Cloud and precipitation from satellites: 20 years and 4 joint workshops

Alan Geer

Joint workshops on satellite cloud and precipitation data assimilation

But first... "ancient" history

2005: 1st Workshop
Landsdowne,VA,USA

2010: 2nd Workshop
ECMWF, Reading

2015: 3rd Workshop
NOAA-NWS, USA

2020: 4th Workshop
ECMWF, Reading

1980 - 2000

Development of operational NWP as we know it today…

… plenty of attempts to assimilate cloud and precipitation, but even humidity assimilation was a struggle.

Optimal Interpolation (OI), Analysis correction (AC), …

- Data assimilation approaches based entirely in model space (e.g. T, q, u, v)
- Direct assimilation of radiances or precipitation rates is impossible
- Heuristic cloud and precipitation assimilation strategies for short-range / mesoscale prediction:
  - Latent heat nudging
    - Boost latent heating directly in the model physics, at locations where precipitation is seen by radar.
    - Experimental work: Ninomiya et al. (1987), Wang and Warner (1988)
    - Operational in the mesoscale model at the Met Office 1996 (Jones and Macpherson, 1997, Met. App.)
  - "Normal mode initialisation", "Physical initialisation"
    - Other paths to inserting latent heating, T or q into the model, from radar or satellite precipitation retrievals
    - Experimental work, e.g.: Krishnamurti et al. (1991, Tellus); Puri and Miller (1990)

Variational data assimilation: 3D-Var

3D-Var cost function

Best estimate of atmospheric state x is at minimum of cost function

Observation operator

Observations

$$2J(\mathbf{x}) = (\mathbf{x}-\mathbf{x_b})^T \mathbf{B}^{-1}(\mathbf{x}-\mathbf{x_b}) + (\mathbf{y}_o - H(\mathbf{x}))^T \mathbf{R}^{-1}(\mathbf{y}_o - H(\mathbf{x}))$$

Background atmospheric state and its error

Observation error

H() is a key first step – an operator to transform from model space (e.g. T, q) to observation space (e.g. radiance, precipitation retrievals)

Possible strategies for cloud and precipitation data assimilation:

1. H() is a radiative transfer operator mapping from model profile to all-sky satellite radiances
2. H() is a simple moist physics model mapping from T,q to e.g. surface rain rate

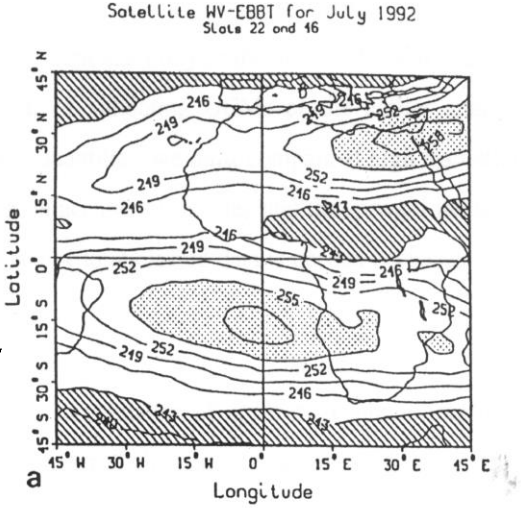
Totally theoretical at this stage, as far as cloud and precipitation is concerned …

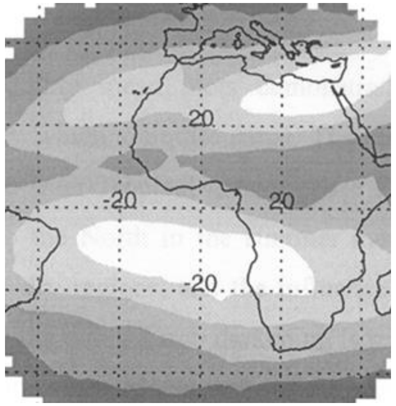
Benefits of 3D variational assimilation on humidity

July 1992 monthly mean TB
(Schmetz and van de Berg, 1994, GRL)

July 1997 monthly mean TB
(Geer, PhD thesis, 1999)

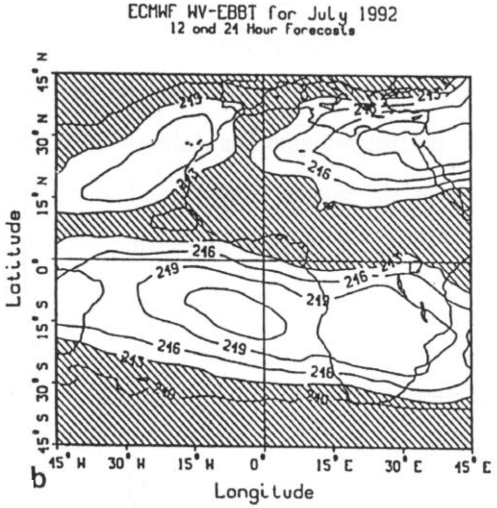
Meteosat clear-sky 6.7 micron TB (CSR)

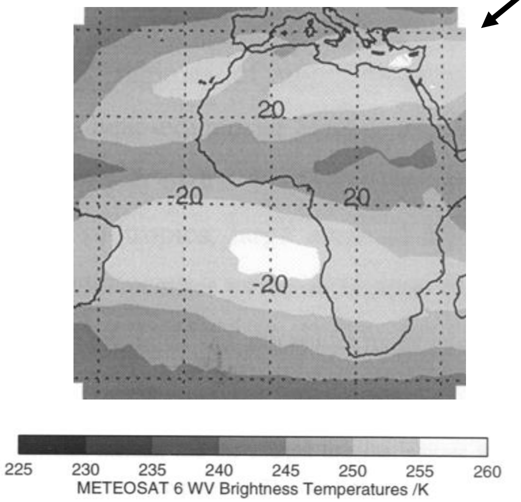




Much better agreement between model and observations

ECMWF operational





DA: OI
Sat obs: 1D-Var retrievals of T from satellite cloud-cleared radiances (TOVS)
Res: T213 (47 km)

DA: 3D-Var
Sat obs: Clear-sky direct assimilation of TOVS radiances (inc. HIRS q channels 10,11,12)
Res: T213 (47 km)

4D-Var strategies for cloud and precipitation data assimilation

What's new: **forecast model**

4D-Var cost function

$$2J(\mathbf{x}) = \left(\mathbf{x}-\mathbf{x_b}\right)^T \mathbf{B}^{-1}\left(\mathbf{x}-\mathbf{x_b}\right) + \left(\mathbf{y}_o - H\left(M\left(\mathbf{x}\right)\right)\right)^T \mathbf{R}^{-1}\left(\mathbf{y}_o - H\left(M\left(\mathbf{x}\right)\right)\right)$$

- To solve 4D-Var we need the tangent linear (TL) $\mathbf{M}$ and adjoint $\mathbf{M}^\mathbf{T}$ of the forecast model $M()$
- And to derive a TL and adjoint model we first need a simplified, regularised version of the forecast model $M_{simple}()$
- 4D-Var is the starting point for modern cloud and precipitation assimilation

Inclusion of moist physics in *M()* for 4D-Var

- Initial modelling in 4D-var was “dry” – i.e. no moist physics
- Early experimental work on “moist” 4D-Var:
  - D. Zupanski (1993, Tellus) – Betts Miller convection scheme TL/AD in 4D-Var
  - Zou et al. (1993, Tellus) – Large-scale and convection scheme TL/AD in 4D-Var
  - Zupanski and Mesinger (1995, MWR) – 4D-Var assimilation of precipitation data
  - Need for smoothing (regularisation) and simplification identified
- Adoption of moist physics TL/adjoint modelling at operational centres for 4D-Var NWP:
  - **Météo-France:** Janisková, Thépaut and Geleyn (1999, MWR)
  - **ECMWF**: Mahfouf and Rabier (2000, QJ), later updated e.g.Tompkins and Janiskova (2004), Lopez and Moreau (2005).
  - **JMA:** non-hydrostatic: (Honda et al., 2005, QJ)

4D-Var converges slower with convection parameterisation, but it converges!

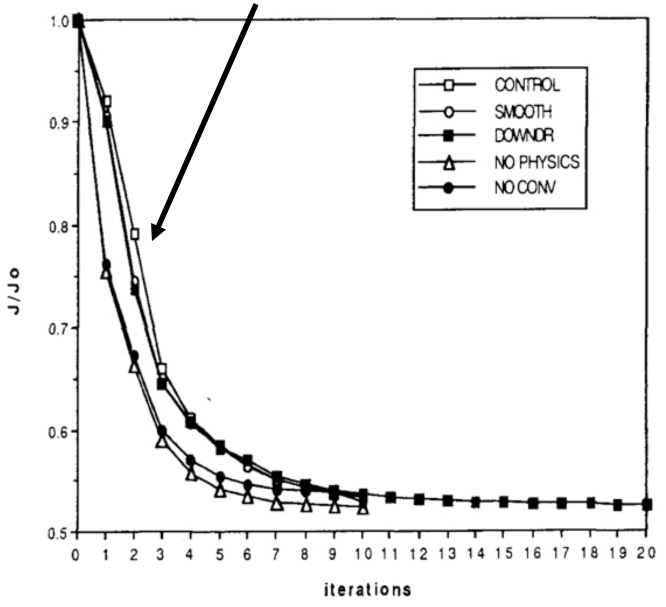
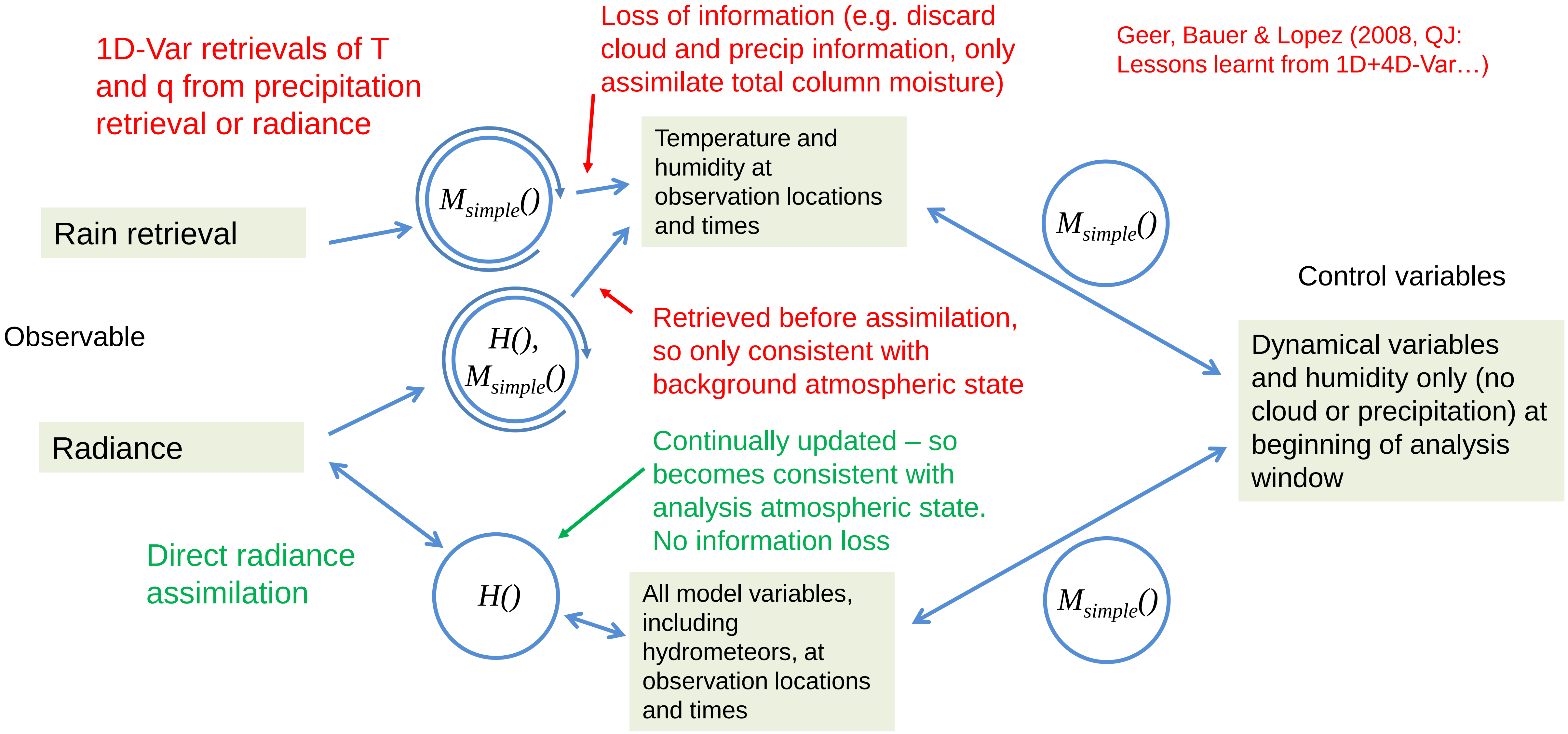


Fig. 4. Functional J, normalized by the initial value J_0, plotted as function of iteration number, for the 5 models (Table 1).

D. Zupanski (1993, https://doi.org/10.3402/tellusa.v45i5.15053)

And there it stopped – most other centres decided not to add moist physics to their DA systems

Strategies for cloud and precipitation assimilation in 4D-Var



Status of operational data assimilation and precipitation retrievals: 2001

Precursors of modern cloud and precipitation assimilation

- **Variational data assimilation for clear-sky radiances**
  - Operational 4D-Var at ECMWF from November 1997
    - At many other centres in the following years
- Nudging methods and similar heuristic techniques at some operational centres, for short-range / mesoscale forecasting
- **Bayesian precipitation retrievals**
  - A 0/1D precursor to particle filters
  - E.g. GPROF (Chris Kummerow and collaborators)
- Ensemble data assimilation methods still have not hit the mainstream

2001 - 2005

International Workshop on Assimilation of Satellite Cloud and Precipitation Observations in Numerical Weather Prediction Models, in Lansdowne, Virginia, in May 2005

2001 – 2005: Gathering the tools for modern cloud/precip DA

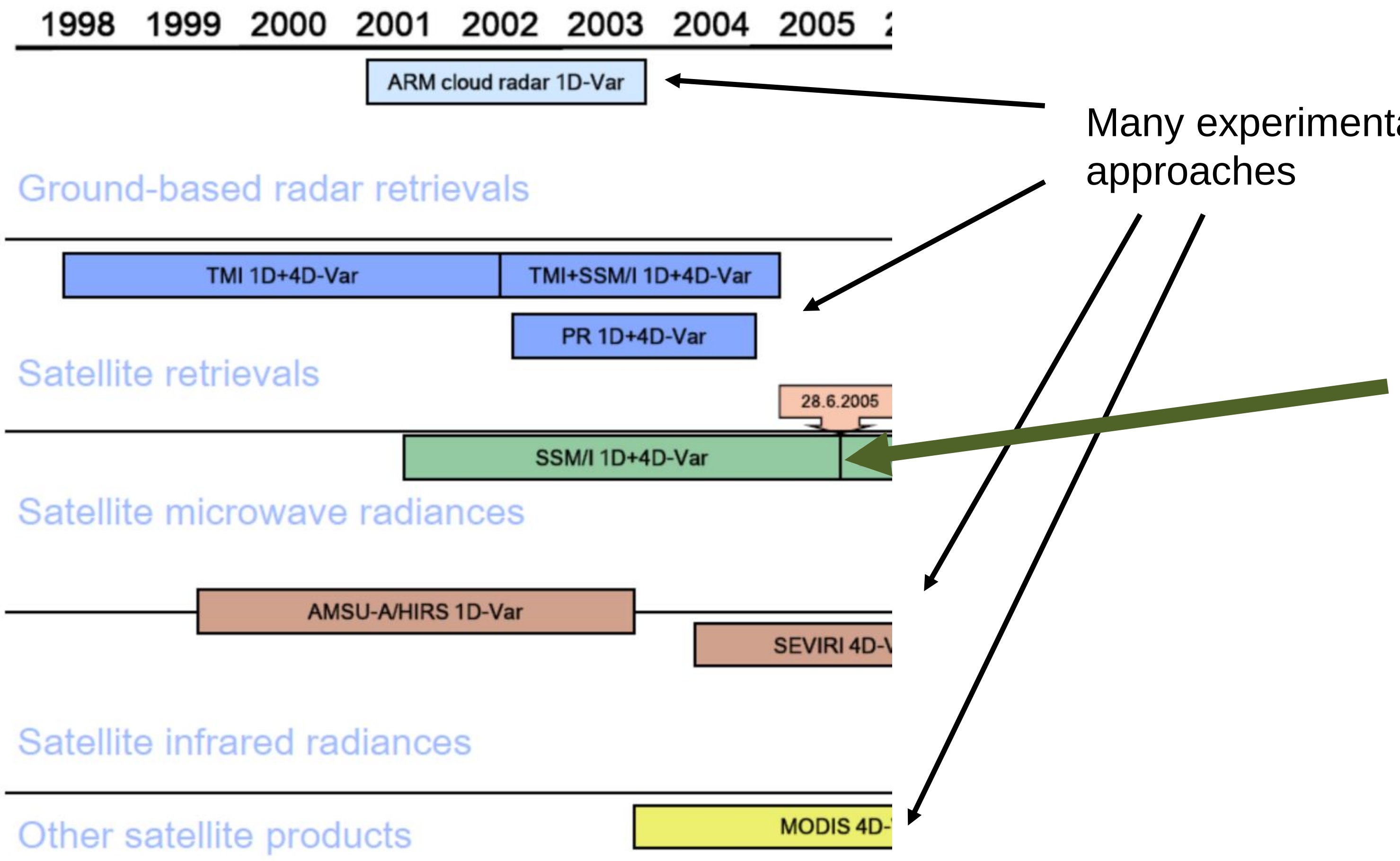
Got

- 4D-Var assimilation
- Moist physics TL and adjoint models
  - Can be used as observation operators in their own right (e.g. for assimilating precipitation retrievals)
- Observations:
  - All-sky radiances, precipitation retrievals

In development

- All-sky radiative transfer models:
  - RTTOV-SCATT developed by Peter Bauer and co. during 2000-2005 (Bauer et al., 2006, QJ)
  - RTTOV scattering IR – Matricardi (ECMWF tech. memo., 2005)
- Assimilation strategies:
  - 1D-Var + 4D-Var
  - Direct 4D-Var

Early cloud and precipitation work at ECMWF:
trying many different techniques and observables…



Many experimental approaches

One operational implementation:
1D+4D-Var of SSM/I and AMSR-E started on 28 June 2005
Bauer et al. (2006, QJ)

Figure from Peter Bauer's 2010 workshop proceedings paper

Cloud and precipitation at other operational centres: 2001-2005

- From 2002: JMA started assimilating rain rates retrieved from ground based radar and microwave imagers, and total column water vapour retrieved from microwave imagers,
  - assimilated in operational mesoscale 4D-Var system

- Latent-heat nudging and similar heuristic techniques at other centres: Met Office mesoscale, NCEP rapid update cycle (RUC)

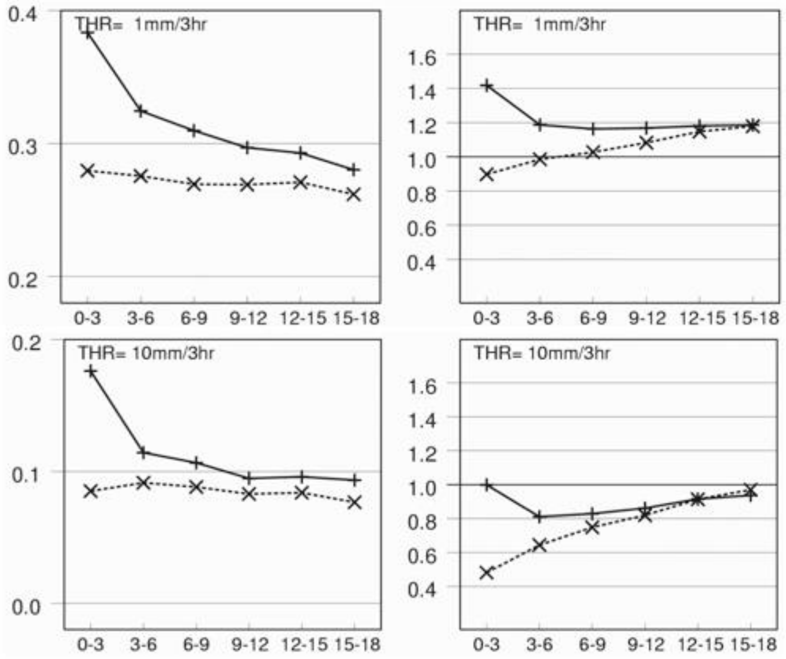


Fig. 4. Threat scores (left) and bias scores (right) for 3-hour precipitation forecast starting from analysis with precipitation assimilation (solid line) and without one (dashed line). The threshold value is 1 mm per 3 hour (top) and 10 mm per 3 hour (bottom).

Better precipitation threat scores with TCWV and RR assimilation in precipitation

Koizumi et al. (2005, SOLA, Vol. 1, 045–048, doi: 10.2151/sola. 2005–013)

Joint workshops on satellite cloud and precipitation data assimilation

Outputs

2005: 1st Workshop
Landsdowne,VA,USA

2007 JAS special collection

2010: 2nd Workshop
ECMWF, Reading

2015: 3rd Workshop
NOAA-NWS, USA

2020: 4th Workshop
ECMWF, Reading

2007 JAS special issue

Authors	Subject	Citations*
Errico, Ohring, F Weng, Bauer, Ferrier, Mahfouf, Turk	Workshop overview and recommendations	40
Stephens, Kummerow	The Remote Sensing of Clouds and Precipitation from Space: A Review	271
Lopez	Cloud and Precipitation Parameterizations in Modeling and Variational Data Assimilation: A Review	51
Errico, Bauer, Mahfouf	Issues Regarding the Assimilation of Cloud and Precipitation Data	114
F Weng	Advances in Radiative Transfer Modeling in Support of Satellite Data Assimilation	141
Surussavadee, Staelin	Millimeter-Wave … Observed-versus-Simulated Radiance Distributions	41
Q Yue, K. Liou, S. Ou, Kahn, P Yang, Mace	Interpretation of AIRS Data in Thin Cirrus Atmospheres Based on a Fast Radiative Transfer Model	30
R Chen, F-L Chang, Z Li, Ferraro, and F Weng	Impact of the Vertical Variation of Cloud Droplet Size on … retrievals	53
Evans	SHDOMPPDA: A Radiative Transfer Model for Cloudy Sky Data Assimilation	42
A. Hou, S. Zhang	Assimilation of Precipitation, Weak Constraint, 1+1D-Var	20
Norris, da Silva	Assimilation of Satellite Cloud Data into the GMAO FVDAS using Parameter Estimation	16
O'Dell, Bauer, Bennartz	A Fast Cloud Overlap Parameterization for Microwave Radiance Assimilation	10
F Weng, T Zhu, and B Yan	Data Assimilation … Rain-Affected Radiances from Microwave .. for Hurricane Vortex Analysis	39

* as of Jan 2020, Google Scholar

If lower citations, just as important papers – but ahead of their time:

- High microwave frequencies for snow (e.g 183 GHz)
- Model and error learning
- Making sub-grid cloud overlap affordable for NWP observation operators

Errico, Bauer, Mahfouf (2007): Issues Regarding the Assimilation of Cloud and Precipitation Data

- Observations:
  - Avoid retrievals due to contamination by a-priori
  - Radiances are preferred: DA is sensitive to the atmosphere in every state (even clear-sky) whereas for precipitation observations, DA is not (zero gradient problem)
  - Non-normality of O-B distributions, big outliers, big biases
  - Time averaging as a way of reducing random error
- Models:
  - Nonlinearity and discontinuous processes
- Observation operators
  - Main errors are the microphysical and macrophysical assumptions needed to do cloud / precipitation-affected radiative transfer
- Data assimilation
  - Preserving (or making more appropriate) balance in cloud and precipitation DA
  - Predictability studies needed

2005 Workshop Recommendations

- Observations
  - Ground validation
  - Ground validation
  - Use mm-wave channels
- Models
  - CRM datasets for training
  - Prognostic moist convection including particle characteristics
  - Collaborative approach
- Radiative transfer
  - Satellite / in-situ databases inc. PSDs for validation
  - Characterise radiative transfer error
  - Use IR to characterise particle size
  - More detailed prognostic PSDs in models
  - Develop fast radiative transfer schemes
- Assimilation
  - Use O-B to determine information content
  - Modellers need to assist developing TL/adjoint physics
  - Everyone should estimate their errors
  - Push ahead with assimilation developments even if neutral
  - New forecast skill measures needed for cloud and precipitation
  - Well-conducted experiments into the predictability of cloud and precipitation

Hindsight 2020:

- Paid off very nicely over the next decade
- Important points, but easier said than done – still not fully achieved 15 years later

2006 - 2010

ECMWF/JCSDA Workshop on Assimilating Satellite Observations of Clouds and Precipitation into NWP Models, ECMWF, 15 -17 June 2010

Joint workshops on satellite cloud and precipitation data assimilation

Outputs

2005: 1st Workshop
Landsdowne,VA,USA

2007 JAS special collection

2010: 2nd Workshop
ECMWF, Reading

WG reports

ECMWF proceedings

2011 QJ special issue

2011 JAS meeting summary

2015: 3rd Workshop
NOAA-NWS, USA

2020: 4th Workshop
ECMWF, Reading

2006 – 2010: Using more cloudy infrared data in operational NWP

- Met Office, Météo-France: assimilation of IR above cloud tops: Pavelin et al. (2008), Pangaud et al. (2009), Guidard et al. (2011)
- ECMWF: assimilation of IR with strong sensitivity to cloud tops (McNally, 2009)
  - Requirement on fully overcast scenes severely limits data availability

1. Retrieve cloud top pressure CTP and cloud fraction C from the radiances (various methods)

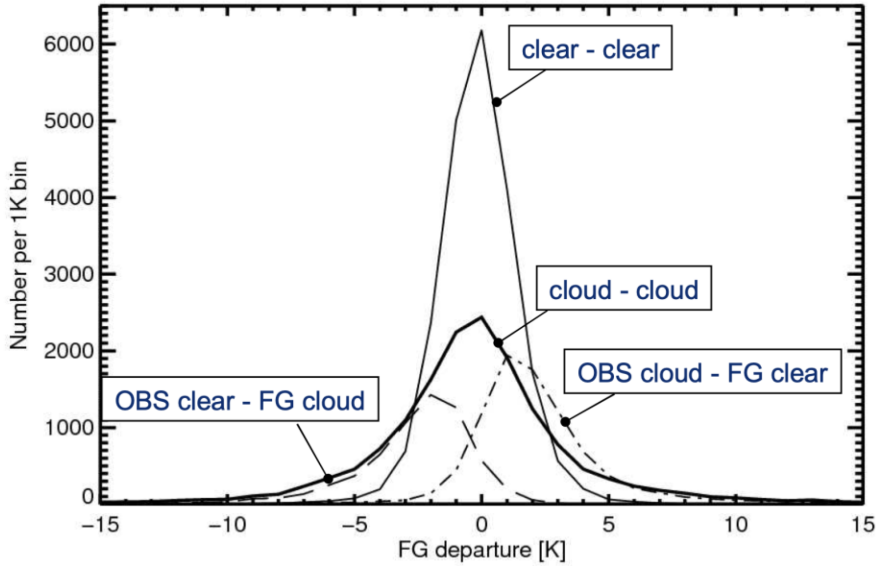
2. Assimilate cloud-affected radiances using retrieved CTP and C as a fixed constraint

2006 – 2010: Using more cloud and precipitation data in operational NWP

- Met Office: SEVIRI cloud top height and fraction retrievals in regional models (Renshaw and Francis, 2011)
  - Via a heuristic assimilation technique
- Météo-France 1D-Bayesian + 3D-Var assimilation of radar reflectivity in regional model AROME: (Caumont et al., 2010)
  - RH is used as a pseudo observation
  - Bayesian technique very similar to GPROF retrievals, but prior database is composed of model FG columns in the local area
- ECMWF: 1D+4D-Var of NEXRAD/gauge precipitation over the contiguous USA. (Lopez and Bauer, 2007, MWR)
  - Competition with other humidity observations means little impact in the full observing system context

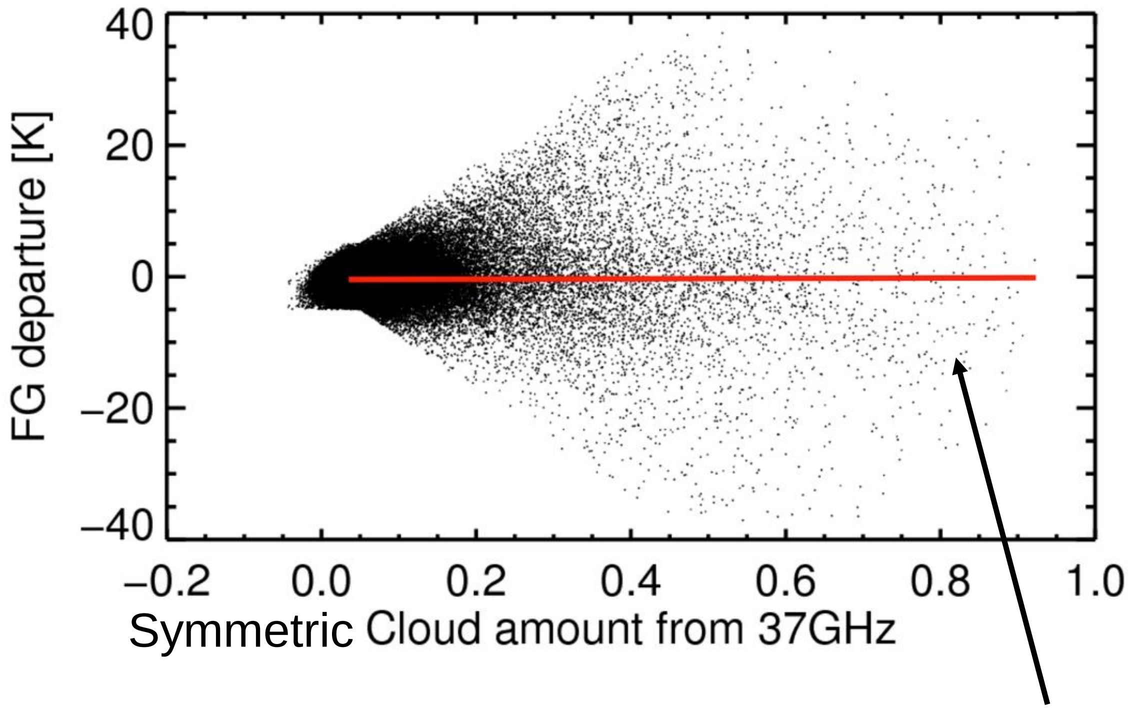
10 March 2009: First operational direct assimilation of all-sky microwave radiances, at ECMWF, using radiances from SSM/I and AMSR-E

- Unified treatment of all scenes using a cloud and precipitation-capable observation operator: “all-sky assimilation”
- Eliminate the problems of 1D+4D-Var (Geer et al., 2009)
- Documented by Bauer et al. (2010, QJ), Geer et al. (2010, QJ)
- Only problem – it has very little impact in its first version!
  - Indeed, quality of fit to some independent data (e.g. water vapour retrievals) is worse than with 1D+4D-Var
  - Reliable forecast verification of the change was very difficult



9 November 2010: First operational direct all-sky with decent impact – thanks to some key improvements

- Two main themes to getting a practical, beneficial version of all-sky assimilation:
  - Dealing with **error of representation** (or predictability / model error if you prefer) in cloudy and precipitating conditions:
    - Superobbing onto 80km grid
    - Observation error inflation in cloudy areas (symmetric error, Geer and Bauer 2010, 2011l)
  - Dealing with **model bias**:
    - Screening out CAO regions (forecast model bias)
    - Screening out heavily precipitating regions (observation operator bias due to use of Mie sphere to model snow scattering)



In cloudy situations, the model and the observations are almost guaranteed not to agree.
Geer et al. (2010, presentation, 2nd workshop)

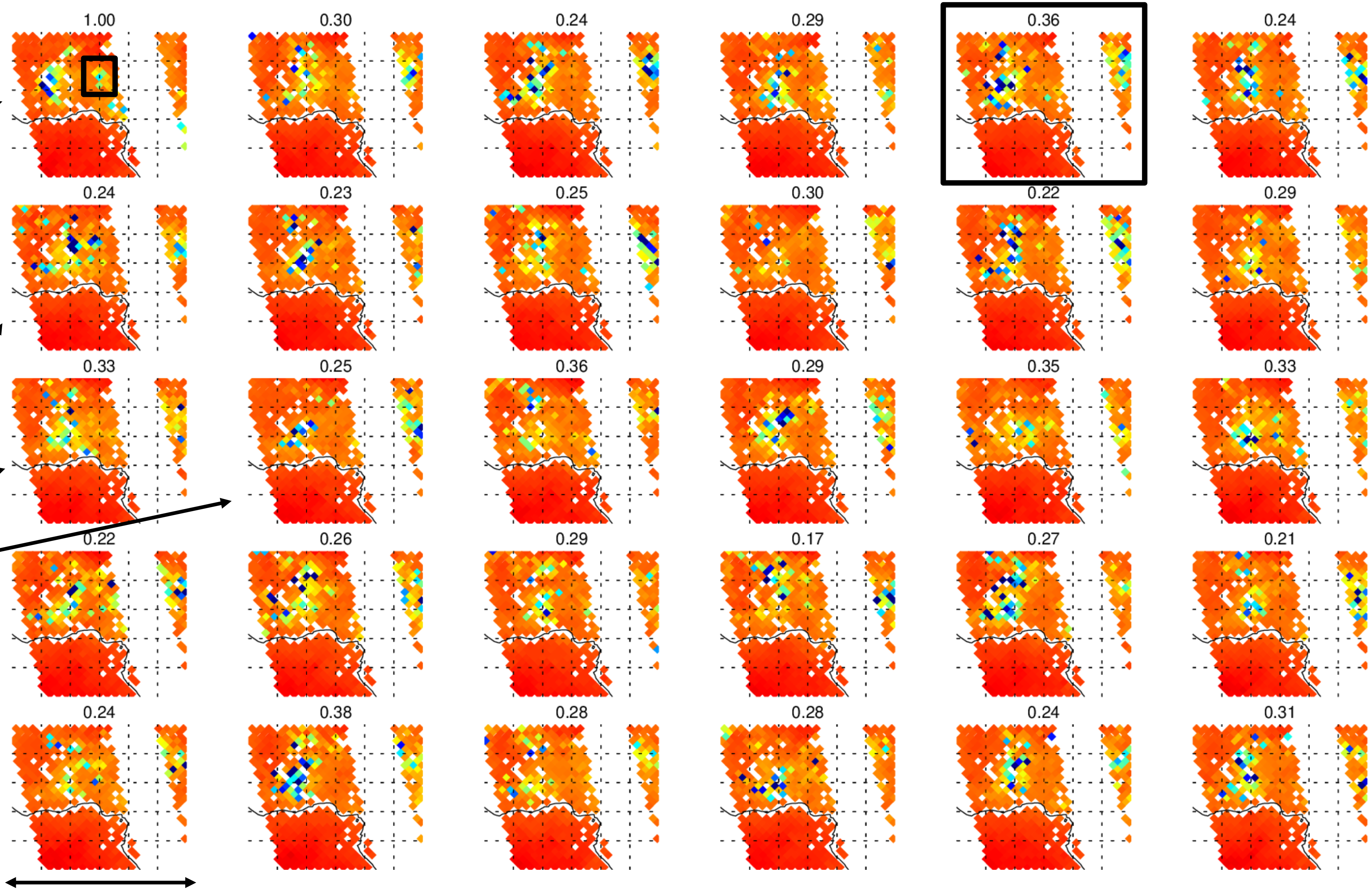
Representation error illustrated by EnKF members (EnKF: see poster by Bonvita, Geer, Hamrud)

183+/-3 GHz SSMIS **observations** (blue = scattering TB depression = convection)

African convection, 6pm, 1/9/2015

29 EnKF members **prior** (background) **forecast** and correlation to observations

Approx 3000 km by 3400 km



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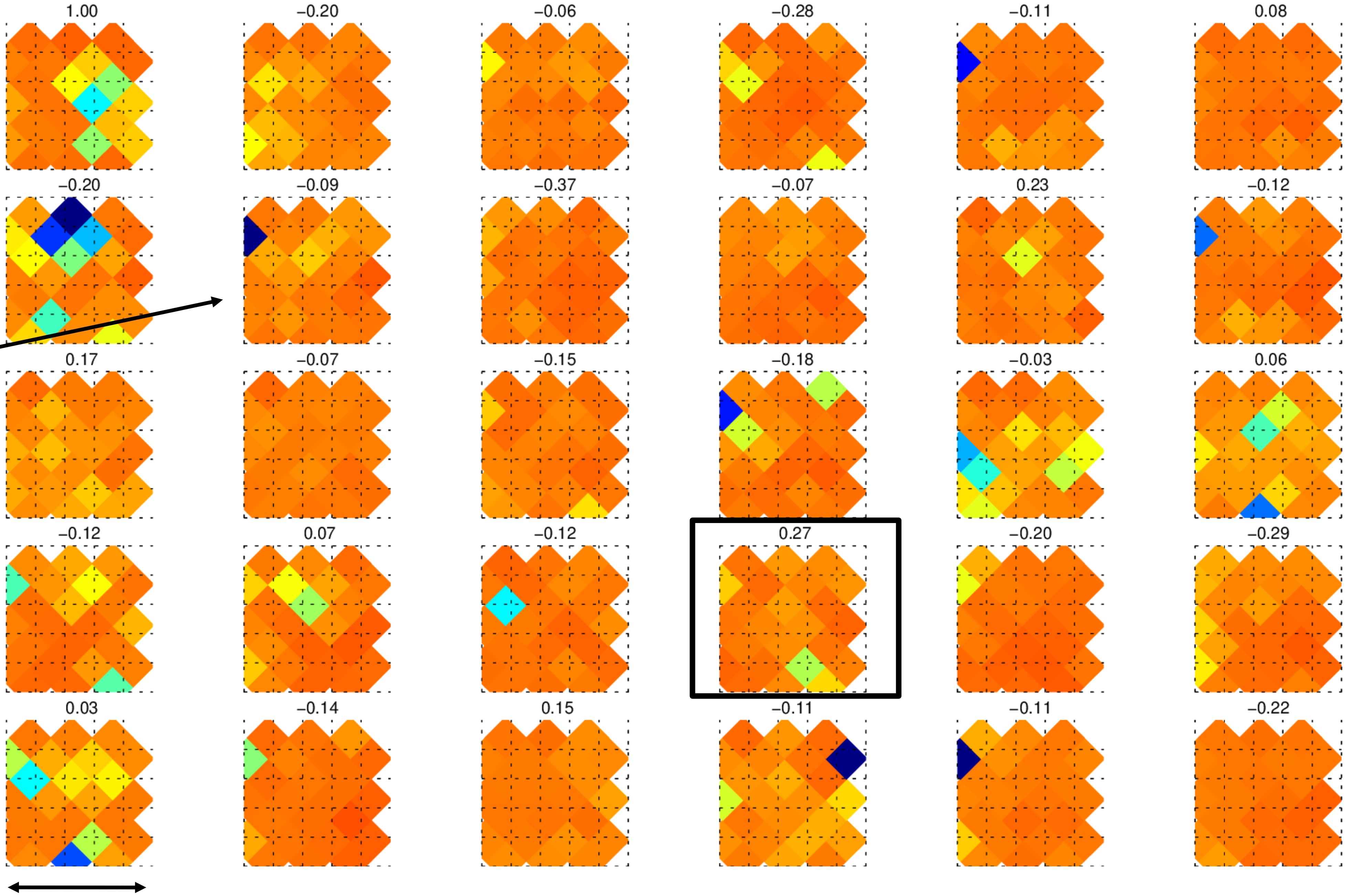
183+/-3 GHz SSMIS **observations** (blue = scattering TB depression = convection)

29 EnKF members **prior** (background) **forecast** and correlation to observations

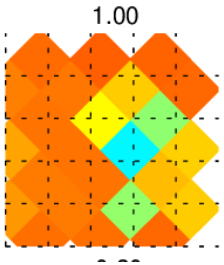
African convection 6pm, 1/9/2015

Approx 550 km by 550 km

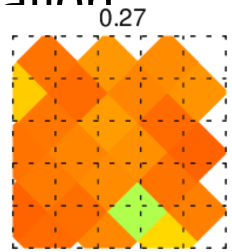


Representation error illustrated by EnKF members (EnKF: see poster by Bonvita, Geer, Hamrud)

observations



- 24 superobs are shown (approx. 100km size superobs)
- For binary (on or off) and completely random independent convection there are 2^24 => ~17 million configurations of convection
- Model space is big – the curse of dimensionality
- How to deal with it:
  - Error correlations
  - Observation error inflation
  - Further superobbing ging
  - Localisation (in ense cle filters)
  - Model constraint



model

Approx 550 km
by 550 km

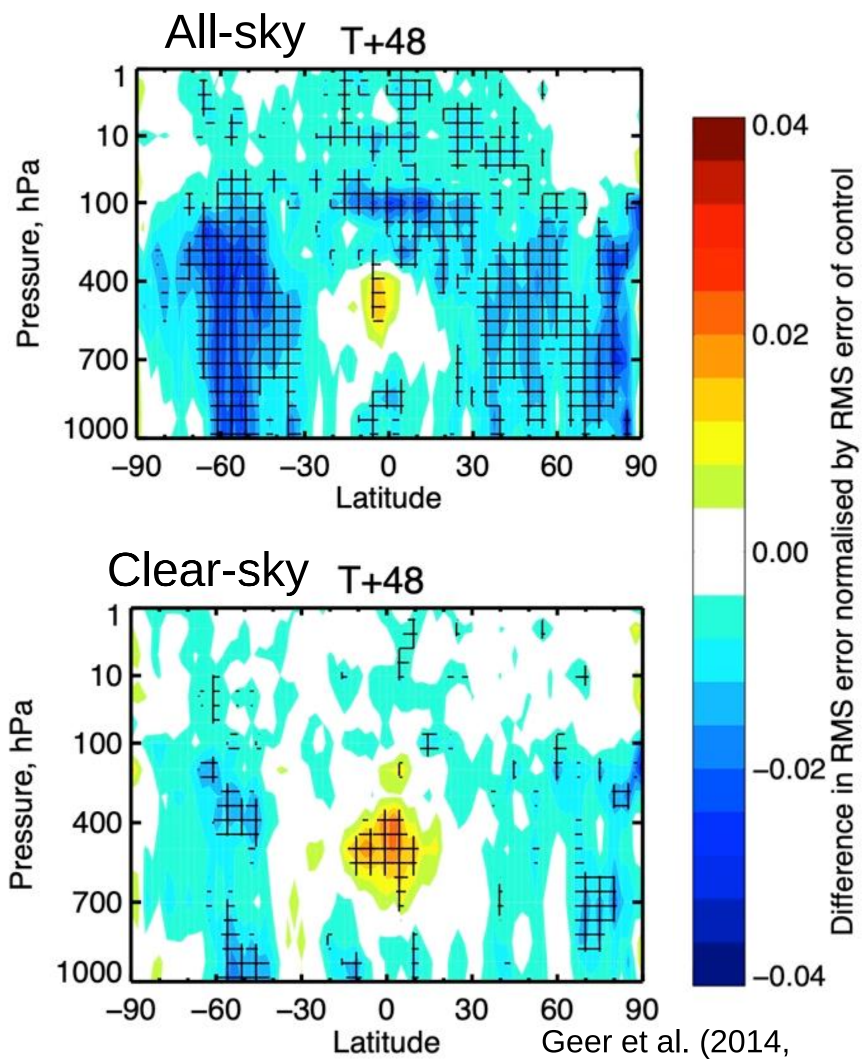
2011 - 2015

The 3rd Joint JCSDA-ECMWF workshop on assimilating satellite observations of clouds and precipitation into NWP models
December 1-3, 2015 - College park, MD, USA

2011 – 2015: All-sky microwave assimilation pays off at ECMWF

- Assimilation of 183 GHz (sensitive to snow and large ice particles)
  - Adoption of DDA sector snowflake in RTTOV-SCATT (Geer and Baordo, 2014) to cure very large biases in radiative transfer in the older Mie-sphere based approach
  - Ability to do dynamic retrievals of surface emissivity over land, snow and sea-ice (Baordo and Geer, 2016, QJ)
- Assimilation of a new generation of microwave imagers:
  - GMI – Lean et al. (2017, ECMWF tech. memo.)
  - AMSR2 – Kazumori et al. (2016, QJ)
- Microwave imagers start not just to identify forecast errors but guide forecast model developments
  - Cold air outbreaks – Kazumori et al. (2016, QJ), Forbes, Geer, Lonitz, Ahlgrimm (2016, ECMWF newsletter)

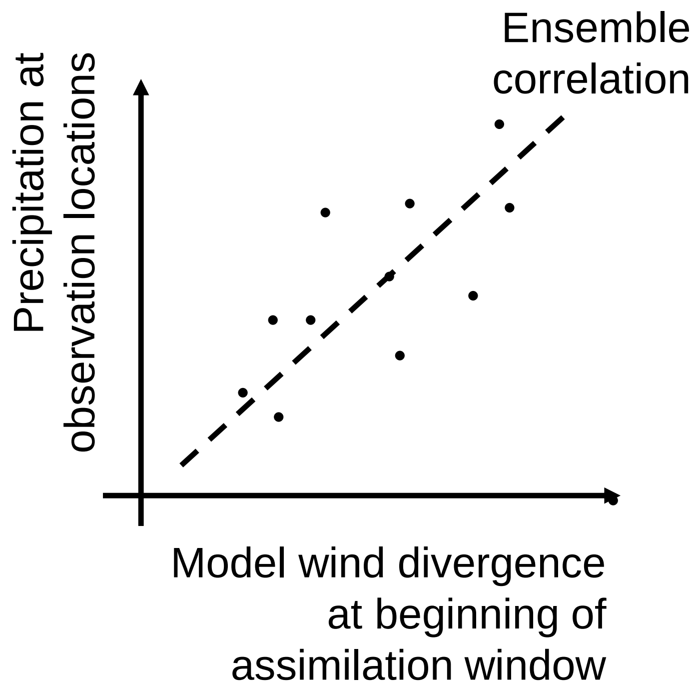
Assimilation of SSMIS F-17 plus 4 x MHS sounders: change in RMS vector wind error



Geer et al. (2014, ECMWF tech. memo.)

2011 – 2015: ensemble assimilation techniques allow cloud and precipitation developments even without TL/AD moist physics

- The start of ensemble-based all-sky assimilation in research contexts, e.g:
  - Otkin et al. (2010, JGR): Clear and cloudy sky infrared brightness temperature assimilation using an ensemble Kalman filter
  - Zupanski et al. (2011, Int J. Rem. Sens.): Assimilating synthetic GOES-R radiances in cloudy conditions using an ensemble-based method
  - S.Q. Zhang et al. (2013, MWR): Assimilation of precipitation-affected radiances in a cloud-resolving WRF ensemble data assimilation system
- NCEP: Operational implementation of all-sky AMSU-A assimilation in non-precipitating scenes - Y. Zhu et al. (2016, MWR)
  - First operational assimilation of all-sky AMSU-A
  - 3D and 4D-EnVar avoid the need for a TL/adjoint forecast model



2011 – 2015: other highlights

- 1D-Bayesian + 4D-Var assimilation of radar reflectivity at JMA (Ikuta et al., 2011, WGNE)
- Direct 4D-Var assimilation of NEXRAD/gauge rainfall over the USA (Lopez, 2011, MWR)

2015 Workshop Recommendations

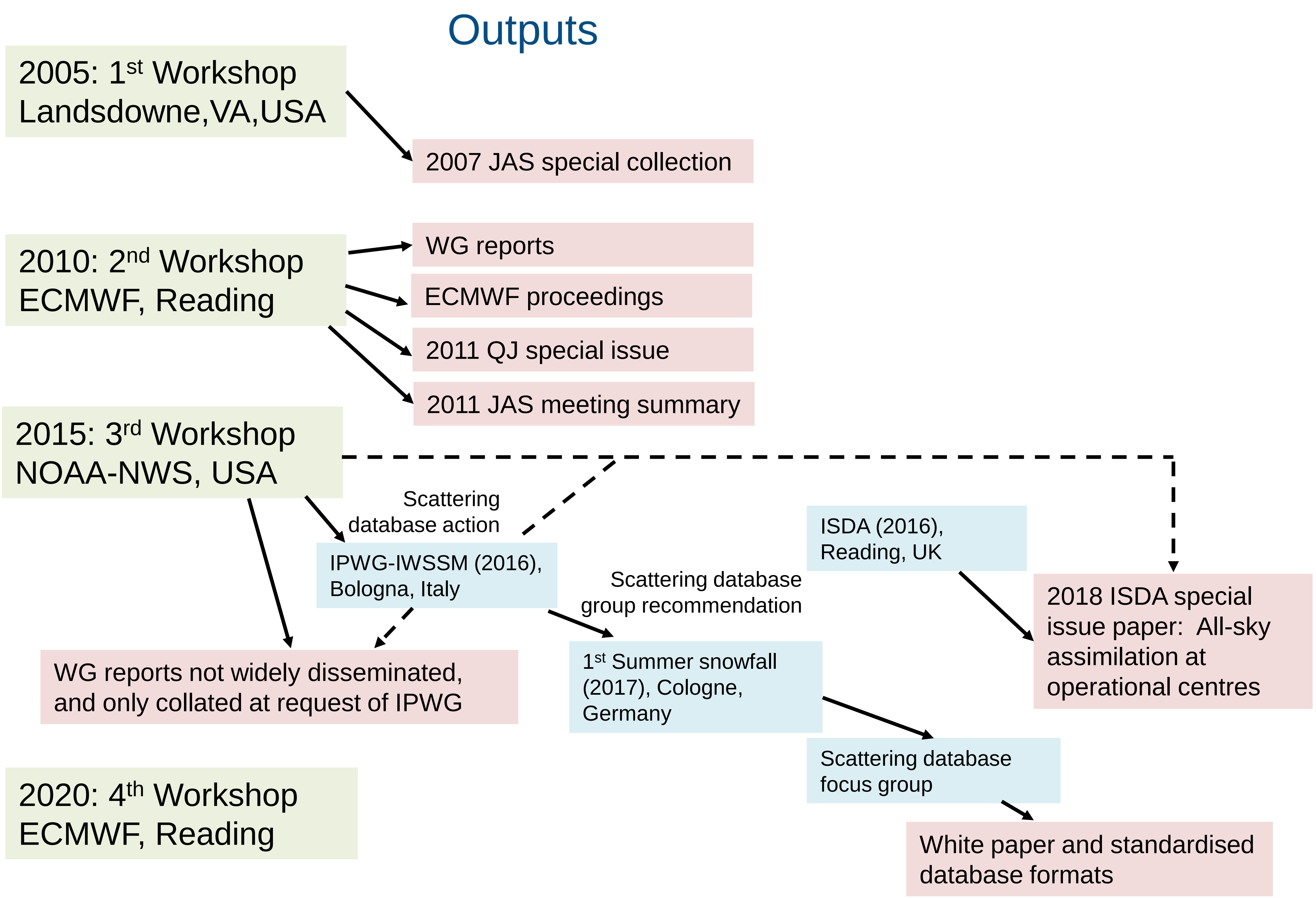
- Radiative transfer
  - Scattering databases:
    - Work towards standardised database formats for easy interchange of particle optical properties in radiative transfer models
    - Form a particle scattering working group at IPWG/IWSSM 2016
  - Need for more sophisticated BRDF-type surface reflection / emissivity models to couple to multi-stream scattering solvers.
  - Fast models must include cloud subgrid heterogeneity / overlap
  - Start dealing with 3D radiative transfer issues

- Observations
  - NASA to consider making CERES (radiation budget) NRT for assimilation
  - Assimilation community to start using DPR
  - Community to come together to support future provision of active and passive microwave instruments (to support operational assimilation plans)

- Physical inversion and assimilation
  - Extend error models and superobbing to the infrared
  - Make it easier for users to change scattering properties in radiative transfer, especially IR
  - (+ Many detailed recommendations on data assimilation)

- Modelling
  - Use O-B to document model and observation operator biases
  - Move towards microphysical consistency across the model and observation operators
  - Use observations to help improve forecast models

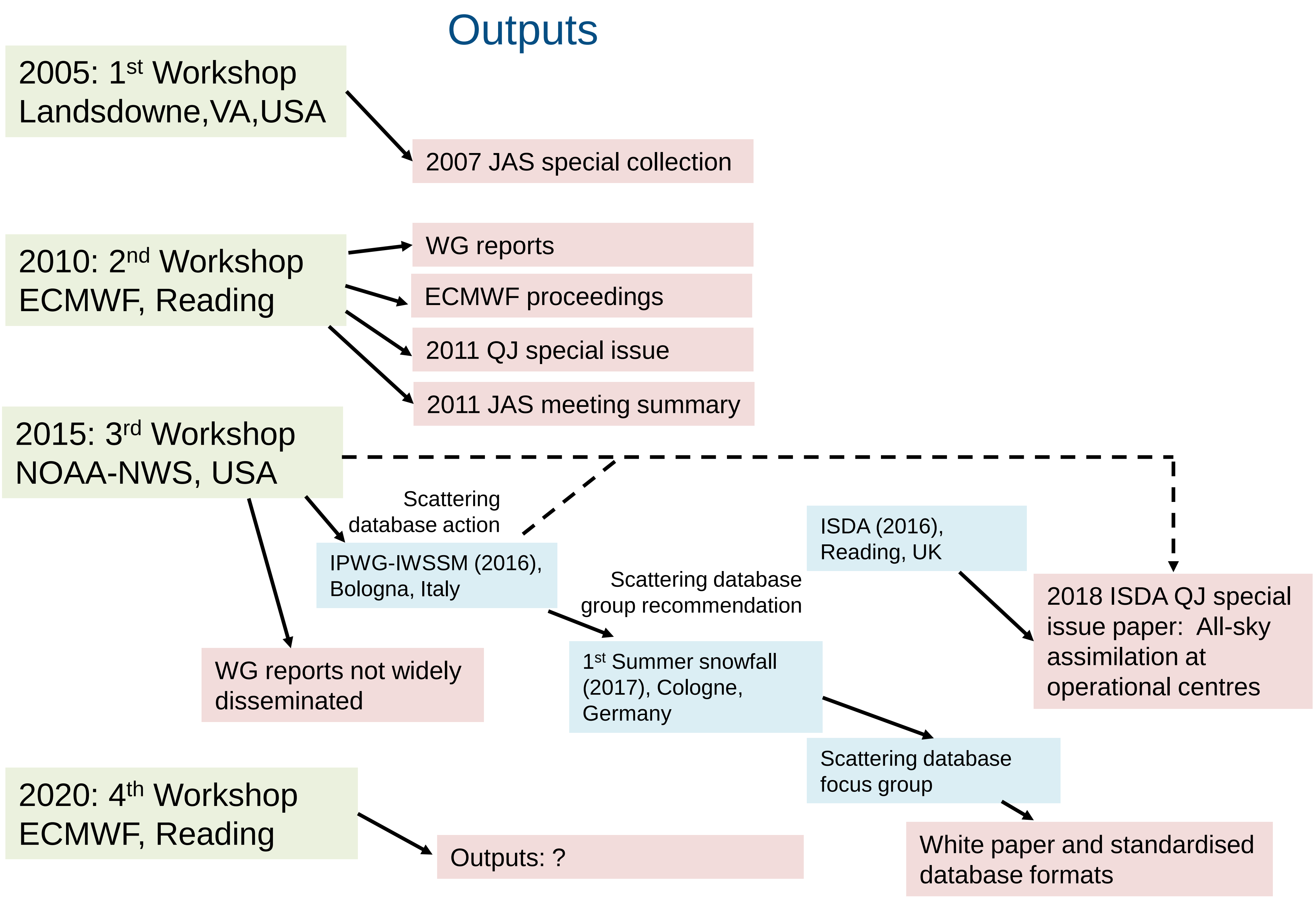
Joint workshops on satellite cloud and precipitation data assimilation



2016 - 2020

4th workshop on assimilating satellite cloud and precipitation observations for NWP
ECMWF / JCSDA / EUMETSAT NWP-SAF
February 3-6th, ECMWF, Reading, UK

Joint workshops on satellite cloud and precipitation data assimilation



2020+

Looking ahead

Looking ahead

- Diminishing returns / increasing difficulties rolling out all-sky assimilation?
  - All-sky IR assimilation of IASI – slightly better forecasts in tropics, but it will be difficult to get operational (Geer et al., 2019, AMT)
    - Big struggle with correlated observation errors (Geer, 2019, AMT)
  - All-sky assimilation of AMSU-A – just marginally worse than clear-sky assimilation on critical measures (Weston et al., 2019, ECMWF tech. memo.)

Successful 2005 recommendation: Push ahead with assimilation developments even if neutral to start with

- "Microphysical and macrophysical closure"
  - Use all-sky radiances and reflectivities and precipitation observations to constrain and help develop forecast models
  - Consistent assumptions in observation operators and models
  - ECMWF tech. memo. / SAC special topic paper on cloud and precipitation assimilation strategy (2017, Geer et al.)
- Assimilate everything (even if passive, to diagnose model biases)
  - Cloud and precipitation radar, lightning, broadband radiation budget
- All-surface assimilation, following the example of all-sky
- Better understanding of predictability / representation error of cloud and precipitation – and how to deal with it (e.g. particle filters?)