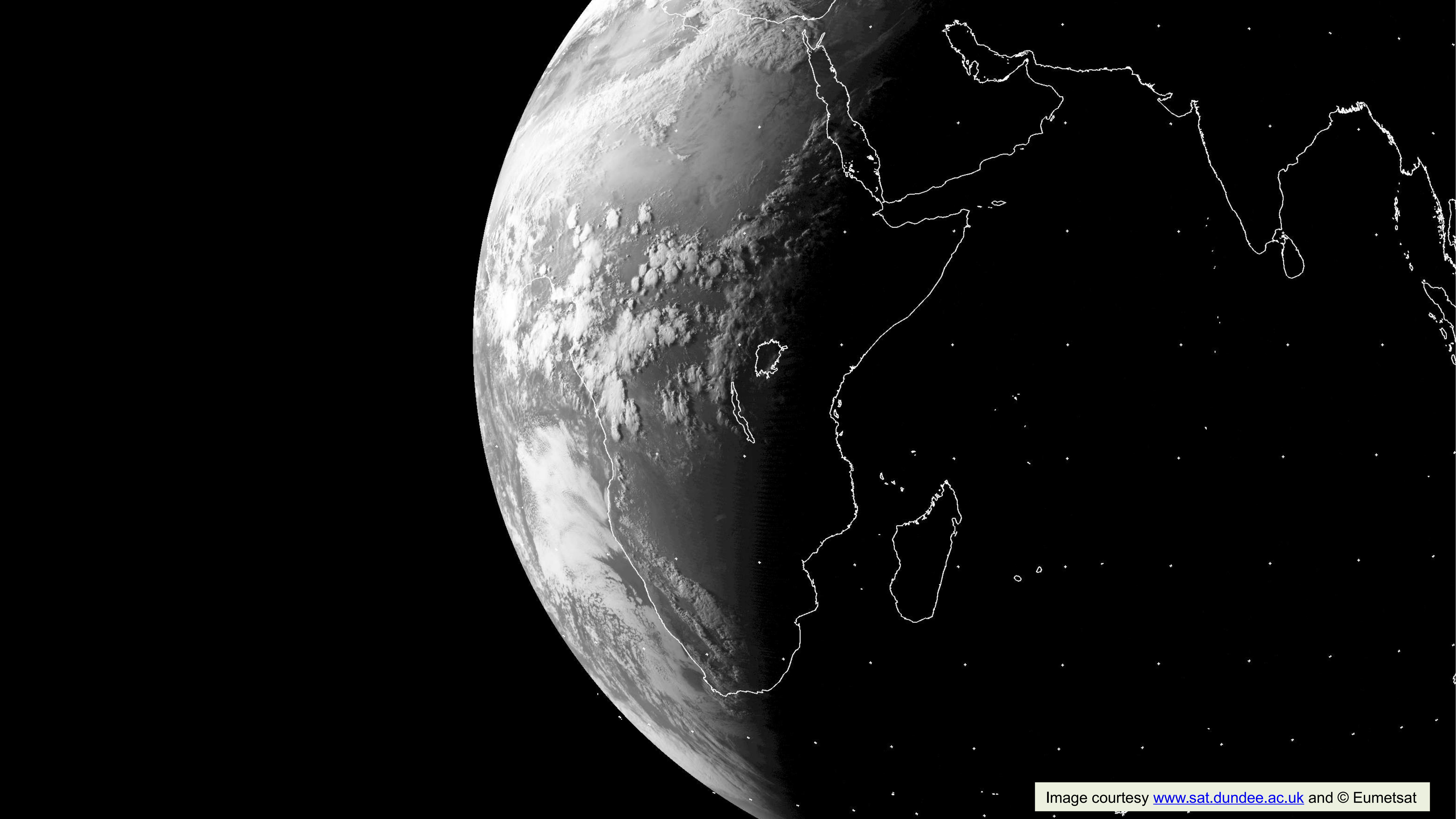
All-sky assimilation of satellite radiances for global weather forecasting

Alan Geer

with thanks to: Maike Ahlgrimm, Peter Bechtold, Massimo Bonavita, Niels Bormann, Stephen English, Mark Fielding, Richard Forbes, Robin Hogan, Elias Hólm, Marta Janisková, Katrin Lonitz, Philippe Lopez, Marco Matricardi, Irina Sandu, Peter Weston, Masahiro Kazumori, Kozo Okamoto, Yanqiu Zhu, Emily Huichun Liu, Andrew Collard, William Bell, Stefano Migliorini, Philippe Chambon, Nadia Fourrié, Min-Jeong Kim, Christina Köpken-Watts, Christoph Schraff, Heather Lawrence, Cristina Lupu

ECMWF



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Overview

1. Recap of all-sky radiance assimilation
    - Tools for all-sky assimilation
    - Benefits and limitations

2. Some current developments at ECMWF
    - All-sky IR and the gravity wave problem
    - Introducing inter-channel error correlations to the all-sky symmetric error model

1. All-sky assimilation - recap

Tools for all-sky radiance assimilation

- Observations
- A forecast model that represents cloud and precipitation:
  - For all its issues (see e.g. Katrin's talk) the IFS has an extremely good representation of cloud and precipitation
- A fast observation operator that represents cloud and precipitation:
  - E.g. RTTOV:
    - RTTOV-SCATT for the all-sky passive microwave (and hopefully active in future)
    - RTTOV with Chou scaling for the all-sky IR
    - MPHASIS for all-sky visible
- A data assimilation system
  - that can handle nonlinearity (e.g. Massimo Bonavita's talk)
  - that can infer increments in T, q, wind, cloud & precip from all-sky radiances
  - E.g. at ECMWF
    - incremental 4D-Var
    - TL and adjoint of moist physics
    - But no cloud or precipitation control variables
- An observation error model
  - includes error of representation (small-scale unpredictability of cloud and precip)

Why do all-sky assimilation? See the ISDA 2016 special issue…

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All-sky satellite data assimilation at operational weather forecasting centres

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ECMWF

How observations sensitive to cloud and precipitation benefit NWP

T, q and wind:
better initial conditions
= better forecasts

1. Use more satellite observations, even if there's no benefit from the cloud and precipitation information itself
   – e.g. try to recover some of the 80% of data lost to cloud in lower-sounding IR channels

2. Directly improve dynamical initial conditions through the observation of cloud and precipitation
   – e.g. infer the strength of a low pressure system from the intensity of its frontal precipitation: the "generalised 4D-var tracer effect"

Cloud and precipitation:
- better nowcasting and short-range forecasts
- better modelling

3. Initialise cloud and precipitation itself

4. Help improve the forecast model – the indirect effect
   – Benefits all forecast ranges, even when initial conditions are lost

How observations sensitive to cloud and precipitation benefit NWP

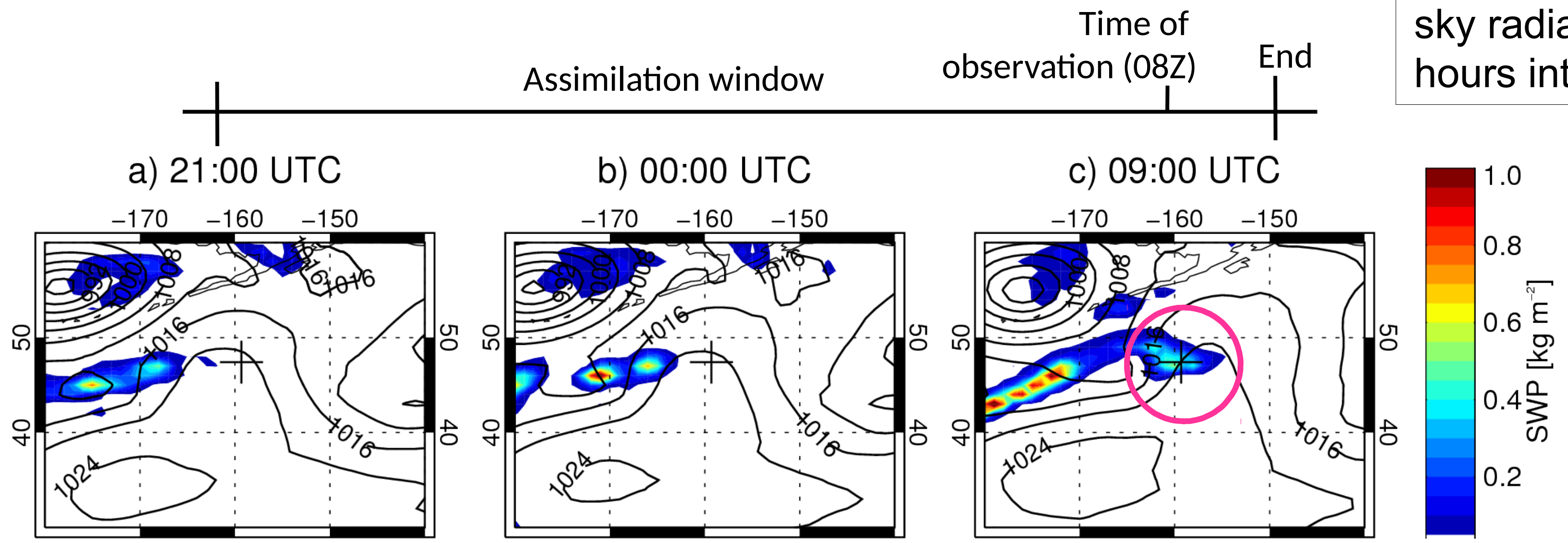
T, q and wind:
better initial conditions = better forecasts

Cloud and precipitation:
- better nowcasting and short-range forecasts
- better modelling

Generalised “tracer effect” in 4D-Var

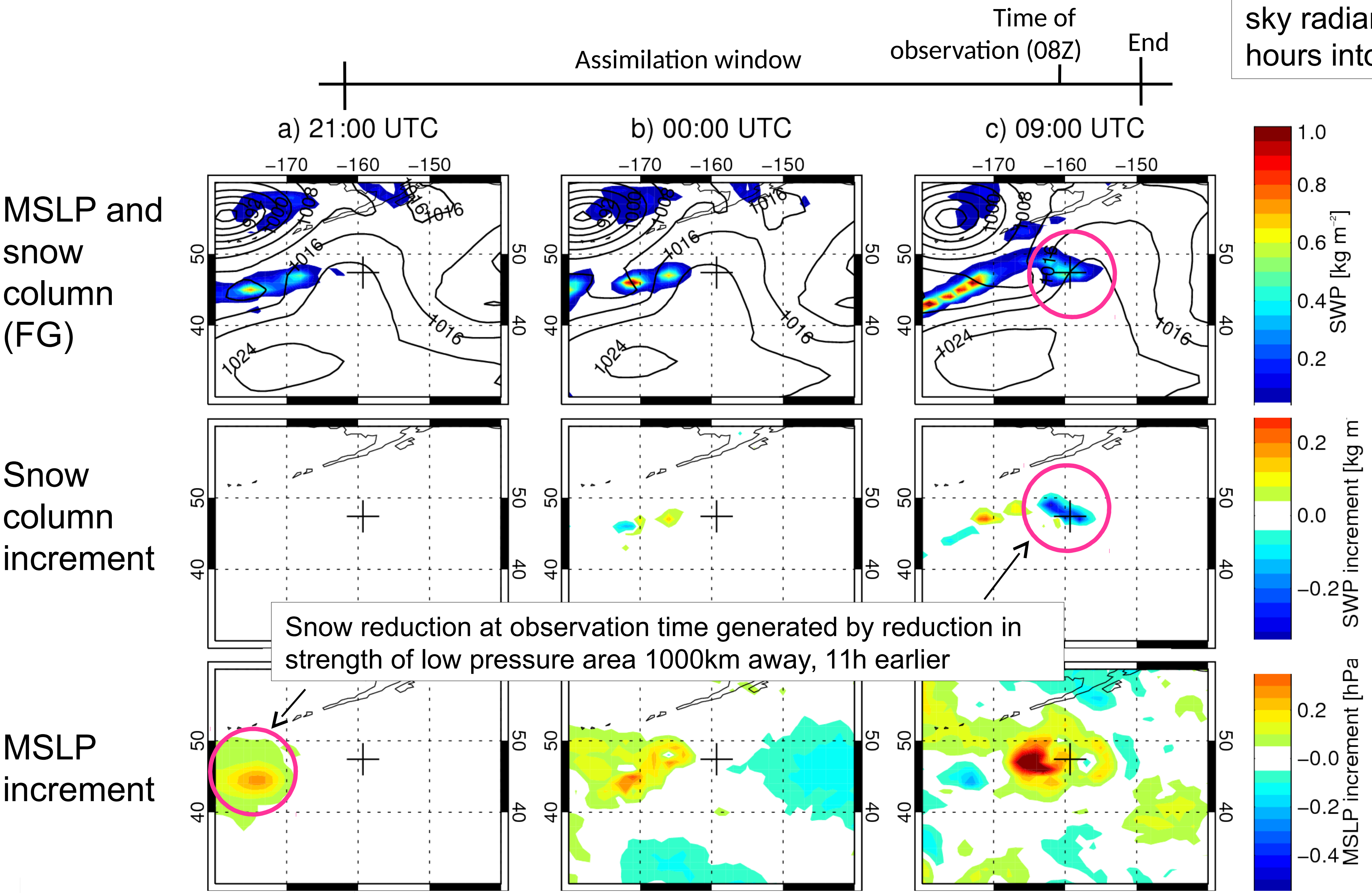
Single observation test case: all-sky radiance observation valid 11 hours into the 4D-Var window

MSLP and snow column (FG)



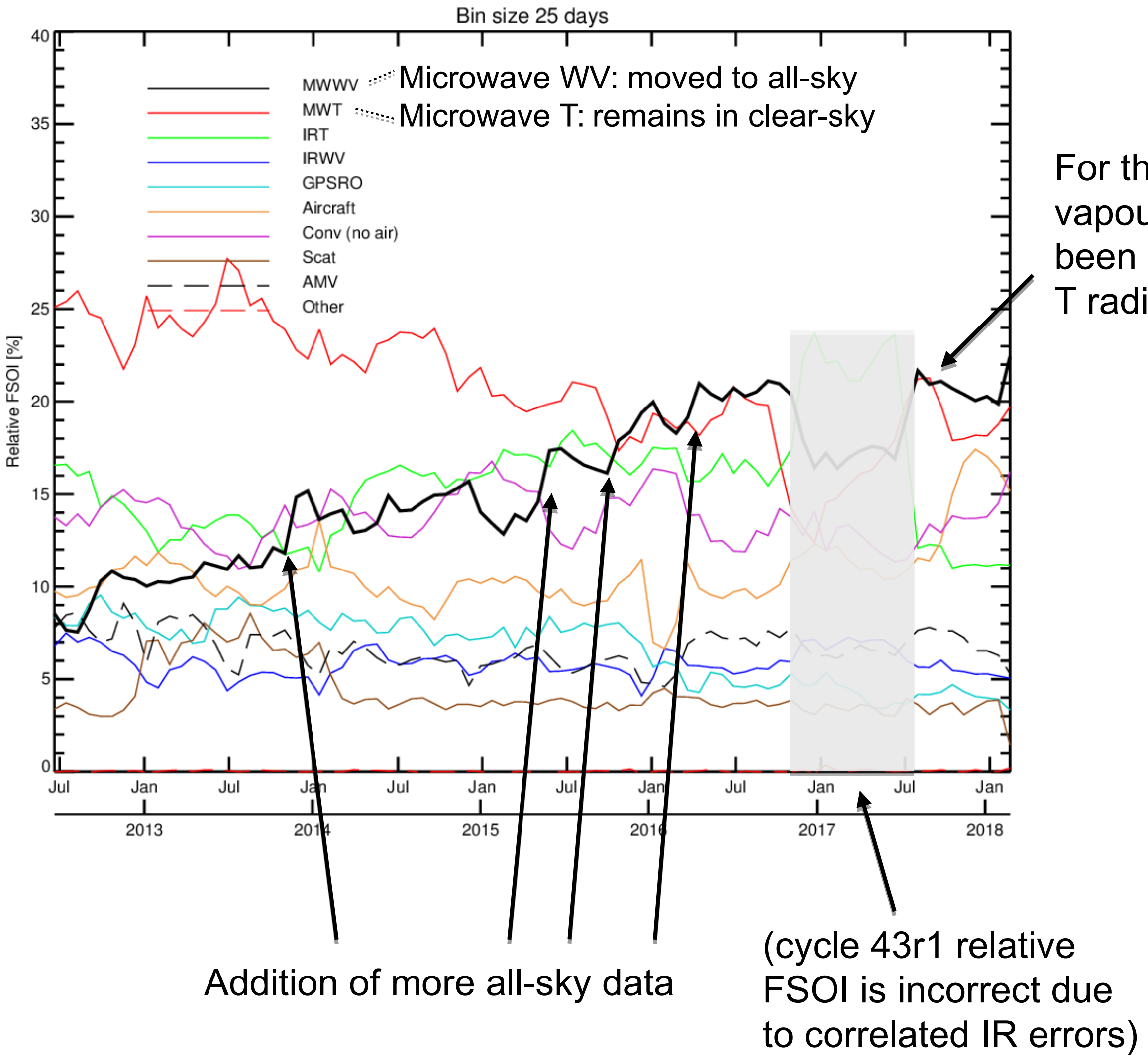
Generalised “tracer effect” in 4D-Var

Single observation test case: all-sky radiance observation valid 11 hours into the 4D-Var window



All-sky microwave WV / imager radiances improve initial conditions → improve forecasts

Relative FSOI from different observing system components
(= adjoint-based measure of short-range forecast impact)



For the last two years at ECMWF, microwave water vapour, cloud and precipitation radiances have been providing as much information as microwave T radiances

How observations sensitive to cloud and precipitation benefit NWP

T, q and wind:
better initial conditions = better forecasts

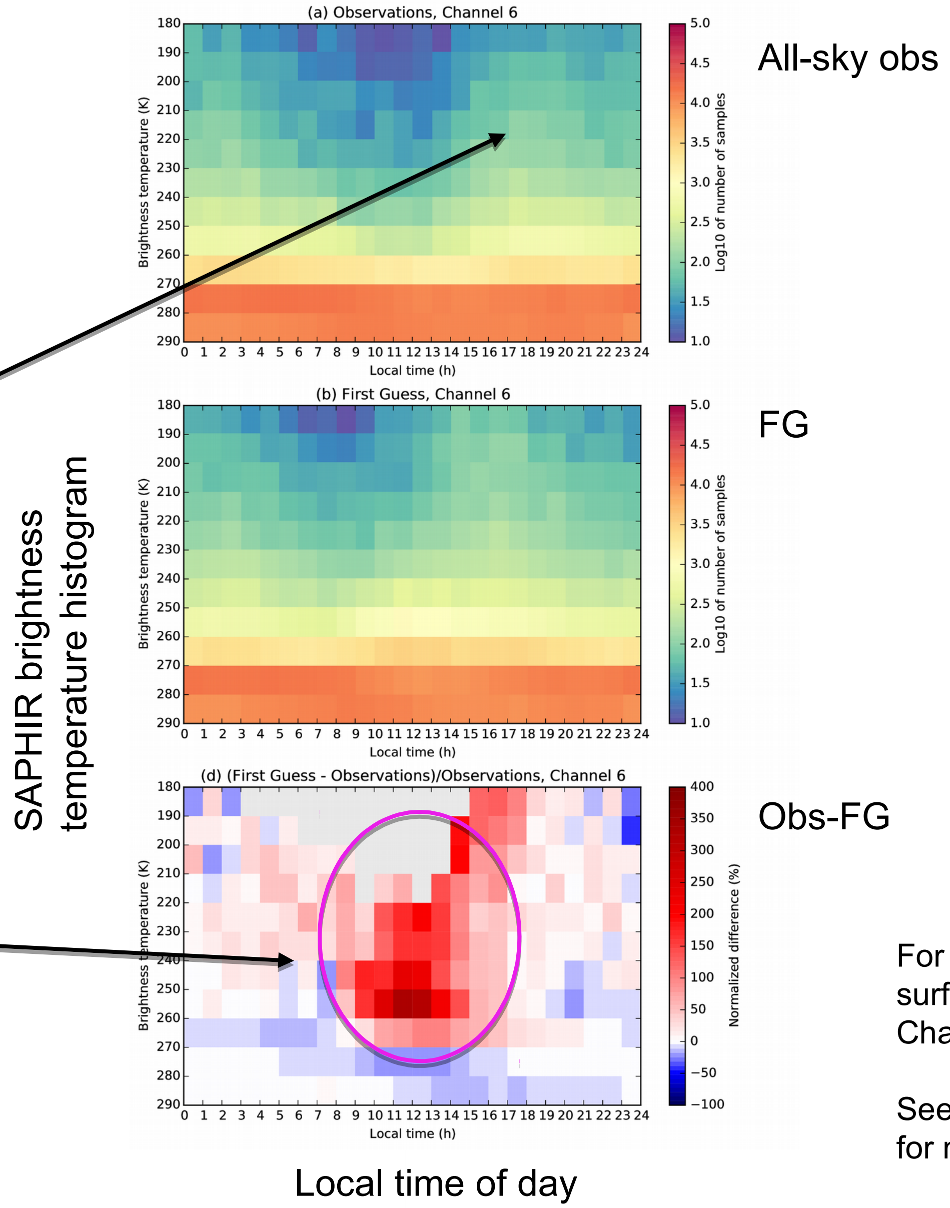
Cloud and precipitation:
- better nowcasting and short-range forecasts
- better modelling

Cloud and precipitation: feedback between DA and modelling

E.g. SAPHIR tropical microwave WV sounder gives feedback on the diurnal cycle of convection in the model

Low 183 GHz brightness temperatures = scattering from large frozen hydrometeors = deep convection

Onset of glaciated phase of deep convection is too early by about 4 hours



For tropical land surfaces, taken from Chambon & Geer (2017)

See Katrin Lonitz's talk for more examples

Recent ECMWF “SAC paper”: a strategy for cloud and precip assimilation & issues to think about


TECHNICAL MEMORANDUM

815

Assimilating observations sensitive to cloud and precipitation

Alan Geer, Maike Ahlgrimm, Peter Bechtold, Massimo Bonavita, Niels Bormann, Stephen English, Mark Fielding, Richard Forbes, Robin Hogan, Elias Hólm, Marta Janisková, Katrin Lonitz, Philippe Lopez, Marco Matricardi, Irina Sandu, Peter Weston

Research Department

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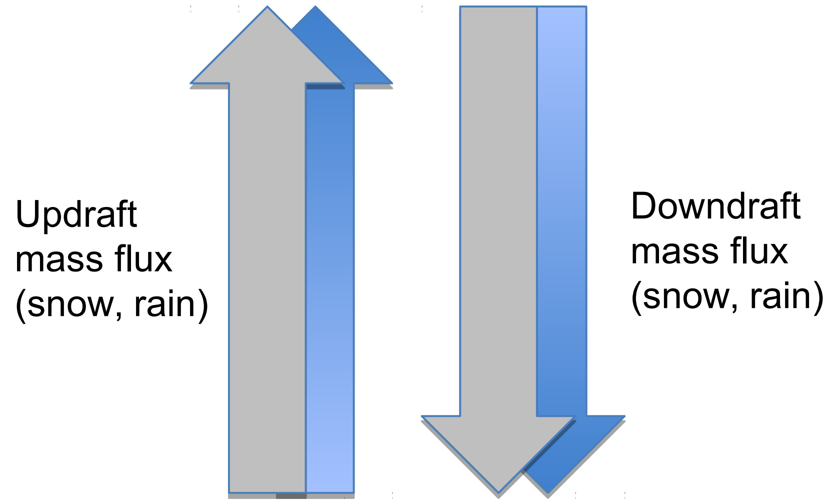
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen terme

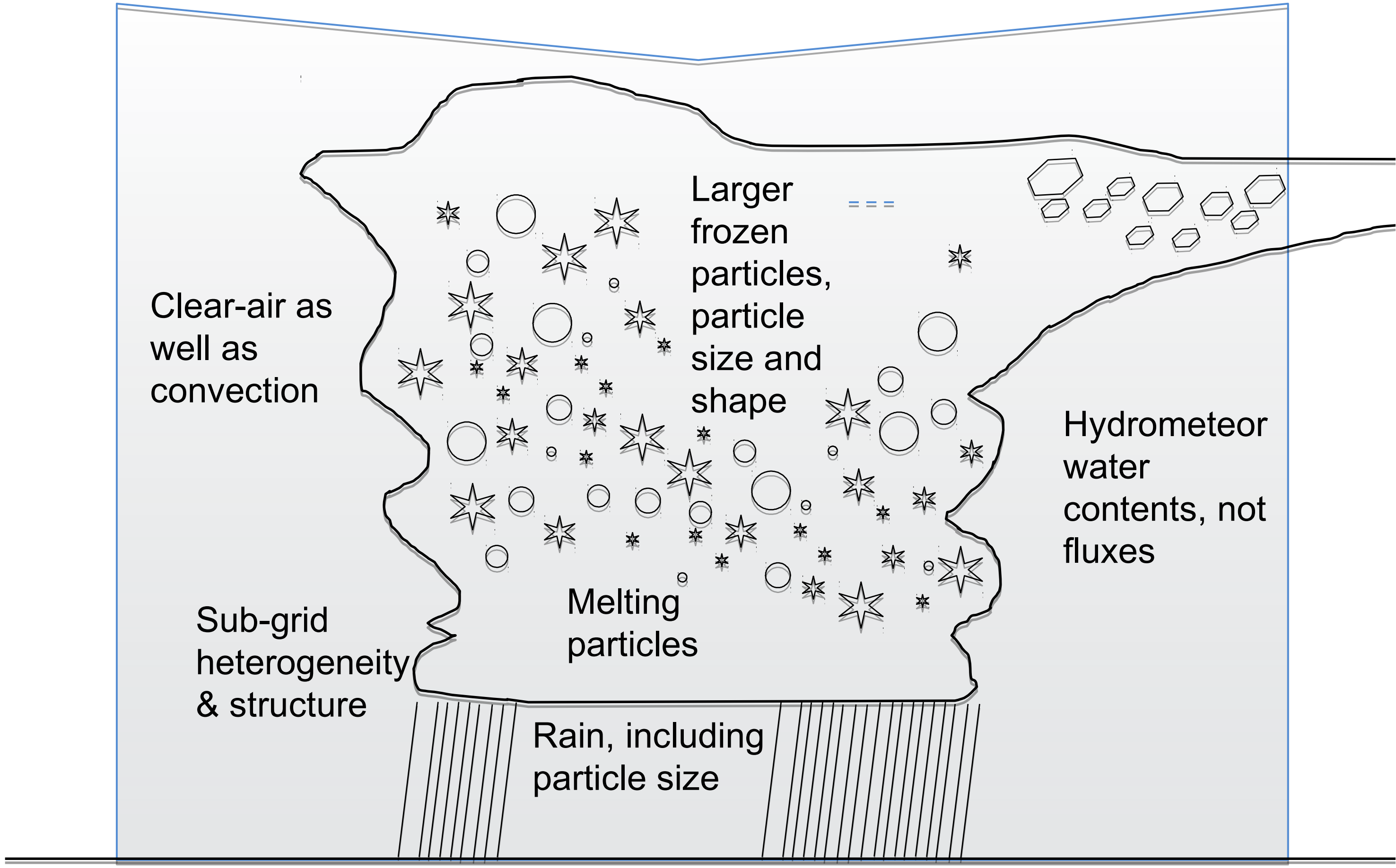
Issues - does the model represent what the observations see?

Model convection



Not predicted:
- microphysical information (e.g. particle shapes & sizes, riming, hail, graupel)
- sub-grid layout of convection
- hydrometeor mass
- fall-speeds

All-sky microwave radiance observations



Issues - the need for sub-grid and microphysical closure

- Current inconsistency in sub-grid and microphysical assumptions, e.g:

Assumption	Large-scale condensation	Convection	Radiation	Microwave	Infrared	Radar/lidar
Precipitation overlap	Max-random (with cloud)	Max	Exponential-exponential	Implied max	Implied max	Max-random

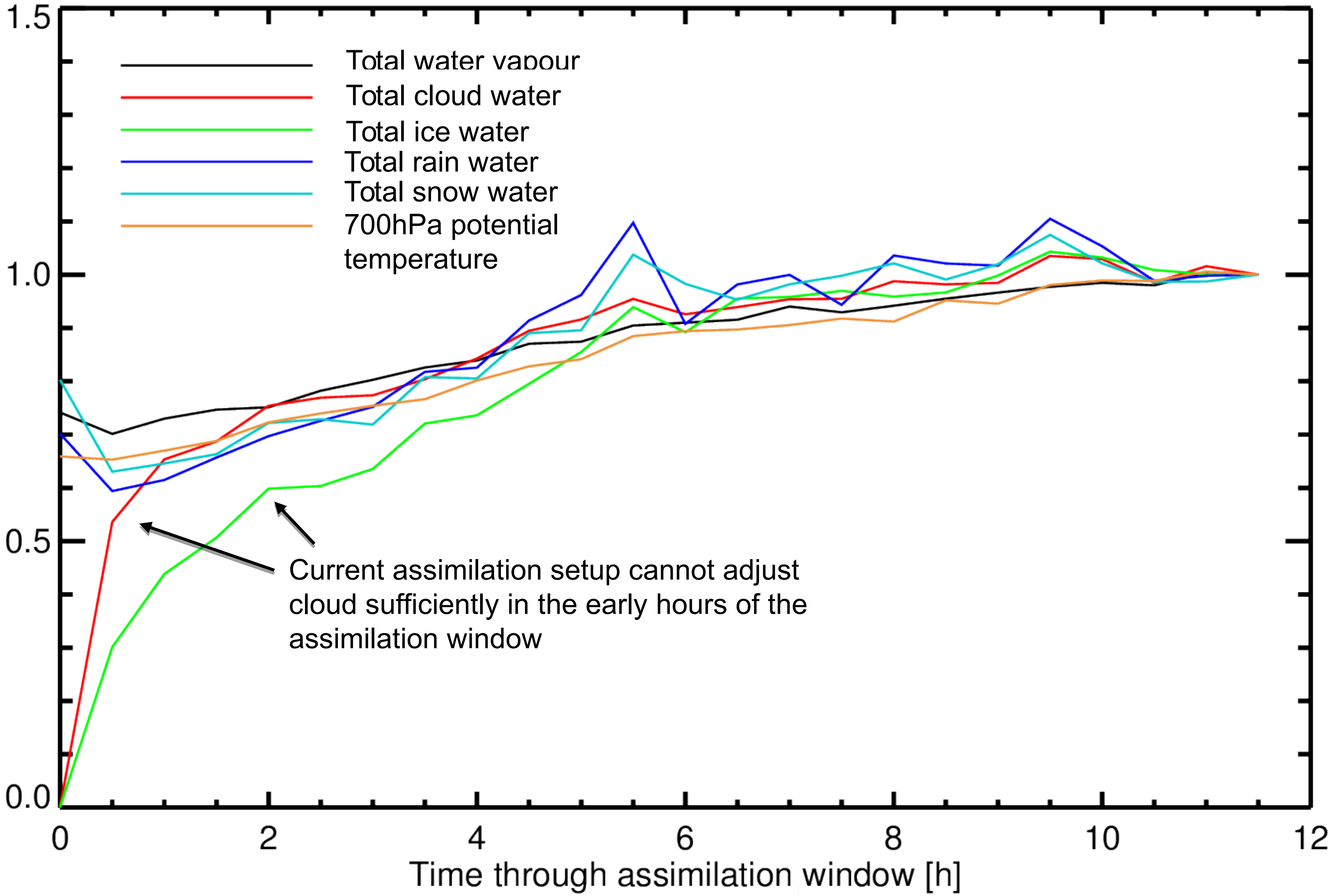
- Future: work to make these assumptions consistent (where possible) throughout the forecast and observation operator modelling chain. Use the observations as a constraint.
  - Start to add prognostic / diagnostic detail in the physics (multi-moment, riming?)

- Ultimate, maybe unreachable, goal: sub-grid and microphysical closure
  - Between the model and the observations, all assumptions are fully constrained
    - Any poor assumptions show up as a degradation in fit to some of the observations
  - On a climatological, not instantaneous basis

Issues - need for cloud (but not yet precipitation) control variables in ECMWF DA

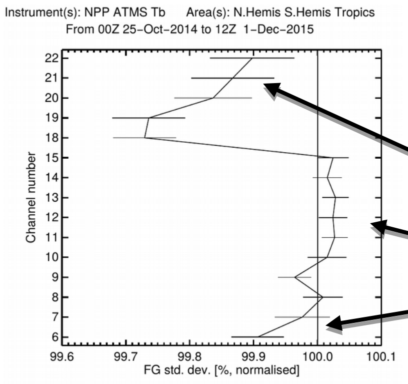
Standard deviation of analysis increment at GMI observation locations

[normalised to 1.0 at end of window]



Issues - it is hard work getting benefit from all-sky observations

- Despite the many benefits of all-sky radiance assimilation:
  - We can’t assimilate more than three all-sky microwave imagers a ECMWF without degrading forecast quality
  - GMI results (microwave imager data, active)
  - All-sky AMSU-A degrades stratosphere (in dev.)
  - All-sky infrared also degrades stratosphere (in dev.)



Impact of all-sky GMI on FG fits to ATMS:

WV much better

Stratosphere T worse

Troposphere T and q better

Tools for all-sky radiance assimilation

The problem could be anywhere!

… and possibly everywhere!

- Observations
- A forecast model that represents cloud and precipitation:
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- A fast observation operator that represents cloud and precipitation:
  - E.g. RTTOV:
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  - E.g. at ECMWF
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- An observation error model
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2. Current developments at ECMWF

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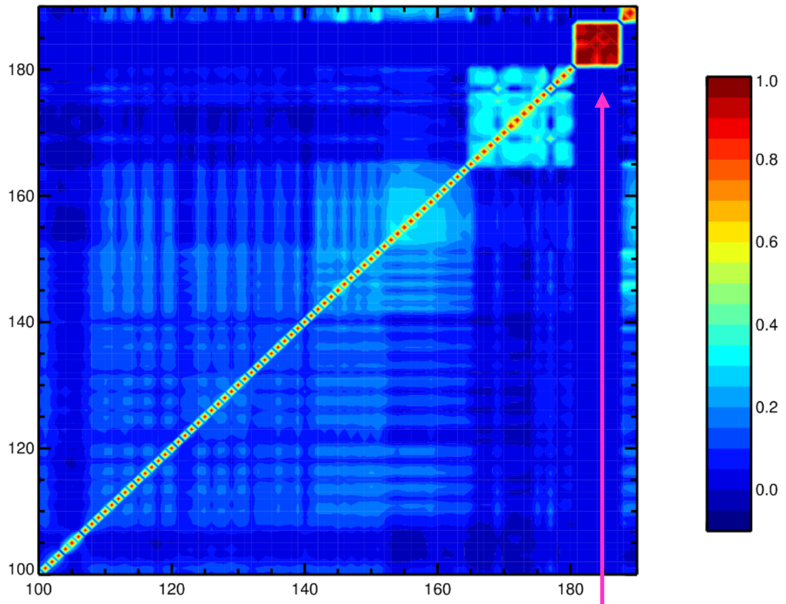
(i) – all-sky IR sees (and generates) gravity waves

Current method: assimilation of IASI

- Assimilate other IASI channels as normal, but move the 7 water vapour channels to all-sky framework

- Symmetric observation error model following Geer and Bauer (2010, QJ):
  - Clear-sky error ~1.5 K as Bormann et al. (2016, QJ)
  - Cloudy error inflated with Okamoto et al. (2014, QJ) predictor
  - All-sky error correlation (new)

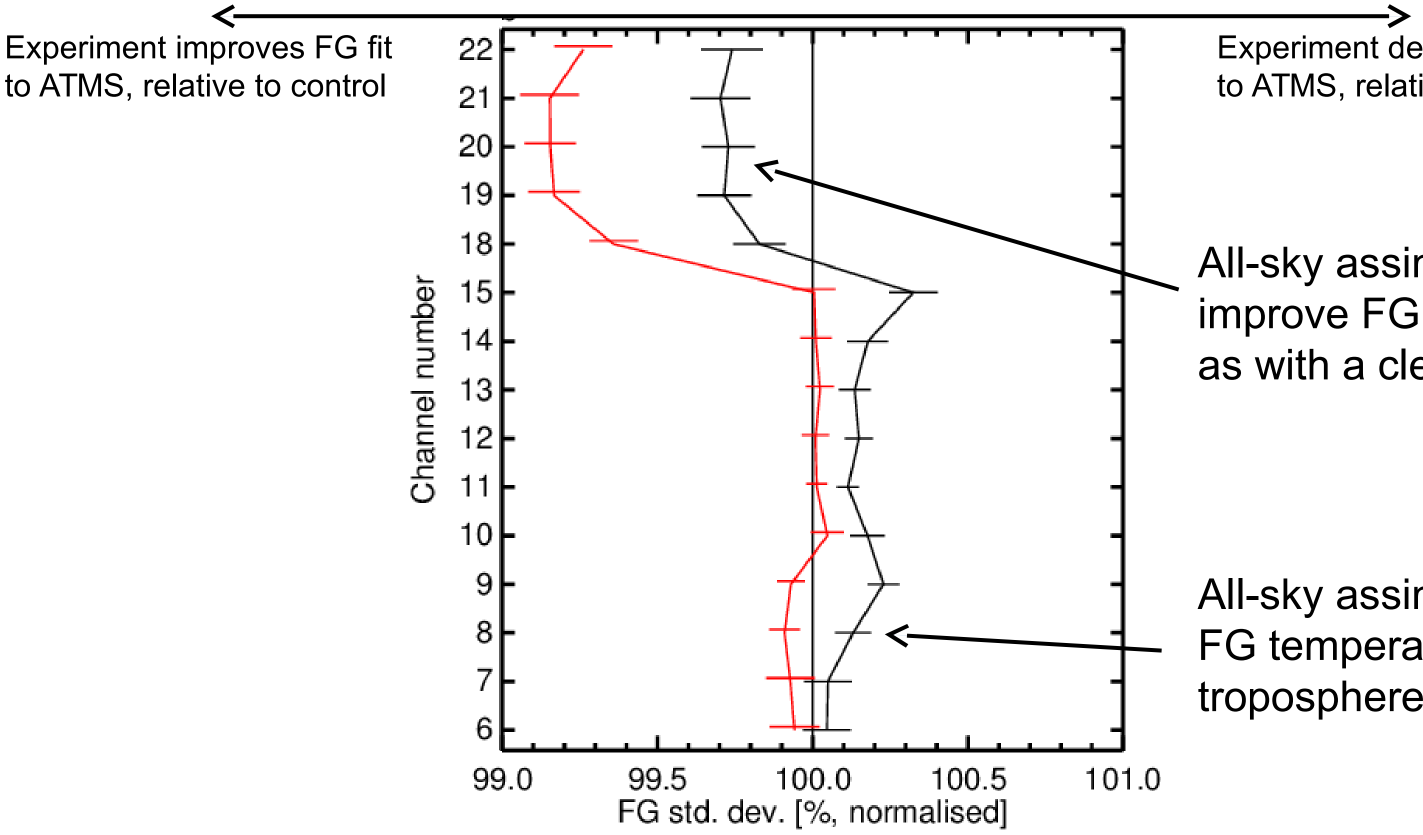
New IASI observation error correlation matrix



Other channels untouched (except that correlations with all-sky channels have been set to zero)

7 all-sky WV channels

2017 results: first guess fits to ATMS observations



All-sky assimilation cannot improve FG humidity as much as with a clear-sky approach

All-sky assimilation degrades FG temperature in upper-troposphere and stratosphere

(black line)	all–sky	= add 7 IASI WV channels in all-sky framework
(red line)	clear–sky	= add 7 IASI WV channels in clear-sky framework
100% =	control	= Full observing system minus 7 IASI WV channels

IR all-sky assimilation results presented at ISDA 2014

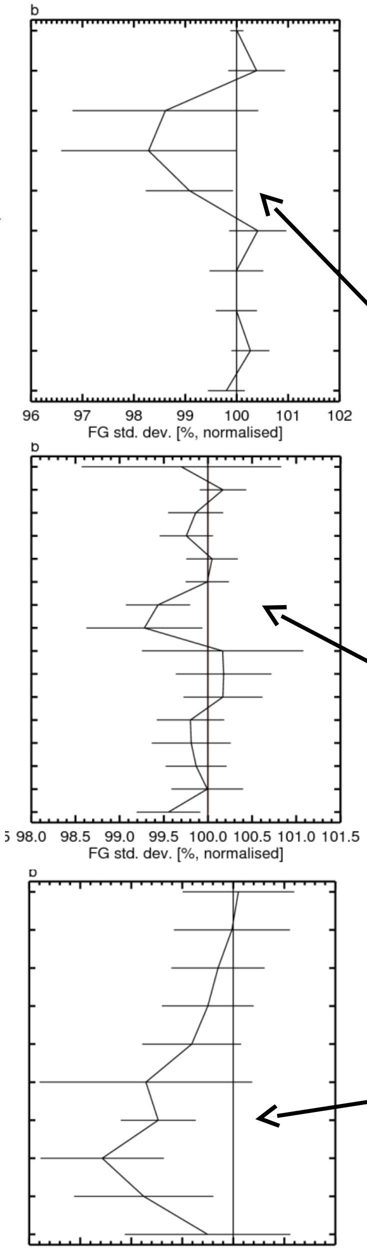
HIRS ch. 11&12 (from 2013)

- Control = full observing system minus HIRS
- Experiment = control +
  - Assimilation of HIRS channels 11 and 12 in all-sky situations from Metop-A, NOAA-19
  - Constant observation error: 6K in channel 11, 4K in channel 12

Sonde humidity

In-situ u-wind

AMSU-A



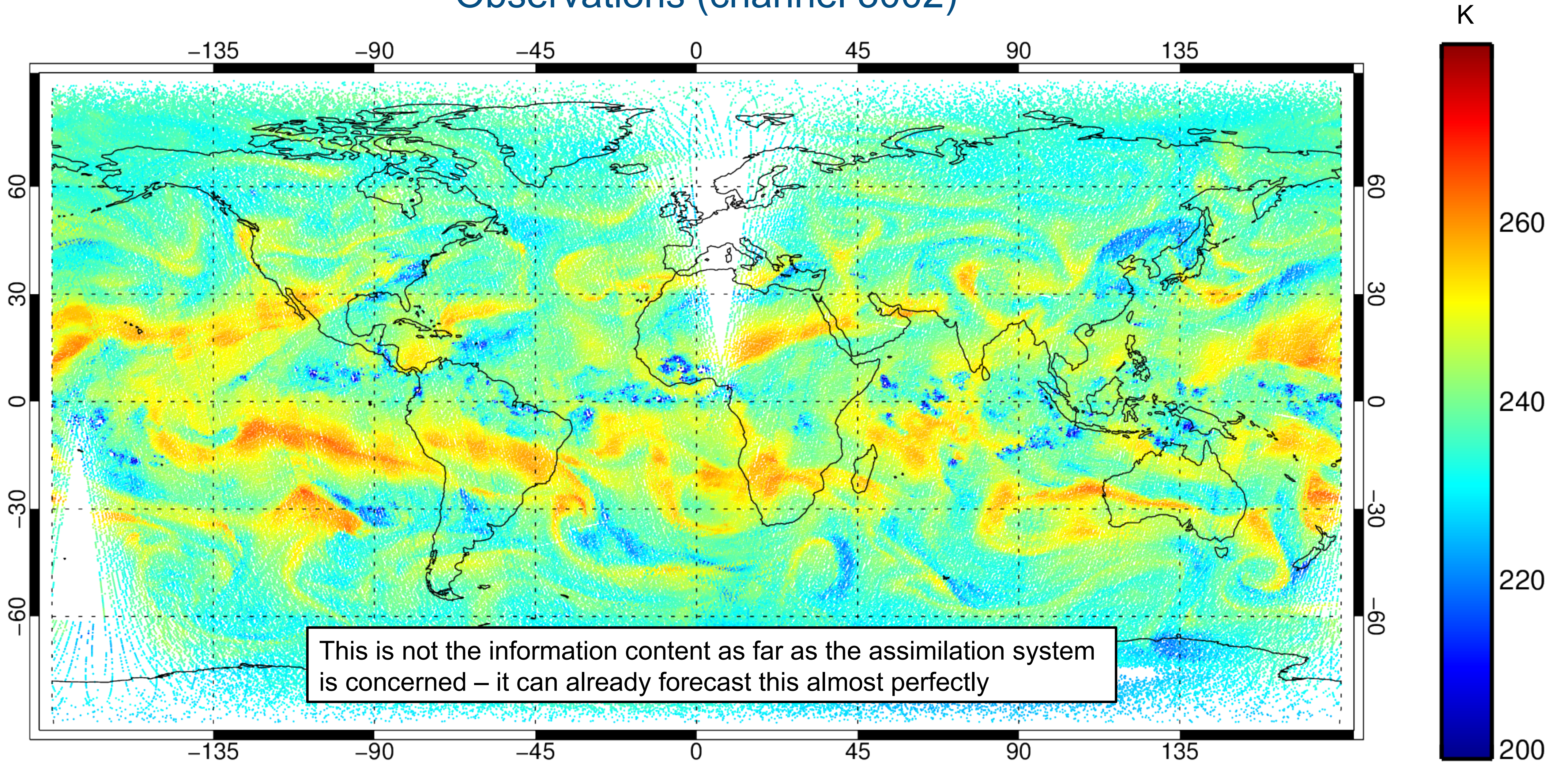
Upper tropospheric humidity improved by 1.5%

UTLS wind improved by 0.5%

UTLS temperature improved by 0.1%

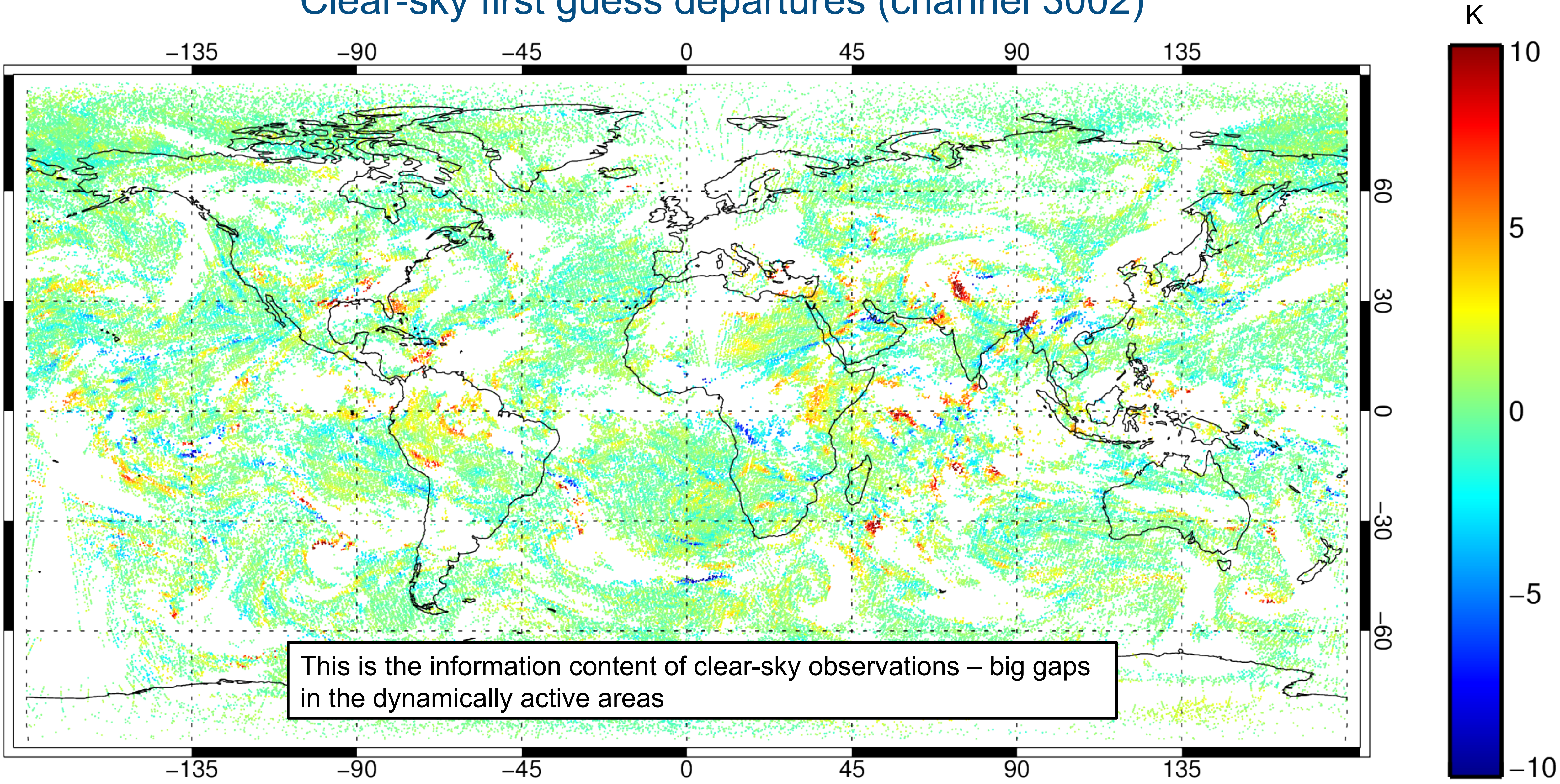
What is going on with IASI all-sky?

Observations (channel 3002)

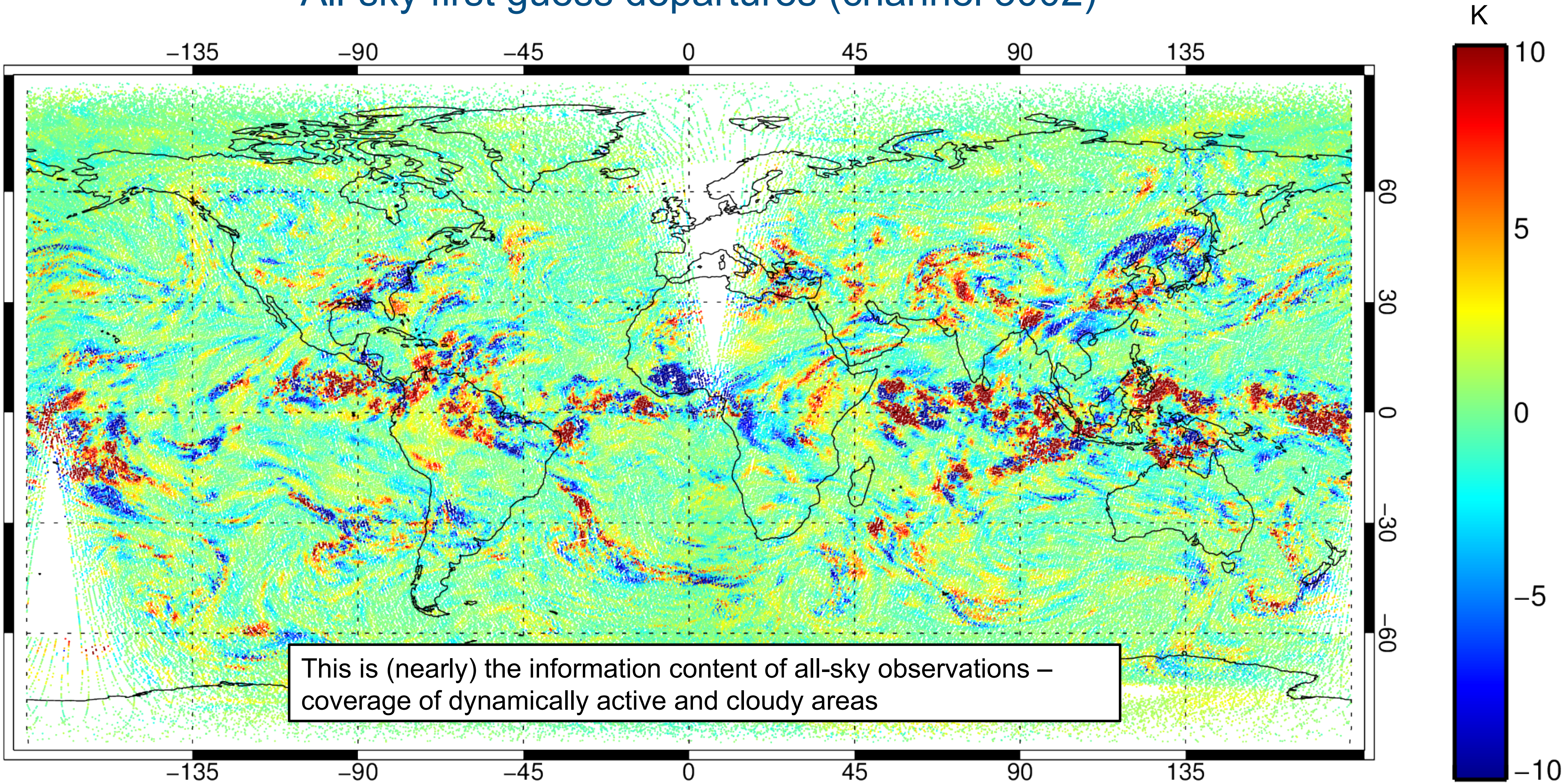


This is not the information content as far as the assimilation system is concerned – it can already forecast this almost perfectly

Clear-sky first guess departures (channel 3002)

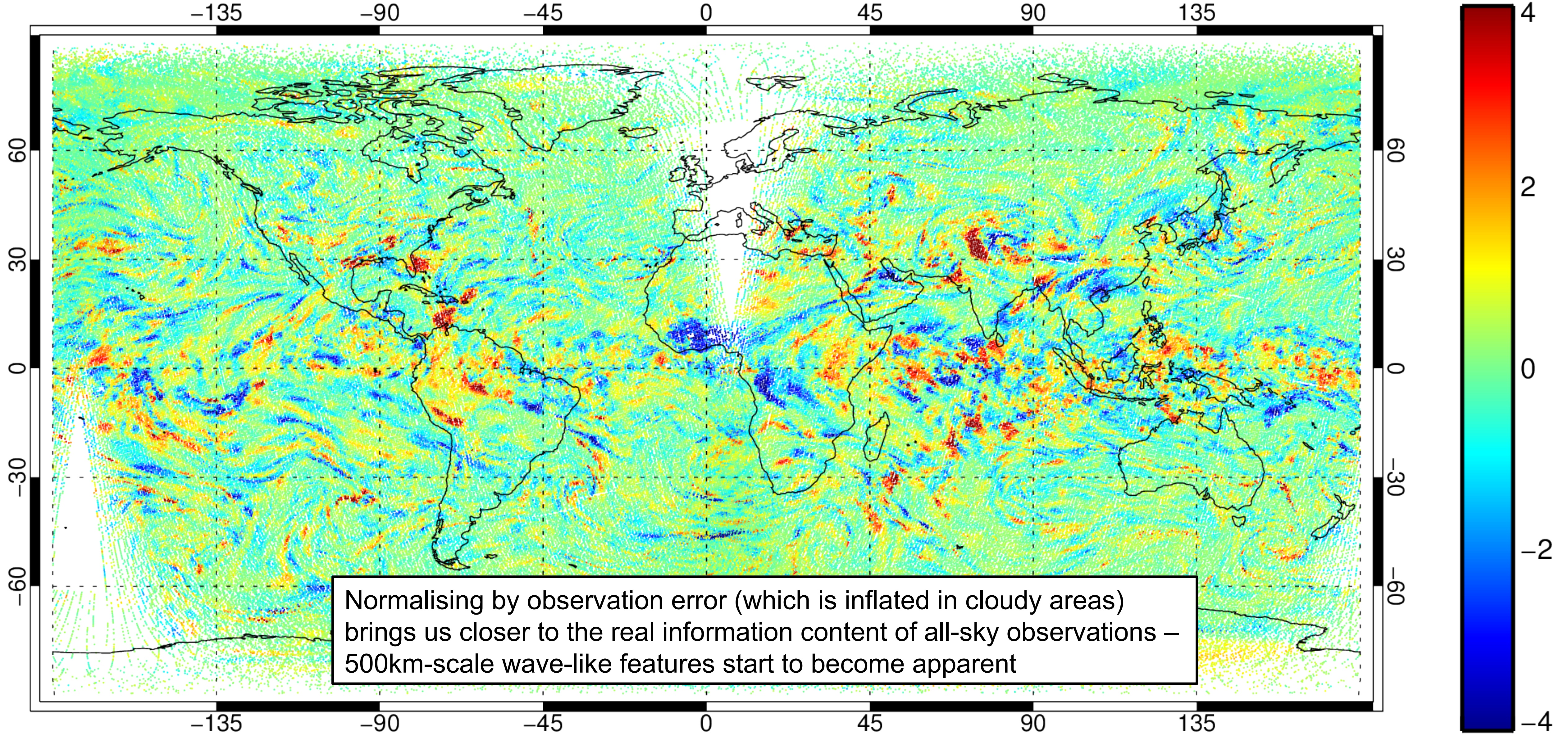


All-sky first guess departures (channel 3002)



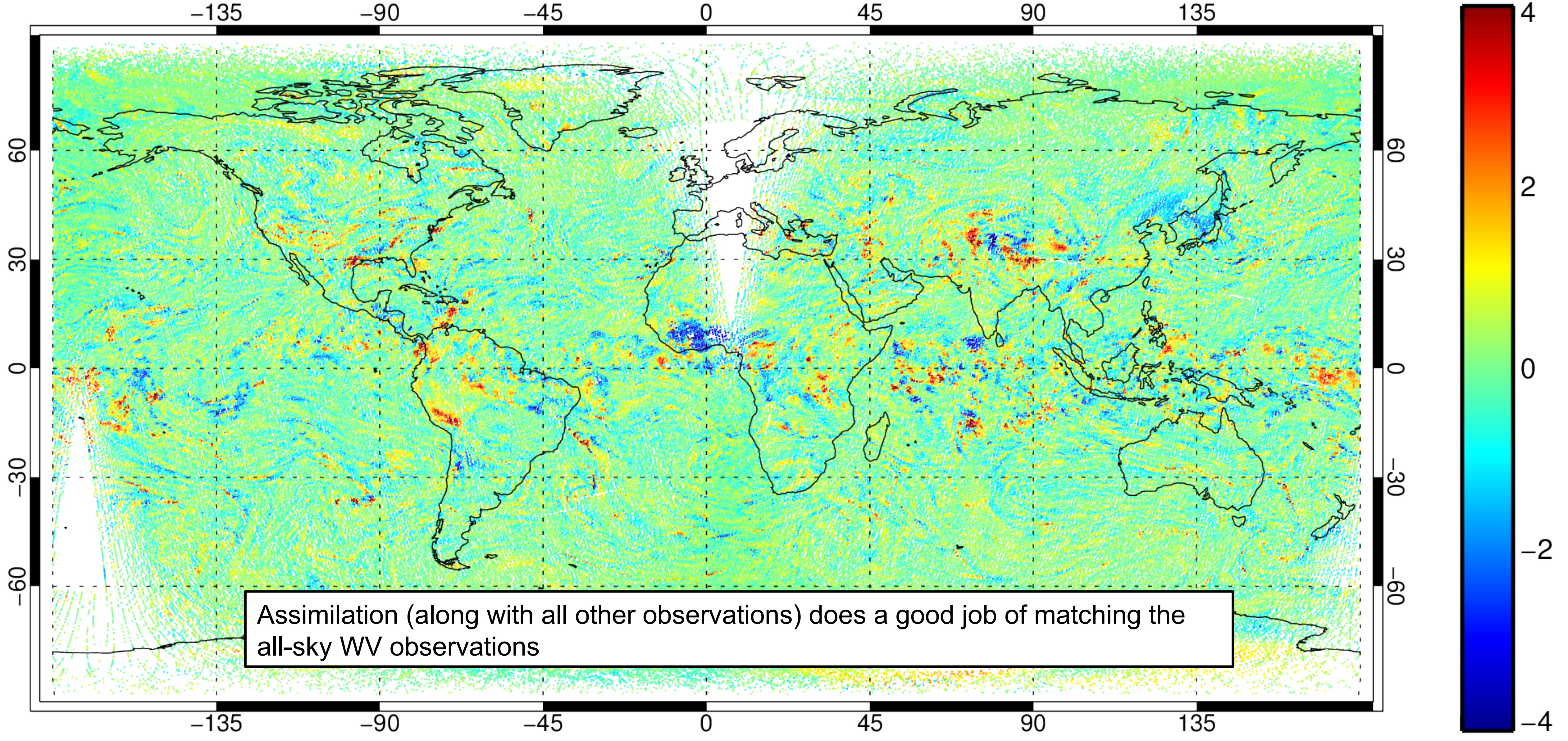
This is (nearly) the information content of all-sky observations – coverage of dynamically active and cloudy areas

All-sky normalised first guess departures ((O-B)/obs error)



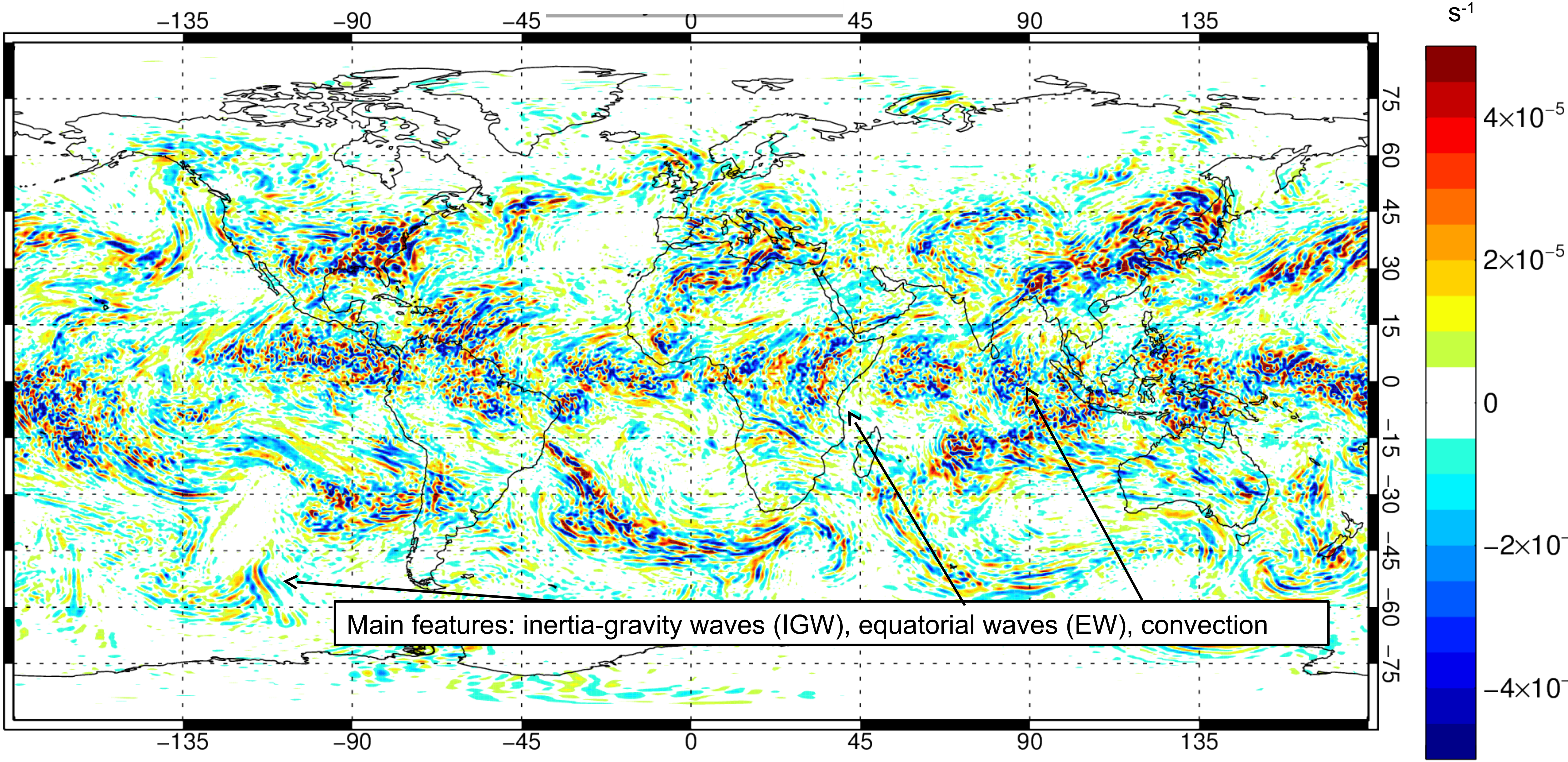
Normalising by observation error (which is inflated in cloudy areas) brings us closer to the real information content of all-sky observations – 500km-scale wave-like features start to become apparent

All-sky normalised analysis departures ((O-A)/obs error) - IASI WV active

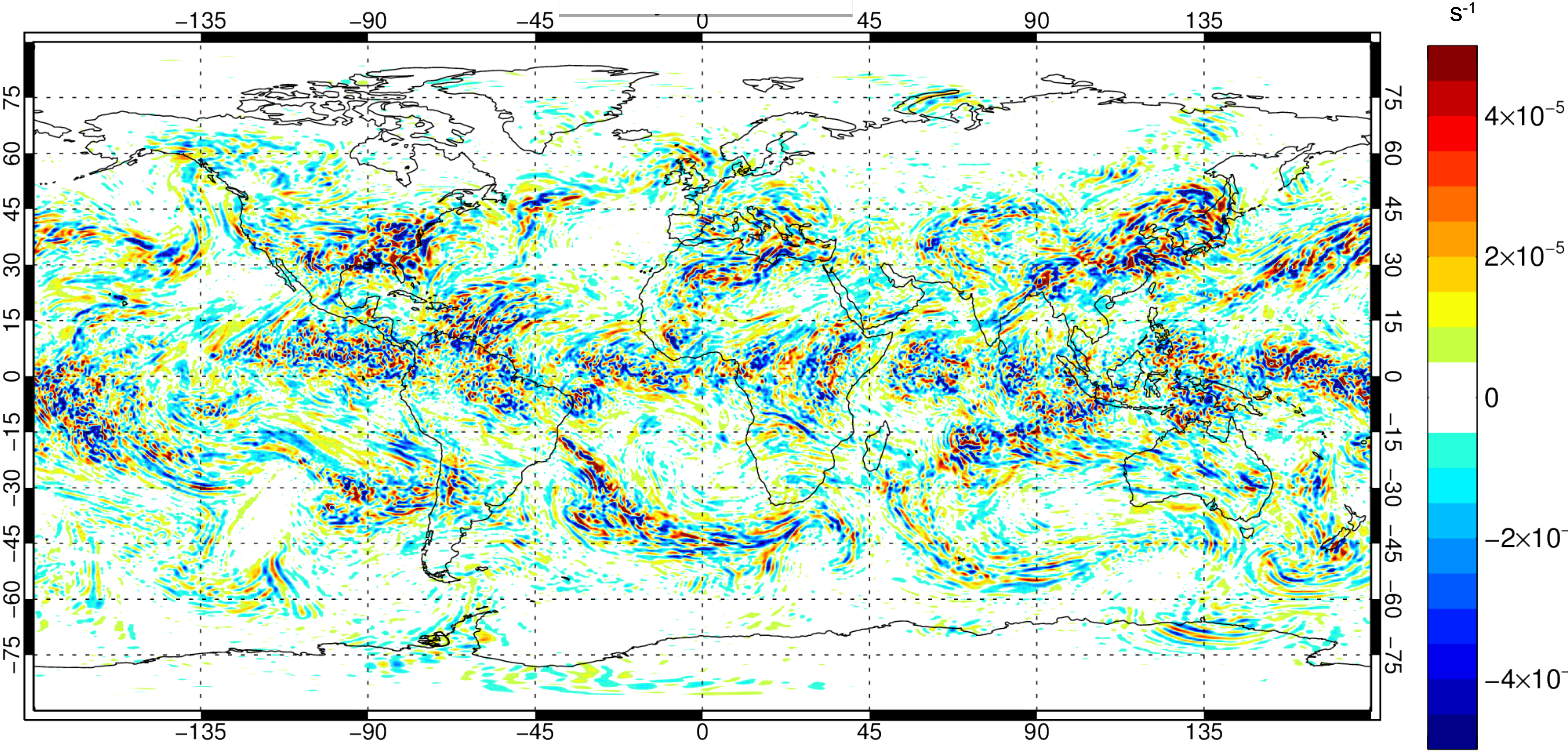


Assimilation (along with all other observations) does a good job of matching the all-sky WV observations

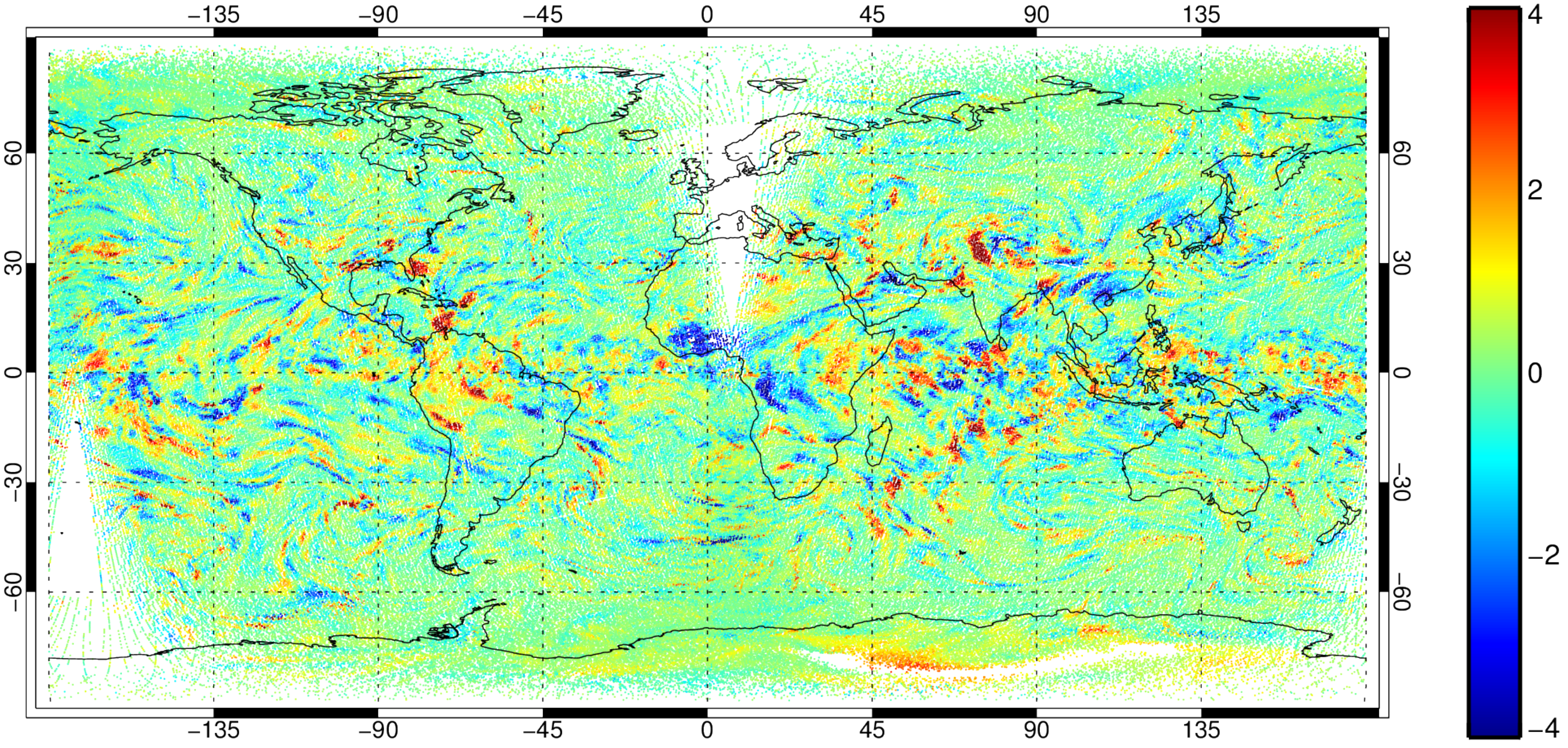
Increments in wind divergence at 200hPa, 00Z, coming from all observations



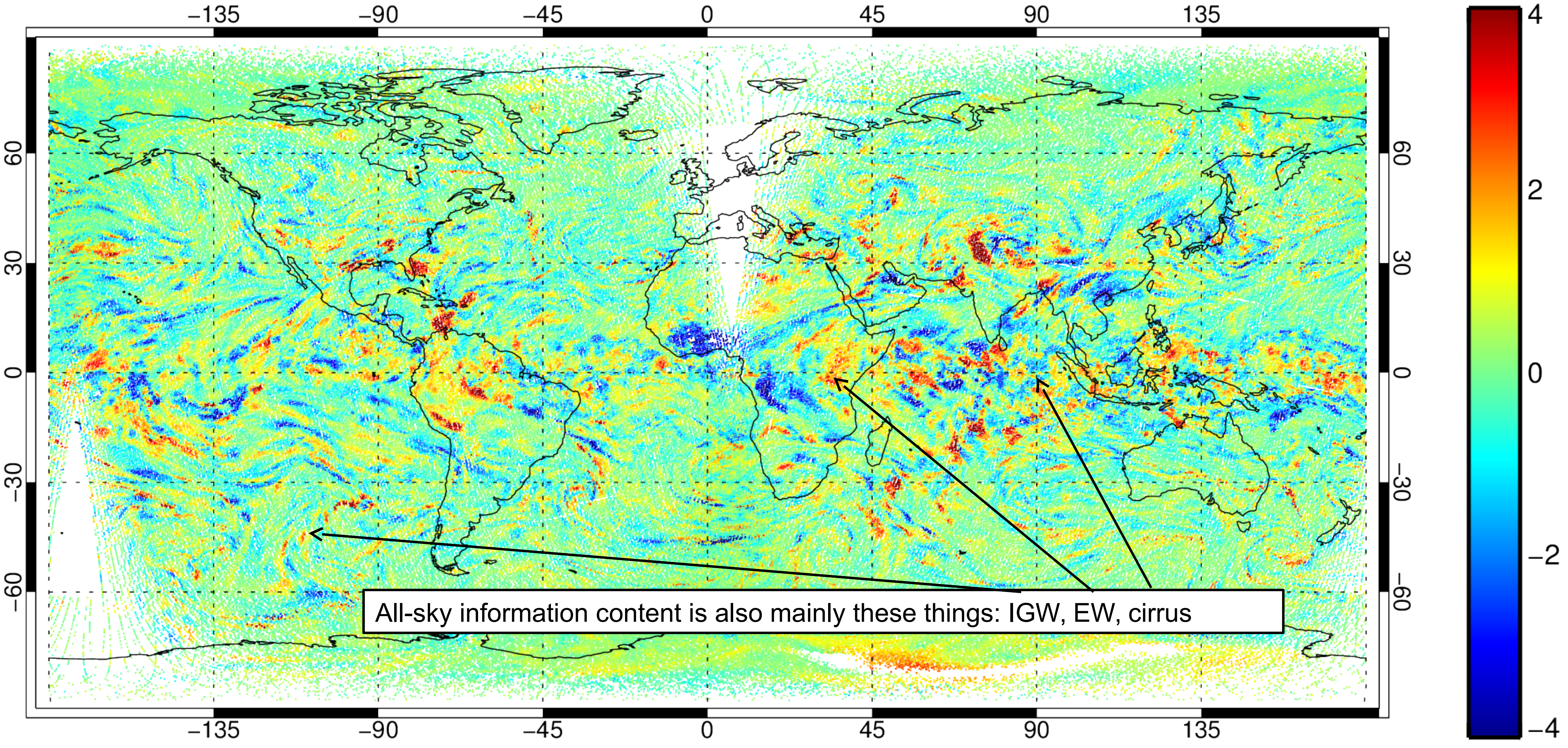
Increments in wind divergence at 200hPa, 00Z, coming from all observations



All-sky normalised first guess departures ((O-B)/obs error)



All-sky normalised first guess departures ((O-B)/obs error)



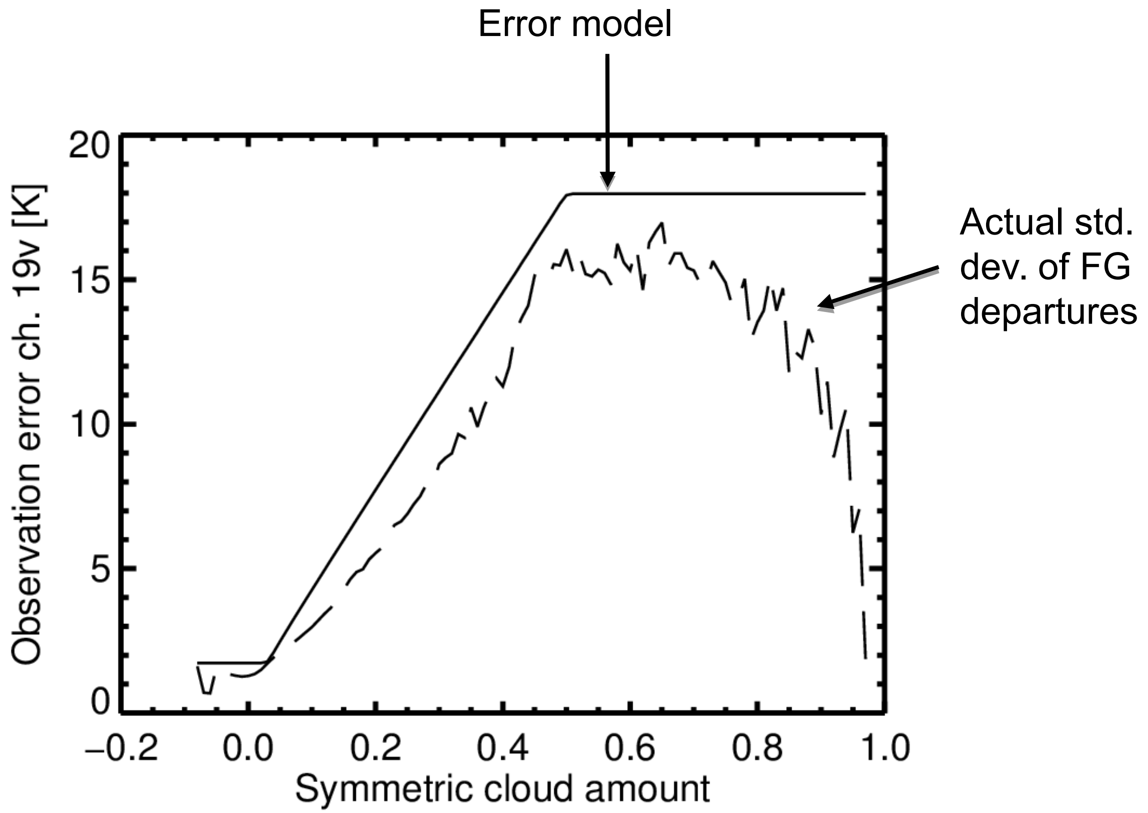
2. Current issues at ECMWF

(ii) – all-sky microwave: interchannel error correlations

Current error model – no interchannel error correlations

$$\mathbf{R}_i = \begin{matrix} \sigma^2_{19V} & 0 & 0 & \dots & 0 \\ 0 & \sigma^2_{19H} & 0 & \dots & 0 \\ 0 & 0 & \sigma^2_{22V} & \dots & 0 \\ \dots & \dots & \dots & \dots & 0 \\ 0 & 0 & 0 & 0 & \sigma^2_{183\pm7} \end{matrix}$$

Observation error covariance matrix tailored to one SSMIS observation (i)

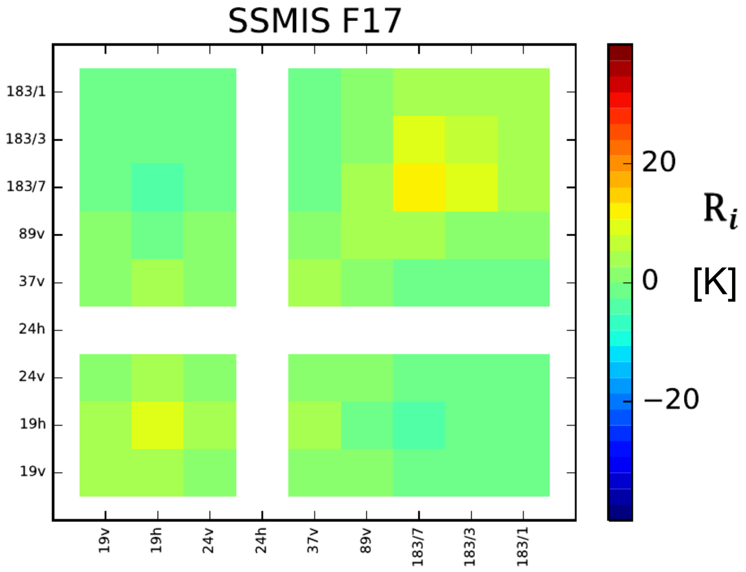


(C37 = average amount of “cloud” from observation and first guess)

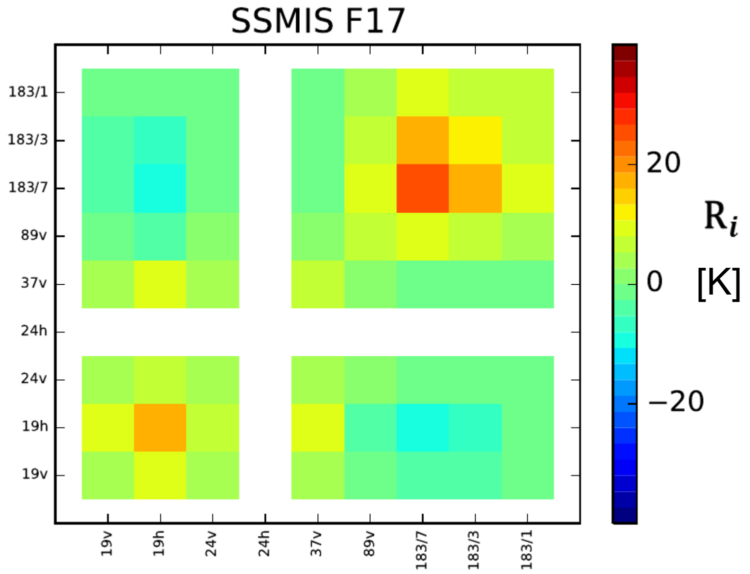
New error model – one fully specified covariance matrix per symmetric cloud bin

Increasing amount of cloud at observation location

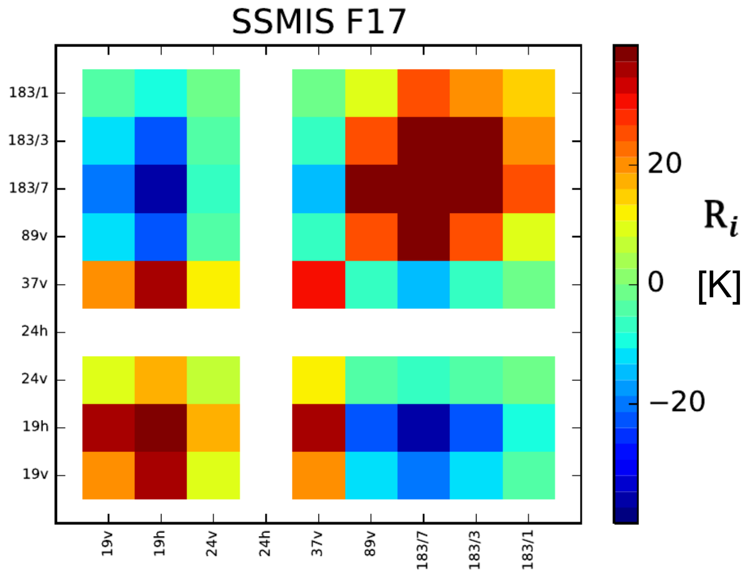
C37 bin: -1.00 to 0.02



C37 bin: 0.04 to 0.05



C37 bin: 0.12 to 0.13



Specifying and assessing the error model

•For one observation i, with FG departure $\mathbf{d}_i = \mathbf{y}_i - H_i(\mathbf{x})$

•Expected covariance is $\mathbf{R}_i + \mathbf{H}_i\mathbf{B}\mathbf{H}_i{}^{\mathrm{T}}$

•If observation error and background error are correctly specified and Gaussian then then $\mathbf{d}_i{}^{\mathrm{T}}\left(\mathbf{R}_i + \mathbf{H}_i\mathbf{B}\mathbf{H}_i{}^{\mathrm{T}}\right)^{-1}\mathbf{d}_i$ is distributed according to the chi squared distribution

•The all-sky "trick": typically for water vapour, cloud and precipitation radiances, $\mathbf{R}_i \gg \mathbf{H}_i\mathbf{B}\mathbf{H}_i{}^{\mathrm{T}}$ due to predictability-representation error. So aim for an observation error model:

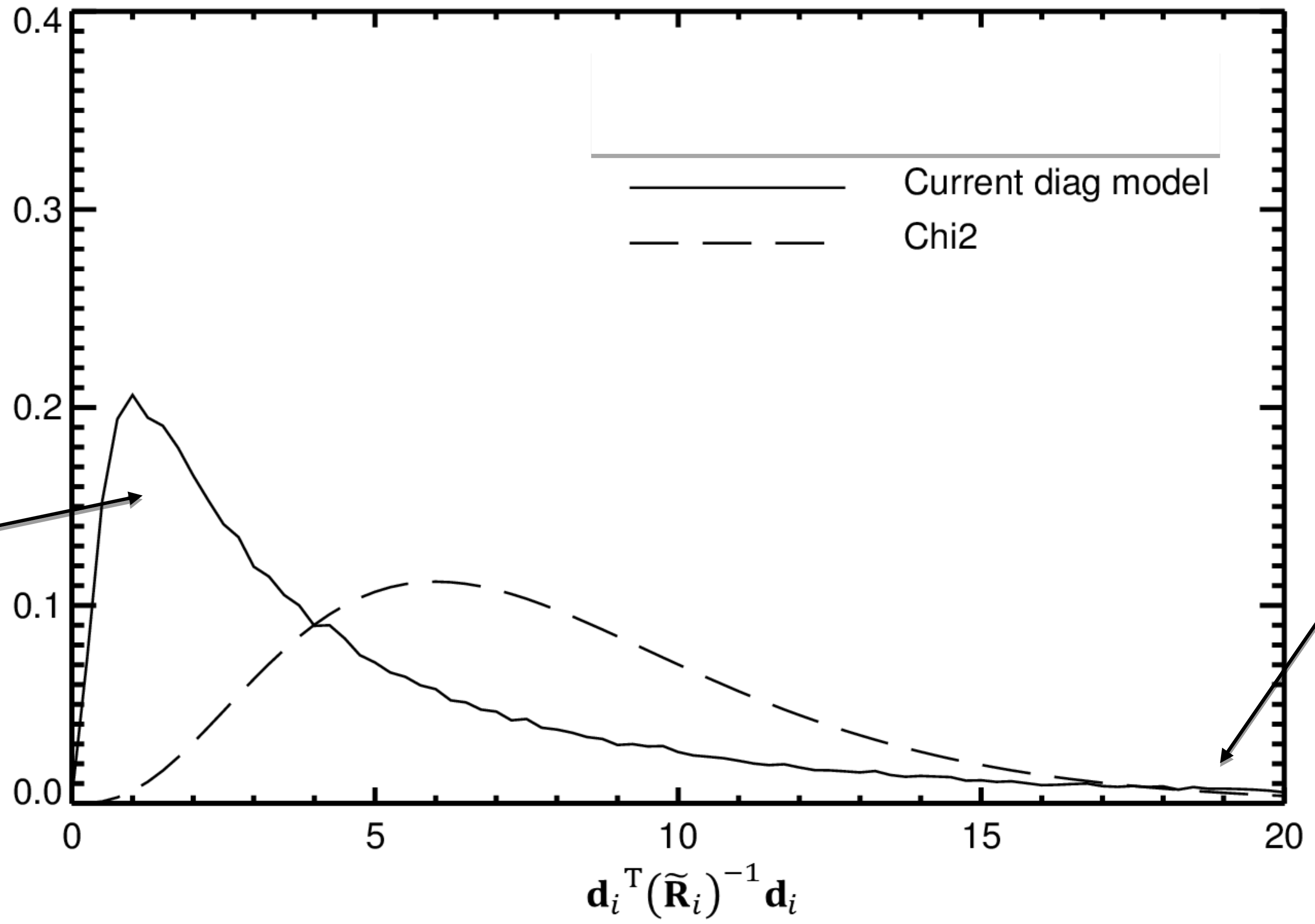
$$\widetilde{\mathbf{R}}_i \approx \mathbf{R}_i + \mathbf{H}_i\mathbf{B}\mathbf{H}_i{}^{\mathrm{T}} \approx \mathrm{E}[\mathbf{d}_i\mathbf{d}_i{}^{T}]$$

•We can then check that $\mathbf{d}_i{}^{\mathrm{T}}\left(\widetilde{\mathbf{R}}_i\right)^{-1}\mathbf{d}_i$ follows chi-squared. This quantity is also the cost per observation in the 4D-Var costfunction

In all-sky assimilation, $\mathbf{R}_i$ varies from one observation to the next depending on the cloud and precipitation state

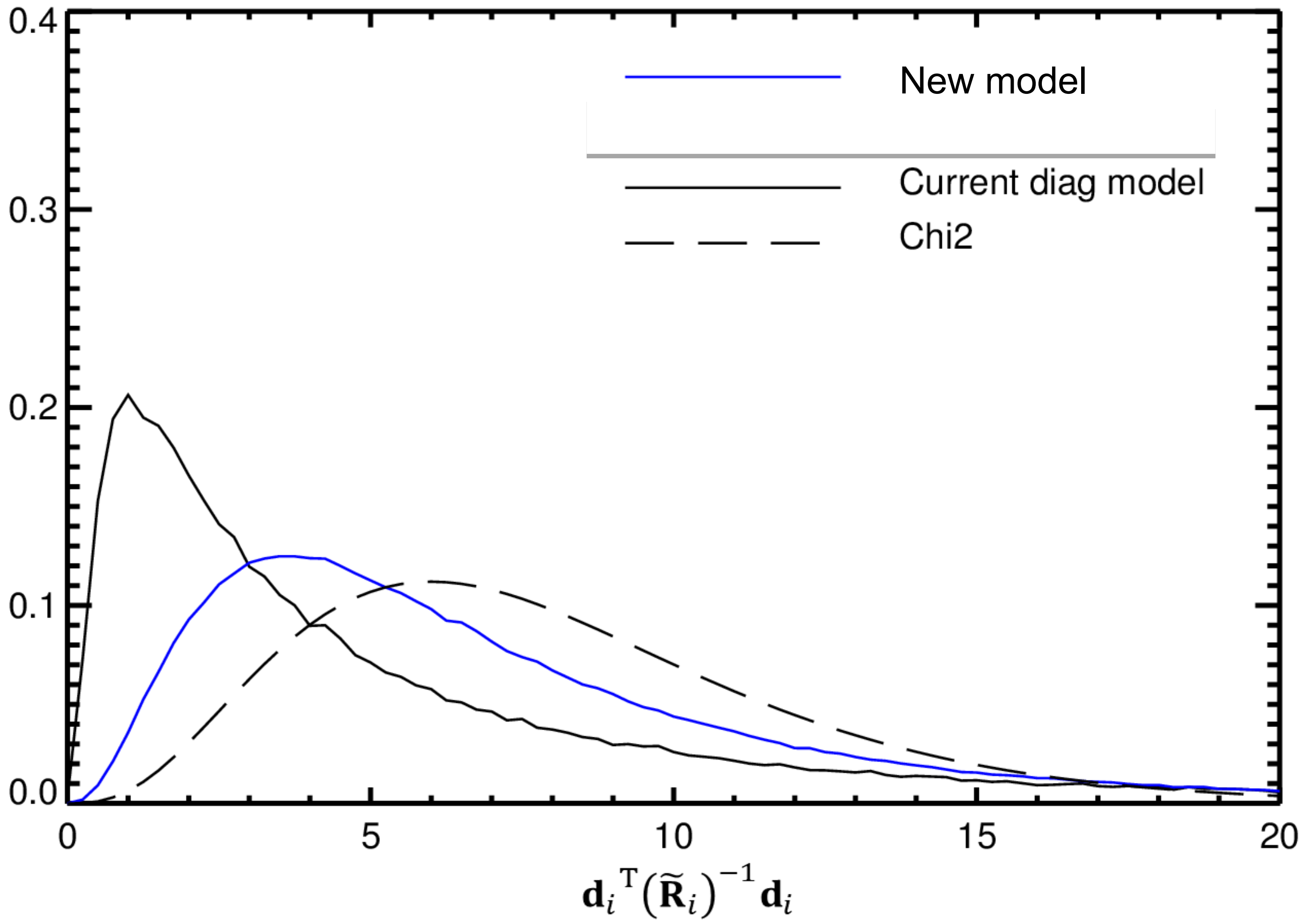
Current diagonal error model

too little weight to
most observations

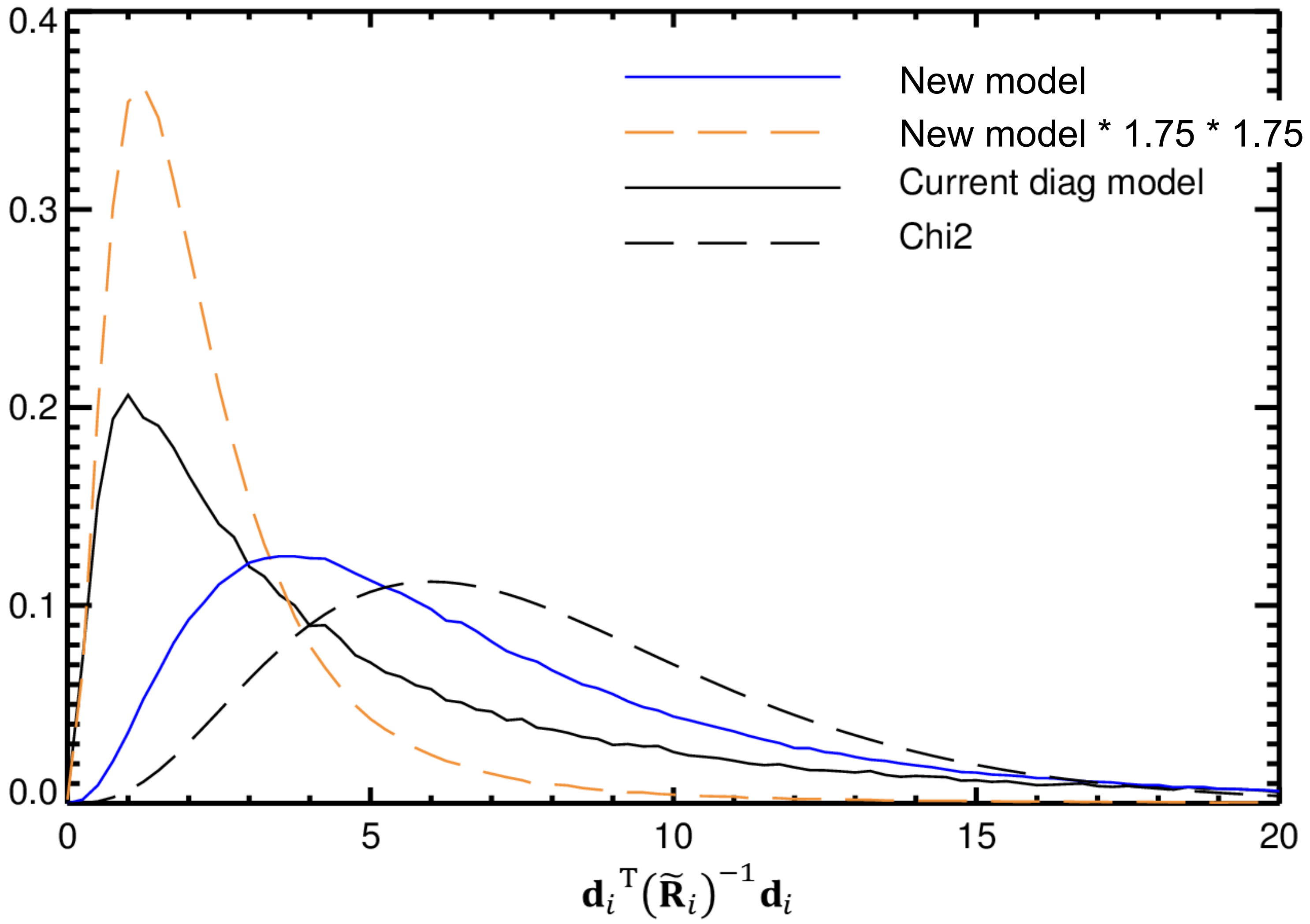


too much weight to
some observations

New full covariance model, raw



New full covariance model, inflated

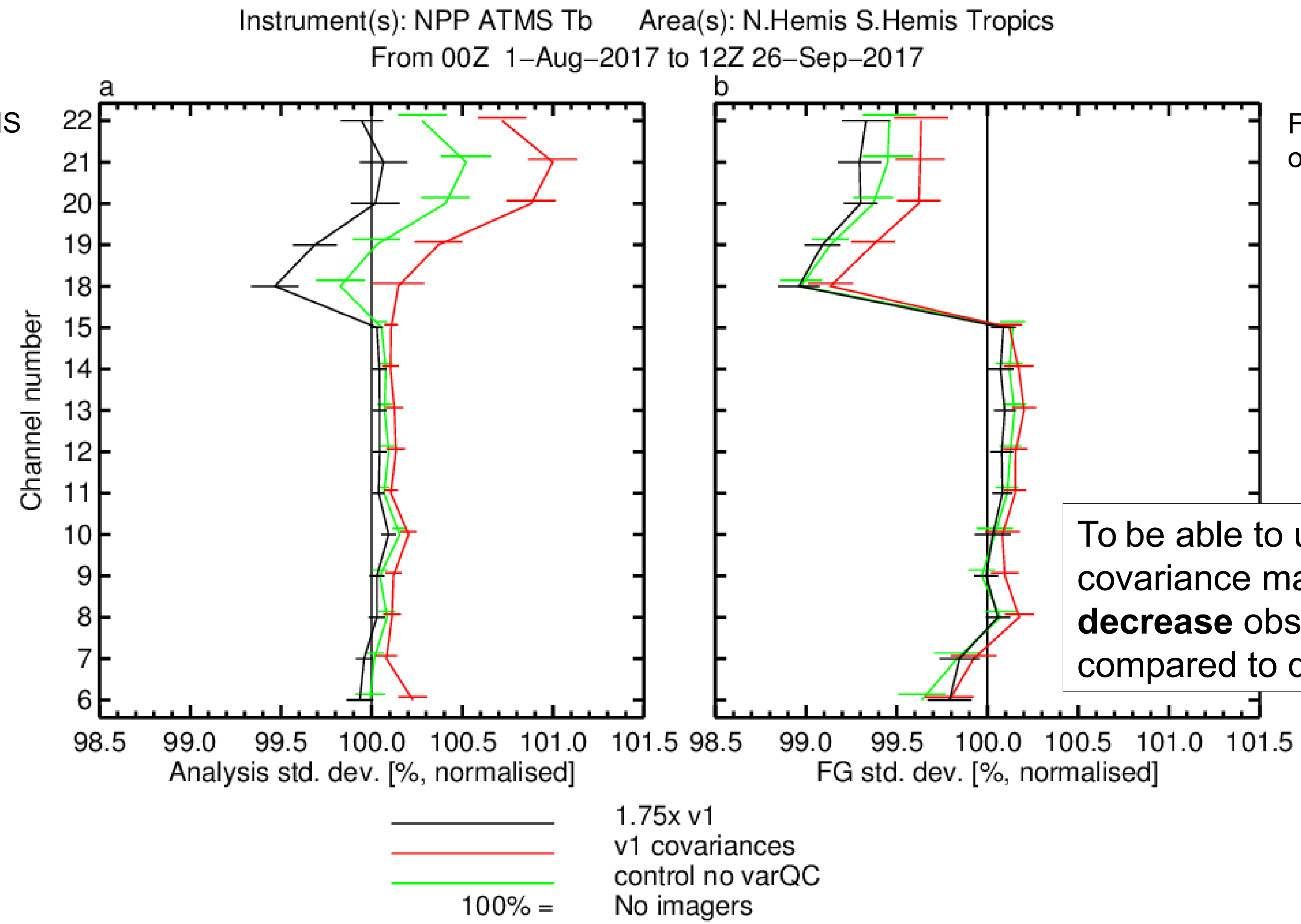


Interchannel observation error correlations – impact of SSMIS, GMI, AMSR2

Experiments without VarQC

Analysis fit to ATMS observations

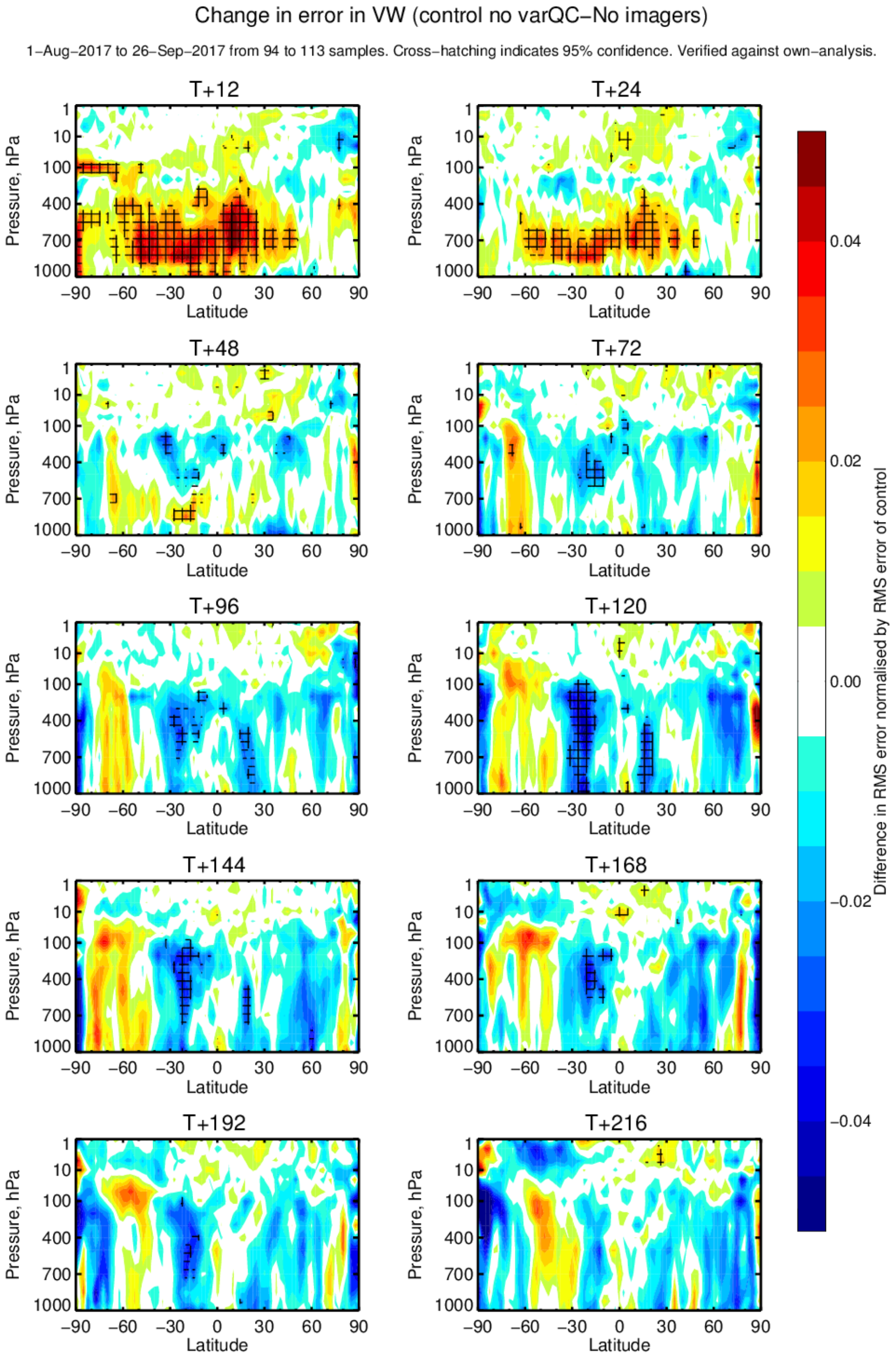
FG fit to ATMS observations

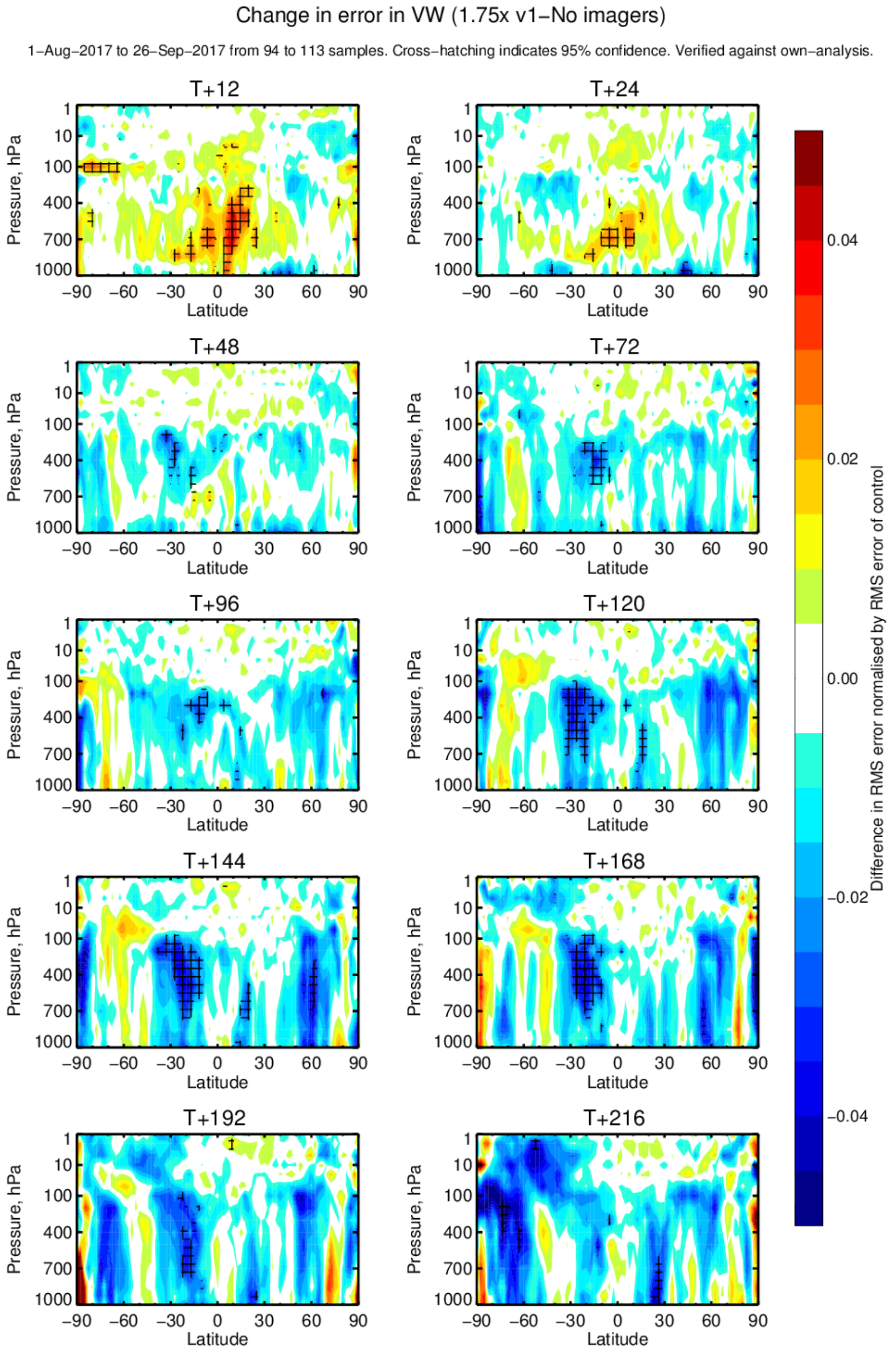


To be able to use full error covariance matrix we need to **decrease** observation weight compared to diagonal control

Impact of 3 imagers

(~control, with all-sky diagonal errors)





Impact of 3 imagers

(inter-channel correlated obs errors, 1.75x inflation)

red: imagers increase RMSE of wind forecasts

blue: imagers decrease RMSE of wind forecasts

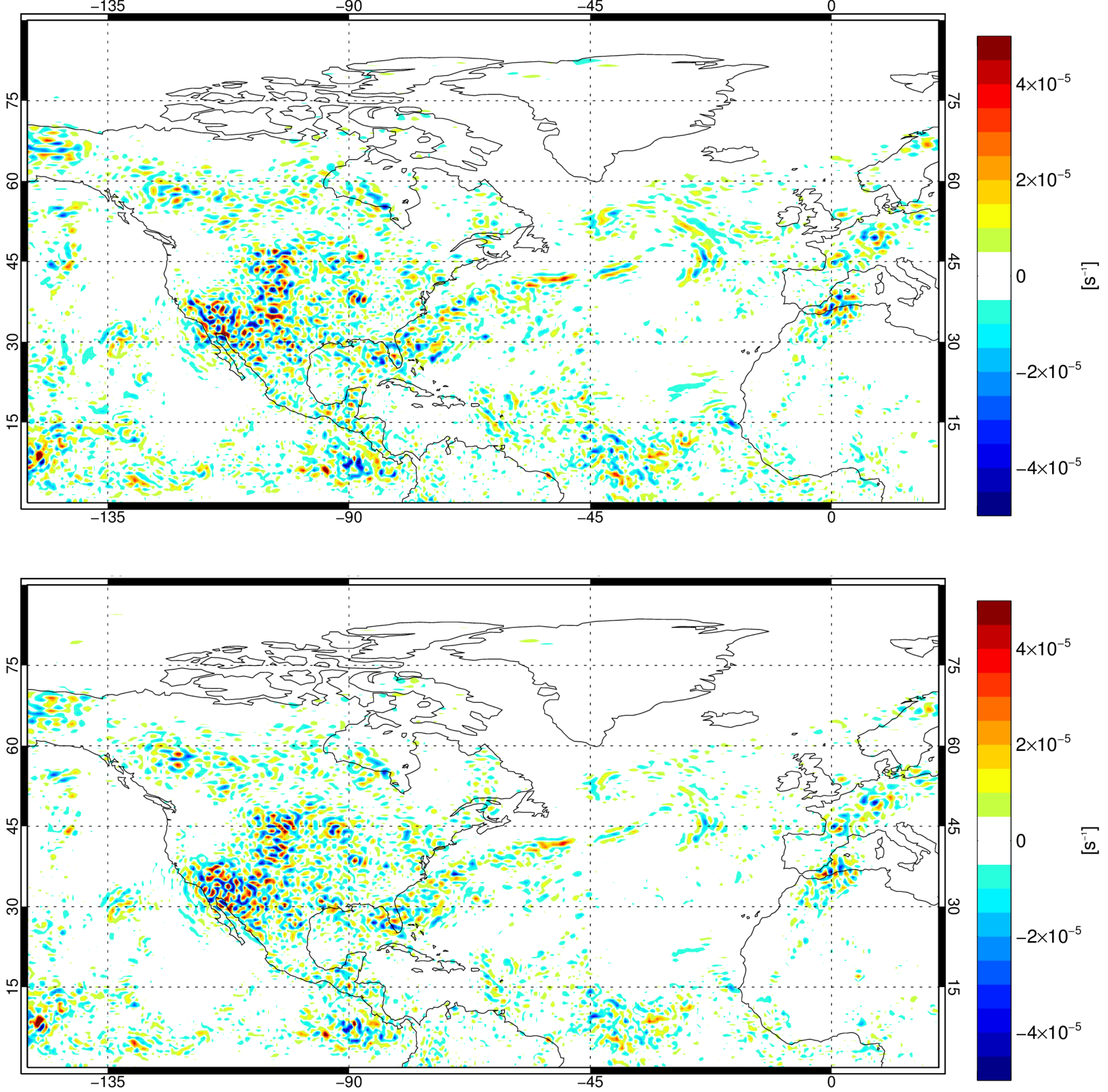
Own-analysis verification

Divergence increments coming from 3 all-sky microwave imagers: 850hPa

Diagonal, symmetric observation errors

~10% reduction in std. dev.

Full interchannel observation error covariances (1.75x inflation)

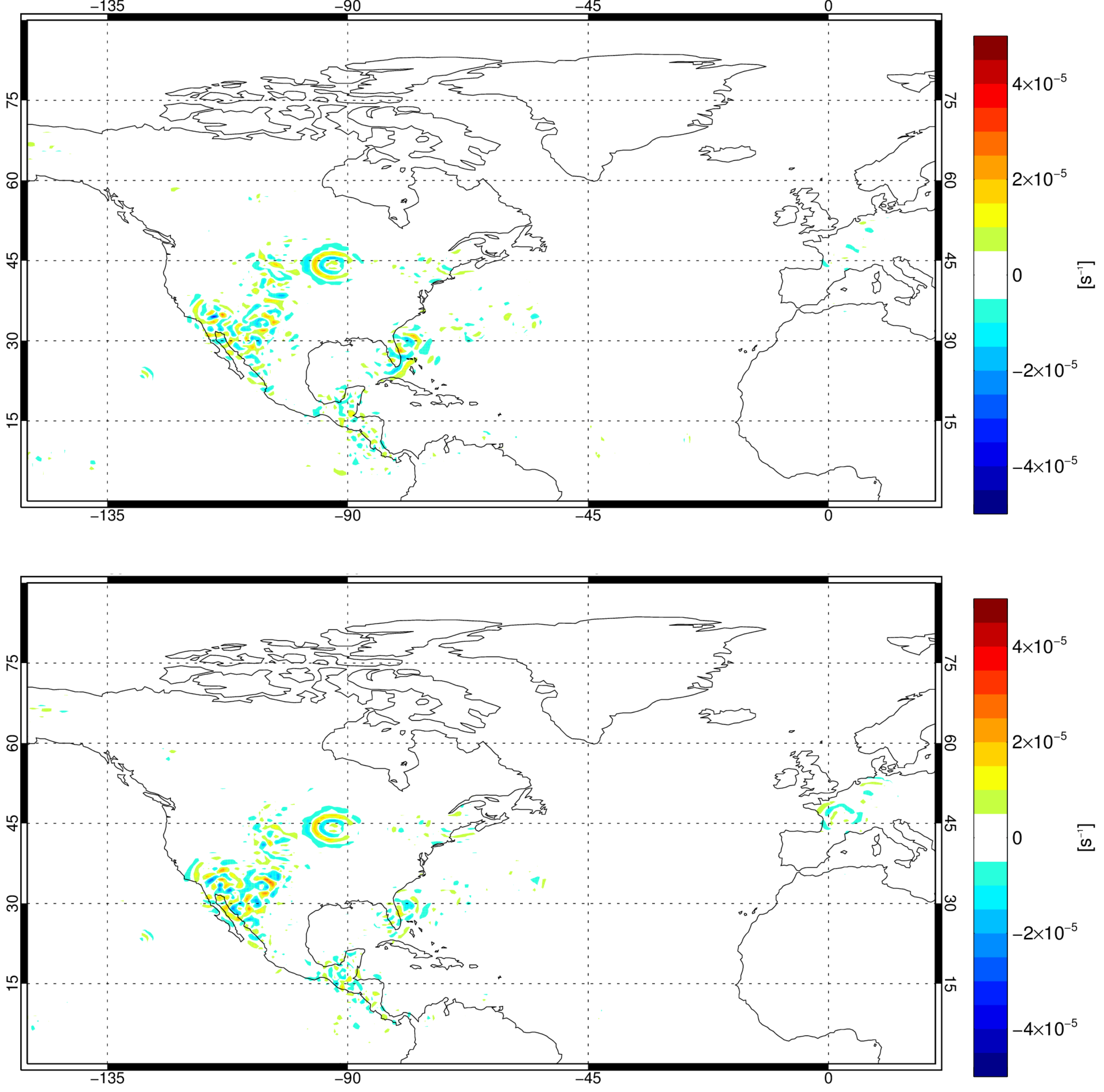


Divergence increments coming from 3 all-sky microwave imagers: 50hPa

Diagonal, symmetric observation errors

~10% reduction in std. dev.

Full interchannel observation error covariances (1.75x inflation)



Conclusions

Conclusions

- To get all-sky data assimilation to work well requires attention to almost every aspect of data assimilation:
  - observations
  - forecast model's representation of cloud and precipitation
  - observation operator
  - data assimilation system
  - observation error

- Currently it is hard to add more all-sky data at ECMWF:
  - All-sky IR: the dominance of gravity waves and equatorial waves in the information content of the data
  - All-sky microwave: using observation error covariance matrices to **reduce** the impact of the data (reduce the amount of gravity waves generated)

  → Gravity waves (convectively or spontaneously generated) and equatorial waves are real features of the atmosphere that are closely coupled to the cloud and precipitation fields. But assimilating these features may require significant evolution of DA systems