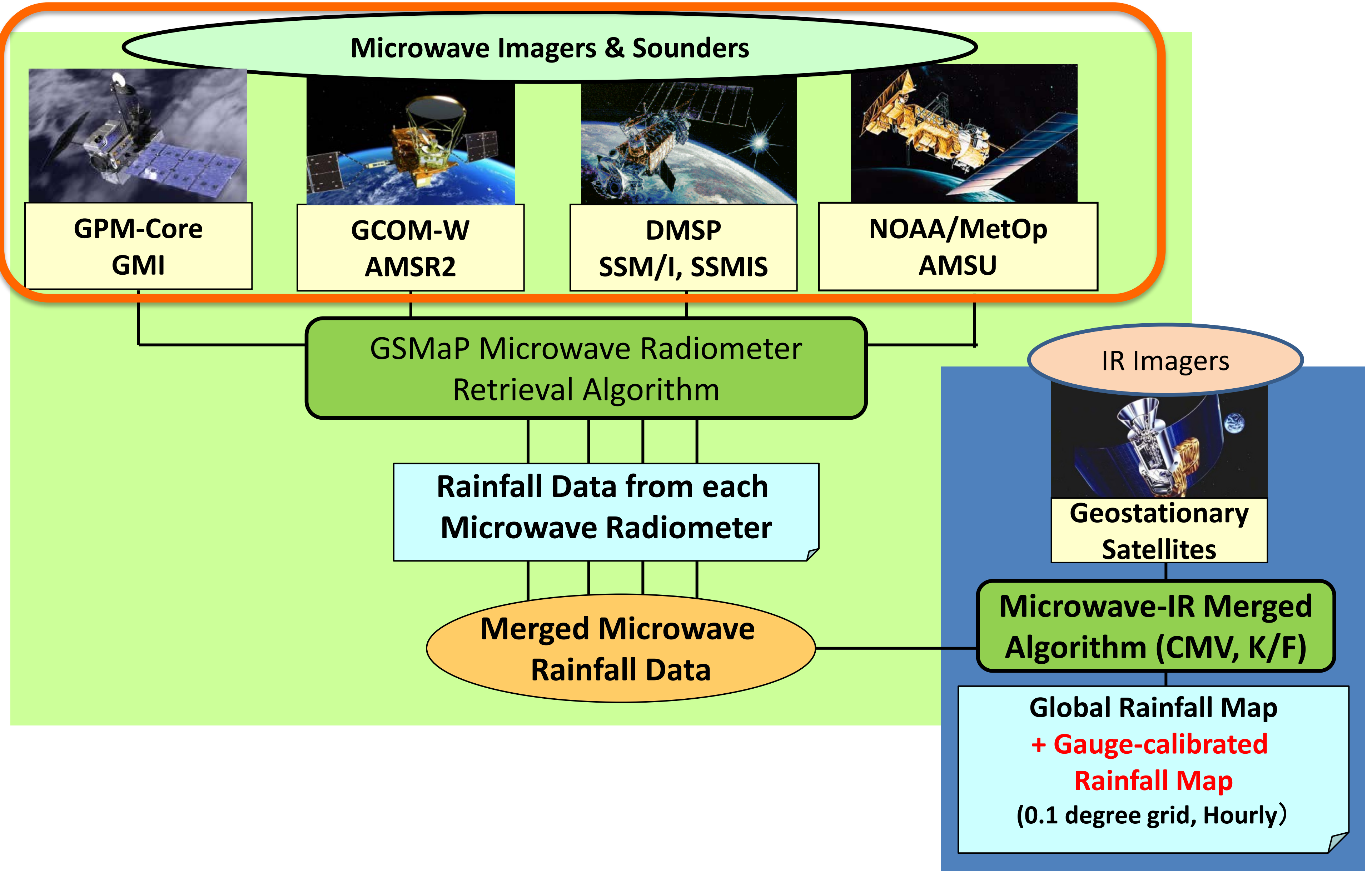
高分解能GSMaPアルゴリズムの構造と考え方

牛尾知雄（大阪大）

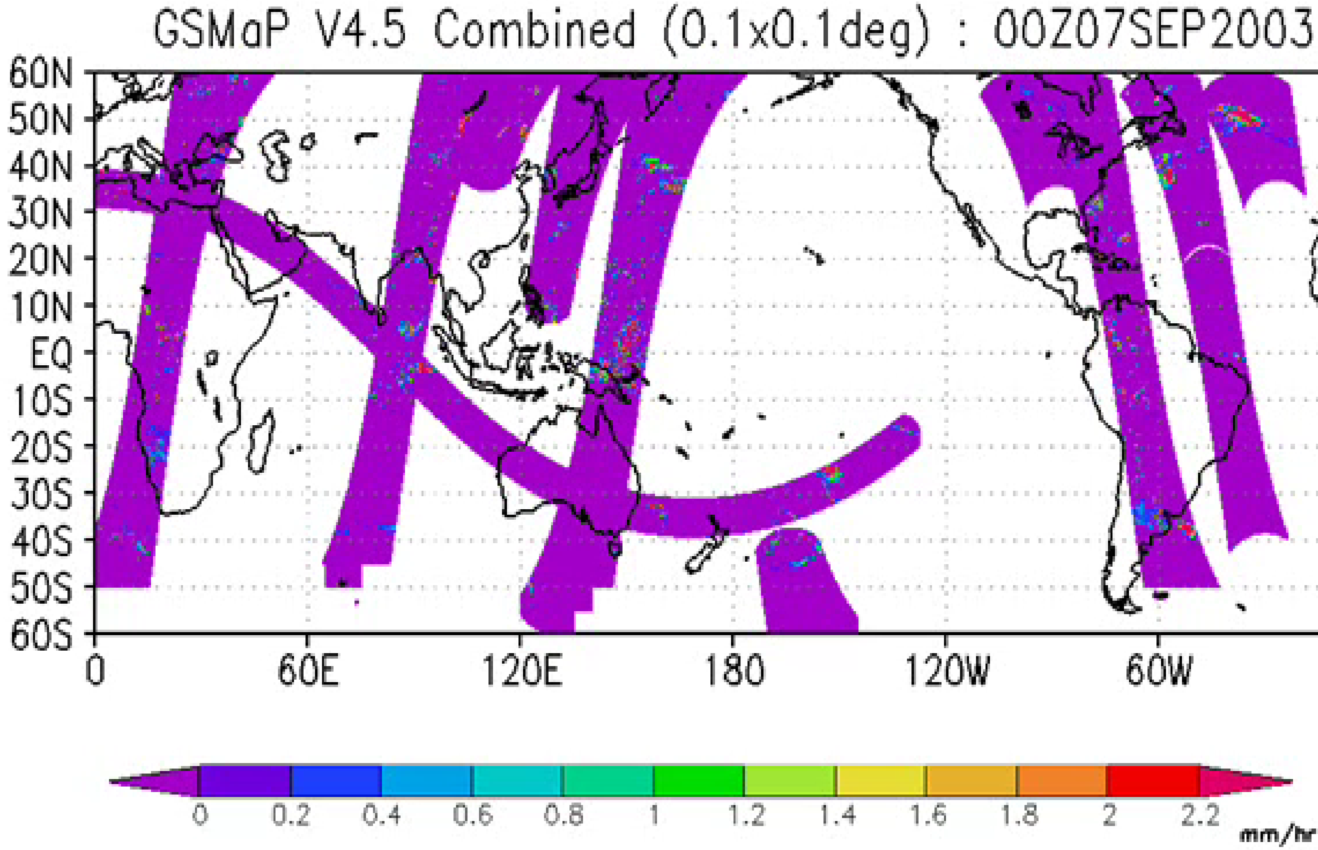
Current GSMaP products

- GSMaP_MWR
  - Microwave radiometer product
- GSMaP_MVK
  - Global precipitation mapping from microwave and infrared radiometric data
- GSMaP_Gauge
  - Gauge adjusted GSMaP_MVK
- GSMaP_NRT and GSMaP_Now
  - Near real time version of the GSMaP_MVK product
- GSMaP_Gauge_NRT
  - Near real time product of GSMaP_Gauge

GSMaP sensors

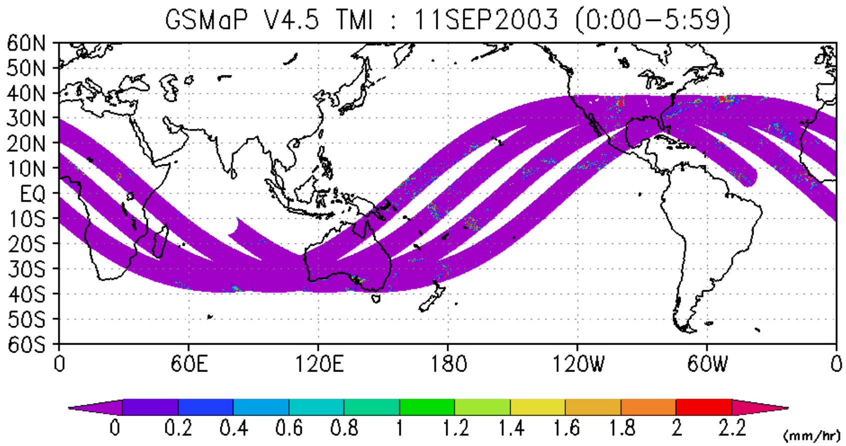


Coverage of the 6 MWRs in 1 hour

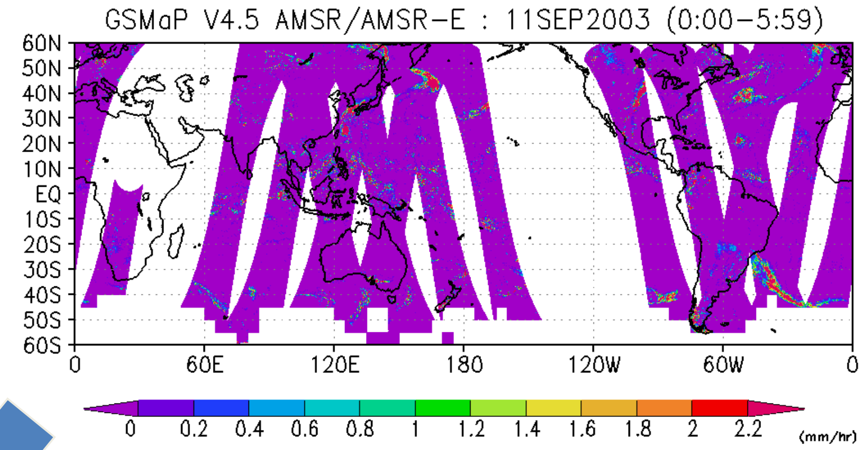


6 hourly MWR combined map

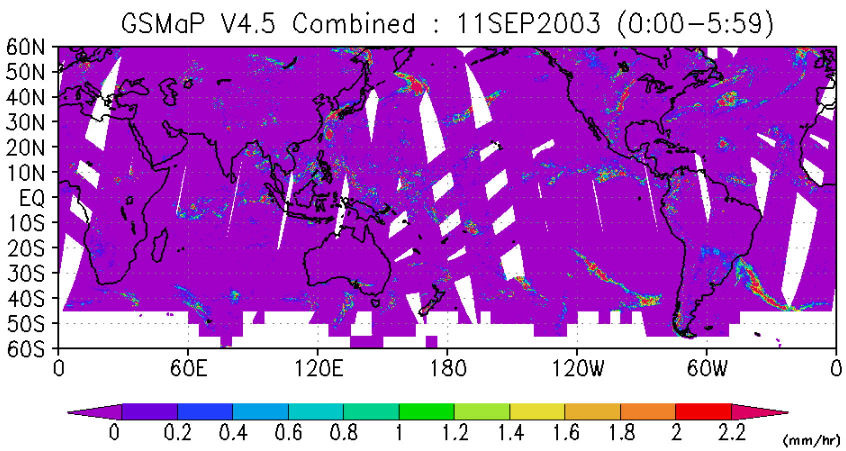
TMI



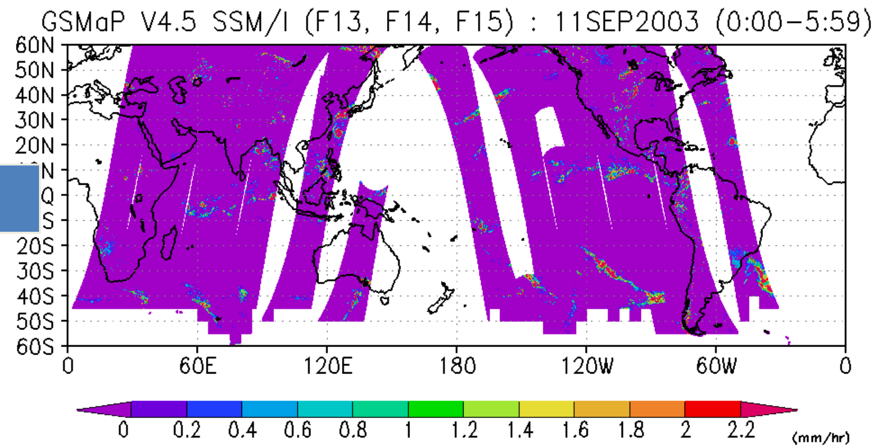
AMSR & AMSR-E



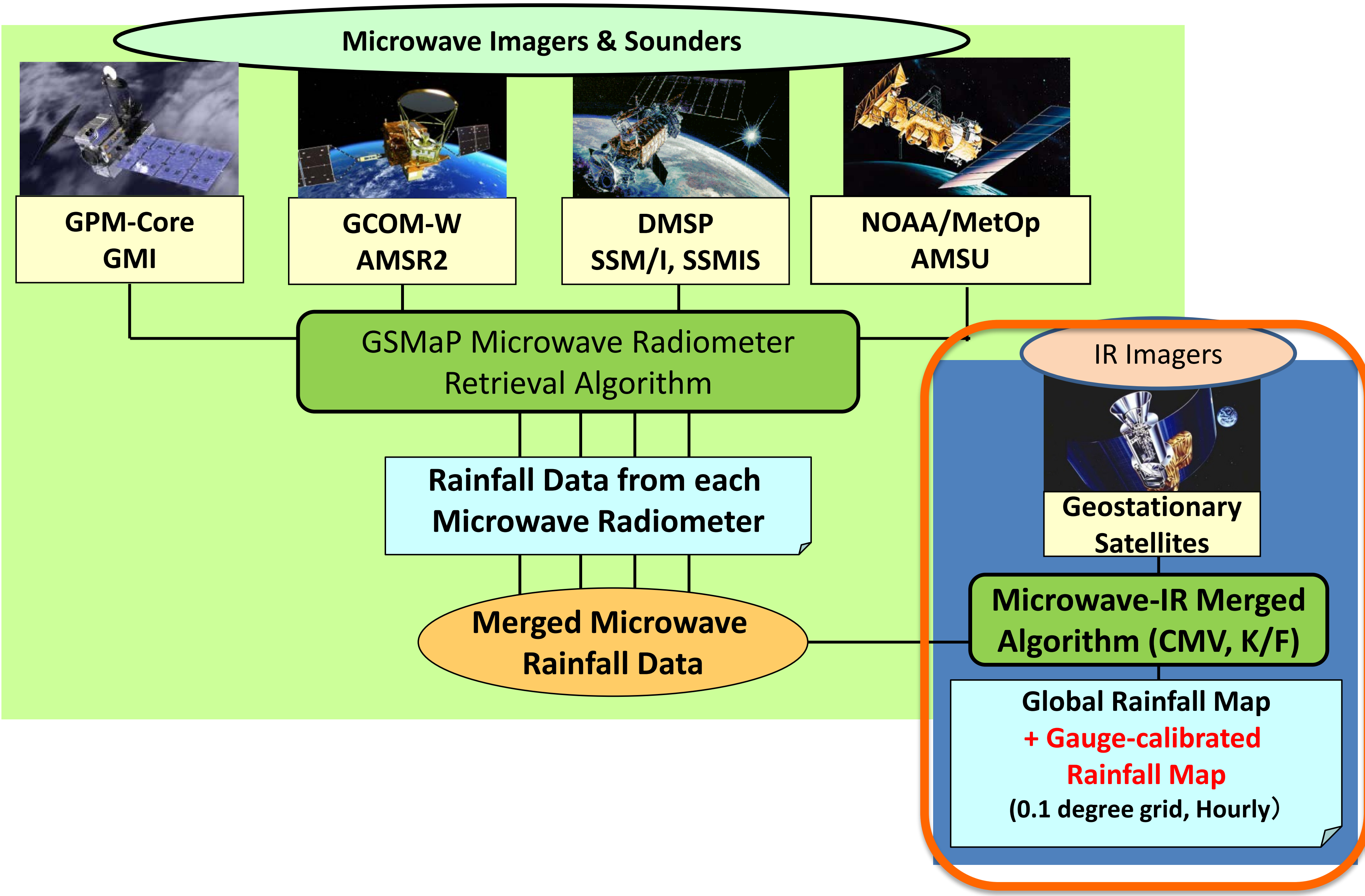
Combined
6 hourly



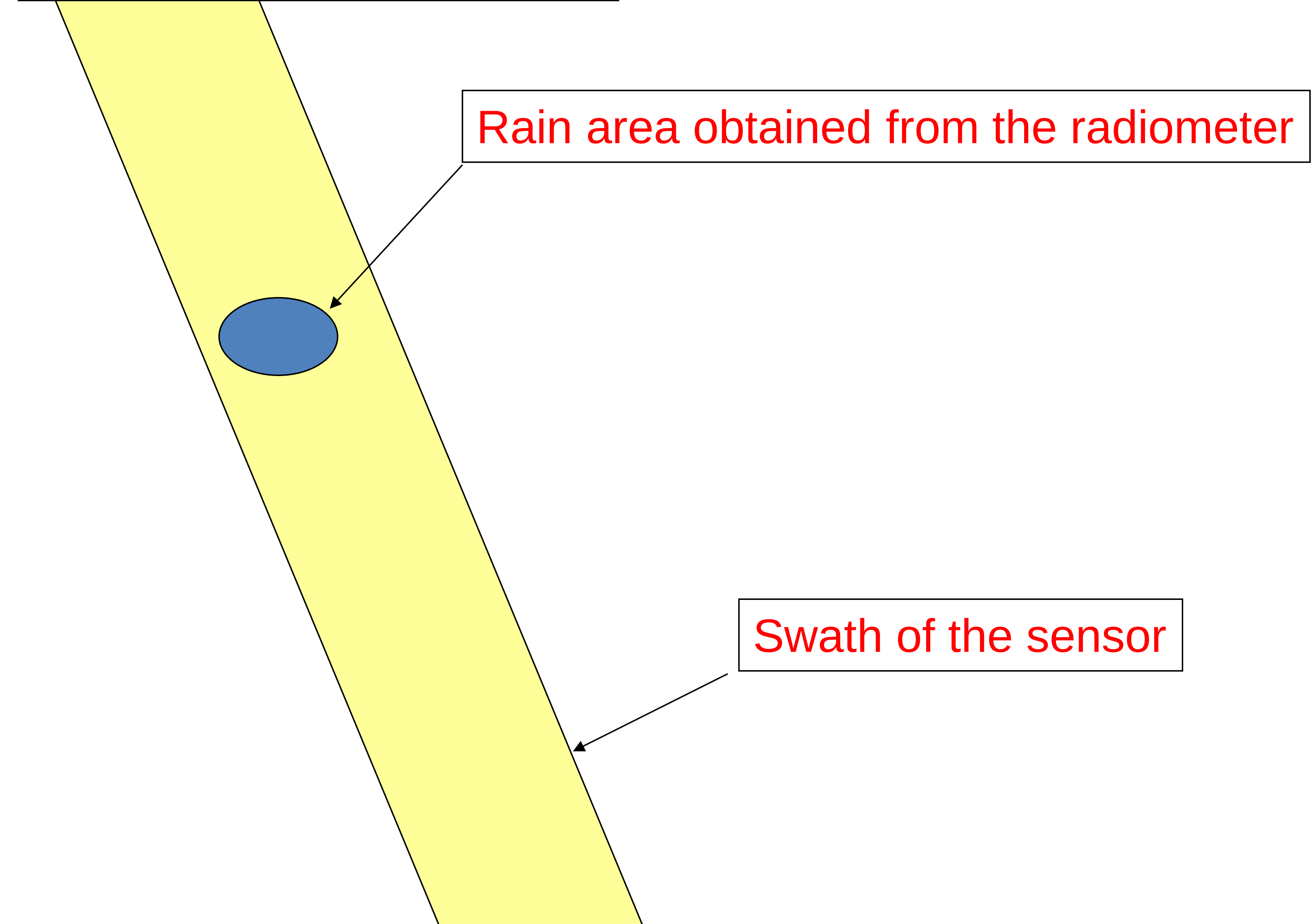
SSM/I （F13, F14, F15）



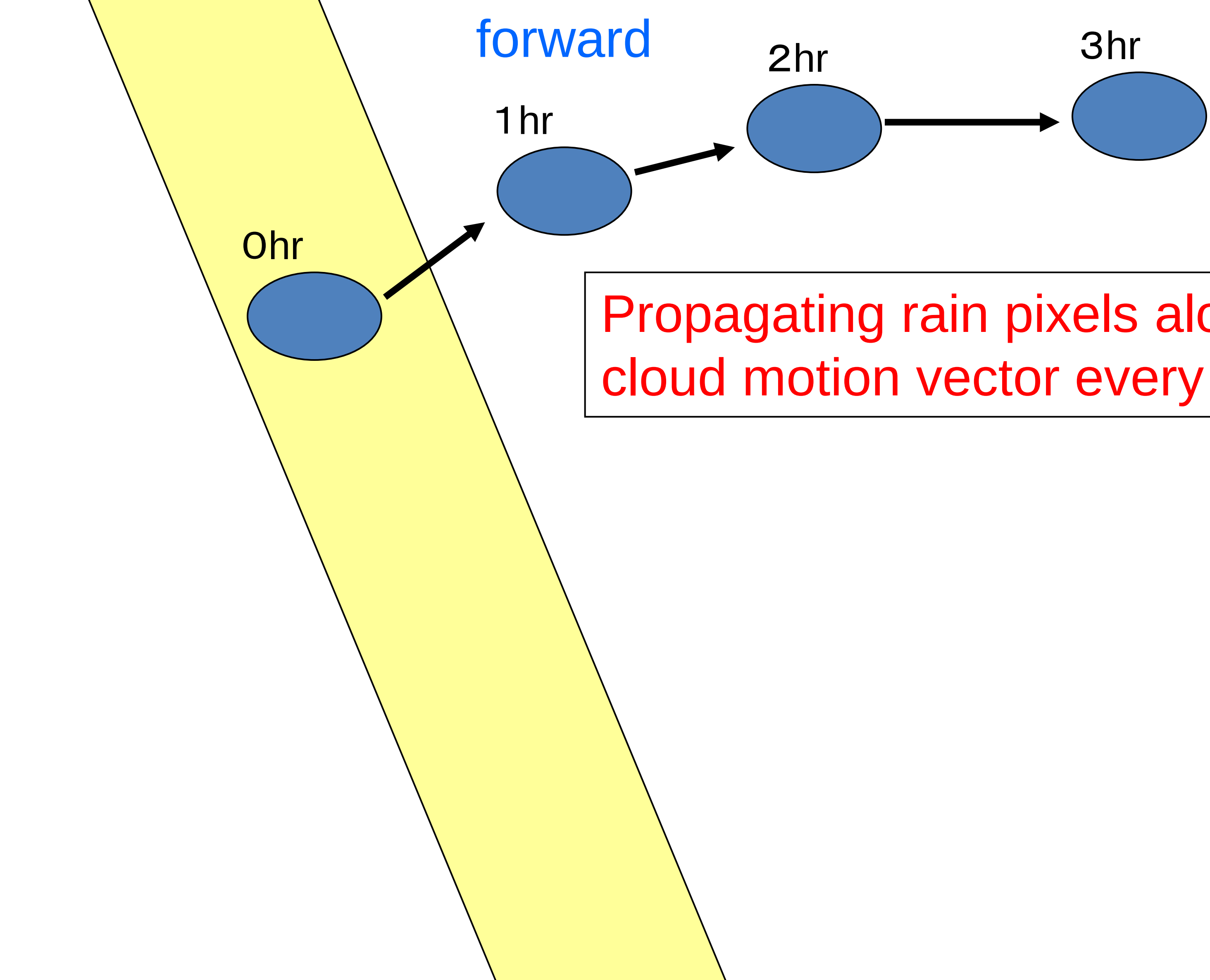
GSMaP sensors



Forward process

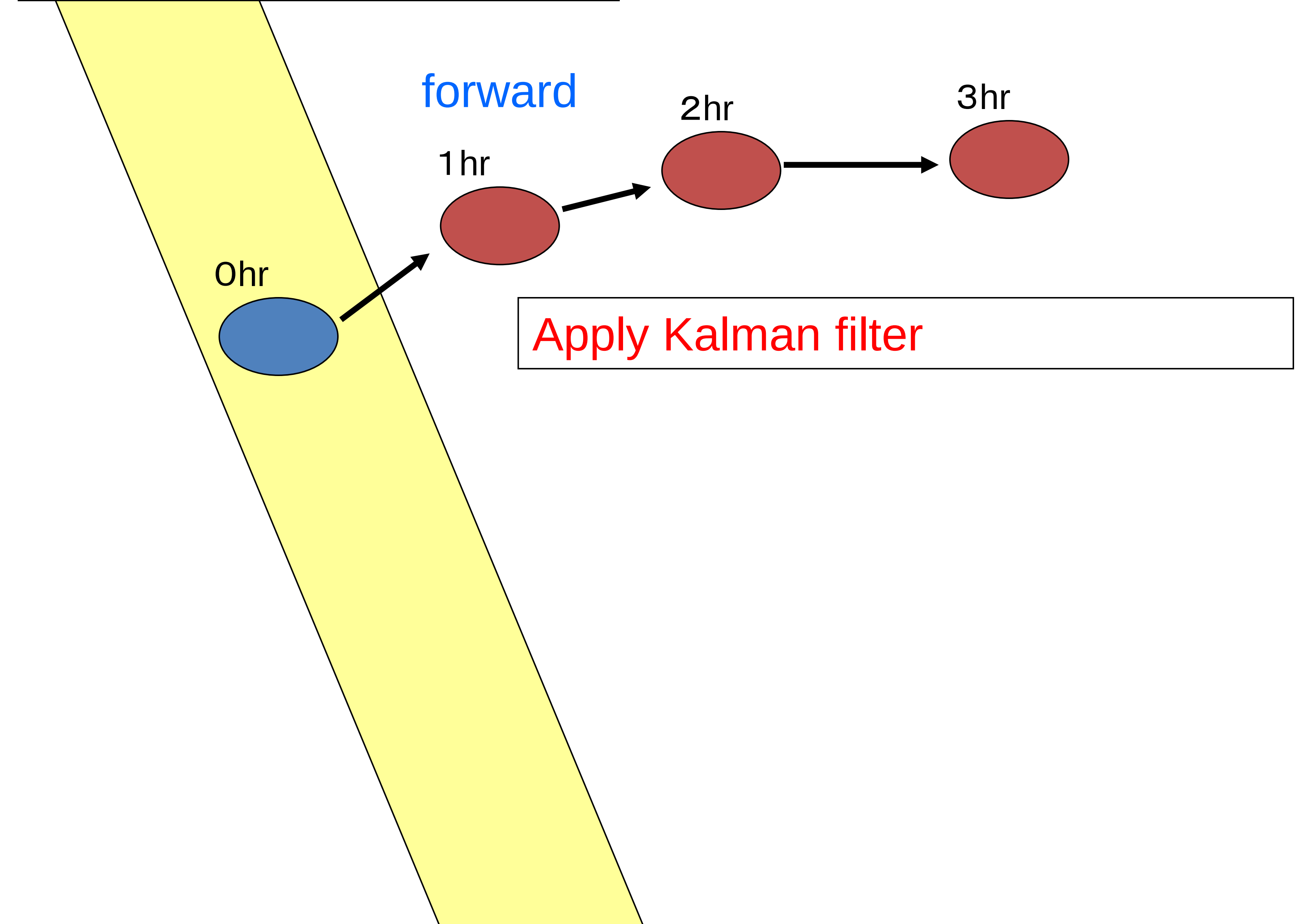


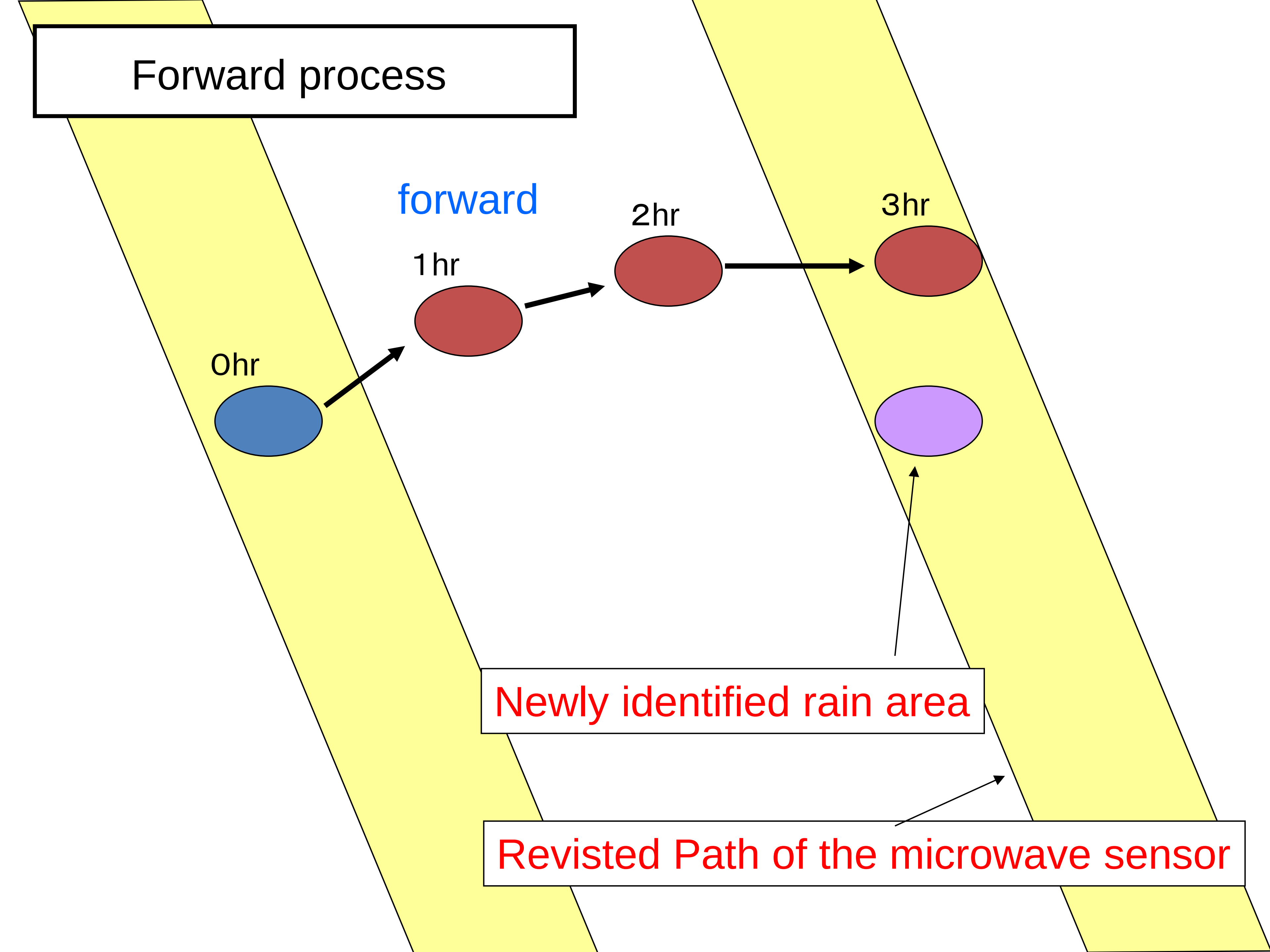
Forward process



Propagating rain pixels along with cloud motion vector every hour

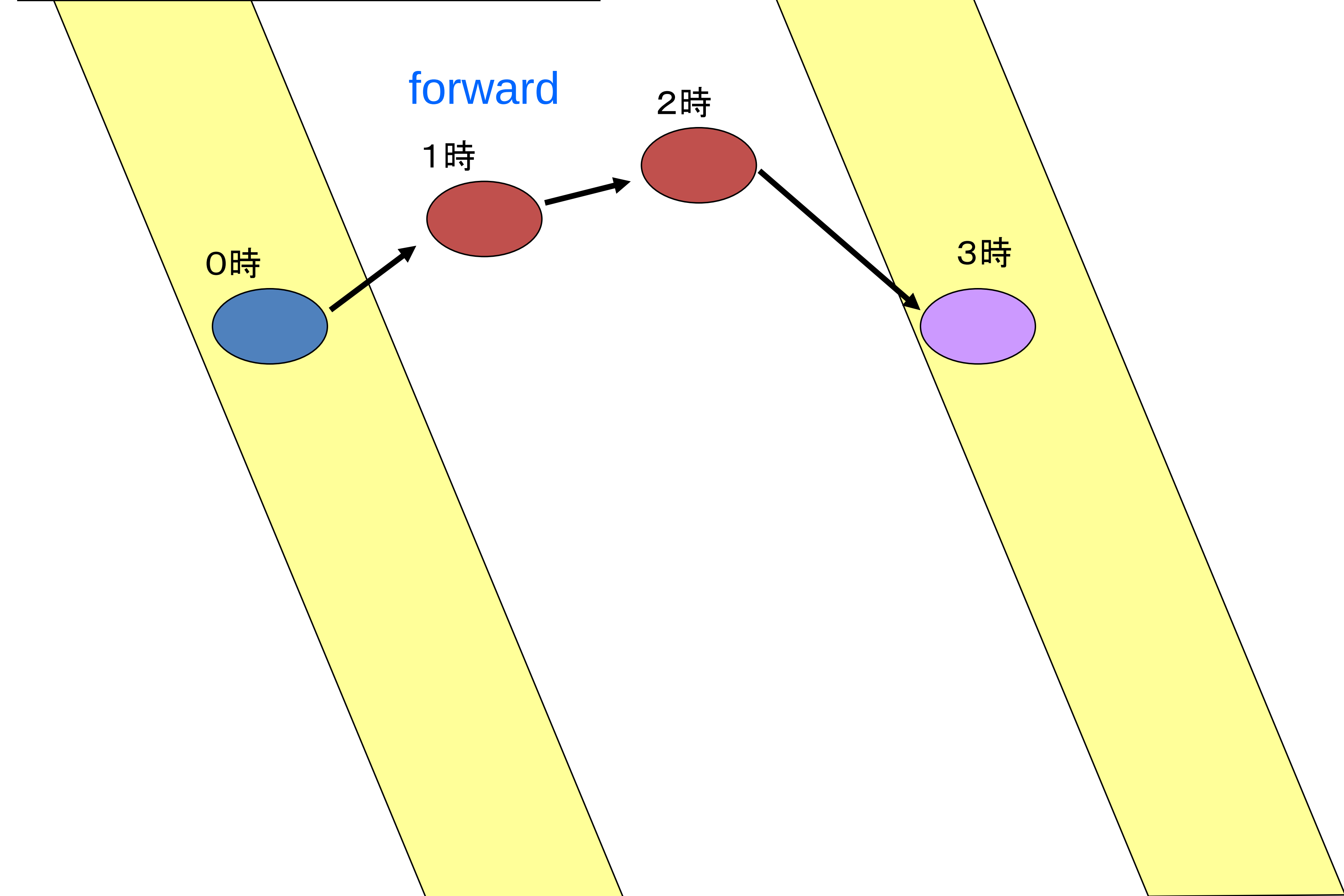
Forward process



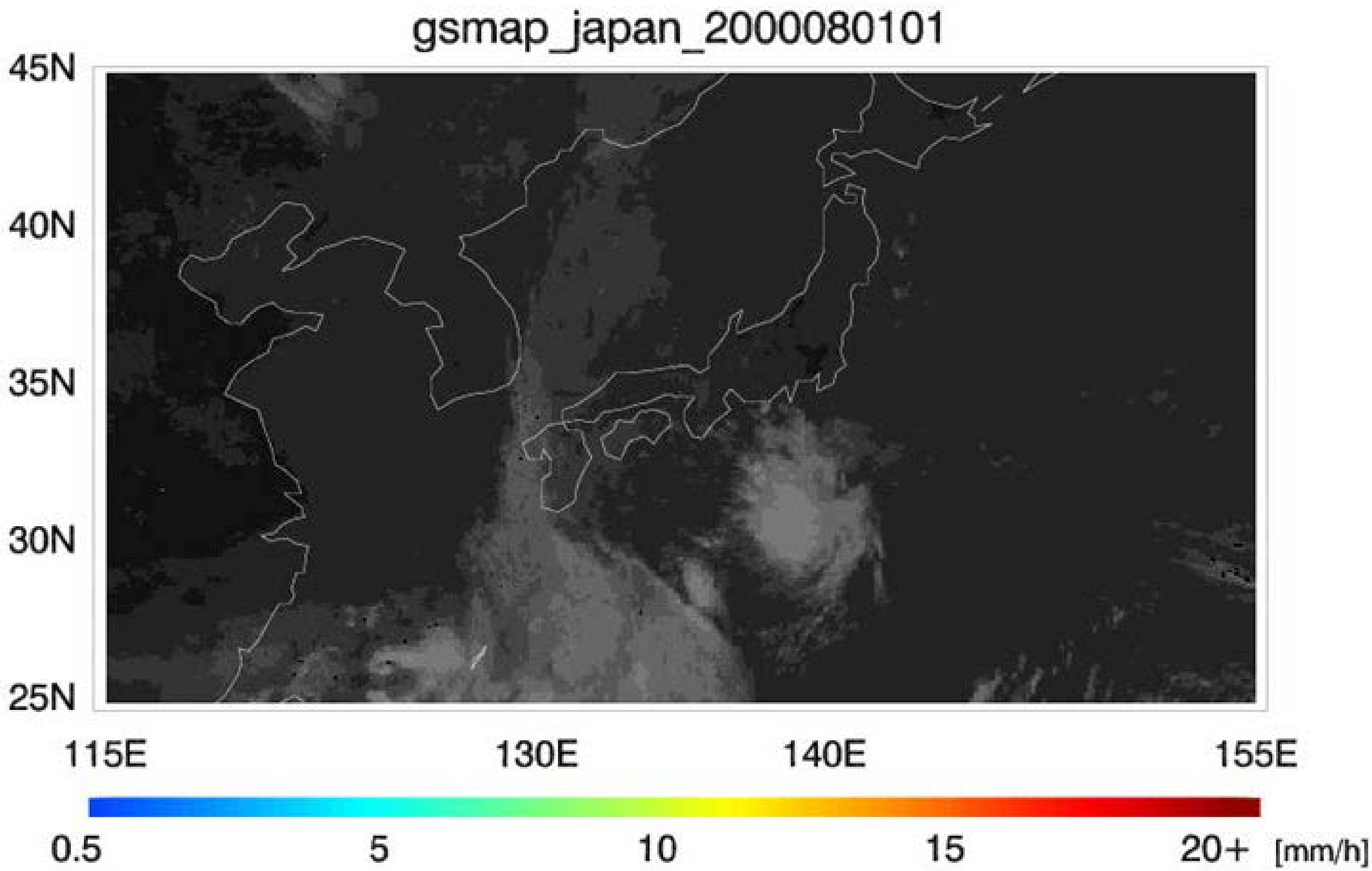


Forward process
forward
0hr
1hr
2hr
3hr
Newly identified rain area
Revisted Path of the microwave sensor

Forward process



GSMaP_NRT

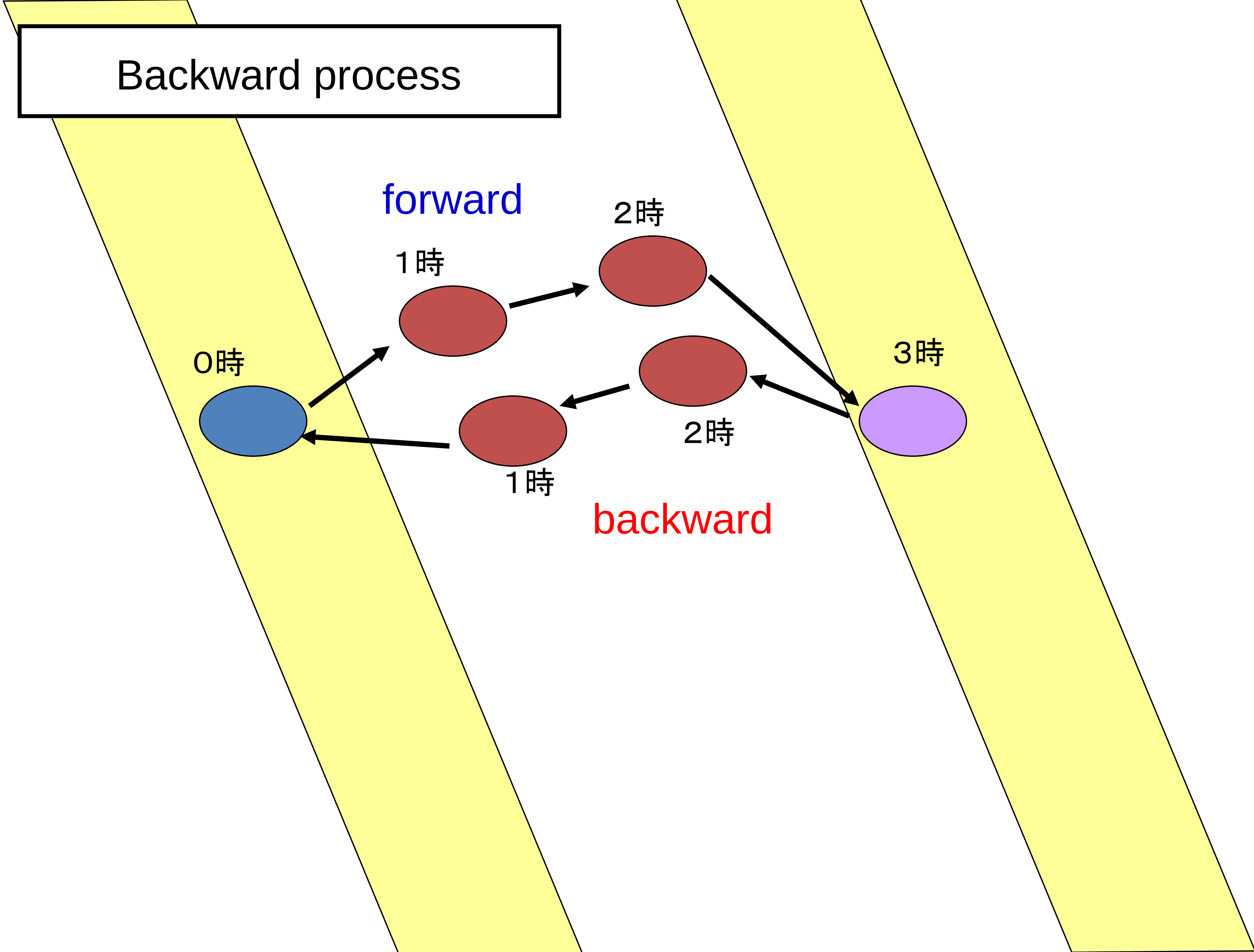


gsmap_japan_2000080101
45N
40N
35N
30N
25N
115E
130E
140E
155E
0.5
5
10
15
20+
[mm/h]

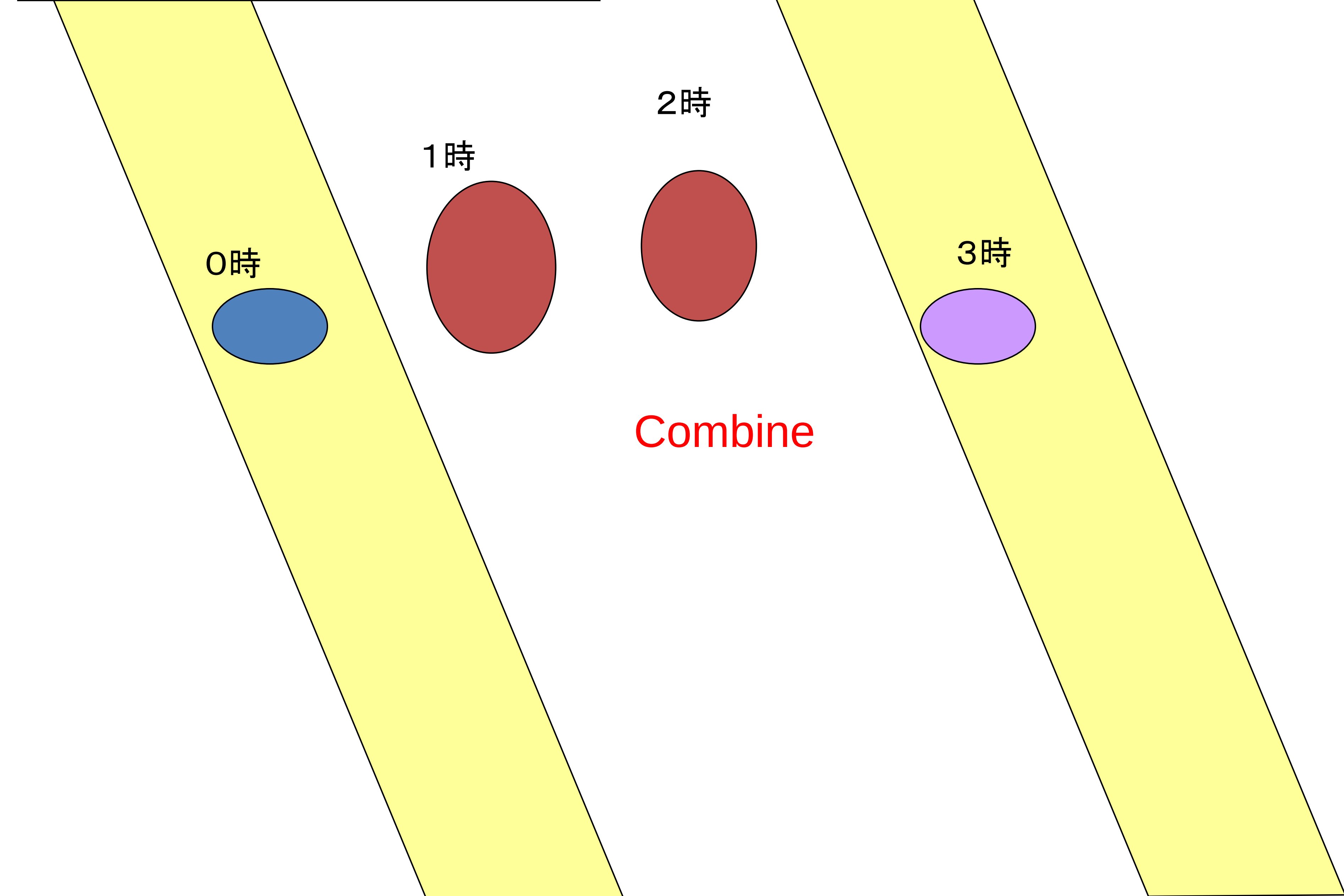
GSMaP_NRT

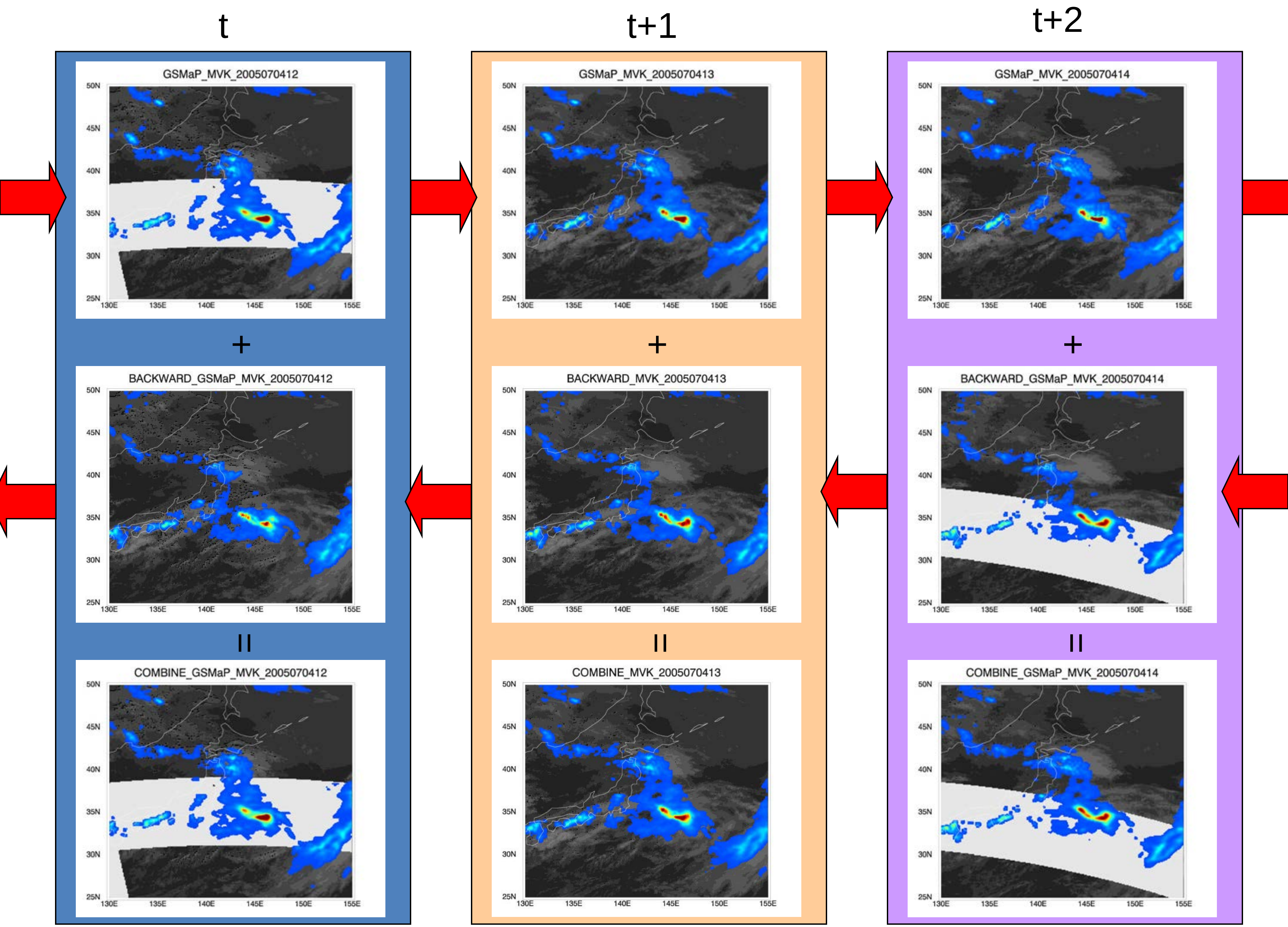
- This is the basic methodology for the GSMaP_NRT product.
- However, sometimes the error can be large for this near real time product.
- To reduce the bias error, not only the forward process but the backward process are introduced in the GSMaP_MVK product.

Backward process

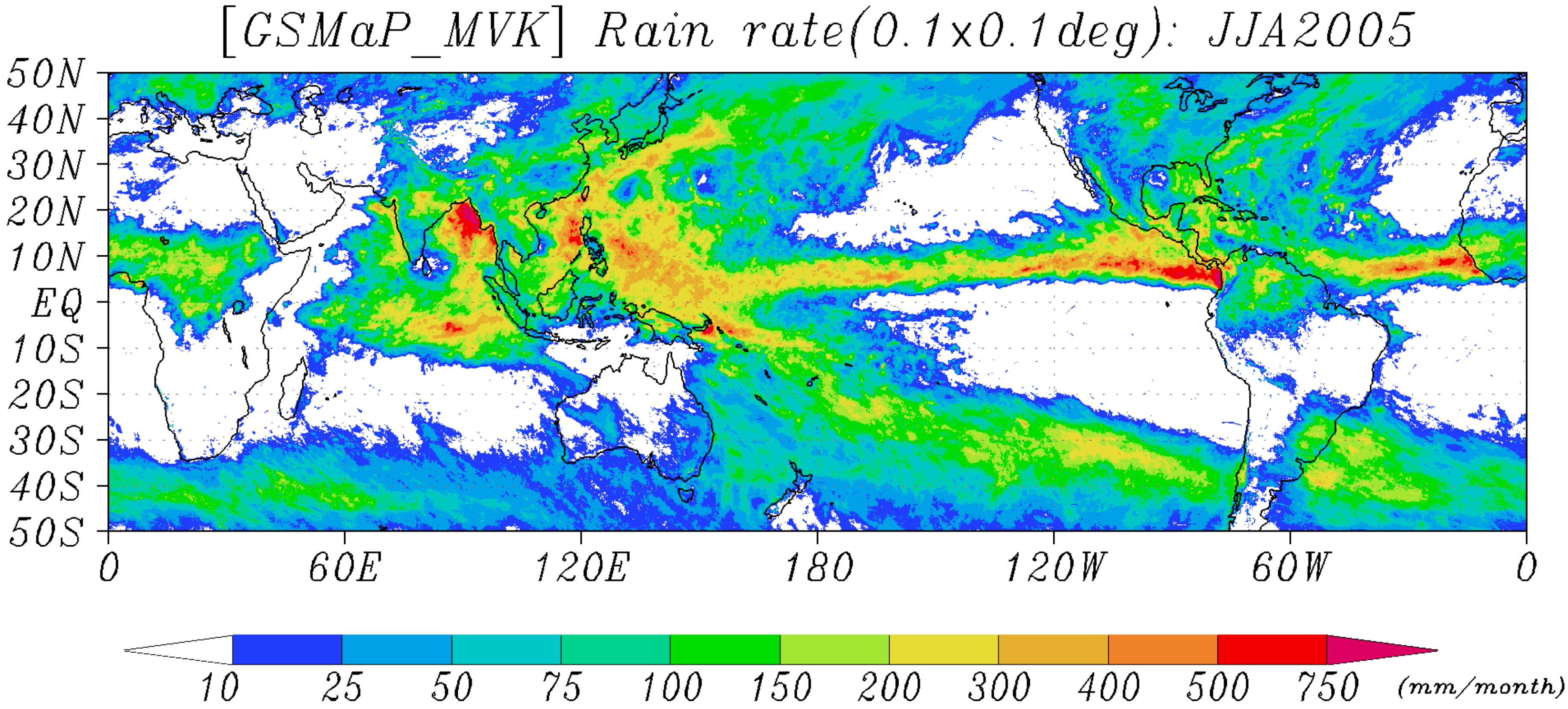


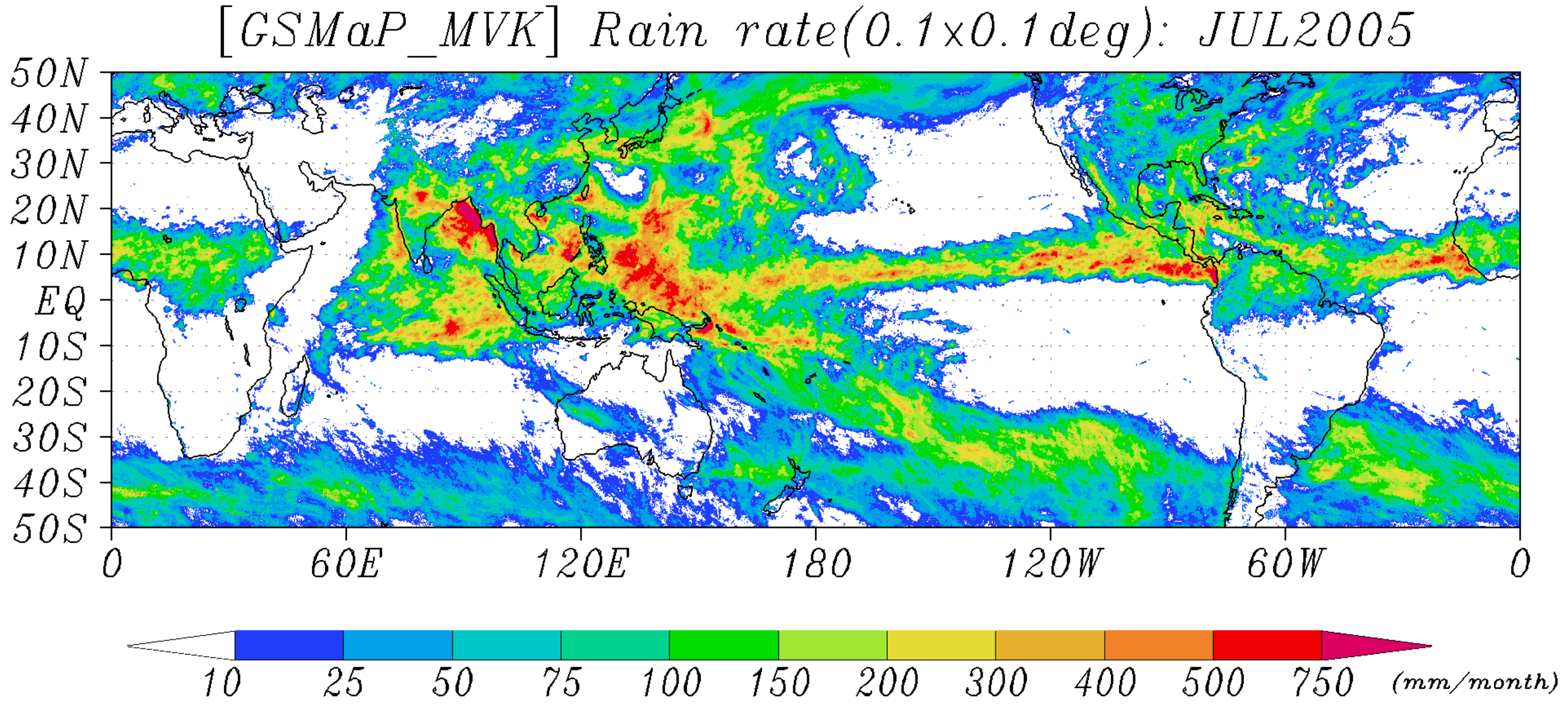
Combine



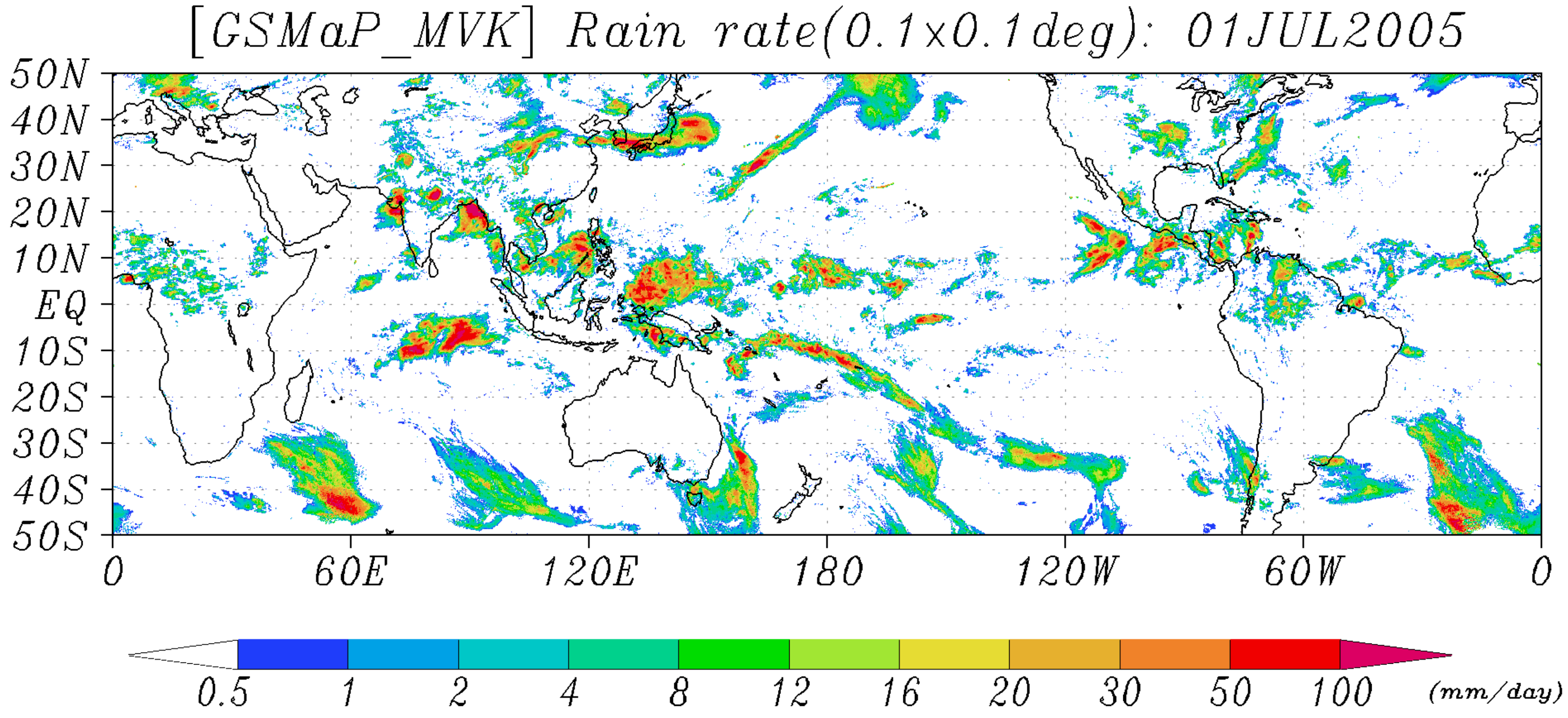


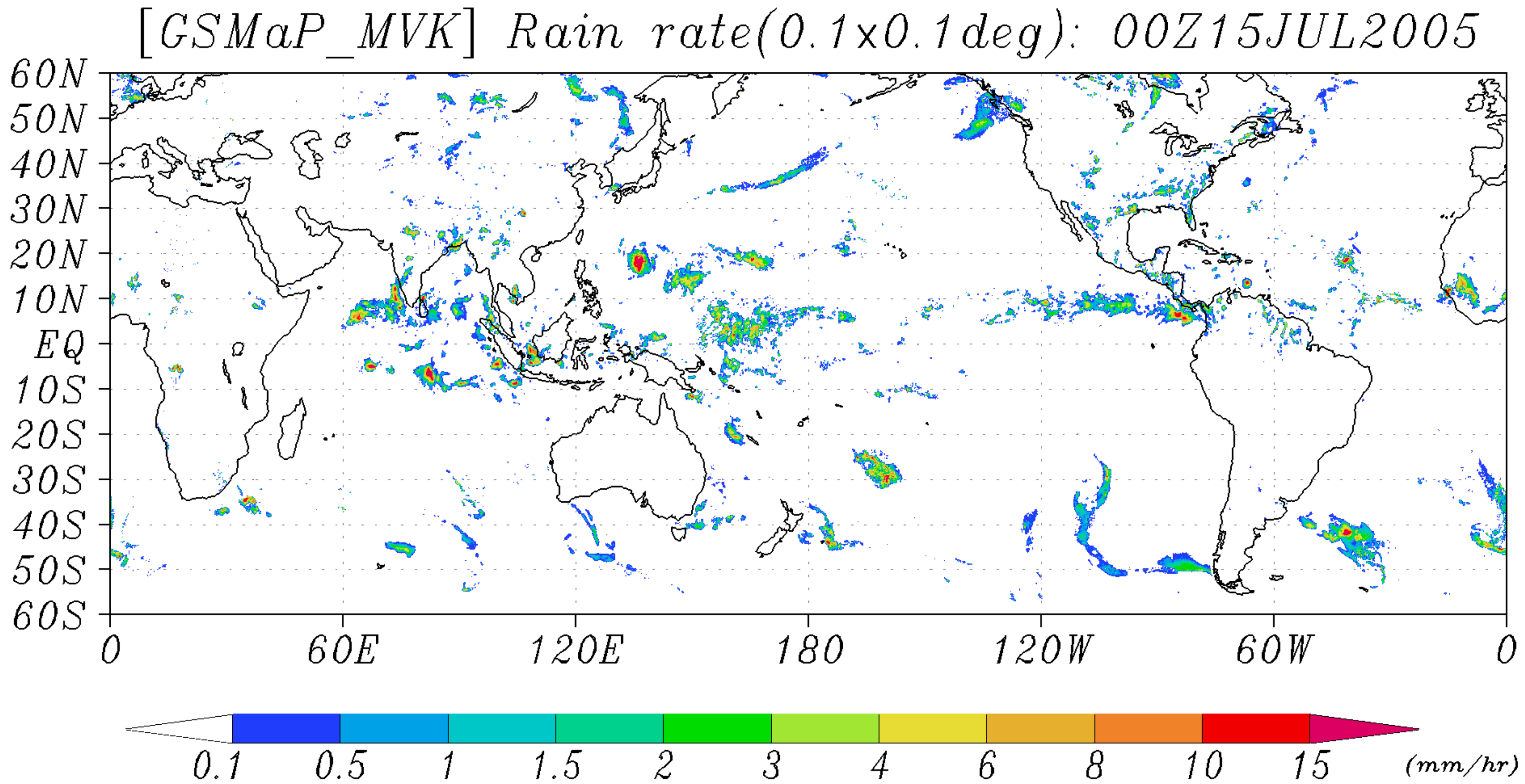
t
t+1
t+2
GSMaP_MVK_2005070412
GSMaP_MVK_2005070413
GSMaP_MVK_2005070414
+
BACKWARD_GSMaP_MVK_2005070412
BACKWARD_MVK_2005070413
BACKWARD_GSMaP_MVK_2005070414
=
COMBINE_GSMaP_MVK_2005070412
COMBINE_MVK_2005070413
COMBINE_GSMaP_MVK_2005070414
50N
45N
40N
35N
30N
25N
130E
135E
140E
145E
150E
155E


[GSMaP_MVK] Rain rate(0.1x0.1deg): JJA2005
50N
40N
30N
20N
10N
EQ
10S
20S
30S
40S
50S
0
60E
120E
180
120W
60W
0
10
25
50
75
100
150
200
300
400
500
750
(mm/month)



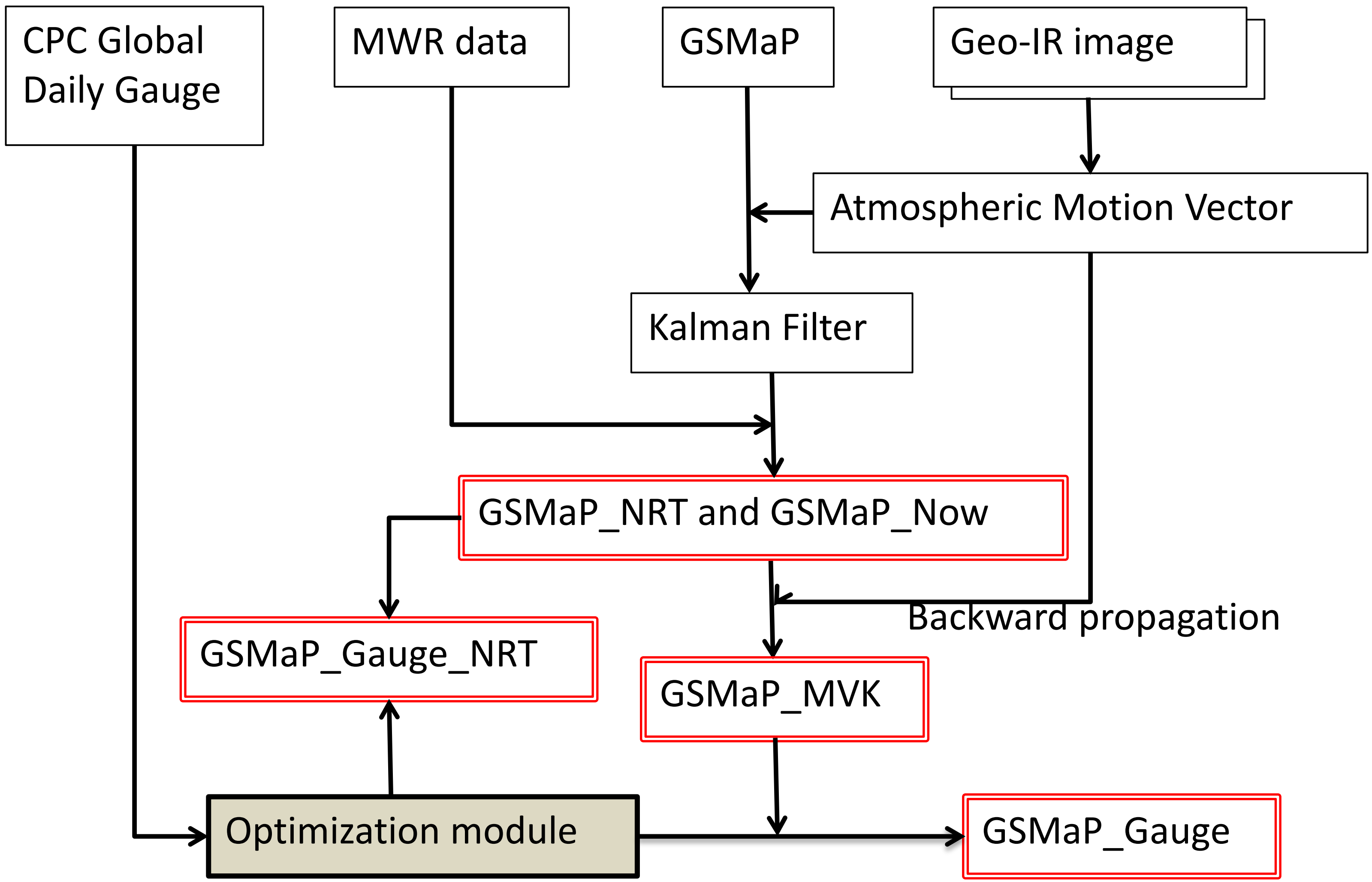
[GSMaP_MVK] Rain rate(0.1x0.1deg): JUL2005
50N
40N
30N
20N
10N
EQ
10S
20S
30S
40S
50S
0
60E
120E
180
120W
60W
0
10
25
50
75
100
150
200
300
400
500
750
(mm/month)


[GSMaP_MVK] Rain rate(0.1x0.1deg): 01JUL2005
50N
40N
30N
20N
10N
EQ
10S
20S
30S
40S
50S
0
60E
120E
180
120W
60W
0
0.5
1
2
4
8
12
16
20
30
50
100
(mm/day)

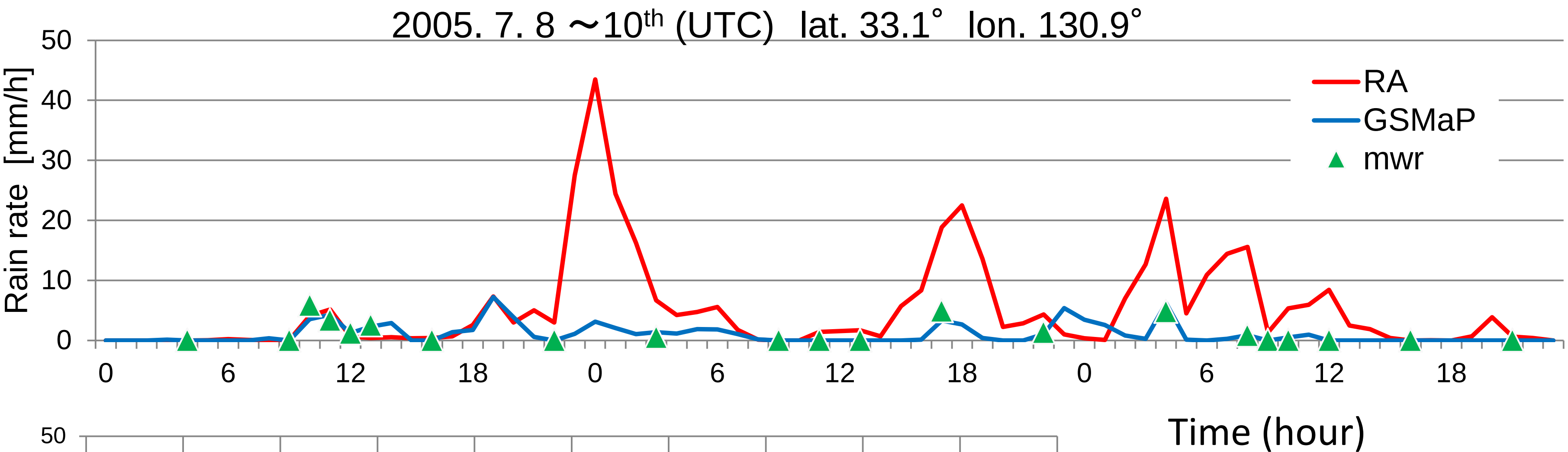


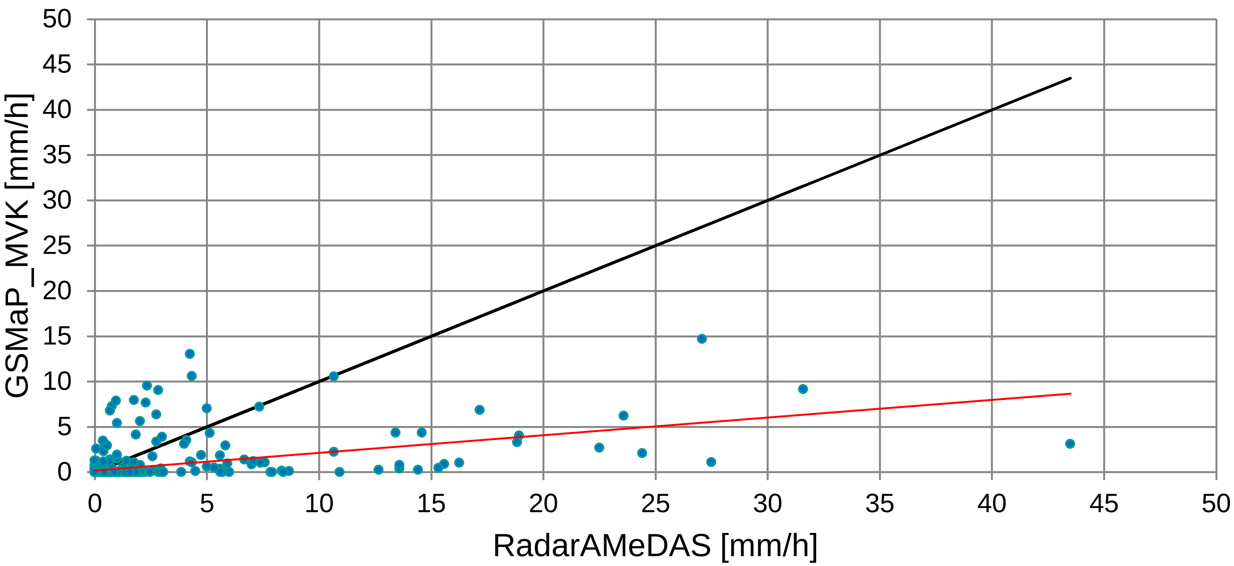
[GSMaP_MVK] Rain rate(0.1x0.1deg): 00Z15JUL2005
60N
50N
40N
30N
20N
10N
EQ
10S
20S
30S
40S
50S
60S
0
60E
120E
180
120W
60W
0
0.1
0.5
1
1.5
2
3
4
6
8
10
15
(mm/hr)

GSMaP algorithm flow



Comparison with radar-rain gauge network in Japan





- GSMaP_MVK tends to underestimate the rain fall rate with 1 hour resolution
- But, basically the GSMaP_MVK's estimates strongly depends on the estimates from microwave radiometer

What is our approach?

- Problem
  - Potential data sources for the gauge adjusted GSMaP_MVK product
    - GPCC data set
      - Monthly base/ 0.5 degree grid
      - Conversion of the time resolution of Monthly -> Hourly is difficult
    - CPC global gauge data analysis
- Solution
  - CPC global gauge data analysis by Chen et al. (2008)
  - Daily base/ 0.5 degree grid

GSMaP_Gauge algorithm

$$\begin{cases} \boldsymbol{x}_{n+1} & = \boldsymbol{x}_n + \mathcal{N}(\mu_w, \sigma_w^2) \\ \boldsymbol{y}_n & = c\boldsymbol{x}_n + \mathcal{N}(\mu_v, \sigma_v^2) \end{cases}$$

$$J(\boldsymbol{x}) = J_1(\boldsymbol{x}) + \lambda J_2(\boldsymbol{x}, W)$$

$$J_1(\boldsymbol{x}) = -\ln \Pr(\boldsymbol{x}, \boldsymbol{y})$$

$$J_2(x) = \frac{1}{2}\left(\sum_{n=1}^{24} \boldsymbol{x}_n - W\right)^2$$

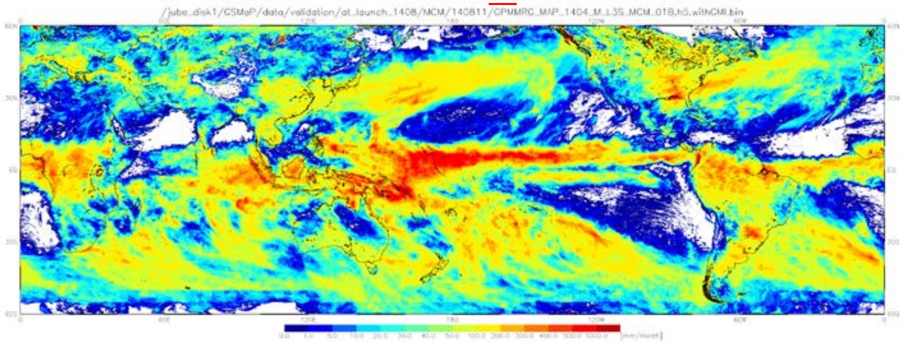
$\boldsymbol{y}_n$	:	Estimated precipitation rate (GSMaP MVK)
$\boldsymbol{x}_n$	:	Precipitation Rate
c	:	Coefficient of proportionality of the estimation of precipitation
$\mathcal{N}$	:	Standerd distribution
μ_v	:	Variance of estimation errorb
μ_w	:	Change rate of precipitation
σ_v	:	Estimation error
σ_w	:	Variance of precipitaton
W	:	Daily precipitation
n	:	hour
$\Pr(\boldsymbol{x}, \boldsymbol{y})$	:	Probability of $\boldsymbol{x}$ and $\boldsymbol{y}$ (Gaussian distribution)
λ	:	weight

- Data used in the GSMaP_Gauge algorithm
  - NOAA CPC Unified Gauge-Based Analysis of Global Daily Precipitation (CPC).
  - The data is a daily and 0.5 grid precipitation fields on a global basis.
- Based on the assumption that the GSMaP_Gauge – CPC Gauge data (Gauge term) has the gaussian distribution, the probability density function of the GSMaP_Gauge estimation multiplied by the Gauge term is maximized

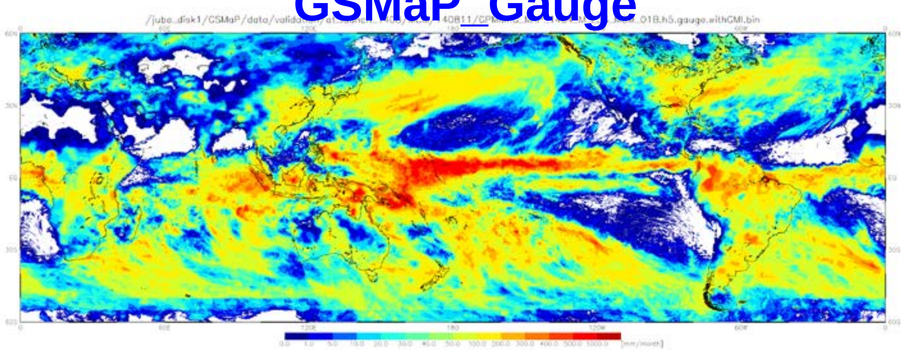
Example of GPM-GSMaP monthly

- Monthly Mean in April 2014（V03A）

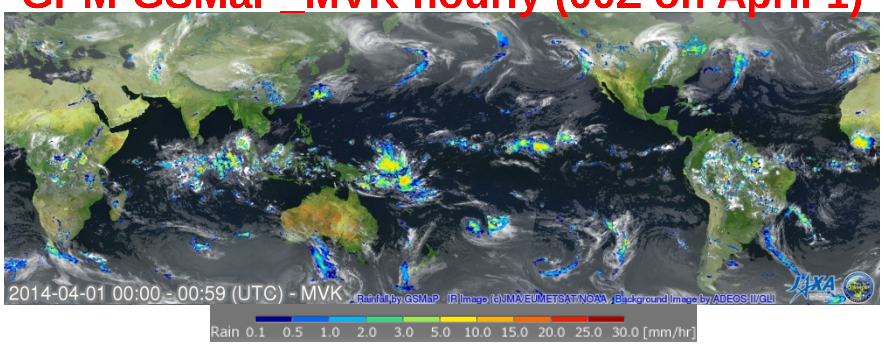
GSMaP_MVK



GSMaP_Gauge

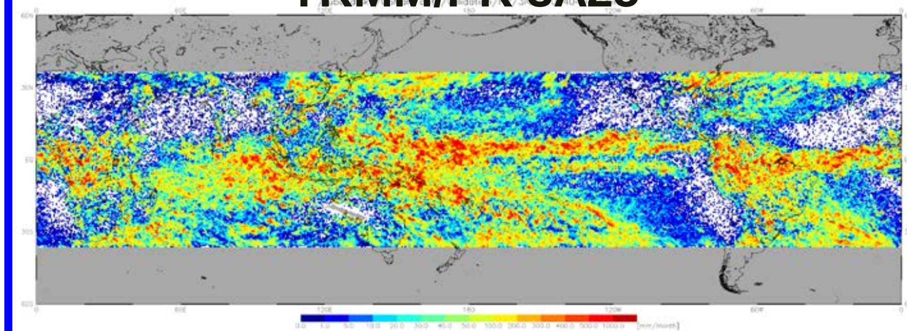


GPM-GSMaP_MVK hourly (00Z on April 1)

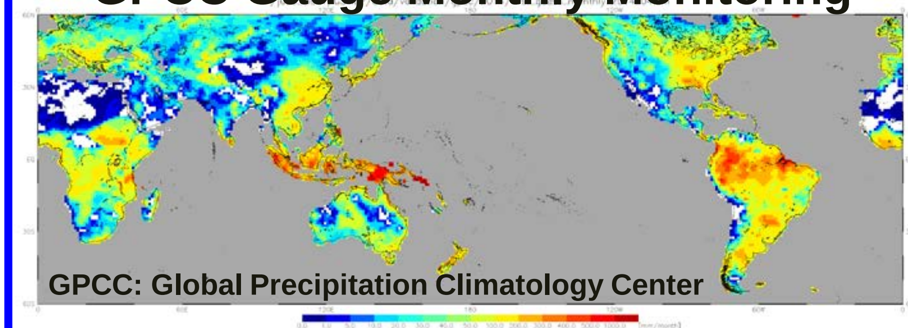


Reference

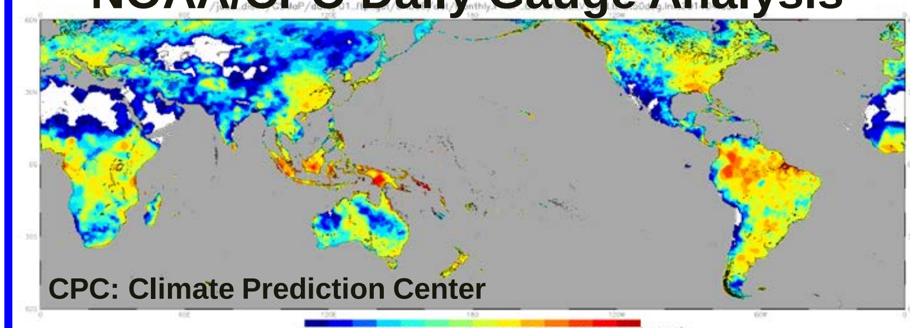
TRMM/PR 3A25



GPCC Gauge Monthly Monitoring

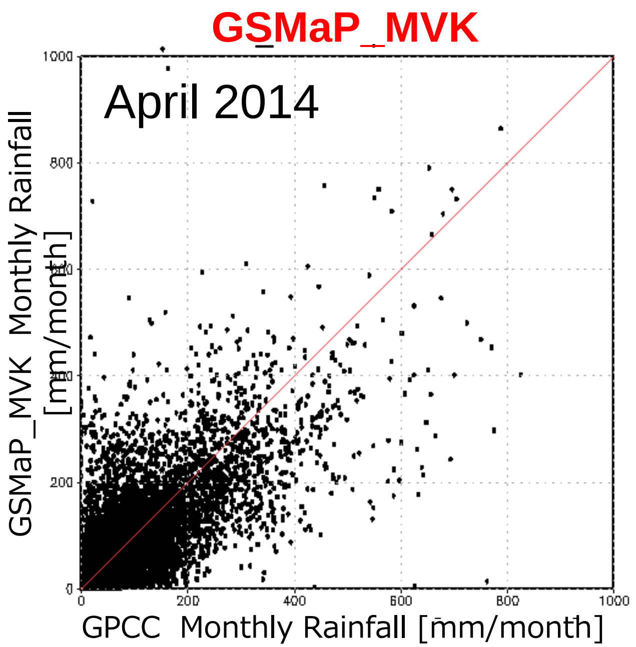


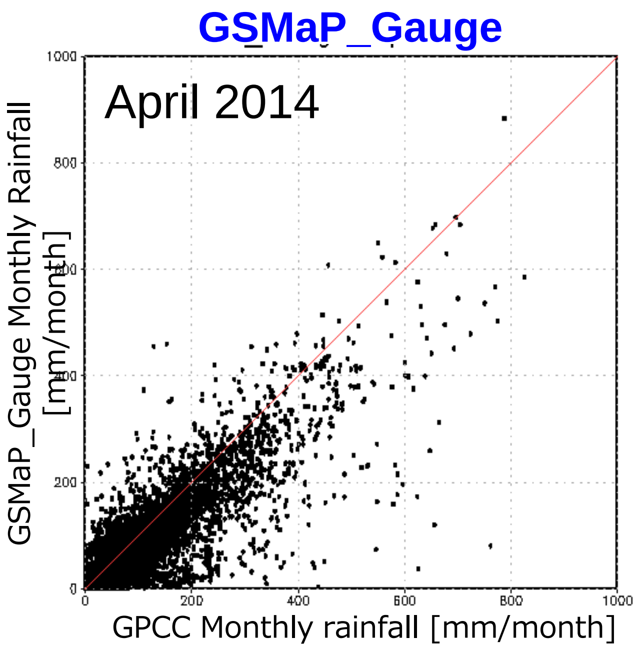
NOAA/CPC Daily Gauge Analysis



Evaluation of GPM-GSMaP

- GPM-GSMaP compared with GPCC Monthly accumulated Gauge data. GSMaP_Gauge (calibrated by NOAA CPC Daily Gauge Analysis) shows 20-30% better accuracy in RMSE than GSMaP_MVK.





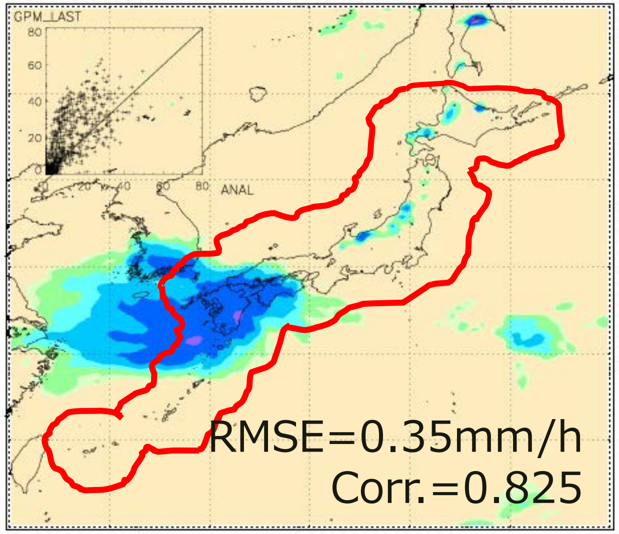
	GSMaP_MVK [mm/month]			GSMaP_Gauge [mm/month]		
	Bias	R	RMSE	Bias	R	RMSE
April 2014	-0.54	0.73	62.45	-15.58	0.88	44.26
May 2014	1.64	0.68	72.22	-17.93	0.87	47.99
June 2014	-4.40	0.69	83.10	-12.70	0.82	64.16

Evaluation of GPM-GSMaP

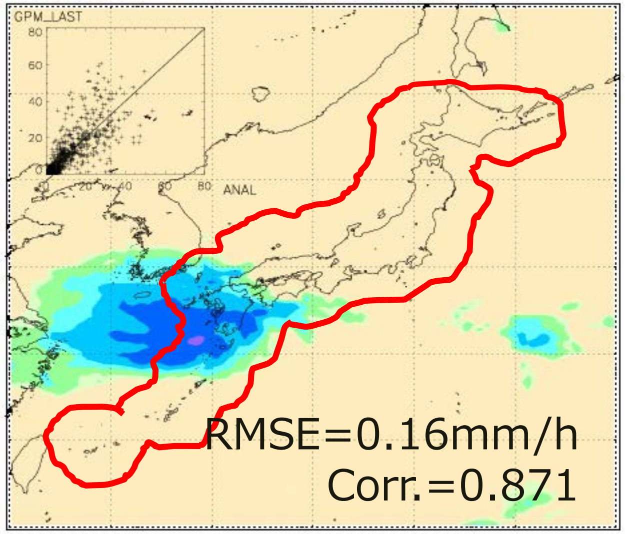
- Daily averaged rainfall around Japan in 0.25 degree grid was compared with JMA's Radar AMeDAS (gauge-calibrated radar analysis rainfall).

An example on Apr. 12, 2014

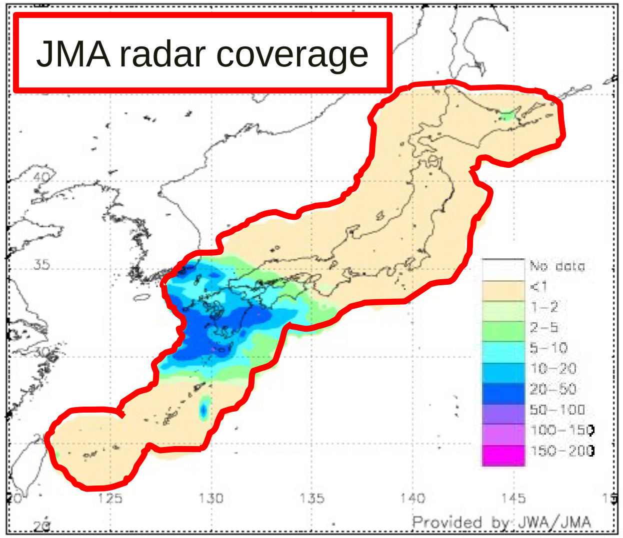
GSMaP_MVK



GSMaP_Gauge



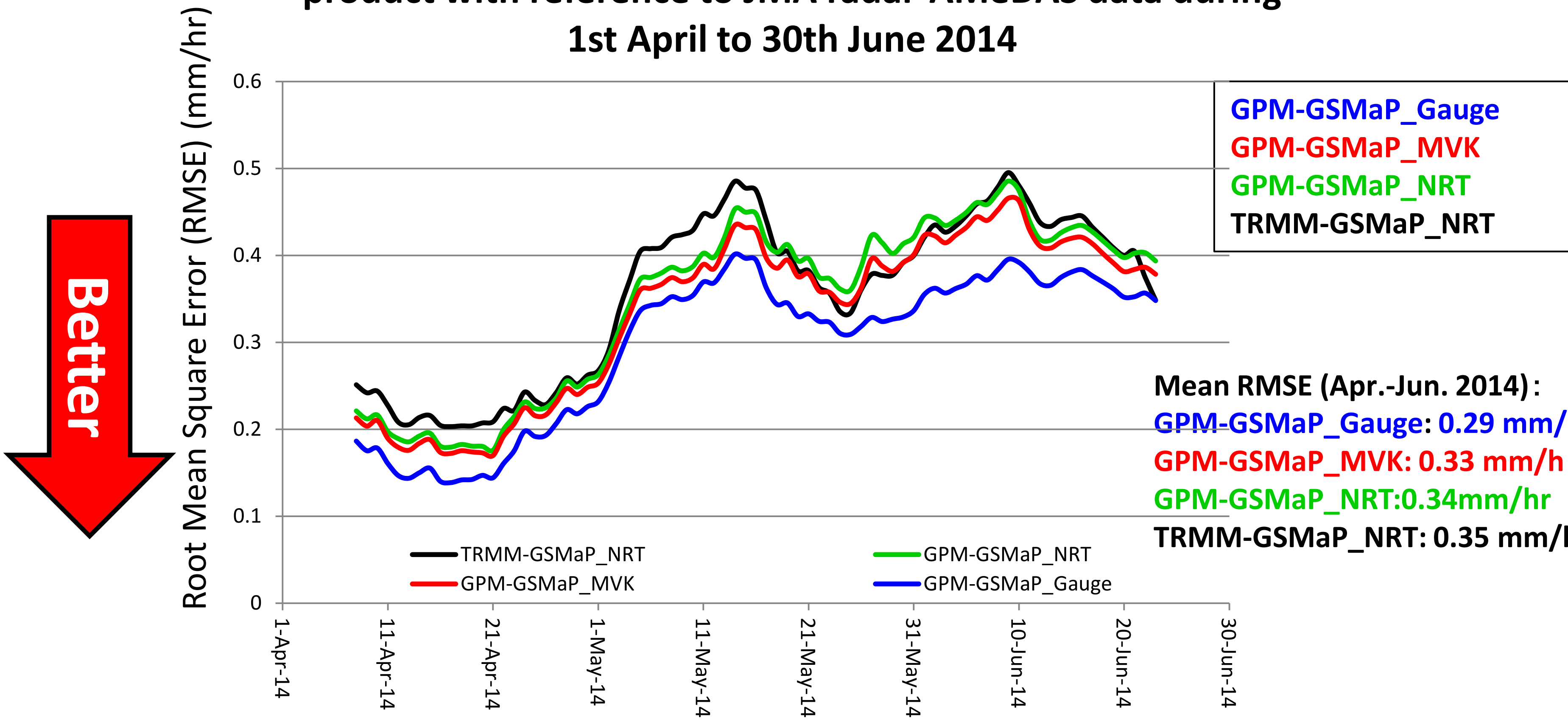
Gauge-Radar Analysis



→ **GSMaP_Gauge** shows better correlation with less Root Mean Square Error (RMSE) on Apr. 12, 2014.

Evaluations by RMSE

Daily series of Root Mean Square Error (RMSE) for GSMaP product with reference to JMA radar-AMeDAS data during 1st April to 30th June 2014



Mean RMSE (Apr.-Jun. 2014):
GPM-GSMaP_Gauge: 0.29 mm/h
GPM-GSMaP_MVK: 0.33 mm/h
GPM-GSMaP_NRT:0.34mm/hr
TRMM-GSMaP_NRT: 0.35 mm/h

- **GSMaP_Gauge** shows the least RMSE.
- GSMaP_Gauge algorithm is working well.

However…..

- GSMaP_Gauge has latencies of a few days.
- The latencies of the GSMaP_Gauge sometimes cause problem for real time applications (ex. Flash flood warning system…).
- I received so many requests for real time version of the GSMaP_Gauge product.

GSMaP_Gauge_NRT algorithm

$$
\begin{cases}
\boldsymbol{x}_{n+1} & = \boldsymbol{x}_n + \mathcal{N}(\mu_w, \sigma_w^2) \\
\boldsymbol{y}_n & = c\boldsymbol{x}_n + \mathcal{N}(\mu_v, \sigma_v^2)
\end{cases}
$$

$J(\boldsymbol{x}) = J_1(\boldsymbol{x})$ ~~$+ \lambda J_2(\boldsymbol{x}, W)$~~

$$J_1(\boldsymbol{x}) = -\ln \Pr(\boldsymbol{x}, \boldsymbol{y})$$

~~$J_2(\boldsymbol{x}) = \frac{1}{2}\left(\sum_{n=1}^{24} \boldsymbol{x}_n - W\right)^2$~~

$\boldsymbol{y}_n$	: Estimated precipitation rate (GSMaP MVK)
$\boldsymbol{x}_n$	: Precipitation Rate
c	: Coefficient of proportionality of the estimation of precipitation
$\mathcal{N}$	: Standerd distribution
μ_v	: Variance of estimation errorb
μ_w	: Change rate of precipitation
σ_v	: Estimation error
σ_w	: Variance of precipitaton
W	: Daily precipitation
n	: hour
'r$(\boldsymbol{x}, \boldsymbol{y})$	: Probability of $\boldsymbol{x}$ and $\boldsymbol{y}$ (Gaussian distribution)
λ	: weight

In the real time product, unfortunately, we do not have real time gauge data.
Instead, we prepare the data base which characterize the precipitation in this model. Those are sigmaw, sigmav and c.

GSMaP Gauge

x : True precipitation rate

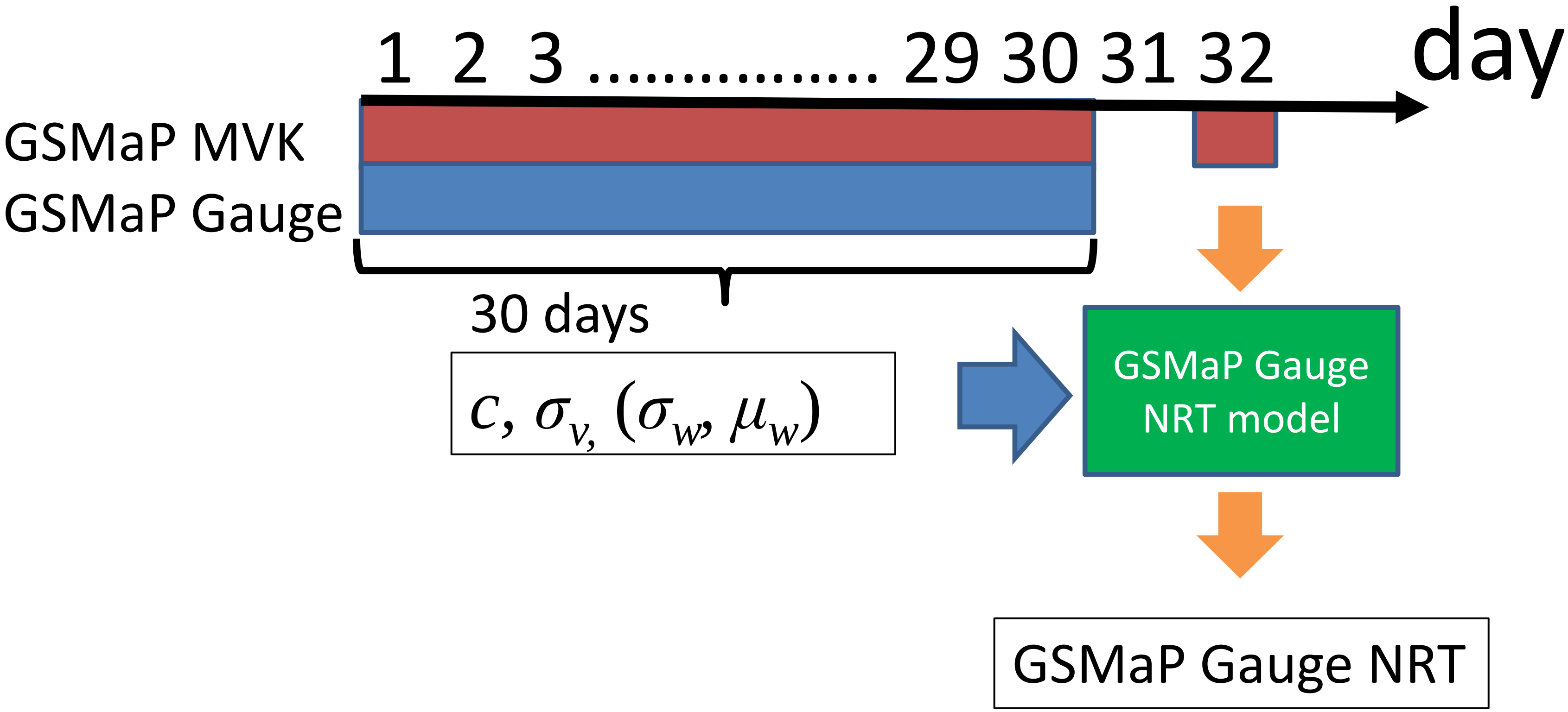
y: Observation

In order to have the model parameters (N, C) in GSMaP Gauge NRT,

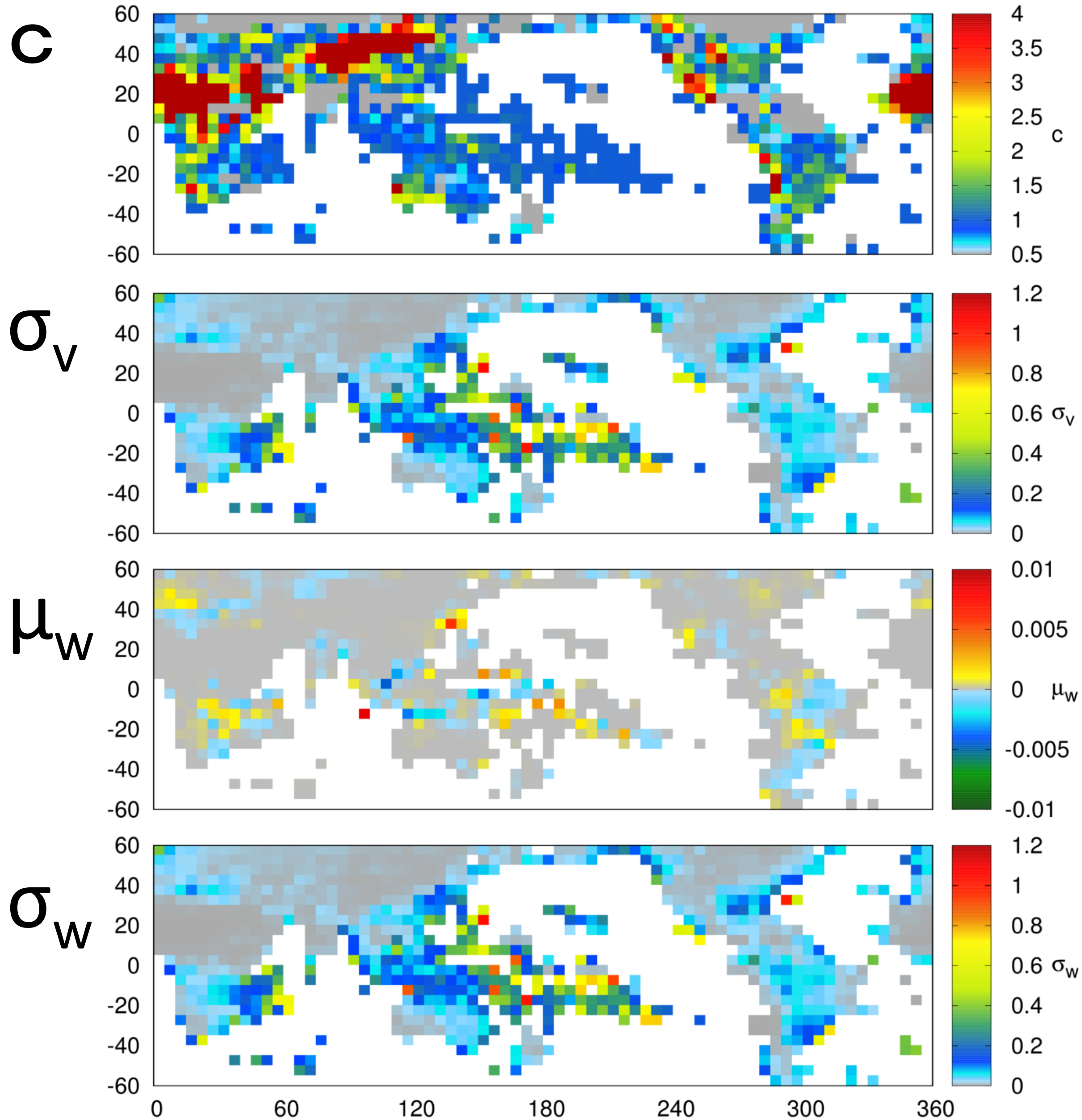
x : GSMaP Gauge precipitation rate

y: GSMaP MVK precipitation rate

How to get model parameters



Distribution of Parameters of GSMaP Gauge NRT



GSMaP Gauge

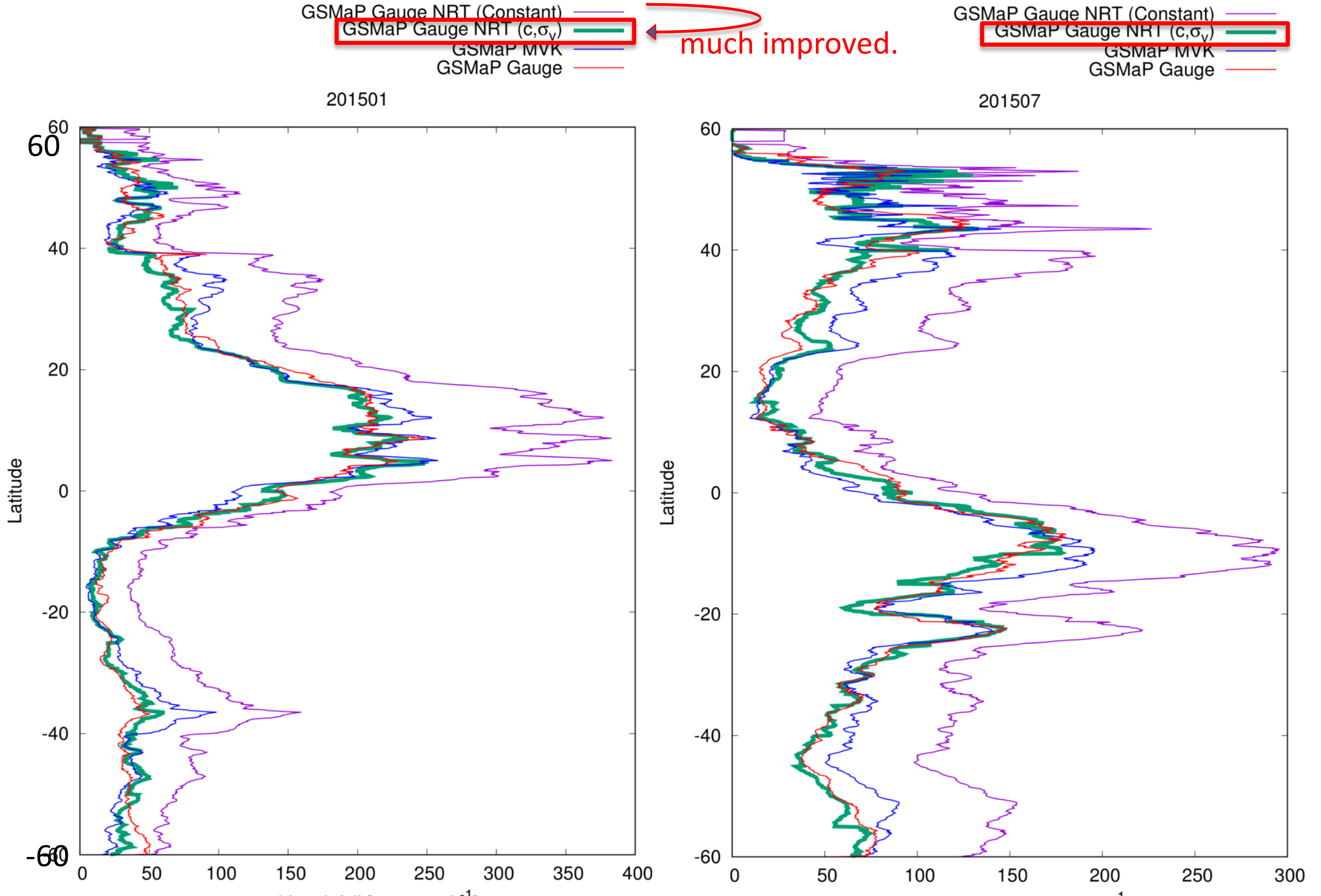
c : 0.7

σ_v : 1.0

μ_w : 0

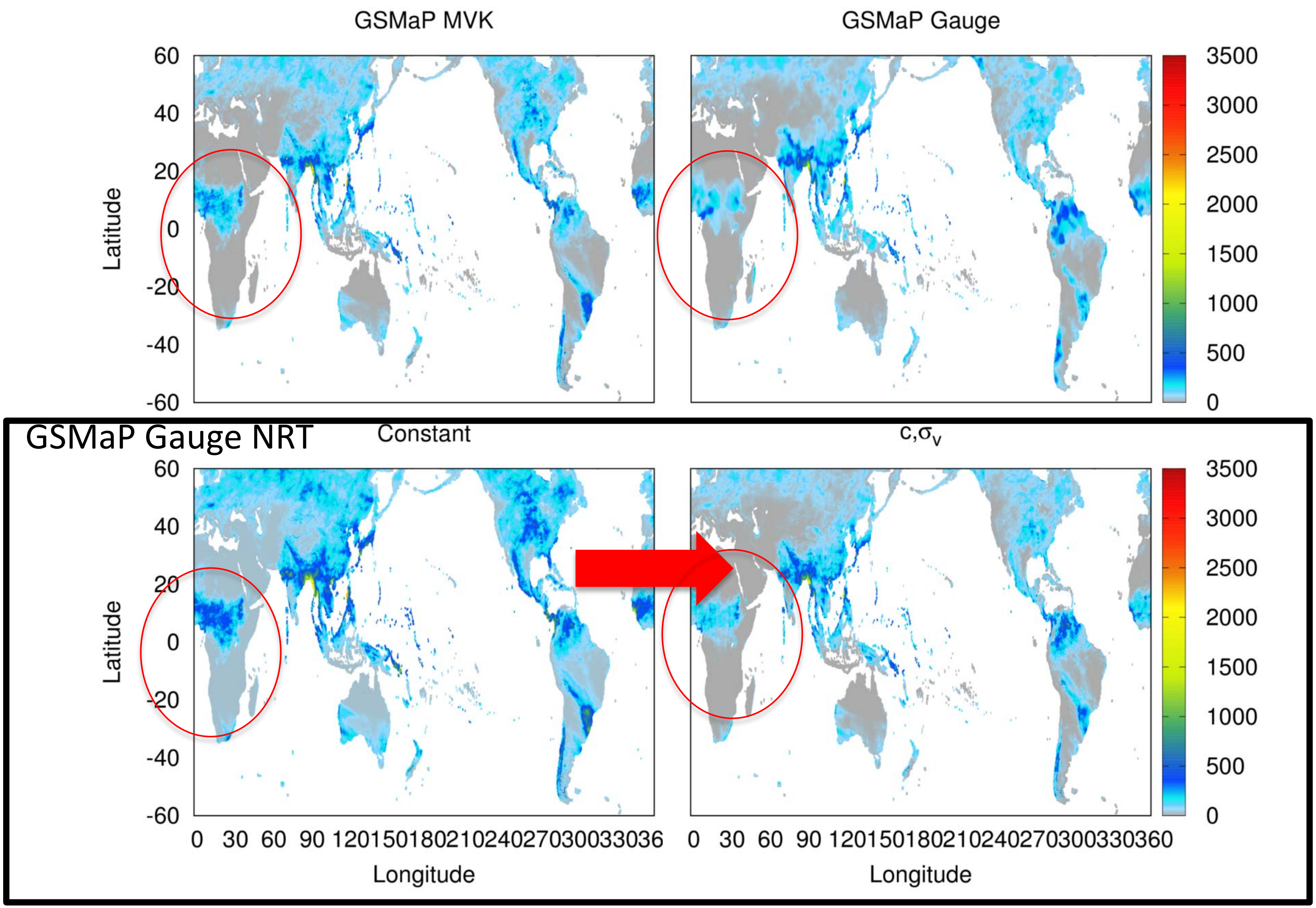
σ_w :1.5

Zonal Mean



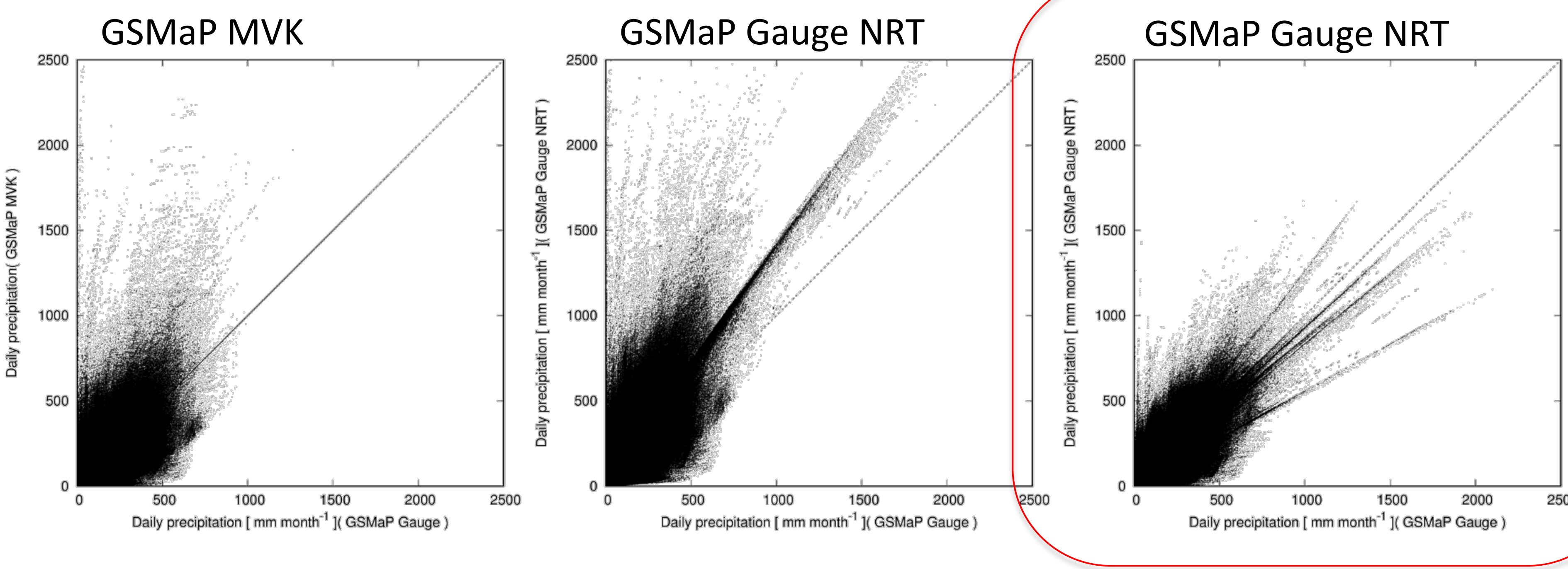
GSMaP Gauge NRT (Constant)
GSMaP Gauge NRT (c,σv)
GSMaP MVK
GSMaP Gauge
much improved.
201501
201507
Latitude
60
40
20
0
-20
-40
-60
0
50
100
150
200
250
300
350
400

Monthly rainfall distribution, June 2015



Daily precipitation amount, January 2015

Vs GSMaP Gauge



	Correlation	RMSE	Coefficient of regression line
GSMaP MVK	0.844	40.3	0.894
Gauge NRT (Constant)	0.853	62.3	1.26
Gauge NRT (c, σ_v)	0.873	34.0	0.873

Current GSMaP products

- GSMaP_MWR
  - Microwave radiometer product
- GSMaP_MVK
  - Global precipitation mapping from microwave and infrared radiometric data
- GSMaP_Gauge
  - Gauge adjusted GSMaP_MVK
- GSMaP_NRT and GSMaP_Now
  - Near real time version of the GSMaP_MVK product
- GSMaP_Gauge_NRT
  - Near real time product of GSMaP_Gauge

Summary and Conclusions

- Methodology and algorithm structure of the high resolution GSMaP was described.

System Model of the GSMaP_Gauge product

$$\begin{cases} a_{n+1} = a_n + w_n \\ x_n = \alpha a_n + v_n \\ \sum_{n=1}^{24} a_n = W \end{cases}$$

a: Rain rate at each pixel

W: Rain rate from CPC global gauge data sets

n: Time, a: Rain rate from GSMaP_Gauge

x: Rain rate from GSMaP_MVK, v, w: Noise

$w_n \approx N(\mu_w, \sigma_w^2) \qquad v_n \approx N(\mu_v, \sigma_v^2)$

System Model of the GSMaP_Gauge product

$$\begin{cases} a_{n+1} = a_n + w_n \\ x_n = \alpha a_n + v_n \end{cases}$$

a: Rain rate at each pixel

W: Rain rate from CPC global gauge data sets

n: Time, a: Rain rate from GSMaP_Gauge

x: Rain rate from GSMaP_MVK, v, w: Noise

$w_n \approx N\left(\mu_w, \sigma_w^2\right) \qquad v_n \approx N\left(\mu_v, \sigma_v^2\right)$

$$L(a) = -\ln \Pr(\mathbf{x}, \mathbf{a}) = -\ln\left[\Pr(a_1)\prod_{m=1}^{24}\Pr(a_m | a_{m-1})\prod_{n=1}^{24}\Pr(x_n | a_n)\right]$$

System Model of the GSMaP_Gauge product

$$\begin{cases} a_{n+1} = a_n + w_n \\ x_n = \alpha a_n + v_n \\ \sum_{n=1}^{24} a_n = W \end{cases}$$

a: Rain rate at each pixel

W: Rain rate from CPC global gauge data sets

n: Time, a: Rain rate from GSMaP_Gauge

x: Rain rate from GSMaP_MVK, v, w: Noise

$w_n \approx N\left(\mu_w, \sigma_w^2\right) \qquad v_n \approx N\left(\mu_v, \sigma_v^2\right)$

Cost Function

Gauge term

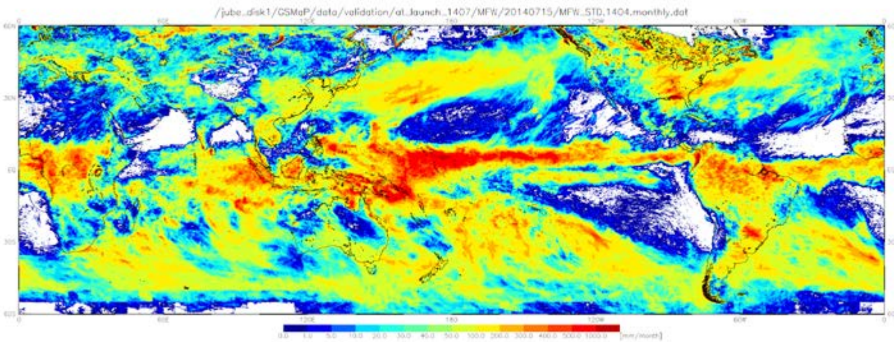
$$L(a) = -\ln\left\{ \Pr(\mathbf{x},\mathbf{a}) \times e^{\frac{\lambda}{2}\left(\sum_{n=1}^{N} a_n - W\right)^2} \right\}$$

$$= -\ln\left[\Pr(a_1)\prod_{m=1}^{24}\Pr(a_m | a_{m-1})\prod_{n=1}^{24}\Pr(x_n | a_n) \times e^{\frac{\lambda}{2}\left(\sum_{n=1}^{N} a_n - W\right)^2} \right]$$

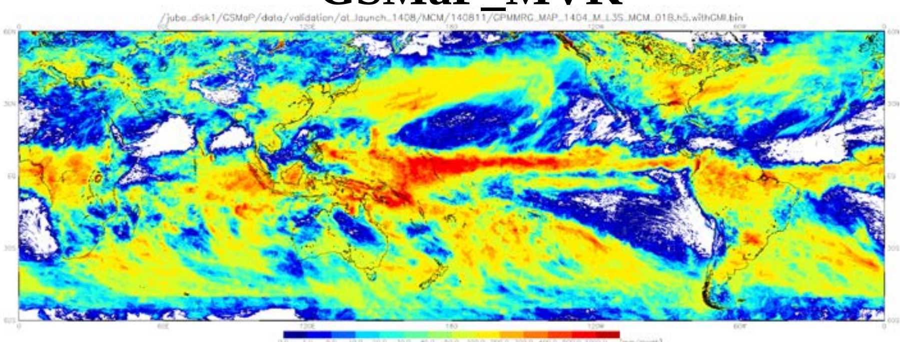
- In a word, based on the assumption that the GSMaP_Gauge – CPC Gauge data (Gauge term) has the gaussian distribution, we maximize the probability density function of the GSMaP_Gauge estimation multiplied by the Gauge term.
- The solution can be determined by calculating the dL/da = 0 equation

Examples

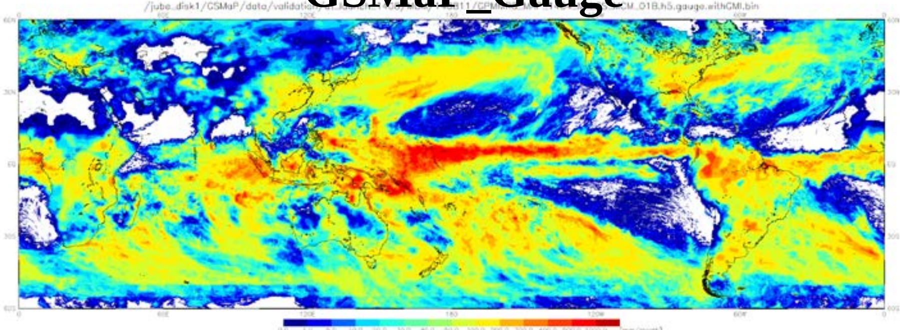
GSMaP_NRT (FW)



GSMaP_MVK

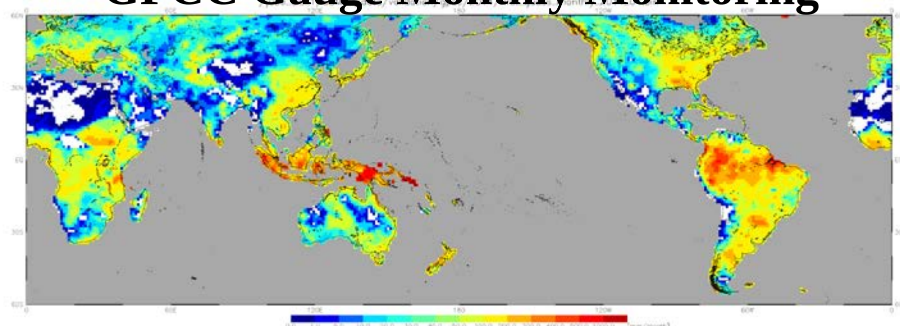


GSMaP_Gauge

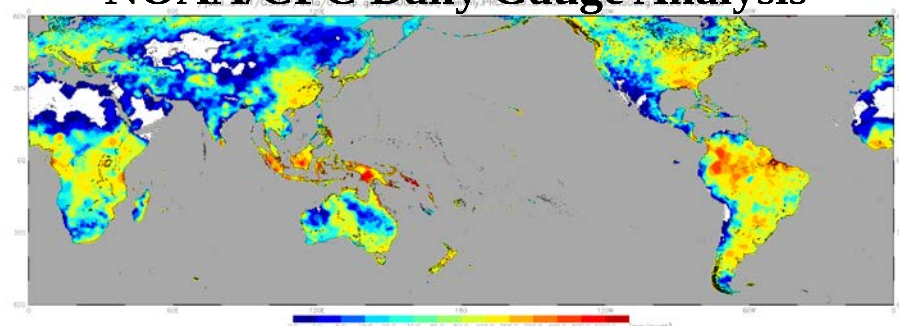


Monthly Mean in April 2014（V03A）

GPCC Gauge Monthly Monitoring



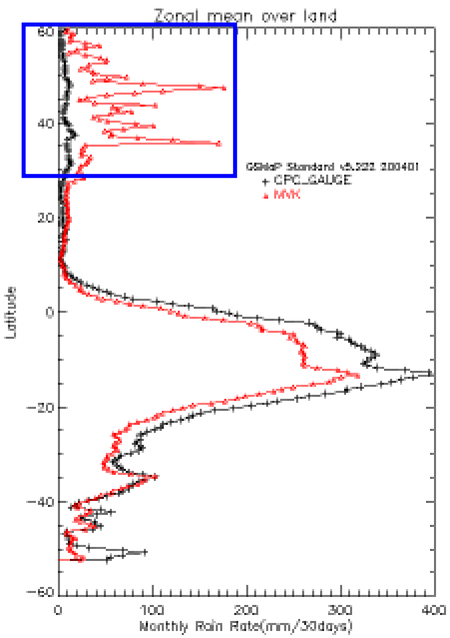
NOAA/CPC Daily Gauge Analysis



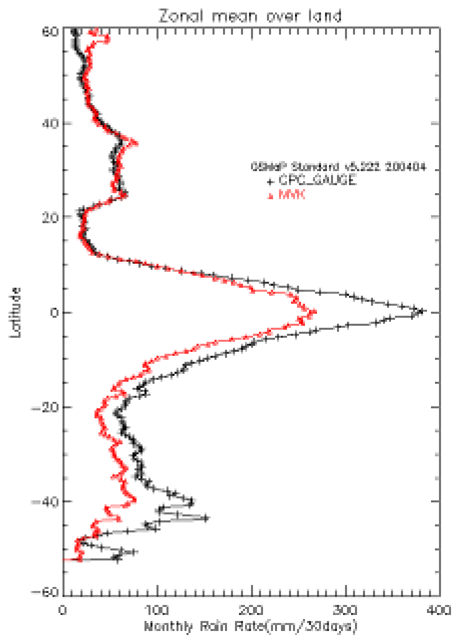
From JAXA

Zonal mean analysis
Comparison between MVK（red） and GSMaP_Gauge（black）

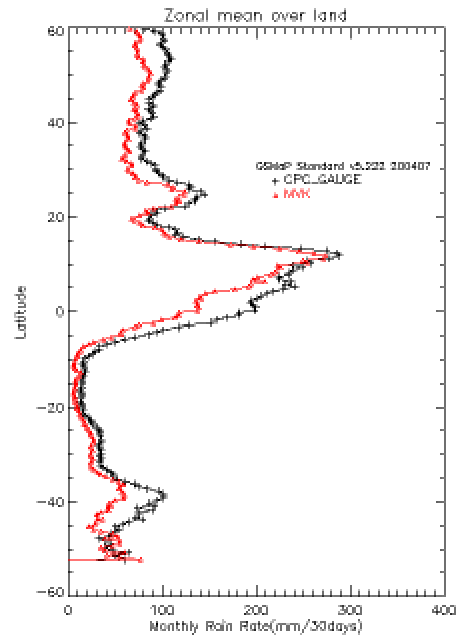
2004/01



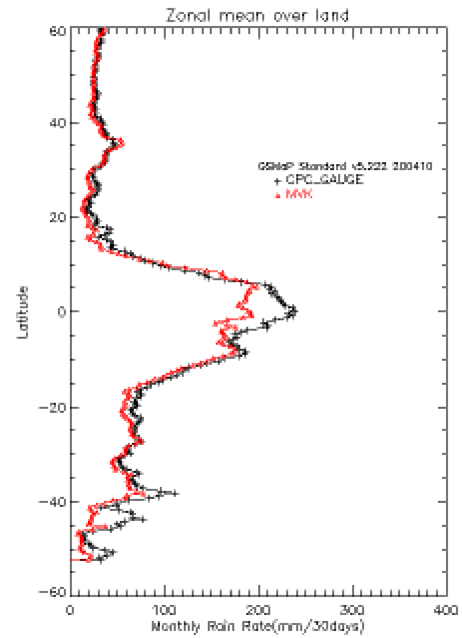
2004/04



2004/07

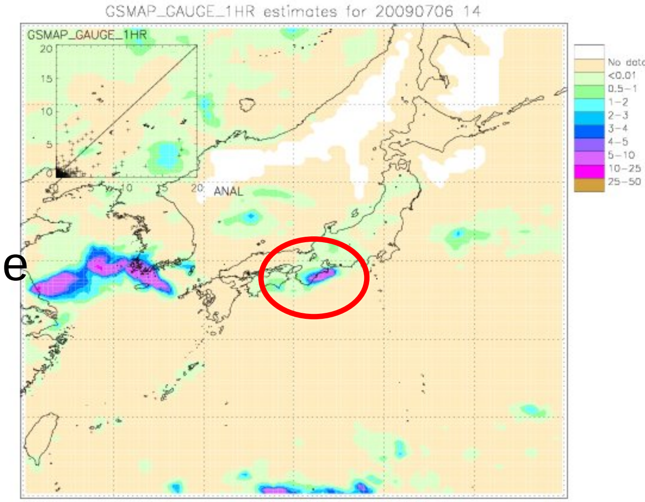


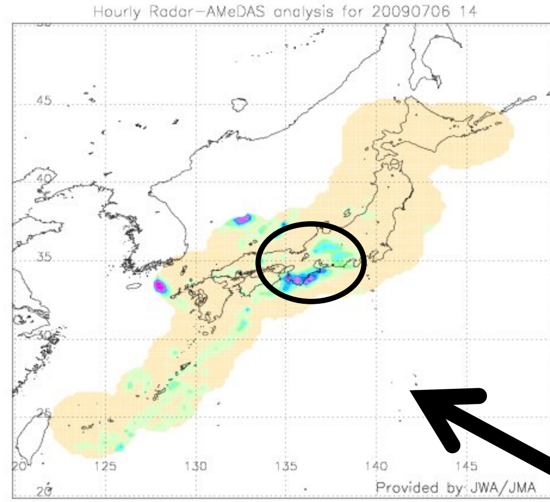
2004/10



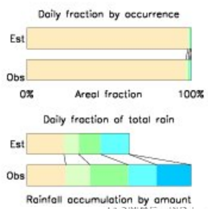
Estimation from the GSMaP_Gauge product tends to be larger than that from the GSMaP_MVK

GSMaP_Gauge





Radar Rain Gauge Network



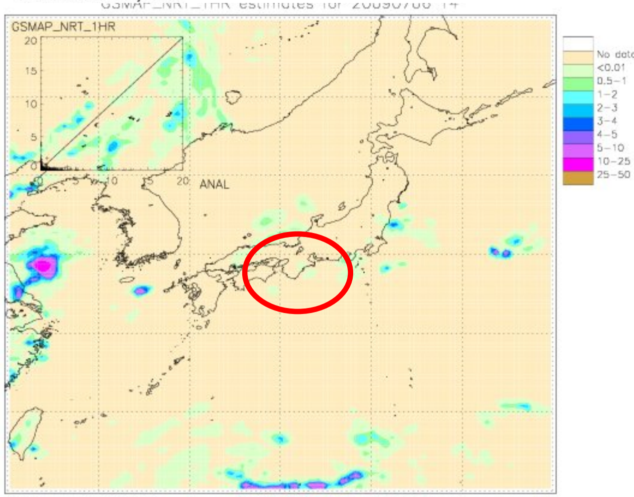
		GSMAP_GAUGE_1HR	
		<1	≥1
Observed	<1	2801	20
	≥1	58	35

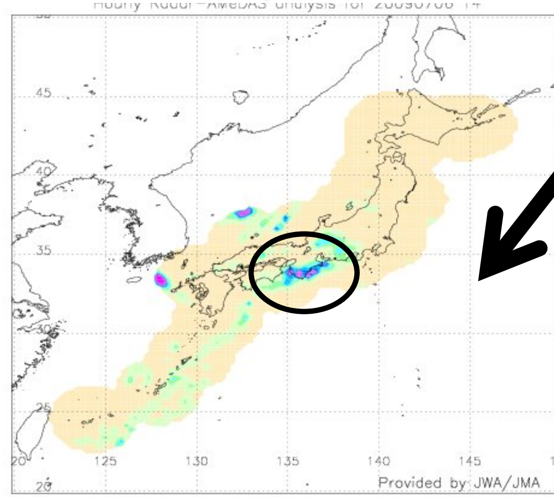
Verification statistics for 20090706 14 n=2914 Verif. grid=0.25° Units=mm/hr

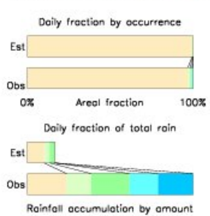
	Analysed	GSMAP_GAUGE_1HR
# gridpoints raining	93	55
Average rain	0.1	0.1
Conditional rain	4.5	4.7
Rain volume (mm*km²x10⁶)	0.3	0.2
Maximum rain	17.8	8.9

Mean abs error = 0.1
RMS error = 0.7
Correlation coeff = 0.599
Frequency bias = 0.591
Probability of detection = 0.376
False alarm ratio = 0.364
Hanssen & Kuipers score = 0.369
Equitable threat score= 0.299

GSMaP_NRT







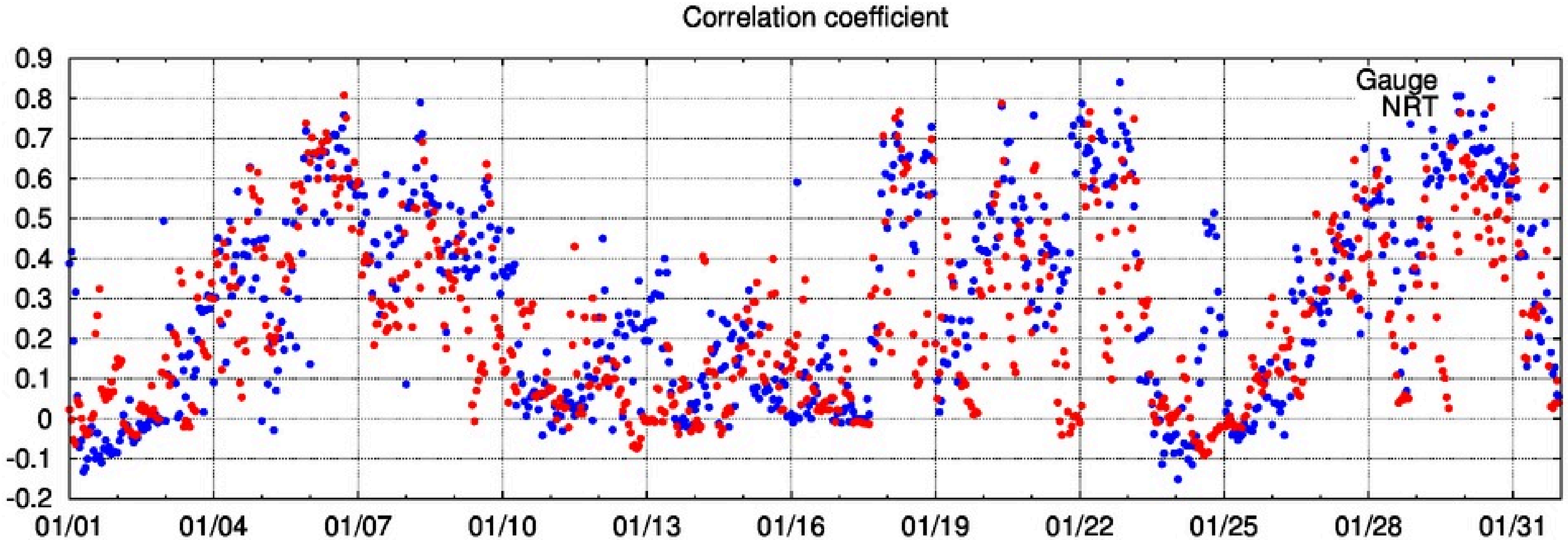
		GSMAP_NRT_1HR	
		<1	≥1
Observed	<1	2955	14
	≥1	93	0

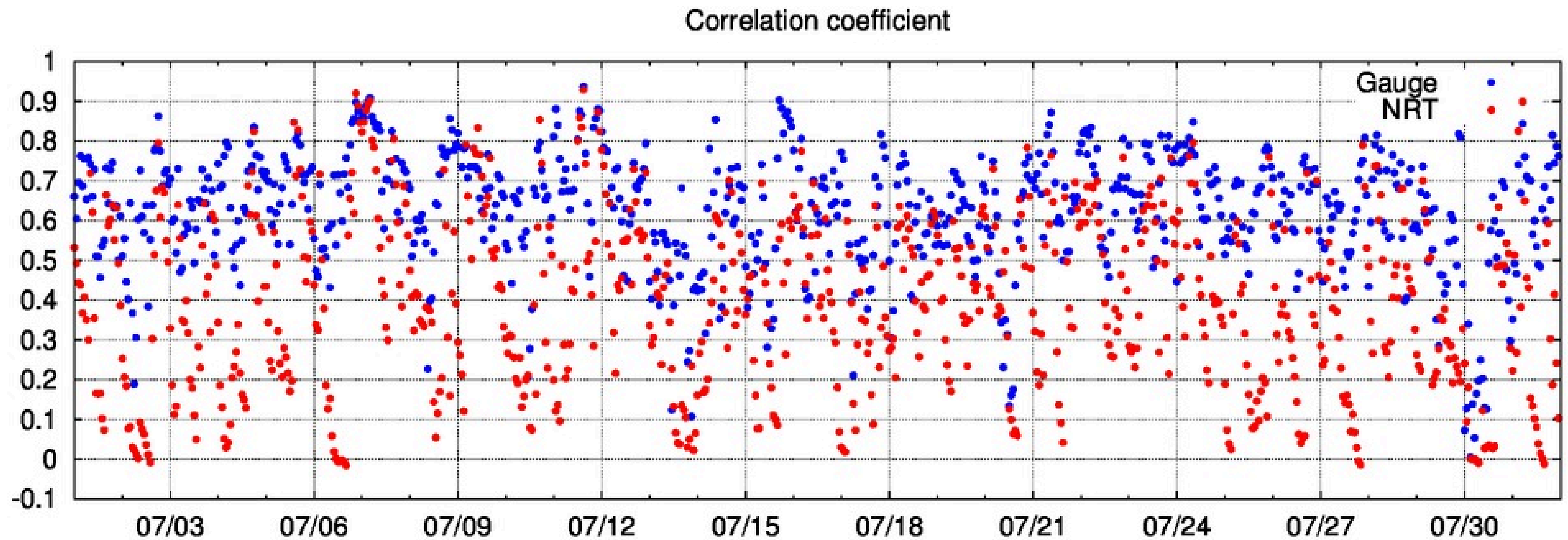
Verification statistics for 20090706 14 n=3062 Verif. grid=0.25° Units=mm/hr

	Analysed	GSMAP_NRT_1HR
# gridpoints raining	93	14
Average rain	0.1	0.0
Conditional rain	4.5	4.9
Rain volume (mm*km²x10⁶)	0.3	0.0
Maximum rain	17.8	4.0

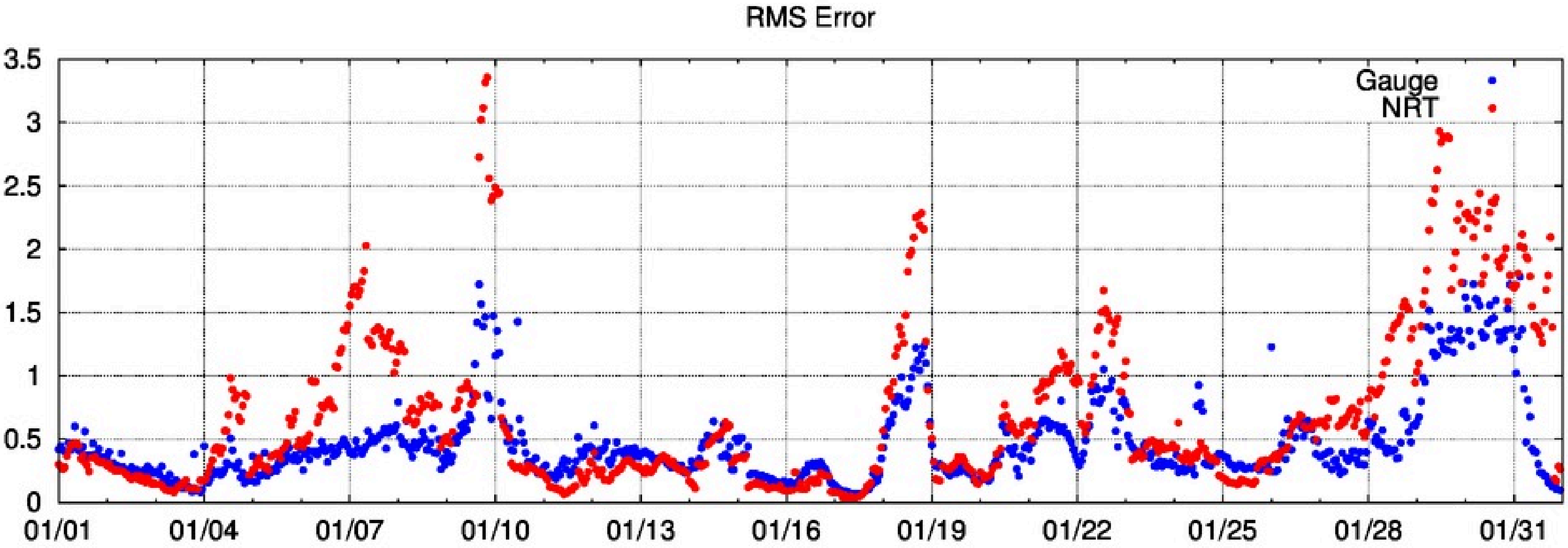
Mean abs error = 0.2
RMS error = 0.9
Correlation coeff = −0.003
Frequency bias = 0.151
Probability of detection = 0.000
False alarm ratio = 1.000
Hanssen & Kuipers score = −0.005
Equitable threat score= −0.004

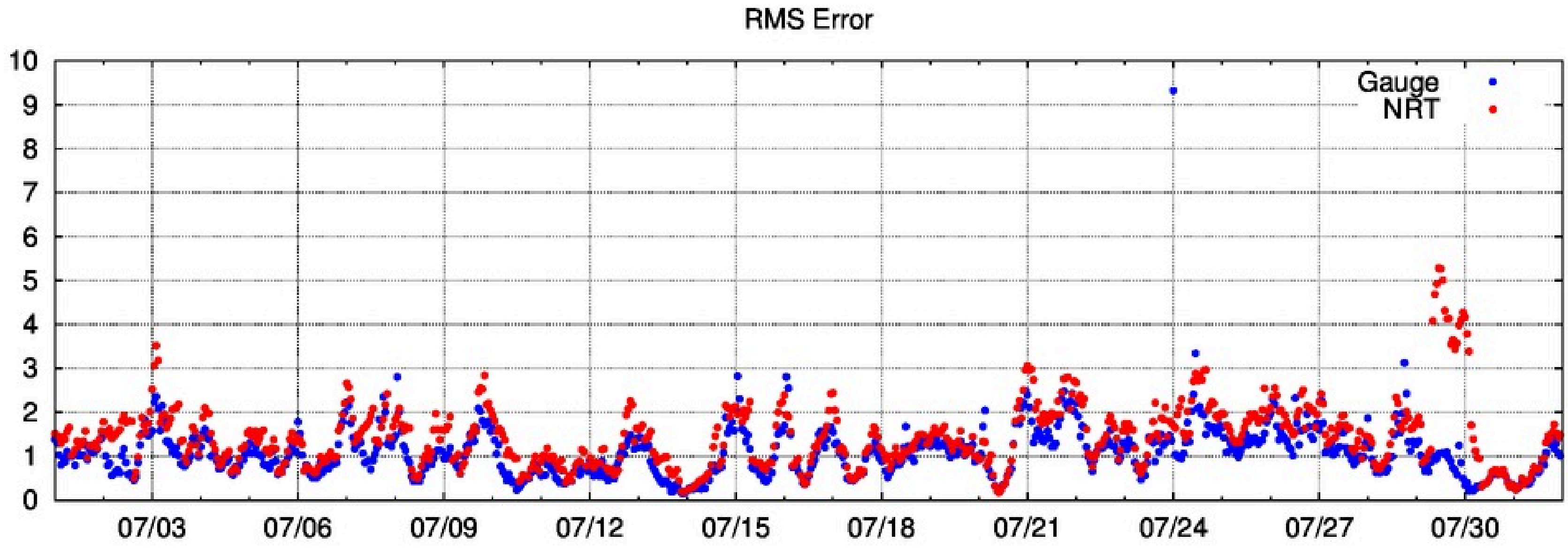
Correlation





RMS Error


RMS Error
Gauge
NRT
3.5
3
2.5
2
1.5
1
0.5
0
01/01
01/04
01/07
01/10
01/13
01/16
01/19
01/22
01/25
01/28
01/31


RMS Error
Gauge
NRT
10
9
8
7
6
5
4
3
2
1
0
07/03
07/06
07/09
07/12
07/15
07/18
07/21
07/24
07/27
07/30

モデルへの期待

- 大気移動ベクトルが，過去から将来まで多層にわたって求まる
  - GSMaP_MVK, GSMaP_Now, GSMaP_Futureまで使用することが可能となる
  - より効果的な高度のベクトルの使用が可能となる
- モデルによる地表面降水強度の使用
  - 高緯度では観測より精度が良い？
  - 一方，熱帯では？？？
  - MVKでのカルマンフィルタの観測方程式のyにモデルからの地表面降水量を追加することが可能

モデルとの複合案

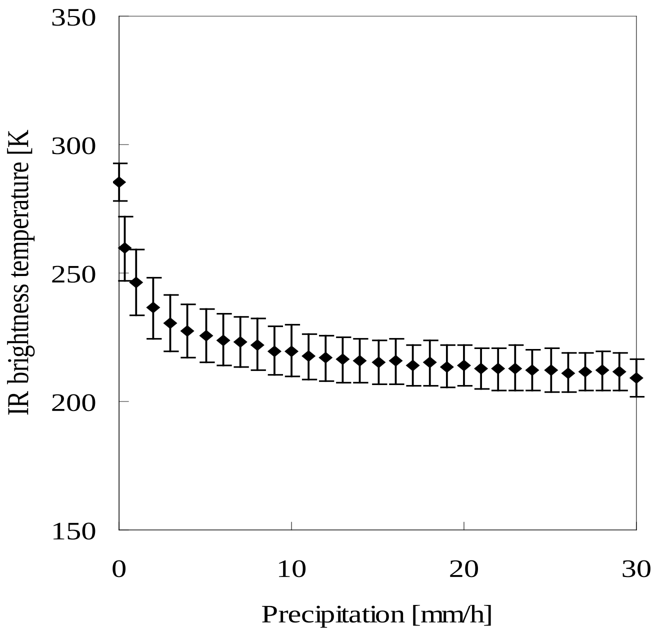
- モデルからの移動ベクトルを使用
  - 多層で使えるか。
  - GSMaP_MVK
  - GSMaP_Nowにも使用できる
  - さらに, GSMaP_Futureも作れそう
- MVKでのカルマンフィルタ
  - 観測方程式のyにモデルからの地表面降水量を追加

State and observation equation used in Kalman filter

$$x_{k+1} = x_k + \sigma w \qquad (State\ Equation)$$

$$\mathbf{y}_k = \mathbf{H} x_k + \mathbf{s_v} \quad Observation\ Equation$$

$$\begin{bmatrix} y_k^0 \\ y_k^1 \end{bmatrix} = \begin{bmatrix} H_0 \\ H_1 \end{bmatrix} x_k + \begin{bmatrix} \sigma_v^0 \\ \sigma_v^1 \end{bmatrix}$$



x_k : Rain rate at time k

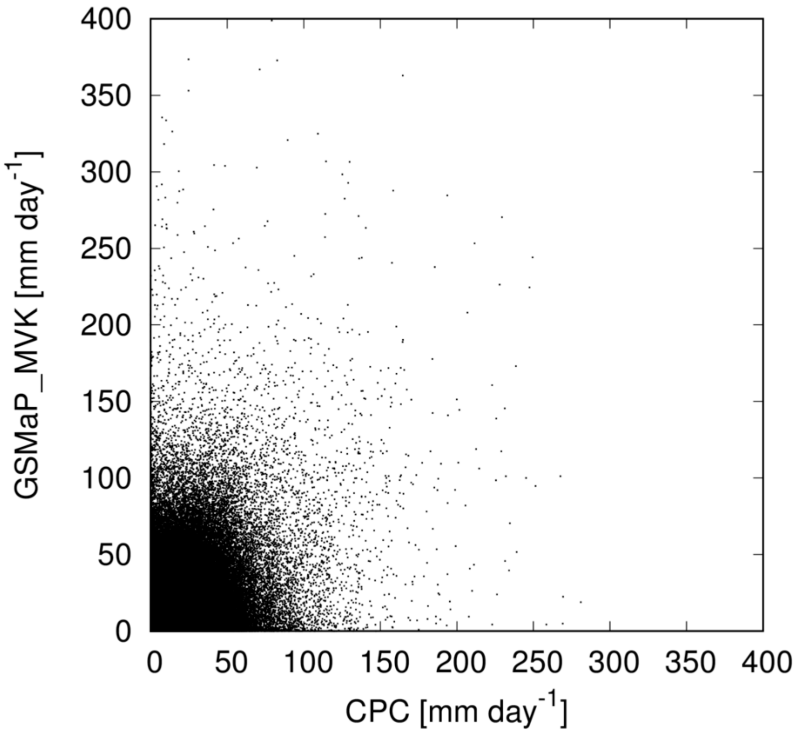
y_k : Infrared Tb, R from model

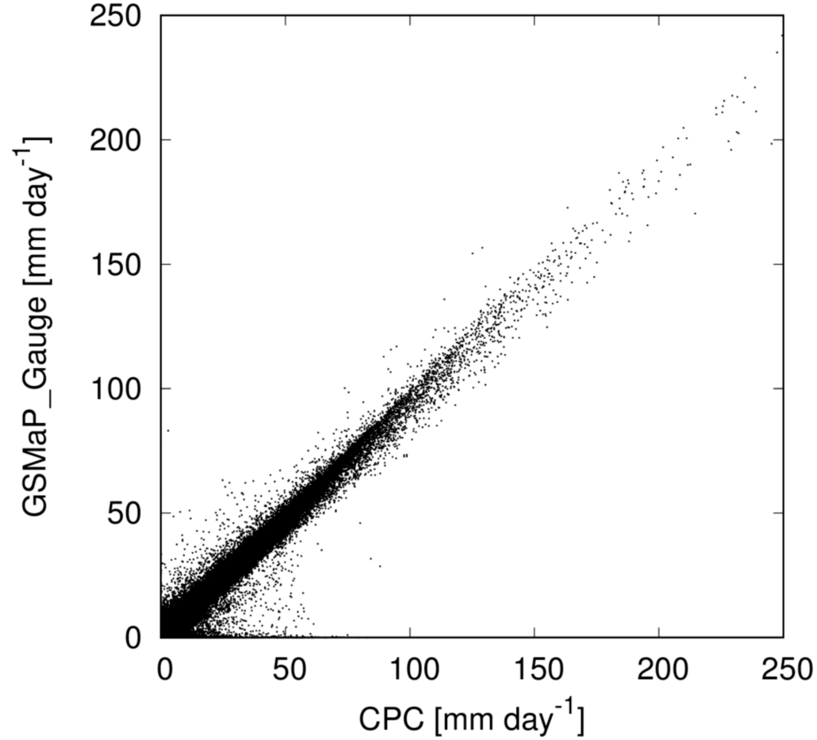
x_{k+1}: Rain rate at time k+1

w : System noise

v : Observation noise

CPC vs GSMaP_MVK and GSMaP_Gauge





State and observation equation used in Kalman filter

$$x_{k+1} = x_k + \sigma w \qquad (State\ Equation)$$

$$y_k = Hx_k + \sigma v \qquad (Observation\ Equation)$$

x_k : Rain rate at time k

y_k : Infrared Tb

x_{k+1} : Rain rate at time k+1

w : System noise

v : Observation noise