Typhoon Committee Roving Seminar 2019
CMA Headquarters, Beijing, 11-13 November 2019

Radar Based Nowcast of Typhoon Related Rainfall and its Orographic Effects

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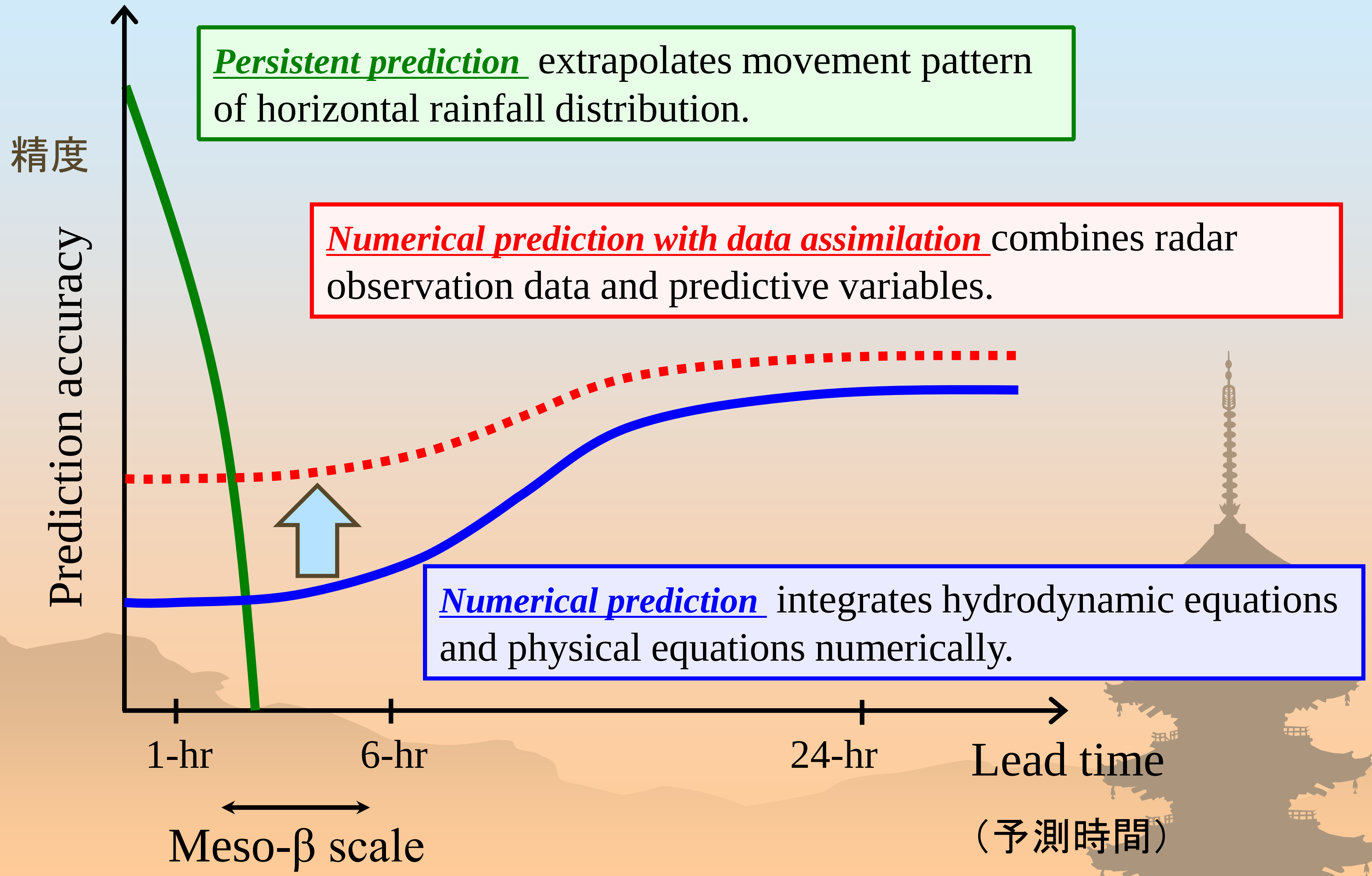
Types of rainfall prediction with radar
レーダーを用いた降雨量予測の種類

- Persistent Prediction (Nowcast) （運動学的手法）
  - Extrapolates movement pattern of horizontal rainfall distribution (rainfiled)
- Meso-scale numerical model with assimilation of radar data （レーダー情報を同化したメソ大気数値モデル）
  - Numerical integration of physical equations with grid scale less than 10km
  - The ultimate goal is physically based 4D data assimilation of information such as radar reflective factor, Doppler velocity and various type of remotely sensed observations by non-hydrostatic MS model with main cloud physics

Present State of Rainfall Prediction Accuracy
降雨量予測の精度



Persistent prediction :

extrapolates movement pattern of horizontal rainfall distribution.

Method by Translation model

(移流モデルによる方法)

(as a still widely used traditional method)

Translation model:移流モデル

$$\frac{\partial R(x,y,t)}{\partial t}+u(x,y)\frac{\partial R(x,y,t)}{\partial x}+v(x,y)\frac{\partial R(x,y,t)}{\partial y}=w(x,y)$$

where, $R(x,y,t)$ is rainfall intensity at point (x,y) and time t.

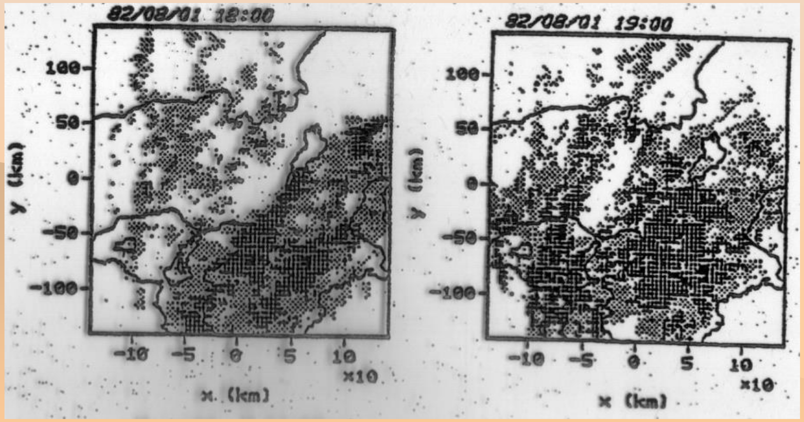
Components of translation vector $\vec{u}(x,y)$ of rainfall distribution:

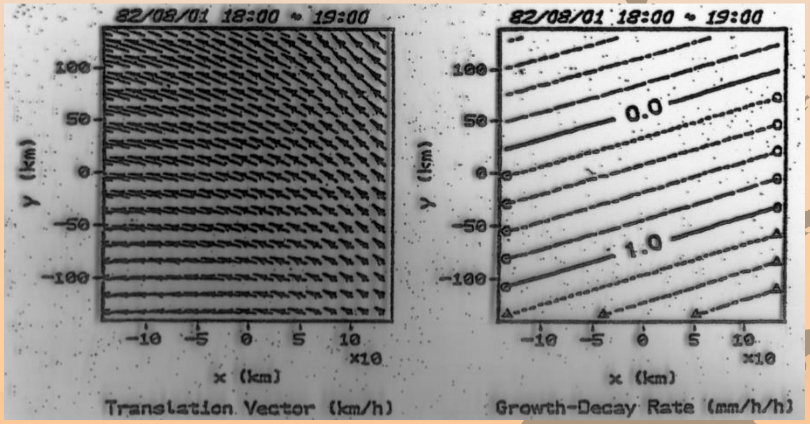
$$u(x,y)=c_1x+c_2y+c_3,\quad v(x,y)=c_4x+c_5y+c_6$$

Growth-decay rate:

$$w(x,y)=c_7x+c_8y+c_9$$

線型な移動と発達・衰弱場





By Shiba, Takasao and Nakakita (1984)

Identification of parameters c_1~c_9

パラメータの同定方法

Discrete expression of (x,y,t) (離散化）

$$x_i = (i-1/2)\Delta x, \quad i=1,.....,M$$

$$y_j = (j-1/2)\Delta y, \quad j=1,.....,N$$

$$t_k = k\Delta t, \quad k=0,.....,-K-1$$

where, $\Delta x \times \Delta y \times \Delta t$ is spatial and temporal resolution of radar observation

Finite difference approximation of partial differentiation

偏微分の差分化

$$\left[\frac{\partial R}{\partial t}\right]_{ijk} = \frac{R(x_i, y_j, t_{k+1}) - R(x_i, y_j, t_{k-1})}{2\Delta t}, \quad \left[\frac{\partial R}{\partial x}\right]_{ijk} = \frac{R(x_{i+1}, y_j, t_k) - R(x_{i-1}, y_j, t_k)}{2\Delta x},$$

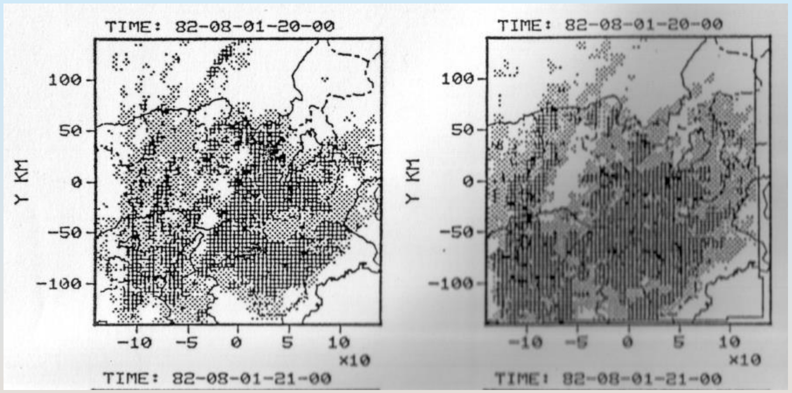
Identification of parameters c_1~c_9（パラメータの同定）

$$J_c = \sum_{k=-K}^{-1} \sum_{i=2}^{M-1} \sum_{j=-2}^{N-1} v_{ijk}^2 \quad \Rightarrow \quad \text{min.}$$

$$v_{ijk} = \left[\frac{\partial R}{\partial t}\right]_{ijk} + (c_1 x_i + c_2 y_j + c_3)\left[\frac{\partial R}{\partial x}\right]_{ijk} + (c_4 x_i + c_5 y_j + c_6)\left[\frac{\partial R}{\partial y}\right]_{ijk} - (c_7 x_i + c_8 y_j + c_9)$$

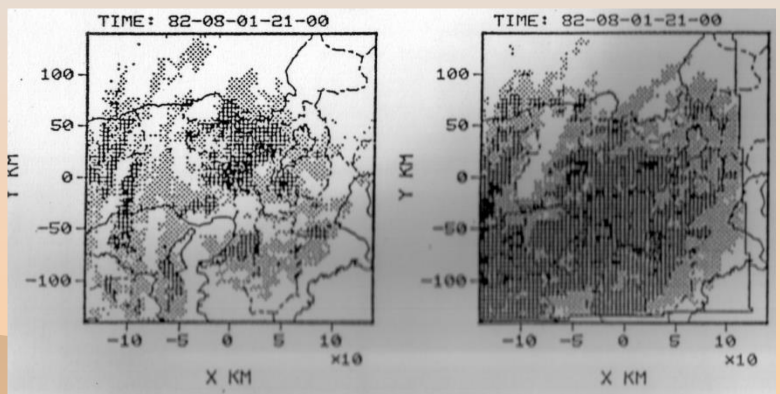
By Shiba, Takasao and Nakakita (1984)

Example of a Case Study (予測事例）



Observed Predicted

1 hour ahead prediction



Observed Predicted

2 hours ahead prediction

By Shiba, Takasao and Nakakita (1984)

Problem in original translation model when target area is whole Japan （日本全体を対象とした場合の問題）

Images by 26 whether radar is being operationally composed into single image.

In such a wide target area, rainfall fields from different meteorological disturbances frequently co-exist. Especially, when typhoon and stationary front co-exist, movement of rain field can not be expressed by single linear field of translation vector.

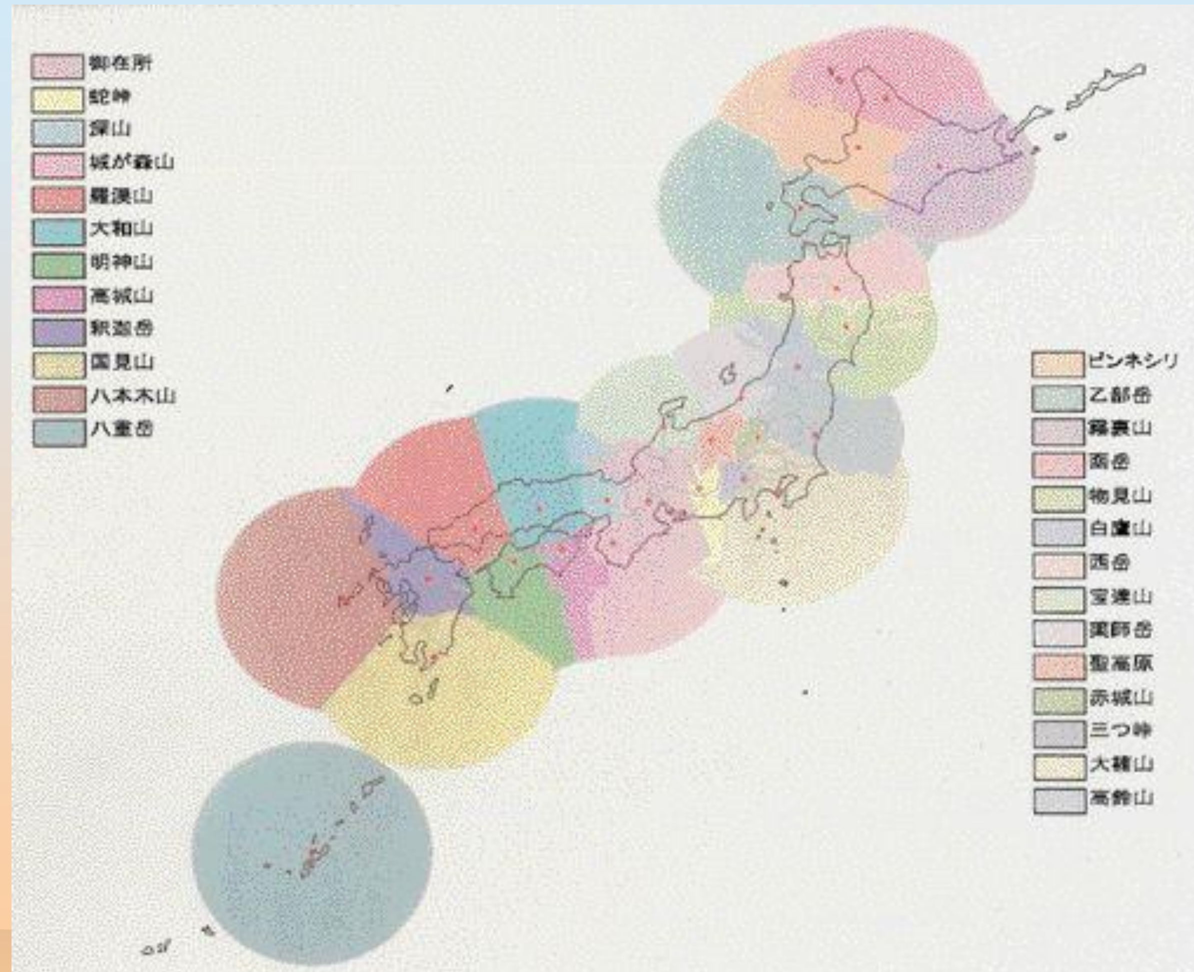
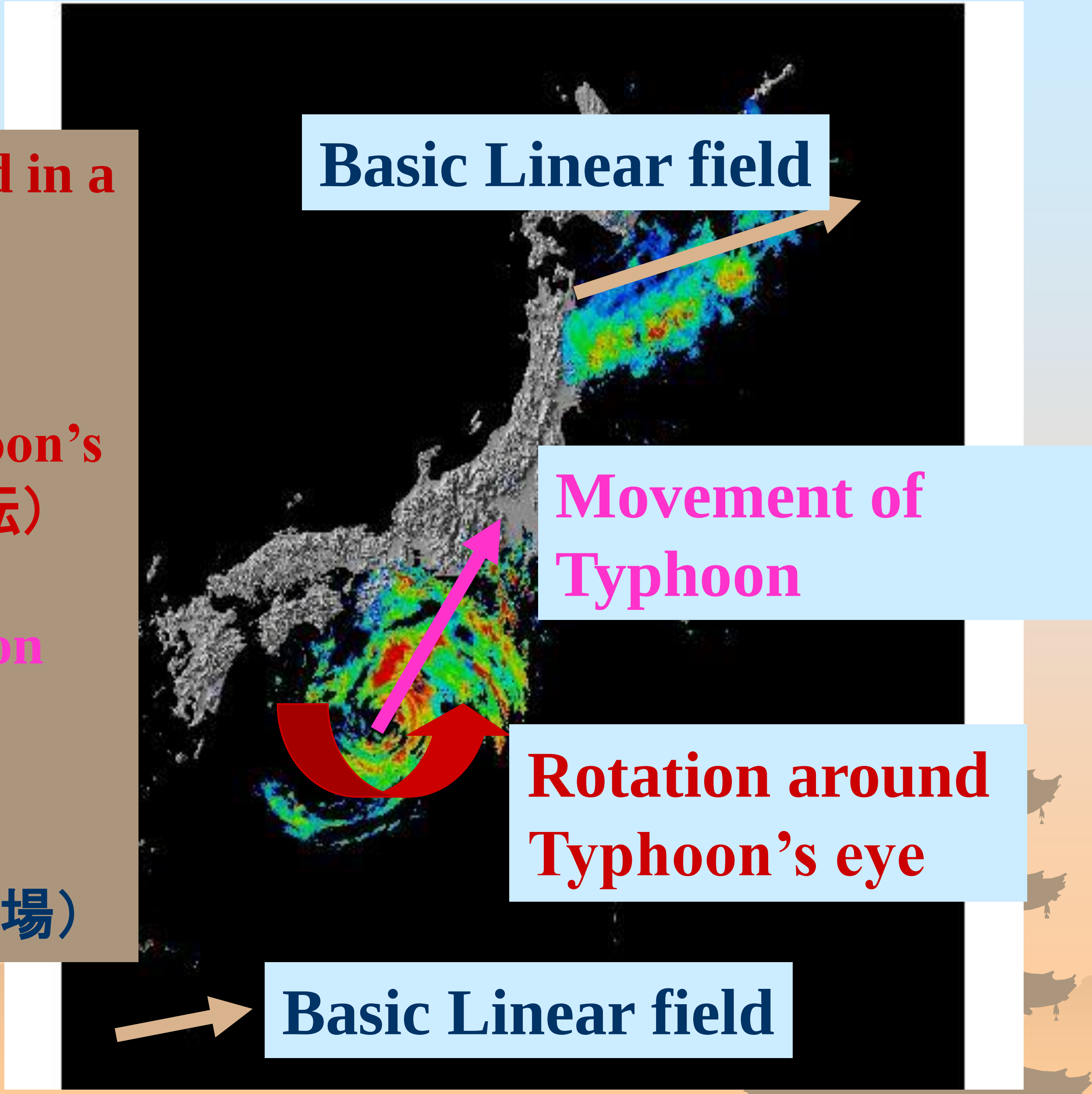


図-3.10 全国合成マップ（平成15年6月現在）

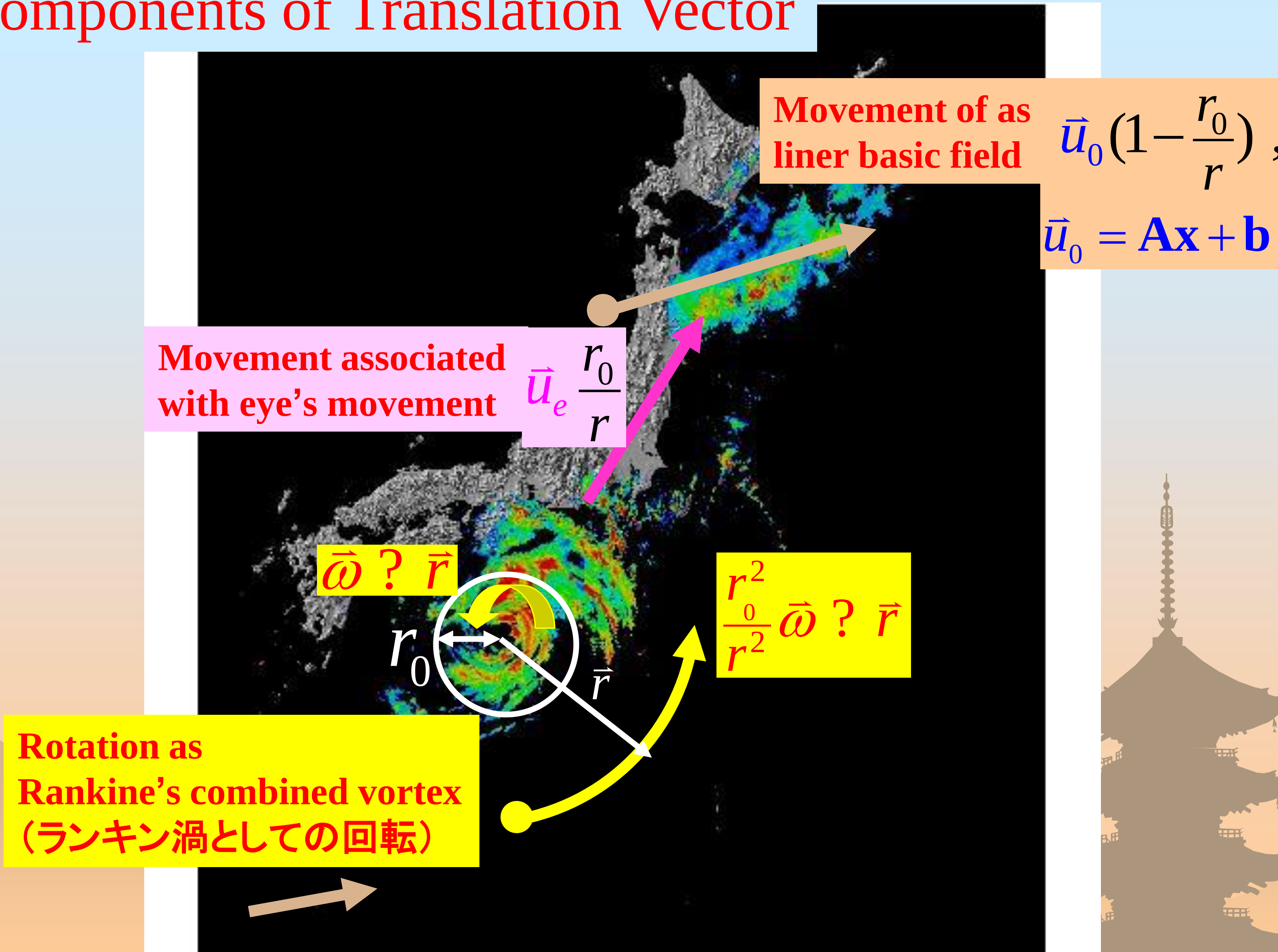
Advances of traditional method for Typhoon related rainfall

Movement of Rain Field in a Wide Area
(広域での移動場）
=
Rotation around Typhoon's eye （台風周りの回転）
＋
Movement of Typhoon
(台風の目の移動）
＋
Basic Linear field
（基本手法の線型移動場）



By Nakakita, Adachi and Kitai (2007)

Components of Translation Vector



By Nakakita, Adachi and Kitai (2007)

Tvector field for Typhoon

$$\begin{cases} \vec{u} = \vec{\varpi} \; ? \; \vec{r}(x,y) + \vec{u}_e, & (r(x,y) < r_0) \quad (1) \\ \vec{u} = \dfrac{r_0^2}{r(x,y)^2} \vec{\varpi} \; ? \; \vec{r}(x,y) + \vec{u}_e \dfrac{r_0}{r(x,y)} + \vec{u}_0 \left(1 - \dfrac{r_0}{r(x,y)}\right), & (r(x,y) > r_0) \quad (2) \end{cases}$$

Rotation Around Eye of Typhoon

Movement of Typhoon's Eye

Basic Linear Filed

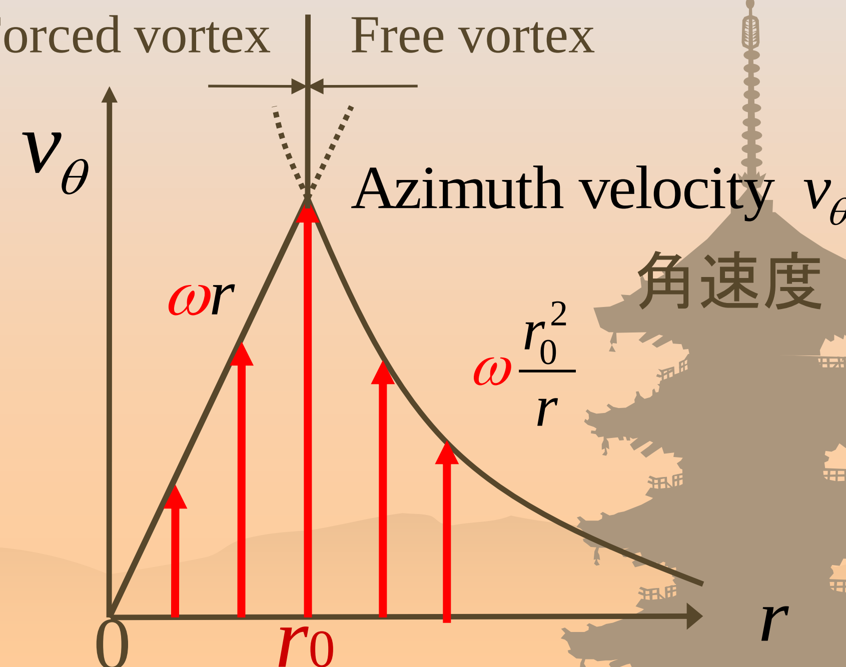
$$\begin{cases} \vec{u}_0 = \mathbf{Ax} + \mathbf{b}, \quad (3) \\ \mathbf{x} = \begin{pmatrix} x \\ y \end{pmatrix}, \quad \mathbf{A} = \begin{pmatrix} c_1 & c_2 \\ c_4 & c_5 \end{pmatrix}, \quad \mathbf{b} = \begin{pmatrix} c_3 \\ c_6 \end{pmatrix} \quad (4) \end{cases}$$

Rotation around eye of Typhoon as Rankine's combined vortex

Radius Velocity v_r, Azimuth velocity v_θ

$$v_r = 0$$

$$v_\theta = \begin{cases} \omega r & (0 \le r \le r_0) \\ \omega \dfrac{r_0^2}{r} & (r_0 < r) \end{cases}$$



By Nakakita, Adachi and Kitai (2007)

Procedure of identifying Parameter

パラメータの同定方法

(0) Assume a first guess of r_0.

⇩

(1) Identify ω using observations within a circle with radius r_0

$$\vec{u} = \vec{\varpi} \times \vec{r} + \vec{u}_e \quad (r < r_0)$$

⇩

(2) Identify ωr_0^2 outside the circle and within a circle with radius of 300 km. Then estimate r_0 using already estimated ω.

$$\vec{u} = \frac{r_0^2}{r^2} \vec{\varpi} \times \vec{r} + \vec{u}_e \quad (r > r_0)$$

⇩

(3) If the identified r_0 lies outside the range of $r_0 \pm 20\text{km}$, then go back to the step (1) replacing r_0 by $(r_0 + r_0)/2$.

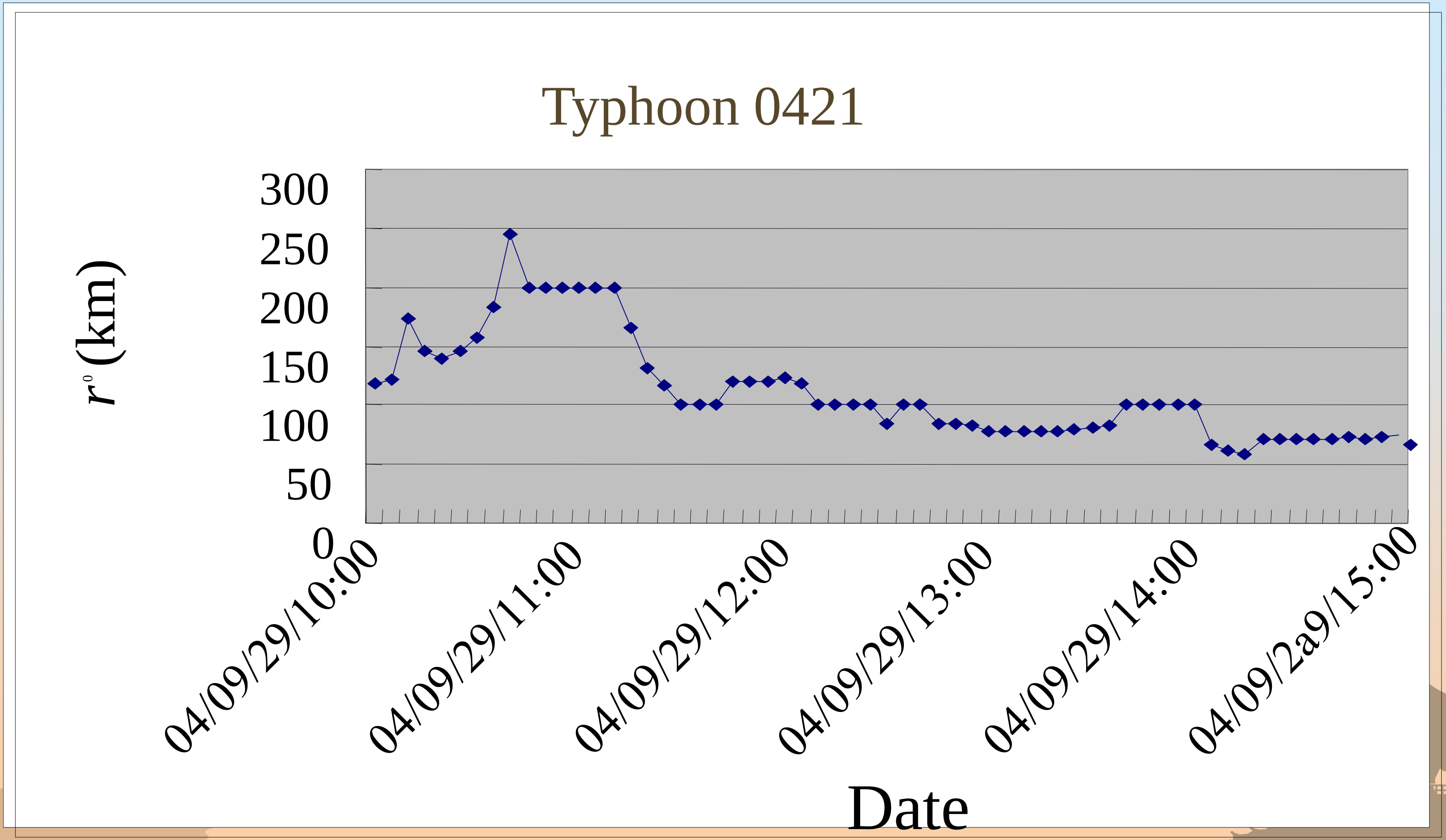
⇩

(4) Identify parameters $c_1, \cdots, c_6$ of linear basic field with radar observations outside the circle.

$$\vec{u} = \frac{r_0^2}{r^2} \vec{\varpi} \times \vec{r} + \vec{u}_e \frac{r_0}{r} + \vec{u}_0 \left(1 - \frac{r_0}{r}\right) \quad (r > r_0)$$

By Nakakita, Adachi and Kitai (2007)

Example of time series of identified r_0



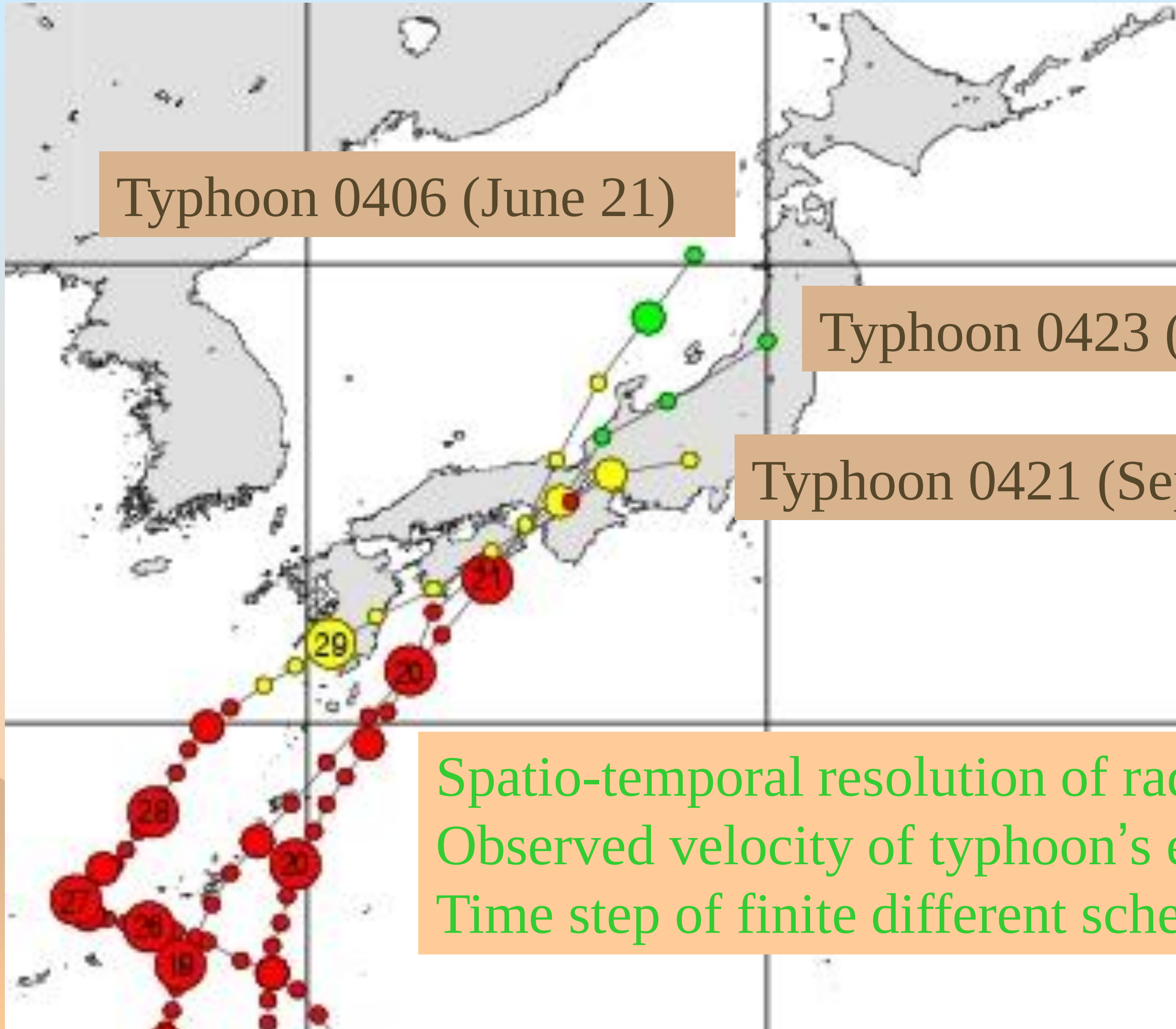
r_0 is stably estimated and
represents the decreasing of spatial scale of the typhoon.

By Nakakita, Adachi and Kitai (2007)

Applications and Results

(適用と結果）

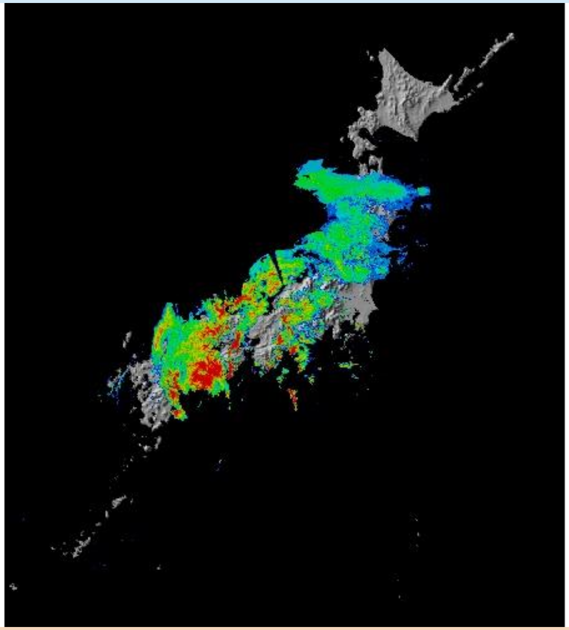
Cases to which proposed method was applied

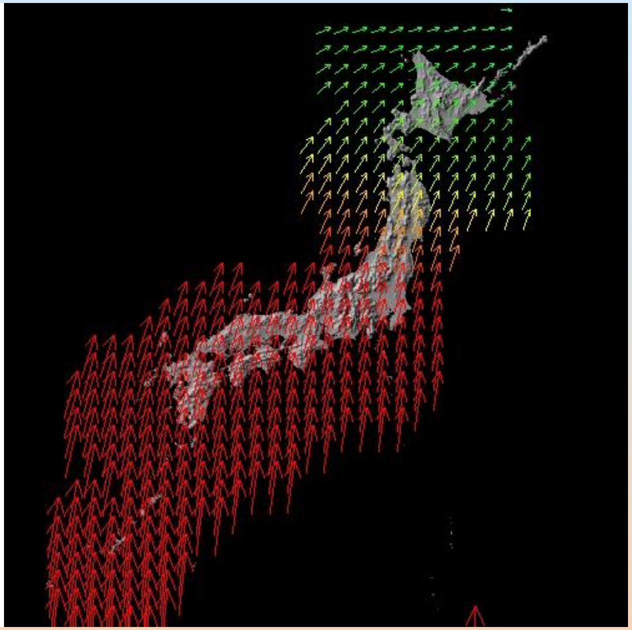


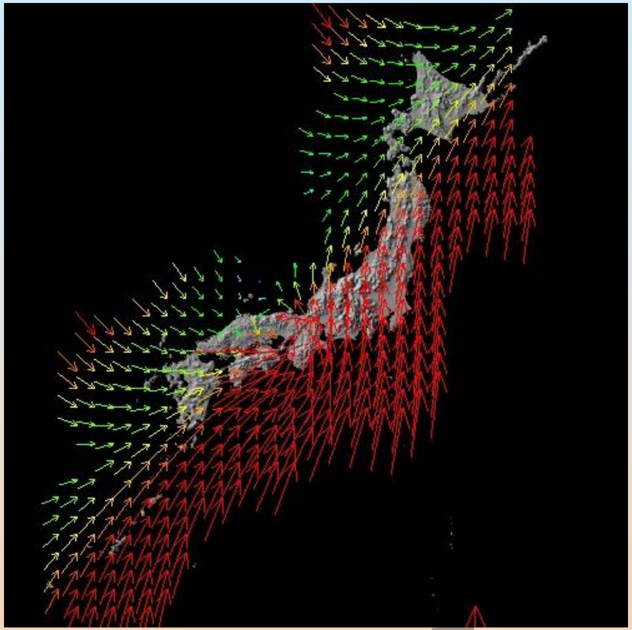
Spatio-temporal resolution of radar: 1 km and 5 min.
Observed velocity of typhoon’s eye is used.
Time step of finite different scheme is 20 sec.

Example of Identified Advection Vector

（Typhoon0421, time:15:00, June 21）







Rainfall Distribution

0 30(mm/h)

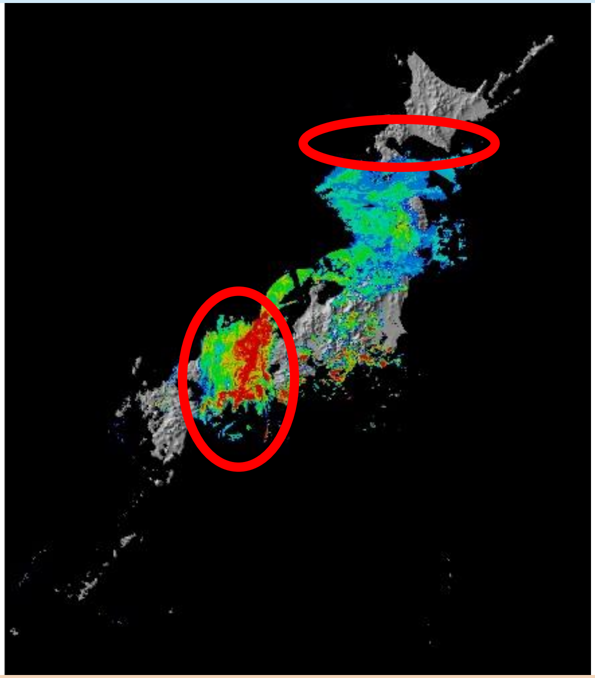
Identified by Original Method

Identified by New Method

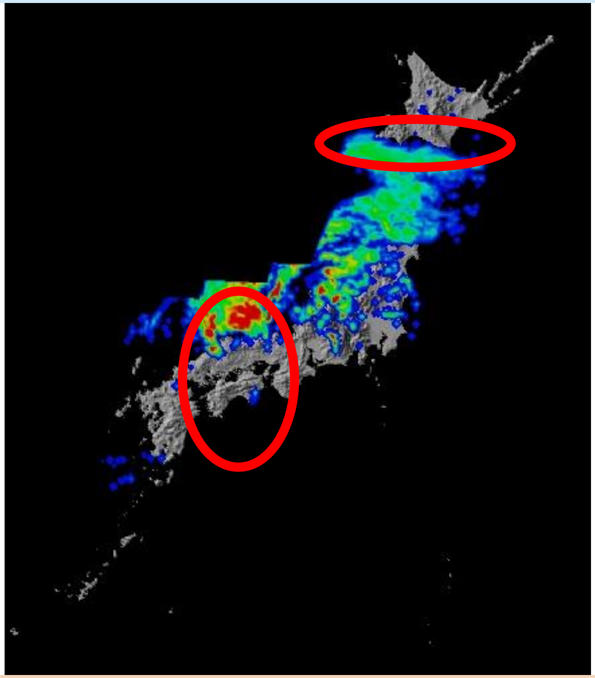
By Nakakita, Adachi and Kitai (2007)

Three hours ahead Prediction

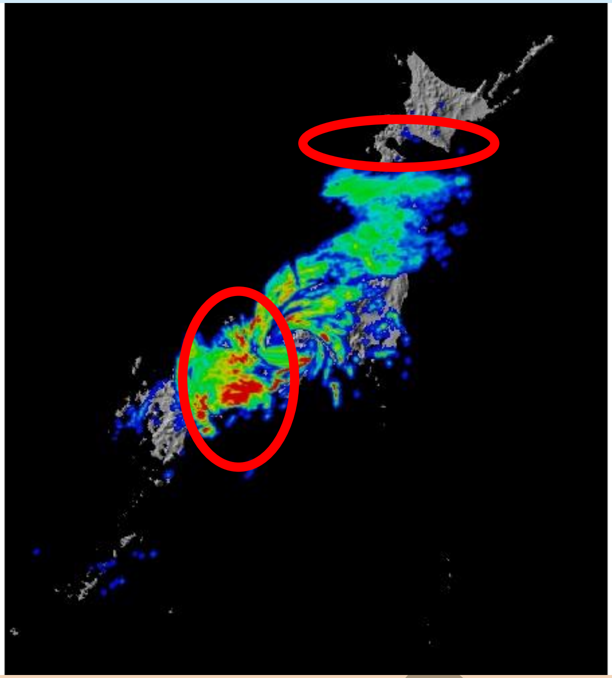
（Start time: 15:00）



Observed Rainfall (18:00)



Predicted Rainfall by Original Method



Predicted Rainfall by New Method

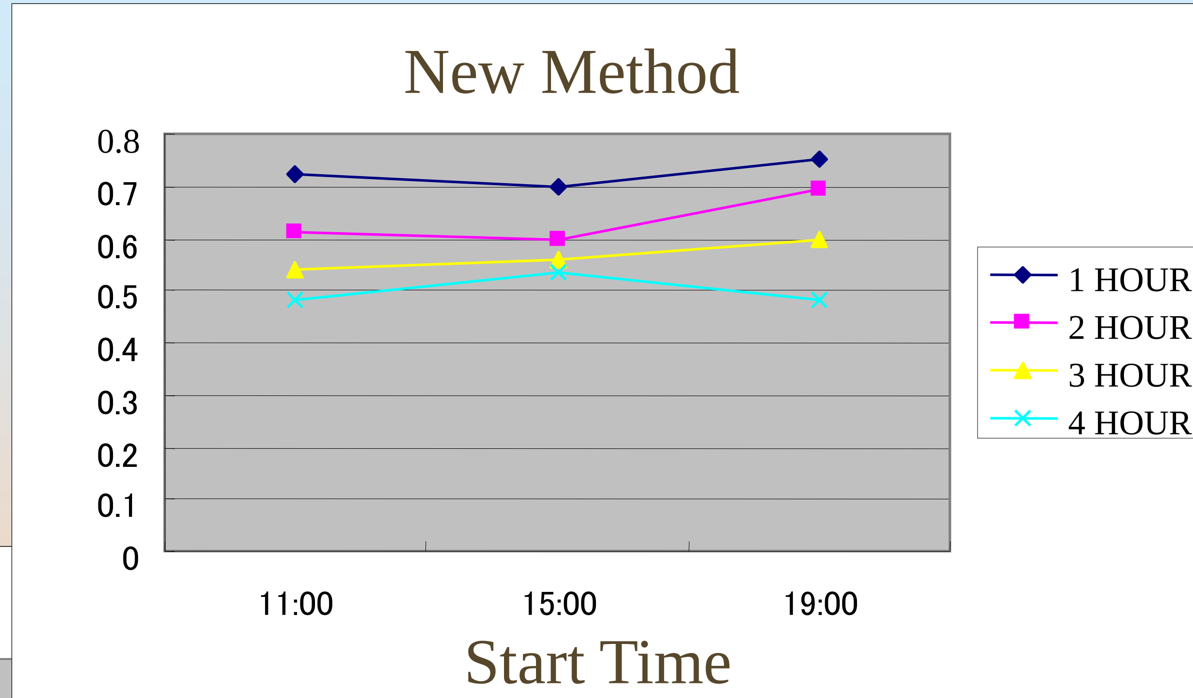
0 30(mm/h)

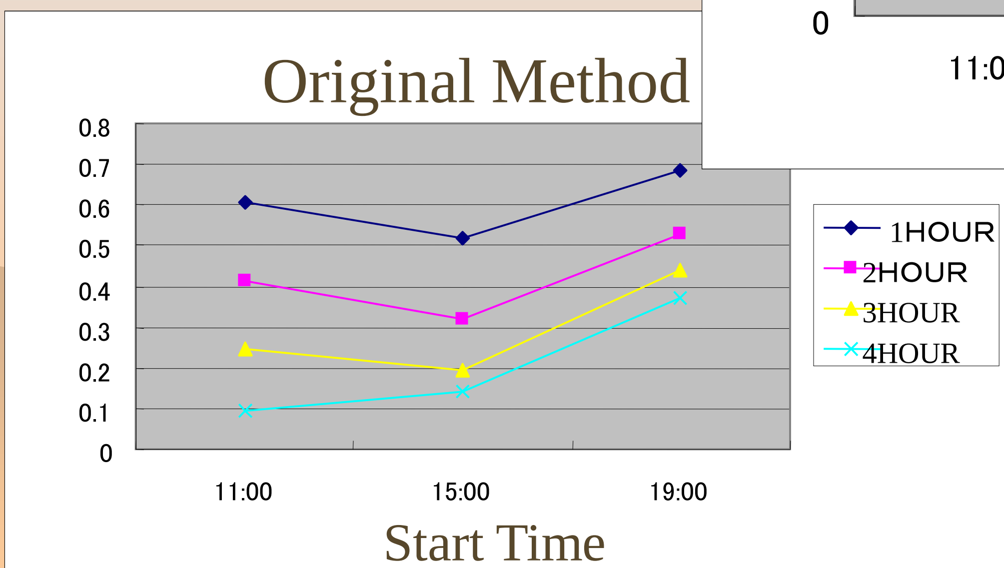
By Nakakita, Adachi and Kitai (2007)

Correlation Coefficient between observed and predicted rainfall distributions (snapshots)

(Typhoon 0421)

観測降雨分布と
予測降雨分布の
相関係数

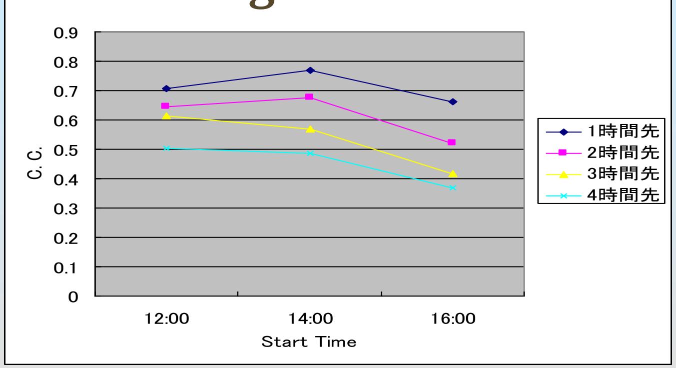




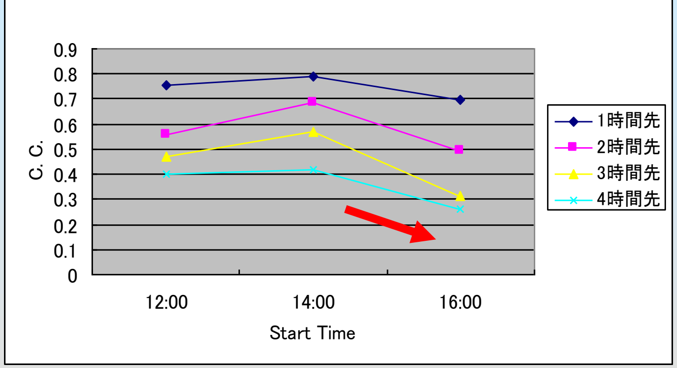
Correlation Coefficient between observed and predicted rainfall distributions for all three cases

Typhoon 0406

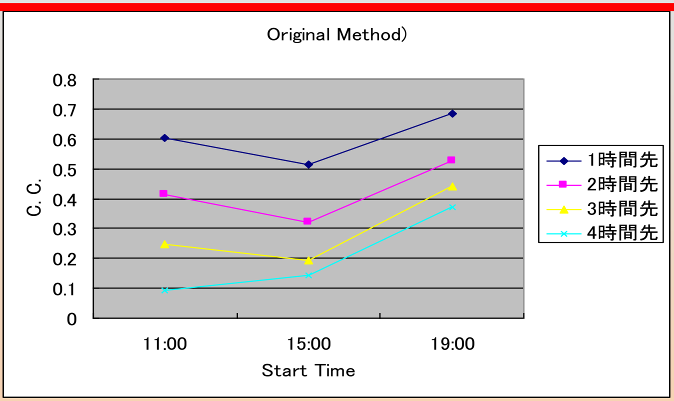
Original Method

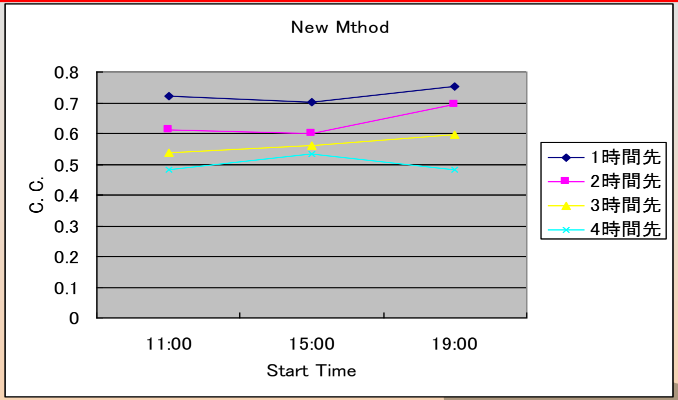


New Method

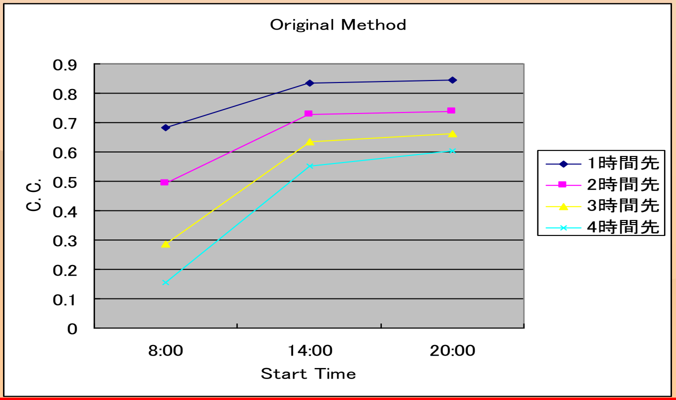


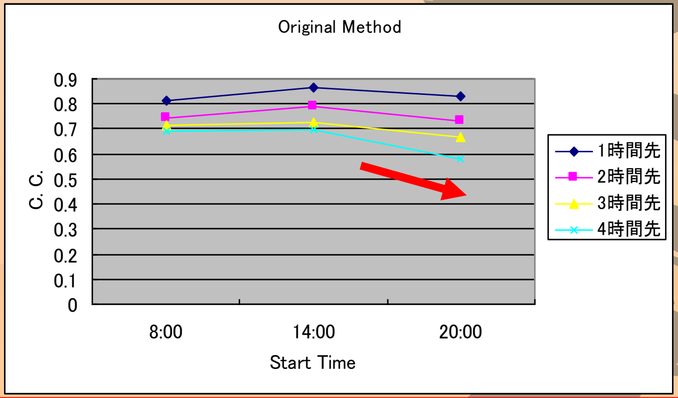
Typhoon 0421





Typhoon 0423





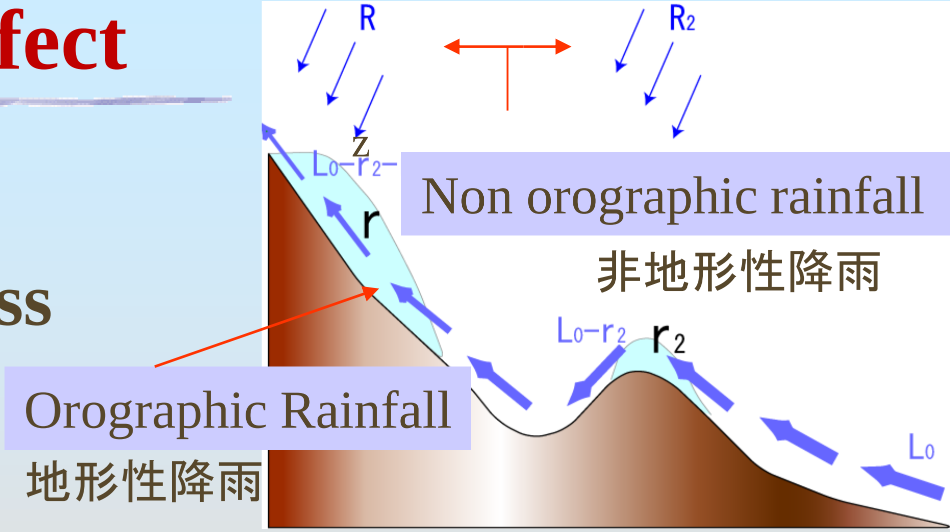
Orgraphic effect:

Seeder-feeder mechanizm

Introducing orographic effect
（地形性降雨の導入）

Tatehira's Model

A widely used model to express rainfield lingering due to orographic effects



Cloud water generated by condensation of ascending water vapor along mountain slop is taken into consideration （斜面に沿って上昇する水蒸気の凝結による雲水の生成）

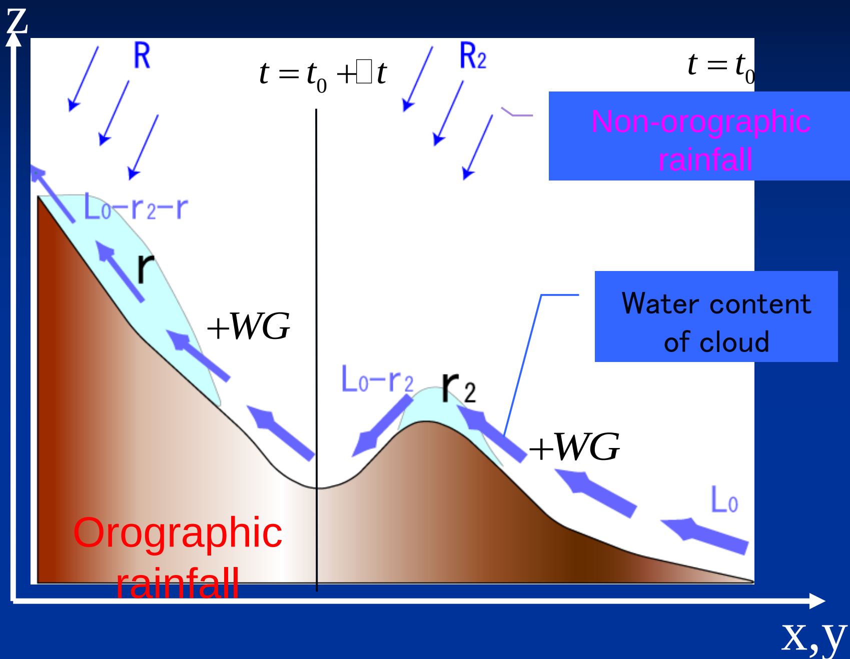
Conversion from cloud drop to raindrop is taken into consideration

The conversion is assume to occur by two types of processes:

- **Auto conversion of cloud drops**
- **Capturing cloud drops by non-orographic falling raindrop**

Of course conservation of water vapor and cloud water content should be taken into consideration

Introducing orographic effect



Tatehira's Model

Cloud water generated by condensation of ascending water vapor along mountain slop is taken into consideration.

Conversion from cloud drop to raindrop is taken into consideration

The conversion is assume to occur by two types of processes:

- Auto conversion of cloud drops
- Capturing cloud drops by non-orographic falling raindrop (Seeder feeder)

Capturing rate of cloud drop **Ascent velocity**

$$\frac{dL}{dt} = -cL - a(L - L_c) + WG - WL\frac{\partial \ln P}{\partial z}$$

Seeder feeder Auto conversion Condensation Compaction property

Integration (t=0:L=L_0)

$$L = (L_0 - \frac{aL_c + WG}{c+a})e^{-(c+a)\Delta t} + \frac{aL_c + WG}{c+a}$$

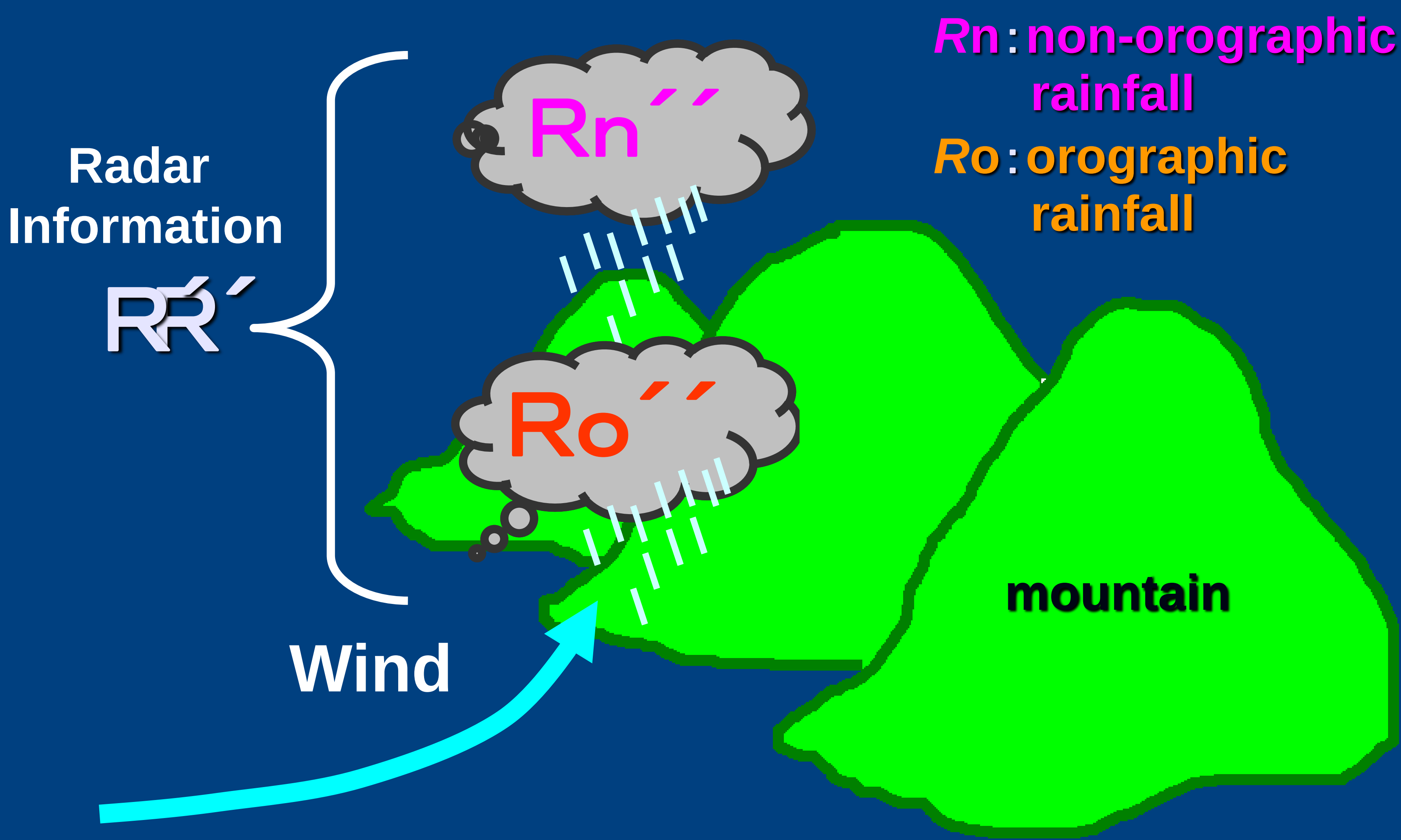
$$L_0 + WG\Delta t - L$$

↓

$$Ro = ((L_0 + WG\Delta t - L)/\Delta t) \times \text{(thickness)} \times \text{(3600(s))}$$

Δt : air parcel 's transition time over 1 mesh

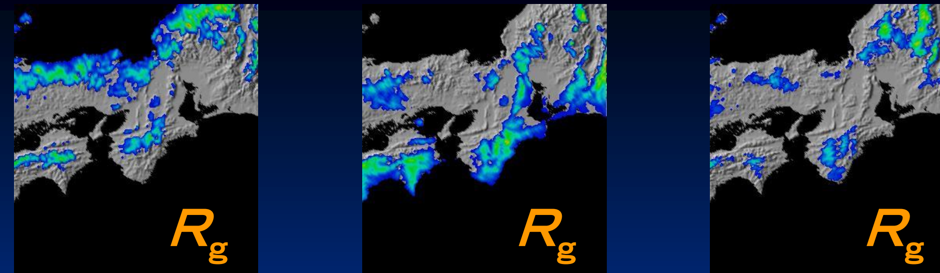
Basic Procedure on prediction



history of rainfall separation method

$$R_O = R_g \times \frac{R_N}{4} \times \frac{V}{10}$$

wind direction : north / south east / west – south west



$$R = Rn + Ro$$

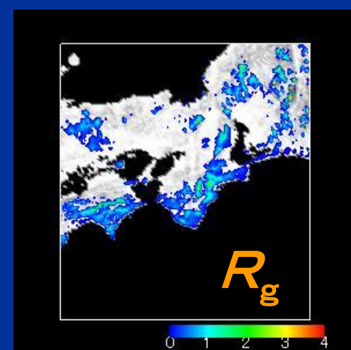
Radar information

Standard orographic rainfall distributions generated from wind velocity 10 m/s in each wind directions (16 directions)

$$R_O = R_g \times \frac{R_N}{4}$$

$$R = Rn + Ro$$

Radar information



Standard orographic rainfall

Grid Point Value of Operational Numerical Atmospheric Prediction

GPV･AMeDAS combination wind (about 1000m height)

$$c = 0.6778 Rn^{0.731}$$

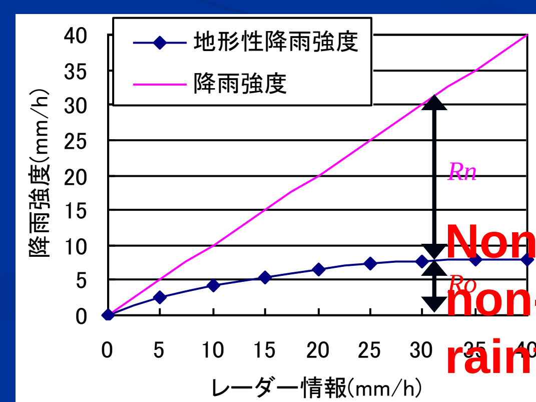
Capturing rate of cloud drop

$$\frac{dL}{dt} = -C_{(Rn)} L + WG$$

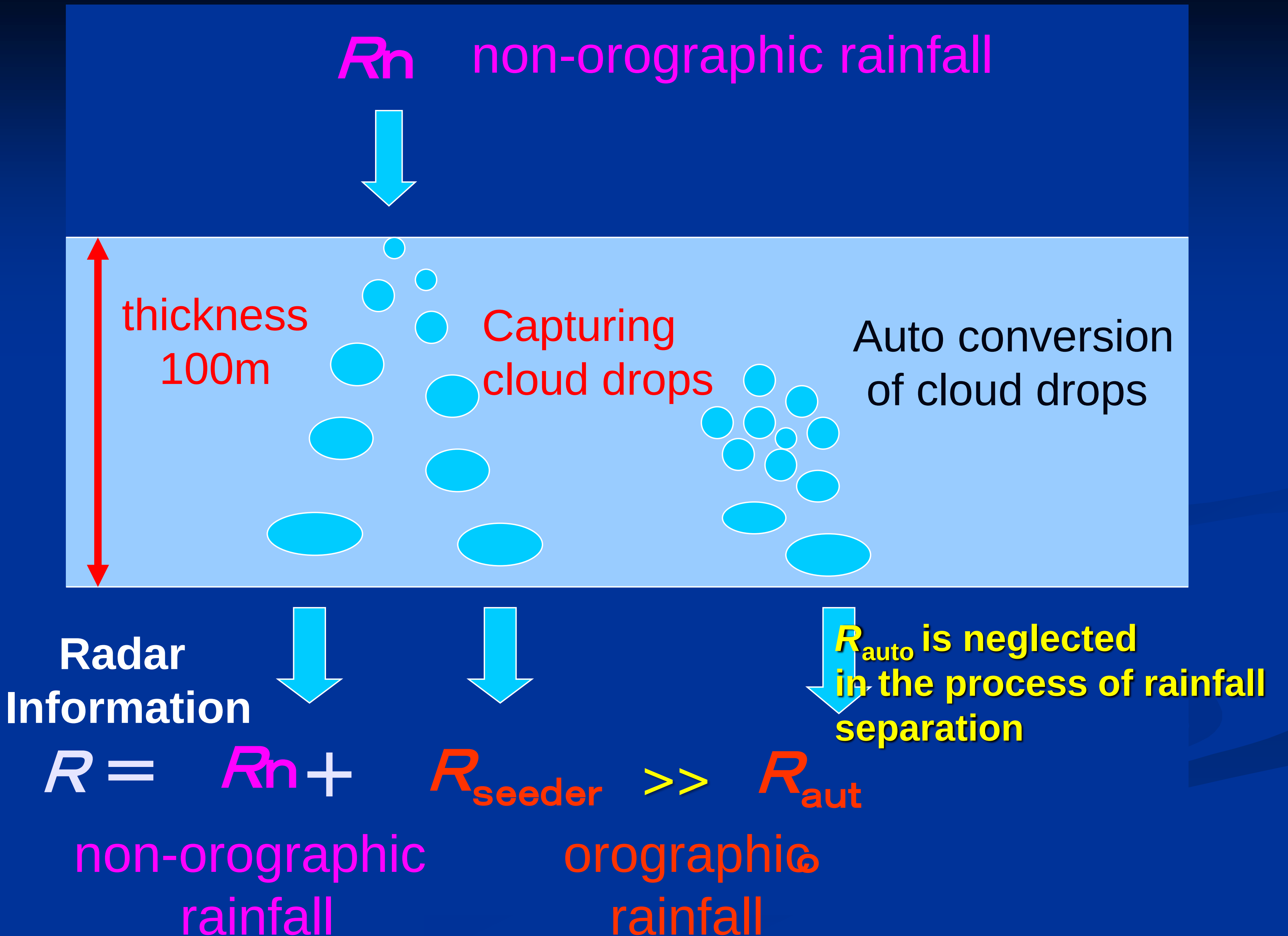
Conservation equation of cloud drop

$$R = Rn + Ro$$

Radar information



Nonlinear effect of non-orographic rainfall



Rn non-orographic rainfall
thickness
100m
Capturing
cloud drops
Auto conversion
of cloud drops
Radar
Information
R_{auto} is neglected
in the process of rainfall
separation
$R = Rn + R_{seeder} >> R_{auto}$
non-orographic
rainfall
orographic
rainfall

New Method of rainfall separation

Capture rate of cloud drop by non-orographic rainfall

$$c = 0.6778 Rn^{0.731}$$

$$\begin{cases} \dfrac{dL}{dt} = -C_{(R_n)} L + WG \\ R = Ro_{seeder}(Rn) + Rn \end{cases}$$

（conservation equation of cloud drop）

（Radar Information）

Simultaneous equation

Numerical iteration calculation

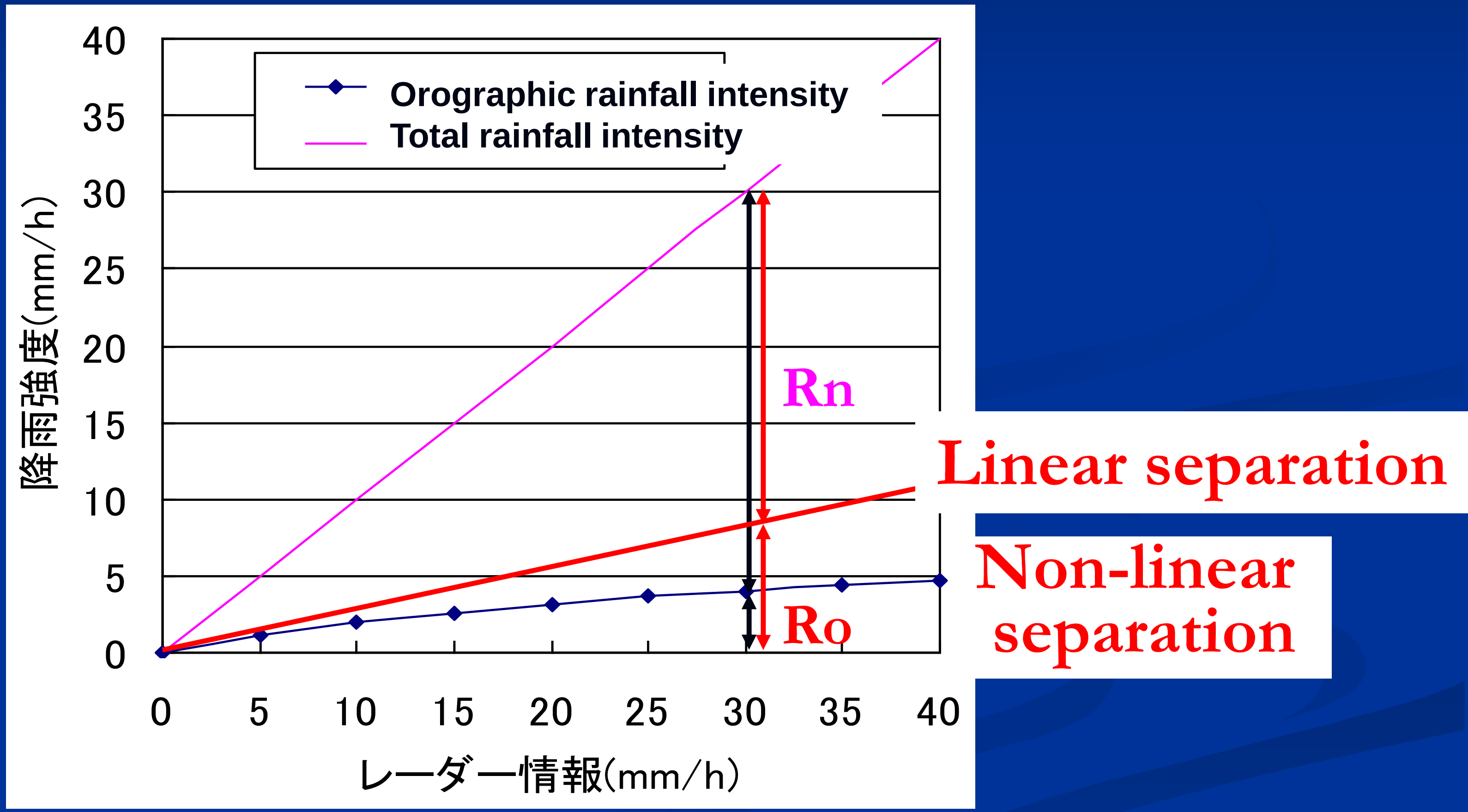
$Rn\ (L, W, \Delta t)$

L : cloud water content (g/m^3)

W : ascent velocity (m/s)

Δt : transition time for 1 mesh (s)

Preliminary analysis assuming that cloud water conopntent L=0.2[g/m^3], ascent velocity W=1.0[m/s], transition time Δt=600.0[s]



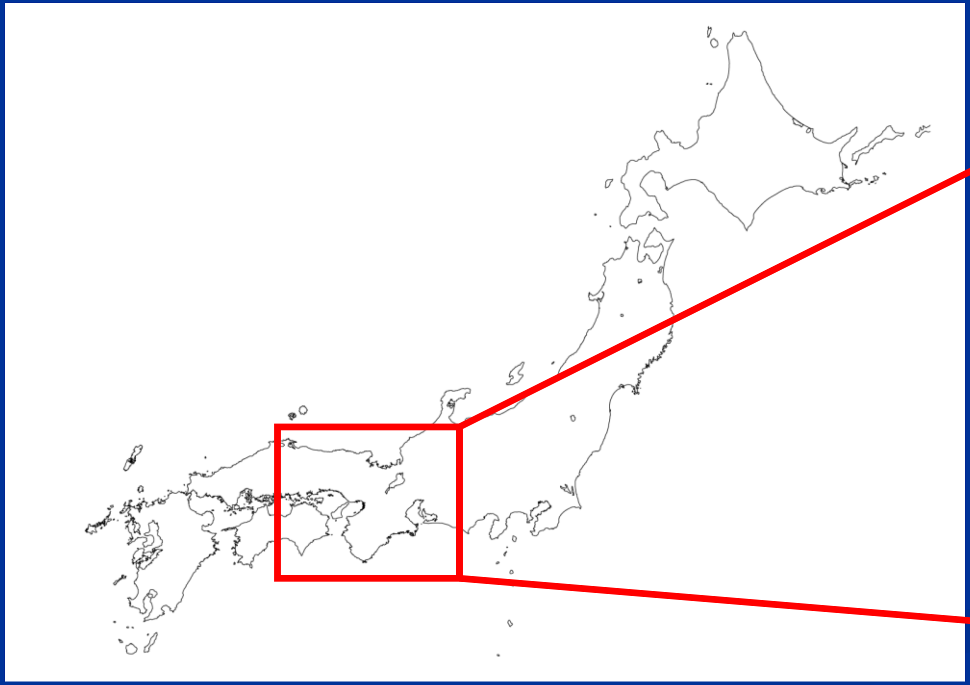
In the previous method, orographic rainfall was over estimated.

Case study (T2304)

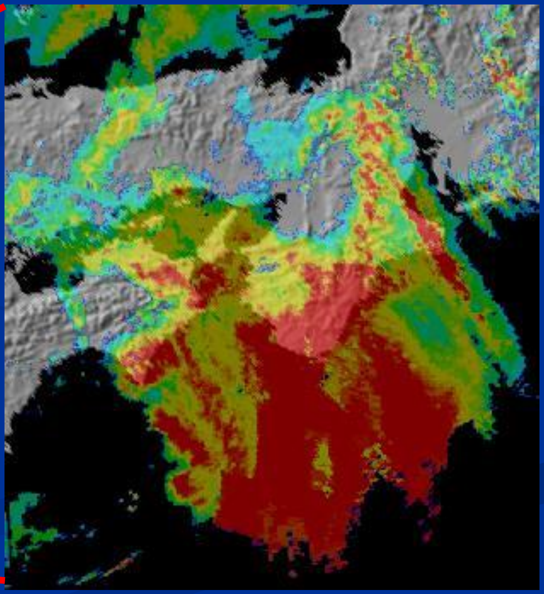
Initial Time : 2004 6/21 10:00JST

Model domain : Kinki in JAPAN

Radar information

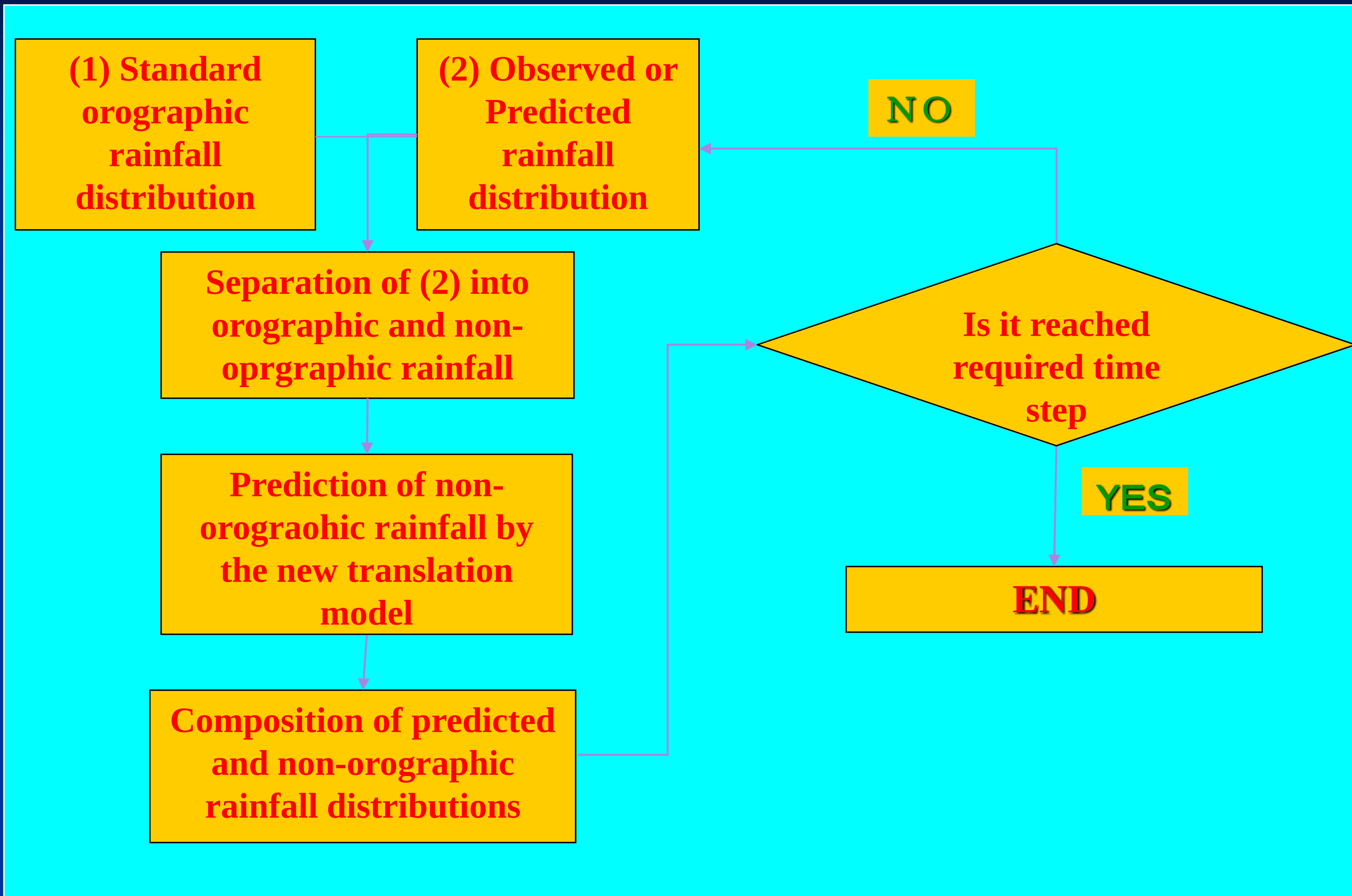


JAPAN

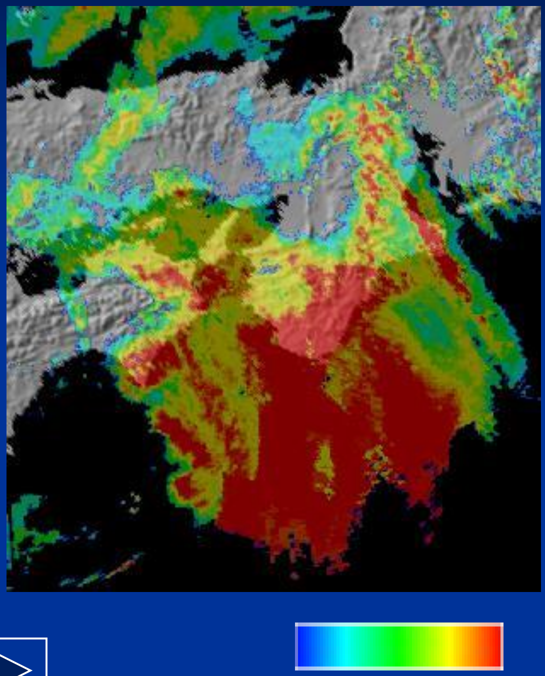


Observed Rainfall
(2004 6/21 10:00JST)

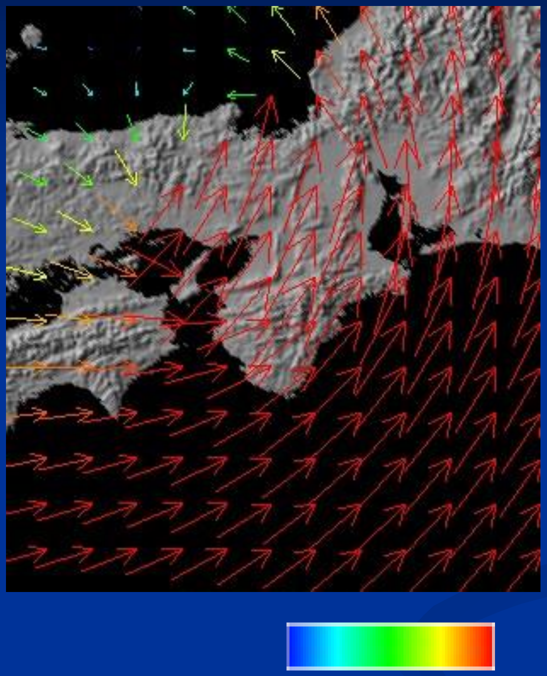
Procedure of prodection (予測手順)



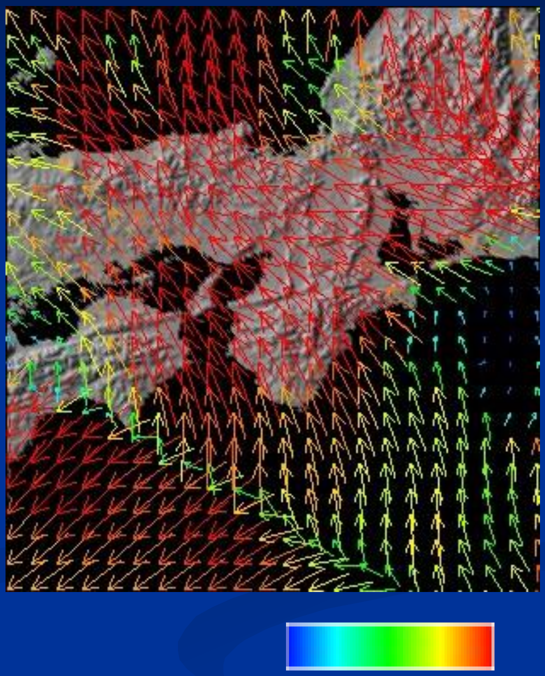
Case Study (T2306 Initial Time 6/21 10:00)



Observed Rainfall
(6/21 10:00)



Identified advection vector
(6/21 10:00 ）

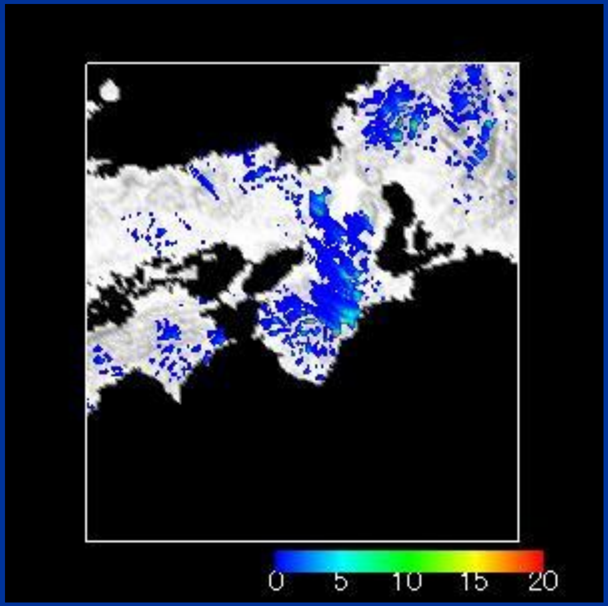


Wind vector from GPV
and AMeDAS(6/21 10:00 ）

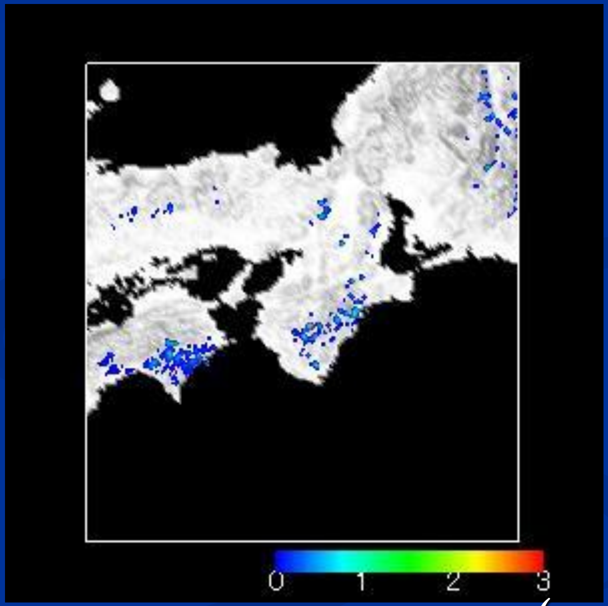
By Nakakita, Adachi and Kitai (2007)

Orographic rainfall

Existing Method



New Method



Estimated orographic rainfall
is too small in the new method

As a result, Intensity and spatial range of orographic rainfall are much smaller in new method than in existing method.

This shows that 100 m thickness in the previous model is unrealistically very thin.

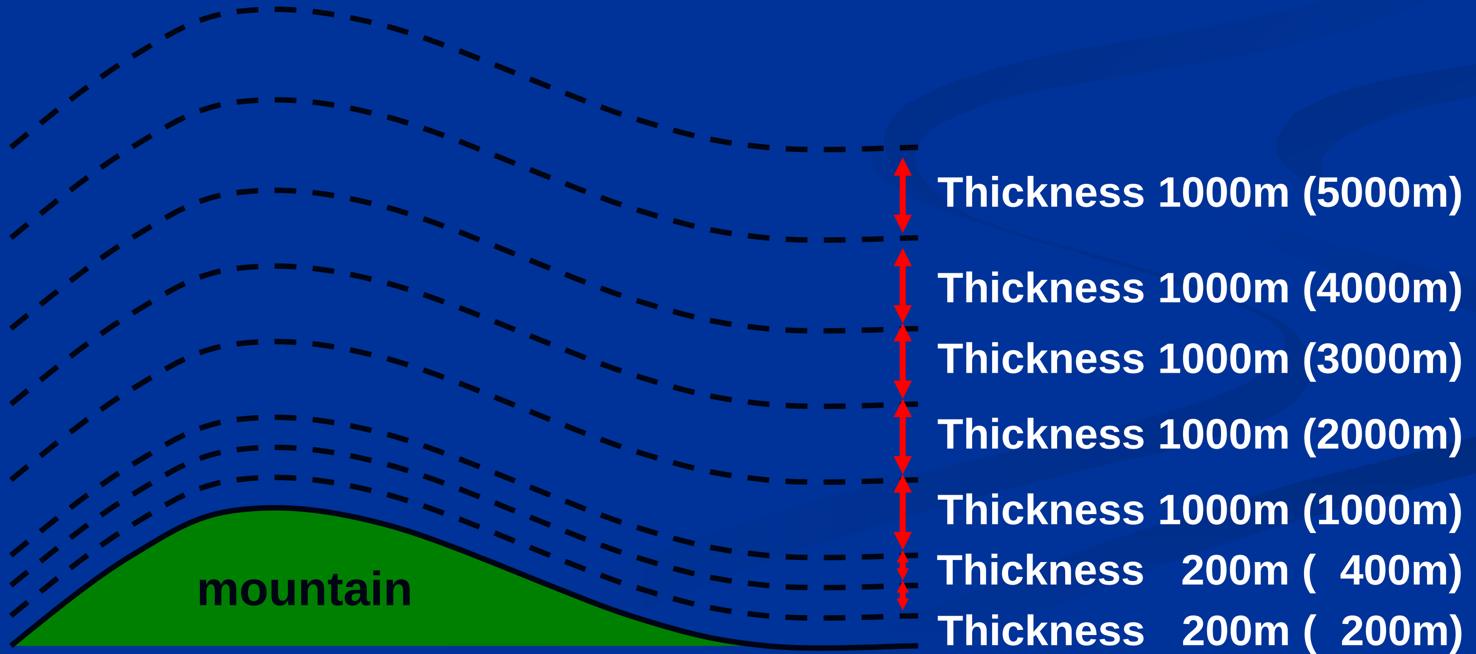
↓ Therefore

Considering multi layers, proposed procedure should be applied into every layer.

Definition of atmospheric layers

Atmosphere is divided into 7 layers, which represent at 200m, 400m, 1000m, 2000m, 3000m, 4000m, 5000m in σ-coordinate. Those layers has thickness of 200m, 200m, 1000m, 1000m, 1000m, 1000m, 1000m.

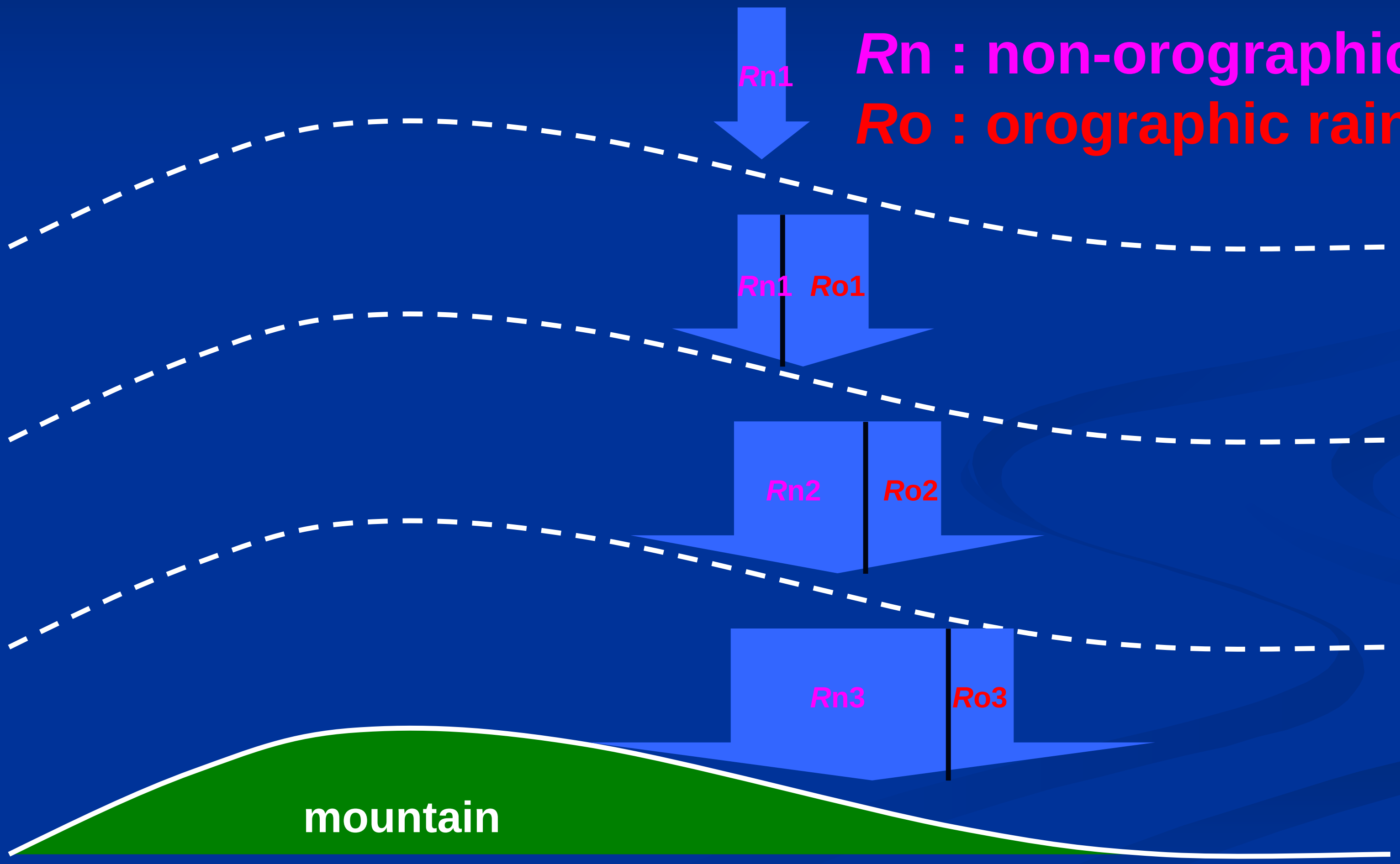
The orographic rainfall is calculated from wind direction, wind velocity, water vapor and saturated water vapor at each layer.



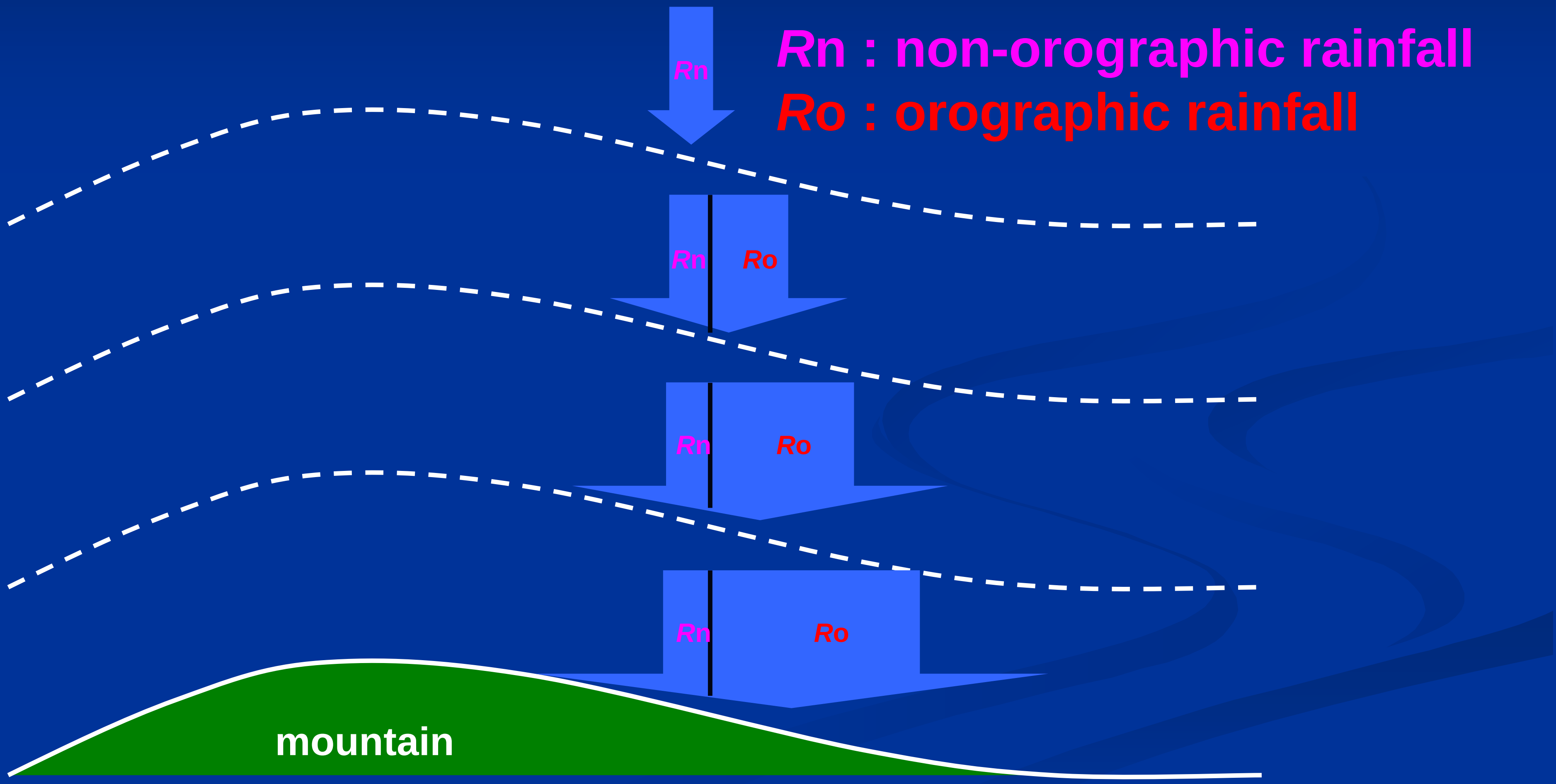
Orographic rainfall generated from multi layers

*R*n : non-orographic rainfall

*R*o : orographic rainfall



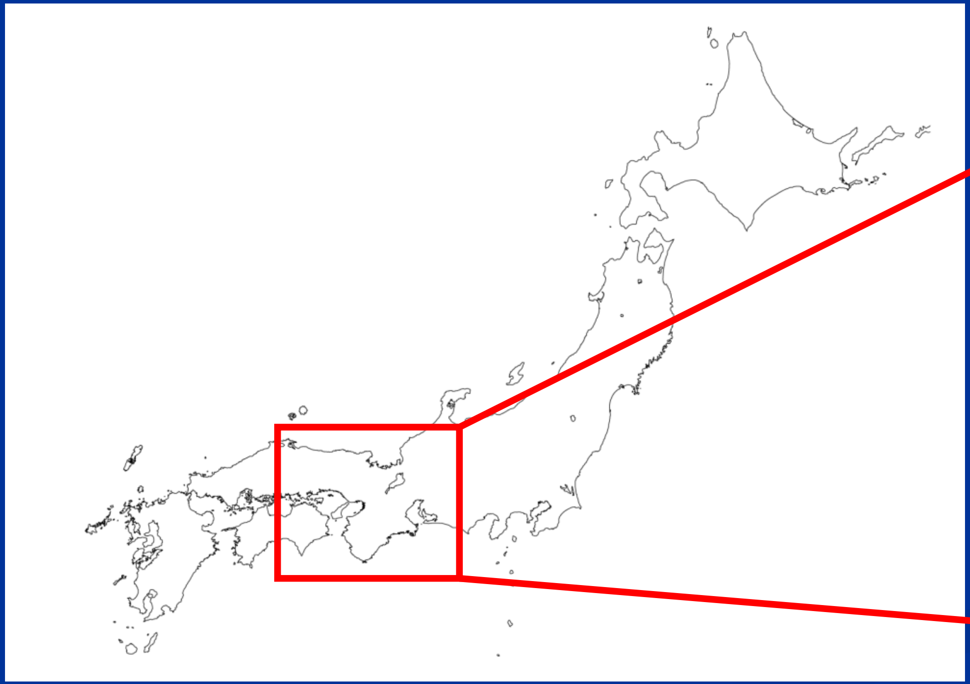
Orographic rainfall generated from multi layers



Case study (T2304)

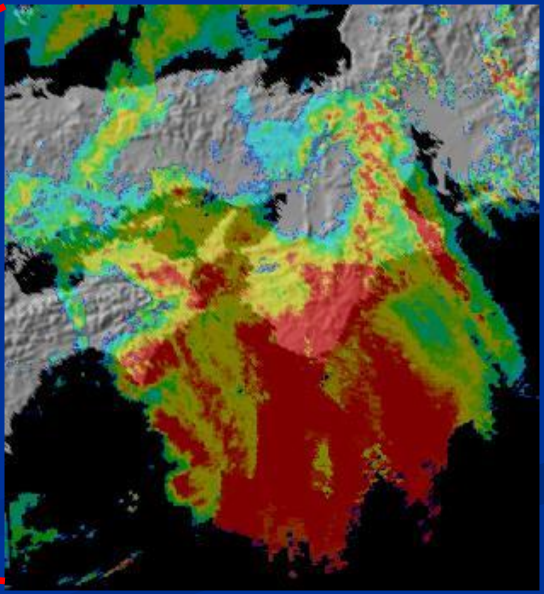
Initial Time : 2004 6/21 10:00JST

Model domain : Kinki in JAPAN



JAPAN

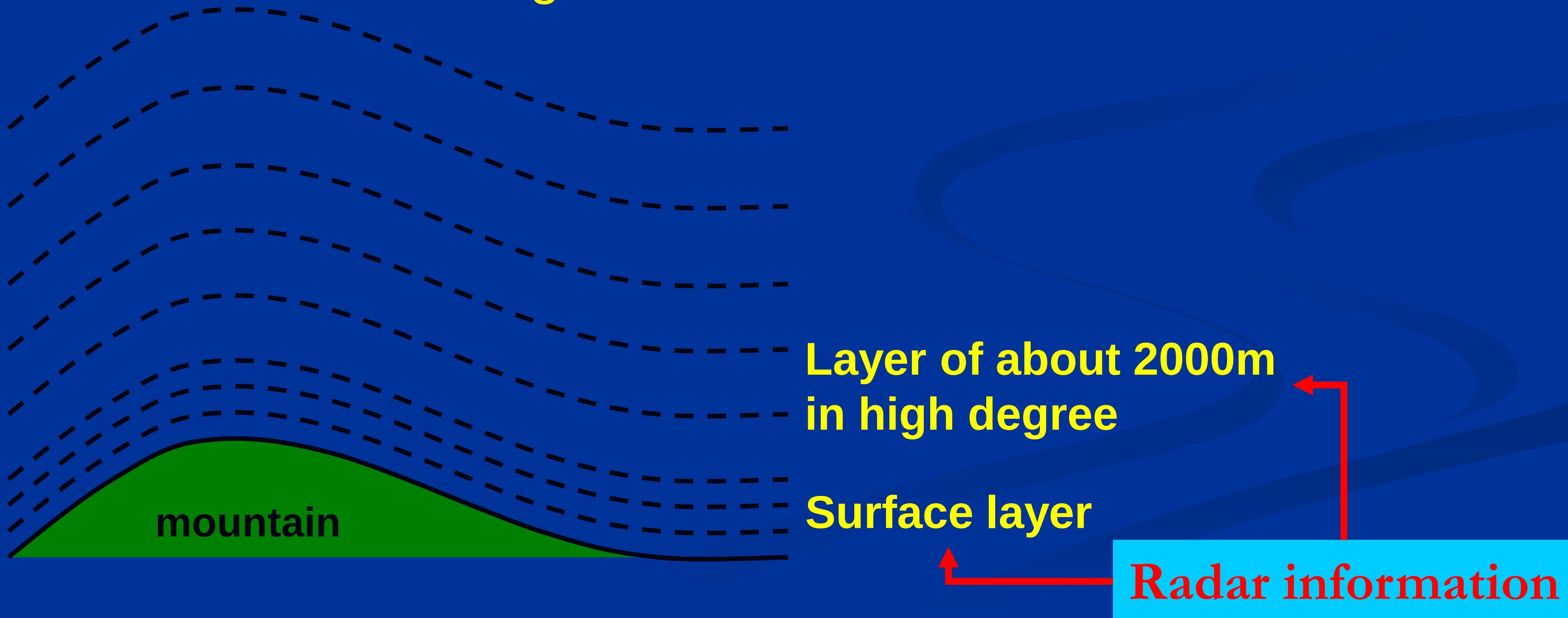
Radar information



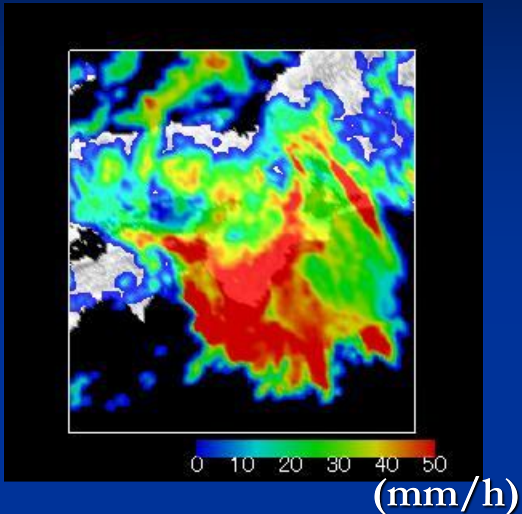
Observed Rainfall
(2004 6/21 10:00JST)

Method A : Radar information is assumed to be rainfall intensity at surface layer

Method B : Radar information is assumed to be rainfall intensity at layer of about 2000m height.

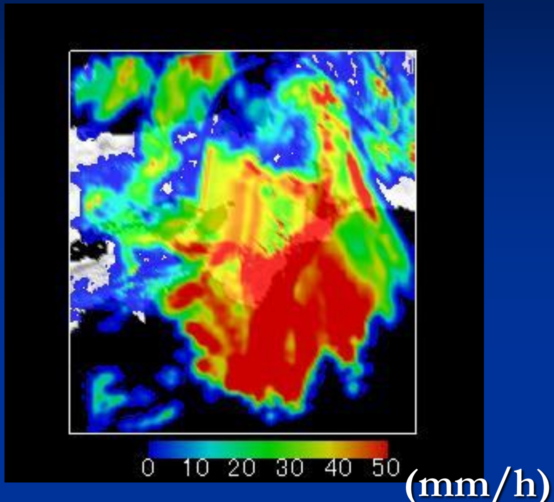


Results

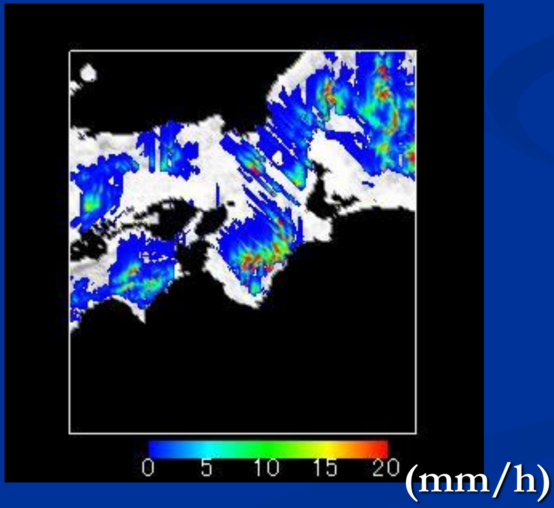


Observed rainfall
(2004 6/21 11:00JST)

Method A

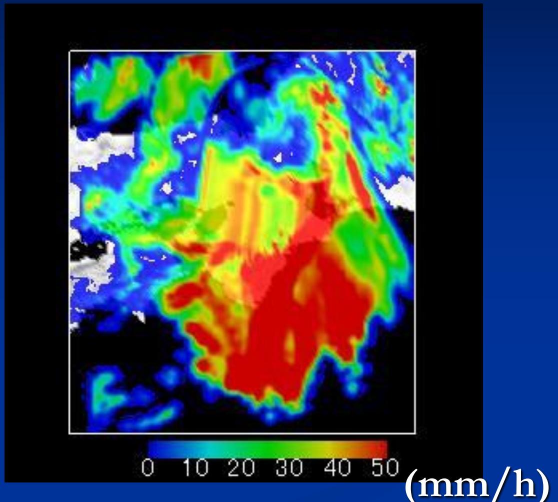


Predicted rainfall distribution

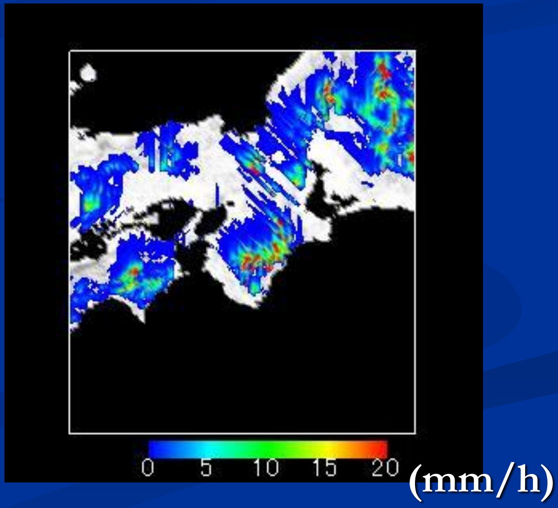


Predicted Orographic rainfall

Method B



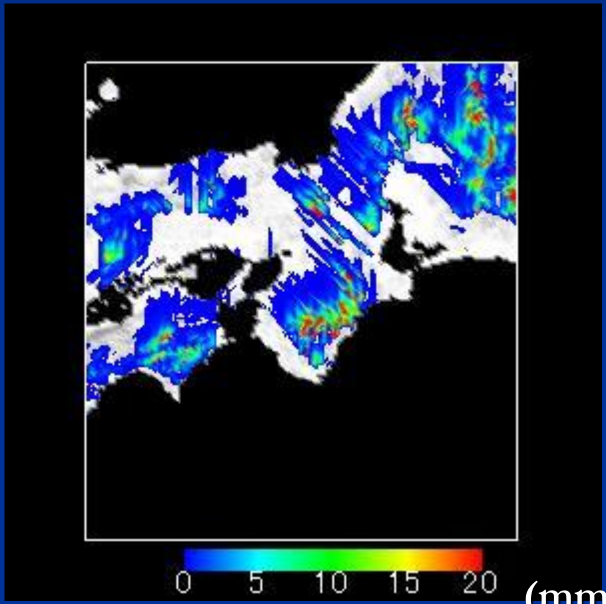
Predicted rainfall distribution



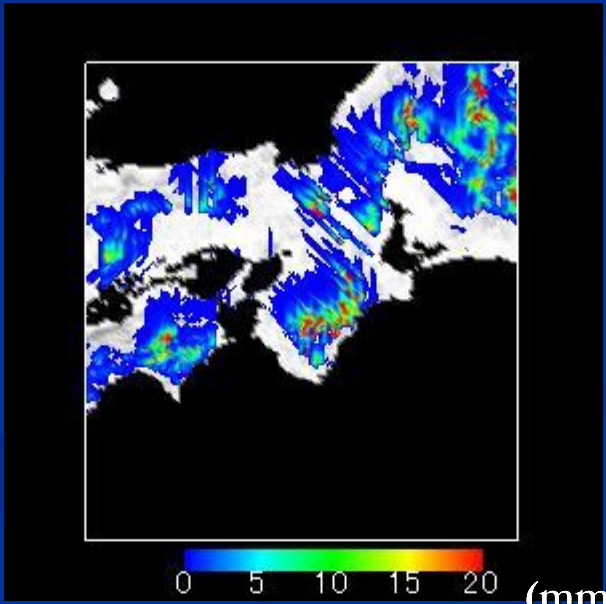
Predicted Orographic rainfall

Orographic rainfall

Method A



Method B



Much higher than the previous method When using only 100 m thickness.

Any differences can not be seen between both methods.

Conclusion

In this presentation, a method of considering nonlinear effect of non-orographic rainfall on orographic rainfall was proposed .

Conclusion

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1. It is found that Intensity and spatial range of orographic rainfall are much smaller in new method than in existing method. This shows that 100 m thickness in the previous model is unrealistically very thin.

Conclusion

In this presentation, a method of considering nonlinear effect of non-orographic rainfall on orographic rainfall was proposed .

1. It is found that Intensity and spatial range of orographic rainfall are much smaller in new method than in existing method. This shows that 100 m thickness in the previous model is unrealistically very thin.

2. Then, the model is modified so that orgraphic effect in the multi-layers can be considered. As a result, computed intensity and spatial range of predicted orographic rainfall became much more realistic than previous method.

Conclusion

3. Also, sensitivity analysis of the height of radar beam was performed with in a range of radar beam height (bottom to 2000 m height)
    - As a result the sensitivity is small within the range of realistic beam heights.
    - Because the height information is sometimes unclear depending on the type of the real-time radar information (ex. composite information with various radars), this result shows us that we do not have to mind its height as long as we know the range of the beam heights is not un-realistic.
    - Of cause, the proposed method can take actual height of radar beam into consideration as long as the height information is provided.