Assimilation of cloud and precipitation from satellite

Alan Geer

Thanks to: Katrin Lonitz, Richard Forbes, Masahiro Kazumori, Fabrizio Baordo, Peter Lean, Philippe Lopez, Marta Janiskova, Niels Bormann, Stephen English … and many others

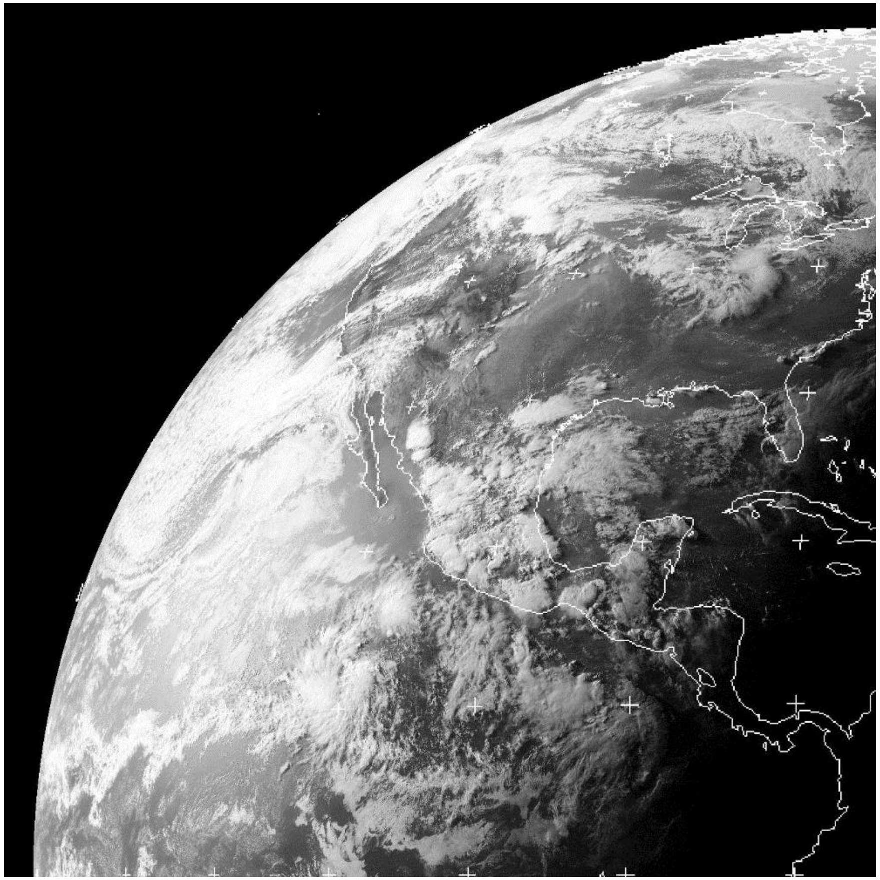
Assimilating hydrometeors: putting together the pieces

- Cloud and precipitation radiative transfer
  - Talks by Keith Shine and Robin Hogan on Tuesday:
    - Model radiation schemes simulate broadband **fluxes** approximately; a satellite observation operator computes narrow-band **radiances** as accurately as possible
    - But the basic principles are the same (e.g. two-stream solvers…)
  - Grant Petty's "A first course in atmospheric radiation" (2006)
- Cloud and precipitation-capable forecast models (all seminar)
- Radiance observations (NOT derived products)
- Data assimilation methods: variational data assimilation
- Tangent linear and adjoint models of the full nonlinear physics:
  - cloud and precipitation schemes (Philippe Lopez and Marta Janiskova talks)
  - satellite radiative transfer

Information content in microwave radiances

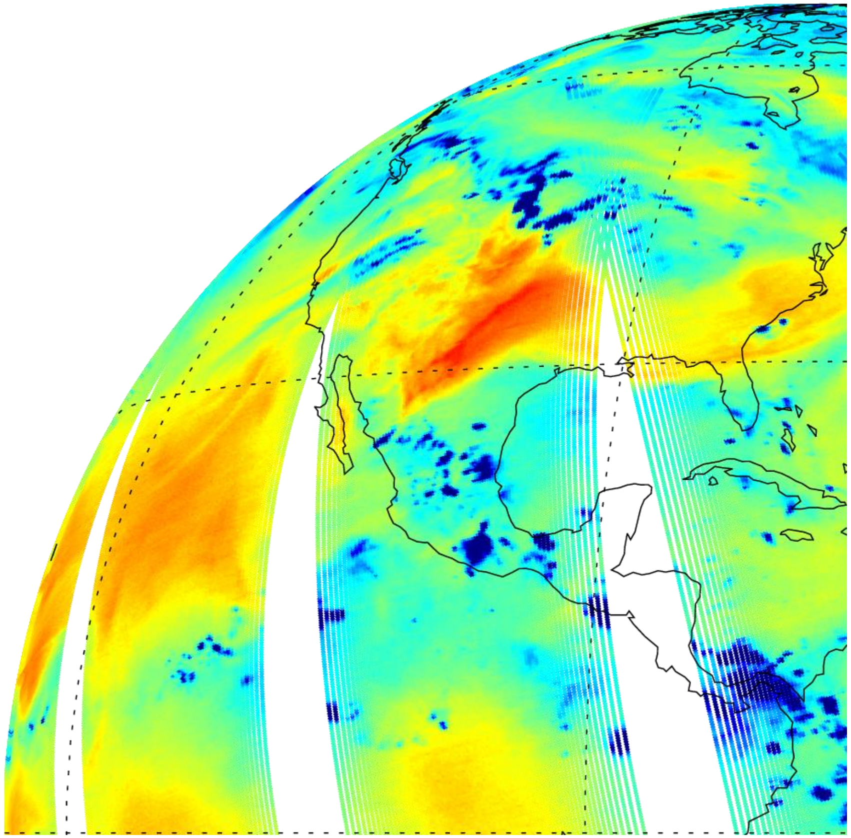
GOES visible - 00Z

Dundee receiving station / NOAA / EUMETSAT



Microwave WV - 00-05Z

Metop-B 190 GHz

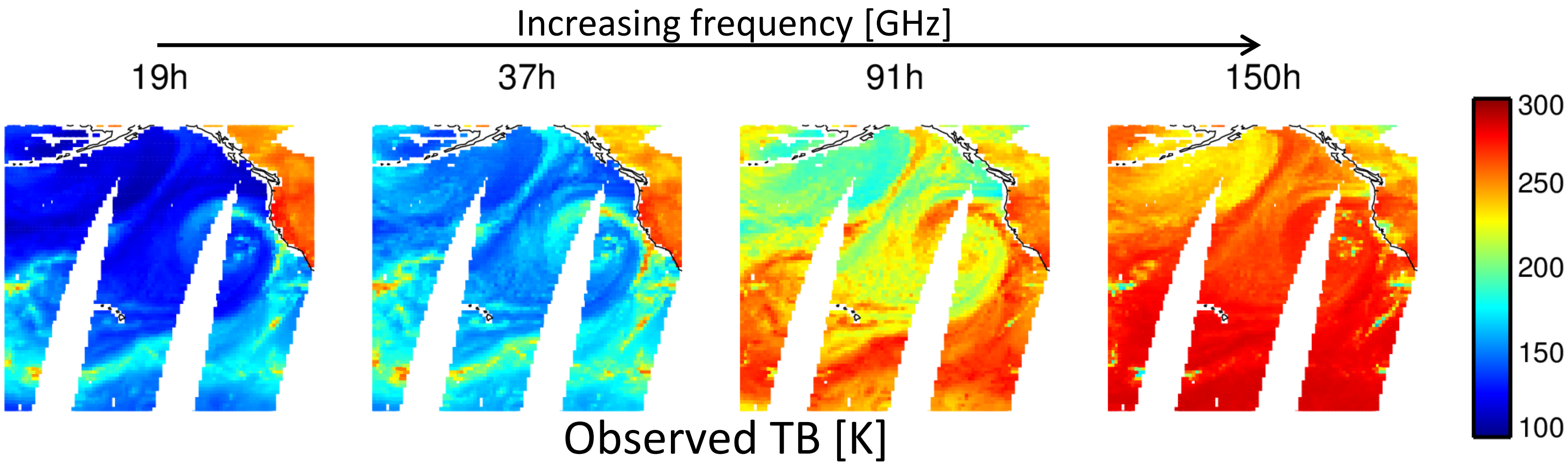


June 12 2013

ECMWF

Window channels ("imaging"):

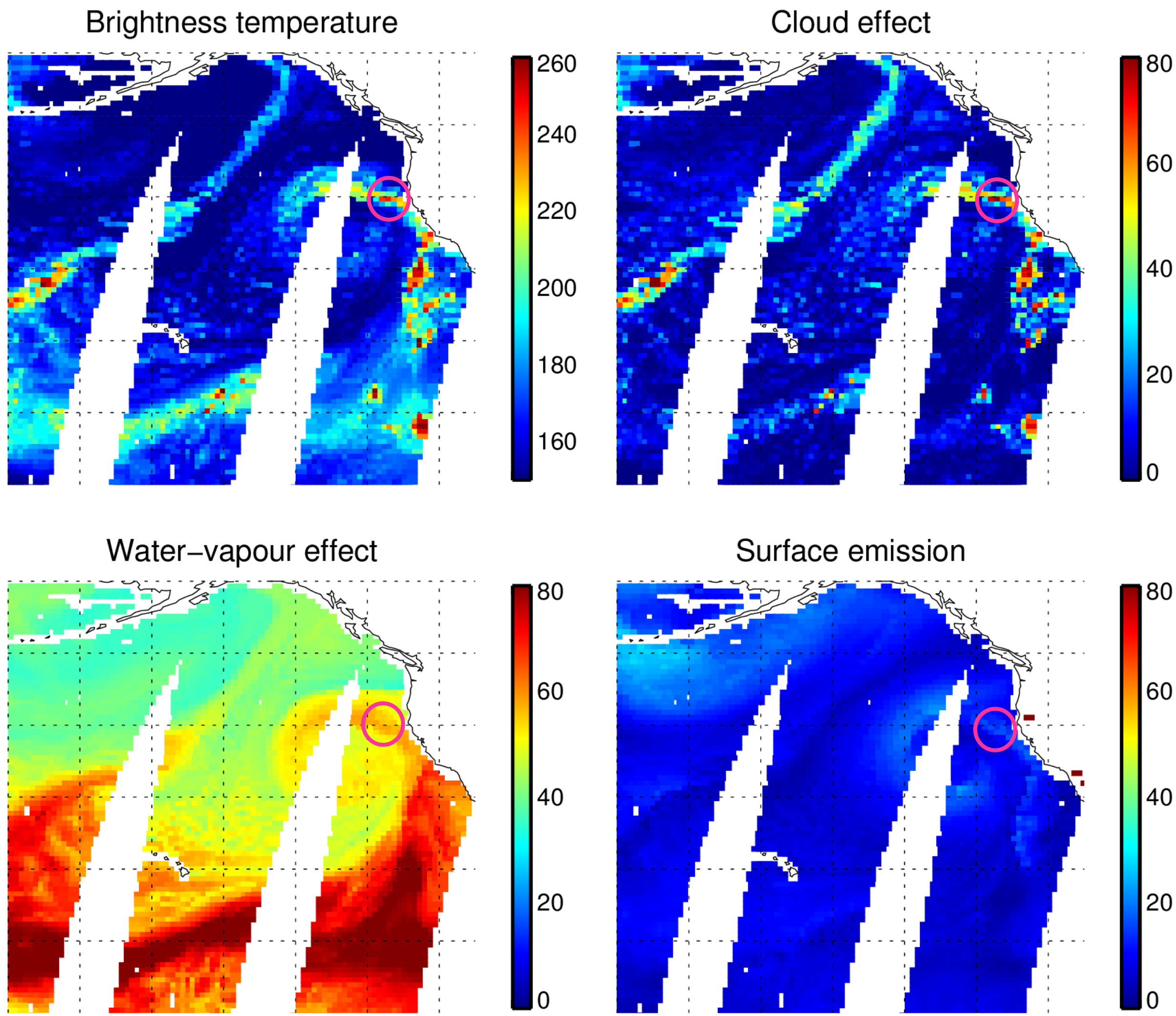
surface properties, water vapour, cloud and precipitation



Separating the components: 37h GHz (h=horizontal polarisation)

TB [K]

TB - TB^{CLEAR} [K]



TB^{CLEAR} – $TB^{NO\_ATMOSPHERE}$ [K]

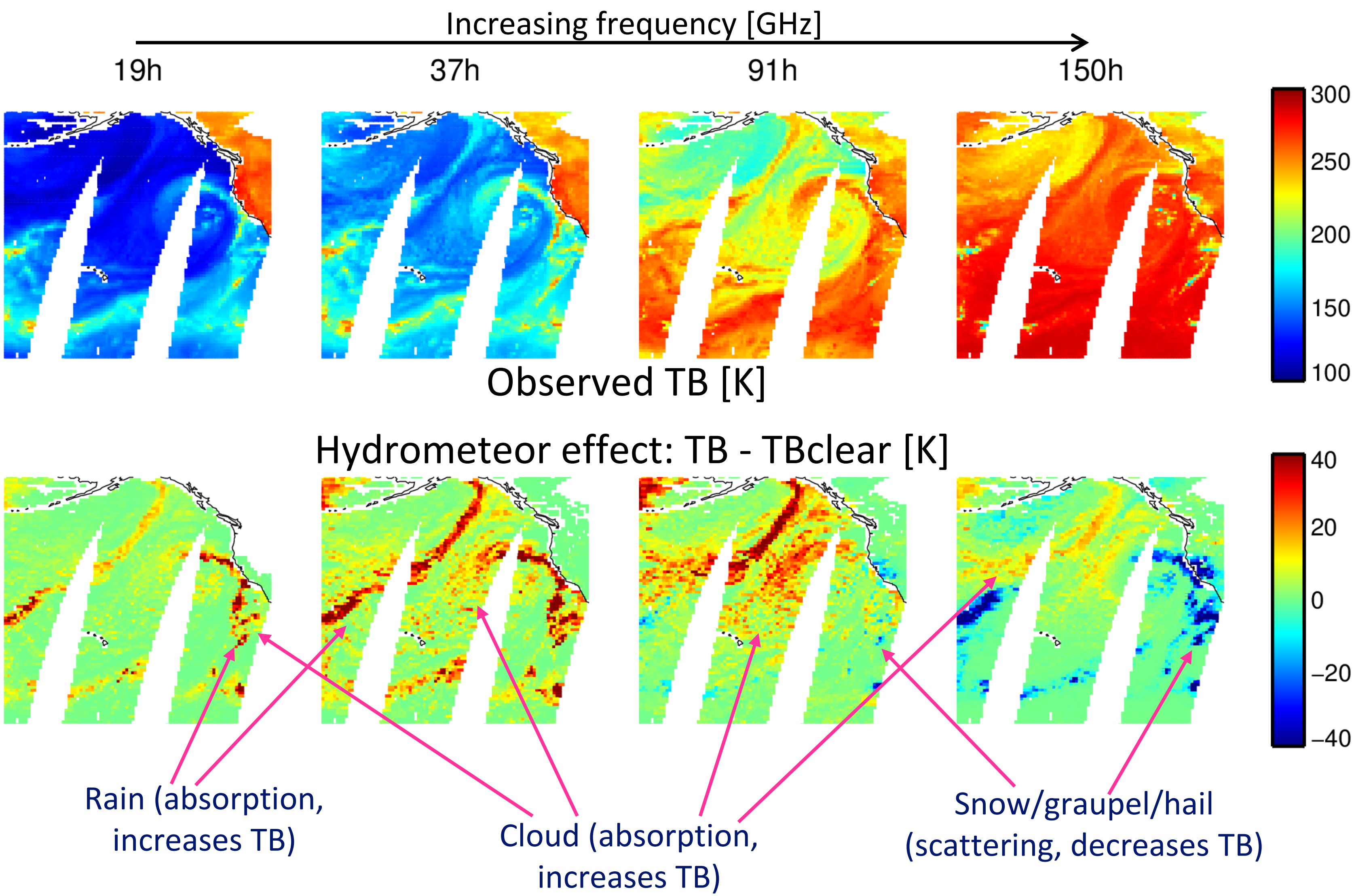
$TB^{NO\_ATMOSPHERE}$ - 90 [K]

TB = $\Delta TB^{HYDROMETEOR}$ + ΔTB^{WATER_VAPOUR} + $\Delta TB^{WIND\_AND\_SURFACE\_EMIS}$ + $TB^{BASELINE}$

= 80 + 60 + 30 + 90 = 260

Window channels ("imaging"):

surface properties, water vapour, cloud and precipitation



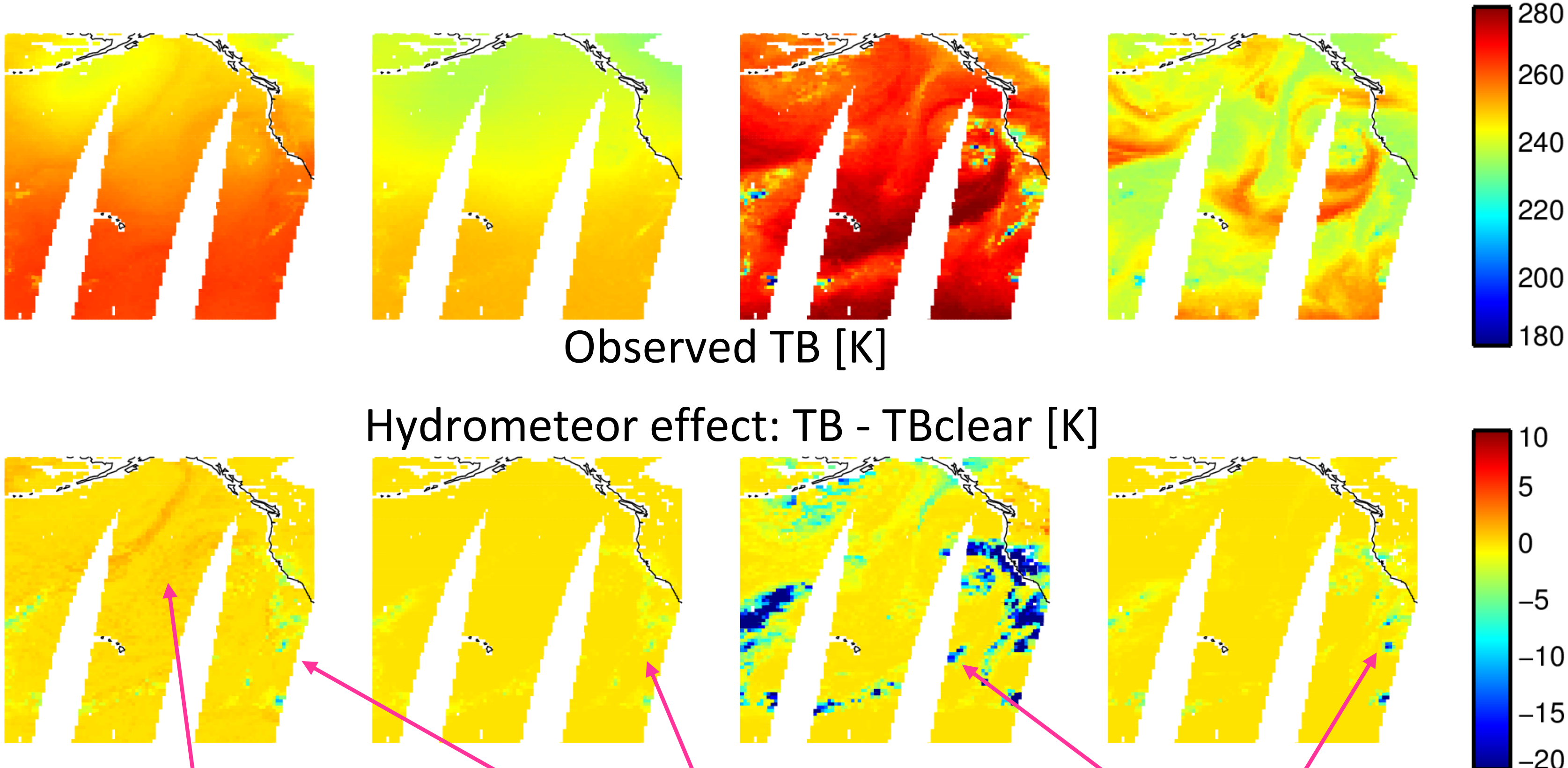
Sounding channels: temperature, water vapour, cloud and precipitation

Temperature sounding:

Lower troposphere 52.8 | Mid troposphere 53.6

Water vapour sounding:

Mid troposphere 183±7 | Upper troposphere 183±1



Cloud (absorption, increases TB)

Cloud and rain (absorption, pushes up weighting function altitude, decreases TB)

Cloud and snow/ice/graupel (absorption and scattering, decreases TB)

ECMWF

All-sky assimilation

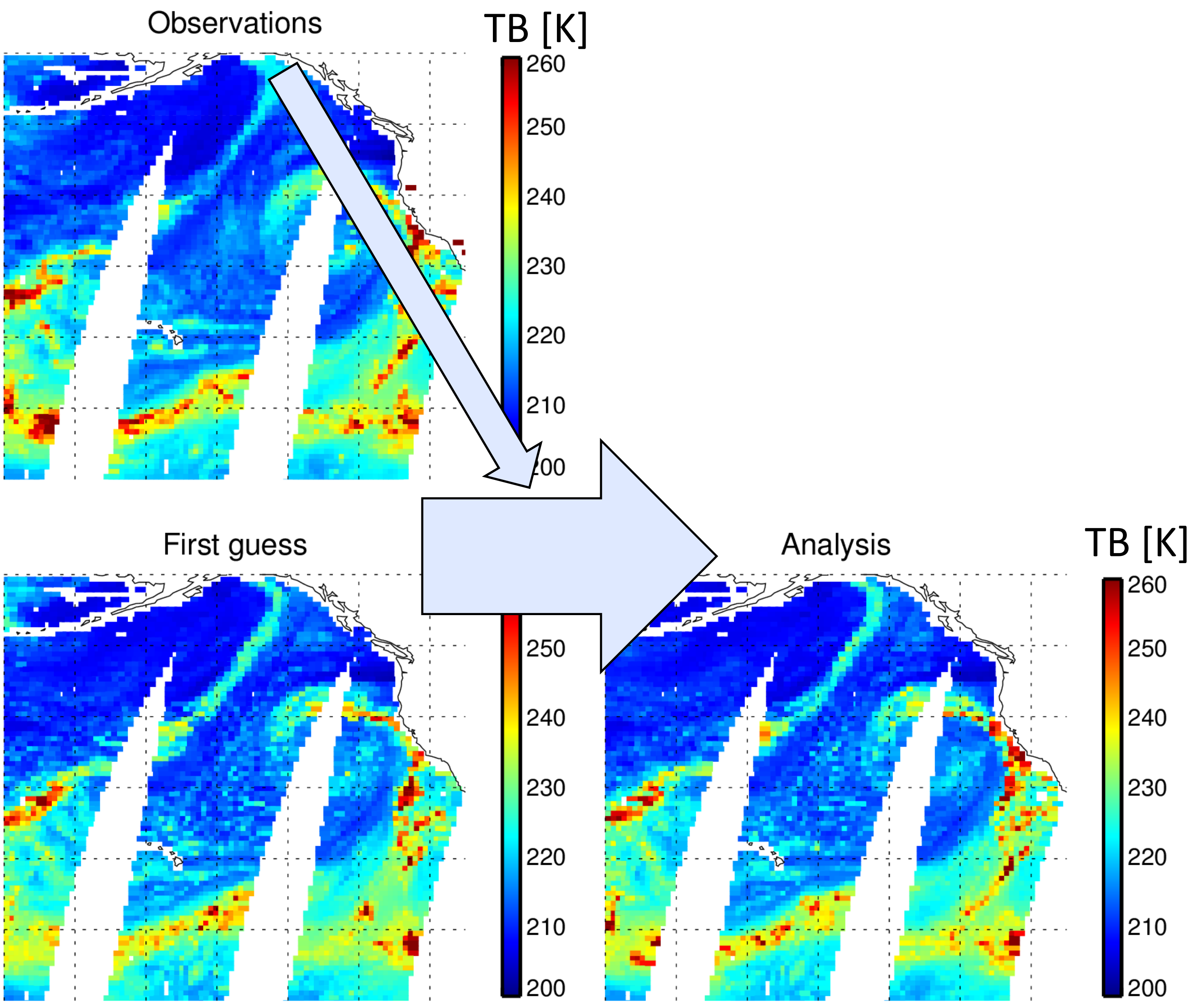
- **Most satellite radiances are sensitive not just to cloud and precipitation but also temperature, water vapour, surface properties:**
  - **Assimilate all of this information simultaneously, without special treatment, directly as radiances, in "all sky conditions"**

Current status of cloud and precipitation assimilation in microwave

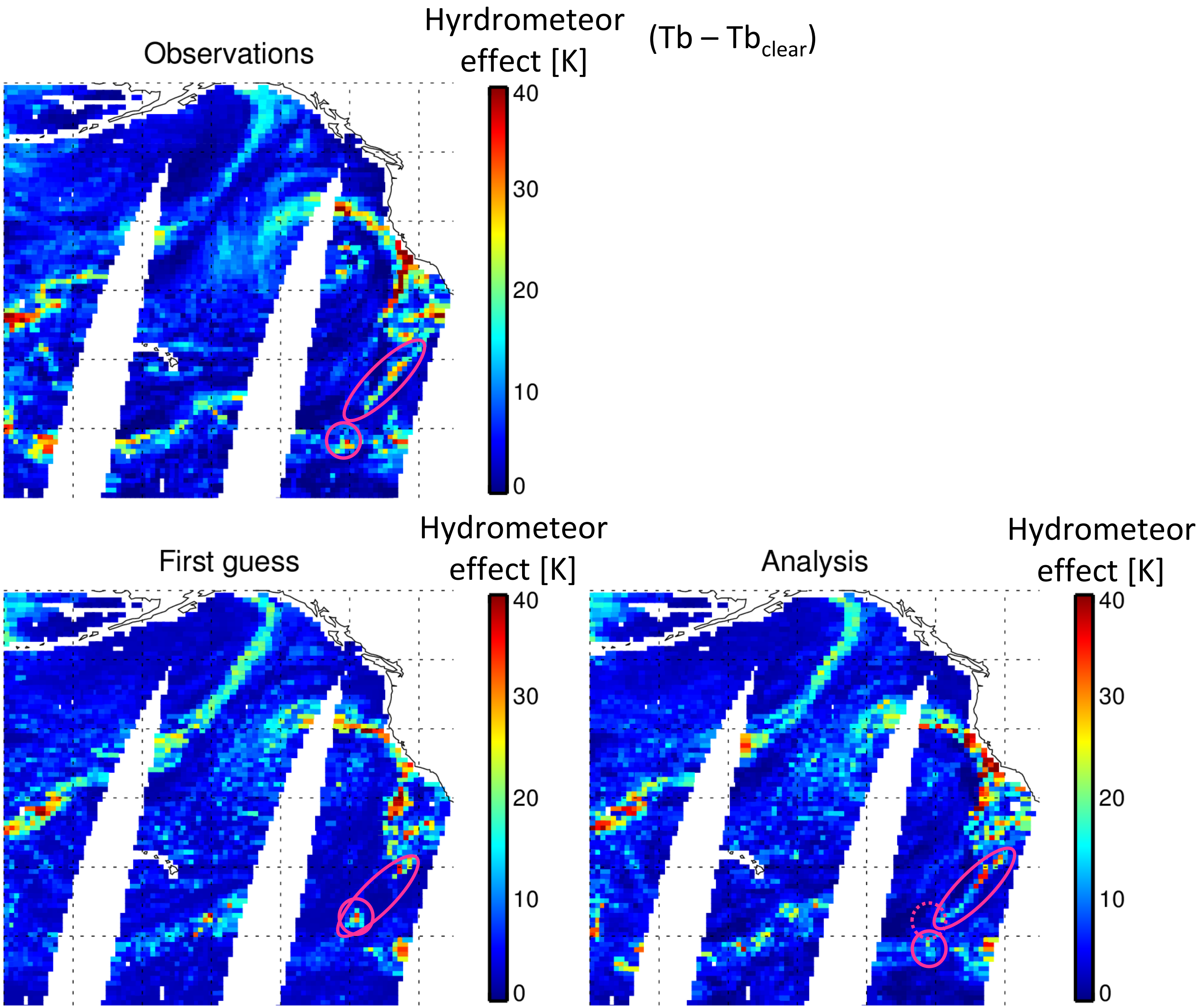
All-sky microwave status in ECMWF operations (41r1)

	Instrument	Ocean	Land	Sea-ice
Imager channels 19-90 GHz	SSMIS-F17 imager	✓	×	×
	GMI	✓	×	×
	AMSR2	✓	×	×
183 GHz WV channels	SSMIS-F17 sounder	✓	✓	✓
	4×MHS	✓	✓	✓
	ATMS, MWHS	Clear-sky (no cloud assimilation)		
50 GHz temperature	SSMIS	Not assimilated – instrument issues		
	6×AMSU-A	Clear-sky (no cloud assimilation)		
	ATMS	Clear-sky (no cloud assimilation)		

Routine cloud and precipitation assimilation: 37 GHz



Routine cloud and precipitation assimilation: 37 GHz



Importance of all observations in the NWP system

- Even without the assimilation of cloud-affected observations, all other observations in the assimilation system (e.g. satellite temperature-sensitive observations, radiosondes, and many more) do a very good job of improving cloud and precipitation features in the analysis.

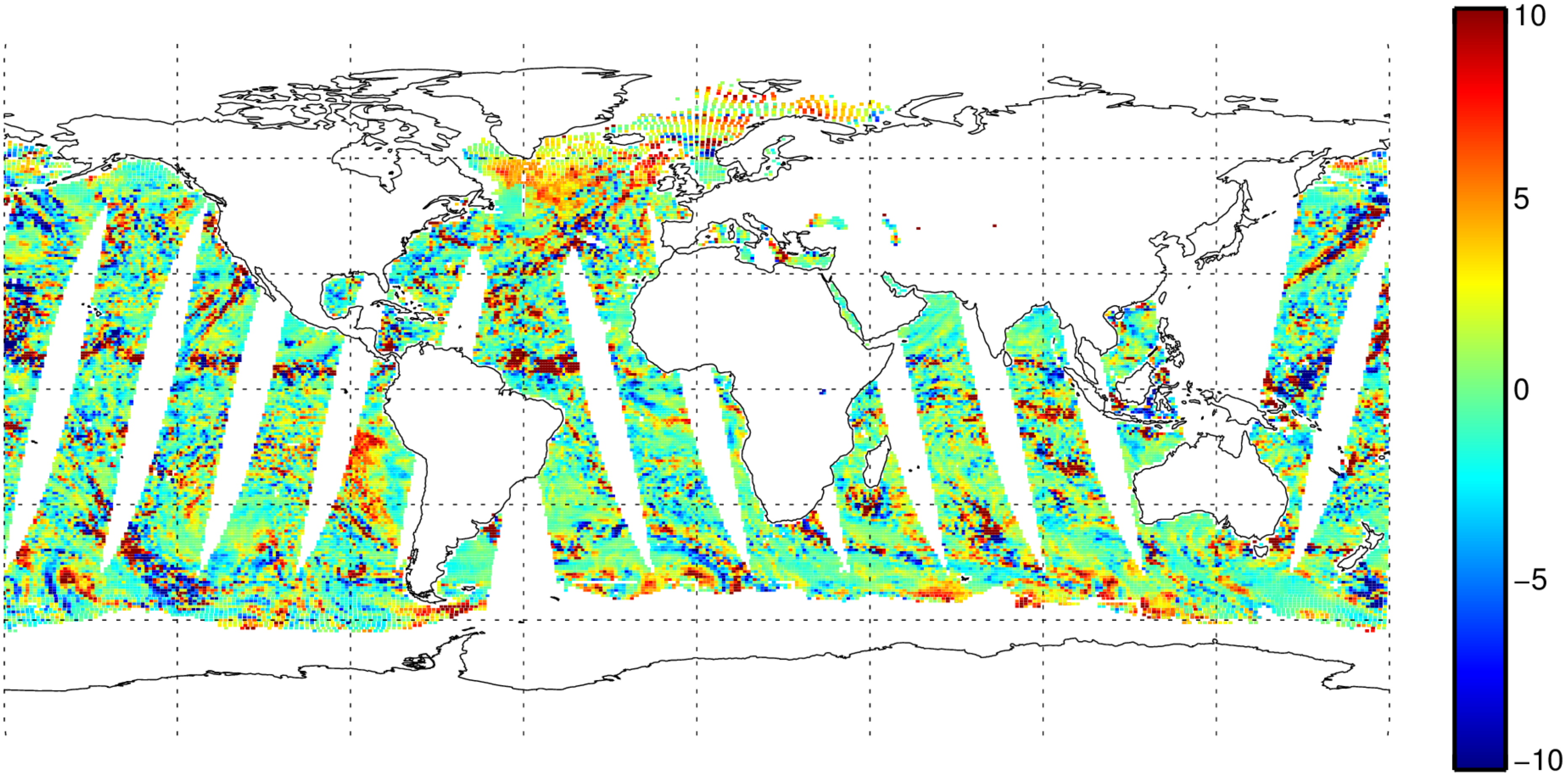
- Everything (dynamics, cloud and precipitation) is inter-dependent

Observation – model (i.e. FG departure) at 37v GHz

Important: 4D-Var assimilation aims to fit all observations within a time window, at ECMWF usually 12 hours

SSMIS observations 0900 UTC – 2100 UTC, 3 Dec 2014

FG departure [K]



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

That ubiquitous 4D-Var costfunction

1. We will vary model state x
   to find the best analysis

2. Aiming to improve the fit between observations
y and simulated observations H(M(x))

$$J(\mathrm{x}) = (\mathrm{y} - H(\mathrm{M}(\mathrm{x})))^T \mathbf{R}^{-1} (\mathrm{y} - H(\mathrm{M}(\mathrm{x}))) + (\mathrm{x} - \mathrm{x}_b)^T \mathbf{B}^{-1} (\mathrm{x} - \mathrm{x}_b)$$

3. But it must not get too far away
from the model background x_b

4. The relative weight given to observations versus
model background is controlled by their respective
error matrices R and B

To find the costfunction minimum, follow the gradient:

- For observation i at start of minimisation (at background x_b), gradient of the cost function J is:

Gradient of cost function with respect to control variables

Adjoint of forecast model including moist physics

Adjoint observation operator

Observation error

Observed value

Nonlinear observation operator

Nonlinear forward forecast model timesteps 1-15

Model background

First guess departure

$$\nabla J(\mathrm{x})\Big|_i^{\mathrm{x}_b} = \mathbf{M}_1^T \mathbf{M}_2^T \ldots \mathbf{M}_{14}^T \mathbf{M}_{15}^T \mathbf{H}_i^T \mathbf{R}^{-1} \left(\mathrm{y}_i - H_i\left(M_{1-15}(\mathrm{x}_b)\right)\right)$$

$$\begin{pmatrix} \mathrm{u}^* \\ \mathrm{v}^* \\ \mathrm{T}^* \\ \mathrm{q}^* \end{pmatrix} \quad \begin{pmatrix} \mathrm{u}^* \\ \mathrm{v}^* \\ \mathrm{T}^* \\ \mathrm{q}^* \end{pmatrix} \quad \begin{pmatrix} \mathrm{u}^* \\ \mathrm{v}^* \\ \mathrm{T}^* \\ \mathrm{q}^* \\ \mathrm{clw}^* \\ \mathrm{ciw}^* \\ \mathrm{rain}^* \\ \mathrm{snow}^* \end{pmatrix} \quad \mathrm{tb}^* \quad \mathrm{tb} \quad \begin{pmatrix} \mathrm{u} \\ \mathrm{v} \\ \mathrm{T} \\ \mathrm{q} \\ \mathrm{clw} \\ \mathrm{ciw} \\ \mathrm{rain} \\ \mathrm{snow} \end{pmatrix} \quad \begin{pmatrix} \mathrm{u} \\ \mathrm{v} \\ \mathrm{T} \\ \mathrm{q} \\ \mathrm{clw} \\ \mathrm{ciw} \\ \mathrm{rain} \\ \mathrm{snow} \end{pmatrix}$$

z* is shorthand for ∂J/ ∂z*

Key components needed for a cloud and precipitation assimilation system

- An existing assimilation system:
  - and all the conventional and satellite observations that go with it
  - a good first guess forecast
- Extra components:
  - Cloud and precipitation-sensitive observations
  - Simplified moist physics model (direct, TL and adjoint) – Philippe's talk
  - Cloud and precipitation capable radiative transfer model (direct, TL and adjoint) – for simulating observations

RTTOV-SCATT

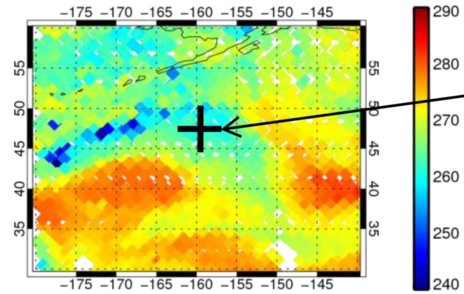
Forward, TL and adjoint radiative transfer model for NWP

- Inputs are:
  - profiles of: pressure, temperature, water vapour, cloud water, cloud ice, rain water, snow, cloud fraction, precipitation fraction
  - surface properties including emissivity or wind speed, skin temperature
- Gas optical depths (water vapour, oxygen, …) are parametrised
- Bulk hydrometeor optical properties:
  - Cloud liquid water – gamma distribution; Mie sphere
  - Cloud ice water – gamma distribution; Mie sphere
  - Rain – Marshall-Palmer distribution, Mie sphere
  - Snow – Field et al (2007), Liu (2008) DDA sector snowflake
- Scattering solver: two-stream delta-Eddington
- Subgrid representation with “effective cloud fraction” C:
  - $T_{total} = C \times T_{cloud} + (1-C) \times T_{clear}$

ECMWF

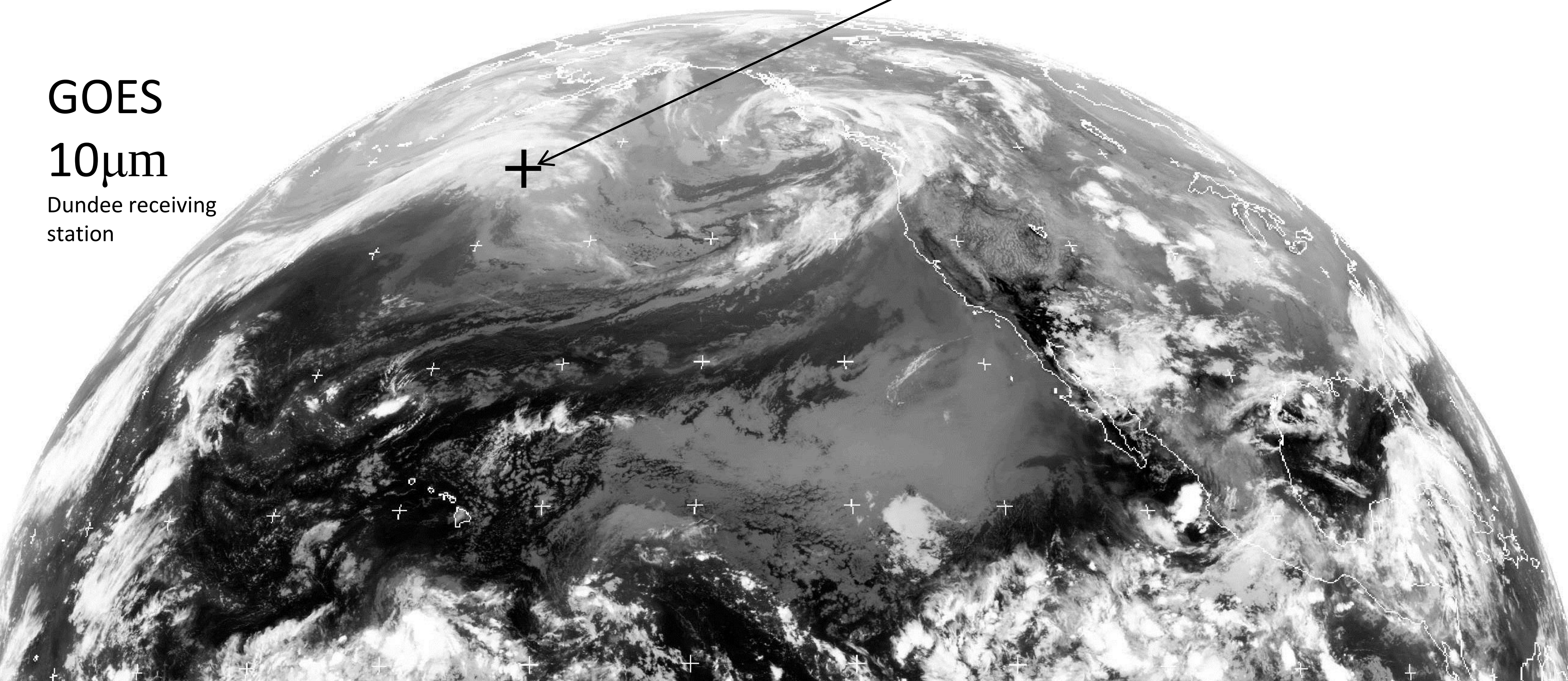
Frontal cloud and precipitation: single-observation example at 190 GHz

Metop-B MHS
190 GHz

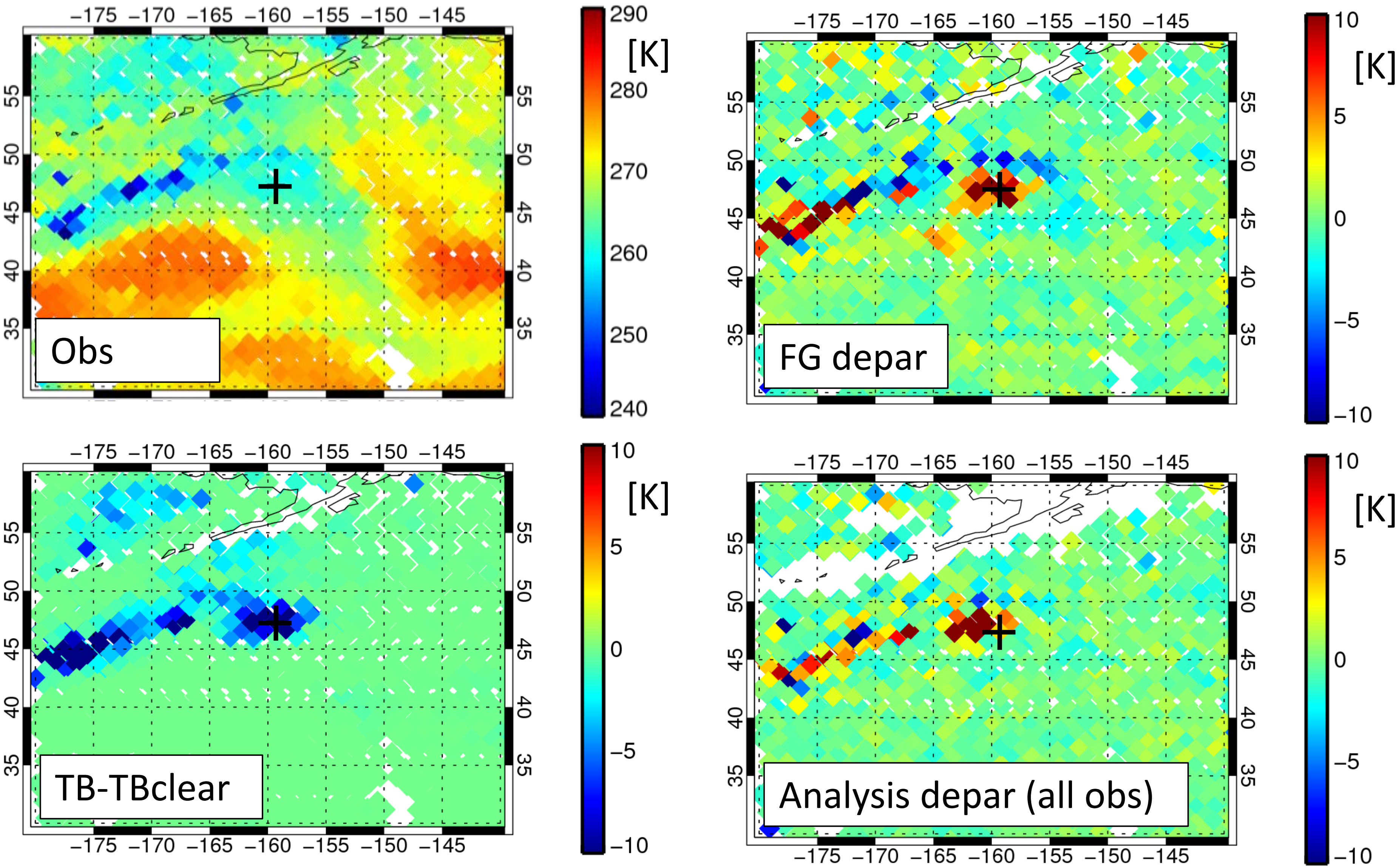


08Z, 15 Aug 2013
47°N 159°W

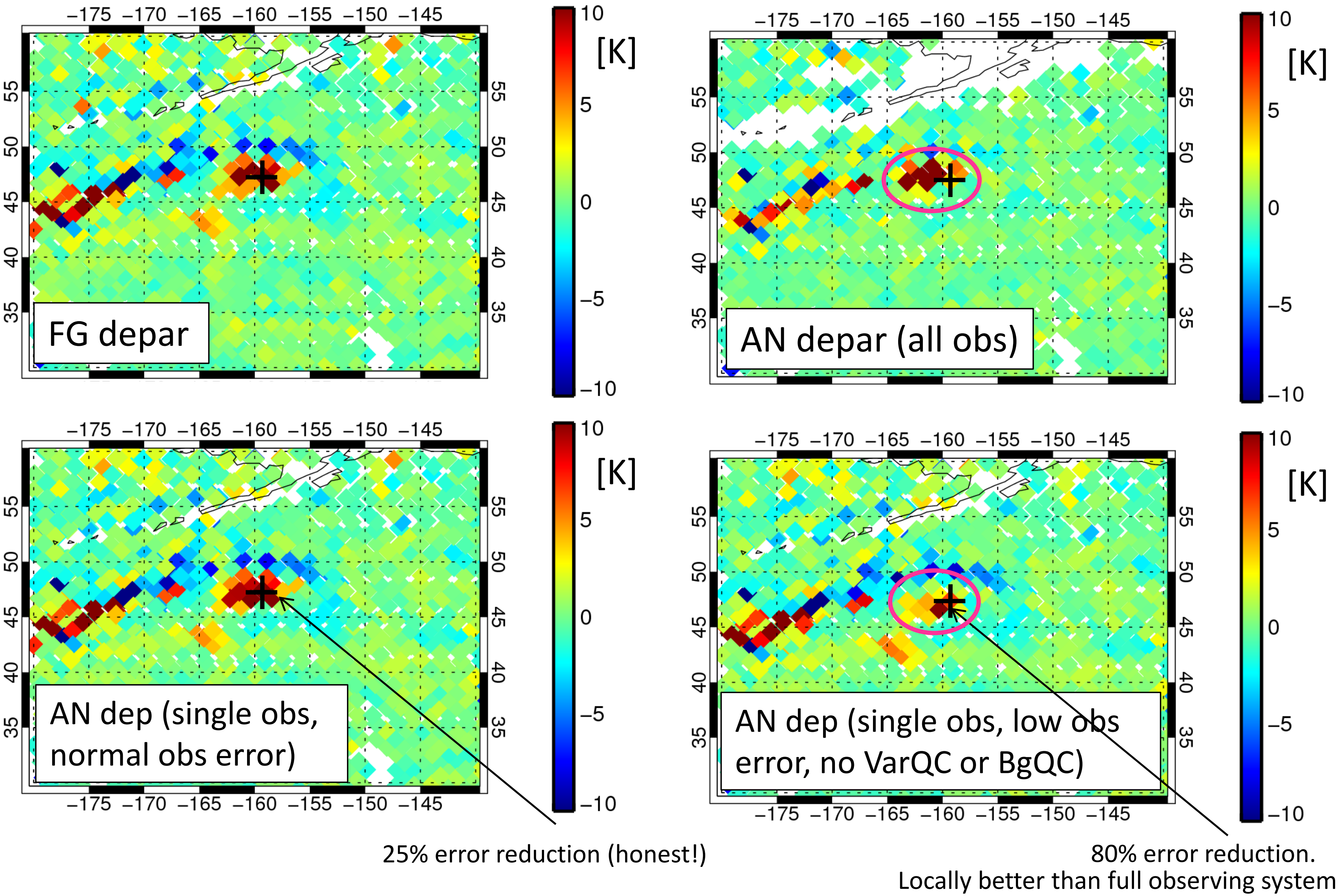
GOES
10μm
Dundee receiving station



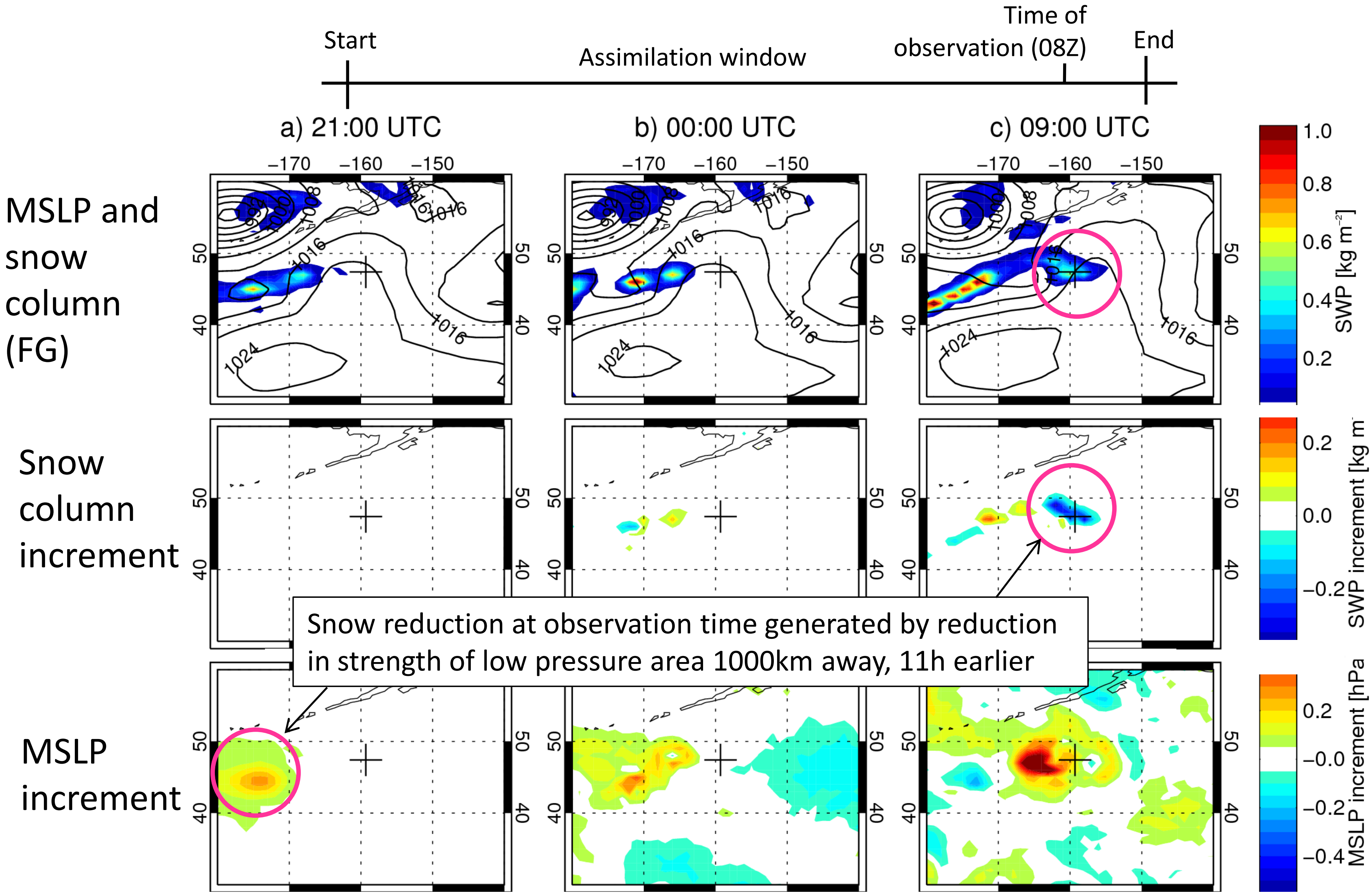
Frontal cloud and precipitation – all observations



Frontal cloud and precipitation – single all-sky obs



B) Frontal cloud and precipitation – 190 GHz



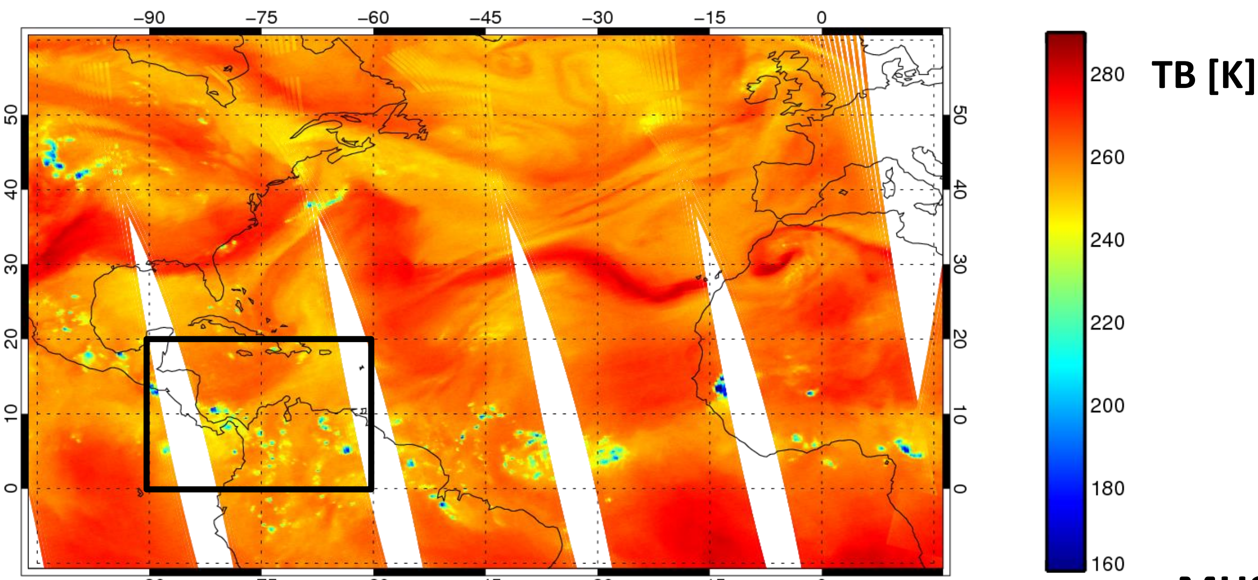
Why assimilate cloud and precipitation in a global model?

- Infer wind, humidity and temperature increments to better fit observed cloud and precipitation (and other things observed simultaneously, like temperature and water vapour)
  - Assimilating water vapour and temperature in the presence of cloud
  - Assimilating cloud and precipitation itself
- Better wind, humidity and temperature analysis leads to better forecasts
  - Removing "all-sky" microwave instruments from the operational system would degrade forecast quality at day 5 by about 3%

One catch: representivity / predictability

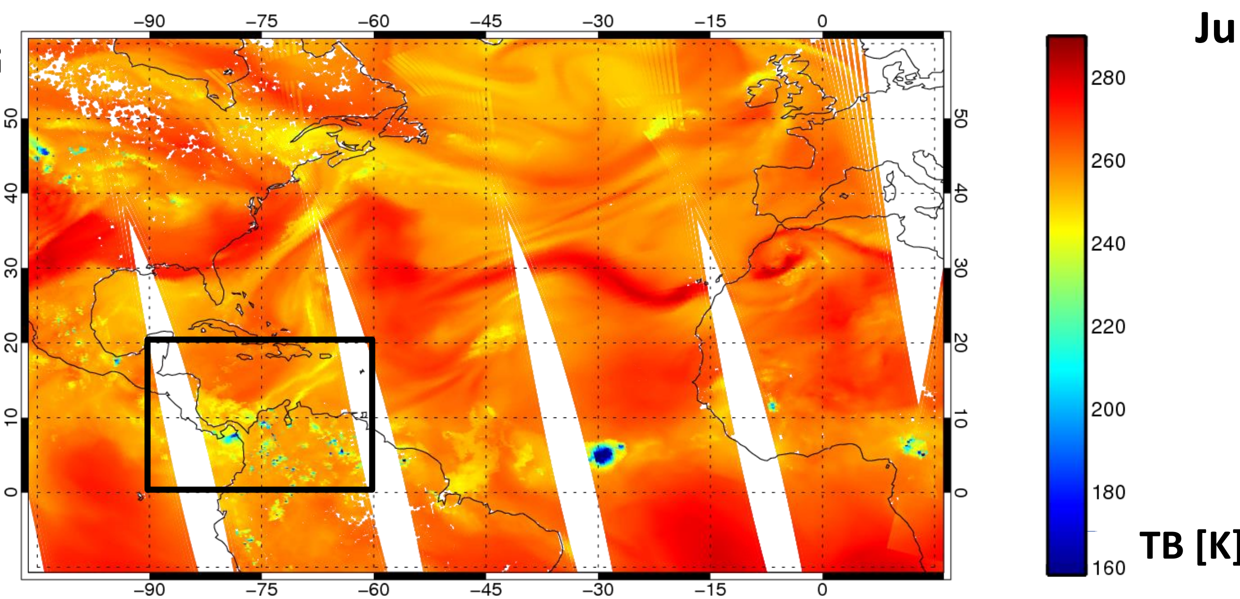
Representing cloud and precipitation in models

Observations



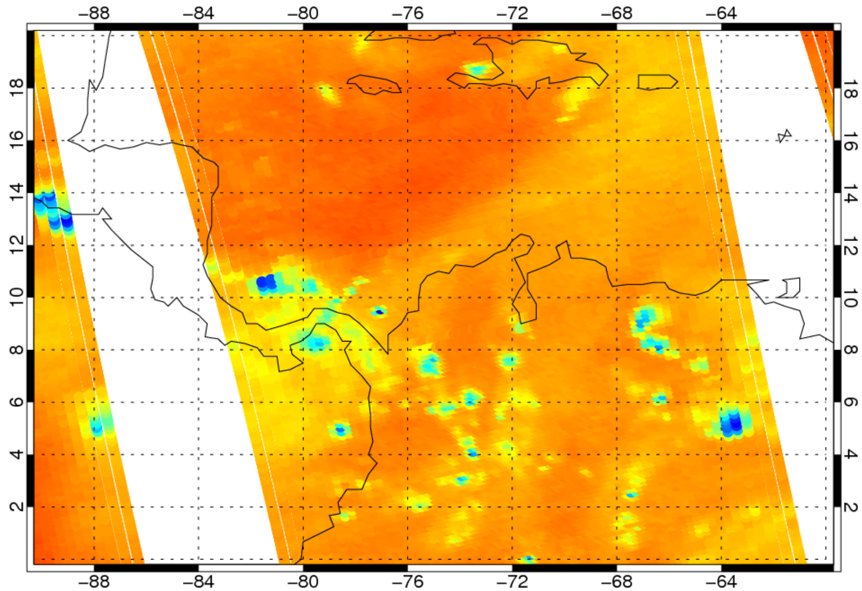
MHS 183±3 GHz
June 12th 2013

ECMWF FG

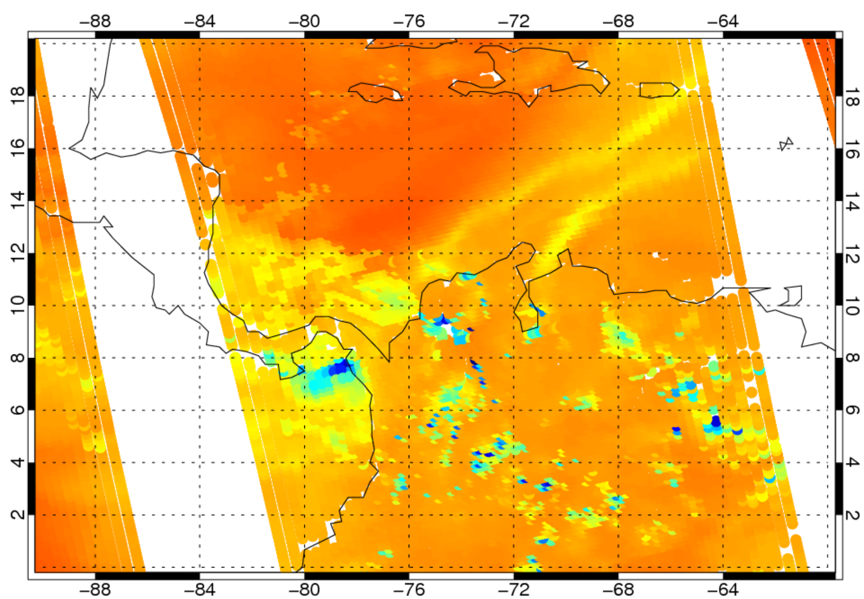


Representing cloud and precipitation in models

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)

How to deal with the representivity issue

- We don’t aim to put every cloud and precipitation feature “in the right place” in the analysis:
  - this is currently impossible, at least not without destroying the large-scale dynamical analysis
  - “convective error growth” saturates in about 3 hours (see e.g. Martin Köhler’s talk) but we are assimilating within a 12h window.
- We apply relatively large observation errors:
  - No single observation can push the analysis too far
  - But many observations working together, in combination with temperature and wind observations, push the dynamical analysis to a point where it produces “on average” better hydrometeor features:
    - we can shift fronts
    - we can shift large convective systems

Impact of all-sky microwave humidity sounders and imagers -

on top of the otherwise full observing system

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

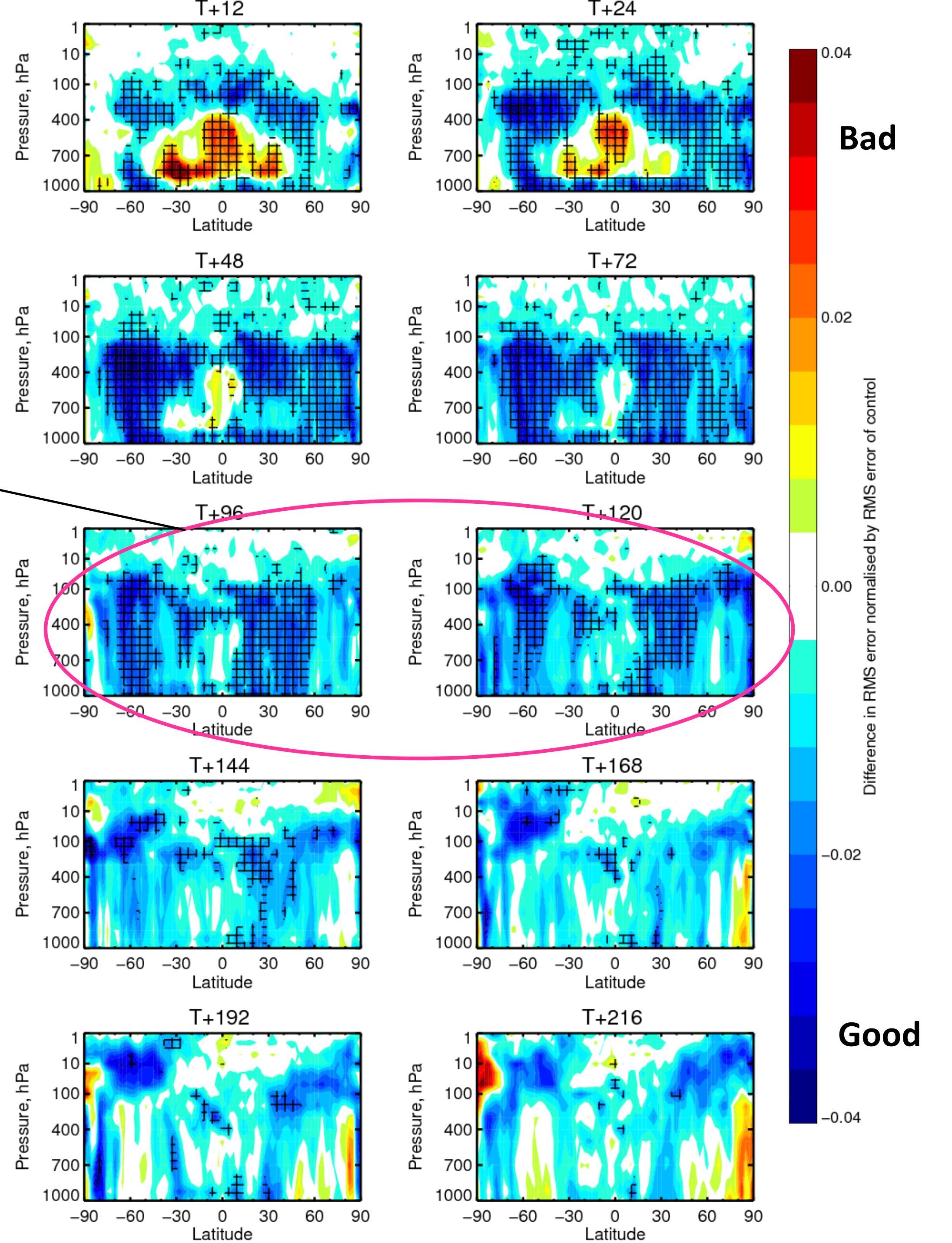
Change in RMS error of vector wind

Verified against own analysis

Blue = error reduction (good)

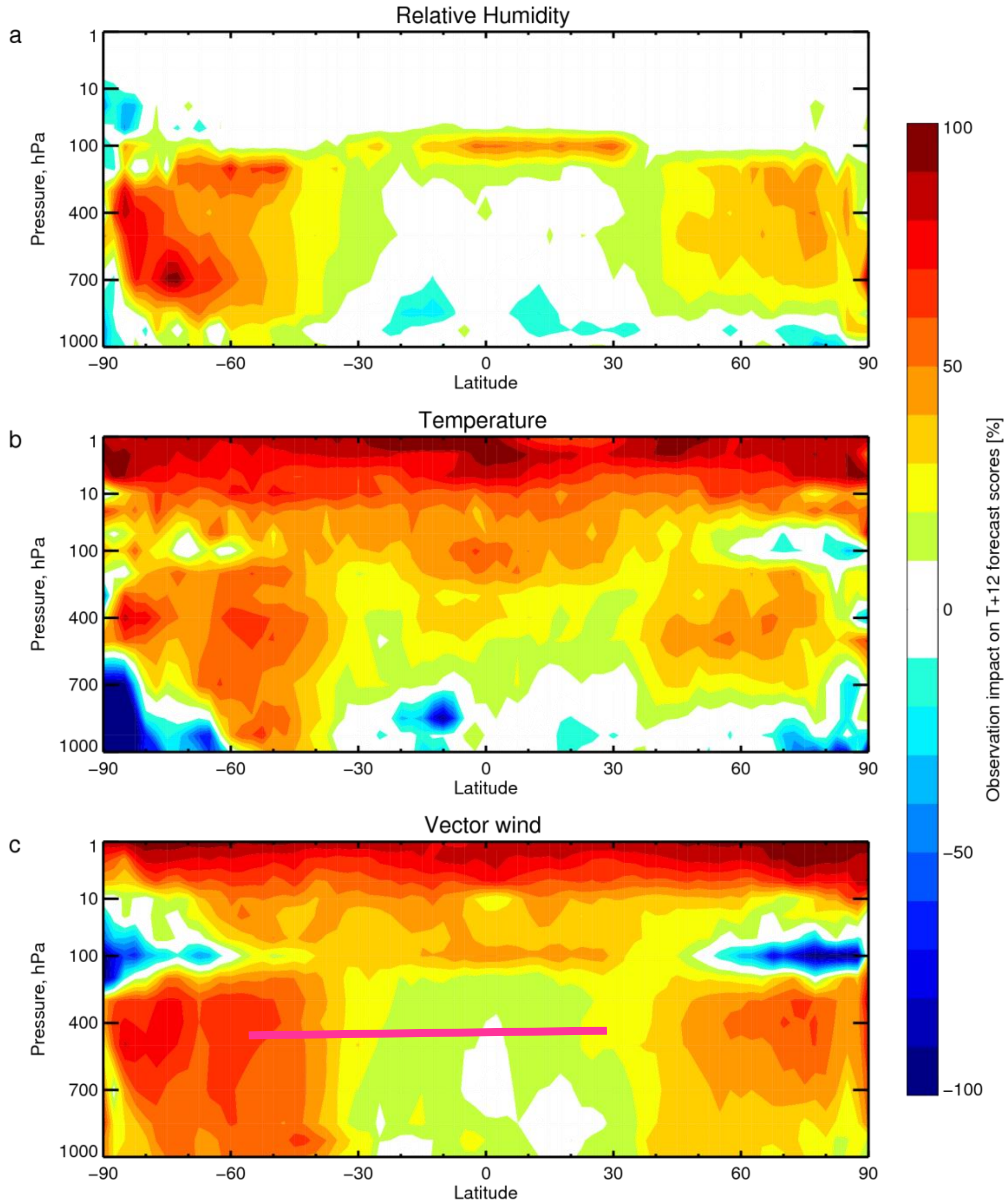
Based on 322 to 360 forecasts

Cross hatching indicates 95% confidence



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

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



How much of the impact of the full observing system can be recovered by a partial set of observations?

T+12 RMS forecast error reduction

100% = full observing system

0% = no observations

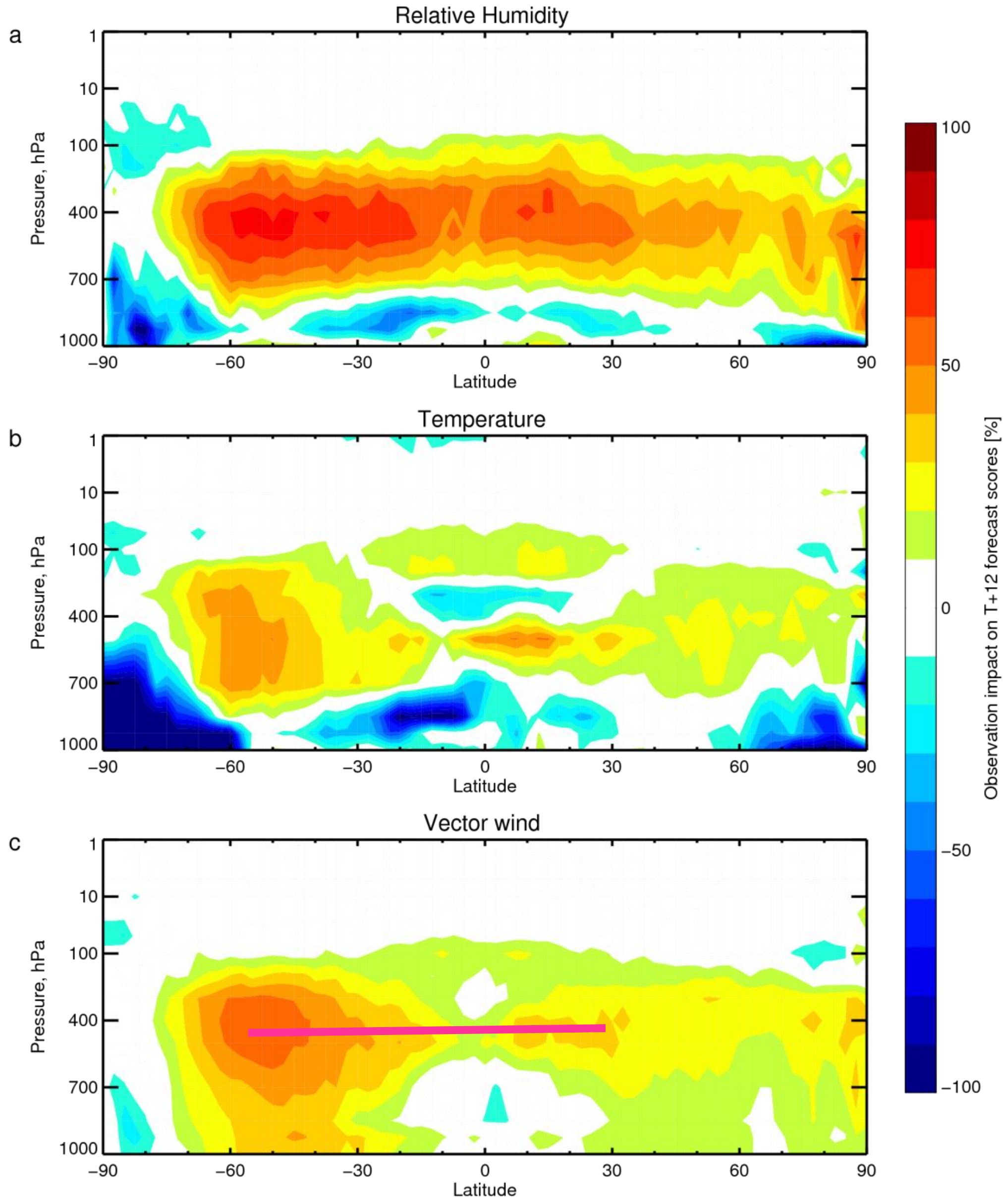
-100% = worse than that!

Storm track winds: to 60%

Tropical winds: to 10%

Assimilate only all-sky WV sounding observations (4 MHS, 1 SSMIS)

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



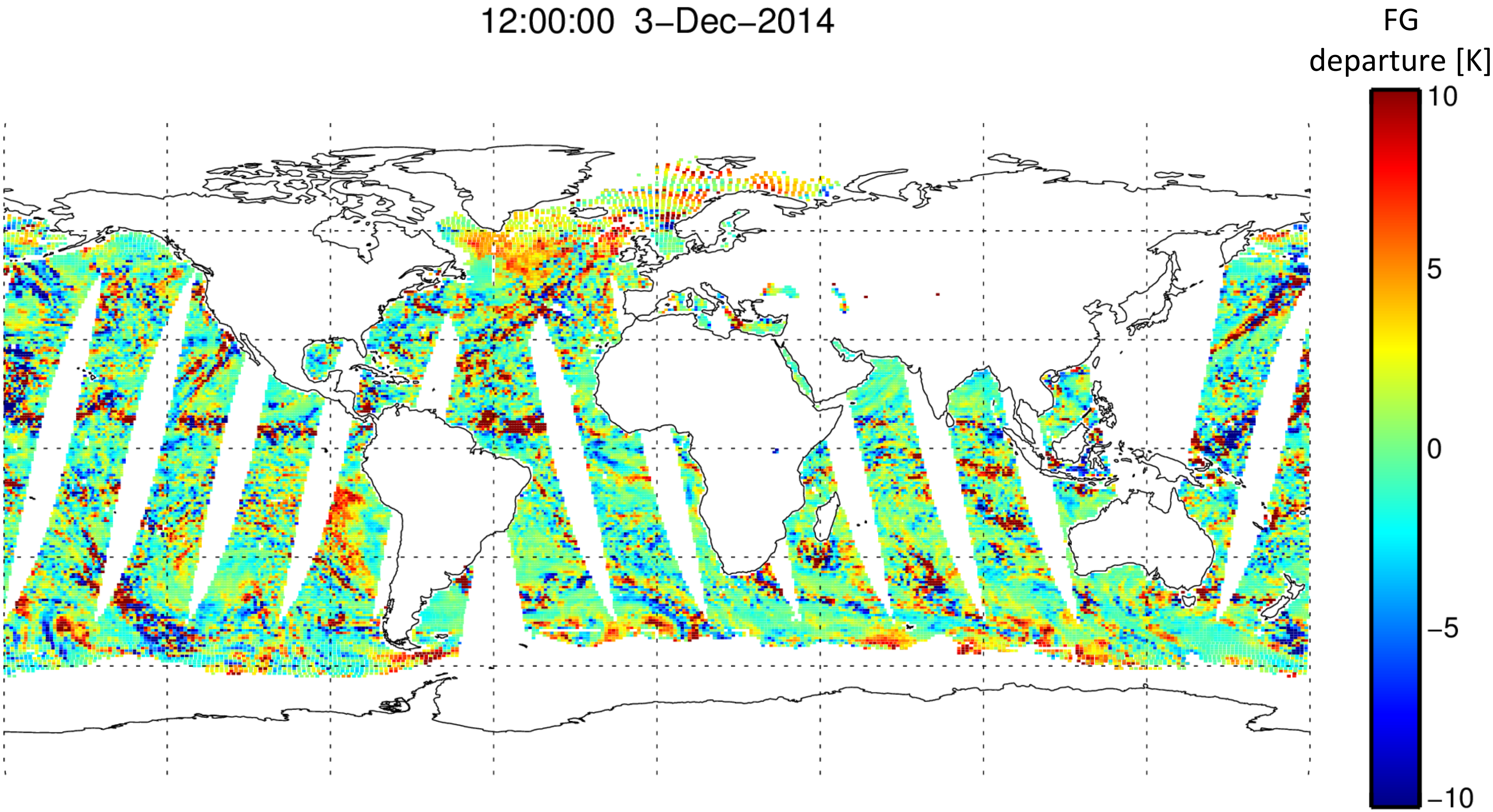
T+12 RMS forecast error reduction

100% = full observing system
0% = no observations
-100% = worse than that!

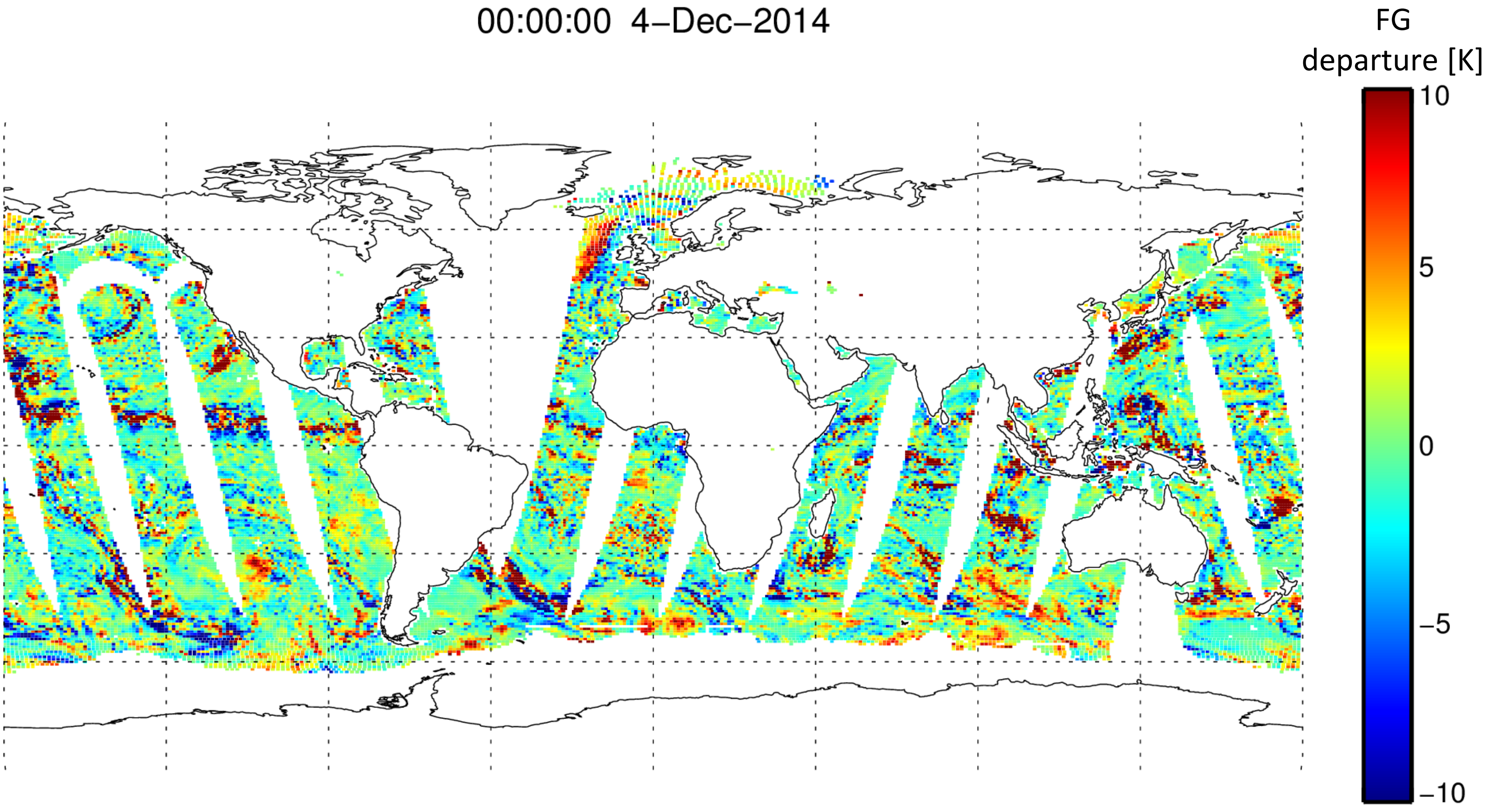
Storm track winds: to 50%
Tropical winds: to 30%

Improving modelled cloud and precipitation

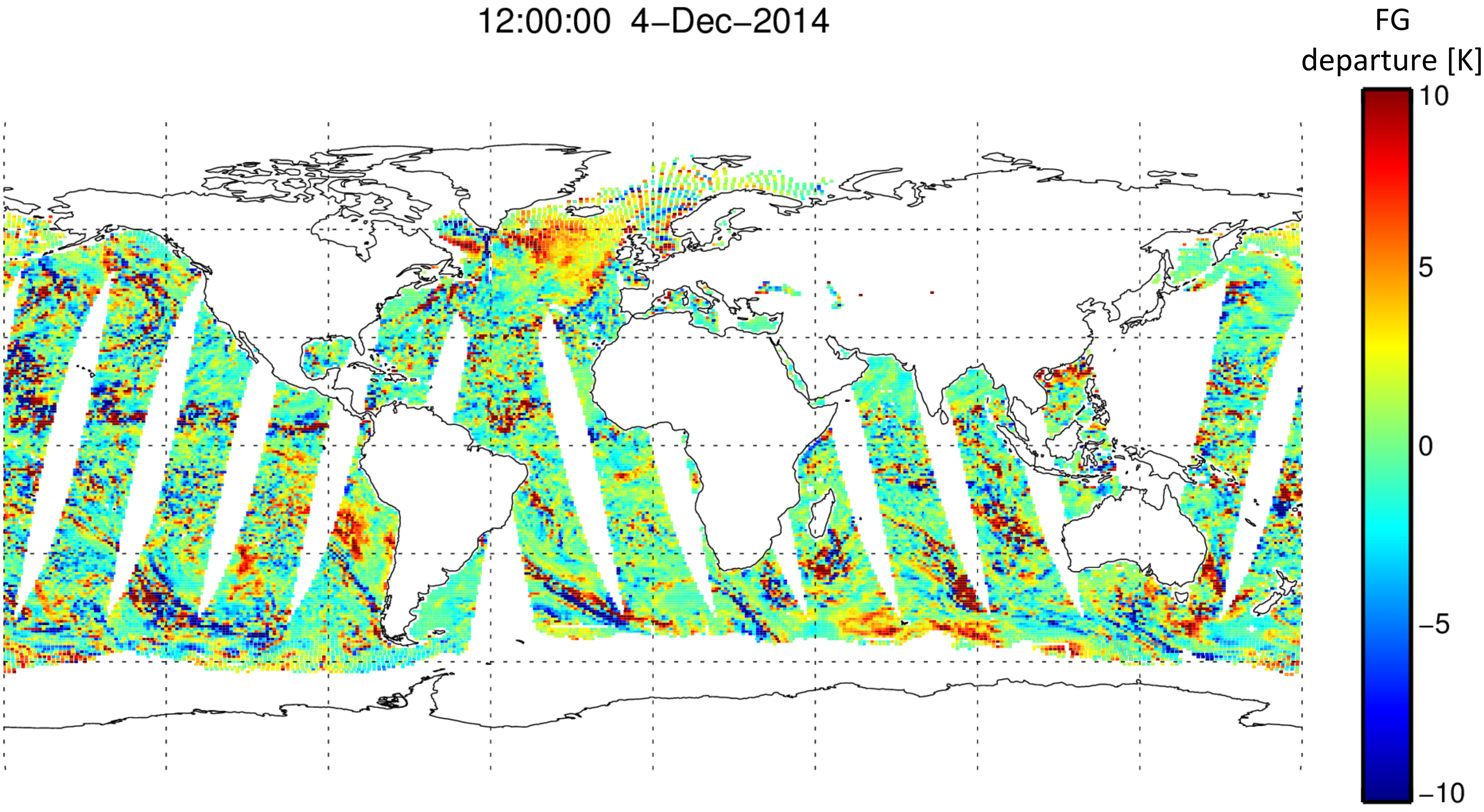
Observation – model (i.e. FG departure) at 37v Ghz



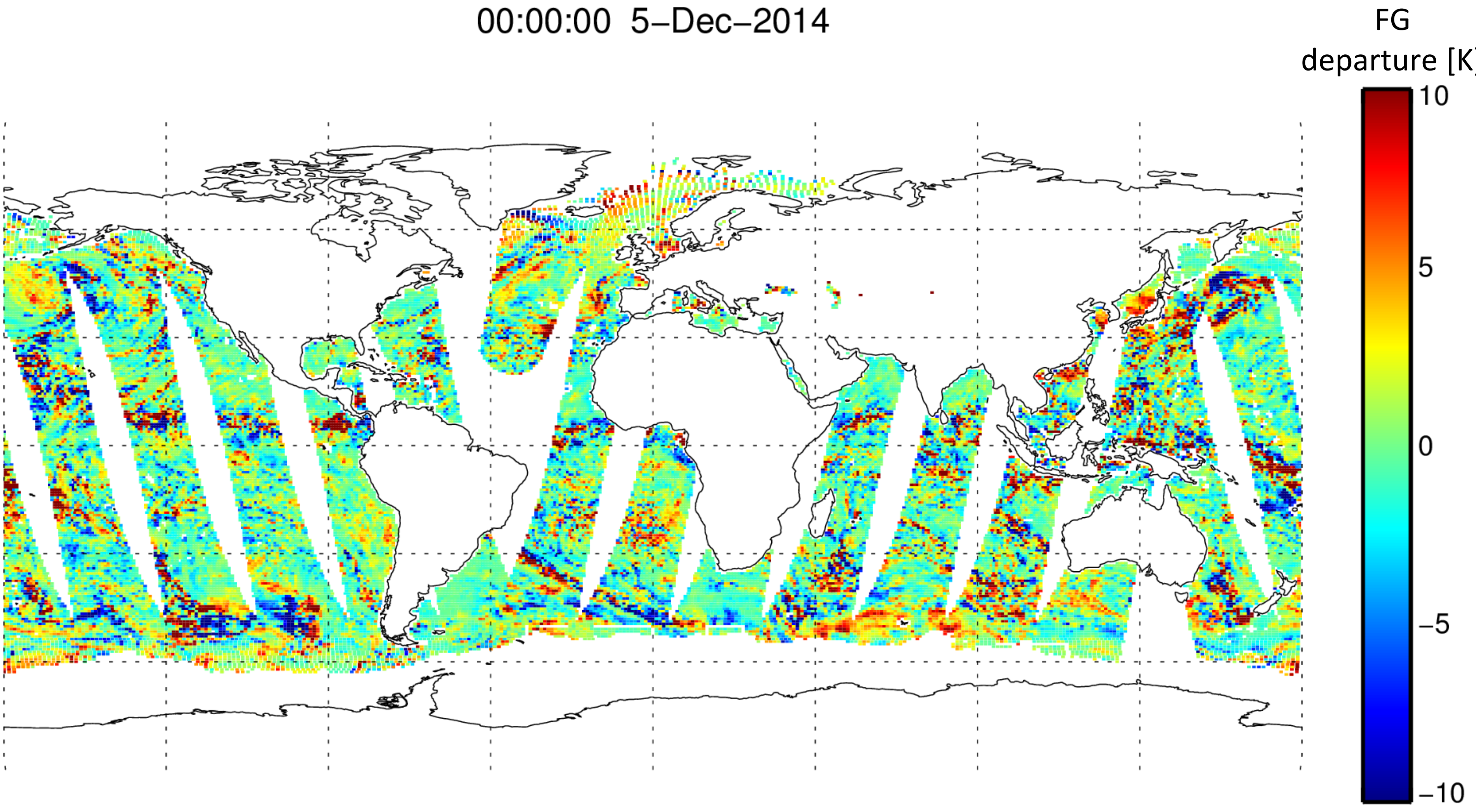
Observation – model (i.e. FG departure) at 37v Ghz



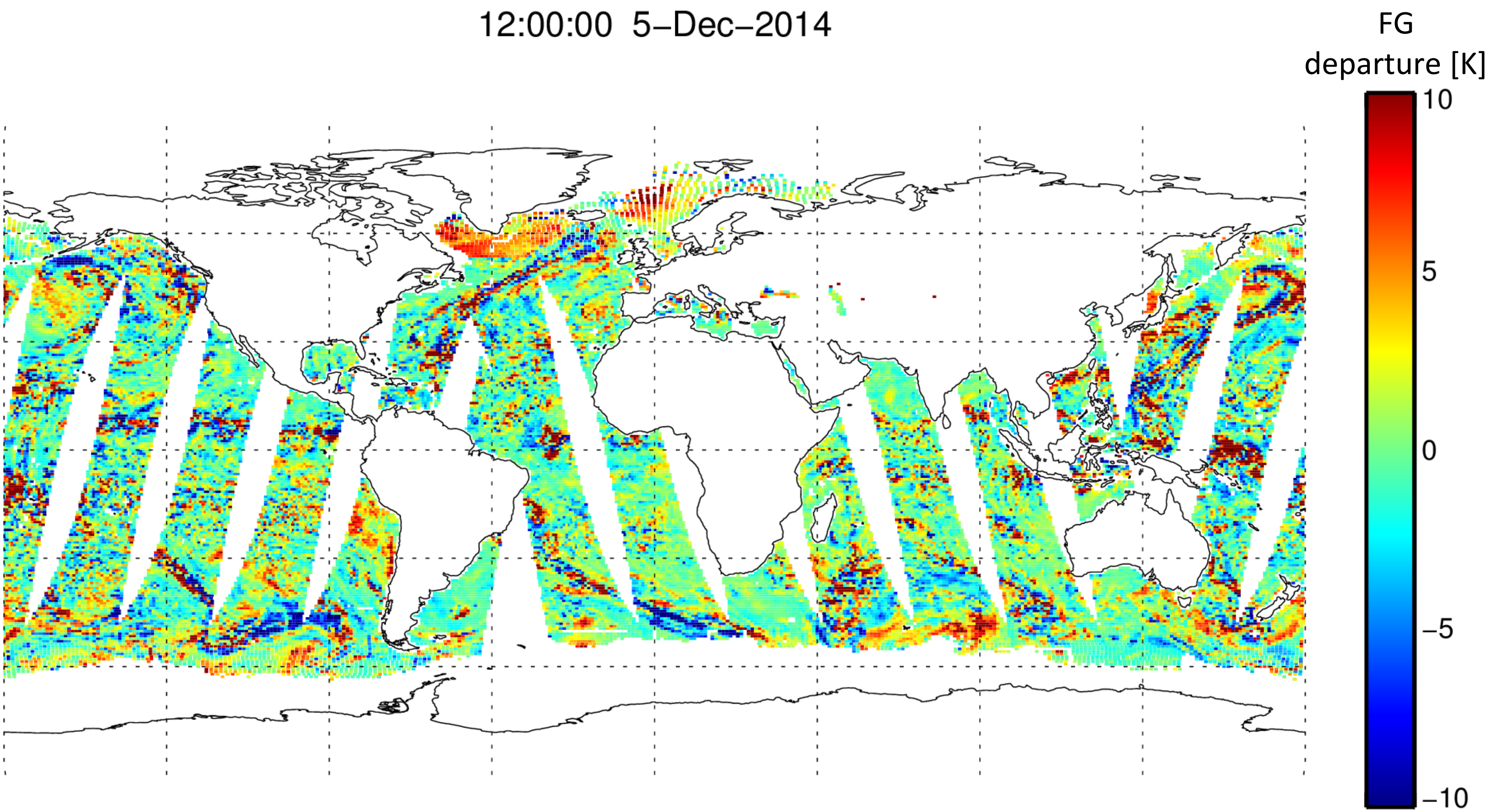
Observation – model (i.e. FG departure) at 37v Ghz



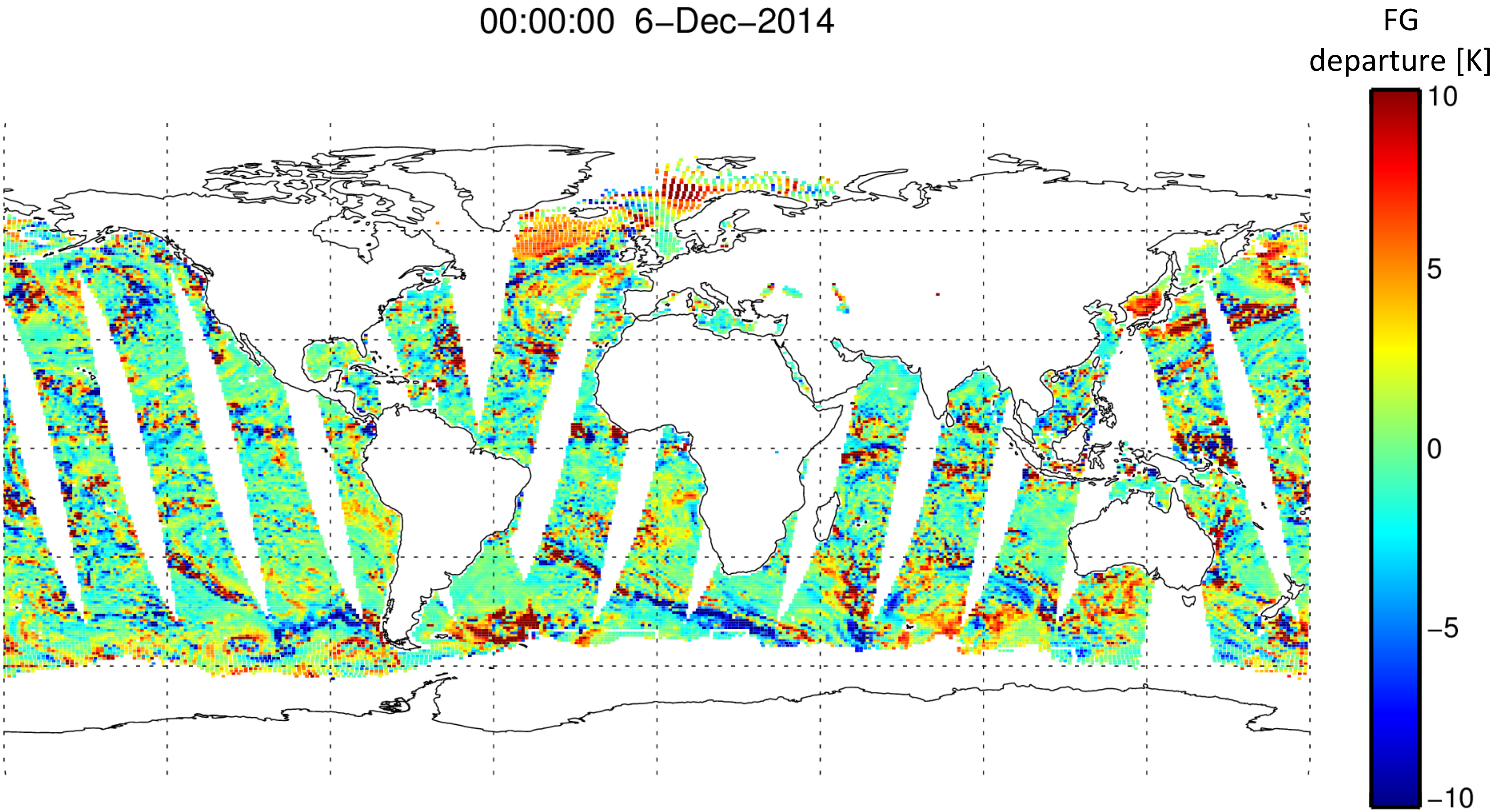
Observation – model (i.e. FG departure) at 37v Ghz



Observation – model (i.e. FG departure) at 37v Ghz

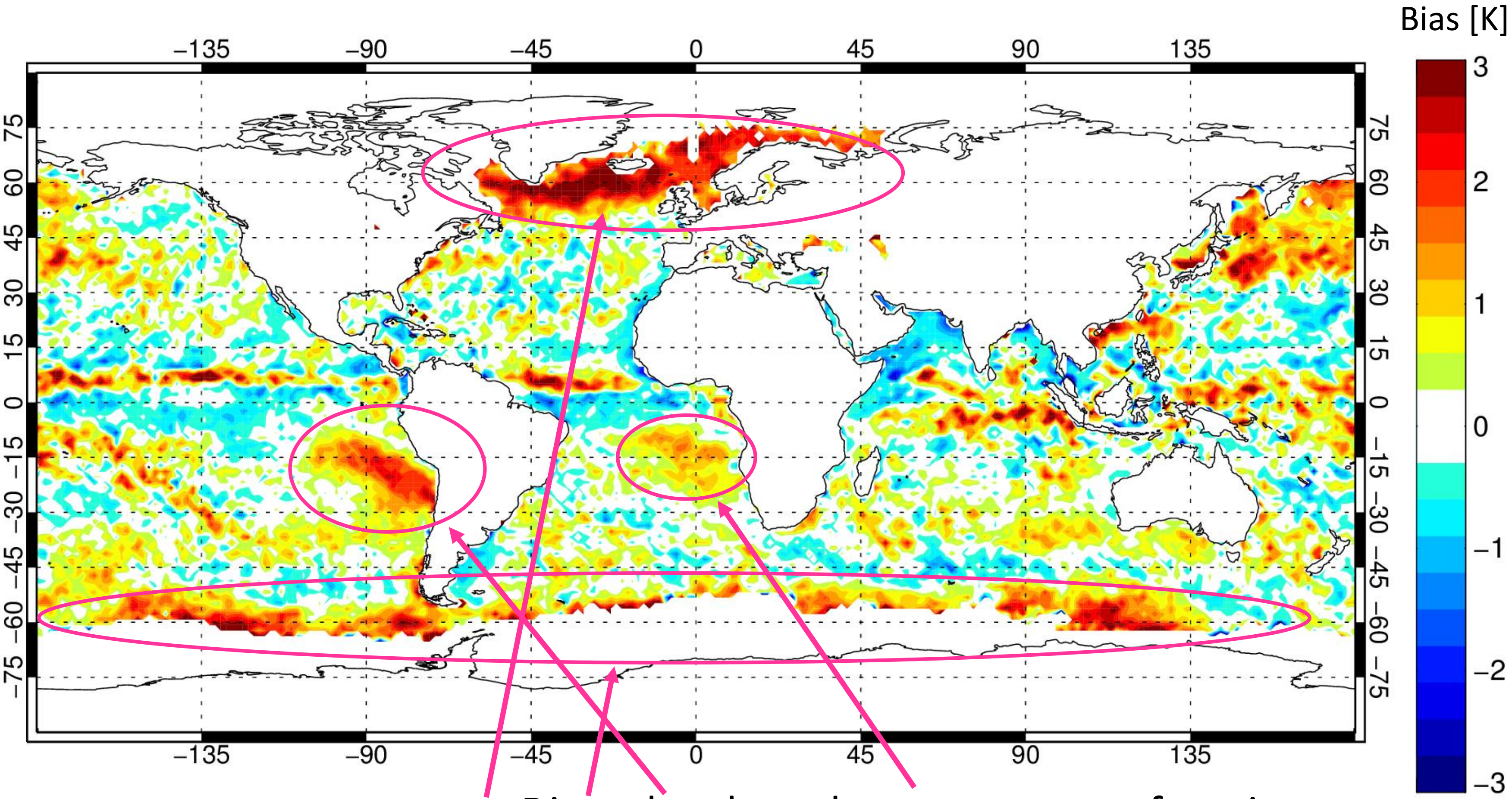


Observation – model (i.e. FG departure) at 37v Ghz



Monthly mean biases at 37 GHz (sensitive to cloud, water vapour and rain)

SSMIS channel 37v, December 2014 – all data over ocean, including observations usually removed by QC



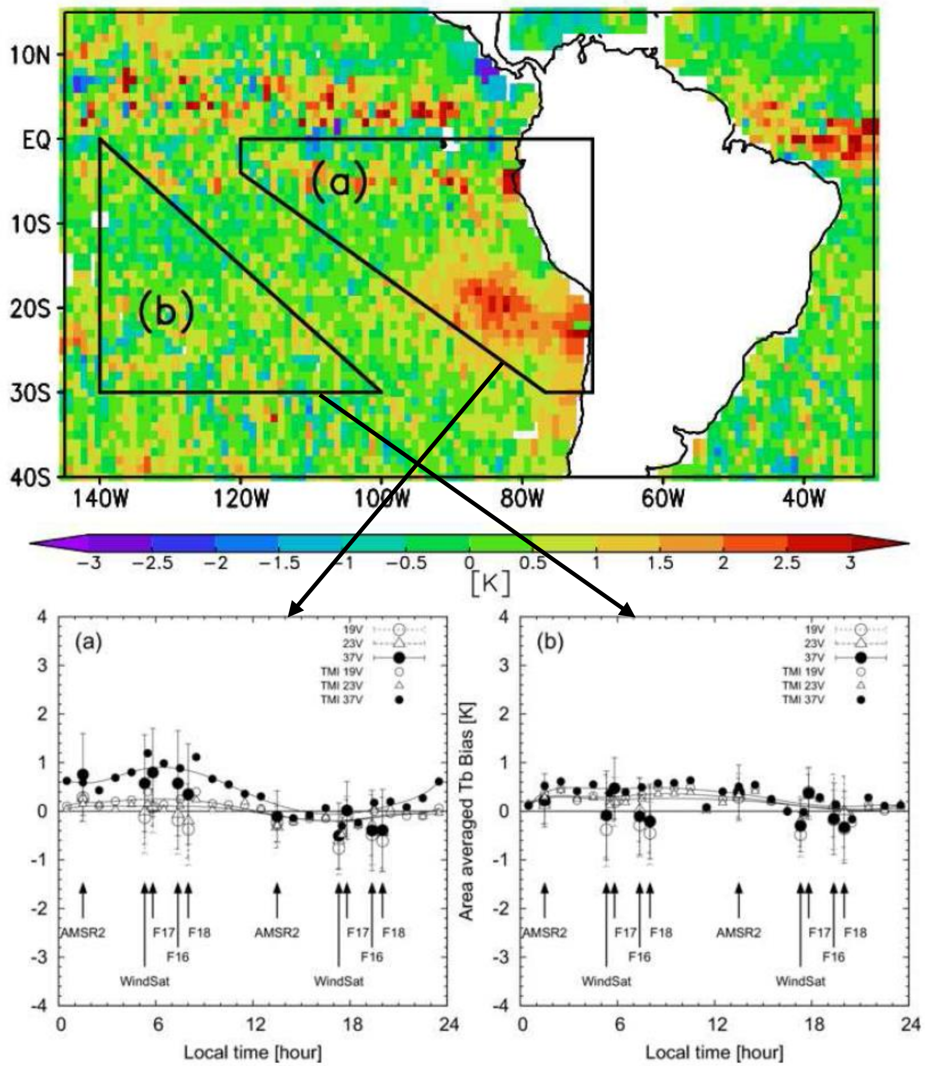
Lack of supercooled liquid water (see also Andrew Gettleman and Chris Bretherton talks)

Diurnal cycle and water content of marine stratocumulus

Diurnal cycle of marine stratocumulus

Bias analysed for June-Sep 2013 by Kazumori et al. (2015, QJRMS, submitted)

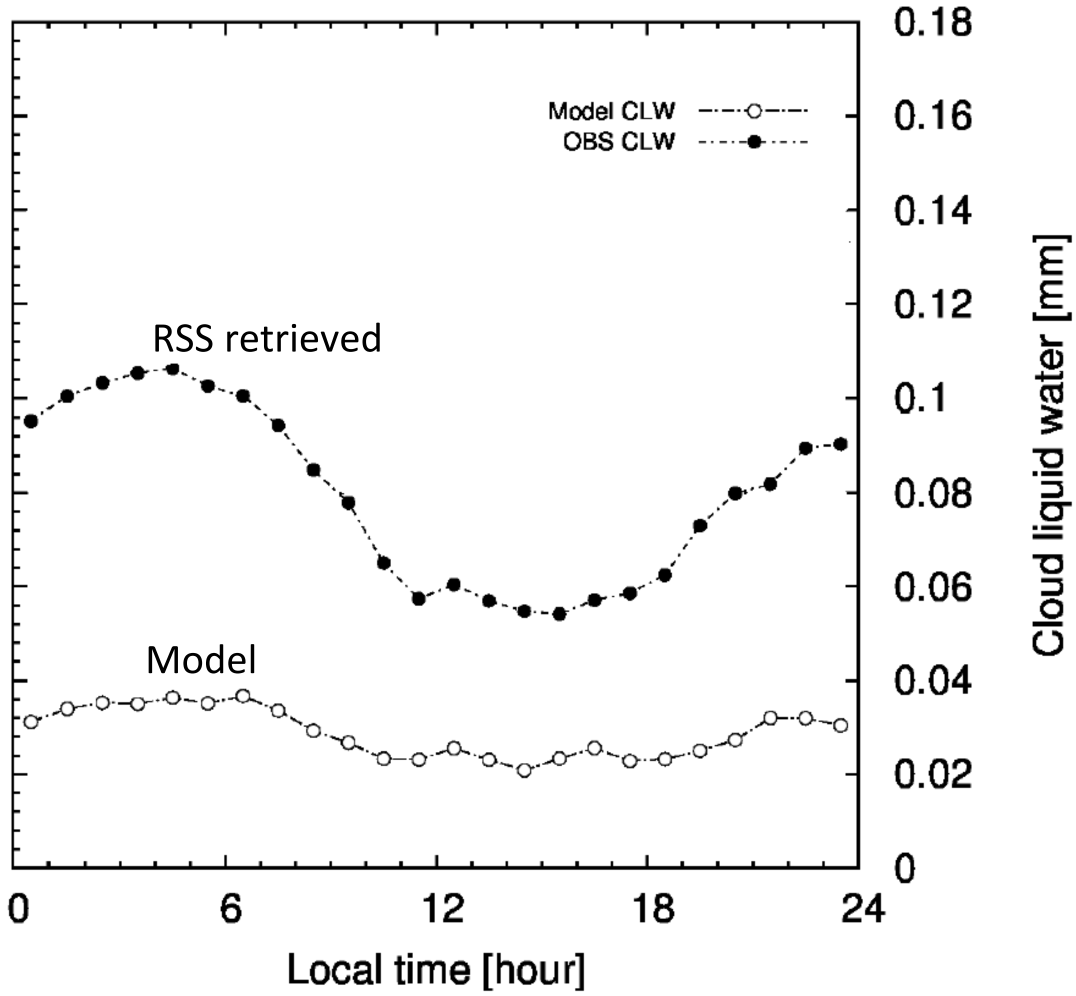
AMSR2 37v mean FG departure [K]



Mean FG departure (all satellites, resolved by local time) [K]

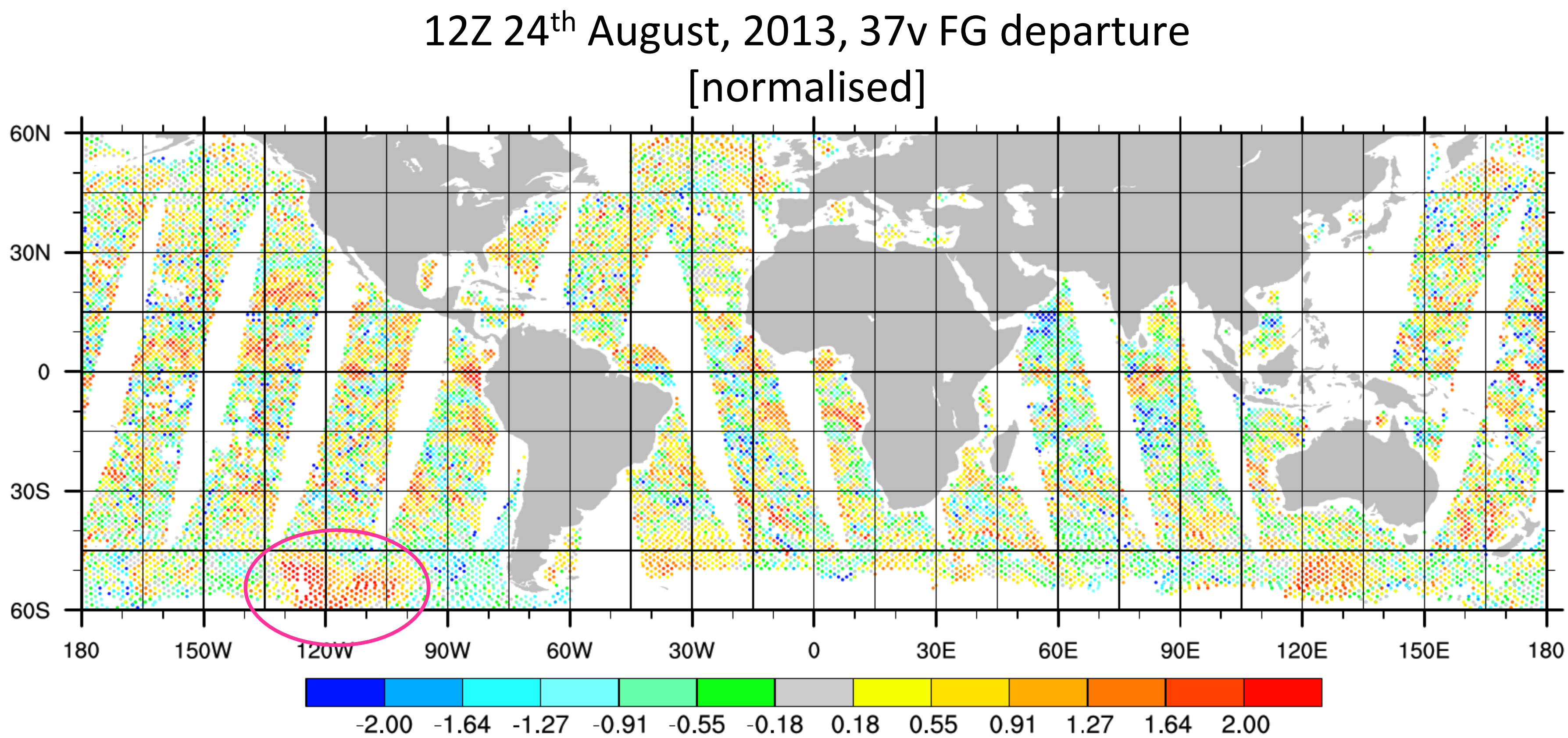
Diurnal cycle of marine stratocumulus

Bias analysed for June-Sep 2013 by Kazumori et al. (2015, QJRMS, submitted)



Cold air outbreaks

Thanks to Katrin Lonitz and Richard Forbes



ECMWF

Cold air outbreaks

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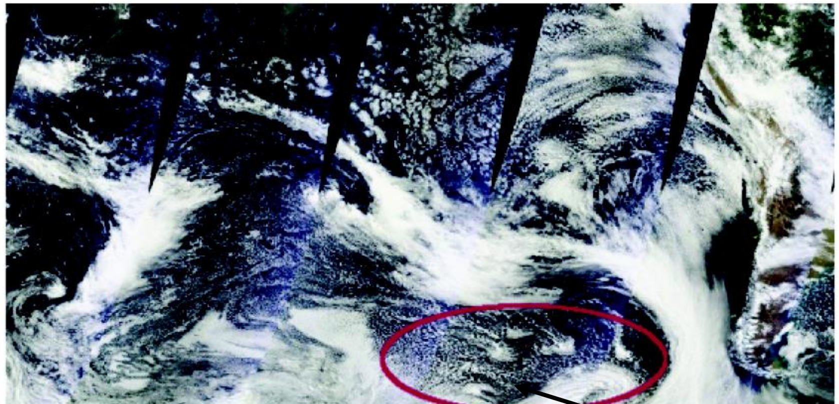
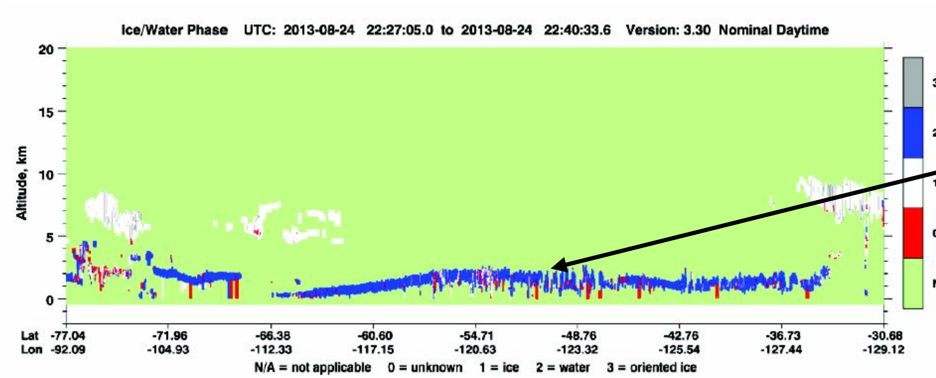


Composite MODIS image on 24 August 2013 at 08 Z. The whole area shown spans from 180° W to 60° W and from the equator to 60° S.

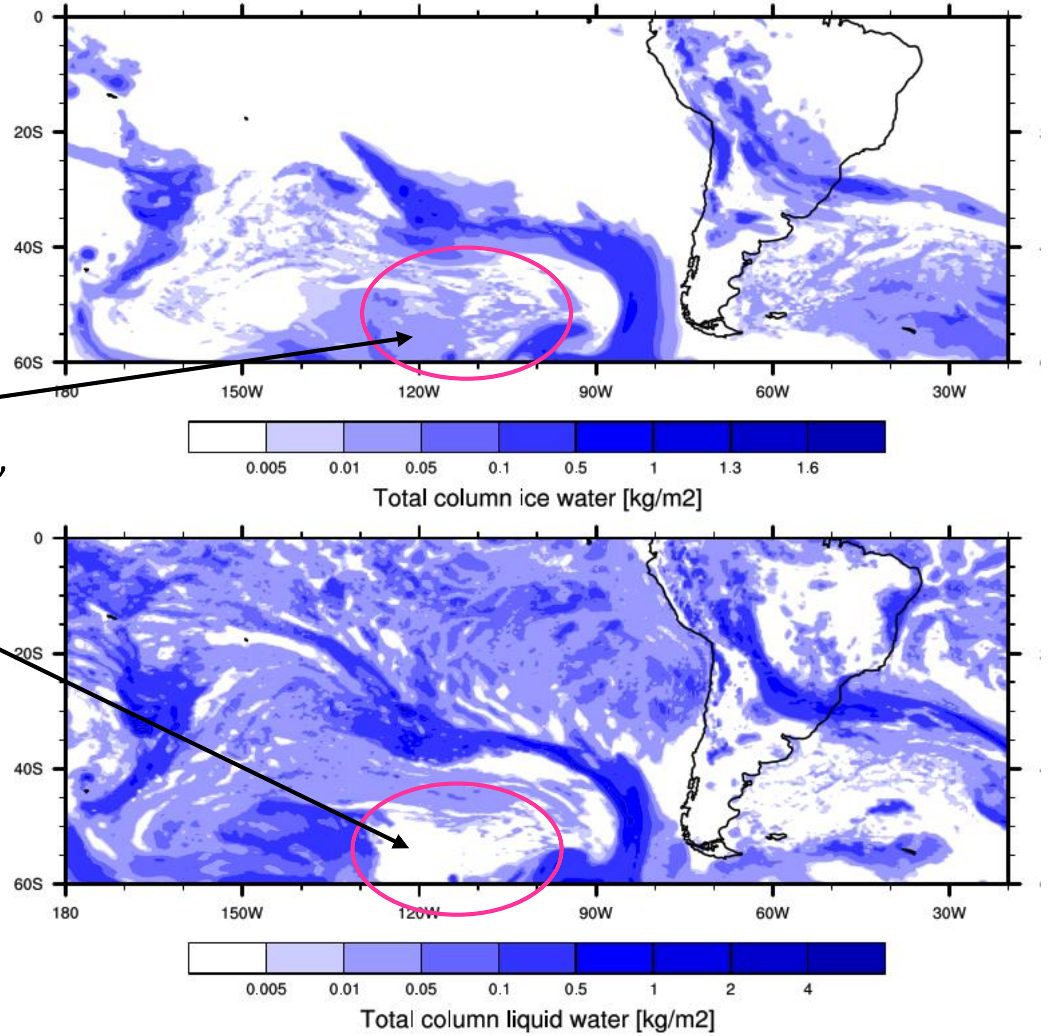


Calipso shows liquid water, not ice in this area

www.calipso.larc.nasa.gov/products/lidar/browse_images/show_dat
30&browse_date=2013-08-24

Cold air outbreaks

Thanks to Katrin Lonitz and Richard Forbes



IFS model simulates ice, not liquid water

Investigation shows it is the shallow convection scheme that is active here

Cold air outbreaks: detrainment from shallow convection

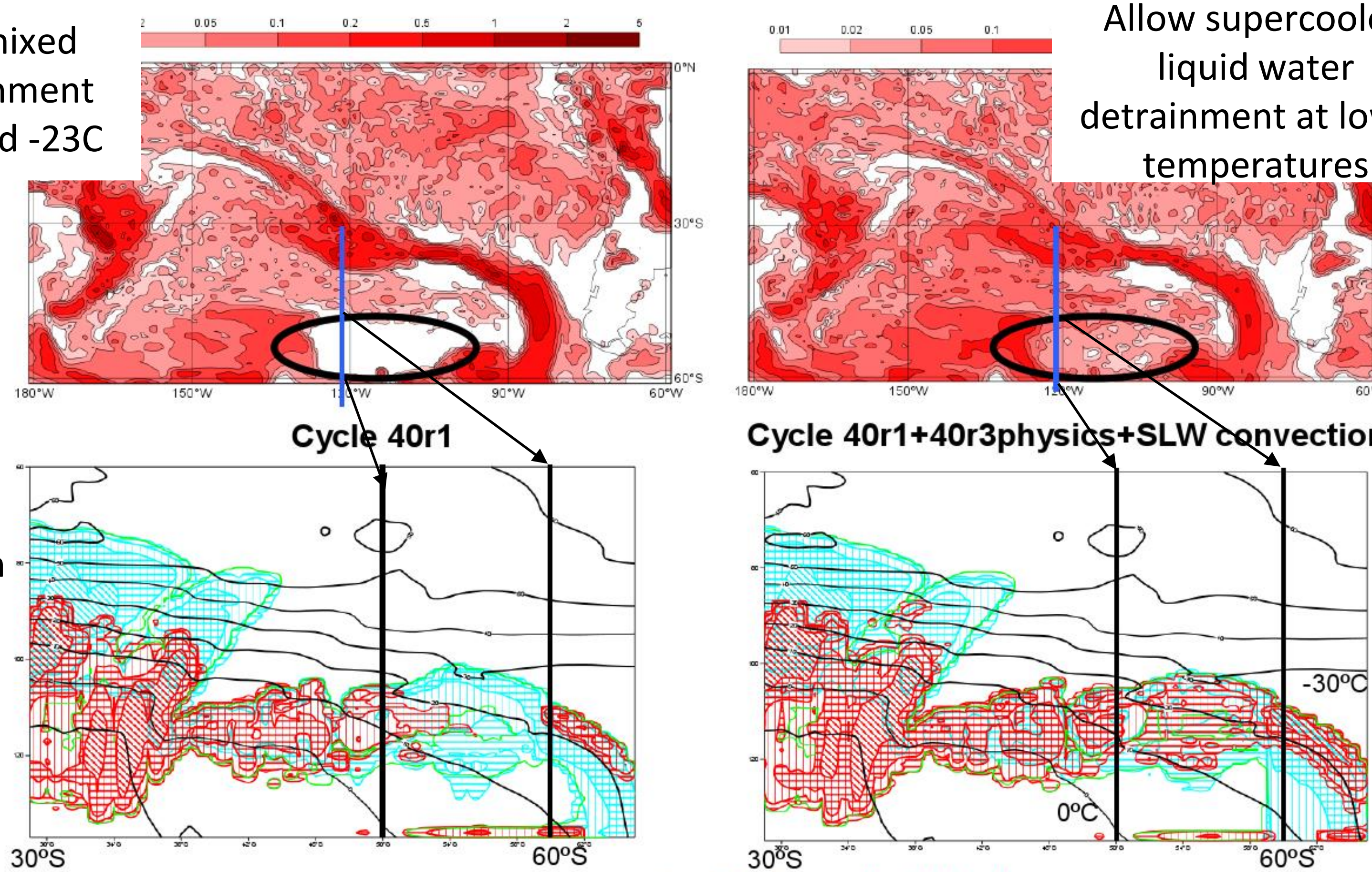
Thanks to Richard Forbes and Katrin Lonitz

IFS T+12 total column liquid water path (kg m^{-2})

Diagnostic mixed phase detrainment between 0 and -23C

Allow supercooled liquid water detrainment at lower temperatures

Vertical cross section through CAO



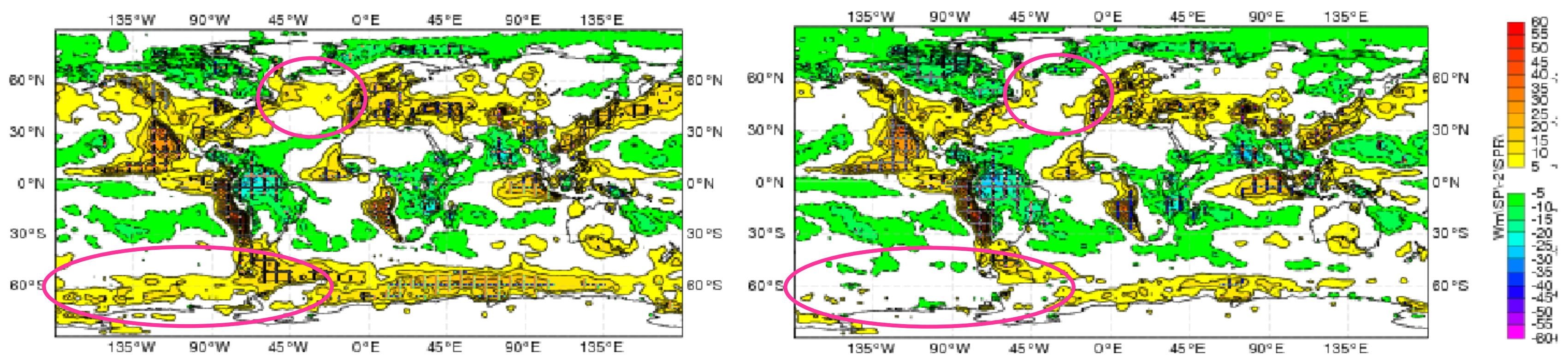
IFS T+12 cross section along 122W showing ice (blue) and liquid (red) water contents (log scale) and temperature (black contours)

Cold air outbreaks – SLW detrainment improvements

Thanks to Richard Forbes and Katrin Lonitz

CERES Net TOA SW discrepancy before improvement

CERES Net TOA SW discrepancy after improvement

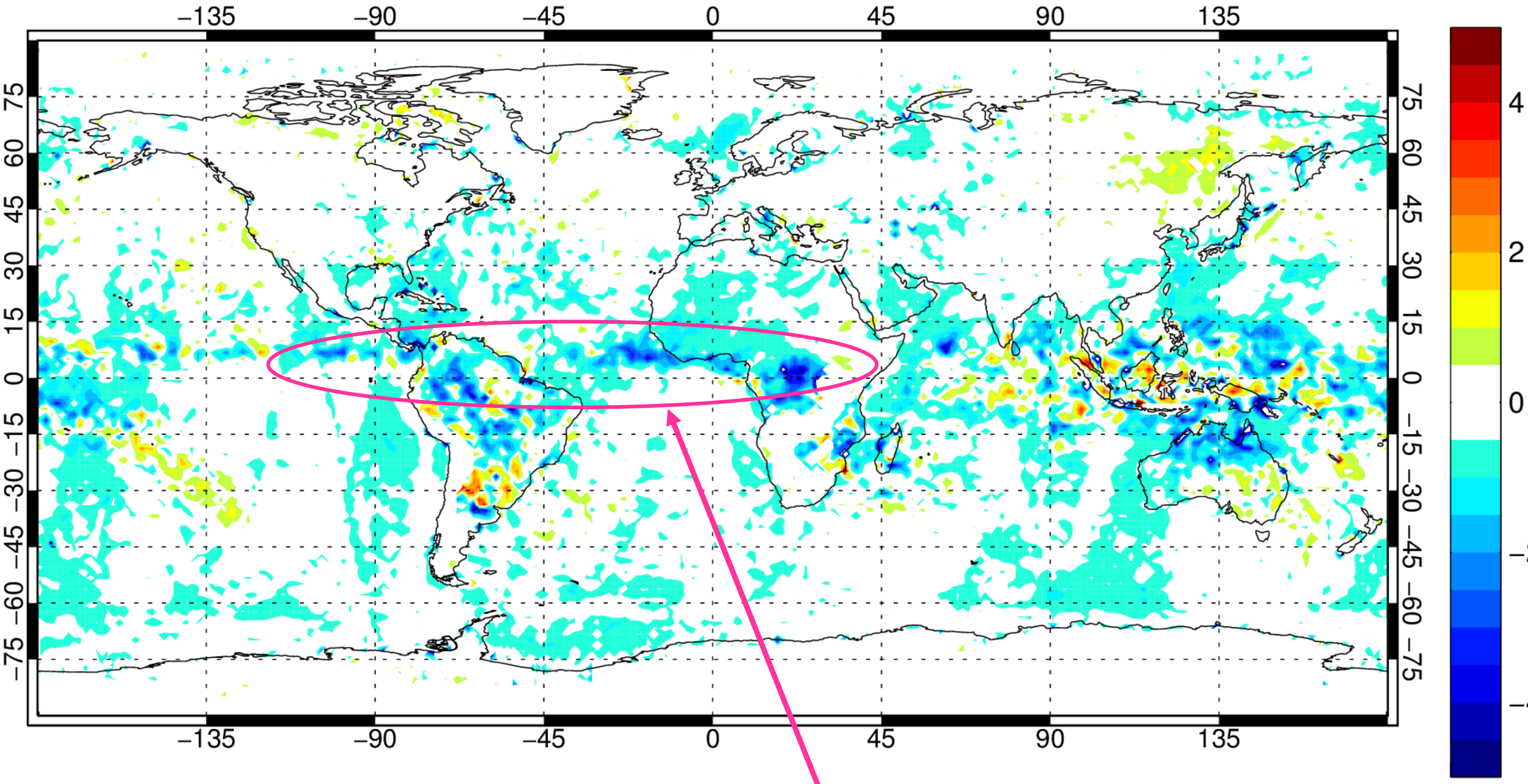


Just as important in the NH as in the SH

Biases at 183±3 GHz

sensitive to mid-troposphere humidity and scattering from frozen hydrometeors

Monthly mean bias December 2014 [K]



Insufficient scattering in radiative transfer model?
Insufficient convective ice/snow particles in IFS physics?

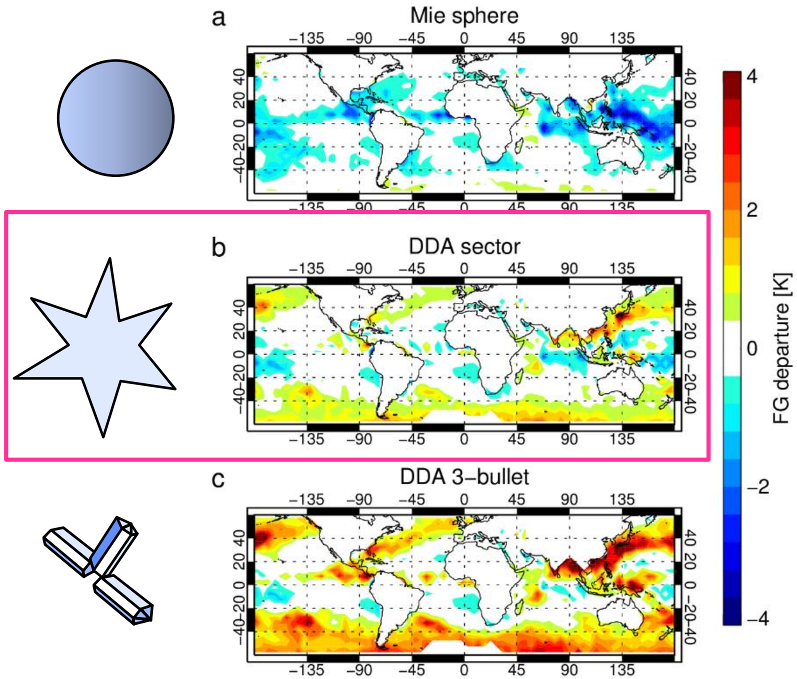
ECMWF

Insufficient scattering (i.e. perhaps insufficient frozen particles) in tropical convection?

NO

- “Snow” scattering is tuned to the model!
- Geer and Baordo (2014, AMT) selected between Liu (2008) frozen particle shapes to find the best fit between IFS and observations, assuming the Field et al. (2007) size distribution a-priori.

One of dozens of constraints on the tuning: the 183±7 GHz monthly mean bias [K]



ECMWF

Why should modellers care about data assimilation?

- Cloud and precipitation observations are now routinely constraining NWP models:
  - Moist parametrisation “upgrades” really have to work – there’s fewer places to hide now!
  - Cloud and precipitation observations can guide these upgrades
  - A joint activity for modellers and observation specialists:
    - Liquid phase, low microwave frequencies: radiative transfer models are relatively insensitive to physical assumptions → good confidence to attribute of biases to the forecast model (e.g. SLW in CAO, marine SCu)
    - Ice phase, high microwave frequencies: far more tuning and physical assumptions required → much more difficult to attribute biases

Why should modellers care about data assimilation?

- Forward simulations (NWP) versus retrievals (traditional approach) – see also Andrew Gettleman's talk
  - Climate mean versus instantaneous comparisons
  - In retrieval space, all the assumptions, errors and sampling limitations are completely hidden
  - In observation space, assumptions are clear (e.g. ice hydrometeor shape and size distributions)

Why should modellers care about data assimilation?

- Variational cloud and precipitation assimilation <u>depends on</u> moist physics tangent linear and adjoint models
  - We need to keep maintaining the TL and adjoint models
  - No, they are not necessary in ensemble data assimilation, but it is so far only in 4D-Var that we see routine operational cloud and precipitation assimilation with benefit to forecasts
    - Ability of incremental 4D-Var to handle nonlinearities?

Some other cloud and precipitation assimilation activities:

- Operational at ECMWF:
  - Overcast infrared assimilation
  - Assimilation of ground radar and in-situ rain-accumulations
- In development at ECMWF:
  - EarthCARE assimilation (Marta Janiskova)
  - All-sky infrared assimilation
  - Ensemble approaches to cloud and precipitation assimilation
- Elsewhere:
  - Assimilation at visible wavelengths
  - Ensemble assimilation