



# **I WORKSHOP BRASILEIRO SOBRE MODELAGEM DA ATMOSFERA APLICAÇÕES NA ÁREA DE ENERGIA EÓLICA**

CTGAS-ER | NATAL-RN  
14 e 15 junho de 2018

## **Avaliação da sensibilidade do modelo WRF-ARW (física da camada limite atmosférica, domínios e condições iniciais)**

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# Teoria do Modelo Numérico de Tempo: Componente crucial

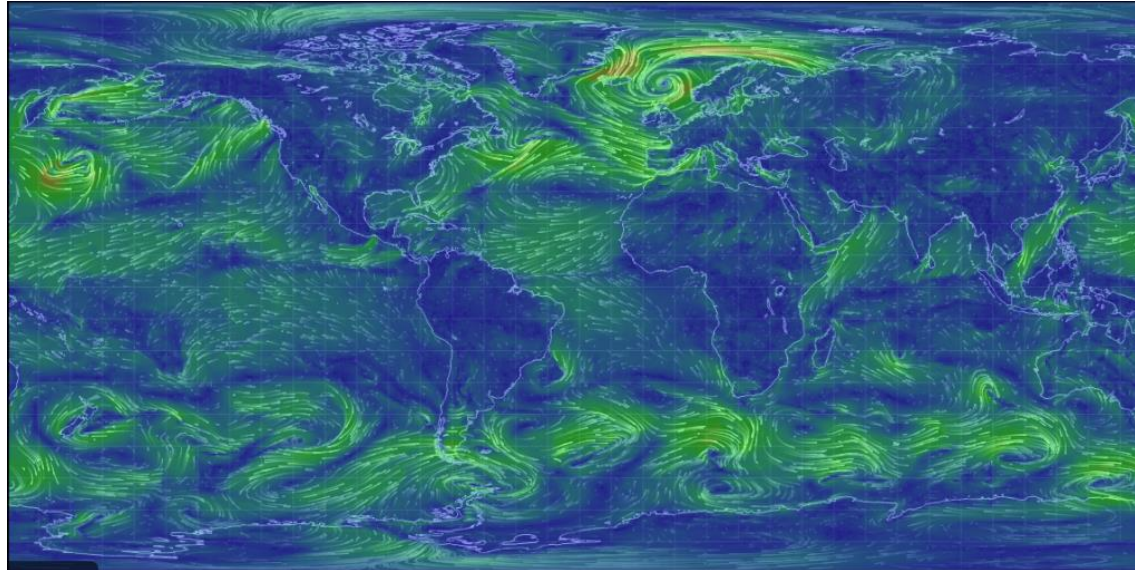
Observação

Previsões

Análise de  
Dados

Pós-processo  
Análise

Modelo  
Numérico



# Teoria do Modelo Numérico de Tempo: Atmosfera é Conservada

- Momentum

$$F = ma$$

Força = massa x aceleração

- Massa

$$\frac{1}{M} \frac{dM}{dt} = 0$$

Massa de um fluído é conservada

- Umidade

$$\frac{dq}{dt} = E - C$$

Mudança da Umidade = evaporação – condensação

- Energia

$$Q = C_v \frac{dT}{dt} + p \frac{d\alpha}{dt}$$

Calor = mudança energia interna – trabalho realizado

- Gás ideal

$$p\alpha = RT$$

Pressão x volume específico = constante do gás x temperatura



# Teoria do Modelo Numérico de Tempo: Equações governantes

V. Bjerkens (1904) determinou pela primeira vez à presença de conjunto completo com 7 equações e 7 incógnitas que governam a evolução da atmosfera.

$$\frac{dv}{dt} = -\alpha \nabla p - \nabla \phi + \mathbf{F} - 2\boldsymbol{\Omega} \times \mathbf{v}$$

Leste-oeste, norte-sul e vertical  
(três equações)

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v})$$

$$p = \rho R T$$

$$\frac{dq}{dt} = E - C$$

$$\frac{ds}{dt} = C_p \frac{1}{\theta} \frac{d\theta}{dt} = \frac{Q}{T}$$

7 equações, 7 variáveis desconhecidas (u, v, w, p,  $\rho$ , T e q)



# Fatores para a melhoria

- Supercomputadores
- Processos físicos
- Condição inicial

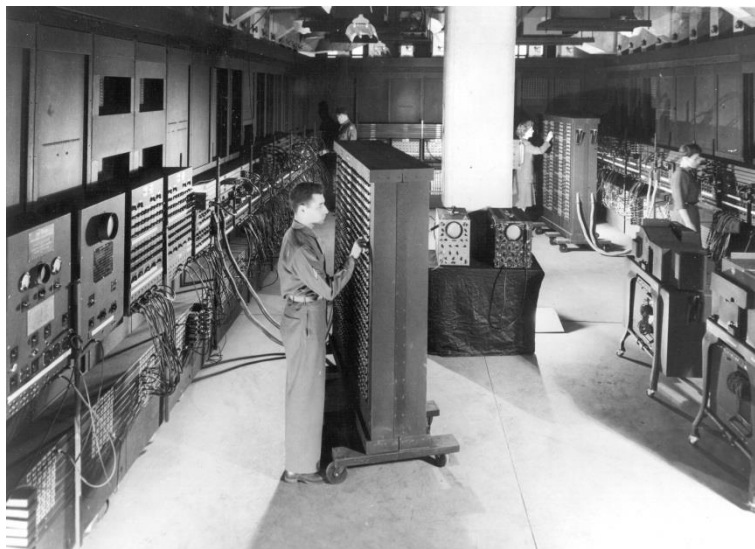
Kalnay (2002)





# Supercomputadores para modelos de tempo

ENIAC (500 FLOPS)



Sunway (125 peta =  $10^{15}$  FLOPS)



XC40 (2.9 PETA)



K-computer (11.2 PETA)



# Dinâmica : Método Numérico

## ESPACIAL

Método diferença finita  
Método Espectral  
Método elemento finito

### 1) Diferença Finita

$$\frac{\Delta \phi}{\Delta t} = \frac{\phi_2 - \phi_1}{t_2 - t_1}$$

## TEMPORAL

$$a) \frac{u^{n+1} - u^{n-1}}{2\Delta t} = F(u^n) \quad \text{Leap-frog}$$

Bom para hiperbólico  
Instável para parabólico

$$\frac{u^{n+1} - u^n}{\Delta t} = F(u^n) \quad \text{Euler-forward}$$

Bom para difusão  
Instável para hiperbólico

$$\frac{u^{n+\frac{1}{2}*} - u^n}{\Delta t/2} = F(u^n) \quad : \quad \frac{u^{n+1*} - u^n}{\Delta t} = F\left(u^{n+\frac{1}{2}*}\right)$$

$$\frac{u^{n+1} - u^n}{\Delta t} = \frac{1}{6} \left[ F(u^n) + 4F\left(u^{n+\frac{1}{2}*}\right) + F(u^{n+1*}) \right]$$

: RK(Runge-Kuta)-3rd order



# Classificação dos Modelos

- Núcleo dinâmico

Hidrostático	Não-Hidrostático
Larga-Escala	Pequena-Escala

- Escala

Global	Regional
10 km – 200 km  (Modelo Numérico de Previsão - Climático)	1 km – 50 km  (Modelo Numérico de Previsão – Tempo e pesquisa)

- Propósito

Dado Inicial – Previsão	Forçante - Resposta
Numérico de Tempo – semanas a meses	MCG (Modelo de circulação geral)



## 2) Subgrid scale process & Reynolds averaging

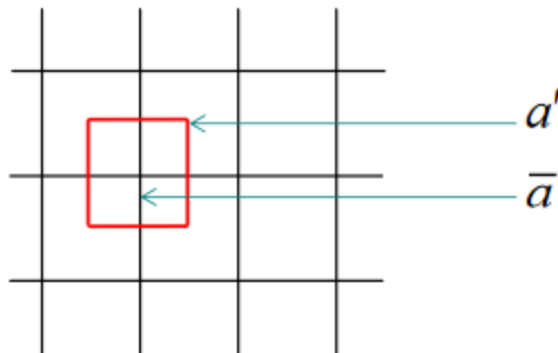
Consider prognostic water vapor equation

$$\frac{\partial \rho q}{\partial t} = -\frac{\partial \rho u q}{\partial x} - \frac{\partial \rho v q}{\partial y} - \frac{\partial \rho w q}{\partial z} + \rho E - \rho C \quad \dots(1)$$

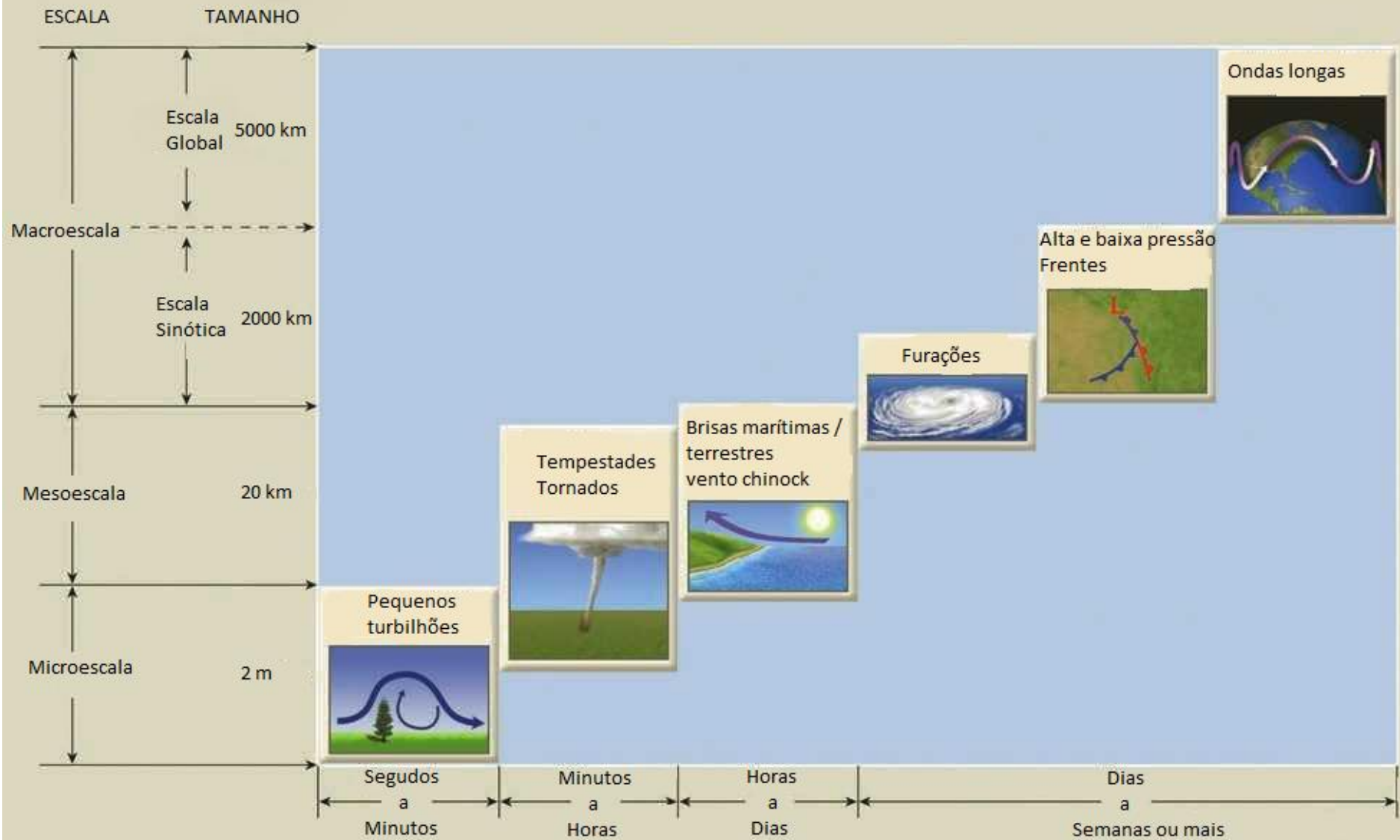
In the real atmosphere,

$$u = \bar{u} + u', \quad q = \bar{q} + q' \quad \left( \begin{array}{l} \text{※} \bar{a} : \text{grid-resolvable} \\ a' : \text{subgrid scale perturbation} \end{array} \right)$$

$\rho'$  is neglected



# Circulação Atmosférica : Escalas Temporal e Espacial



Fonte: Orlanski (1975). Adaptado por Ahrens e Henson (2017).

# ENTÃO QUAL É O PROBLEMA ?

- Domínio de grade grosseira para resolver escoamento de microescala ;
- Problema relacionado a parametrização CLA;
- E quanto à rugosidade do terreno na sub-grade do modelo que não resolve.
- Topografia do terreno

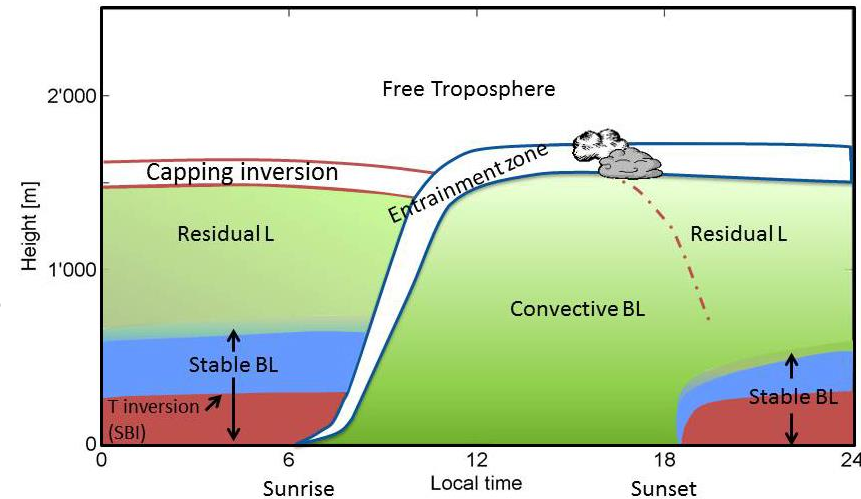


# PROBLEMA COM SIMULAÇÃO DO WRF PARA CAMPO DE VENTO

- O WRF (*Weather Research Forecasting*) geralmente apresenta uma superestimação da velocidade do vento, menos para vento fracos ;
- Não há um contraste térmico sobre o continente e mar;
- Esses problemas são evidentes em praticamente todos os lugares e parece ocorrer em todas as parametrizações da camada limite atmosférica (CLA) disponíveis no modelo WRF.

# O que é Camada Limite Atmosférica (CLA)?

- Camada Inferior da Troposfera;
- Processos turbulentos;
- Altura varia de dezenas de metros (m) a vários quilômetros (km);
- Sujeito a fortes variações diurna;
- Interação com a camada superficial;
- Influências da fricção e fluxos de calor;
- Importante para monitoramento e previsão numérica.



## Tipos CLA:

1. Dia (Convectiva)
2. Noturna (Inversão)

Stull (1988)



# Síntese CLA

- Camada inferior da troposfera influenciada pela superfície;
- Presença de turbilhões oriundos dos efeitos dinâmicos e térmicos;
- Controla o transporte de *momentum*, calor e umidade entre atmosfera livre e a camada superficial;



# Processos da CLA no Modelo Mesoescala WRF-ARW

- Processos turbulentos são pequenos para serem resolvidos para modelos em escala de km;
  - Processos de escala subgrade devem ser parametrizados
- Descrever o meio de transporte vertical turbulento de calor, *momentum* e umidade pelos turbilhões;
  - Duas abordagens comuns são por meio dos esquemas de difusão locais e não locais.
- O modelo WRF-ARW 3.9.1 possui 12 esquemas de parametrizações da CLA.

# Esquemas de parametrização da CLA

- Os fluxos turbulentos usam as equações de difusão da turbulência:

$$\frac{\partial c}{\partial t} = -\frac{\partial}{\partial z} \overline{w'c'} = \frac{\partial}{\partial z} \left[ K_c \left( \frac{\partial c}{\partial z} \right) \right] \quad \text{Penchah et al. 2017}$$

$K_c$  é a difusividade para uma variável escala  $c$  (*momentum* horizontal, temperatura e mistura).

$\overline{w'c'}$  é fluxo turbulento médio vertical da variável escalar

- MYJ (Janjic', 1994), QNSE (Sukoriansky, 2005) e MYNN (Nakanishi e Ninno, 2004)– Esquema de fechamento da energia cinética turbulenta.

$$K_c = l \sqrt{e S_c}$$

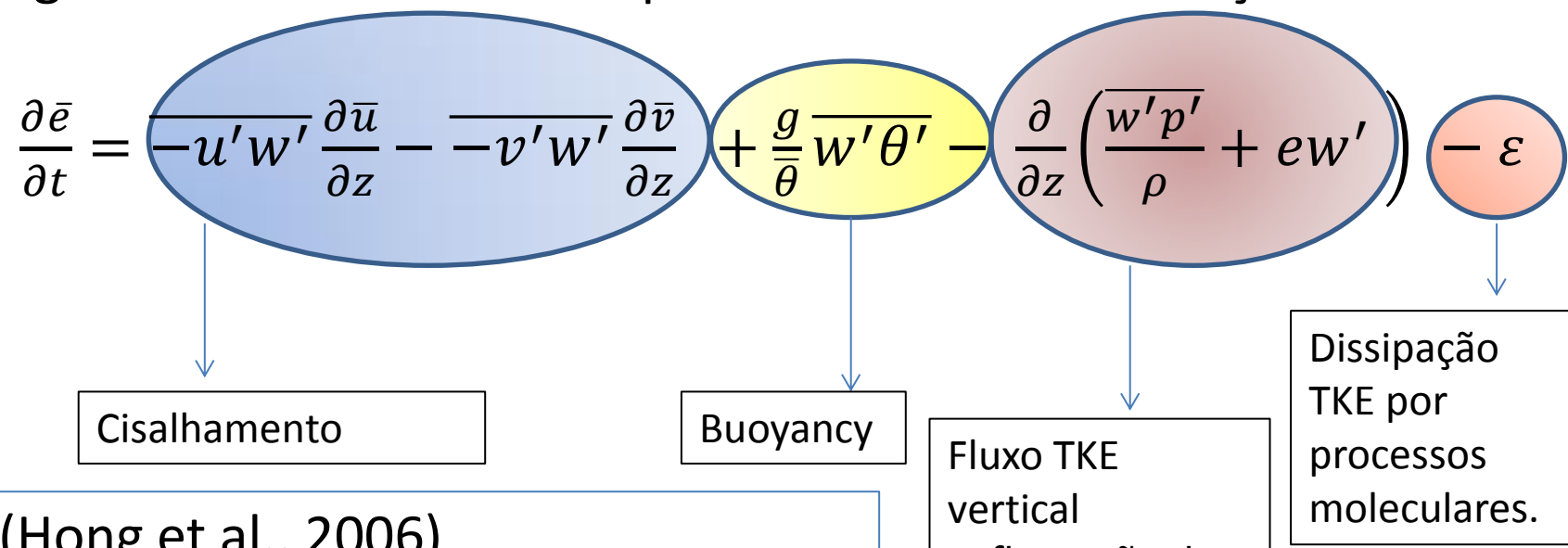
$l$  é comprimento de mistura

$S_c$  é coeficiente proporcional

**Gunwani e Mohan (2017)**

# Esquemas de parametrização da CLA

- A energia cinética turbulenta é prevista utilizando a relação :



- YSU (Hong et al., 2006)

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial z} \left[ K_c \left( \frac{\partial c}{\partial z} - \gamma_c \right) - \overline{(w'c')}_h \left( \frac{z}{h} \right)^3 \right]$$

$h$  é altura da CLA  
 $z$  é altura

$\overline{(w'c')}_h$  é fluxo turbulento vertical.

Hariprasad et al. (2014)

- 1 ordem
- Não Local



# Esquemas de parametrização da CLA

- ACM2

$$\frac{\partial c_i}{\partial t} = f_{conv} M u c_i - f_{conv} M d_i c_i + f_{conv} M d_{i+1} \frac{\Delta z_{i+1}}{\Delta z_i} + \left[ k c (1 - f_{conv}) \frac{\partial c}{\partial} \right]$$

$Mu$  é taxa de mistura convectiva ascendente não local  
 $i$  para  $i - 1$ ,  $\Delta z_{i+1}$  é a espessura da camada  
 $f_{conv}$  é o fator de ponderação que controla o grau do local versus comportamento não local.

- Fechamento da ordem 1.
- Capaz de alternar entre condições estáveis e instáveis.
- Em condições estáveis ou neutra usa o fechamento local em vez de transporte não local.

Gunwani e Mohan (2017)



# Esquemas de parametrização da CLA

- MYJ

Fechamento local da order 1.5, nível 2.5.  
Prognostico TKE  
Altura CLA determinada pelo diagnóstico TKE.

**Gunwani e Mohan (2017)**

$$l_m = l_o \frac{k_z}{k_z + l_o}$$

$k$  é constante von Karman

- MYNN

Fechamento local da ordem 1.5  
Nível 2.56.  
Fechamento TKE

**Penchah et al. 2017**

$$\frac{l}{l_m} = \frac{l}{l_s} + \frac{l}{l_t} + \frac{l}{l_b}$$

$l_s$  é comprimento da camada superficial  
 $l_t$  é comprimento da camada turbulenta  
 $l_b$  é comprimento de *buoyancy* (flutuabilidade)

# Esquemas de parametrização da CLA

- QNSE

- Fechamento local ordem 1.5.
- Predição TKE.
- Fechamento espectral (modelo espectral quase-guassiano).
- Regiões estratificadas estavelmente.

$$l = \frac{l}{l_b^{-1} + l_s^{-1}}$$

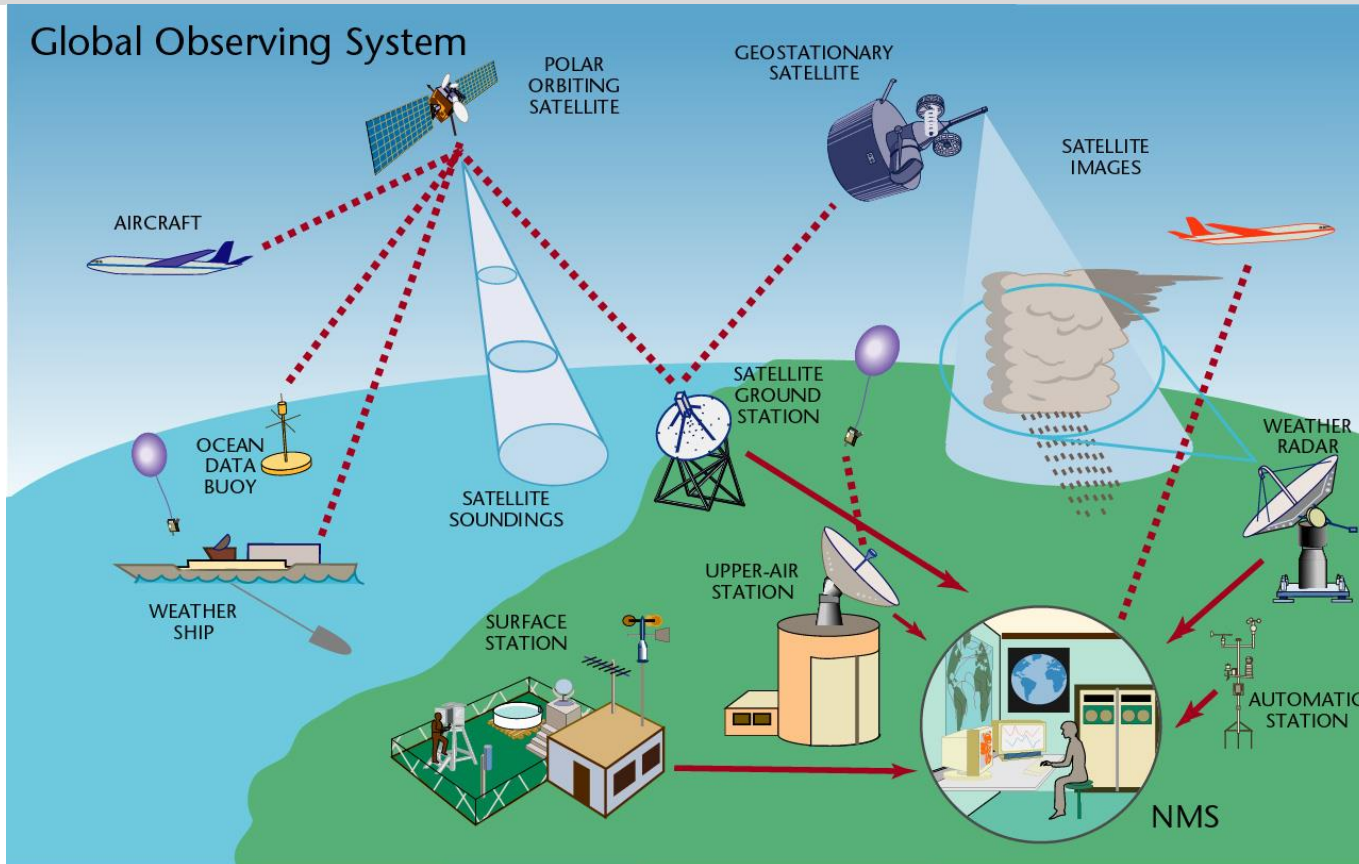
$l_s$  é limitação do comprimento de escala.

$l_b$  é escala Blackadar.

Gunwani e Mohan (2017)


# Condições iniciais e de contorno: Dados de Reanálises e Modelos

- A reanálise é baseada em métodos de análise desenvolvidos para fornecer estados iniciais para previsão numérica de tempo.
- Assimilação de dados observados de vários tipos.




<http://www.wmo.ch/web/www/OSY/GOS.html>


# Estudo de sensibilidade : Estudos científicos



Atmospheric Research  
Volume 194, 15 September 2017, Pages 43–65



## Sensitivity of WRF model estimates to various PBL parameterizations in different climatic zones over India

Preeti Gunwani, Manju Mohan 


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<https://doi.org/10.1016/j.atmosres.2017.04.026>


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### Highlights

- WRF model sensitivity for different PBL schemes – YSU, MYJ, ACM2, QNSE and MYNN
- Model performance evaluated for Tropical, Temperate and Arid Climatic Zones over India.



Atmospheric Research  
journal homepage: [www.elsevier.com/locate/atmosres](http://www.elsevier.com/locate/atmosres)



## Sensitivity analysis of WRF model PBL schemes in simulating boundary-layer variables in southern Italy: An experimental campaign

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### ARTICLE INFO

**Keywords:**  
WRF model  
Planetary boundary layer (PBL)  
PBL parameterization schemes  
Experimental campaign  
Wind lidar


### ABSTRACT

The sensitivity of boundary layer variables to five (two non-local and three local) planetary boundary-layer (PBL) parameterization schemes, available in the Weather Research and Forecasting (WRF) mesoscale meteorological model, is evaluated in an experimental site in Calabria region (southern Italy), in an area characterized by a complex orography near the sea. Results of 1 km × 1 km grid spacing simulations are compared with the data collected during a measurement campaign in summer 2009, considering hourly model outputs.

Measurements from several instruments are taken into account for the performance evaluation: near surface variables (2 m temperature and relative humidity, downward shortwave radiation, 10 m wind speed and direction) from a surface station and a meteorological mast; vertical wind profiles from Lidar and Sodar; also, the aerosol backscattering from a ceilometer to estimate the PBL height.



Atmospheric Research  
journal homepage: [www.elsevier.com/locate/atmos](http://www.elsevier.com/locate/atmos)



## Numerical simulation and intercomparison of boundary layer structure with different PBL schemes in WRF using experimental observations at a tropical site

K.B.R.R. Hariprasad<sup>a</sup>, C.V. Srinivas<sup>a,\*</sup>, A.Bagavath Singh<sup>a</sup>, S. Vijaya Bhaskara Rao<sup>b</sup>, R. Baskaran<sup>a</sup>, B. Venkatraman<sup>a</sup>

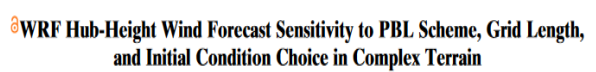
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### ABSTRACT

In this study the performance of seven PBL parameterizations in the Weather Research and Forecast (WRF-ARW) mesoscale model was tested at the tropical site Kalpakkam. Meteorological observations collected during an intense observation campaign for wind field modeling called Round Robin Exercise (RRE) were used for comparison. High resolution simulations were conducted for a warm summer condition on 22–24 September 2010. The observations included GPS Sodar vertical profiles, surface level data from meteorological towers and turbulent fluxes




DAVID SIUTA, GREGORY WEST, AND ROLAND STULL

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(Manuscript received 23 June 2016, in final form 9 December 2016)

### ABSTRACT

This study evaluates the sensitivity of wind turbine hub-height wind speed forecasts to the planetary boundary layer (PBL) scheme, grid length, and initial condition selection in the Weather Research and Forecasting (WRF) Model over complex terrain. Eight PBL schemes available for the WRF-ARW dynamical core were tested with initial conditions sources from the North American Mesoscale (NAM) model and Global Forecast System (GFS) to produce short-term wind speed forecasts. The largest improvements in forecast accuracy primarily depended on the grid length or PBL scheme choice, although the most important factor varied by location, season, time of day, and bias-correction application. Aggregated over all locations, the Asymmetric Convective Model, version 2 (ACM2) PBL scheme provided the best forecast accuracy, particularly for the 12-km grid length. Other PBL schemes and grid lengths, however, did perform better than the ACM2 scheme for individual seasons or locations.



Applied Energy  
journal homepage: [www.elsevier.com/locate/apenergy](http://www.elsevier.com/locate/apenergy)



## Sensitivity of the WRF model wind simulation and wind energy production estimates to planetary boundary layer parameterizations for onshore and offshore areas in the Iberian Peninsula

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### HIGHLIGHTS

- WRF model near surface wind simulation sensitivity to different PBL and SL parameterizations was assessed.
- Simulations were evaluated using onshore and offshore measured data in the Iberian Peninsula.
- ACM2-PX PBL-SL schemes provided the best overall results in terms of wind and wind energy flux simulation.
- QNSE-QNSE PBL-SL schemes presented the best energy flux estimates for offshore areas.
- This study provides valuable guidelines for future offshore and onshore wind energy assessment applications.

### ARTICLE INFO

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Accepted 20 August 2014

### ABSTRACT

This work aims to assess the Weather and Research Forecasting (WRF) model wind simulation and wind energy production estimates sensitivity to different planetary boundary layer parameterization schemes. Five WRF simulations considering different sets of planetary boundary layer (PBL) and surface layer (SL) parameterization schemes were performed, and their results compared to measured wind data collected



# Estudo de sensibilidade : Condições iniciais e de contorno

Parâmetro / Dados	ERA-INTERIM	CFSR/CFSv2	FNL	GFS*
Níveis verticais	60	64	27 (pressão)	27 (pressão)
Resolução Horizontal	~80km	~55 km	~110 km	~27 km
Resolução Temporal	6-horas	1-hora	6-horas	1-hora
Tipo de grade espacial	Gaussiana	Gaussiana	Gaussiana	Gaussiana
Modelo assimilação	IFS Cycle 31r2	Interpolação estatística ponto-grade	Interpolação estatística ponto-grade	Interpolação estatística ponto-grade
Período	1979-presente	CFSR:1979-2010 CFSv2: 2011-presente	1999-present	2015-presente

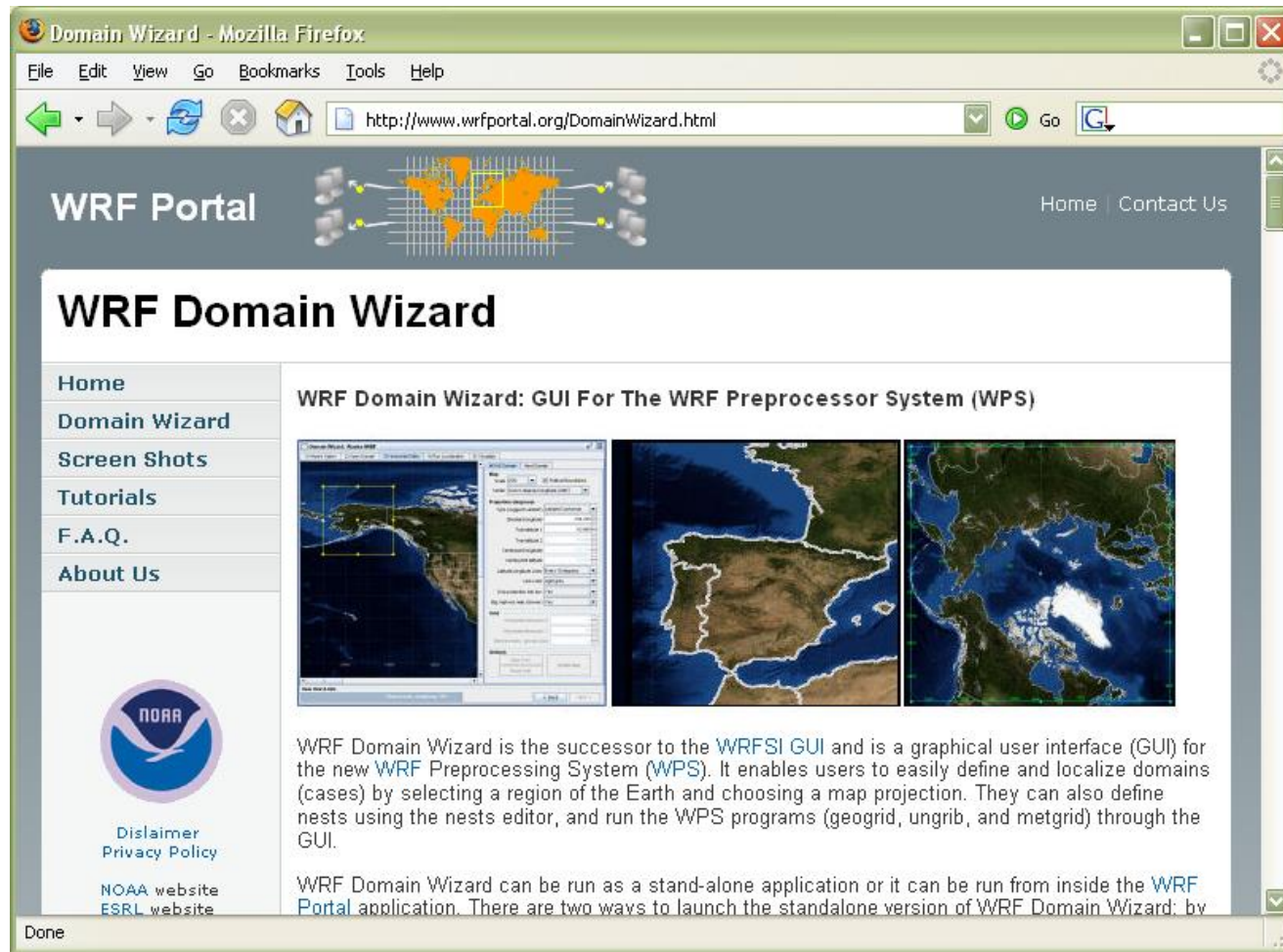
**Fonte:** rda.ucar.edu

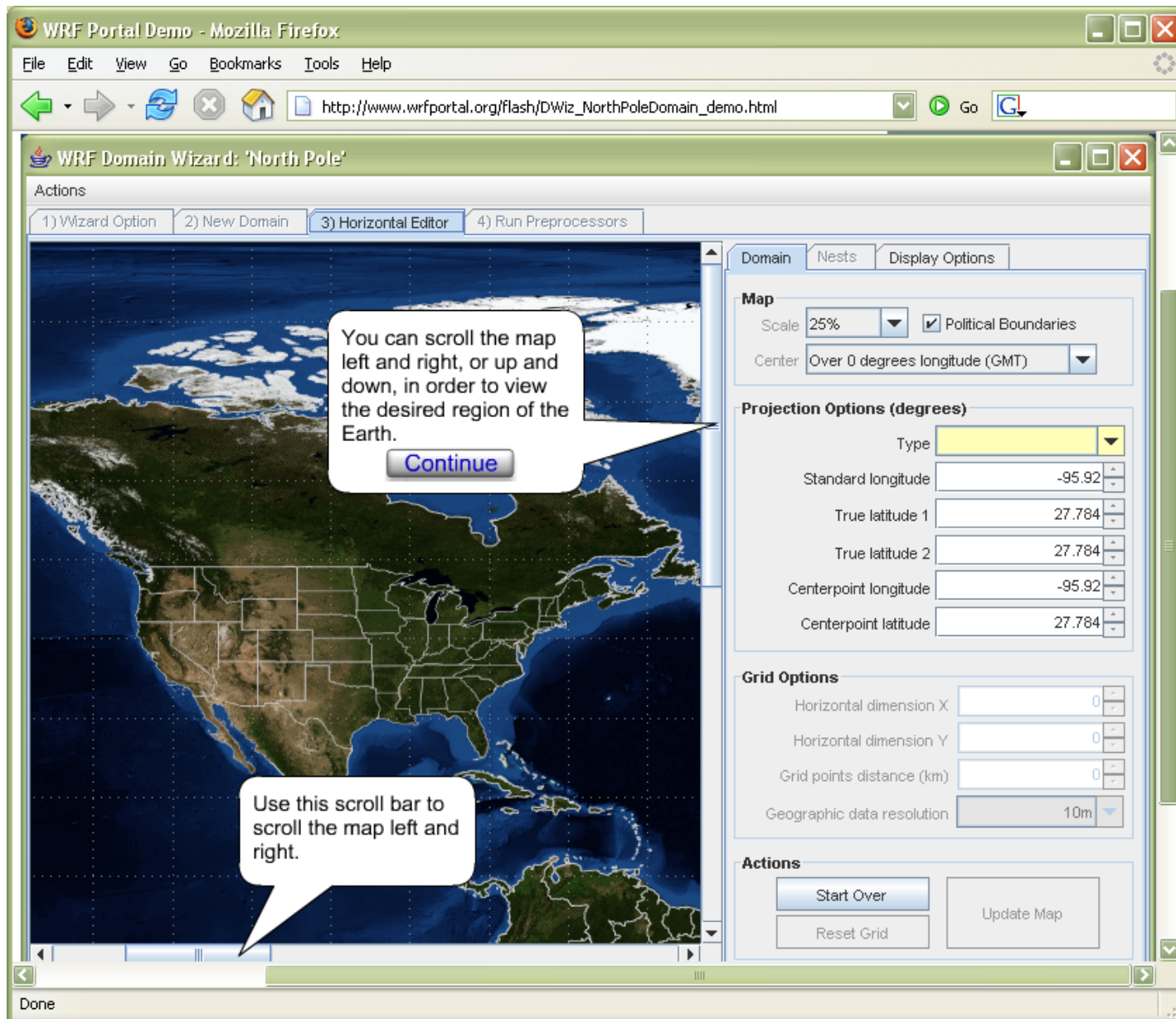




# Estudo de sensibilidade : Domínio de Grade

<http://www.wrfportal.org/DomainWizard.html>





WRF Portal Demo - Mozilla Firefox

File Edit View Go Bookmarks Tools Help

http://www.wrfportal.org/flash/DWiz\_OpenDomainCreateNests\_demo.ht

WRF Domain Wizard: 'Alaska'

Actions

1) Wizard Option 2) Open Domain 3) Horizontal Editor 4) Run Preprocessors

Domain Nests Display Options

**Nested Domain Properties**

ID	PID	Ratio	Left	Right	Top	Bot	NX	NY	Res
1	1	1	1	101	124	1	100	123	10m
2	1	3	6	51	63	6	135	171	5m

Your child nest also appears here, in the list. Note that this nest is named (2)

The child nest you have defined appears on the map. You can resize or move it by clicking on the rectangle (or box).

Continue

New Edit Delete Clear

Done

# Estudo de sensibilidade : Domínio de Grade

- 15km: 100x86 pontos de grade.
- 5km: 88x76 pontos de grade.
- 1.666km: 76x64 pontos de grade.
- 0.555km: 64x52 pontos de grade.

# Estudo de sensibilidade : Parametrizações da CLA no modelo WRF

Opção Física	Camada Limite Superficial	CLA
Simulação 1	MM5	YSU
Simulação 2	ETA	MYJ
Simulação 3	Pleim-Xiu	ACM2
Simulação 4	MYNN	MYNN 2.5
Simulação 5	QNSE	QNSE



# Estudo de sensibilidade : Configuração do modelo WRF

Modelo	WRF-ARW V3.9.1.1
Dinâmica	Equações primitivas, não hidrostático, totalmente compreensível, coordenada sigma-eta.
Resolução vertical	50 níveis.
Radiação	Dudhia para radiação de onda curta e RRTM para radiação de onda longa.
Superfície do Solo	NOAH.
Microfísica	WSM6.
Convecção cumulus	Kain-Fritsch.
Período de Simulação	55 horas

**Parametrização:** Tymvios et al. (2017); Avolio et al. (2017); Penchah et al. (2017); Santos et al. (2016).

# Estudo de sensibilidade : Níveis do Modelo WRF

NÍVEL	ETA	ALTURA	dZ
1	1	0	
2	0.9985	12.0	12
3	0.997	24.1	12.1
4	0.995	40.1	16.0
5	0.993	56.2	16.1
6	0.991	72.4	16.1
7	0.988	96.6	24.2
8	0.985	120.9	24.3
9	0.98	161.5	40.6
10	0.97	243.2	81.7
11	0.96	325.6	82.4
12	0.95	408.6	83.0
13	0.94	492.3	83.7
14	0.93	576.6	84.4
15	0.91	747.5	170.9
16	0.89	921.2	173.8
17	0.87	1098.0	176.8
18	0.84	1369.1	271.1



# Estudo de sensibilidade : Spin-up do modelo WRF

Legenda:

—

 Observado

—

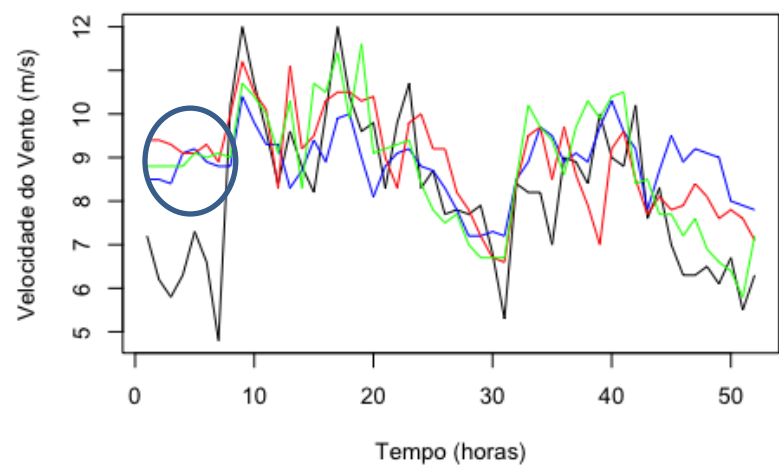
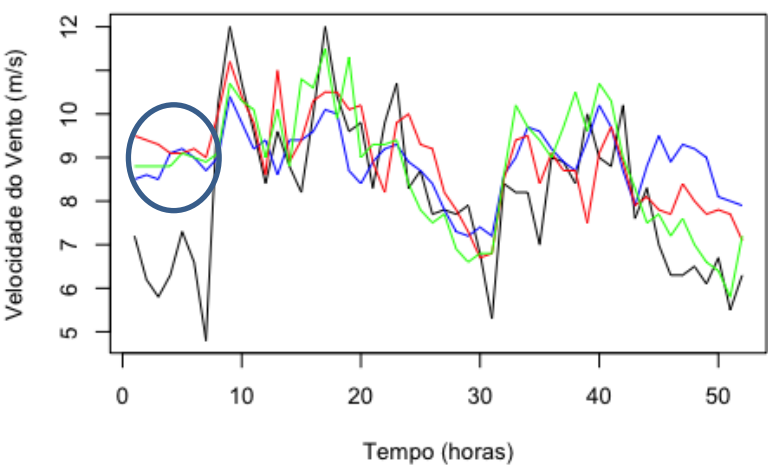
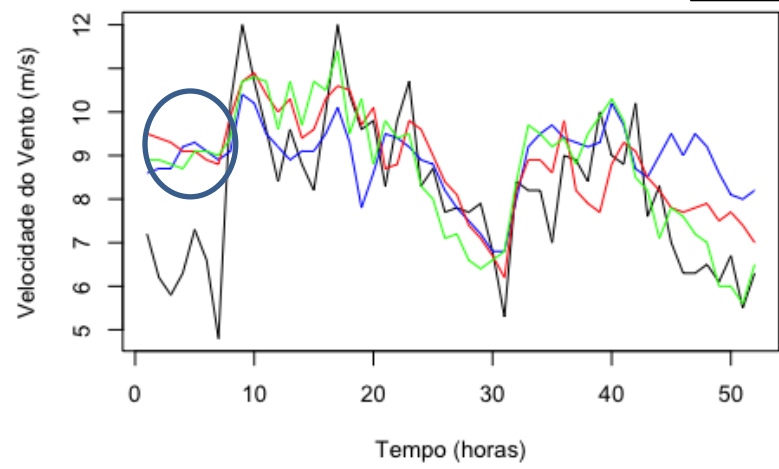
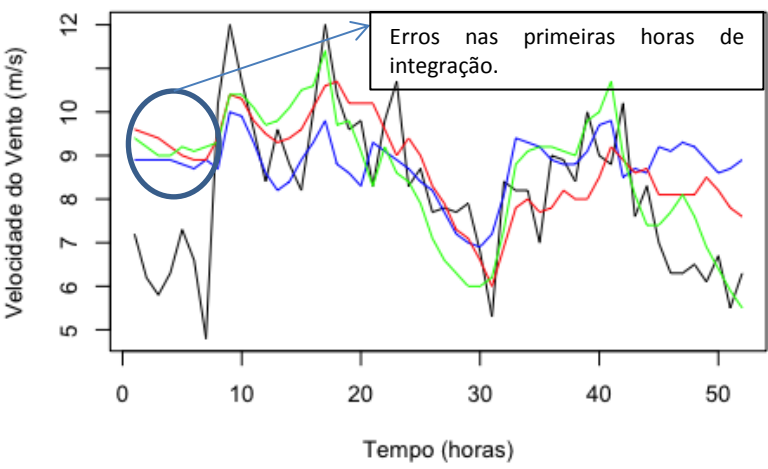
 WRF-CFSv2

—

 WRF-ERAJNTERIM

—

 WRF-GFS



# Variabilidade sazonal da velocidade do vento

Hindawi Publishing Corporation  
The Scientific World Journal  
Volume 2013, Article ID 490857, 10 pages  
<http://dx.doi.org/10.1155/2013/490857>



## Research Article

### Seasonality, Interannual Variability, and Linear Tendency of Wind Speeds in the Northeast Brazil from 1986 to 2011

Alexandre Torres Silva dos Santos<sup>1,2</sup> and Cláudio Moisés Santos e Silva<sup>3</sup>

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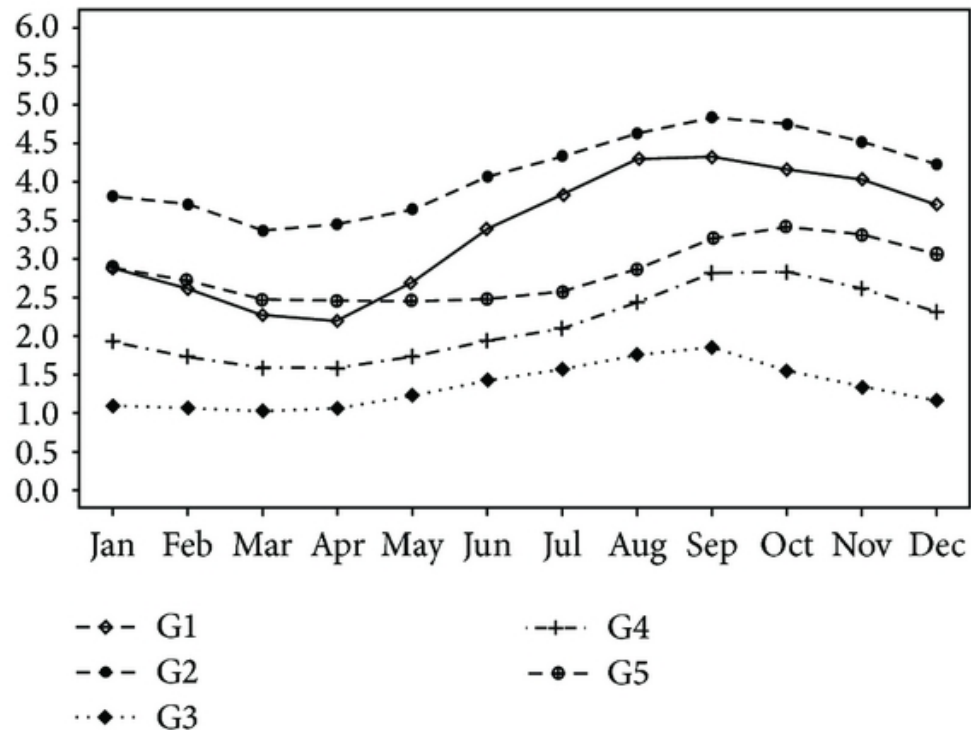
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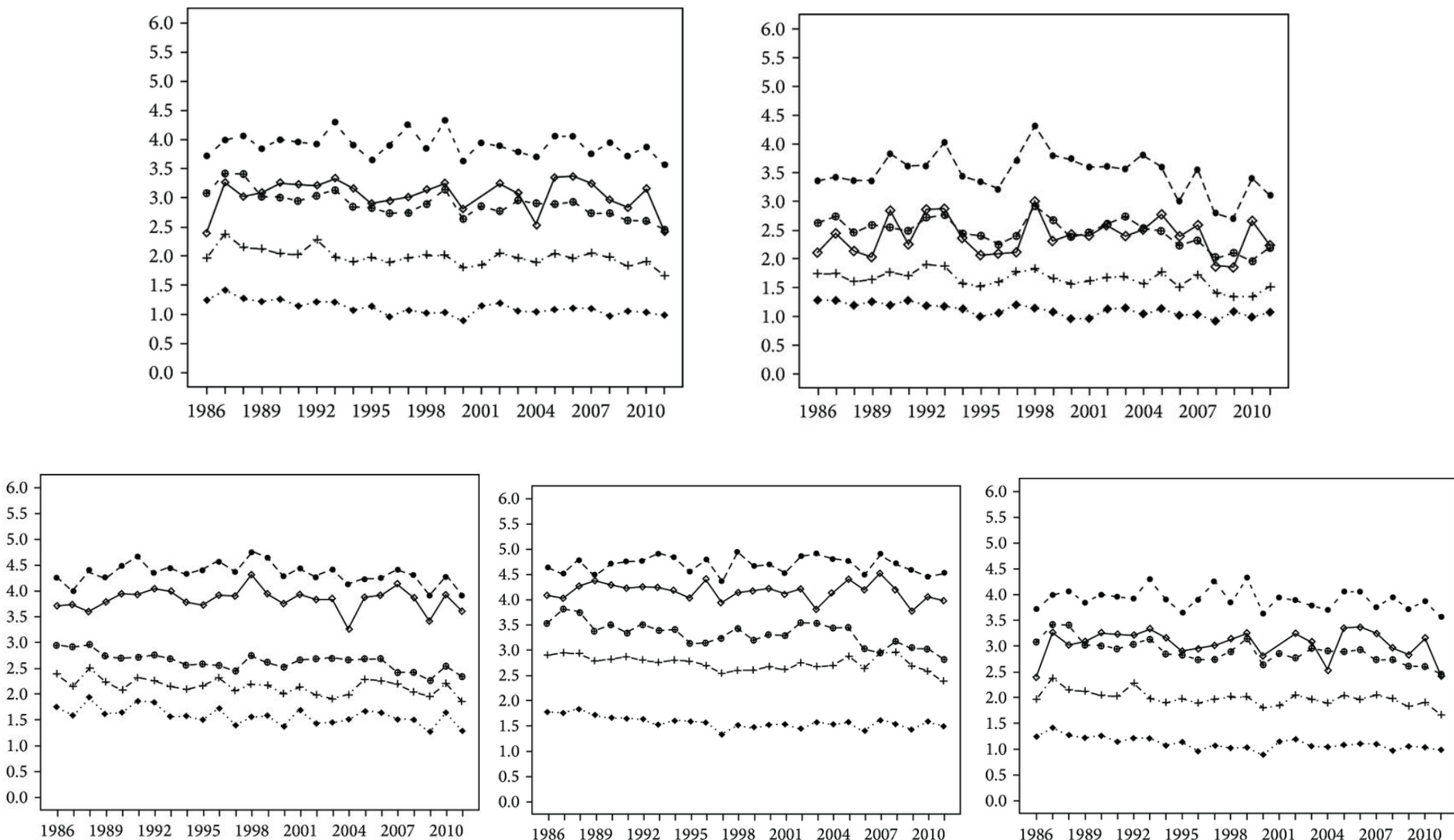


Média mensal da velocidade do vento para análise em grupo no período de 1986 a 2011 no Nordeste Brasileiros.

Santos e Silva e Santos (2013)



# Variabilidade Interanual e sazonal da velocidade do vento



Santos e Silva e Santos (2013)



## Review

# Assessment of wind resources in two parts of Northeast Brazil with the use of numerical models

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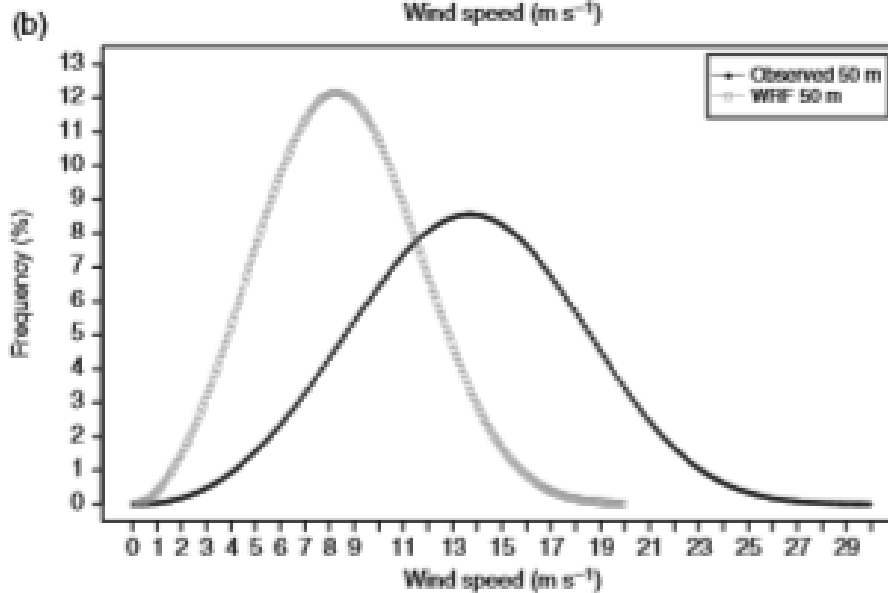
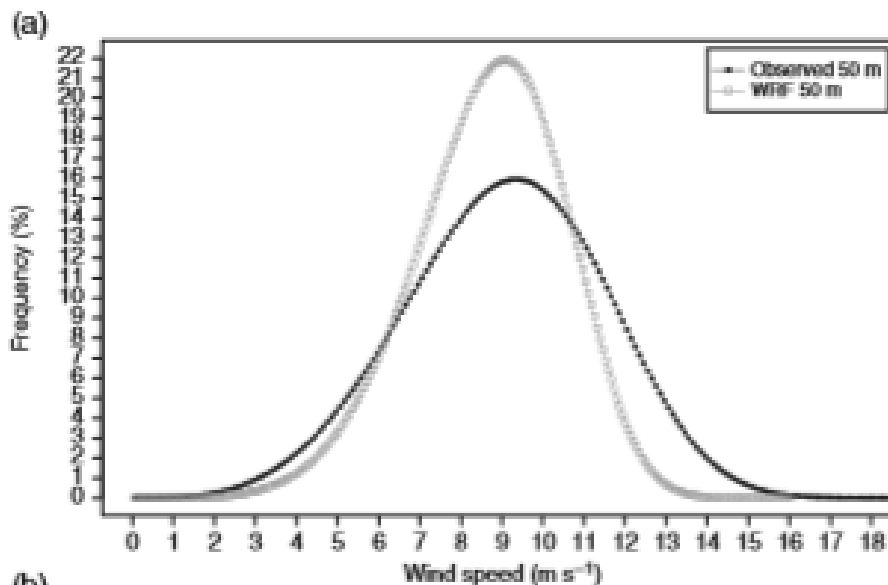
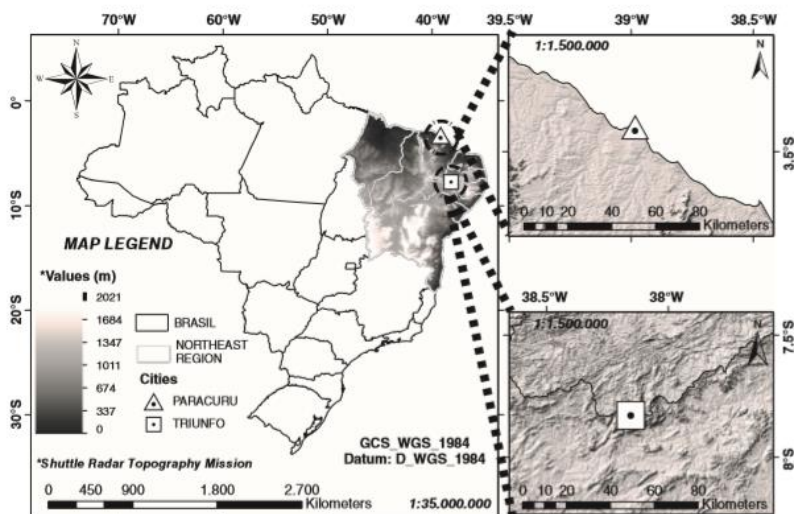
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**ABSTRACT:** A study was conducted to quantify the wind resources in two locations (municipalities of Paracuru and Triunfo) with different topographical conditions (flat and complex) in the Northeast Region of Brazil (NEB). To this end, data collected *in situ* with anemometer towers and a simulation of the mesoscale numerical Weather Research and Forecasting (WRF) model were used. These served as initial conditions for simulations of the microscale numerical model from the Wind Atlas Analysis and Application Program (WASP). The WASP model enabled estimation of the annual wind potential and its power density, parameters of the Weibull probability density function (an estimate of the mean annual power density and wind potential), were used to compare the simulations and the observations. The results show that both locations, Paracuru and Triunfo, have a favourable annual wind potential for the implementation of wind farm projects. The power density estimated through measured and simulated data exceeded  $400 \text{ W m}^{-2}$  at heights of 60 and 50 m above the ground.

**KEY WORDS** WRF; WASP; wind speed

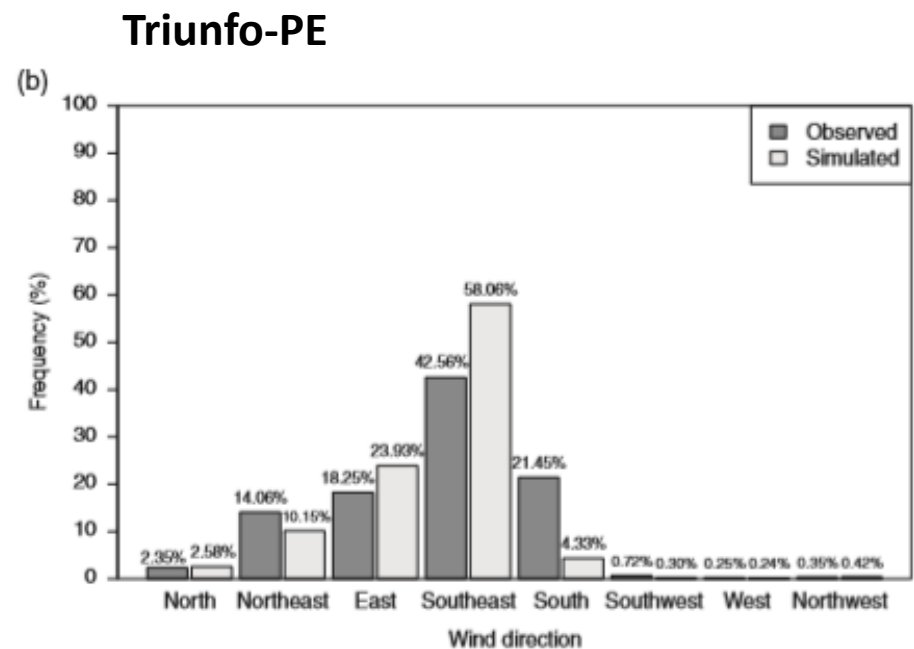
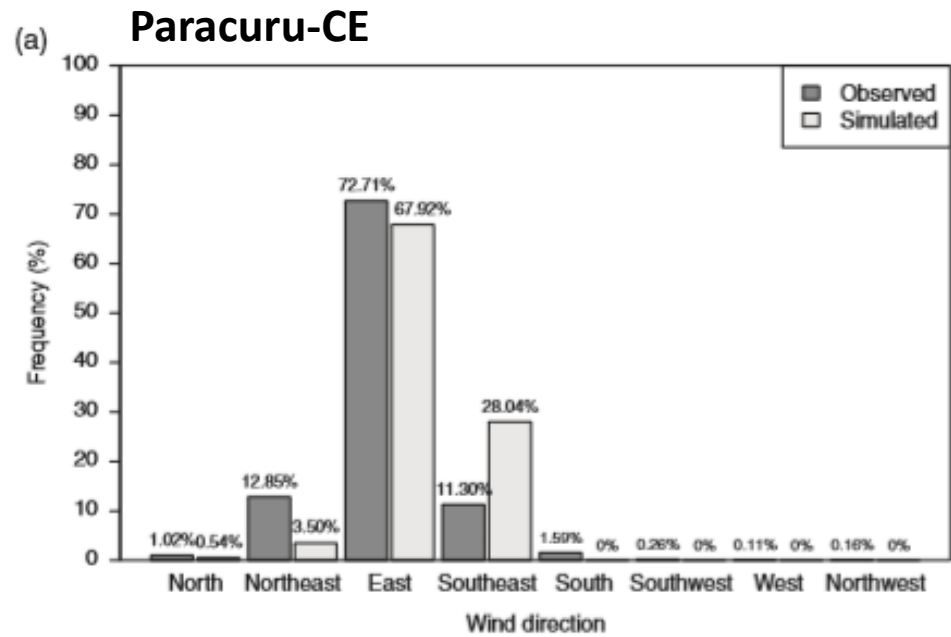
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Wind resources in two parts of Northeast Brazil



Santos et al. 2016

# Direção do Vento : WRF-ARW 5kmx5km

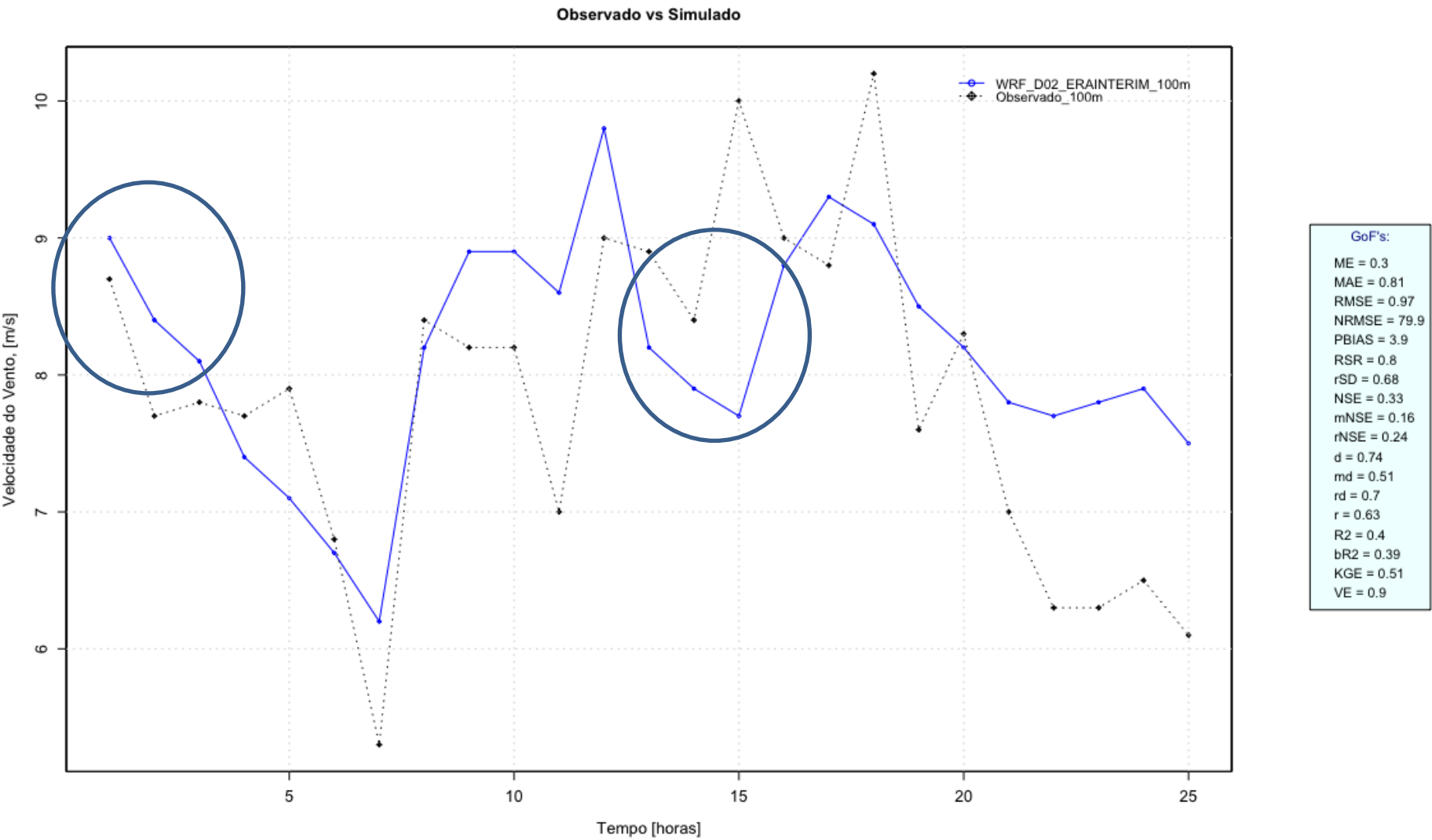


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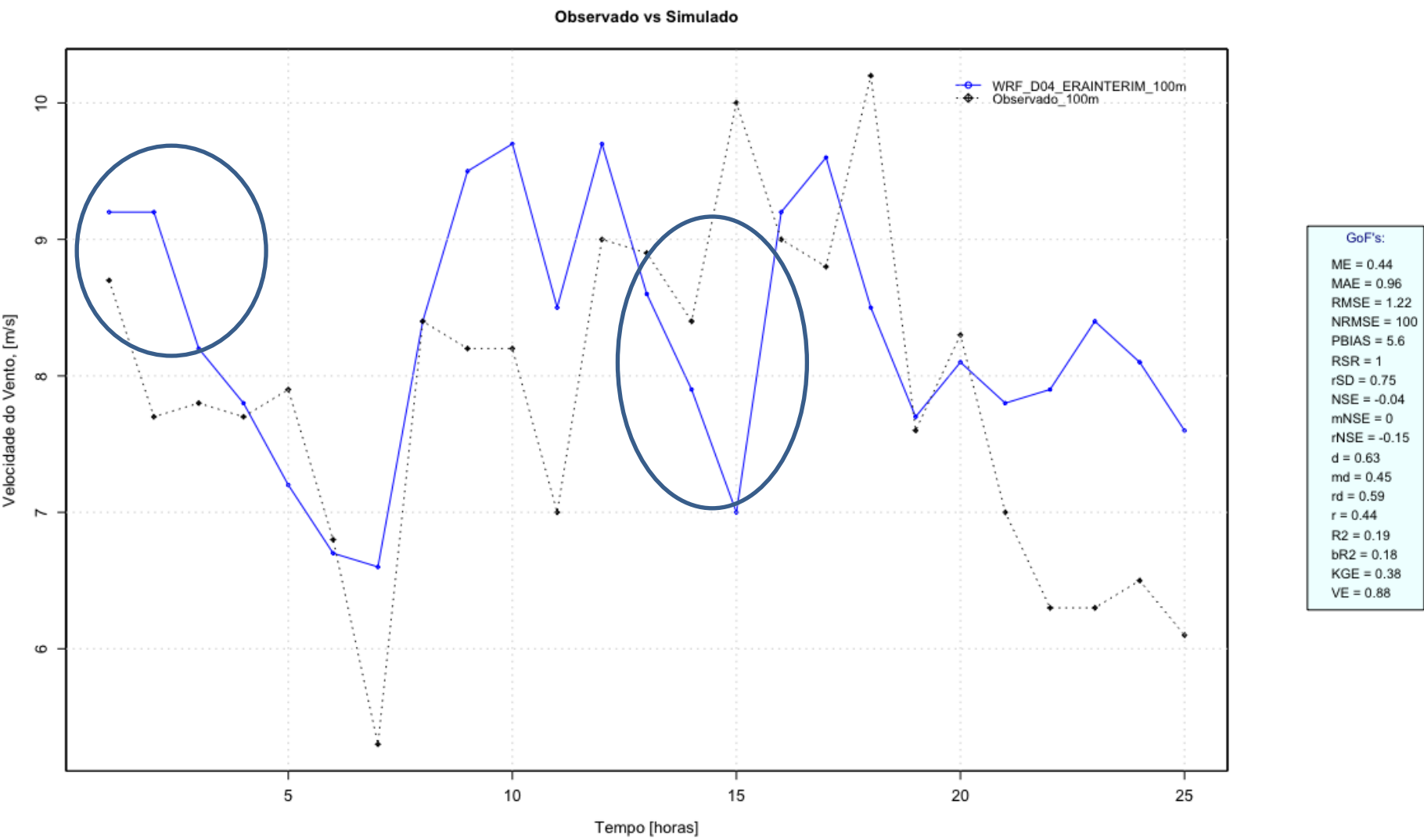




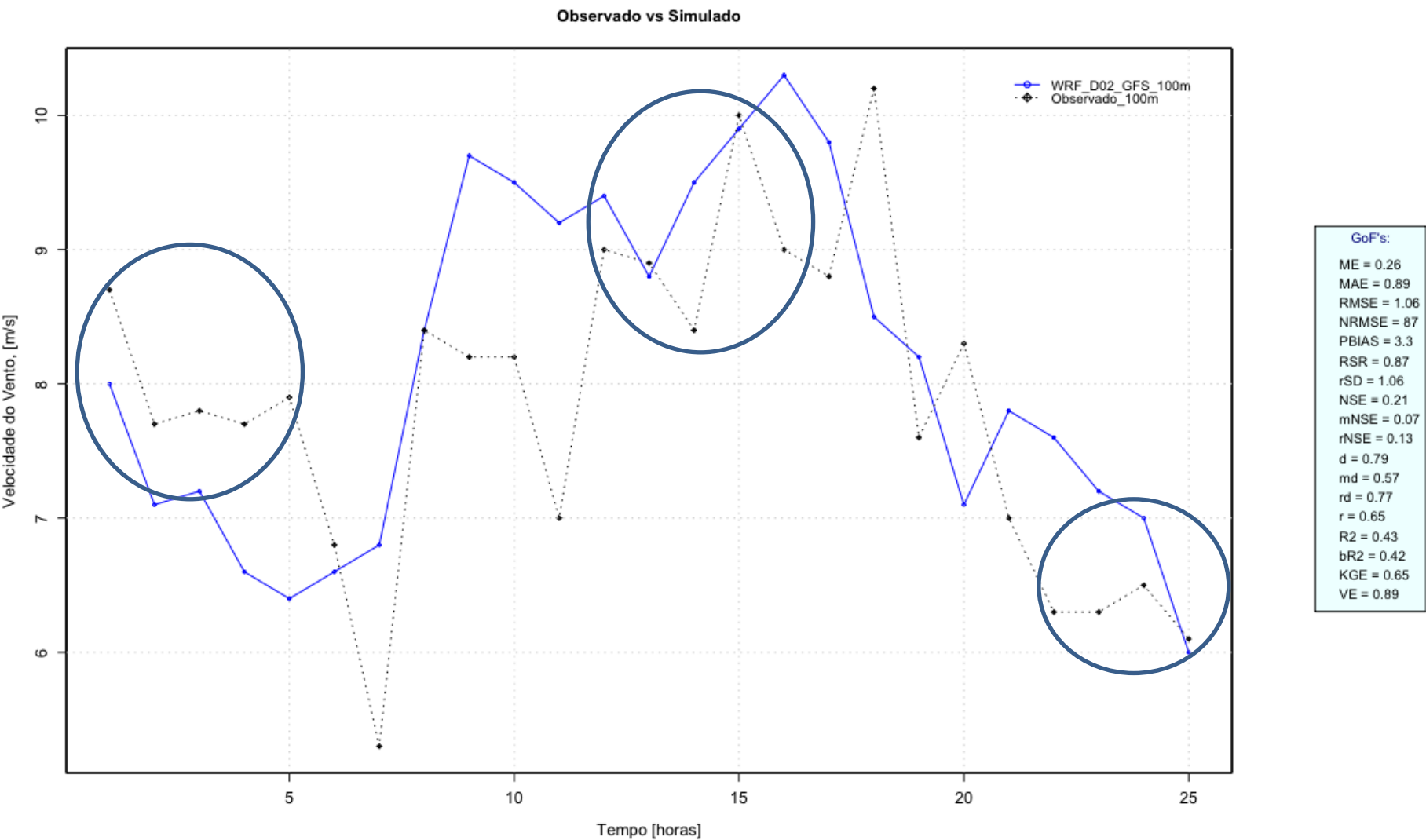
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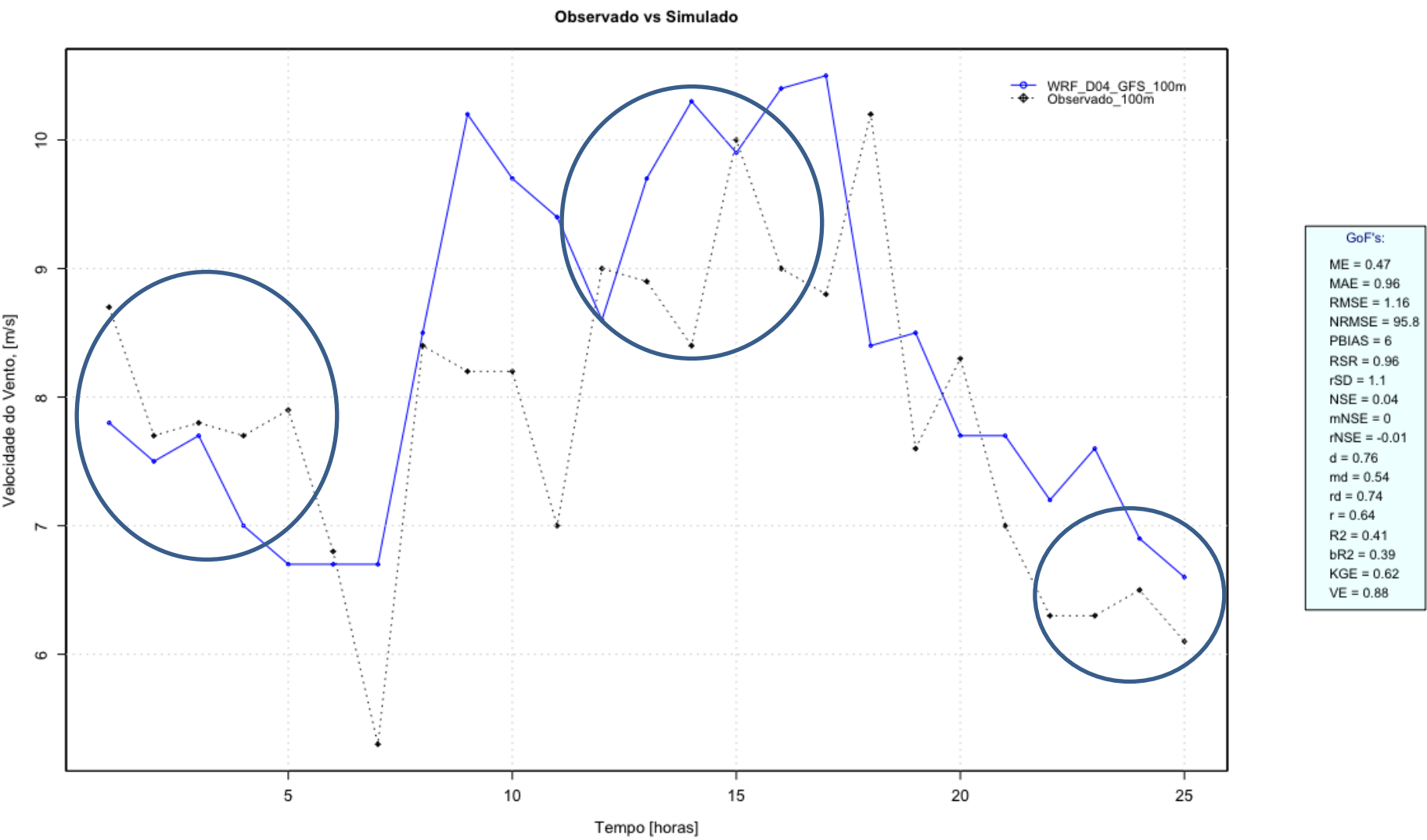
# Estudo de sensibilidade : Domínio de Grade



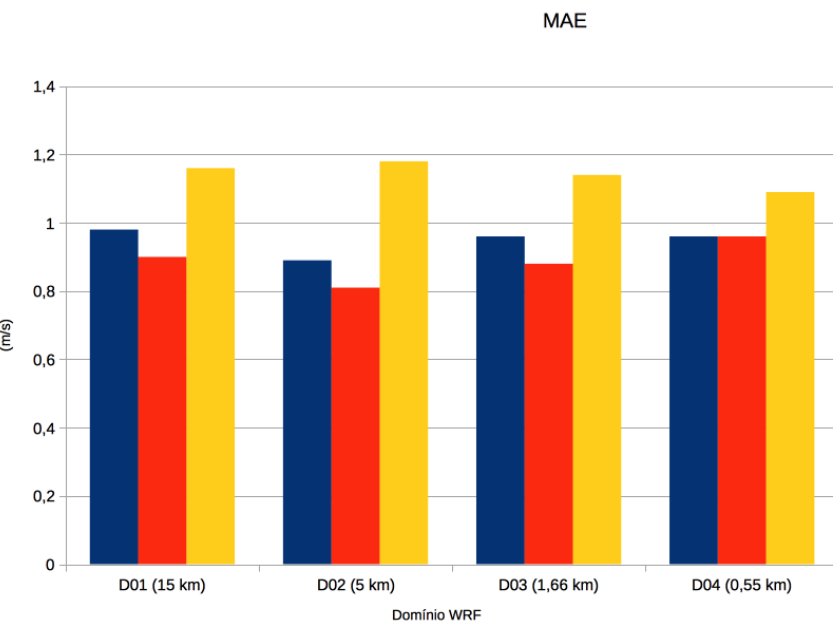
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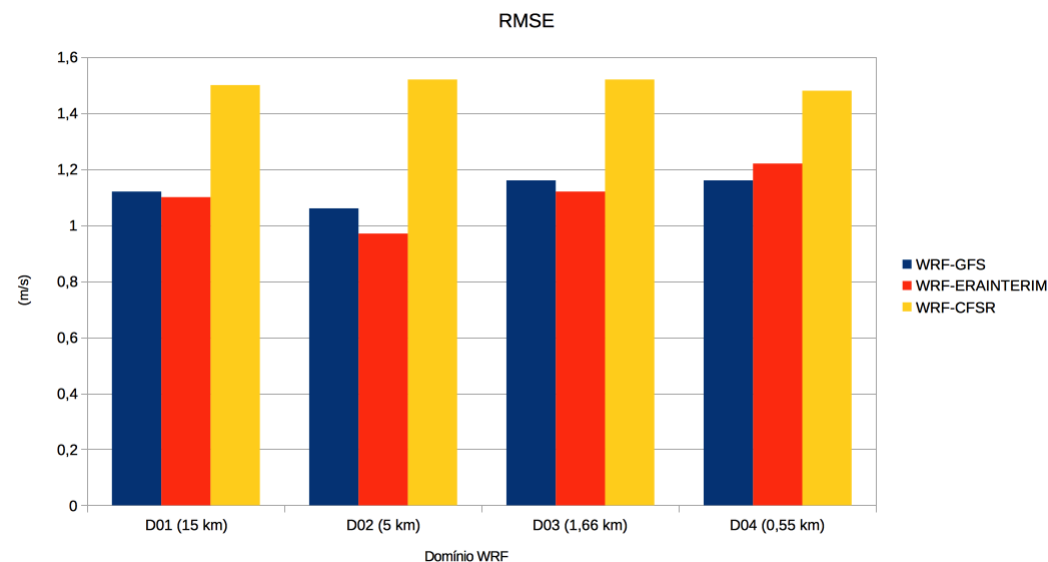
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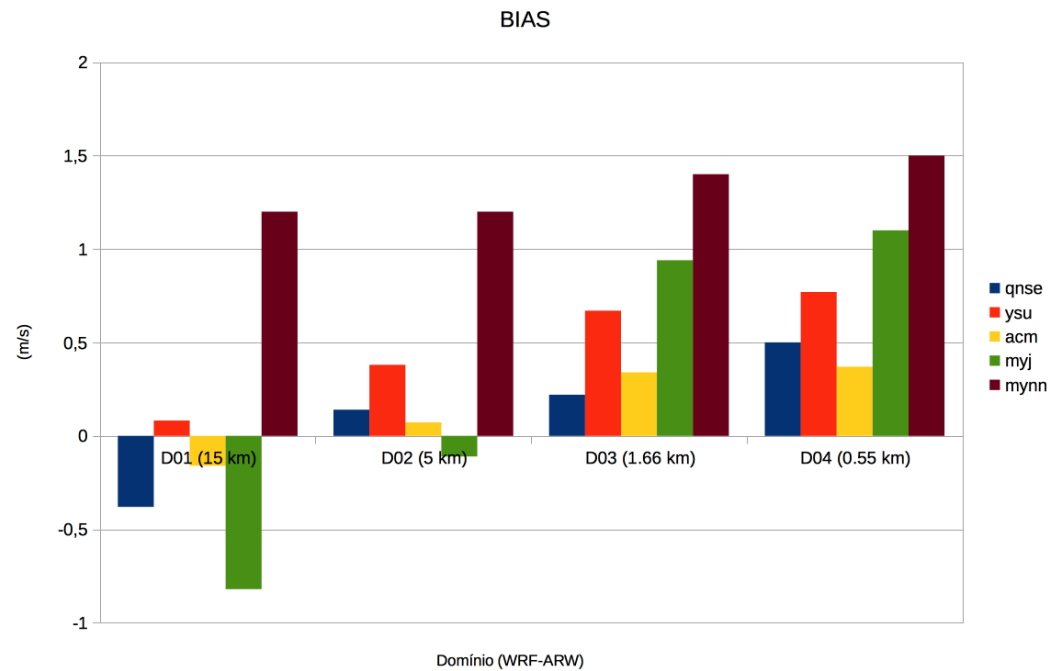
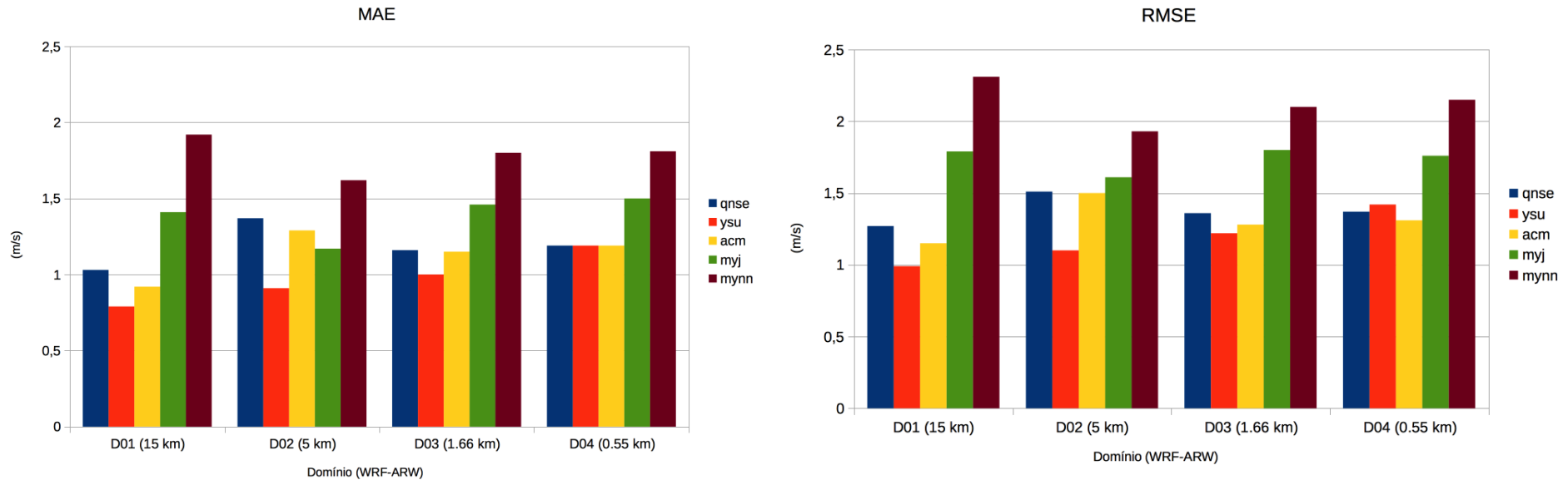
# Estudo de sensibilidade : Erro por Domínio de Grade



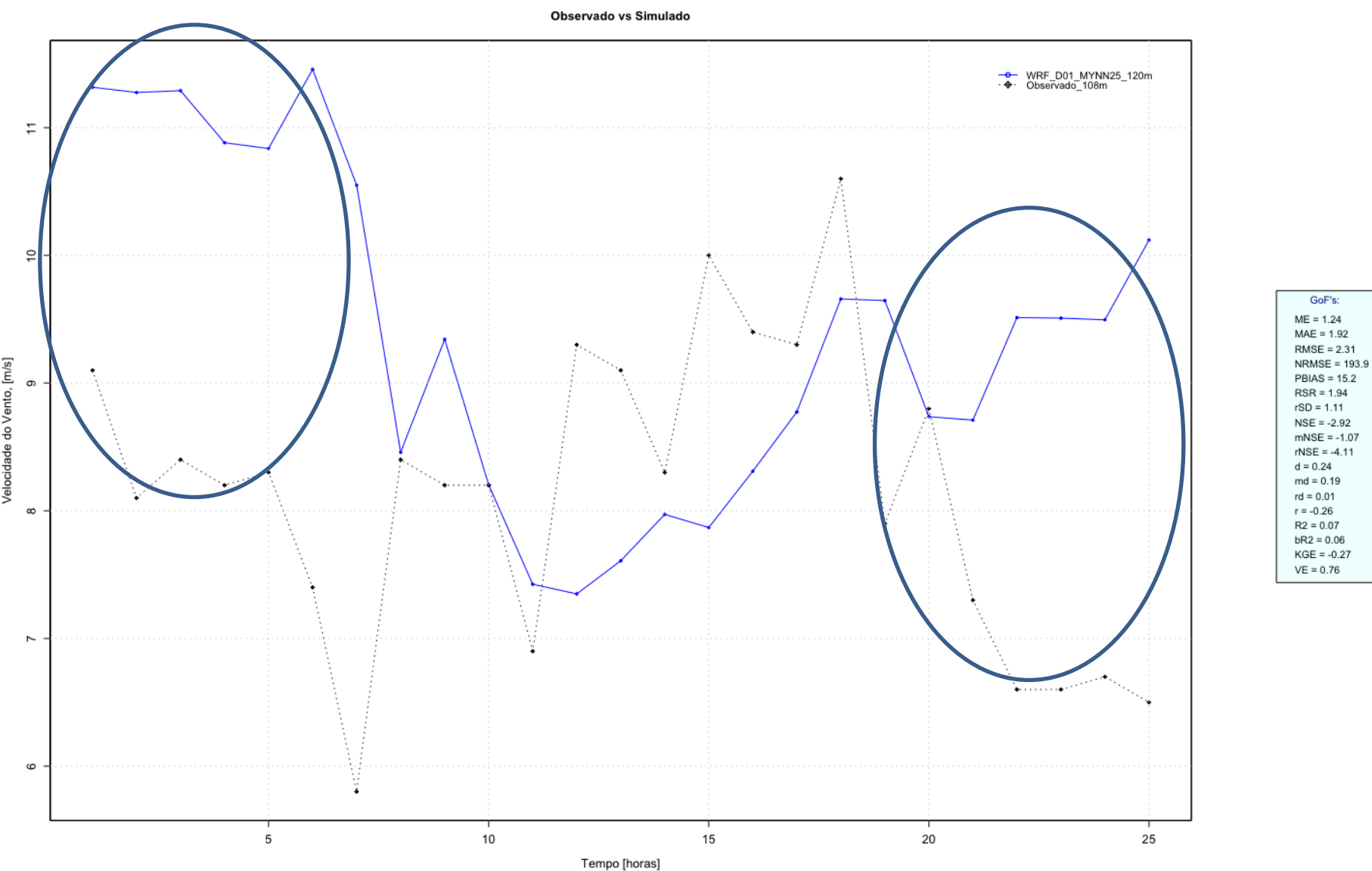
- Bias positivo : erro médio de 0.18 m/s;
- Menores erros: WRF-ERAINTERIM e GFS;
- Domínio 2 com menores erros.



# Erro : Parametrização CLA

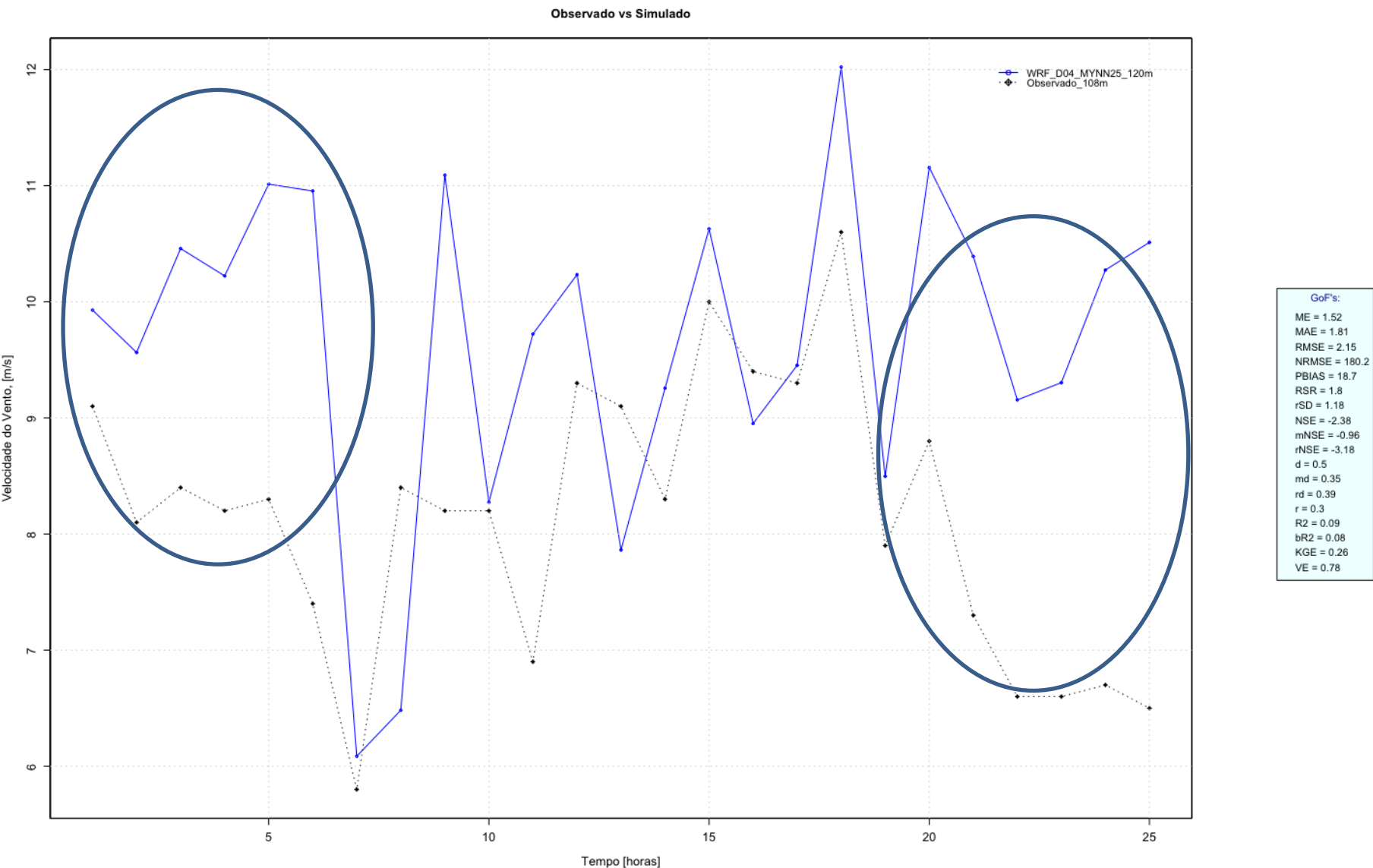


# Estudo de sensibilidade : Parametrização CLP

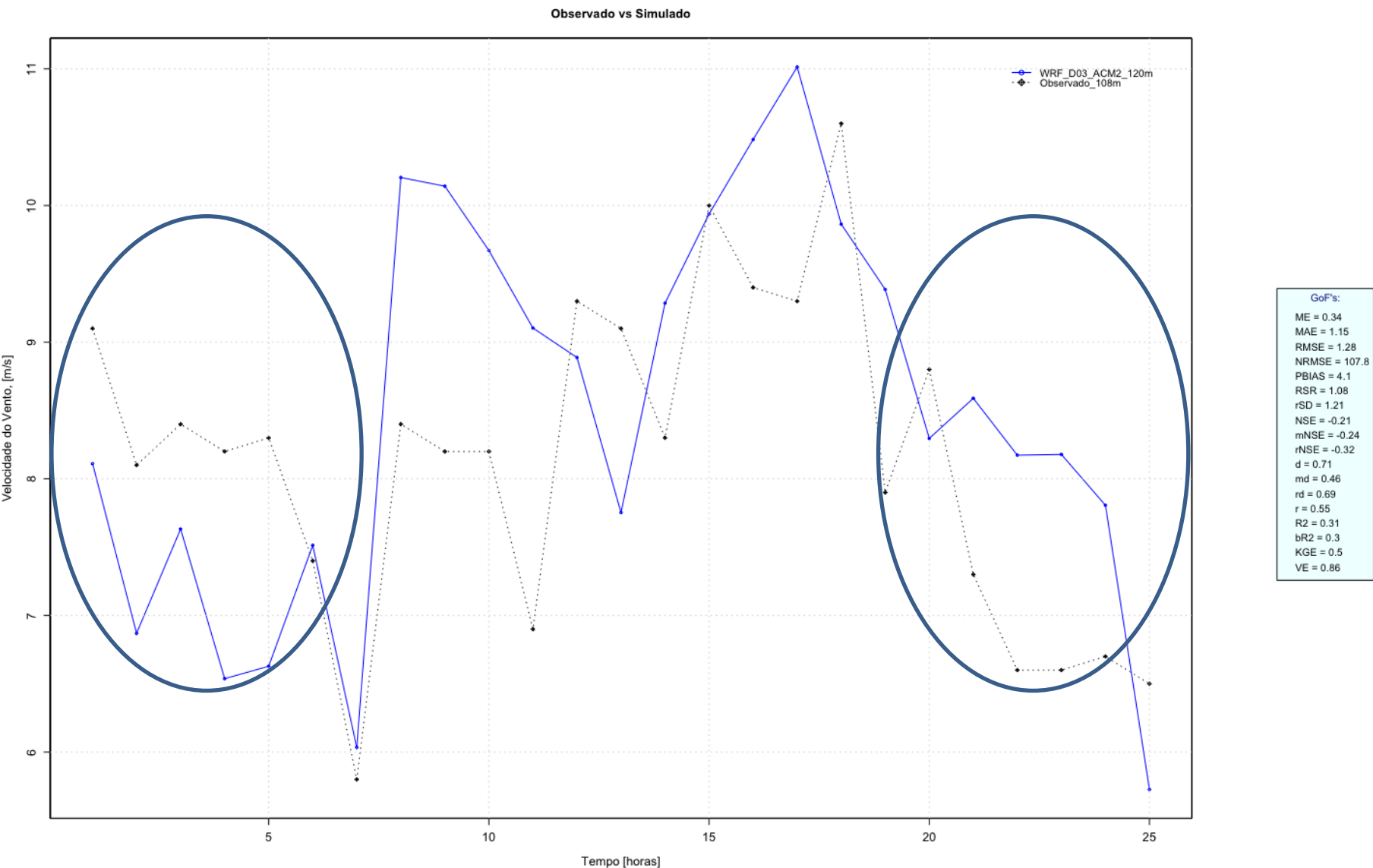




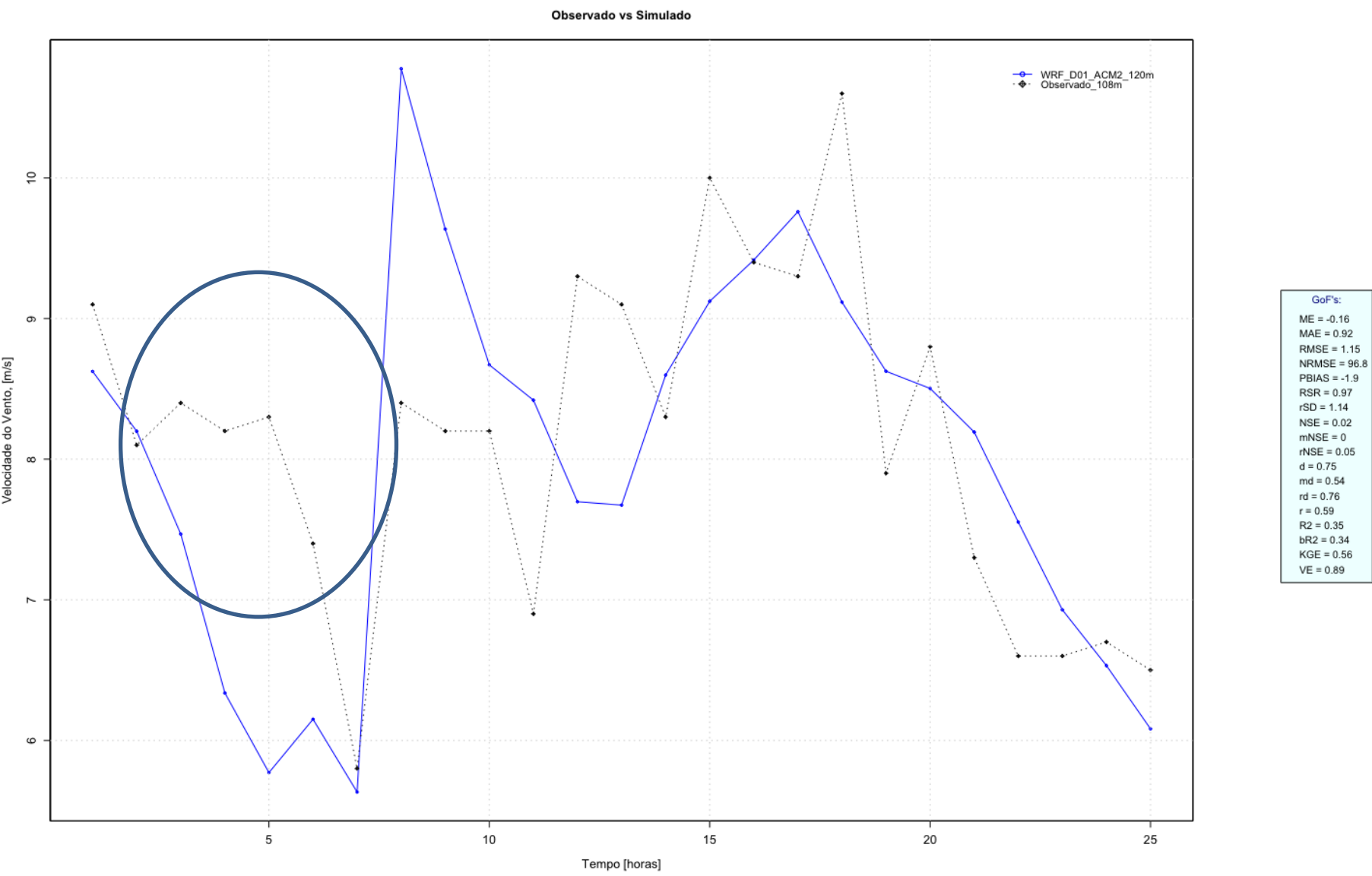
# Estudo de sensibilidade : Parametrização CLP



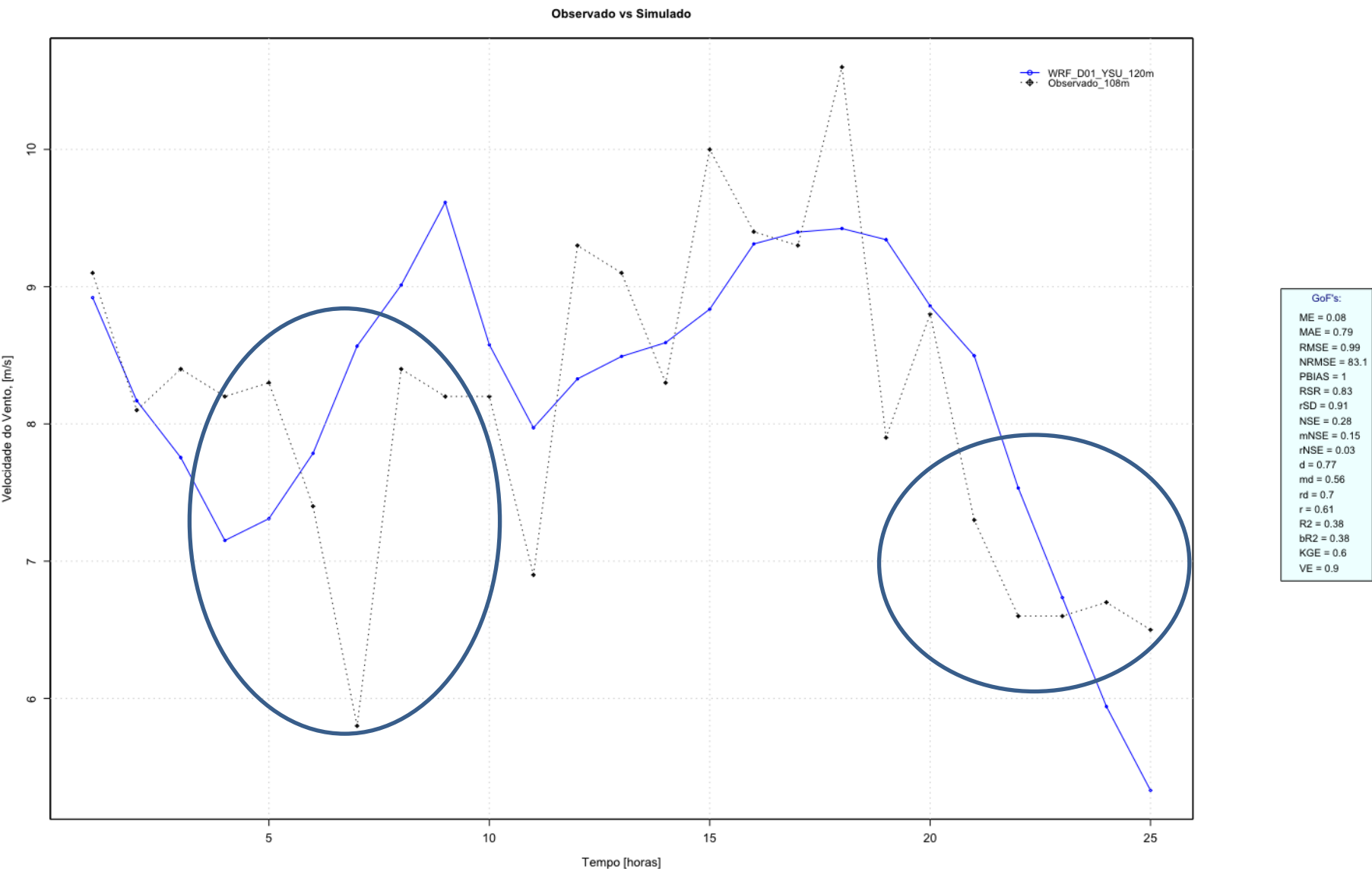
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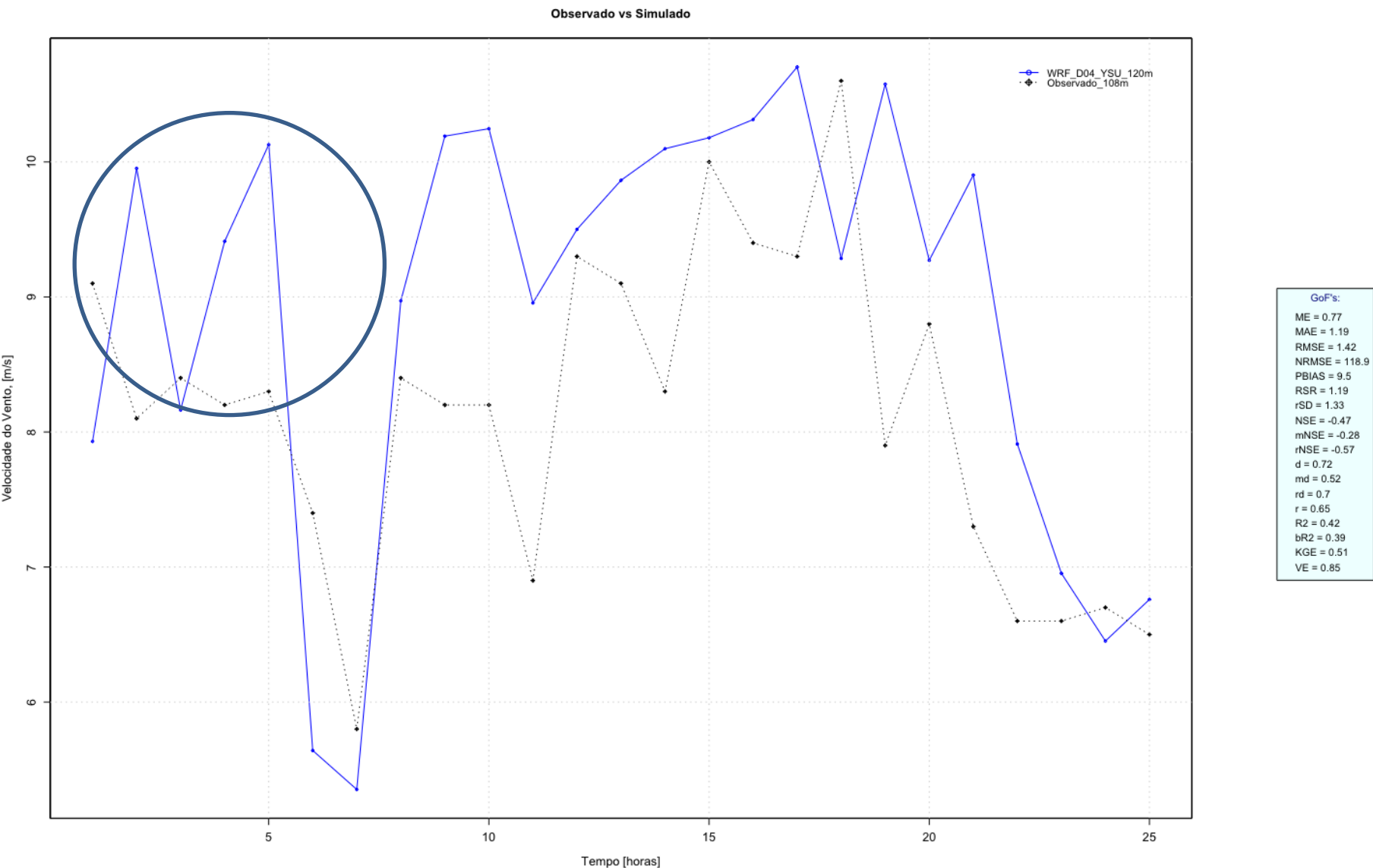
# Estudo de sensibilidade : Parametrização CLP



# Estudo de sensibilidade : Parametrização CLP



# Estudo de sensibilidade : Parametrização CLP



# Obrigado pela Atenção

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