



UK Research and Innovation



Natural Environment Research Council



Department for Science, Innovation & Technology



CSSP-Brazil



SoGE | School of Geography and the Environment



Seamless simulation to prediction of delays to southern monsoons: *From projections to early warnings*

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School of Geography and the Environment, University of Oxford

With thanks to collaborators:



National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL



Republic of Zambia
Ministry of Green Economy and Environment
Zambia Meteorological Department



South African Weather Service



Met Office



Summary

Goal: *Illustrate the power of the UM's "seamlessness" from a model user and physical climate science perspective.*

Also a recognition of the huge value that Met Office scientists contribute to enabling research in wider UK and internationally

Headline Problem: Summer Rains in the Southern Hemisphere are Arriving Later.

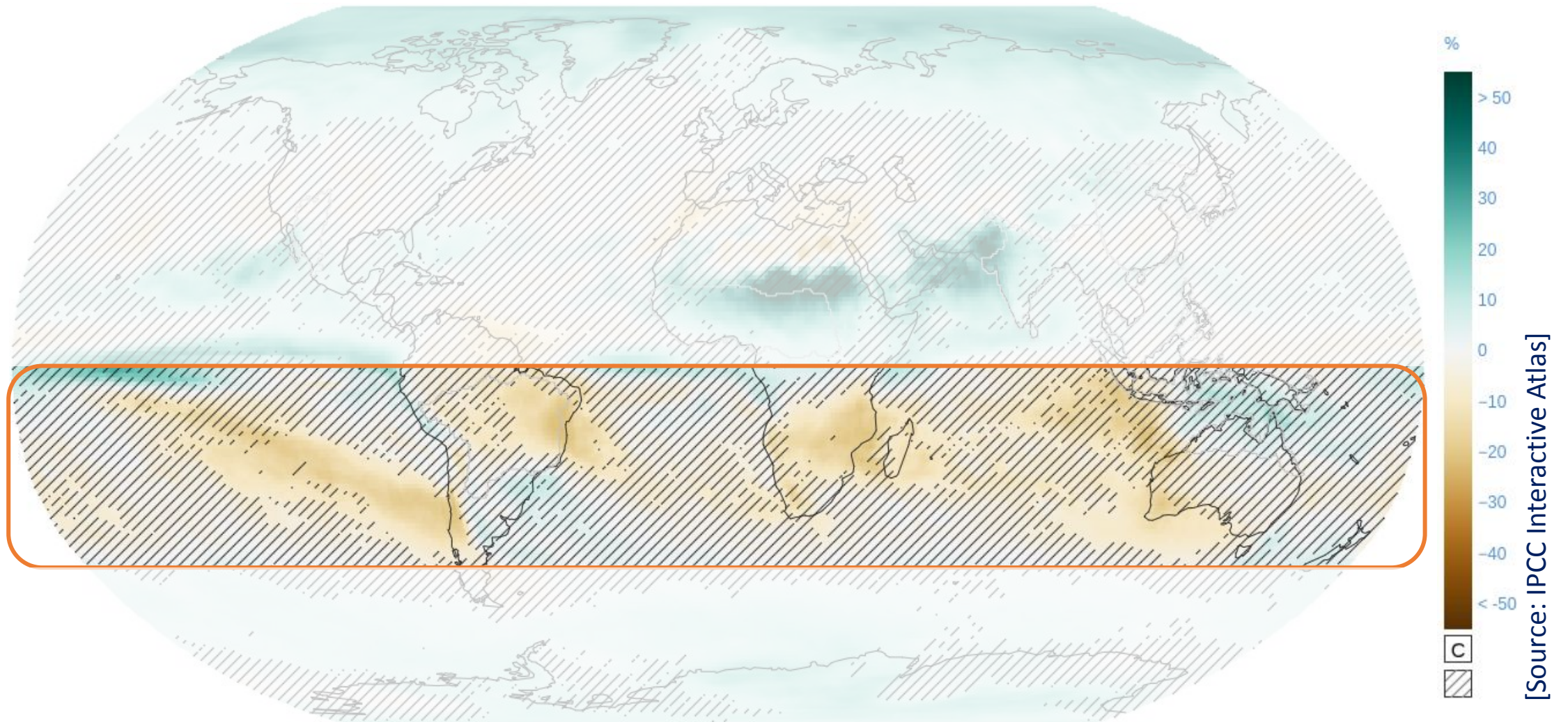
Linked to:

- **Hemispheric Scale:** Changes in Hadley cell seasonality
- **Continental Scale:** Decline of crucial rain-bearing systems –
Tropical Extratropical Cloud Bands
- **Local Scale land surface:** Less evapotranspiration in warmer CO₂ world

Talk's Aim: To show how family of Unified Model (UM) configurations has been instrumental to:

- Diagnosing this risk.
- Understanding the driving processes.
- Moving towards prediction and management strategies.

An emerging climate problem across southern monsoons

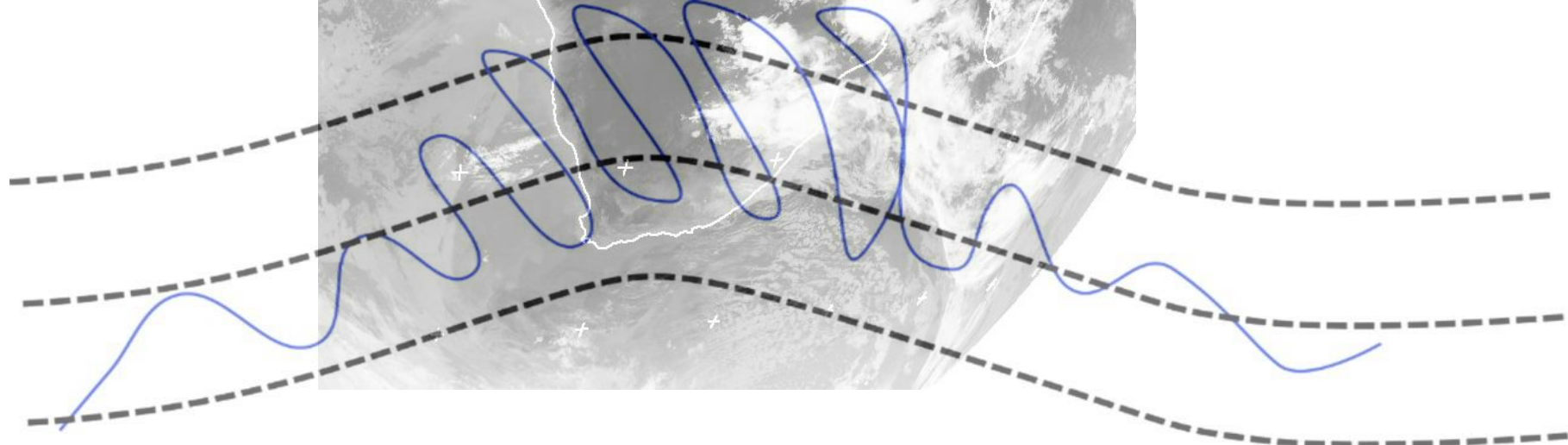
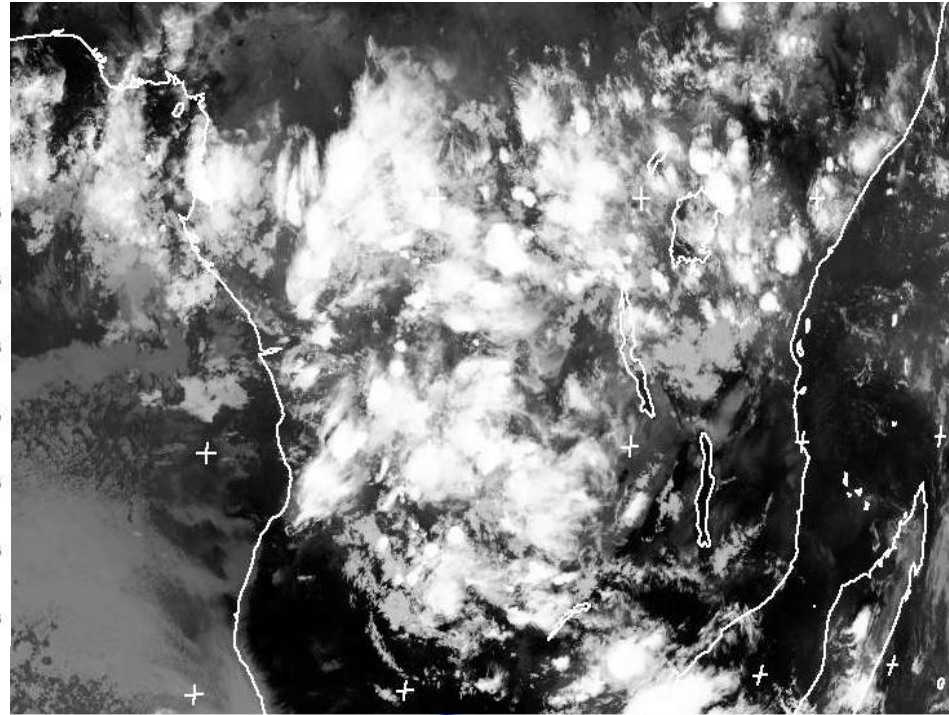
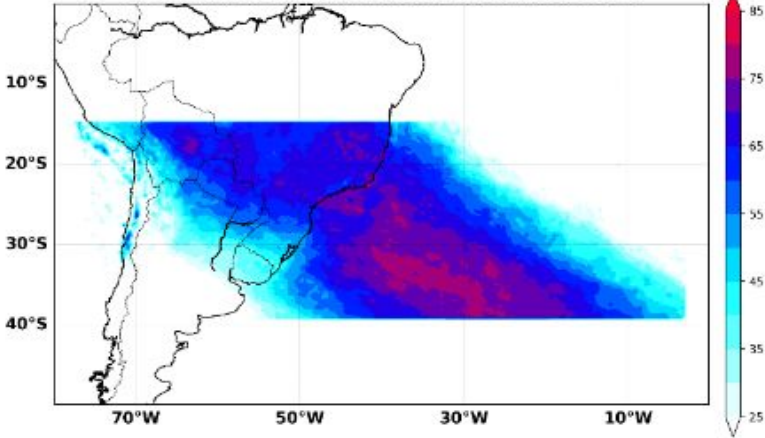


Precipitation change (%) for Sept-Nov: near term (2021-2040) **SSP1-2.6** (rel. to 1961-1990)

Summer peaks in tropical-extratropical cloudbands

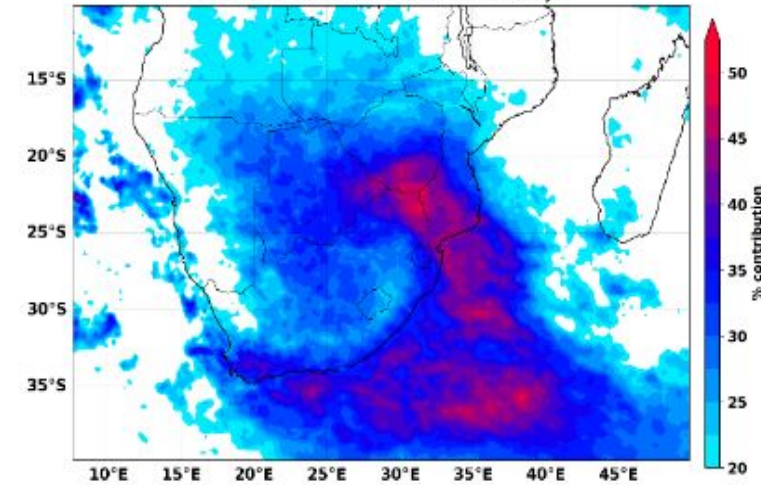
South America

Contribution of TE Cloudbands to Oct-Mar Rainfall Clim.

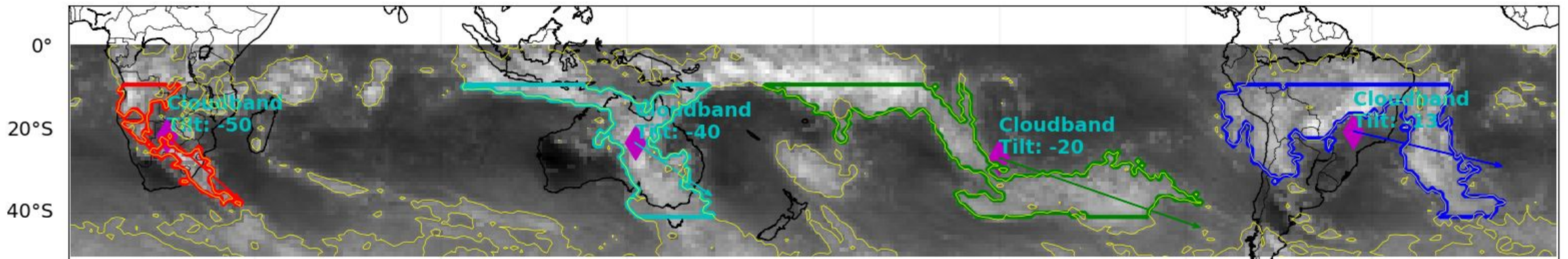


Southern Africa

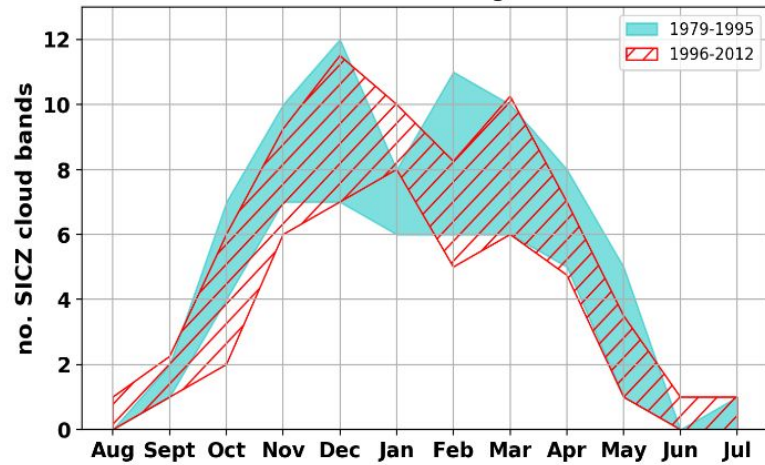
% Oct-Mar Rainfall on TE cloud band days



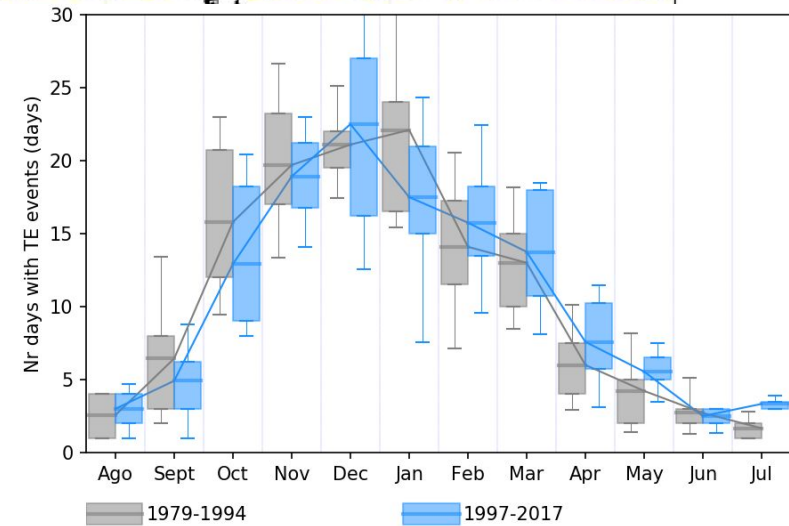
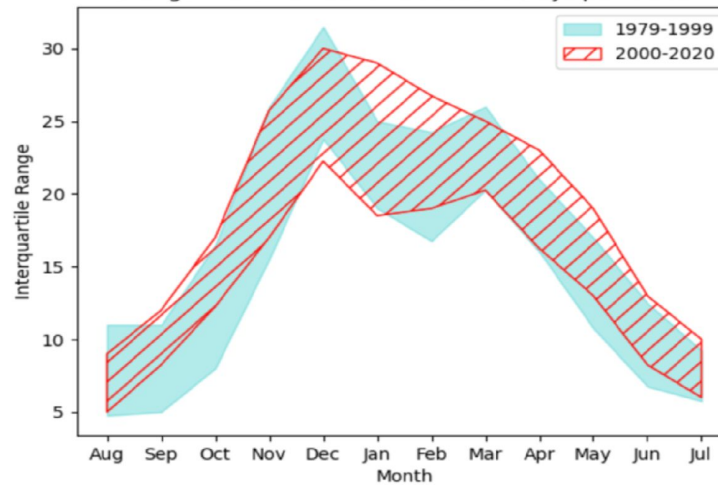
Summer peaks in tropical-extratropical cloudbands



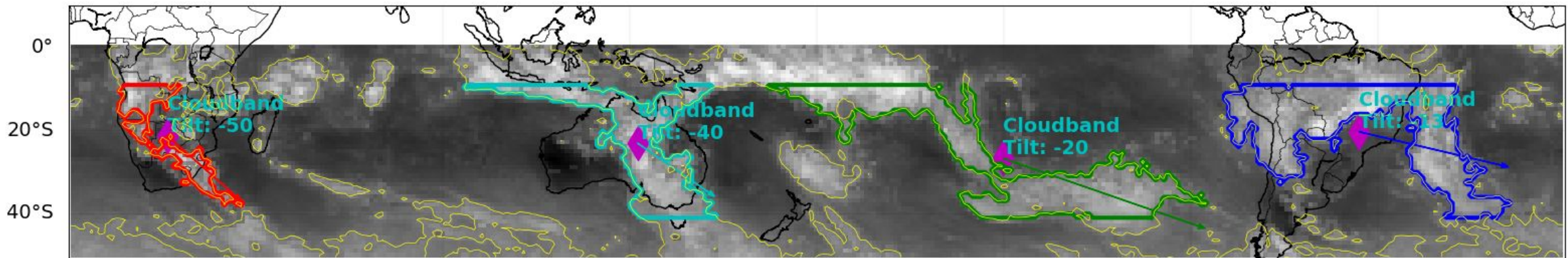
Observed Change



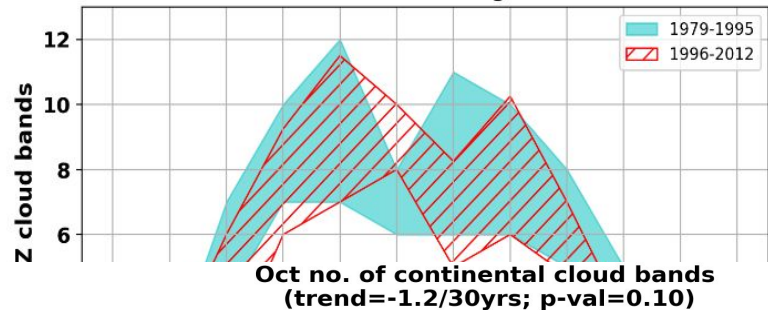
Change in the Number of Cloudband Days per month



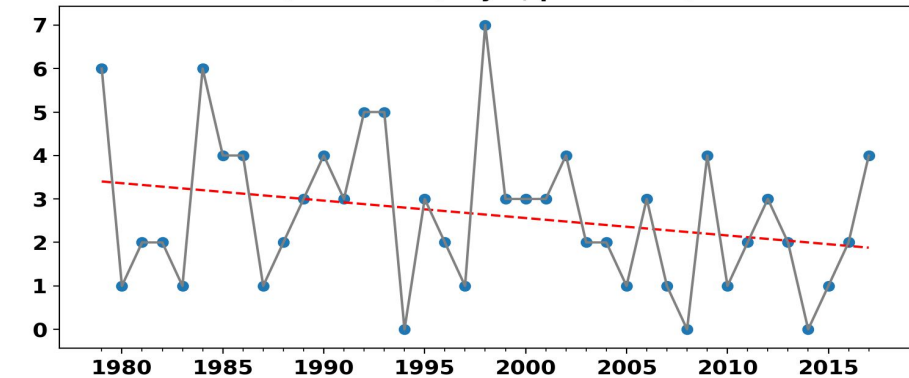
Recent years have not been good....



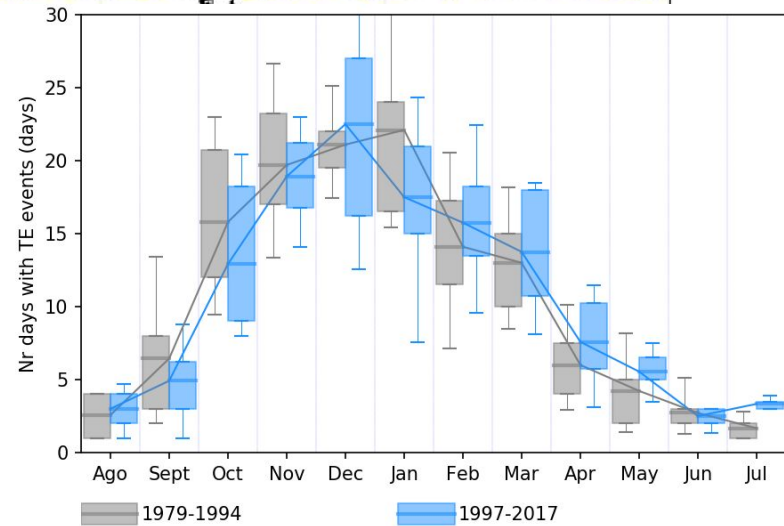
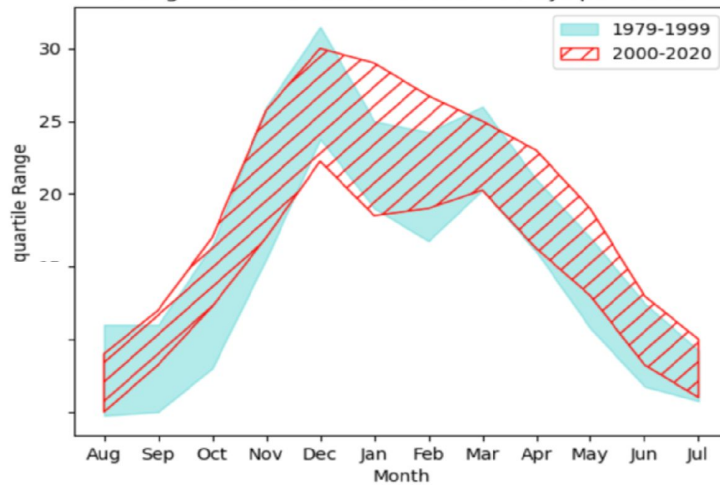
Observed Change



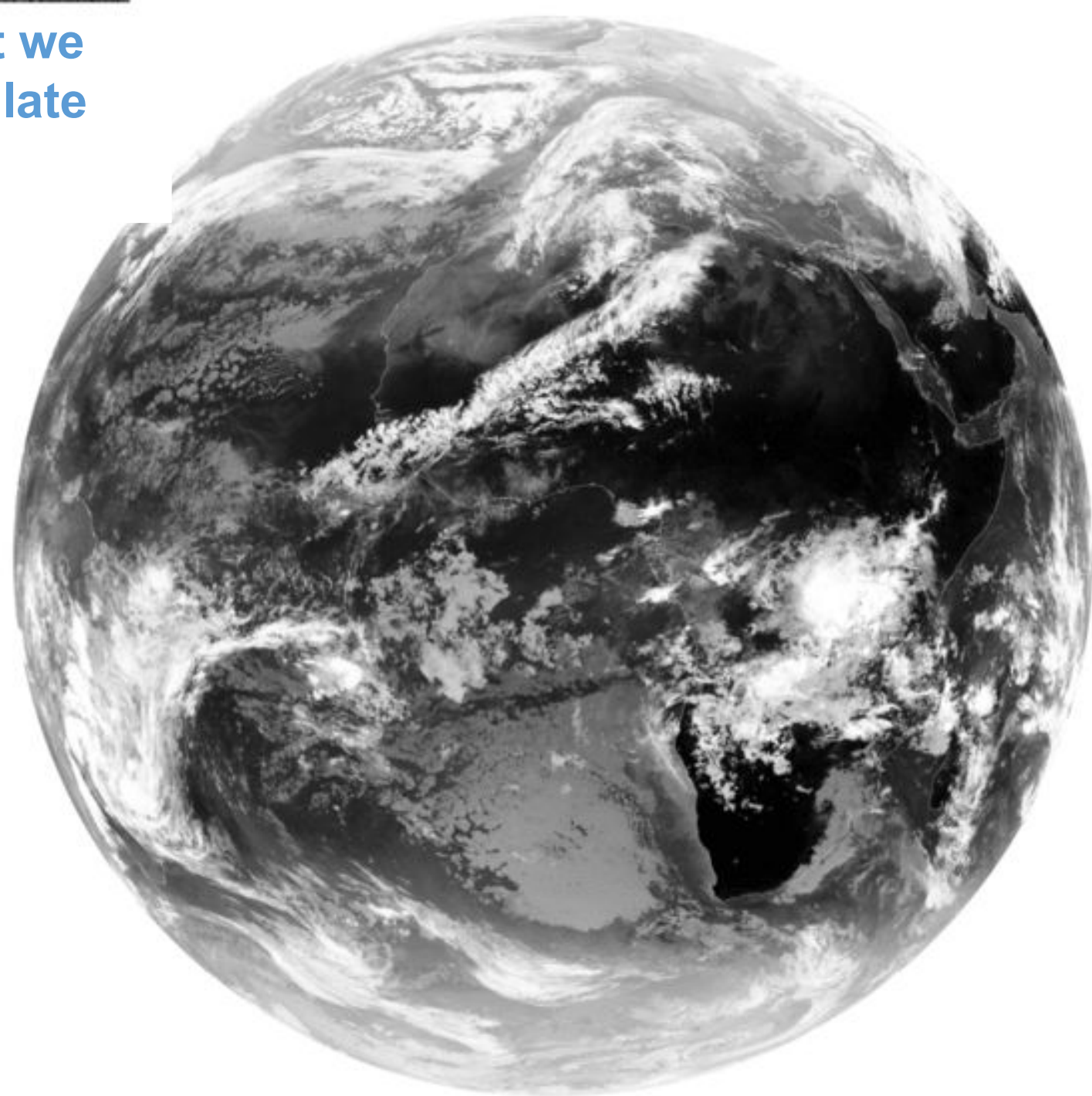
Oct. no. of continental cloud bands
(trend=-1.2/30yrs; p-val=0.10)



Change in the Number of Cloudband Days per month



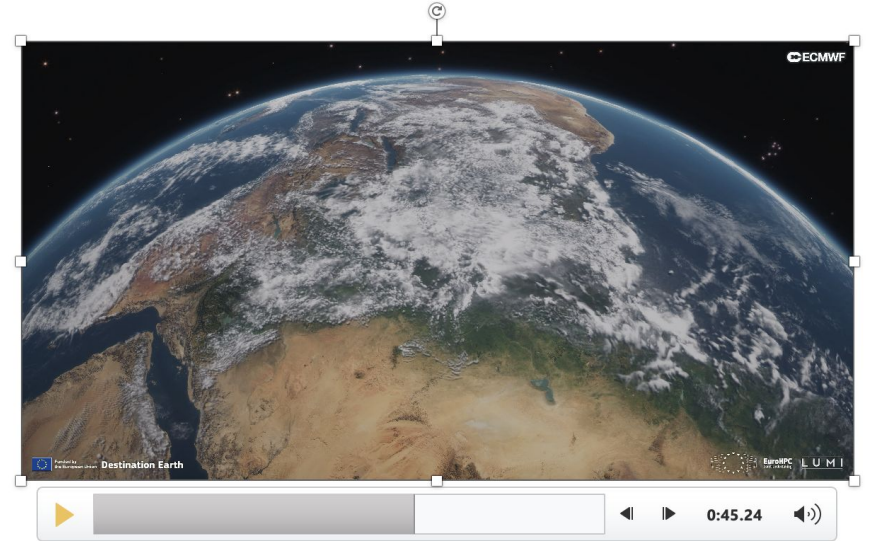
**Reminder of what we
are trying to simulate**



Reminder Annelize's slide from this morning

What we *hope* is better represented at km-scales

- Orography
- Convection
- Large-scale circulation
- Tropical Cyclones



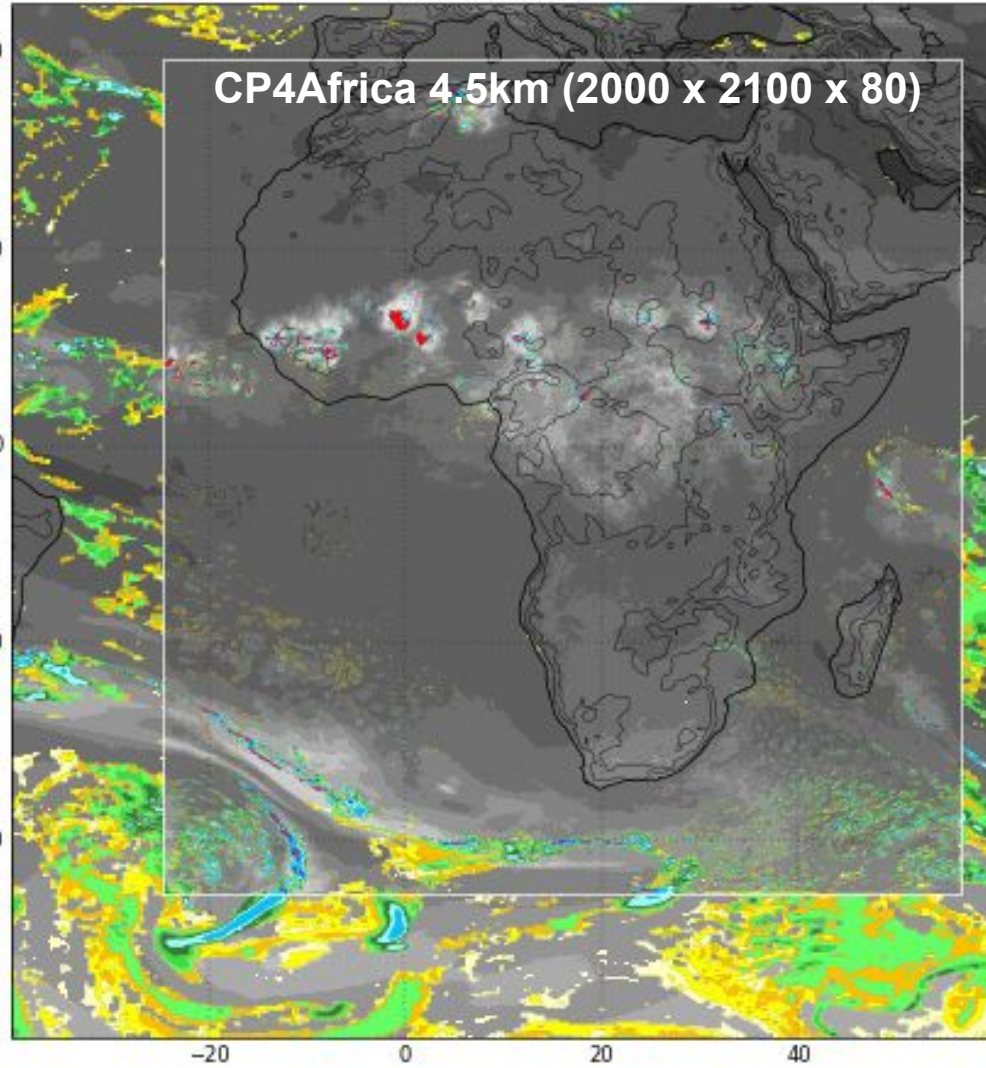
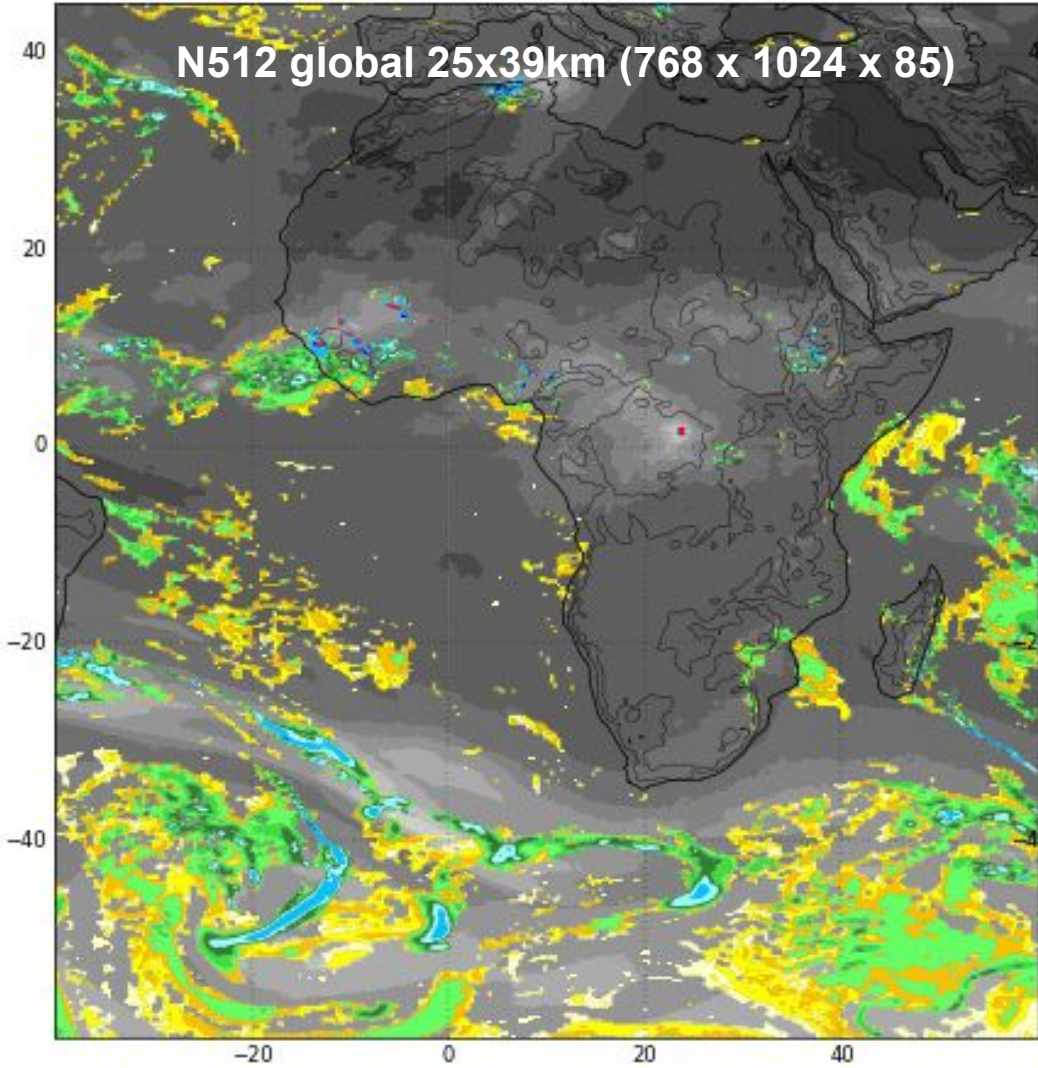
km-scale 'out of the box'

The Unified model with explicit convection gives somewhat different "out the box" results

New Model (2015-2018): Convection permitting Africa (CP4-Africa) simulations

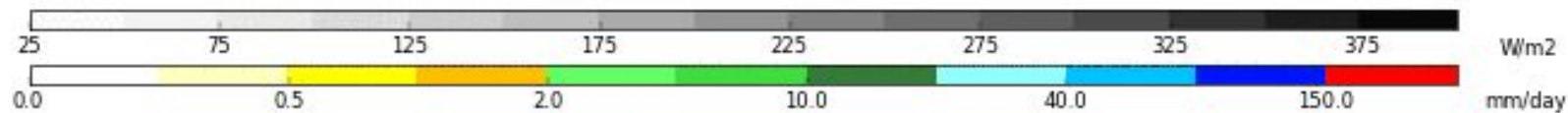
2003-08-02 00:30

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- 10 year simulations:
- present-day (1997/03-2007/02)
 - future RCP8.5 (2097/03-2107/02)

Segolene Berthou, Rachel Stratton, Simon Tucker, Sonja Folwell

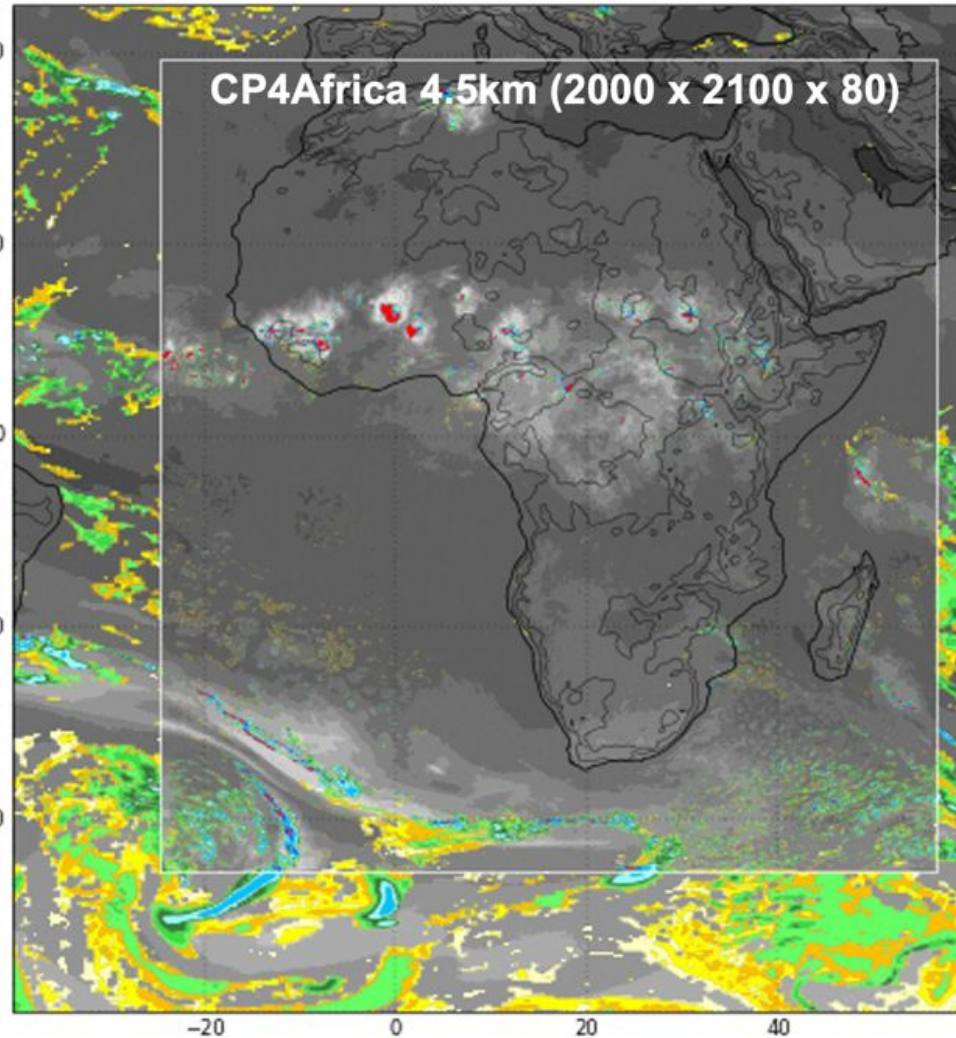
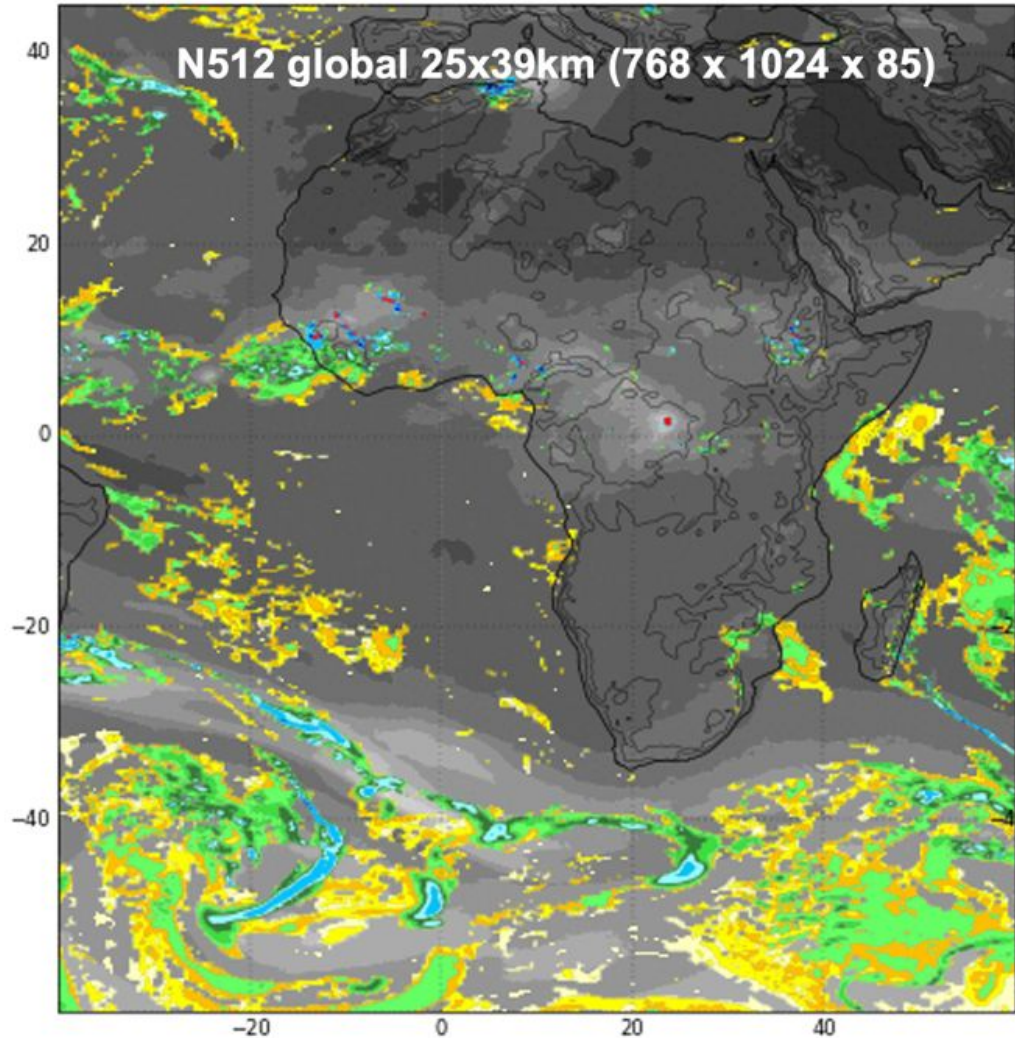


New Model (2015-2018): Convection permitting Africa (CP4-Africa) simulations



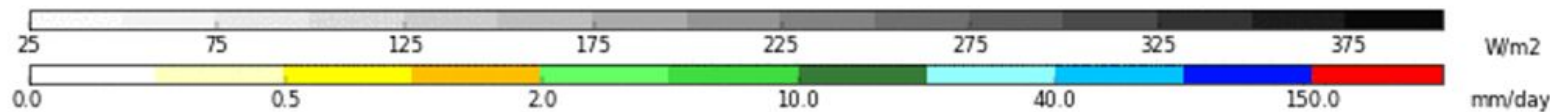
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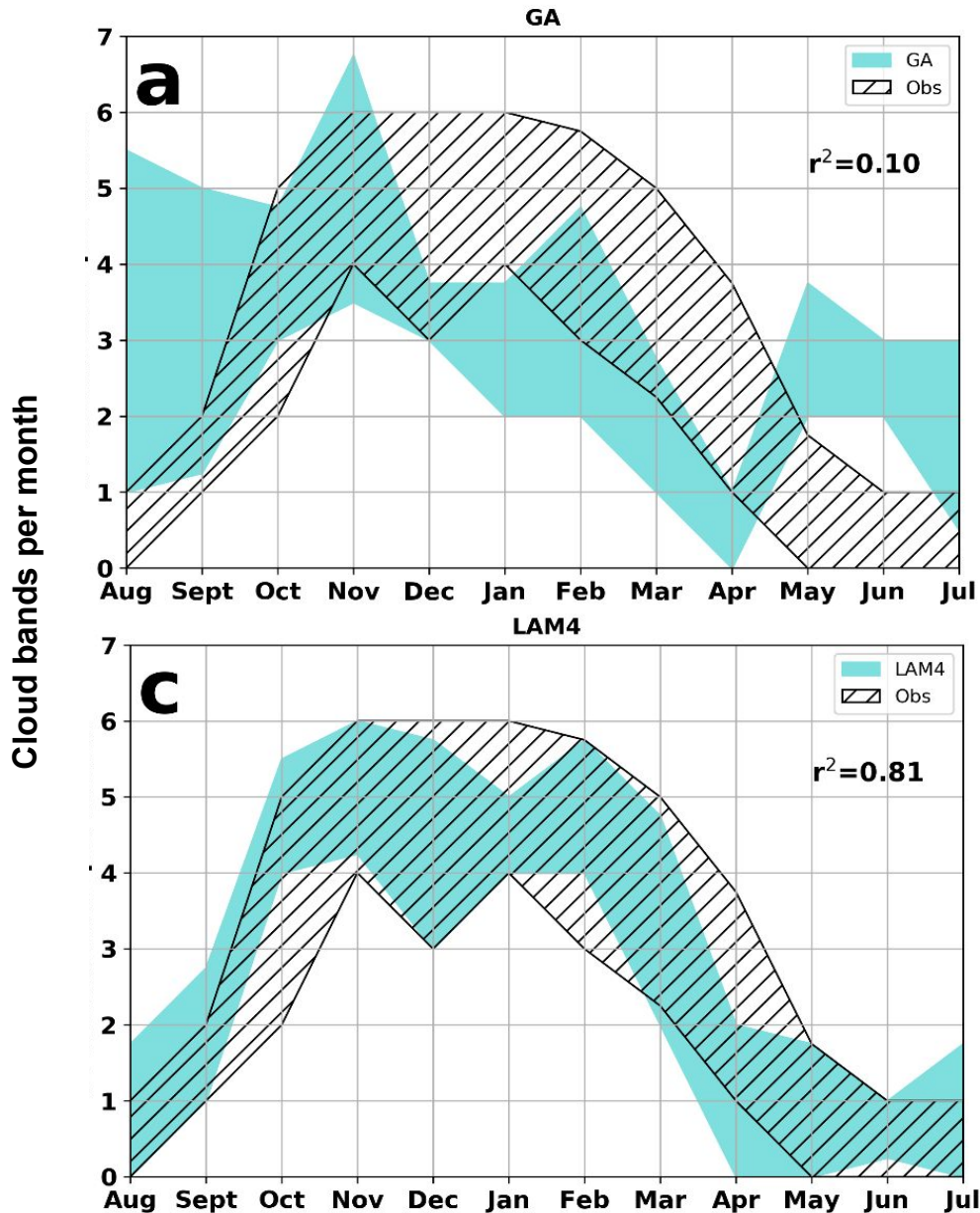
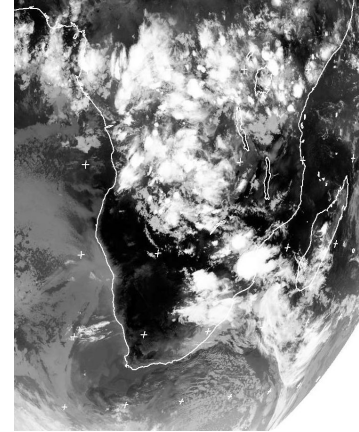


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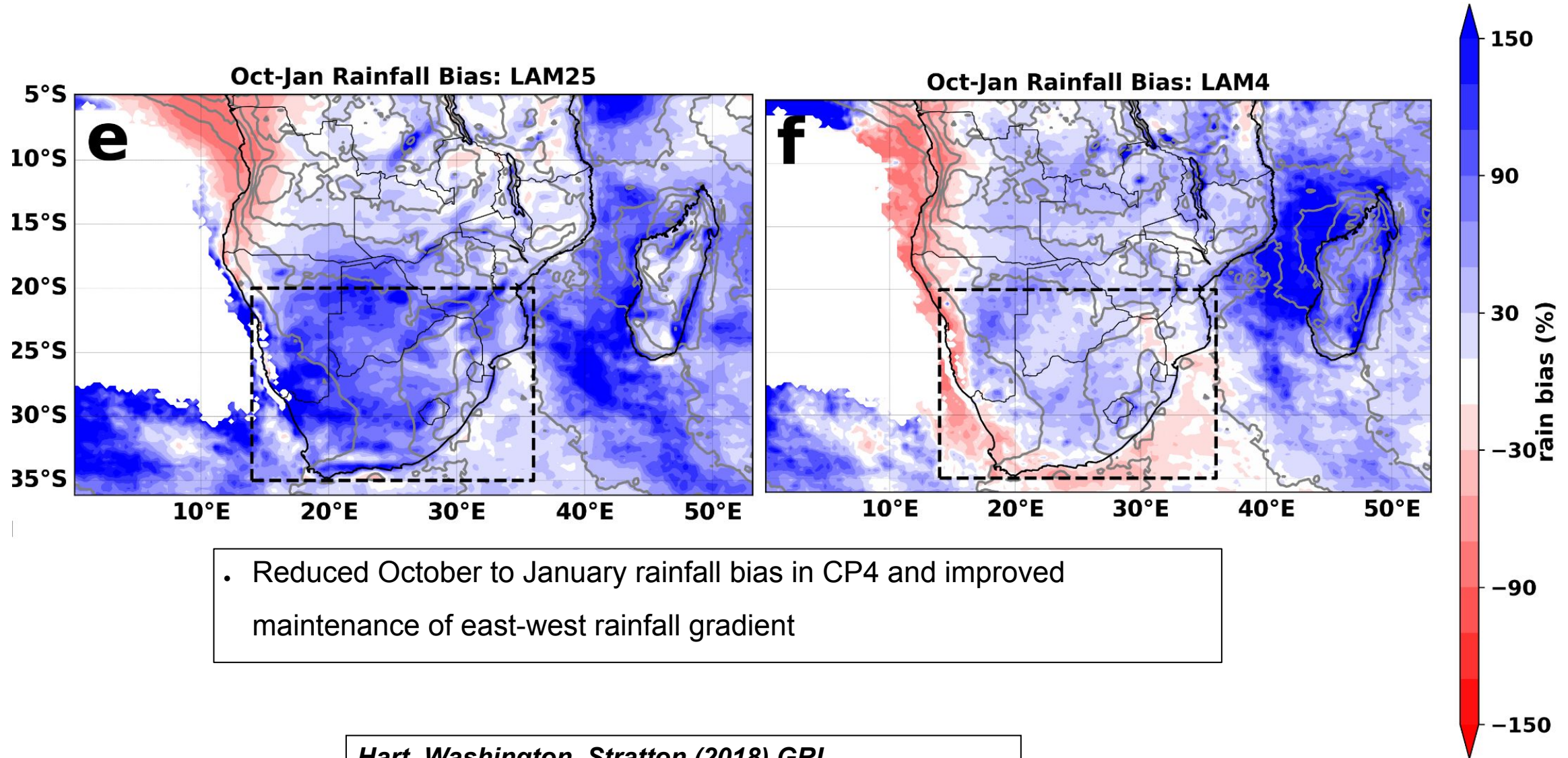
Result 1: Annual Cycle Improves



- CP4 dramatically improves annual cycle
 - Increased event frequency during core summer months
 - Few events during winter
- Indicates regional forcing is a strong component of simulated biases in tropical-extratropical interaction frequency

Hart, Washington, Stratton (2018) GRL

Result 2: Reduction of wet bias in CP4



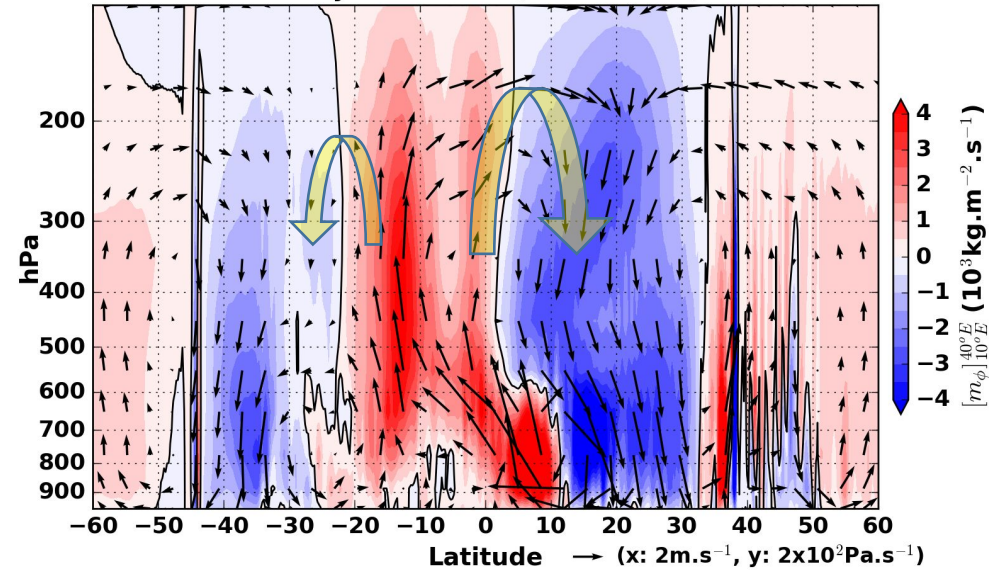
Hart, Washington, Stratton (2018) GRL

Nov-Jan Local Overturning Circulation

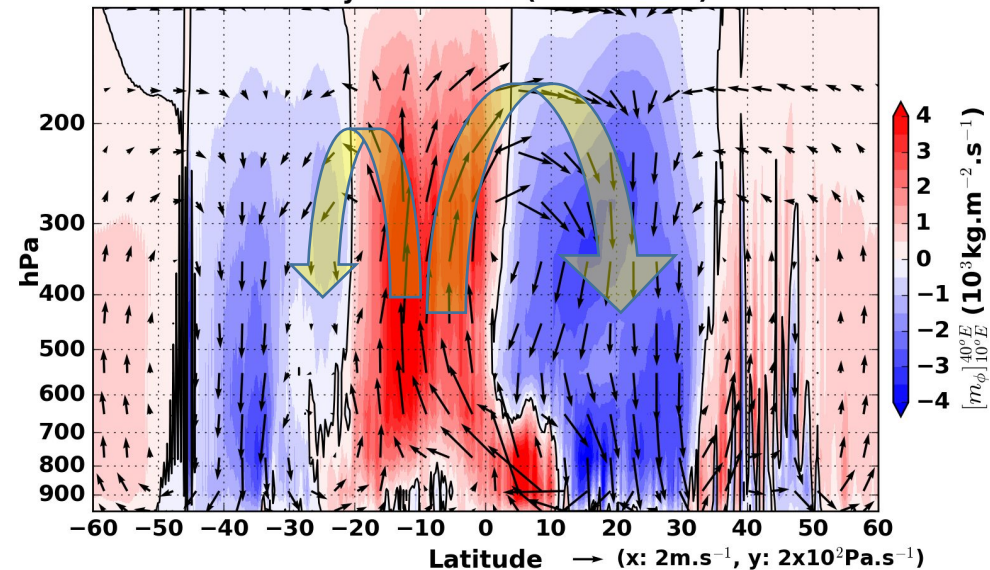
Large tropical domain RCM with explicit convection can overcome parent model biases!

- Vertical mass flux is locally decomposed into meridional and zonal components of circulation following **Schwendike et al 2014**
- Zonal mean of meridional components across southern African sector gives the local Hadley circulation
- CP4 produces greater tropical ascending mass flux than regional model with parameterised convection
- CP4 simulates strengthened poleward flow into summer hemisphere, and associated increase in subtropical descent

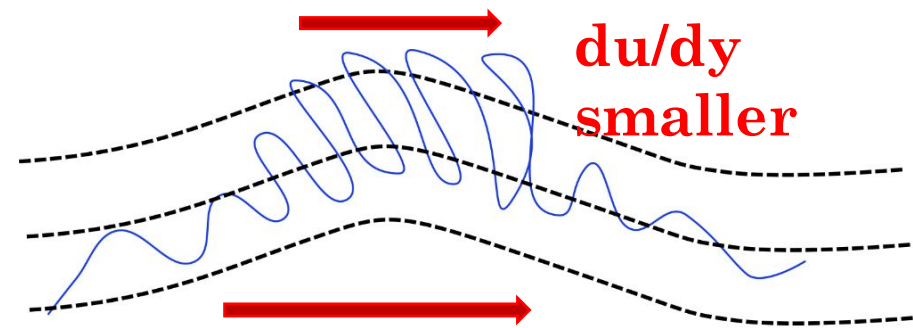
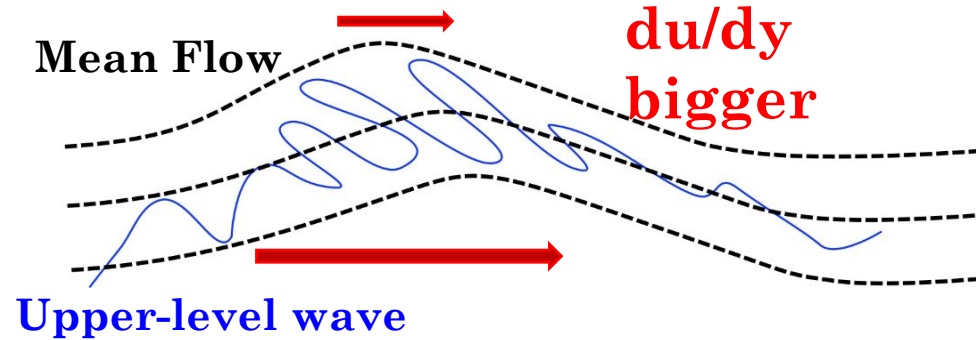
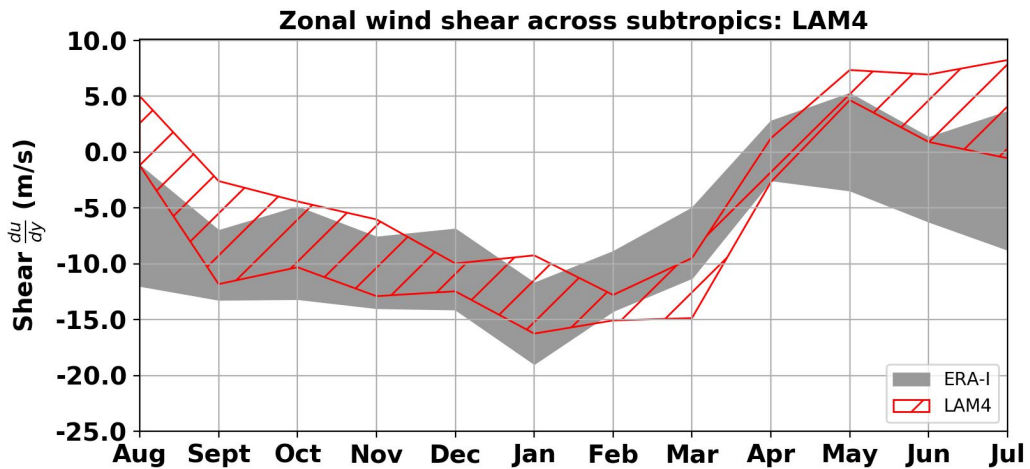
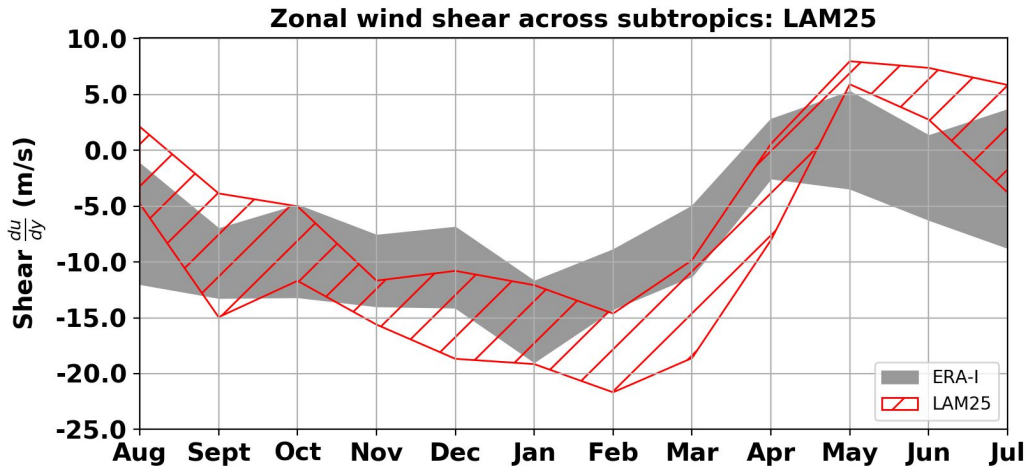
Local Hadley Circulation (SA 10°-40°E) : RA25



Local Hadley Circulation (SA 10°-40°E) : CP4



TTT improvements: subtropic shear

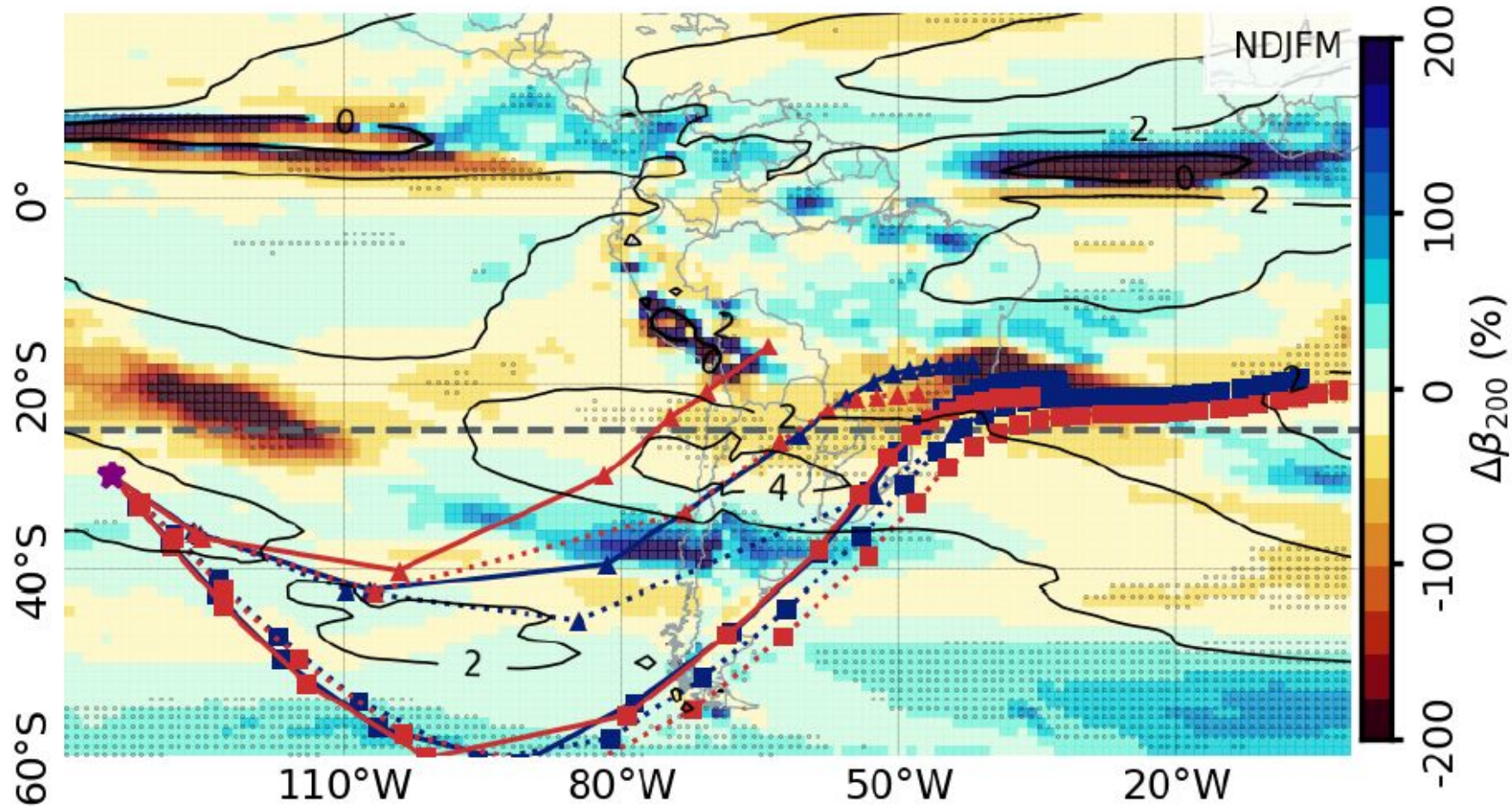


Hart, Washington, Stratton (2018) GRL

- The lower meridional shear is likely to favour upper-level westerly wave structures that form cloud bands, since $\frac{du}{dy}$ important term in wave deformation

TTT improvements: subtropic shear

(b) *HadGEM3_n96-amip* – ERA5 - β_M and RW

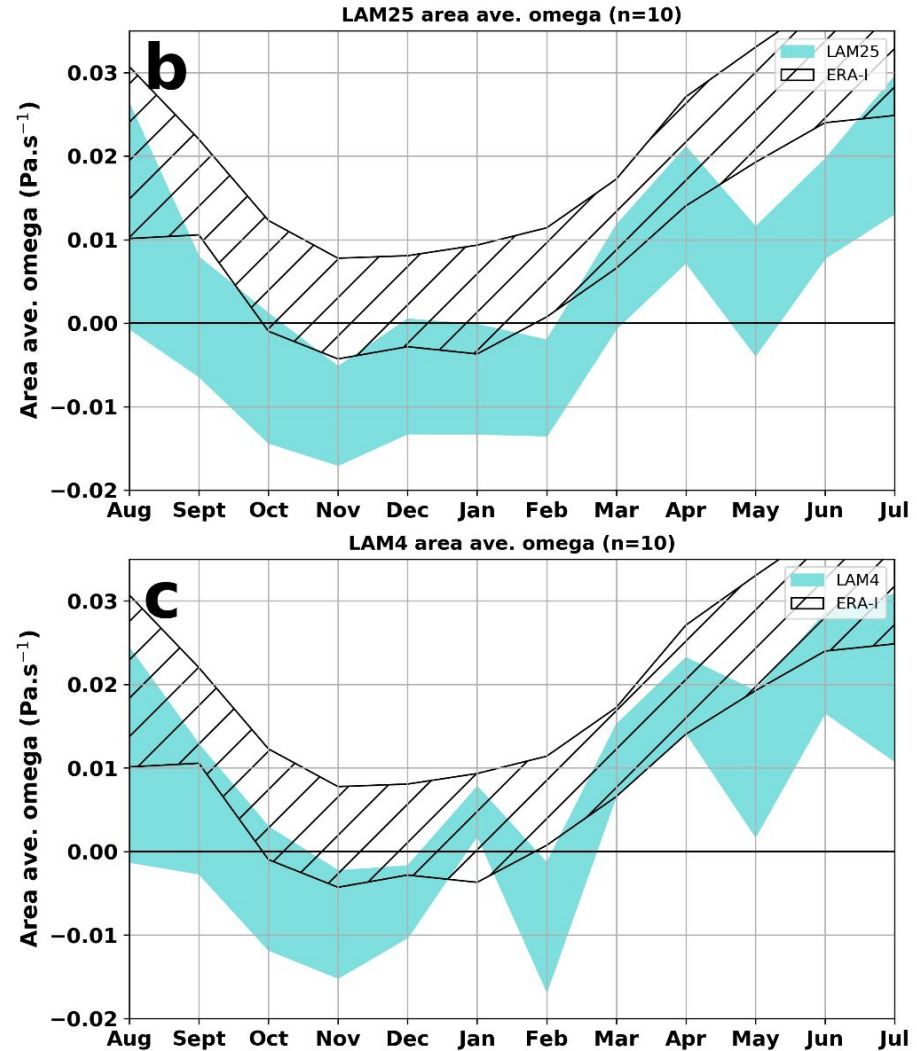


Meridional gradient of the absolute vorticity at 200 hPa with RW rays.

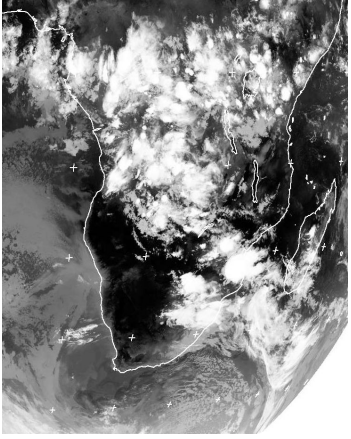
Zilli et al 2023, Clim. Dyn.

Rain bias reduction: Reduce ascent

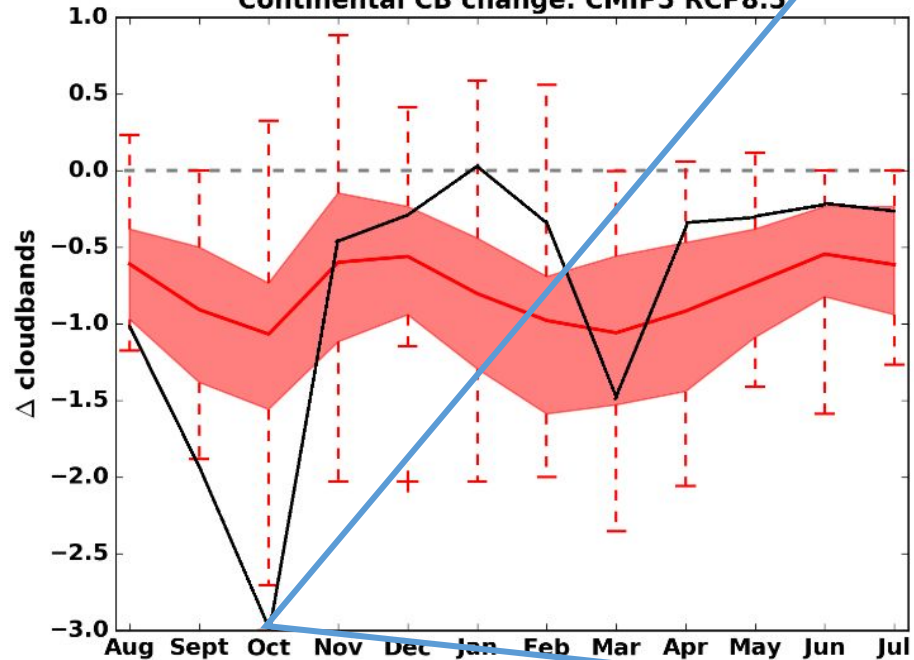
- ERA-Interim shows mid-level (500mb) descent over subtropical southern Africa
- Models simulate mid-level ascent, consistent with wet bias in rainfall
- Ascent bias is halved in CP4 simulation, consistent with reduced wet bias



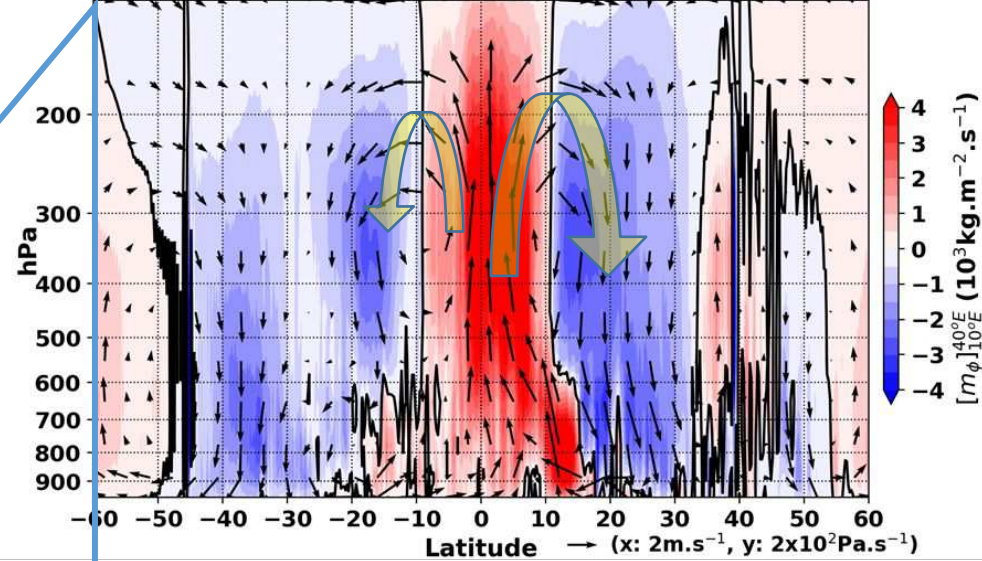
What of S. Africa in future CP4?



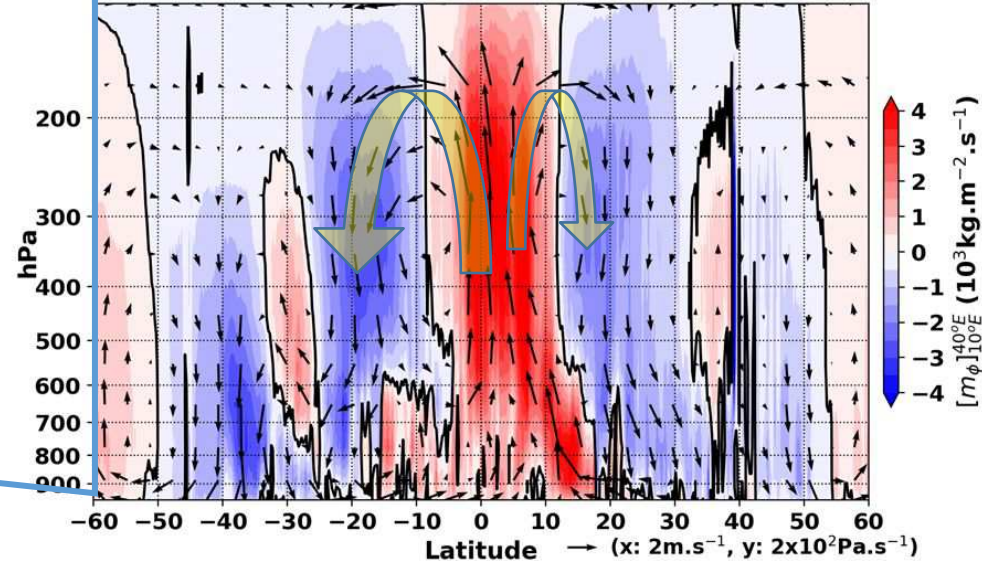
Continental CB change: CMIP5 RCP8.5



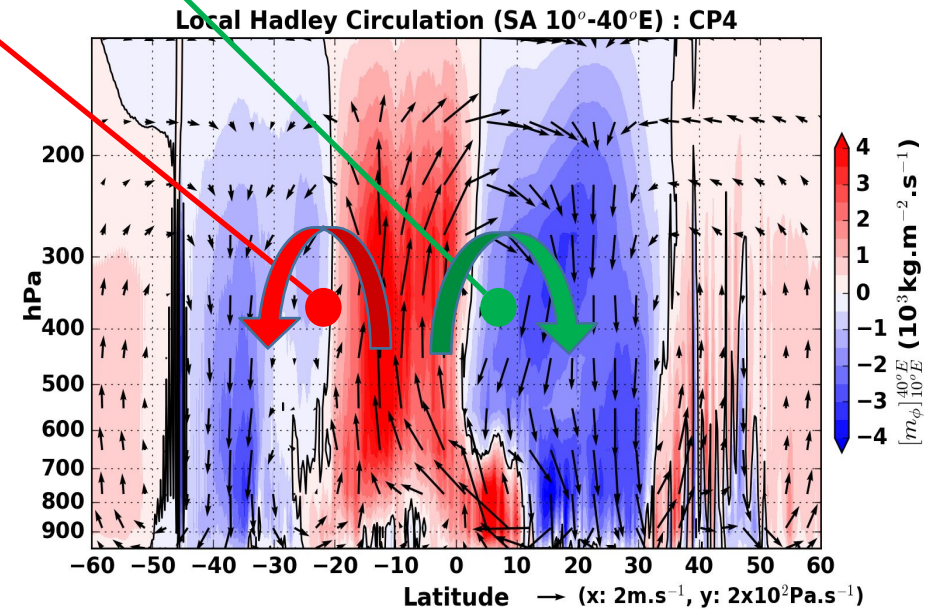
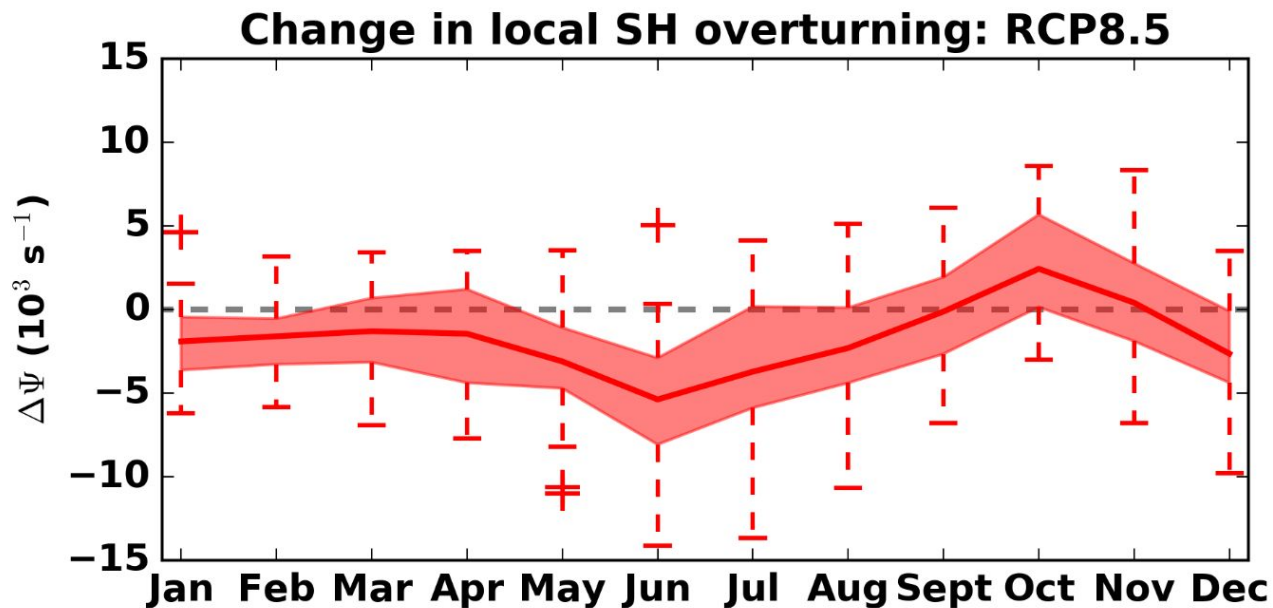
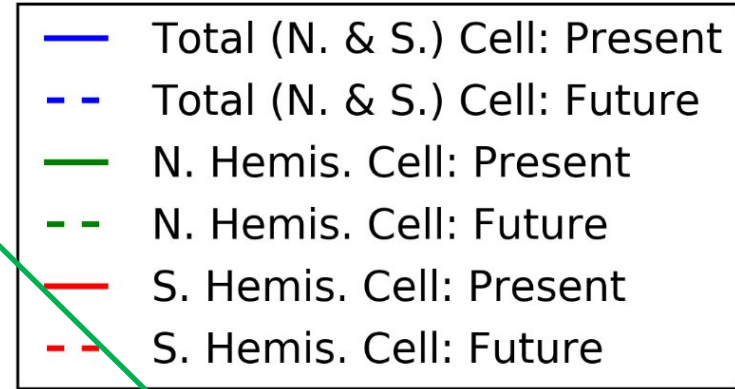
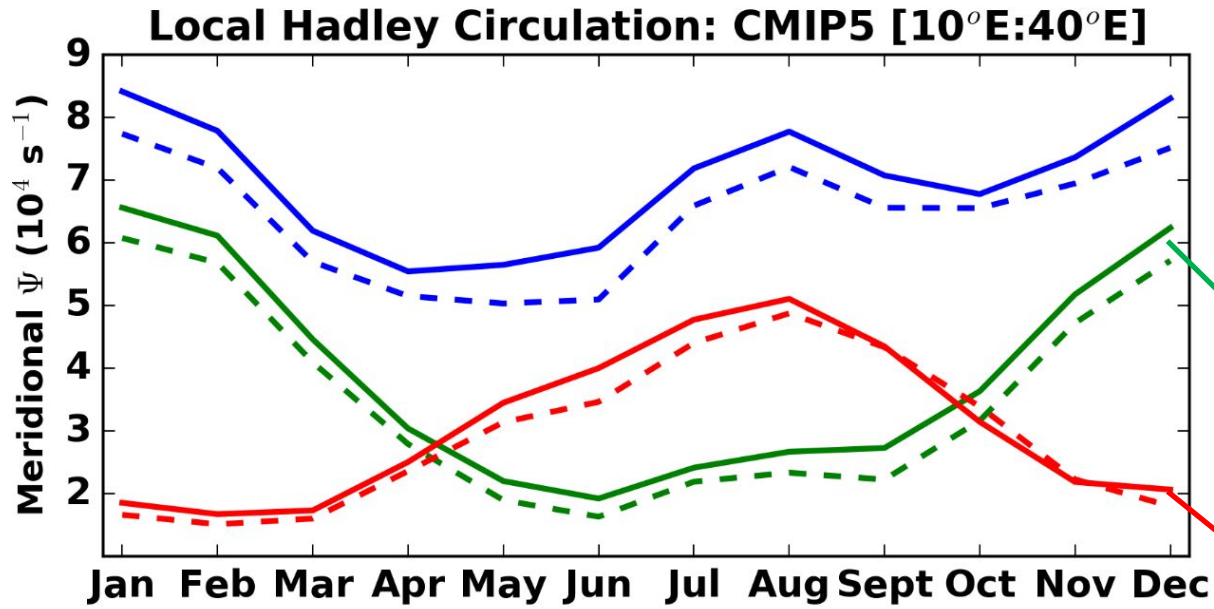
Oct Local Hadley Overturn. (SA 10°-40°E) : CP4 Present



Oct Local Hadley Overturn. (SA 10°-40°E) : CP4 Future

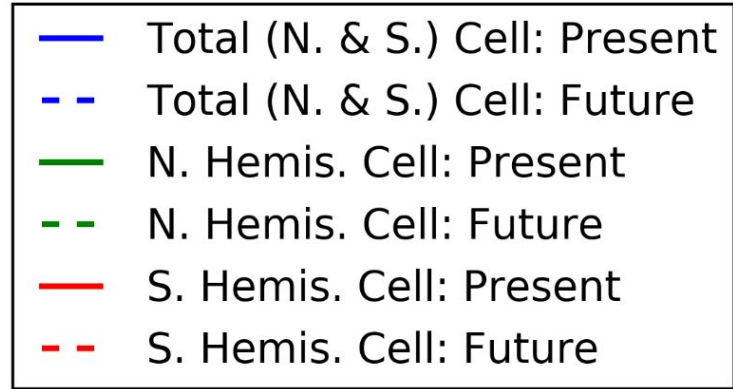
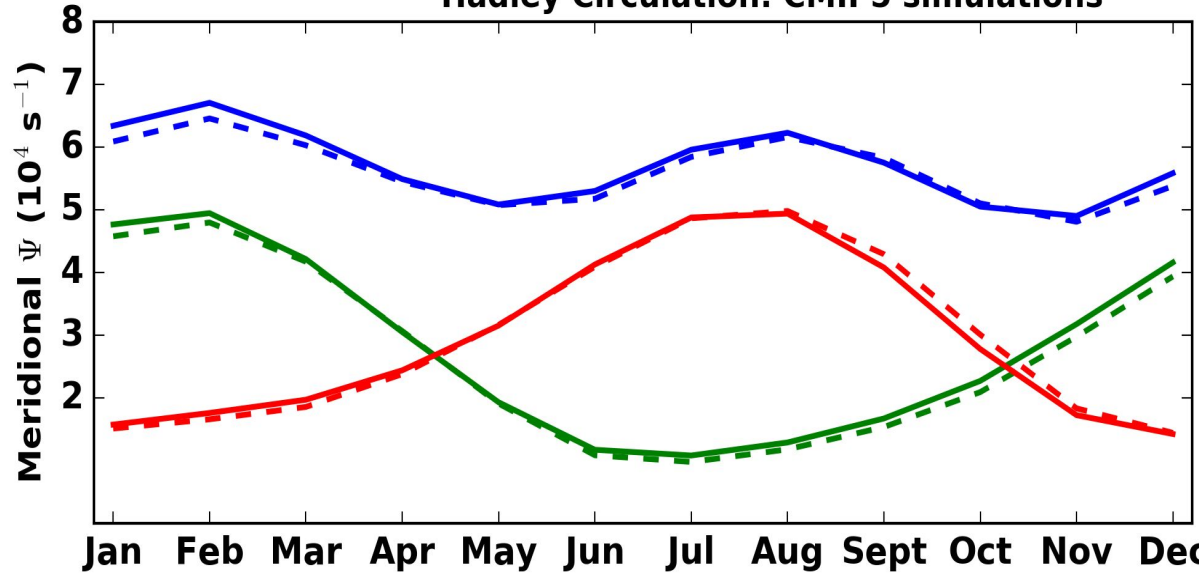


Local Hadley cell seasonality change: CMIP5

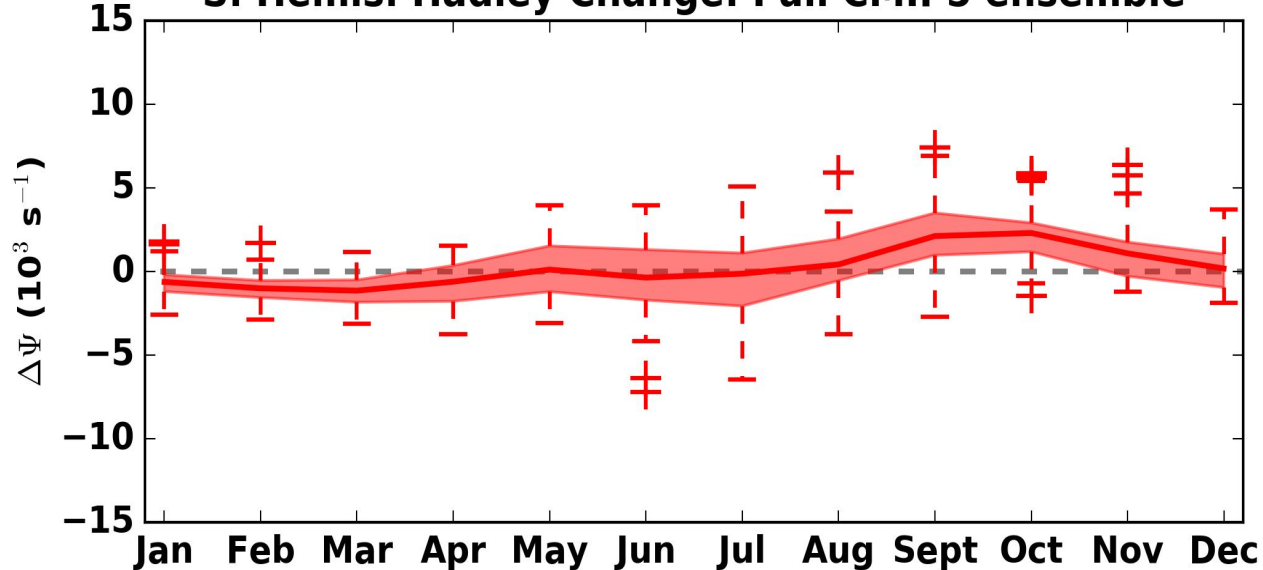


Hadley cell seasonality change: SH

Hadley Circulation: CMIP5 simulations

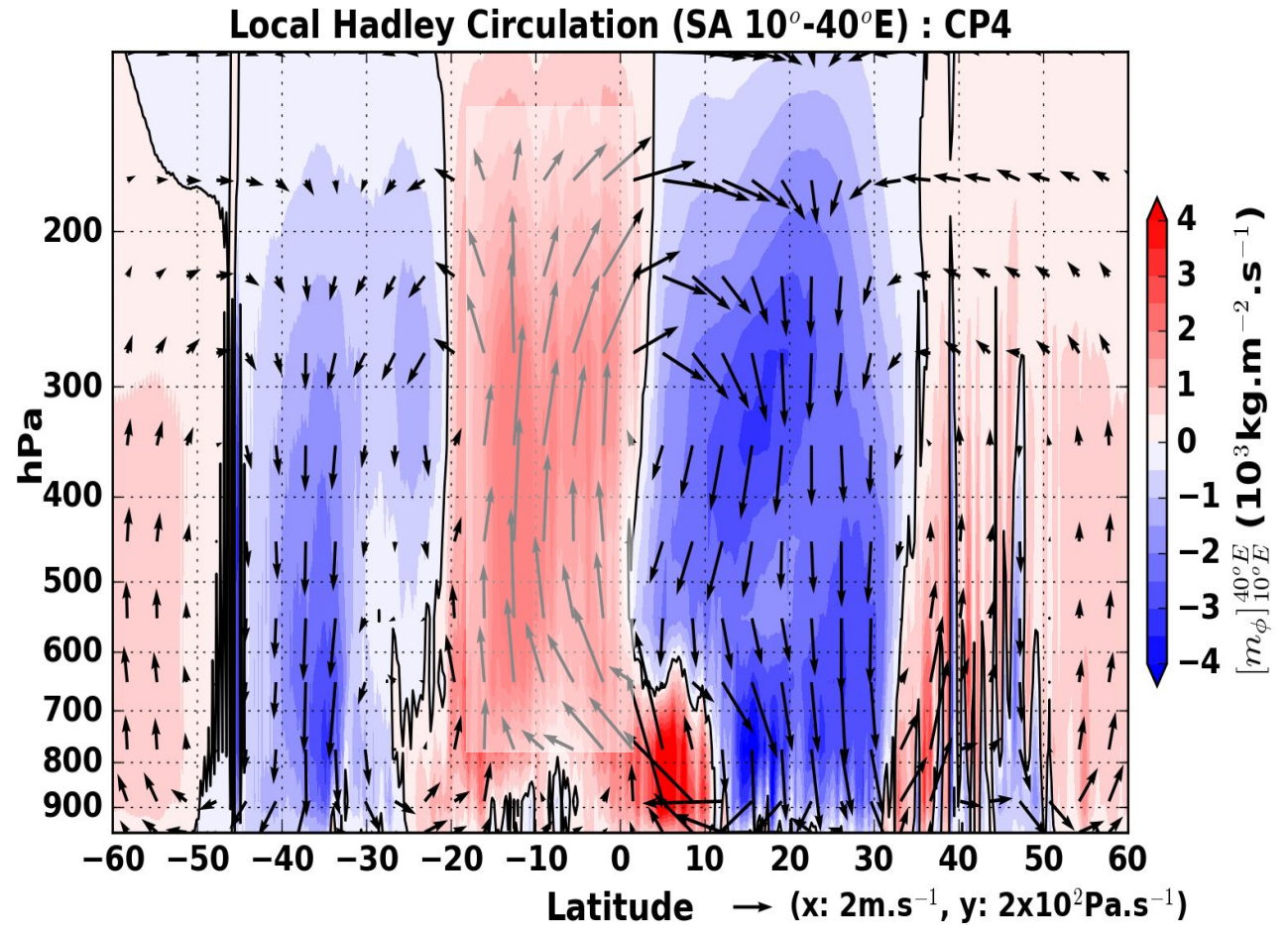


S. Hemis. Hadley Change: Full CMIP5 ensemble



New Puzzle with new CP4?

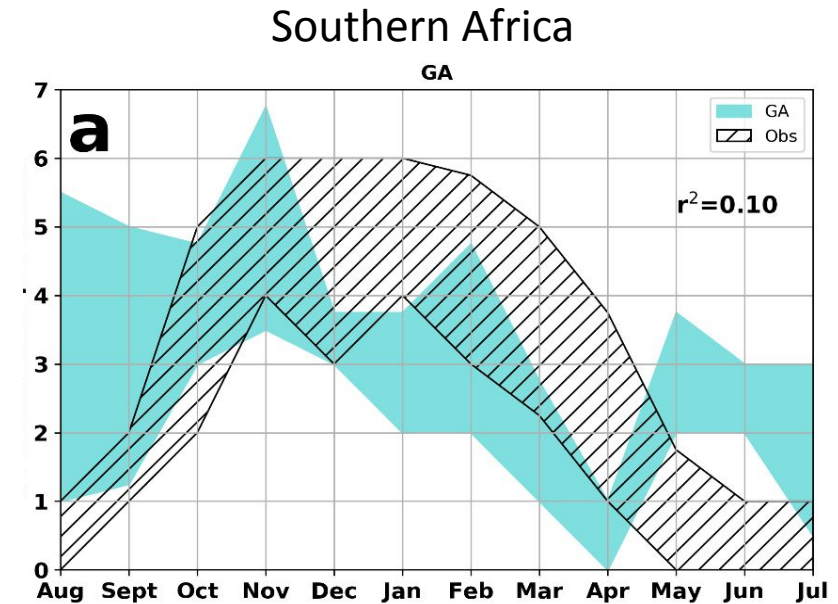
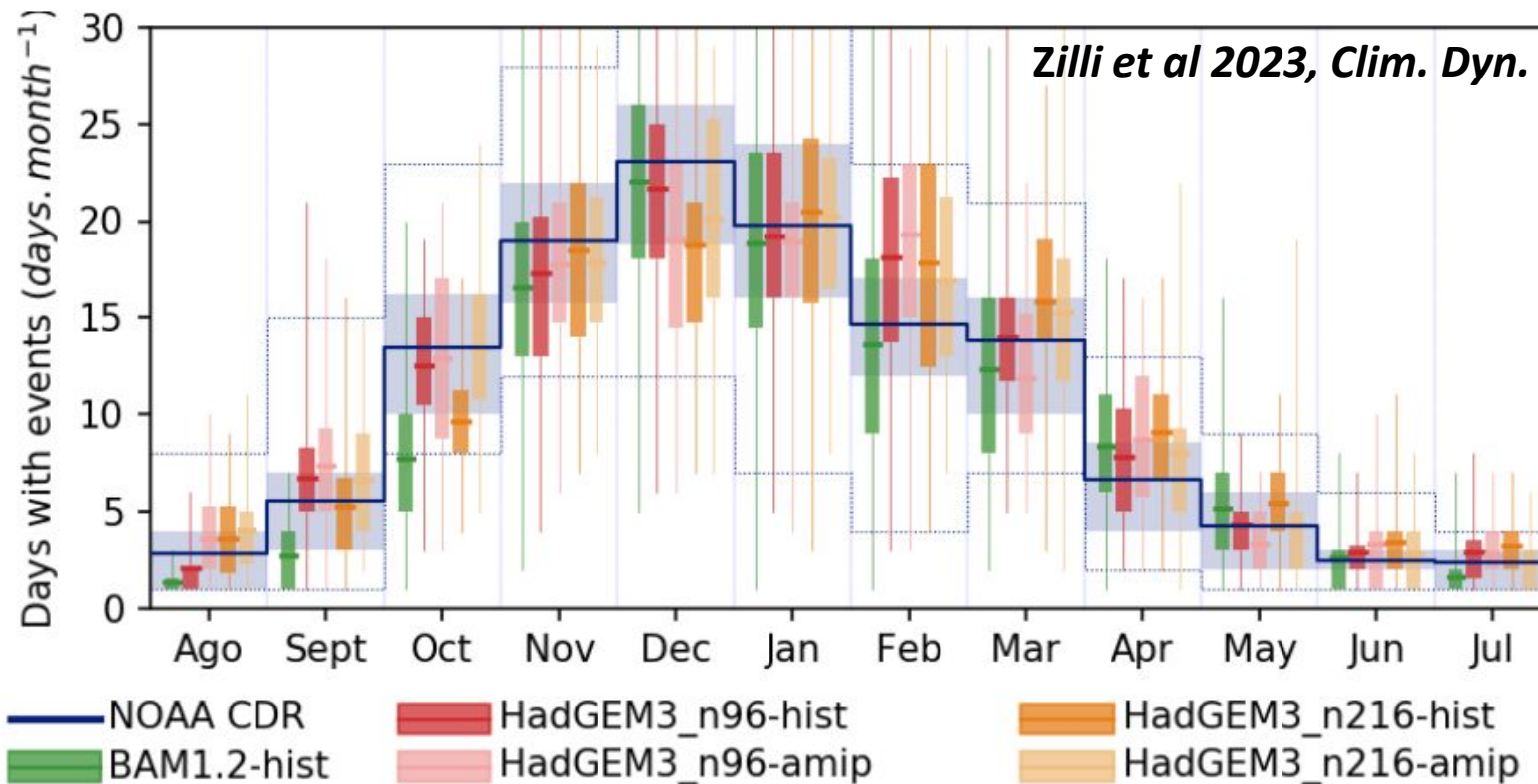
1. Original CP4-Africa was using RA1T
2. New CP4 simulations (multimodel ensemble boundary conditions) uses RAL3.1 with Flake
3. Enhanced subsidence over subtropical Africa maintained....
4. ...but with weaker vertical velocities in African rain belt!?!



What of South American cloudbands?

- South American mean climate simulated more faithfully in HadGEM models than Africa.
- **Convection-permitting model has less *error* to potentially correct, less dramatic mean state improvement**
- *However, what of extreme rainfall?*

(a) Number of days with events



Identifying the Cloud Bands

☁ Cloud band detection algorithm developed by Hart et al. (2012, 2013) and adapted to South America [Zilli and Hart 2021].

☁ Minimum OLR threshold defined per dataset

SIMULATIONS

Unified Model

OBSERVATIONS

Event Id
OLR
 NOAA CDR 1.2
 [1° lat/lon]

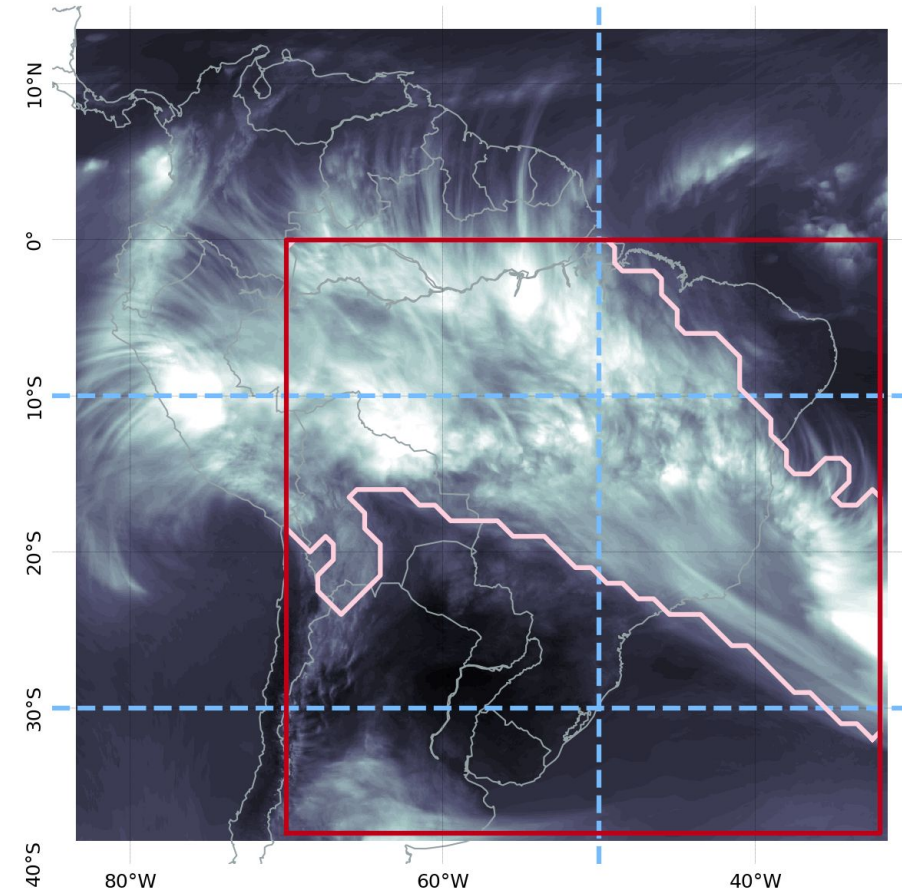
Event Intensity
PRECIPITATION
 CHIRPS
 [0.25° lat/lon]

UM N512 → CPM
 @ 25 km @ 4.5 km
 Present Day, Future
 [RCP8.5]

HadGEM3-GC3.1
 UM N216 UM N96
 @ 60 km @ 135 km
 Present Day, Future
 [SSP585]

CPRCM-PD, GCM
 CPRCM-2100,
 GCM-2100

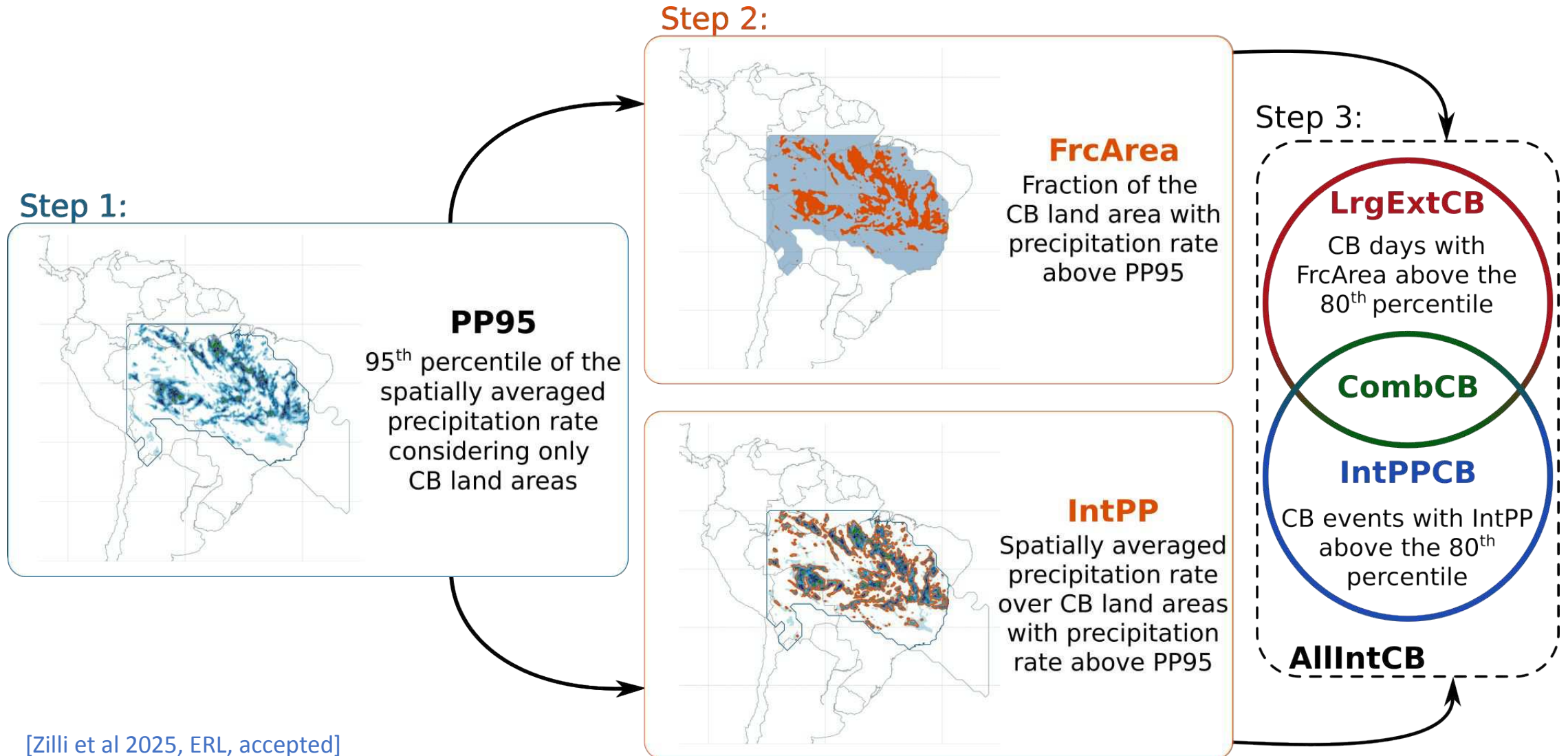
N216,
 N216-ssp585
 N96,
 N96-ssp585



CPM simulation 02 Jan 2000.
 Threshold at 240 W/m²

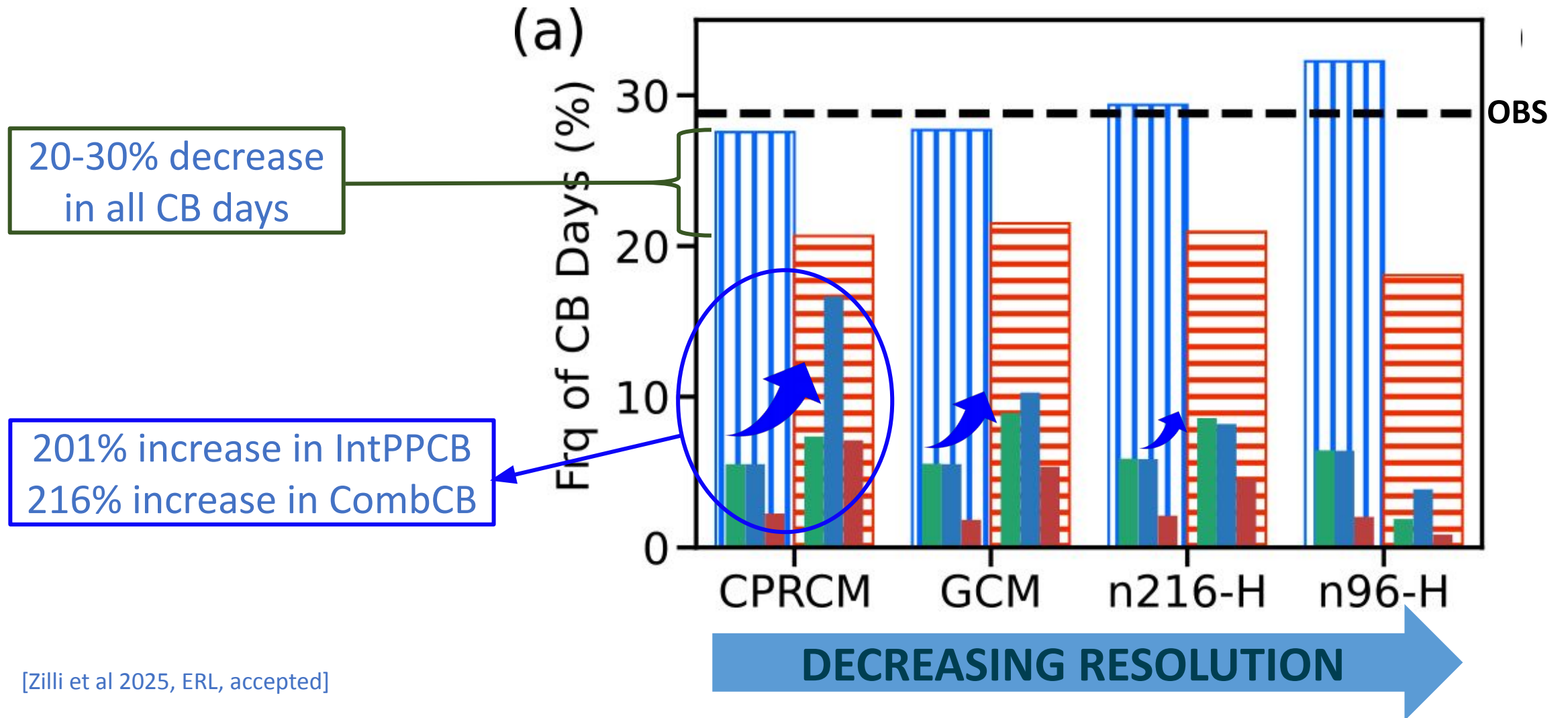
[Zilli et al 2024, Clim Dyn]

Intense Cloud Band Days



[Zilli et al 2025, ERL, accepted]

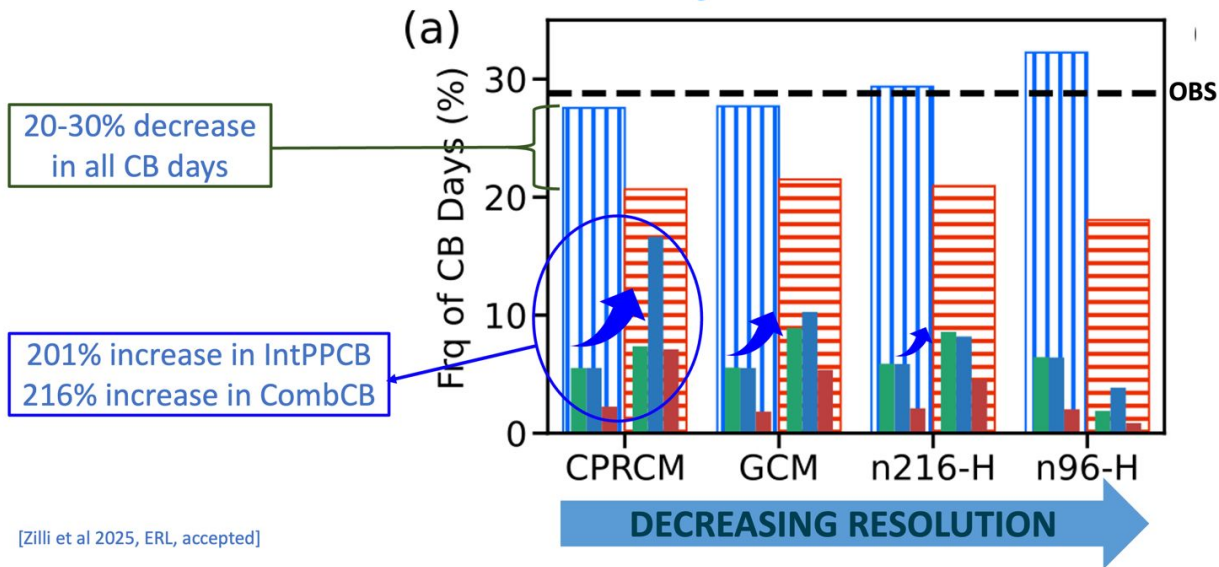
Changes in Frequency and Contribution of Intense CB days



[Zilli et al 2025, ERL, accepted]

True for southern African cloud bands too in CMIP5

Changes in Frequency and Contribution of Intense CB days

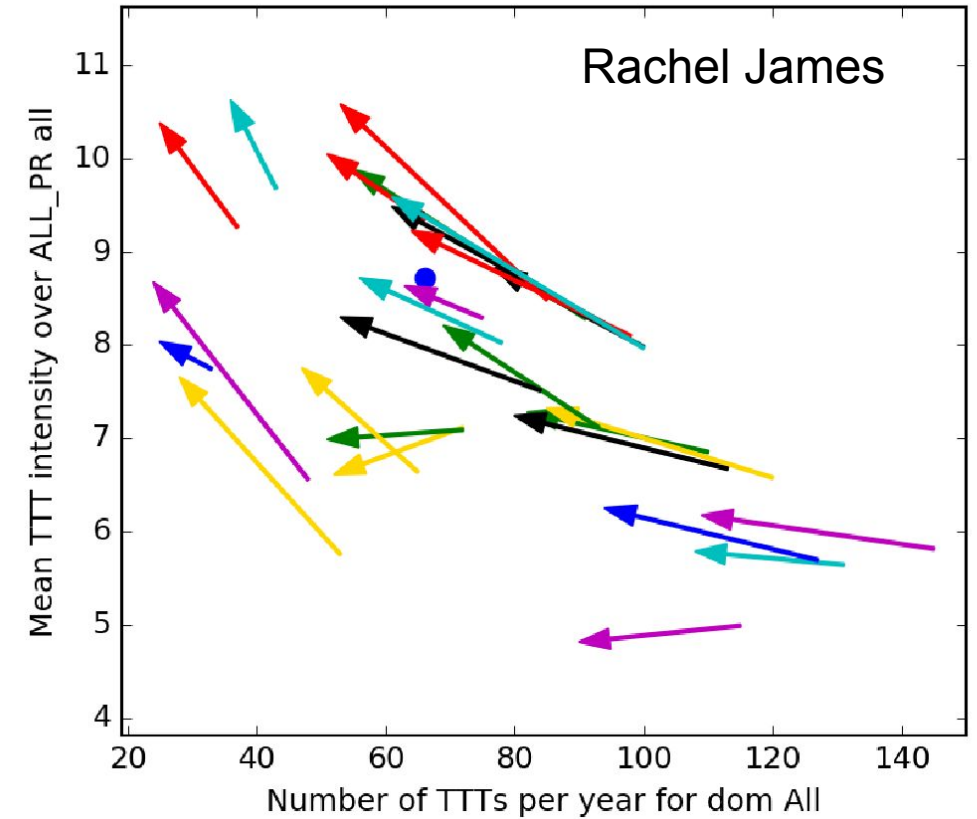


[Zilli et al 2025, ERL, accepted]

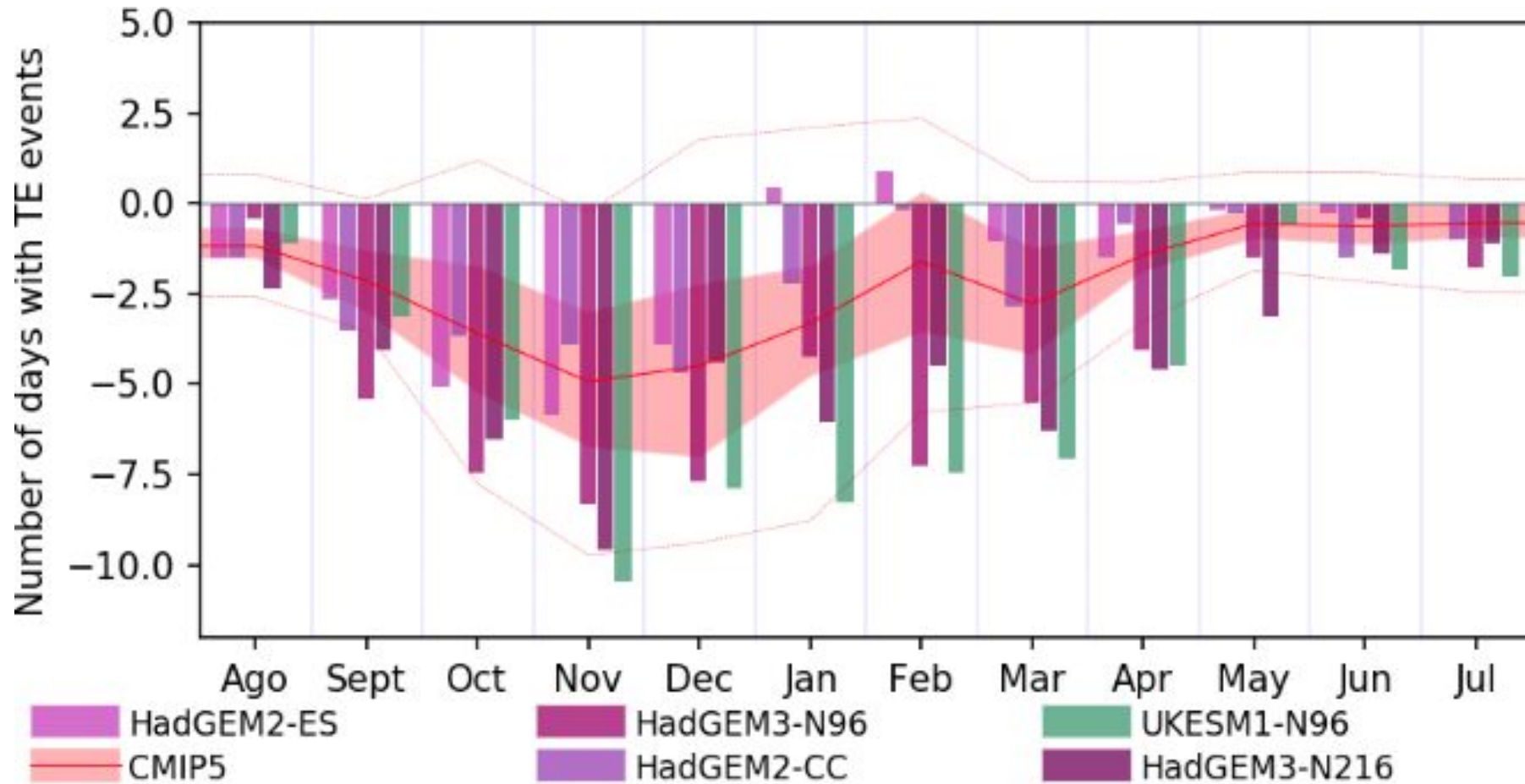
04/06/2025

25

CMIP5 RCP8.5 2100 Change



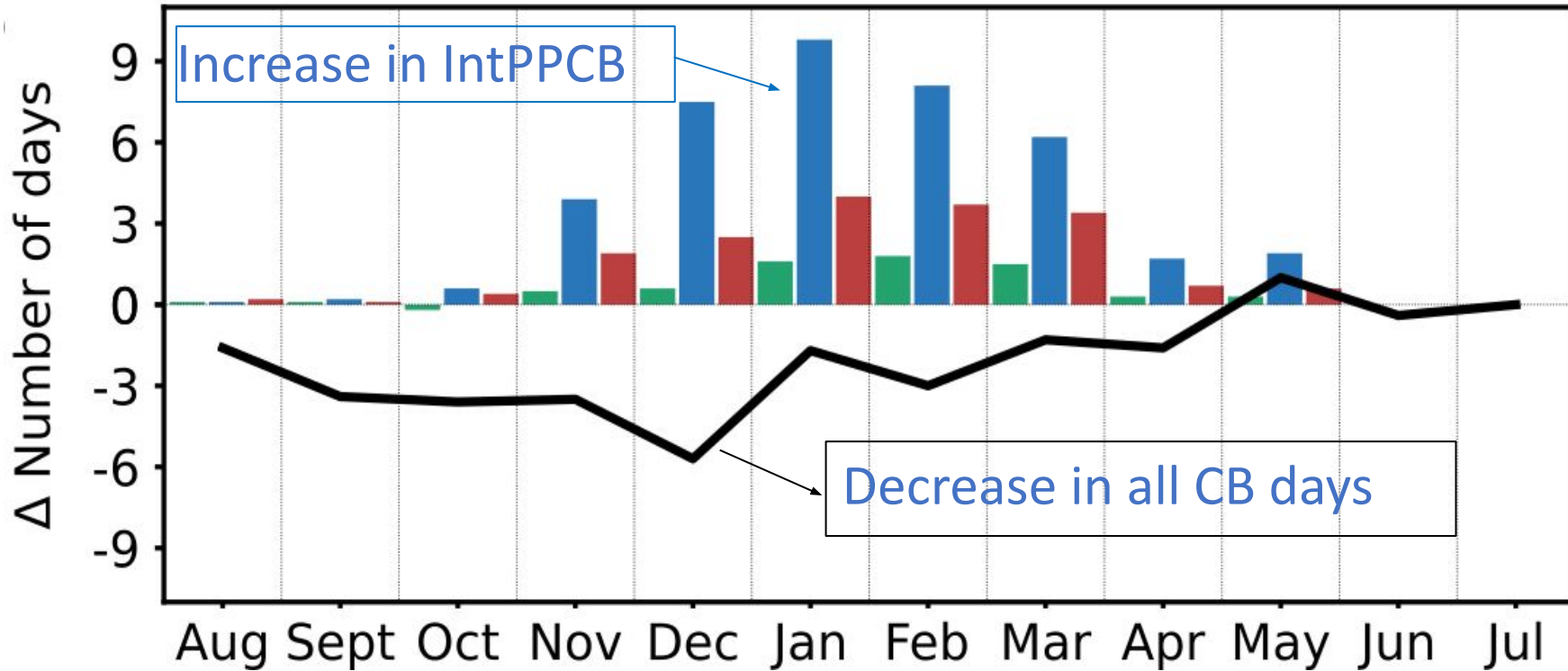
Changes in Intense CB days despite CB decline



Threefold increase in most intense South Atlantic Convergence Zone events by 2100 in convection-permitting simulation, *Zilli et al 2025, ERL, accepted*.

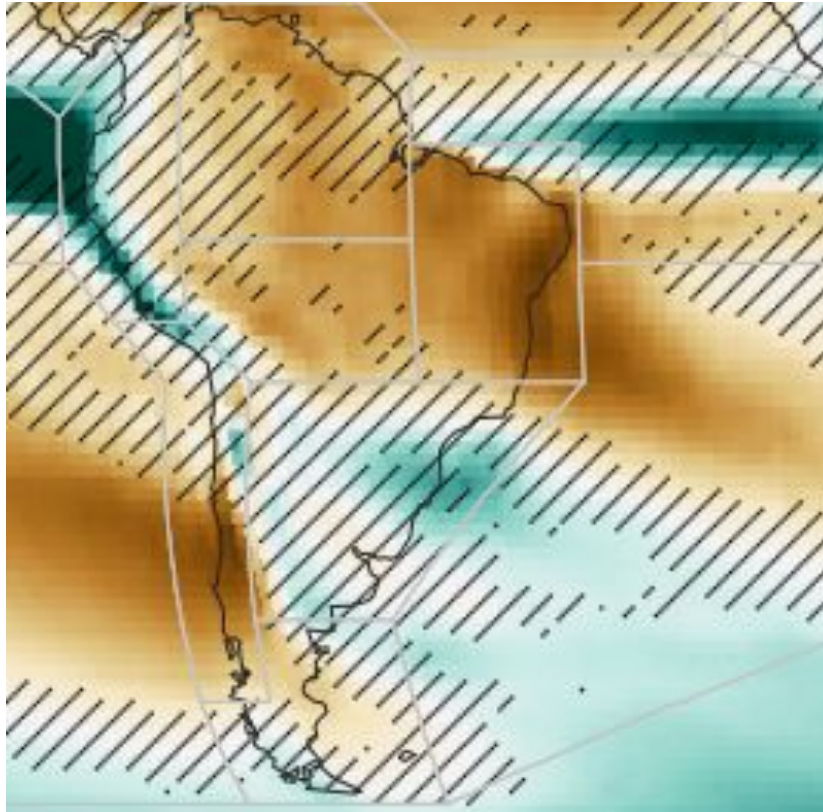
Changes in Intense CB days despite CB decline

Explicit convection simulation suggests CMIP ensemble is underestimate rainfall intensification risk.



Threefold increase in most intense South Atlantic Convergence Zone events by 2100 in convection-permitting simulation, *Zilli et al 2025, ERL, accepted.*

The land surface matters for the spring delay too...

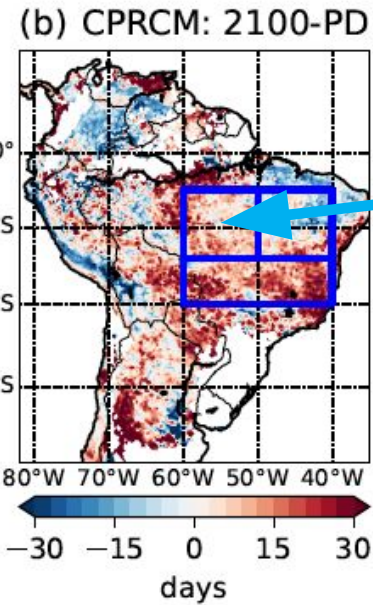
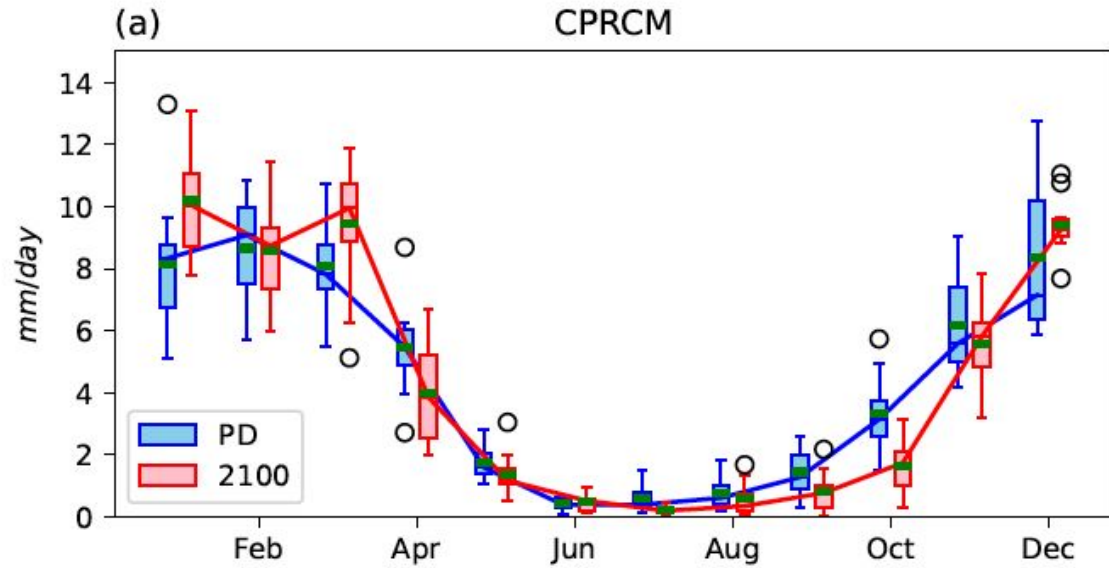


Simulated delay in the onset of the rainy season in Central East Brazil under global warming influenced by plant physiological response

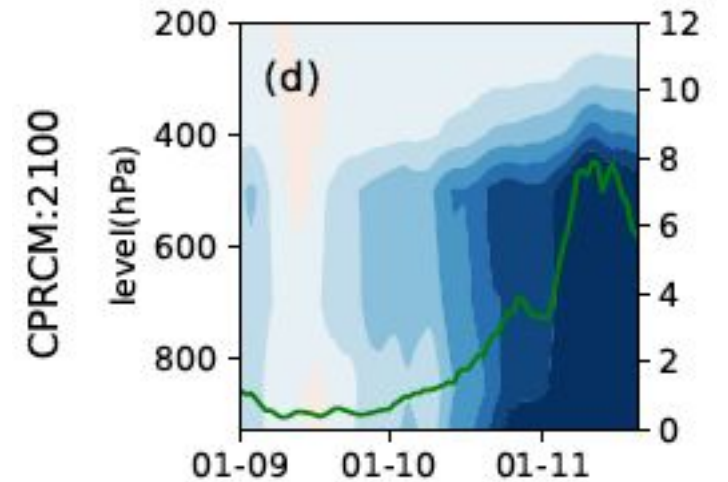
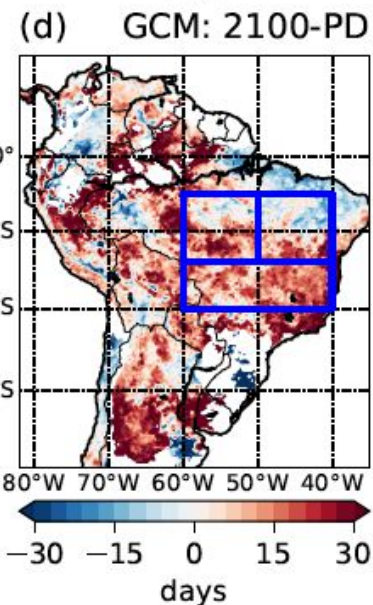
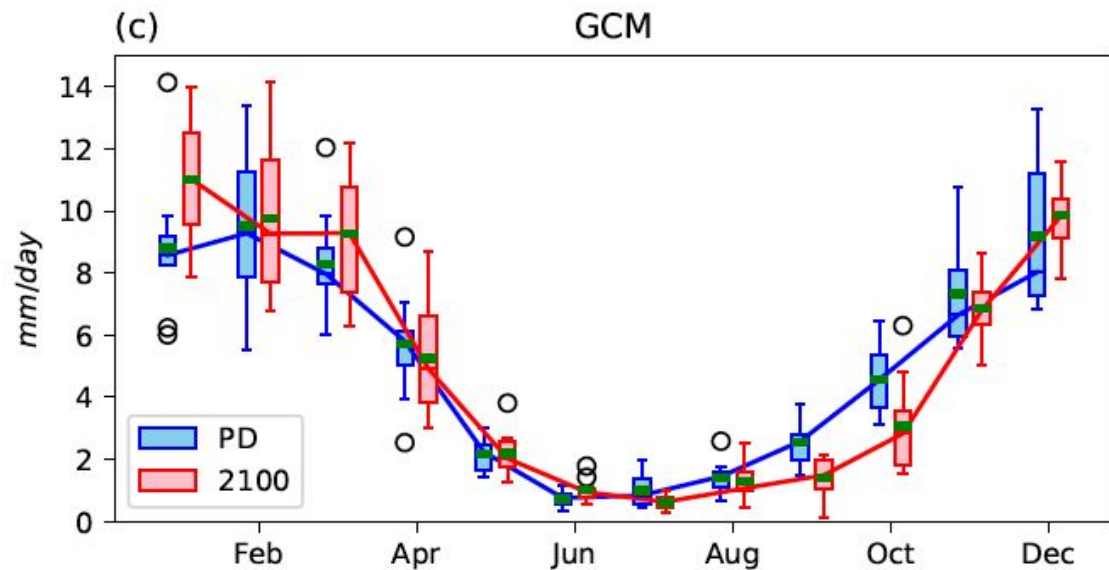
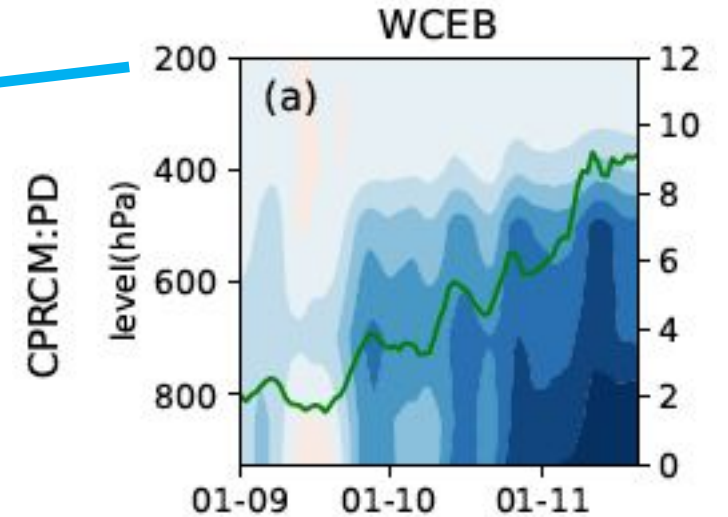
Jerry B Samuel,^a Marcia T. Zilli,^a Neil C. G. Hart,^a Kate Halladay,^b Ron Kahana,^b Robin Chadwick,^{b,c} Sonja Folwell,^d

Journal of Climate, under 2nd review

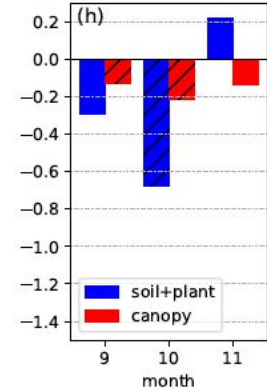
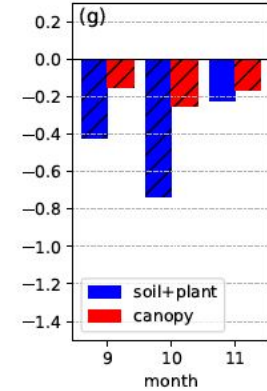
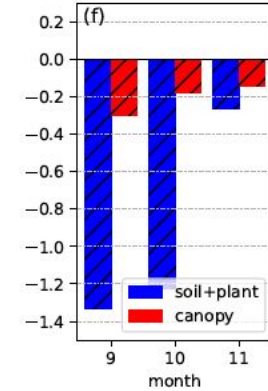
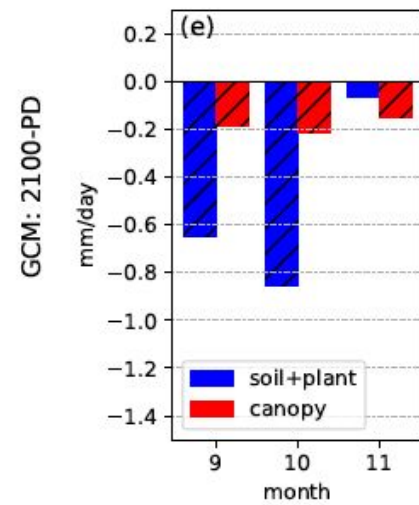
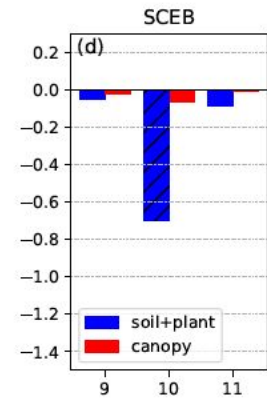
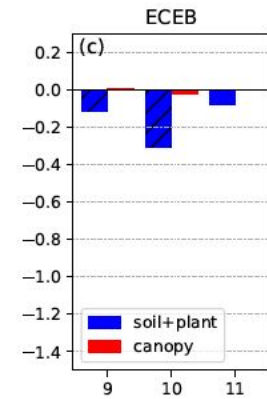
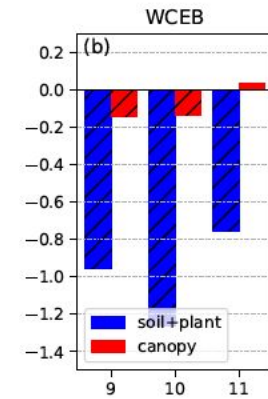
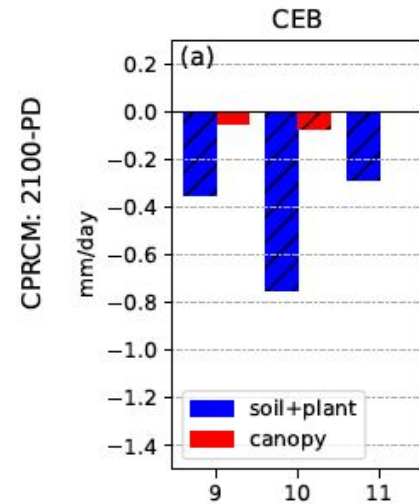
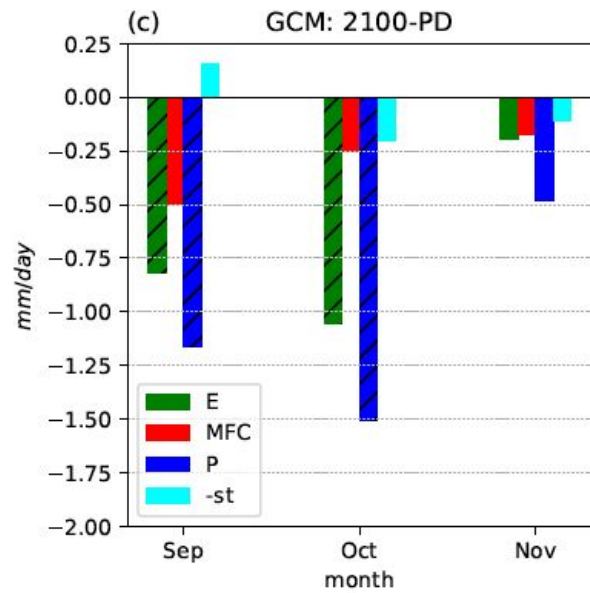
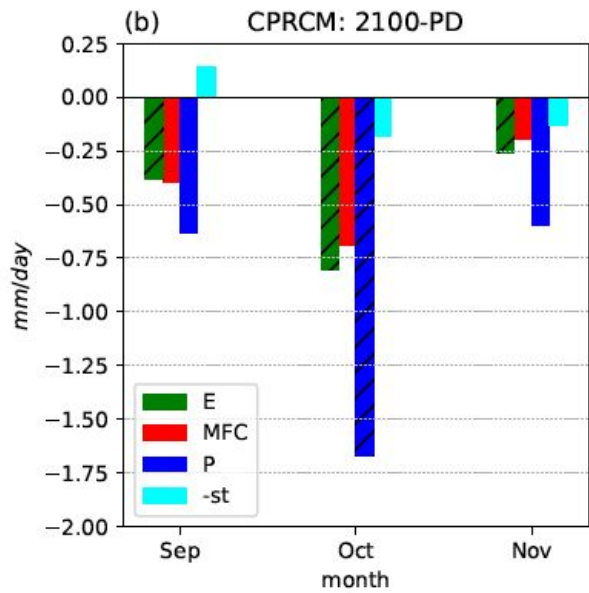
What of South America?



Lq evolution (relative to August)



Decline in October Evaporation



Vegetation-land surface may cause or amplify delayed onset

Conclusions

ATMOSPHERE

Increased stability and lower evapotranspiration during the dry-to-wet season transition reduces the precipitation

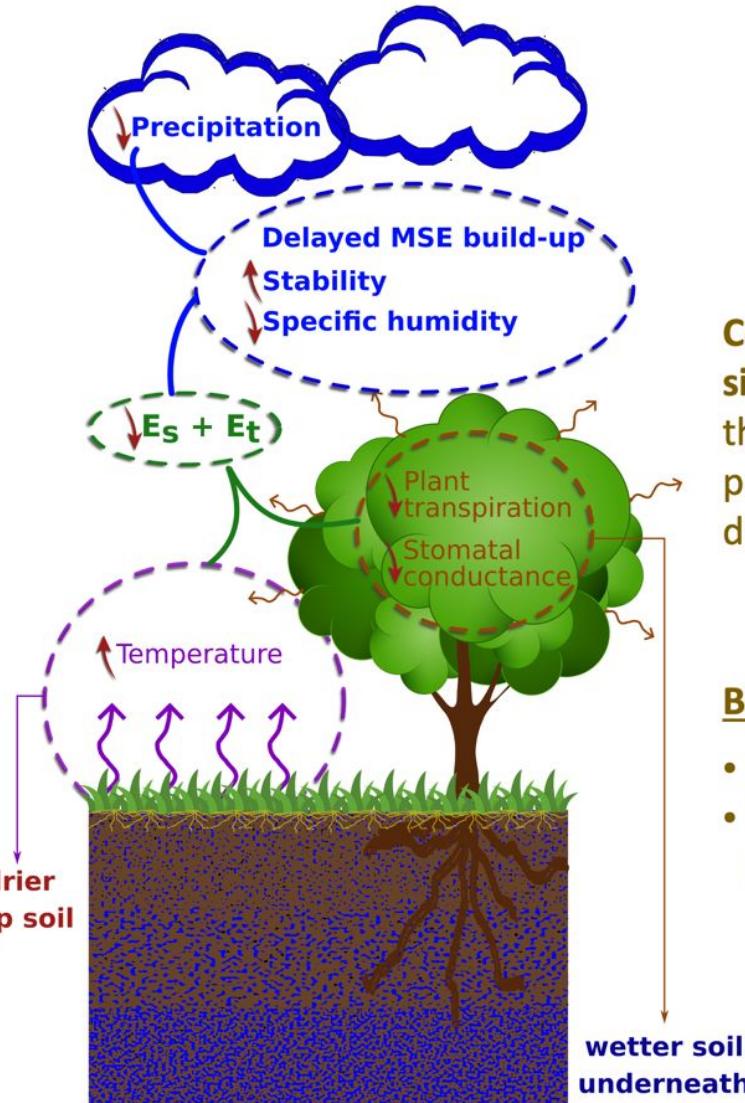
SURFACE

Drier top-soil layer due to larger temperatures (more evaporation)
Wetter deeper layers due to reduced plant transpiration

PLANT PHYSIOLOGY

Reduced stomatal conductance due to larger temperatures and CO_2 concentration
drier top soil

[Samuel et al 2025, J Clim (in review)]



Convection-permitting simulations better represent the diurnal cycle of precipitation and its distribution

BUT...

- One single simulation
- Large dependence on the land surface model (JULES)

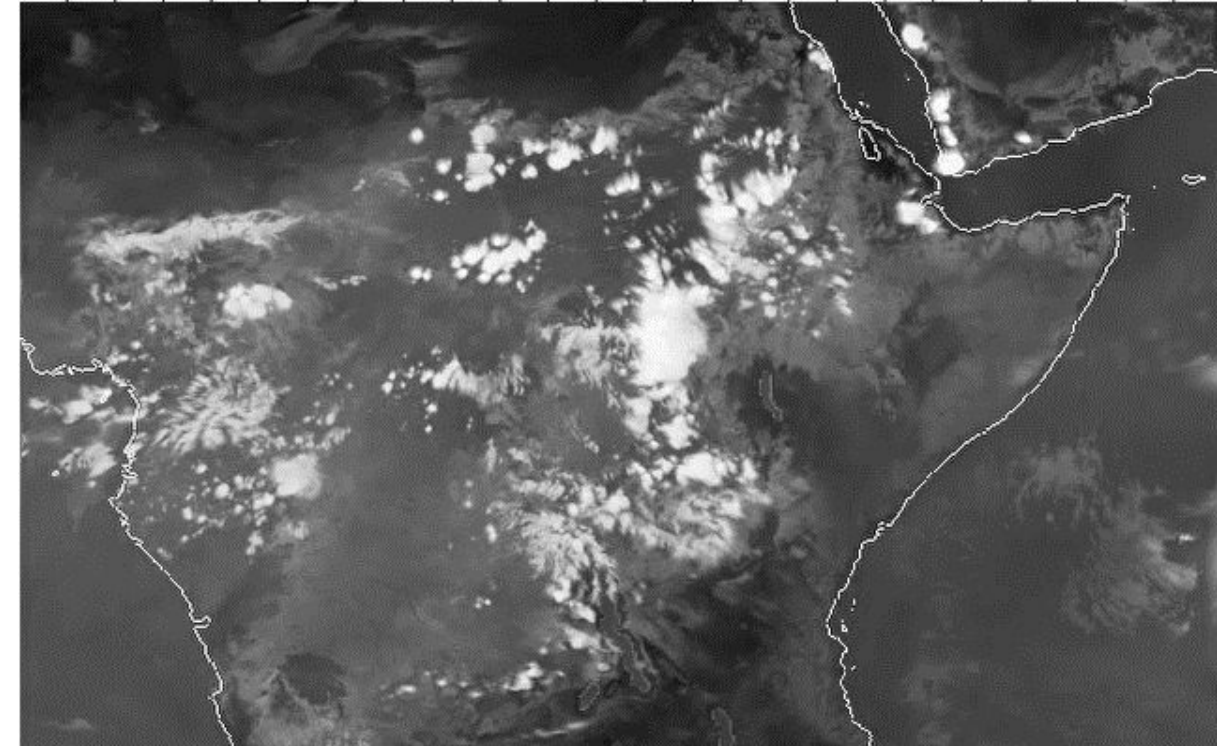
Bleak outlook, can we manage this?

- Curbing GHG emissions essential of course
- But warming continues and risks already here
- So...
- Early Warning informing anticipatory actions shown much success for other weather and climate risks.
- *First Rains* is our project focused on advancing onset prediction across these at-risk regions
- Aligns with the United Nations Early Warnings for all initiative announced in 2022.



Will km-scale models give more skill?

- Met Office Unified Model; RAL3.1
- 2.2km resolution (2500x3000 grid)
- 3-month duration ensemble simulations (9-12 members)
- ERA-5 boundary forcing
- Flake lake scheme
- Corresponding parameterised LAM for comparison (12km resolution)
- Experiments with different initial conditions & lateral boundary conditions
- *Fran Morris leading on this.*
- *Visit her poster*



Quantifying Ensemble Divergence in Large-Domain Convective-Scale Simulations over Africa

F. A. Morris¹, N. C. G. Hart¹, M. T. Zilli¹, J. B. Samuel¹
¹ School of Geography and the Environment, University of Oxford, UK

FIRST RAINS

The goal of the First Rains project is to develop new techniques to improve the characterisation and prediction of seasonal monsoon onset, in order to provide relevant information to decision-makers in Southern Africa and South America. The project attempts to do this through two key approaches: firstly, through the development of novel techniques to characterise and understand monsoon onset, taking advantage of existing datasets, and secondly, through running a new ensemble of convection-permitting model experiments to investigate the added value of high-resolution simulations for onset prediction.

Convective-scale simulations are known to enhance predictive skill in numerical weather forecasts in the tropics. Studies of convective-scale simulations suggest they can also alter representation of climatological mean-state features relative to their driving global climate models. For example, convective-scale climate simulations can strengthen the Hadley circulation, thus reducing precipitation biases in subtropical regions such as Southern Africa (Hart et al. 2018). Does such a result hold over multiple realisations of convective-scale ensemble simulations?

1 Model Configuration

- Met Office Unified Model
- Regional Atmosphere Land (RAL) 3.1 science configuration
- 2.2km grid spacing
- No deep convection parameterisation
- Boundaries driven by ERA5 data
- Flake one-dimensional lake scheme (Boony & Bonville 2017)

2 Quantifying Ensemble Spread

Figure 1: Schematic illustrating how members of the ensemble are initialised using different SDOs and times.

Figure 2: Time-series of outgoing longwave radiation (OLR, W m⁻²) and rainfall (mm day⁻¹) for SDOs (left column) and ensemble members over four days during the 10-day simulation.

Figure 3: Difference in OLR (W m⁻²) and rainfall (mm day⁻¹) between the control and ensemble members.

Figure 4: Daily ensemble spread (standard deviation) of OLR (W m⁻²) and rainfall (mm day⁻¹) over the 10-day simulation.

3 Further Simulations

- Due to technical constraints, an equivalent ensemble simulation with parameterised convection could not be run.
- Running to 3 months to investigate how subseasonal predictability is affected by using convective-scale simulations.
- SSTs will be updated daily.
- This initialisation technique is not appropriate for 3-month simulations, so instead we will initialise using M2020P4 global ensemble (Bowler et al. 2020).
- Further experiments will quantify the response of CP ensembles to seasonal controls such as ENSO & MJO states.

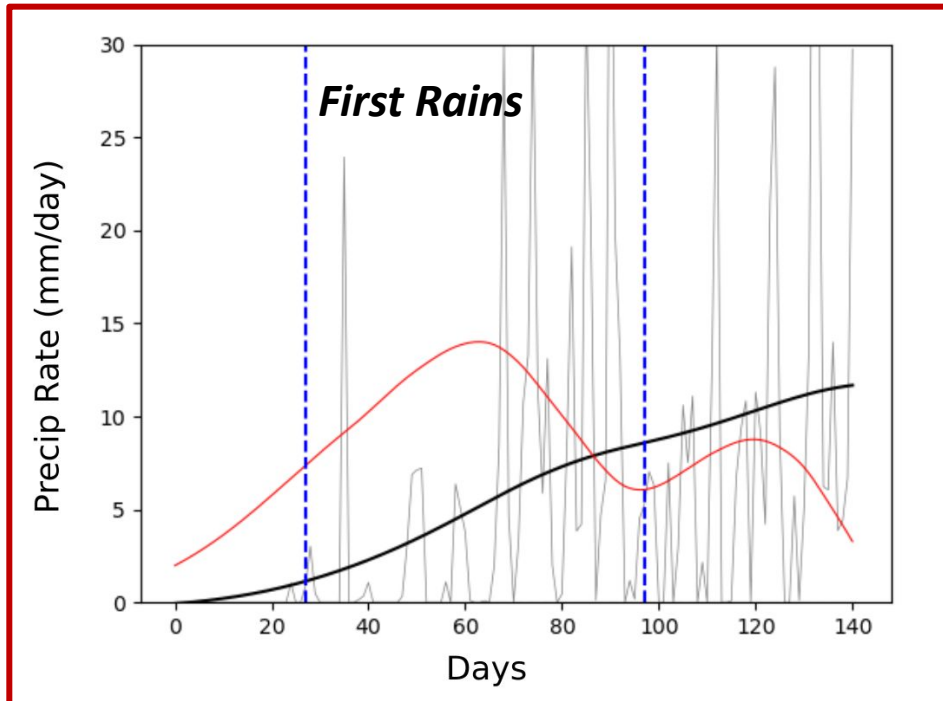
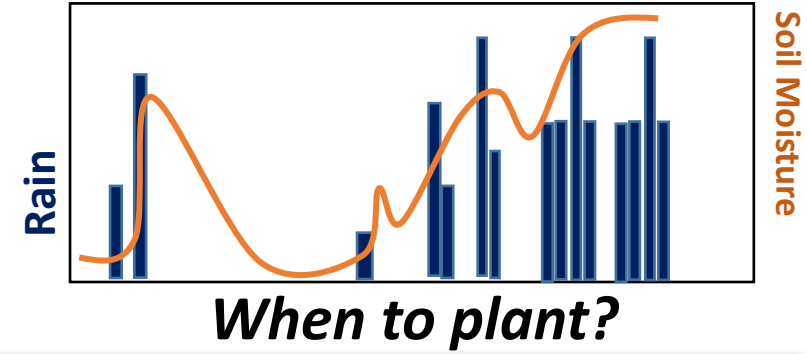
With large perturbations to initial conditions, a large-domain convective-scale ensemble's spread will decrease as members converge towards a mean state controlled by lateral boundary conditions. However, a convective-scale ensemble's domain-mean signals may deviate from its driving model.

References
Boony, A., & Bonville, A. (2017). The impact of lake ice on the Hadley circulation in the Met Office Unified Model. *Journal of Climate*, 30, 100-110.
Bowler, B., & Bonville, A. (2020). Convective-scale simulations of the monsoon onset over the Congo basin. *Journal of Climate*, 33, 1020-1030.
Hart, N. C. G., & Bonville, A. (2018). The performance of the Met Office Unified Model in the Tropics. *Journal of Climate*, 31, 100-110.

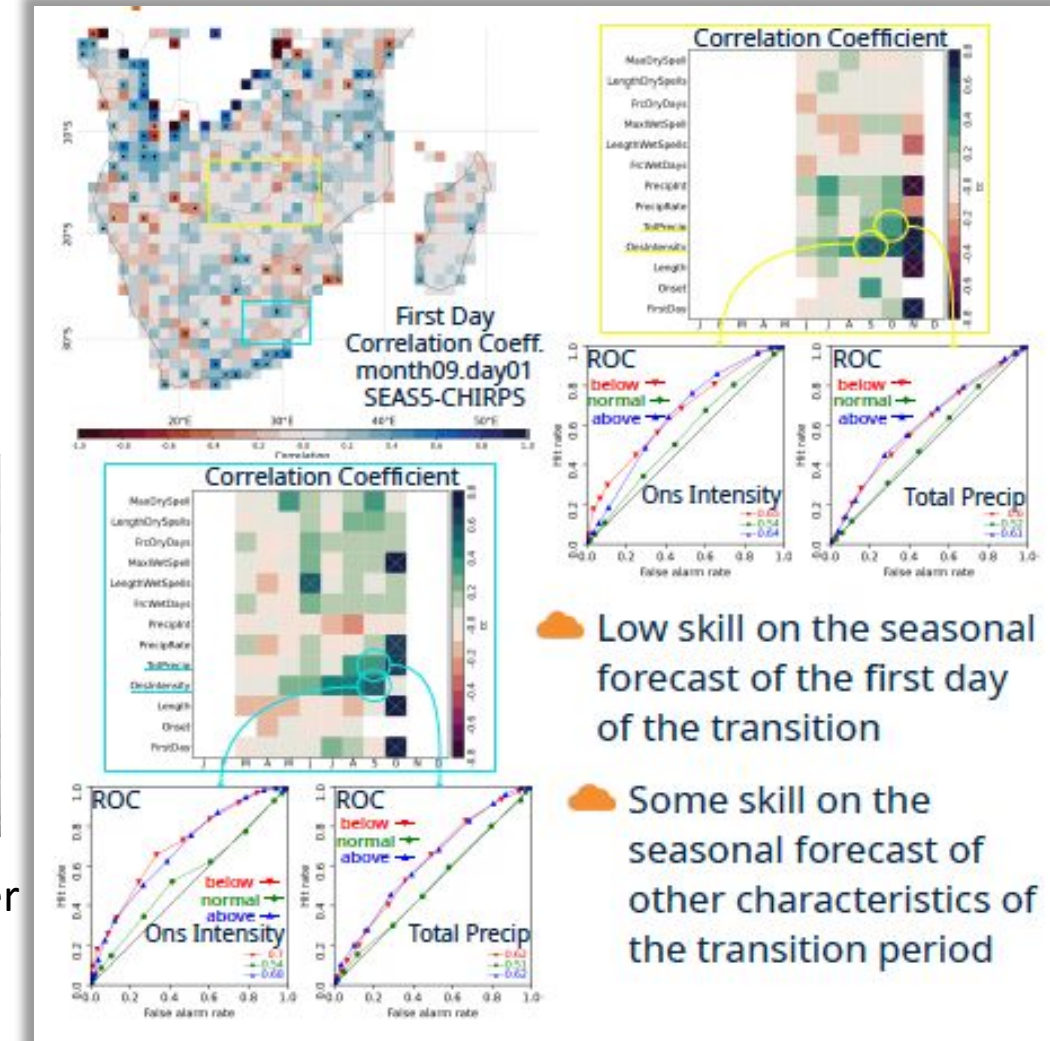
Predicting Onset period

Within same model family, we can explore predictability of late onset seasons

- Identify dry-to-wet transition period
- Within period compute:
 - First day & length
 - Intensity of onset
 - Fraction of dry days and wet days



See Marcia Zilli's Poster



☁ Low skill on the seasonal forecast of the first day of the transition

☁ Some skill on the seasonal forecast of other characteristics of the transition period

Outlook

- Suite of explicit convection simulations – k-scale, DYAMOND, Destination Earth - pose lots of opportunity to move these results and working hypotheses forward.
 - How do different science configurations matter?
 - What is the gain in global over regional km-scale?
- Gaining as much skill as possible is essential to early warning systems...what will ML models deliver in S2S skill when they include oceans?
- Exploring future climates with explicit convection climate models (and emulators) is also going to be critical.
 - Further confirmation that representing (or emulating) convective-scale process are crucial for many aspects of climate risk prediction and projection.

Additional slides



DRY-CAB project

Richard Washington, Edson Nkonde, Felix Imbwae, Wallace Kasongo, Rodney Mulenga, Neil Hart, Kitty Attwood, Charlie Knight, Sebastian Engelstaedter, James Warner, Emma Howard, Alice Jardine, Chris Edmunds, Callum Munday, Chris Reason, Ross Blamey, James Warner, Sophie Harbord, Ben Paterson, Orlando Bell, Emma Howard

Univ of Oxford, Zambian Met Department, University of Cape Town, Met Office

DRY-CAB



UMFULA

UKRI UK Research and Innovation

SoGE School of Geography and the Environment UNIVERSITY OF OXFORD

Can we predict the start of the summer rains, yet?

Neil Hart, Marcia Zilli, Fran Morris, Jerry Samuel
School of Geography and the Environment, University of Oxford

With thanks to collaborators:

Newton Fund Met Office

SoGE School of Geography and the Environment UNIVERSITY OF OXFORD

Commodian INPE INPA

South American monsoon onset as simulated in the convective-permitting model

Authors: Marcia Zilli, Neil Hart
School of Geography and the Environment, U. of Oxford

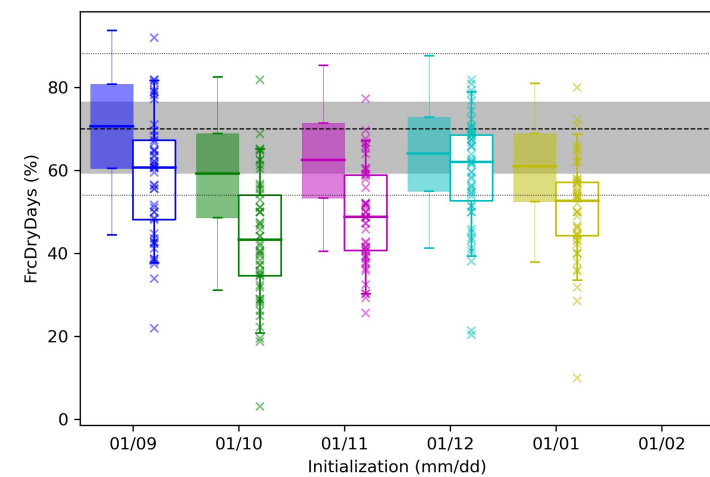
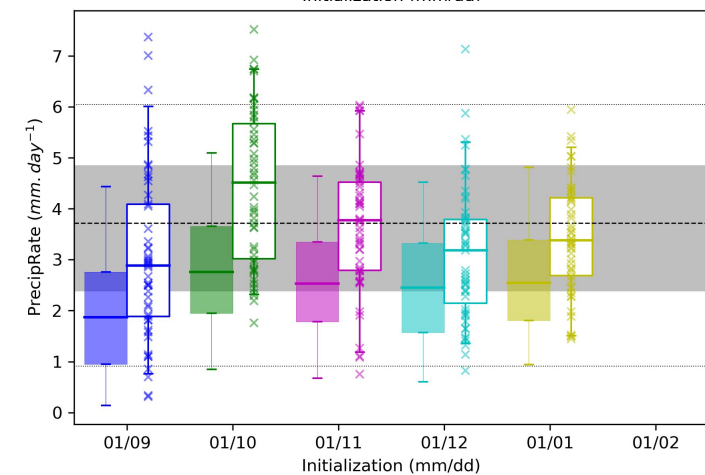
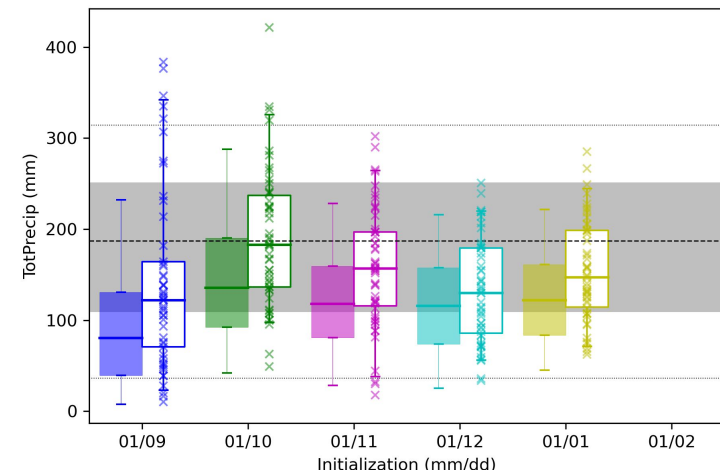
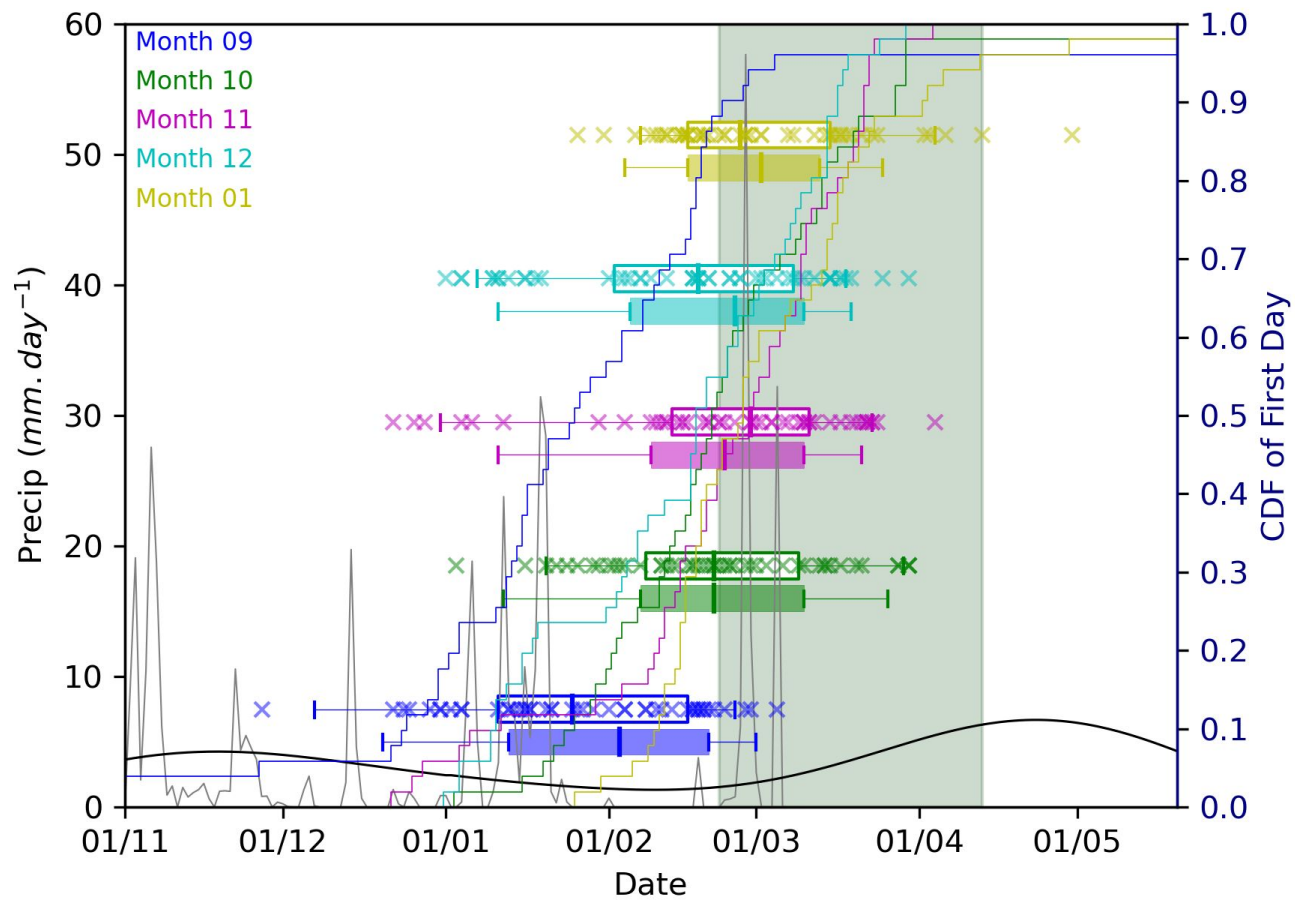
Kate Halladay & Ron Kahana
Met Office

CSSP Brazil Workshop – S. J. Campos, June 2022
29/08/2023 Marcia Zilli

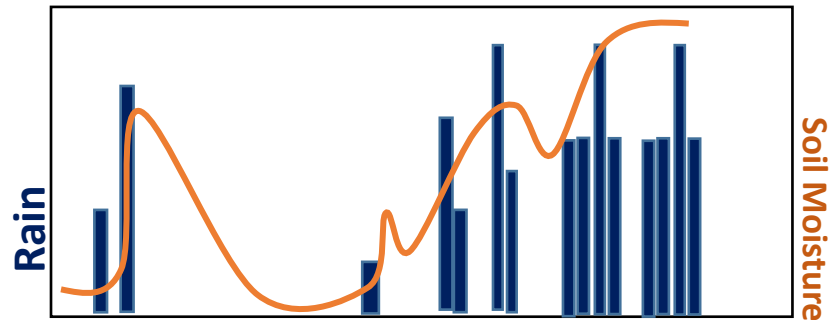
CSSP-Brazil

Met Office K-Scale Initiative

Nairobi example: Onset period



Rain fed agriculture: A key decision



When to plant?



Also for farmers: Seed varieties? Irrigation options?

For countries: Early indication of food aid requirements?

Beyond agriculture, rainfall onset matters for:

- **Water resource management, hydropower especially small-scale**
- **Health: heat stress, disease (meningitis outbreaks across West Africa)**

The Annual March of the Tropical Rainbelt

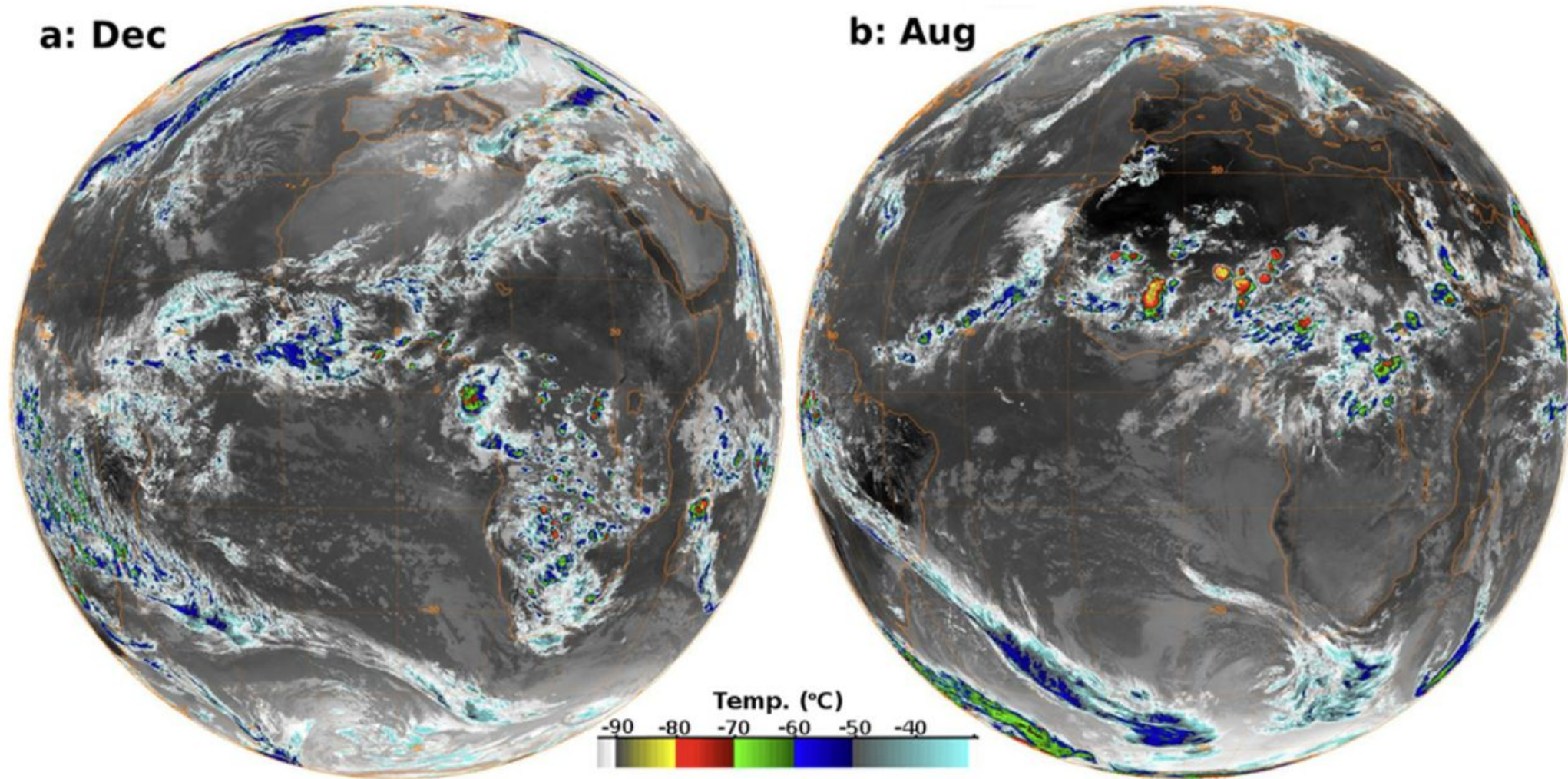
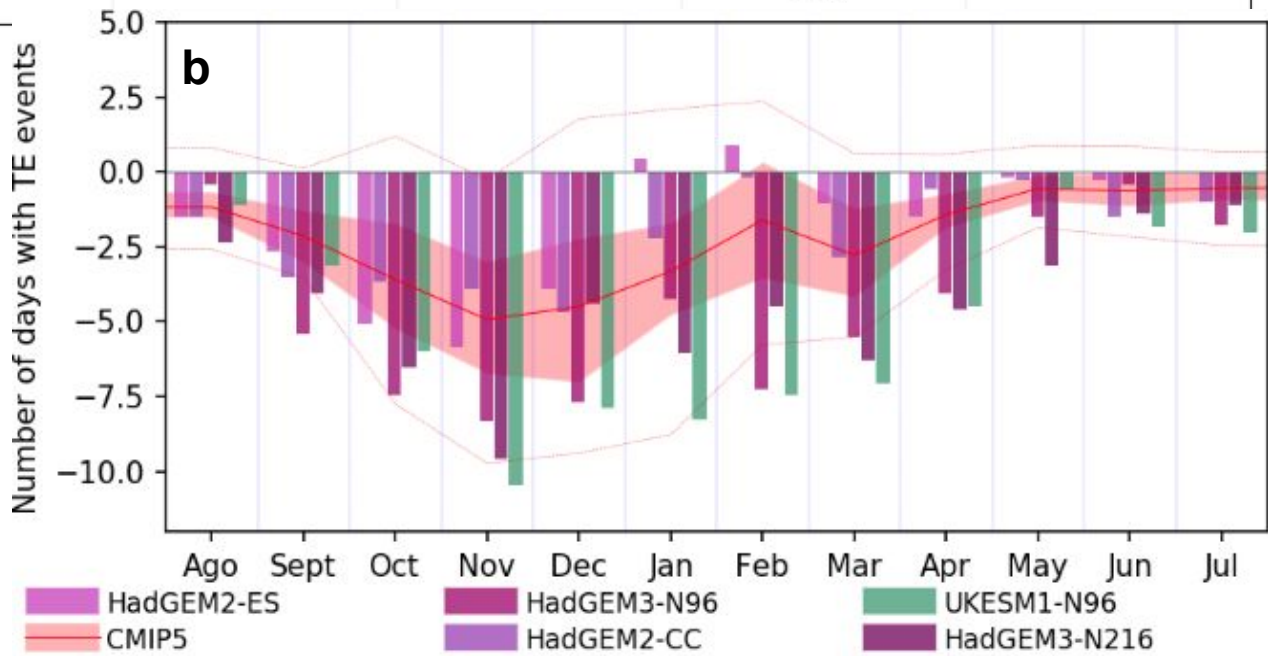
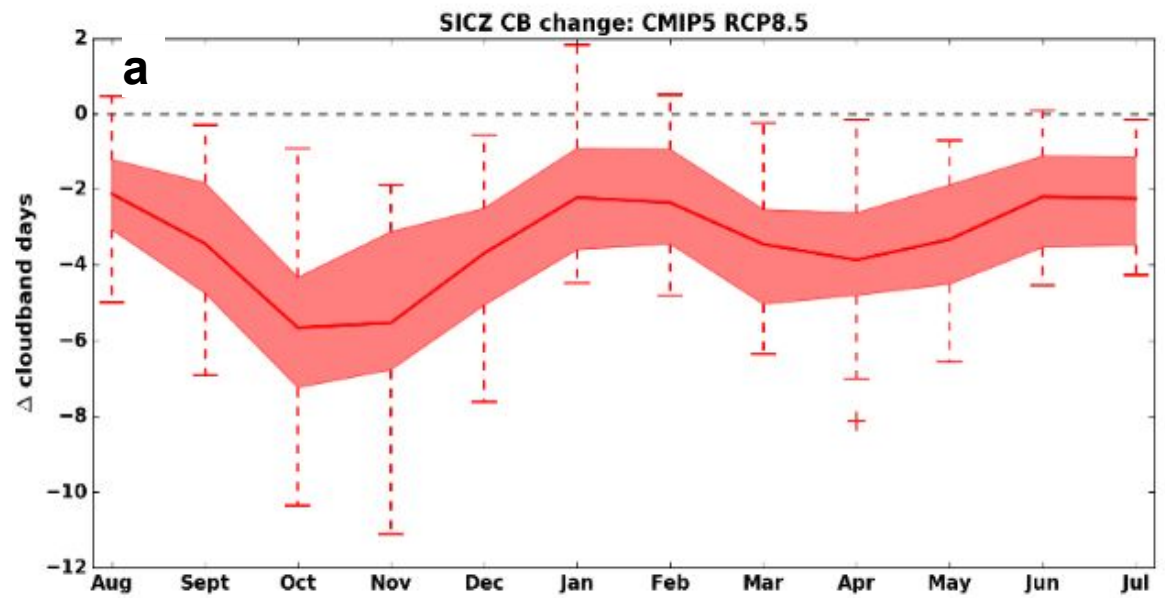
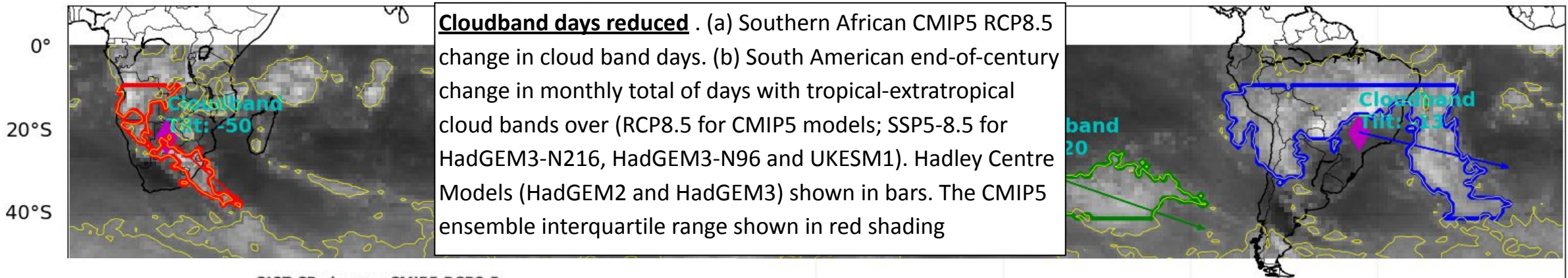


FIG. 1. Typical geostationary satellite imagery of convective outbreaks over Africa during (a) austral summer, taken at 1812 UTC 21 Dec 2017, and (b) boreal summer, taken at 1812 UTC 21 Aug 2017. (Courtesy: NOAA-NCEI Global ISCCP B1 Browse System; [Knapp 2008](#)).

Recent years have not been good....



Decline projected across S. Hemisphere

