H13-92

Estimate of acid deposition through fog using numerical models in the Kinki Region of Japan

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Background

- Acid deposition has been widely recognized as a regional environmental problem, and has caused damage to sensitive ecosystems

- Fog deposition can lead to considerable amount of acid deposition in mountainous forest areas
  - Ionic concentrations in fog are much higher than those in rain
  - Fog water deposition through interception by vegetation can be an important part of the hydrologic budget of forests

- Few fog monitoring sites exist and fog is highly variable according to region

Introduction

Objective

- Establish a method to estimate spatial distribution of the amount of acid deposition including fog deposition

Approach

- 2-dimensional model to predict fog water deposition (FDM) was developed and verified
- FDM was applied with meteorology and air quality model to estimate acid deposition in Kinki Region of Japan

2-dimensional Fog Deposition Model (FDM)

- **Description of FDM**
- **Features of FDM**
- **Comparison of FDM with field measurement**

Description of FDM

- Equation of mean motion

$$\frac{\partial u}{\partial t} = \frac{\partial}{\partial t}\left(K_M \frac{\partial u}{\partial z} \right) - C_d a_S(z) u|u|$$

K_M: eddy diffusivity, C_d: drag coefficient,
a_S: surface area density

$$a_S(z) = \frac{SAI}{h_{fc}} \hat{a}(Z) \quad \text{for} \quad Z = z/h_{fc}, \quad 0 \le Z \le 1$$

$$\hat{a}(Z) = a_m \frac{1-Z}{1-Z_m} \exp\left[\frac{1}{2}(Z_m - \lambda)^2 - \frac{1}{2}(Z - \lambda)^2 \right], \quad \int_0^1 \hat{a}(Z) dZ = 1$$

$$Z_m \begin{cases} = \dfrac{\lambda + 1 - \sqrt{(\lambda - 1)^2 + 4}}{2} & \text{for} \quad \lambda > 1 \\ = 0 \quad \text{for} \quad \lambda \le 1 \end{cases}$$

SAI: surface area index (= *LAI*+*NLAI*), h_{fc}: height of forest canopy
λ: parameter

by Kondo and Arakashi (1976, *Boundary-Layer Meteorol.*, **10** (3), 255)

Description of FDM

- Equation of liquid water content of fog (*LWC*)

$$\frac{\partial LWC}{\partial t} = -u\frac{\partial LWC}{\partial x} - w\frac{\partial LWC}{\partial z} + \frac{\partial}{\partial z}\left(K_M \frac{\partial LWC}{\partial z}\right) - Dep$$

$$Dep = f_L a_L \, \varepsilon_{IM} |u| LWC$$

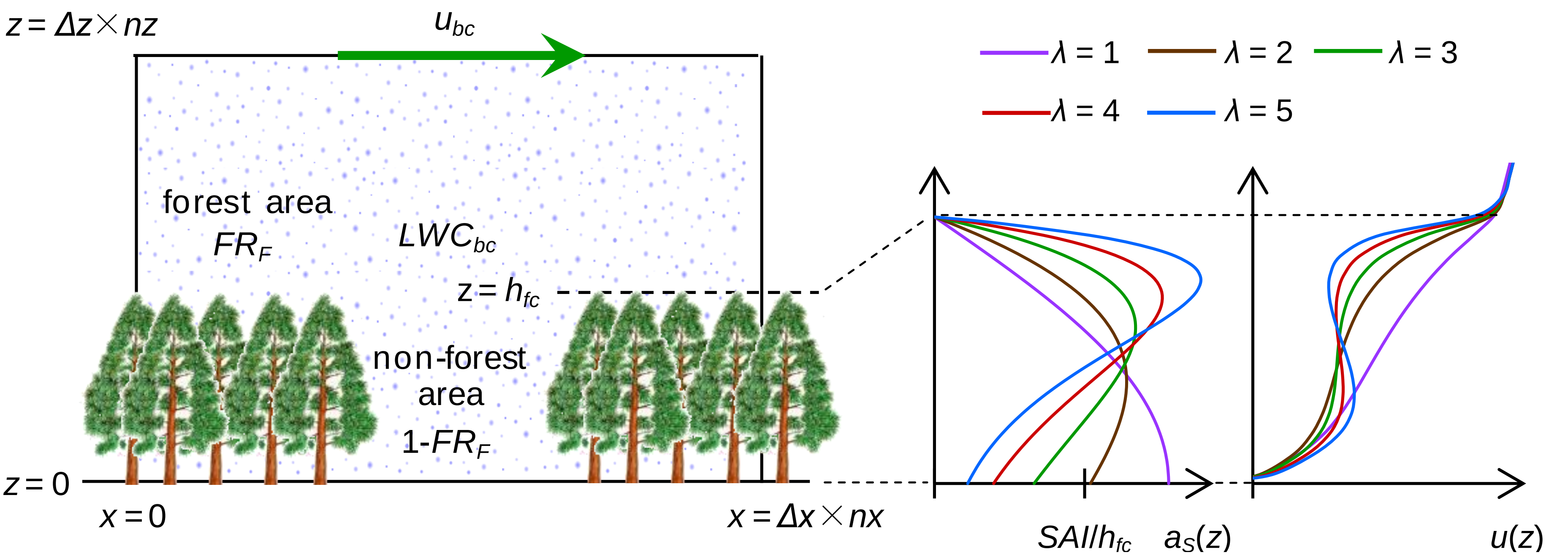
f_L: portion of the effective leaf area, a_L: leaf area density,
ε_{IM} : impaction efficiency of fog droplet

$$\varepsilon_{IM} = \left(\frac{\gamma St}{\gamma St + \alpha}\right)^{\beta}, \quad St = \frac{\rho_W d_p^2 |u|}{9\mu_A d_L}$$

α, β, γ: 5.0, 1.05 and 1 for needle leaf
0.5, 1.90 and 5 for broad leaf
d_L: characteristic leaf length
(=0.001 m for needle leaf and 0.030 m for broad leaf)
d_p: mean diameter of fog droplet (= 17.03LWC×10^{-3}+9.72×10^{-6} m)

by Katata et al. (2008, *J Appl. Meteorol. Climatol.*, **47** (8), 2129)

Description of FDM

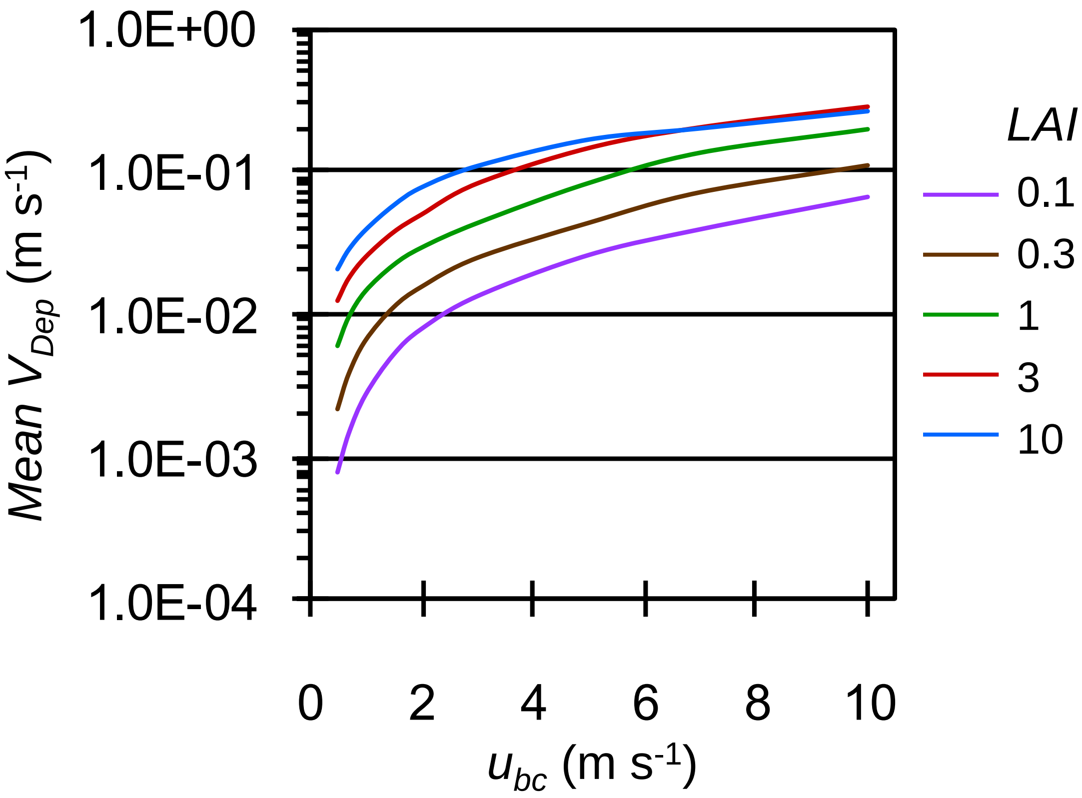


- Forests are allocated to the computational area from its horizontal edges according to fraction of forest (FR_F)
- Vertical distributions of $a_S(z)$ vary with λ, and u(z) vary with $a_S(z)$
- FDM predicts steady state fog deposition velocity (V_{Dep} = fog water deposition flux/LWC_{bc}) for each run
- FDM configuration

  $\lambda = 3$, $NLAI = 0.5$, $\Delta x = 40$ m, $nx = 50$, $\Delta z = 1.5$ m, $nz = 30$

- Sensitivity to parameters
  - FDM configuration

LWC_{bc} = 0.0003 kg m^{-3},
h_{fc} = 18 m,
FR_F = 0.96,
needle-leaved forest



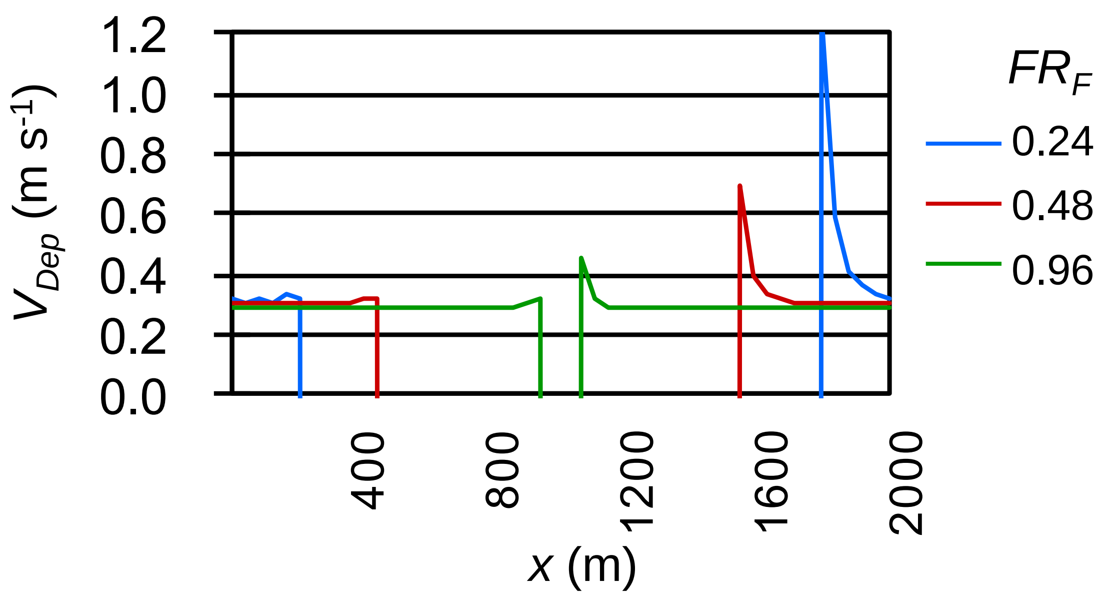
- Since ε_{IM} increases with *u*, V_{Dep} increases with u_{bc}
- When forest areas are thin, V_{Dep} considerably increases with *LAI*
- When forest areas are dense, V_{Dep} does not very increase or can decrease with an increase in *LAI* because of large drag force

Features of FDM

- Horizontal distribution of V_{Dep}

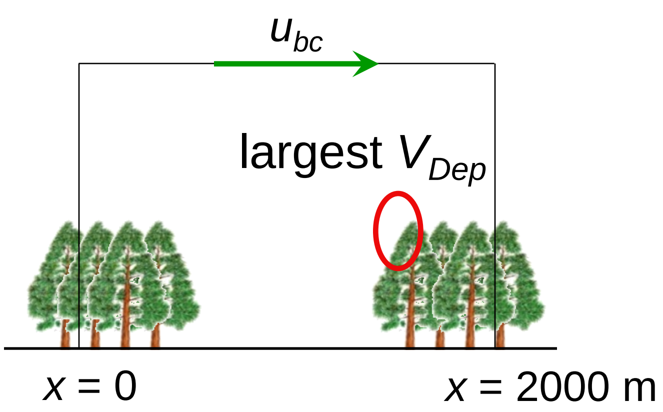
  – FDM configuration

  u_{bc} = 10 m s^{-1},
  LWC_{bc} = 0.0003 kg m^{-3},
  h_{fc} = 18 m,
  FR_F = 0.96,
  LAI = 3,
  needle-leaved forest



  – V_{Dep} at the windward edge of forest is the largest in every cases

  – Ratio of (V_{dep} at edge/V_{Dep} in inner forest) increases with increasing width of the gap between forest areas



Comparison with field measurement

- Measurement site
  - Burkard et al. (2003, *Atmos. Environ.*, **37** (21), 2979) measured the turbulent fog water flux by the eddy covariance method at 45 m on a tower (15 m above the forest canopy)
  - The measurement site is situated at 690 m on the south slope of the Lägeren Mountain, ~15 km northwest of Zurich, Switzerland
  - The vegetation cover around the site is mixed forest dominated by beech and Norway spruce

Eddy covariance measurement

Lägeren forest

(cited from http://www.gl.ethz.ch/infrastructure/research_sites/switzerland/laegeren)

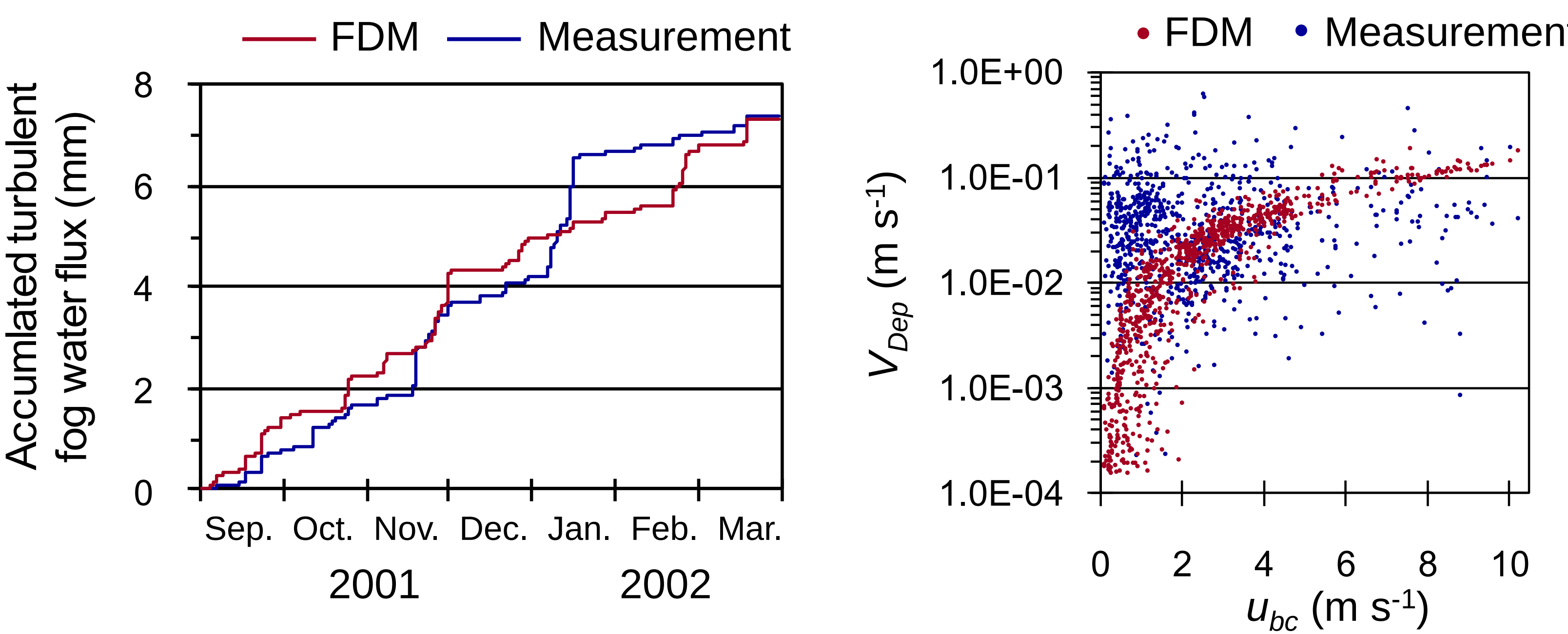
  - FDM configuration

    h_{fc} = 30 m, *LAI* derived from dataset of MODIS LAI product,

    FR_F = 1, 50 % of needle-leaved and 50 % of broad-leaved trees

Comparison with field measurement

- Fog water flux and V_{dep}



– Total fog water flux in FDM (7.3 mm) agreed with that in the measurement (7.4 mm)

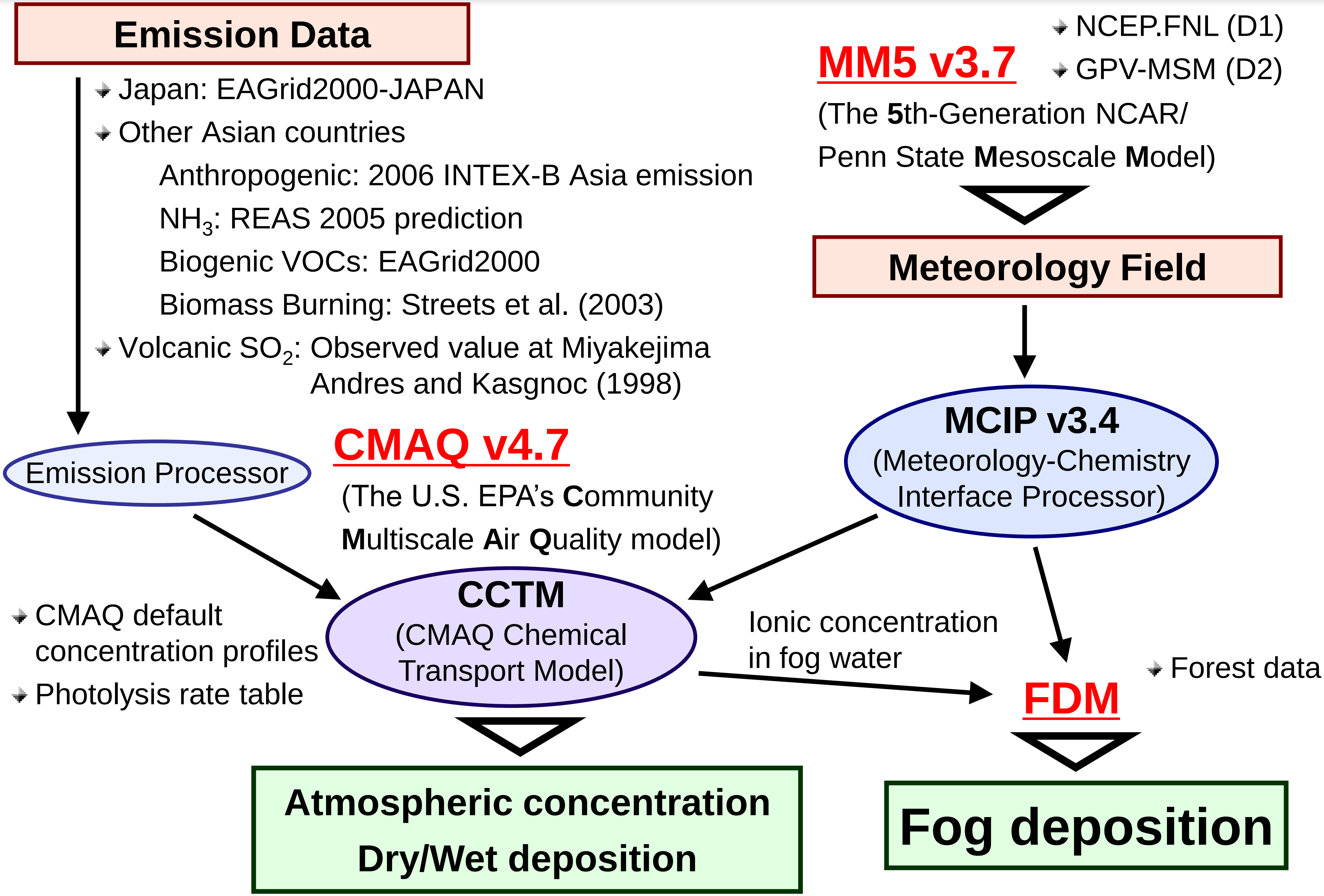
– As V_{Dep} in FDM strongly depend on u, FDM underestimated fog water flux when measured V_{Dep} was large despite low u_{bc}, and overestimated when measured V_{Dep} was small despite high u_{bc}

Estimate of fog deposition in Kinki Region of Japan

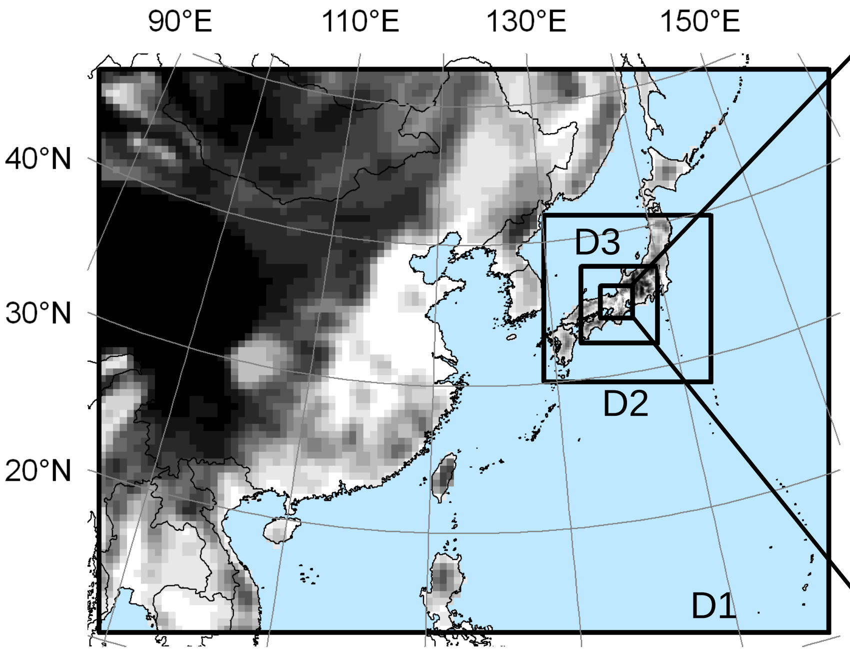
- **Modeling system**
- **Modeling domain**
- **Air quality prediction in March 2005**
- **Forest data**
- **Fog water deposition and corresponding NO_Y deposition in March 2005**

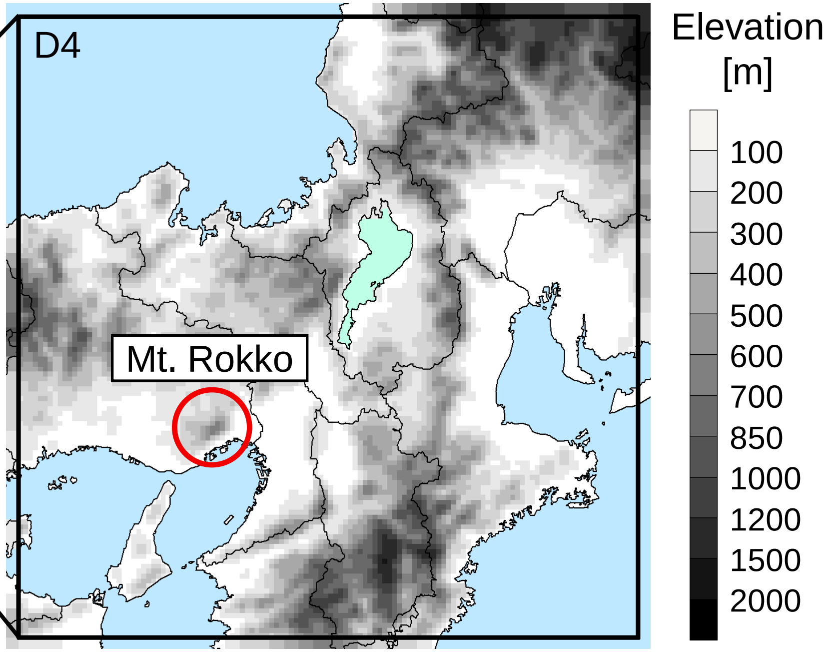
***** $NO_Y = NO + NO_2 + NO_3 + N_2O_5 + HNO_3 + HONO$ + aerosol nitrate

Modeling system



MM5/CMAQ modeling domain



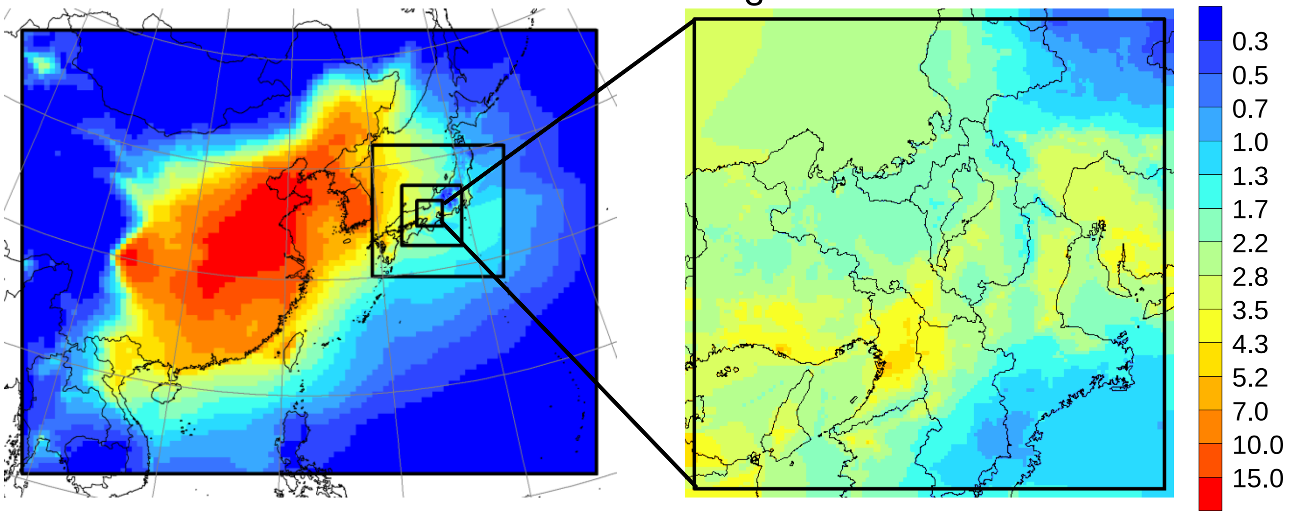


- Horizontal resolution
  - D1: 54km-grid cells (105×81)
  - D2: 18km-grid cells (72×72)
  - D3: 6km-grid cells (99×99)
  - D4: 2km-grid cells (126×126) **for estimate of fog deposition**
- Vertical resolution
  - 24 layers from surface to 100hPa
    (the middle height of the 1st and 2nd layers are ~15 and 50m)

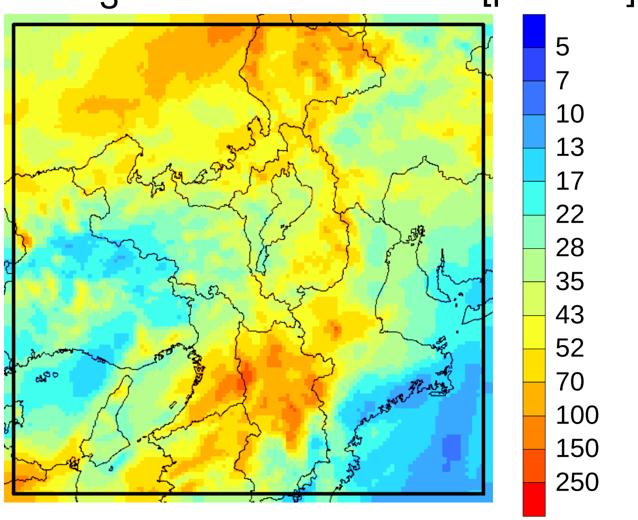
Air quality prediction in March 2005

- Spatial distributions of monthly mean NO_3^- concentrations

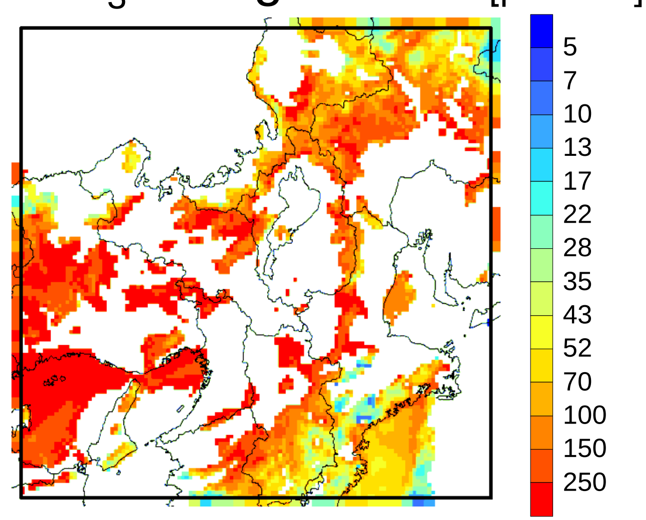
Aerosol NO_3^-



NO_3^- in rain

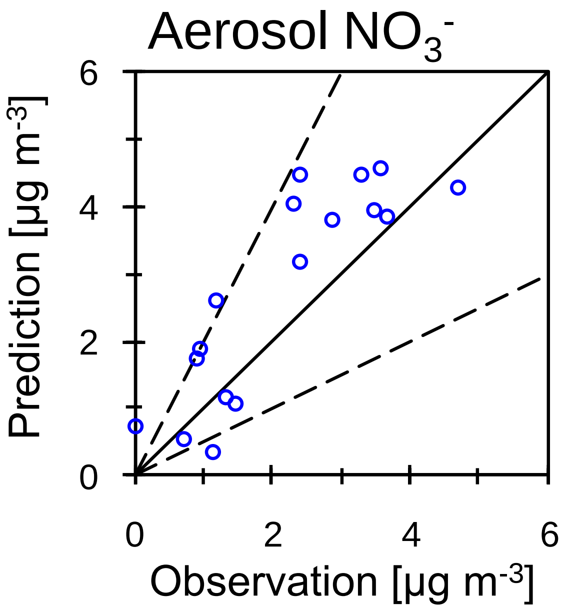


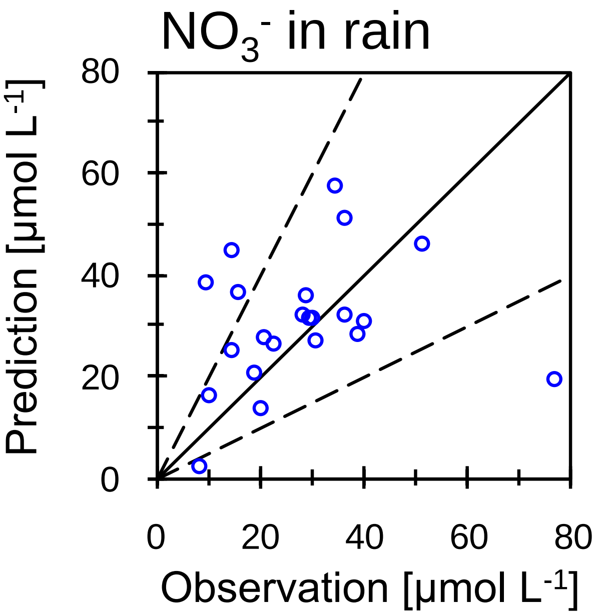
NO_3^- in fog

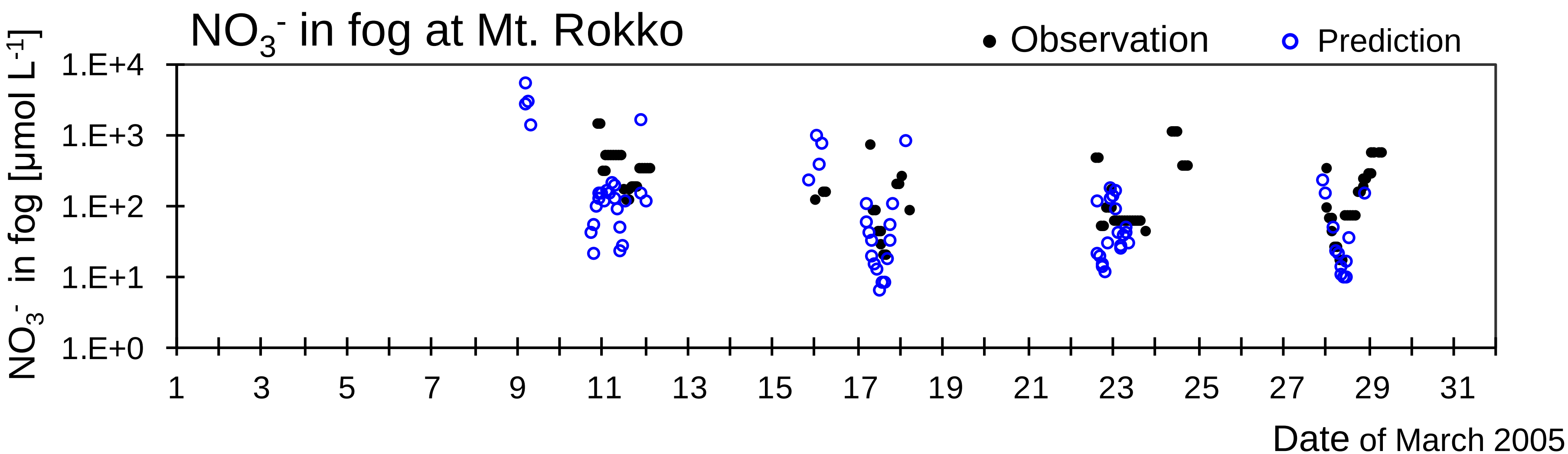


Air quality prediction in March 2005

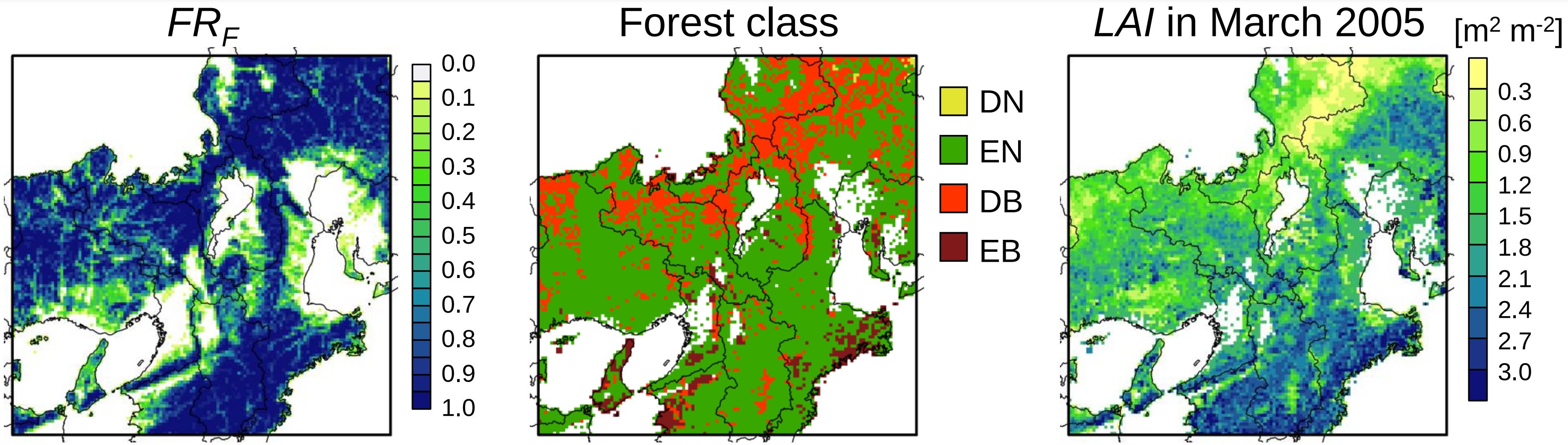
- Comparisons of predictions with observations





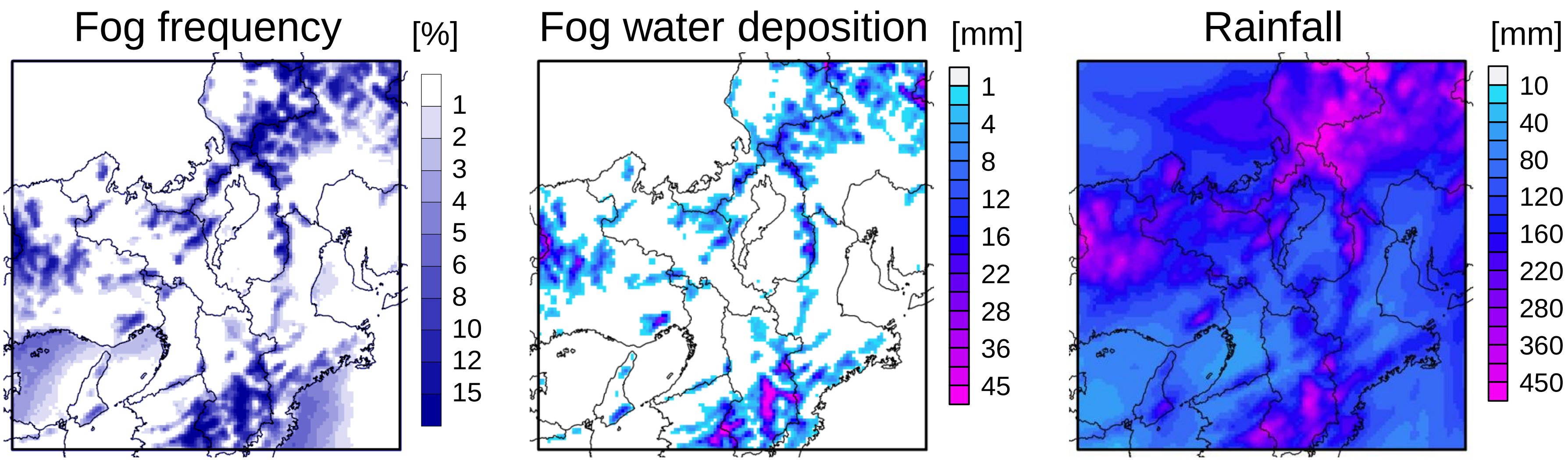


Forest data



- FR_F, forest class and LAI were obtained from dataset of MLIT in Japan, MOE in Japan and MODIS LAI product
- Forest areas account for 65 % of the land areas and 95 % of the mountainous areas with elevation > 500 m
- Needle-leaved (DN + EN) forest account for 67 % of the forest area and broad-leaved (DB + EB) forest account 33 %
- Because March is before or at the beginning of the vegetation growing season, most of the forest areas tend to be thin
- North-eastern areas covered with deciduous broad-leaved (DB) forest show the lowest *LAI*

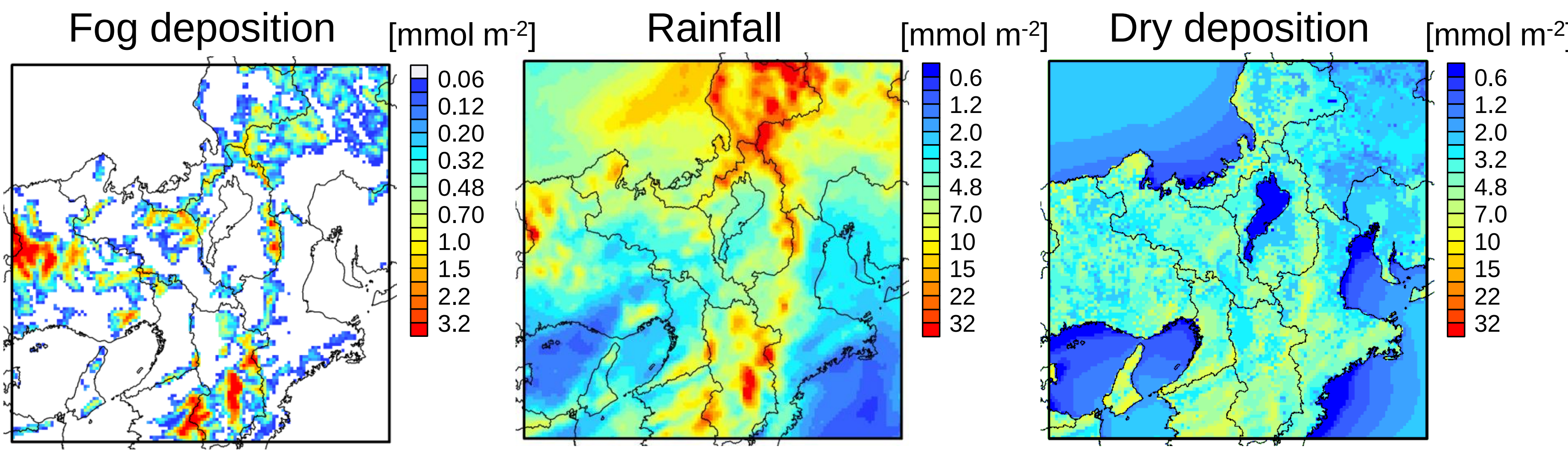
Fog water deposition in March 2005



- Fog frequency, fog water deposition and rainfall generally increased with increasing elevation
- While fog frequency and rainfall were the highest in the north-eastern area dominantly covered with deciduous broad-leaved forest, fog water deposition was not due to the thin vegetation cover
- Ratios of (Fog water deposition/Rainfall) reached up to 23 % (mean = 3 %) in mountainous areas
- The ratio may change in the vegetation growing season

NO_Y deposition through fog in March 2005

NO_Y deposition corresponding to



- Ratios of (NO_Y depositions through fog/NO_Y depositions through rain) reached up to 97 % (mean = 8 %) in mountainous areas
- Contribution of fog deposition to NO_Y depositions was larger than that of dry deposition in some mountainous areas
- Fog water deposition is an important pathway for acid deposition in some mountainous areas in Kinki Region, Japan

Conclusions

- Fog deposition model (FDM) was developed and verified
  - V_{Dep} calculated by FDM considerably varied with *u* and parameters on forest
  - Despite some discrepancies between FDM and the measurement, FDM captured the total fog water deposition
- Fog deposition was estimated with FDM and MM5/CMAQ in Kinki Region, Japan in March 2005
  - Fog water deposition can contribute significantly to acid deposition in some mountainous areas
  - Long-term prediction (1year ~) is required for further study, because contribution of fog deposition vary with seasonal variations in meteorology, air quality and vegetation structure

Thank you