Investigation of the dispersion of air pollutants by the RePLaT model

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Lagrangian dispersion models

- “ghost” particles (computational particles)
  - point-like particles
  - with artificial, ***time-dependent*** mass (e.g. m_p = 1 kg) → mass decreases exponentially due to deposition: $\Delta m_p/\Delta t = -C\cdot m_p$
  - trajectory is determined by the atmospheric flows + in some models ***mean*** settling/terminal velocity
  - e.g.: FLEXPART, HYSPLIT

- “real” particles
  - particles with ***fixed, realistic*** size and density (e.g. r = 1 µm, ρ_p = 2000 kg/m^3)
  - trajectory is determined by the atmospheric flows + terminal velocity of ***individual*** particles
  - e.g. for fast prediction of volcanic ash dispersion
  - no wet deposition
  - e.g.: PUFF, VAFTAD

RePLaT model[1]

(Real Particle Lagrangian Trajectory model)

- a Lagrangian model tracking ***"real" aerosol particles***
- the particles have fixed, realistic size (e.g. r = 1–10 μm) and density (e.g. ρ_p = 2000 kg/m³)
- equation of motion ← Newton's equation
  - advection
  - turbulent diffusion

$\mathbf{r}_p$	particle position
r	particle radius
ρ_p, ρ	density of particle, air
ν	kinematic viscosity of air
$\mathbf{v}_p$, $\mathbf{v}$	velocity of particle, air
g	gravitational acceleration
ξ	noise
$\mathbf{K}$	turbulent diffusion
$\mathbf{n}$	unit vector pointing upwards

$$\frac{d\mathbf{r}_p}{dt} = \mathbf{v} + w_{term}\mathbf{n} + \xi \cdot \mathbf{K}$$

←

$$w_{term} = -\frac{2}{9}\frac{\rho_p r^2 g}{\rho \nu}$$

terminal velocity

↑

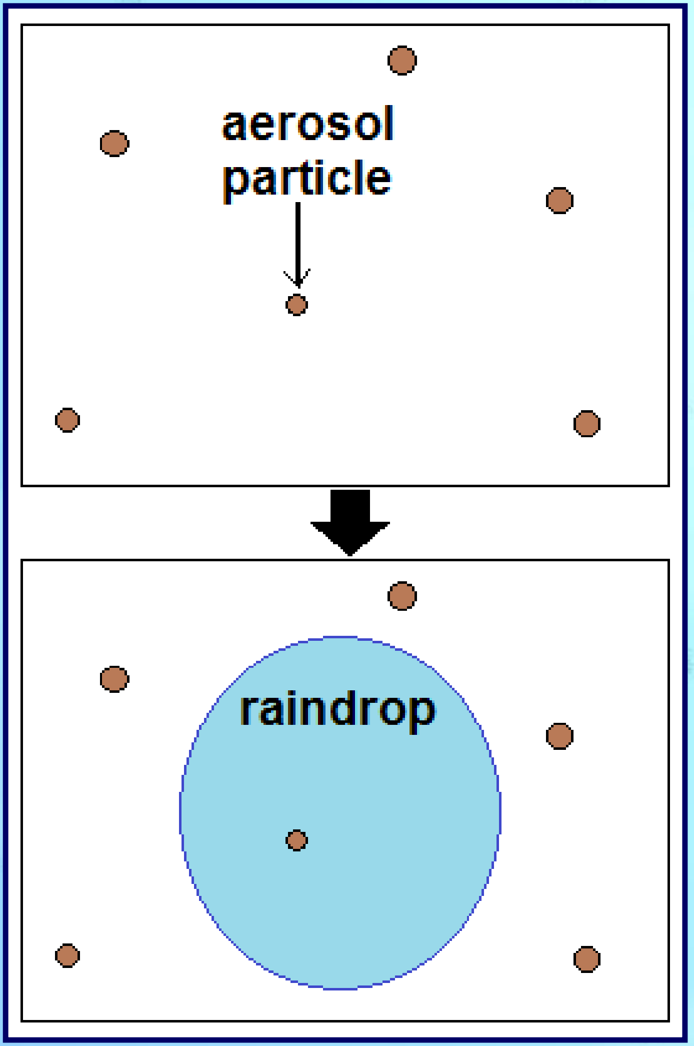
Stokes law
(aerosol particles, $r \lesssim$ 10 μm)

[1] Haszpra, T. and Tél, T. (2013) *Nonlin. Proc. Geophys.* 20(5), 867–881.

RePLaT model

(Real Particle Lagrangian Trajectory model)

- **wet deposition**
  - ***random*** process: a particle is captured by a raindrop with a certain $p_{r,rain}$ *probability*
  - $\rightarrow r' = r_{rain}, \rho_p' = \rho_{rain}$
  - r_{rain} and $p_{r,rain}$ depend on precipitation intensity



RePLaT model

(Real Particle Lagrangian Trajectory model)

- **wet deposition**

based on the Eulerian approach:

m mass

k_w scavenging coefficient

$$\frac{dm}{dt} = -k_w m$$

$$\frac{m(\Delta t)}{m(0)} = \exp(-k_w \Delta t) \leftarrow \text{in}$$

$$1 - \frac{m(\Delta t)}{m(0)} = 1 - \exp(-k_w \Delta t) \leftarrow \text{out}$$

a particle is captured by a raindrop with probability

$p_{r,rain} = 1 - \exp(-k_w \Delta t)$

k_w, r_{rain}: depend on P precipitation intensity

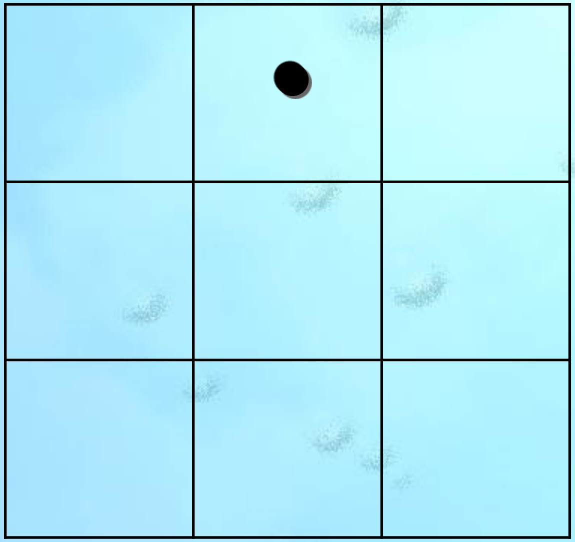
→ $r' = r_{rain}$, $\rho_p' = \rho_{rain}$

→ $w'_{term} \gg w_{term}$

$$w_{term} = -\frac{8}{3}\frac{\rho_{rain} r_{rain} g}{\rho C_d}$$ ← quadratic drag force

RePLaT model
(Real Particle Lagrangian Trajectory model)

- meteorological data in λ, φ, p coordinates
  (e.g. ERA Interim database,
  European Centre for Medium-Range Weather Forecasts)
  ↓
- equation of motion: $\lambda_p, \varphi_p, p_p$
- interpolation:
  - bicubic spline in horizontal
  - linear in time and vertical
- numerical solution: Euler method



Equation of motion

$$\lambda_{\mathrm{p}}(t+\Delta t)=\lambda_{\mathrm{p}}(t)+\frac{u}{R_{\mathrm{E}}\cos\varphi}\Delta t+R\sqrt{24K_{\lambda}\Delta t}$$

$$\varphi_{\mathrm{p}}(t+\Delta t)=\varphi_{\mathrm{p}}(t)+\frac{v}{R_{\mathrm{E}}}\Delta t+R\sqrt{24K_{\varphi}\Delta t}$$

$$p_{\mathrm{p}}(t+\Delta t)=p_{\mathrm{p}}(t)+(\omega+\omega_{\mathrm{term}})\Delta t+R\sqrt{24K_{p}\Delta t}+\frac{\partial K_{p}}{\partial p}\Delta t$$

advection — turbulent diffusion

$$K_{\lambda}=\frac{K_x}{\left(R_{\mathrm{E}}\cos\varphi_{\mathrm{p}}\right)^2}$$

$$K_{\varphi}=\frac{K_y}{R_{\mathrm{E}}^2}$$

R [–0.5; 0.5] uniform distribution random number

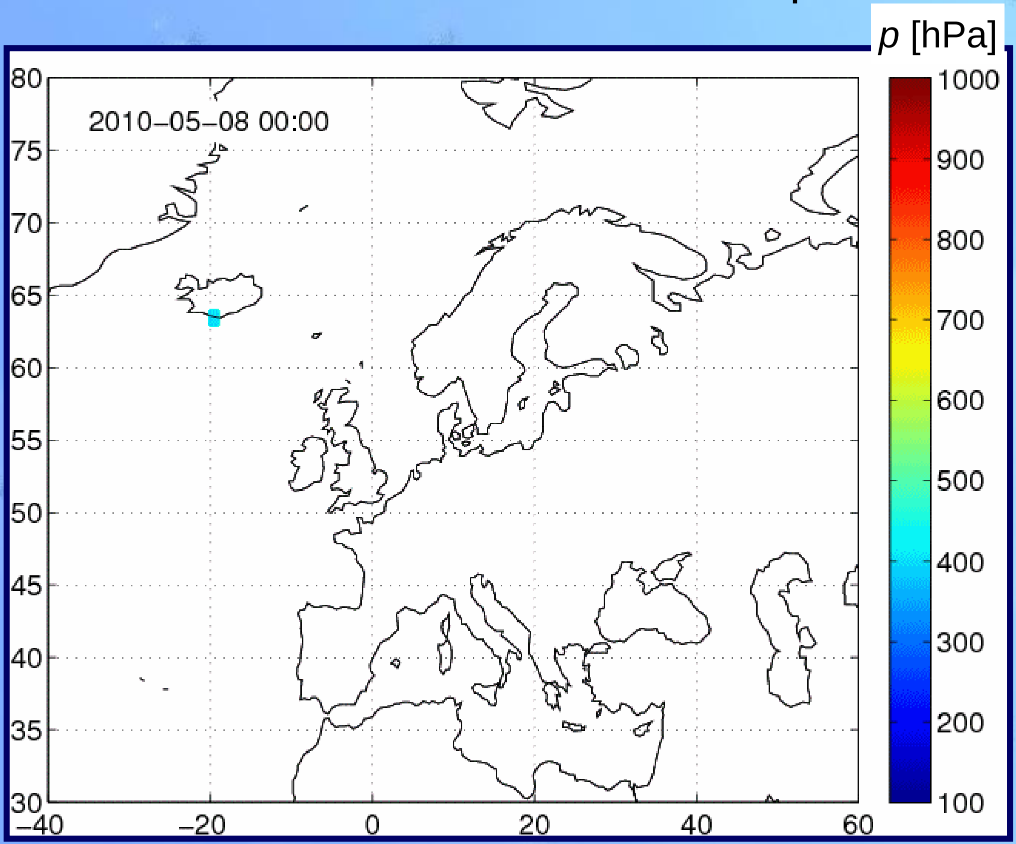
R_{E} Earth's radius

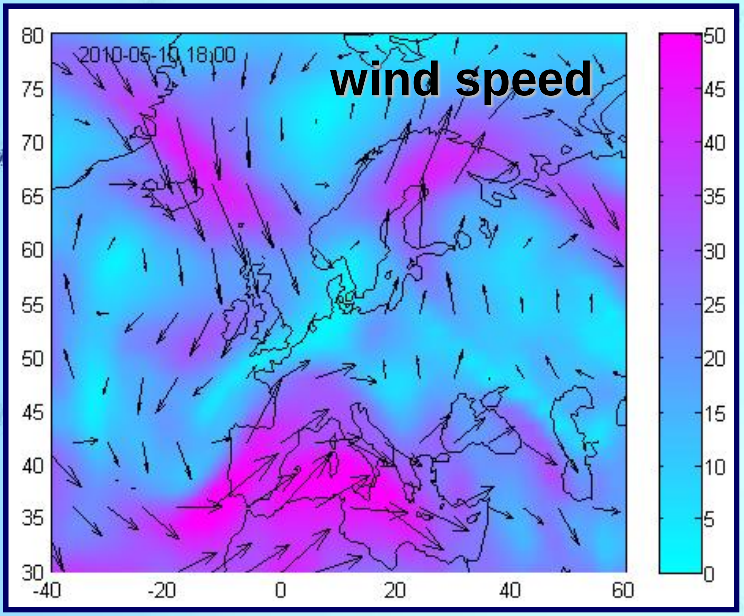
K_x, K_y constant horizontal turb. diff

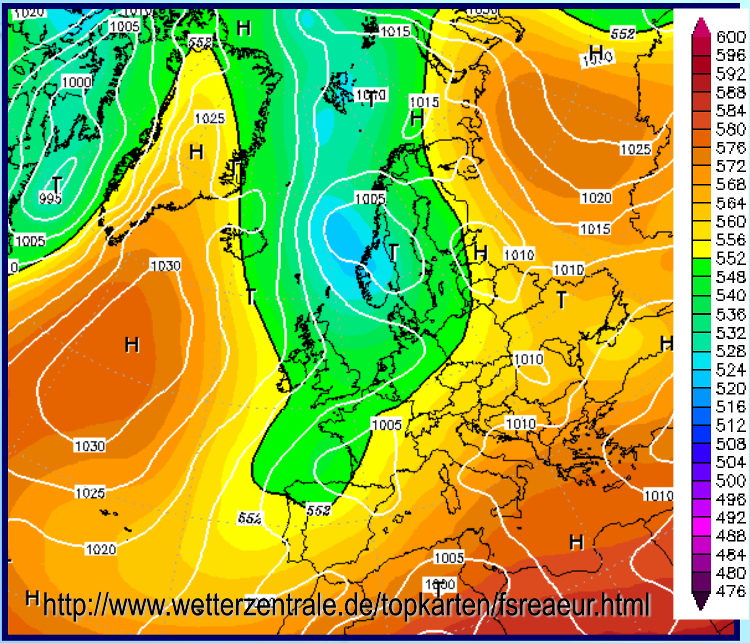
$K_p \leftarrow K_z$ vertical turb. diff.
(Monin–Obukhov similarity theory)

Eyjafjallajökull simulation
(May 8–19, 2010)

r = 1 µm, ρ_p = 2000 kg/m^3
$n = 7 \cdot 10^4$ particles
simulation: adv., turb. diff., no wet dep.

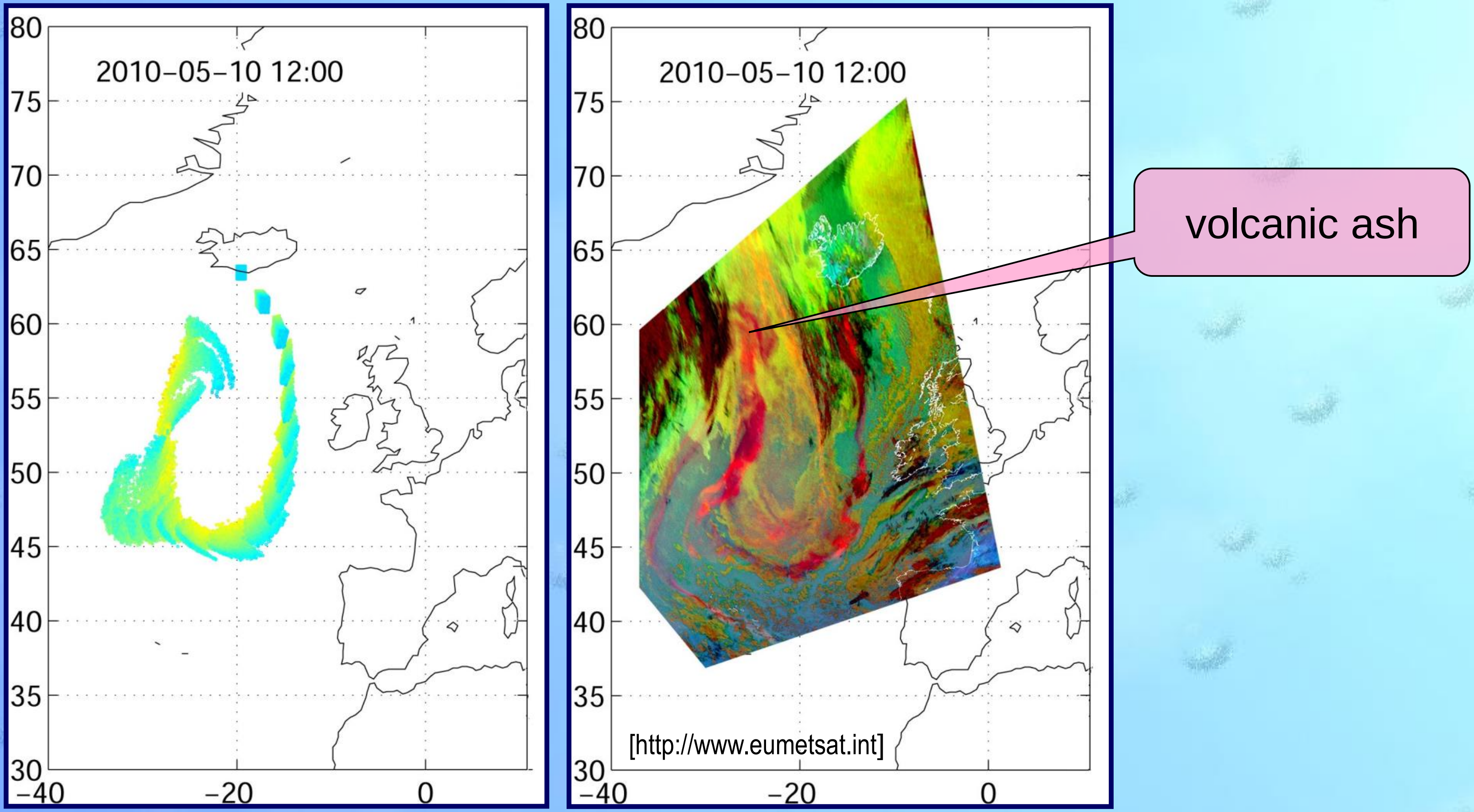




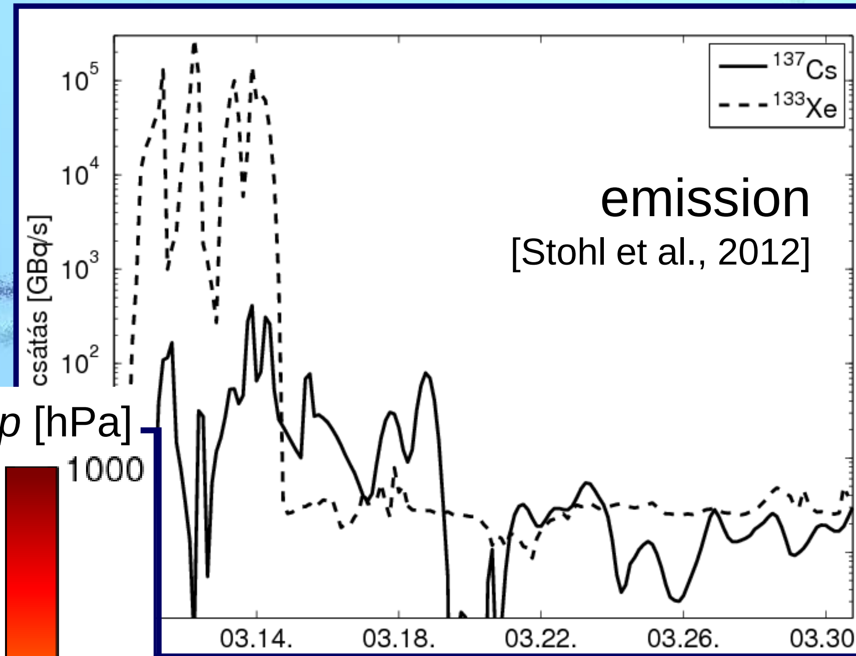


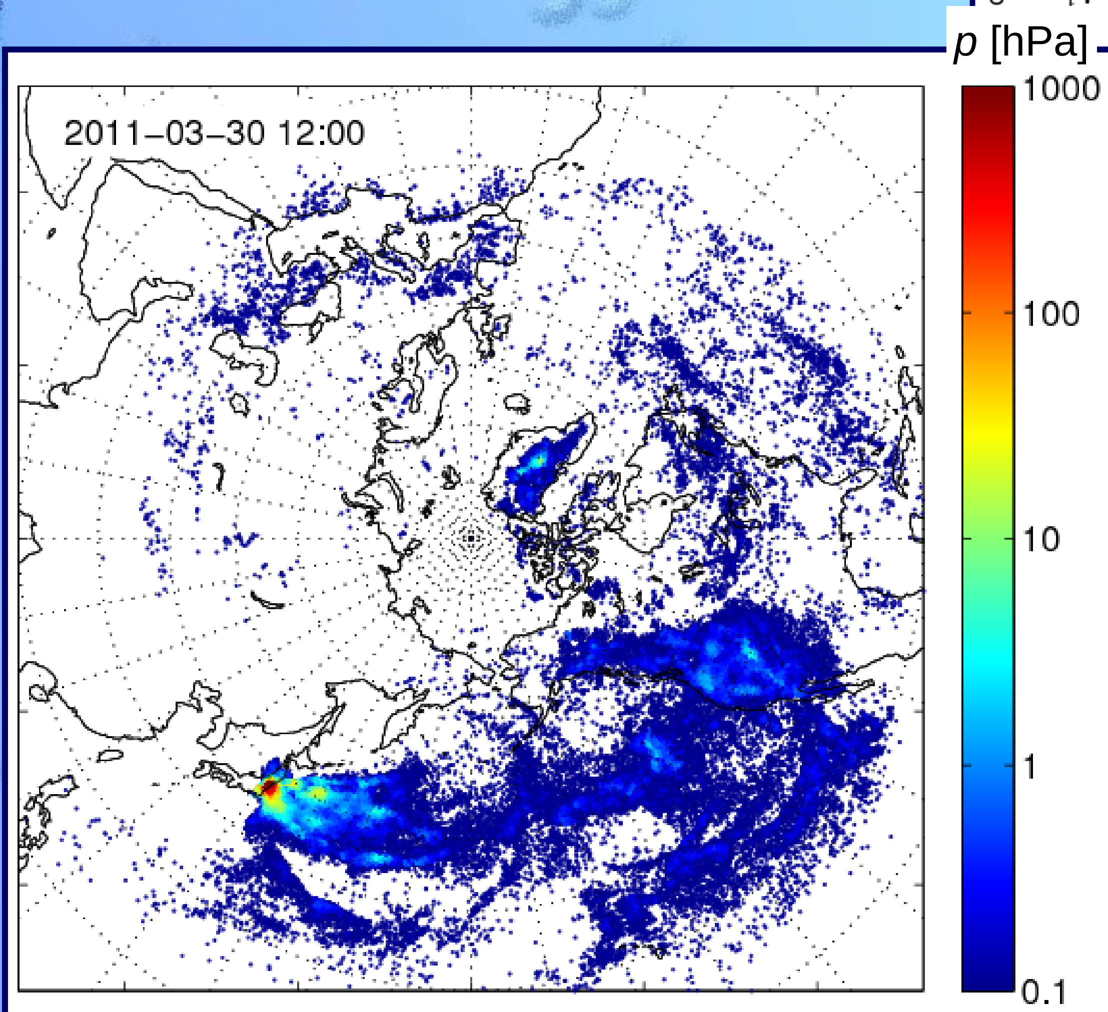
Eyjafjallajökull simulation
(May 8–19, 2010)

- *comparison*: simulation and satellite measurement



Fukushima simulation
(March 10–30, 2011)





aerosol-bound ^{137}Cs isotope

r = 0.2 µm, ρ_p = 1900 kg/m^3
n = 10^6 particles

simulation: advection
turb. diff.
wet deposition

deposition field
[kBq/m^2]

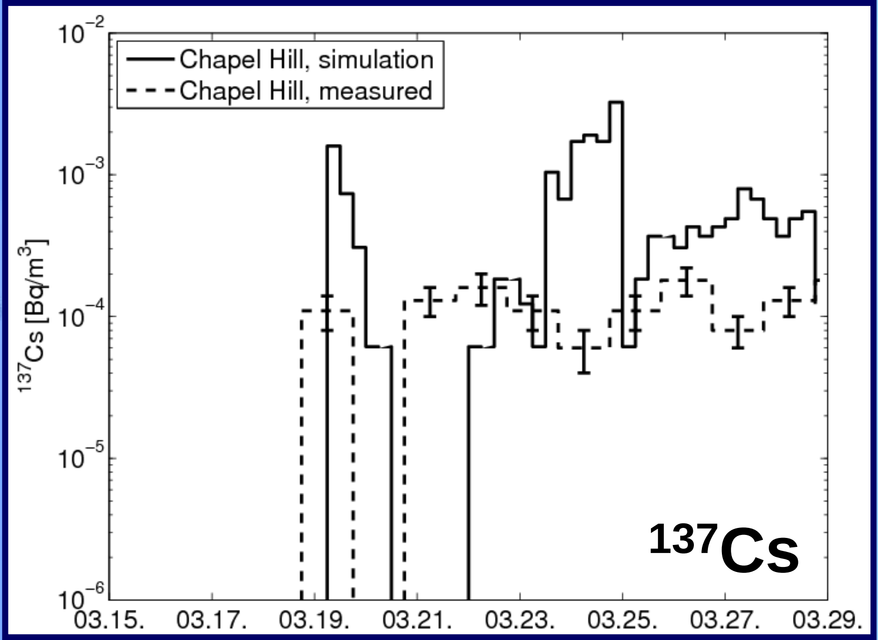
Fukushima simulation
(March 10–30, 2011)

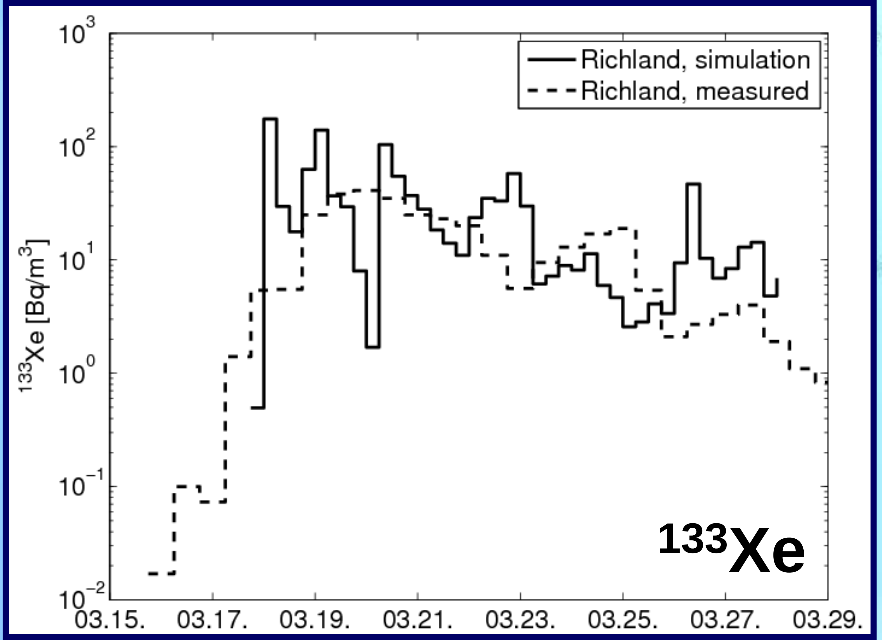
- *comparison*: measurement and simulation
- arrival times coincide reasonably well

- ^{133}Xe: simulations were able to reproduce the measured concentrations
- ^{137}Cs: sometimes overestimations

uncertainties:

- estimated emission data
- coarse resolution of the meteorological data (6h) → heavy precipitation events smoothed out
- parameterizations …





Uncertainties in the dispersion forecasts

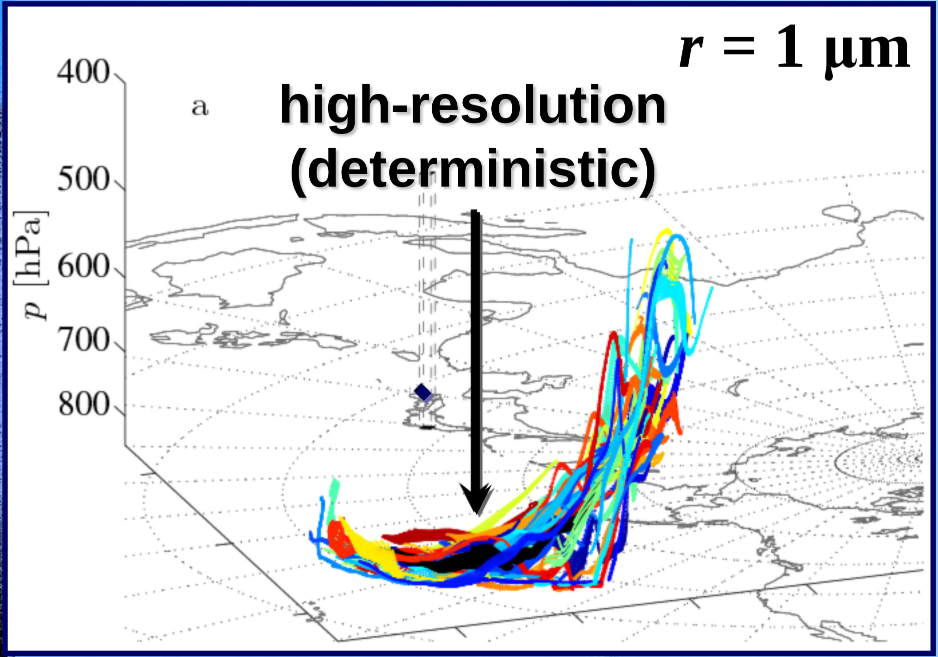
- **input data** for the dispersion model
  - emission data
  - meteorological data → ensemble forecasts
- uncertainties associated to the **dispersion model**
  - processes taken into account, parameterizations
  - numerical approximations
- **chaotic advection** of pollutants [Aref, 1984]
  (sensitivity to the initial conditions, irregular motion, complex structures)

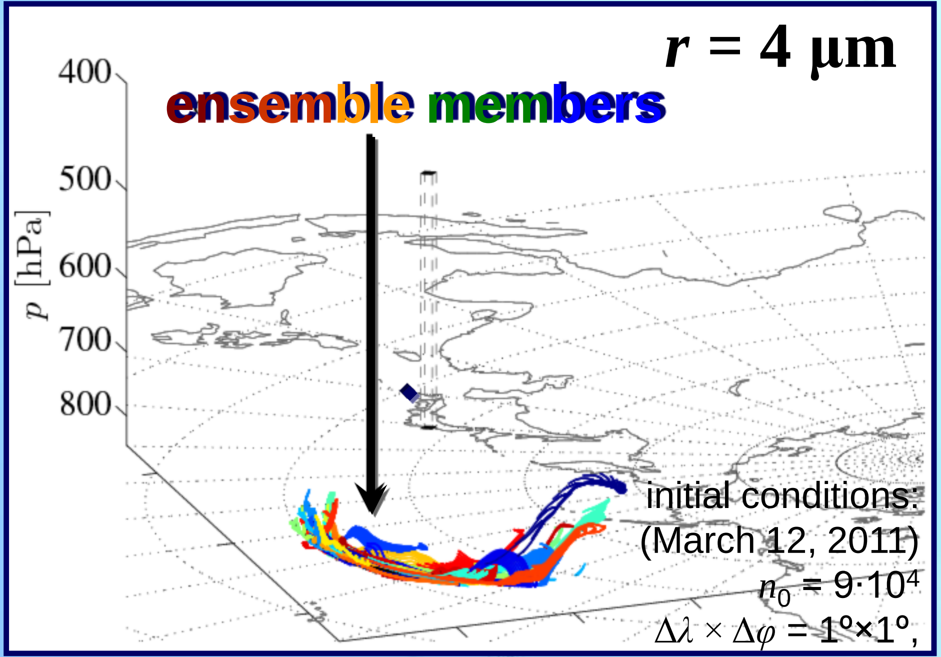
Impact of the meteorological data

General overview

- 50 perturbed + 1 unpertubed member (CF) + HRES
- ρ_p = 2000 kg/m^3, r = 1, 2,…, 10 μm
  aerosol particles
- 3D particle distribution after 2.5 days

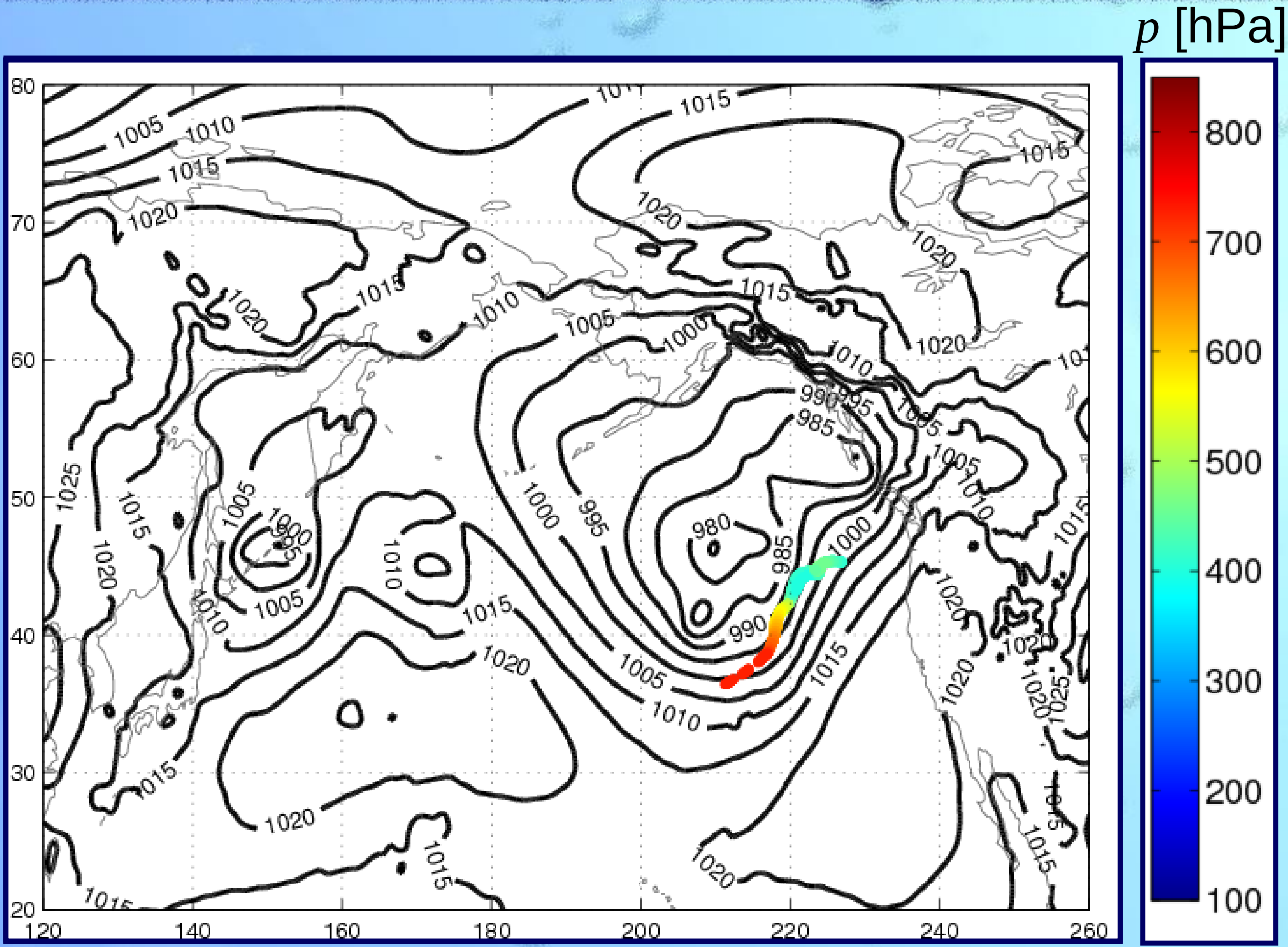
- **simulations:**
  advection
  no turb. diff.
  no wet dep.





Impact of the meteorological data

Types of pollutant clouds for r = 1 µm

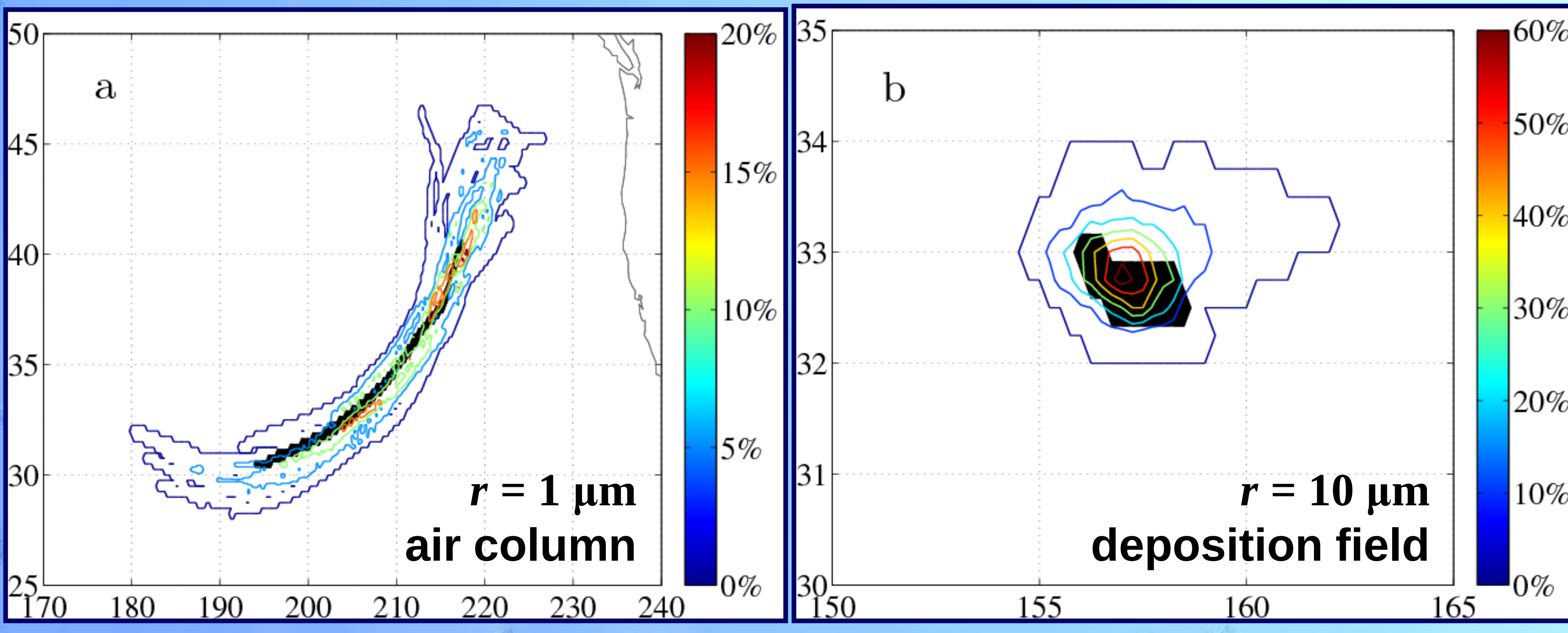


Impact of the meteorological data

Horizontal distribution for r = 1 and 10 μm

- ***Colored contours*** indicate the percentage of the ensemble dispersion simulations that predict a concentration above a threshold
- ***Black:*** the same by using the HRES forecast

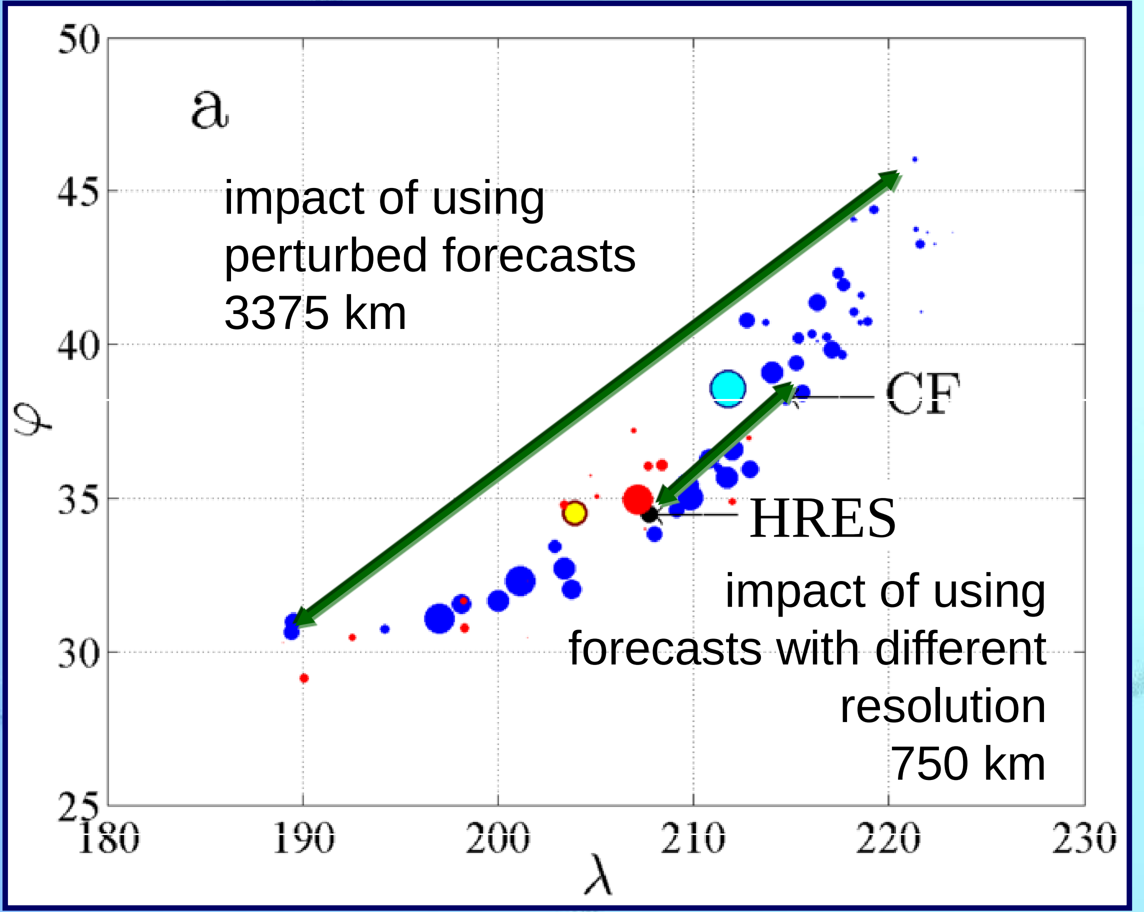
- ensemble pollutant clouds expand to a 5–10 times larger area than that of the HRES forecast



Impact of the meteorological data

Center of mass for r = 1 µm

- for particles in ensemble dispersion members that
  blue: remain in air
  red: deposited
- radius: proportional to the standard deviation of particles around the center of mass
  35–960 km



Haszpra, T., Lagzi, I., Tél, T. (2013): Dispersion of aerosol particles in the free atmosphere using ensemble forecasts. *Nonlin. Proc. Geophys*. 20(5) 759–770

Haszpra, T., Horányi, A. (2014): Some aspects of the impact of meteorological forecast uncertainties on environmental dispersion prediction. *Időjárás* (accepted)

Summary and Outlook

- ***RePLaT*** Lagrangian dispersion model
- future work: RePLaT should be improved by additional factors (e.g. more detailed description of the wet deposition)

- the simulations carried out by the RePLaT model agree reasonably well with observations

- effect of ***uncertainties*** in the meteorological data on the dispersion calculation, and its dependence on the particle size
- ensemble pollutant clouds expand to a larger area than that of the HRES forecast
- ***risk assessment*** → where and when does the concentration exceed a certain threshold with what probability?
- Note: it is only one of the error sources! → it would be useful to take into account ***other uncertainty sources***

Thank you for your attention!