

Dynamical downscaling for research applications

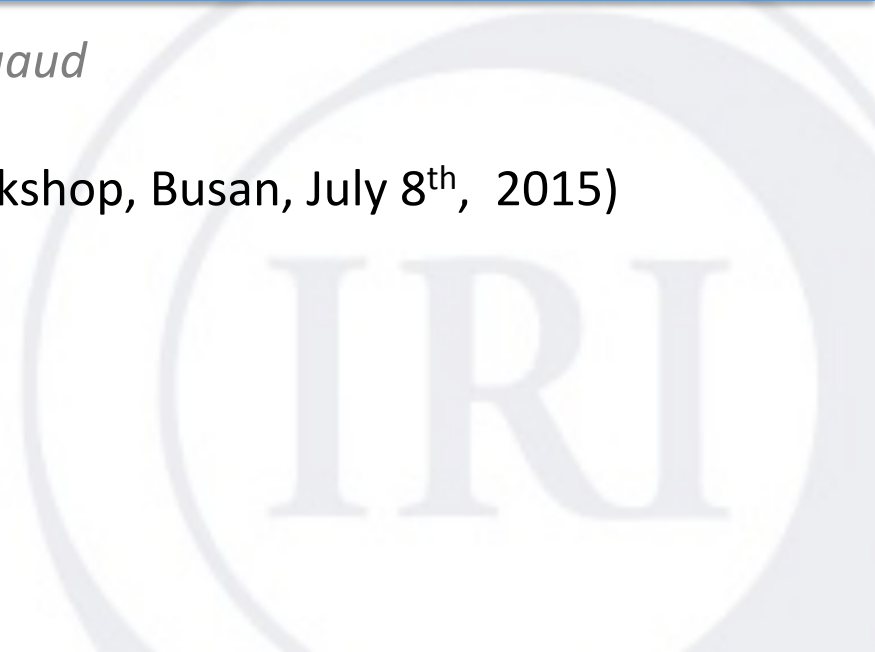
Regional climate modeling & sub-seasonal variability

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(APCC Dynamical Downscaling Workshop, Busan, July 8th, 2015)

The International Research Institute
for Climate and Society

EARTH INSTITUTE | COLUMBIA UNIVERSITY



OUTLINE

1. DYNAMICAL DOWNSCALING & REGIONAL CLIMATE MODELS

1.1. The downscaling problem

1.2. Dynamical Downscaling

1.3. Regional Climate Modeling

1.3.1. The Weather Research & Forecast model (WRF)

1.3.2. Experimental setup & Uncertainties

2. APPLICATIONS TO SUB-SEASONAL PREDICTABILITY IN AFRICA

2.1. Sub-seasonal climate variability

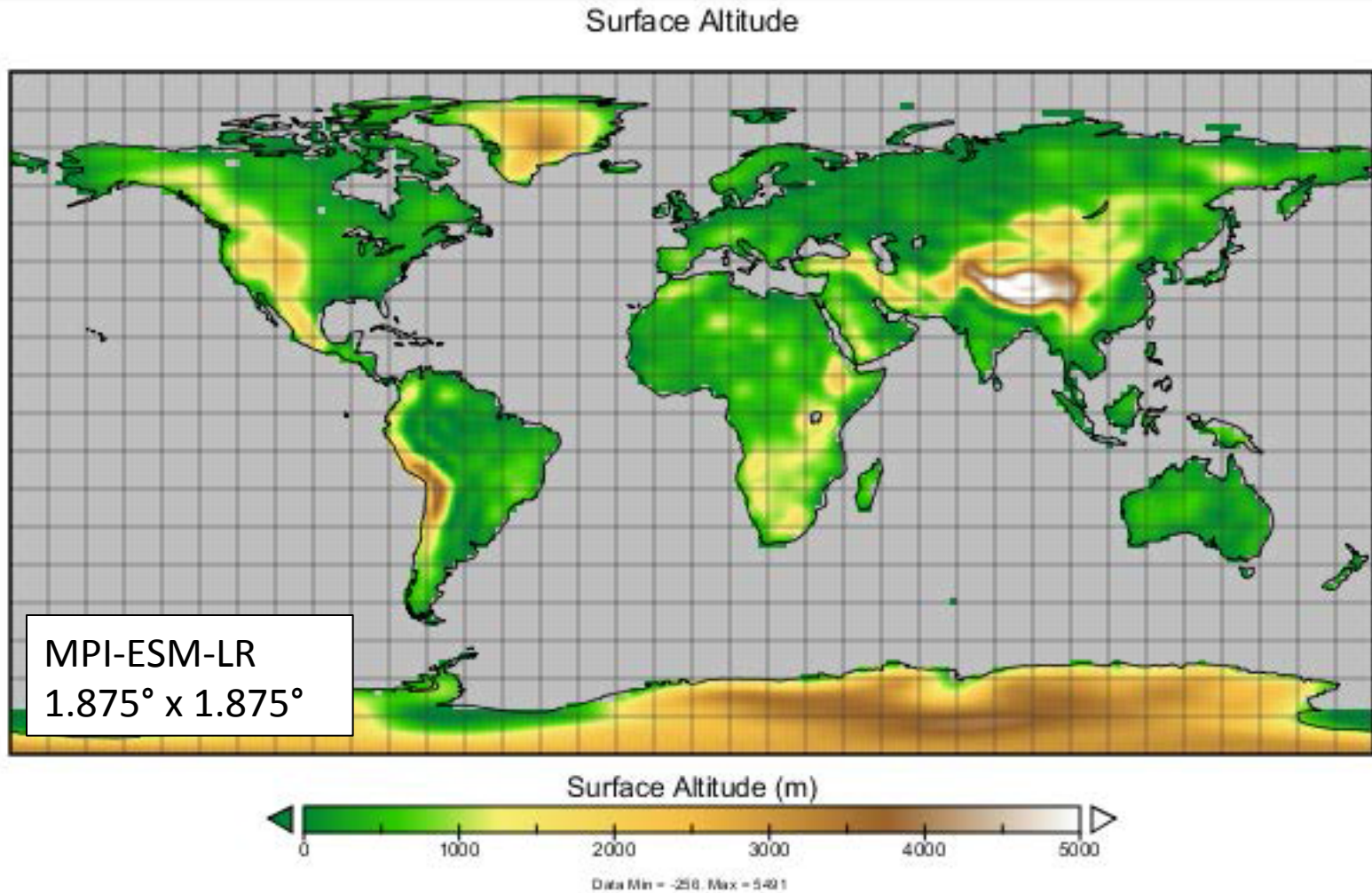
2.2. East Africa recent drought conditions during the long rains

2.3. Tropical-temperate interactions over Southern Africa

PART 1: Dynamical Downscaling & Regional Climate Models

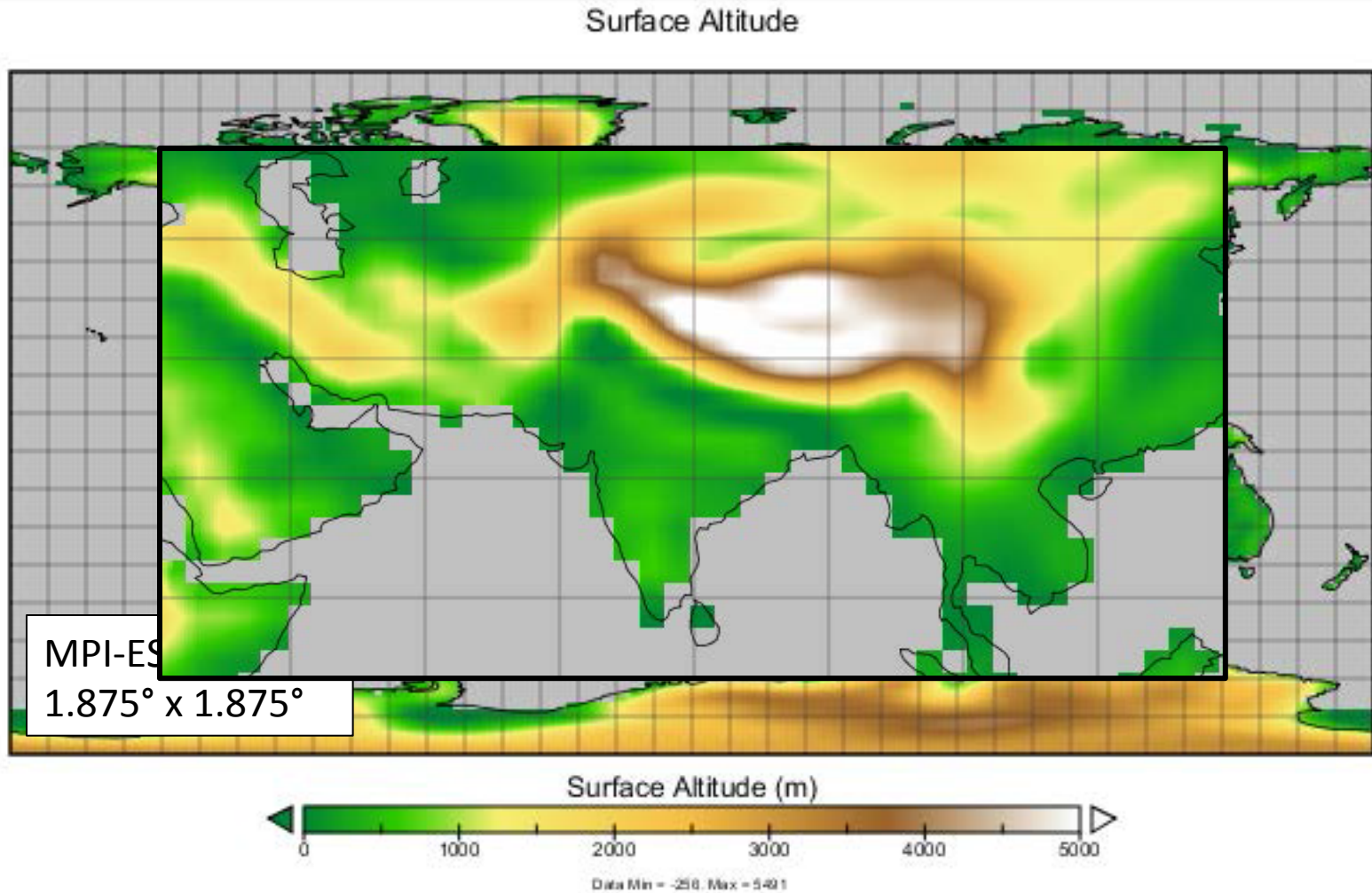


1.1. THE DOWNSCALING PROBLEM



GCMs coarse resolution (100s km)
Limited by computing resources

1.1. THE DOWNSCALING PROBLEM



GCMs coarse resolution (100s km)

⇒ Mesoscale circulation are **not resolved**

⇒ Regional scale feedback processes **poorly represented**

1.1. THE DOWNSCALING PROBLEM

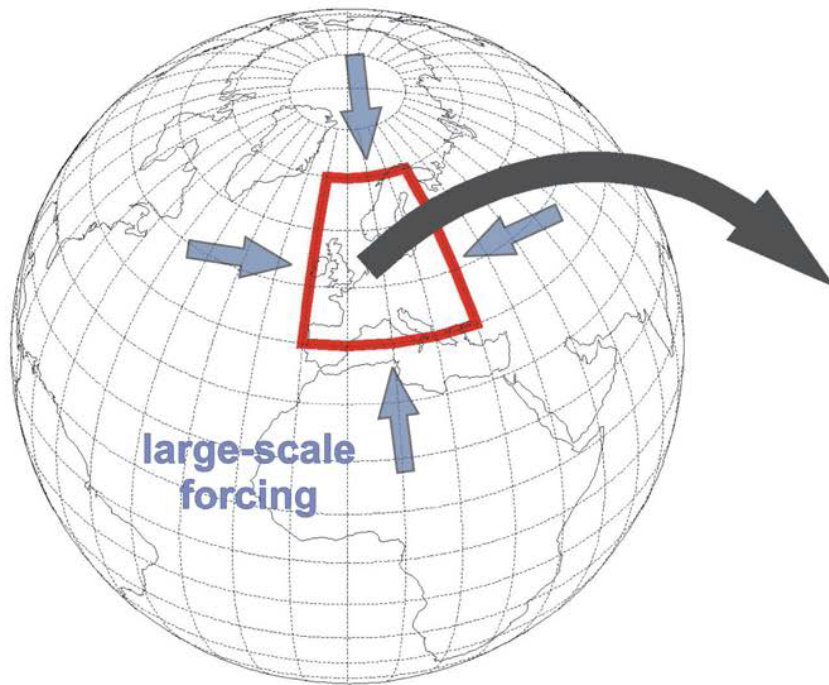
Given: Large scale as provided by a GCM experiment

Downscaling

Wanted: Regional / local scale conditions corresponding to large scale



1.2. DYNAMICAL DOWNSCALING

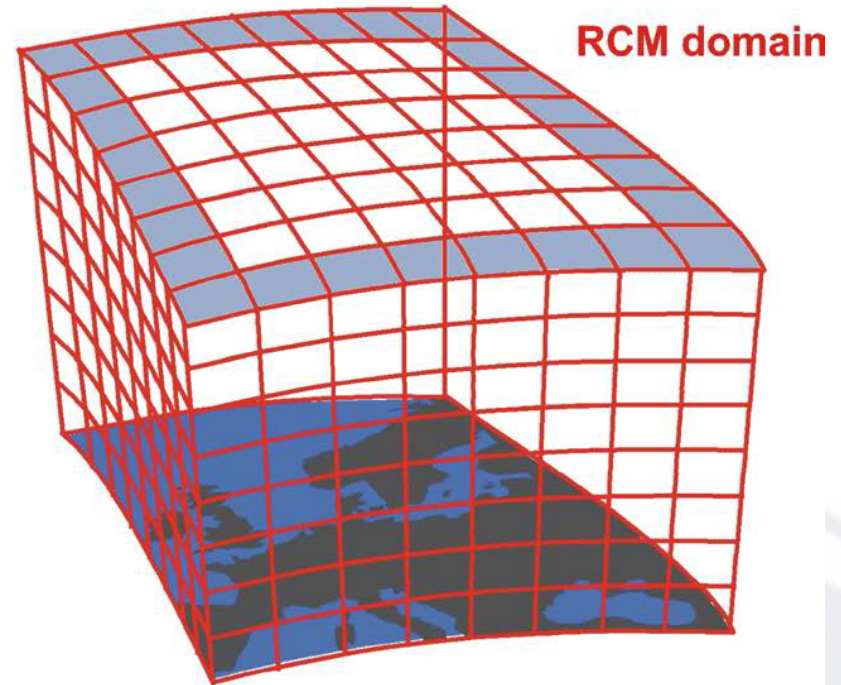


GCM output/Re-analysis

Horizontal resolution: 100s km

Impacts on:

- > Land-sea mask
- > Topography
- > Convection, clouds, rainfall
- > Land-atmosphere interactions

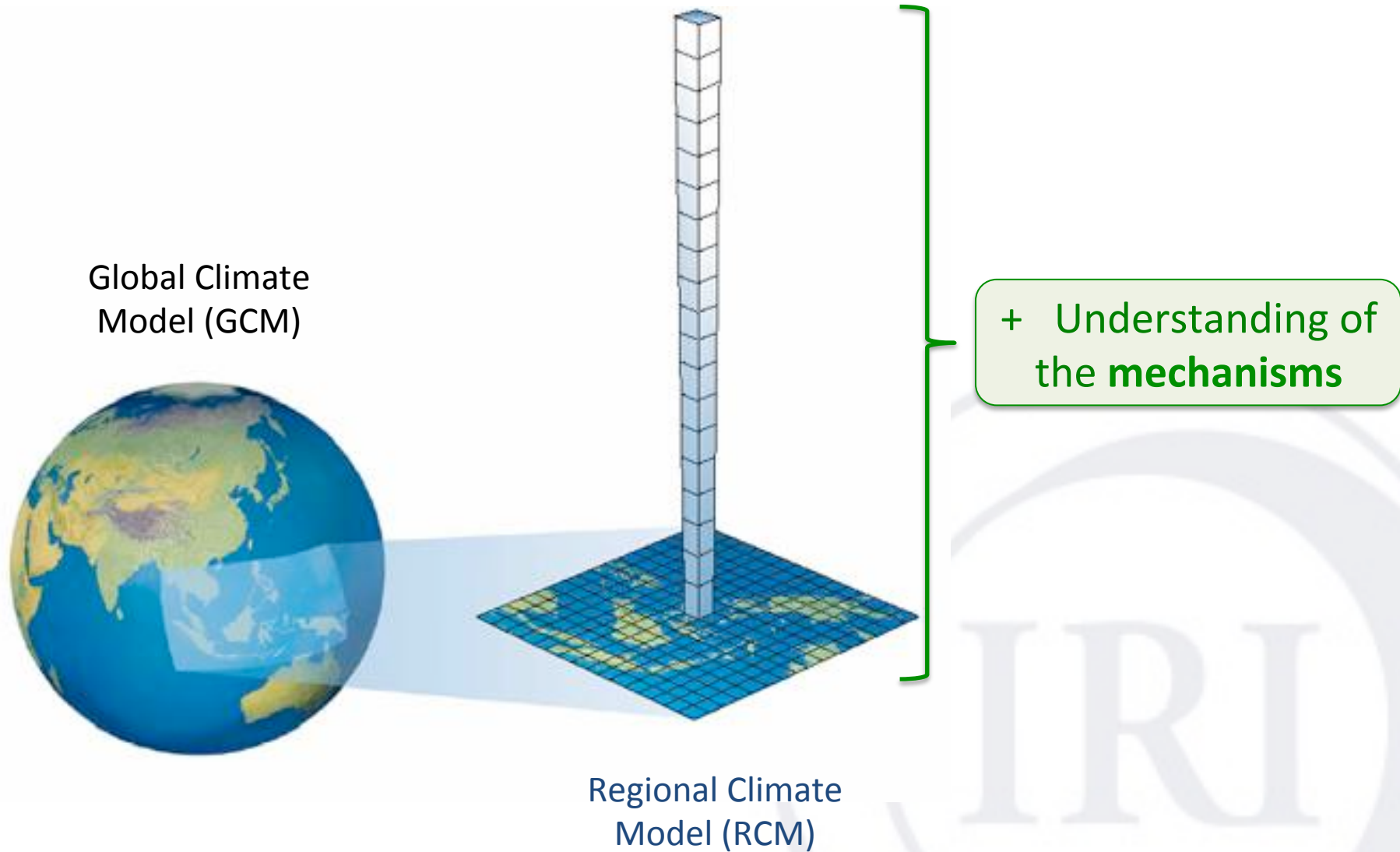


RCM output

Horizontal resolution: 10s km

=> Better local representation

1.2. DYNAMICAL DOWNSCALING



1.3. REGIONAL CLIMATE MODELING

1.3.1. The Weather Research & Forecast Model (WRF)

(Skamarock et al., 2008)

- ❖ Widely used over the past decade as both a mesoscale weather model and a Regional Climate Model (RCM)
- ❖ Includes several physical parameterizations for:
 - Planetary Boundary Layer (PBL)
 - Cumulus
 - Micro-physics
 - Short-/long-wave radiation
 - Land Surface Model (LSM)amongst others ...
- ❖ Also available, nudging and internal coupling with a slab Ocean Mixed Layer (OML)

1.3. REGIONAL CLIMATE MODELING

1.3.2. Experimental setup & Uncertainties

Whenever working with a new region, first choices have to be made regarding the following

- ❖ Simulation **domain** (extent & resolution) to be used
- ❖ Physical **parameterizations** favored

=> **Control simulations** need to be performed and simulated output **compared to observation** prior to any further study

1.3. REGIONAL CLIMATE MODELING

1.3.2. Experimental setup & Uncertainties

① Control simulations

- ❖ **Control run** can be expected to simulate actual weather events, and can therefore be **evaluated using actual observations** (e.g., from stations)
- ❖ The run **identifies model strengths and weaknesses** in simulating the climate of a given region, and hence can be used to **identify model biases**
- ❖ 3-5 years minimum while longer is better, but high-resolution simulations are quite expensive for both computer and human resources
=> **find the right balance between resolution & domain size**

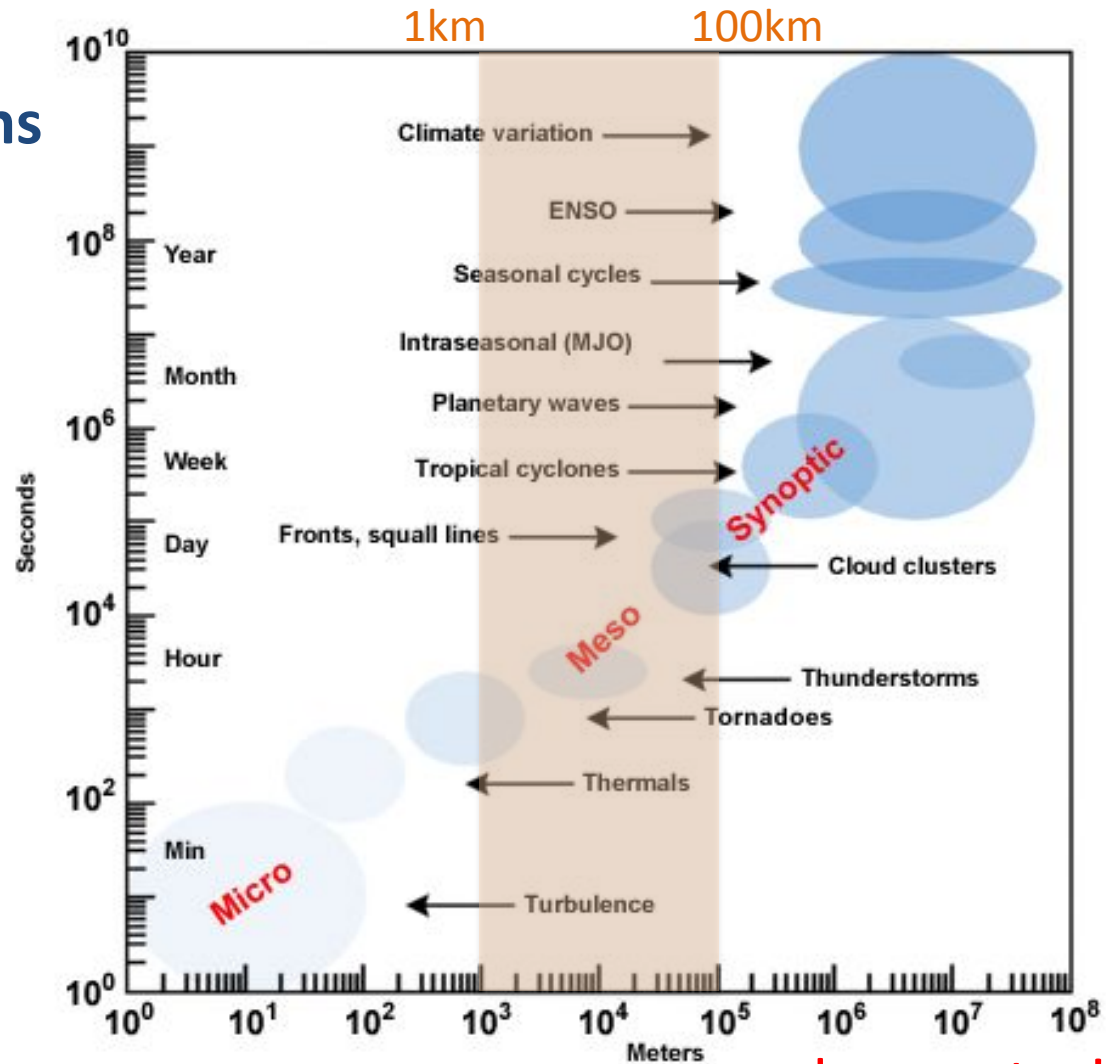
⇒ Make a **control run forced by re-analyses** to evaluate how the RCM simulates **present-day climate** of the region

1.3. REGIONAL CLIMATE MODELING

1.3.2. Experimental setup & Uncertainties

① Control simulations

And keep in mind...



... scales matter!

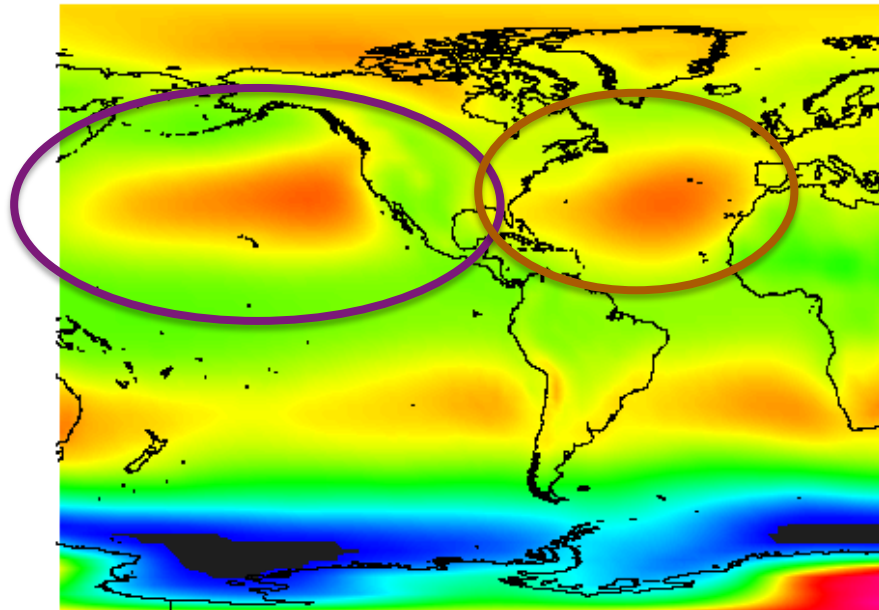
1.3. REGIONAL CLIMATE MODELING

1.3.2. Experimental setup & Uncertainties

① Control simulations

Experimental domain & large-scale features of climate: the Caribbean example

North Pacific HP



North Atlantic/
Bermuda-Azores HP

Mean May-Nov NCEP2
MSLP (1980-2009)

May



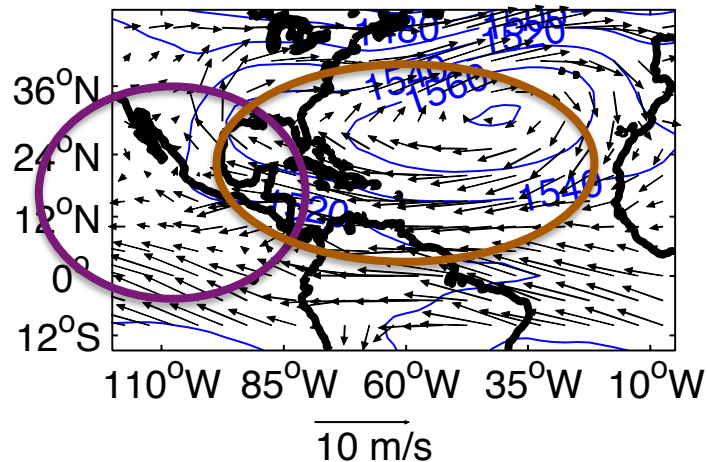
1.3. REGIONAL CLIMATE MODELING

1.3.2. Experimental setup & Uncertainties

① Control simulations

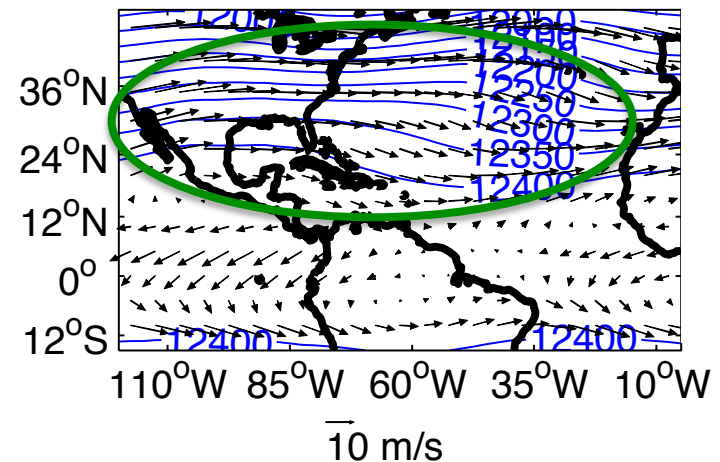
Experimental domain & large-scale features of climate: the Caribbean example

a) Mean MJJASON NCEP2 UV & GPH 850hPa



Both HP cells actually control **surface winds patterns** over the region

b) Mean MJJASON NCEP2 UV & GPH 200hPa



Jet Stream

Importance of the jet stream at **upper-tropospheric levels**



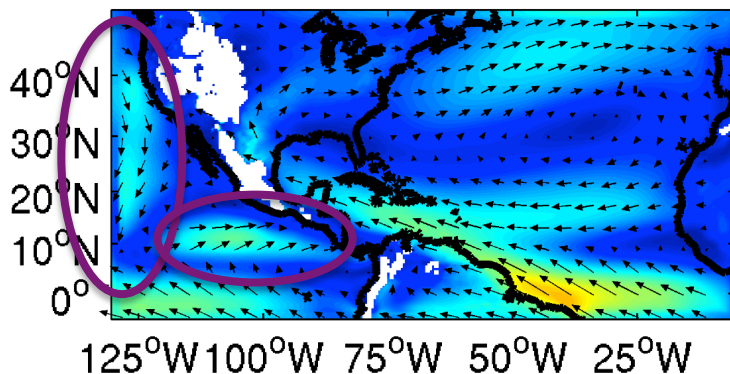
1.3. REGIONAL CLIMATE MODELING

1.3.2. Experimental setup & Uncertainties

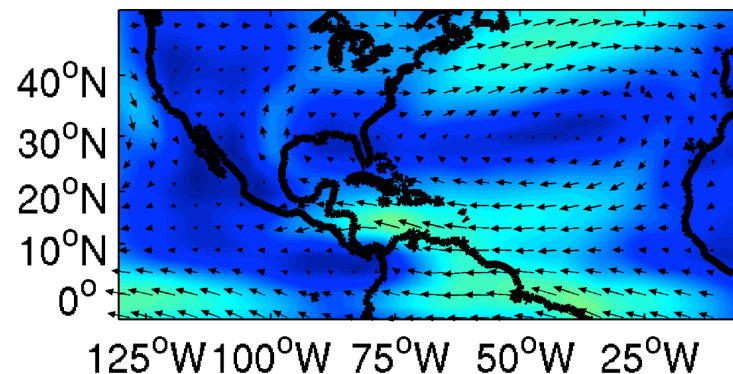
① Control simulations

Biases in the circulation associated with N Pacific HP & trades

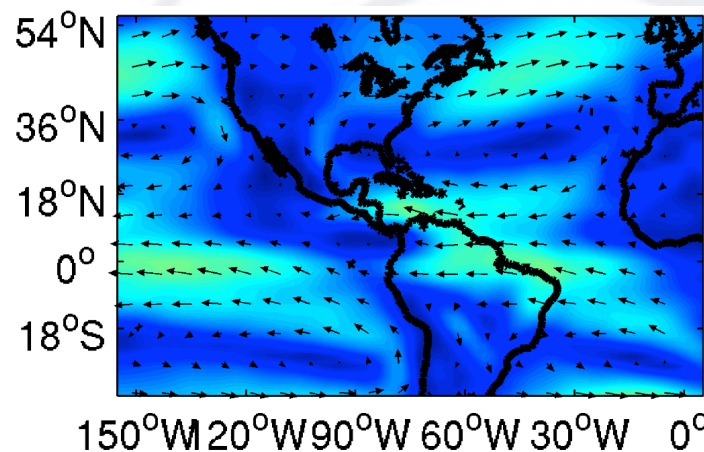
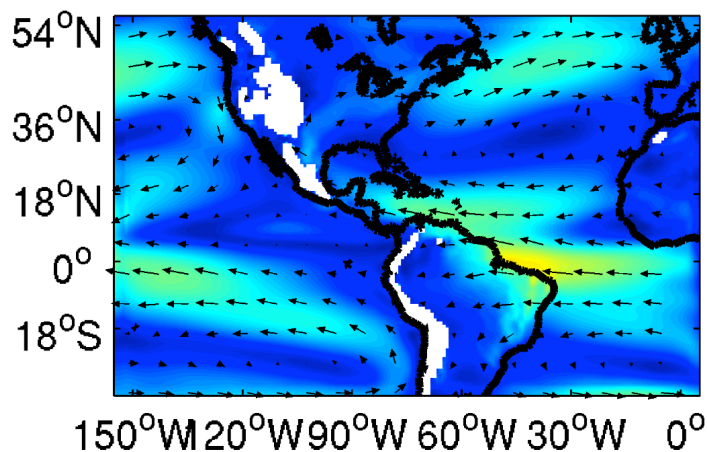
WRF 50km



NCEP2 forcings



WRF 90km



Mean May-Nov WRF simulated and NCEP2 850 hPa winds and zonal velocities (shadings)

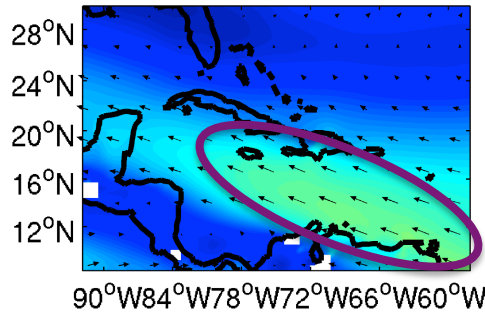
1.3. REGIONAL CLIMATE MODELING

1.3.2. Experimental setup & Uncertainties

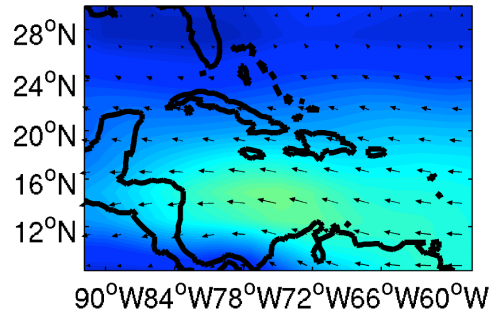
① Control simulations

With impacts on regional patterns!!!

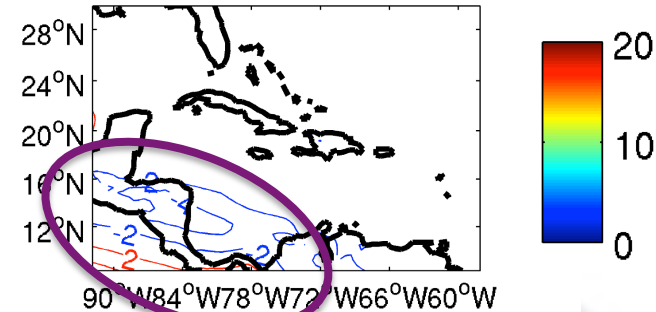
WRF 50km



NCEP2

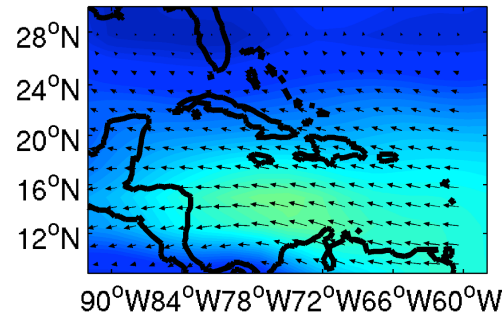
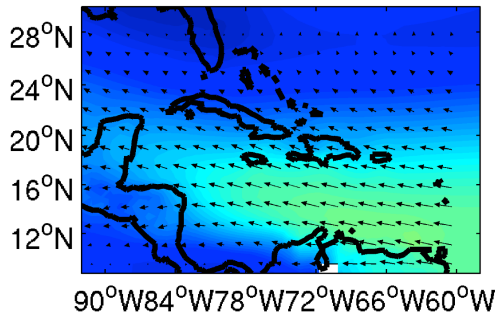


Differences

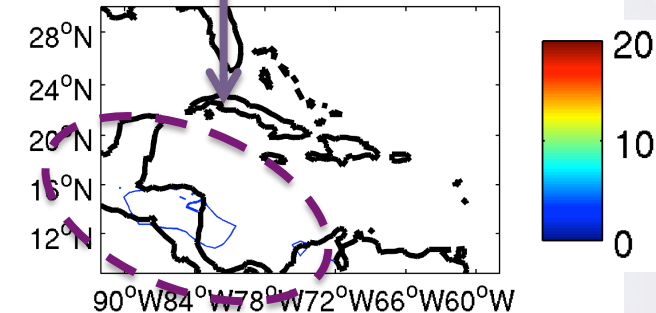


CLLJ shifted to the NW
+ SE/NW tilt not found in observation

WRF 90km



More discrepancies
for smaller domain!!!



Border effects can affect simulated dynamics dramatically!!!

1.3. REGIONAL CLIMATE MODELING

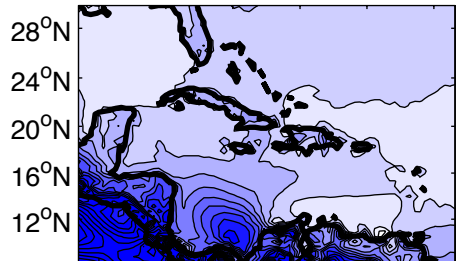
1.3.2. Experimental setup & Uncertainties

① Control simulations

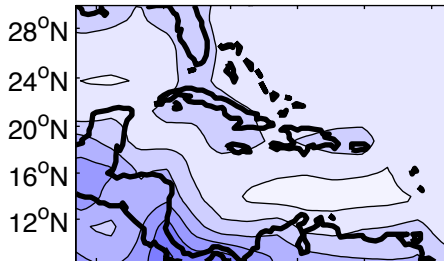
GPCP

CMAP

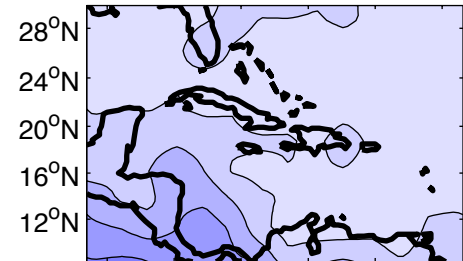
WRF 50km



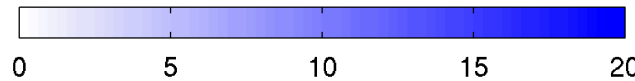
90°W84°W78°W72°W66°W60°W



90°W84°W78°W72°W66°W60°W

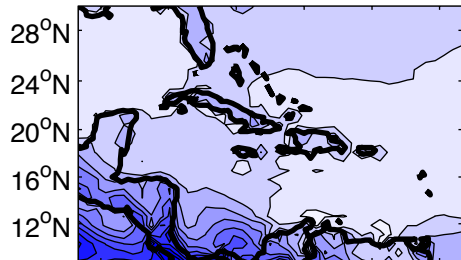


90°W84°W78°W72°W66°W60°W

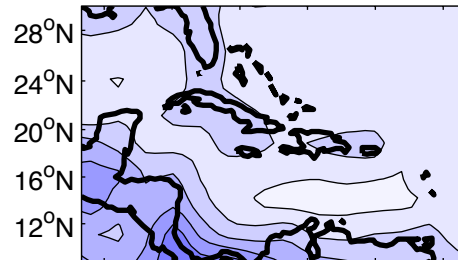


0 5 10 15 20

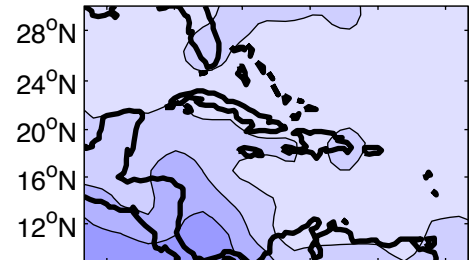
WRF 90km



90°W84°W78°W72°W66°W60°W



90°W84°W78°W72°W66°W60°W



90°W84°W78°W72°W66°W60°W

Leading to consequent biases in simulated rainfall!!!

1.3. REGIONAL CLIMATE MODELING

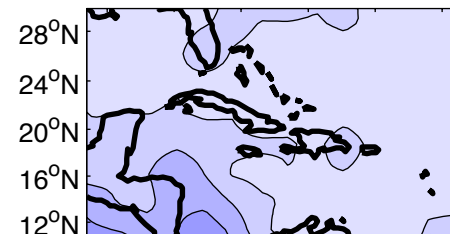
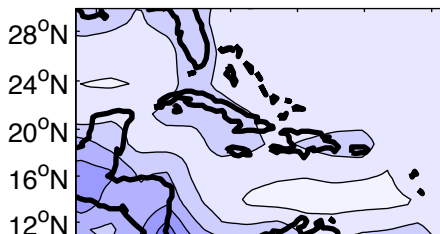
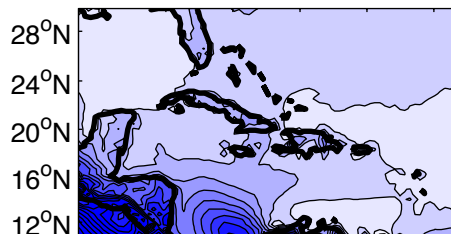
1.3.2. Experimental setup & Uncertainties

① Control simulations

GPCP

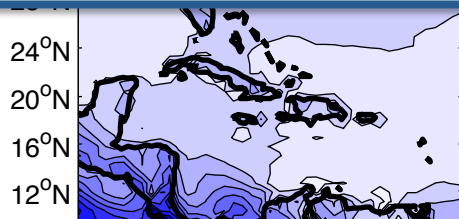
CMAP

WRF 50km

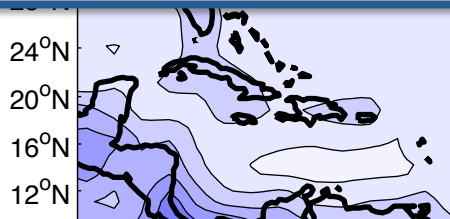


Need to reproduce the **key features of local climate**
=> **Large-scale circulation patterns versus border effects**

WRF 90km



90°W84°W78°W72°W66°W60°W



90°W84°W78°W72°W66°W60°W



90°W84°W78°W72°W66°W60°W

Leading to consequent biases in simulated rainfall!!!

1.3. REGIONAL CLIMATE MODELING

1.3.2. Experimental setup & Uncertainties

② Sensitivity simulations

❖ **Physical parameterizations:** many at disposal depending on the RCM, these need to be tested as they translate in different numerical solutions

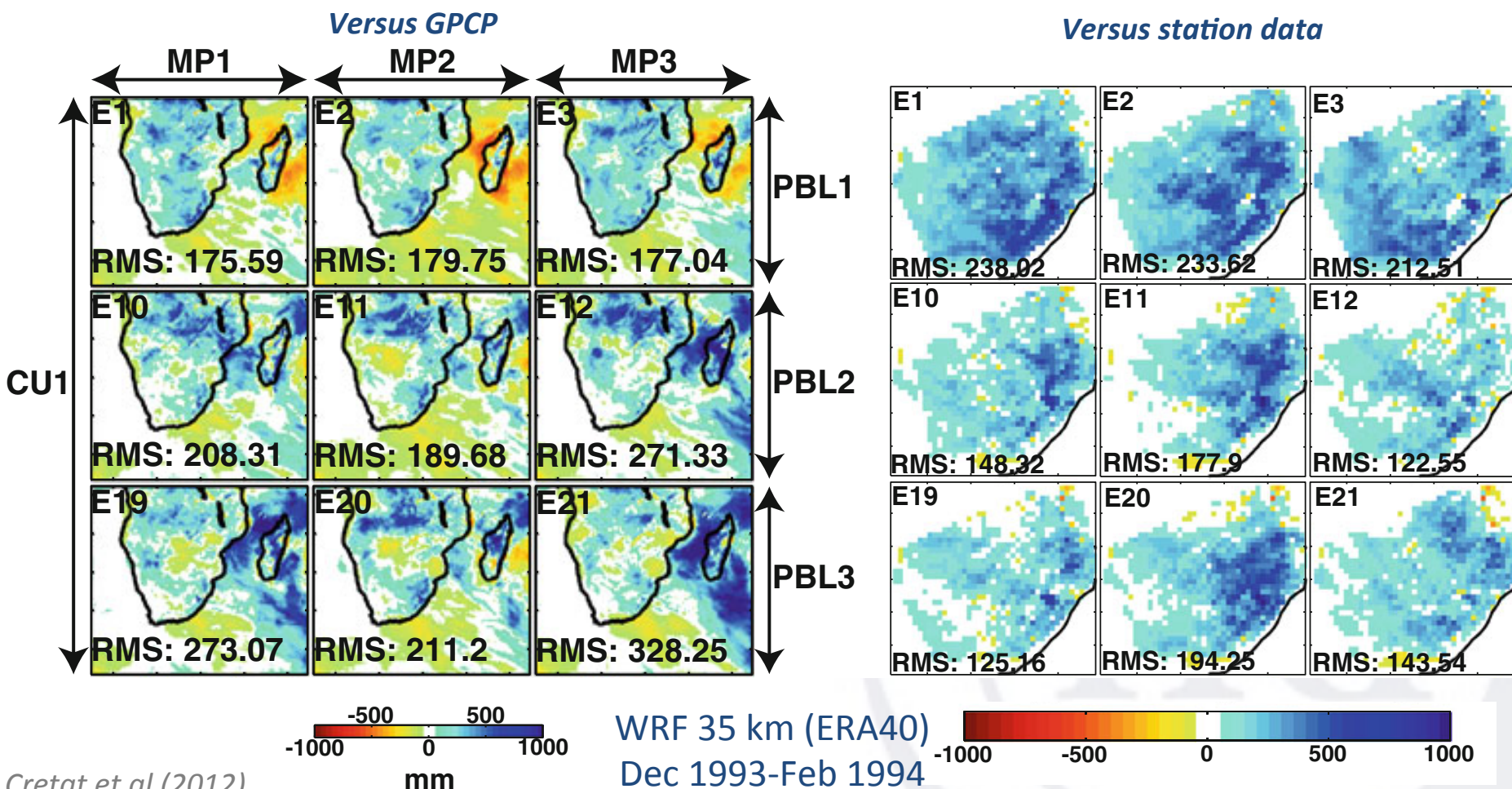
⇒ Make **sensitivity runs to physical parameterizations** to identify the best combination using regional observations

(still forced by re-analyses)

1.3. REGIONAL CLIMATE MODELING

1.3.2. Experimental setup & Uncertainties

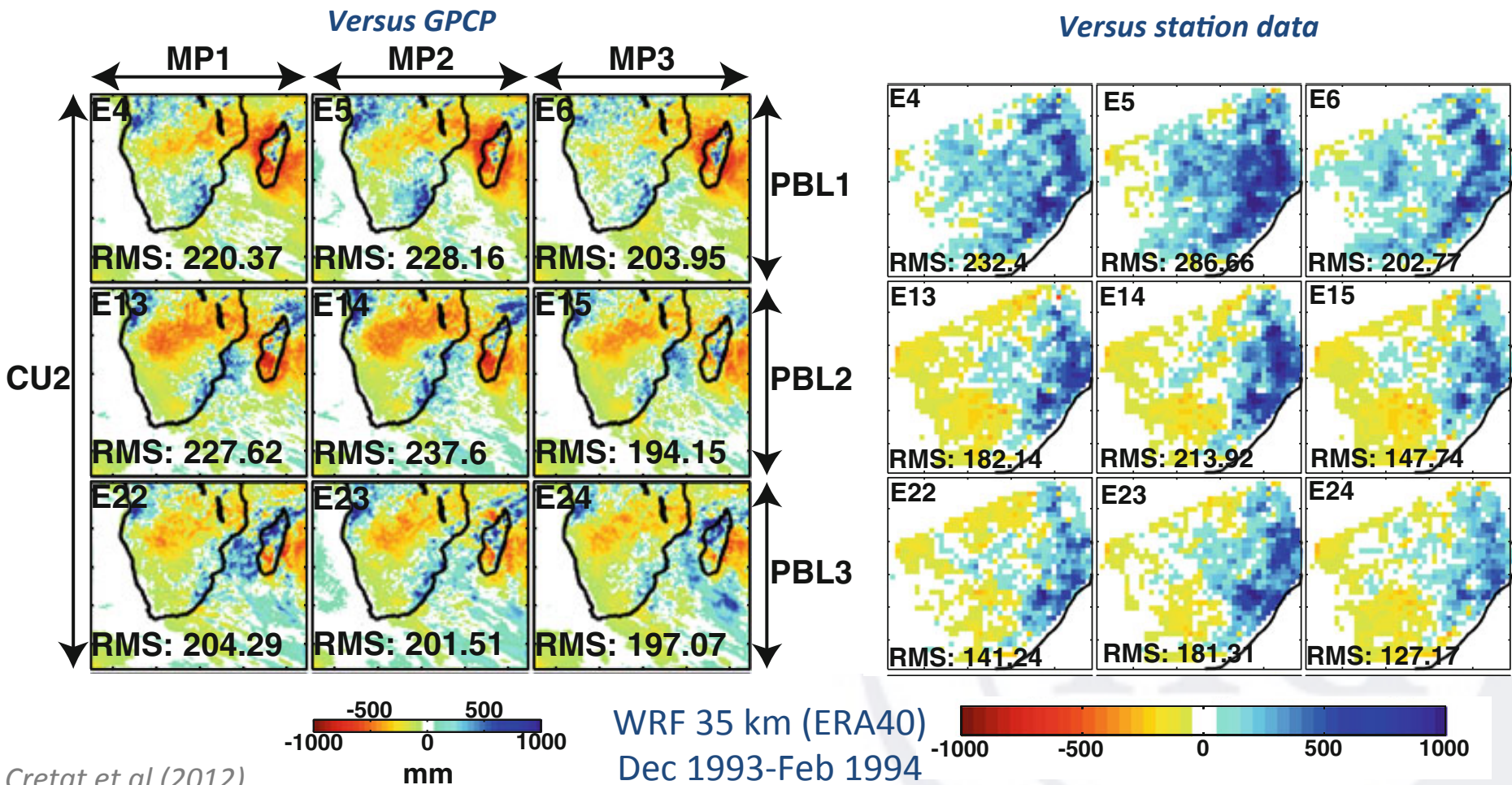
② Sensitivity simulations Microphysics versus PBL schemes



1.3. REGIONAL CLIMATE MODELING

1.3.2. Experimental setup & Uncertainties

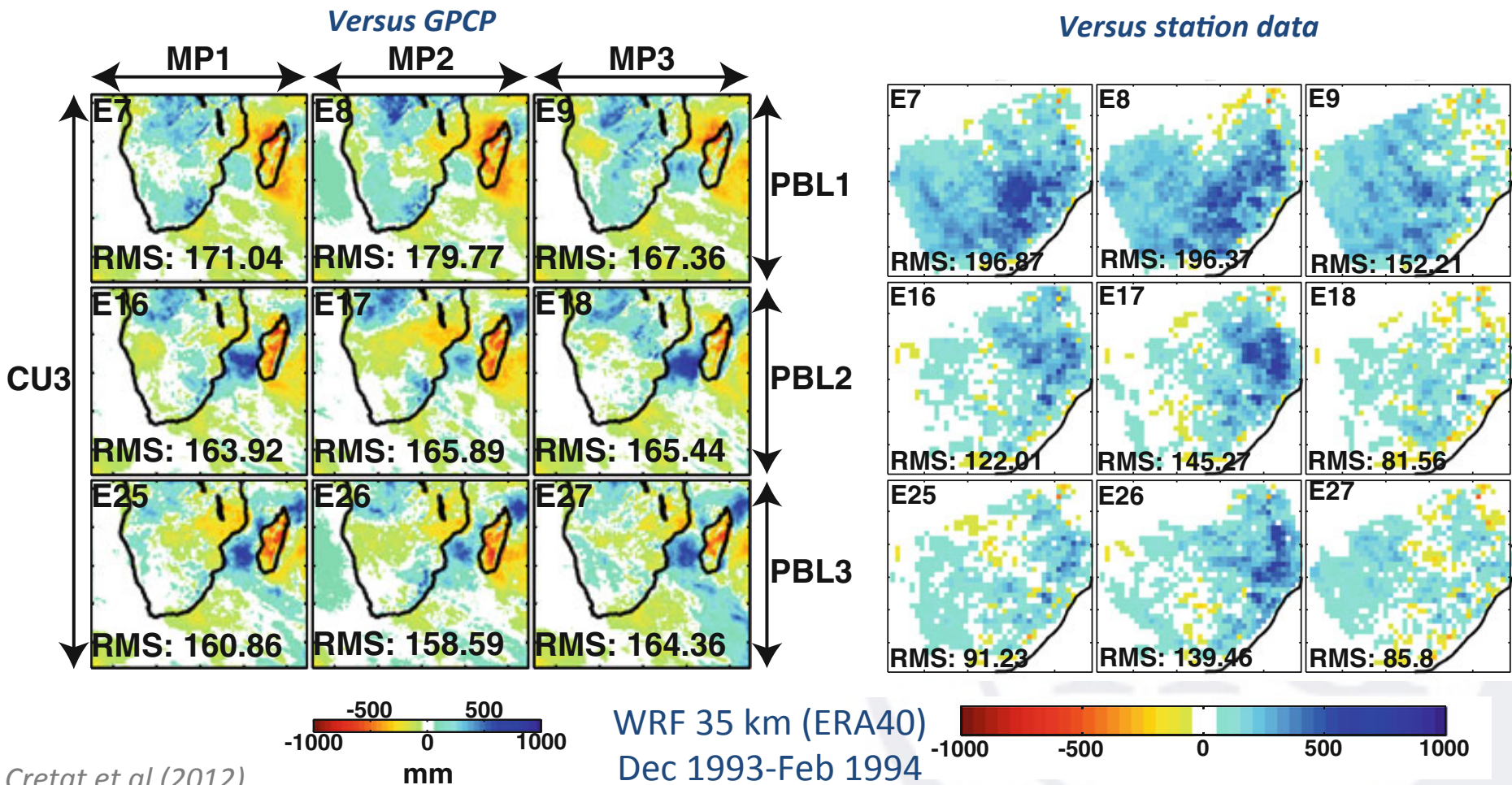
② Sensitivity simulations + for different cumulus schemes!



1.3. REGIONAL CLIMATE MODELING

1.3.2. Experimental setup & Uncertainties

② Sensitivity simulations + for different cumulus schemes!



PART 2: Applications to sub-seasonal predictability in Africa



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1.1. The downscaling problem

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2. APPLICATIONS TO SUB-SEASONAL PREDICTABILITY IN AFRICA

2.1. Sub-seasonal climate variability

2.2. East Africa recent drought conditions during the long rains

2.3. Tropical-temperate interactions over Southern Africa

2.1. SUB-SEASONAL CLIMATE VARIABILITY



2.1. SUB-SEASONAL CLIMATE VARIABILITY

« Bridging the gap between weather & climate »

❖ The WWRP/WCRP Sub-seasonal to Seasonal (S2S) initiative:

- The WMO Commission of Atmospheric Sciences (CAS) requested at its 15th session (Nov 2009) that WCRP, WWRP and THORPEX set up an appropriate **collaborative structure for sub-seasonal predictions**,
- A WCRP/WWRP/THORPEX workshop held in Dec 2010 recommended the formation of a Planning Group for an **S2S project under WCRP-WWRP-THORPEX sponsorship**
- The **implementation plan** written in 2012, was endorsed by the WWRP and WCRP, and **creation of the S2S prediction project** was approved by the WMO Executive
- The project will last 5 years starting in 2013 with the option to extend based on a review of progress, achievements and remaining gaps

2.1. SUB-SEASONAL CLIMATE VARIABILITY

« Bridging the gap between weather & climate »

- ❖ **The WWRP/WCRP Sub-seasonal to Seasonal (S2S) objectives:**
 - To **improve forecast skill and understanding** on the **S2S timescale** with special **emphasis on high-impact weather events**
 - To **promote the initiative's uptake** by **operational centers** and exploitation by the **applications community**
 - To **capitalize on the expertise of the weather and climate research communities** to address issues of importance to the **Global Framework for Climate Services (GFCS)**

The IRI logo is a large, light-colored watermark in the bottom right corner of the slide. It consists of the letters 'IRI' in a serif font, enclosed within a circular border.

2.1. SUB-SEASONAL CLIMATE VARIABILITY

« Bridging the gap between weather & climate »

❖ S2S time-scales of relevance to society needs:



Sub-seasonal time-scales

Red Cross - IRI example

2.1. SUB-SEASONAL CLIMATE VARIABILITY

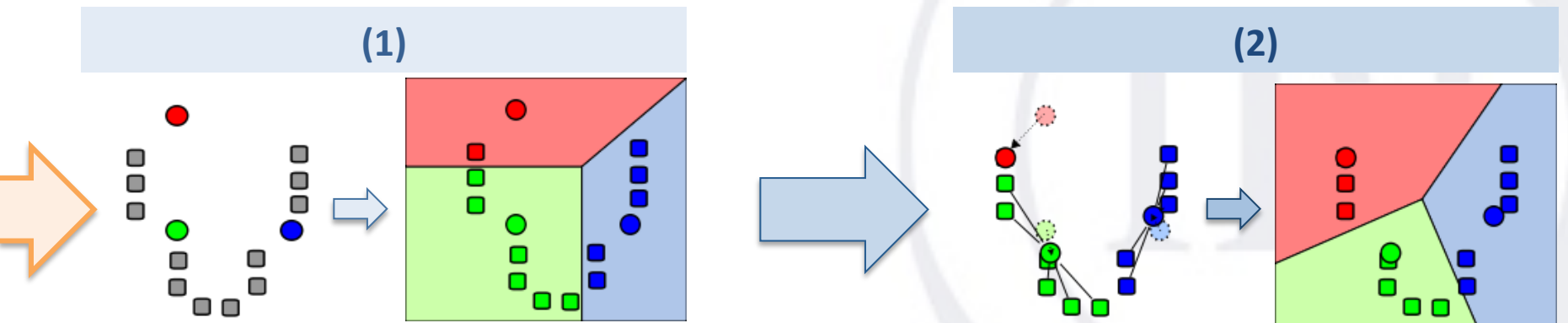
« Bridging the gap between weather & climate »

❖ Weather-typing approach:

- ***k-means clustering***: aims to partition n observations into k clusters in which each observation belongs to the cluster with the nearest mean

- (1) Assignment step**: assign each observation to the cluster with the "nearest" using Euclidean distances,
- (2) Update step**: calculate the new means to be the centroids of the observations in the new clusters.

Repeat until
convergence



2.2. EAST AFRICA RECENT DROUGHT CONDITIONS DURING THE LONG RAINS

Vigaud, N., B. Lyon and A. Giannini (2015) Recent dry conditions in East Africa and convection regimes observed during the long rains, *Clim Dyn*, submitted

2.3. TROPICAL-TEMPERATE INTERACTIONS OVER SOUTHERN AFRICA

Vigaud, N., B. Pohl and J. Cretat (2012) Tropical-temperate interactions over southern Africa simulated by a regional climate model, *Clim Dyn*, 39:2895-2916

2.3. TROPICAL-TEMPERATE INTERACTIONS IN SOUTHERN AFRICA

« Local versus large-scale climate variability over southern Africa and consequences on rainfall regimes »

- ❖ A **significant amount of SA summer rainfall** (30% between October and December, up to 60% in January) is **attributed to the occurrence of synoptic-scale tropical-temperate-troughs (TTTs)** characterized by NW/SE orientated cloud bands, convection and rainfall.

Harrison (1984, 1986)

- ❖ **Interannual SA summer rainfall variability** could significantly relate to the preferred **location and frequency** of synoptic-scale TTT systems,

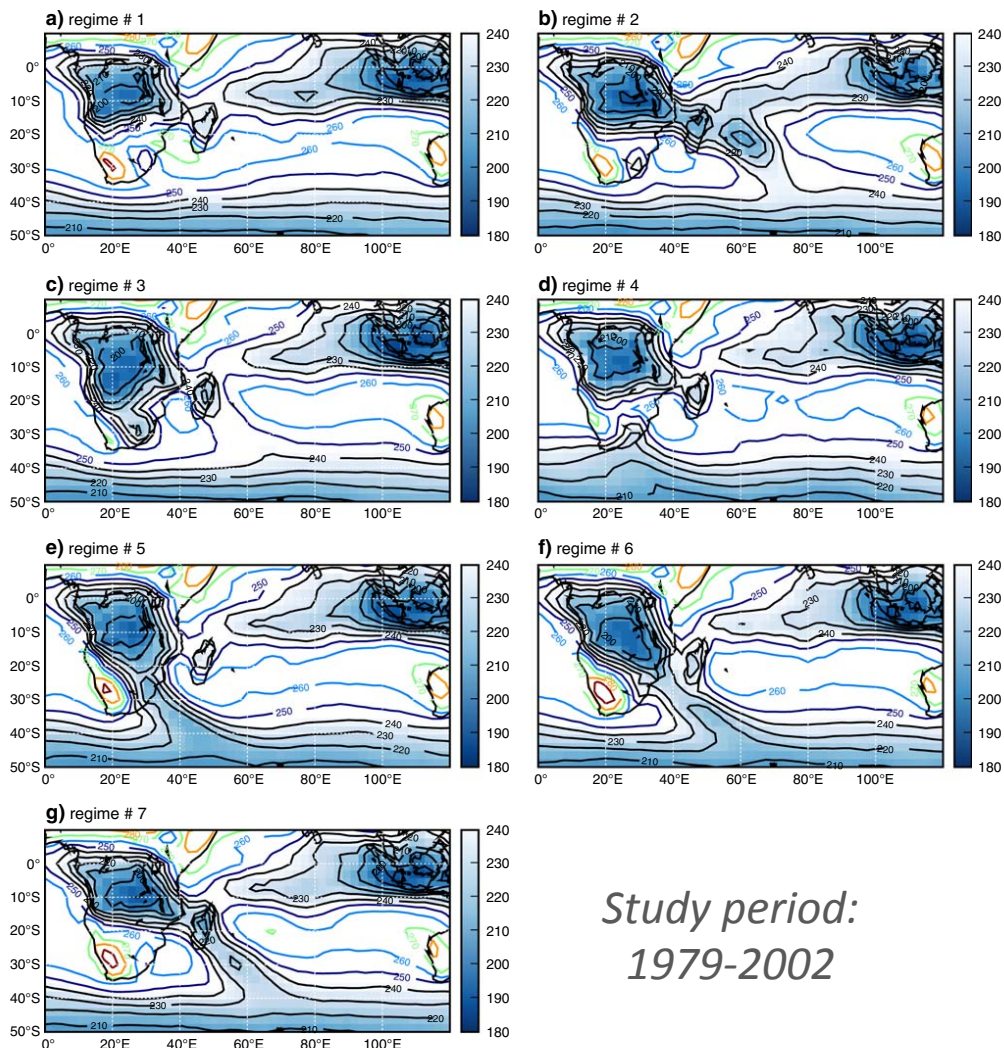
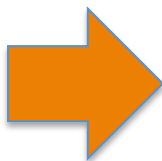
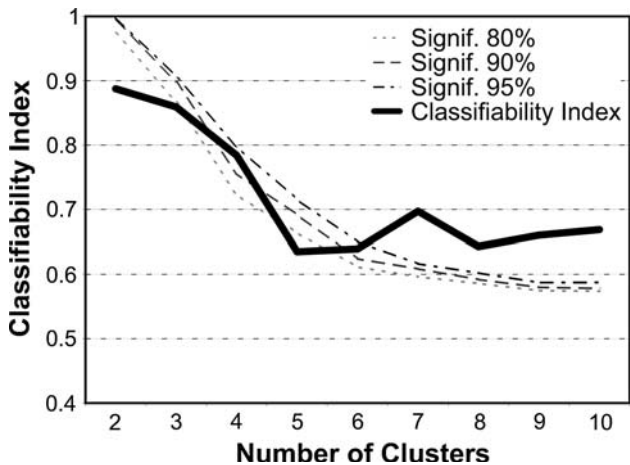
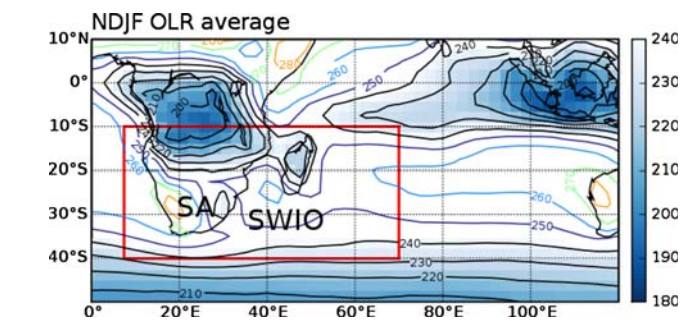
Cook (2000), Washington and Todd (1999), Todd and Washington (1999)

- ❖ TTTs are often described as the conjunction between a **lower-layer tropical perturbation** and a **mid-latitude trough in the upper atmosphere**.

However, the mechanisms at the origin/development of these interactions are not fully understood => **Dynamical downscaling for studying processes**

2.3. TROPICAL-TEMPERATE INTERACTIONS IN SOUTHERN AFRICA

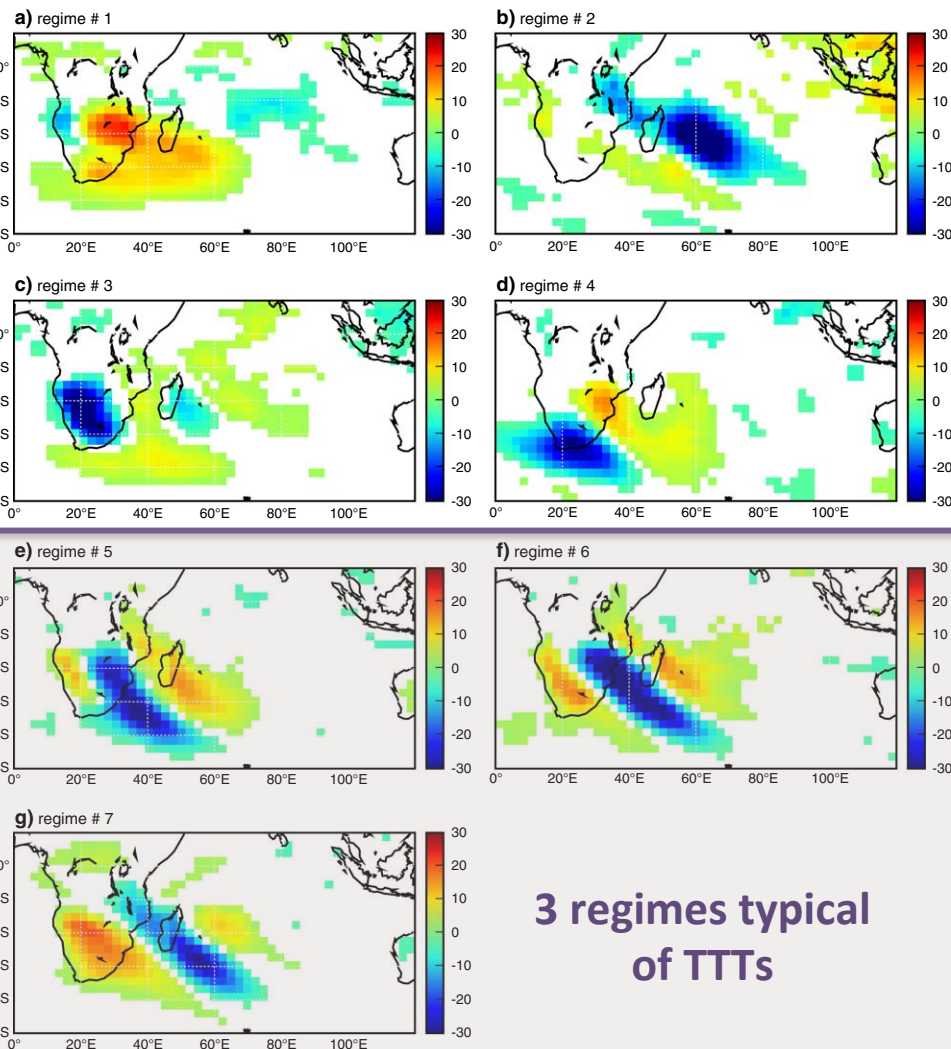
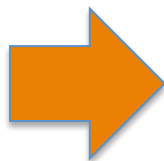
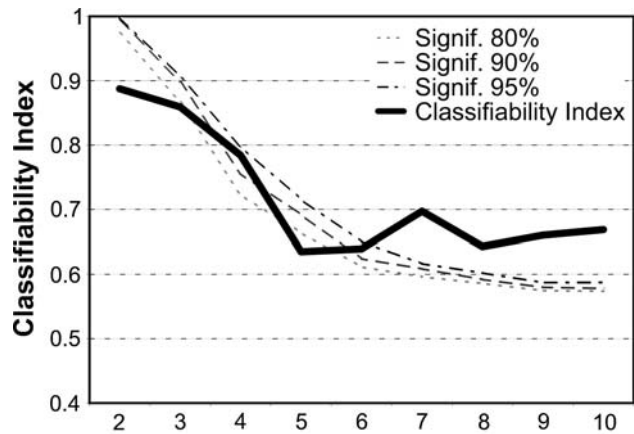
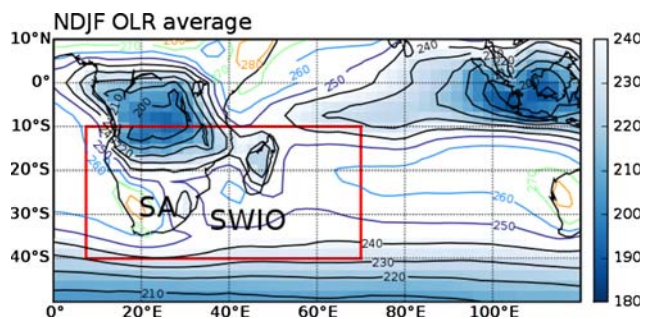
« Recurrent daily OLR patterns in the southern Africa/SWIO region, implications for South African rainfall & teleconnections »



Study period:
1979-2002

2.3. TROPICAL-TEMPERATE INTERACTIONS IN SOUTHERN AFRICA

« Recurrent daily OLR patterns in the southern Africa/SWIO region, implications for South African rainfall & teleconnections »



3 regimes typical of TTTs

2.3. TROPICAL-TEMPERATE INTERACTIONS IN SOUTHERN AFRICA

Data & experimental design

- **Regional atmospheric model:** Weather Regional Forecast model (WRF) version 3.2.1. developed by NCAR with the following physics,
 - Yonsei University (YSU) Planetary Boundary Layer scheme (*Hong et al.*, 2006),
 - NOAA Land Surface Model,
 - Monin-Obukhov Surface Layer scheme,
 - Grell-Devenyi Cumulus parametrization scheme (*Grell and Devenyi*, 2002),
 - RRTM/Dudhia Long/Shortwave Radiation schemes,
 - Morrison 2-mom microphysics scheme (*Morrison et al.*, 2009).
- **Experimental setup:** Regional experiments for a domain between 1.5-48.5°S and 0.5-79.5°E,
 - From October 1st to March 31st with ERA-40 (2.5°x2.5°) boundary conditions imposed every 6hrs,
 - WRF output every 6hrs at a 35km x 35km horizontal resolution (28 sigma levels on the vertical) after a 1 month spin-up,
 - 3 types of simulations: **WRF E (without spectral nudging and oceanic mixed layer)**,
WRF S with spectral nudging (above the PBL, keeping wave number 2-4),
WRF M with oceanic mixed layer,

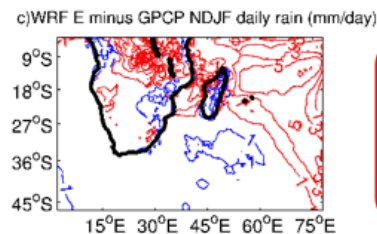
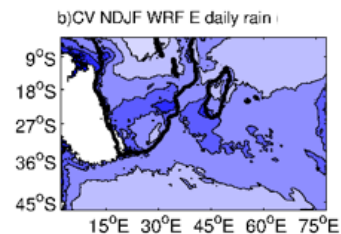
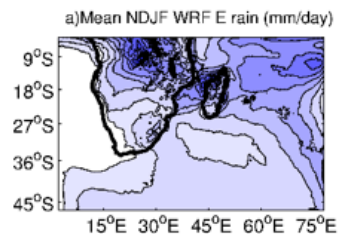
=> **30-year climatology (1971-2000)** was thus constructed,
3x **15 members-ensembles** for years of interest (1996 here presented).

- **Data**
 - **Rainfall:** Water Research Commission (WRC) rain-gauges database over 1971-99 (*Lynch*, 2003), GPCP rainfall estimates at 2.5°x2.5° spatial resolution from 1979 onwards,
 - **Convection:** NOAA OLR from 1979 at 2.5°x2.5° spatial resolution (*Liebmann and Smith*, 1996),
- **Objective OLR partitioning:** In order to detect the TTTs occurrences k-means technique has been used on simulated WRF OLR field similarly to previous studies (*Fauchereau et al.*, 2007).

2.3. TROPICAL-TEMPERATE INTERACTIONS IN SOUTHERN AFRICA

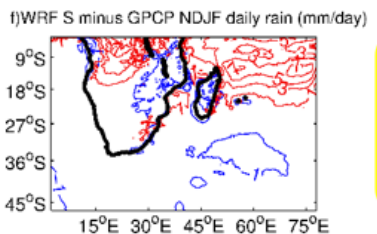
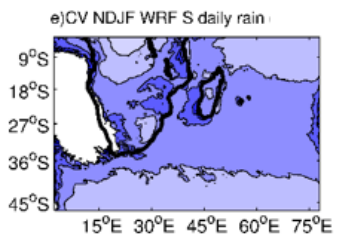
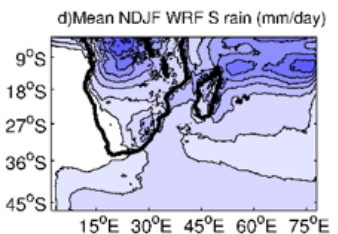
Mean Nov-Feb WRF rainfall (1971-2000)

WRF E



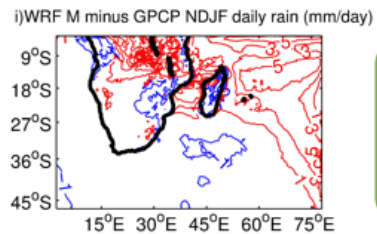
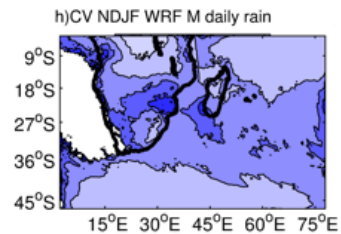
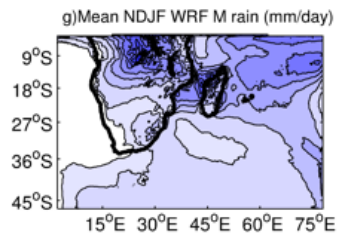
No nudging
No oceanic mixed layer

WRF S



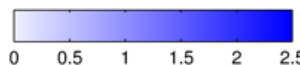
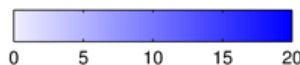
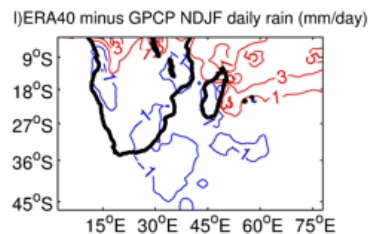
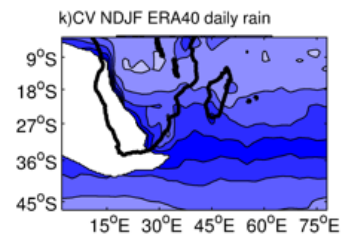
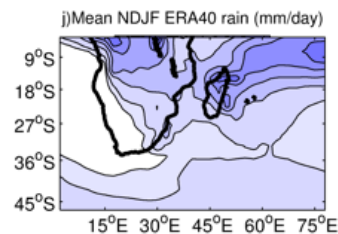
with nudging

WRF M



with oceanic mixed layer

ERA40

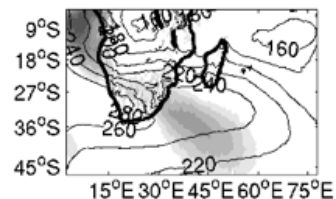


2.3. TROPICAL-TEMPERATE INTERACTIONS IN SOUTHERN AFRICA

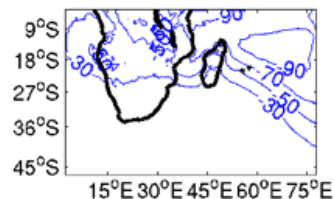
Mean Nov-Feb WRF OLR & ZDEF 200 hPa (1971-2000)

WRF E

a) Mean NDJF WRF E OLR & 200hPa ZDEF



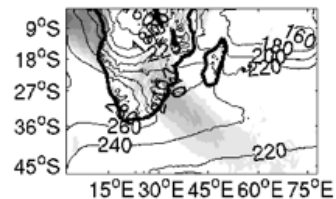
b) WRF E minus NOAA NDJF daily OLR (W/m2)



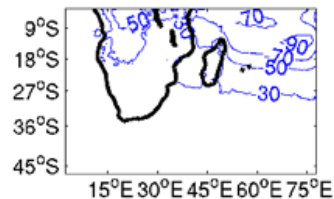
No nudging
No oceanic mixed layer

WRF S

c) Mean NDJF WRF S OLR & 200hPa ZDEF



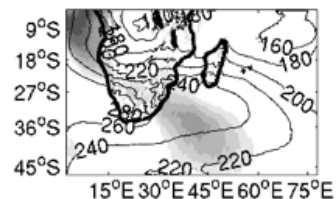
d) WRF S minus NOAA NDJF daily OLR (W/m2)



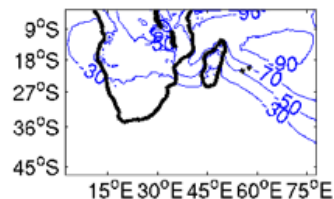
with nudging

WRF M

e) Mean NDJF WRF M OLR & 200hPa ZDEF



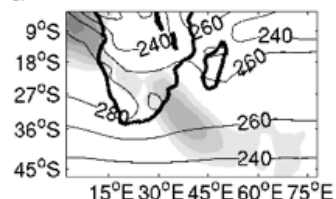
f) WRF M minus NOAA NDJF daily OLR (W/m2)



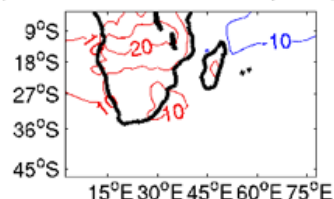
with oceanic mixed layer

ERA40

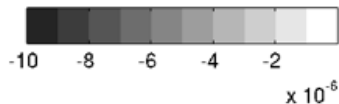
g) Mean NDJF ERA40 OLR & 200hPa ZDEF



h) ERA-40 minus NOAA NDJF daily OLR (W/m2)

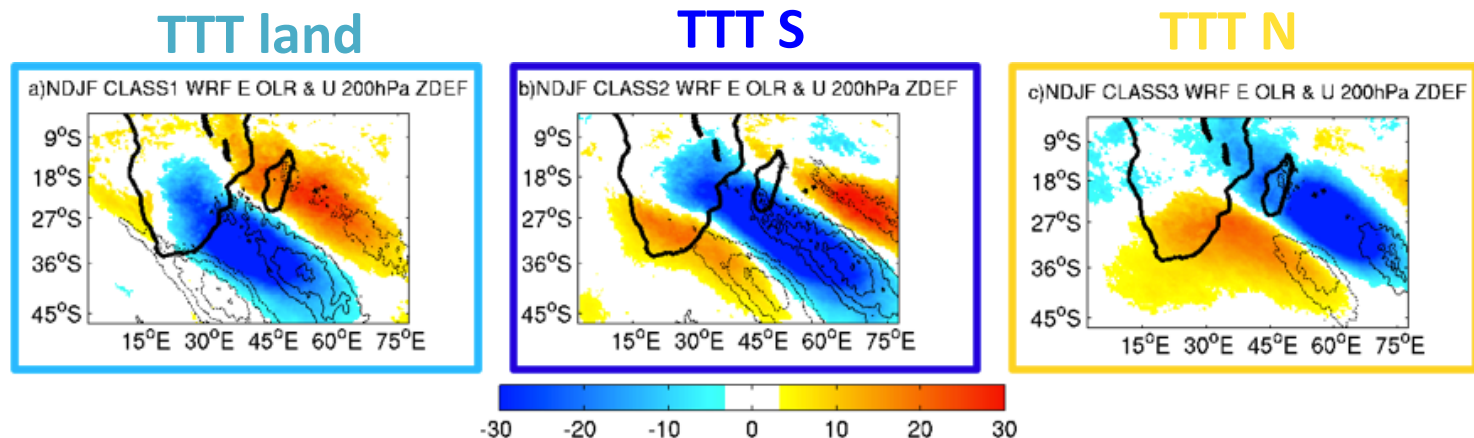


Negative zonal stretching deformation (Widlansky, 2010):
 $d\bar{U}/dx < 0$

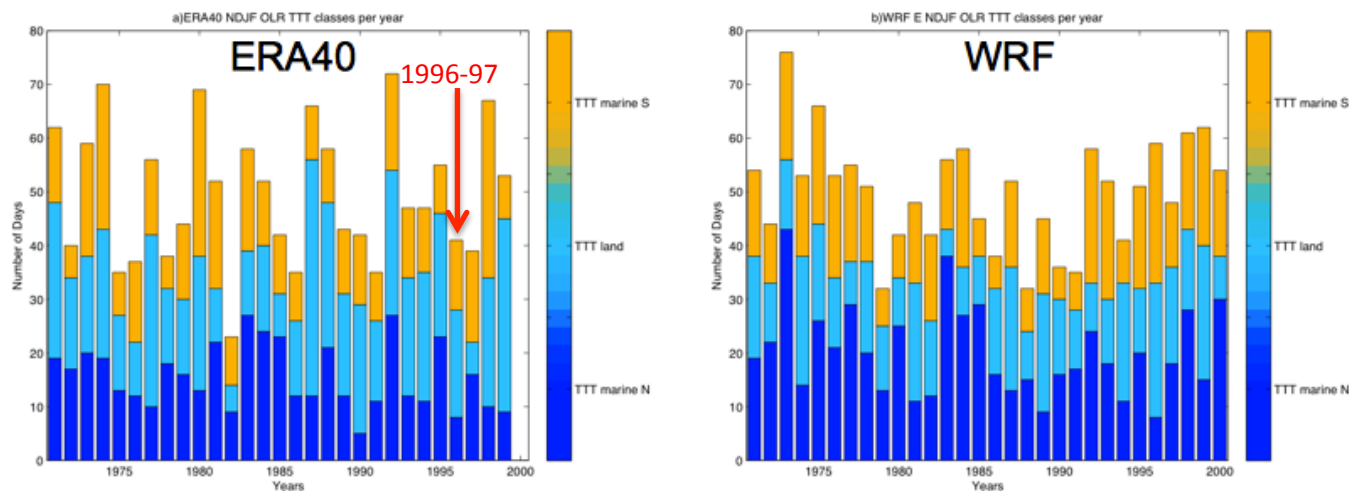


2.3. TROPICAL-TEMPERATE INTERACTIONS IN SOUTHERN AFRICA

Nov-Feb WRF simulated daily OLR clustering (1971-2000)



K-means clustering of daily OLR simulated in WRF regional experiments forced by ERA40 used to identify recurrent convective systems typical of TTTs over southern Africa

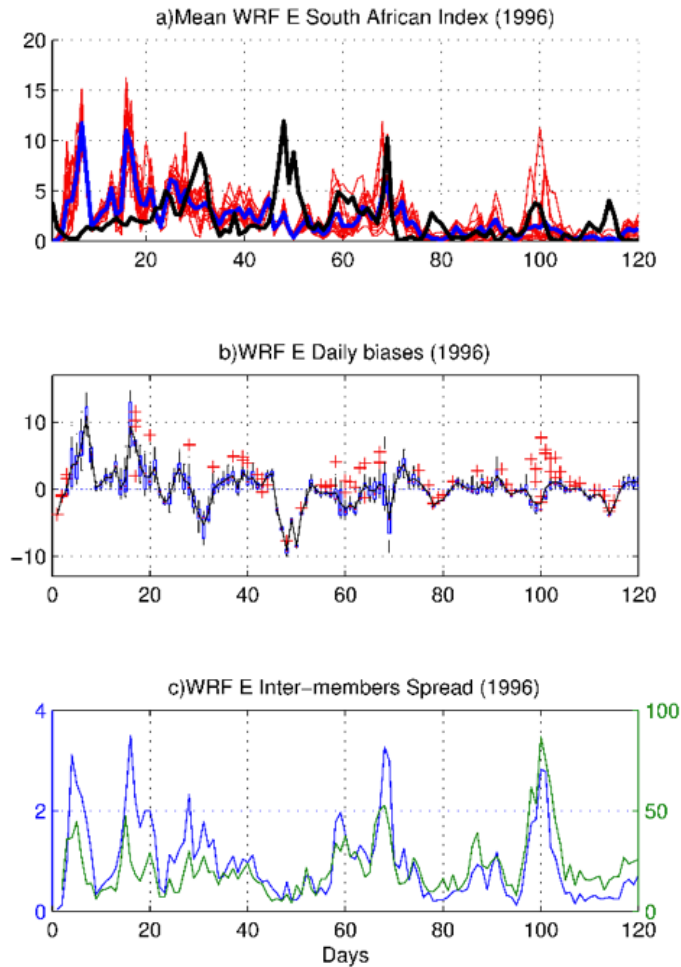


Occurrences for each of these three modes typical of TTTs for the 1971-2000 period in ERA40 forcings (a) and WRF experiments (b)

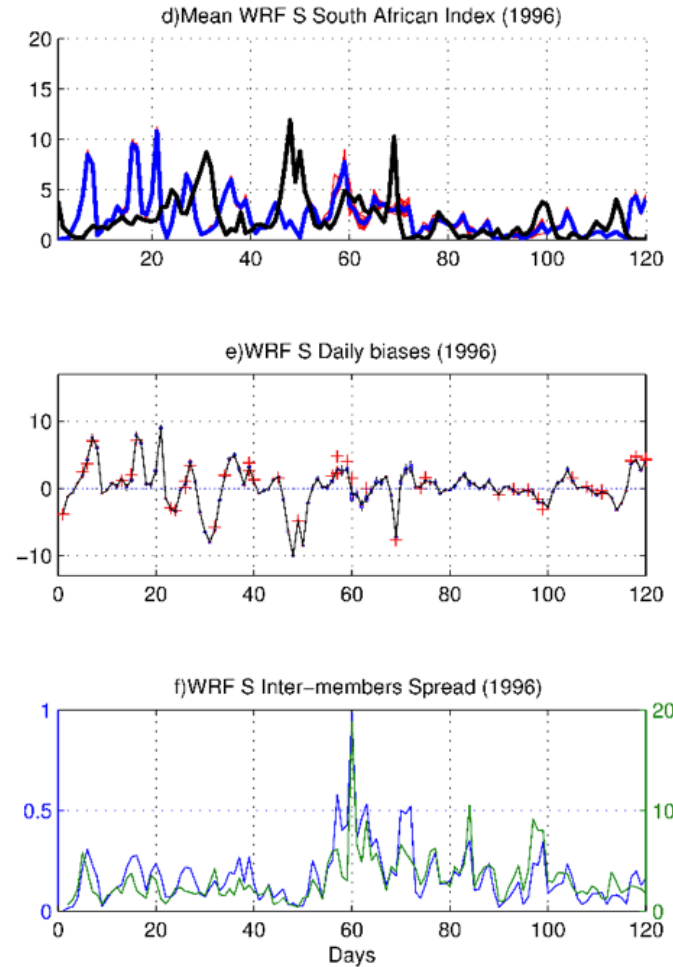
2.3. TROPICAL-TEMPERATE INTERACTIONS IN SOUTHERN AFRICA

MEAN SA RAINFALL INDEX (Nov 1996-Mar 1997)

WRF E (no spectral nudging)



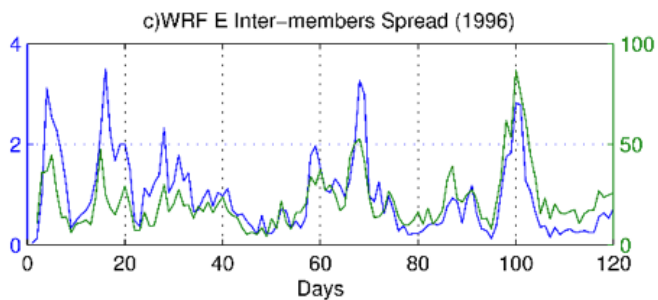
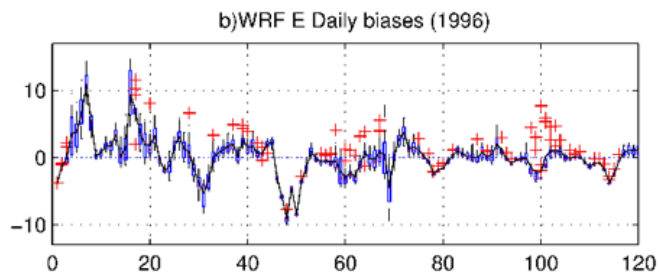
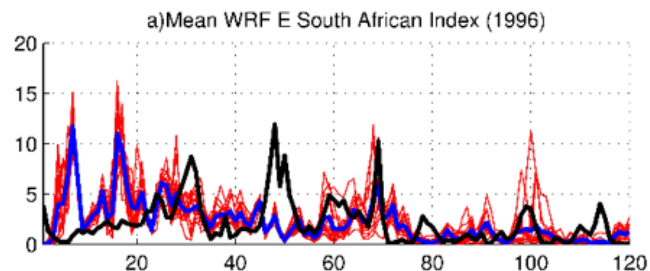
WRF S (with spectral nudging)



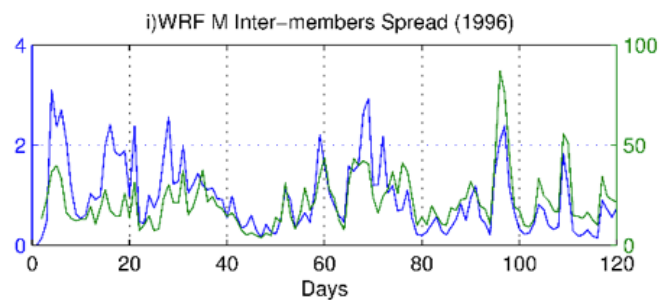
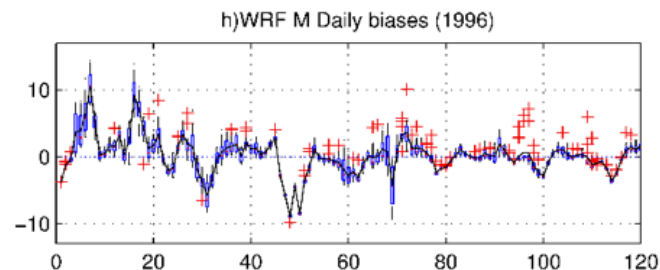
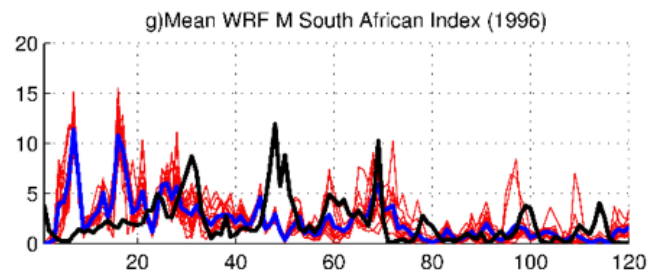
2.3. TROPICAL-TEMPERATE INTERACTIONS IN SOUTHERN AFRICA

MEAN SA RAINFALL INDEX (Nov 1996-Mar 1997)

WRF E (no ocean mixed layer)



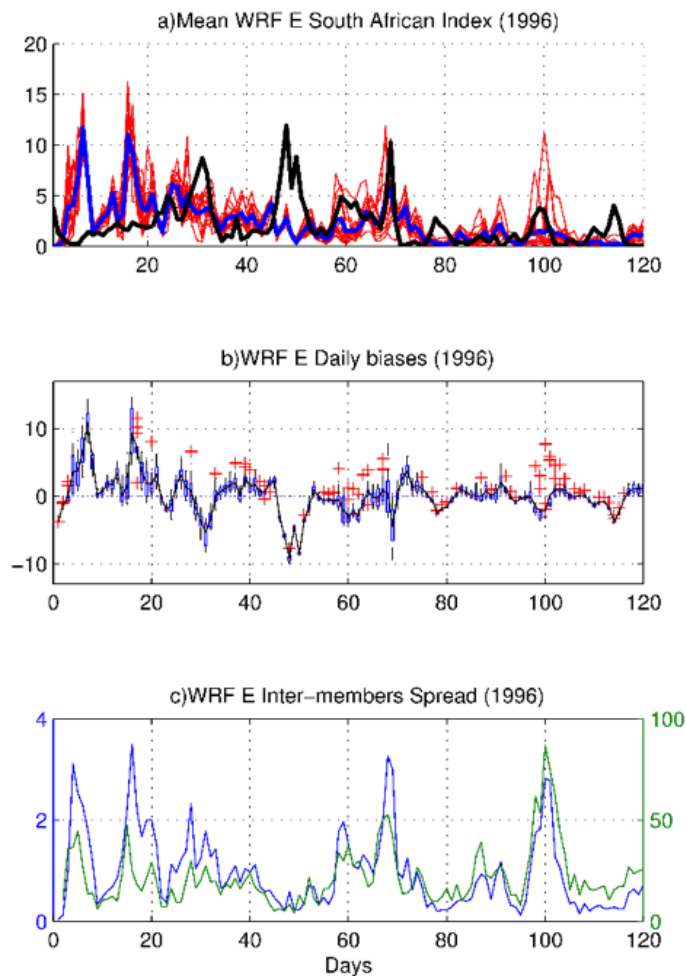
WRF M (with ocean mixed layer)



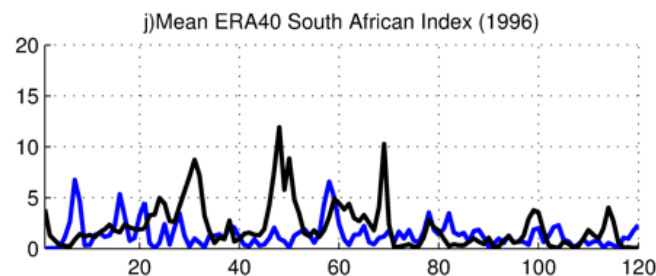
2.3. TROPICAL-TEMPERATE INTERACTIONS IN SOUTHERN AFRICA

MEAN SA RAINFALL INDEX (Nov 1996-Mar 1997)

WRF E (no ocean mixed layer)



ERA40



R	ERA40	WRC
WRF E	0.49*	0.17
WRF S	0.75*	0.02
WRF M	0.49*	0.16
ERA40	-	-0.02

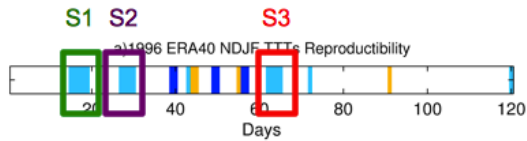
Scores indicated with a star (*) are significant at 95% level using Monte Carlo simulations

Discrepancies between WRF simulated and observed rainfall conditioned by large-scale forcings

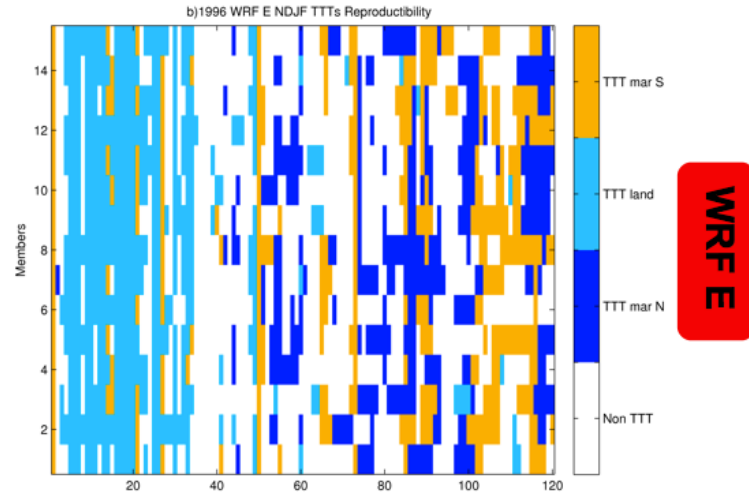
2.3. TROPICAL-TEMPERATE INTERACTIONS IN SOUTHERN AFRICA

Reproducibility of TTT land events (Nov 1996-Mar 1997)

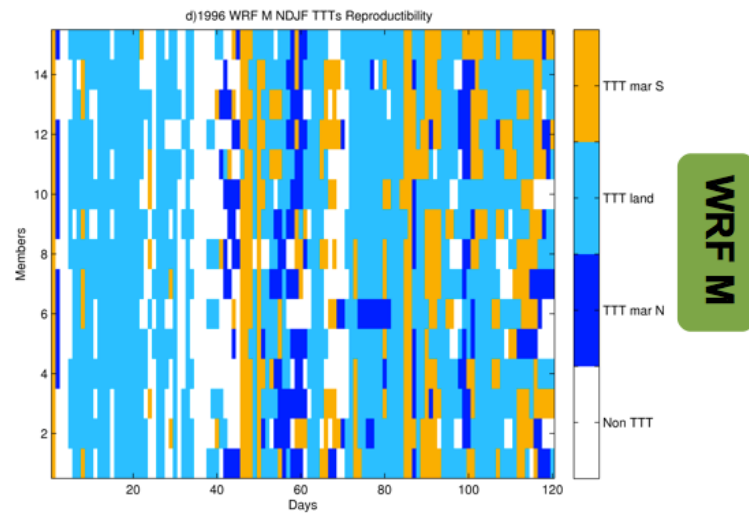
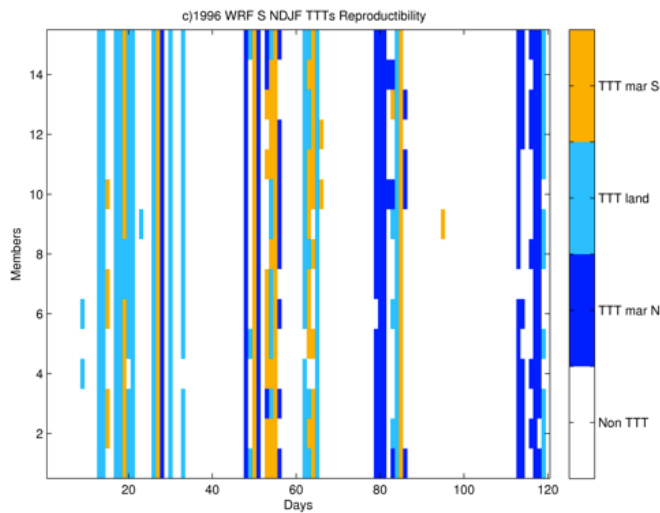
3 TTT land sequences lasting for few days



ERA40

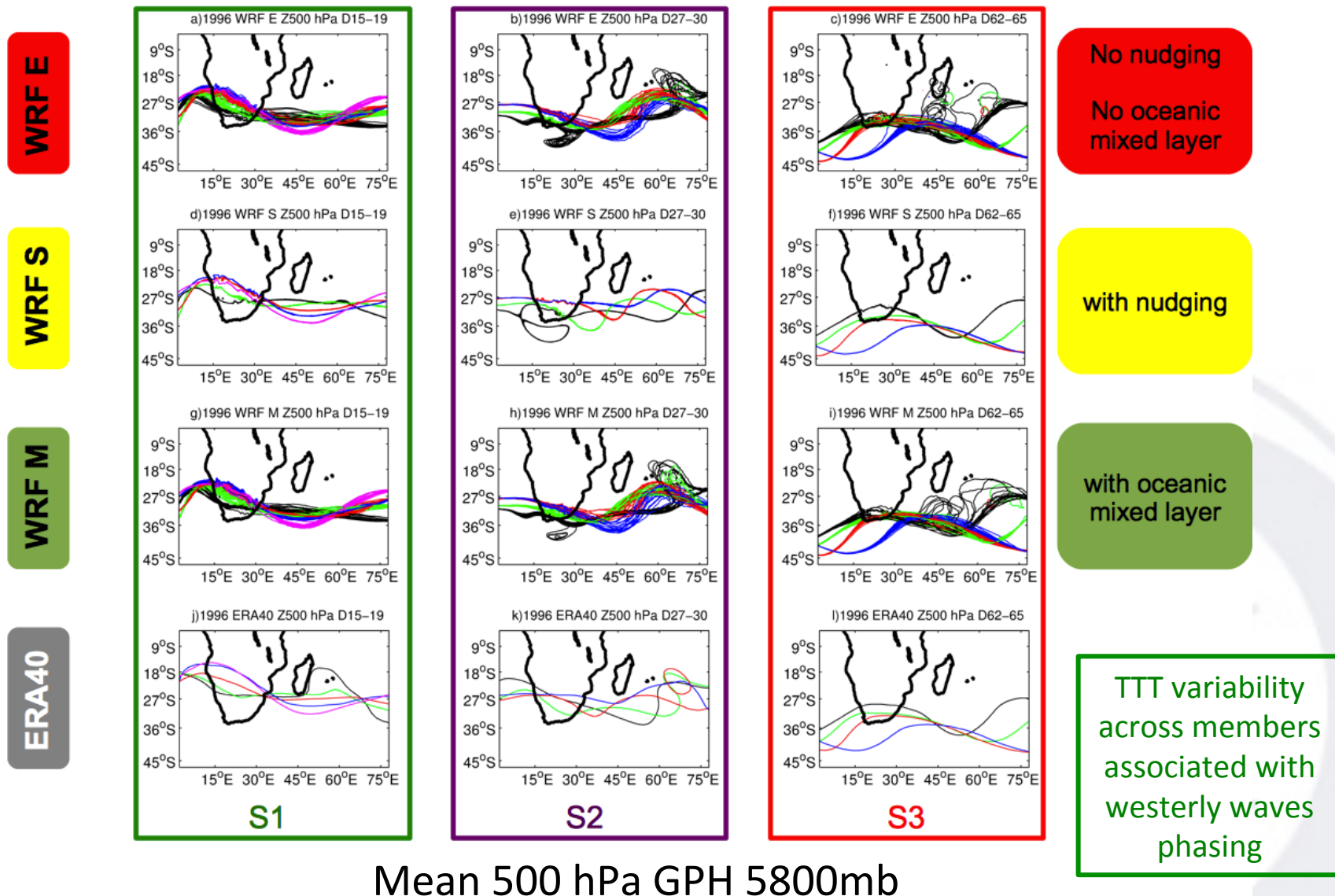


WRF S



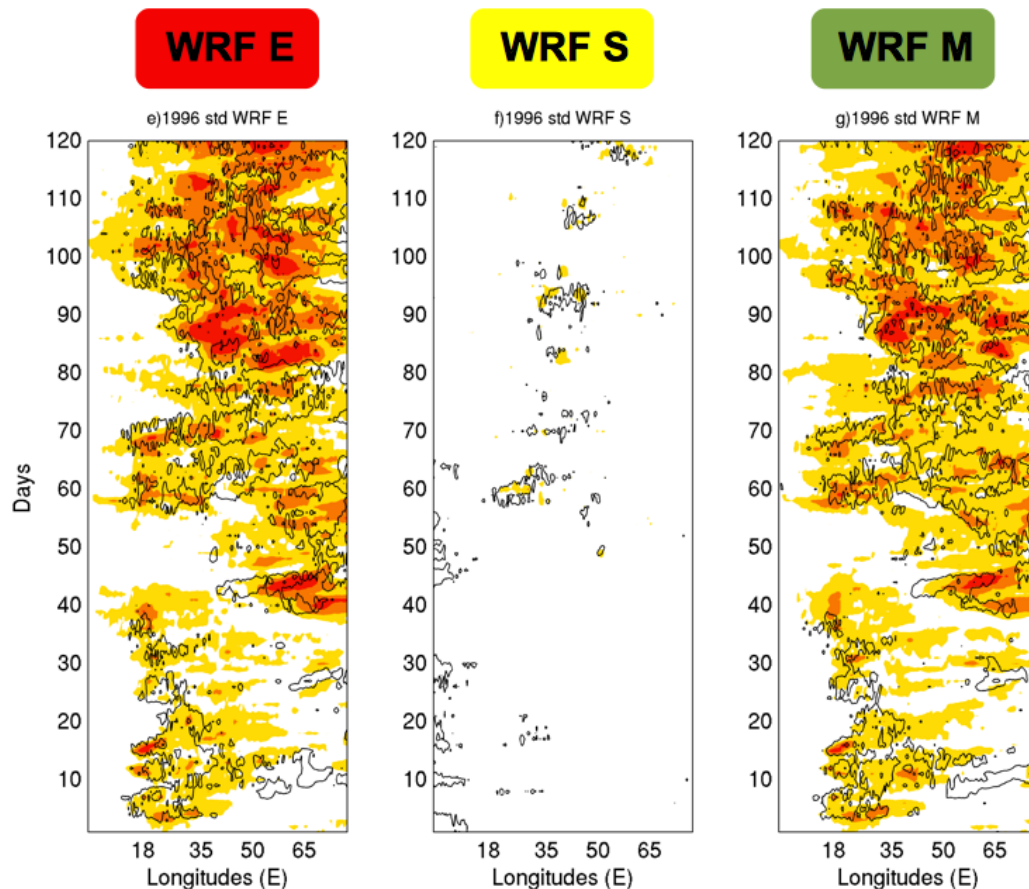
2.3. TROPICAL-TEMPERATE INTERACTIONS IN SOUTHERN AFRICA

WRF simulated TTT spatial variability (Nov 1996-Mar 1997)



2.3. TROPICAL-TEMPERATE INTERACTIONS IN SOUTHERN AFRICA

WRF simulated TTT spatial variability (Nov 1996-Mar 1997)

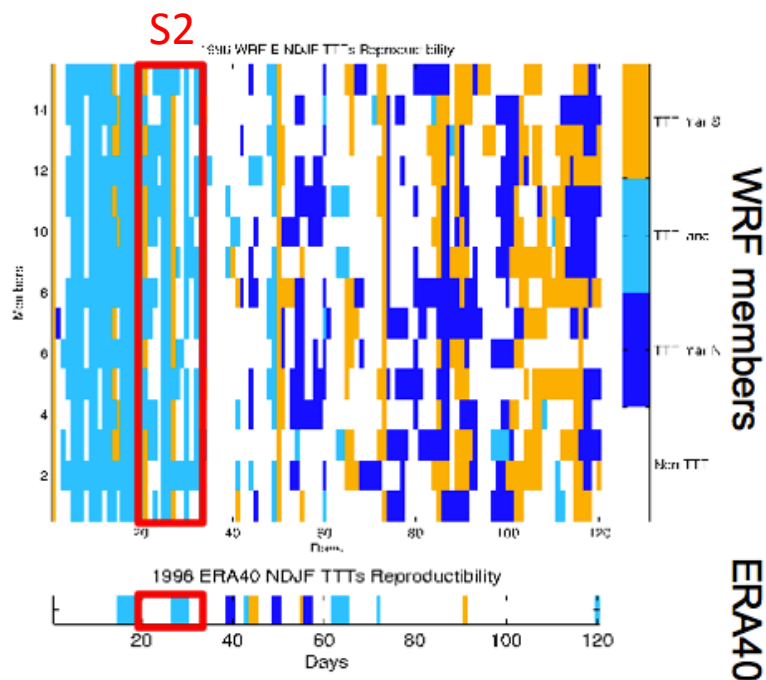


Maximum inter-member variations within
200 hPa ZDEF associated with
substantial modulation of local convection

[25-30S] STD 15 OLR (shadings) & 200hPa ZDEF (black contours)

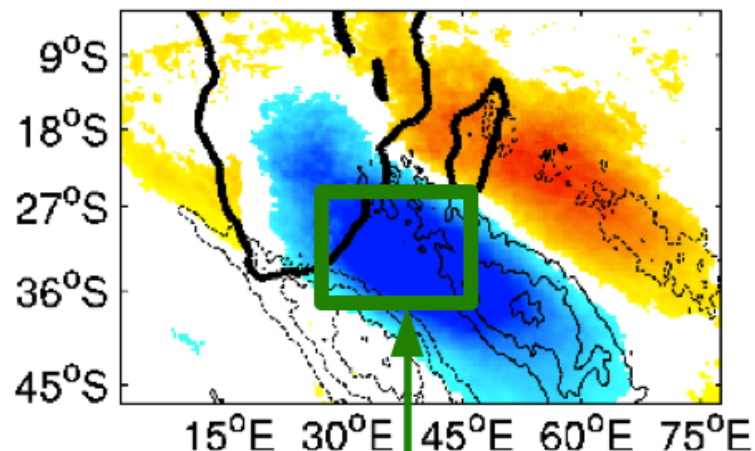
2.3. TROPICAL-TEMPERATE INTERACTIONS IN SOUTHERN AFRICA

WRF ensemble simulations for sequence S2



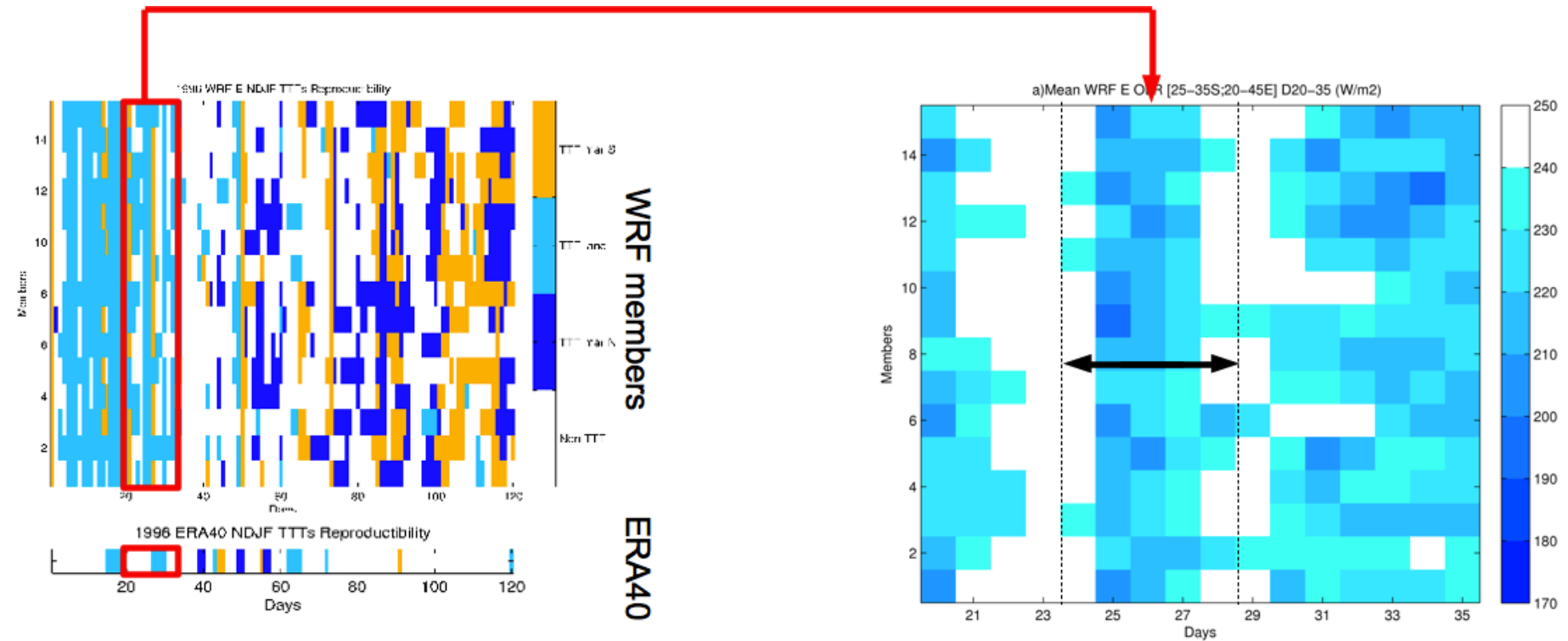
Occurrences for TTTs regimes in WRF ensemble simulations (top) forced by ERA40 (bottom) from November 1996 to March 1997

NDJF CLASS1 WRF E OLR & U 200hPa ZDEF



Indicator of continental TTTs live span :
mean OLR over [25-35°S;20-45°E]

2.3. TROPICAL-TEMPERATE INTERACTIONS IN SOUTHERN AFRICA



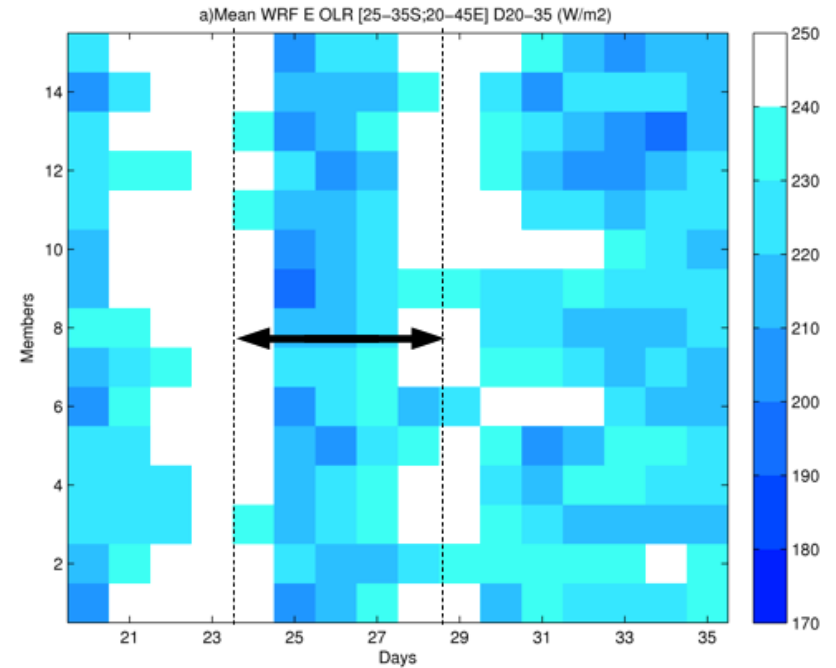
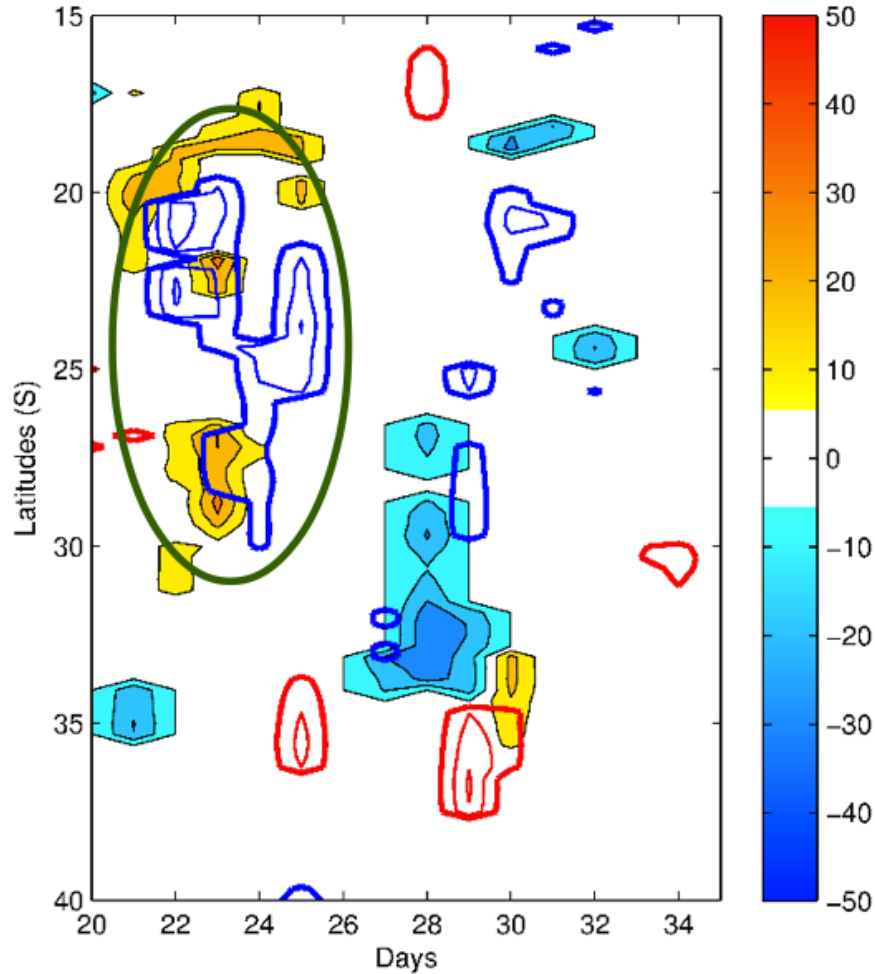
Occurrences for TTTs regimes in WRF ensemble simulations (top) forced by ERA40 (bottom) from November 1996 to March 1997

Shorter or longer episodes simulated by the different members

Using WRF ensemble members to identify precursors for simulated episodes

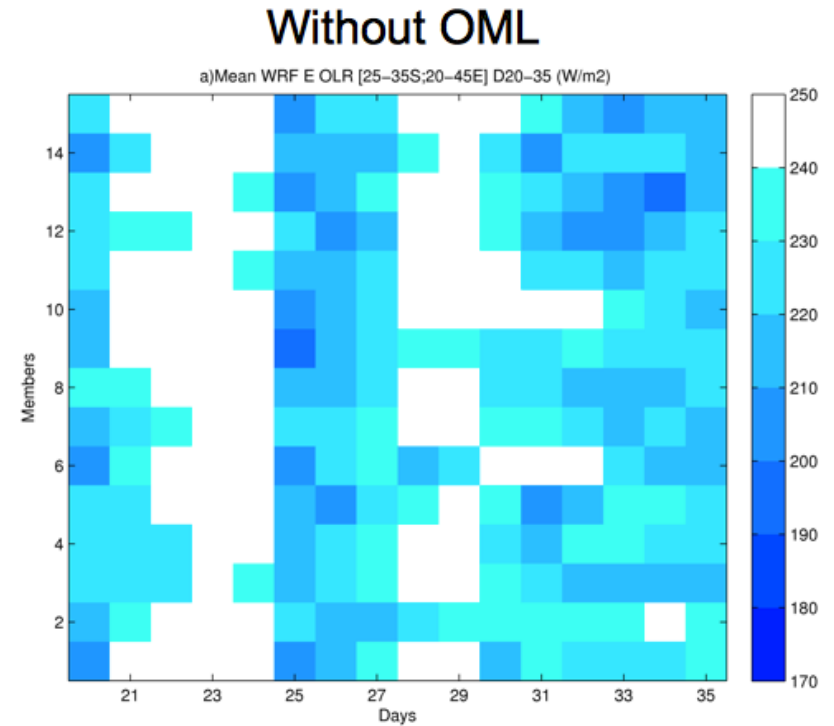
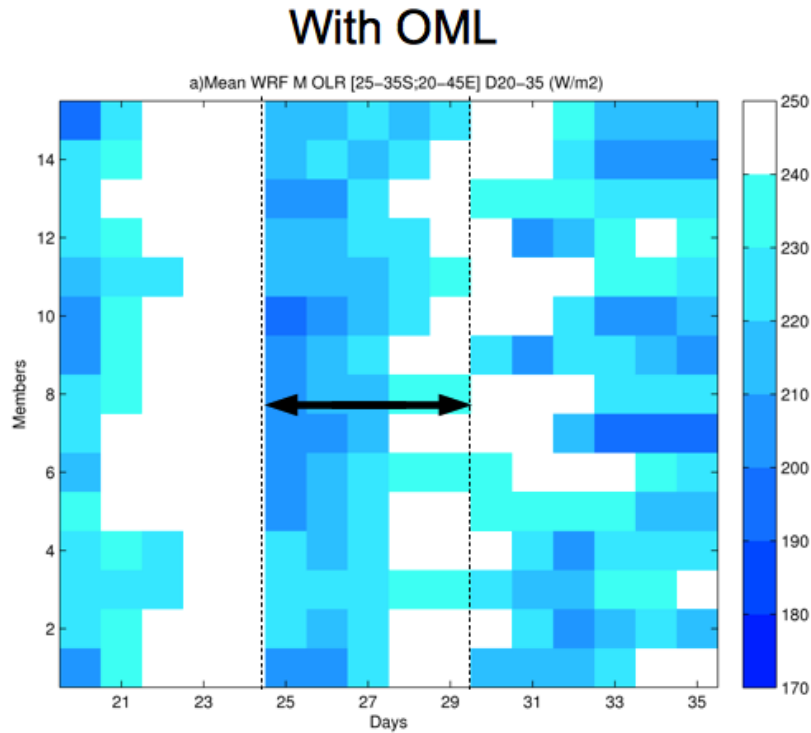
2.3. TROPICAL-TEMPERATE INTERACTIONS IN SOUTHERN AFRICA

ZDEF U200hPa & OLR Differences



TTTs persistence significantly linked with westerly wave and their phasing up to 5 days lead

2.3. TROPICAL-TEMPERATE INTERACTIONS IN SOUTHERN AFRICA

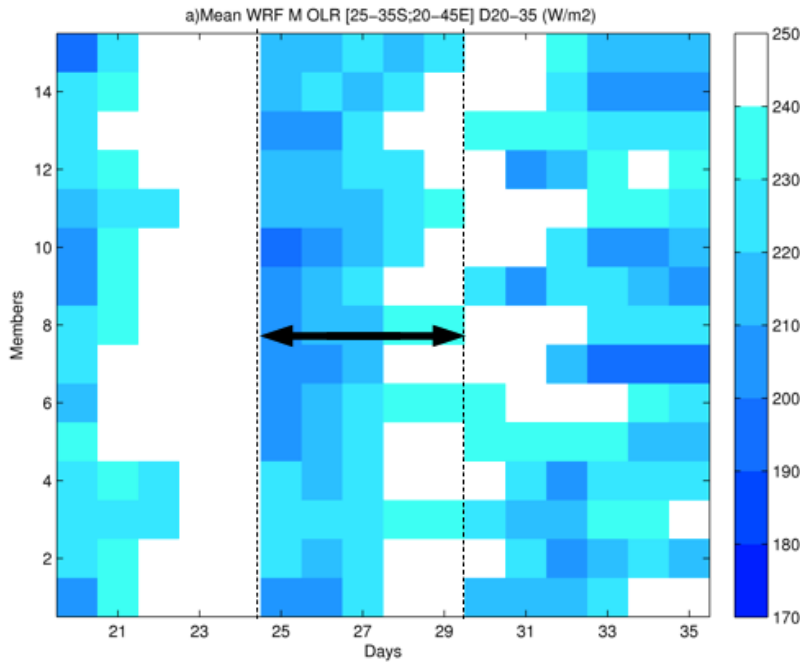


Longer episodes in average
→ influence from neighbouring
oceanic basins

Examining oceanic contributions using an Oceanic Mixed Layer (OML)

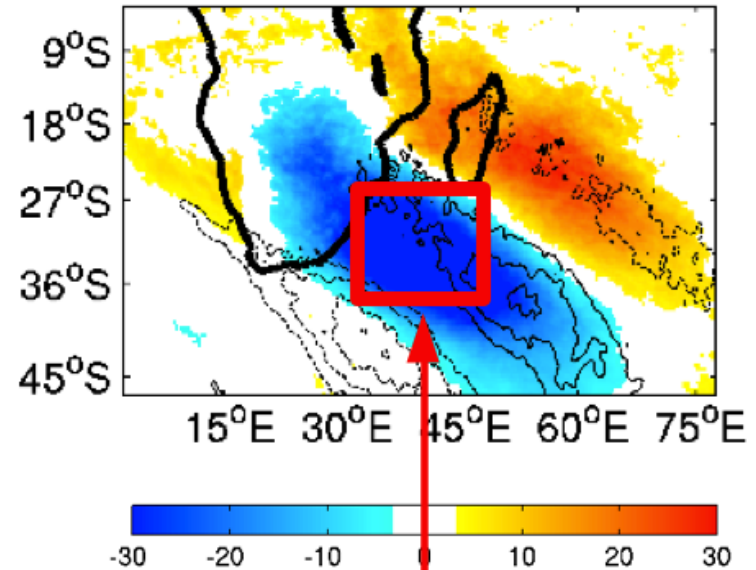
2.3. TROPICAL-TEMPERATE INTERACTIONS IN SOUTHERN AFRICA

With OML



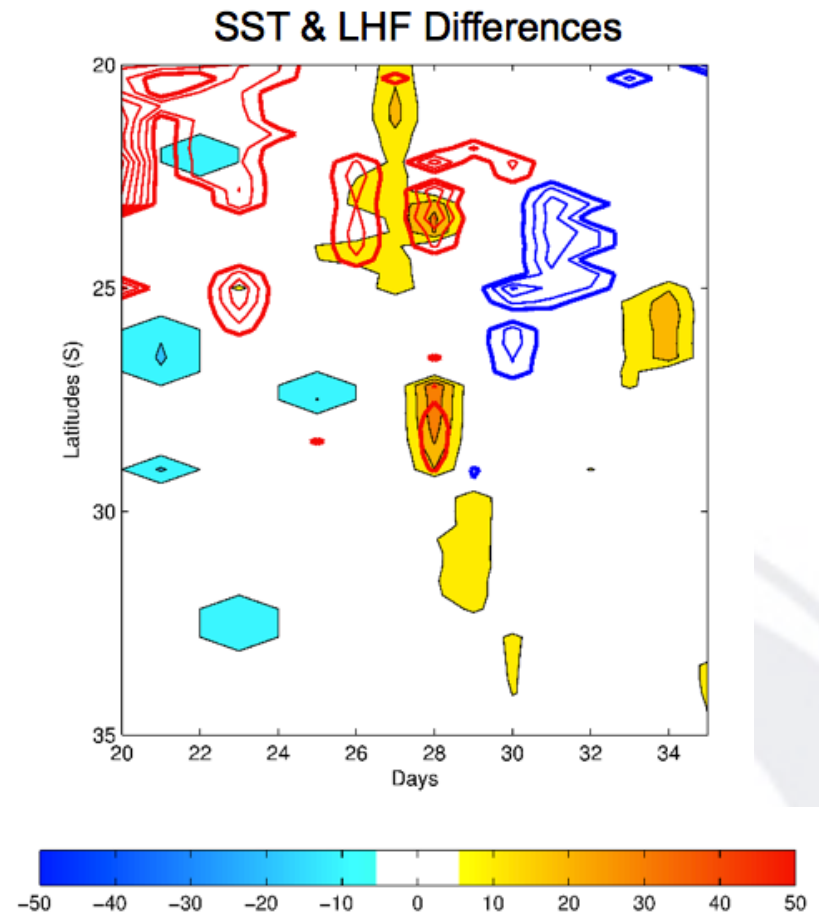
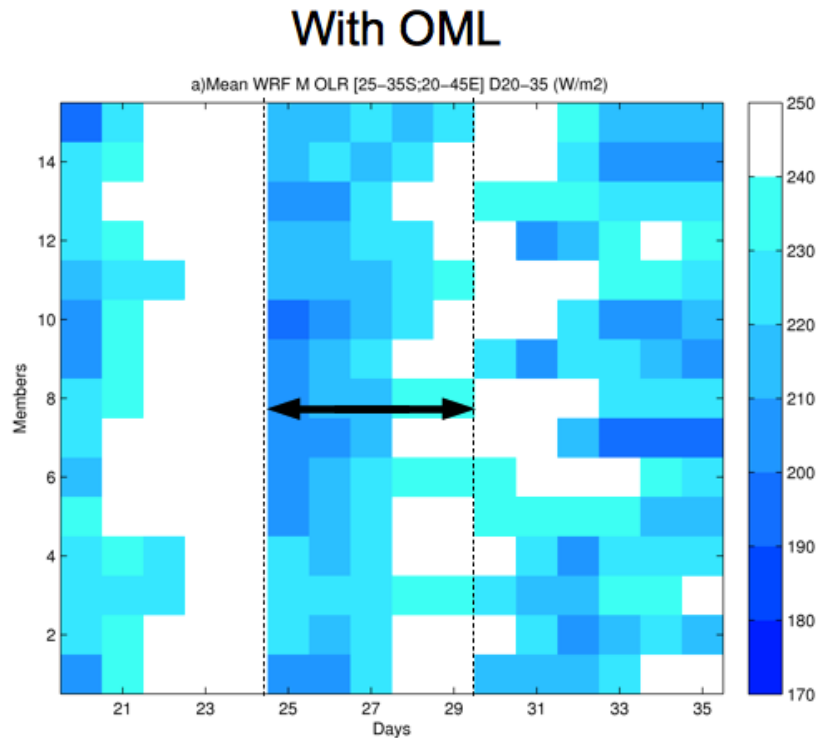
Longer episodes in average
→ influence from neighbouring
oceanic basins

NDJF CLASS1 WRFM OLR & U 200hPa ZDEF



Mean area used for considering SWIO
influence on continental TTTs
persistence

2.3. TROPICAL-TEMPERATE INTERACTIONS IN SOUTHERN AFRICA



**Warming within Agulhas current region of the SWIO
→ increased latent heat exchange from the Ocean to the atmosphere
favouring baroclinic instability and thus convection**

REFERENCES

- Cook K.H. (2000)** The South Indian Convergence Zone and interannual rainfall variability over Southern Africa, *J. Clim.*, 13:3789-3804
- Crétat J., Macron C., Pohl B., Richard Y. (2010)** Quantification of the reproducible part of climate variability in Southern Africa using a regional model, *Clim. Dyn.*, online,
- Fauchereau N., Pohl B., Reason C.J.C., Rouault M., Richard Y. (2007)** Recurrent daily OLR patterns in the Southern Africa/Southwest Indian Ocean region, implications for South African rainfall and teleconnections, *Clim. Dyn.*, 32:575-591
- Harrison M.S.J. (1984)** A generalized classification of South African rain-bearing synoptic systems, *J. Climatol.*, 4:547-560
- Harrison M.S.J. (1986)** A synoptic climatology of South African rainfall variations, PhD thesis, University of Witwaterstrand, Johannesburg, 341 p.
- Liebmann B., Smith C.A. (1996)** Description of a complete (interpolated) outgoing longwave radiation dataset, *Bull. Am. Meteorol. Soc.*, 77:1275-1277
- Lynch S.D. (2003)** Development of a RASTER database of annual, monthly and daily rainfall for Southern Africa, Report no. 1156/1/03, Water Research Commission, Pretoria, 78p.
- Todd M., Washington R. (1999)** Circulation anomalies associated with tropical-temperate troughs in Southern Africa and the South West Indian Ocean, *Clim. Dyn.*, 15:937-951
- Washington R., Todd M. (1999)** Tropical-temperate links in Southern Africa and Southwest Indian Ocean satellite-derived daily rainfall, *Int. J. Climatol.*, 19:1601-1616

CONCLUSIONS

A few messages to take home...

1. The notion of uncertainties in RCM simulations

- ❖ **Domain size versus spatial resolution:** a balance needs to be found, border effects to be kept in mind in order to reproduce key features of the large-scale circulation over the region => **Importance of control runs prior to full experiments**
- ❖ **Physical parameterizations:** these lead to differing numerical solutions and need to be tested => **Importance of sensitivity runs prior to full experiments**

A large, faint watermark of the IRI logo is visible in the bottom right corner of the slide. The logo consists of the letters 'IRI' in a serif font, centered within a circular border.

CONCLUSIONS

A few messages to take home...

1. The notion of uncertainties in RCM simulations

- ❖ **Domain size versus spatial resolution:** a balance needs to be found, border effects to be kept in mind in order to reproduce key features of the large-scale circulation over the region => **Importance of control runs prior to full experiments**
- ❖ **Physical parameterizations:** these lead to differing numerical solutions and need to be tested => **Importance of sensitivity runs prior to full experiments**

2. RCMs potentials for understanding local climate at sub-seasonal time-scales

- ❖ **RCM systematic biases versus simulated variability:** despite systematic biases, regional experiments can still be **able to simulate sub-seasonal climate variability** reasonably allowing the study of underlying atmospheric processes
- ❖ **RCM ensemble simulations:** these can be helpful in separating **large-scale forcing versus internal variability** and thus bear potentials for sub-seasonal studies
- ❖ **Ocean Mixed Layer coupling:** allows to consider better the influence from oceanic heat content and thus to examine **controls exerted by neighboring oceanic basins**

Thank you

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