Special Lecture on Assimilation of Radar Data

Dr. Klaus Stephan

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Outline

1. Motivation
2. Basics on Radar meteorology
3. Radar measurement and its assmilation
   - ➔ Reflectivity
     - LHN
   - ➔ Radial Wind Component
     - VAD
     - Nudging
   - ➔ Polarisation
4. Brief introduction on Radar Forward Operator (for the LETKF era)

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Motivation

What have you learned already?

- Theoretical background on DA
  - To obtain a good analysis you need suitable measurements: Measuring of relevant parameter with a high resolution in space and time and a reasonable quality
- Satellite Observations:
  - Indirect measurement
  - reasonable resolution in space or time (normally not both together)
- Conventional Observations (Synops, Radio sondes):
  - direct measurement of relevant parameters
  - Sparse in space and/or time
- Further observation systems are available, but most of them will lack of high resolution in space (at least in one dimension) or time.

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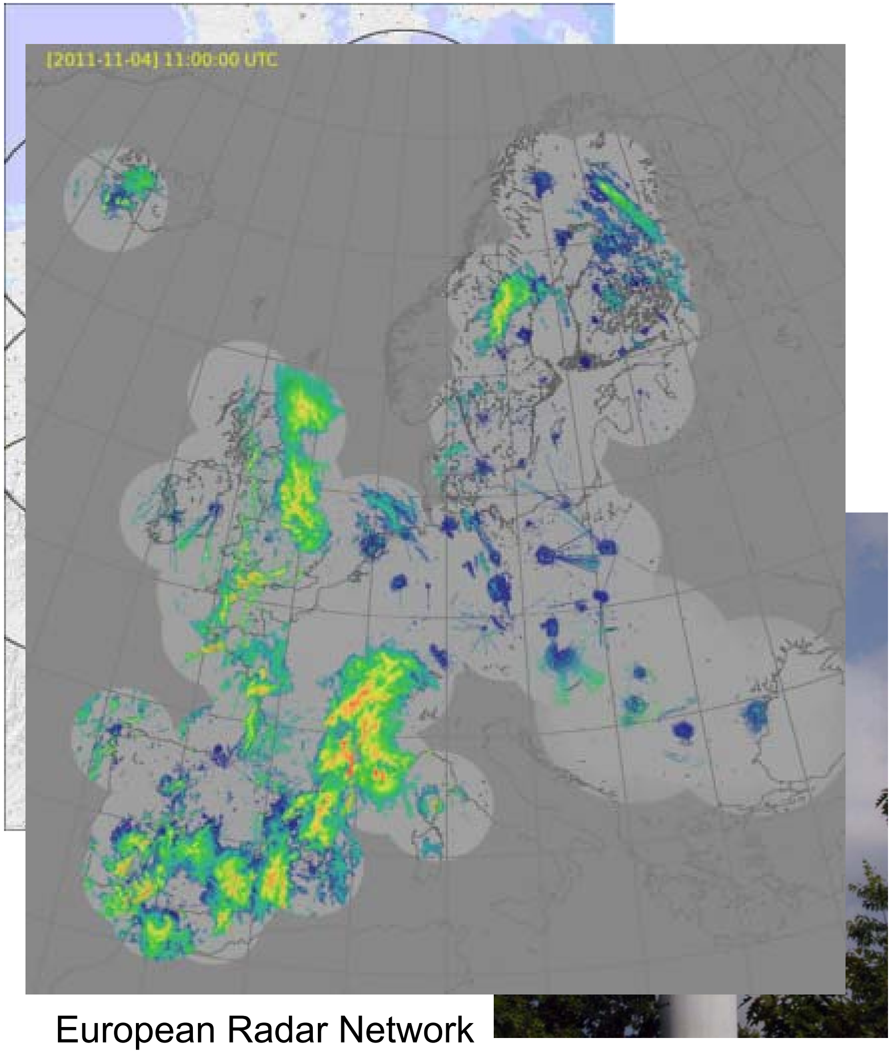
Motivation

- High resolution NWP requires observation with a high resolution
- Radar observations will be of great potential for this purpose.
- Current resolution at DWD:
  - 250 m in range (150 km)
  - 1° in azimuth
  - 18 elevation (0.5 – 37°)
  - every 15 min
  - (every 5 min precipitation scan with an elevation above topography)
- Data coverage is very good:
  17 Stations in Germany
  ~ 200 in Europe



European Radar Network (OPERA)

Hannover

Radar Basics

- **RADAR:** acronym standing for **Ra**dio **D**etection **a**nd **R**anging
- Pulses of electromagnetic waves at radio frequency (2-10 GHz, 15-3 cm, S,C,X-Band) are send and received (reflected by a target) at the same site.

- Each target returns a tiny bit of the transmitted energy
  - Air planes, insects, birds, rain drops, hail …
- The first application was during the World War 2 to detect air planes
- Measuring the elapsed time between sending and receiving the signal

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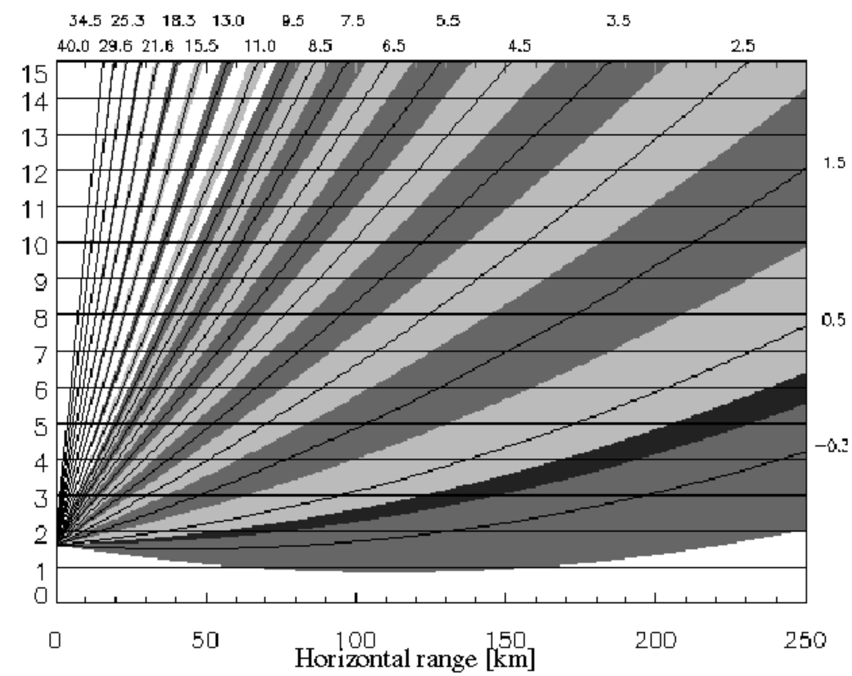
Radar Basics

- Radar Antenna is turning around continuously (1-3 rpm)
- A very short pulse is send (~ 1 µs) and the respond is received (~ 10 ms)
- After a turn is completed the next elevation is adjusted

<u>Some facts</u>:

- beam is broadening with distance (~ 1 km³ at 100 km)
- bended due to the refractivity of the atmosphere (normally back to the ground)
- resolution decreases with distance (vertically and azimuthally)



- elapsed time of the signal, azimuth and elevation of the Radar beam yield the location of a target (air craft, rain droplet, insects, etc..)

Radar Basics

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

- Beside the time delay of the signal Weather Radar measures:
  - **Reflectivity**
    - Estimation of Precipitation Amount (QPE)
  - **Doppler Velocity** (only for Dopplerised Radar)
    - Measurement of radial wind component
    - Estimation of vertical profile of horizontal wind (VAD)
  - **Polarimetric Parameters** (only for polarised Radar)
    - Improvement of QPE
    - Distinction of different precipitation types
- This information can be used for NWP in
  - Data assimilation, verification, validation, process studies
- Requires well equipped Radar
  - currently DWD runs 4 DualPol-Doppler-Radar, but will update the whole network in 2013

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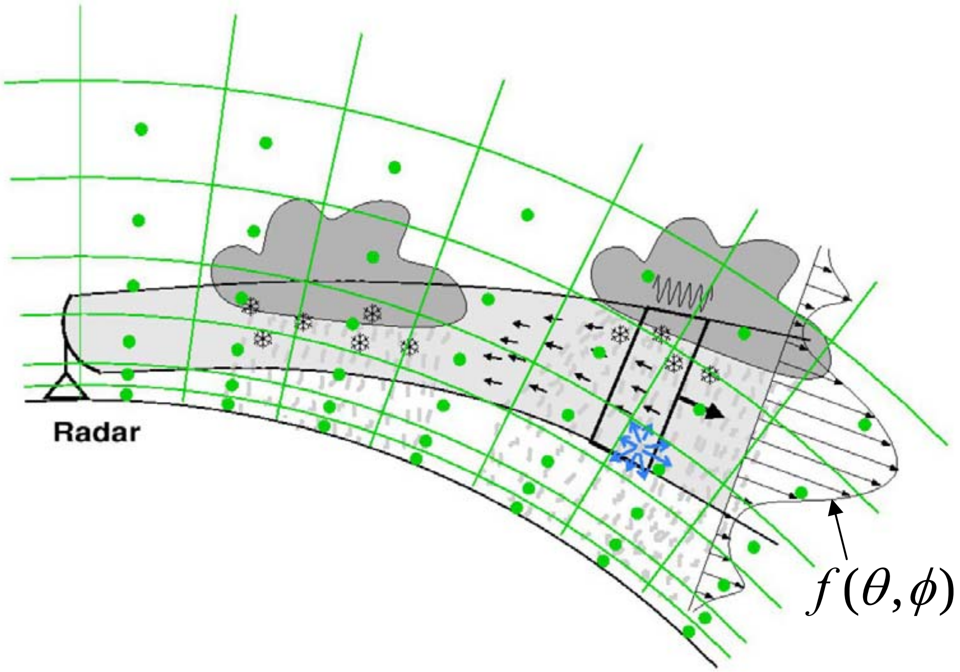
Reflectivity

- Weather Radar measures returning power (P_r)of all particles within the radar beam volume (pulse length h x beam width $\Delta\theta$) with an effective radar cross section σ_v



- This yield a Radar Equation of the form

$$P_r = \int P_o \frac{\lambda^2}{(4\pi)^3 r^4} \cdot G^2 \cdot f(\theta,\phi)^2 \cdot \sigma_V \, dV$$

P_0=emitted power, G: radar gain, λ wave length, r distance

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Reflectivity

This yields:

$$P_r = P_o \frac{\lambda^2 G^2}{64\pi^3} \cdot \int_r^{r+h/2} \frac{1}{r^2} dr \int_0^\infty N(D)\,\sigma_B(D)\,dD \int_0^{2\pi}\int_0^{\pi} f(\theta,\phi)^2 \sin\theta\, d\theta\, d\phi$$

$$\approx P_o \frac{\lambda^2 G^2}{64\pi^3} \cdot \frac{h}{2r^2} \cdot \eta \cdot \frac{\pi\Delta\theta^2}{8\ln(2)} \qquad = \frac{P_o (\lambda G \Delta\theta)^2 h}{1024\pi^2} \cdot \frac{\eta}{r^2}$$

From Rayleigh theory (D < λ/10):

$$\eta = \frac{\pi^5}{\lambda^4}\left|\frac{\varepsilon - 1}{\varepsilon + 2}\right|^2 \cdot \sum D^6 = \frac{\pi^5}{\lambda^4} \cdot |K|^2 \cdot z$$

This yields:

$$P_r = \frac{C|K|^2}{r^2} \cdot z$$

With:

η: Radar reflectivity

z: Reflectivity

ε,K: dielectric constant (variable for water (0.93) and ice (0.18))

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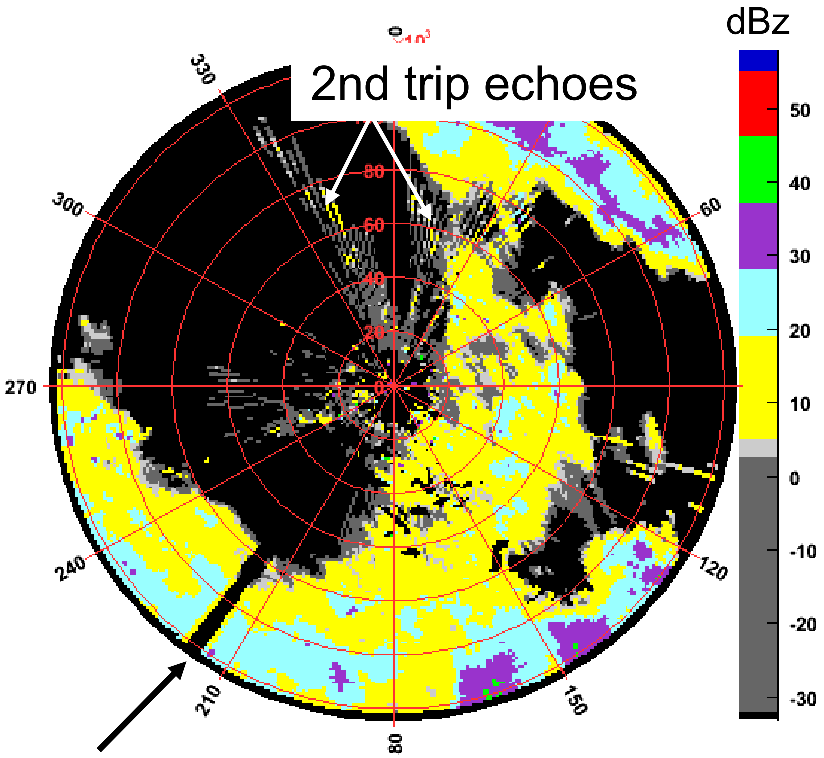
Reflectivity

PPI of Reflectivity (lowest elevation)



Beam blockage due to obstacles

Beside this there are a lot more sources of error

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Reflectivity

Measure of z might be affected by

- Incorrect calibration
- Attenuation → underestimation of z
- Anomalous beam propagation due to super- or under-refraction
  → over- or underestimation of z, erroneous localisation
- Second-Trip-Echoes, Echoes from side lopes, multi path scattering
- Non Rayleigh targets (D ~ λ)
- Misinterpretation of snow reflectivity
- „Non rain echoes“ (birds, insects,…)
- Brightband → melting snow leads to huge overestimation
- …

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Attenuation

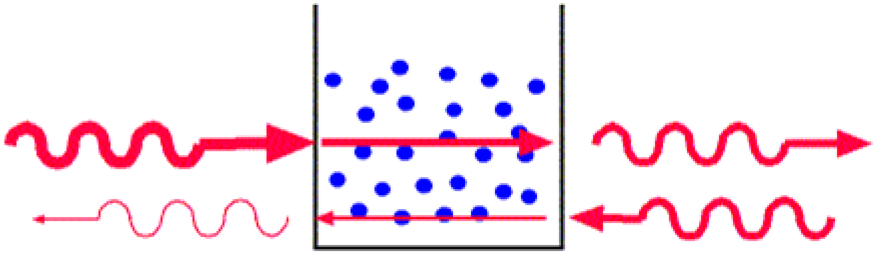
- Scattering and absorption at hydrometeors and atmospheric gases
- Occurs mainly behind strong precipitation and in case of wet radome (Radar globe)
- Can be calculated by

Bouguet-Lambert-Beer'sches Law

$$P(s) = P(0)\exp\left(-\delta(s)\right) = P(0)\exp\left(-\int_0^{\infty} \sigma_e(s')\, ds'\right)$$

P - Power [W]
$\boldsymbol{\sigma_e}$ - extinction coefficient [m^{-1}]
s - range [m]
$\boldsymbol{\delta}$ - optical thickness

Attenuation will happen twice



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Reflectivity

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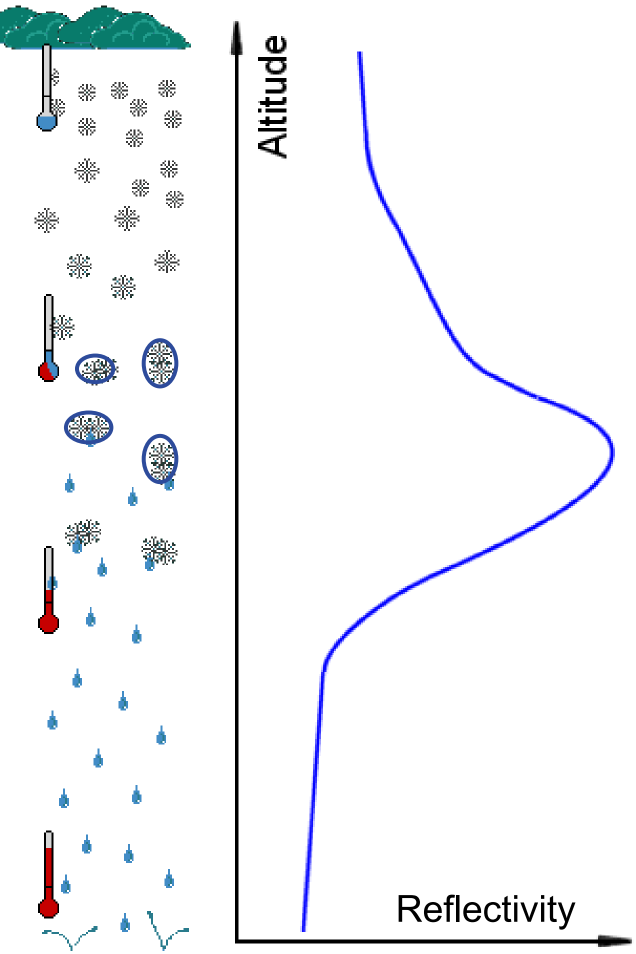
Bright Band Effect

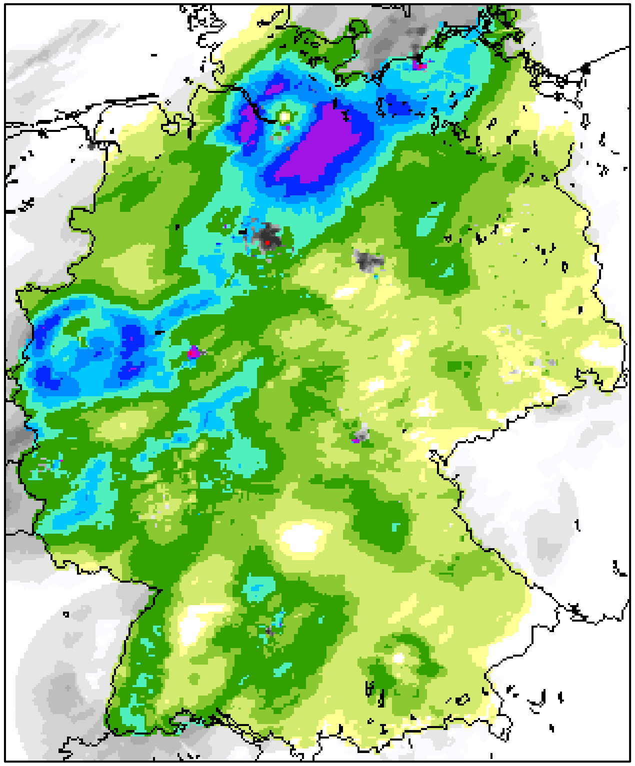
Deutscher Wetterdienst
Wetter und Klima aus einer Hand



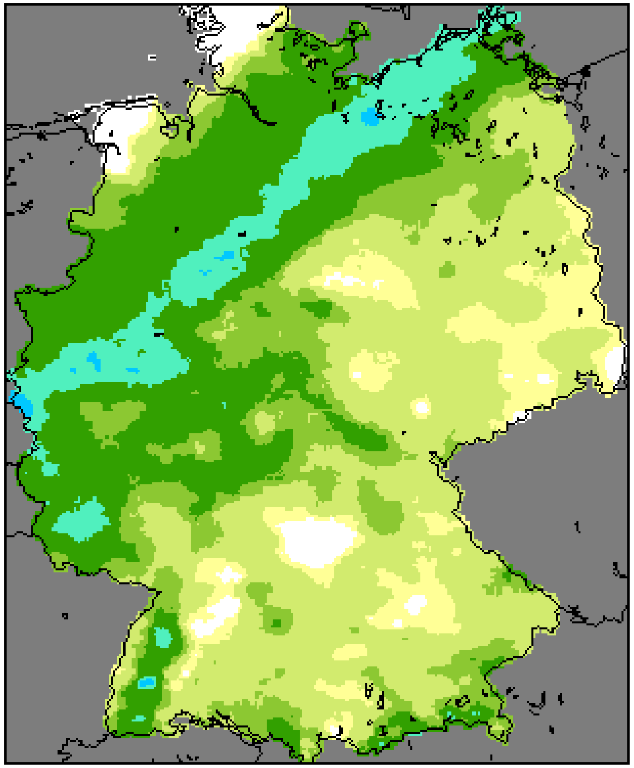
(wikipedia.com)

24h Precipitation sum

Radar estimation



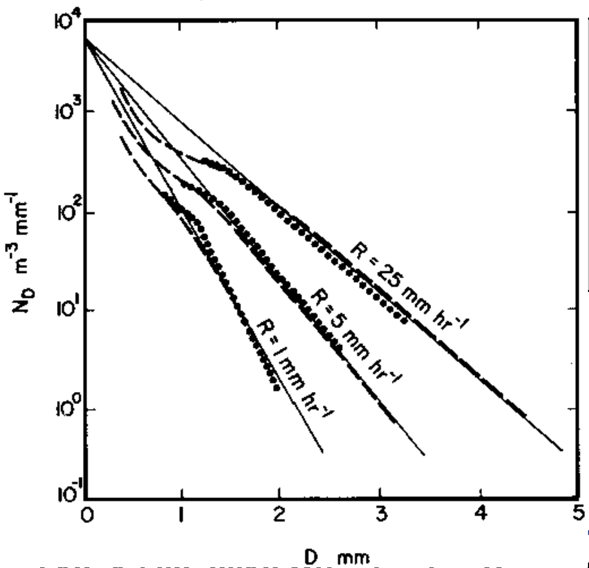
Gauge measurement



19. November 2006

Reflectivity → QPE

- Most users are not interested in Reflectivity
- Transformation of z in precipitation rate (R) is applied
- z and R are both two different moments of the drop size distribution
  - $z \sim D^6$ and $R \sim D^{3.7}$ → non linear relation ship $z=aR^b$
  - Using Marshall-Palmer DSD yields $z=200R^{1.6}$
  - z-R relationship very variable, depends on weather conditions
  - QPE using z-R relation is uncertain (polarisation might be improving)



$$N(D) = N_0 e^{-\Lambda D}$$

$$\Lambda = 41 R^{-0.21}$$

$$N_0 = 0.08 cm^{-4}$$

(Marshall & Palmer, 1948)

Reflectivity → Data Assimilation

- Both z and R can be used in DA
  - MeteoFrance: 1dVar using z → retrieving T,q to be used in 3(4)dVar
  - UKMO and COSMO: Latent heat nudging (LHN) of R
  - Applying a Radar forward operator to obtain modelled z and estimation of observation increment → could be used in LETKF approach

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Reflectivity → LHN

Assimilation of Radar-Derived Precipitation by Latent Heat Nudging

➔ **Required:** relation: precipitation rate $\leftrightarrow$ model variables
(observed) (info required by nudging)
precipitation $\leftrightarrow$ condensation $\leftrightarrow$ release of latent heat

➔ **Assumption:** vertically integrated latent heat release $\propto$ precipitation rate

➔ **Approach:** modify latent heating rates such that the model responds by producing the observed precipitation rates
→ Latent Heat Nudging (LHN)

$$\frac{\partial T}{\partial t} = F(T) + \left(\frac{\partial T}{\partial t}\right)_{nudging} + \left(\frac{\partial T}{\partial t}\right)_{LHN}$$

$$\Delta T_{LHN} = (\alpha - 1) \cdot \Delta T_{LH} \quad with \quad \alpha = \frac{RR_{obs}}{RR_{ref}}$$

\+ adjustment of specific humidity to maintain relative humidity

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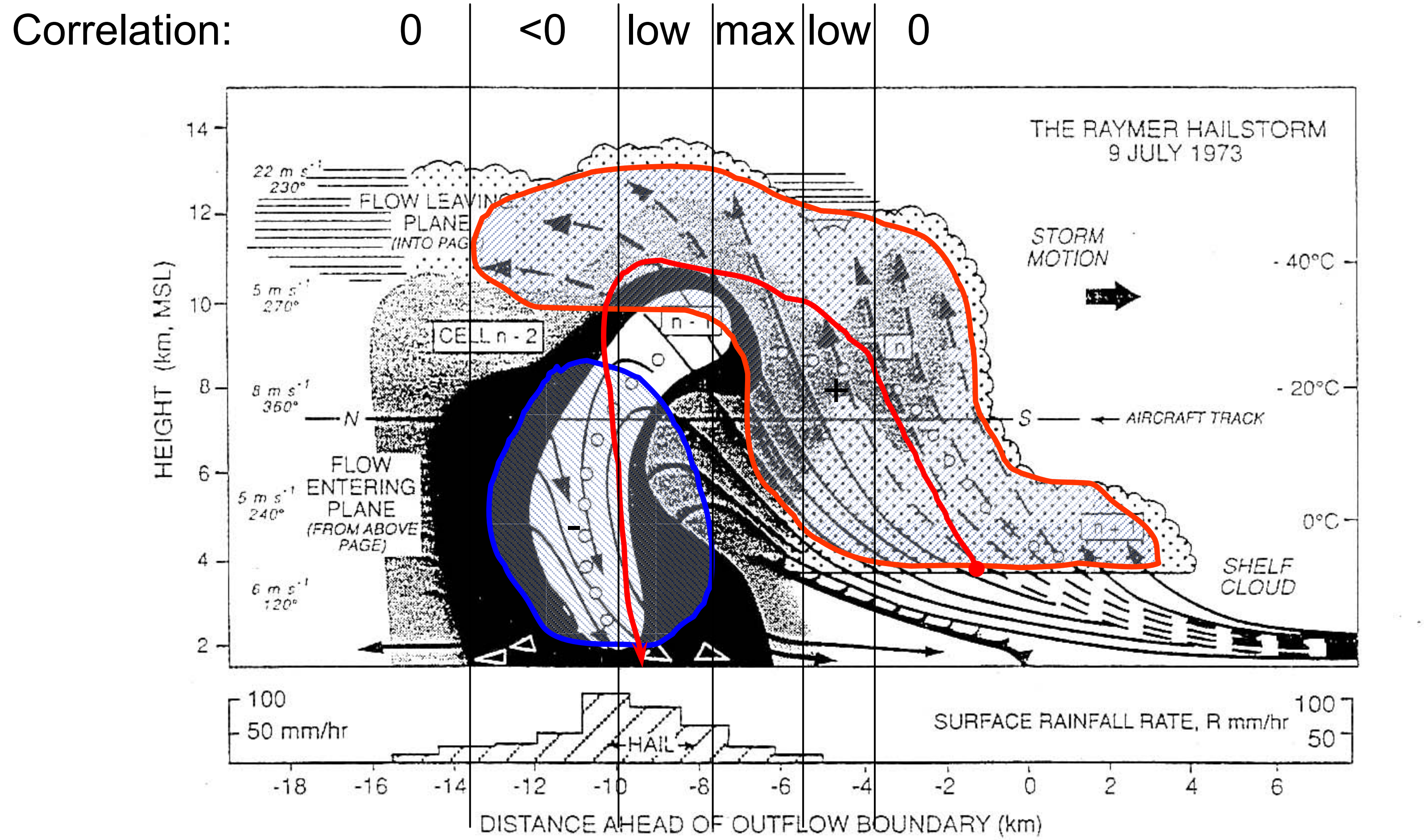

(R. A. Houze, Jr.: Cloud Dynamics, International Geophysics Series Vol. 53)

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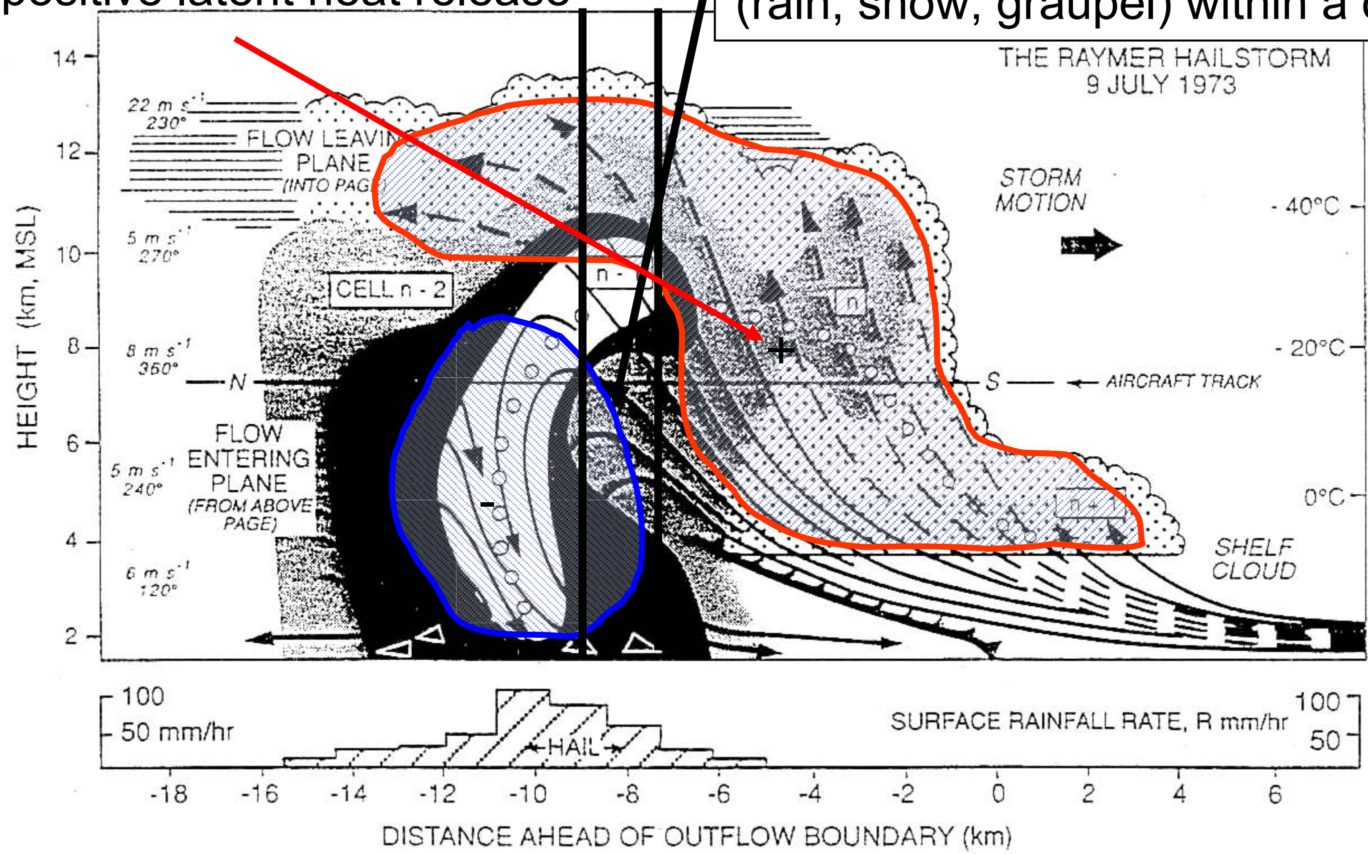
Treatment only of model layers with positive latent heat release

Reference Precipitation:
Vertical mean of precipitation flux (rain, snow, graupel) within a colume



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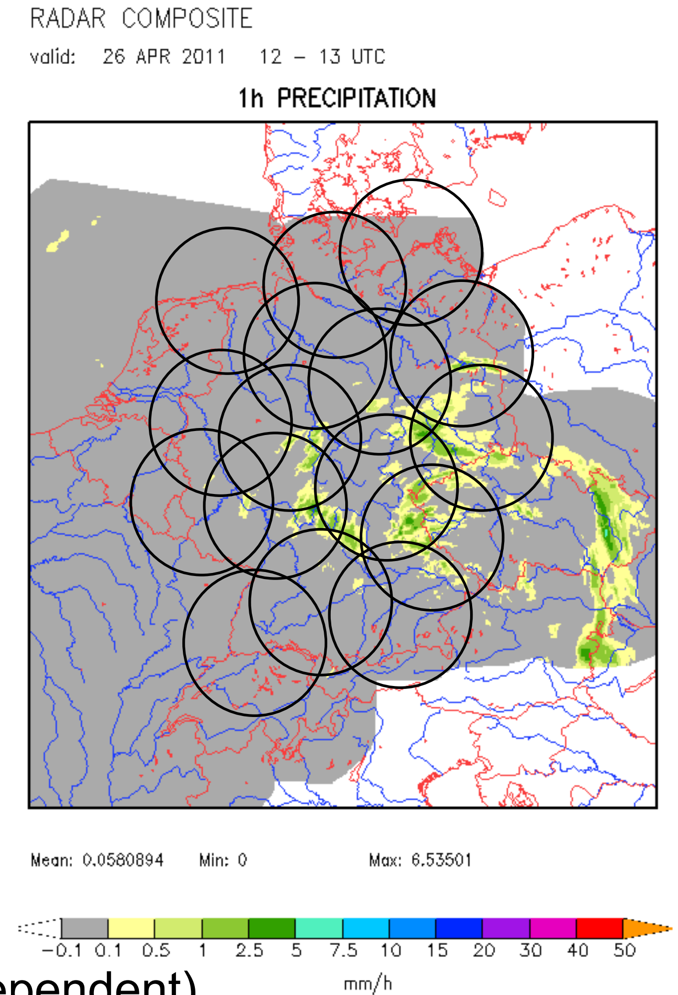
Reflectivity → LHN

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Radar data coverage

- Currently
  - 16 German Doppler radar stations
  - 2 Dutch stations
  - 2 Belgian stations
  - 9 France stations
  - 3 Swiss stations
  - 2 Czech station
- Shortly extended by
  - 1 German station (Memingen)
  - 2 Polish stations



R is derived using a 4 class z-R relation (storm dependent)

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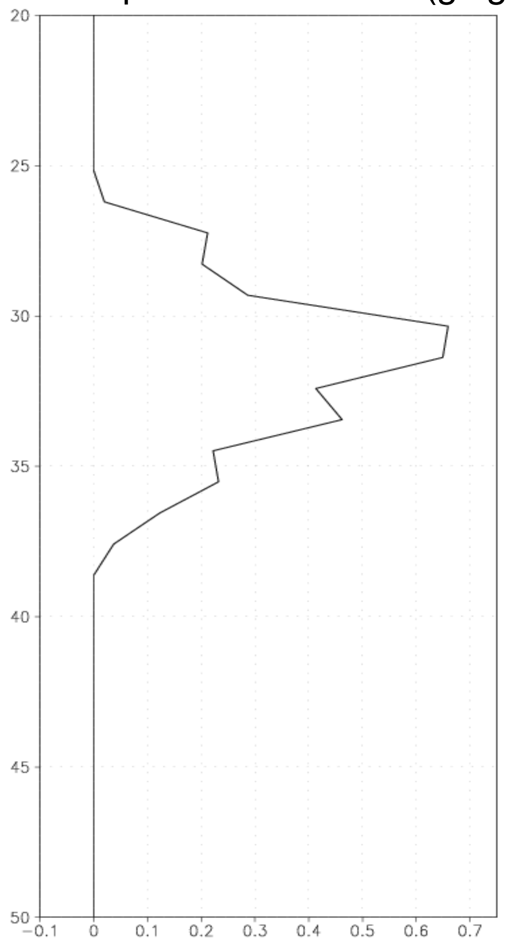
Reflectivity → LHN

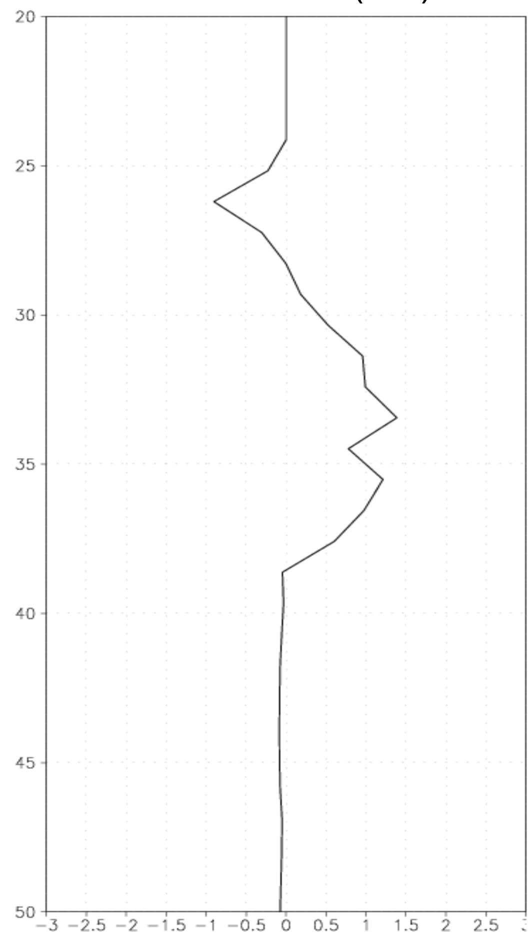
How does it works?

Vertical profiles:

cloud liquid water content (g/kg)



latent heat release (K/h)



temperature increment (K)

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Reflectivity → LHN

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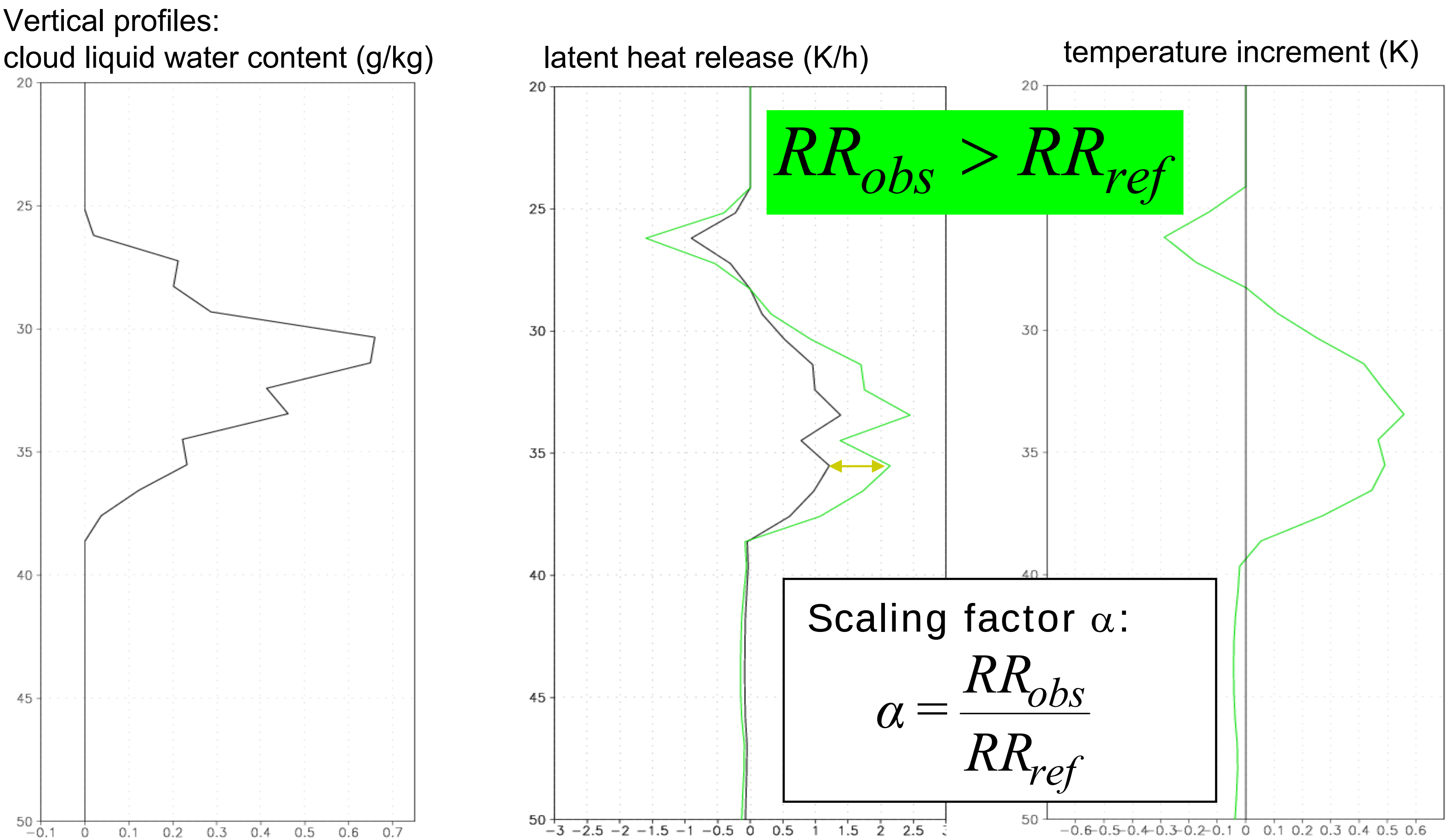
Wetter und Klima aus einer Hand

DWD

How does it works?



$$RR_{obs} > RR_{ref}$$

Scaling factor α:

$$\alpha = \frac{RR_{obs}}{RR_{ref}}$$

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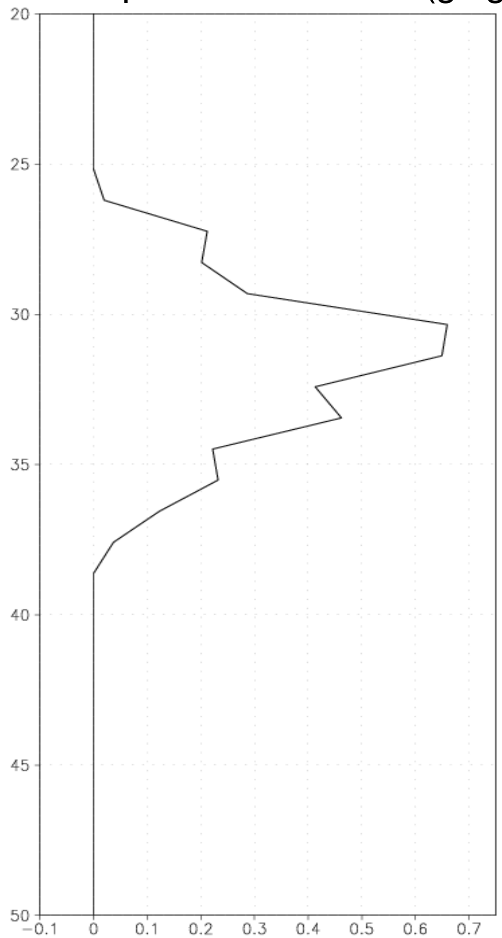
Wetter und Klima aus einer Hand

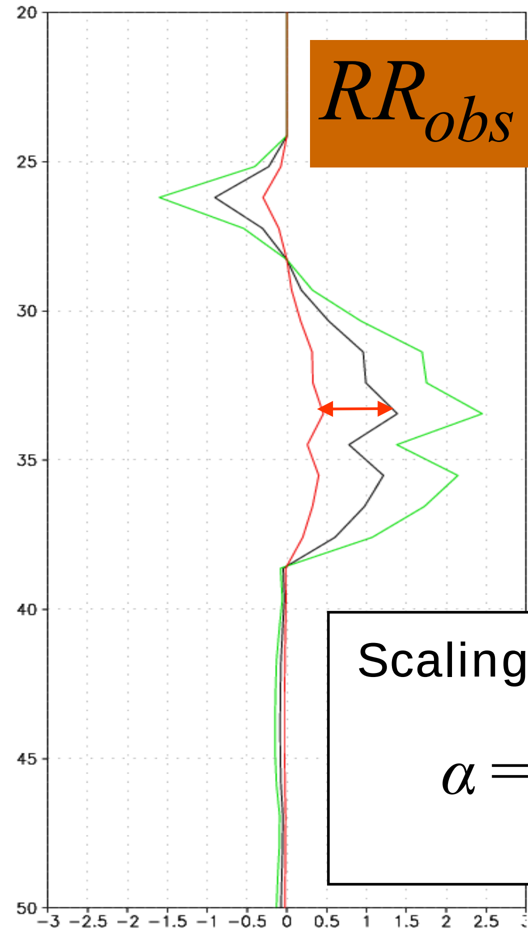
How does it works?

Vertical profiles:

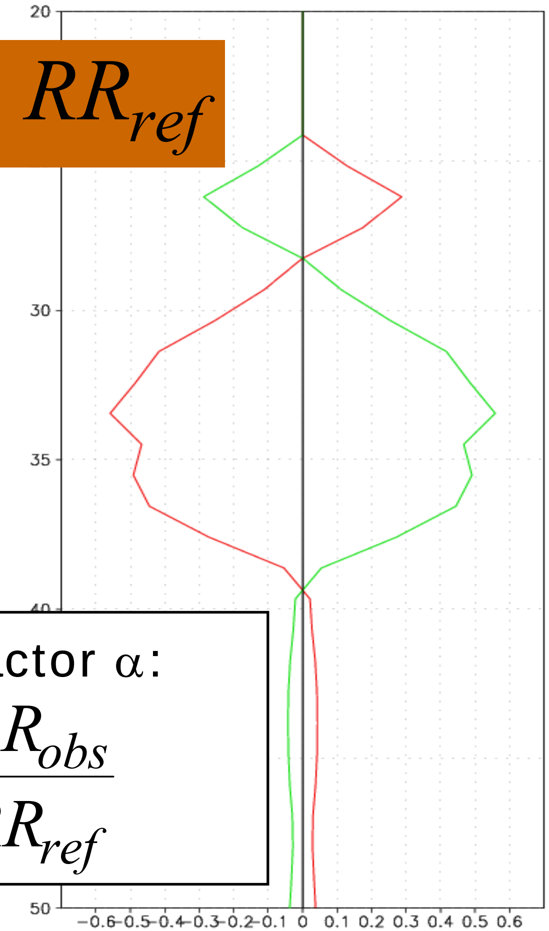
cloud liquid water content (g/kg)



latent heat release (K/h)



temperature increment (K)



$$RR_{obs} < RR_{ref}$$

Scaling factor α:

$$\alpha = \frac{RR_{obs}}{RR_{ref}}$$

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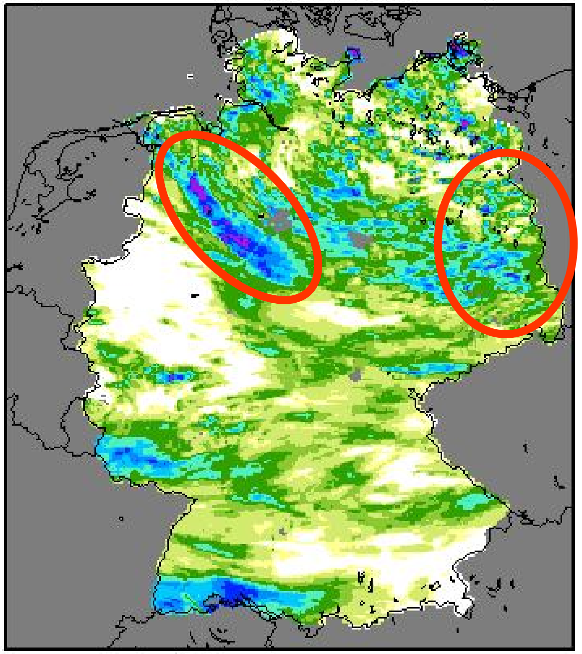
Reflectivity → LHN

24H precipitation sum: 26.08.2006 (6 UTC – 6 UTC)

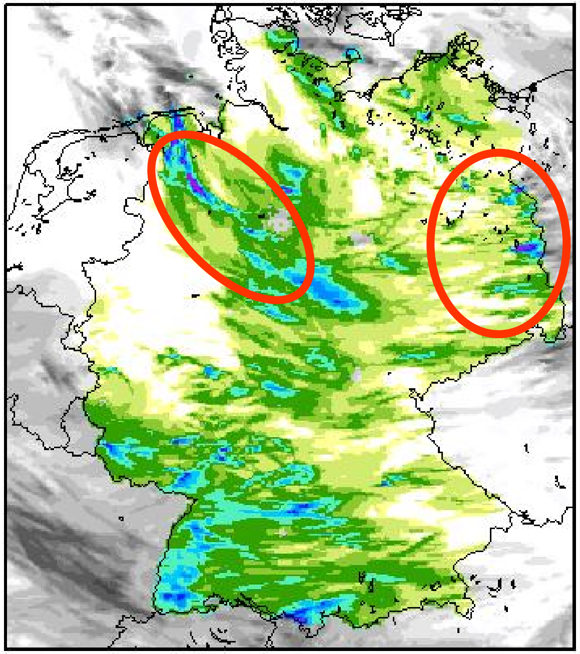
Assimilation

Radar-OBS



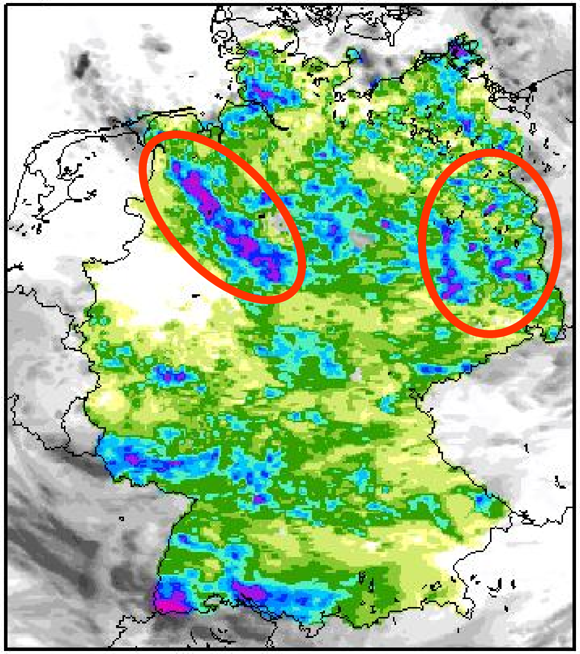
Mean: 5.5961 Min: 0 Max: 70.817 Var: 37.498

No LHN



Mean: 4.4351 Min: 0 Max: 57.605 Var: 23.120

LHN



Mean: 7.9317 Min: 0 Max: 68.924 Var: 58.731

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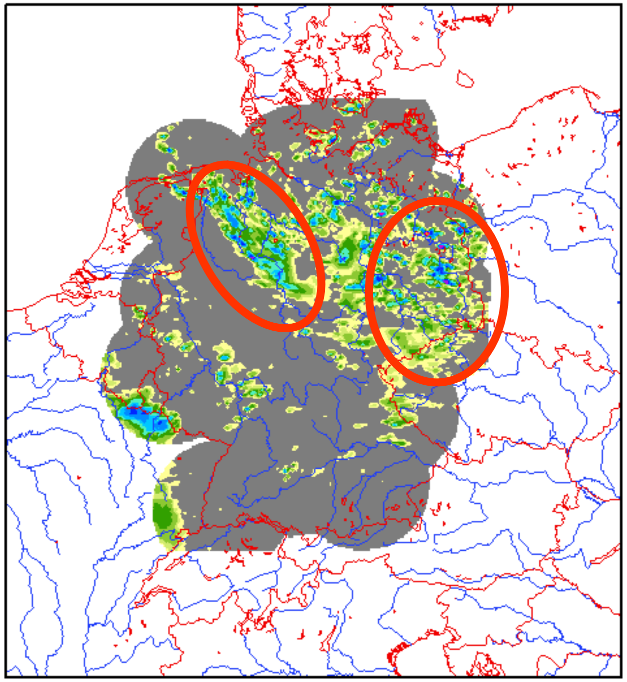
Reflectivity → LHN

Animation of 1H precipitation sum 26. August 2006

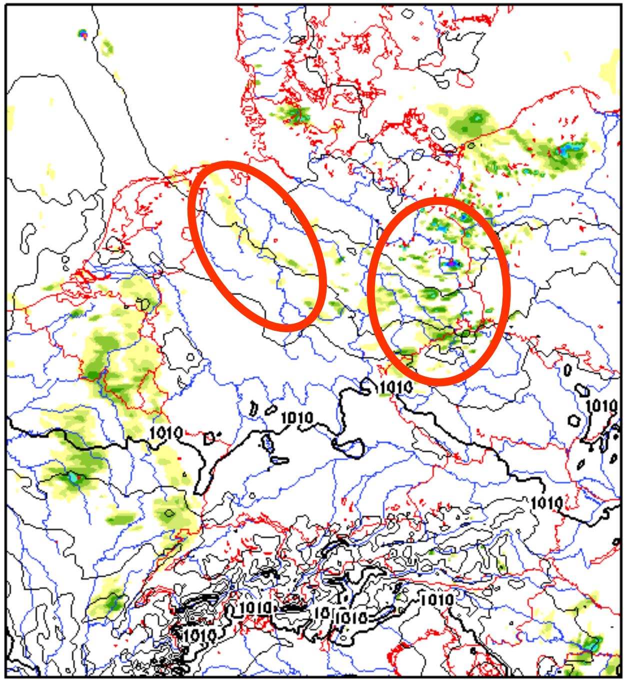
Free Forecast 12 UTC + 1 H

(Assimilation till 12:30 UTC)

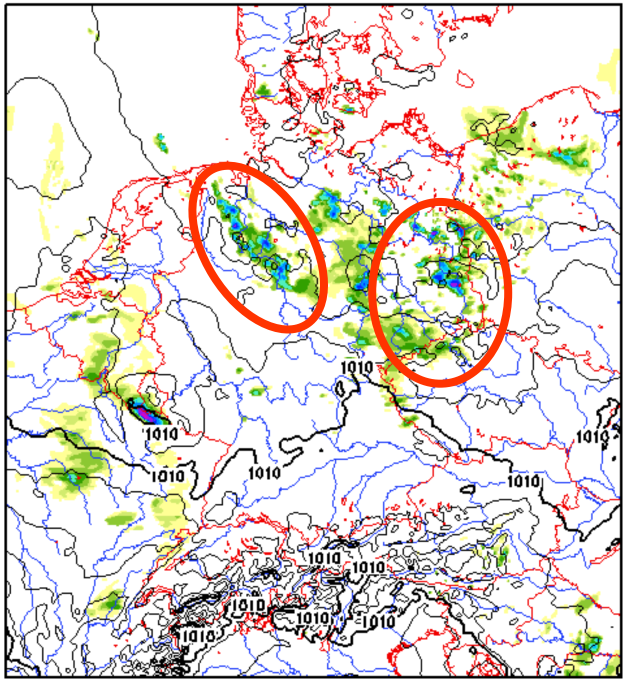
Radar-OBS



No LHN



LHN



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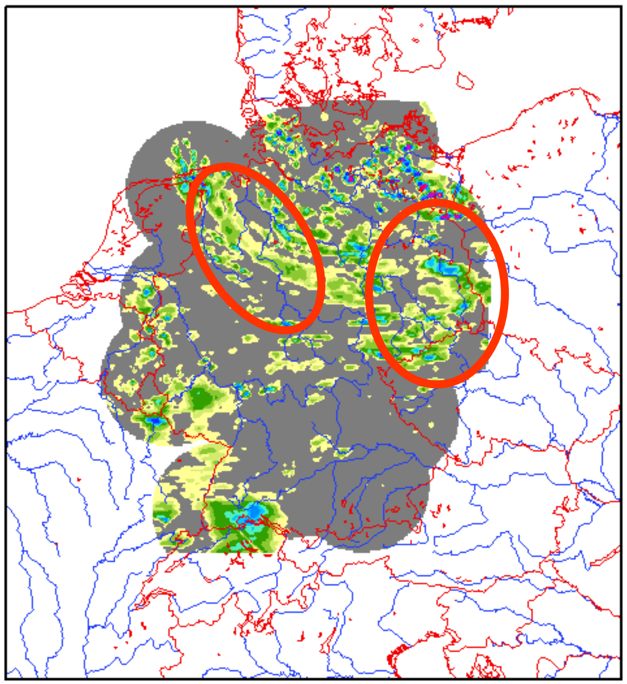
Reflectivity → LHN

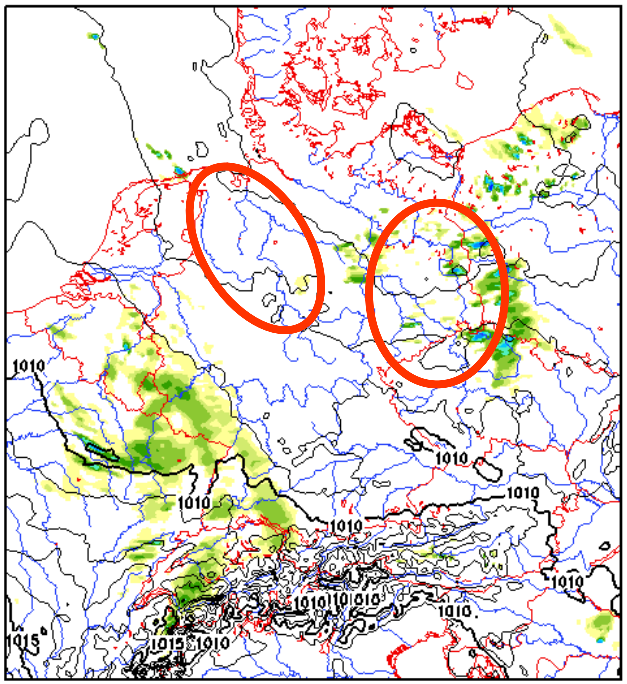
Animation of 1H precipitation sum 26. August 2006

Free Forecast 12 UTC + 4 H

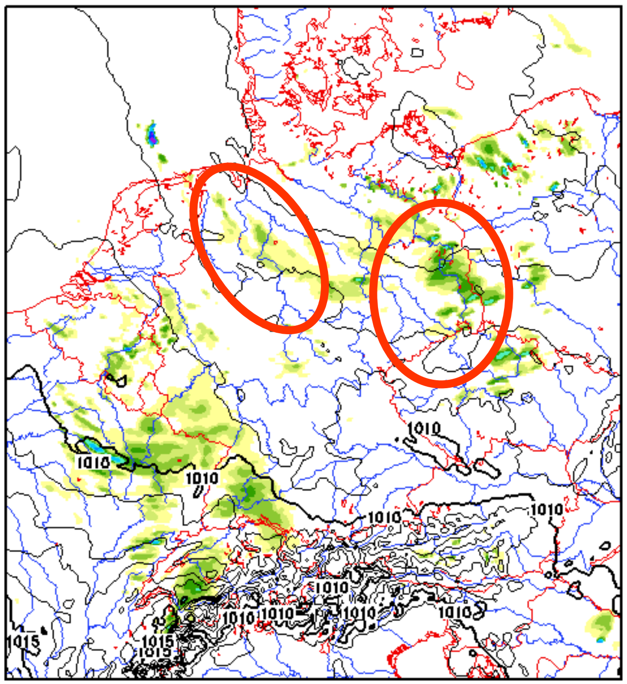
Radar-OBS



No LHN



LHN



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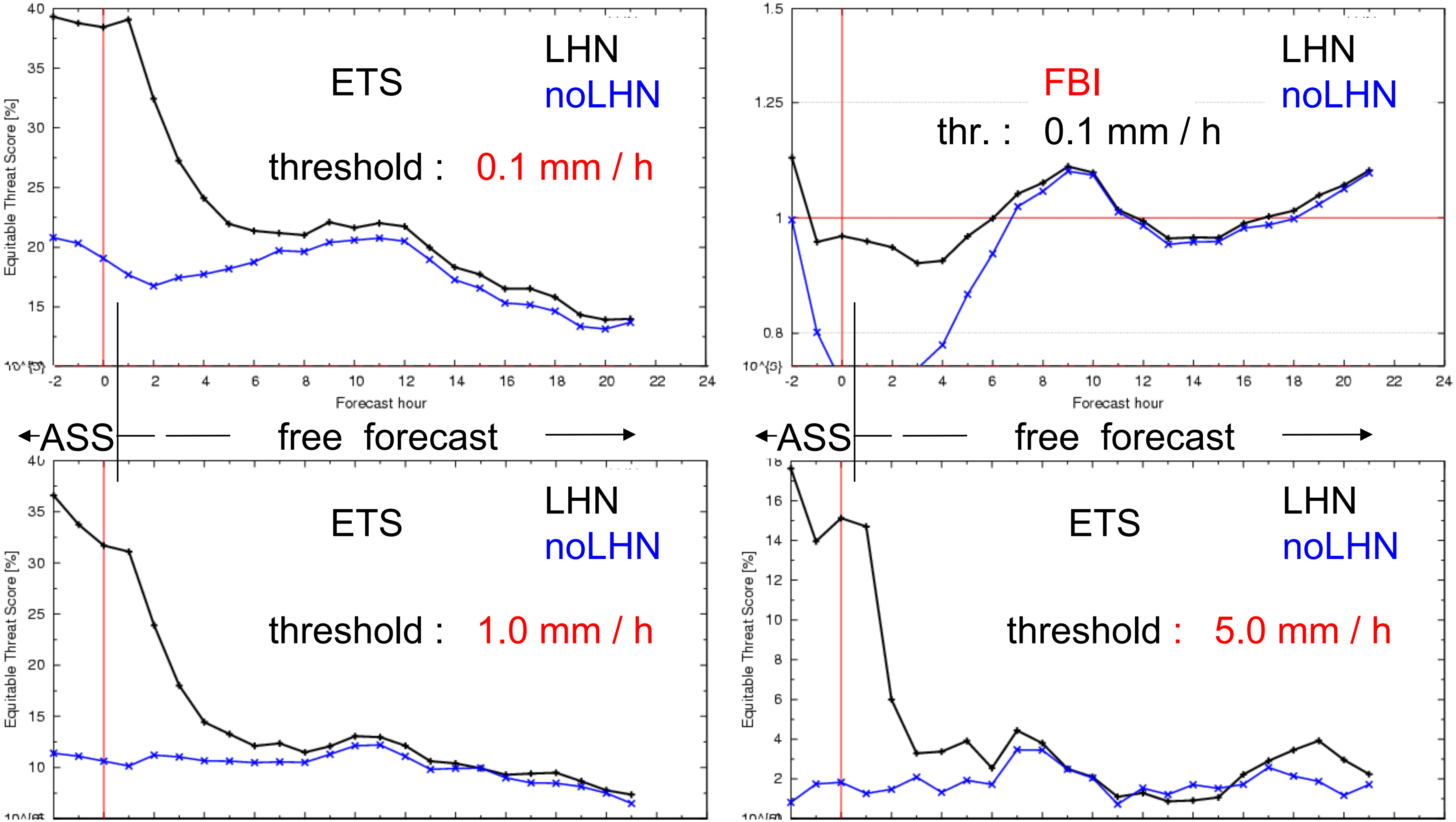
Reflectivity → LHN

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

15 – 30 August 2006, 00 and 12 UTC runs (32 forecasts); threshold : 0.1 mm / h



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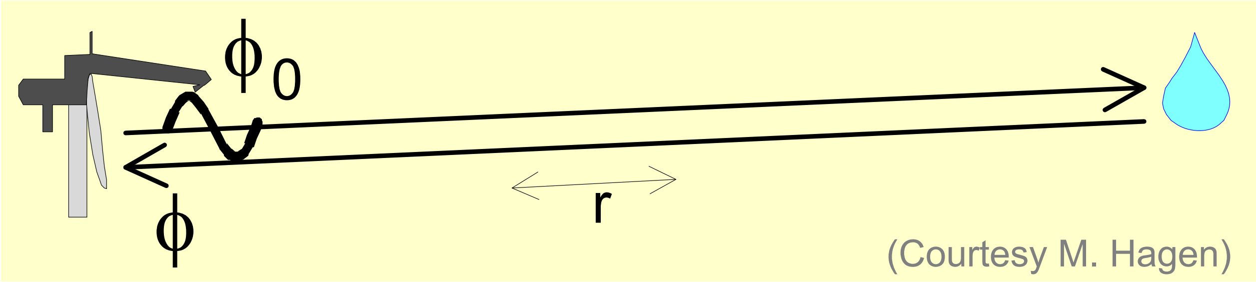
Radial Wind Component

- A so called Doppler Radar is able to measure the phase of the radio wave.
- Moving targets will produce a phase shift due to the Doppler effect
- This shift can be detected and the velocity along the beam can be measured (radial component of the wind vector)

$$\phi = \phi_0 + \frac{4 r \pi}{\lambda} \longrightarrow \frac{\Delta\phi}{\Delta t} = \frac{4\pi}{\lambda} \cdot \frac{\Delta r}{\Delta t} = \frac{4\pi}{\lambda} \cdot v_r$$

$$\boxed{v_r = \frac{\Delta\phi}{\Delta t} \cdot \frac{\lambda}{4\pi}}$$

ΔΦ: phase shift
λ: wave length
Δt: pulse repetition time
r: distance

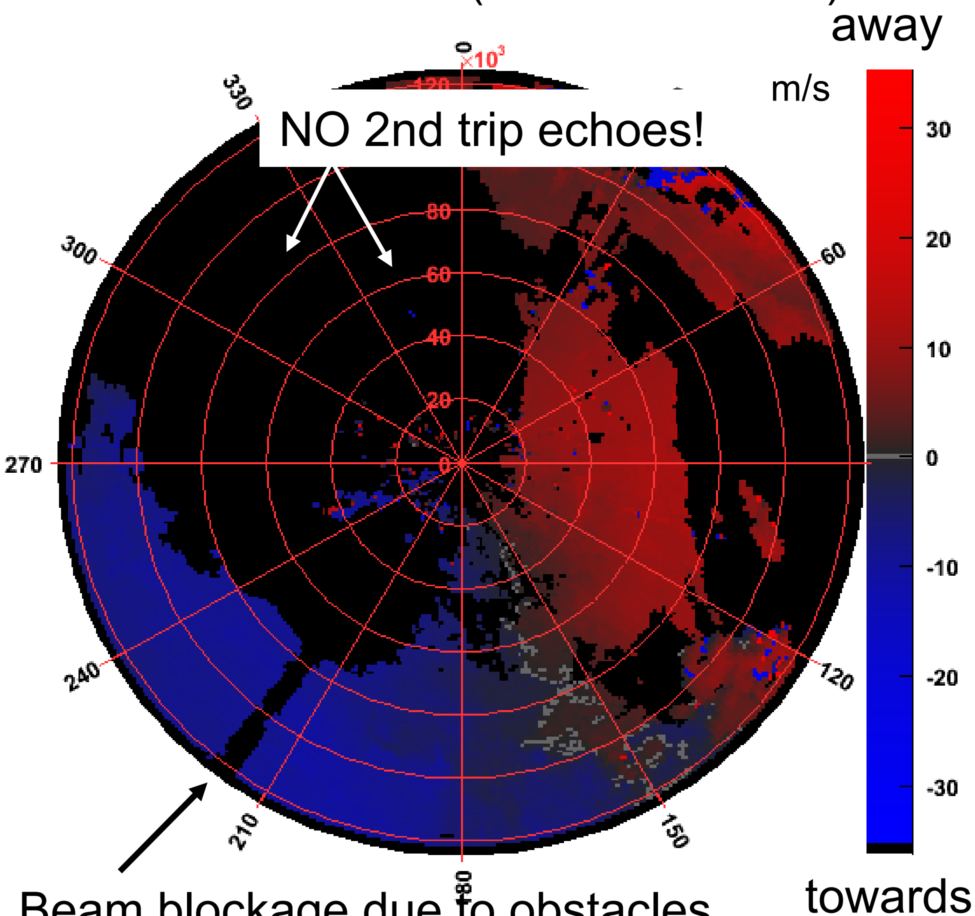


(Courtesy M. Hagen)

Radial Wind Component

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

PPI of radial wind (lowest elevation)



Beam blockage due to obstacles

Radial wind volumes can be used for:

- clutter filtering (stationary ground clutter, but not wind mills)
- 2nd trip detection
- Estimation of vertical profile of horizontal wind (VAD)
- directly used for DA
- Hazard warning: meso cyclone detection

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Radial Wind Component

- Doppler Dilemma:
  - Aliasing effect leads to an unambiguous velocity interval:
  - Nyquist velocity: $$v_{r\max} = \pm \frac{\lambda}{4\Delta t}$$
  - Max Range: $$r_{\max} = \frac{c\Delta t}{2}$$
  - A higher range leads to a smaller Nyquist velocity and vice versa

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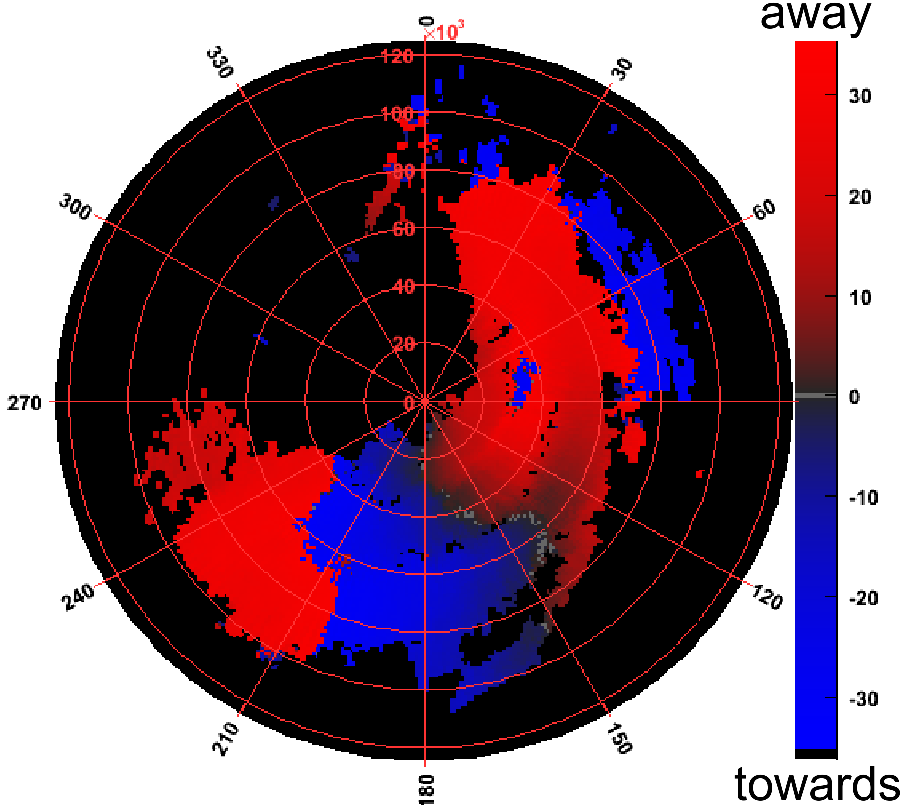
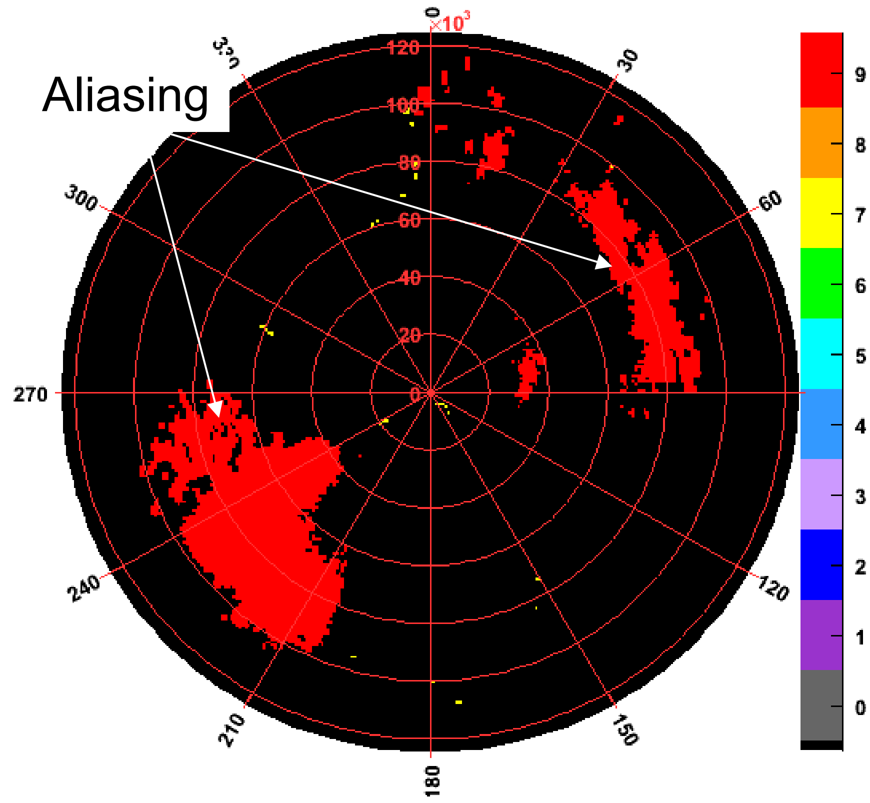
Radial Wind Component

➔ Example for Aliasing effect (easy one)



Quality Index



(Nyquist velocity = 32 m/s)

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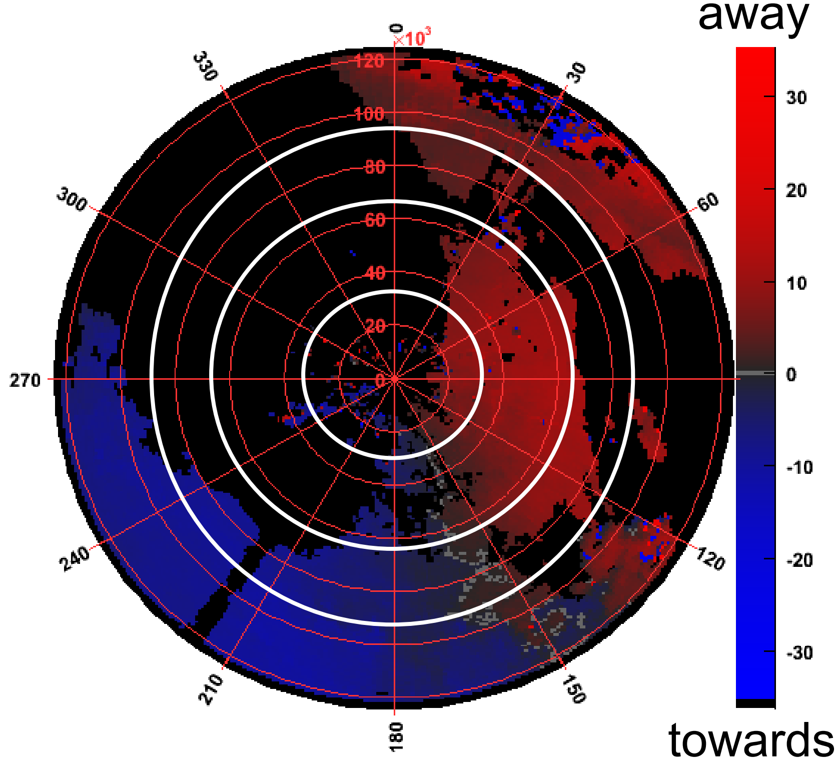
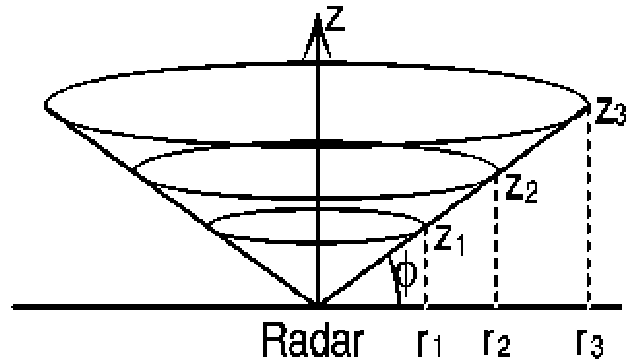
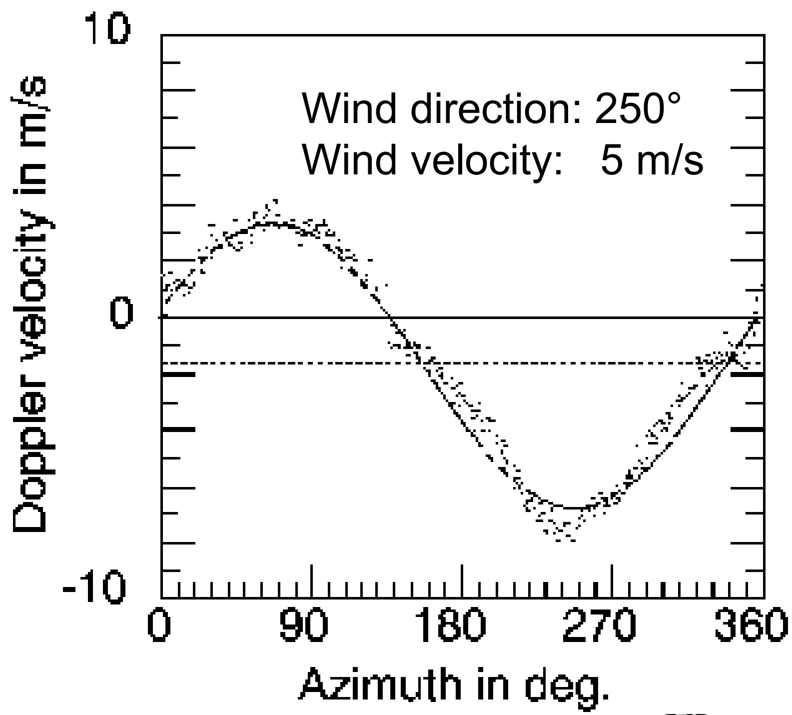
Radial Wind Component - VAD

- at each height layer (500 m bins), a sinus curve is fitted to the measured radial wind components which depends on azimuth
  $\rightarrow$ velocity & direction of mean wind vector
- Assumption: homogeneous wind field !







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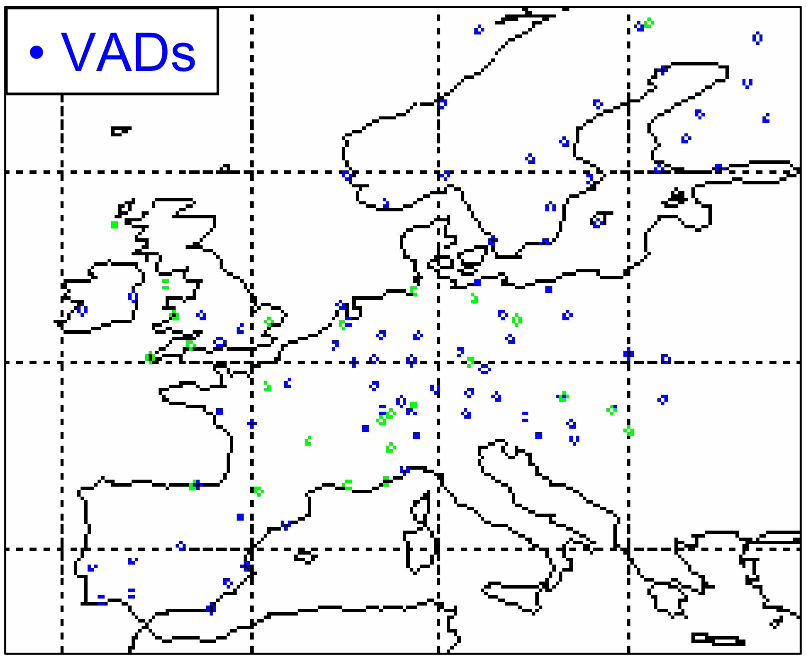
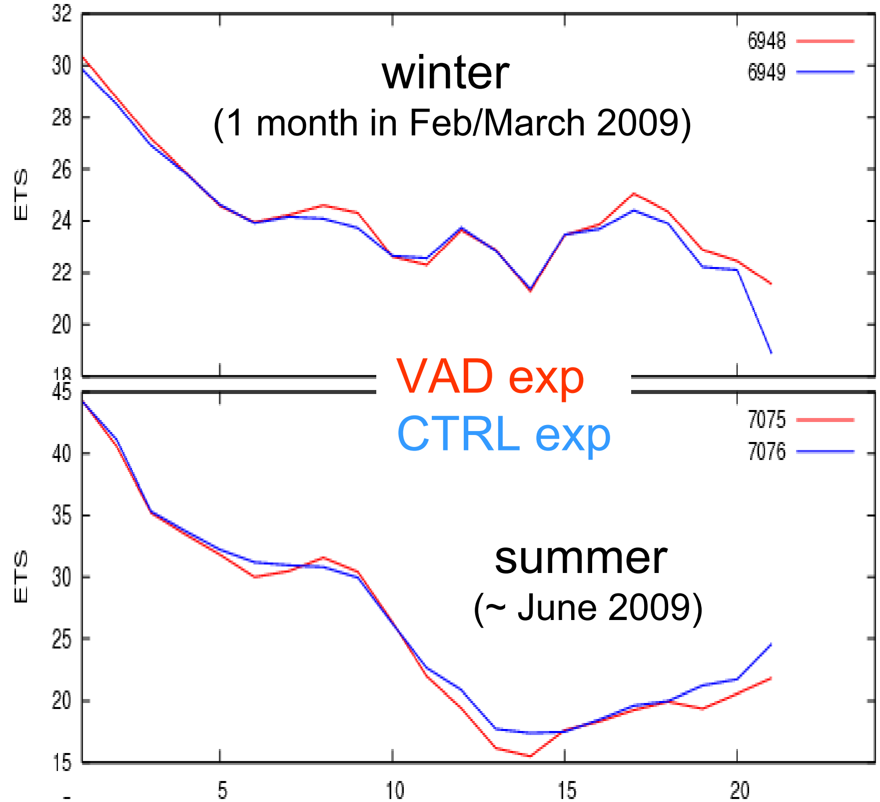
Radial Wind Component -VAD

95 VAD stations available:
50 on whitelist, i.e. used actively
(some height ranges on blacklist)



ETS, threshold 0.1 mm, 00-UTC runs



→ altogether neutral results
→ not used operationally because of monitoring costs
→ VAD will lose much of the information, anyway

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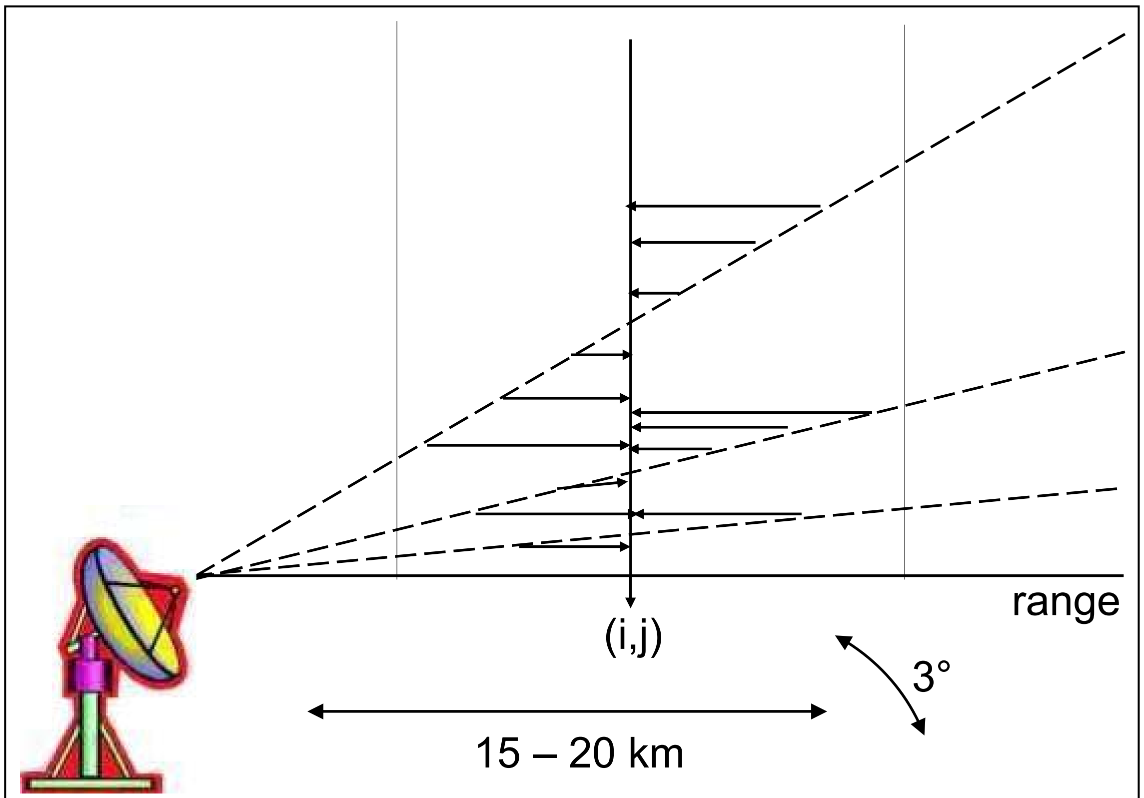
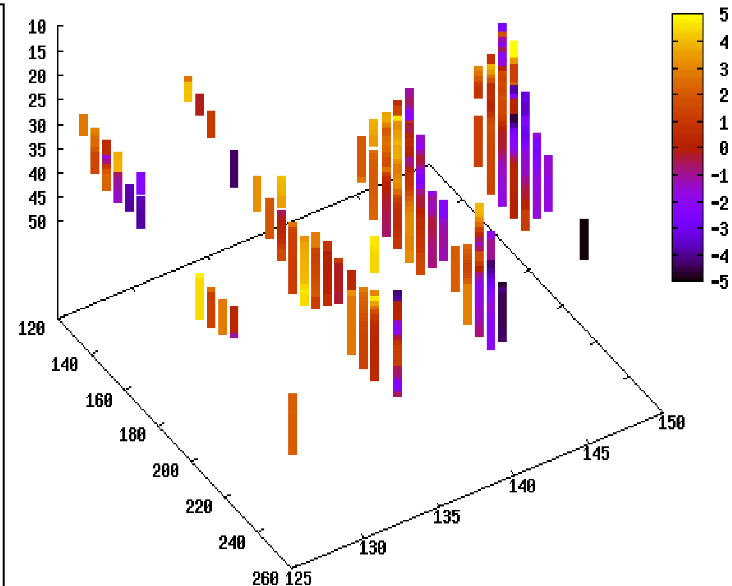
Radial Wind Component → Nudging

- compute differences (obs – model) of radial wind component
- assign (shift) to specified model grid points
  - → vertical profiles of increments or pseudo obs of radial wind component
- ingest in nudging





→ first tests soon

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Outline

1. Motivation
2. Basics on Radar meteorology
3. Radar measurement and its assmilation
   - ➔ Reflectivity
     - LHN
   - ➔ Radial Wind Component
     - VAD
     - Nudging
   - ➔ Polarisation
4. Brief introduction on Radar Forward Operator (for the LETKF era)

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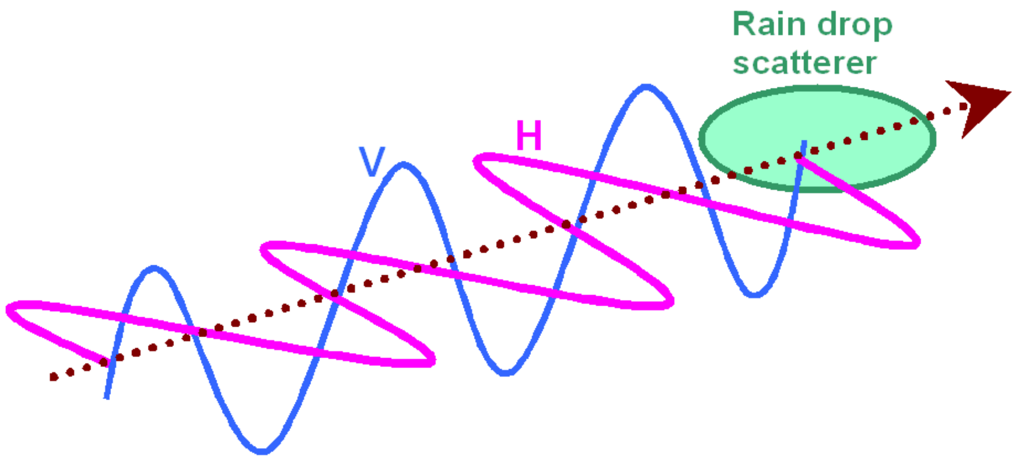
Polarisation

- Weather Radar normally send waves in horizontal polarisation (E field looks in the horizontal)
  - Good for liquid hydrometeor (flat objects)
  - Less good in case of tumbling hail stones (elevated objects)
- Better to send separate waves with both horizontal and vertical polarisation?



→Instead of z and φ measuring of z_h,z_v, φ_h, φ_v

→ number of combinations: z_{DR}, LDR, ρ_{HV},k_{DP}, φ_{DP},…

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Polarisation

- Can be used for
  - Distinction of different hydrometeors (hail, snow, rain)
  - Improvement of Quality-Control (bright band, clutter)
  - Improvement of QPE (better z-R relation)
  - First attempts to assimilate at MeteoFrance

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Outline

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

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Radar Forward Operator

➔ **assimilate 3-D radial velocity and 3-D reflectivity directly**

Uli Blahak (DWD), Yuefei Zeng, Dorit Epperlein (KIT Karlsruhe)

1. implement full, sophisticated observation operators
   Mie- or Rayleigh-scattering,
   combined with different formulations of the effective refractive index of the hydrometeors (mixtures of ice, air, and water)
   - ➔beam attenuation (damping) due to hydrometeors
   - ➔online radar beam propagation (depend. on refractivity)
   - ➔beam smoothing / broadening
   - ➔hydrometeor fall speed (for radial velocities)
   - ➔(superobbing, thinning, obs errors, writing to NetCDF feedback files)
2. apply / test sufficiently accurate and efficient approximations
   - ➔by looking at the simulated obs
   - ➔doing assimilation experiments : OSSE setup

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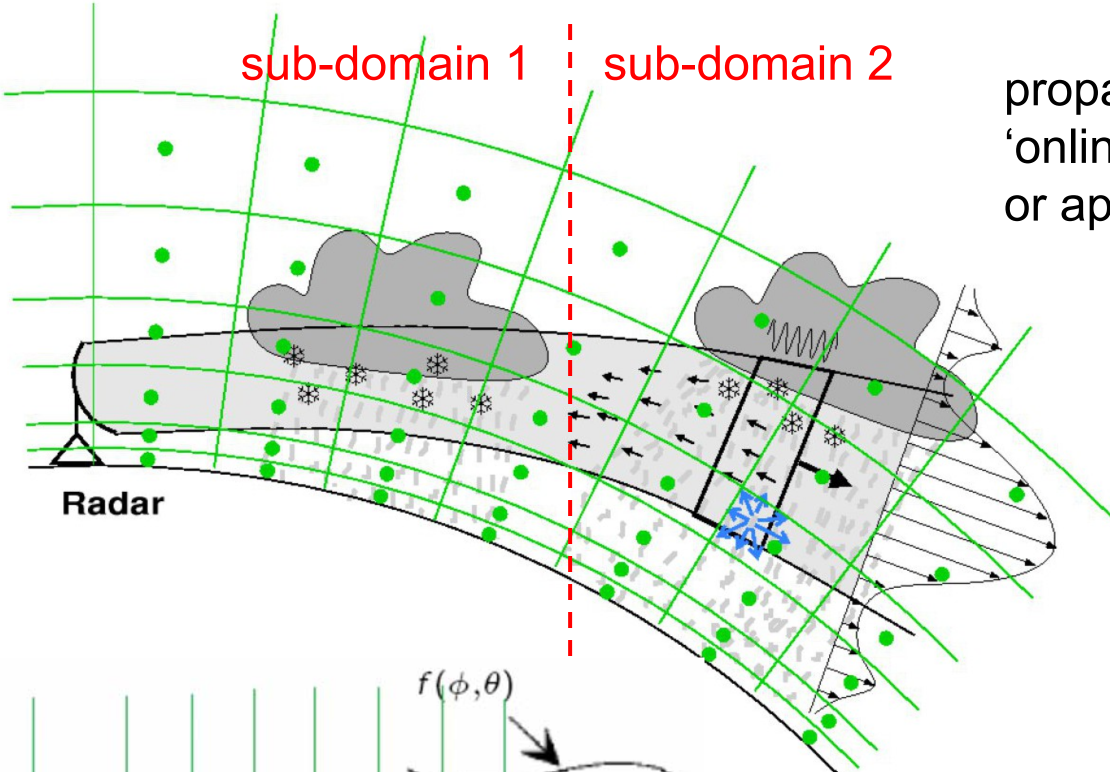
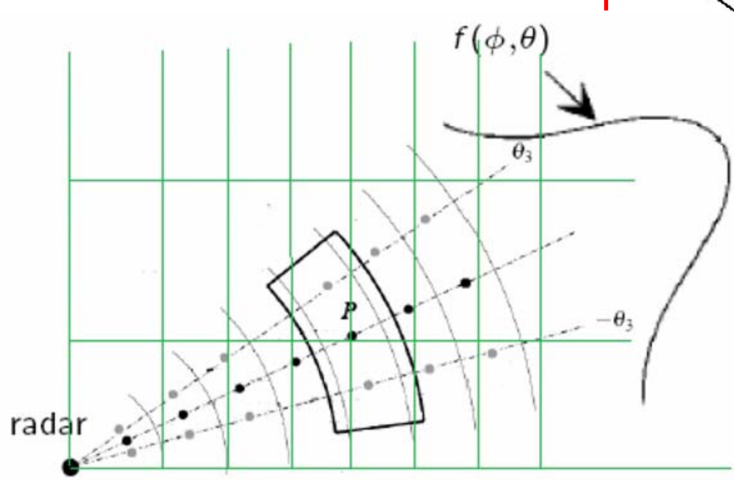
Radar Forward Operator

Deutscher Wetterdienst
Wetter und Klima aus einer Hand



propagation of radar beam :
'online' depend. on refractive index,
or approximate standard atmosphere

MPP parallelisation:
beam in an azimuthal slice
has to be collected on 1 PE



averaging over beam weighting function:
weighted spatial mean over measuring volume
(cross-beam vertically / horizontally)

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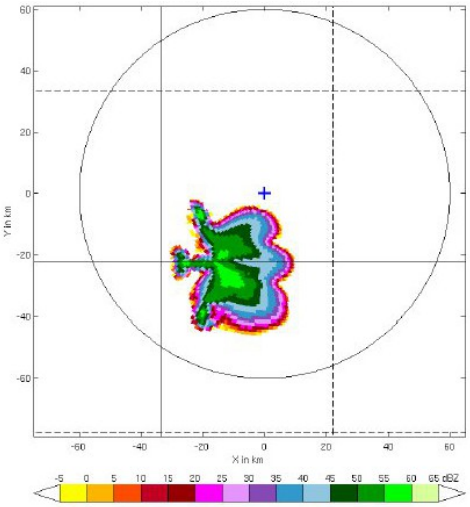
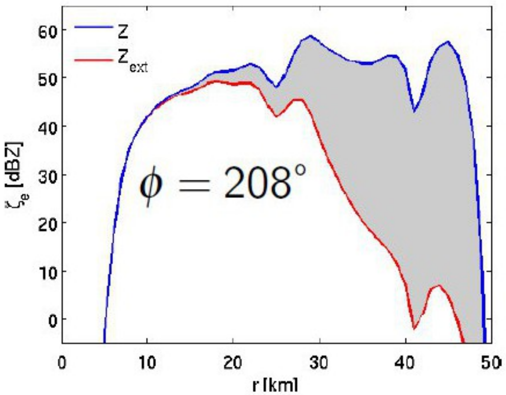
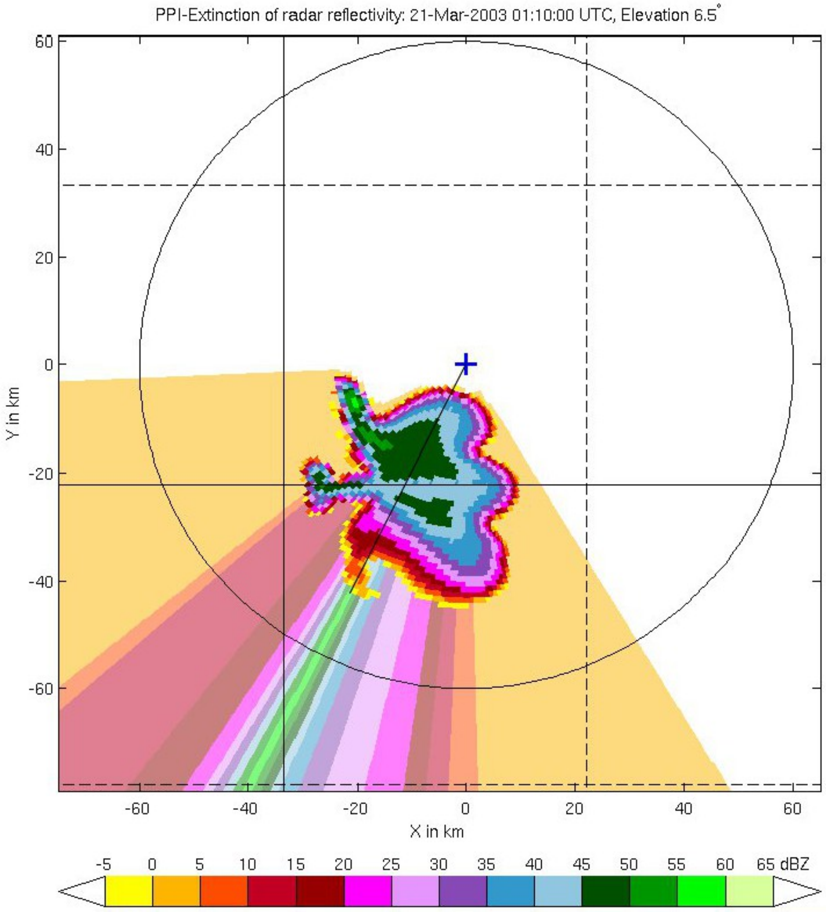
Radar Forward Operator

without attenuation

with attenuation of radar reflectivity
by atmospheric gases + hydrometeors
(using the extinction coefficients)







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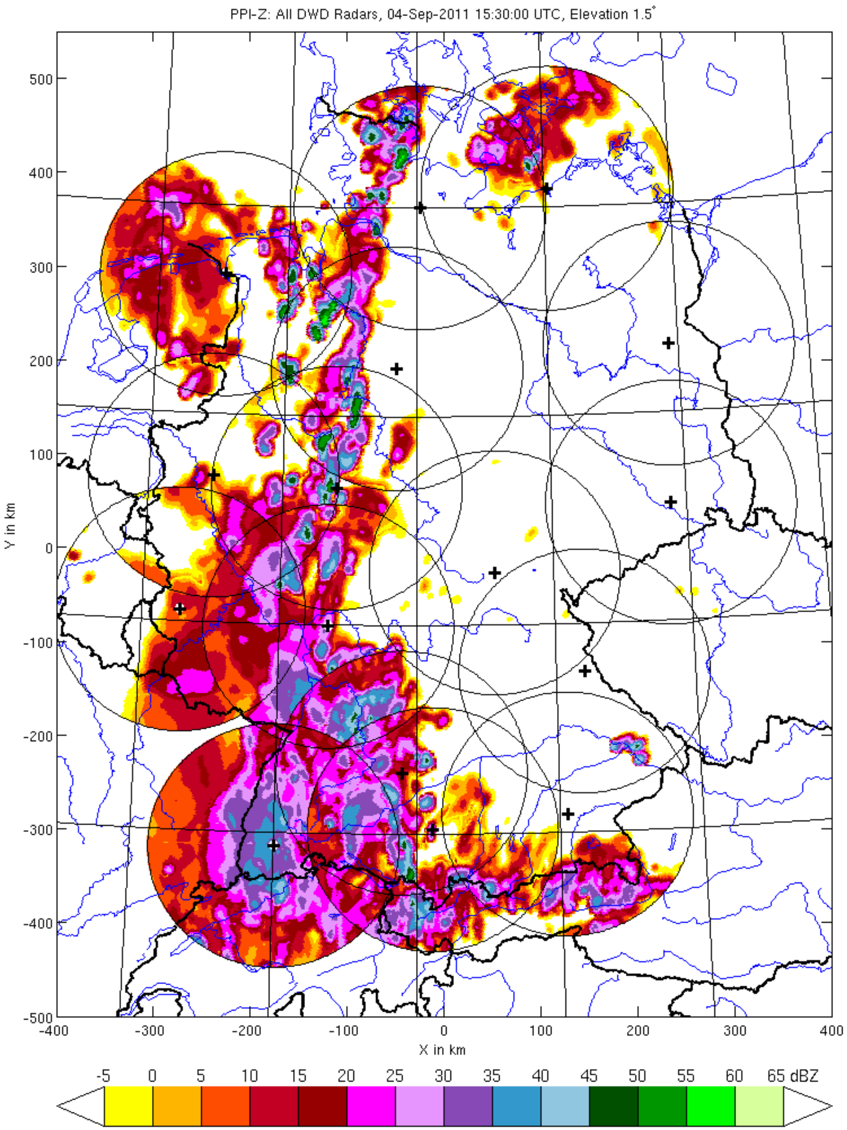
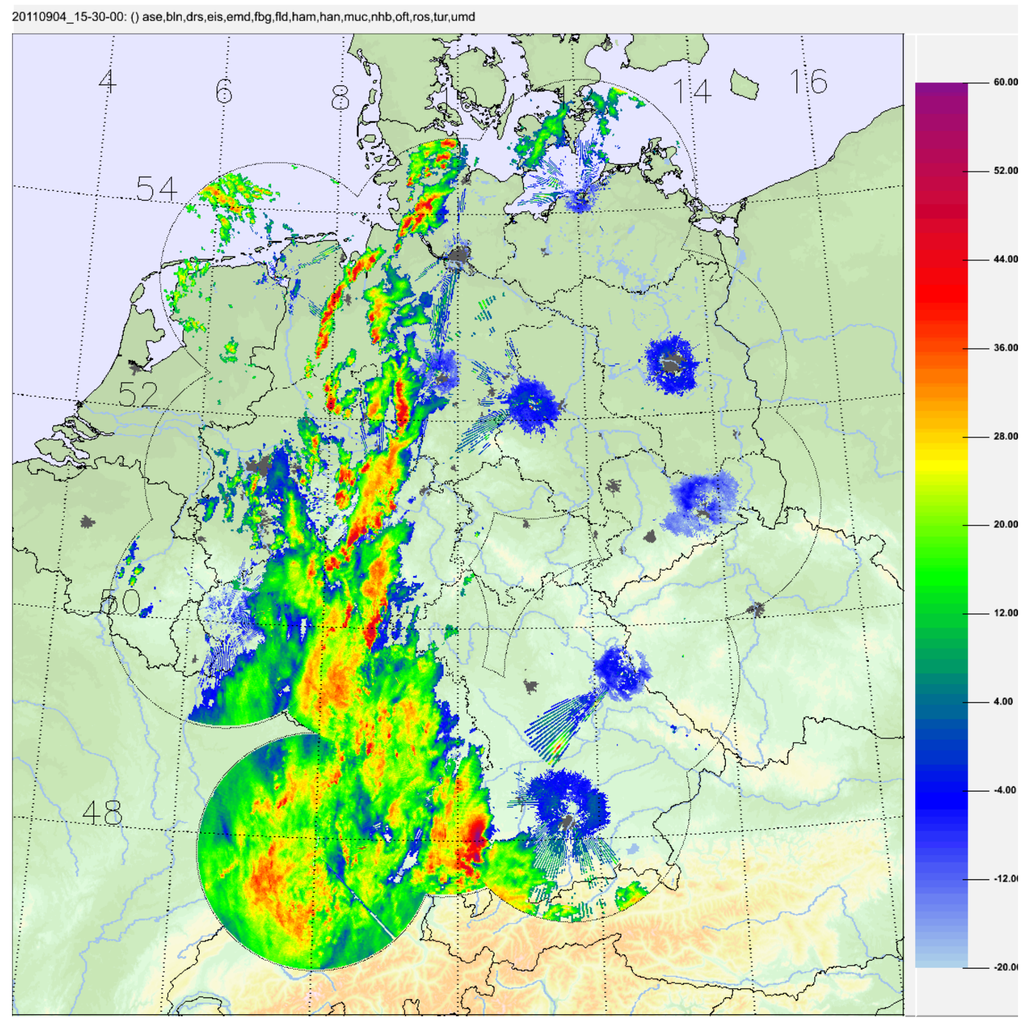
Radar Forward Operator

Reflectivity of Operator against Observation





Final slide…

- Radar provide observation with high resolution in space and time
- Applicable for data assimilation, verification and process studies
- Careful quality check is necessary
- Assimilation of Radar data is applied in many NWP modells
  - Radar wind were used in the first place but
  - Reflectivity is of increasing interest
  - Impact of the assimilation is still limited to the first forecast hours. Greatest benefit is achieved, when both variables are used.
  - further development is required
  - Issues: estimation of observation errors, thinning, superobbing…
  - some approaches try to us refractivity measurements

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Thank you for your attention

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