Status of Cloud and Precipitation Assimilation at ECMWF

Peter Bauer, European Centre for Medium-Range Weather Forecasts

Alan Geer, Philippe Lopez, Tony McNally, William Bell, Deborah Salmond, Carla Cardinali, Niels Bormann, Marta Janisková, Elias Hólm, Jiandong Gong, Gabór Radnóti, Anne Fouilloux, Saleh Abdalla, Fatima Karbou

$$J(\mathbf{x}, \boldsymbol{\beta}) = \frac{1}{2}[\mathbf{y} - \tilde{H}(\mathbf{x}, \boldsymbol{\beta})]^{\mathrm{T}}\mathbf{R}^{-1}[\mathbf{y} - \tilde{H}(\mathbf{x}, \boldsymbol{\beta})] + \frac{1}{2}(\boldsymbol{\beta} - \boldsymbol{\beta}_{\mathrm{b}})^{\mathrm{T}}\mathbf{B}_{\beta}^{-1}(\boldsymbol{\beta} - \boldsymbol{\beta}_{\mathrm{b}}) + \frac{1}{2}(\mathbf{x} - \mathbf{x}_{\mathrm{b}})^{\mathrm{T}}\mathbf{B}^{-1}(\mathbf{x} - \mathbf{x}_{\mathrm{b}}),$$

Philippe Lopez' talk

Alan Geer's talk

Elias Hólm's talk

Richard Forbes' talk: development of model parameterizations
Niels Bormann + Carla Cardinali's talk: development of impact diagnostics

Importance of cloud observations

- Preference for clear-sky observations will bias the analysis
- Clouds occur in sensitive errors where initial conditions are important

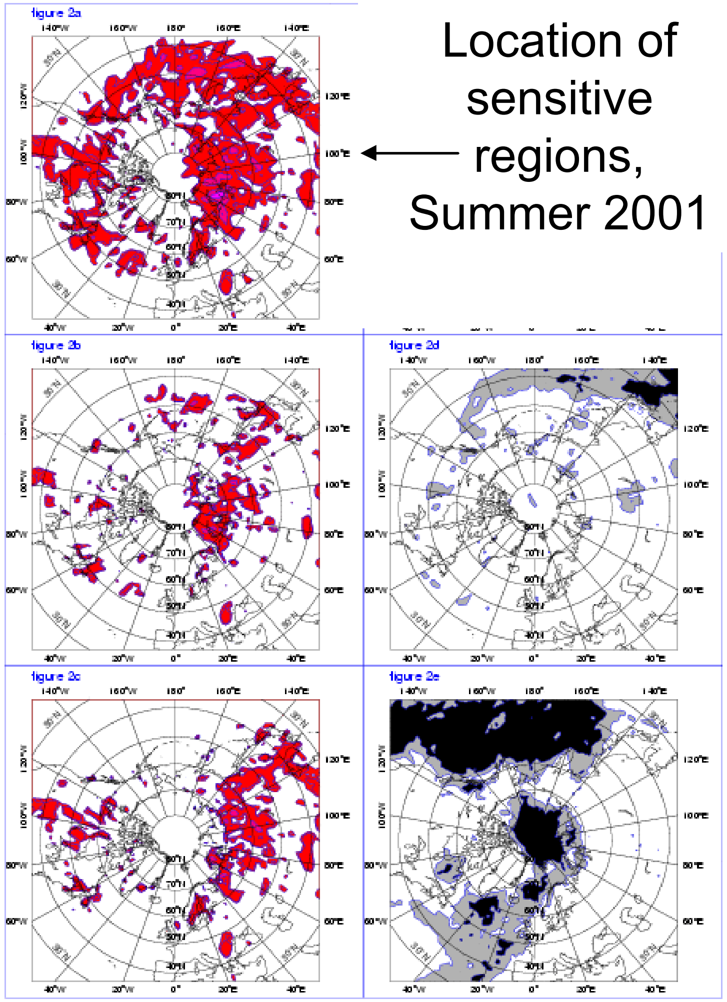
Location of sensitive regions, Summer 2001

sensitivity surviving **high** cloud cover

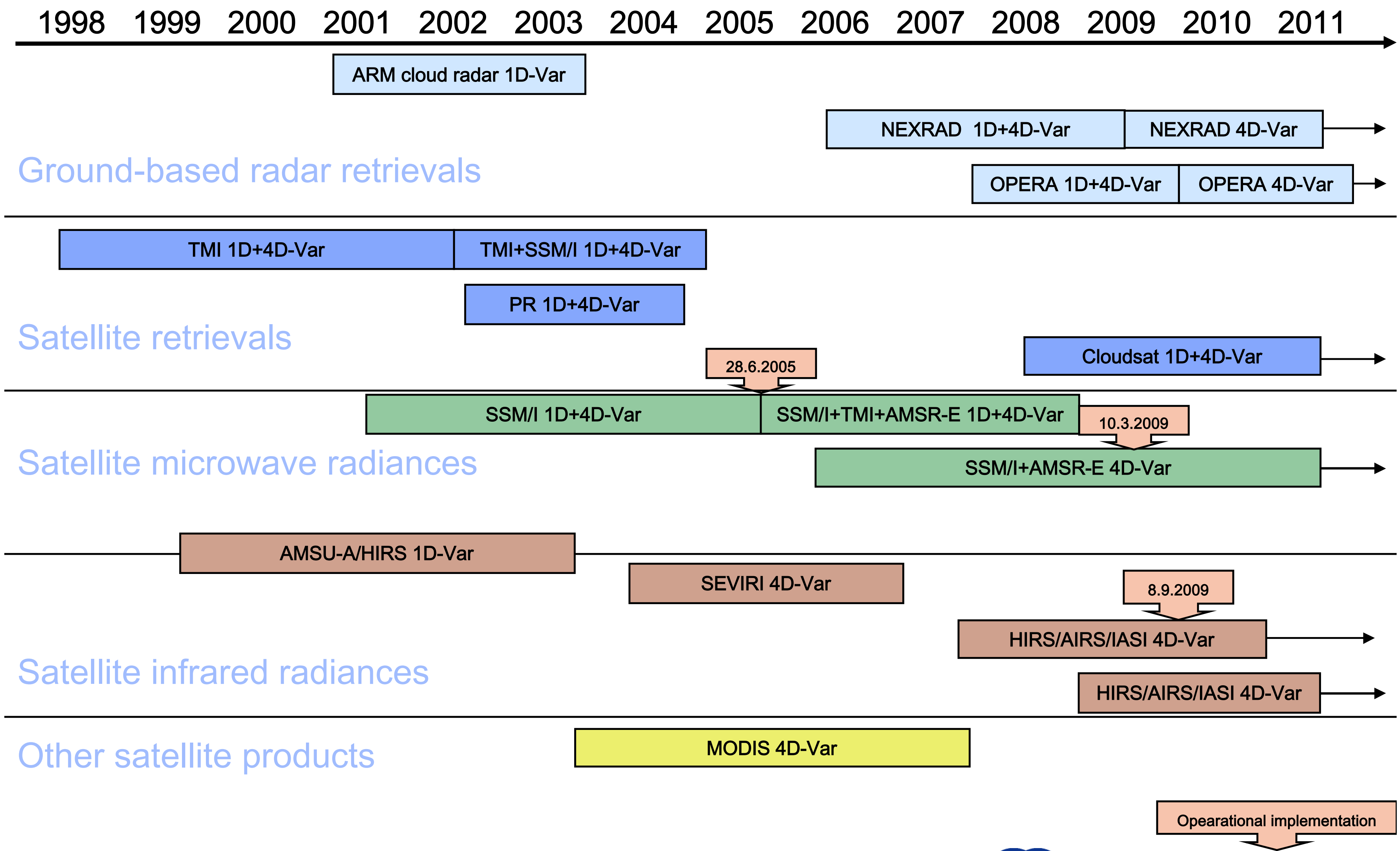
monthly mean **high** cloud cover

sensitivity surviving **low** cloud cover

monthly mean **low** cloud cover



Cloud and precipitation assimilation at ECMWF



ECMWF model changes since 2005

… that are relevant to cloud/precipitation data assimilation

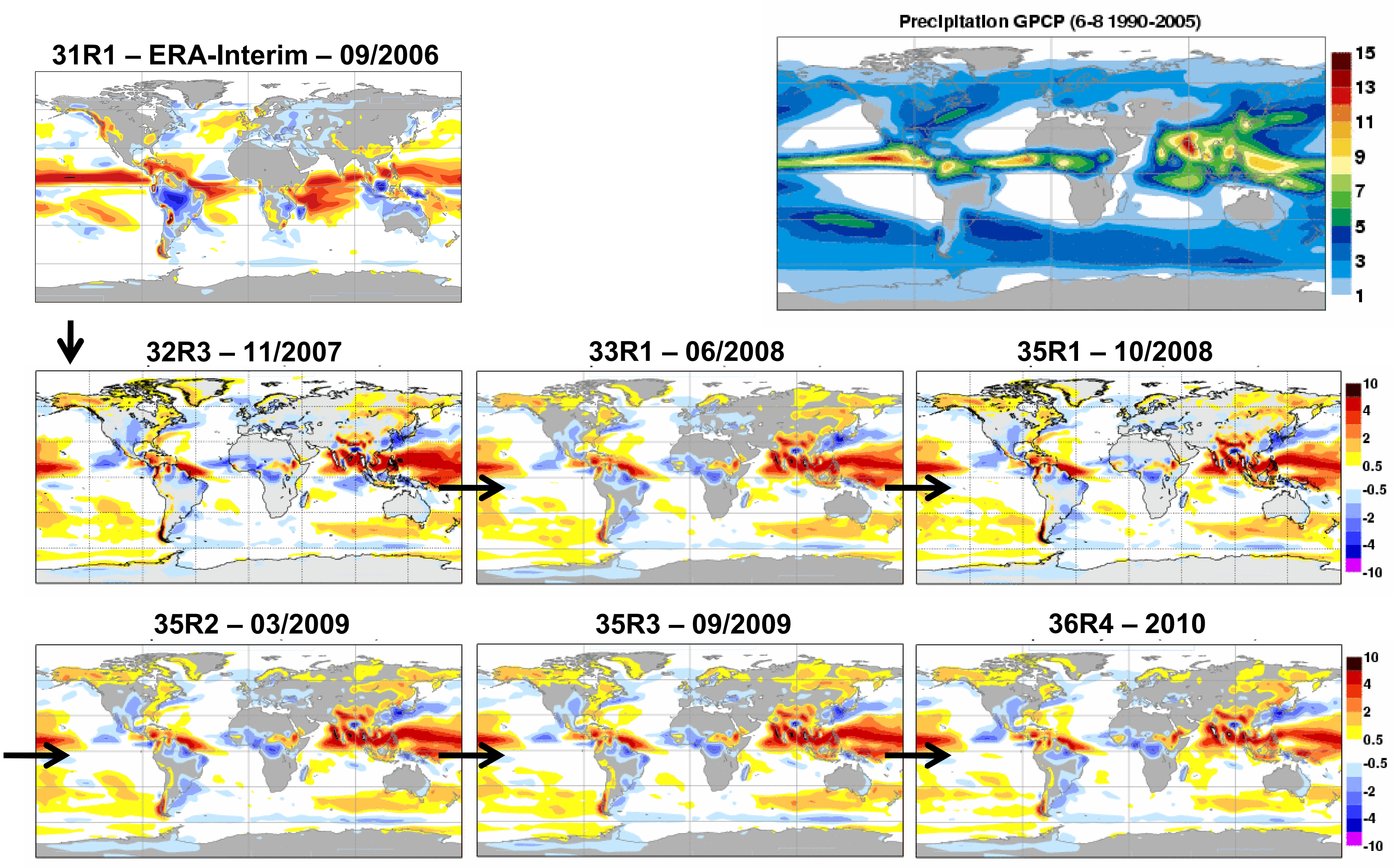
Model:
- 02/2006: spatial resolution/vertical level increase T511L60 → T799L91
- 09/2006: improved convection & cloud scheme, ice super-saturation
- 06/2007: new linearized moist physics
- 11/2007: reformulation of convection scheme (more active model)
- 06/2008: improved linearized moist physics
- 01/2010: spatial resolution increase T799L91 → T1279L91
- 2010: prognostic precipitation formulation

Data assimilation system:
- 02/2006: T95/255 inner loops
- 06/2007: T95/159/255 inner loops, reformulation of moisture analysis

Observations:
- Adjustment to changing observing system (SSM/I, SSMIS, AMSR-E, TMI)
- Tests with active instrument data (Cloudsat/Calipso, surface radar networks)

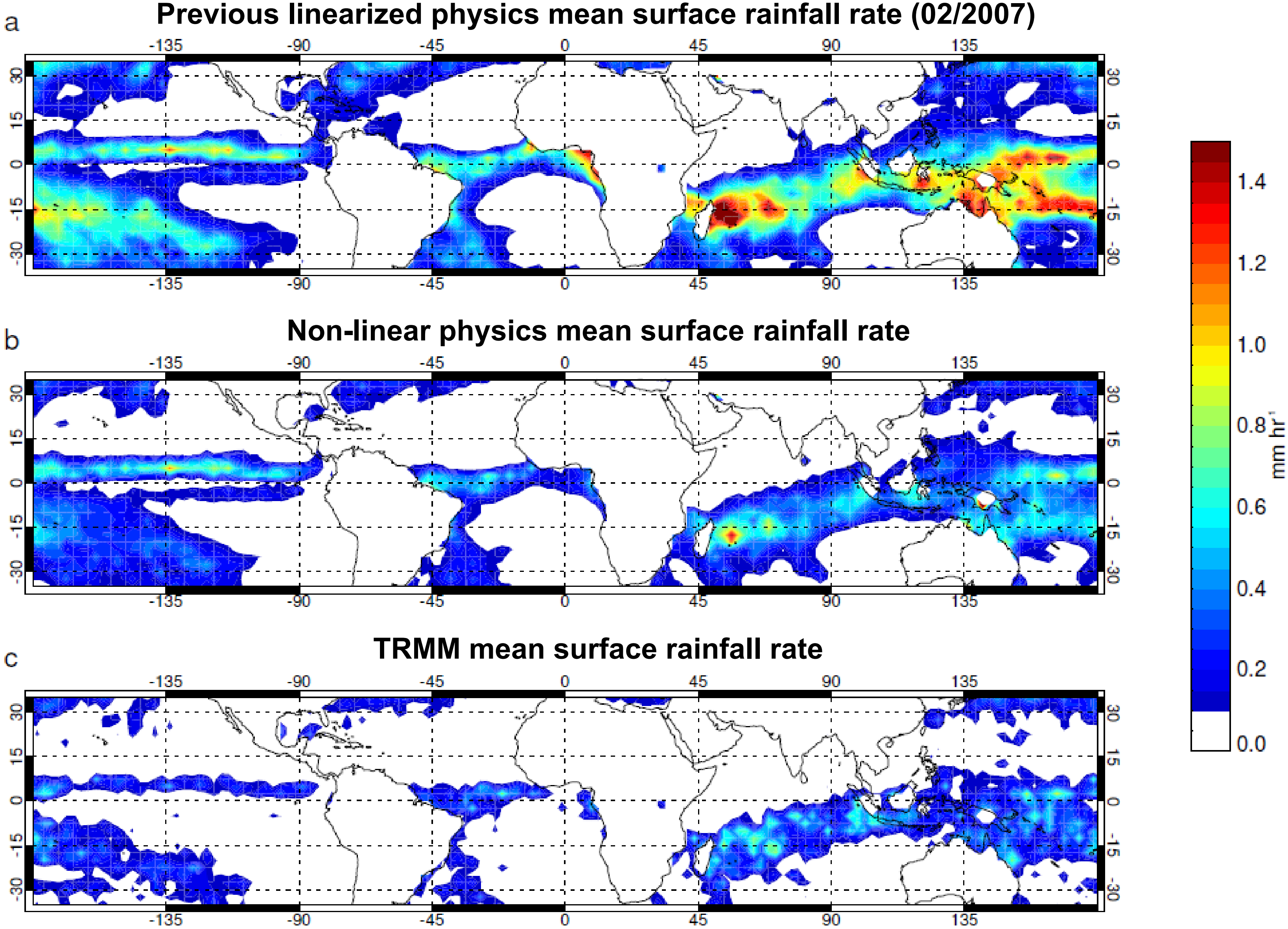
But other changes can also (indirectly) affect moisture analysis:
- Better temperature analysis, background error formulation, quality control, etc.

ECMWF model precipitation



ECMWF

ECMWF model precipitation: outer vs inner loop

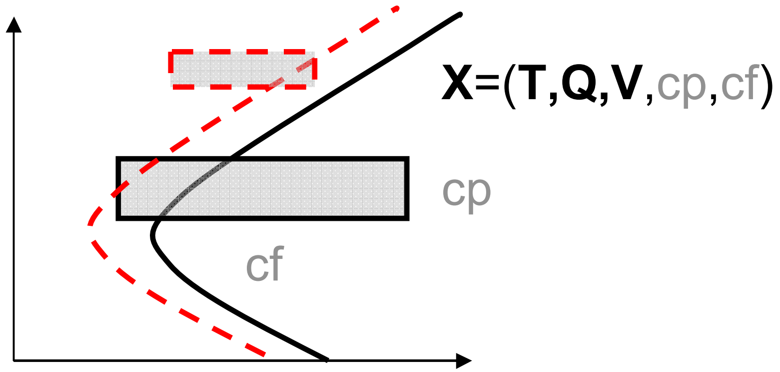


ECMWF

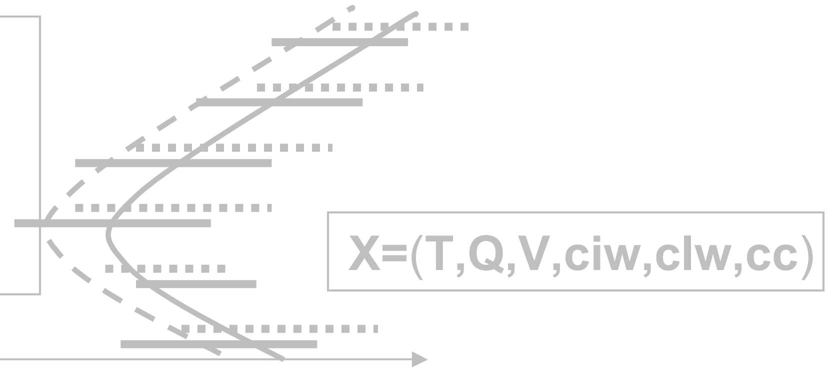
Why treat IR different than MW?

- Variability of cloud parameters produces much larger radiance variations than variability of temperature and moisture
- Sensitivity of radiances to state is highly non-linear and errors in cloud parameter background are too large to serve as linearization point
- Cloud + atmospheric parameters may present too many degrees of freedom

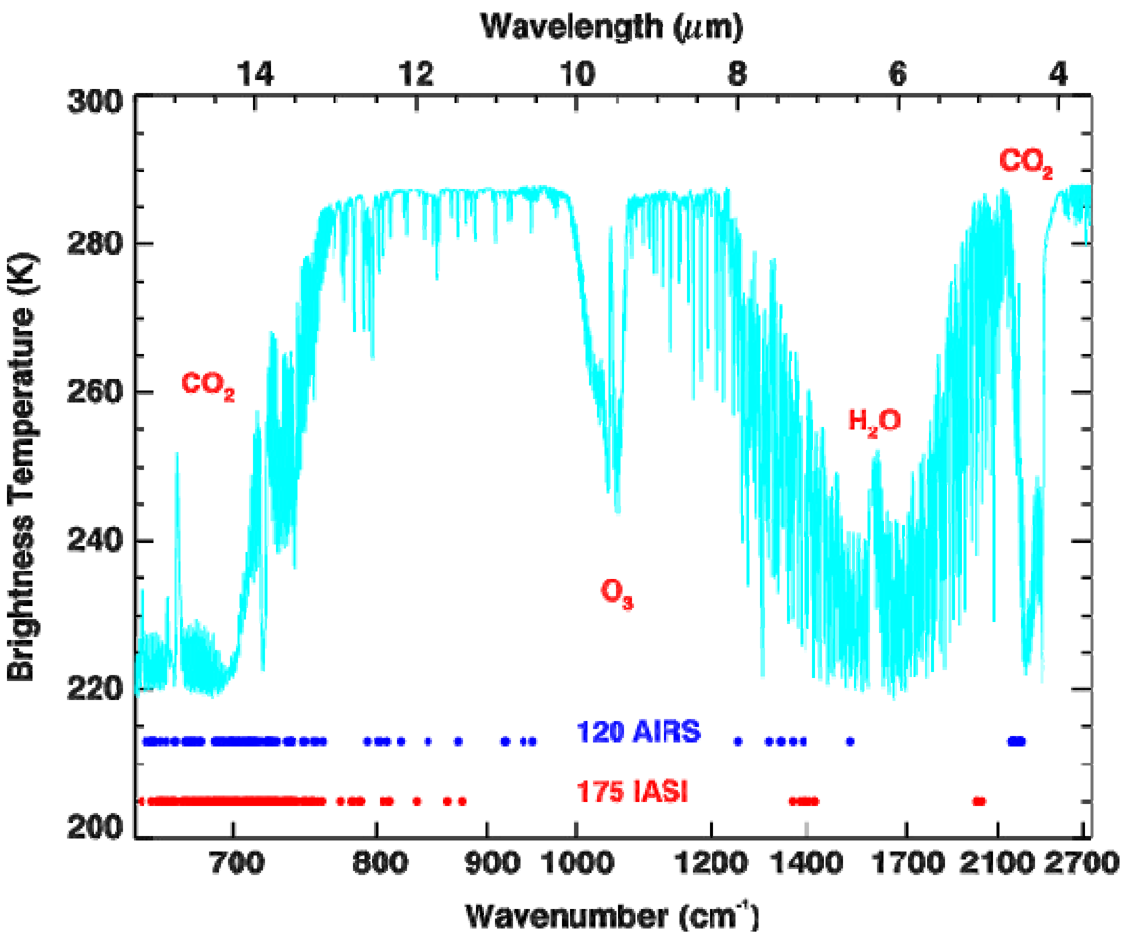
Simplified system:
- very simple cloud representation
- currently limited to overcast scenes
- no information on clouds taken from model
- no back interaction with model via physics



Advanced system:
- very complex cloud representation
- all cloud conditions treated
- information on clouds taken from model
- back interaction with model via physics



Current use of AIRS/IASI data

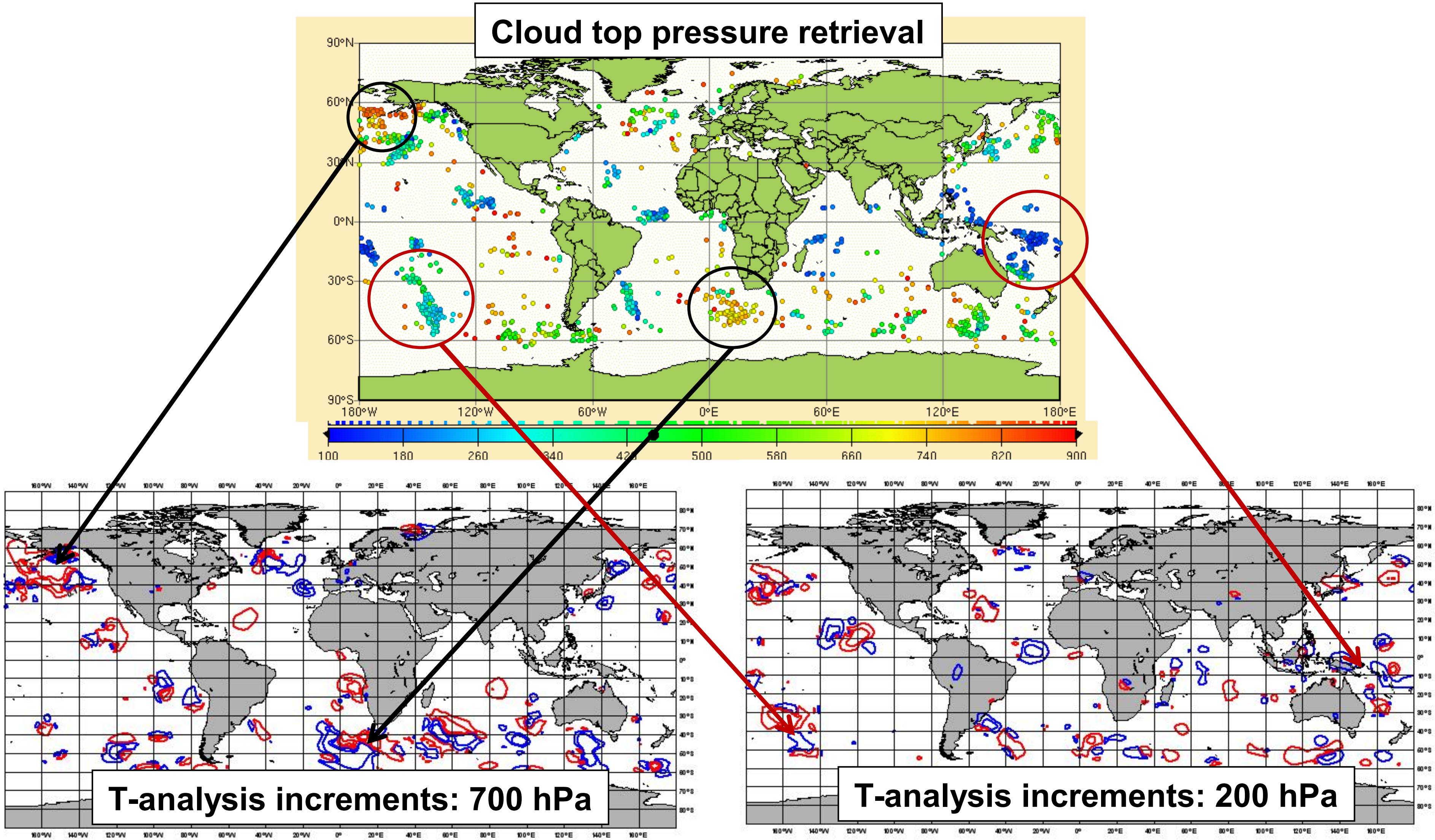


- AIRS CO_2 and H_2O channels assimilated since October 2003.
- IASI CO_2/H_2O channels assimilated since June 2007/March 2009.
- Assimilated in clear-sky areas and above clouds; since March 2009 in fully overcast situations, AIRS (not IASI) over land surfaces/sea-ice.
- Continuous revision of channel usage, quality control.

 © ECMWF

Infrared sounder data impact of overcast clouds

In single analysis cycle overcast cases add ~5% more HIRS, AIRS, IASI data!



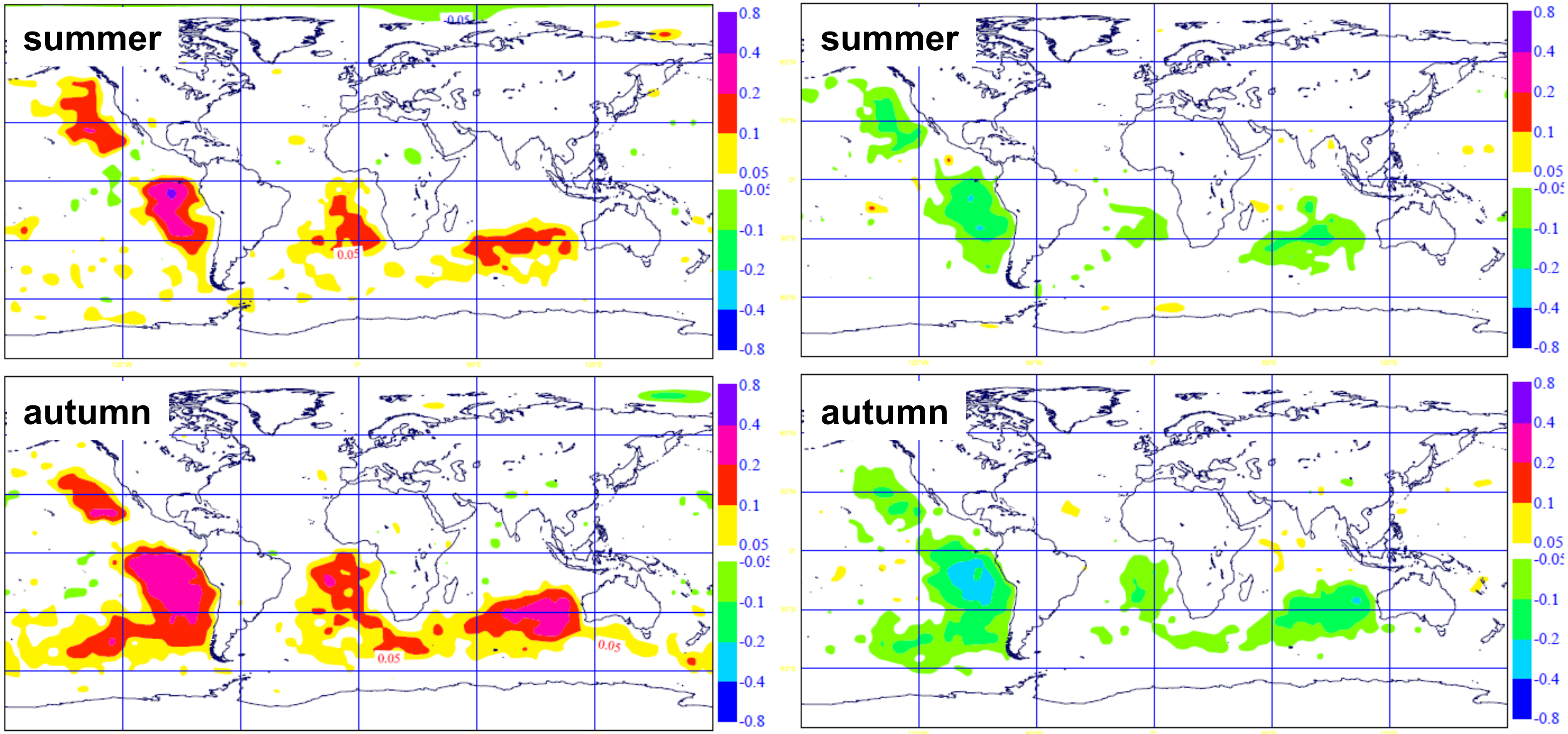
ECMWF

Infrared sounder data usage above clouds

3-month clear-sky minus IR-cloud experiment:

Mean temperature analysis difference

850 hPa **700 hPa**

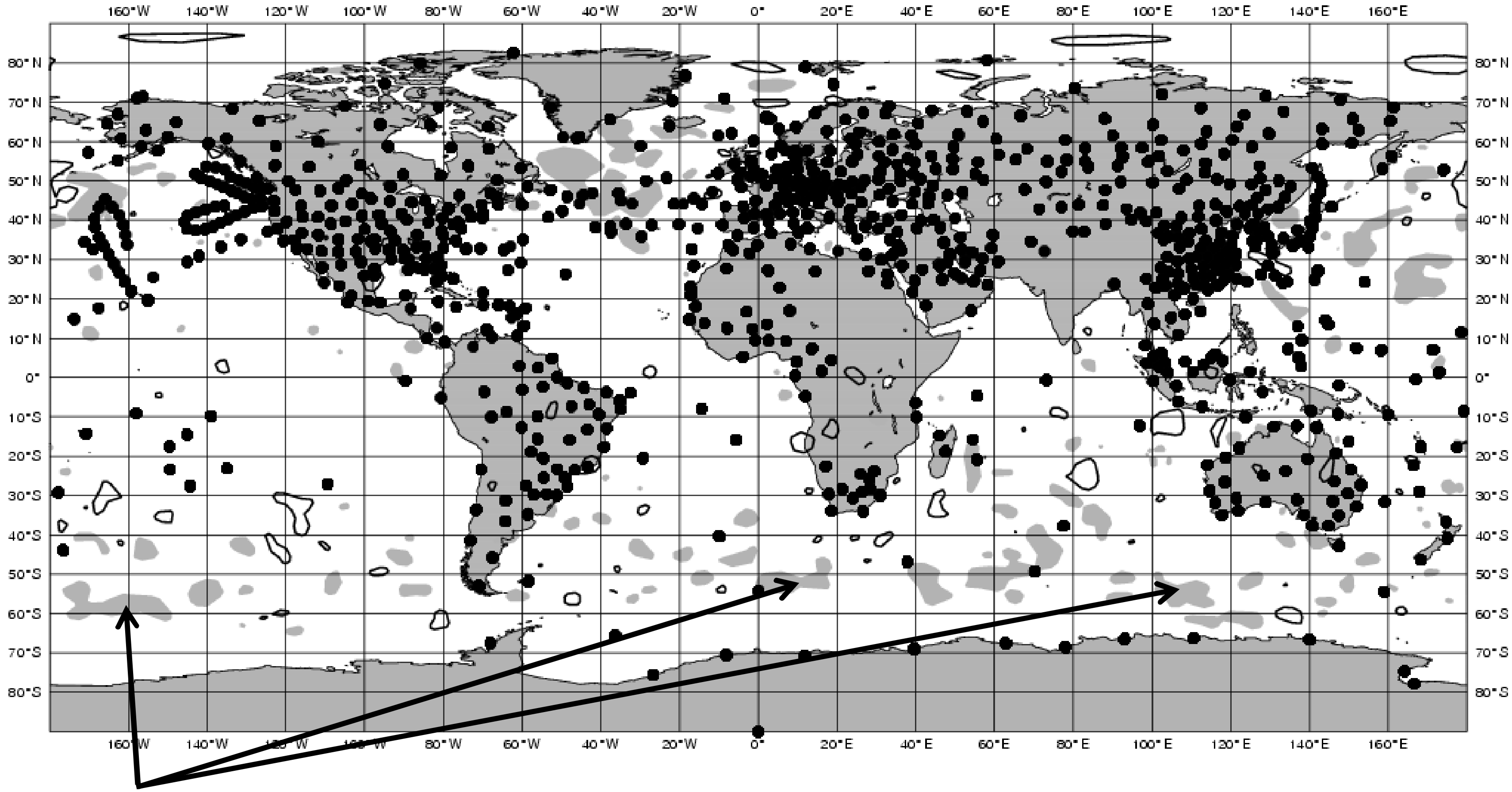


→ Overcast data cools **→ Overcast data warms**

© ECMWF

Impact on temperature analysis increments

Monthly mean RMS of temperature increment difference (cloudy-clear)

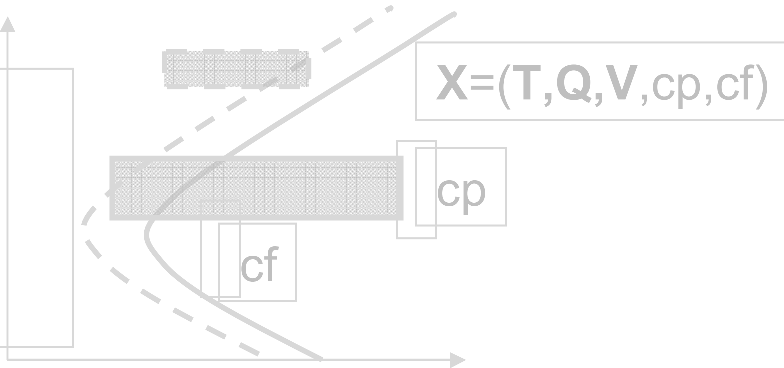


RMS reduction

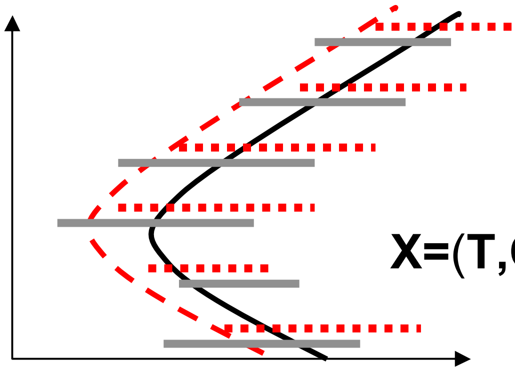
Why treat IR different than MW?

- **Variability of cloud parameters produces much larger radiance variations than variability of temperature and moisture**
- **Sensitivity of radiances to state is highly non-linear and errors in cloud parameter background are too large to serve as linearization point**
- **Cloud + atmospheric parameters may present too many degrees of freedom**

Simplified system:
•very simple cloud representation
•currently limited to overcast scenes
•no information on clouds taken from model
•no back interaction with model via physics

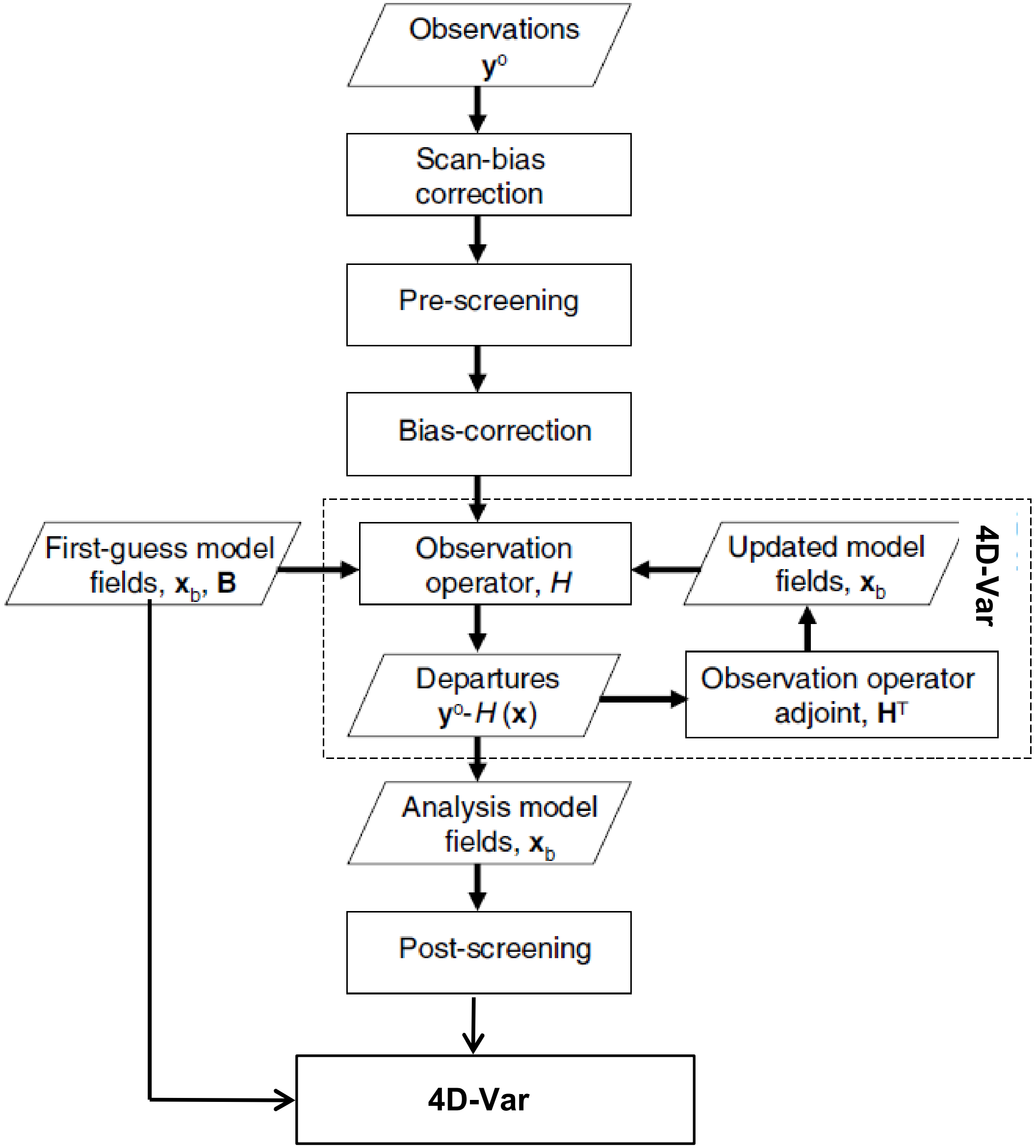


Advanced system:
•very complex cloud representation
•all cloud conditions treated
•information on clouds taken from model
•back interaction with model via physics



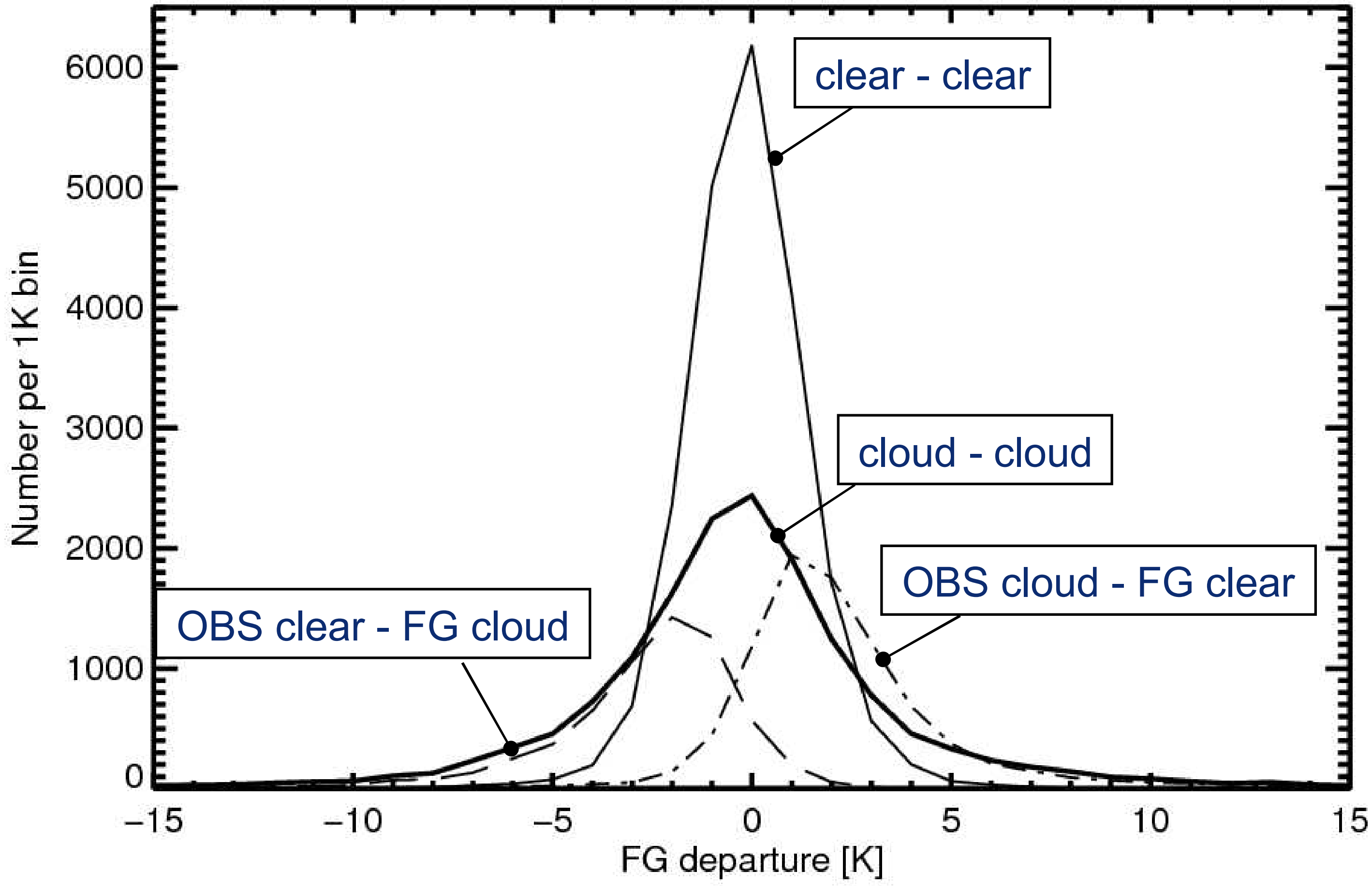
X=(T,Q,V,ciw,clw,cc)

MW: Why 1D+4D-Var, why 4D-Var?



1D+4D-Var:
- Introduces additional quality control
- Can treat less linear inversion problem
- Can present 'smooth' pseudo-observation to 4D-Var
- Computationally expensive
- Can filter impact on other 4D-Var control variables
- Uses **B** twice

Why all-sky?



Current clear-sky radiance assimilation discards observations as cloud affected by observation-minus-model departure checks:

- cloud affected data remain in *pdf* and model clouds are ignored,
- separate streams for clear vs cloudy data do not treat entire *pdf* properly.

Data sources: Satellites

Radiances (→ brightness temperature = level 1):
- AMSU-A on NOAA-15/18/19, AQUA, Metop
- AMSU-B/MHS on NOAA-18/19, Metop
- SSM/I on F-15, AMSR-E on Aqua
- HIRS on NOAA-17/19, Metop
- AIRS on AQUA, IASI on Metop
- MVIRI on Meteosat-7, SEVIRI on Meteosat-9, GOES-11/12, MTSAT-1R imagers

Bending angles (→ bending angle = level 1):
- COSMIC (6 satellites), GRAS on Metop

Ozone (→ total column ozone = level 2):
- Total column ozone from SBUV on NOAA-17/18, OMI on Aura, SCIAMACHY on Envisat

Atmospheric Motion Vectors (→ wind speed = level 2):
- Meteosat-7/9, GOES-11/12, MTSAT-1R, MODIS on Terra/Aqua

Sea surface parameters (→ wind speed and wave height = level 2):
- Near-surface wind speed from ERS-2 scatterometer, ASCAT on Metop
- Significant wave height from RA-2/ASAR on Envisat, Jason altimeters

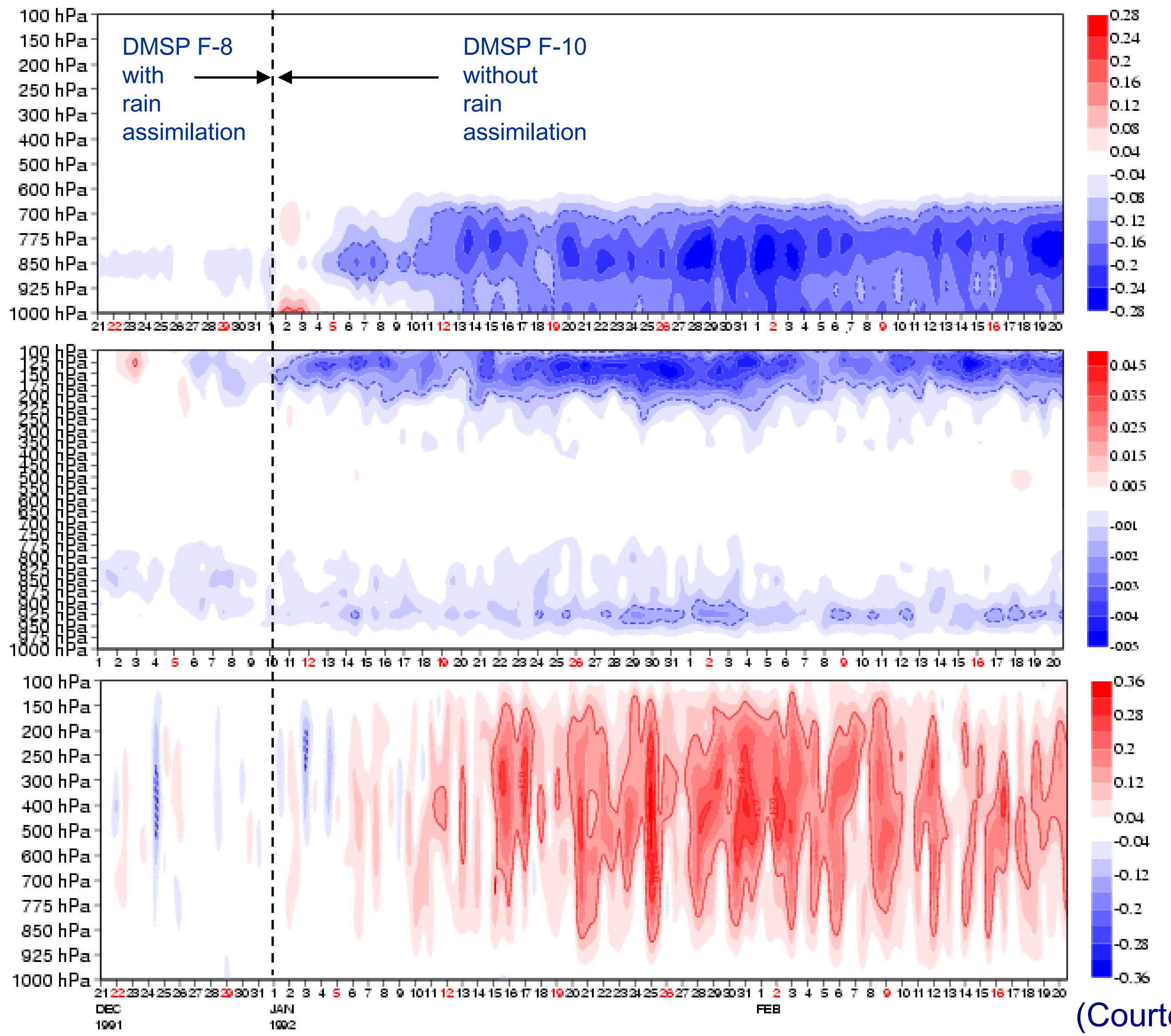
1D+4D-Var assimilation of rain-affected radiances: ERA-interim

Analysis difference b/w 2 ERA expts.

Specific humidity

Cloud cover

Vertical wind



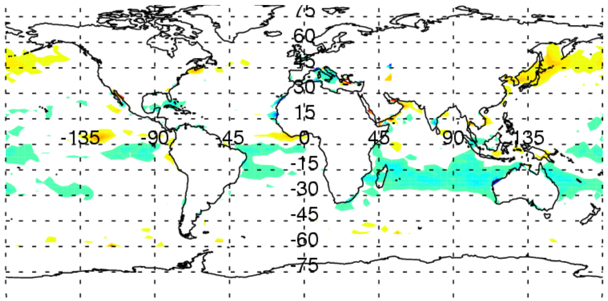
(Courtesy D. Dee)

ECMWF

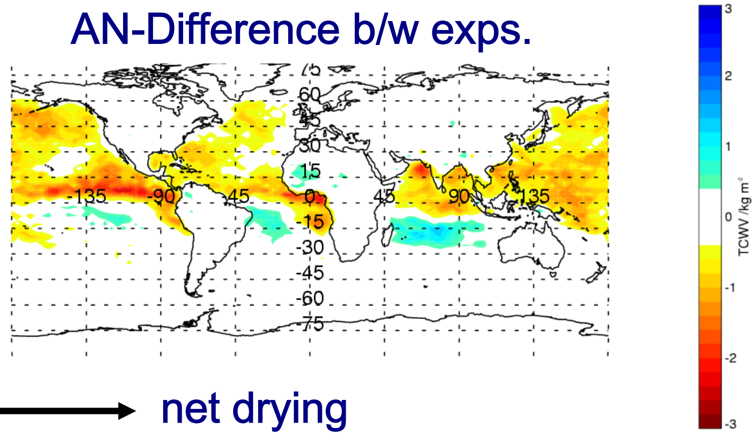
4D-Var analysis using 1D-Var TCWV (SSM/I radiances)

Mean August 2004 TCWV difference:

TCWV FG-Departures



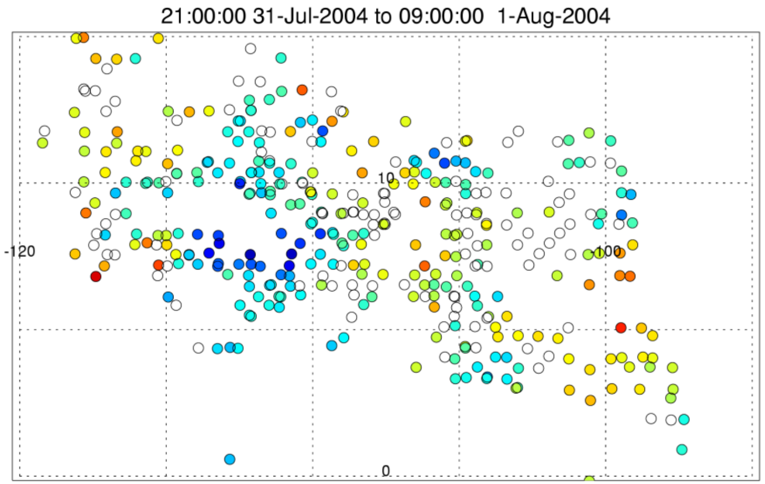
AN-Difference b/w exps.



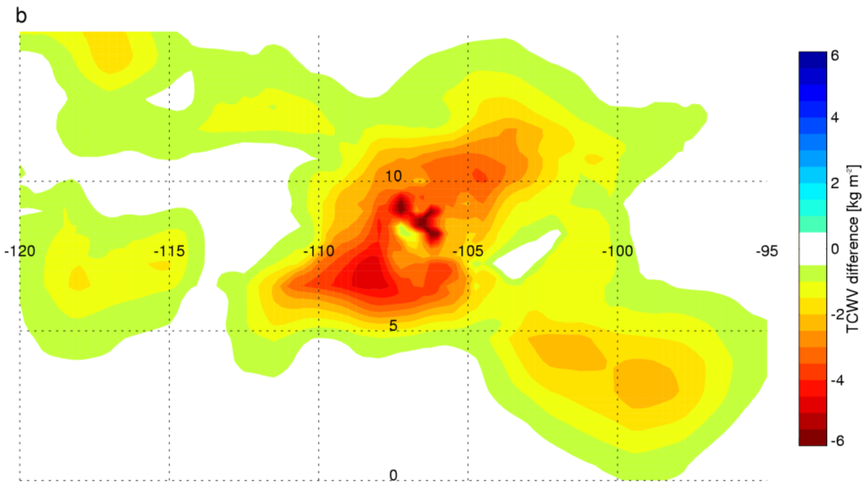
unbiased → net drying

Example: 1st cycle ITCZ East Pacific:

TCWV FG-Departures



AN-Increments

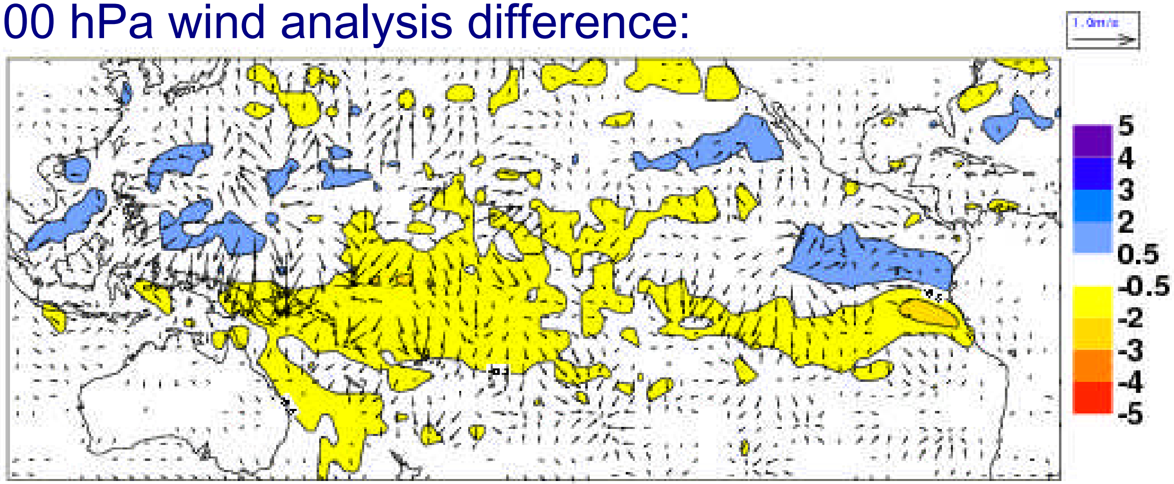


 © ECMWF

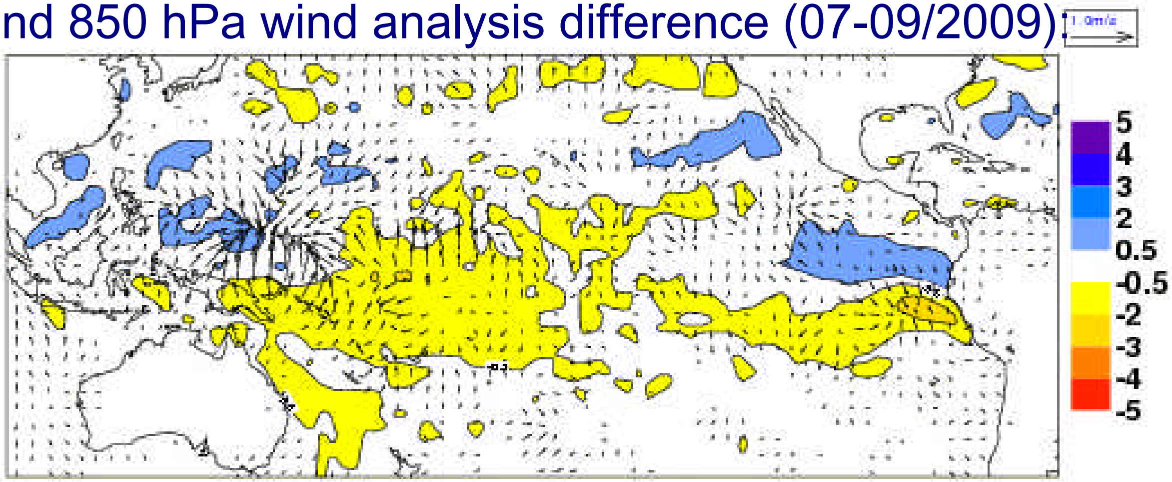
Analysis impact of 4D-Var

Mean TCWV analysis difference in kg m^{-2}

200 hPa wind analysis difference:

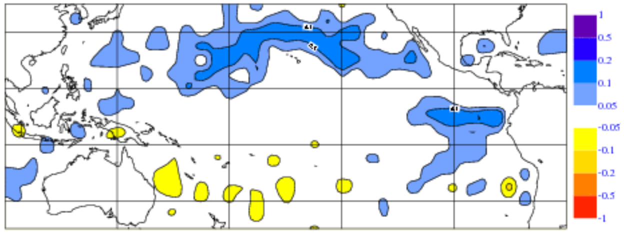


and 850 hPa wind analysis difference (07-09/2009):

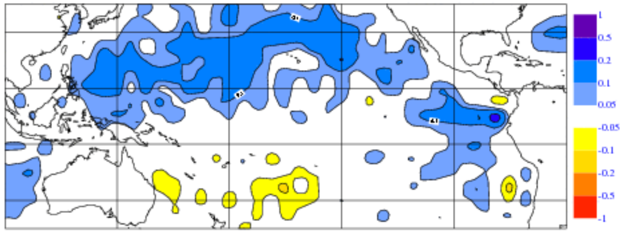


Difference in cloud cover:

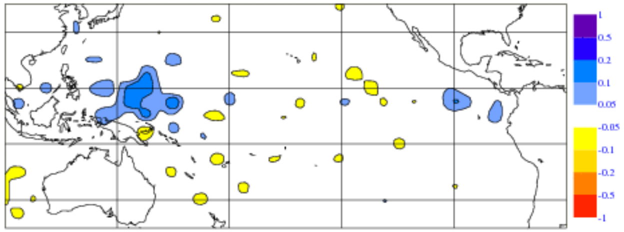
Total



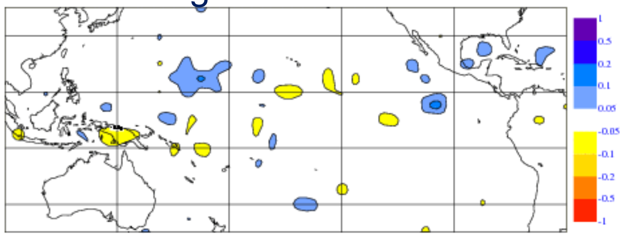
Low –level clouds



Mid-level clouds

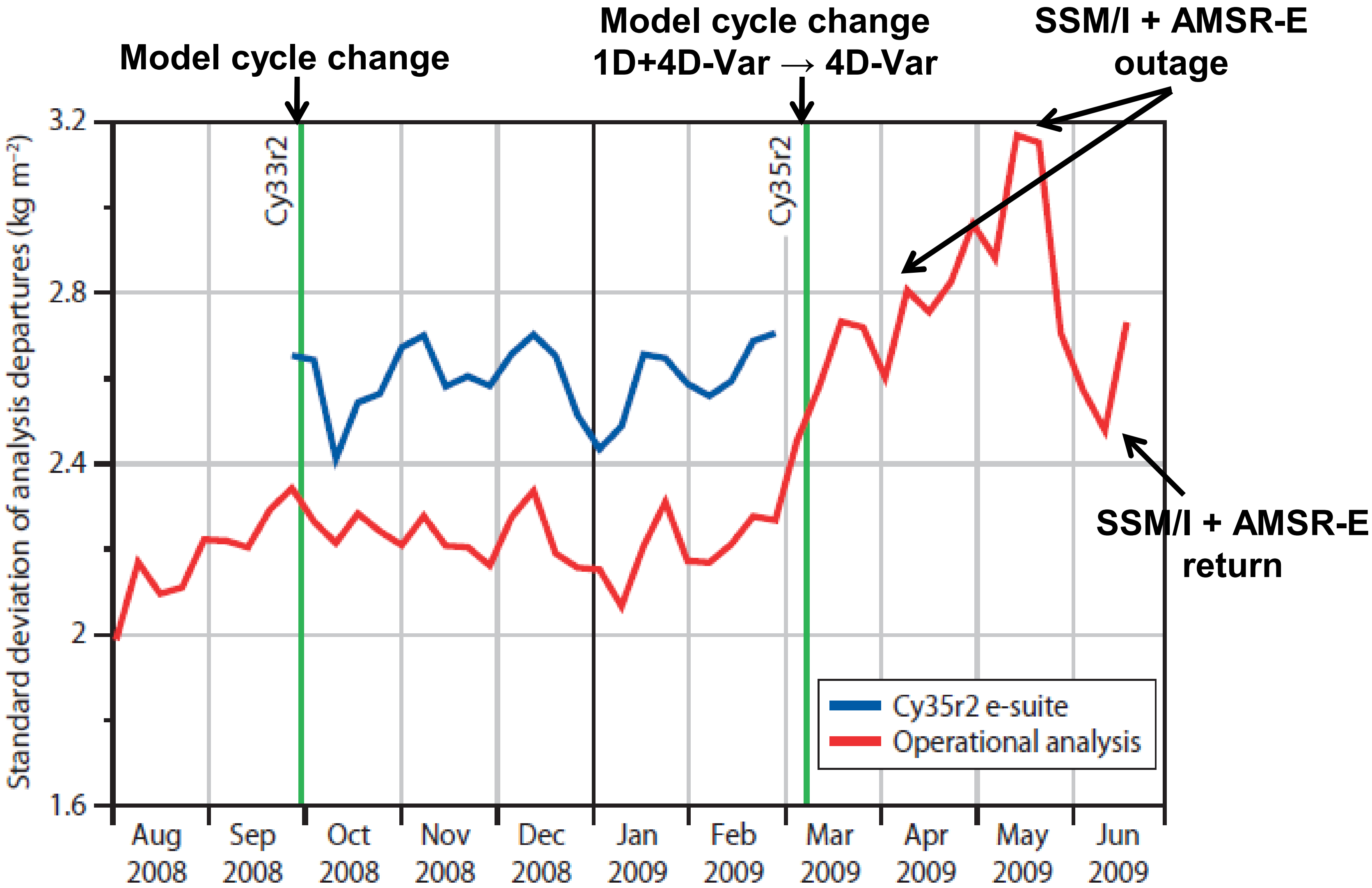


High-level clouds



 © ECMWF

Analysis impact verification

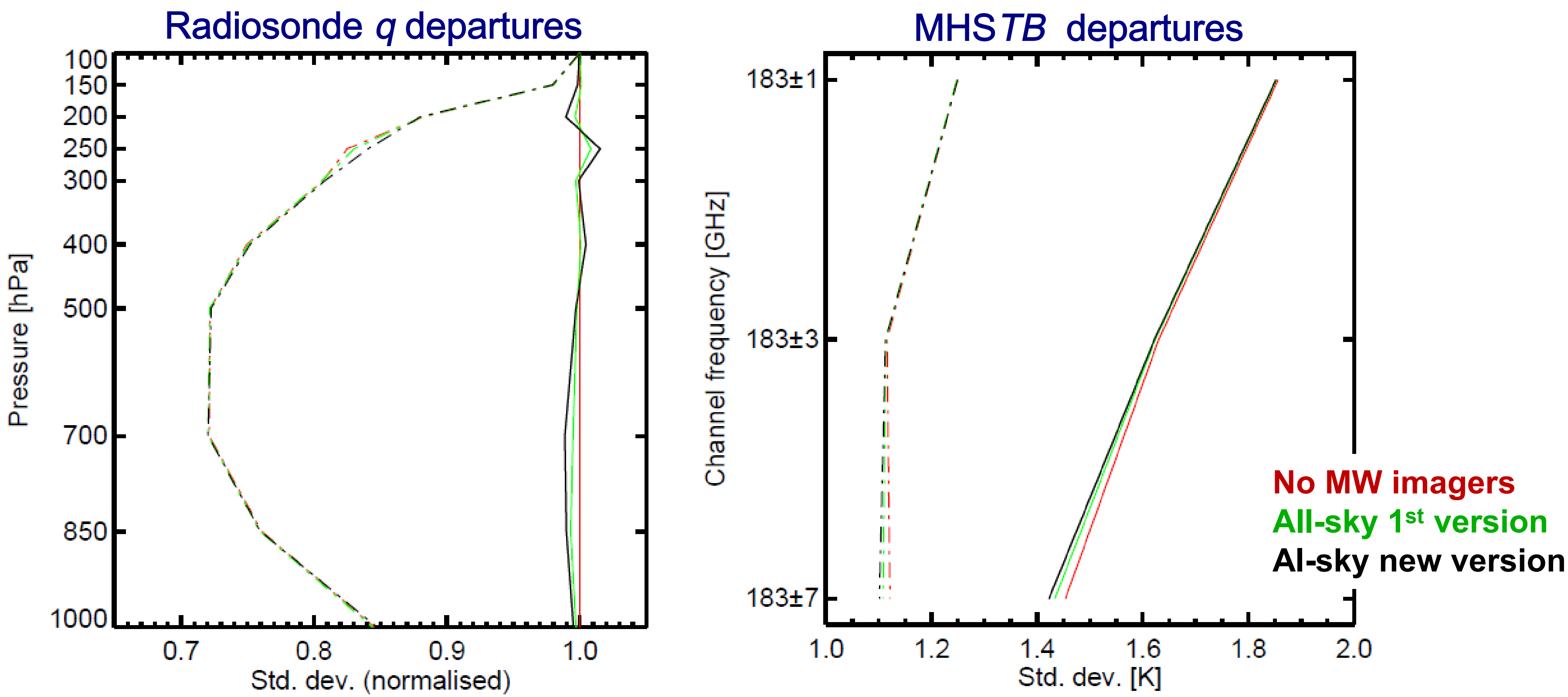


Standard deviation between ECMWF operational model analysis and Envisat MWR total column water vapour retrievals (not assimilated)

ECMWF

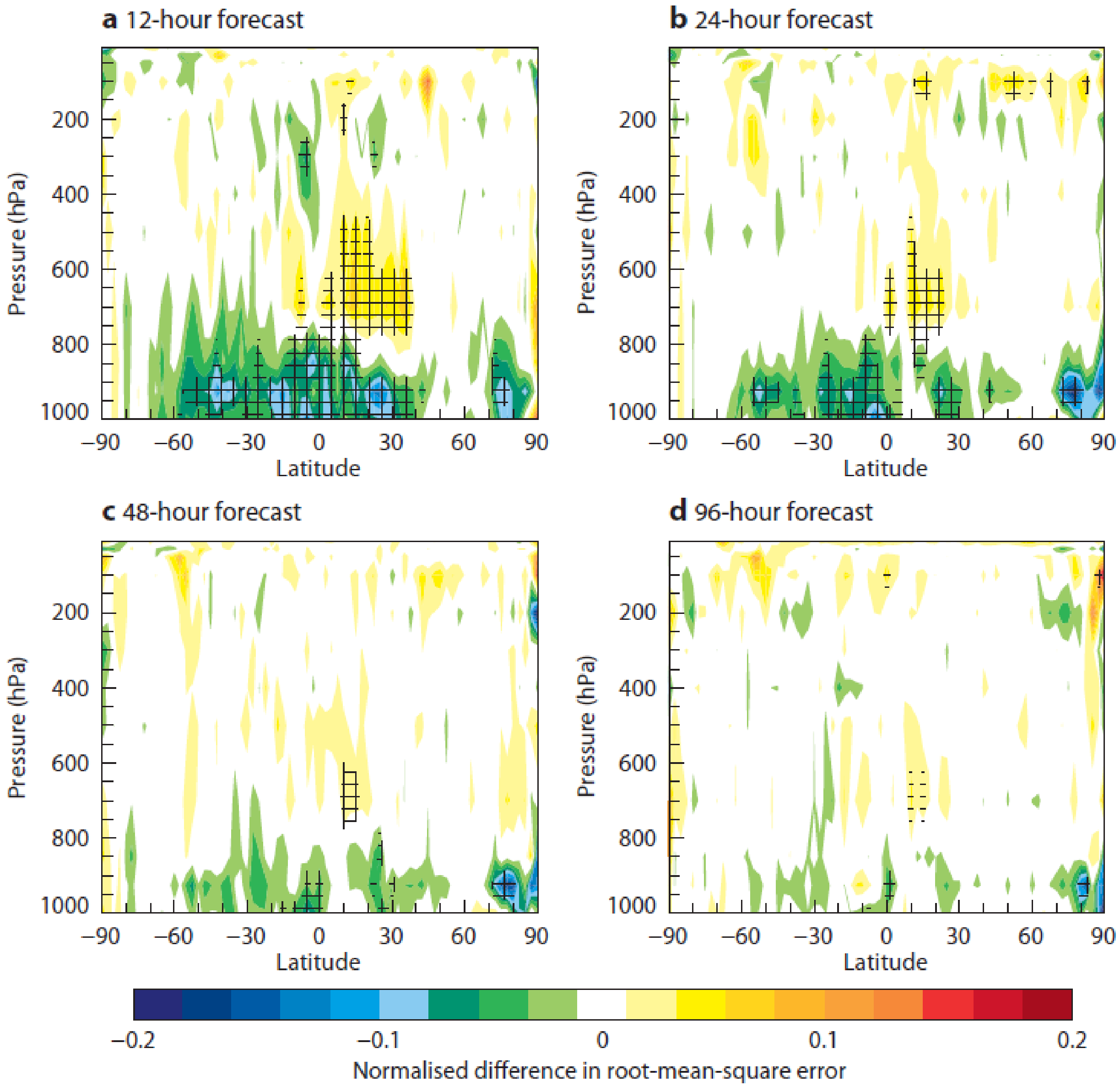
Forecast verification problems

- Adding new observations can increase RMS difference between forecasts and verifying analyses, i.e. scores appear worse
- Model biases add problems and they quickly spin up between analysis and forecast for humidity-related quantities
- Choice of verifying analysis can be crucial for the verification over the first days – humidity observation impact usually does not last longer



 © ECMWF

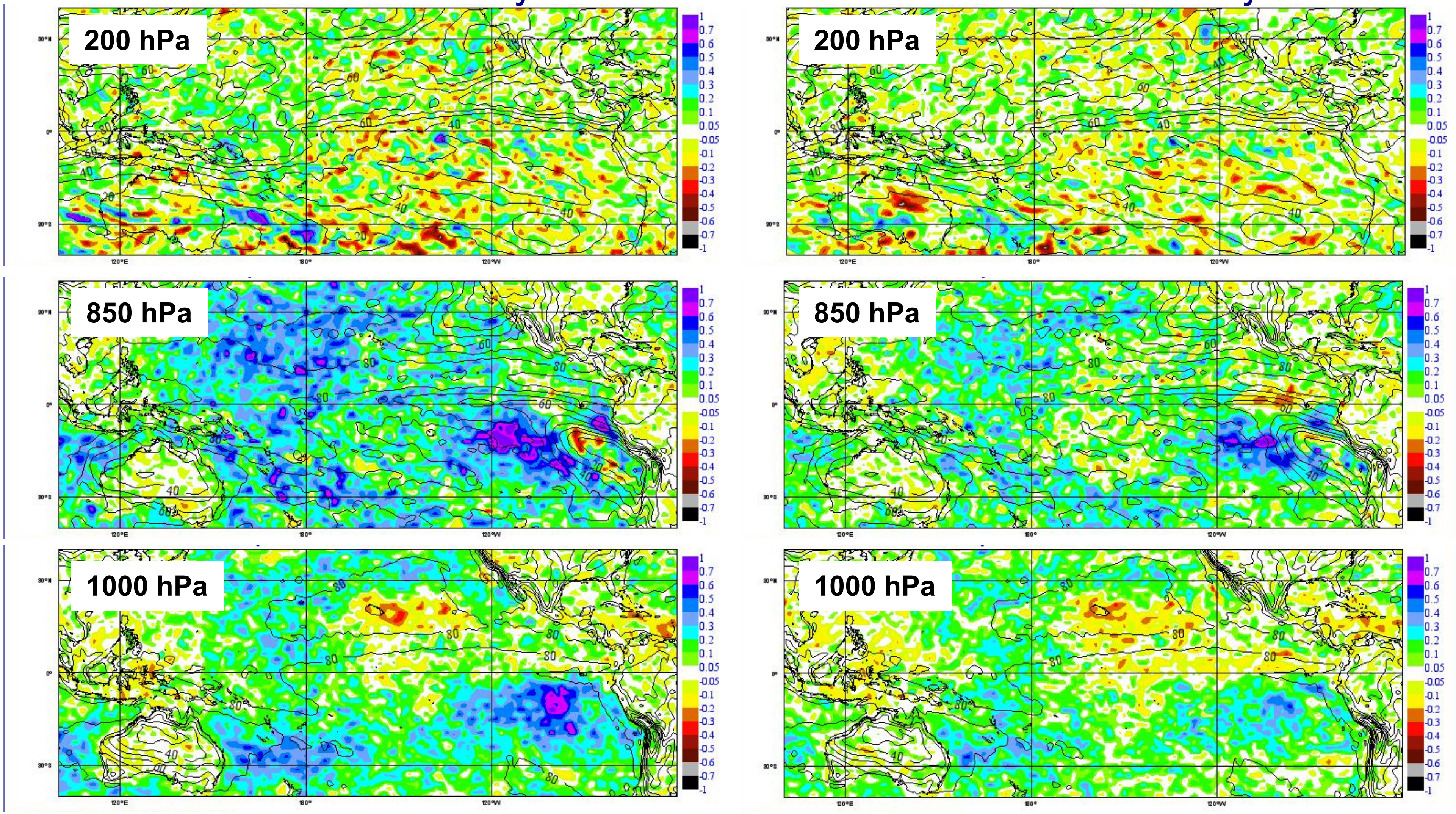
Going from 1D+4D-Var to 4D-Var



Forecast verification with (own) analysis

RMSE difference: 4D-Var -No MW imagers (07-09/2009)

24-hour relative humidity f/c　　　48-hour relative humidity f/c

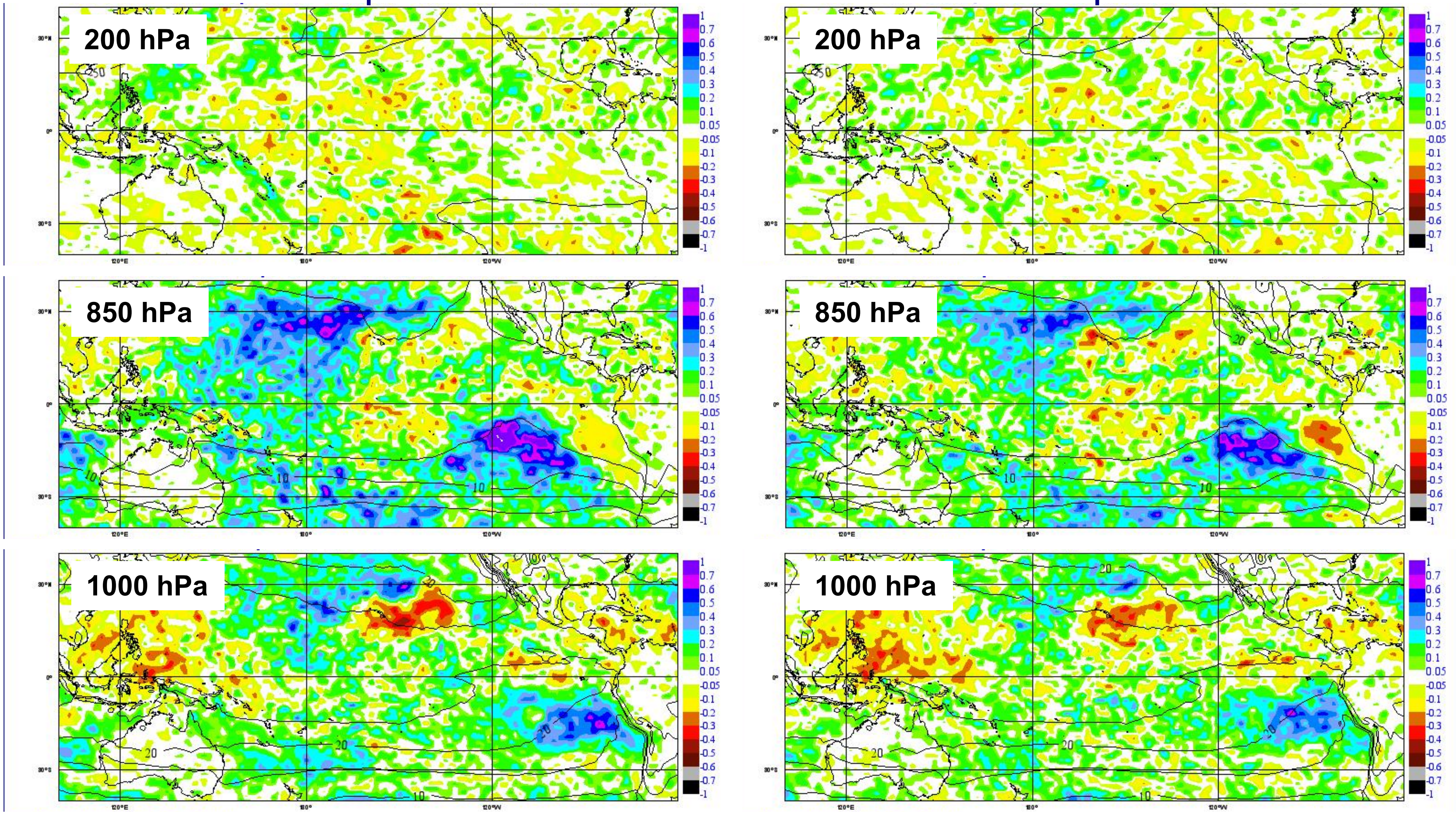


ECMWF

Forecast verification with (own) analysis

RMSE difference: 4D-Var -No MW imagers (07-09/2009)

24-hour temperature f/c   48-hour temperature f/c



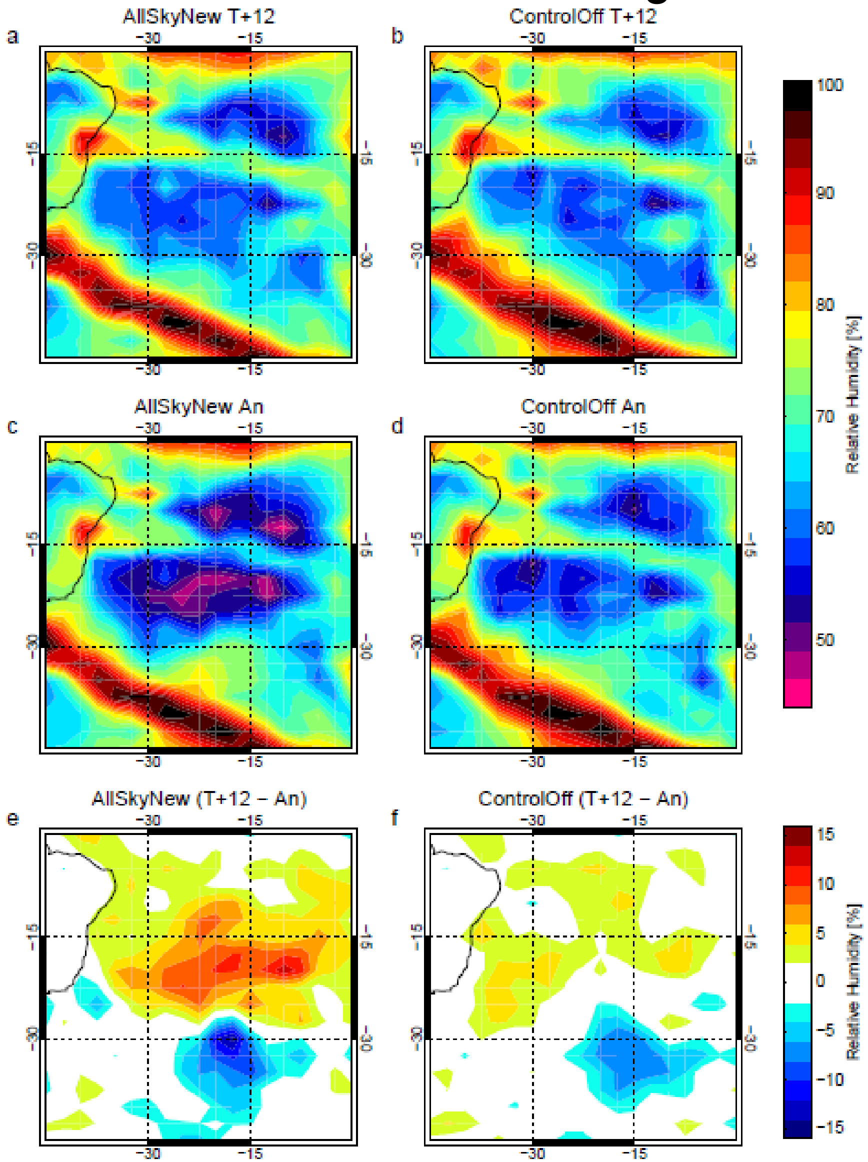
Forecast verification: case study

4D-Var No MW imagers

12-hour forecast

Analysis

‘Analysis increment’



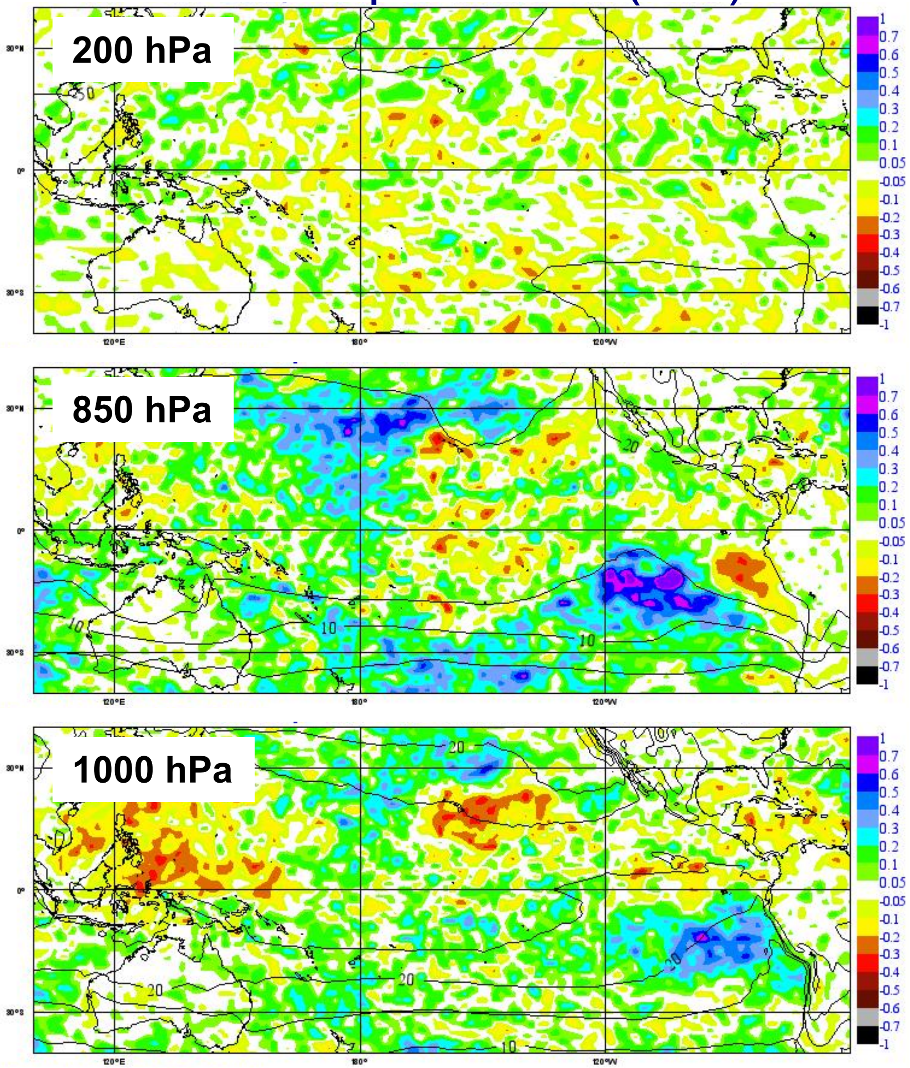
Relative humidity
at 1000 hPa
9 July 2009

ECMWF

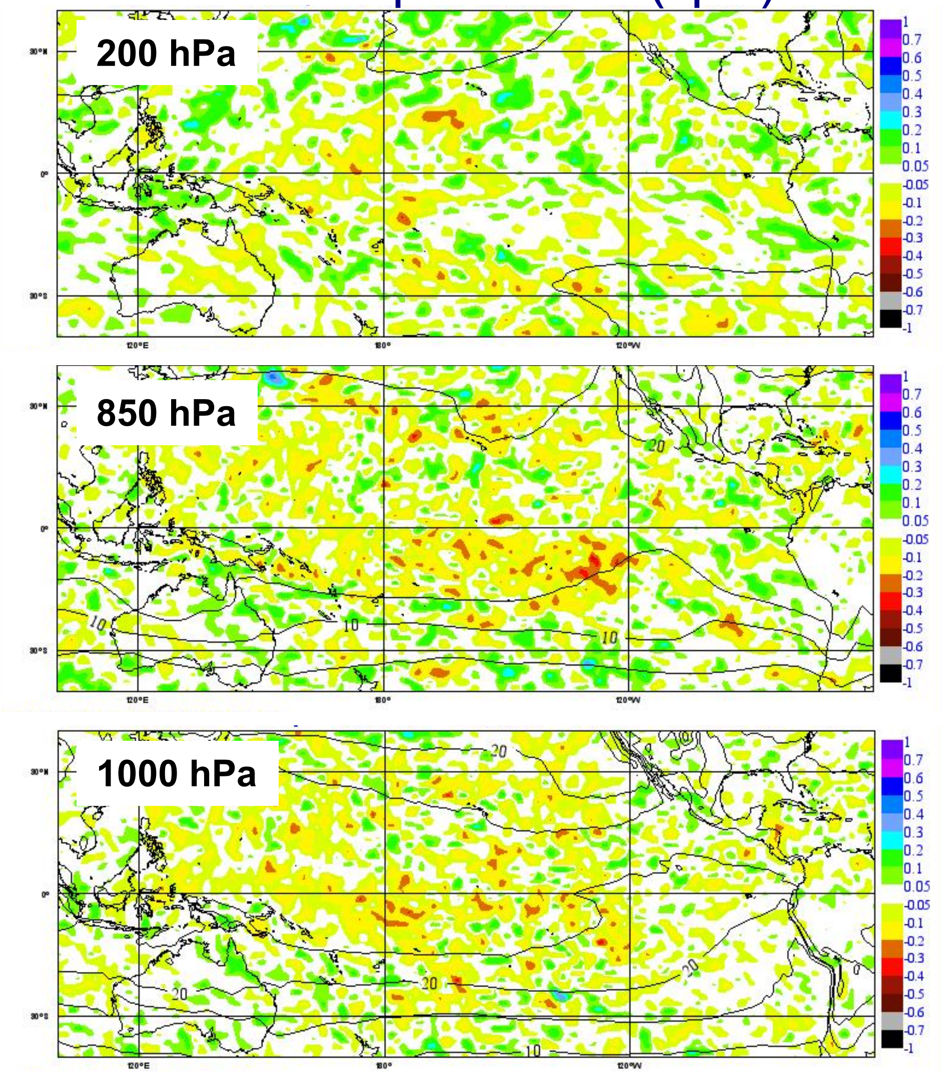
Forecast verification with (own vs oper) analysis

RMSE difference: 4D-Var -No MW imagers (07-09/2009)

48-hour temperature f/c (own)

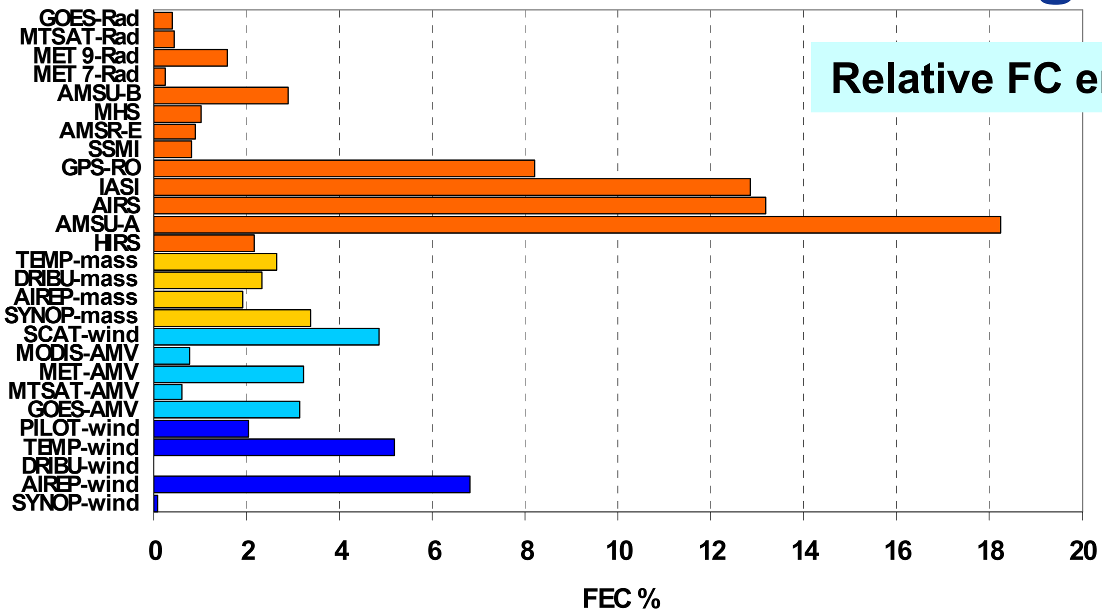


48-hour temperature f/c (oper)

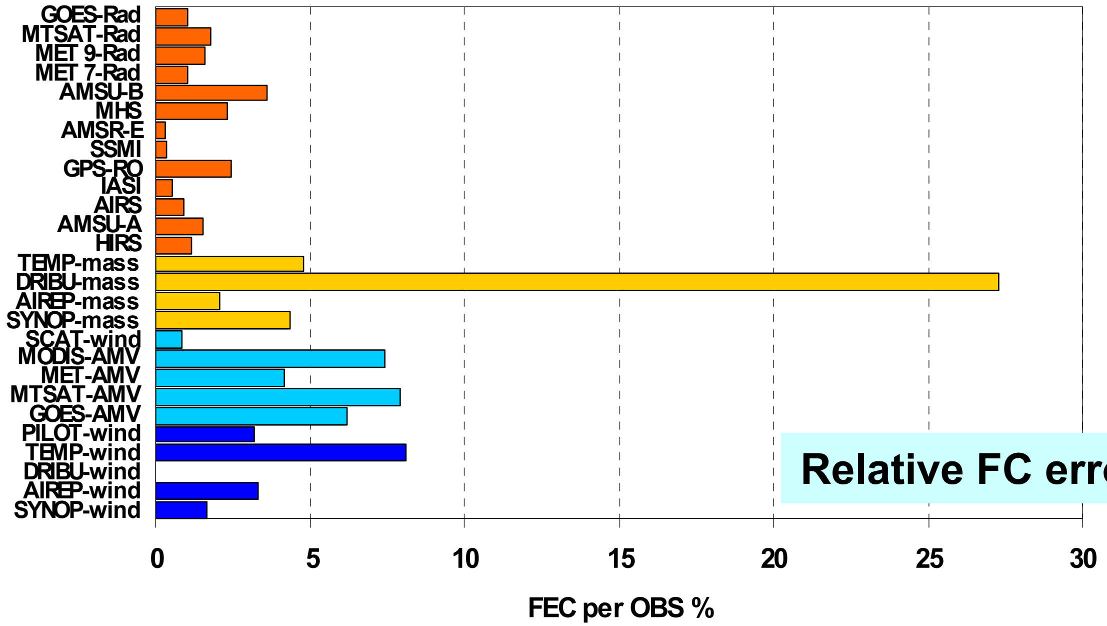


ECMWF

Advanced diagnostics



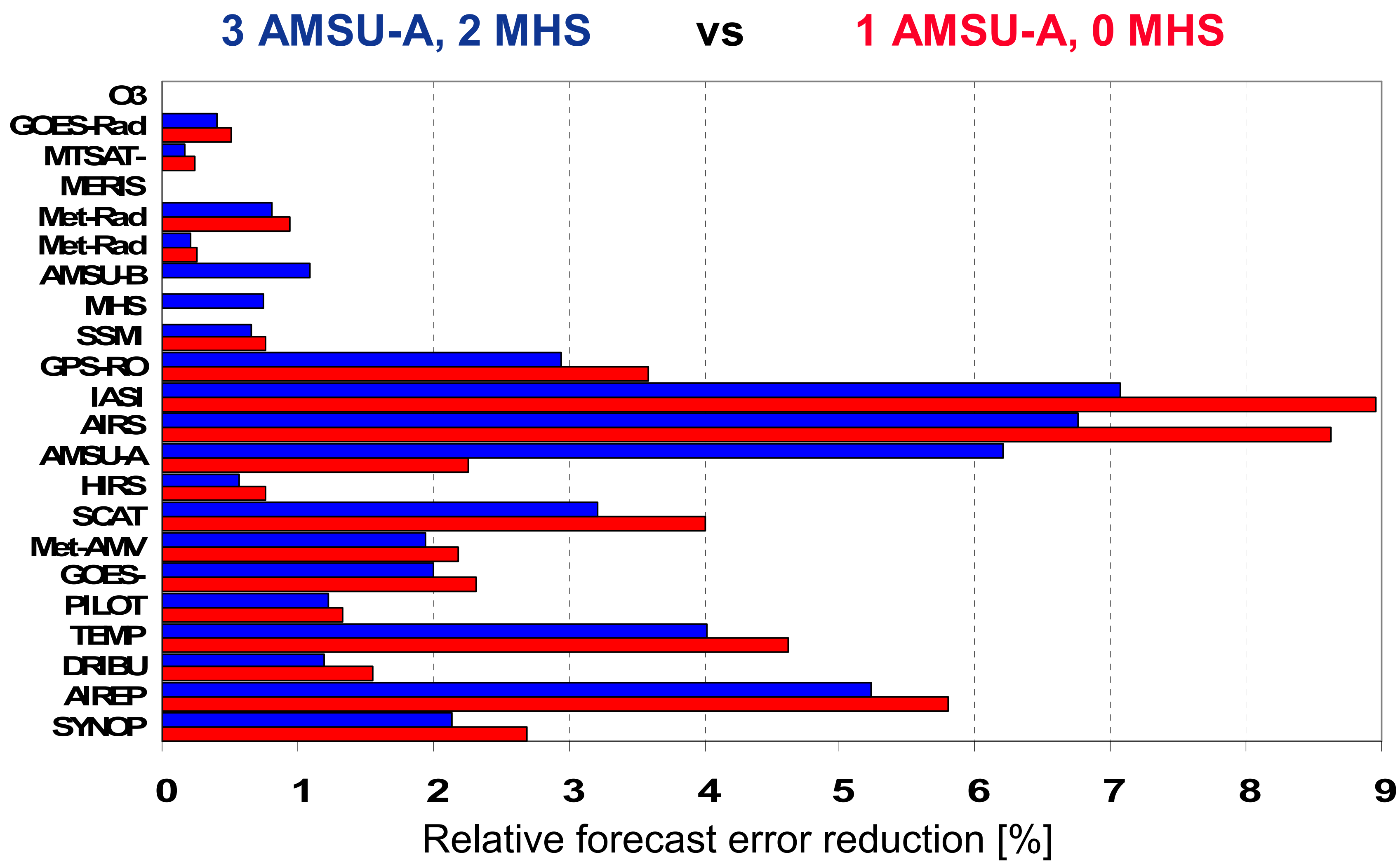
Relative FC error reduction per system



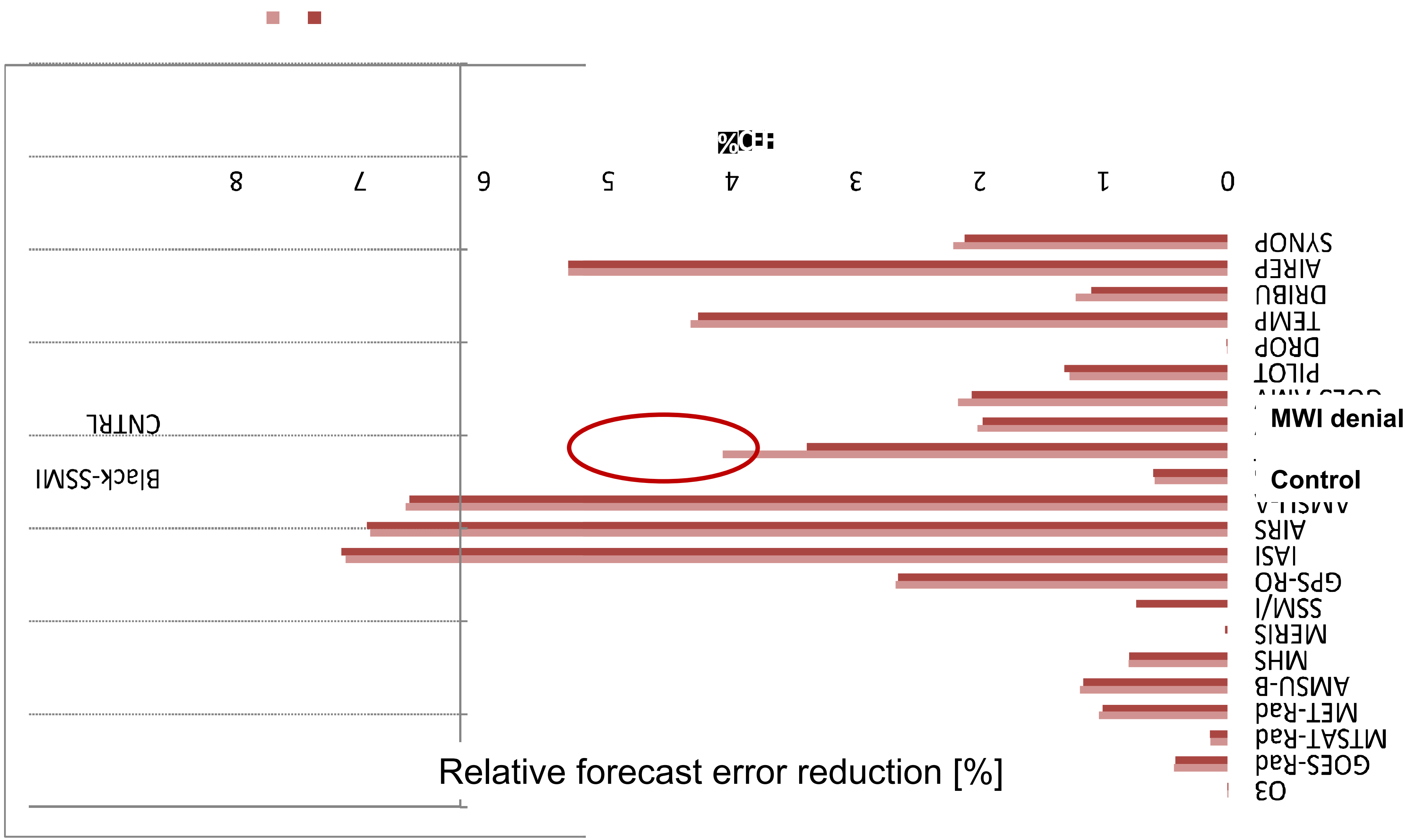
Relative FC error reduction per observation

The *forecast sensitivity* (Cardinali, 2009, QJRMS, 135, 239-250) denotes the sensitivity of a forecast error metric (dry energy norm at 24 or 48-hour range) to the observations. The forecast sensitivity is determined by the sensitivity of the forecast error to the initial state, the innovation vector, and the Kalman gain.

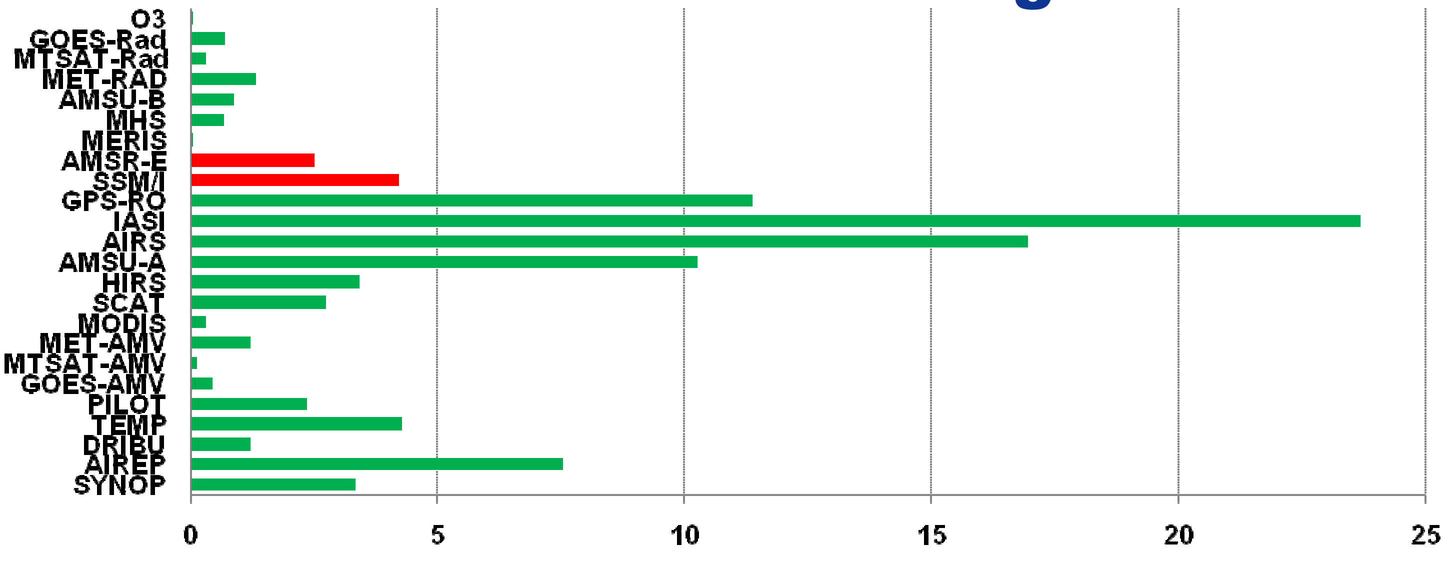
Advanced diagnostics – MW sounder denial



Advanced diagnostics – MW imager denial

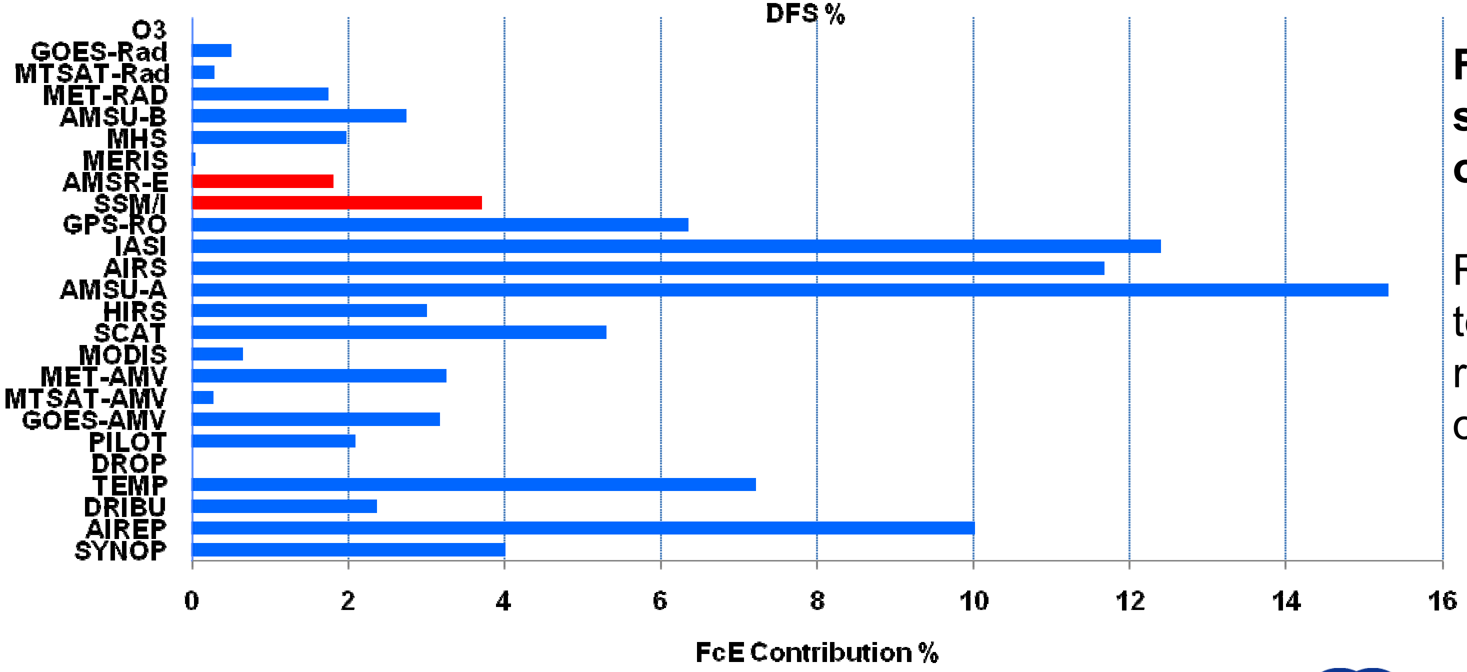


Advanced diagnostics



Analysis sensitivity to observations:

Relative contribution of information to the analysis by each observation type



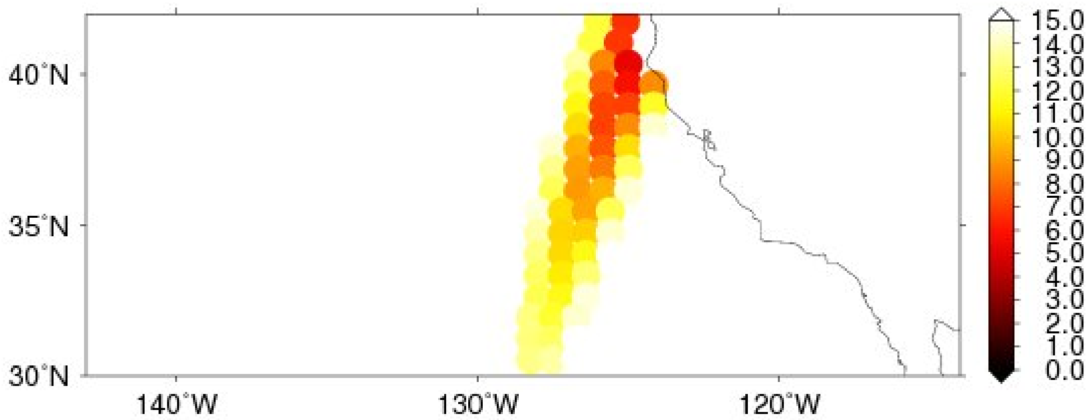
Forecast sensitivity to observations:

Relative contribution to forecast error reduction by each observation type

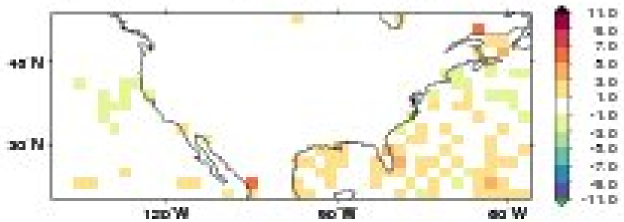
RFI at 18.7 GHz

Reflection of microwave radiation transmitted by geostationary satellites at 18.7 GHz off US West/East coast (→ AMSR-E)

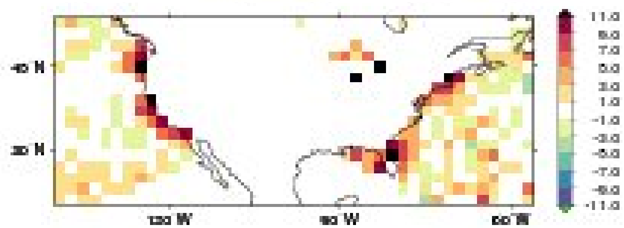
glint angle



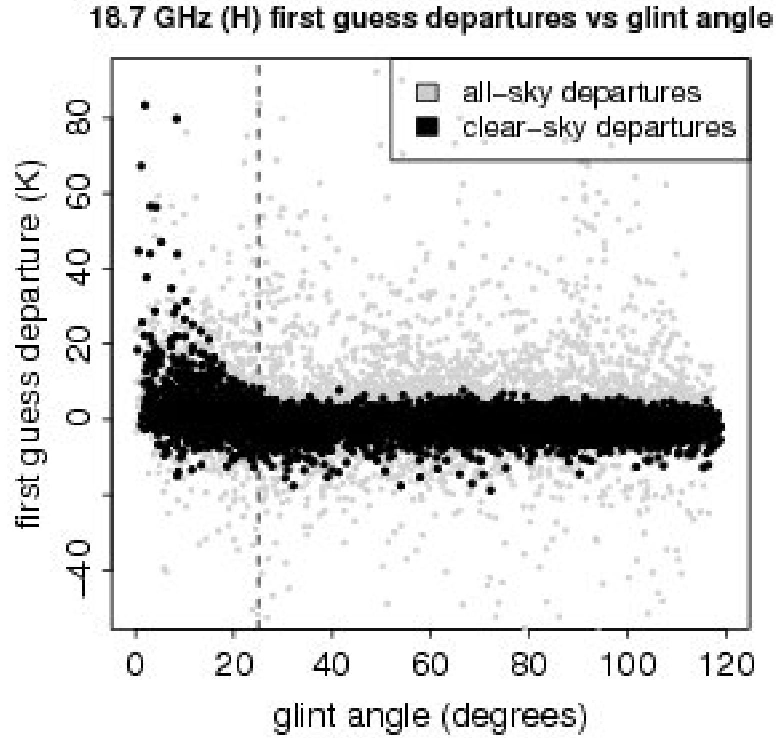
angle > 20º



angle < 20º



Dependence of first-guess departures (model-observation) on glint angle

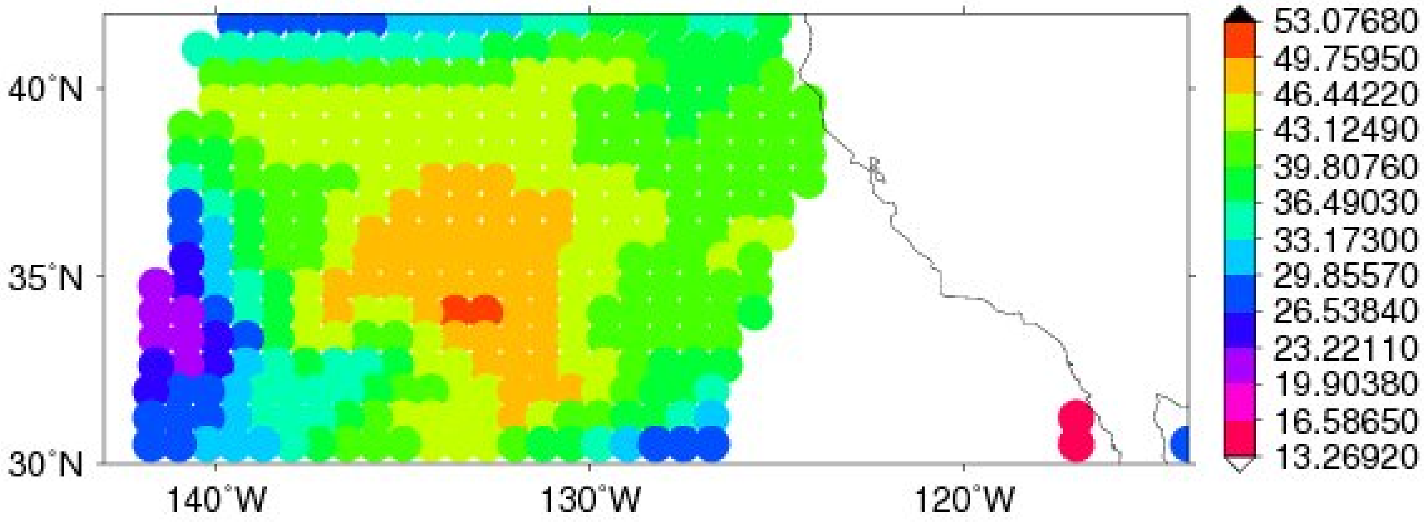


(B. Krzeminski)

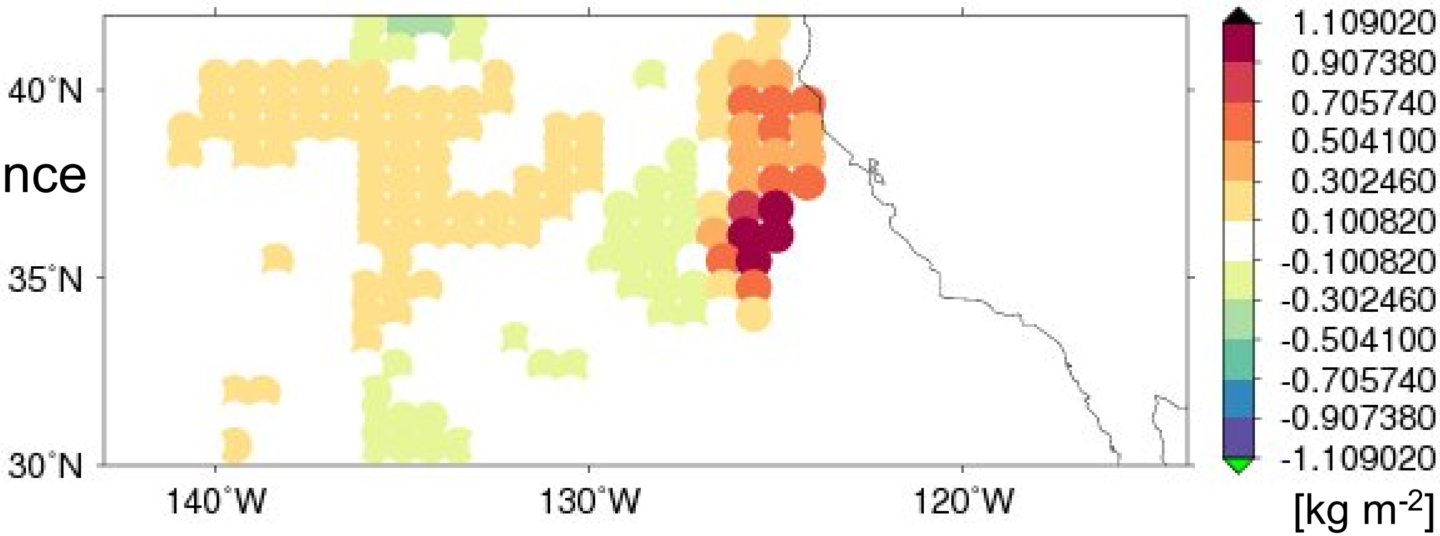
RFI at 18.7 GHz

1-cycle assimilation experiment

Analysis
TCWV (RFI)



Analysis difference
TCWV
RFI – no RFI



(B. Krzeminski)

Conclusions

Motivation

•Satellite observations in cloud and precipitation affected areas promise

- constraining atmospheric analysis in areas where forecast errors grow rapidly and where forecast skill strongly depends on initial conditions,
- constraining moist physics that are currently not observed.

 © ECMWF

Conclusions cont'd

Modelling clouds/precipitation

- Model acts as efficient filter between initial conditions and forecast state.
- Continuous effort to improve non-linear modelling of hydrological cycle.
- Continuous effort to keep up with linearized models.
- Community-type radiative transfer model development ensures best trade-off between accuracy and computational efficiency.

Progress since 2005 workshop

Observations

•Use ARM site and field campaign observations to validate satellite clouds/precipitation

- Run 1D-Var test studies (operators, DA performance, error definition)

•Design validation programs with data assimilation in mind

- N/A; reflected in GPM GV?

•Exploit mm-wave sounding channels (AMSU-B, SSMIS)

- Started with SSMIS, soon AMSU-A.

•Organize communication among and within the modelling, assimilation, and observation (remote sensing and in situ) communities

- Ongoing

Modelling clouds & precipitation

•Construct high-quality, independent cloud and precipitation verification data sets

- Only use available data sets such as GPCP, Cloudsat/Calipso

•Validate process models with cloud resolving model data sets

- Not yet

•Develop moist convective schemes compatible with data assimilation

- Ongoing activity

•Simplify and linearize physics schemes

- Ongoing activity

© ECMWF

Progress since 2005 workshop

Radiative transfer modelling

•Construct a high-quality data set of satellite observations and in-situ information of cloud condensates to fully assess RT model performance

- Not available (like ConcordIASI for clear-sky IASI)?

•Characterize biases and standard deviations of simulated radiances

- Only from DA diagnostics

•Determine mean particle sizes from VIS/IR/microwave observations

- Not available?

•Develop fast, accurate RT model for clouds and precipitation

- Ongoing activity

Progress since 2005 workshop

Data assimilation

- Compare model simulated with observed cloud/precipitation radiances
    - Part of data monitoring
- Entrain model developers in designing physical parameterization schemes for data assimilation applications
    - ?
- Encourage data and model providers to provide error characteristics
    - Difficult, where possible use level-1 observations
- Implement precipitation/cloud assimilation schemes even if impact is initially neutral
    - Done
- Develop new forecast skill measures for cloud/precipitation and their effects on other fields
    - Ongoing activity
- Determine expected increase in cloud/precipitation forecast skill from predictability experiments
    - Ongoing activity

 © ECMWF