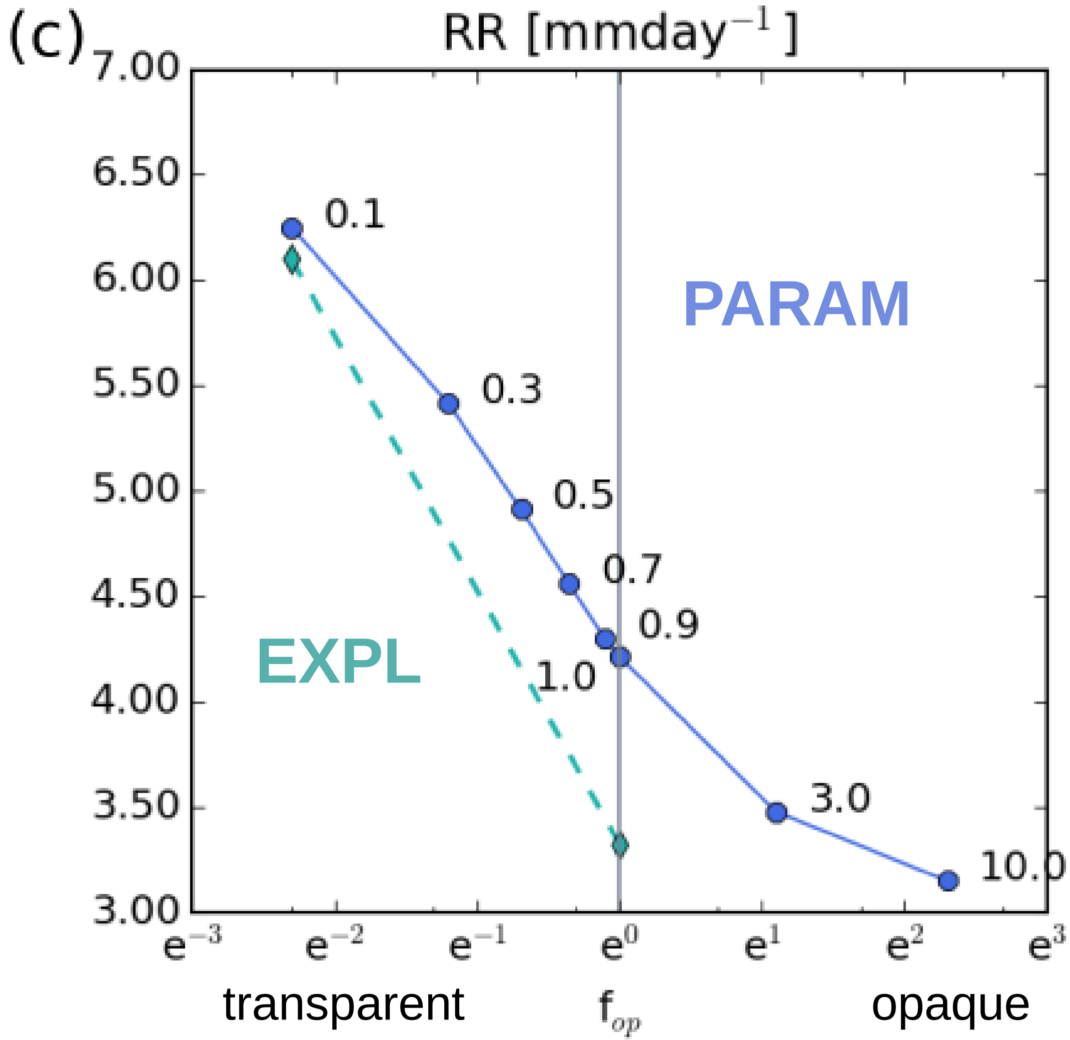
Source: Kniffka et al. (2019, ACP)



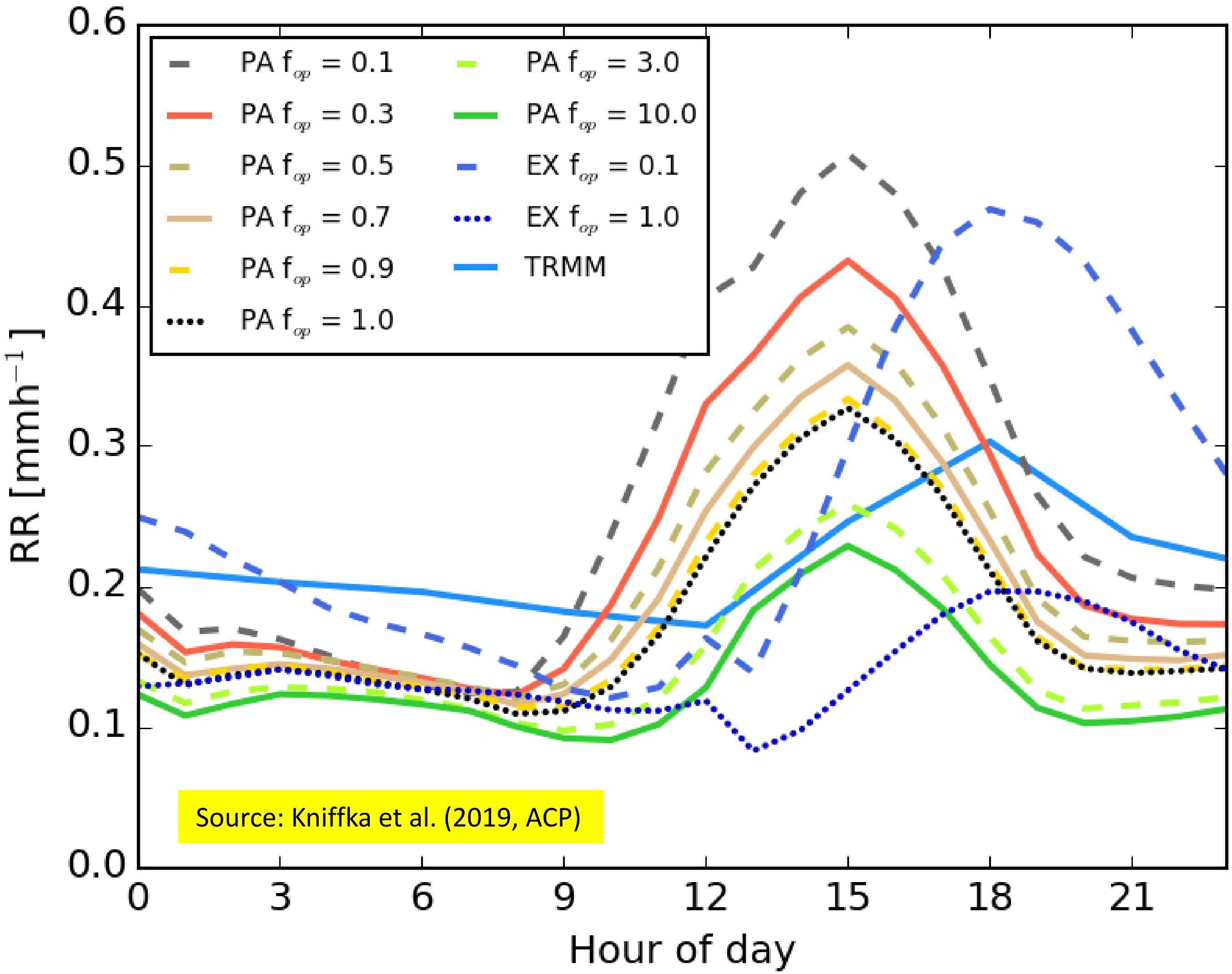
# Sensitivity – rainfall

- Rainfall (RR)
- Mean over DACCIWA box
- Day mean
- Varying opacity factor $f_{op}$

Source: Kniffka et al. (2019, ACP)



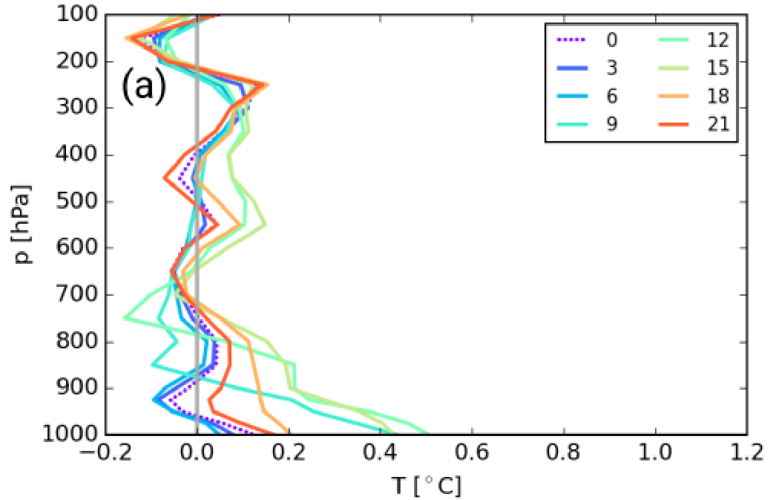
# Rainfall diurnal cycle



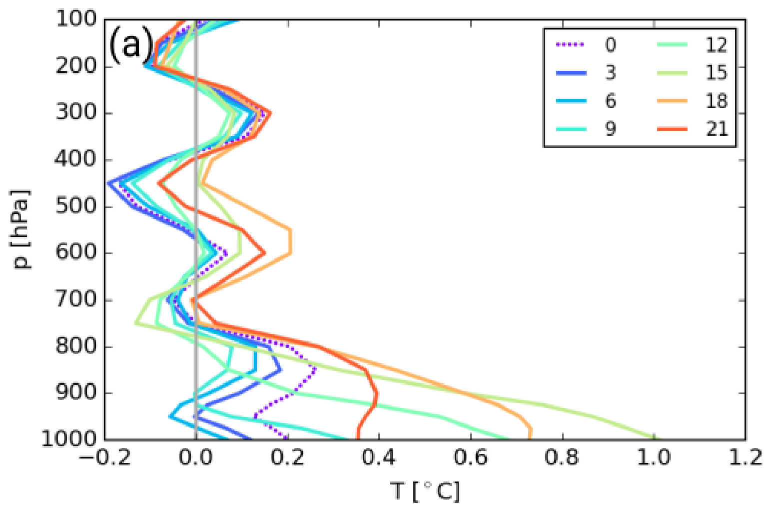
# Vertical profile – temperature

$f_{op} = 0.1$
minus
$f_{op} = 1.0$

Differences for PARAM




Differences for EXPL

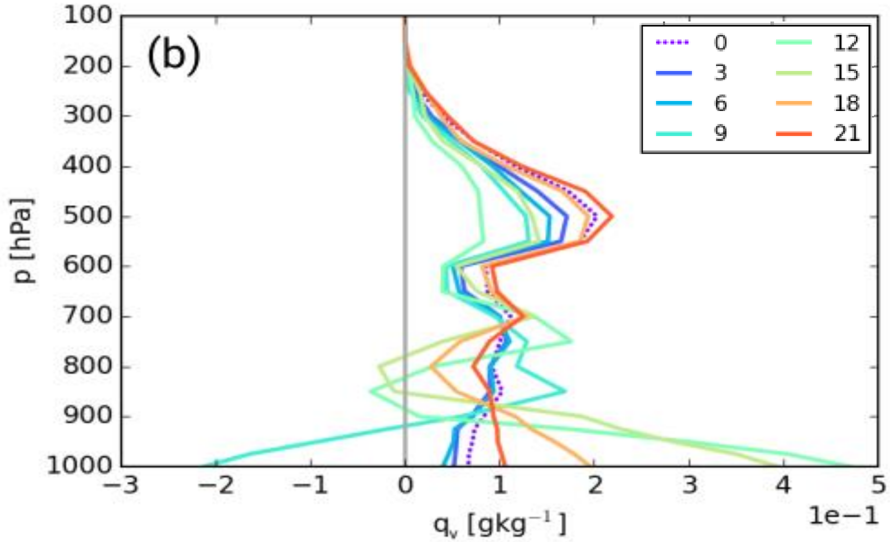



Source: Kniffka et al. (2019, ACP)

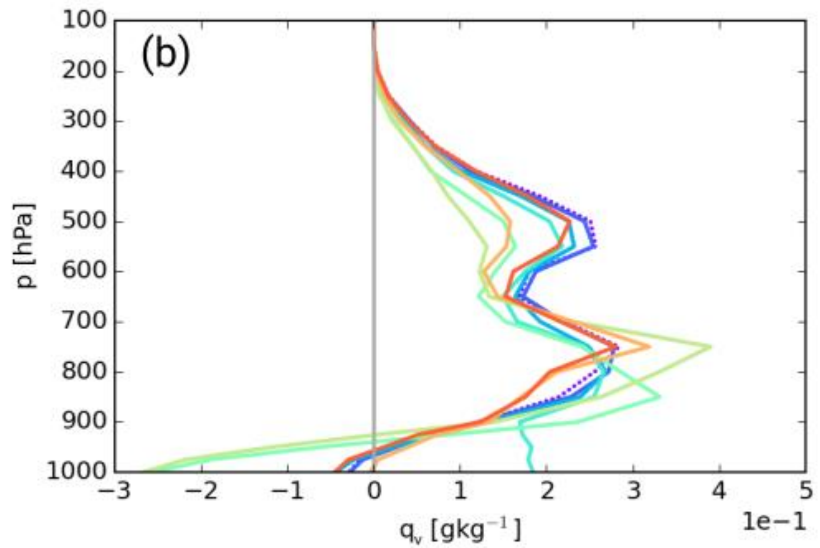
# Vertical profile – water vapor

$f_{op} = 0.1$
minus
$f_{op} = 1.0$

Differences
for PARAM




Differences
for EXPL

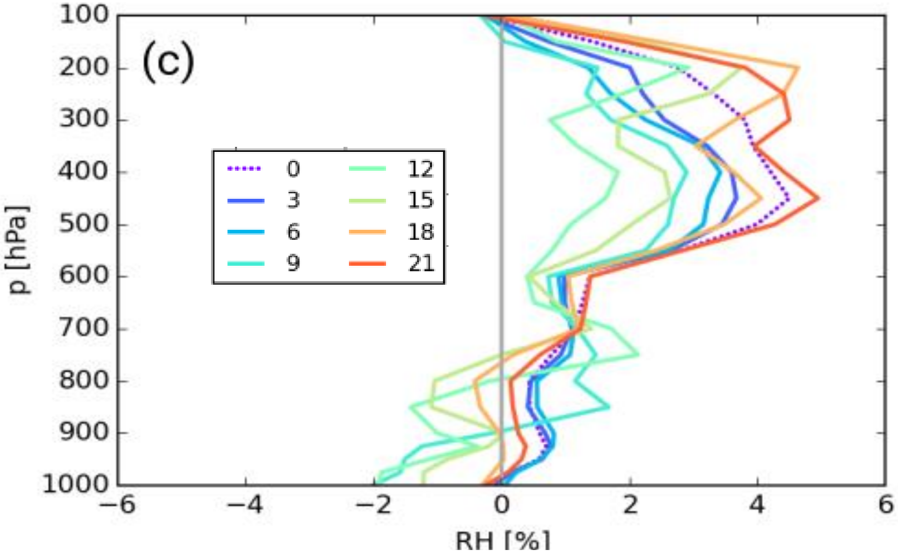



Source: Kniffka et al. (2019, ACP)

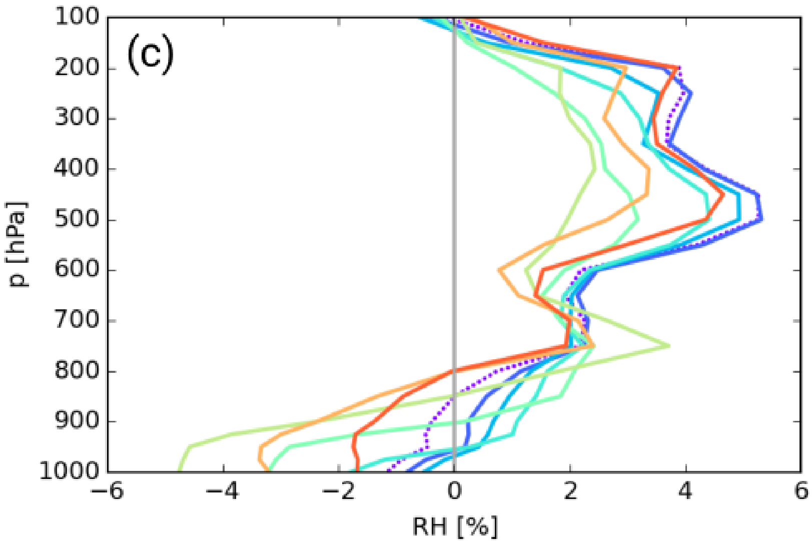
# Vertical profile – rel. humidity

$f_{op} = 0.1$
minus
$f_{op} = 1.0$

Differences for PARAM




Differences for EXPL

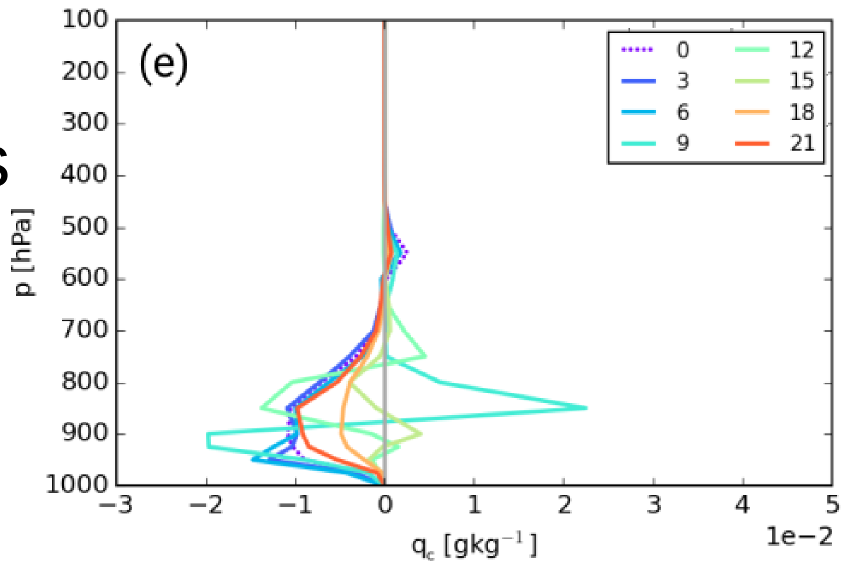



Source: Kniffka et al. (2019, ACP)

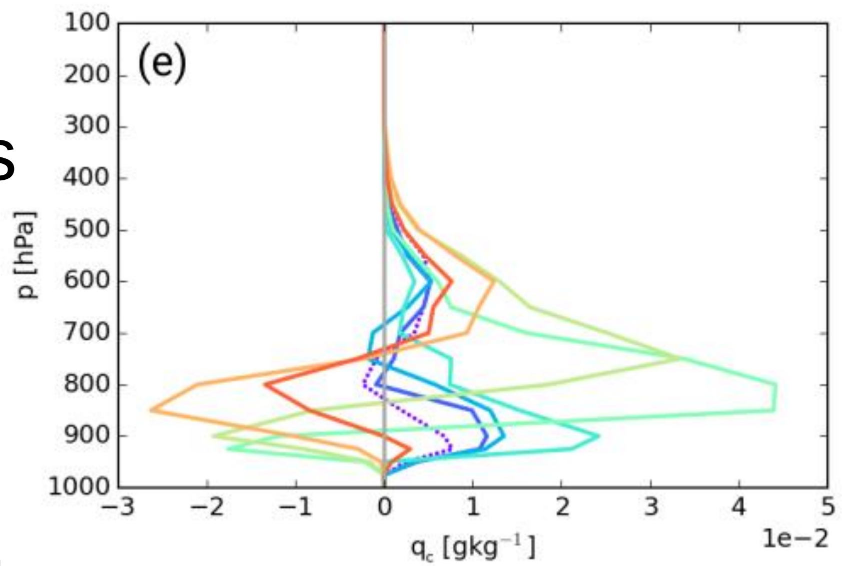
# Vertical profile – cloud water

$f_{op} = 0.1$
minus
$f_{op} = 1.0$

Differences for PARAM



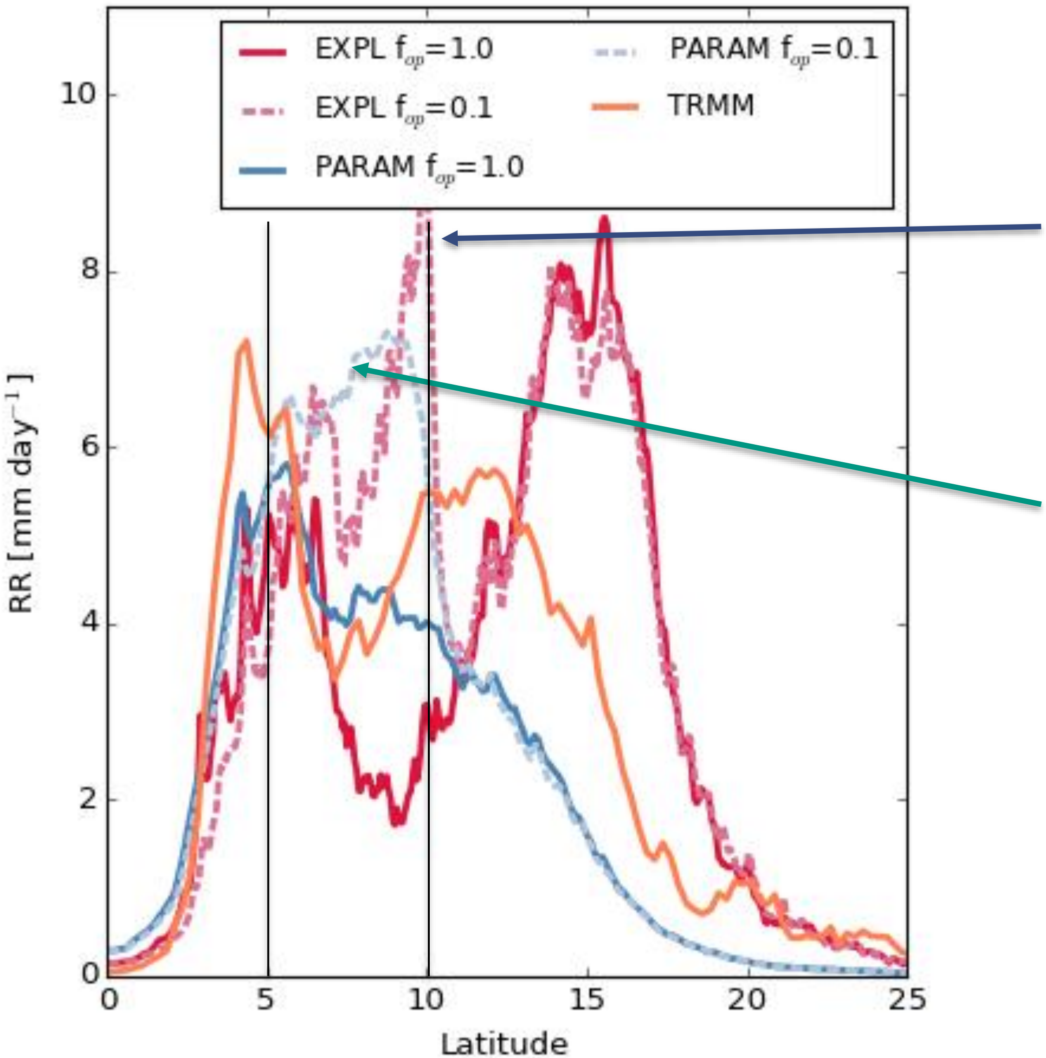

Differences for EXPL




Source: Kniffka et al. (2019, ACP)

# Q2: Do the low clouds affect neighbouring regions?

# Regional impact – rainfall



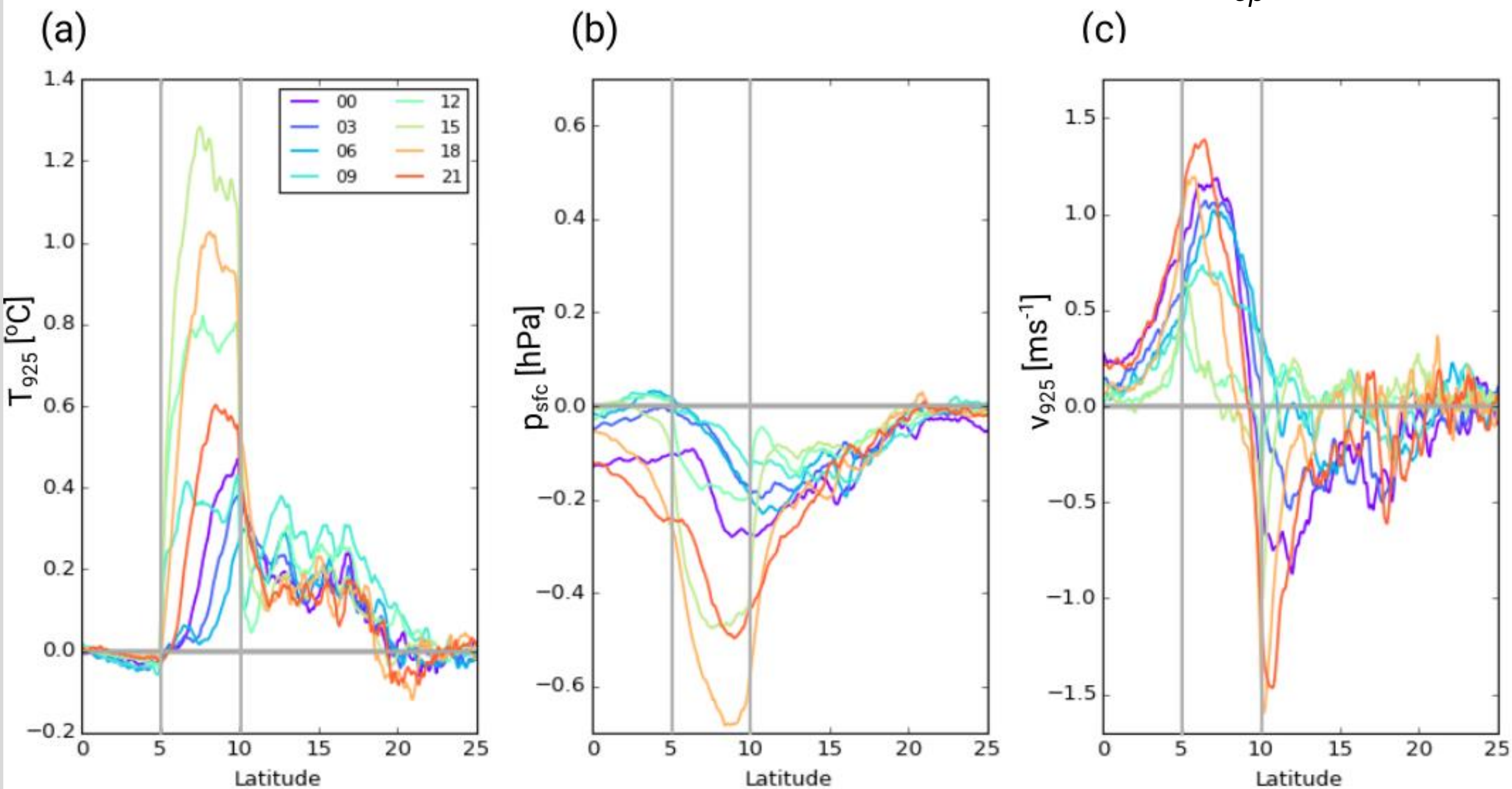

500% increase in **EXPL**

100% increase in **PARAM**

Source: Kniffka et al. (2019, ACP)

# Regional impact – EXPL

$f_{op}$ = 0.1
minus
$f_{op}$ = 1.0




Source: Kniffka et al. (2019, ACP)

# Regional impact – EXPL

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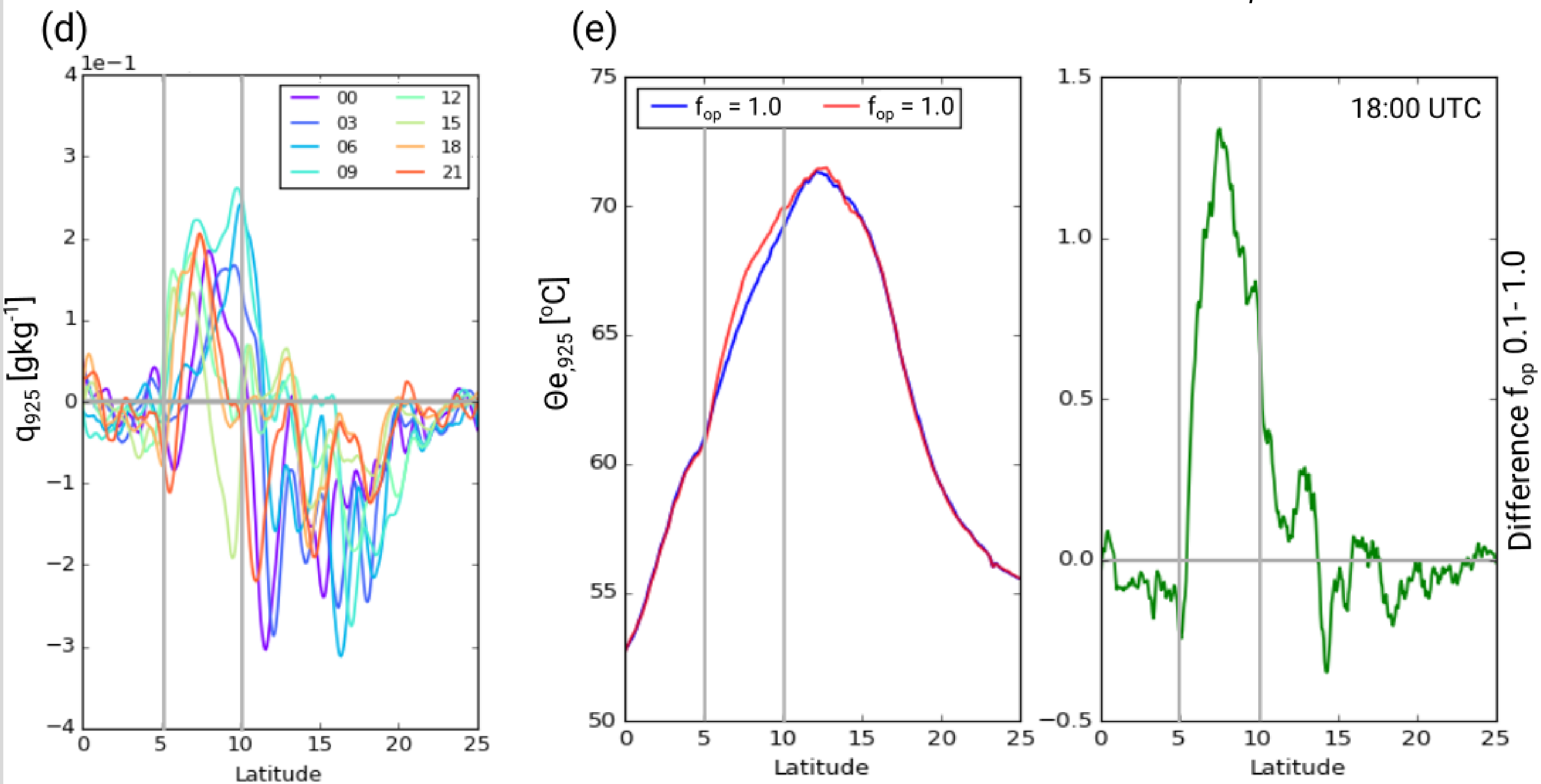
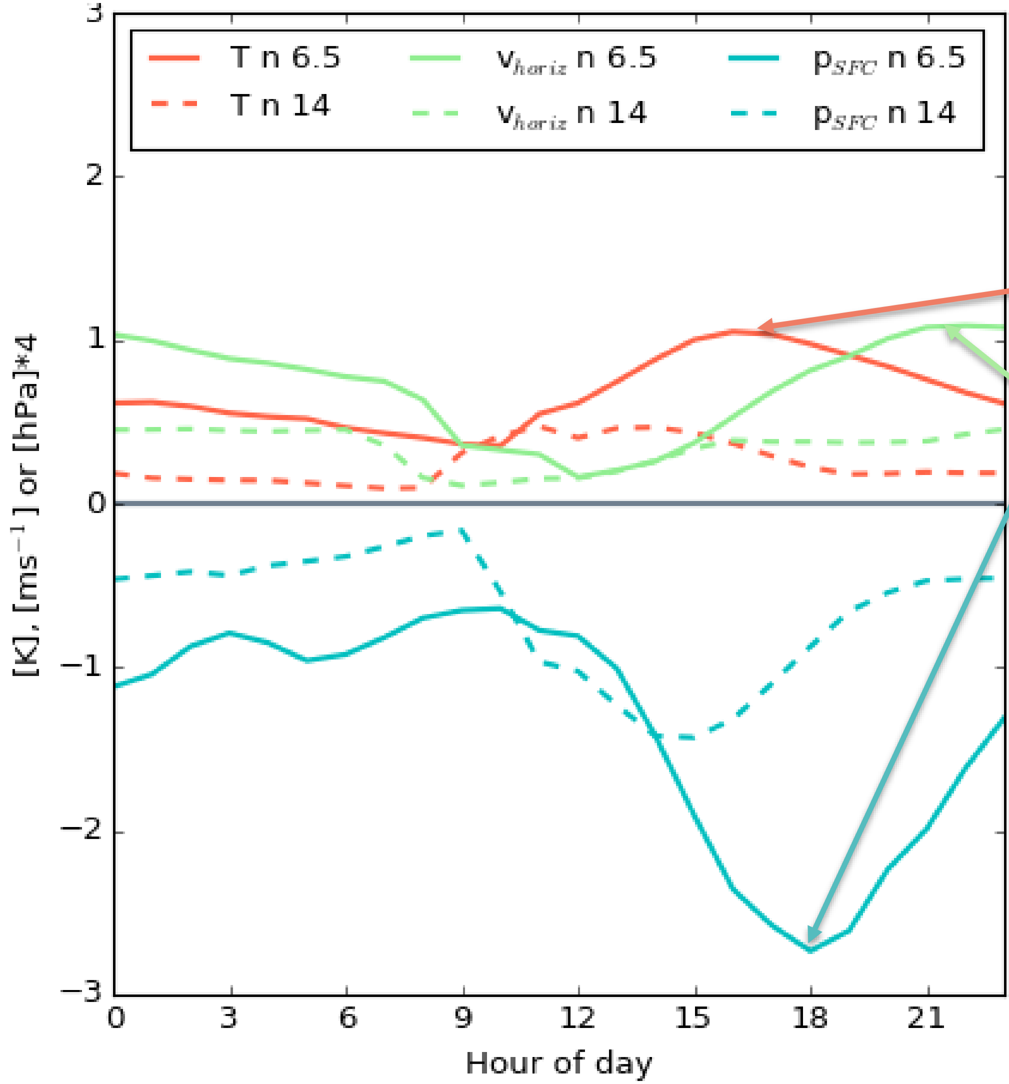



Source: Kniffka et al. (2019, ACP)

# Diurnal max – EXPL vs. PARAM




EXPL shows clear succession of
– temperature max
– pressure min
– wind max

Too early convection in PARAM destroys this!

Source: Kniffka et al. (2019, ACP)

# Conclusions

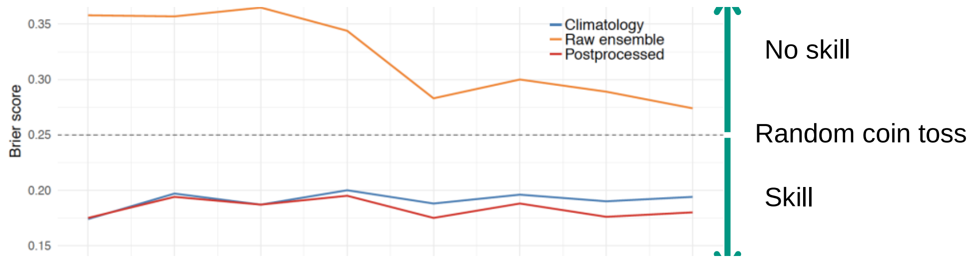
**Q1: How important are the low clouds for the energy balance and rainfall in southern West Africa?**
Very important! They control PBL development and convection. Similar effect from aerosol changes?!

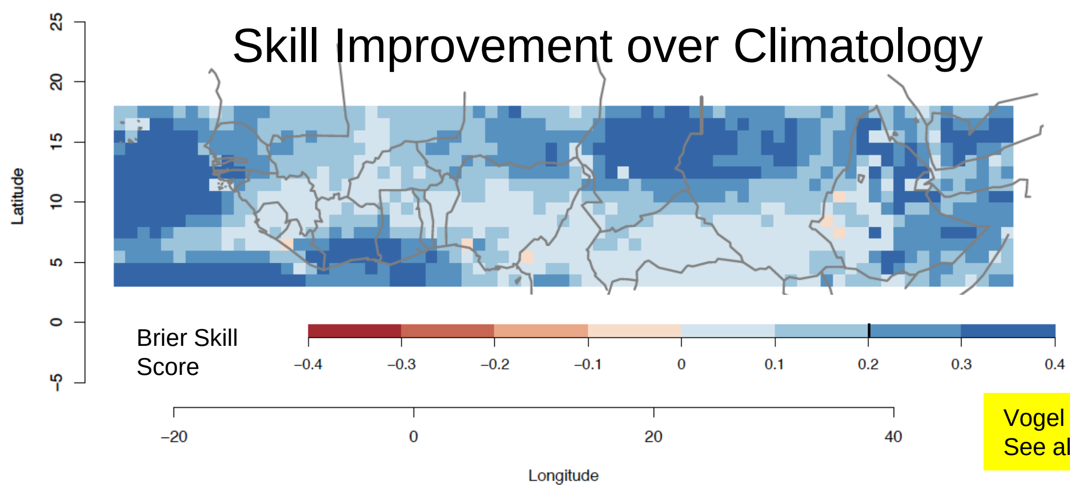
**Q2: Do the low clouds affect neighbouring regions?**
Not much due to compensating effects of temperature and moisture.

**Q3: Does the sensitivity to low clouds depend on convective parametrization?**
Yes! PARAM less sensitive with too early diurnal cycle

# Promising: Statistical & statistical-dynamical methods

ECMWF Ens. Fcst 24-h, PoP (0, 2mm), North Africa



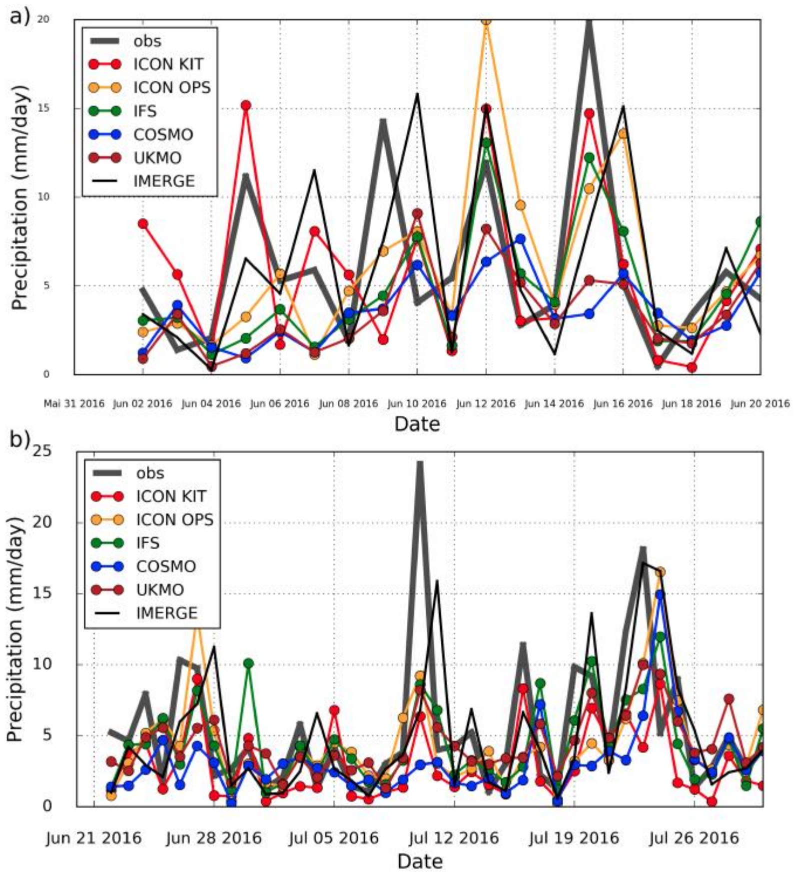




A "simple" logistic regression model based on spatio-temporal correlations of precipitation in West Africa substantially improves skill of Probability of Precipitation (PoP) forecasts over climatology.

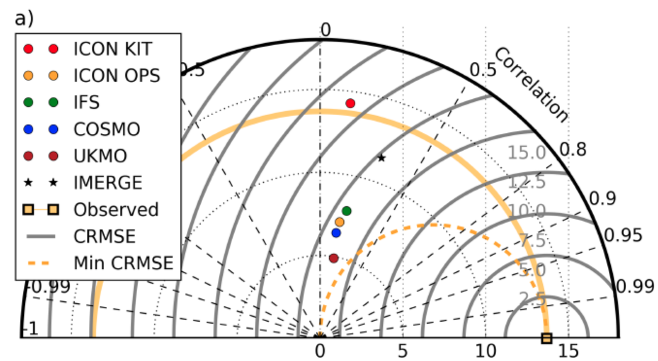
Vogel et al. 2019b, in prep.
See also Vogel et al. (2018, WAF)

# When strong larger-scale (e.g. Synoptic/tropical wave forcing) is present, skill in rainfall predictions is higher

Rainfall over DACCIWA region




Taylor diagram




Kniffka et al., submitted to QJRMS

# Summary

- GCMs and NWP models have various deficiencies over (West) Africa
- One central problem is the poor representation of (organized) convection in coarse resolution models
- High-resolution models do a better job, especially with respect to the diurnal cycle of rainfall and the whole monsoon system
- Yet, these models have deficiencies in amount and locations of rainfall
- Other problems are related to warm SST bias in GCMs, dust and low-level cloud representation
- The latter might be related to deficiencies in daytime boundary layer representation
- Lack of low level clouds changes characteristics of rainfall, but effect not seen in Sahel
- Some hope for improving rainfall forecast is by using skill in large-scale predictable wave features in statistical/machine learning approaches