Application of image processing (warping) techniques to fine-scale storm motion estimation

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1. INTRODUCTION

- Motivation
- Background

Motivation – Why doing this?

- Storm motion ($\mathbf{V}$ – speed and relative direction) proven to have great impact on the response of urban catchment (Singh, 1997)

- Correct estimation of storm motion is critical for urban hydrological applications, especially for:
  - Radar rainfall nowcasting
  - Stochastic spatial-temporal rainfall modelling

Radar rainfall nowcasting (short-term forecasting)

- **Basic idea:** 'extrapolate' future rainfall rates according to currently available radar images

- Accuracy of nowcasting largely depends on:
  - Quality of input radar estimates (*other RainGain activities*)
  - **Extrapolation techniques used to characterise the variation of storms**

- **Assumptions of nowcasting models:**

  In short term, the variation of a storm is dominated by its movement (mainly caused by wind advection); the evolution (i.e. the growth or decay) of storm cells is usually neglected or simulated by rainfall cell merging or separation.

Types of nowcasting techniques

- **(Object-based) storm cell tracking** *(Dixon and Wiener, 1993)*:
  - Subjective thresholds, suitable for small-scale but 'relatively large displacement' applications
  - Cartesian -> polar coordinate systems
- **(Block-based) Tracking Radar Echoes by Correlation (TREC) methods** *(Reinhart, 1981):*
  - Easy and effective, 'Holes' in the wind field, lack of (spatial) continuity, suitable for large-scale applications
  - COTREC (TREC + minimisation of the divergence of the velocities of adjacent blocks), MTREC (Multi-scale TREC)
- **Variational Echo Tracking (VET) methods** *(Laroche and Zawadzki, 1994)*:
  - Smooth (continuous) wind field, numerically time-consuming, unable to handle too large displacement between two consecutive images
  - **Optical flow techniques (used in STEPS)**

2. OPTICAL FLOW TECHNIQUES

- General idea
- Optical flow estimation using warping technique (currently used in image/video processing field)

Formulation of optical flow techniques

- **Grey Value Constancy:**

$$I(x,y,t)=I(x+u\Delta t,y+v\Delta t,t+\Delta t)$$

*(**I** = Intensity; **u,v** = x,y components of storm cell movement; **t** = time)*

  – Rainfall objects are assumed to **remain constant in intensity**, and only change in shape

  -> **this may not be the case, especially for thunderstorms.**

- **Smoothness constraint:**

$$\nabla^2\mathbf{V} \Longrightarrow u(x,y) - \frac{u(x+h,y)+u(x,y+h)+u(x-h,y)+u(x,y-h)}{4}$$

  – Minimisation of the difference between the velocity of each pixel and the average velocity of its neighbouring pixels.

Current methods for solving optical flow model
(in radar rainfall nowcasting applications)

Grey Value Constancy (GVC): $I(x,y,t)=I(x+u\Delta t,y+v\Delta t,t+\Delta t)$

Most methods: Taylor expansion
(simplification, removes higher order terms)

Optical Flow Constraint (OFC): $\partial I/\partial x\ u+\partial I/\partial y\ v+\partial I/\partial t\ =0$

In rainfall nowcasting, currently 2 numerical ways of solving the velocity field:

STEPS Model

(Bowler et al. 2004; 2006)

- Radar (I) field split into blocks
- Velocity that bests satisfies OFC is derived using least squares
- **Smoothness constraint** applied to block velocities afterwards

Variational Methods

(Germann & Zawadzki, 2002; Cheung & Yeung, 2012; MAPLE)

- Global minimisation of **intensity variation function,** which includes **smoothness constraint**:

$$E(u,v)=\boldsymbol{E_{OFC}}+\alpha\cdot E_{smoothness}$$

$$\boldsymbol{E_{OFC}}=[I_{t+\Delta t}-I_{t}]^{2}$$

Improvements to current optical flow variational methods, based on image processing (warping) techniques

1

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Global minimisation of **intensity variation function,** which **includes** **smoothness constraint**:

$$E(u,v) = \boldsymbol{E_{OFC}} + \alpha \cdot E_{smoothness}$$

$$\boldsymbol{E_{OFC}} = [I_{t+\Delta t} - I_t]^2$$

2

Improvements to current optical flow variational methods, based on image processing (warping) techniques

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1

Relaxation of Grey Value Constancy through Gradient Constancy assumption

$$\nabla I(x,y,t)=\nabla I(x+u\Delta t,y+v\Delta t,t+\Delta t)$$

Where $\nabla=(\partial x,\partial y)^T$ denotes the spatial gradient

This allows small variations in rainfall intensity and is helpful to determine the displacement vector by providing an additional criterion

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Variational Methods

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$$E(u,v) = \mathbf{E_{OFC}} + \alpha \cdot E_{smoothness}$$

$$\mathbf{E_{OFC}} = [I_{t+\Delta t} - I_t]^2$$

The original E_{OFC} function is **more sensitive to the noise in the radar image**.

This may be **particularly critical at small scales**!

2

A convex function is introduced, which makes the E_{OFC} term less sensitive to the noise in the radar image:

$$\Psi(s^2) = \sqrt{s^2 + \epsilon^2}$$

where ϵ = 0.001

Ψ is applied to the E_{OFC} function

‘Updated’ Intensity Variation Function (after incorporating improvements)

$$E(u,v) = E_{OFC} + \boldsymbol{\alpha} \cdot E_{smoothness}$$

Where:

$$E_{OFC} = \int_{\Omega} \Psi\left(|I(\mathbf{x}+\mathbf{w}) - I(\mathbf{x})|^2 + \boldsymbol{\gamma}|\nabla I(\mathbf{x}+\mathbf{w}) - \nabla I(\mathbf{x})|^2\right) \mathbf{dx}$$

The parameters α **(degree of smoothness)** and γ **(degree of gradient constancy)** can be tuned to obtain better results

The goal is to find the functions $\boldsymbol{u}$ and $\boldsymbol{v}$, which minimise the Intensity Variation Function $E(u,v)$

Improvements to current optical flow variational methods, based on image processing (warping) techniques

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$$\boldsymbol{E_{OFC}} = [I_{t+\Delta t} - I_t]^2$$

3

A **multi-scale calculation methodology** is introduced, which helps **obtaining the global optimal** wind velocity field (avoids getting stuck in local minima):

- Numerical estimation of wind velocities from coarse to fine (spatial) scales
- Results at coarser resolution are starting point for estimation at next finer resolution

3. EXPERIMENTAL SETUP AND PRELIMINARY RESULTS

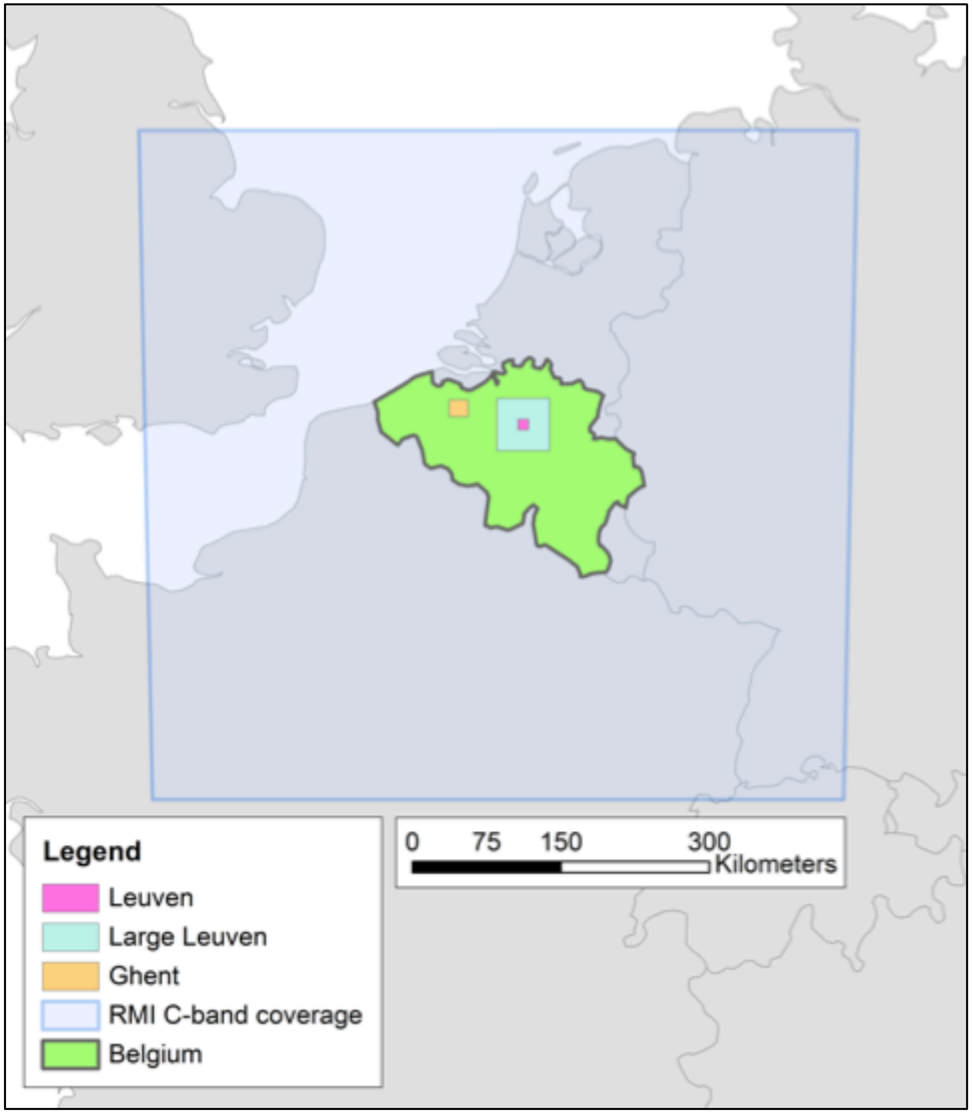
Experimental dataset

- **Selected Event:**

  2012/09/23 22:00 – 23:55

- **RMI C-band radar rainfall product (nowcasting domain):**
  - Composite from 2 radars
  - 5 min / 529 m;
  - Marshall-Palmer Z-R relation

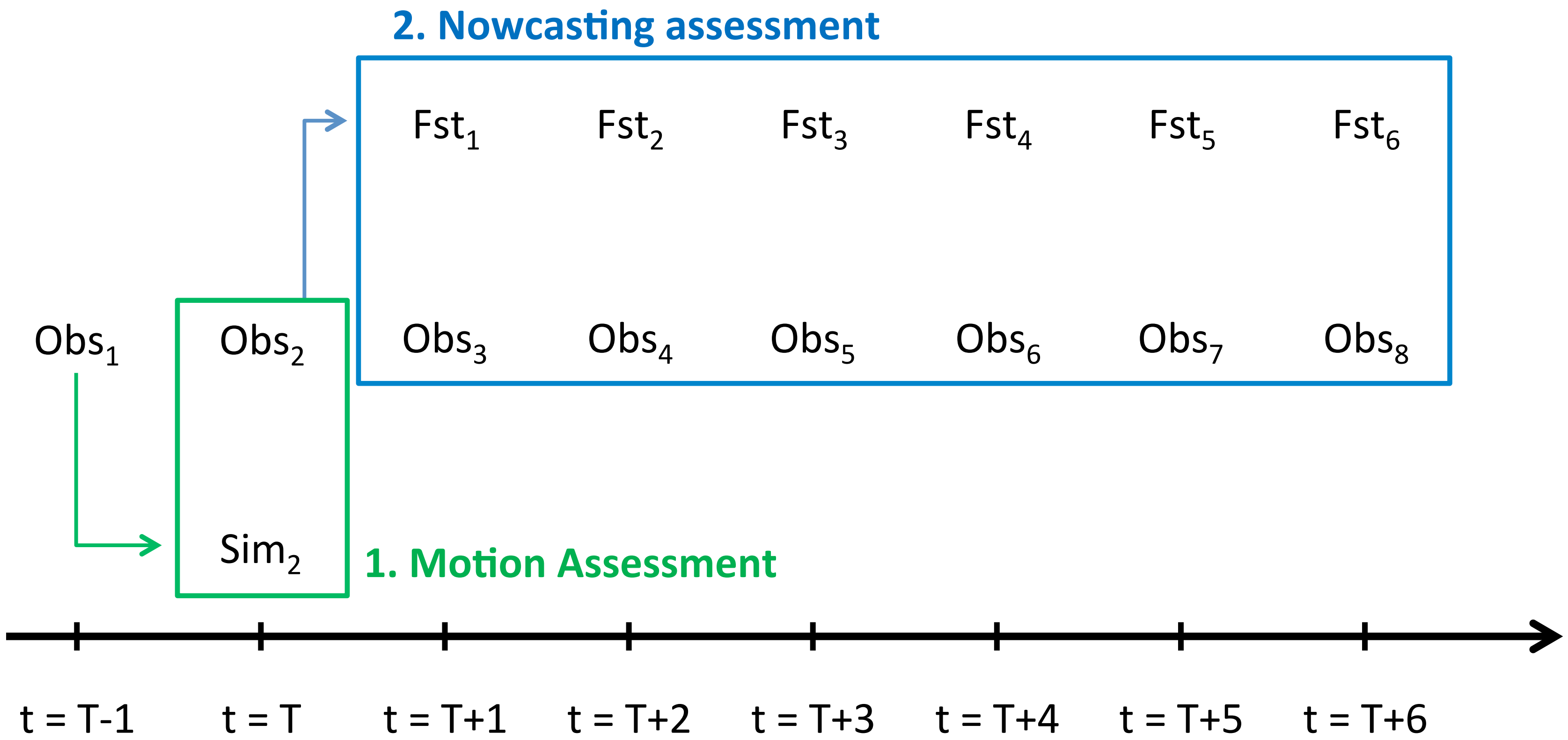
- **Nowcasting analysis areas:**
  - ***Leuven:*** 20 X 20 grids area
  - ***Large Leuven*:*** 100 x 100 grids area centered in Leuven
  - **Ghent:** 32 X 36 grids area



Scope of test: parametric analysis

- **Parameters considered in analysis:**
  - α (degree of smoothness): 0.2, 0.5, 0.9
  - γ (weighting for gradient constancy): 0.0, 50.0
  - Multi-scale (coarsest resolution): ~2 km, ~15 km, ~30 km
- The **independent** effect of each parameter, as well as their **interactions** are analysed
- The **effect** of the different parameters **at small and large geographical scales** is also analysed

2-Stage Assessment



Performance measures (skills)

- Hit Rate: $H = a/a+c$

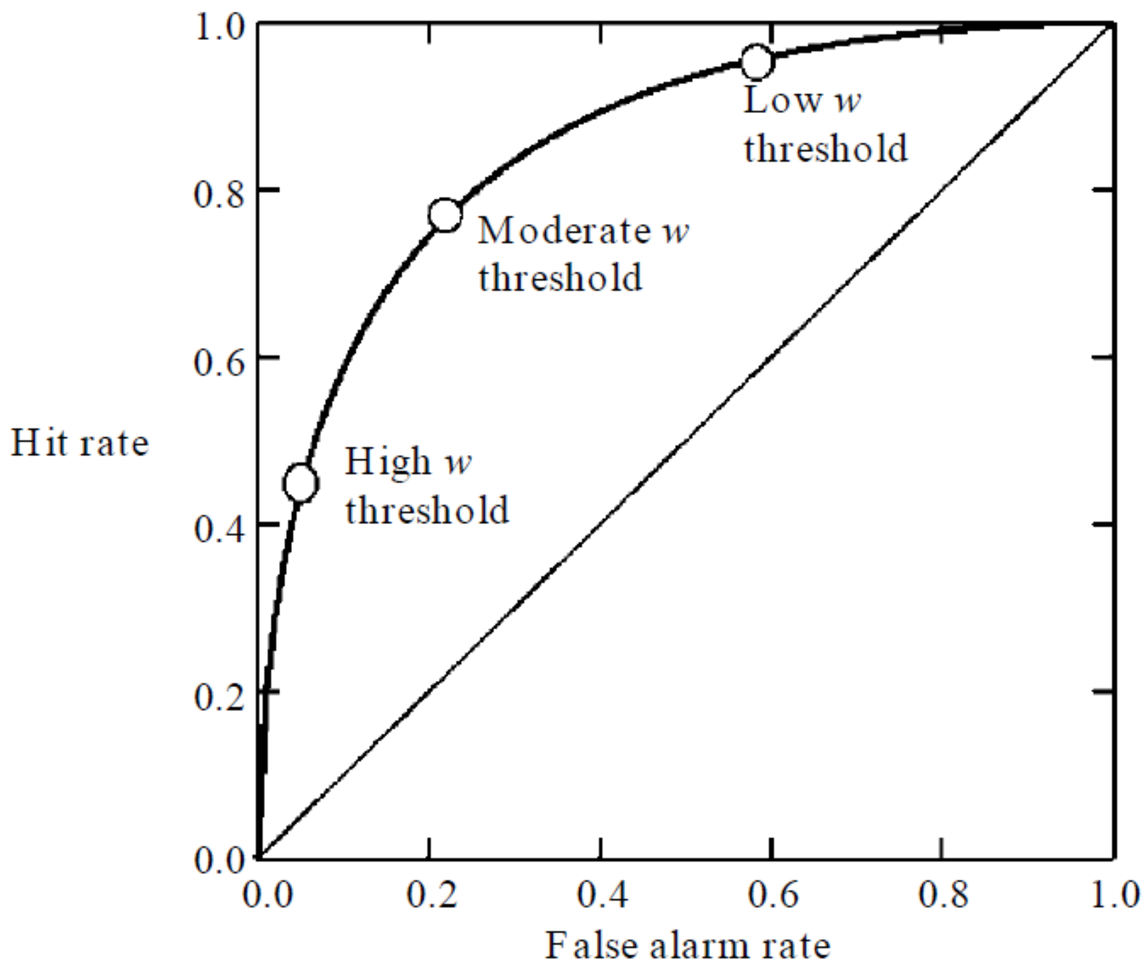
- False Alarm Rate: $F = b/b+d$

Contingency Table, H and F

Forecast	Observed		
	Yes	No	Total
Yes	a	b	$a+b$
No	c	d	$c+d$
Total	$a+c$	$b+d$	$a+b+c+d=n$

Performance measures (skills)

Relative Operating Characteristic (ROC) curve



Thresholds (mm/hr):

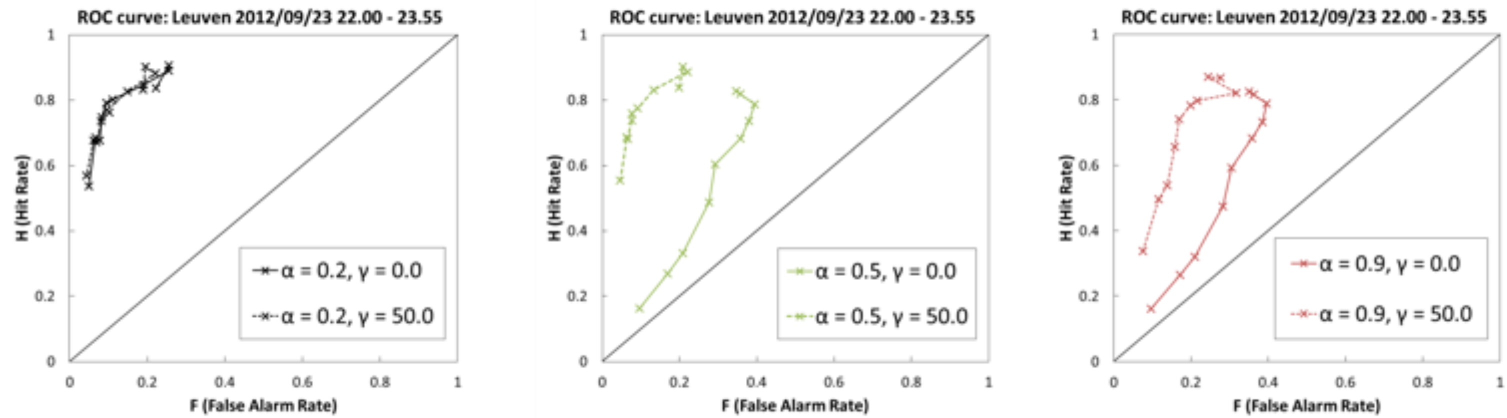
0.125
0.25
0.5
1.0
2.0
4.0
8.0
15.0
20.0
35.0

STAGE 1: ASSESSMENT OF STORM MOTION ESTIMATION

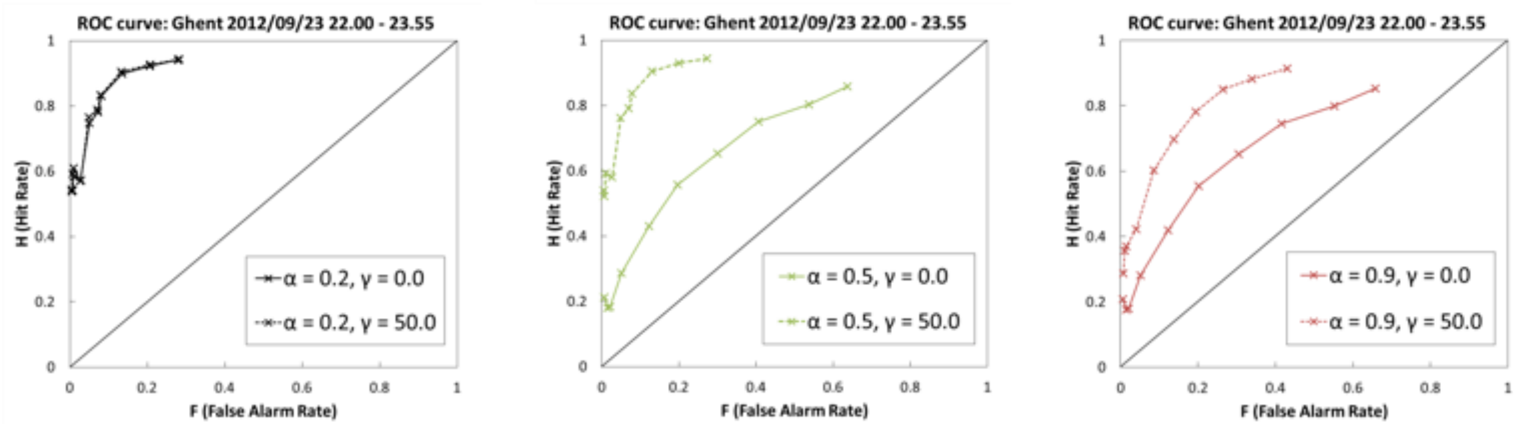
STAGE 1 – Analysis of impact of gradient constancy constraint (fixed α, variable γ)

α= 0.2 | α= 0.5 | α= 0.9

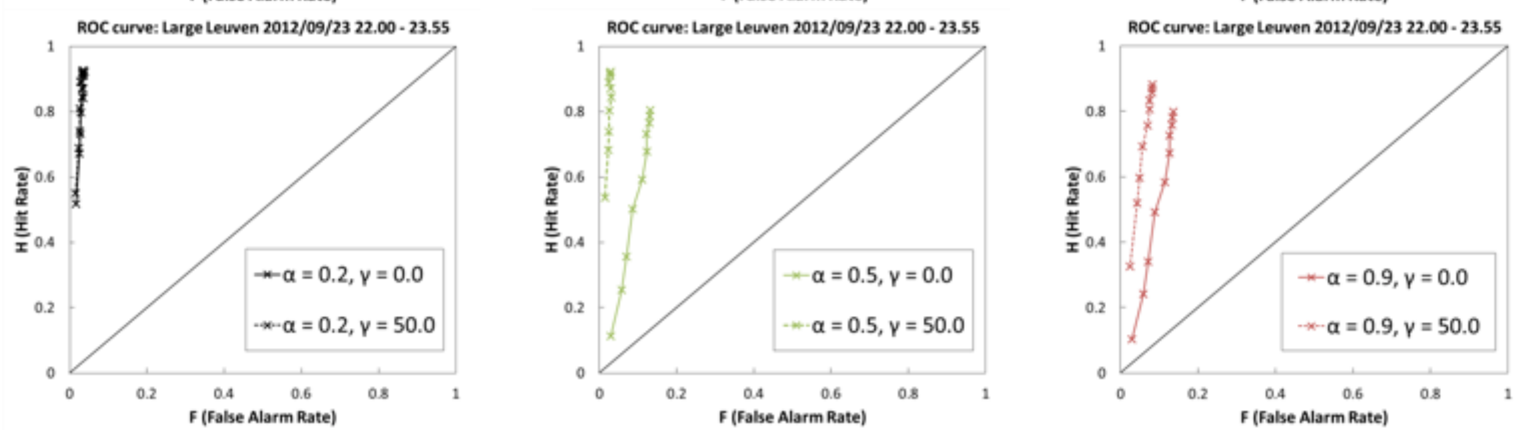
Leuven 20 X 20



Ghent 36 X 32



Large Leuven 100 X 100



STAGE 1 – Analysis of impact of gradient constancy constraint (fixed α, variable γ)

- In general, gradient constancy constraint is helpful. However, its degree of improvement depends on the degree of smoothness:
  - At low smoothness, gradient only leads to very small improvements
  - At intermediate and high smoothness, gradient leads to great improvements in skills
- In general, impact of smoothness as well as gradient constancy at large scales is less significant than at small scales.

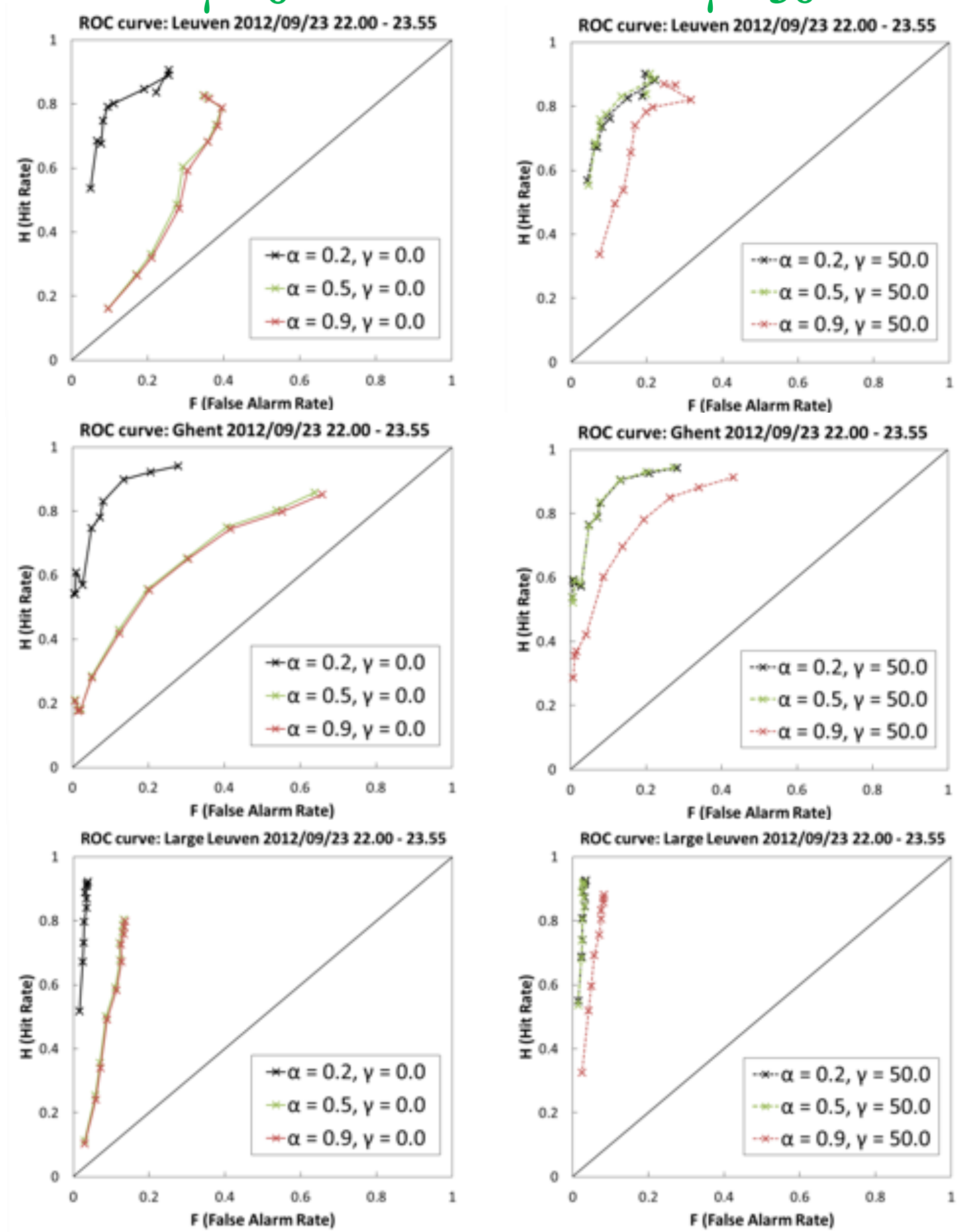
STAGE 1 – Analysis of impact of smoothness constraint (fixed γ, variable α)

γ = 0 | γ = 50

Leuven 20 X 20

Ghent 36 X 32

Large Leuven 100 X 100

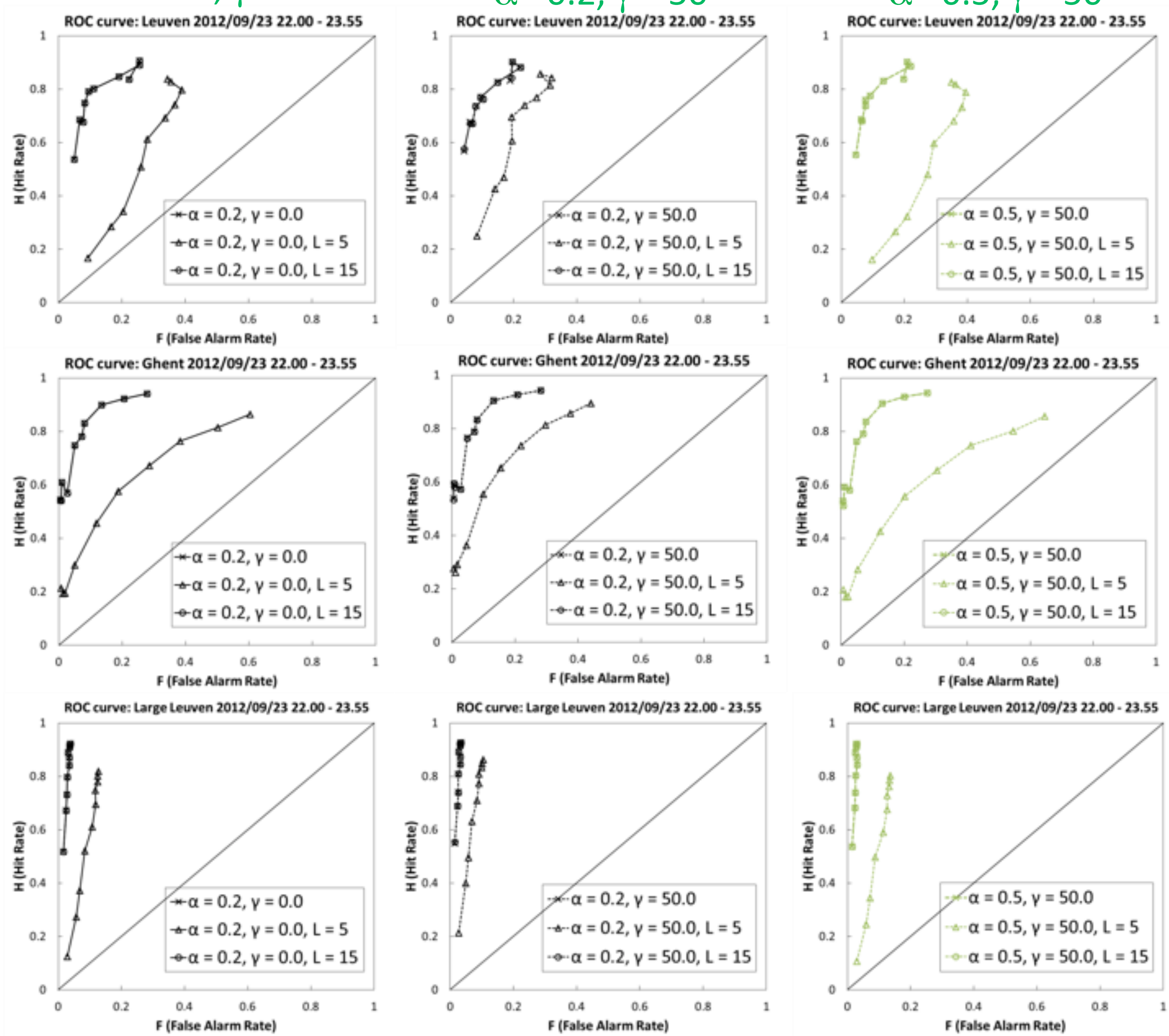


STAGE 1 – Analysis of impact of smoothness constraint (fixed γ, variable α: 0.2, 0.5 & 0.9)

- In general, lower smoothness constraint results in better performance
- However, there is interaction between smoothness and gradient constancy
- Intermediate level of smoothness can perform as good or even better than low smoothness when gradient constancy is considered

STAGE 1 – Analysis of impact of number of layers, L (fixed α and γ, variable L)

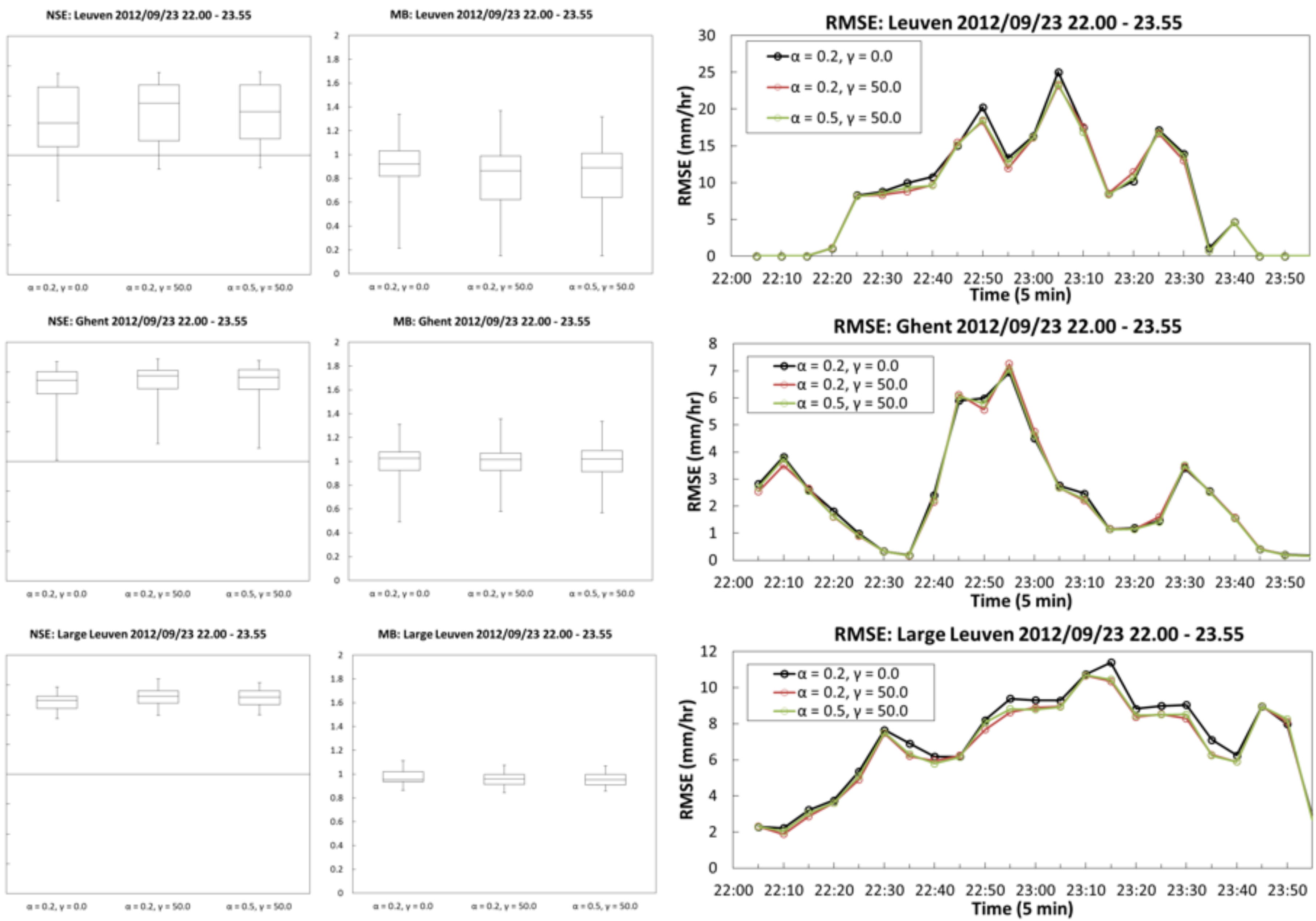
	α= 0.2, γ = 0	α= 0.2, γ = 50	α= 0.5, γ = 50
Leuven 20 X 20			
Ghent 36 X 32			
Large Leuven 100 X 100			



STAGE 1 – Analysis of impact of number of layers, L
(fixed α and γ, variable L: ~2 km, ~15 km, ~30 km)

- In general, a larger number of multi-scale layers (i.e. larger coarsest resolution) results in better performance.

- However, no significant difference in performance is observed between the two highest numbers of layers (i.e. coarsest resolutions of ~15 km and ~30 km, respectively).


NSE: Leuven 2012/09/23 22.00 - 23.55
MB: Leuven 2012/09/23 22.00 - 23.55
RMSE: Leuven 2012/09/23 22.00 - 23.55
NSE: Ghent 2012/09/23 22.00 - 23.55
MB: Ghent 2012/09/23 22.00 - 23.55
RMSE: Ghent 2012/09/23 22.00 - 23.55
NSE: Large Leuven 2012/09/23 22.00 - 23.55
MB: Large Leuven 2012/09/23 22.00 - 23.55
RMSE: Large Leuven 2012/09/23 22.00 - 23.55
α = 0.2, γ = 0.0
α = 0.2, γ = 50.0
α = 0.5, γ = 50.0
RMSE (mm/hr)
Time (5 min)

STAGE 2: ASSESSMENT OF NOWCASTING

(Assessment done at 30 min lead time)

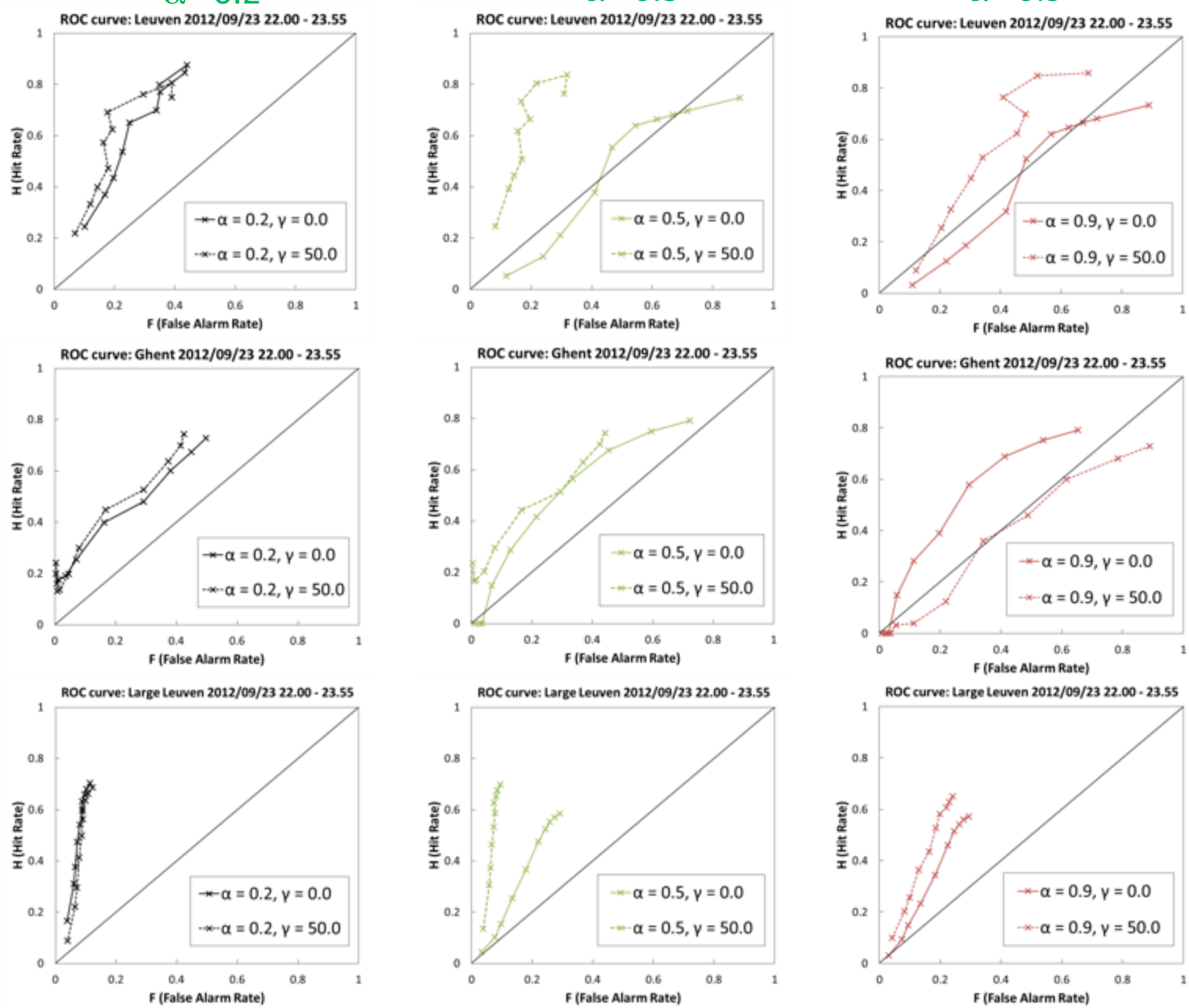
STAGE 2 – Analysis of impact of gradient constancy constraint (fixed α, variable γ)

α= 0.2 | α= 0.5 | α= 0.9

Leuven 20 X 20

Ghent 36 X 32

Large Leuven 100 X 100



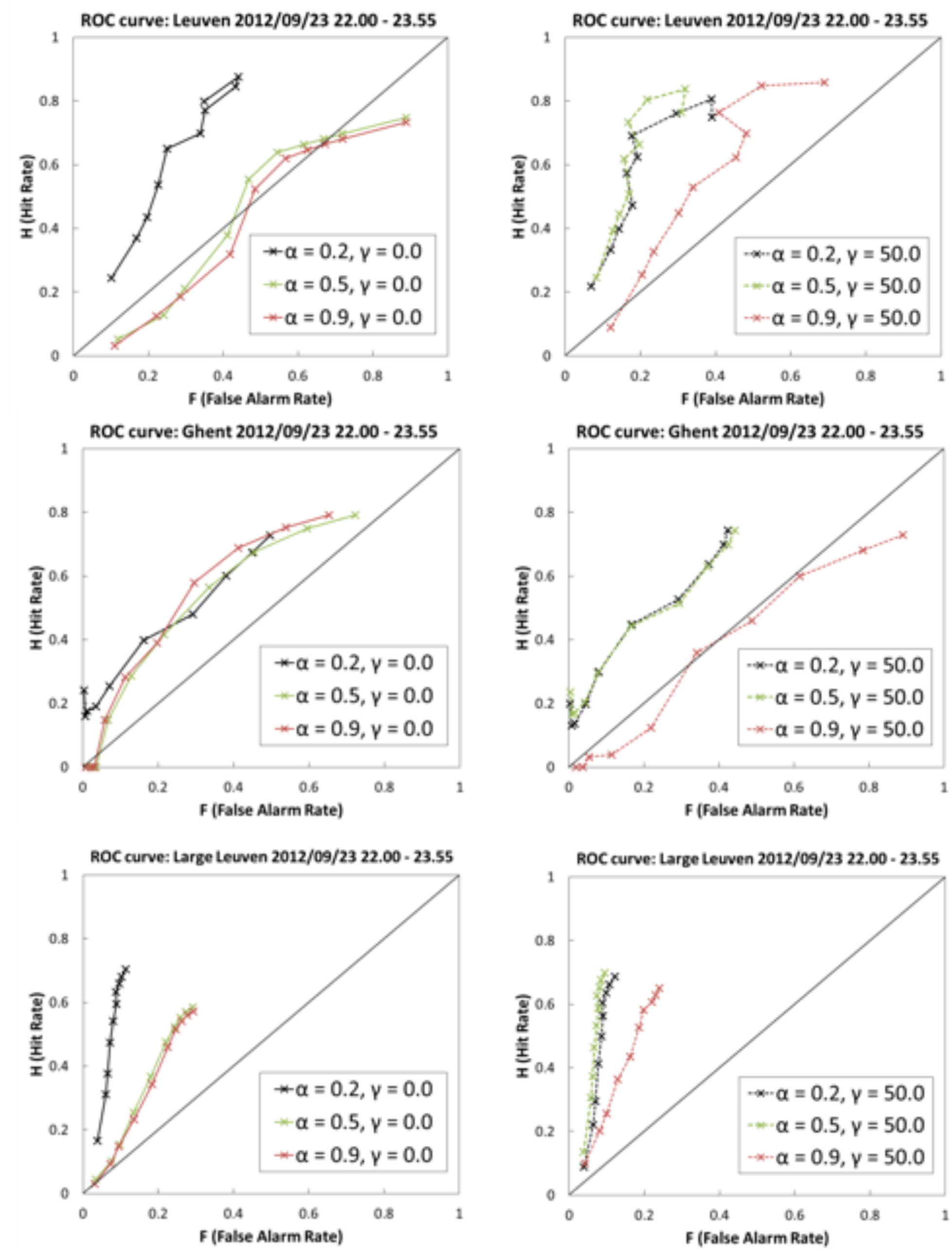
STAGE 2 – Analysis of impact of smoothness constraint (fixed γ, variable α)

$\gamma = 0$ $\gamma = 50$

Leuven
20 X 20

Ghent
36 X 32

Large
Leuven
100 X 100



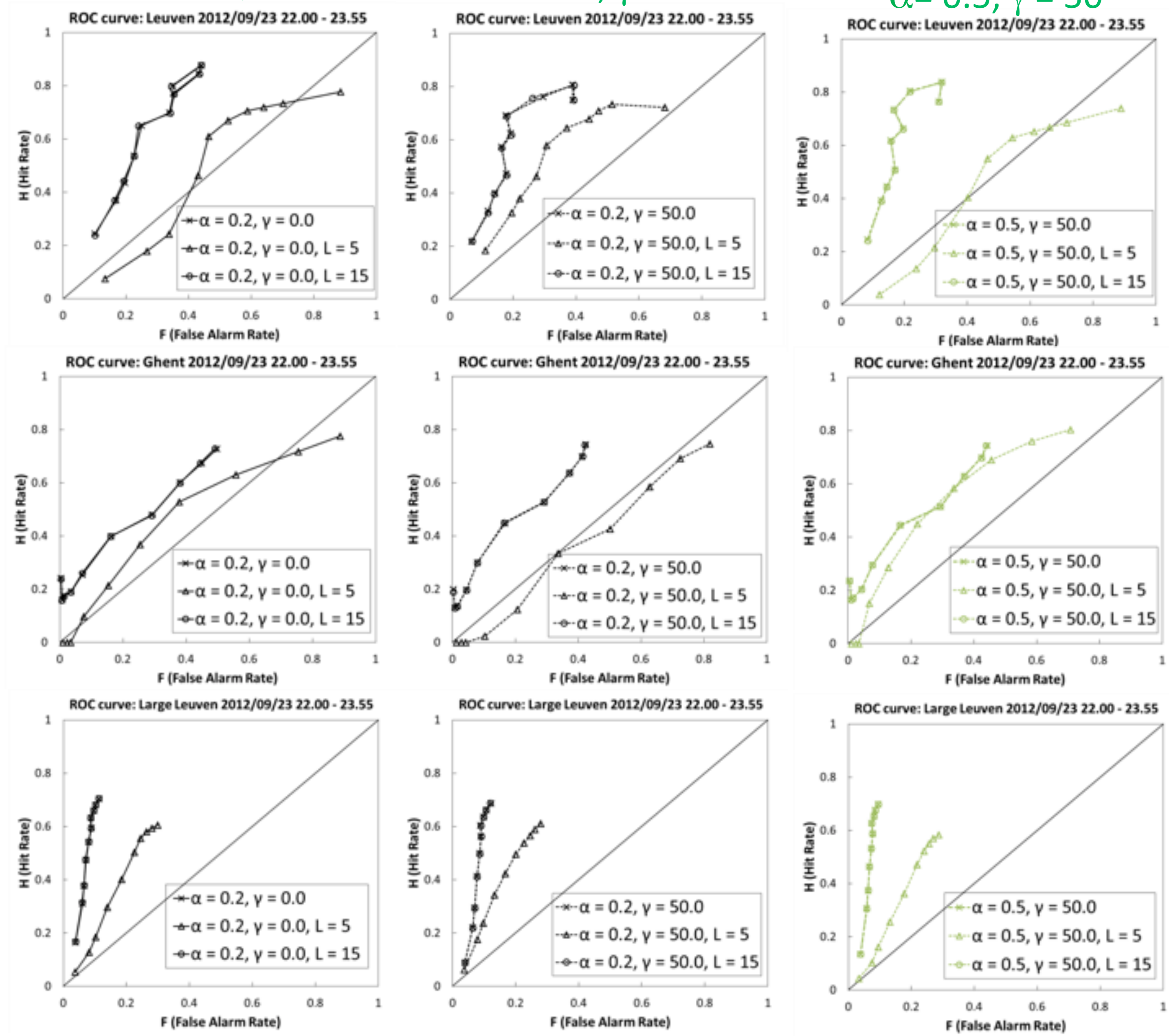
STAGE 2 – Analysis of impact of number of layers, L (fixed α and γ, variable L)

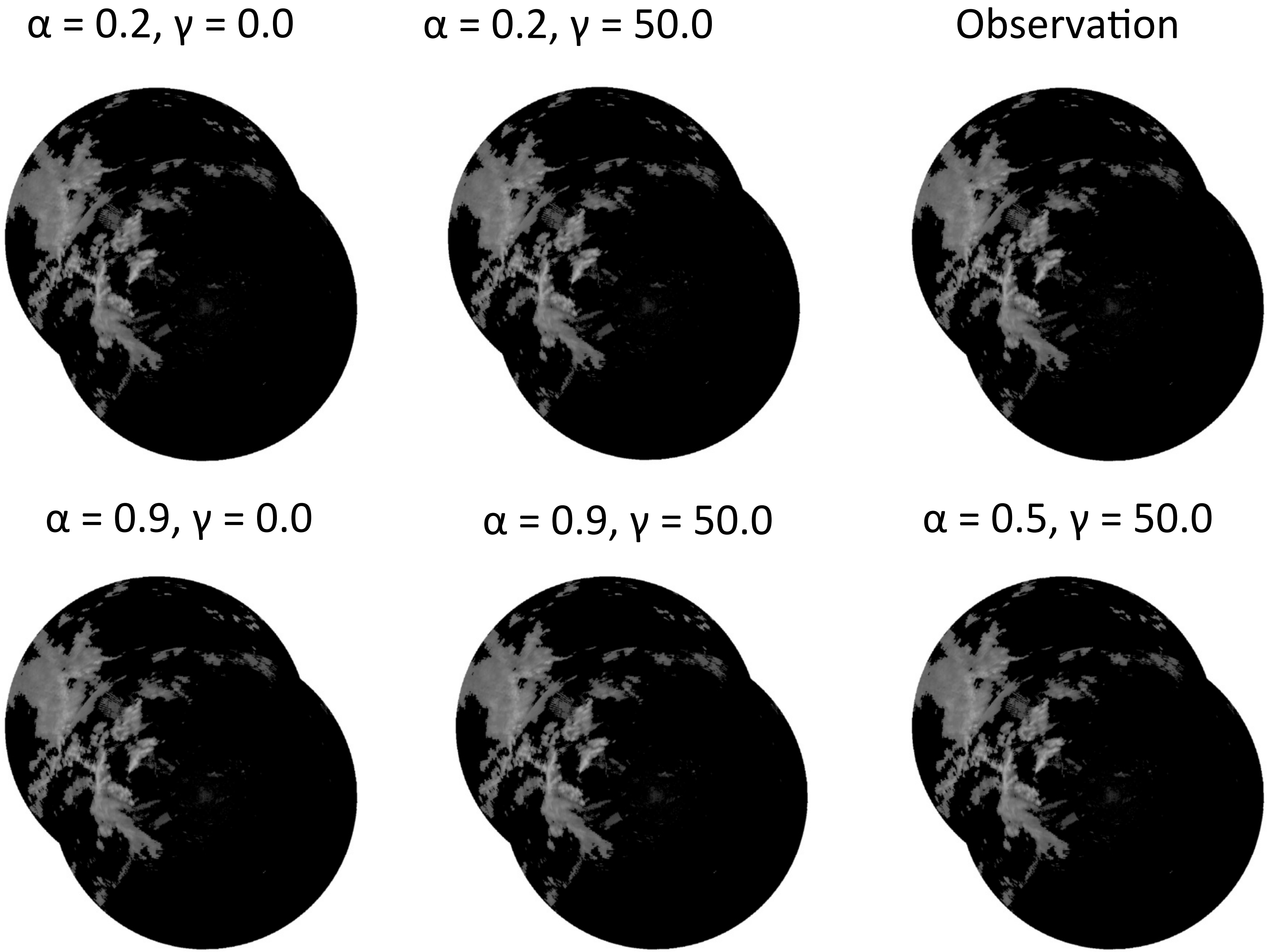
α= 0.2, γ = 0 | α= 0.2, γ = 50 | α= 0.5, γ = 50

Leuven 20 X 20

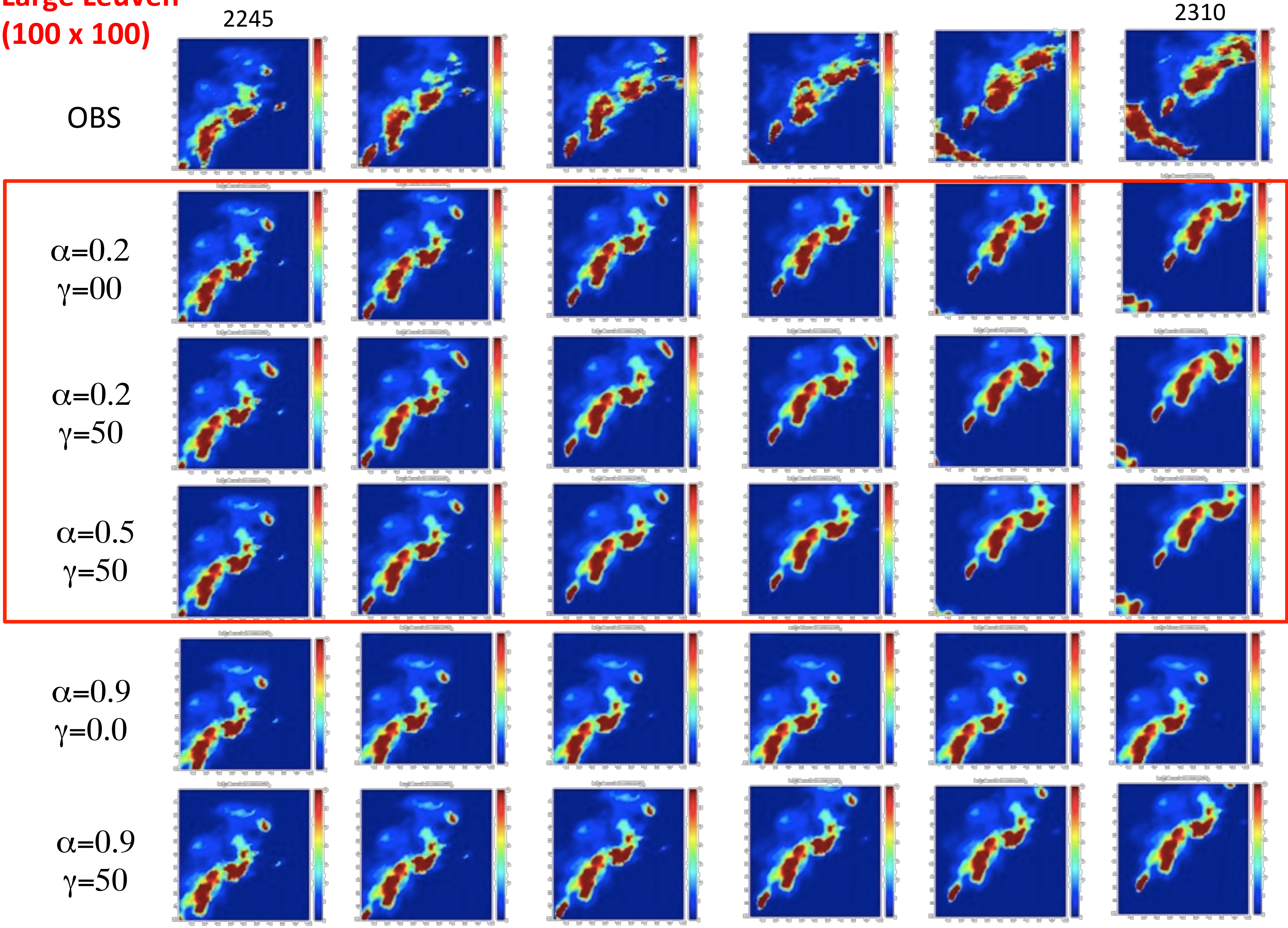
Ghent 36 X 32

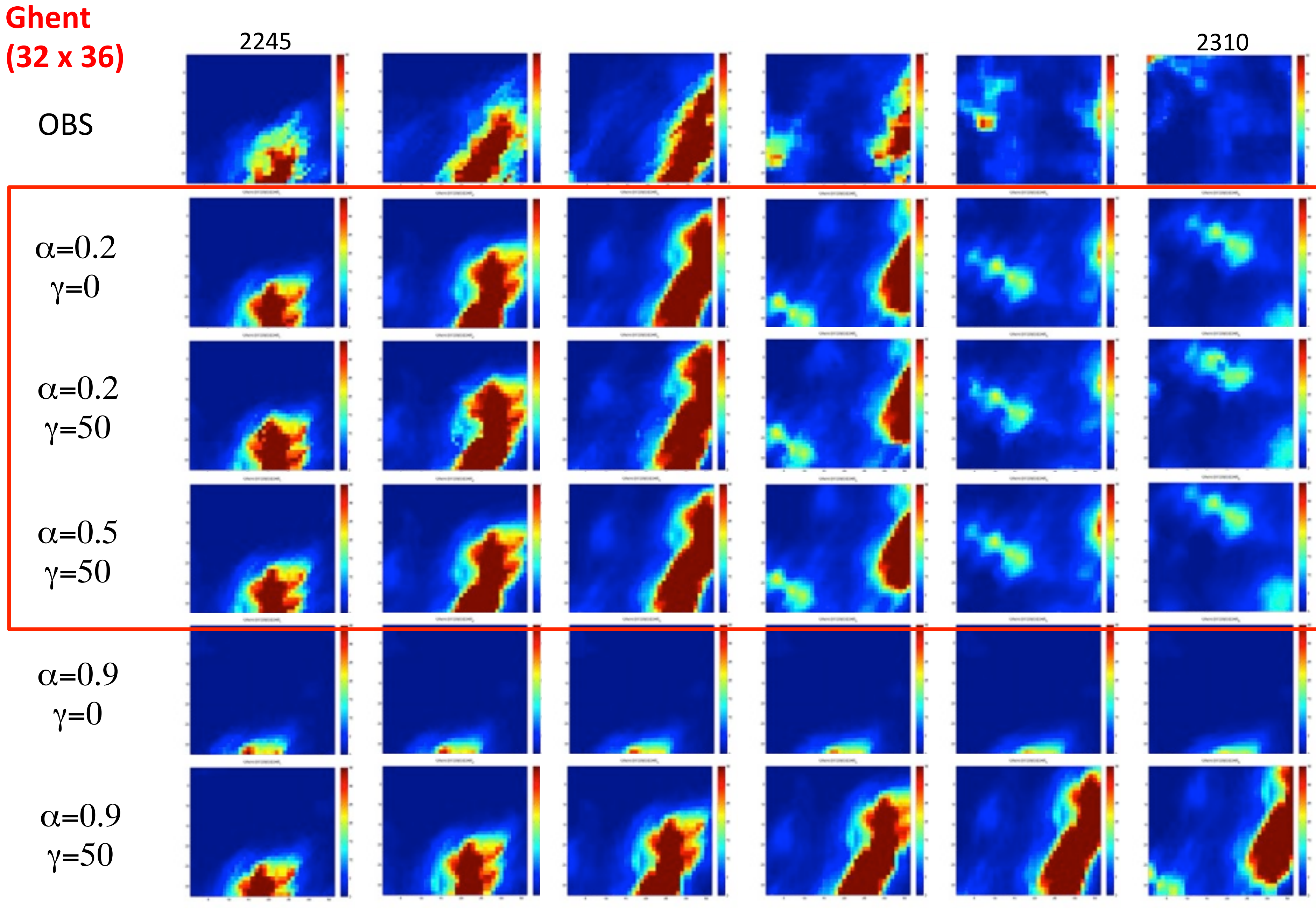
Large Leuven 100 X 100

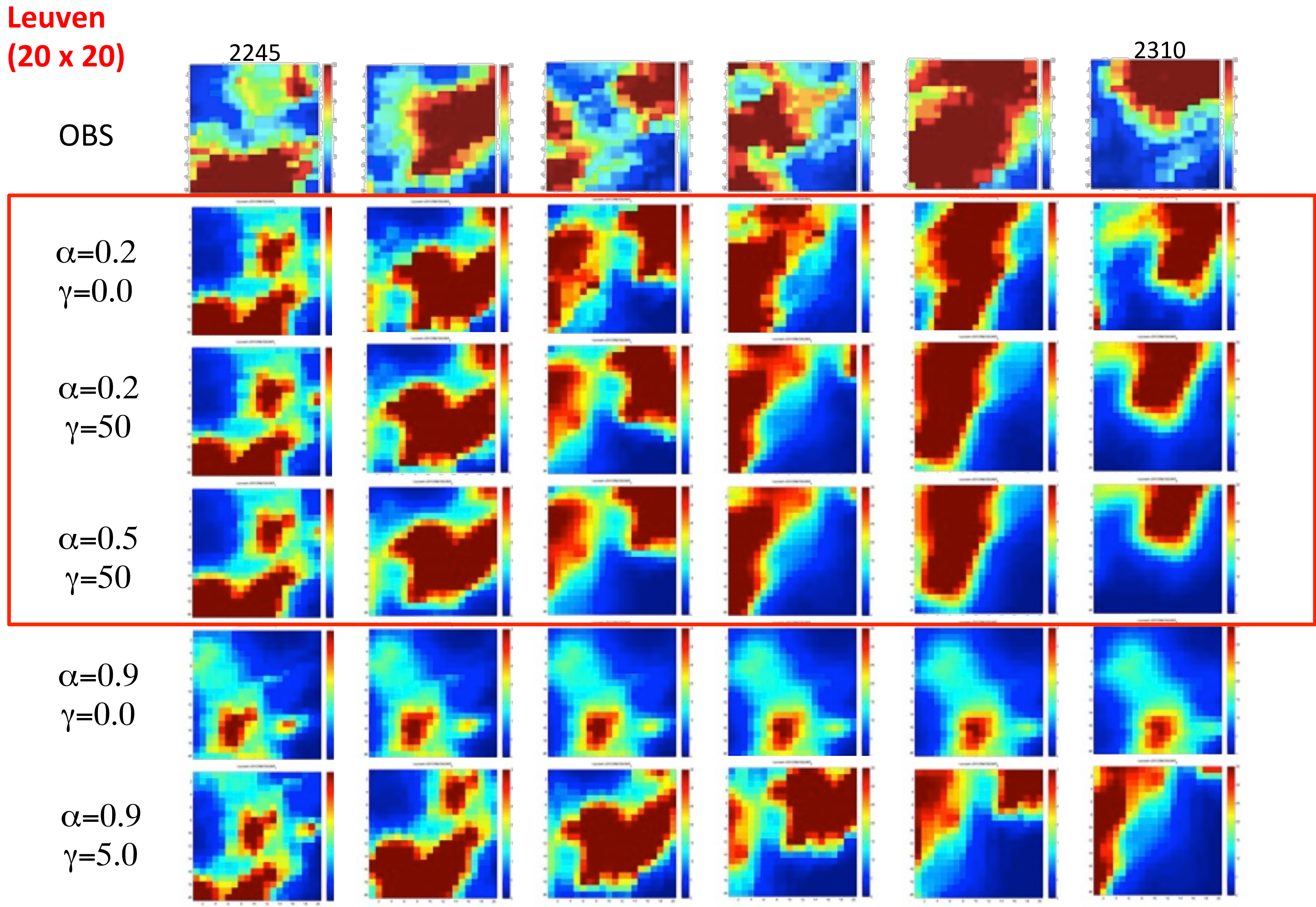



α = 0.2, γ = 0.0
α = 0.2, γ = 50.0
Observation
α = 0.9, γ = 0.0
α = 0.9, γ = 50.0
α = 0.5, γ = 50.0

Large Leuven (100 x 100)




Ghent
(32 x 36)
2245
2310
OBS
α=0.2
γ=0
α=0.2
γ=50
α=0.5
γ=50
α=0.9
γ=0
α=0.9
γ=50


Leuven
(20 x 20)
2245
2310
OBS
α=0.2
γ=0.0
α=0.2
γ=50
α=0.5
γ=50
α=0.9
γ=0.0
α=0.9
γ=5.0

4. CONCLUSIONS & FUTURE WORK

CONCLUSIONS

- A variational optical flow model was tested with additional constraint and multi-scale numerical approach. It shows the potential to better capture the storm motion at small scale.

- The gradient constancy constraint has proven to be helpful, and low or intermediate smoothness values are recommended.

- In general, impact of smoothness constraint as well as gradient constancy at large scales is less significant than at small scales. Improvements are seen at small as well as large scales, but these are more evident at small scales.

- So far, the best parameter set is the combination of intermediate smoothness value with gradient constancy constraint ($\alpha = 0.5$, $\gamma = 50$).

FUTURE WORK

- Continue to test more storm events
- Evaluate impact of convex function
- Compare this method against STEPS nowcasting
- Compare this method against object-based storm cell tracking

QUESTIONS?

Thank You!

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