Results from data assimilation experiments with ROMEX data at DWD

Harald Anlauf

Research and Development – Data Assimilation and Predictability
Deutscher Wetterdienst, Offenbach, Germany

IROWG-10 – COSMIC/JCSDA Workshop
Boulder, Colorado, USA, 12–18 September 2024

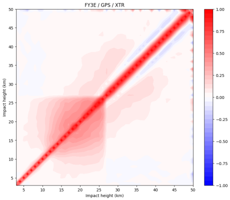
NWP at DWD

- **ICON**-Model: **ICO**sahedral-triangular (Arakawa C) grid, **N**on-hydrostatic core
  - Originally developed by DWD / MPI-M, available via https://icon-model.org/
  - NWP operational configuration
    - Global: 13 km @ 120 layers (det), 26 km @ 120 layers (ens: 40 members), model top: 75 km
    - Europe 2-way nest: 6.5 km @ 74 layers (det), 13 km @ 74 layers (ens), top: 23 km
  - For ROMEX experiments:
    - 26/13 km (det), 40/20 km (ens)
- Hybrid Variational / Ensemble Data Assimilation
  - Deterministic analysis: 3D-EnVar, 3-h cycle
  - Ensemble analysis: LETKF
- Radio Occultation observation operator
  - Based on original code by Michael Gorbunov
  - 1-d Abel integral, tangent-point drift not used

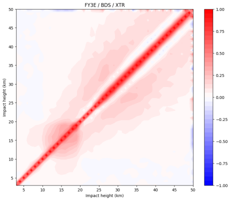
ROMEX experiment status at DWD

- General setup (CTL/EXP) follows recommendations of experiment design subgroup
  - All supplemental data in EXP are used
  - Preliminary results shown at EUMETSAT ROMEX Workshop, Darmstadt, April 2024
  - This talk: results from rerun with technical fixes to initial experiment setup, adjustments to data selection and quality control, observation errors
    - ★ Blacklist all supplemental data above 45 km; FY-3C/D: 35 km, FY-3E: 40 km
    - ★ Blacklist FY-3, Tianmu, Yunyao below 5 km, GeoOptics below 7 km, . . .
    - ★ Observation error inflation for data with strong vertical (O-B) correlations

Example: FY-3E GPS:



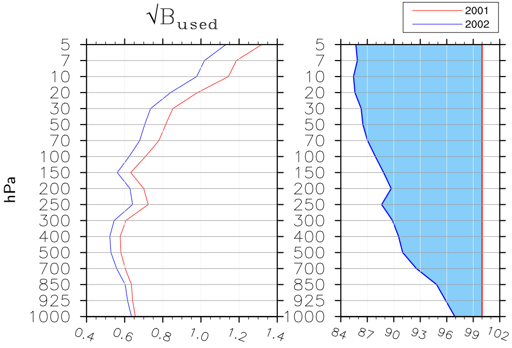
FY-3E BDS:



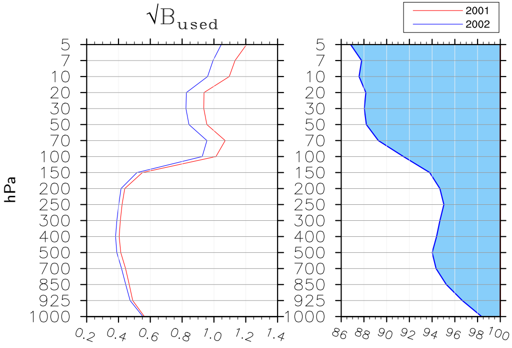
  - Results qualitatively consistent with initial findings, although small improvements
    - ★ Still to be considered far from final!

ROMEX: Impact on background ensemble spread

- 3-h forecast spread of **temperature** at radiosonde locations:
  - NH spread reduction: 10–15 % in upper troposphere/stratosphere; 5–10 % in the troposphere
  - Height-dependence qualitatively consistent with expected RO impact
  - Impact in tropical troposphere significantly lower (of order 5 %)



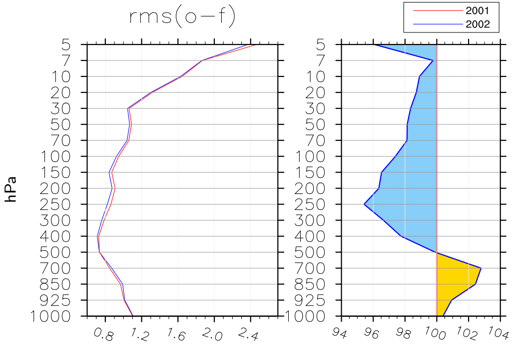
Ensemble T spread, Northern Hemisphere



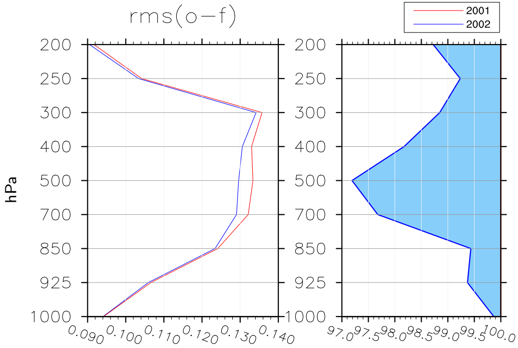
Ensemble T spread, Tropics

ROMEX: Assimilation cycle, fit to radiosondes

- RMSE of deterministic 3-h forecast against radiosondes:
  - Reduction of **temperature** error up to 4 % (UTLS), but degradation in lower troposphere!
  - Reduction of **rel. humidity** error up to 3 % in mid-troposphere
  - Fit of ensemble 3-h forecasts very similar (not shown)



RMSE(O-B), rel. size, TEMP T, NH

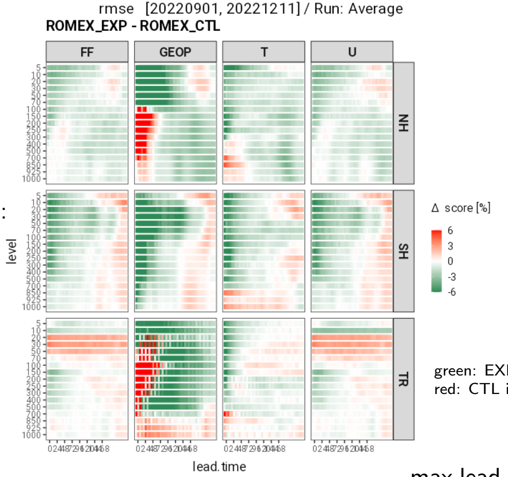


RMSE(O-B), rel. size, TEMP RH, NH

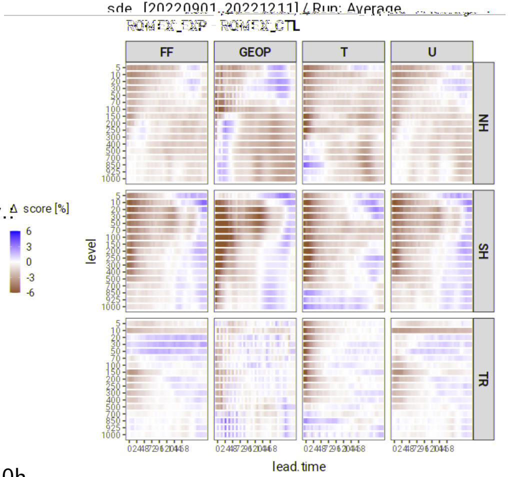
Verification of deterministic forecasts against ERA5 analysis

- Generally strong improvements, but clear sign of tropospheric bias (T, geopotential)!

RMSE:



Std.dev.:

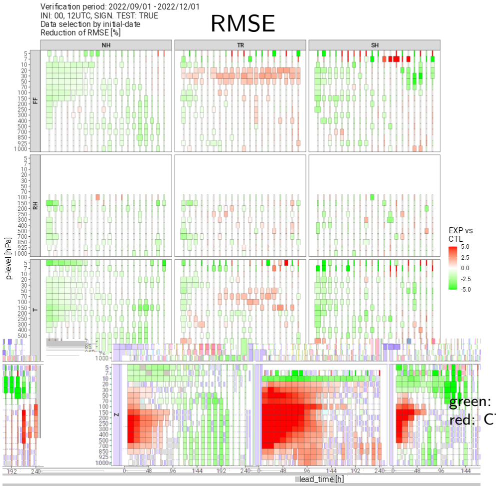


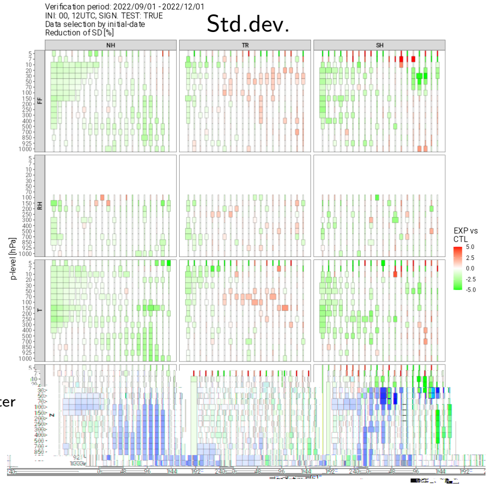
green: EXP is better
red: CTL is better

max.lead time: 240h

Verification of deterministic forecasts against radiosondes

- Similarly strong improvements, confirming significant tropospheric bias (T, geopotential)

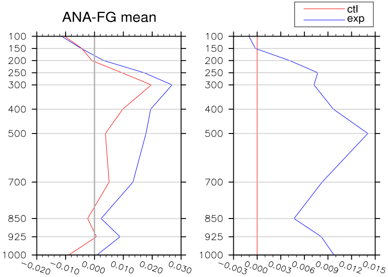


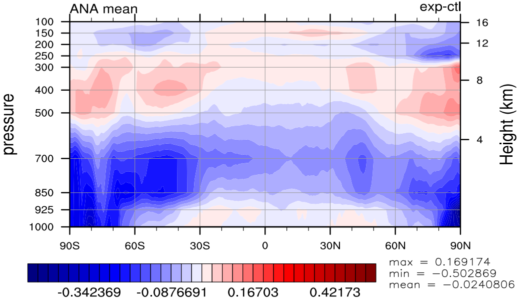


green: EXP is better
red: CTL is better

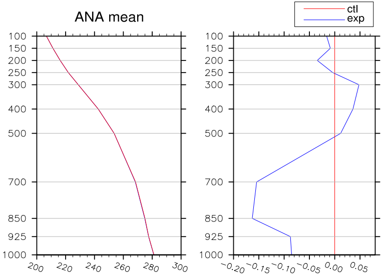
Why do we get what we see?

- Look into mean behavior of assimilation cycle
- **Temperature:** mean analysis colder in EXP than CTL below 500 hPa (up to 0.15 K near 850 hPa)
- Analysis increment: small mean positive increment ($\sim$ 0.01 K) from additional RO over the entire troposphere; no really significant structure





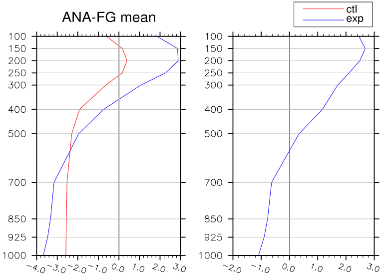
global:



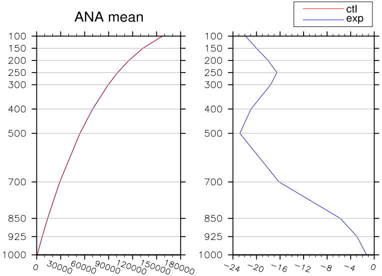
unit: K

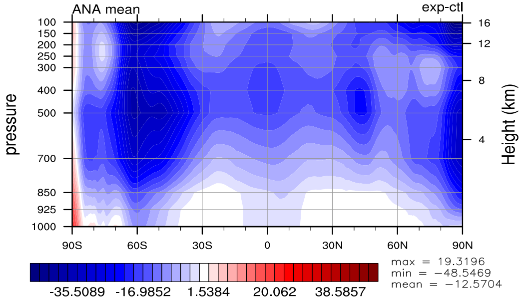
What happens in the assimilation cycle?

- **Geopotential:** analysis mean lower by about 2 gpm (20 m^2/s^2) above 700 hPa
- Slight decrease of geopotential at 1000 hPa
  - due to “hydrostatic tail”, see talk by Katrin Lonitz
  - affects column “below” observation
  - also small (negative) shift of surface pressure



global:





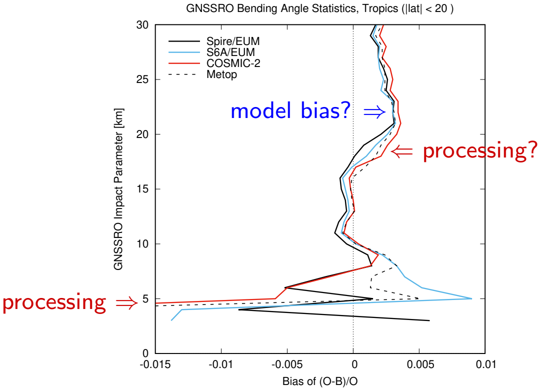
unit: m^2/s^2

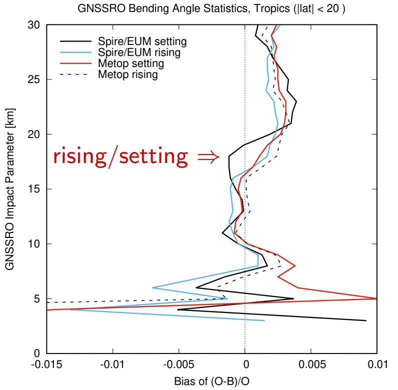
What can cause systematic analysis increments?

1. Systematic differences in $(O - B)$ caused by biased background (model issues)
   - Model dependent, latitude- and height-dependent (see also talk by Neill Bowler)
   - Can alias down into troposphere from core region
2. Systematic differences in $(O - B)$ caused by biased observations
   - example: rising/setting differences point to observations or processing
   - biases seen mostly at low or high impact heights
   - usually dealt with by (partial) blacklisting of data
3. Feedback between data assimilation and model (physics)
   - e.g. change in tropospheric vertical temperature gradient influences convective activity
   - e.g. spin-up/-down, can be studied only in a cycled system (DA + model)!
4. Observation operator
   - Refractivity expression, implementation
     - ★ Plausible overall uncertainties of order 0.05% – 0.1%
     - ★ DWD uses Aparicio and Laroche, JGR 116 (2011) + Non-ideal gas effects
     - ★ Can test sensitivity by changing/reducing refractivity in EXP

Statistics of (O-B) in EXP (incl. blacklisted, excl. FG-rejected)

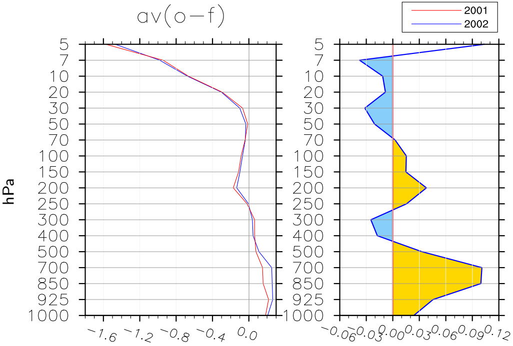
- Tropics ($< 20^\circ$) only for reasonably fair comparison
- Significant differences between different satellites/processings even in core region
- Significant differences between setting and rising occultations



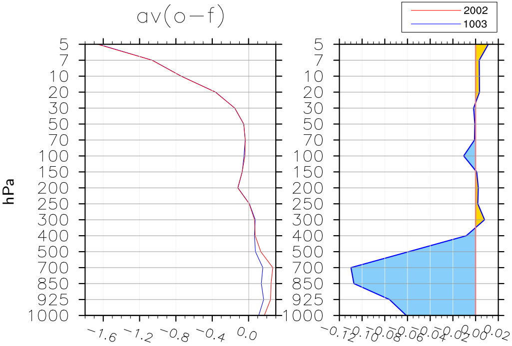


Sensitivity test to changes in refractivity expression

- Comparison of 3-h forecasts against radiosondes:
  - Reduction of N by 0.1% more than compensates the lower tropospheric cooling in NH
  - Qualitatively confirmed by mean analyses of CTL / EXP / EXP(-0.1%)   (not shown)



TEMP T, NH: mean(O-B), diff. EXP vs CTL



TEMP T, NH: mean(O-B), EXP(-0.1%) vs. EXP

Conclusions

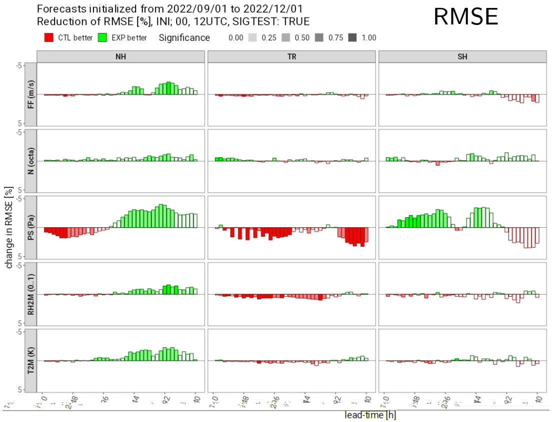
- Experiments with a large number of GNSS radio-occultation data (as in ROMEX) confirm their high impact in global NWP
  - Strong reduction of ensemble spread (maybe too much?)
    - May need major retuning of DA system to not lose impact from other observations!
  - Mostly improved fit of 3-h forecasts to radiosondes except in lower troposphere, but:
    - Increased geopotential bias/cooling of lower troposphere ☹
  - Partial deterioration of forecasts at shorter lead times ☹
  - In general significantly improved forecasts in the medium-range, extra-tropics ☺
- Biases seen may need to be addressed for getting even better impact:
  - Model: work on lower to mid-stratospheric biases (primarily tropics)
  - Observations: check differences between different satellites in the core region (10–30 km)
  - Check accuracy of forward models (incl. refractivity expressions)

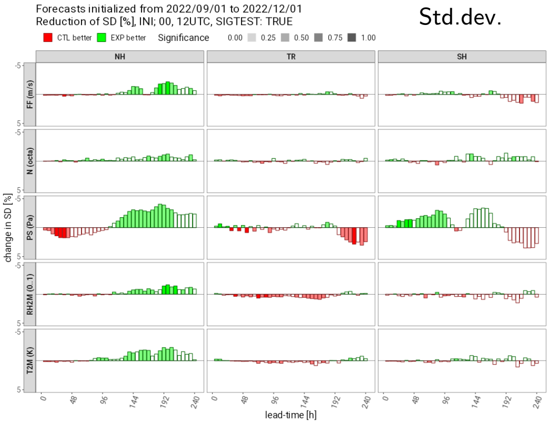
    (Target: uncertainties equivalent to $\ll 0.1\,\mathrm{K}$)

Spare Slides

Verification of deterministic forecasts against SYNOP

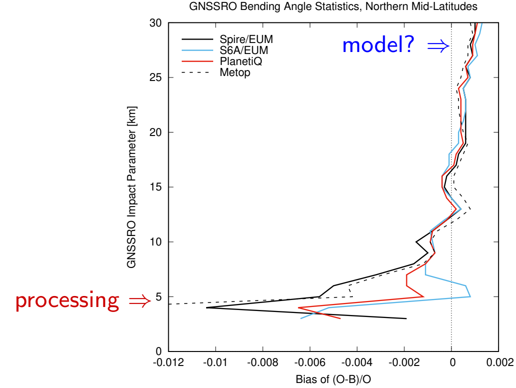
- Degradation in surface pressure at shorter lead-times
- General improvements at longer lead-times, often significant

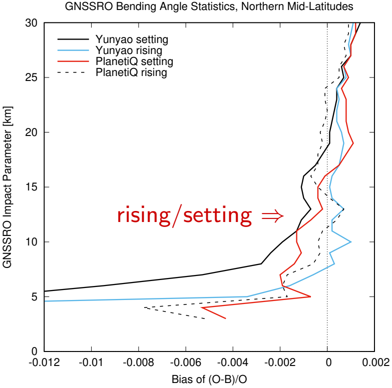




Statistics of (O-B) in EXP (incl. blacklisted, excl. FG-rejected)

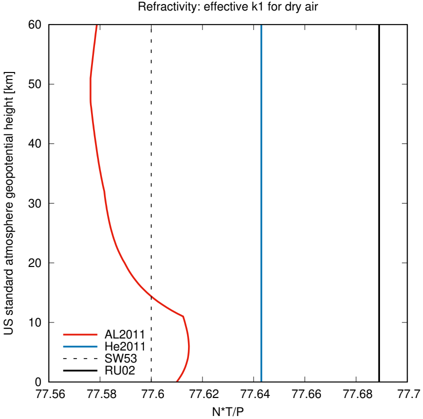
- Northern Mid-Latitudes (20°N – 60°N) with high density of conventional observations
- Expect significantly smaller background systematic error in lower/mid-stratosphere
- Significant differences between setting and rising occultations



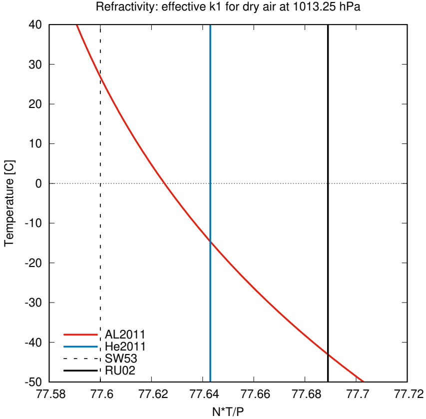


Comparison of refractivity expressions: dry air, normalized

- (NT/P): US Standard Atmosphere profile (sea level: 15°C); temperature dependence
  - Aparicio & Laroche (2011), Healy (2011), Smith-Weintraub (1953), Rüeger (2002)



indicative height dependence



temperature dependence (standard pressure)