Understanding and Modeling Mesoscale Convective Systems and related Precipitation Extremes in West Africa: Where do we stand?

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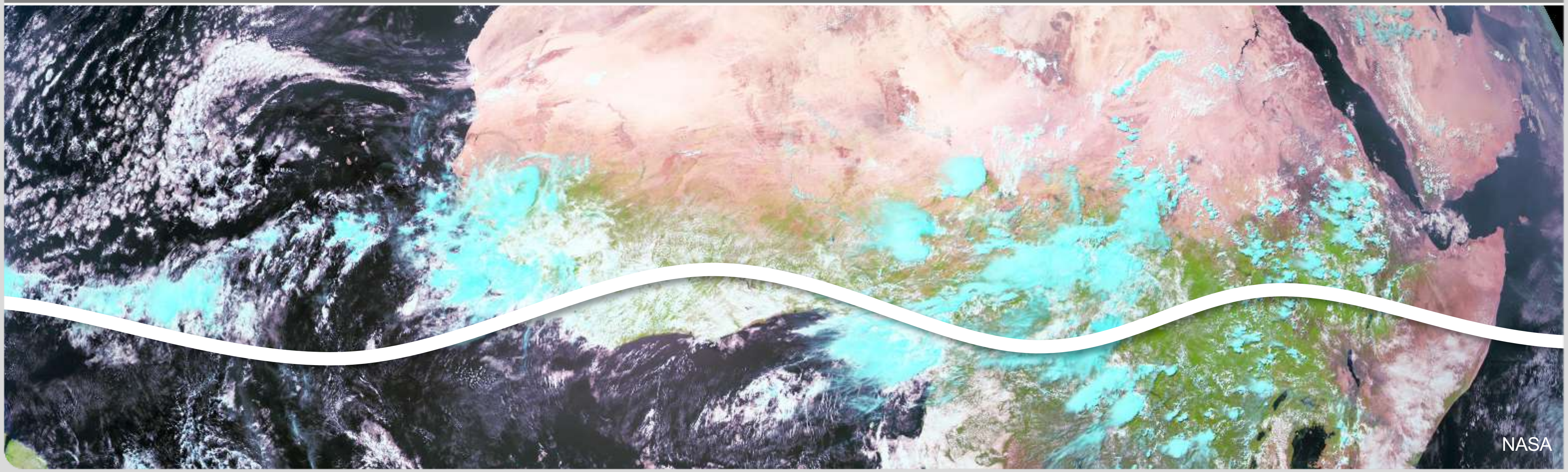
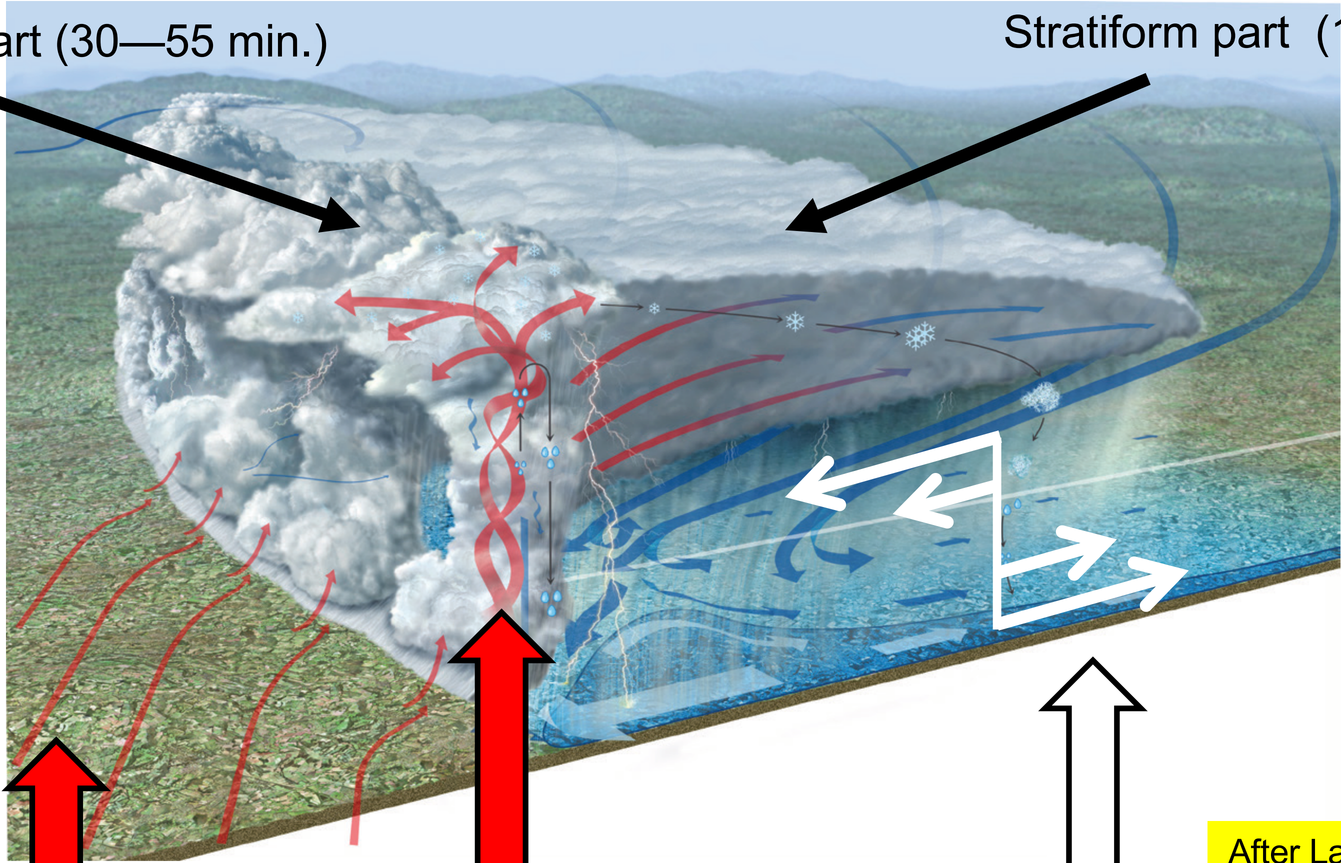
3rd Workshop on Cloud Organisation and Precipitation Extremes - WCO3 , Trieste, 04–08. Sept. 2023



Squall Lines: The main rain-bearing weather system in the Sahel

Convective part (30—55 min.)

Stratiform part (1-4 hrs)



After Lafore et al (2017)

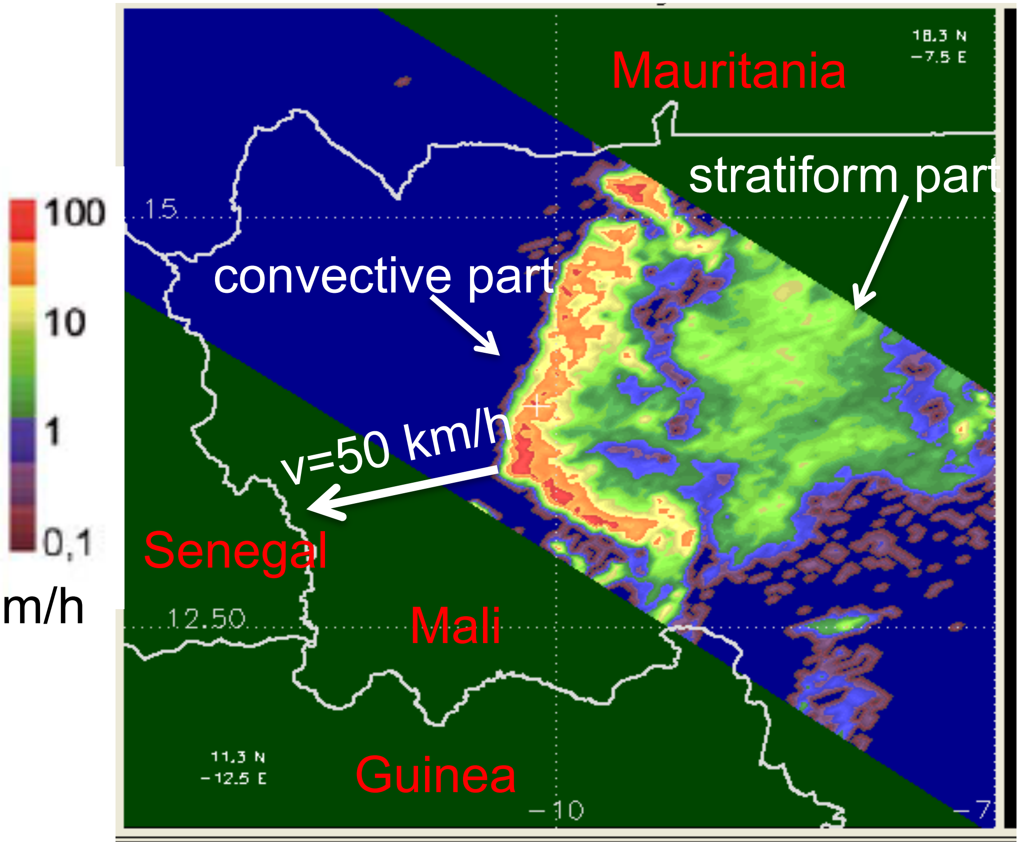
Low-level moist southwesterly monsoon flow

High CAPE (Convective Available Potential Energy) realized by lifting of monsoon air by cold pool

High easterly wind shear and dry air inflow enhances cold pool generation

A "classical" Sahelian squall line

Rain rates mm/h, 07 Sept. 2002 21:45



after Fink (2006)

- Fast (~50 km/h) propagating system with convective part & trailing stratiform part
- CAPE is "zeroed" after passage
- Rainfall totals limited due to fast propagation (~20-70 mm per system)

The Ouaga 2009 case: Rainfall

Gauge-Interpolated rainfall, 31 Aug. 2009

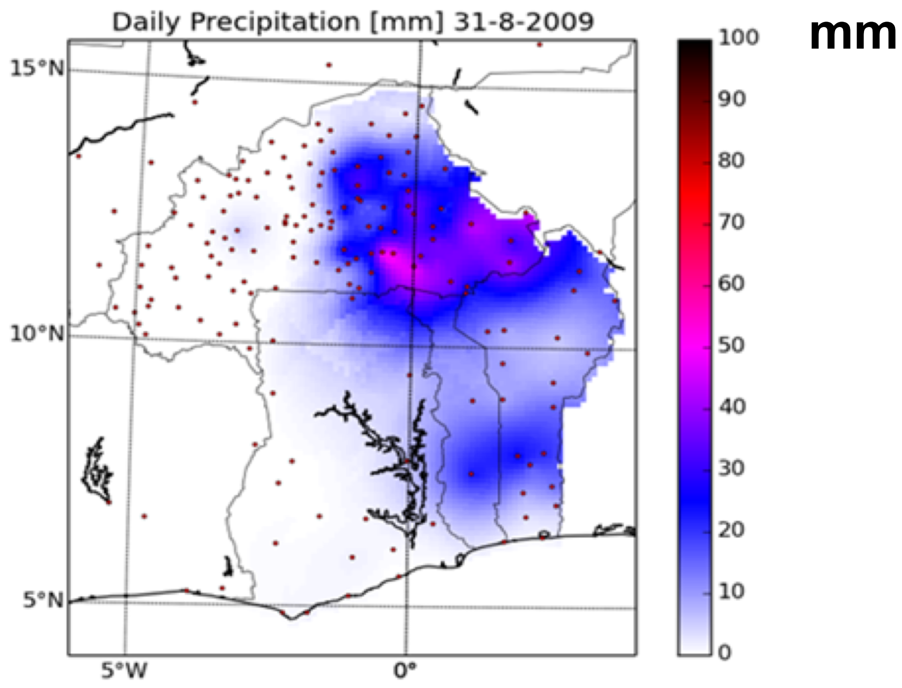
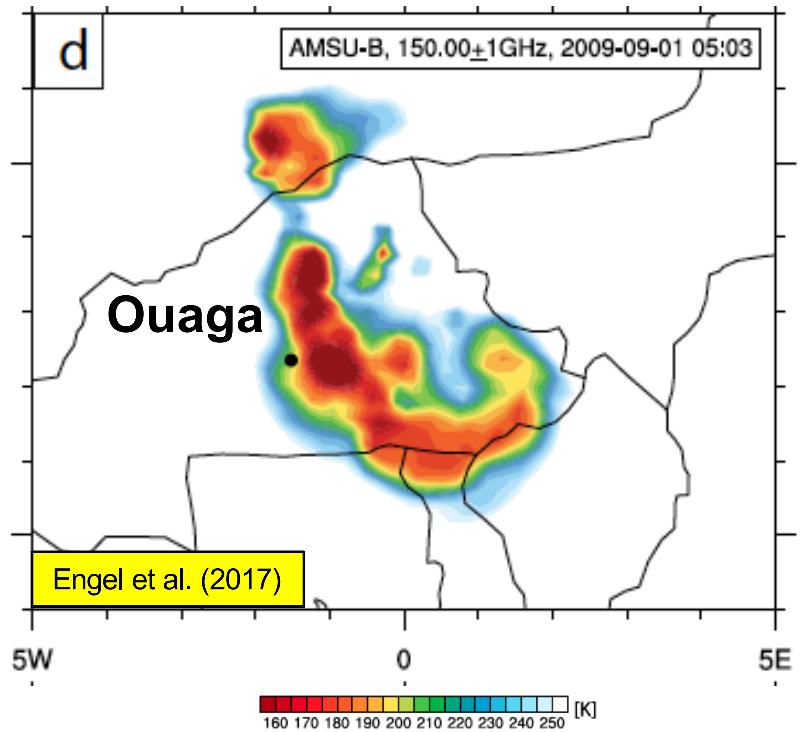


Figure courtesy of Jan Bliefernicht (Univ. Augsburg)

150 GHz MW brightness temperature (01 Sept. 2009 05:03 UTC)

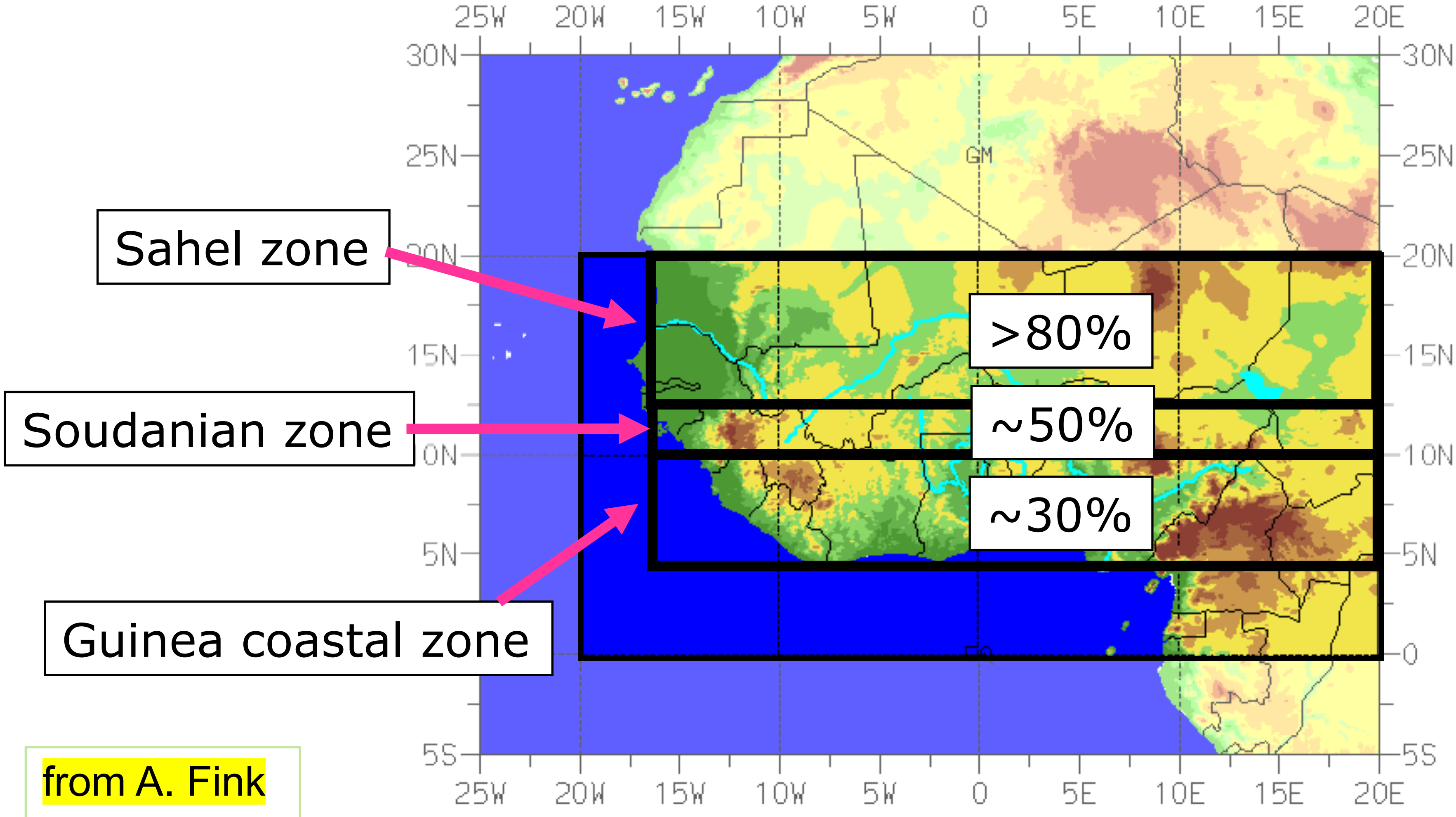


Engel et al. (2017)

- The Mesoscale Convective System (MCS) was a “classical” squall line upstream (to the east) of Ouagadougou (total rain 20-70 mm)

Climatological MCSs relevance

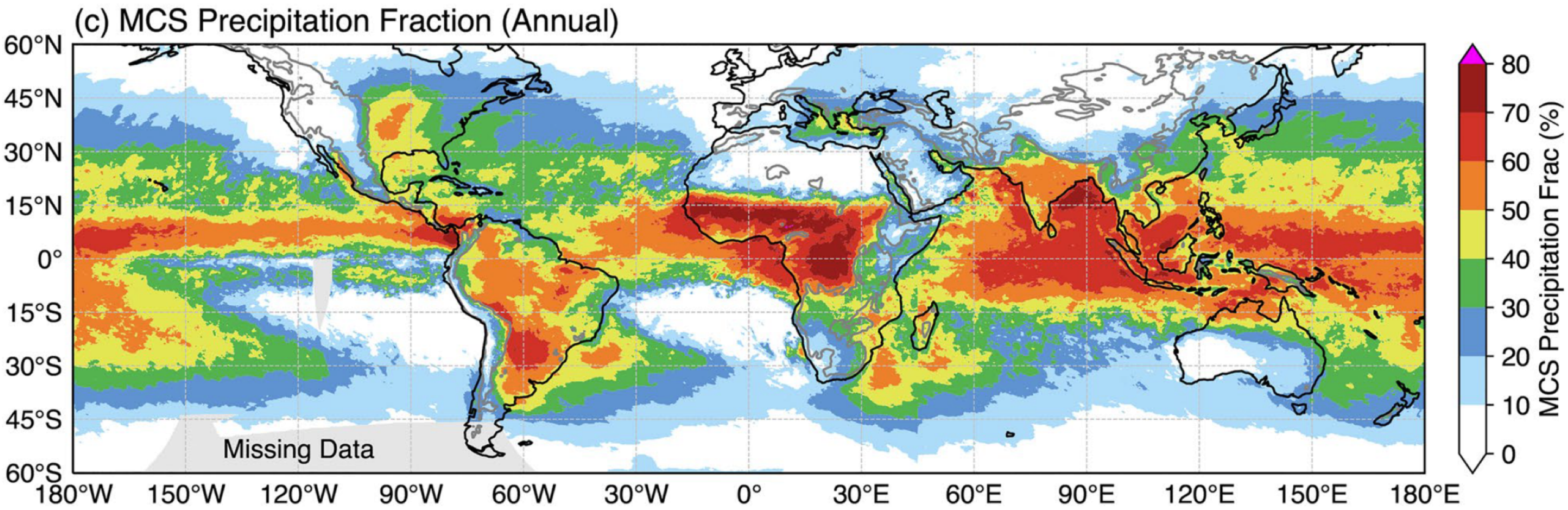
Estimated contribution of squall lines to annual total rainfall
(from various publications)



from A. Fink

Climatological relevance

Estimated contribution of Mesoscale Convective Systems (MCSs) to annual total rainfall



Note: the Feng et al. (2021) uses GPM IMERG and IR Brightness temperature to identify and track MCSs.

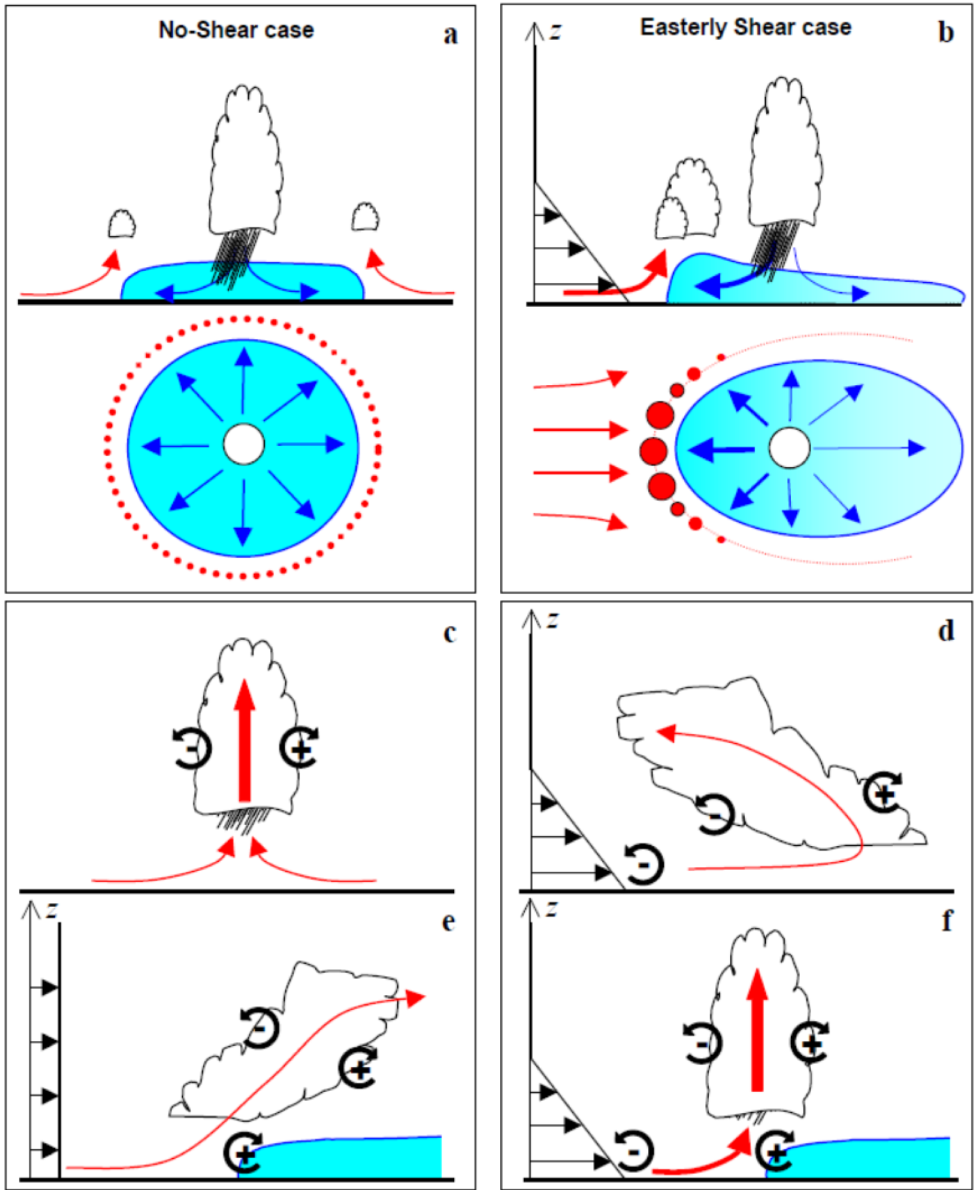
Feng et al. (2021)

Environmental factors known to make (Sahelian) Squall Lines (Mesoscale Convective Systems) more likely and/or more intense:

(Low-level*) wind shear

* Mostly 600–925 hPa

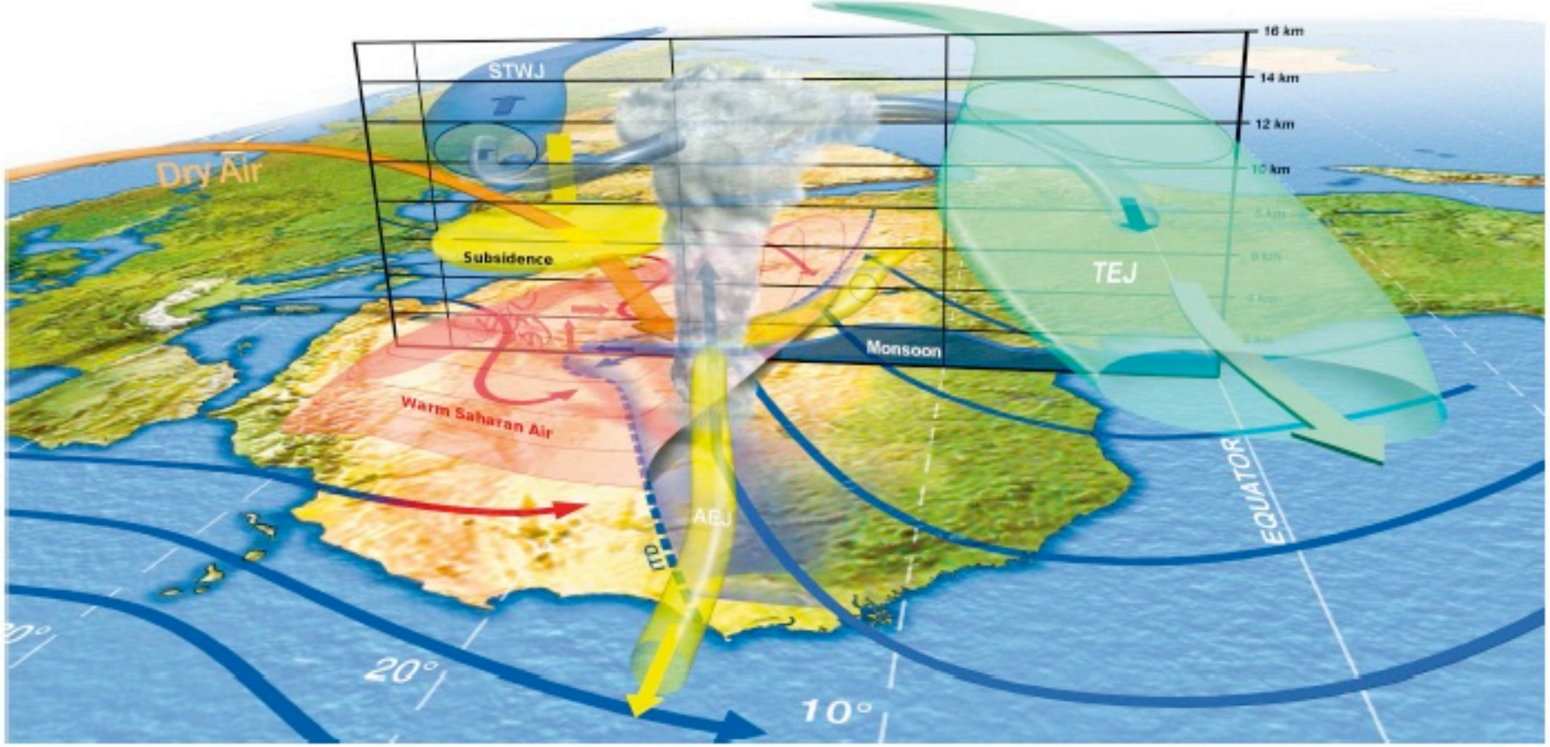
Effects of shear on convection



Lafore et al. (2017)

- Asymmetric lateral spreading favors new cells downshear: panels (a) vs (b).
- Classical Rotunno et al. (1988) argument: Tilted updraft and upright udraft at head of cold pool: panels (c,e) vd (d,f).
- Strong low-level shear favors broad updrafts that are less vulnerable to dry air entrainment (e.g. Mullholand et al. (2021)

The West African monsoon system

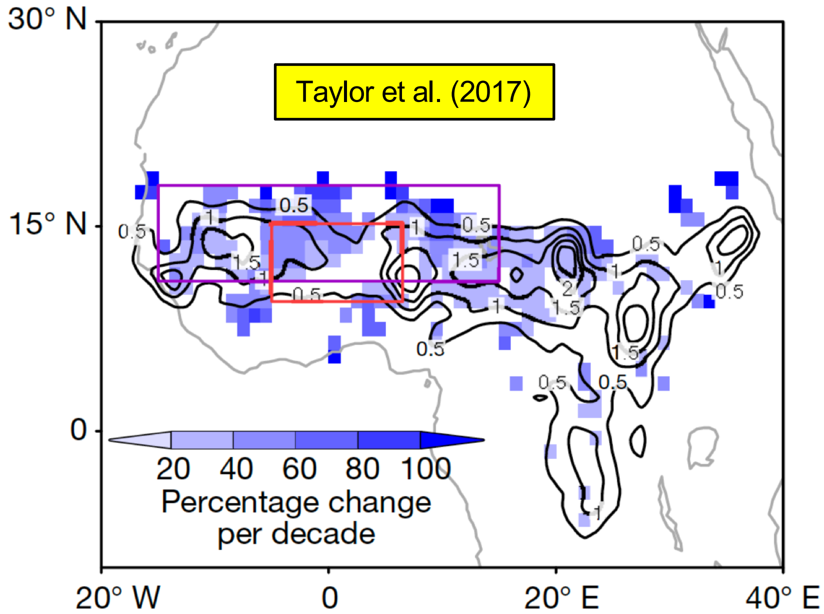


Lafore et al. (2011)

The thermally driven African Easterly Jet (AEJ) provide basic low-level (mostly unidirectional) shear that is modulated by African Easterly Waves (AEW).

Role of low-level shear for SLs/MCS

Trends in the coldest MCS over the Sahel, 1982-2015



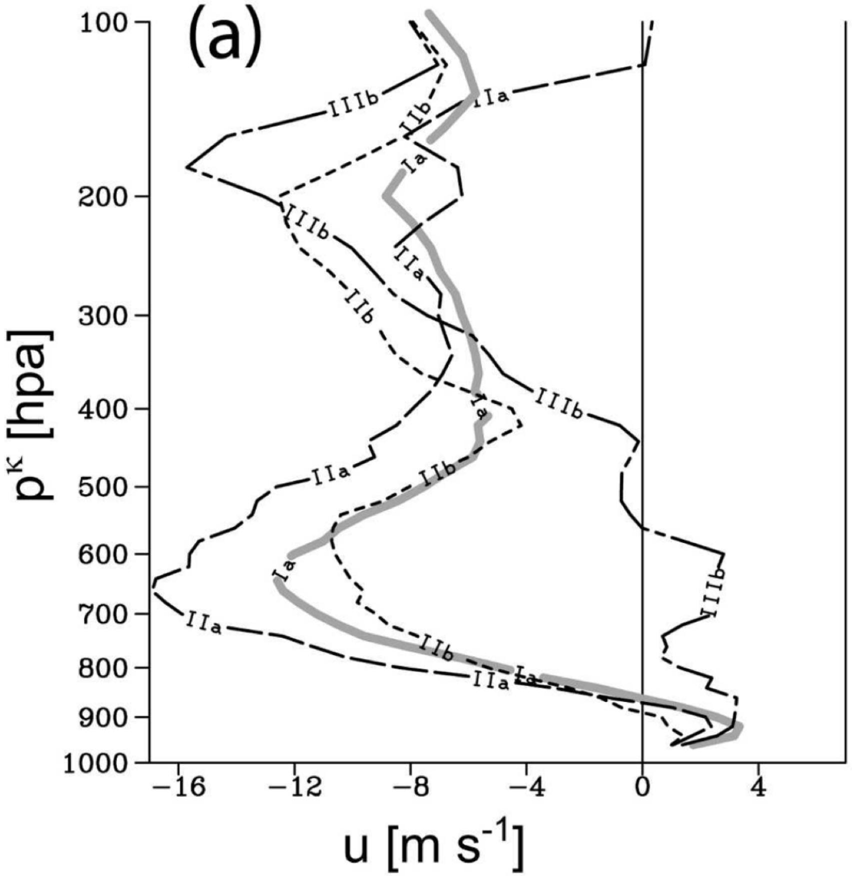
Case type	AEJ speed (m s^{-1})	AEJ height (m)	LL shear ($\times10^{-3}$; s^{-1})	ML shear ($\times10^{-4}$; s^{-1})	DL shear ($\times10^{-4}$; s^{-1})
Nonintense	9.4	2970	−2.8	−2.8	9.7
Intense	11.6	3180	−4.4	−3.3	9.6
p value	**<0.01**	**0.01**	*<0.01*	0.46	0.48

Nicholls and Mohr (2010)

- Distinction between roles for SL/MCS occurrence and rainfall intensity necessary, but often not considered.
- Forecasters use shear for MCS occurrence.
- Some studies suggest a (climatological) relation to intensity (Taylor et al. 2017) others find a week relation (Nicholls and Mohr, 2010).

Role of low-level shear for SLs/MCSs

Radiosonde profiles, Parakou (9°N), 2002
before passage of rainfall systems

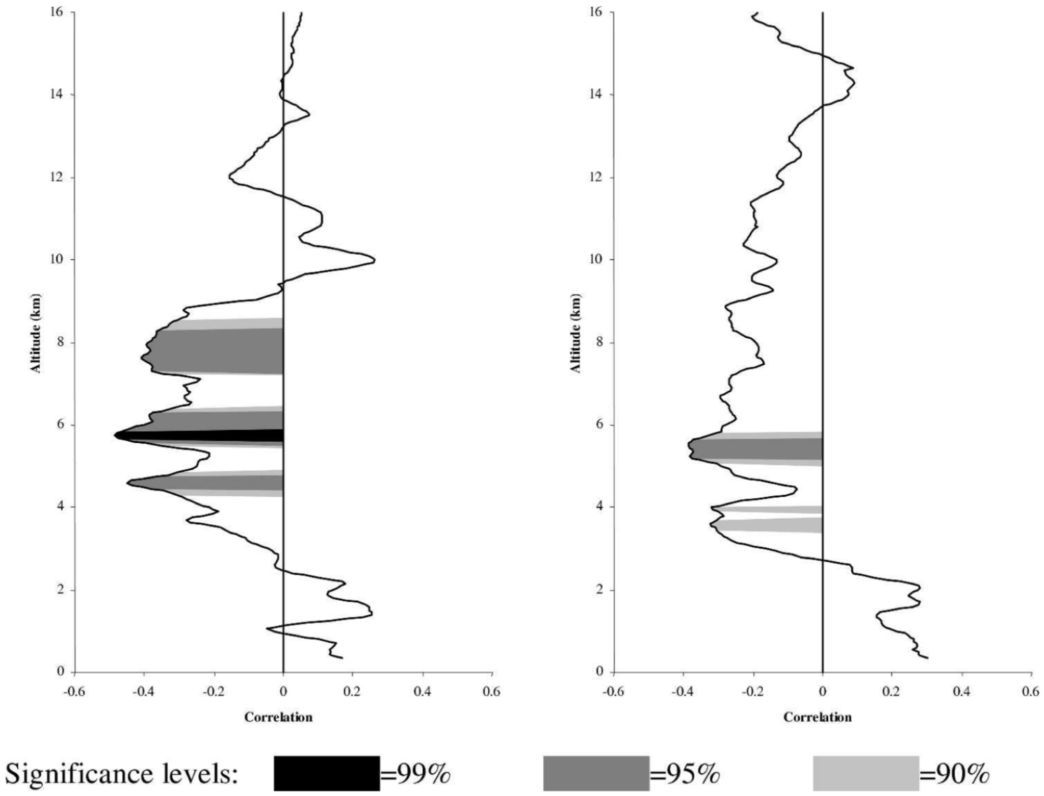


Ia: remotely developing cold/fast MCSs
IIa: locally developing cold/fast MCSs
IIb: locally developing warmer/slower MCSs
IIIb: Vortey-related rainfall

- There appears to be a relation between shear strength and occurrence/propagation speed of the MCSs/SLs
- South of the Sahel, MCSs/SLs are slower have a lower longevity
- In the southern latitudes, vortex-related rainfall gets more important

Fink et al. (2006)

Role of low-level shear for SLs/MCSs



Schrage and Fink (2007)

- Speed of rainfall system determined by a dense raingauge network
- Low mid-level humidities in radiosonde data best correlated with forward speed

Role of shear/humidity for SLs/MCSs

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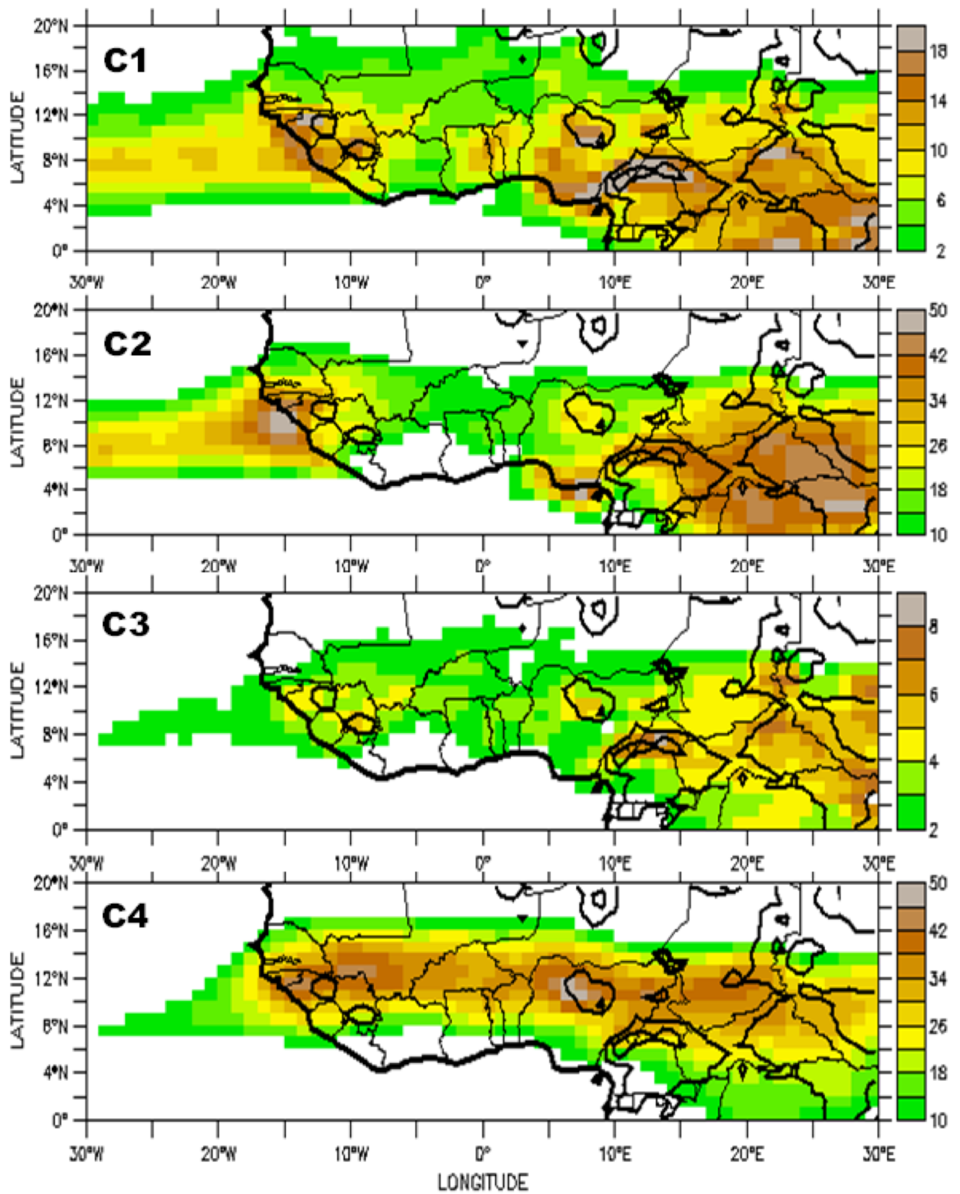


C1 *= slow+short-lived;*
C2 *= slow+long-lived;*
C3 *= fast+short-lived;*
C4 *= fast+long-lived;*

slow/fast *is a translation speed < ≥ 10 m/s*

short-lived/long-lived *is a lifetime < ≥ 9 h*

Lafore et al (2017)

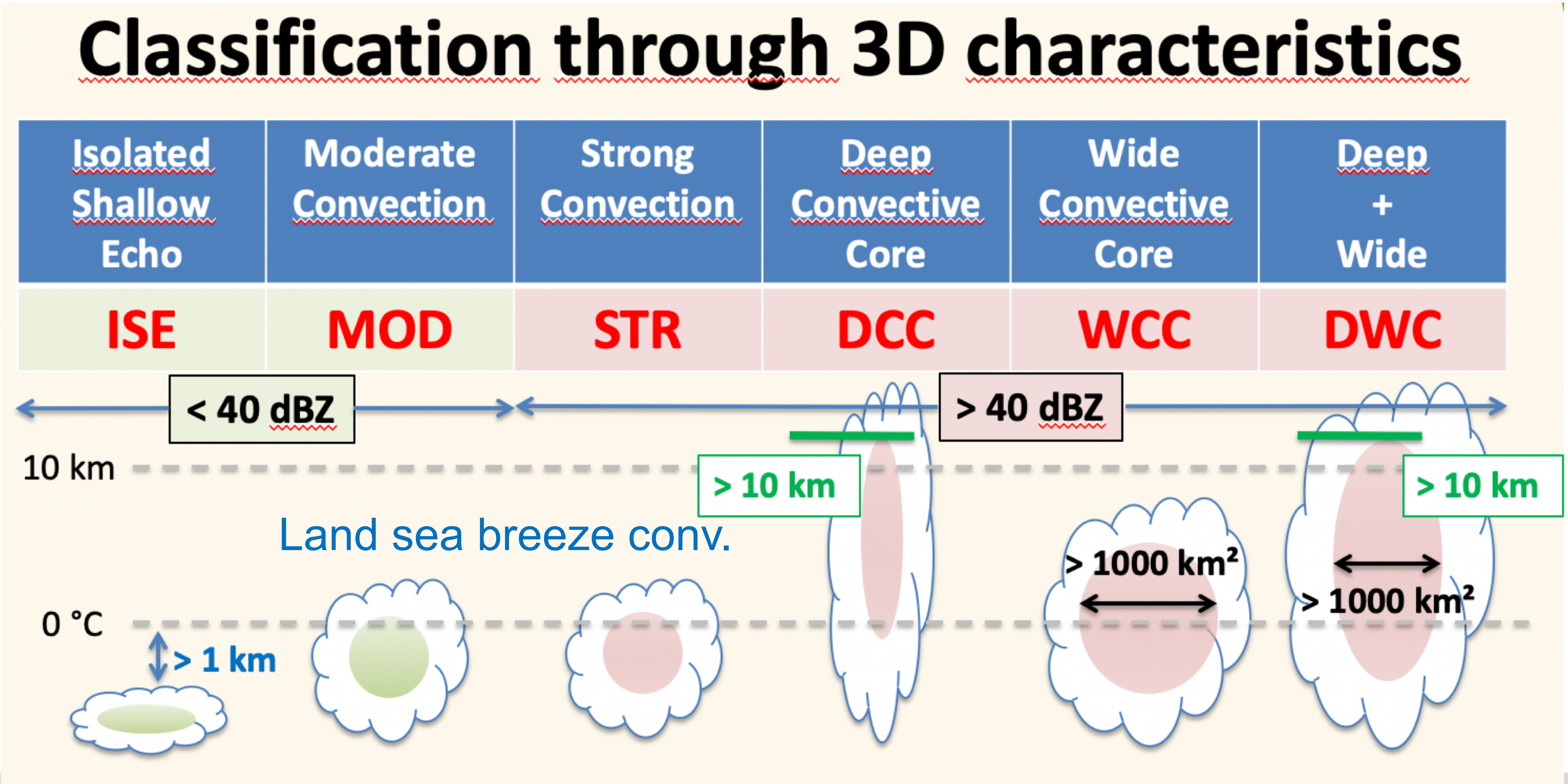
WAVES TO WEATHER

What other organised and not-organised convective systems do occur in West Africa?

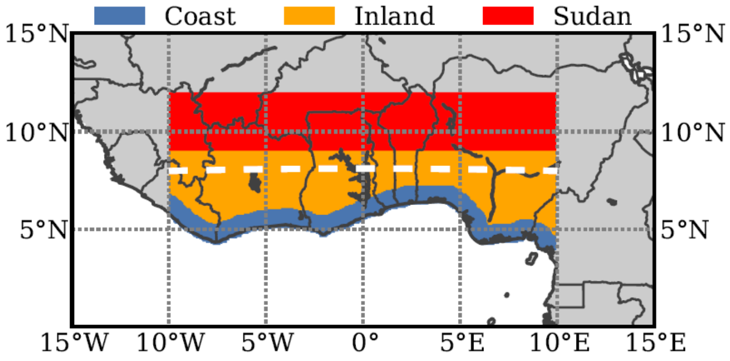
Classification of Rainfall Types in southern West Africa

- Based on Houze et al. (2015)
- Data: TRMM-PR products (Level 2) with e.g. 3D rainfall reflectivity field
- Period: 1998 – 2013

Maranan et al. (2018)

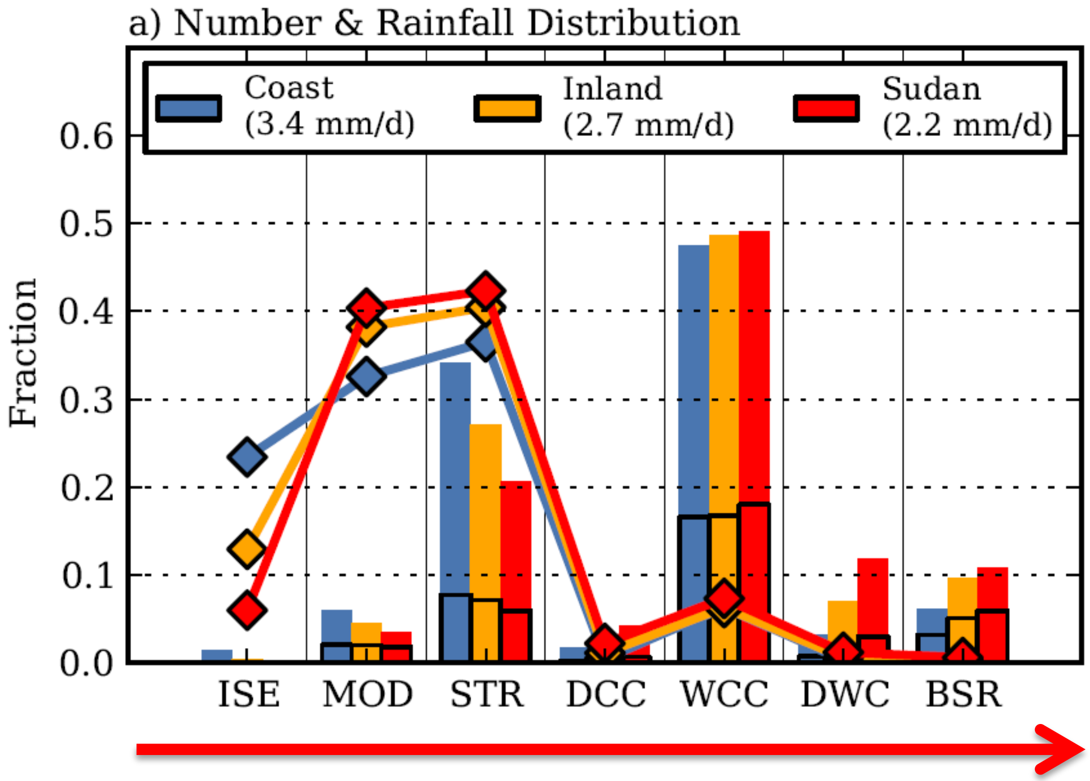


Rainfall Types: Fractional # & amount



- **Period: 1998-2013**
- *Number distribution (lines)*
- *Rainfall contribution (bars)*

- MCSs strongly outnumbered by weaker convection (-> 90%)
- Highest rainfall contribution from MCSs in all subregions…
- However, contribution decreases southwards towards the coast

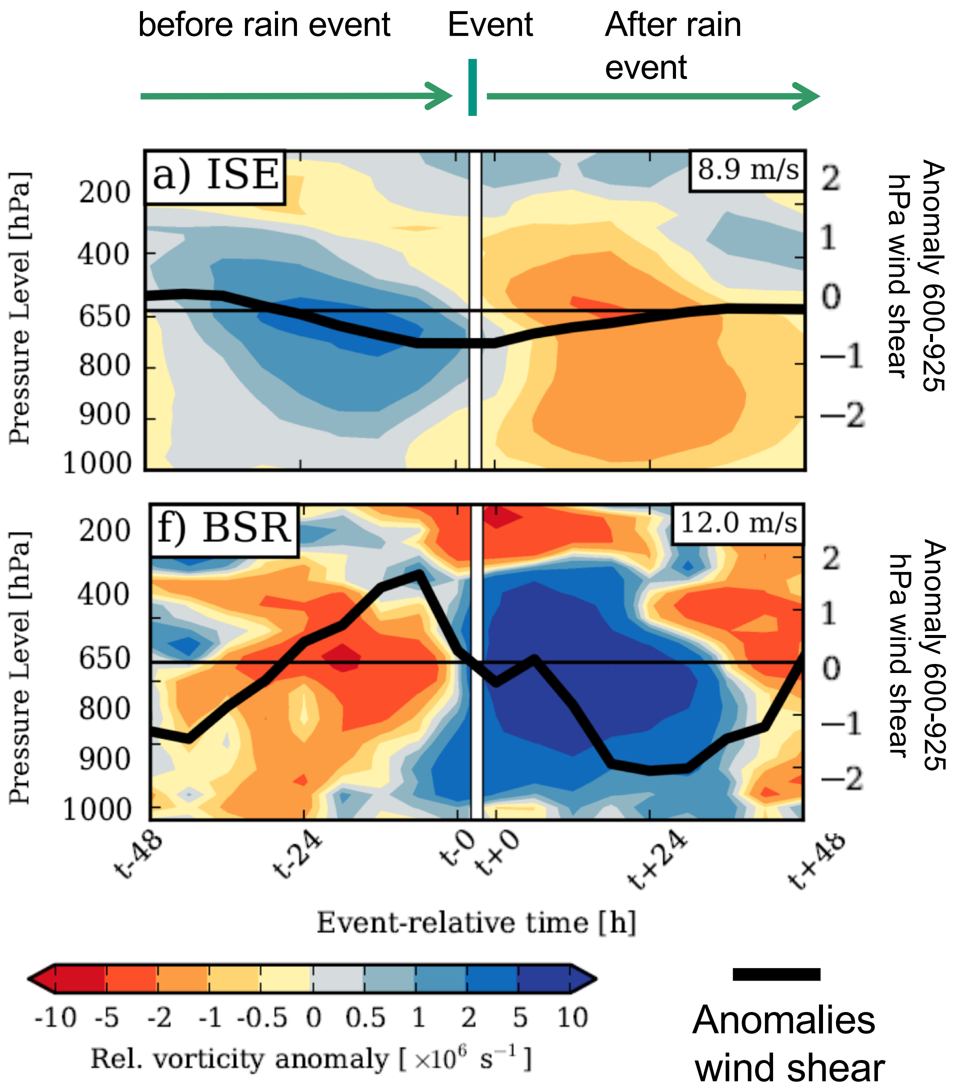


Diurnal convection	Young/Mature MCS
44% - 29%	56% - 71%

Contribution to total rainfall

Maranan et al. (2018)

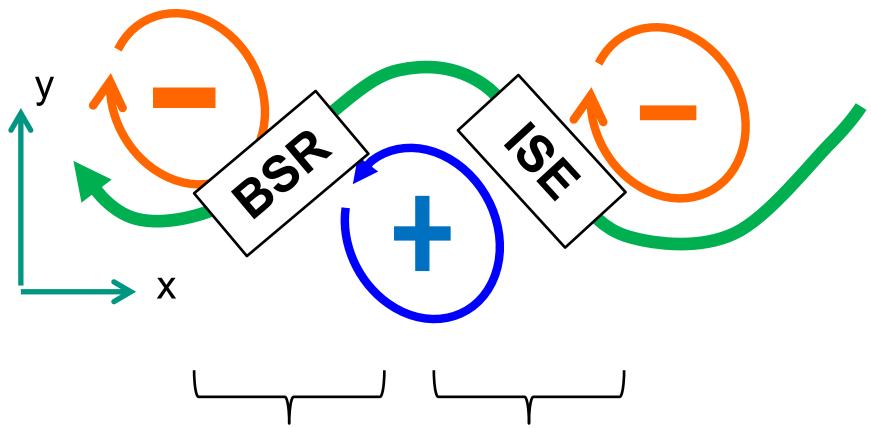
Rel. Vorticity & vertical wind shear



Relative Vorticity:

$$\zeta = \vec{k} \cdot (\nabla \times \vec{v}) \begin{cases} > 0 & \text{cyclonic} \\ < 0 & \text{anticyclonic} \end{cases}$$

Middle Troposphere (~650 hPa):
African Easterly Waves (AEWs)



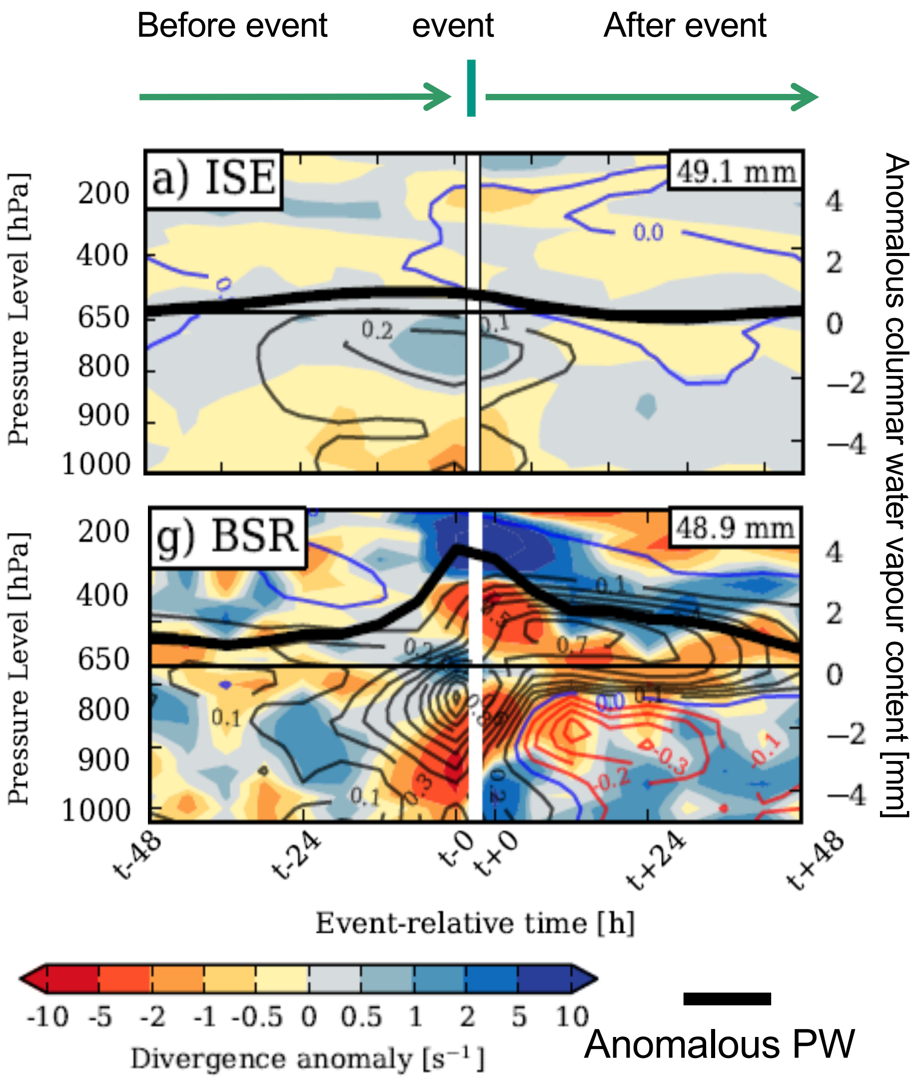
Enhanced vertical wind shear

Decreased vertical wind shear

After Maranan et al. (2018)

DACCIWA

Moisture convergence



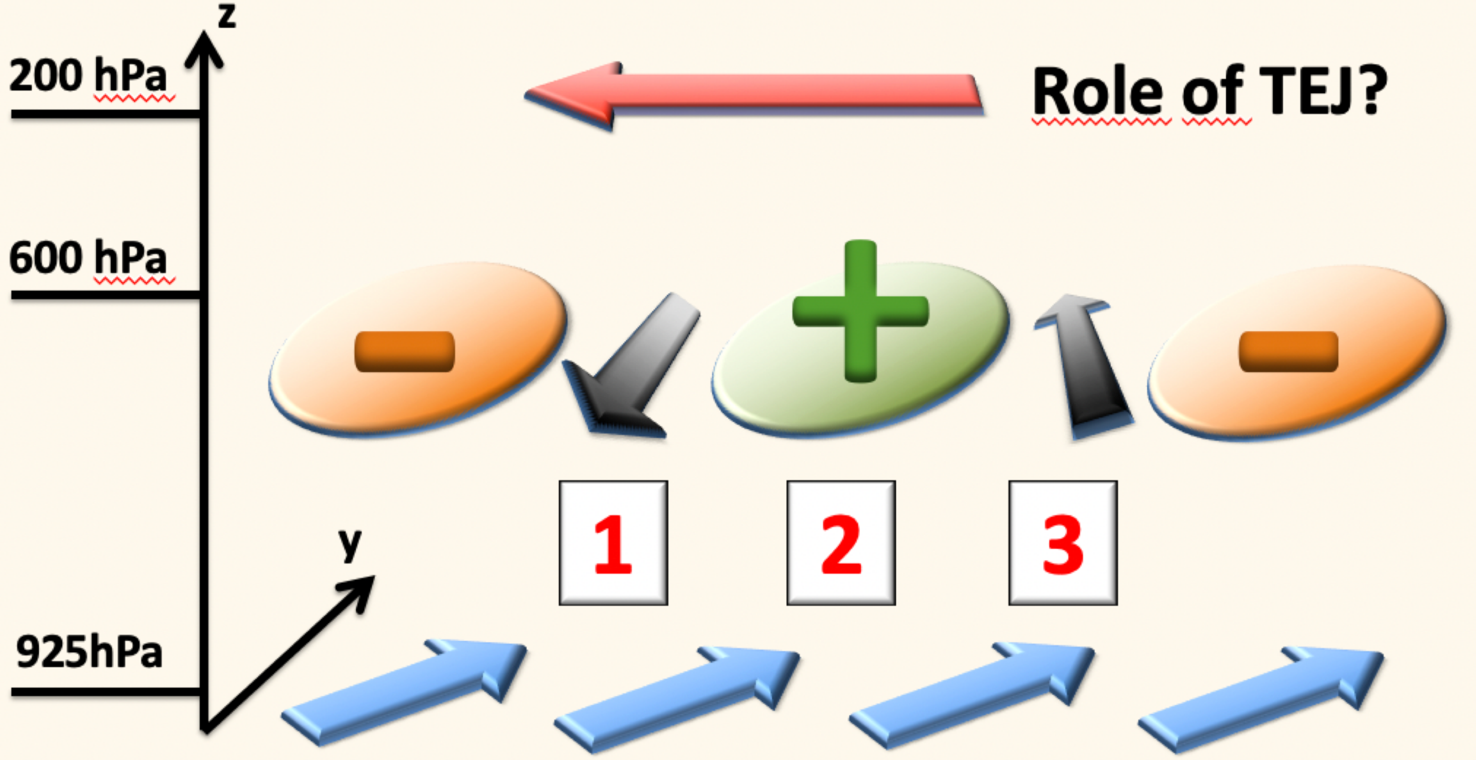
Divergence:

$$\nabla \cdot \vec{v} \begin{cases} > 0 & \text{Divergence} \\ < 0 & \text{Convergence} \end{cases}$$

- Low-level, convergent flow related to increase in specific humidity atop (black contours)
- Consequence: Increase in columnar precipitable water (PW, bold black line)
- Largest anomalies with BSRs

After Maranan et al. (2018)

Synoptic-scale regimes of the TRMM-PR based rainfall types

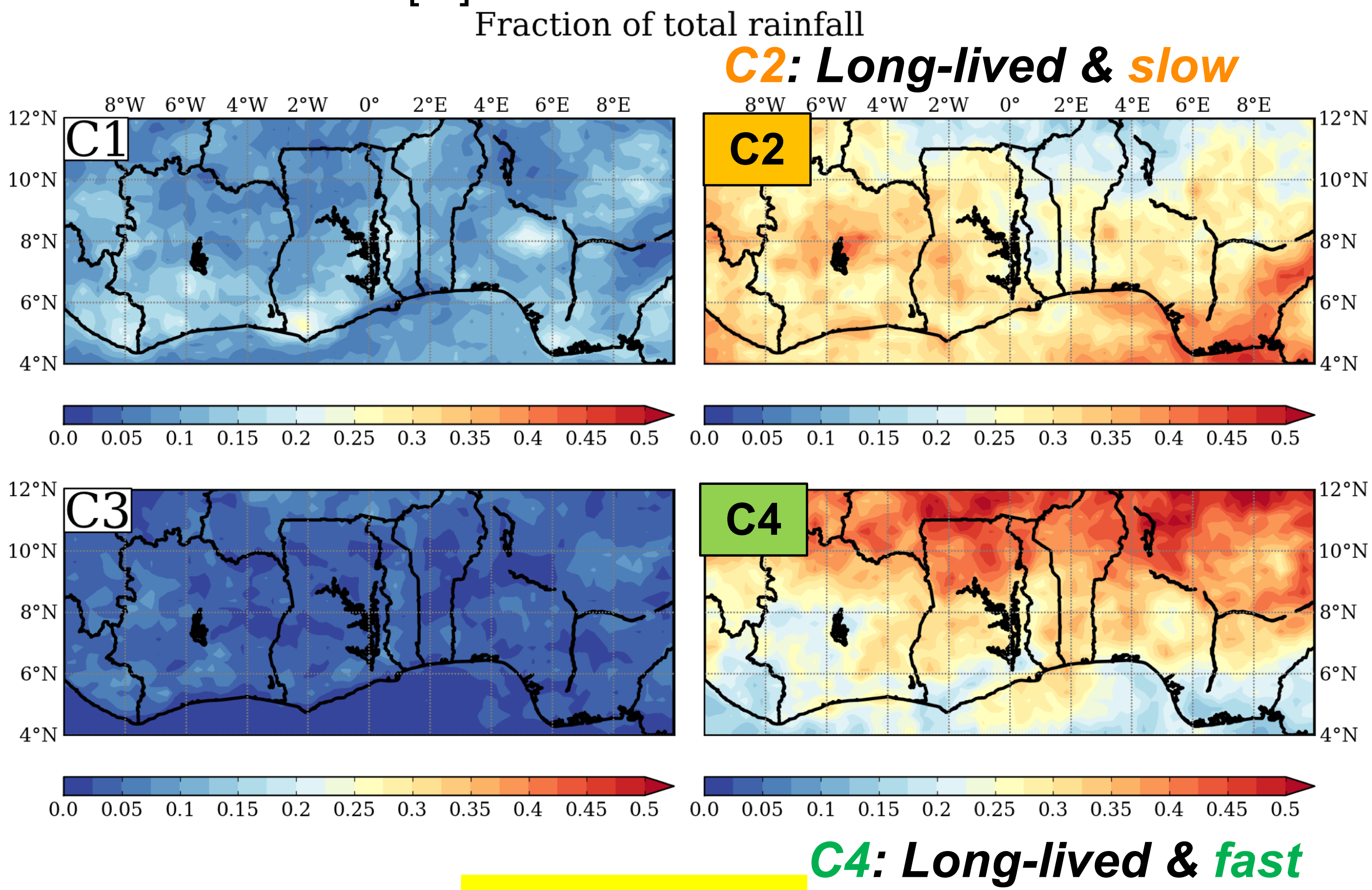


Regime	Typical Rainfall Types	CAPE	CIN	DCAPE	SHEAR
1	DCC, WCC, DWC	++	++	++	++
2	MOD, STR	+	+	+	+
3	ISE	-	-	-	-

After Maranan et al. (2018)

Rainfall systems: Combined TRMM 3B42 + IR

- Fraction to total rainfall [%]



Maranan et al. (2018)

Summary: MCSs over Africa

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Fast, and long-lived, cold-cloud top MCSs (mostly squall lines) dominate over the Sahel and provide almost all of the annual rainfall.

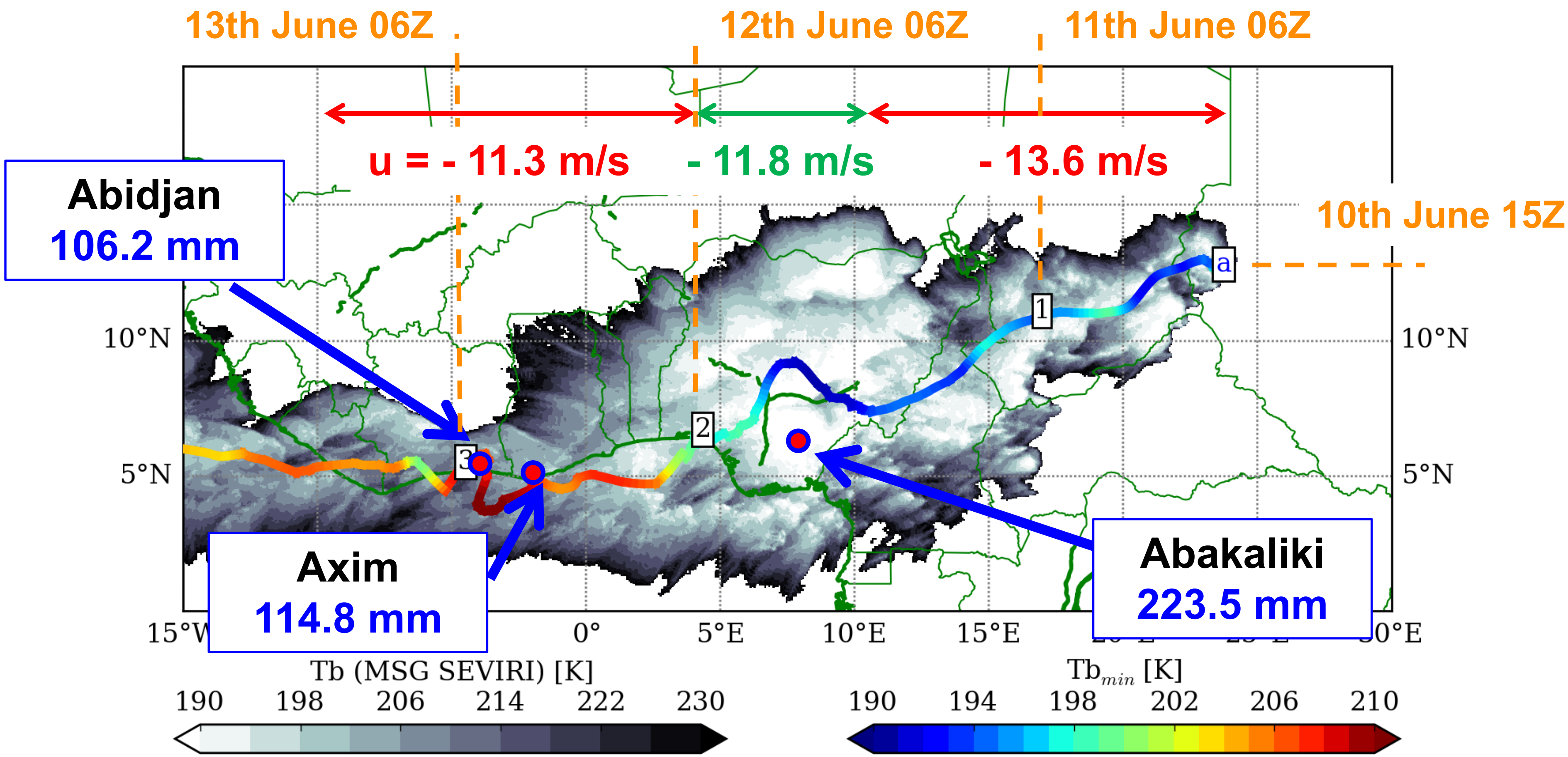
At least climatologically, strong low-level shear is related to cold/intense MCSs, but low-to-mid-level dryness seems to be important too (e.g. for propagation speed)

In southern West Africa, various types of rainfall systems occur: From "warm isolated showers" to "strong convection" related to land-sea breeze to "broad stratiform regions" – with varying importance of (D)CAPE, CIN, shear.

Current work shows a poor relation between rainfall and antecedent shear, but a reasonably good correlation between mid-level dryness and rainfall in the rainbelt (Walz et al., in preparation)

What is the role of MCS in extreme rainfall events?

Extreme (near-)coastal event: Abakaliki, Nigeria, 12 Jun. 2016



Maranan et al. (2019)

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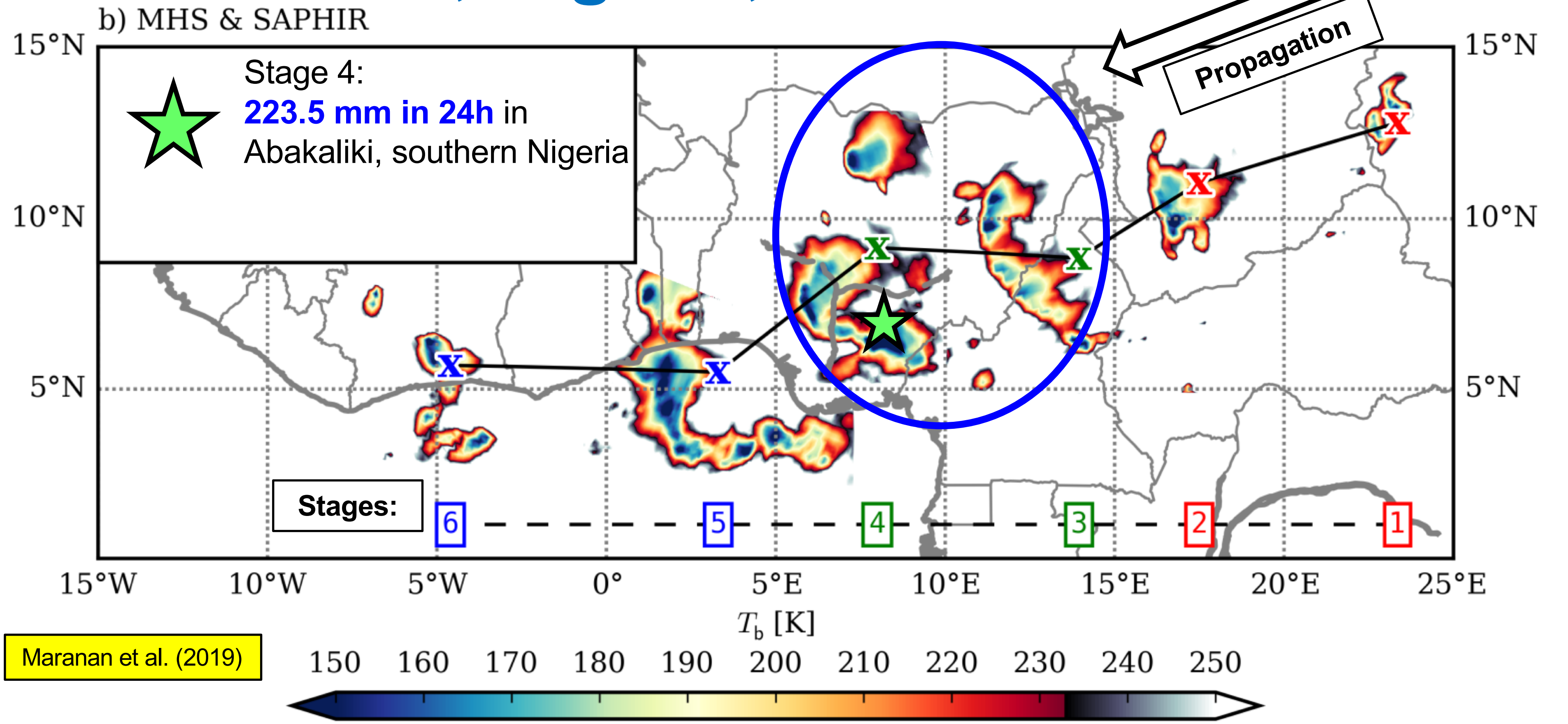
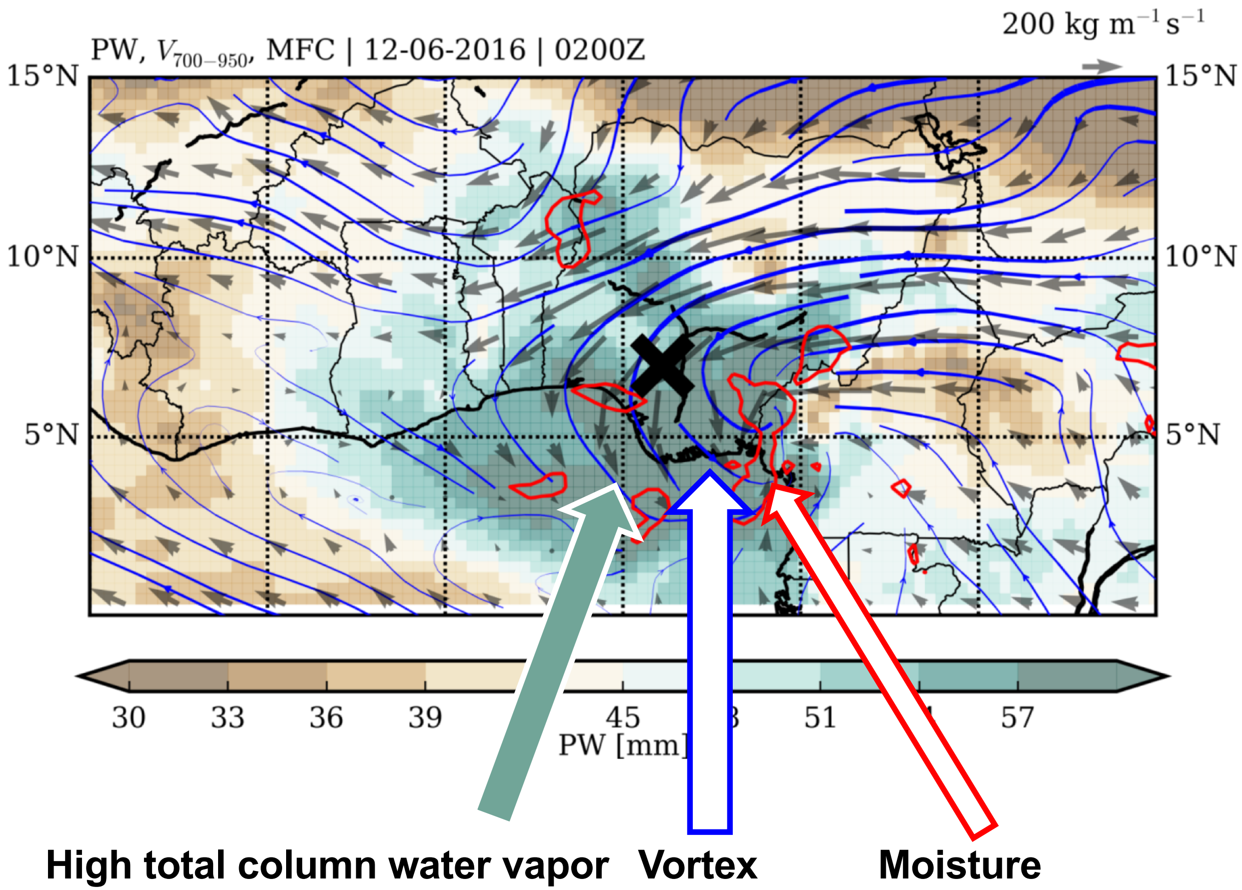


Maranan et al. (2019)

- A "classical" squall line (stages 1–3) transformed (again) into a "moist vortex" at stage 4 -> some similarities to the Ouaga event (Engel et al. 2017)

Abakaliki 12 Jun. 2016: Moist vortex

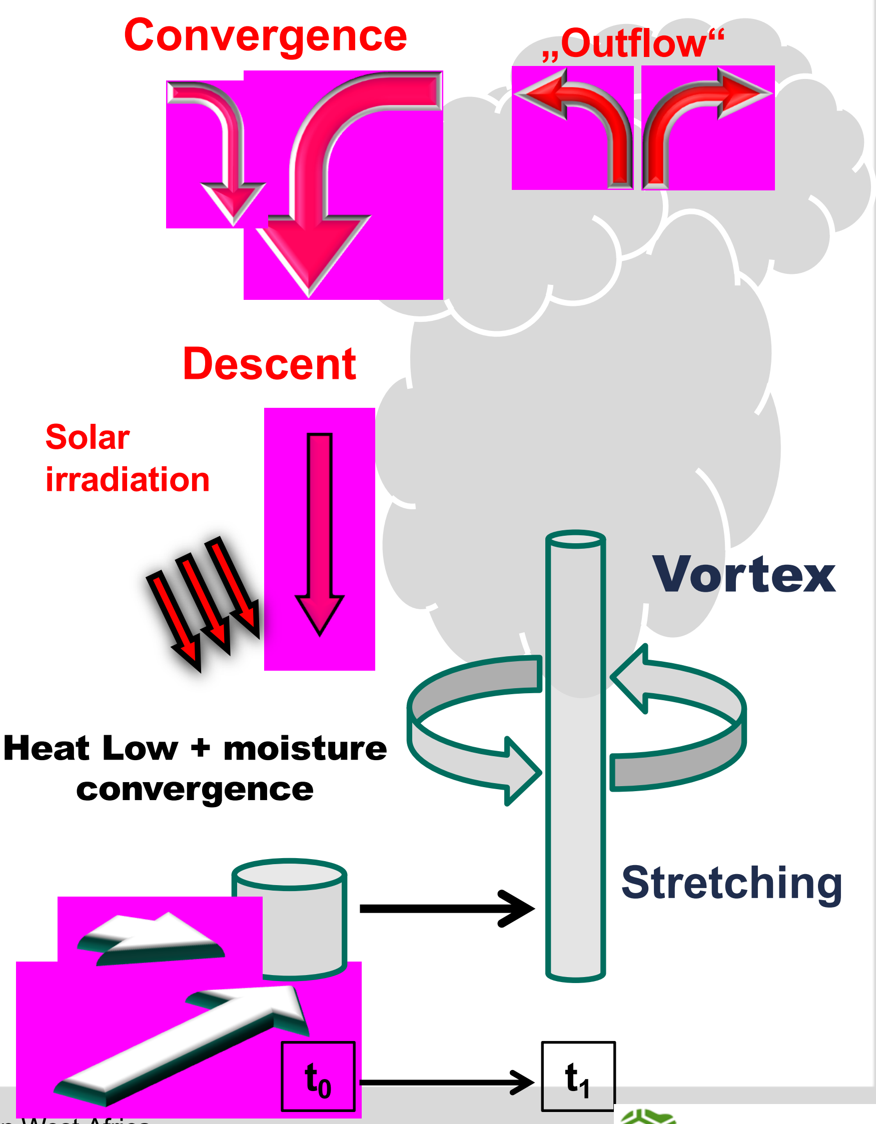


Maranan et al. (2019)

- Low-tropospheric vortex encloses region with high column water vapor content
- Local accumulation of moisture -> Extreme precipitation possible
- Similar case with "moist vortex": Ouagadougou 2009 with 263 mm in 24h (Engel et al., 2017, Lafore et al., 2017)
- How predictable are such extreme events?

Moist vortex: mesoscale process chain proposed for genesis

1. **Upper-tropospheric convergence in the far distance due to convective "outflow" at the MCS.**
   - Descending air masses + cloud dissipation
   - Unhindered solar irradiation



After Maranan et al. (2019)

Moist vortex: mesoscale process chain proposed for genesis

1. Upper-tropospheric convergence in the far distance due to convective "outflow" at the MCS.
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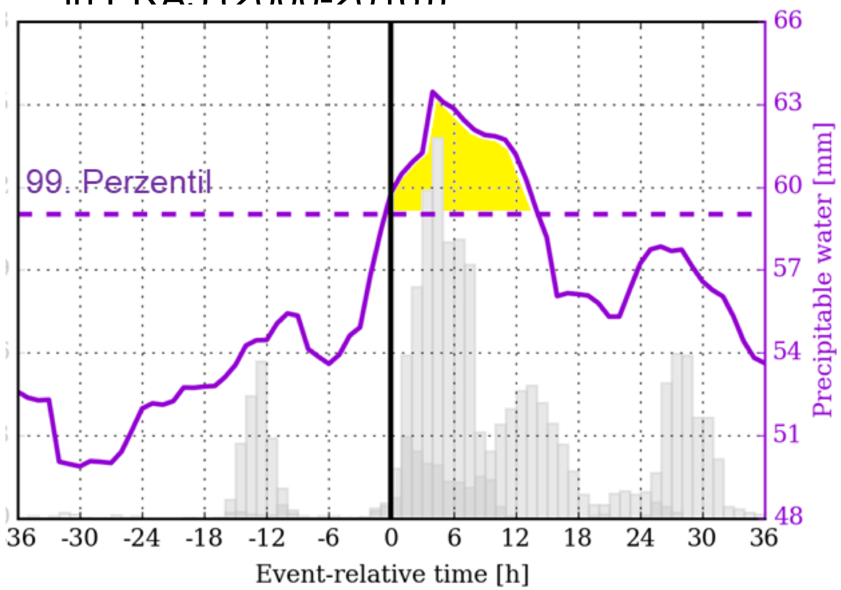
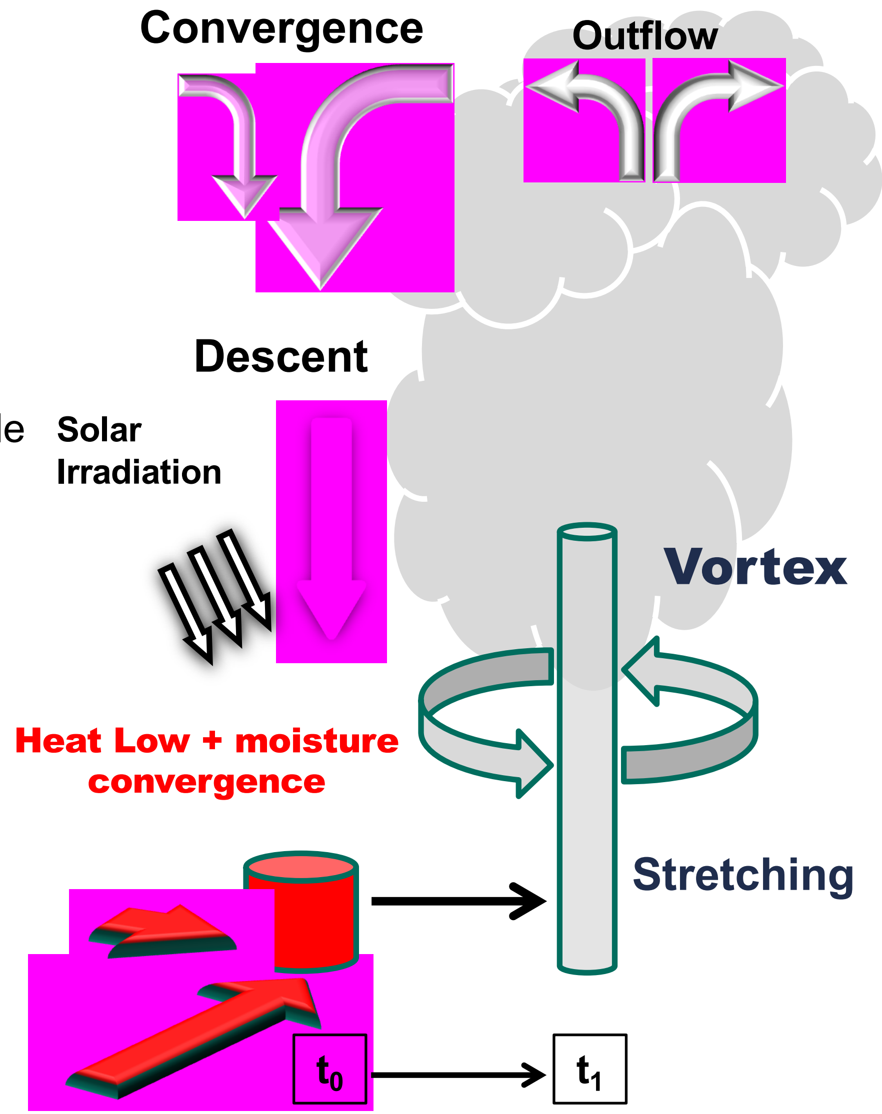
2. **Net warming in the tropospheric column**
   - Formation of a surface low
   - Moisture convergence -> extreme vertically integrated water vapour content (> 99th percentile in ERA5 (2000-2016))



After Maranan et al. (2019)



25.01.2019

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2. **Net warming in the tropospheric column**
   - Formation of a surface low
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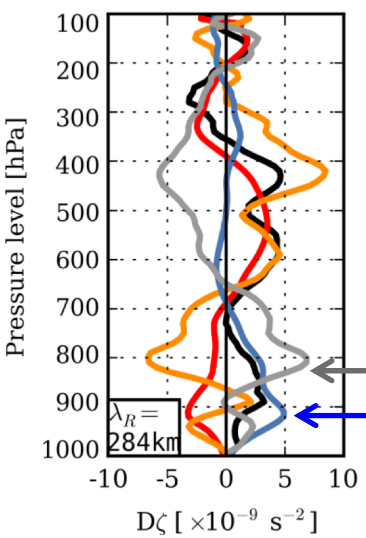
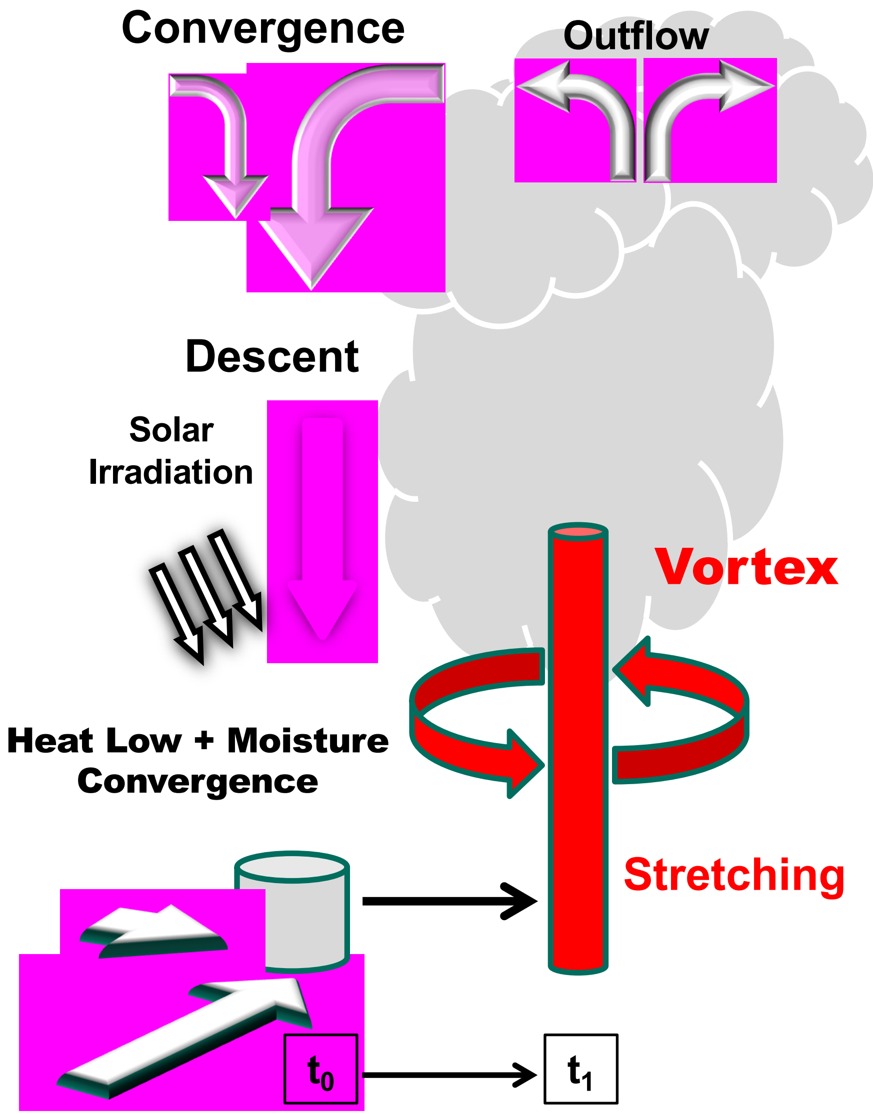
3. **Formation of a vortex on arrival of the MCS**
   - Formation through "stretching" (divergence term DIV) and "tilting" (TILT) in the lower troposphere.



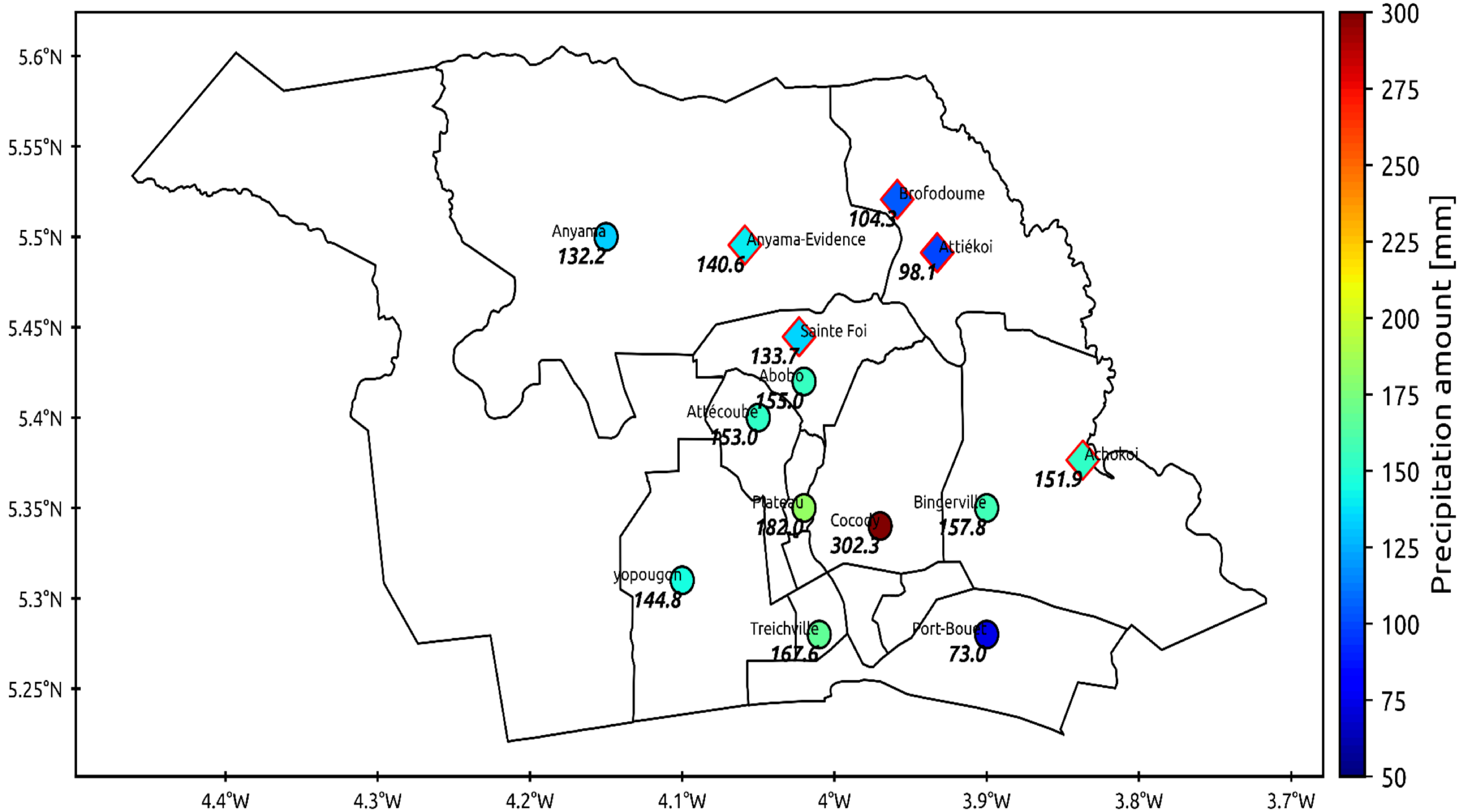
$$\frac{\partial\zeta}{\partial t} = \underbrace{-\boldsymbol{v}_h\cdot\nabla\eta}_{HADV}\ \underbrace{-\,\omega\frac{\partial\zeta}{\partial p}}_{VADV}\ \boxed{\underbrace{-\,\eta\nabla\cdot\boldsymbol{v}_h}_{DIV}}\ \boxed{\underbrace{+\,\boldsymbol{k}\cdot\left(\frac{\partial\boldsymbol{v}_h}{\partial p}\times\nabla\omega\right)}_{TILT}}$$

After Maranan et al. (2019)



Extreme daily rainfall in Abidjan (19 June 2018)

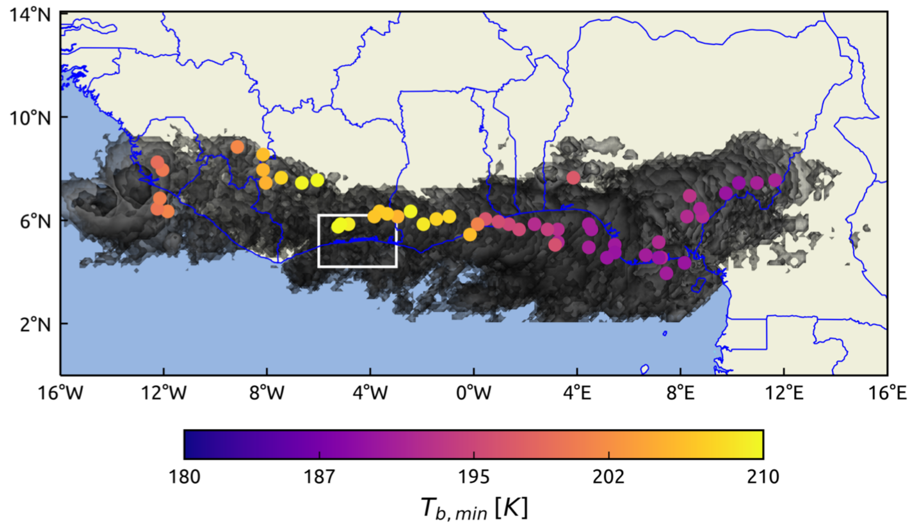
Precipitation recorded at different Sodexam (circle) and Evidence (square) stations in Abidjan on June 19, 2018 - > Verified 302,3 mm in at Cocody station (Abidjan)



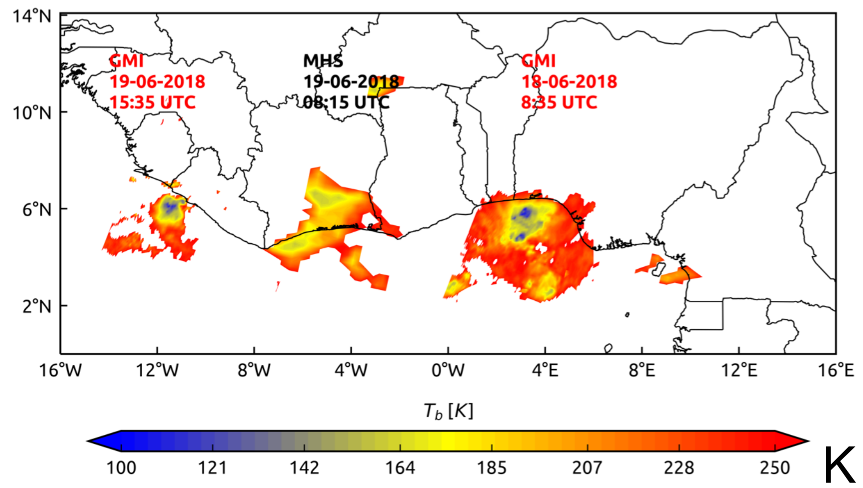
Salifou Touré et al. (in preparation)

Extreme daily rainfall in Abidjan
MCS time evolution, 17–19 Jun. 2019

Shading: BT < 233 K (Feng et al. 2021)
Dots: coldest 1-h IR BT (cf. Marlon et al., 2019)



BT passive microwave imagers

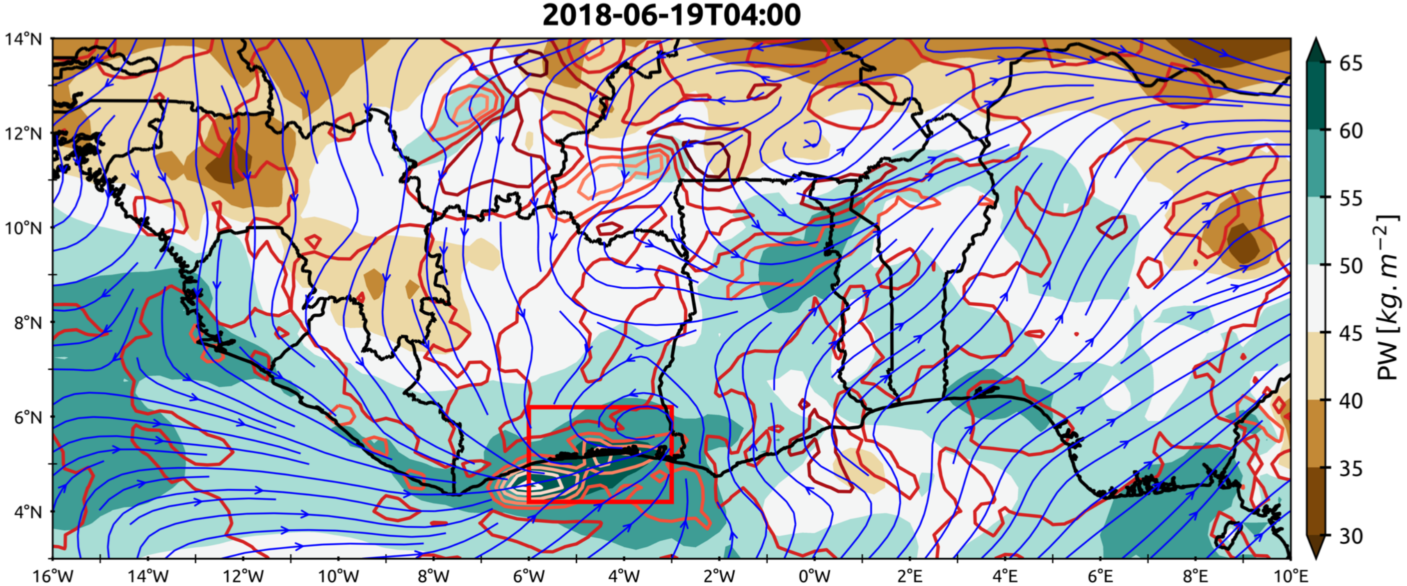


- MCS formed over the Cameroon line mountains on 17 June 2019 and grew to a cold cloud system over and south of the Niger delta
- It travelled along the coast and over Abidjan, and both IR and MW do not show cold temperatures.

Salifou Touré et al. (in preparation)

Extreme daily rainfall in Abidjan
Moist vortex formation

Precipitable water (color shaded), 600–950-hPa mass-weighted flow (blue streamlines), and moisture flux convergence (MFC, red contours) at 04 UTC 19 June 2019.

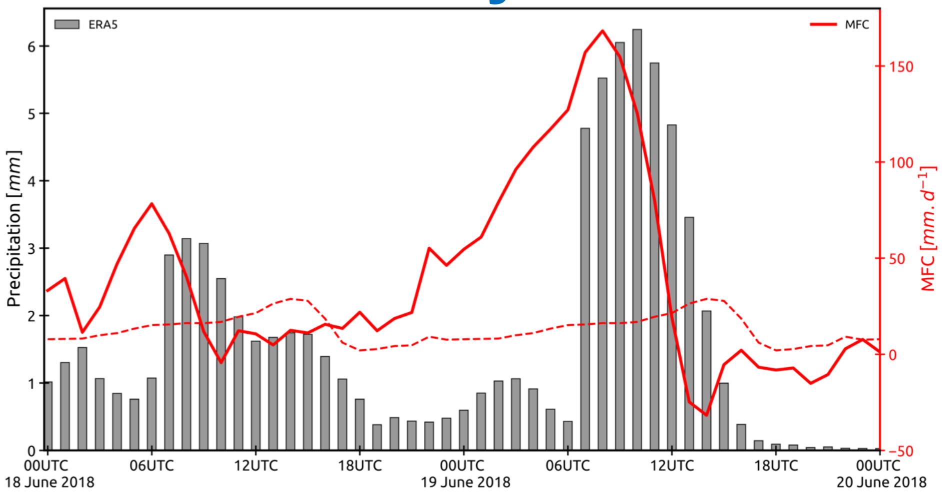


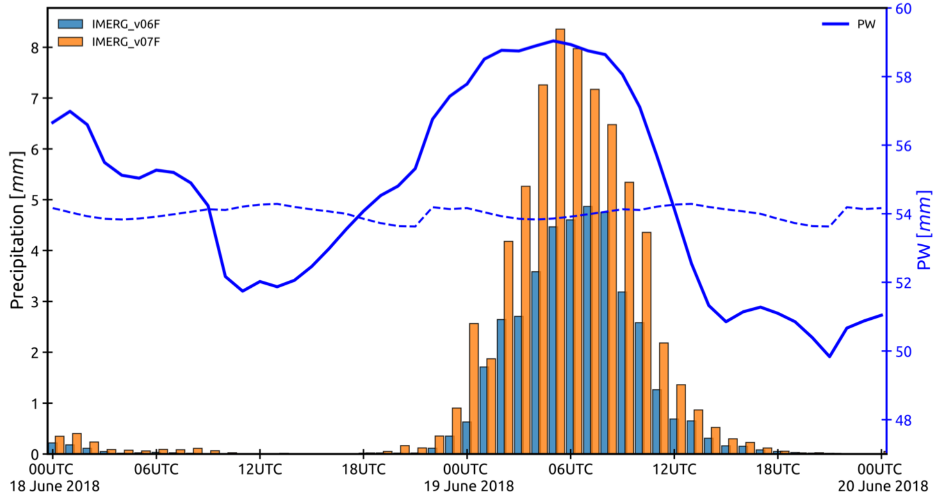
Salifou Touré et al. (in prep.)

- Very high values of PW (> 98th percentile of PW for the entire 1991–2020)
- Streamlines indicates the formation of a cyclonic vortex with its center being located over the Abidjan which was there since 01 UTC
- Strong Moisture Flux Convergence around Abidjan

Extreme daily rainfall in Abidjan

Sub-daily evolution in IMERG and ERA5





- Averaged (5–6°N, 3–5°W) in a ±24 h window centered around 00 UTC of 19 June 2018
- PW and moisture Flux Convergence (MFC) are extreme when compared to the 30-yr-based 99th percentile (dashed line)
- ERA5 recorded slight hourly rainfall 18th June, but almost no rainfall for IMERG v6/v7 ERA5 has stronger rains later on 19 June 2019.
- IMERG V7 sees more intense rains

Salifou Touré et al. (in preparation)

Summary: MCSs and extremes

Detailed studies on the Ouaga 2009, the Abakaliki 2016 and Abidjan 2019 case all show that a meso-to-synoptic scale moist vortex was involved

It is associated with a slow down of the MSCs, in two cases after a conversion from a linear squall line to a more oval/circular shaped cloud/rainfall feature

The moist vortex can originate form an African Easterly Wave, but may be related to the MCSs itself. For the two cases shown, no AEW was involved.

The vortex leads to a strong moisture convergence /swift moisture refuelling

ECWMF model starts to see the strong rainfall after the vortex is present, but underestimates it and has a temporal delay

How do models perform in strong rainfall events?

Modelling rainfall/MCS in West Africa

Karlsruhe Institute of Technology

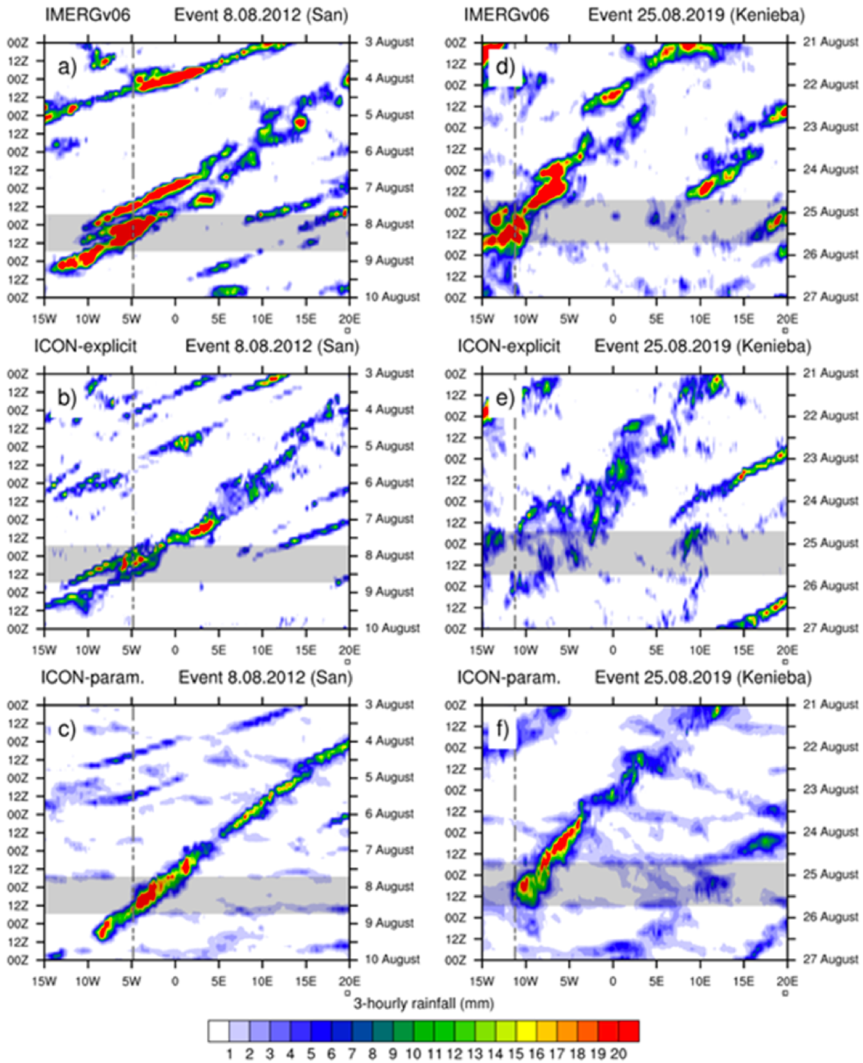
Most convection schemes do not account for cold pools, thus they do not represent mesoscale convective organisation/systems.

Ensemble forecast of the next day 24-h precipitation from ECMWF Ens sometimes and regionally have inferior skill to ensemble forecasts from climatology or from a simple statistical model (Vogel et al. 2018; 2021)

Convection permitting models show improved mesoscale organisation, remove the phase error in the diurnal cycle, but rainfall often too intense and still to localized (e.g. Becker et al. 2021)

The latter reference, other and own work indicate that convective parameterization can still be superior to explicit in cases when large-scale vortices organize the convection

Modelling two extremes in Mali



- Daily rainfall in San (Keniebia) was 127 (126 mm) on 08 Aug. 2012 (25. Aug. 2019)
- San case featured an AEW, the Kenieba case developed in an extremely moist lower troposphere related by a moist vortex.
- Two sets of ICON model experiments, PARAM and EXPLC, both at 6.5 km grid spacing
- Detailed validation, also using FSS and SAL scores:
  PARAM better in the Keniebia case, EXPL better in the San case

Ways forward

Need for more sub-daily ground observations, including radar, as well as upper-air observations and campaigns -> challenging due to the political instability.

Remote sensing: Mini cubesats with space-based rain radar for a better sampling, Aeolos follow up mission, a space-based water vapour lidar.....

Working on improved parameterizations of cold pools/mesoscale convective organisation (including machine learning approaches) still needed since explicit convection is NOT the game changer - at least not for rainfall forecasting where we need to increase ensemble members to better assess uncertainties.

Improve on the education and training of many young African researchers and their access to HPC facilities –> needed to advance on the problem and the take up of results in weather forecasting practice and climate change adaptation and mitigation.