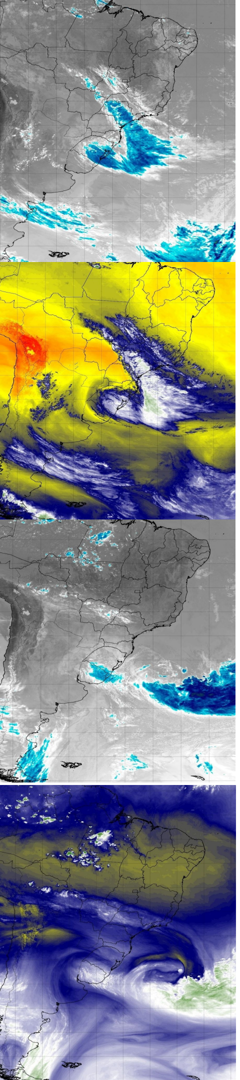

How convection-permitting simulations improve the representation of synoptic-scale cyclones

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Introduction

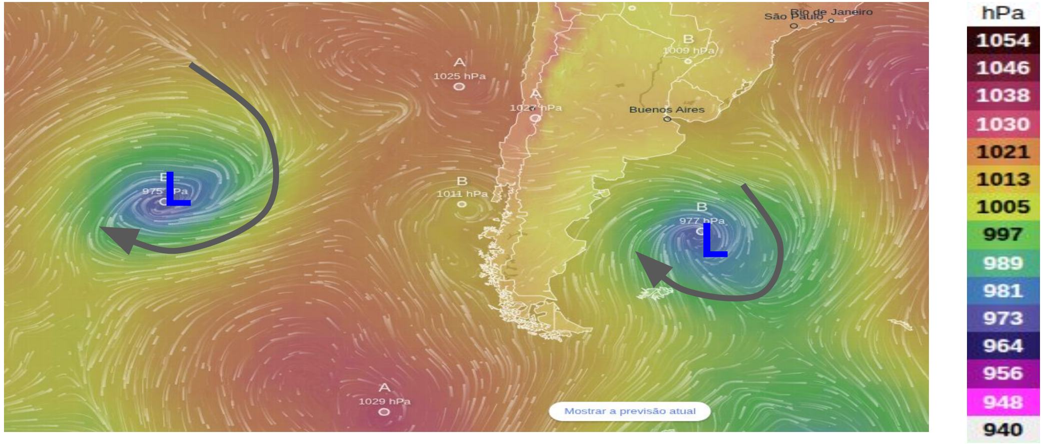
Synoptic-scale cyclones:

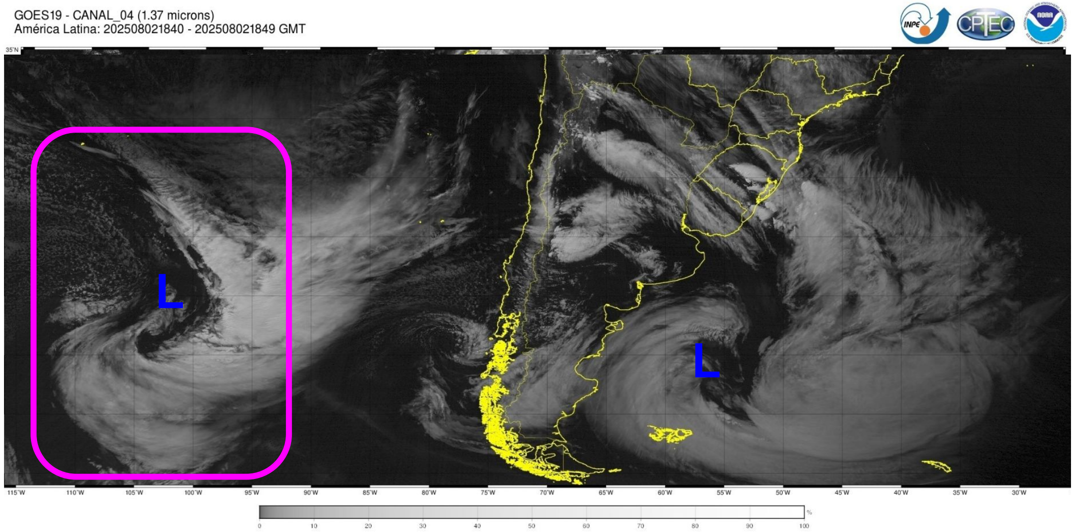
low-pressure centers

clockwise rotation in the **SH**
anticlockwise rotation in the **NH**

Extratropical systems:
clouds with **inverted comma** shape in the **SH**
clouds with **comma** shape in the **NH**

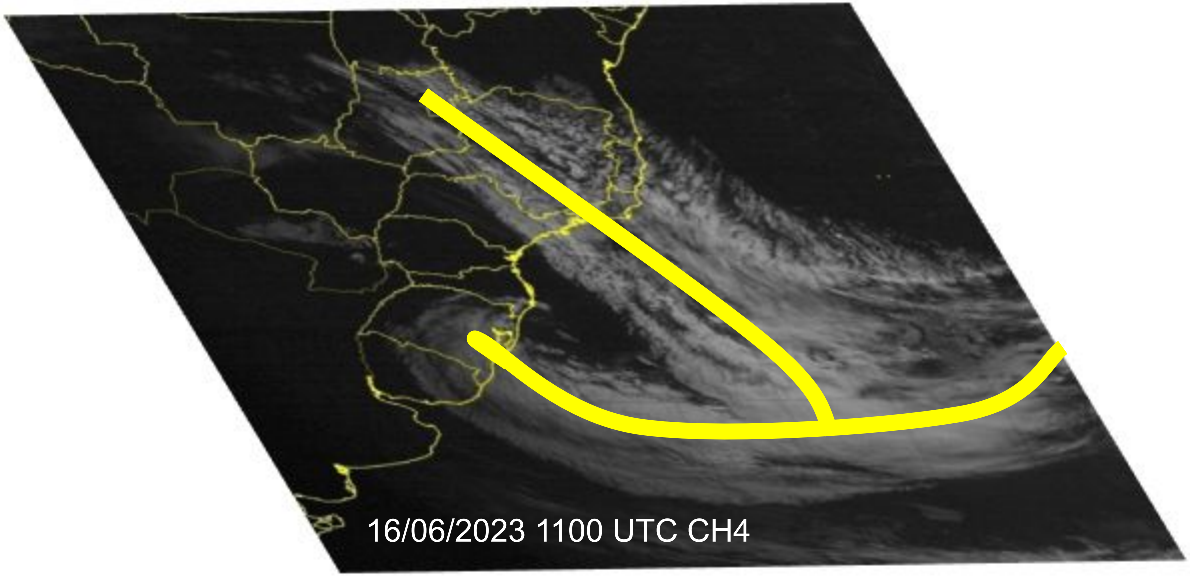
but also…



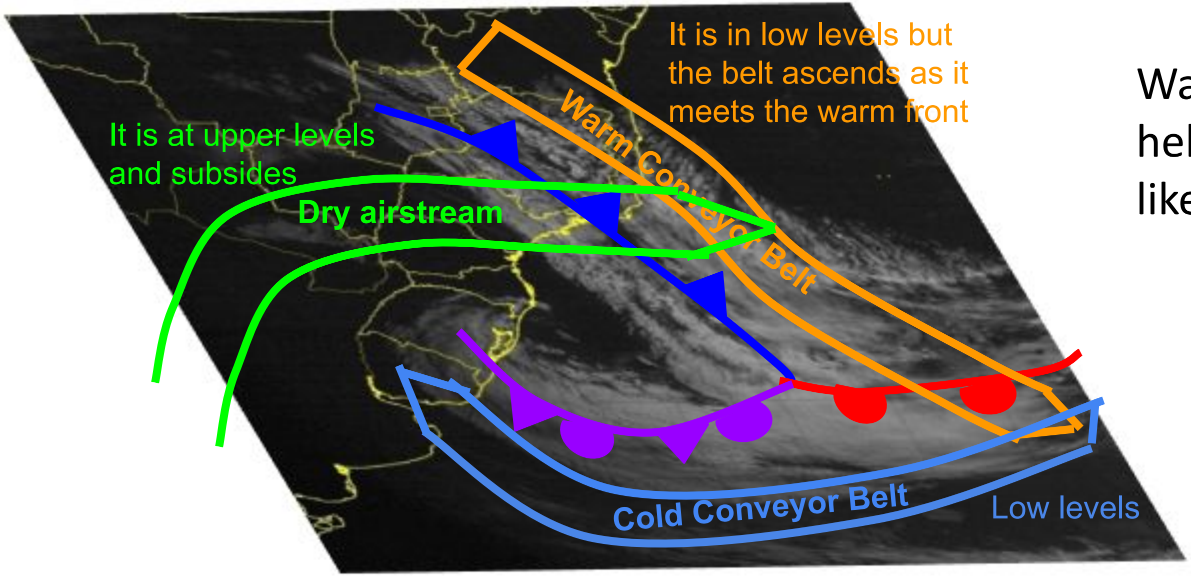


Introduction

Inverted T like-pattern,
which is associated with…



Introduction



Warm and cold conveyor belts

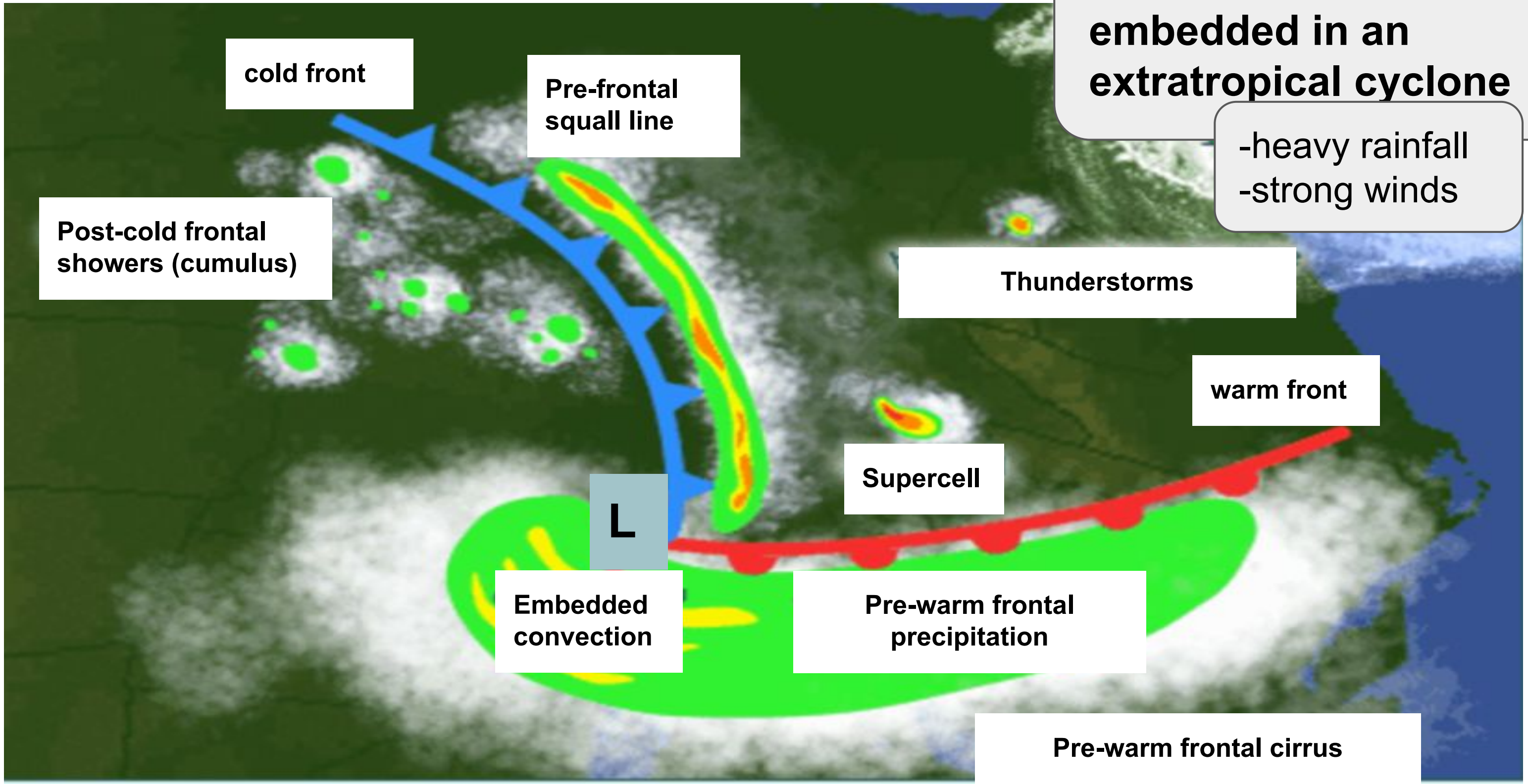
Warm and cold conveyor belts help to explain the **inverted T** like-pattern

and with a dry airstream they create an environment favorable for the **mesoscale structures** embedded in a cyclone

Introduction From synoptic to mesoscale view

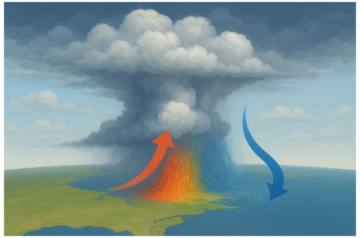
Mesoscale structures embedded in an extratropical cyclone

- heavy rainfall
- strong winds

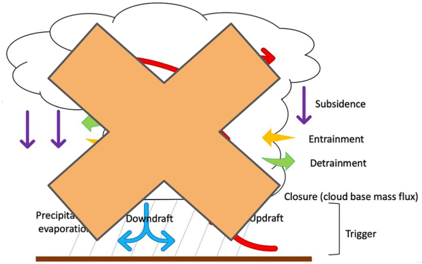


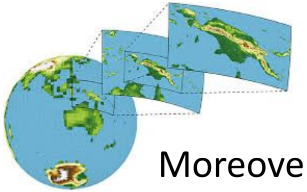
How do convection-permitting (CP) simulations improve the representation of synoptic-scale cyclones?

High resolution allows **convection to be explicitly solved by the RCMs**,



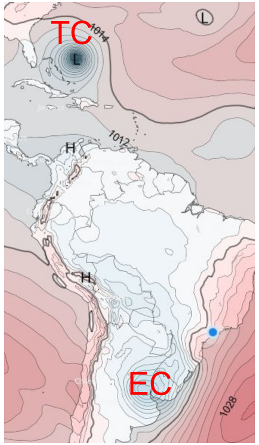
eliminating the need for cumulus convection parameterization, which is a source of model errors and uncertainties (Prein et al., 2013, 2015; Lucas-Picher et al., 2021).





Moreover, increased resolution leads to a more realistic representation of the **orography** and **land-sea contrasts** (Meredith et al., 2015).

CP simulations improve the
→ **representation of mesoscale structures** and therefore can better represent
→ **"the intensity and timing of strong winds and heavy precipitation"** associated with cyclones.



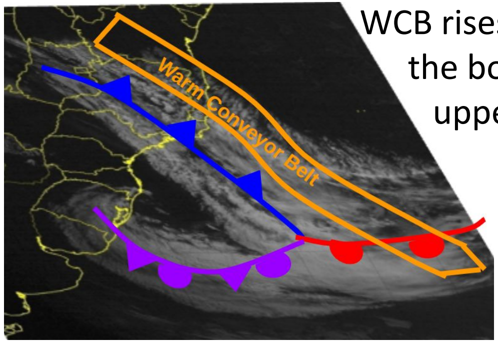
But how are RCMs in CP mode distinct from regional weather models?

RCMs are used to simulate **larger areas** than those typically covered in weather forecasts as well as **longer periods** (Magalhães et al., 2025).

RCMs lateral boundary conditions are driven by data with a horizontal resolution of ~0.25°, so they **do not require multiple nested grids to reach the CP scale**, as is often the case in weather models (Torma and Giorgi, 2024; Magalhães et al., 2025).

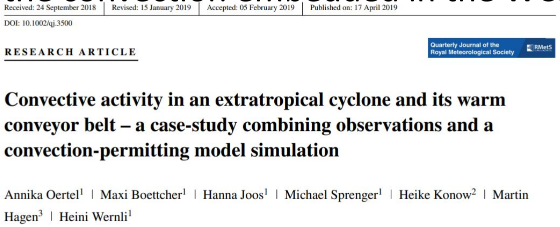
Case Studies

There are few case studies of cyclones using RCMs in CP mode



WCB rises continuously from the boundary layer to the upper troposphere with ascent rates of less than **50 hPa/h**

Oertel et al. used COSMO-CP to identify the ascent rates and the convection embedded in the WCB


Received: 24 September 2018 | Revised: 15 January 2019 | Accepted: 05 February 2019 | Published on: 17 April 2019

DOI: 10.1002/qj.3500

RESEARCH ARTICLE

Quarterly Journal of the Royal Meteorological Society RMetS

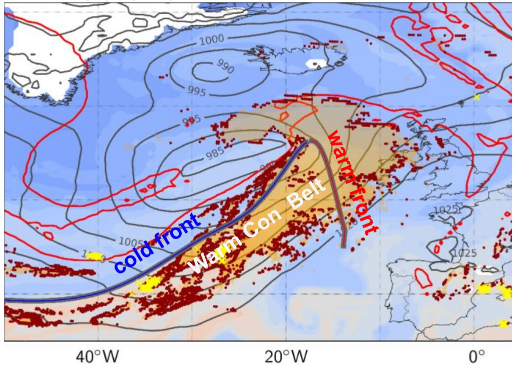
Convective activity in an extratropical cyclone and its warm conveyor belt – a case-study combining observations and a convection-permitting model simulation

Annika Oertel[1] | Maxi Boettcher[1] | Hanna Joos[1] | Michael Sprenger[1] | Heike Konow[2] | Martin Hagen[3] | Heini Wernli[1]

Model: COSMO (2.2 km)
Period: 22 - 25 Sep., 2016
Initial and boundary conditions: ECMWF analyses (0.1°) every 6 h

Cyclogenesis of Vladiana (North Atlantic) registered ascent rates exceeding 100–200 hPa/h

Vladiana



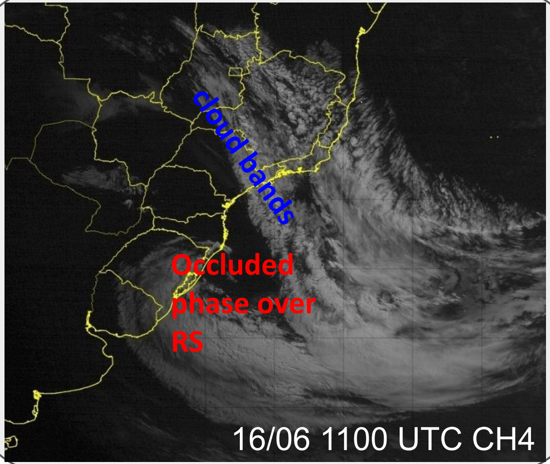
Results

The simulation shows that the **ascent rate exceeds 160 hPa/h** and ***is not homogeneous*** *along the entire WCB trajectory (CP model provides this clear information)*.

The most strongly ascending WCB air parcels occur in the southern part of the warm sector.

In this same sector, **CAPE exceeds 500 J/kg**. However, during most of the WCB ascent, the **embedded convective clouds are not necessarily associated with high CAPE values**.

Extratropical Cyclone in June 2023



Cyclogenesis: June 14-22
-Damages in the early hours on June 16th
-16 deaths
-15 thousand homeless

Two Studies

Reboita et al. (2024)

Focus on the cloud bands of the cold front

↓

RegCM

↓

Horizontal resolution: 3 km
Microphysics: NoTo
PBL scheme: Holtslag
Land-Surface: CLM4.5

Magalhães et al. (2025)

Focus on the occluded phase of the cyclone

↓

WRF

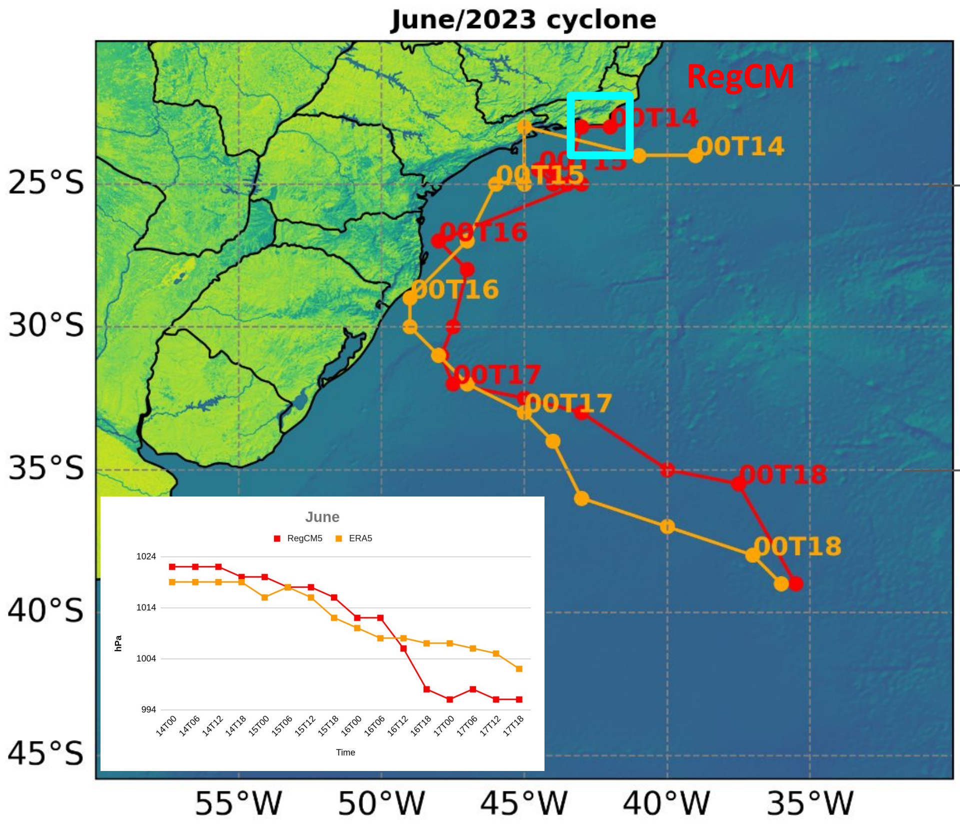
↓

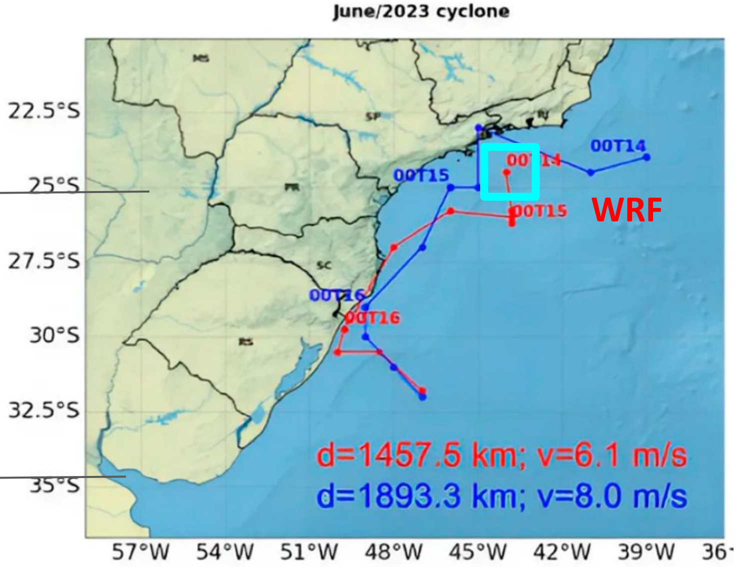
Horizontal resolution: 4 km
Microphysics: Thompson
PBL scheme: BouLac
Land-Surface: Noah-MP

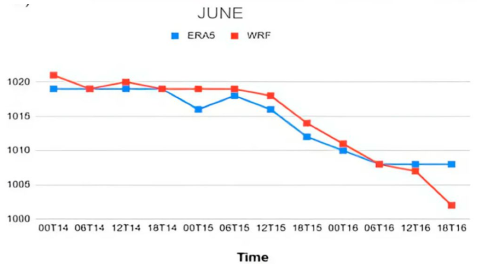
Results

Tracking

- We defined the same domain in ERA5 as in each model for tracking cyclones
- In RegCM, we simulated the cyclone for 2 days longer than in WRF
- The cyclogenesis occurs at the same time in the three datasets but with some differences in location and intensity

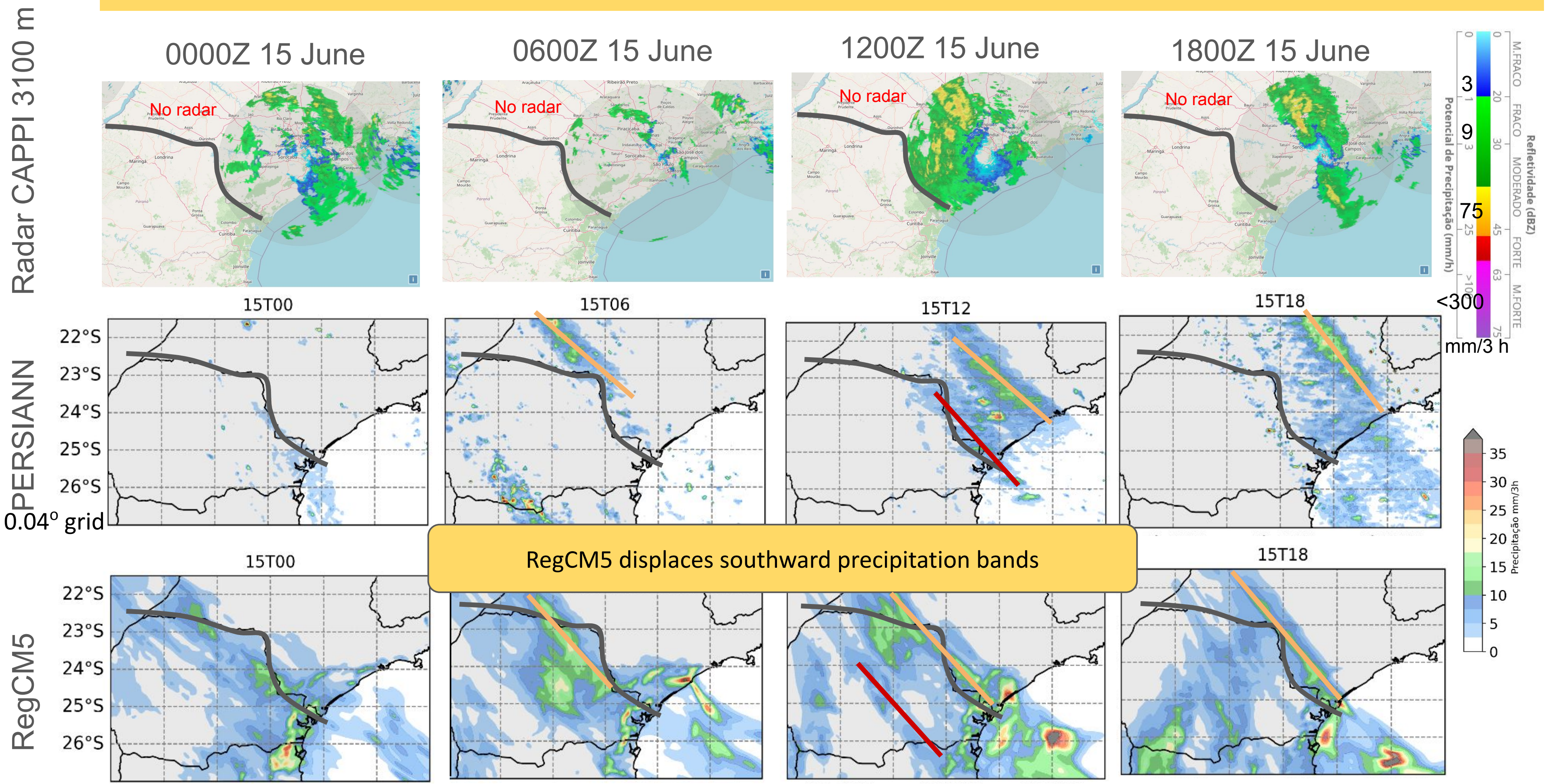






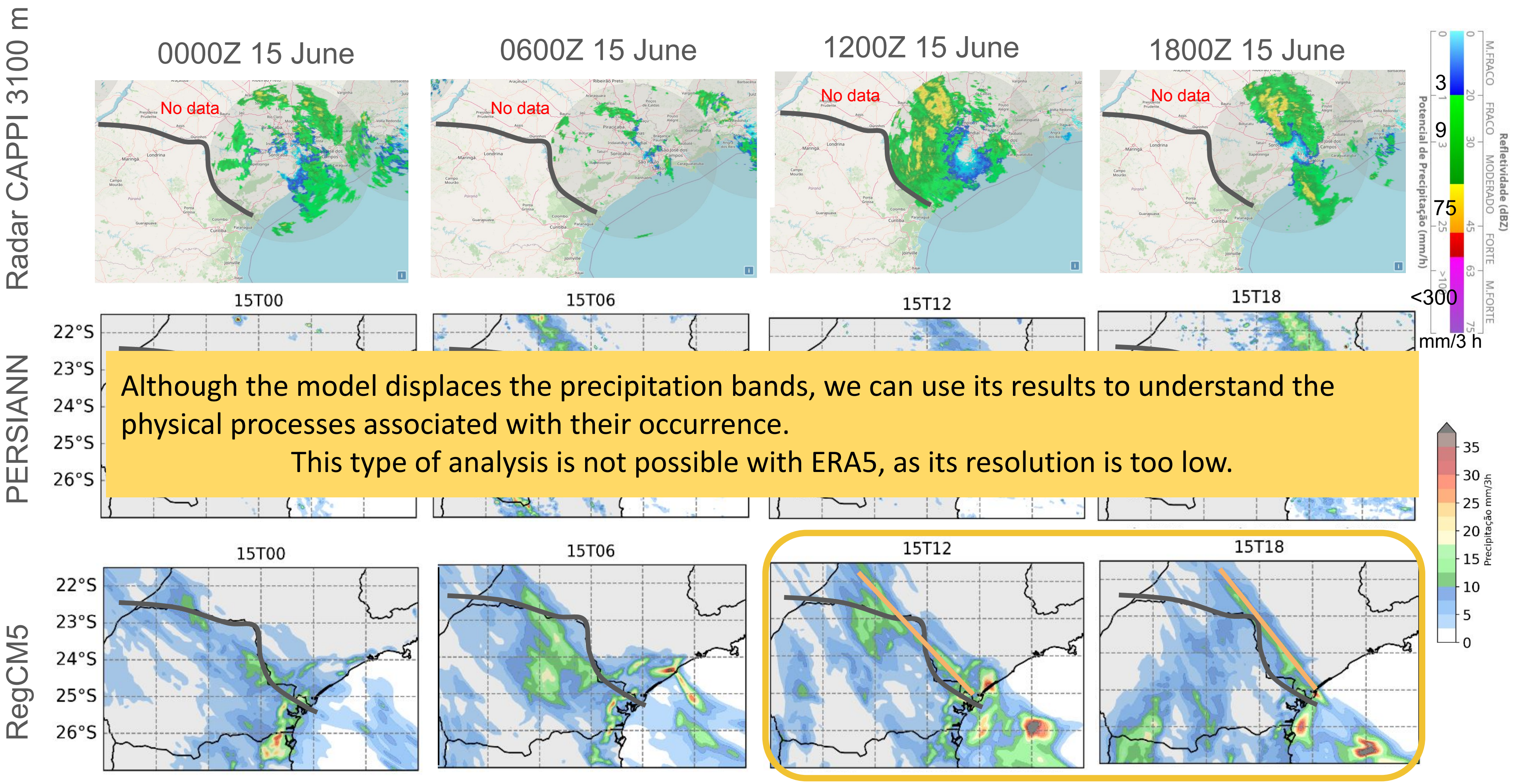
Cyclone central pressure

2023 **Cloud bands in the cold front**: We will not compare the prec volume, but we will compare the location of the prec.



Reboita et al. (2024) EGU

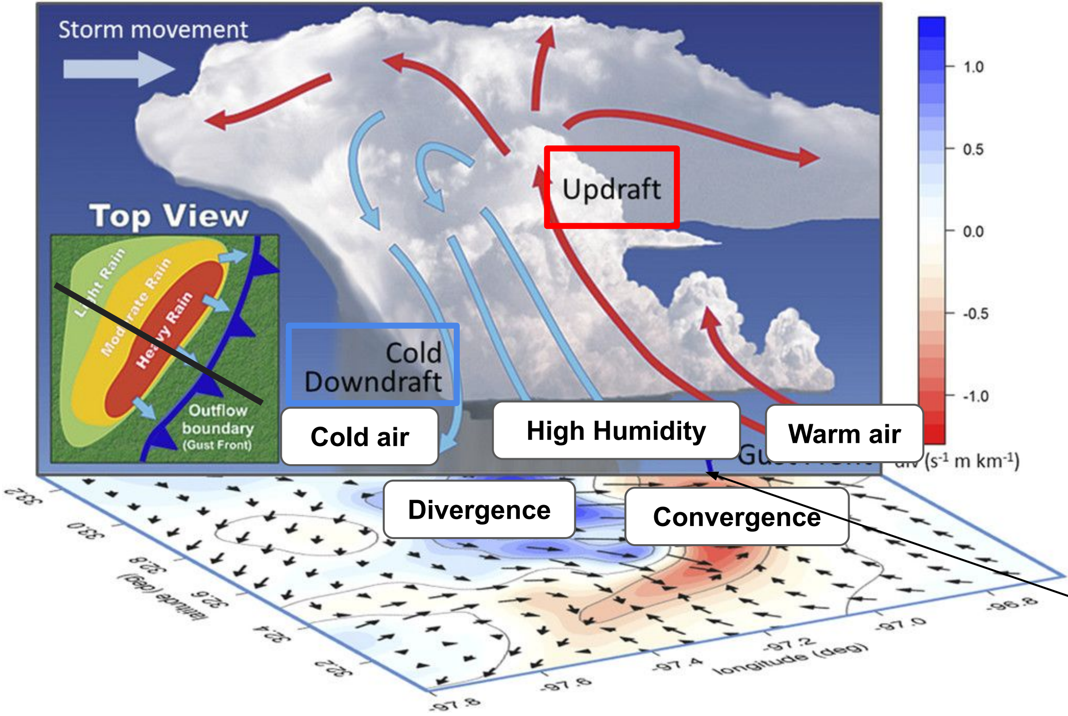
2023



Although the model displaces the precipitation bands, we can use its results to understand the physical processes associated with their occurrence.

This type of analysis is not possible with ERA5, as its resolution is too low.

What do we expect to see in mesoscale rainfall bands?



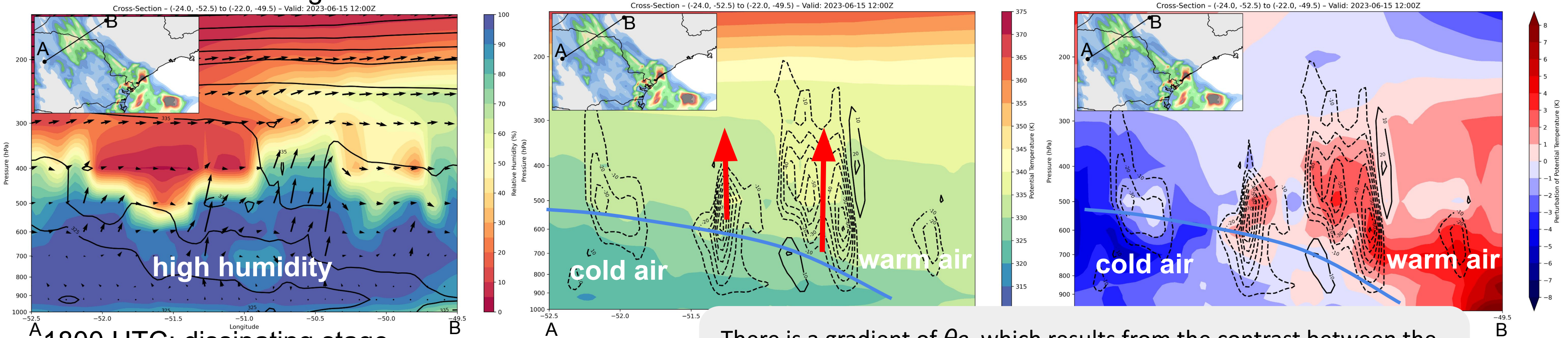
Region of horizontal temperature gradient

Source:https://journals.ametsoc.org/view/journals/atot/34/12/jtech-d-17-0110.1.xml

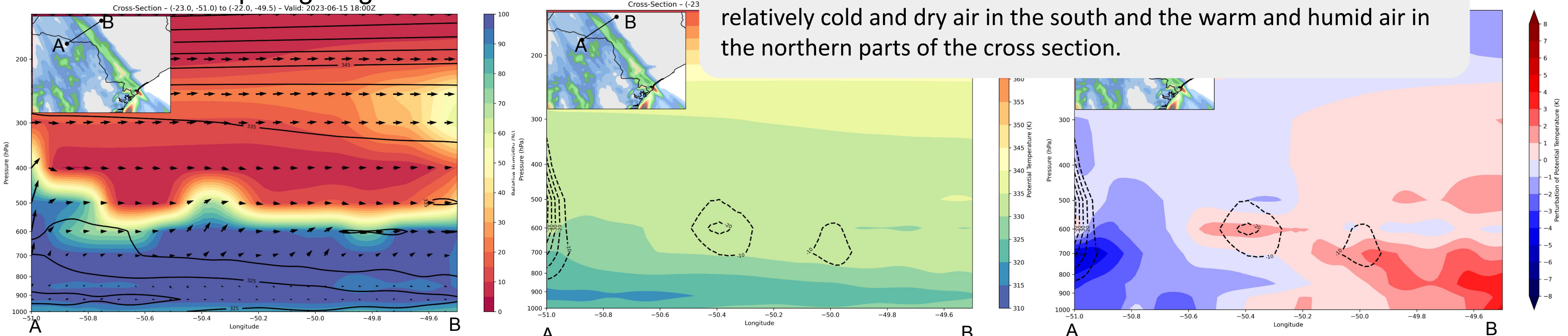
Results

15 June 2023: Mesoscale rainfall bands simulated by RegCM5

1200 UTC: mature stage



1800 UTC: dissipating stage



There is a gradient of *θe*, which results from the contrast between the relatively cold and dry air in the south and the warm and humid air in the northern parts of the cross section.

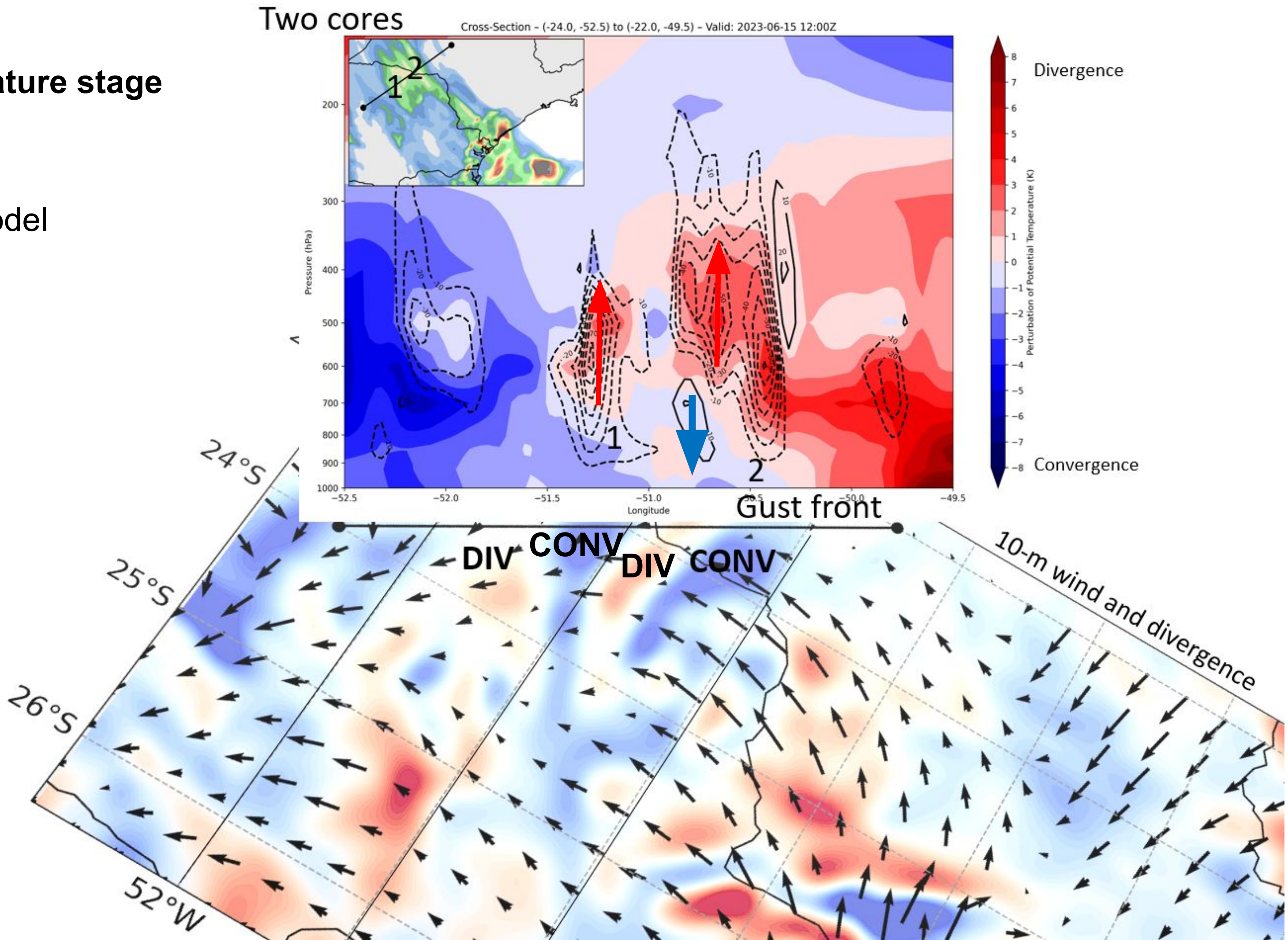
Relative humidity = shaded
θe = black lines
u,w = vectors

θe = shaded
-w < -10 = dashed line (negative = upward mov)

Zonal deviation of *θe* = shaded
-w = dashed line (negative = upward mov)

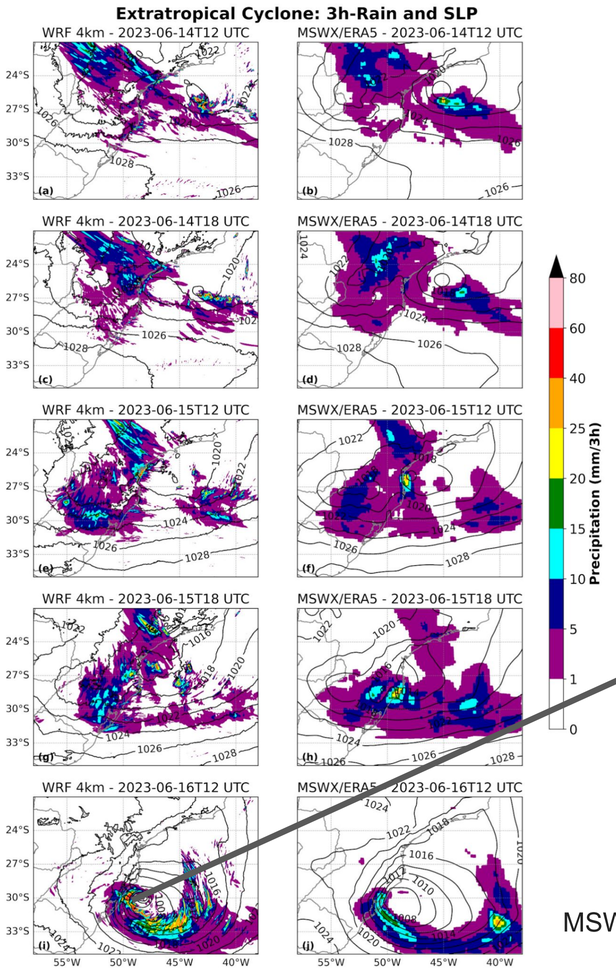
1200 UTC: mature stage

Following the conceptual model

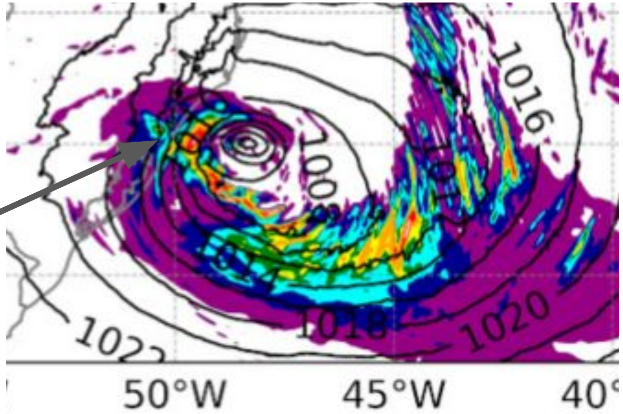


2023

WRF simulated prec compared with MSWX and MSLP with ERA5 → spatial pattern of prec is well simulated



We are interested in the occlusion of the cyclone, because it caused a lot of daily rainfall over the continent.



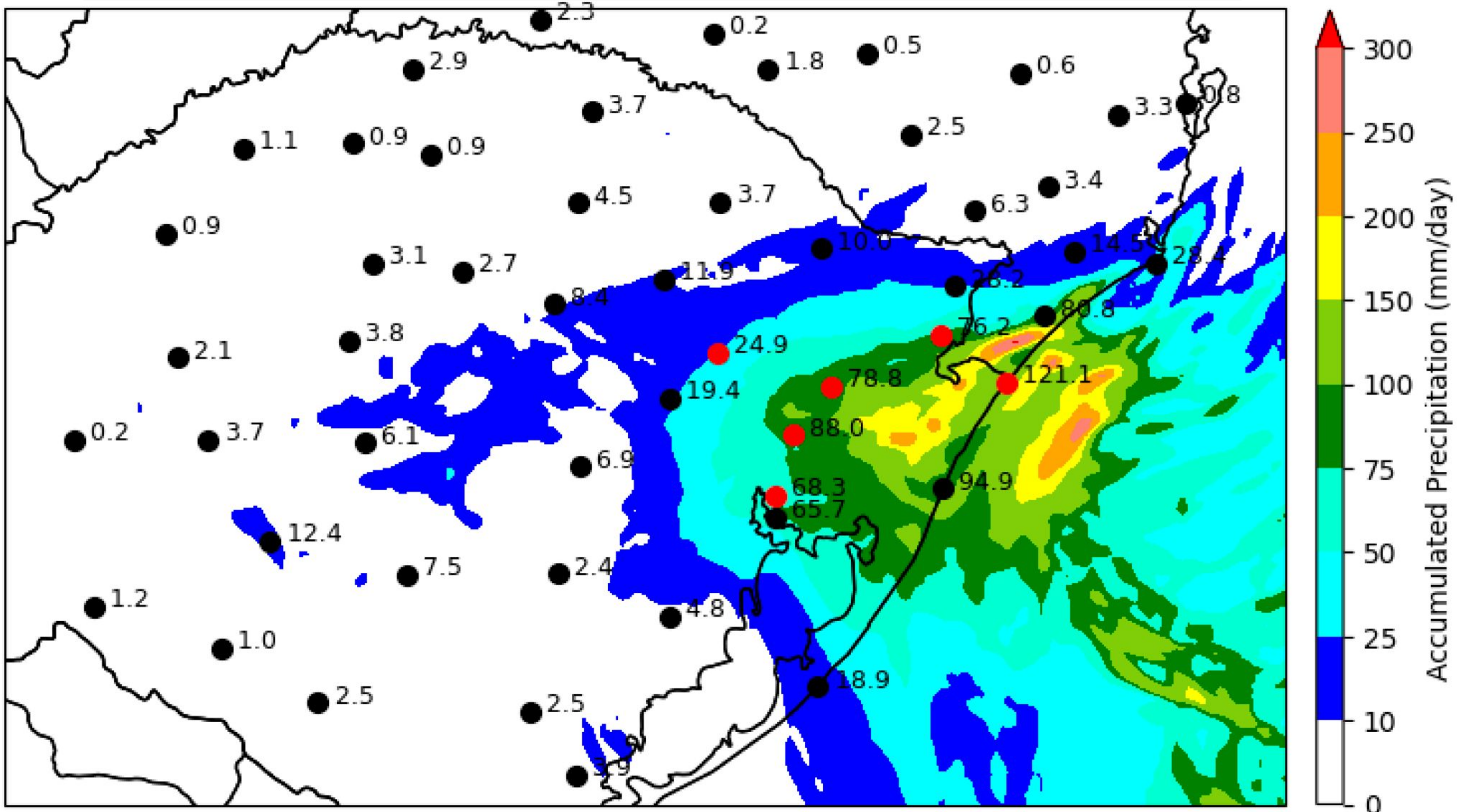
MSWX 0.1° × 0.1° horizontal resolution

Magalhães et al. (2025)
https://doi.org/10.3390/atmos16060675

Results

Shaded = WRF
Points = INMET stations

Total precipitation (mm/day) during the cyclone's occlusion on 16 June 2023



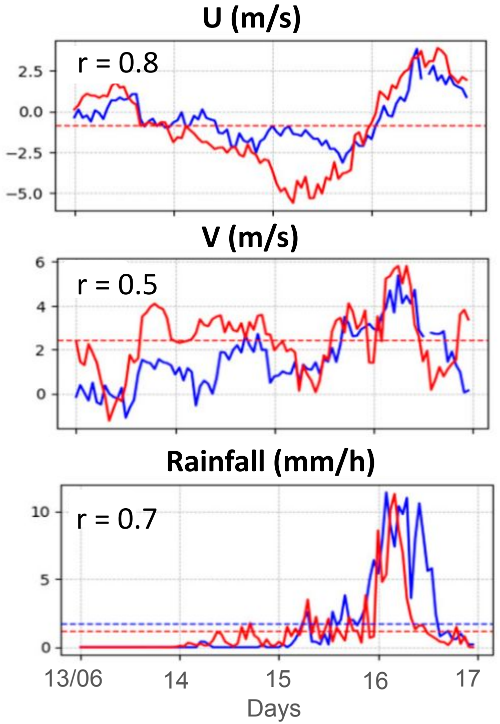
Red points indicate the locations of the stations selected for hourly time series analysis.

The model captures the **west-to-east prec gradient** and correctly locates the region of **maximum rainfall**, although it tends to overestimate precipitation in some areas near the coast.

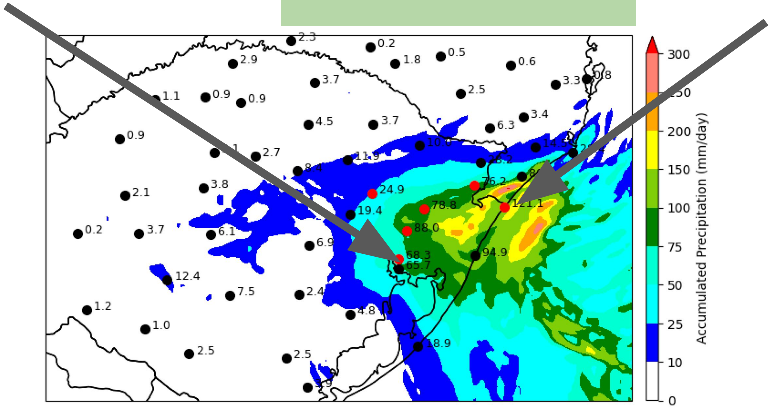
Results

INMET Stations
WRF

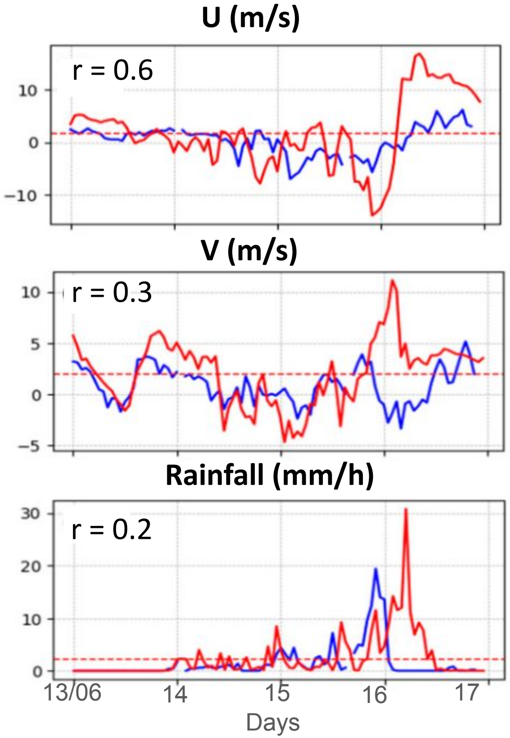
Porto Alegre

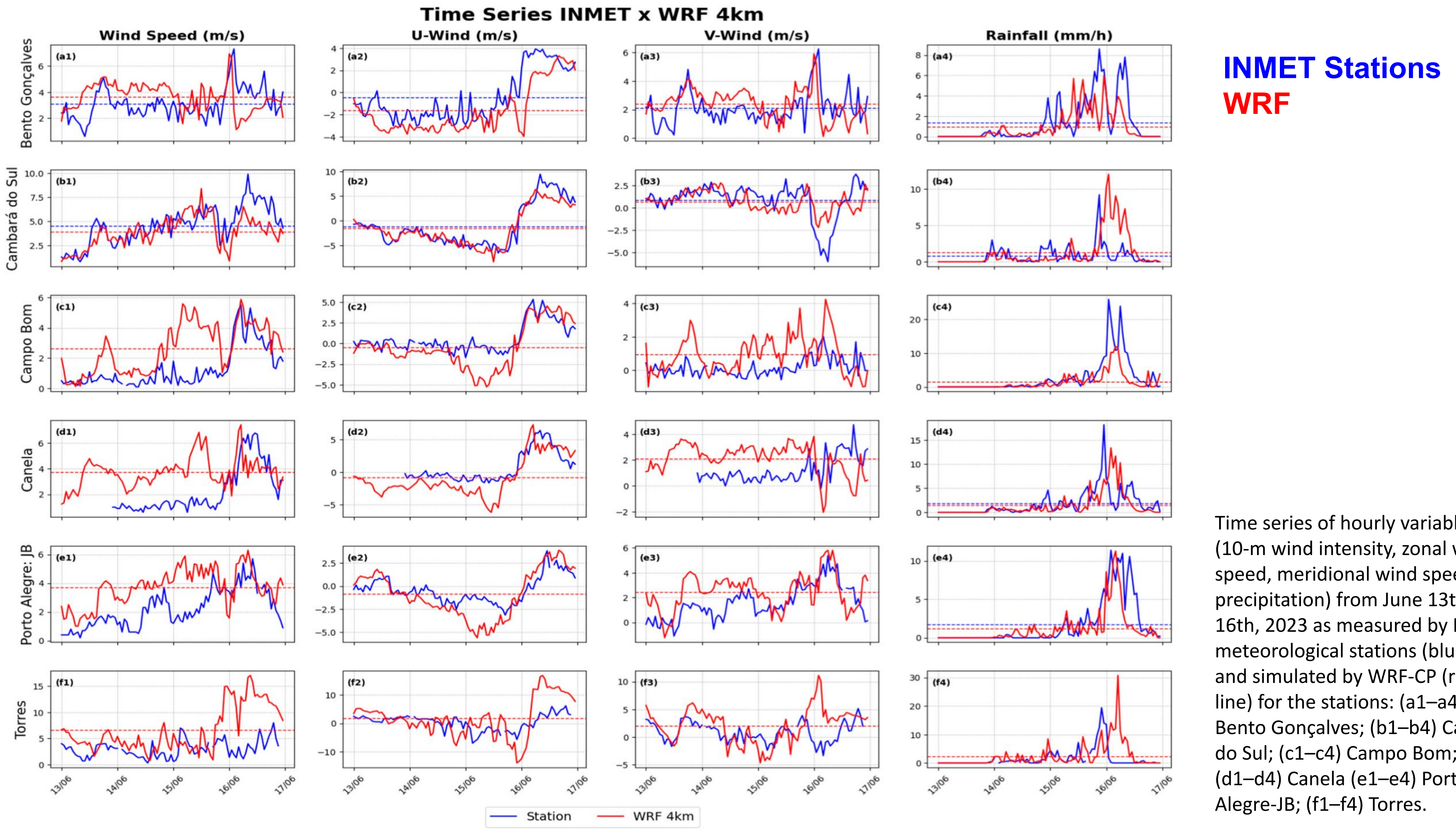


Shaded = WRF
Points = INMET stations



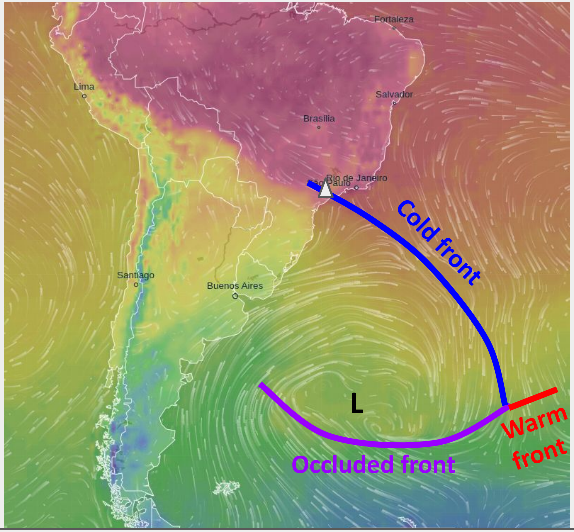
Torres





Time series of hourly variables (10-m wind intensity, zonal wind speed, meridional wind speed and precipitation) from June 13th to 16th, 2023 as measured by INMET meteorological stations (blue line) and simulated by WRF-CP (red line) for the stations: (a1–a4) Bento Gonçalves; (b1–b4) Cambará do Sul; (c1–c4) Campo Bom; (d1–d4) Canela (e1–e4) Porto Alegre-JB; (f1–f4) Torres.

Extratropical Cyclone in July 2019



△ Metropolitan Region of São Paulo (MRSP)
Prec 24h (from 12 UTC 4 to 5 July) = **116.2 mm**
Monthly climatology = **48.4 mm**
Extreme compared to P90th = **15.7 mm/day**
winds > **12 m/s**

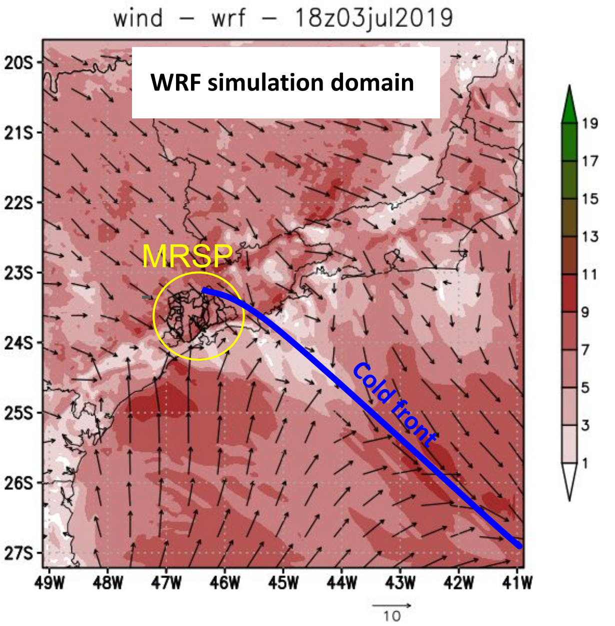
da Rocha et al. (2024): SAAG workshop

Focused on the evolution of weather conditions in the MRSP

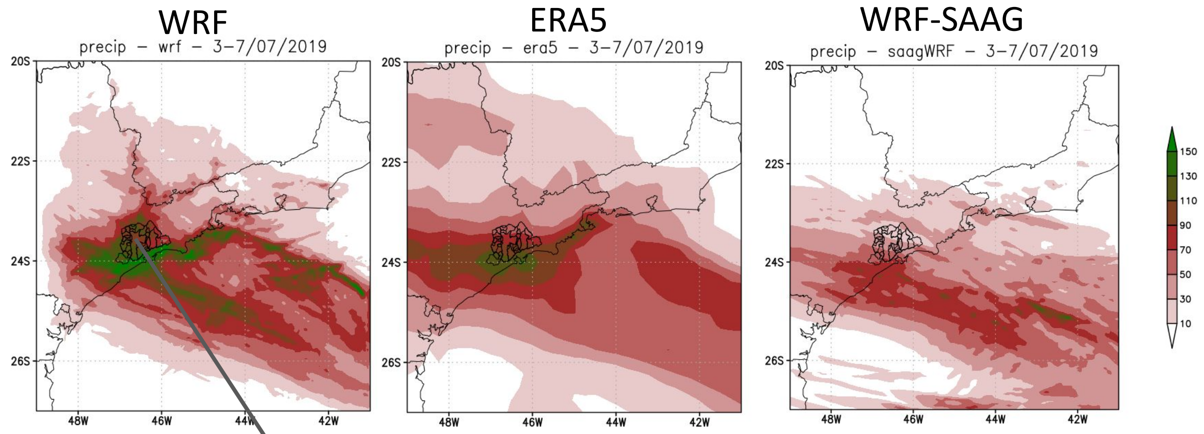
WRF

Horizontal resolution: 4 km
 # vertical levels: 45
Microphysics: Goddard
PBL scheme: BouLac
Land-Surface: Noah-MP
Initial and BC: ERA5

Results are also compared with SAAG/NCAR long run (4 km)

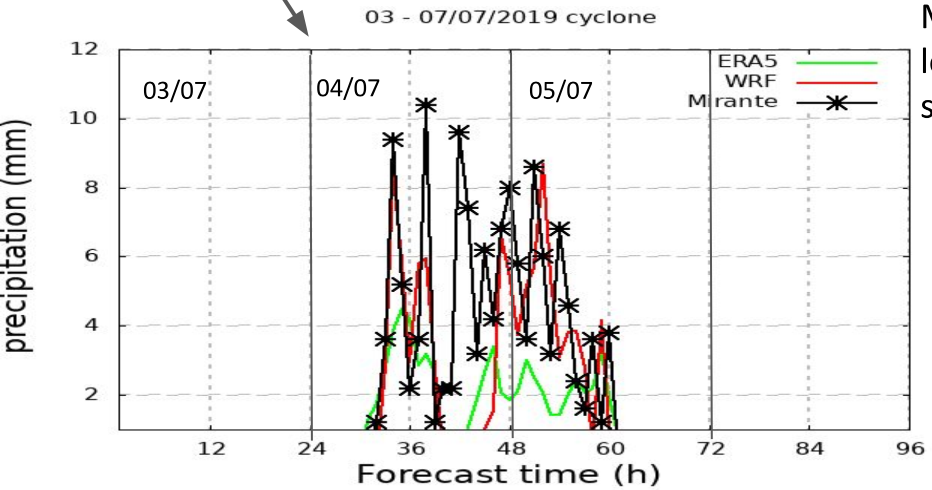


Accumulated precipitation (03-07 Jul, 2019)



WRF simulated rainfall reaches **~120 mm/day** only in the south sector of MRSP and coastal areas.

WRF-SAAG is the driest.



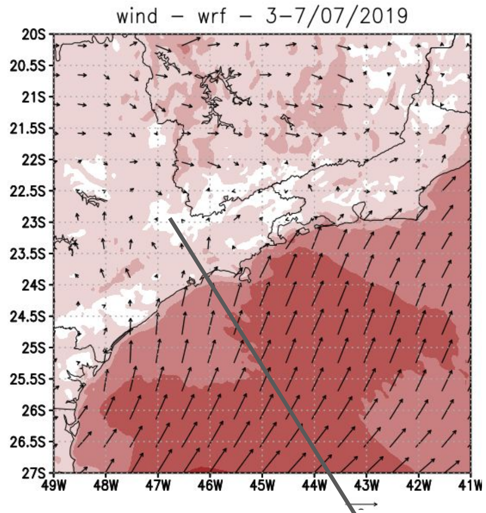
Mirante de Santana station located in the northern sector of the region

Station prec 24h (from 12 UTC 4 to 5 July) = **116.2 mm**

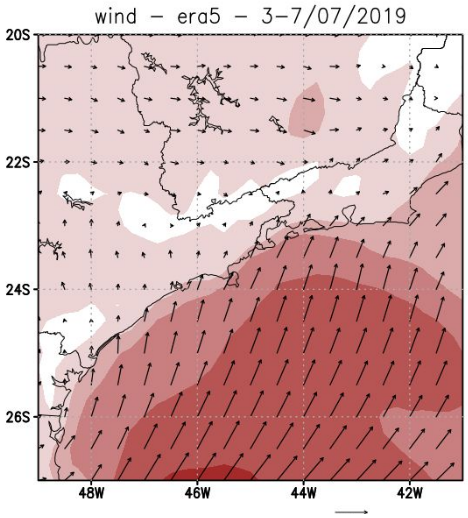
WRF → Much of the variability is captured. But in the total, there is underestimation. The rainfall does not advance to the north of the MRSP as observed by local station.

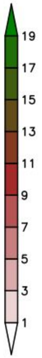
10-m wind (average 03 -07 Jul)

WRF

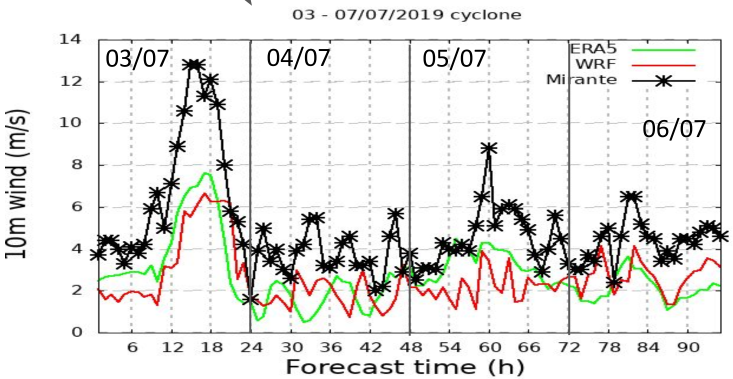


ERA5





WRF and ERA5 show a similar spatial pattern of both intensity and wind direction.



WRF has better correlation with observed data than ERA5, but both underestimate the wind intensity.

Conclusions

CP models are able to represent the physical processes associated with mesoscale systems embedded in the synoptic cyclones.

More case studies are needed for a better understanding of the mesoscale structures responsible for extreme events in the synoptic-scale cyclone environment.

Thanks

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