Assimilation of water vapour, cloud and precipitation from microwave sounders

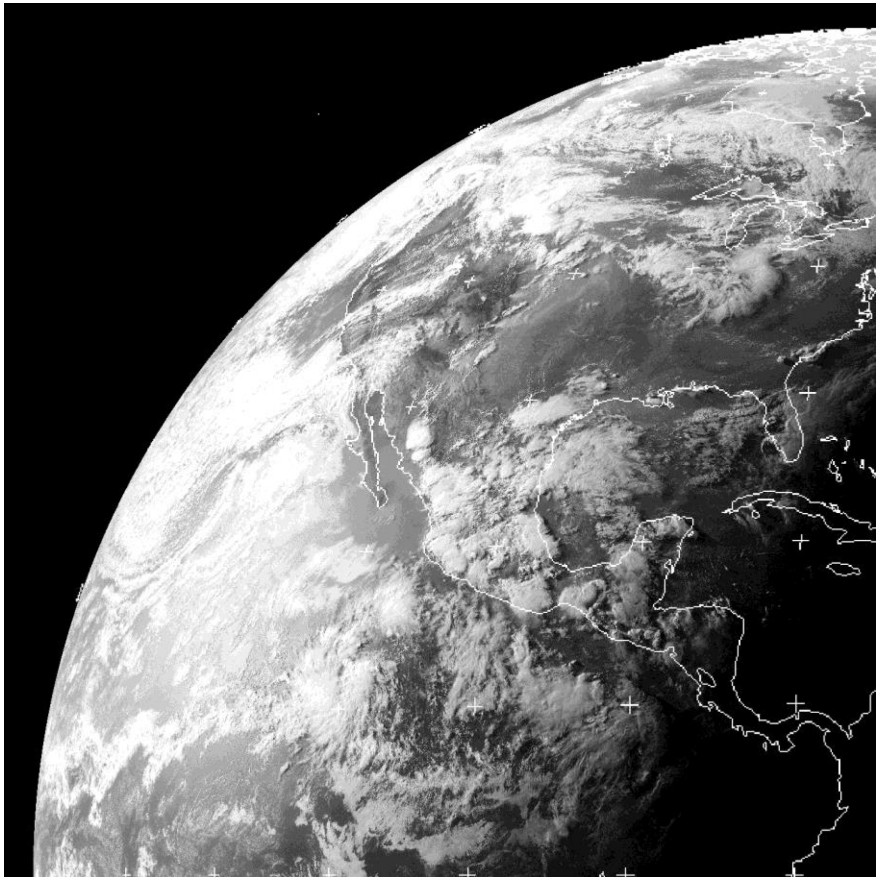
Alan Geer, Fabrizio Baordo, Niels Bormann, Stephen English

Thanks to:

Peter Bauer, Philippe Lopez, Marta Janiskova, Deborah Salmond, William Bell, Enza Di Tomaso, Elias Holm, Katrin Lonitz, Peter Lean, Masahiro Kazumori, Stefano Migliorini, Richard Forbes … and many others

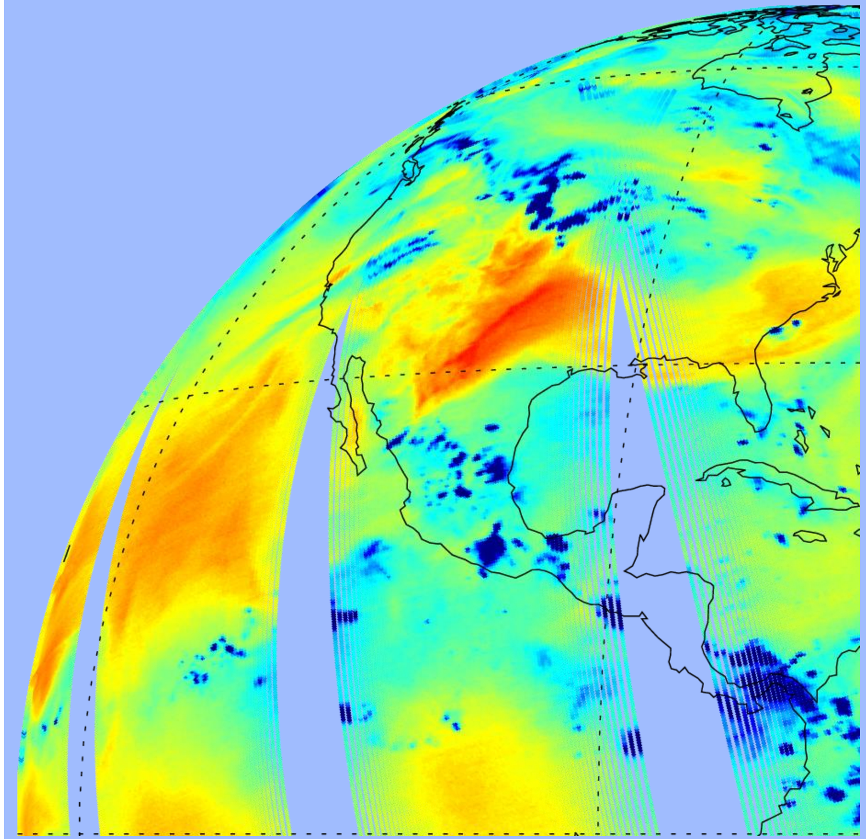
GOES visible - 00Z

Dundee receiving station / NOAA / EUMETSAT



Microwave WV - 00-05Z

Metop-B 190 GHz



June 12 2013

“direct assimilation of cloudy radiances is still experimental” (…., 2014)

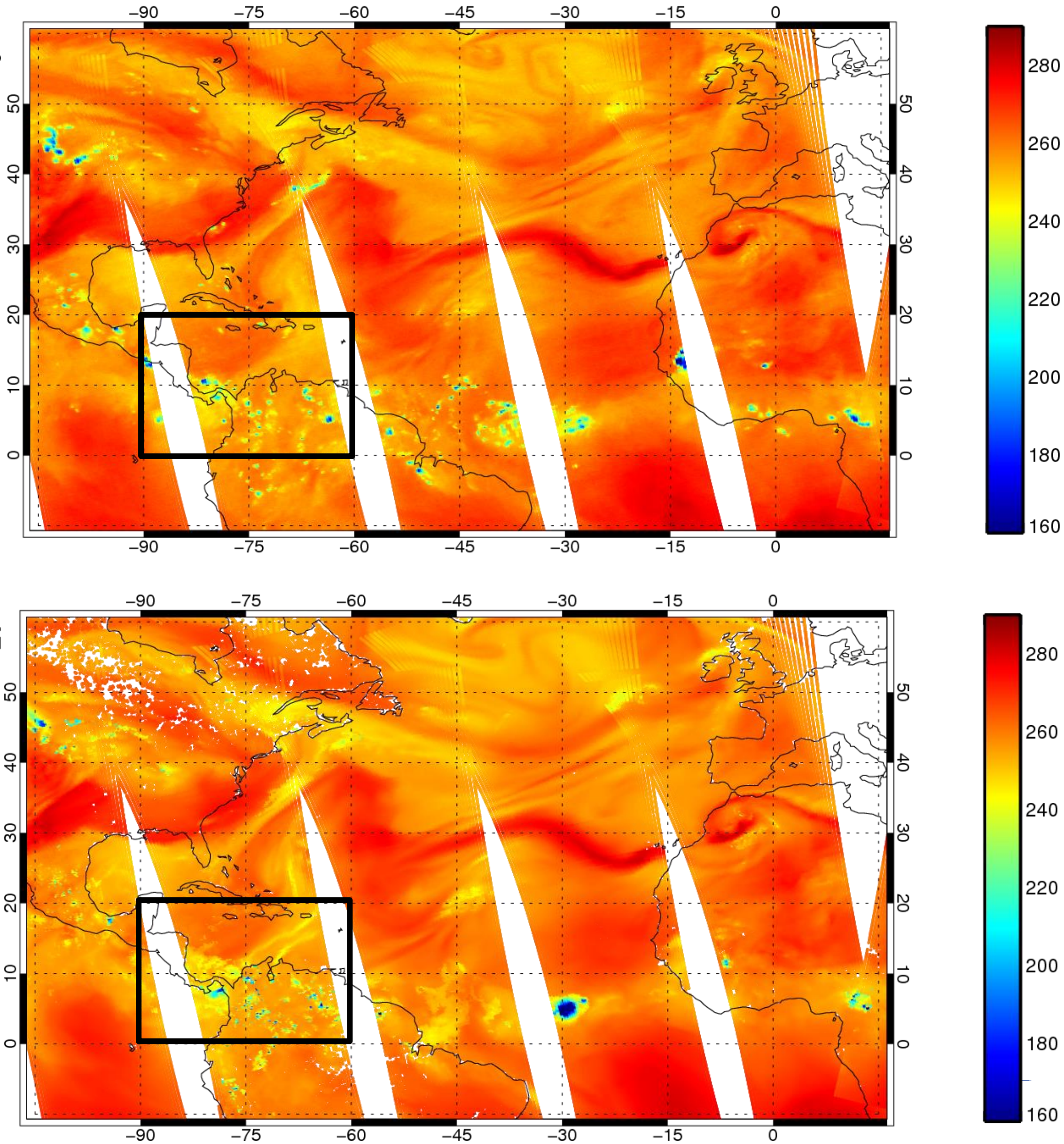
Fair enough, there are reasons to question whether operational all-sky assimilation really assimilates cloud and precipitation (some more valid than others):

- cloud and precipitation cannot be assimilated without a cloud control variable?
- the high observation errors assigned in cloudy areas mean that no information is taken from the cloudy radiances?
- 4D-Var tracing is still not proven?
- we want clouds and precipitation moved to *exactly where they should be?*

The biggest issue: representing cloud and precipitation in models

Observations

ECMWF FG



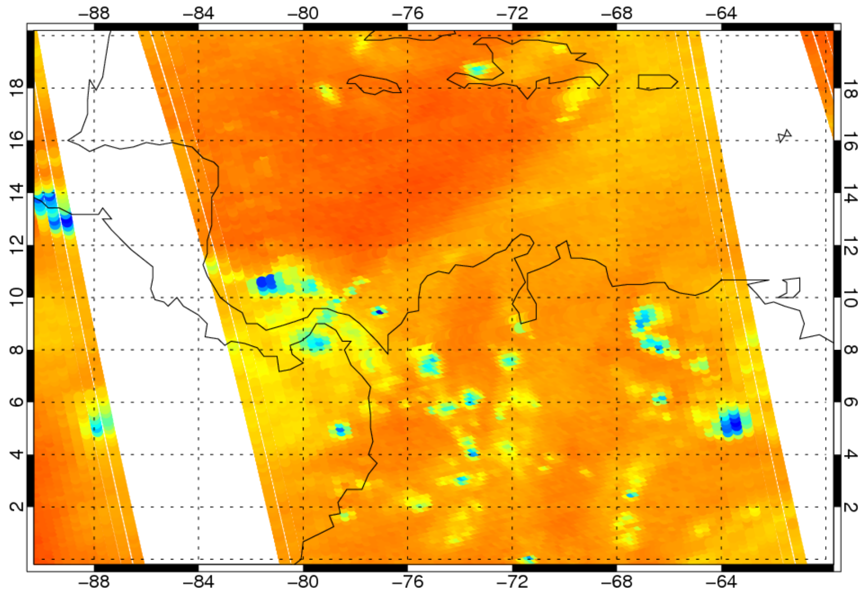
TB [K]

MHS 183±3 GHz
June 12th 2013

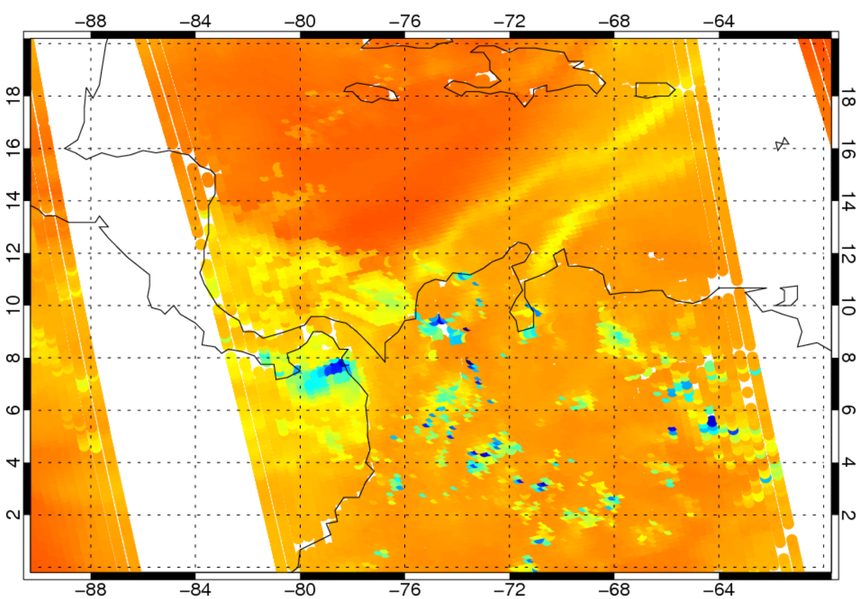
TB [K]

The biggest issue: representing cloud and precipitation in models

Observations



ECMWF FG

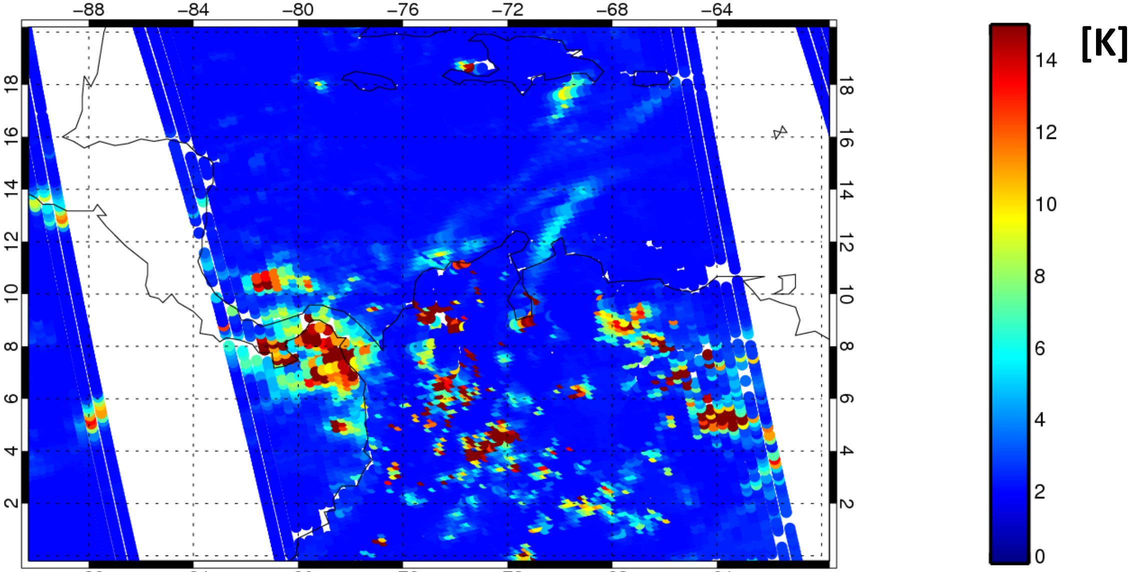


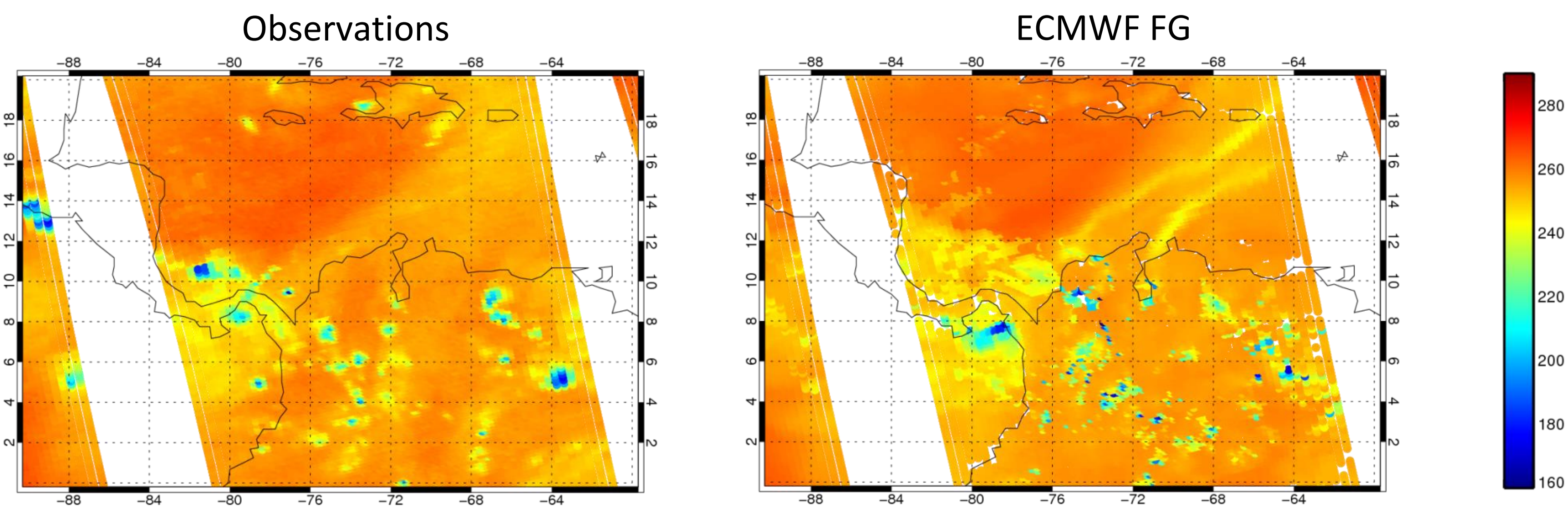
Why such large errors?

- Poor *predictability and/or representivity* of cloud and precipitation, particularly in convective situations
- Accuracy of forecast model's cloud and precipitation parametrization
- Accuracy of the observation operator (scattering radiative transfer simulations)

But if you can describe the observation error correctly, and the observations are unbiased, you can assimilate

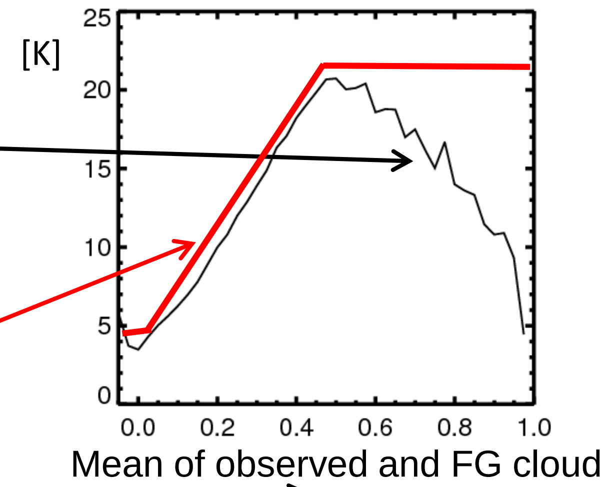
MHS 183±3 GHz adaptive observation error
from a "symmetric error model"

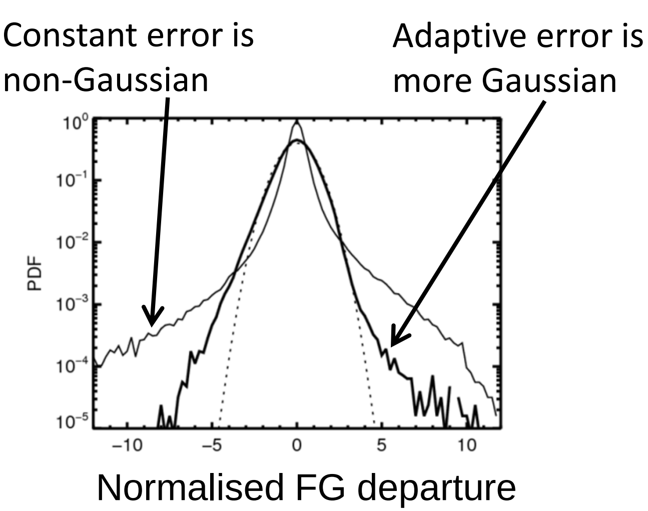




Symmetric error models

- **FG departure standard deviation is a function of the “symmetric cloud amount” – the average of observed and simulated cloud**
- **An error model is fitted to (or binned from) the FG departures**
- **Cloud predictors:**
  - **37 GHz polarisation difference (imagers)**
  - **Scattering index (land, MHS)**
  - **LWP retrieval (AMSU-A)**
  - **Cloud – clear TB (IASI)**





All-sky assimilation components in 4D-Var

Observation minus first-guess* departures in clear, cloudy and precipitating conditions

*FG, T+12, background…

Observation operator including cloud and precipitation (RTTOV) - TL/Adjoint

Rest of the global observing system

Moist physics - TL/Adjoint

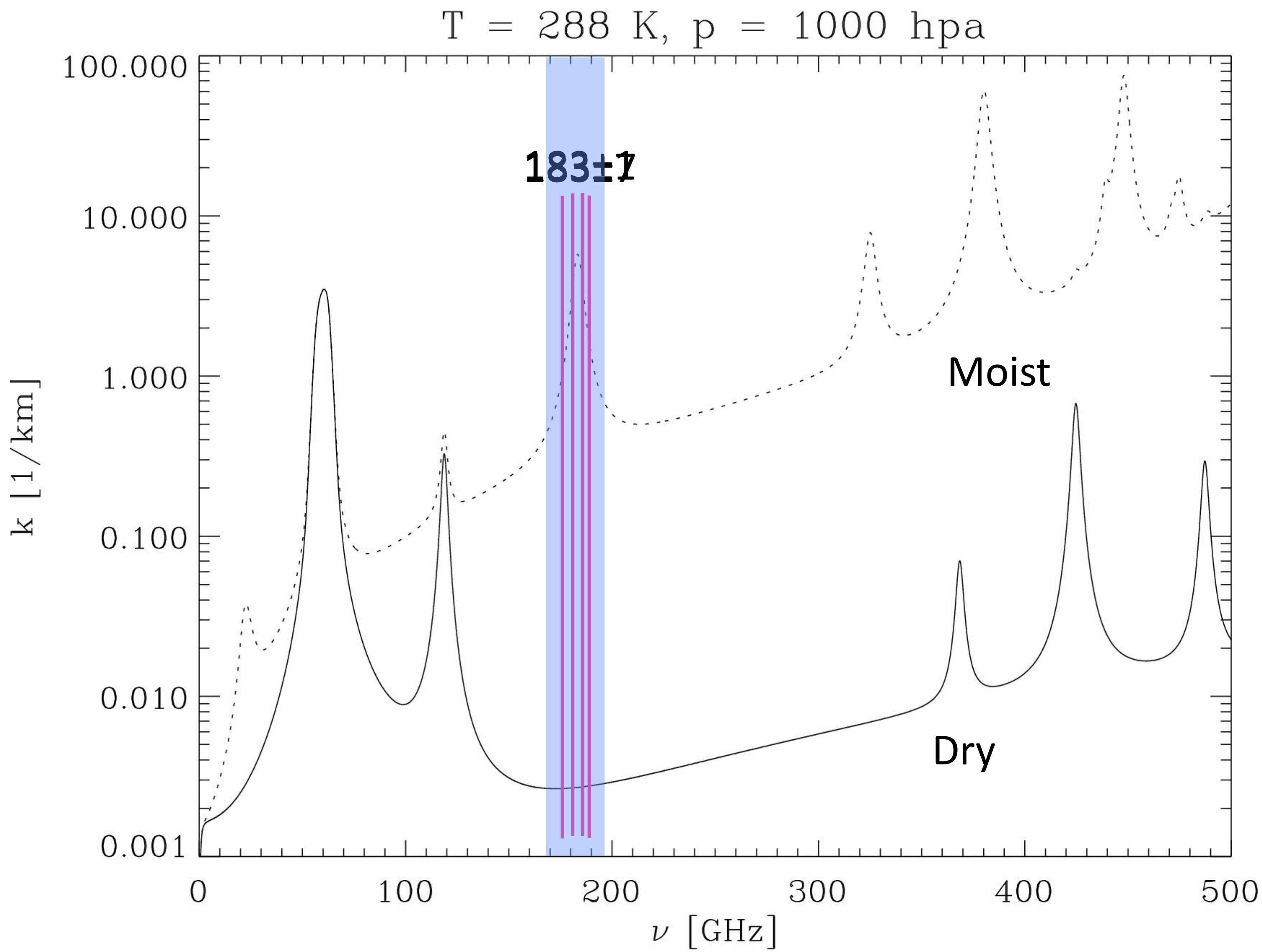
Forecast model - TL/Adjoint

Background constraint

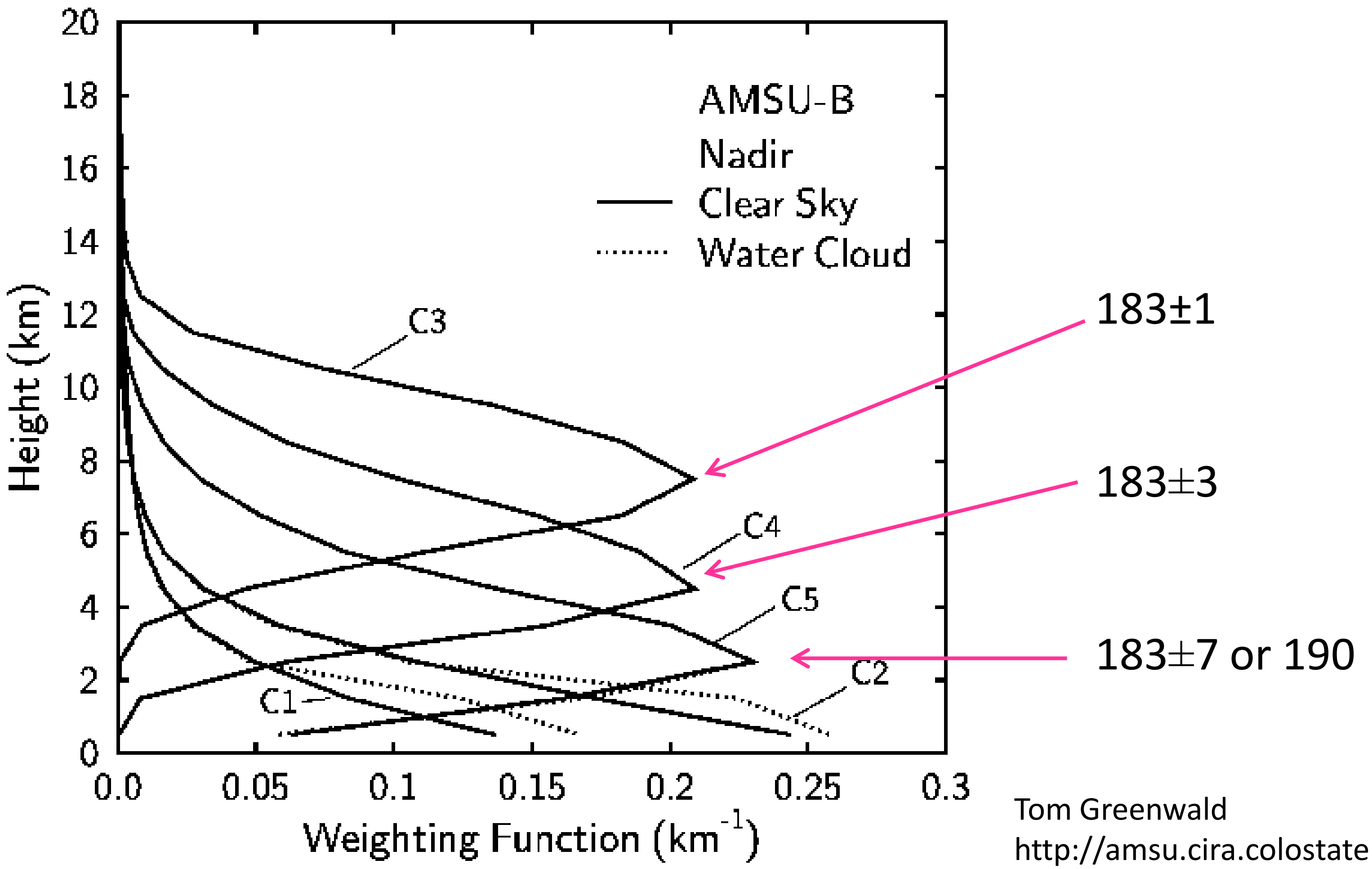
Control variables (winds and mass at start of assimilation window) optimised by 4D-Var

What do microwave water vapour radiances observe?

183 GHz water vapour absorption line



183 GHz clear-sky weighting functions



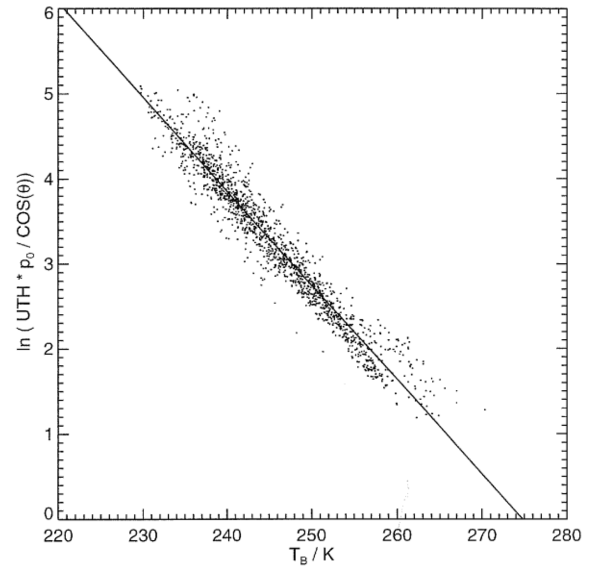
Tom Greenwald
http://amsu.cira.colostate.edu/weights.html

UTH – upper tropospheric humidity

in cloud/precip free scenes

- Soden and Bretherton (1993)
  - 6.3 μm infrared
- Buehler and John (2005)
  - 183 GHz microwave

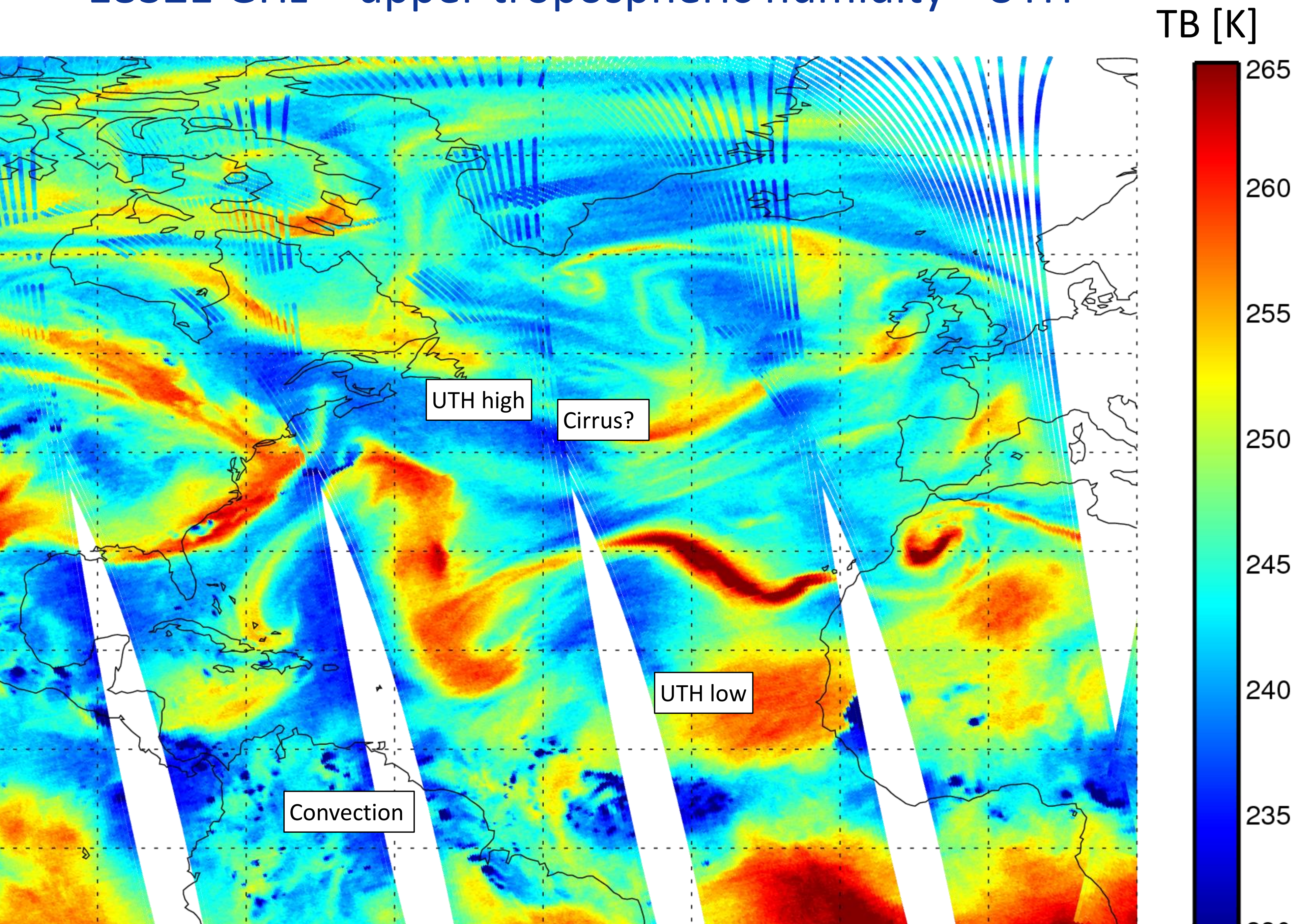
$$\ln(UTH) = a + bT_b$$



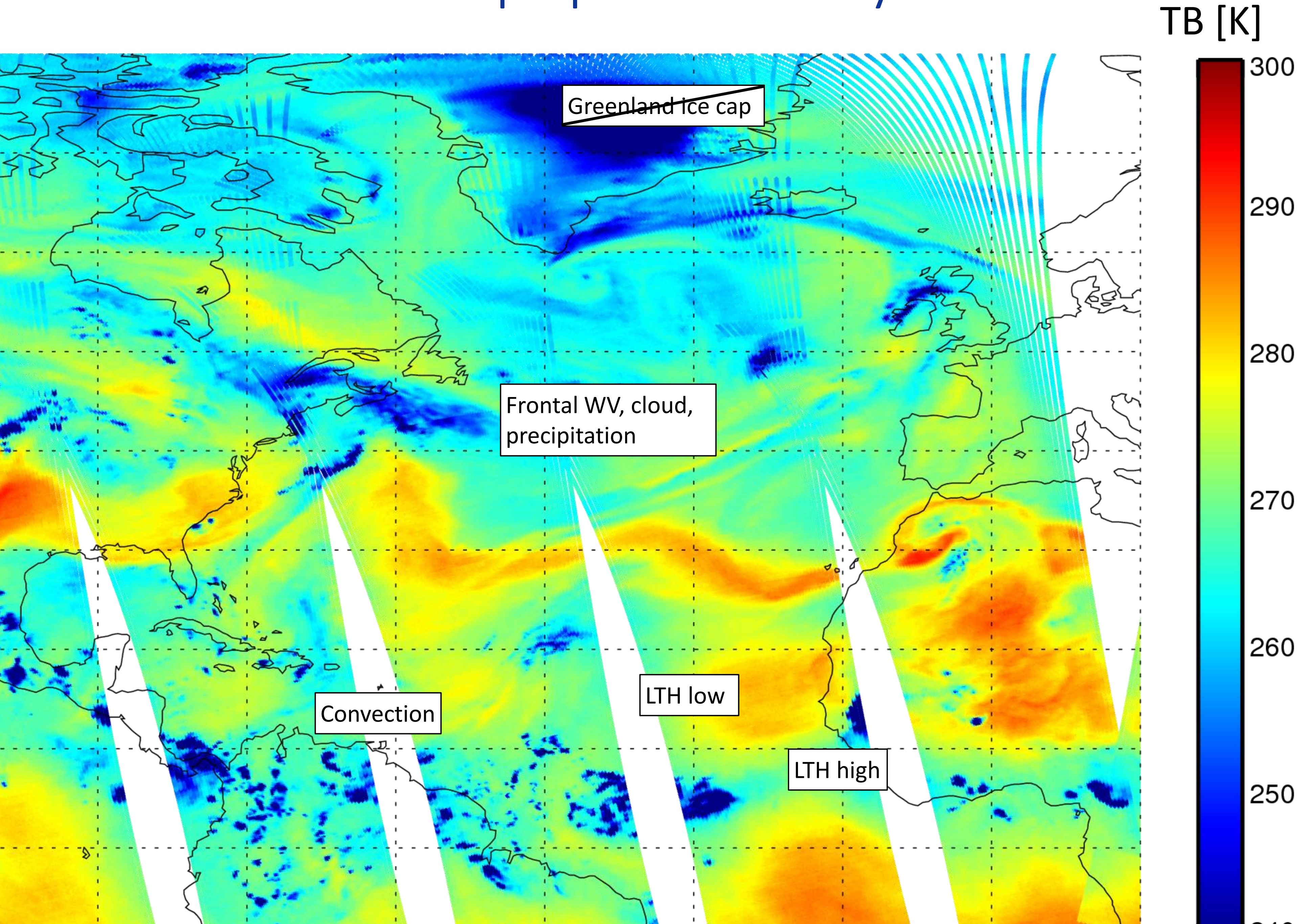
- Simplest definition of UTH:
  - average relative humidity between 200 hPa and 500 hPa

Great similarities between microwave and infrared water vapour sounding channels (and that extends to cloud, too…)

183±1 GHz – upper tropospheric humidity - UTH

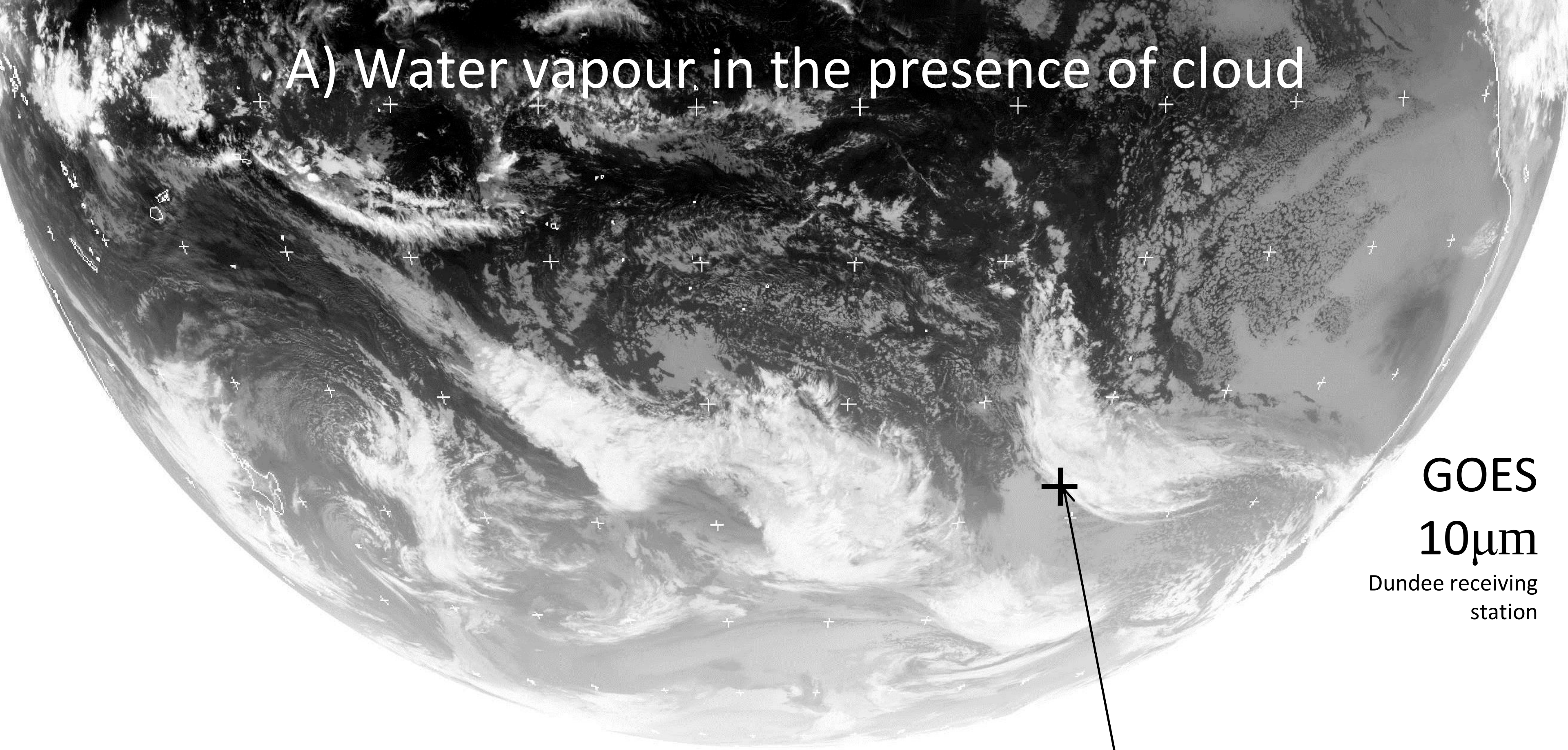


190 GHz – lower tropospheric humidity



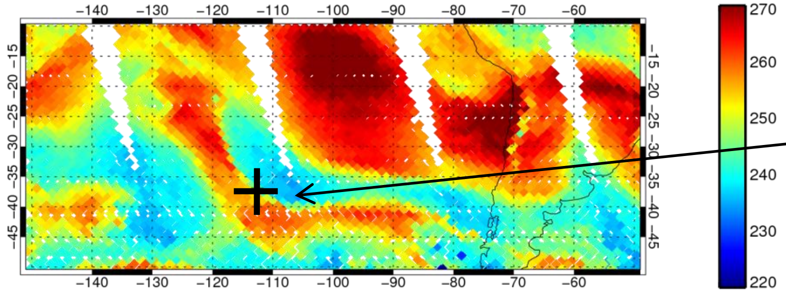
Single observation tests

A) Water vapour in the presence of cloud



GOES
10μm
Dundee receiving station

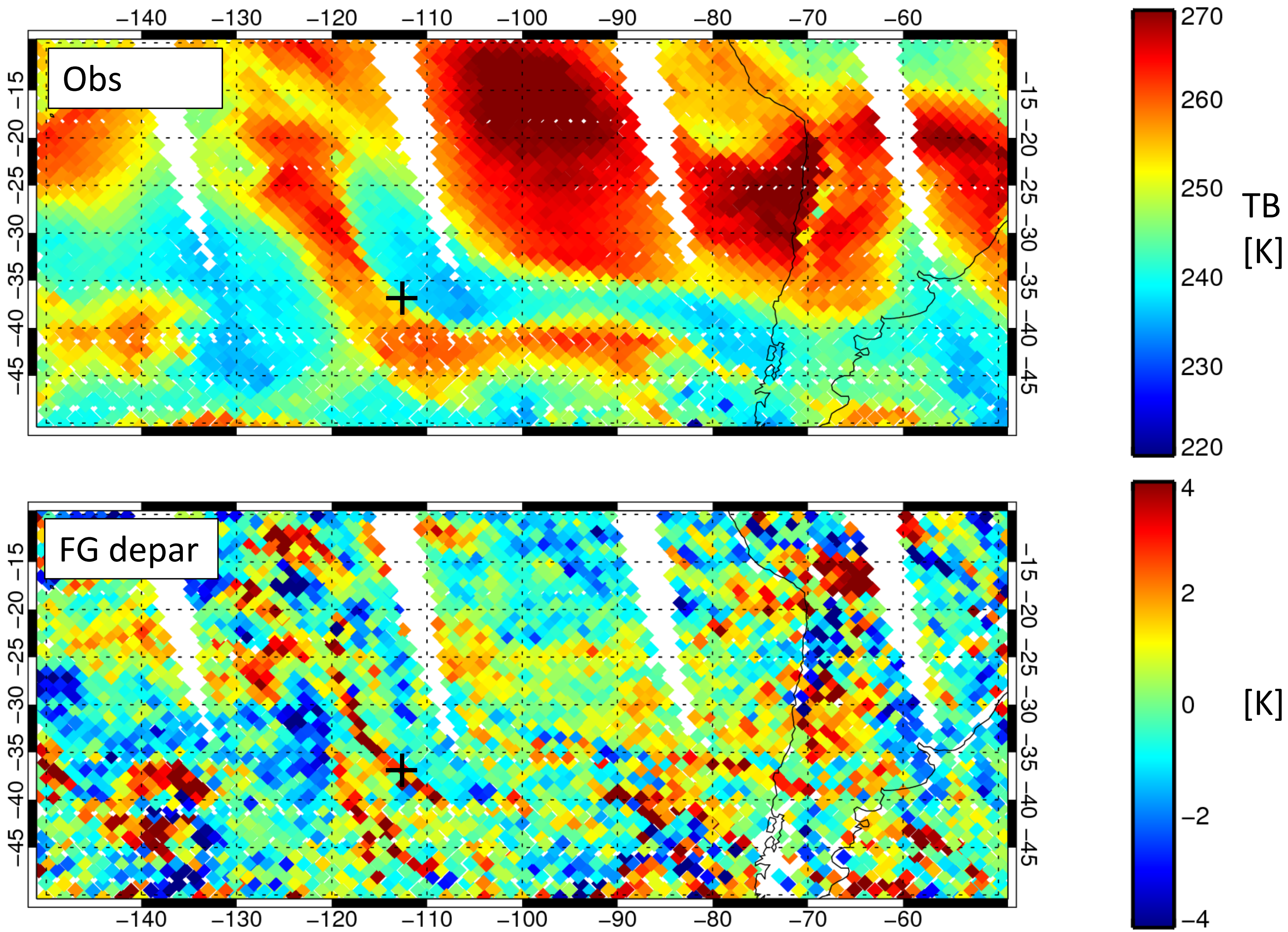
Metop-B MHS
183±1 GHz



06Z, 15 Aug 2013
37°S 113°W
Observation rejected in old `clear-sky' approach

ECMWF

A) Water vapour in the presence of cloud - 183±1



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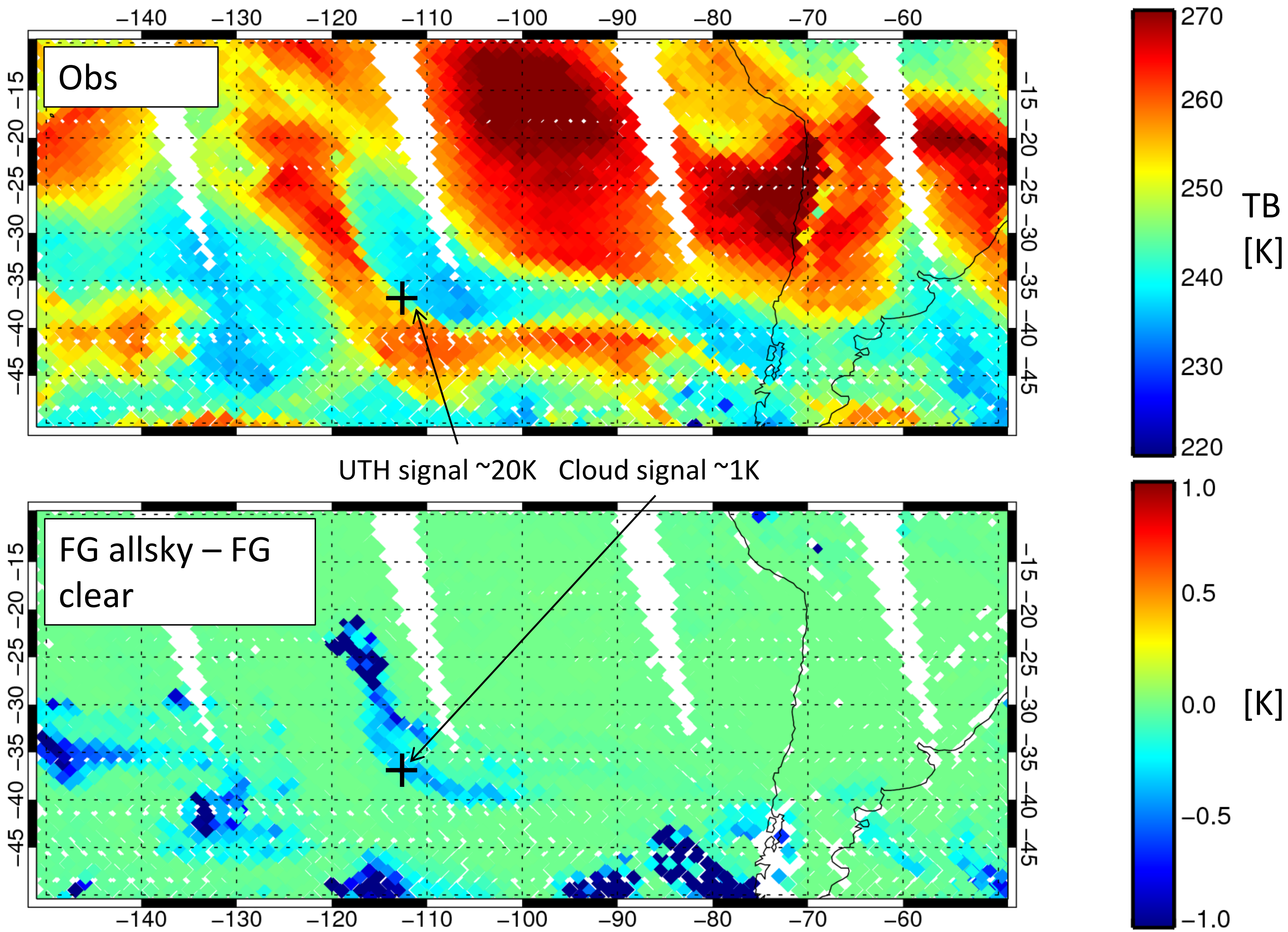

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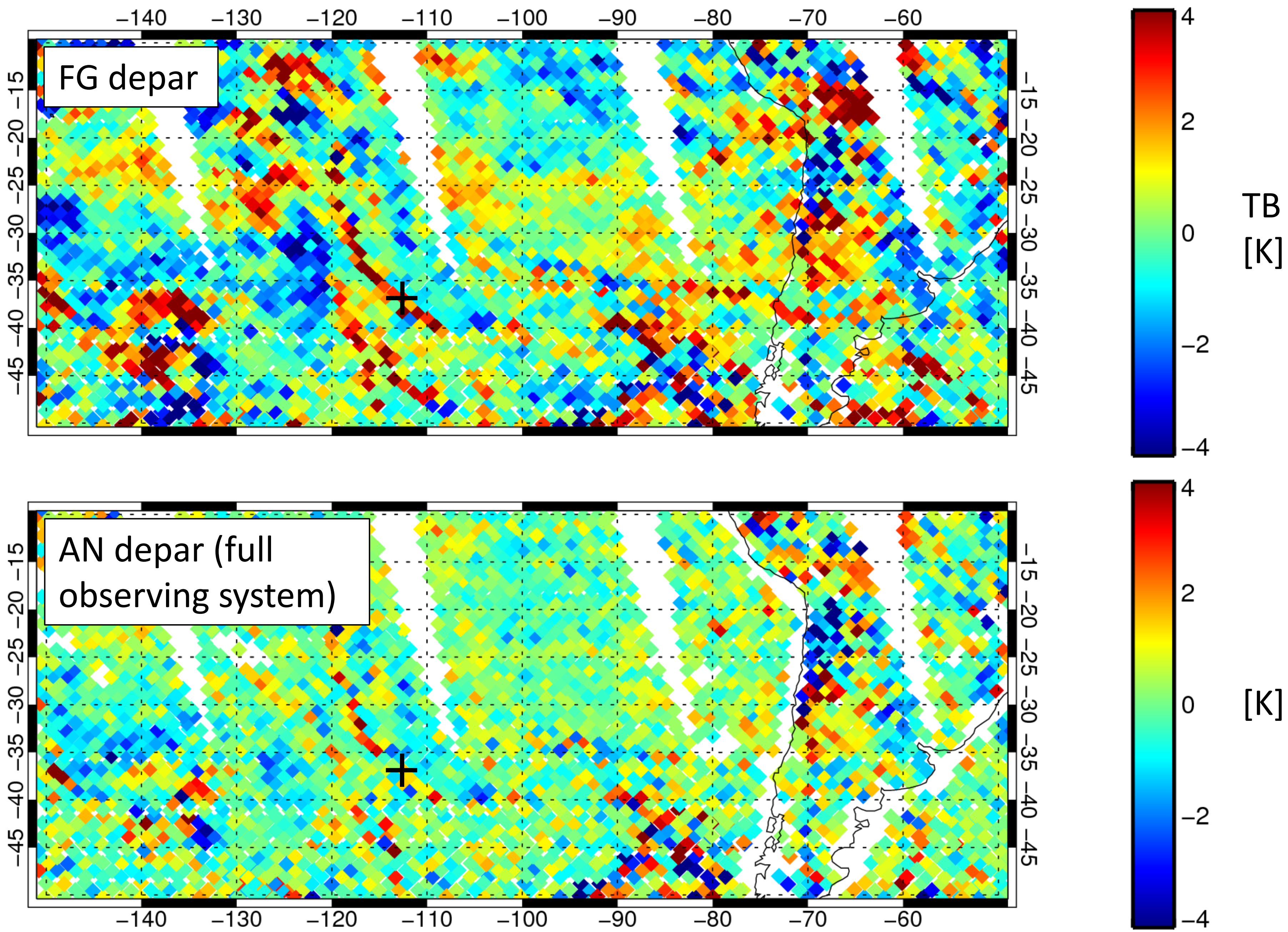
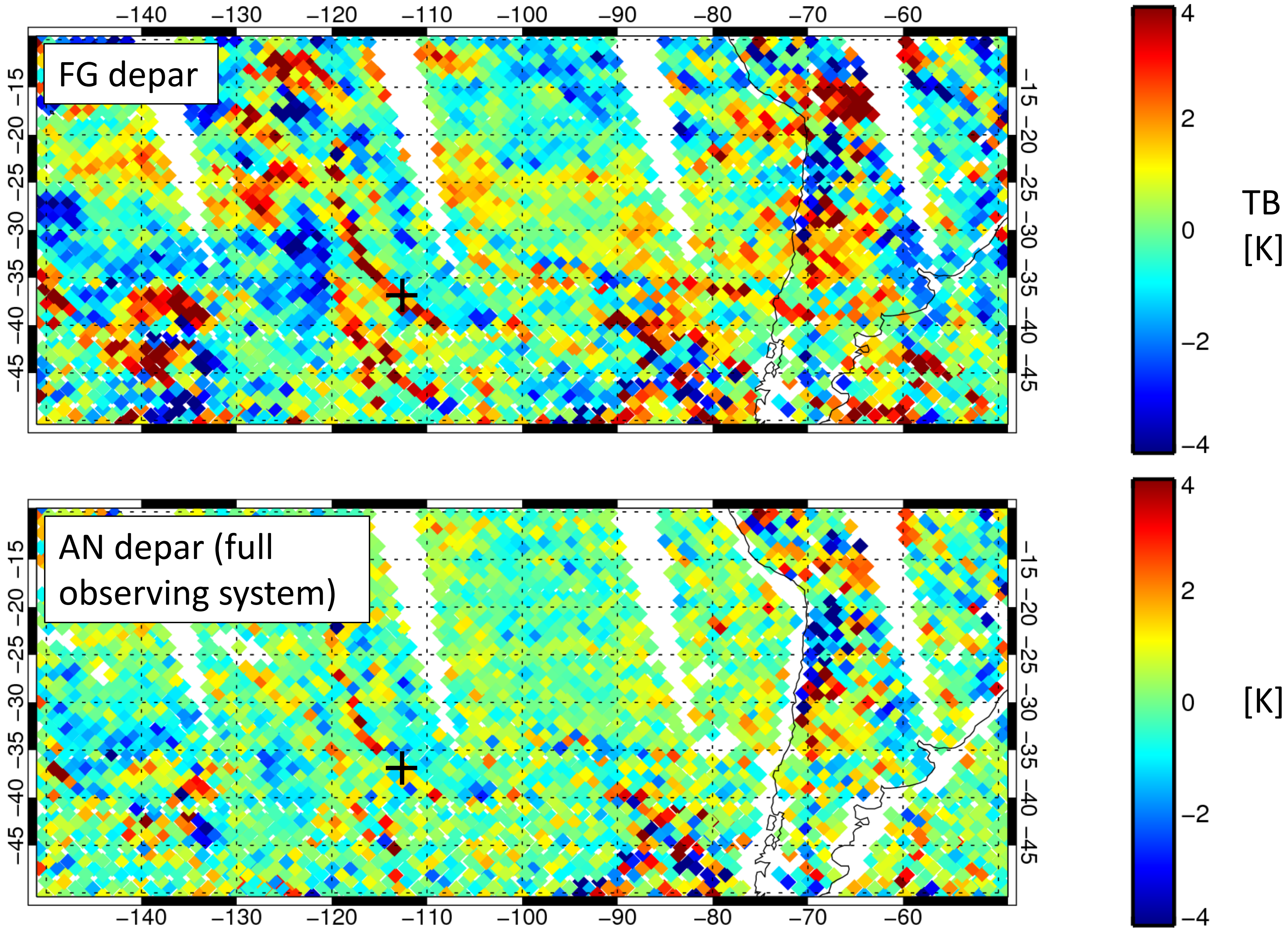


Thoughts

- Cloud and precipitation fields are improved in every analysis - even if we were to remove the all-sky observations
  - **All observations** are cloud and precipitation observations
  - Avoid "univariate" thinking!
    - 4D-Var: the forecast model (along with the background error covariances) ensures increments in winds, mass, water vapour, cloud, precipitation are physically consistent
    - Ensembles: (given a sufficiently representative ensemble) background error correlations will ensure an increment in e.g. temperature will naturally also give an increment in winds, cloud, precipitation and water vapour

A) Water vapour in the presence of cloud - 183±1



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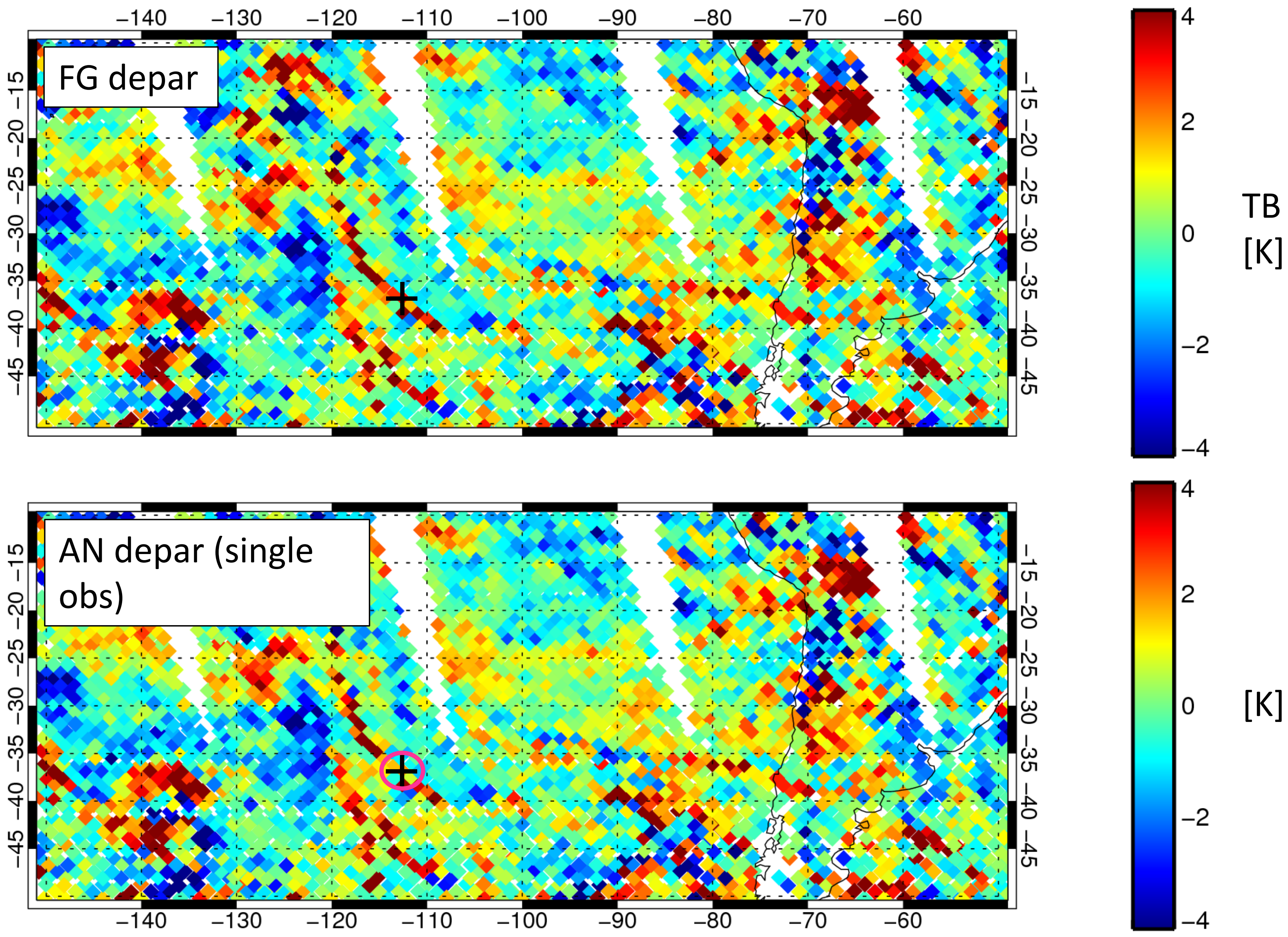

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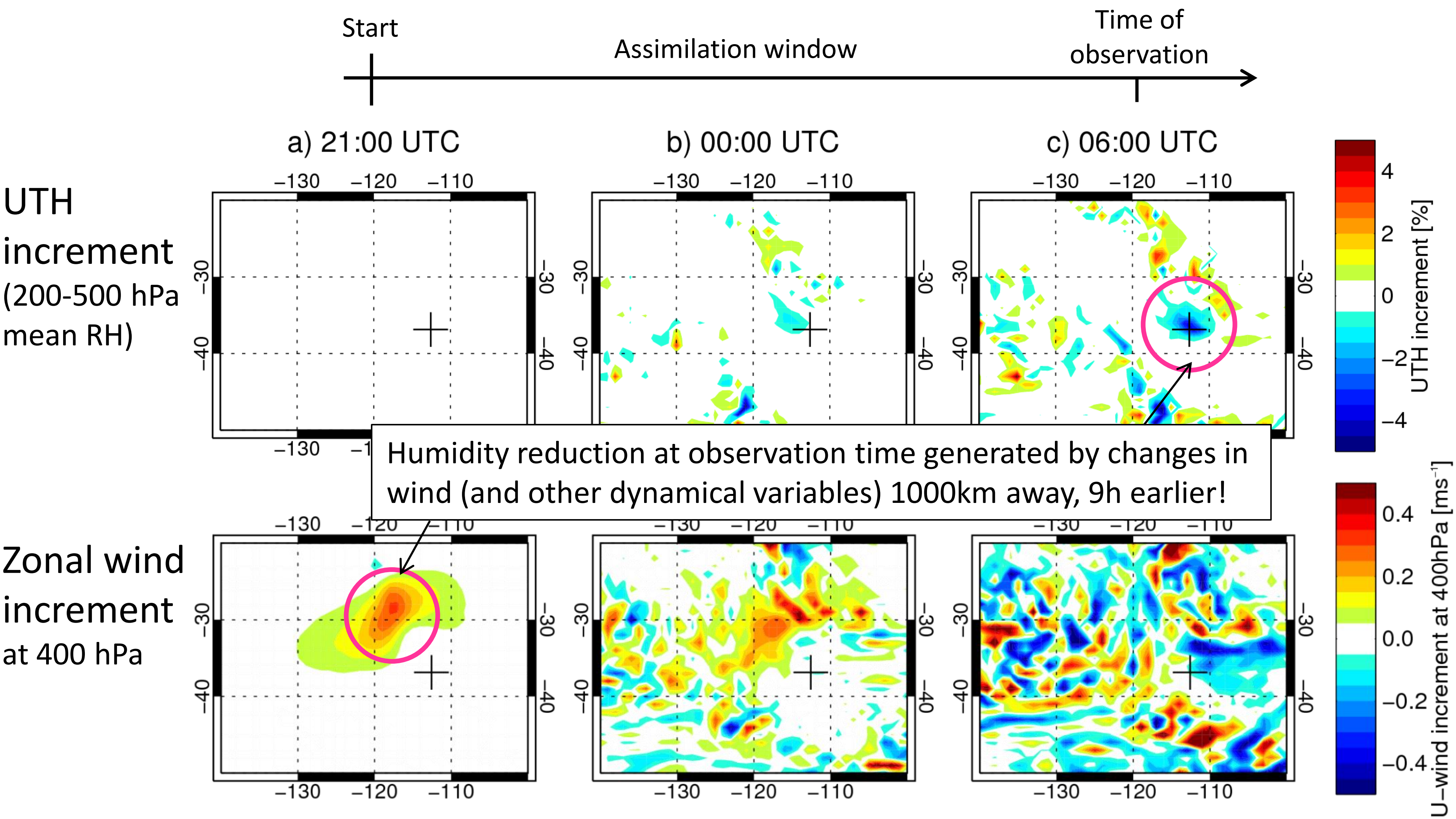
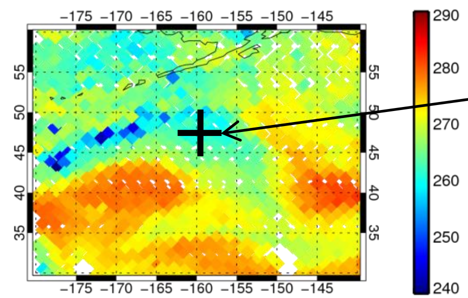


ECMWF

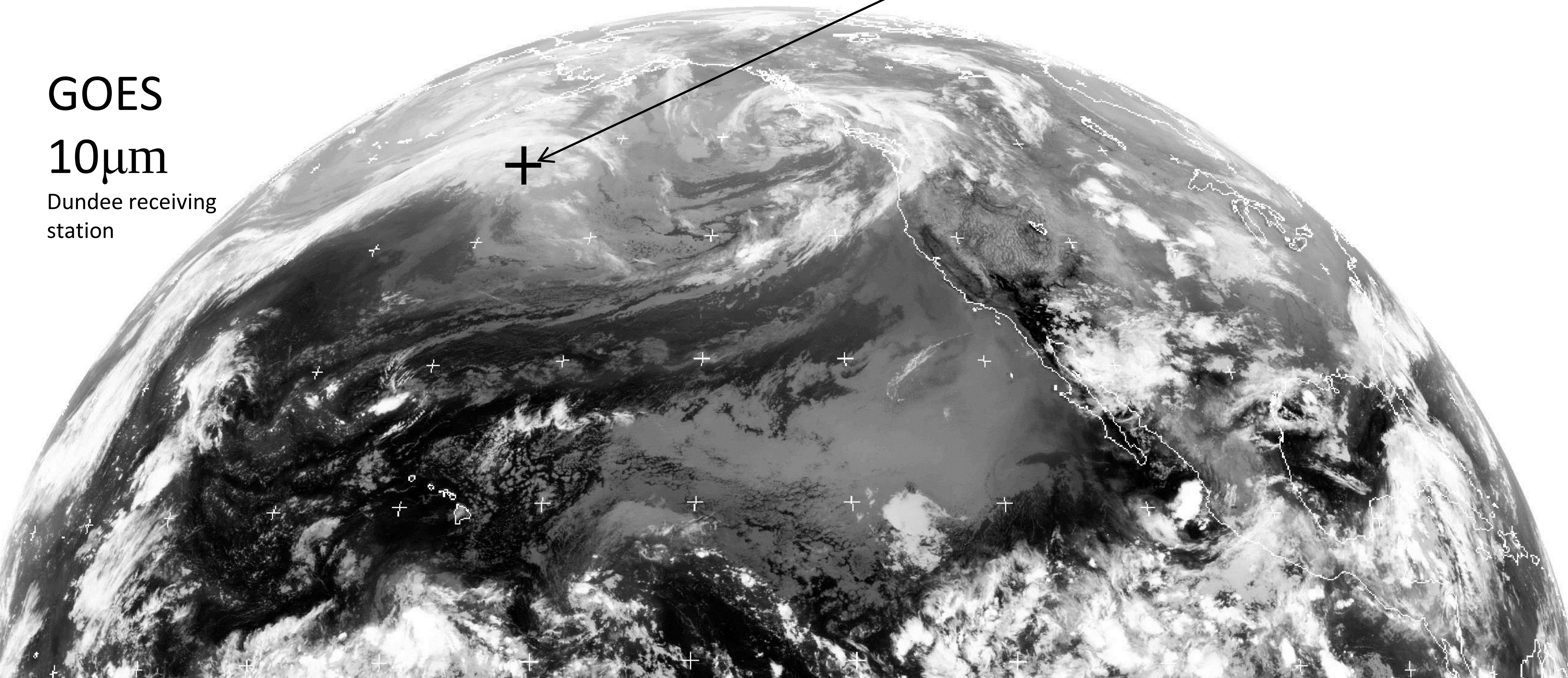
B) Frontal cloud and precipitation – 190 GHz

Metop-B MHS
190 GHz



08Z, 15 Aug 2013
47°N 159°W

GOES
10μm
Dundee receiving station



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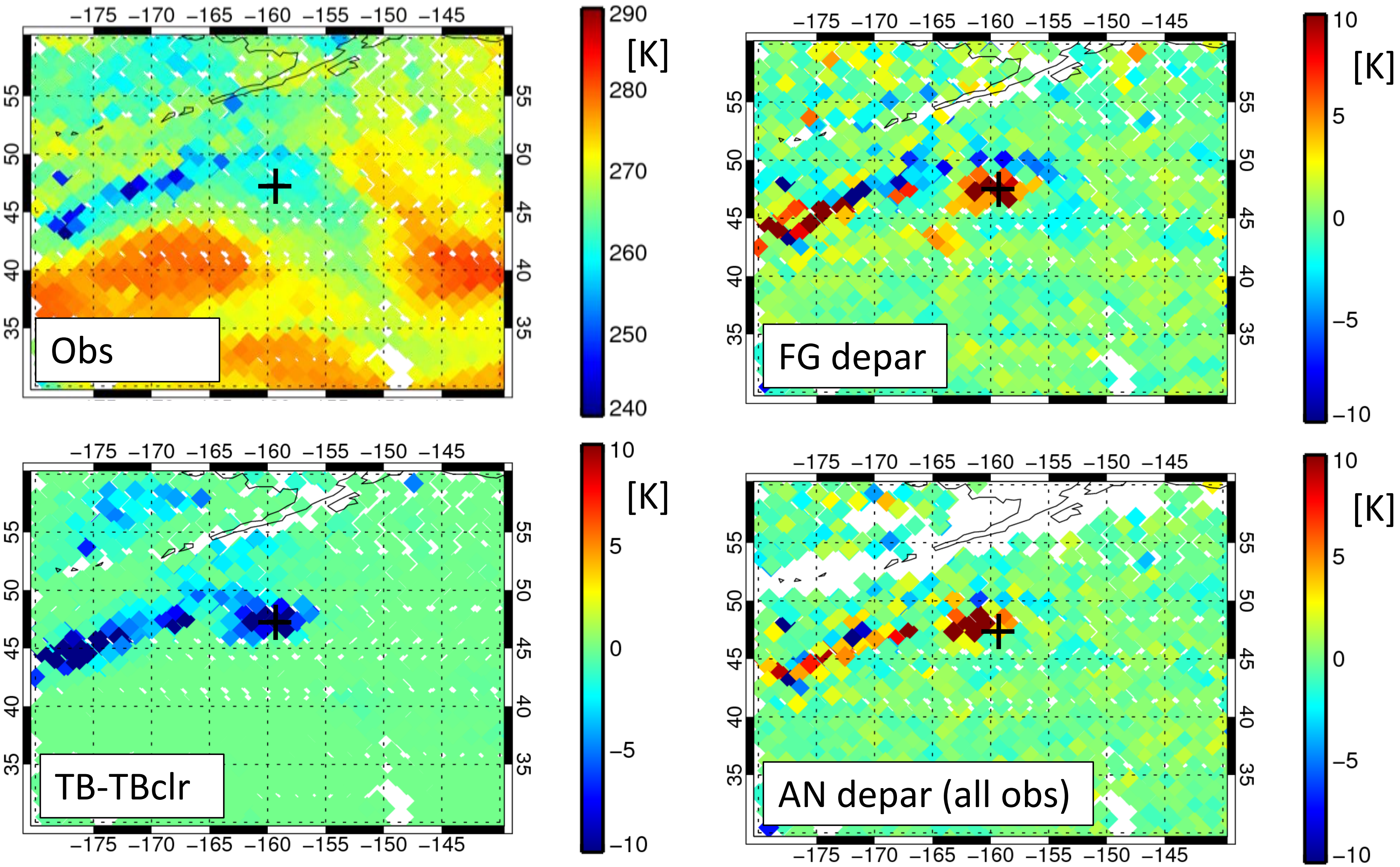

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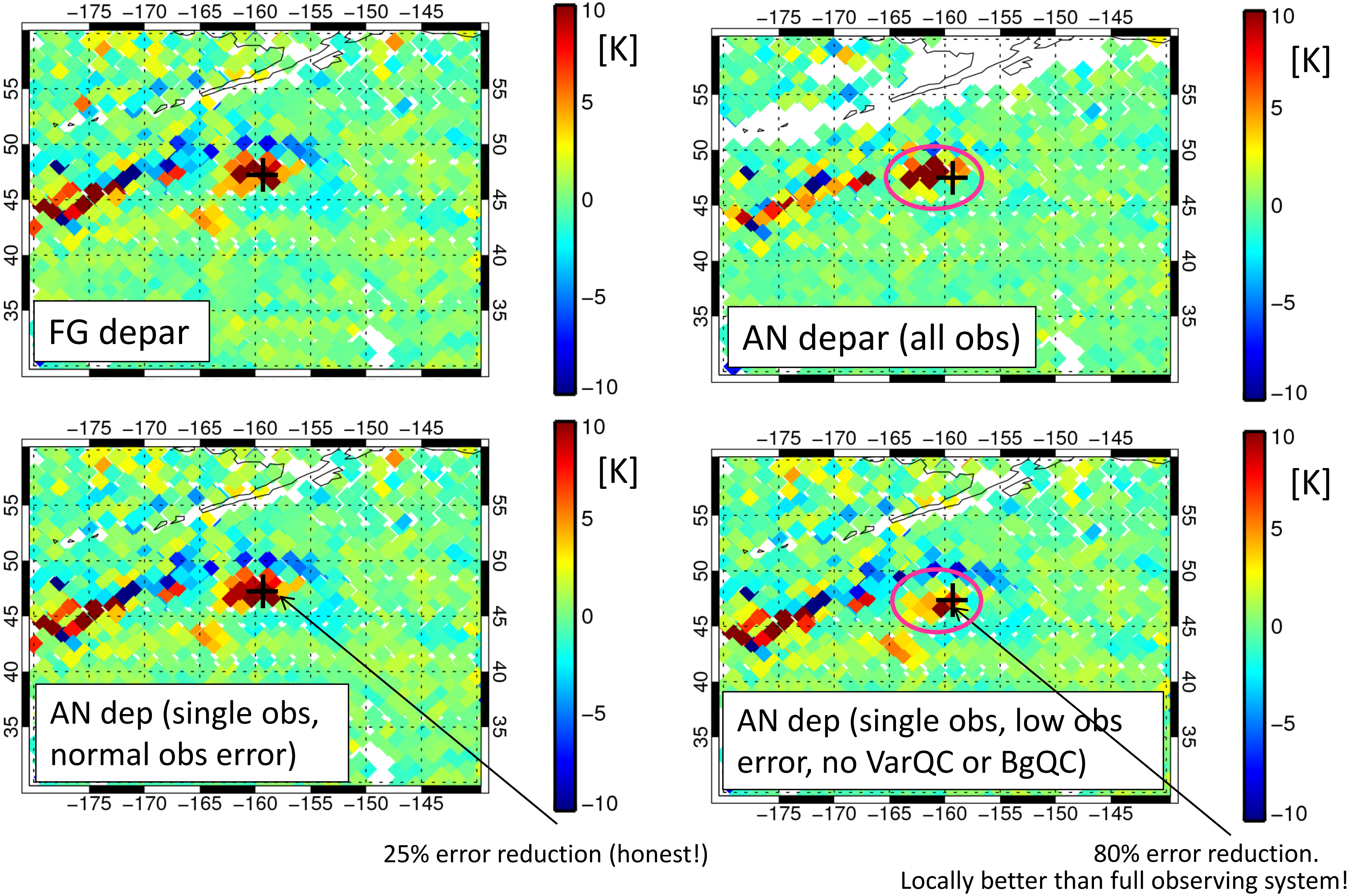


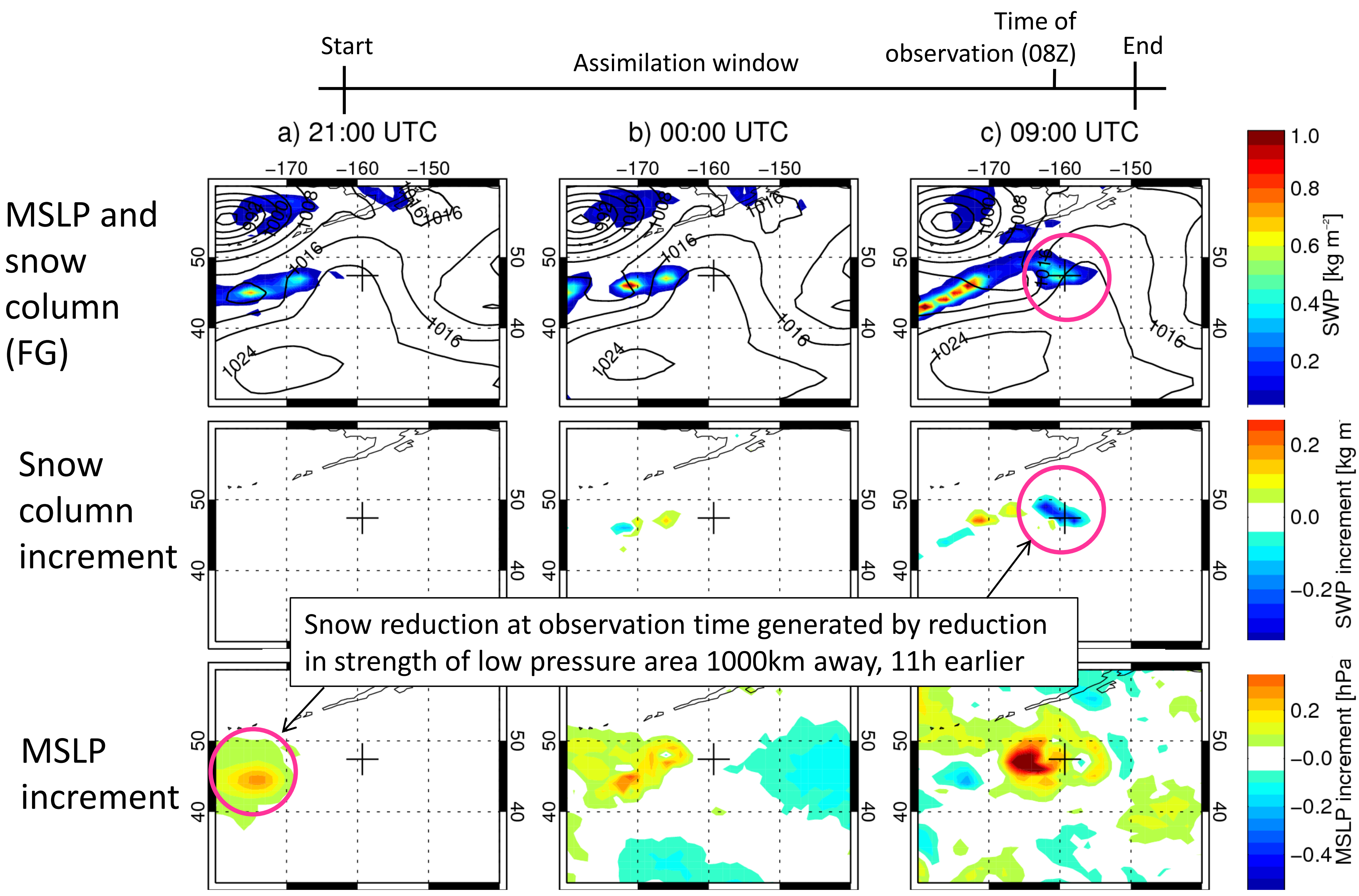
The dilemma of all-sky assimilation

- 4D-Var can almost always fit cloud, precipitation and water vapour features observed in a single microwave observation, if the observation is given enough weight
  - though it gets trickier in tropical convection – in perhaps 30% of single obs cases, 4D-Var fails to fit
- If the full observing system analysis does a "worse" job of removing excessive precipitation, why?
  - because we don't put enough weight on the cloudy/precipitating obs in the full system?
  - because the model cannot simultaneously fit the cloudy/precipitating observations while still fitting all the other observations?

→ representivity / predictability, bias?

→ other non-optimalities in the system?

B) Frontal cloud and precipitation – 190 GHz



Thoughts II

- All observations are cloud and precipitation observations
- All observations are wind observations
- Water vapour, cloud and precipitation observations **are dynamical observations**
    - **Horizontal humidity gradients not necessary!**
    - **A broader “4D-Var tracing” than pure tracer advection**

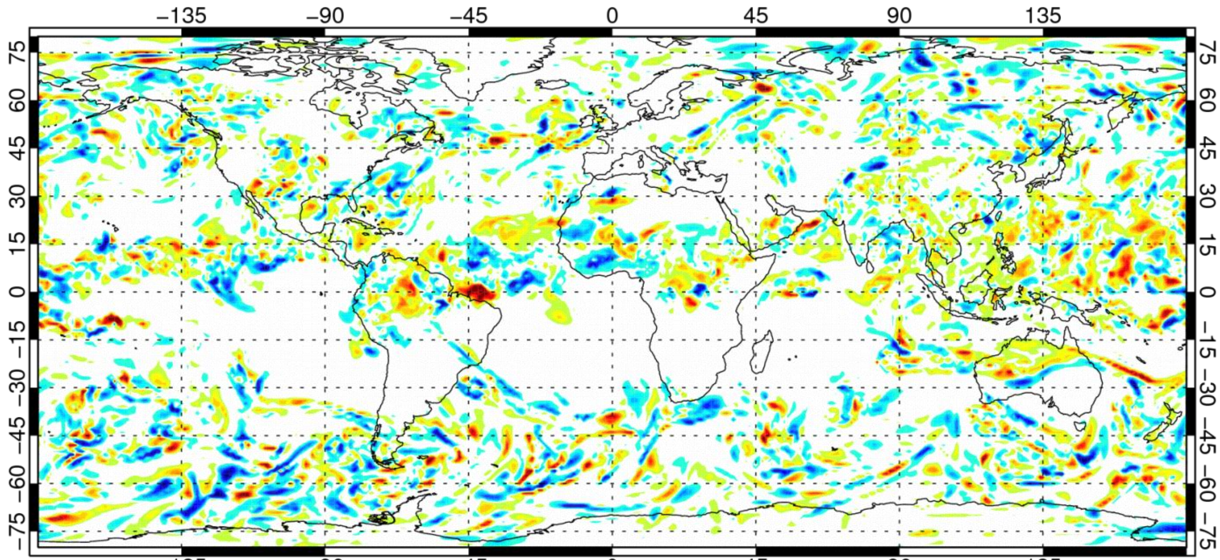
Microwave humidity observations on their own

humidity increments at 500hPa

06Z: 9h into the assimilation window

All-sky WV sounding only

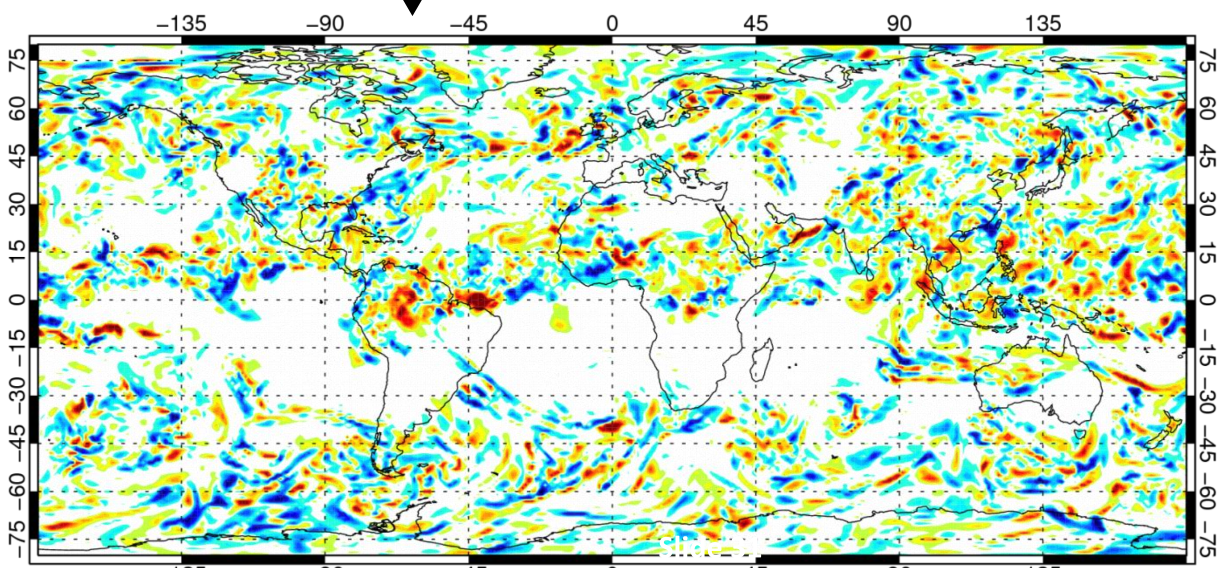
4 MHS, 1 SSMIS

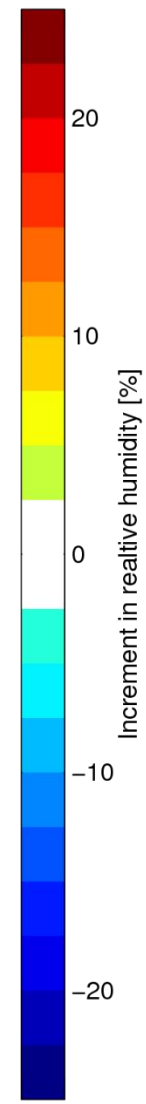


↕ correlation: 0.72

Full observing system

Including all-sky WV





v-wind increments at 500hPa

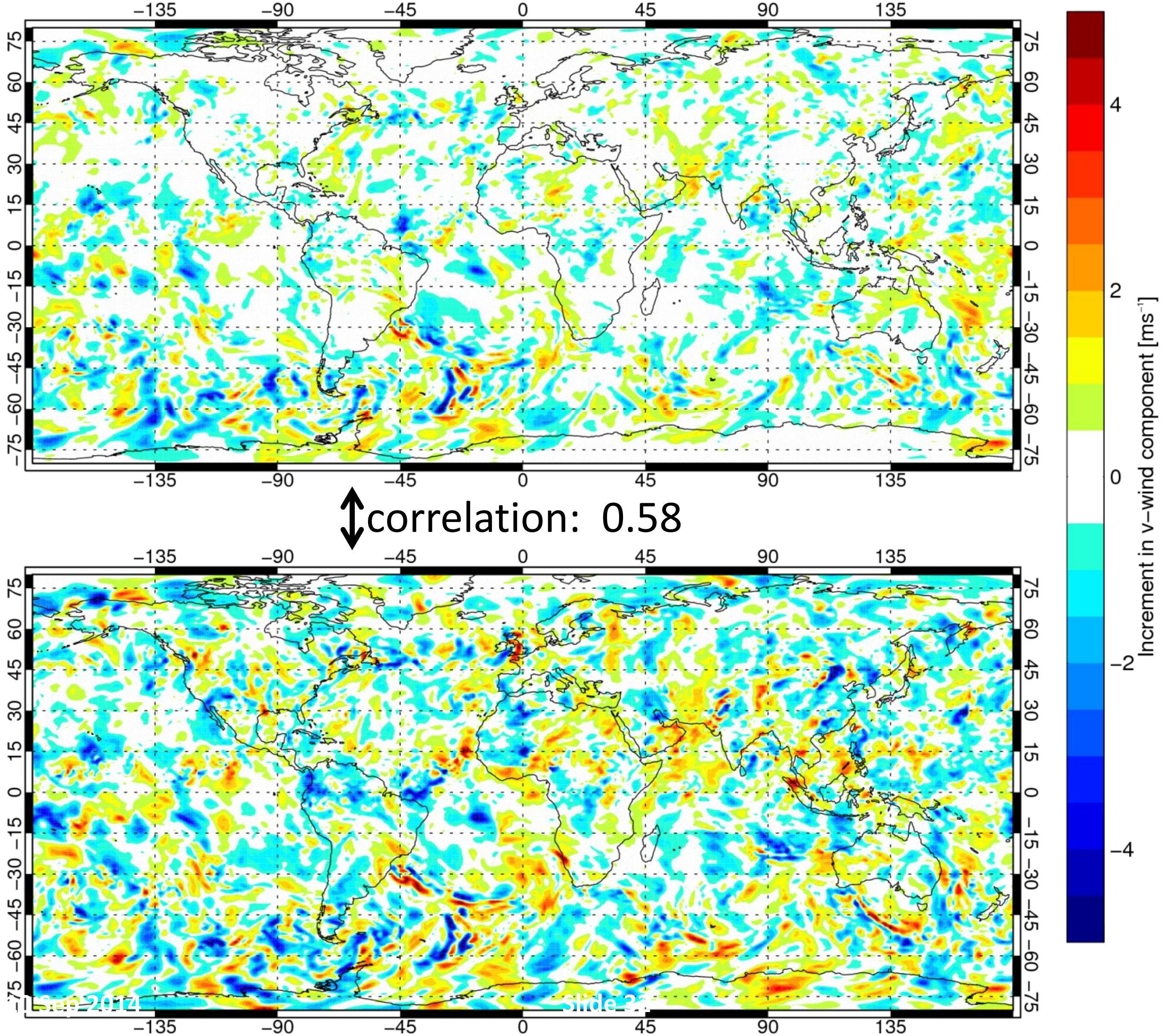
06Z: 9h into the assimilation window

All-sky WV sounding only

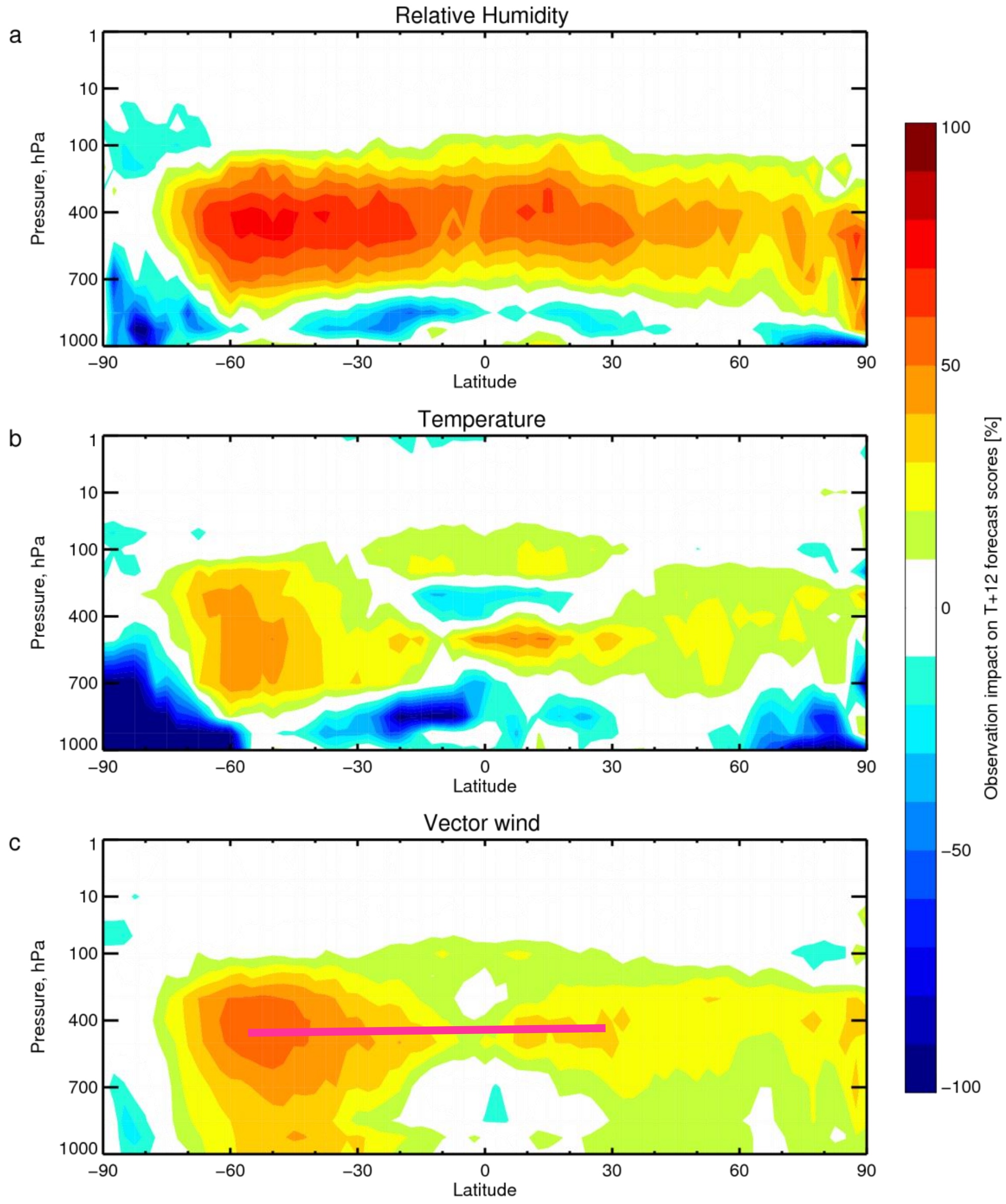
4 MHS, 1 SSMIS

Full observing system

Including all-sky WV



Assimilate only all-sky WV sounding observations (4 MHS, 1 SSMIS)
66 different analyses and forecasts, always from a full-observing system FG



T+12 RMS forecast error reduction

100% = full observing system

0% = no observations

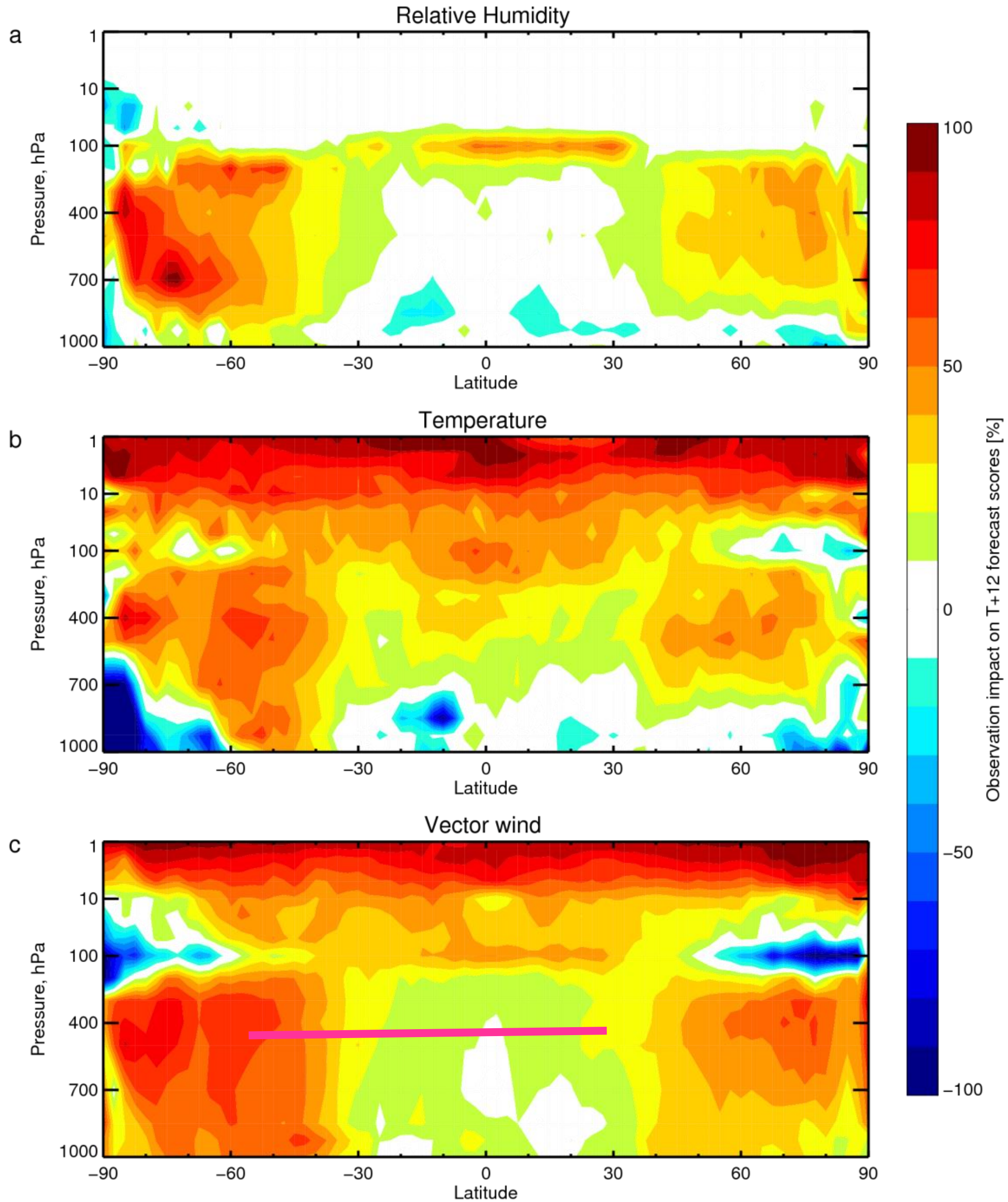
-100% = worse than that!

Storm track winds: to 50%

Tropical winds: to 30%

Assimilate only microwave T-sounding obs (6 AMSU-A, ATMS)

66 different analyses and forecasts, always from a full-observing system FG



T+12 RMS forecast error reduction

100% = full observing system

0% = no observations

-100% = worse than that!

Storm track winds: to 60%

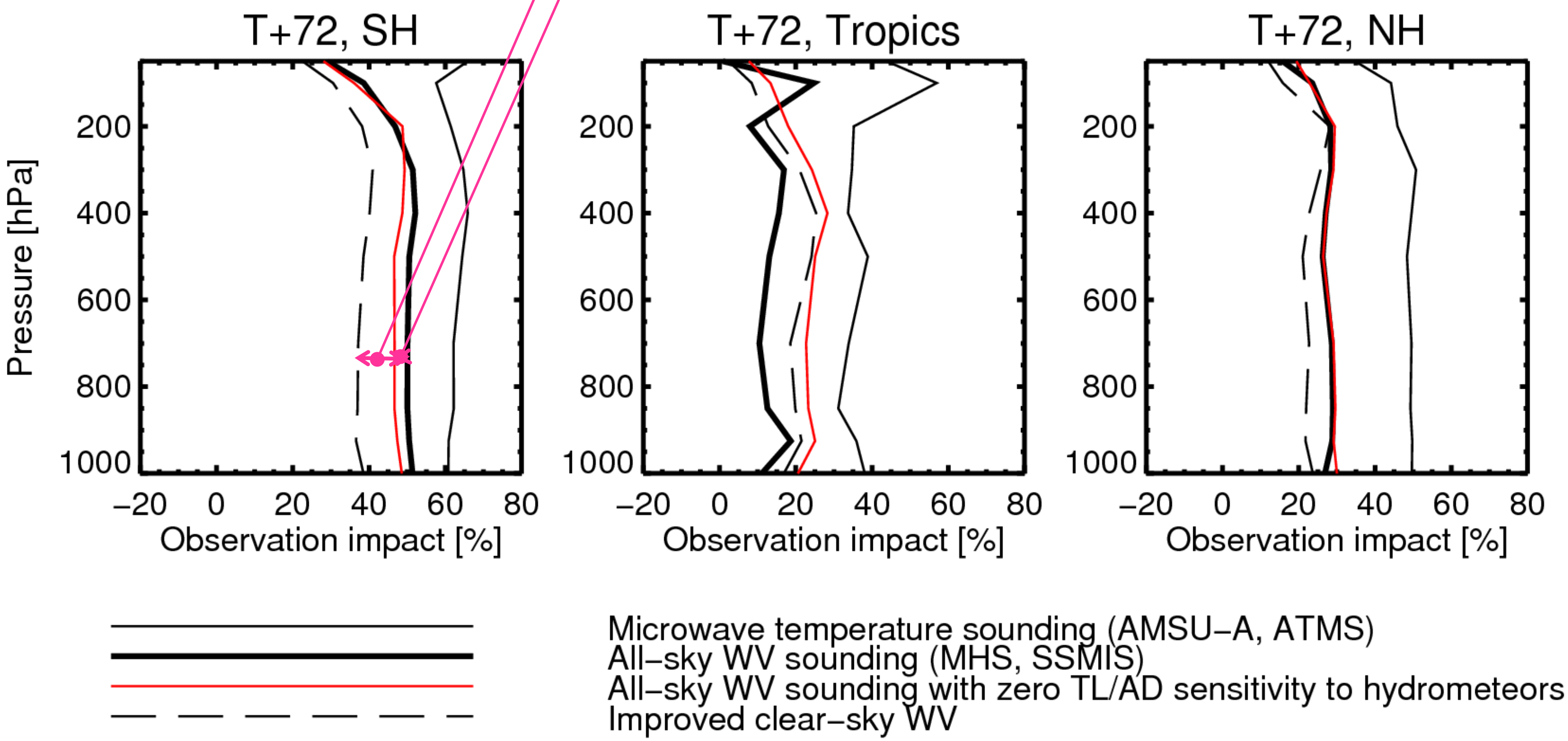
Tropical winds: to 10%

Thoughts III

- All observations are cloud and precipitation observations
- All observations are wind observations
- Water vapour, cloud and precipitation observations **are wind and temperature observations**
  - For humidity sounding - certainly in the mid-upper troposphere
  - All-sky microwave imagers cover the lower troposphere
- Temperature observations are wind and humidity observations
  - Certainly in the extratropics

Impact of individual observing systems on T+72 vector wind

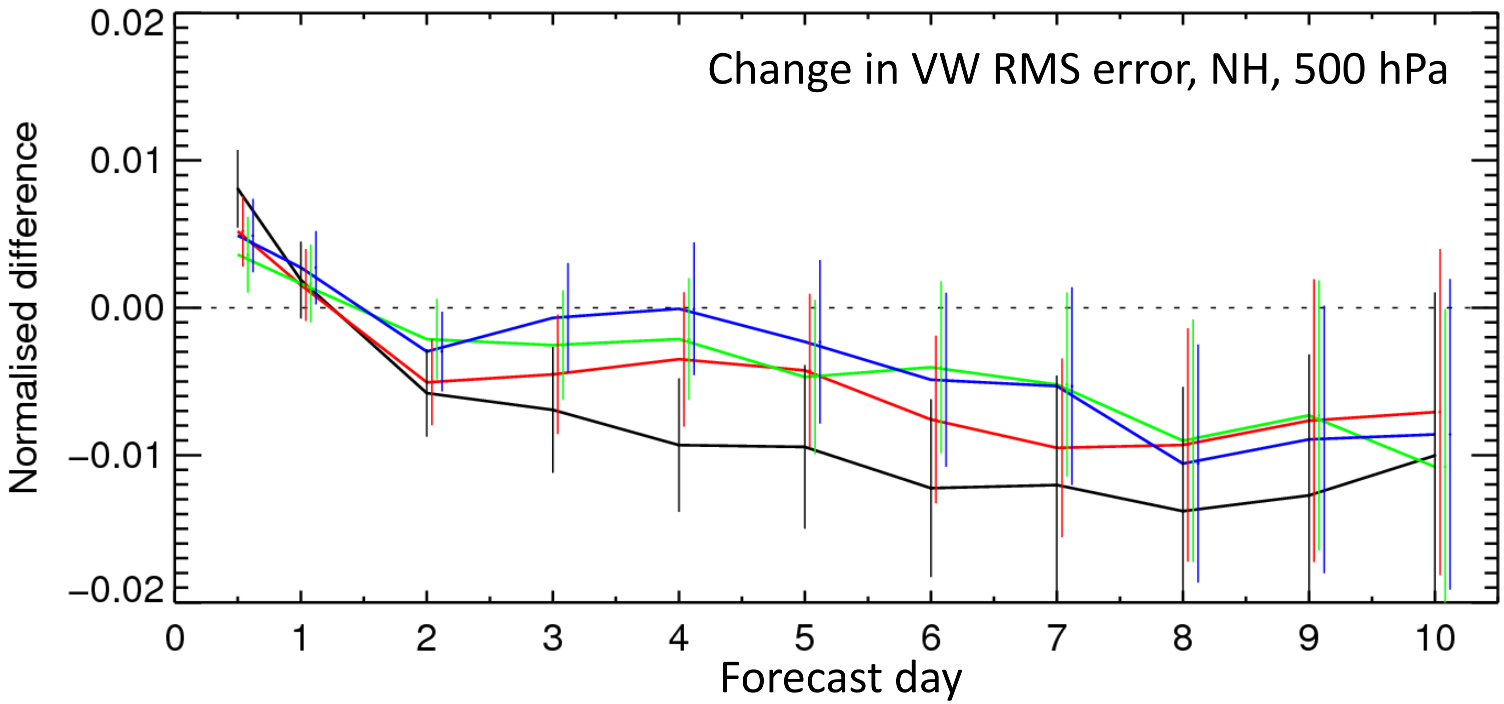
Value of cloudy WV scenes: from 35% to 50% impact
Value of cloud and precipitation?: from 46% to 50% impact



Microwave humidity observations in the full observing system

Development of the clear-sky assimilation approach

Clear-sky microwave WV – No microwave WV



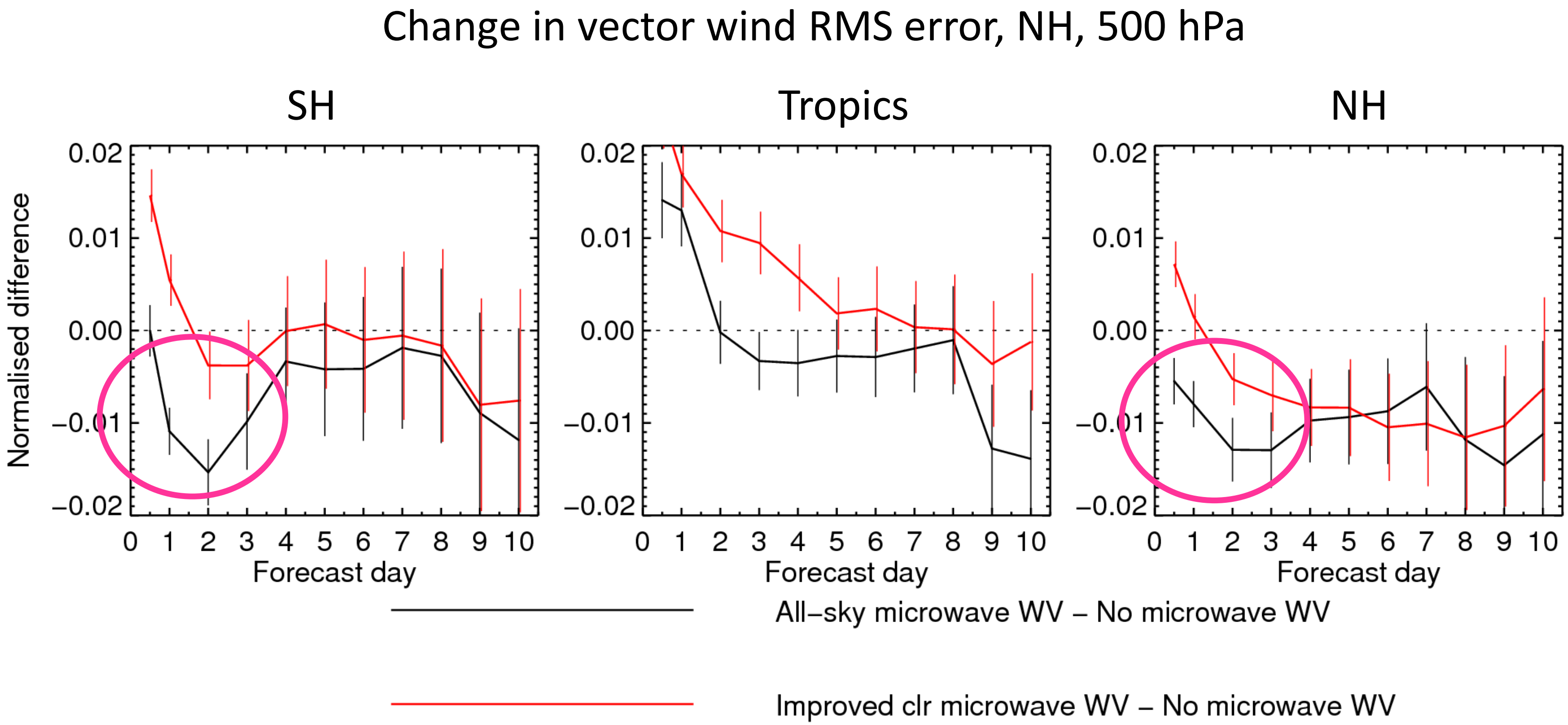
- Blue: Old clear-sky (as of 38r2) – ocean & land – 4 MHS
- Green: as above + "cold ocean"
- Red: as above + sea-ice (as of 40r1)
- Black: as above + add SSMIS and extreme MHS scan angles

"Improved" clear-sky better than current operations

ECMWF

All-sky assimilation of microwave WV

Compared to “improved” clear-sky assimilation



Observation fits – global

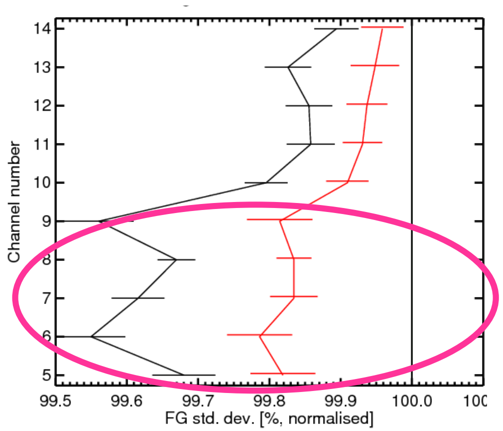
Normalised change in std. dev. of FG dep.

All-sky microwave WV (black line)

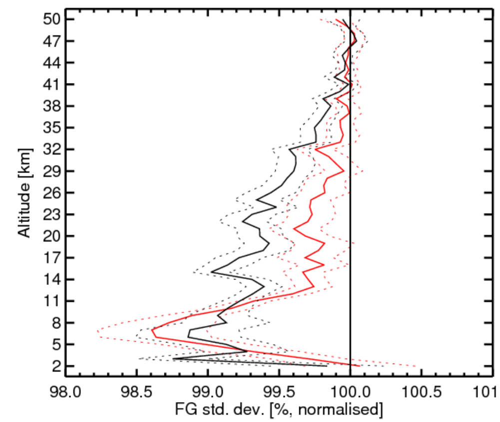
Improved clear-sky microwave WV (red line)

100% = control (no microwave WV)

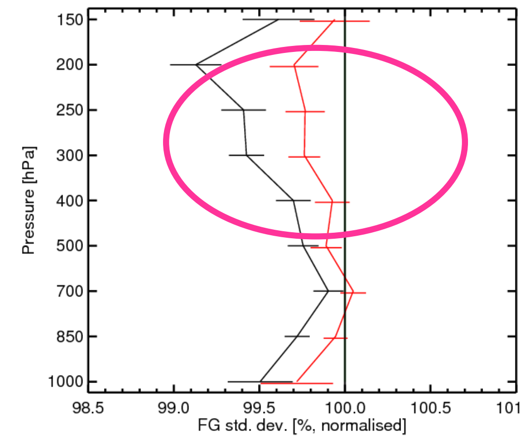
AMSU-A



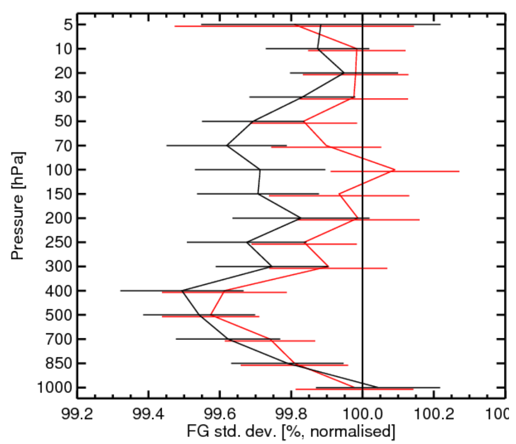
GPSRO



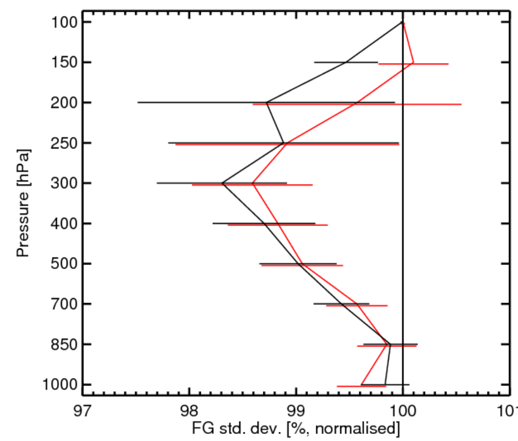
SATOB (AMVs)



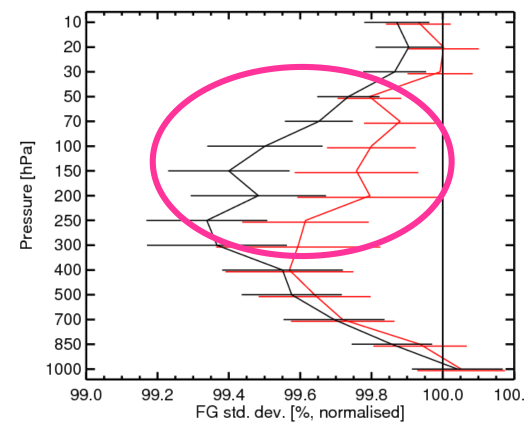
Radiosonde T



Radiosonde q

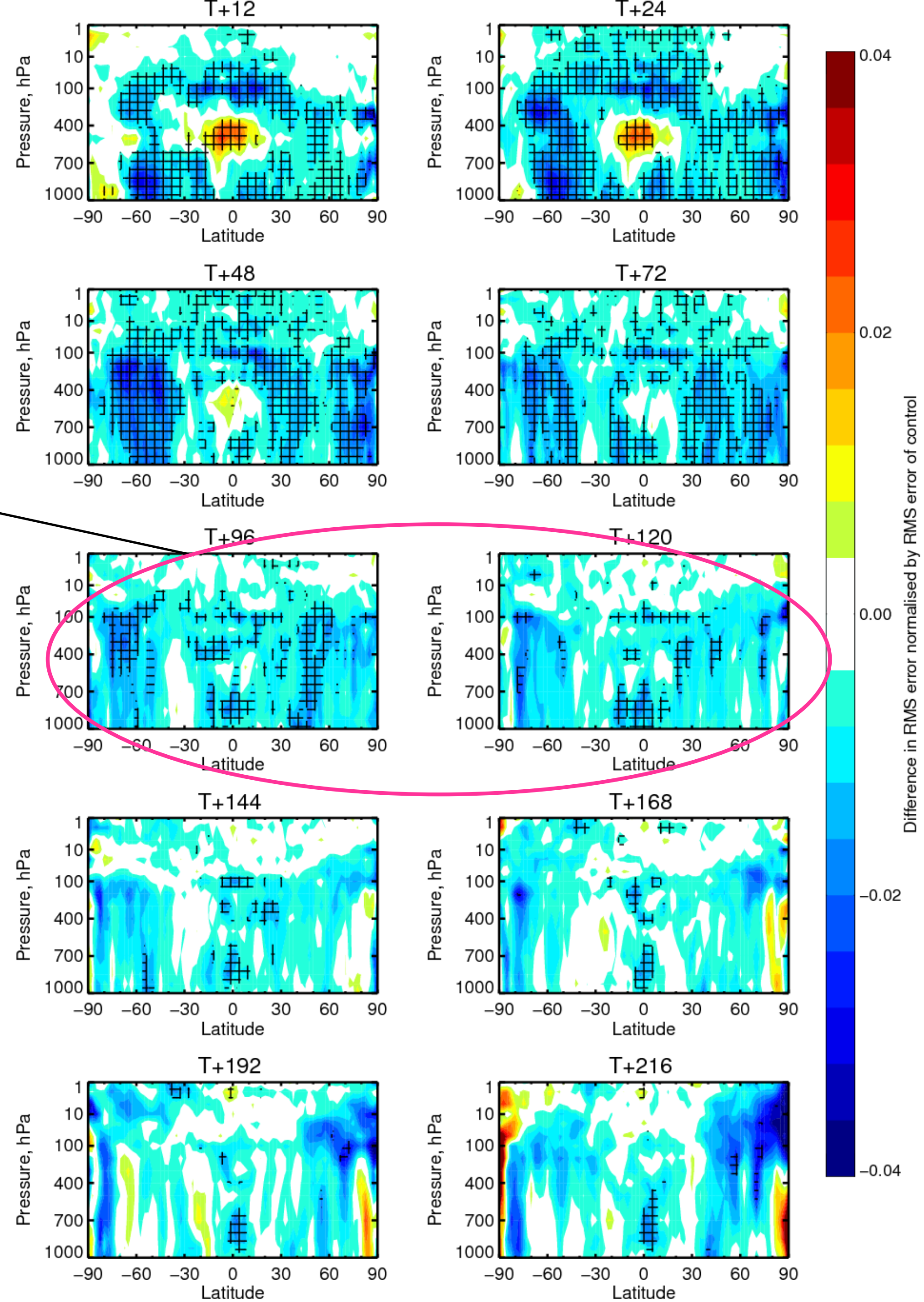


Conventional wind



Impact of all-sky microwave humidity sounders – on top of the otherwise full observing system

Still around 1% impact on day 4 and 5 dynamical forecasts



Change in RMS error of vector wind

Verified against own analysis

Blue = error reduction (good)

Based on 164 to 202 forecasts

Cross hatching indicates 95% confidence

Impact of all-sky microwave humidity sounders **and imagers**

-on top of the otherwise full observing system

-Masahiro is presenting the imagers next!

2-3% impact on day 4 and 5 dynamical forecasts

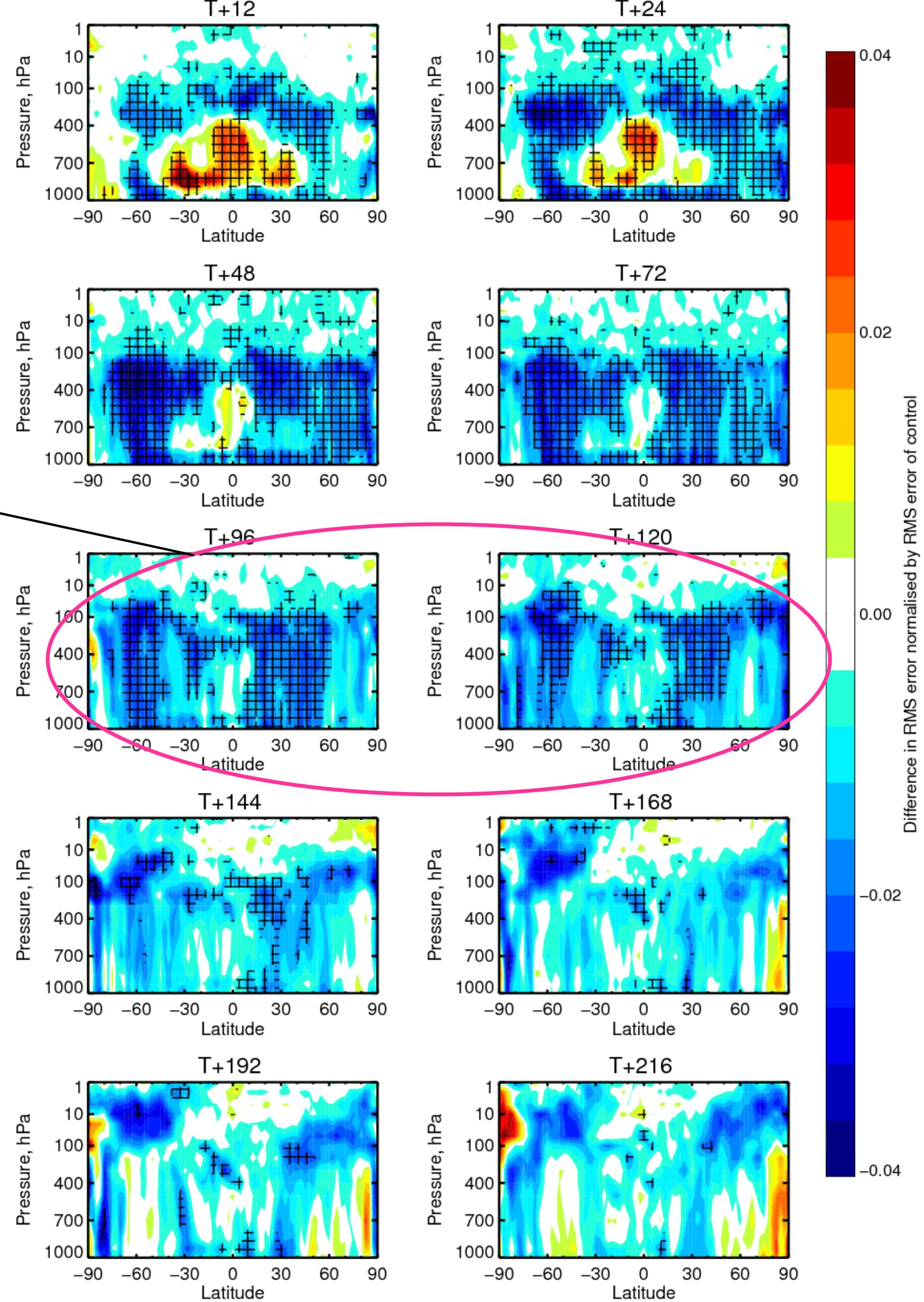
Change in RMS error of vector wind

Verified against own analysis

Blue = error reduction (good)

Based on 322 to 360 forecasts

Cross hatching indicates 95% confidence

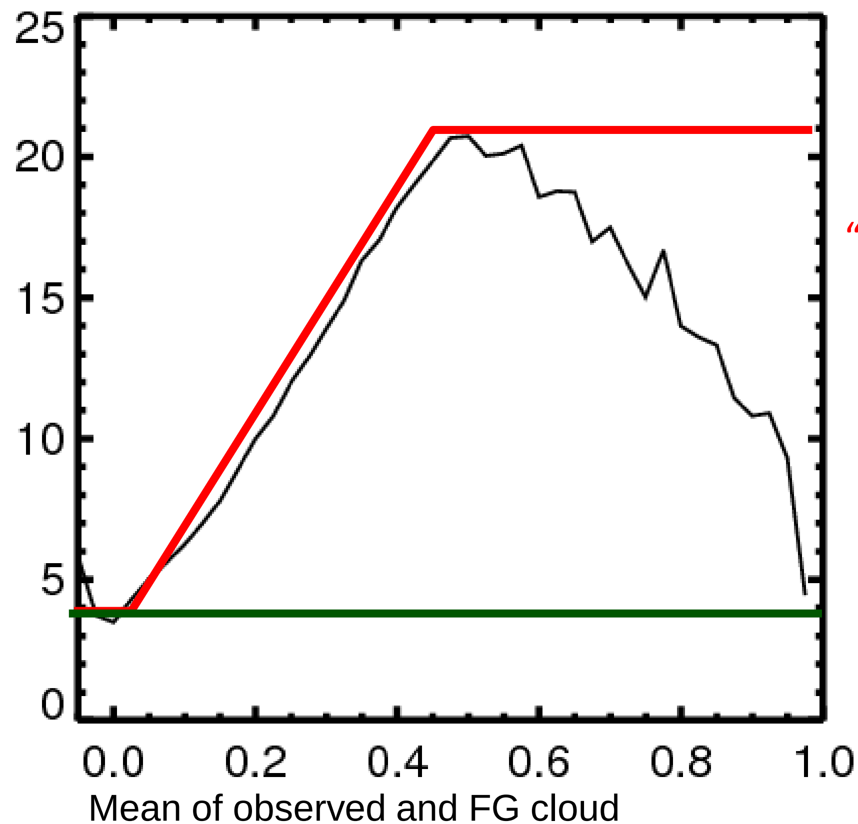


Assimilating more all-sky microwave: “All-sky max”

And ignoring the “all-sky dilemma”

Good results from single observations with low observation errors

Why not use lower all-sky observation errors globally?



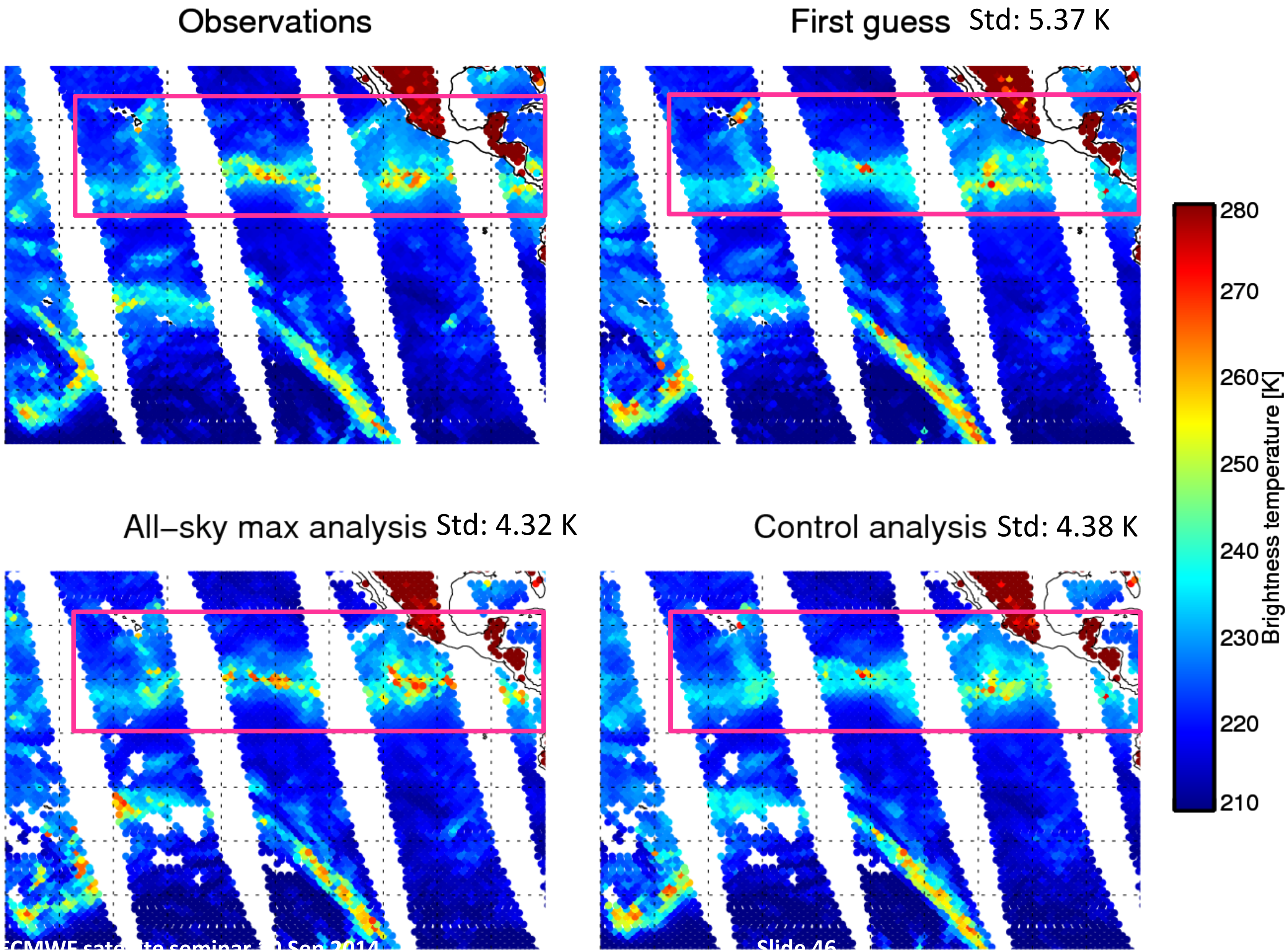
- “All-sky max” will force the model more strongly towards the observed cloud and precipitation distributions

ECMWF

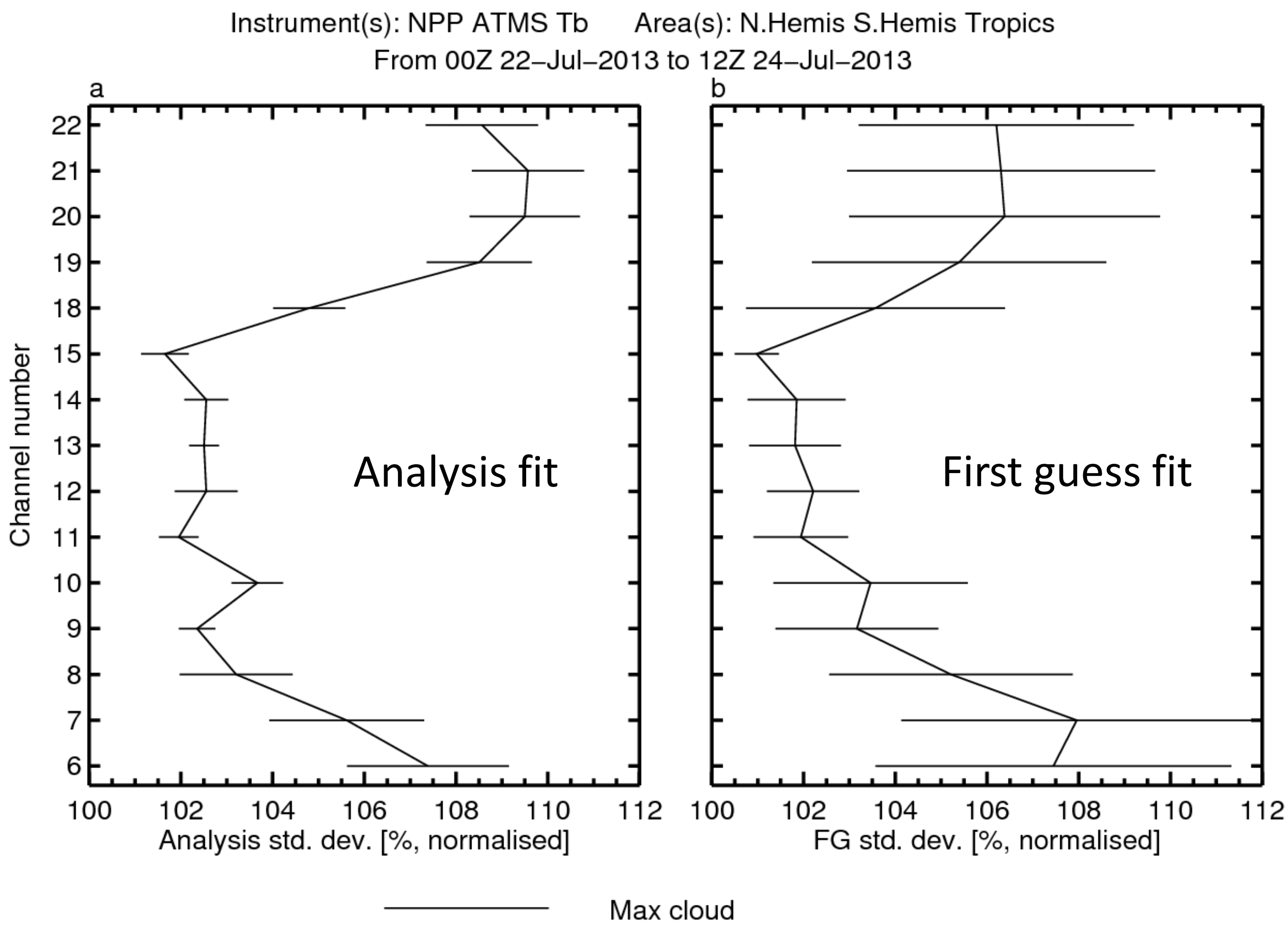
All-sky max: More observations, forcing the model closer to observed cloud and precipitation

- Existing all-sky sensors: 4×MHS, SSMIS F17, TMI
- Add AMSU-A channel 4 from Metop-A and NOAA-19 (a cloud and temperature channel)
- Flat observation errors: same in cloudy and clear situations
- Turn off VarQC for all-sky observations

All-sky max – SSMIS 37v



All-sky max: ATMS observation fits



Water vapour channels degraded

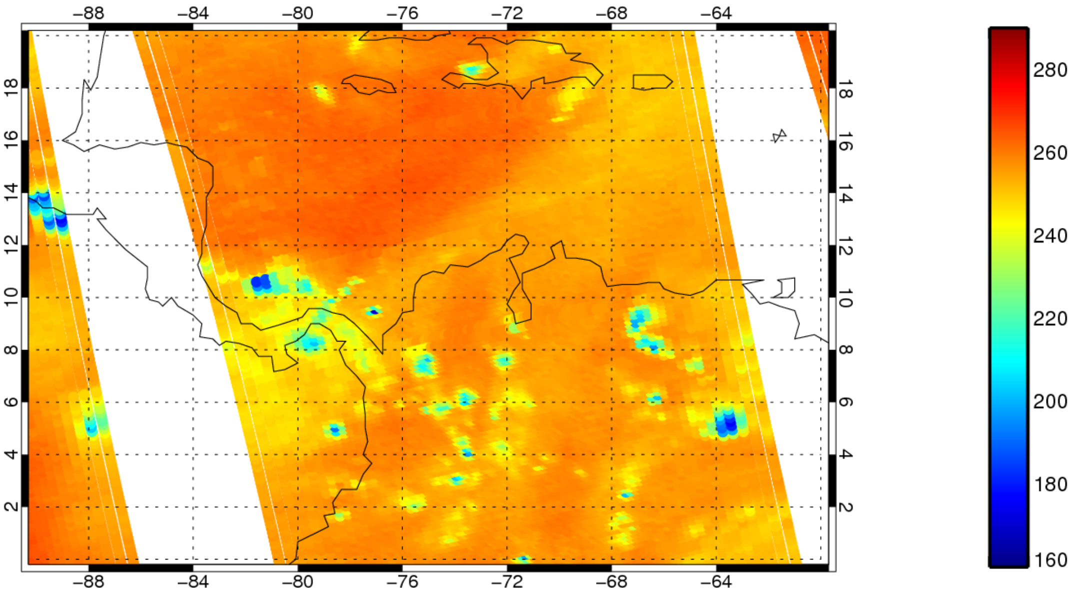
Tropospheric temperature channels degraded

Forcing the model too strongly towards the observed cloud and precipitation causes problems

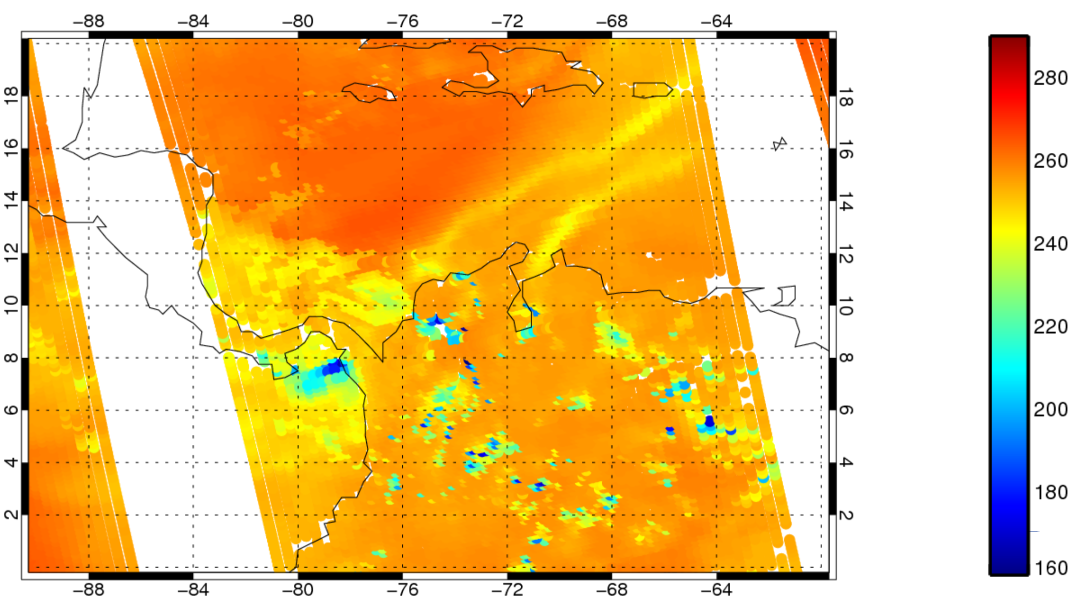
- **Full all-sky (imagers and sounders) gives an improvement in observation fits and forecasts**
- **All-sky max**
  - Can marginally improve fits to all-sky observations (but this is far from universal – often they get worse!)
  - Generally gives a 10% degradation in all other observation types (this will cause a serious degradation in the quality of forecasts)

The biggest issue: representing cloud and precipitation in models

Observations



ECMWF FG



Predictability or representivity or forecast model error?

- Radiances are instantaneous, local observations
- Forecast models do not put cloud and precipitation features in exactly the right place at the right time
- Infinitessimal changes in initial conditions can greatly change the location of cloud and precipitation features in the forecast
  - chaotic error growth timescales of much less than 3h?
- Is it actually possible to adjust initial conditions to fit cloud and precipitation features?
  - to exactly fit all cloud/precip observations across the globe and across a 12h analysis time window?
- Current solutions:
  - Inflated observation error (e.g. all-sky approach)
  - Time or space averaging (e.g. accumulated precipitation from NEXRAD, superobbing to 80 km in all-sky approach)

Accumulated thoughts

- All-sky microwave humidity radiances are a **dynamical** observation
  - 4D-Var tracing of water vapour, cloud and precipitation
  - 1.5% improvement in geopotential height at 500hPa in the NH at day 5
  - Approaching impact of microwave temperature sounding in troposphere
    - day 3 impact, SH: **60%** AMSU-A & ATMS **temperature sounding**
    - vs. **50%** MHS & SSMIS **water vapour sounding**

- All observations work together through the forecast model in 4D-Var
  - Temperature and wind observations are **cloud** observations

What does all-sky bring to 183 GHz humidity sounding?

- T+12 wind impact (SH, % of full observing system):
  - **35%** - upgraded clear-sky sounding (4 MHS, 1 SSMIS)
  - **46%** - all-sky sounding without cloud/precip TL/AD
  - **50%** - full all-sky sounding
- Primary effect: Dynamical information from water vapour features (signal to 6K) in the presence of “light” cloud (signal 1-2K)
- Secondary effect: direct use of stronger cloud and precipitation signals (e.g. 10-20K in midlatitude frontal precipitation) to infer dynamical information
  - Single observation examples in precipitation:
    - Improve fit to single observation in analysis by around 25%
    - by 80% if the observation error is reduced unrealistically

Reasons to question whether operational all-sky assimilation really assimilates cloud and precipitation

- cloud and precipitation cannot be assimilated without a cloud control variable?
- the high observation errors assigned in cloudy areas mean that no information is taken from the cloudy radiances?
- 4D-Var tracing is still not proven?
- we want clouds and precipitation moved to *exactly where they should be?*

- "Cloud assimilation"
  - Is completely **unrealistic** on the level of small-scale cloud and precipitation features – e.g. scales where they are not *representable/predictable*
  - Is **beneficial** to ECMWF operational forecasts – if we avoid trying to over-constrain small-scale features but still act on larger scales

Status and future at ECMWF

- December 2014 – ECMWF operational system:
  - All-sky assimilation of at least two microwave imagers (SSMIS, TMI)
  - All-sky assimilation of water vapour channels from 4 MHS and 1 SSMIS over land, ocean and sea-ice
- Soon after:
  - ATMS humidity channels
  - Presumption that future microwave water vapour sounders and imagers are all-sky by default
- Next few years:
  - All-sky infrared humidity (e.g. HIRS and IASI)
    - Very similar information content to microwave (e.g. UTH, but cloud too!)
- Next decade: all-sky visible radiances

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Challenges

- Forecast model
  - Moist physics biases (Masahiro's talk – next)
  - Maintaining the TL and AD moist physics
  - Model needs to start supplying microphysical information (size distributions, particle shapes) to the observation operator
- Data assimilation
  - Cloud control variable
  - Account for correlated observation error in cloudy areas
  - Huber norm QC
  - All-sky strategies for ensemble assimilation
- Observation operator
  - Further progress on converting microphysics (particle shapes and size distributions) into radiances
  - 3D radiative transfer
  - Fast cloudy observation operators for the IR