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This article reviews developments towards assimilating cloud and precipitation-affected satellite radiances at operational forecasting centres. Satellite data assimilation is moving beyond the 'clear-sky' approach that discards any observations affected by cloud. Some centres already assimilate cloud and precipitation-affected radiances operationally and the most popular approach is known as 'all-sky', which assimilates all observations directly as radiances, whether they are clear, cloudy or precipitating, using models (both for radiative transfer and forecasting) that are capable of simulating cloud and precipitation with sufficient accuracy. Other frameworks are being tried including the assimilation of humidity retrieved from cloudy observations using Bayesian techniques. Although the all-sky technique is now proven for assimilation of microwave radiances, it has yet to be demonstrated operationally for infrared radiances, though several centres are getting close. Assimilating frequently-available all-sky infrared observations from geostationary satellites could give particular benefit for short-range forecasting. More generally, assimilating cloud and precipitation-affected satellite observations improves forecasts into the medium-range globally, and it can also improve the analysis and shorter-range forecast of otherwise poorly-observed weather phenomena as diverse as tropical cyclones and wintertime low cloud.

data assimilation, satellite, microwave, infrared, cloud and precipitation, NWP, all-sky

All-sky satellite data assimilation at operational weather forecasting centres

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1 Introduction

Modern weather forecasting relies on satellite observations to infer the initial state of the atmosphere, particularly in areas that are not well observed by in-situ instrumentation. Forecasts were once much worse in the southern hemisphere (SH) than the northern hemisphere (NH), but that gap has disappeared with the increasing availability of satellite observations, and our developing ability to make use of them [?, e.g.]]simmons2002. One big step forward was the move from assimilating retrievals [?, e.g. temperature profiles derived from sounding channel radiances,]]eyre1993 to assimilating the radiances directly [?, e.g.]]derber1998.

To this day, satellite observations have usually only been assimilated in clear-sky conditions, and their cloud and precipitation information content has been discarded. Particularly for infrared instruments, a majority of observations may be lost due to cloud contamination [?, e.g.]]mcnally2003. In the last few years some weather forecasting centres have started to make use of cloud and precipitation-affected radiances, particularly with the 'all-sky' approach. This uses a cloud and precipitation-capable forecast model and observation operator, and aims to assimilate all radiances, whether or not they are affected by cloud and precipitation [Bauer ~al.(2010)Bauer, Geer, Lopez and Salmond]. It is hoped that moving from clear-sky to all-sky assimilation can bring another step forward in analysis and forecast quality.

In clear-sky conditions, satellite radiances are sensitive mostly to atmospheric temperature (mass) and humidity. However, modern data assimilation systems can also extract wind information from these radiances. For example, the geostrophically balanced part of the wind field can be inferred from the temperature. Further, winds can be inferred from the movement of atmospheric constituents including humidity. In four-dimensional variational data assimilation (4D-Var), wind increments can be inferred through the adjoint of the forecast model equations that describe constituent transport [?, e.g.]]andersson1994,peubey2009. Hence this is known as 'wind tracing' or the 'tracer effect'. Ensemble data assimilation can also infer wind from constituent observations, using correlations derived from the ensemble [?, e.g.]]allen2015wind. However, 4D-Var and ensemble assimilation can make much broader use of the information in satellite radiances. Data assimilation systems are able to infer temperature, humidity and wind information from observed cloud and precipitation [?, e.g.]]geer2014b,lien2016b,zhu2016. It is possible to make use of all the dynamical and physical processes represented in the forecast model, including those that describe hydrometeor formation and evolution. This could be considered a ‘generalised tracer effect’.

All-sky assimilation is expected to give a number of benefits to weather forecasting:

1. Mass, wind and humidity in the presence of cloud: All-sky assimilation increases the number of satellite sounding observations available for assimilation in cloudy areas, often areas of strong meteorological sensitivity [McNally(2002)]. Even ignoring the cloud and precipitation information content, it should be beneficial to get more information on temperature and moisture (and indirectly, wind) in situations where the radiances are sensitive to a combination of temperature, water vapour and hydrometeors (i.e. liquid or frozen water particles). For infrared radiances, the use of clear-air information from just above cloud tops is increasingly common [?, e.g.]]pavelin2008,mcnally2009,pangaud2009. A further advantage of an all-sky approach, even if the hydrometeor information is not assimilated, would be to avoid biases caused by undetected cloud and asymmetric sampling that can affect the clear-sky approach [Geer ~al.(2008)Geer, Bauer and Lopez, Zhu ~al.(2016)Zhu, Liu, Mahajan, Thomas, Groff, van Delst, Collard, Kleist, Treadon and Derber, Geer ~al.(2017)Geer, Baordo, Bormann, English, Kazumori, Lawrence, Lean, Lonitz and Lupu].

2. Mass, wind and humidity from cloud and precipitation: Rather than ignoring the cloud and precipitation information, it can be used to infer additional information on mass, wind and humidity through the generalised tracer effect. For example, the intensity of frontal precipitation can be brought closer to the observations by adjusting the strength of the associated low pressure system [?, e.g.]]geer2014b. Better initialisation of mass and wind fields then leads to improved forecasts into the medium range.

3. Initialising cloud and precipitation: Especially for nowcasting, storm-forecasting, rapid-update cycling (RUC) and regional forecasting (at present typically involving the use of convection-permitting forecast models and short forecast lead times from 0h to 48h) analysing the correct placement of cloud and precipitation is itself of great interest. Precipitation assimilation has been developing in all these areas, from nowcasting [?, e.g]]snyder2003,sun2014use to regional forecasting [?, e.g.]]wattrelot2014, often making use of ground-based observations, particularly radar reflectivity. However, cloud is equally of interest [?, e.g.]]schomburg2015 for applications like forecasting near-surface temperature, and solar power output for the growing renewable energy sector. In stable continental winter high-pressure systems, it might be hoped that once cloud (or its absence) has been analysed correctly, the benefit would persist for some days in the forecasts. Over many areas of the globe, frequently-available geostationary radiances might be the closest alternative to radar and are of particular interest [?, e.g.]]otkin2010,stengel2013,cintineo2016.

4. Improved modelling of cloud and precipitation: Confronting forecast models with cloud and precipitation-affected radiance observations is an optimal way to understand model biases. This is often referred to as the model-to-satellite approach, as opposed to the retrieval approach, and it is a natural output of data assimilation. For example, all-sky microwave departures reveal biases in modelled clouds in maritime stratocumulus regions and in cold air outbreaks in global forecasting models [?, e.g.]]kazumori2016. The bias in cold air outbreaks has been tracked to a lack of supercooled water in the detrainment from the shallow convection scheme, helping to develop a possible fix [Forbes ~al.(2016)Forbes, Geer, Lonitz and Ahlgrimm].

It was initially hard for operational weather forecasting centres to implement cloud and precipitation assimilation techniques or to improve their forecasts by doing so [?, e.g.]]errico2007 but they are now starting to see real benefits. Direct assimilation of all-sky radiances started in the operational system of the European Centre for Medium-range Weather Forecasts (ECMWF) in 2009 [Bauer ~al.(2010)Bauer, Geer, Lopez and Salmond] and is now one of the leading contributors to forecast skill providing around 18% of all short-range forecast impact [Geer ~al.(2017)Geer, Baordo, Bormann, English, Kazumori, Lawrence, Lean, Lonitz and Lupu]. ECMWF has concentrated on microwave imaging and humidity sounding channels, with forecast benefits coming through at least the first two mechanisms (mass and wind in the presence of cloud, and directly from cloud and precipitation). In 2016, the NOAA National Centers for Environmental Prediction (NCEP) started operational all-sky assimilation of a microwave temperature sensor, AMSU-A[1], with benefits including a reduction in cloud-related

[1] For details of satellites, sensors, and their acronyms, see https://www.wmo-sat.info/oscar/

biases [Zhu ~al.(2016)Zhu, Liu, Mahajan, Thomas, Groff, van Delst, Collard, Kleist, Treadon and Derber]. Other centres are developing similar techniques, with operational implementation expected in the next few years. No operational centre yet assimilates infrared observations in an all-sky approach, though this is the focus of much research, in short-range forecasting to take advantage of frequent geostationary data, and in global forecasting to better utilise existing data.

This article describes the current status and plans of operational centres that are close to implementing assimilation of cloud- and precipitation-affected radiances, or have already done so. It summarises developments that have been discussed recently at the JCSDA-ECMWF workshop on cloud assimilation (Washington, 2015), the International Symposium on Data Assimilation (ISDA, Reading, 2016), and the International Precipitation Working Group (IPWG, Bologna, 2016). It follows an earlier review of the state of cloud and precipitation assimilation at operational centres [Bauer ~al.(2011)Bauer, Aulignà Bell, Geer, Guidard, Heillette, Kazumori, Kim, Liu, McNally, Macpherson, Okamoto, Renshaw and Riish] but with focus on all-sky radiance assimilation.

Not all the ongoing developments summarised in this article will necessarily make it into operations, since they are at different stages of the development process. At NWP centres and in the wider community, research often starts on the basis of limited case studies or observing system simulation experiments (OSSEs), and may be performed with low resolution or incomplete use of the global observing system. This is a necessary and important part of development, but developments must also be tested in the full operational context, and shown to improve (or at least not degrade) the quality of forecasts that are already extremely good, across all seasons and across the often global domain of the forecasting system. Also, the need for timely operational forecasts imposes a hard limit on computational cost. However, the future developments reported here are intended to pass these tests and become operational in the next few years

This article has three main sections: first, it describes the current operational status of forecasting centres; second, it reviews ongoing developments; finally, it discusses common experiences and future development plans across the centres.

2 Current status at operational centres

2.1 Overview

Overview of operational NWP systems included in this review, as of August 2017

	Model				Data assimilation				
Centre	Name	Domain	Resolution		Approach	Ens-emble	Moist TL/ adjoint	Moist c variables	
			Horizontal	Vertical				Vapour	Hydrome
ECMWF	IFS	global	T1279co (9km)	L137 (to 0.01hPa)	Hybrid Increm. 4D-Var	EDA	Large-scale + Convection	RH	N
JMA	JMA–GSM	global	TL959 (20km)	L100 (to 0.01hPa)	Increm. 4D-Var	–	Large-scale + Convection	Log. of q_{vapour}	N
gray!15	JMA–MSM	local	5km	L76 (to 22 km)	Increm. 4D-Var	–	Large-scale	pseudo RH	N
NCEP	GFS	global	T1534 (13km)	L64 (to 0.27hPa)	Hybrid 4D-EnVar	EnSRF	Not needed	Norm. RH	N q_{water}
Met Office	Unified Model	global	10 km in mid-latitudes	L70 (to 80 km)	Hybrid Increm. 4D-Var	LETKF	Large-scale + Convection	Norm. total RH moist incrementing op for q_{vapour}, q_{ice}, q_{liquid}	
gray!15	Unified Model	local	1.5 km	L70 (to 40 km)	3D-Var	–	Large-scale + Convection	as above	
Météo		global		L105	Hybrid	EDA	Large-	q_{vapour}	N

France	ARPEGE		T1198c2.2 (7.5–37 km)	(to 0.1hPa)	Increm. 4D-Var		scale		
gray!15	AROME	local	1.3 km	L90 (to 10 hPa)	3D-Var	–	None	q $_{vapour}$	N
DWD	ICON	global	Icosahedral grid 6.5–13 km	L90 (to 75 km)	Hybrid 3D-EnVar	LETKF	None	Gen. RH (EnVar);	
q $_{vapour}$ (LETKF)	None (EnVar);								
q $_{ice}$, q $_{liquid}$ (LETKF)									
gray!15	COSMO	local	2.8 km	L50 (to 22 km)	LETKF	LETKF	Not needed	q $_{vapour}$	q q $_{liquid}$

We will describe each operational centre's system in detail later, but Tab. 2.1 provides an overview. Of the systems examined here, most are global with horizontal resolutions of order 10 km to 20 km, intended for weather prediction out to around 5-10 days. Many centres also run local forecasting systems aimed at short-range prediction out to 2 days, with horizontal resolutions around 1 km to 5 km and the ability to represent convection explicitly, without the need for a parametrisation (i.e. convection-permitting models). Where all-sky assimilation is in development and described in this article, local systems are also listed.

A variety of data assimilation systems are in use, including variational assimilation (3D-Var and 4D-Var), ensemble methods (e.g. local ensemble transform Kalman filter, LETKF), or combinations of the two [?, see]this special issue]kleist2017survey. ECMWF, Japan

Meterological Agency (JMA), NCEP, Météo France, Met Office and Deutscher Wetterdienst (DWD) use variational assimilation for their main global analyses, but mostly these are *hybrid* systems because their background error covariances are a combination of a static climatological part and a part representing the errors of the day, derived from an ensemble that is operated in parallel with the main variational system. The only pure ensemble method is the LETKF used for local forecasting by DWD. For all-sky assimilation, the critical factor is not so much the choice of assimilation method but how a change in the observable (e.g. a precipitation-affected satellite radiance) is linked with a change in the analysis control variables (e.g. temperature, wind, humidity and possibly hydrometeors). Once an all-sky radiative transfer model is available for modelling the observations, an ensemble method like LETKF implicitly provides this link through the ensemble covariances between the state and the simulated observations, so it is in principle straightforward to extend an ensemble system to all-sky assimilation. Alternatively, a variational method normally represents these links explicitly using tangent-linear (TL) and adjoint models for radiative transfer and moist physics. The 4D Ensemble Var (4D-EnVar) operated by NCEP is a hybrid system in which the time-correlations of forecast variables are derived from the ensemble. The TL and adjoint of the observation operator are still required, but not those of the forecast model, so it falls more naturally with DWD's ensemble approach.

All systems have control variables relating to the main dynamical quantities (wind, temperature and pressure) whose details are less important here, plus one or more control variables relating to the moist atmosphere. Water vapour can be represented as a specific humidity q_{vapour}, or its logarithm, or as relative humidity, possibly normalised [Dee and Da~Silva(2003), H_m ~al.(2002)H_m, Andersson, Beljaars, Lopez, Mahfouf, Simmons and Thepaut, Ingleby ~al.(2013)Ingleby, Lorenc, Ngan, Rawlins and Jackson]. JMA and DWD use respectively pseudo and generalised RH (Secs. 2.3 and 2.7). Hydrometeor (condensed water) control variables can also be added. NCEP, Met Office and DWD have added respectively a normalised cloud water mixing ratio variable q_{water} covering liquid and ice, a total relative humidity variable that includes both vapour and cloud, and separate control variables q_{liquid} and q_{ice}. However, because cloud and precipitation are largely driven by the winds, temperature and moisture, to include them in the control vector may not always be necessary, particularly in 4D-Var where the forecast model can diagnose cloud and precipitation from the dynamical variables and humidity.

Table 1: Components of the global observing system assimilated at some or all centres. Satellite radiance usage is described more precisely in Tab. 1.

Satellite radiances and

bending angles
Microwave sounders (e.g. AMSU-A, MHS, ATMS, SSMIS, SAPHIR)
Microwave imagers (e.g. SSMIS, AMSR2, GMI)

Infrared hyperspectral sensors (e.g. AIRS, IASI, CrIS)
Infrared sensors on geostationary platforms (e.g. AHI/Himawari-8, Imager/GOES-13, -15, SEVIRI/Meteosat-8, -10)
GNSS radio occultation
Conventional (in-situ and retrievals)
Ground stations and buoys (e.g. surface pressure)
Radiosondes (e.g. temperature, wind and humidity)
Wind profilers
Aircraft (e.g. temperature, wind and humidity)
GNSS path delay
Atmospheric motion vectors derived from geostationary and polar satellites
Winds from satellite-

borne scatterometers

Table 2: Utilisation of radiances in operational NWP systems, as of August 2017, resolved by sensor and channel type (e.g.

temperature-sounding, humidity-sounding or 'imaging' i.e. any channel with significant surface sensitivity). Grey shading indicates clear-sky radiances are assimilated operationally, whether on their own or through an all-sky approach. All-sky assimilation is indicated by 'A' if active or 'D' if in development (for which see Sec. 3). Sensors may have multiple capabilities (e.g. temperature and humidity sounding) and hence may appear in multiple rows.

		ECMWF	JMA	NCEP	Met Office global	Met Office local	Météo France global	Météo France local	D global
Microwave									
Imaging	SSMIS (F-17)	gray!25 A	gray!25 D		gray!25		gray!25	gray!25	
	SSMIS (F-18)		gray!25 D						
	GMI	gray!25 A	gray!25 D	D			gray!25	gray!25	
	AMSR2	gray!25 A	gray!25 D	D	gray!25		gray!25	gray!25	
	MWRI (FY-3B)		D						
	MWRI (FY-3C)		D						
Humidity	MHS (4× sats.)	gray!25 A	gray!25 D	gray!25 D	gray!25 D	gray!25 D	gray!25 D	gray!25 D	D
	ATMS	gray!25 D	gray!25 D	gray!25 D	gray!25 D	gray!25 D	gray!25 D	gray!25 D	D
	SSMIS								D

	(F-17)	gray!25 A	gray!25 D	gray!25	gray!25 D		gray!25 D	gray!25 D	
	SSMIS (F-18)	gray!25 A	gray!25 D	gray!25			D	D	D
	MWHS-1	gray!25			gray!25				

	MWHS-2	gray!25 A	D		gray!25 D		D	D	D
	SAPHIR	gray!25 A	gray!25 D		gray!25 D		gray!25 D	gray!25 D	D
	GMI	gray!25 A	gray!25 D		D		D	gray!25 D	D
Temp.	AMSU-A (6×)	gray!25 D	gray!25 D	gray!25 A	gray!25 D		gray!25	gray!25	gray!25
	ATMS	gray!25 D	gray!25	gray!25 D	gray!25 D	gray!25	gray!25	gray!25	gray!25
	MWHS-2	gray!25 A			gray!25				
Infrared advanced sounders									
Imaging	IASI (2×sats.)	gray!25		gray!25	gray!25	gray!25	gray!25 D		
	AIRS	gray!25		gray!25	gray!25	gray!25			
	CrIS	gray!25		gray!25	gray!25	gray!25	gray!25		
Humidity	IASI (2×sats.)	gray!25 D		gray!25 D	gray!25	gray!25	gray!25 D	gray!25 D	
	AIRS	gray!25 D		gray!25 D	gray!25	gray!25	gray!25	gray!25	
	CrIS	gray!25 D		gray!25 D	gray!25	gray!25	gray!25	gray!25	

Temp.	IASI (2×sats.)	gray!25	gray!25	gray!25	gray!25	gray!25	gray!25 D	gray!25	gray!25
	AIRS	gray!25	gray!25	gray!25	gray!25	gray!25	gray!25	gray!25	
	CrIS	gray!25	gray!25	gray!25	gray!25	gray!25	gray!25	gray!25	

Geostationary sounders									
Imagin g	Himawari-8								
(Vis. +	Meteosat (2×)								
infrare d)	GOES (2×)								
Humidi ty	Himawari-8	gray!25	gray!25 D		gray!25		gray!25	gray!25	
(infrare d)	Meteosat (2×)	gray!25	gray!25	gray!25 D	gray!25	gray!25	gray!25	gray!25	
	GOES (2×)	gray!25	gray!25	gray!25	gray!25		gray!25	gray!25	

Table 0 summarises the main components of the global observing system, most of which are assimilated in all the global models described here; data use in regional forecasting systems is sometimes more limited. Table 1 details current and potential future utilisation of satellite radiances in areas of cloud and precipitation, by sensor and in some cases also by satellite. Only ECMWF and NCEP are using an all-sky framework operationally, and then only for microwave sensors, so the table also serves as a summary for Sec. 3 which covers future developments. Although it is not indicated in the table, ECMWF, Met Office and Météo France do operationally assimilate some infrared data in the presence of cloud, by retrieving cloud parameters and using them as a fixed constraint in the observation operator [?]]pavelin2008,mcnally2009,pangaud2009. However, to focus on all-sky assimilation of infrared radiances, this is bundled with 'clear-sky' assimilation for the purposes of the table. Other cloud and precipitation-related observations are operationally assimilated at some centres (e.g. ground-based radar, see later).

The assimilation of cloud and precipitation-affected satellite data also requires a fast and accurate radiative transfer model capable of simulating the scattering and absorption effects of hydrometeors. The Community Radiative transfer Model [?, CRTM, e.g.]]han2006jcsda,liu2014community and the Radiative Transfer model for TIROS Operational Vertical Sounder [?, RTTOV,]]saunders2013 satisfy the criteria and are widely used in NWP operational centres (Section 2.8). Among the centres represented here, CRTM is used by NCEP,

and RTTOV by the rest.

2.2 ECMWF

ECMWF operates a global weather forecasting system that assimilates all the main components of the global observing system (Tab. 0) apart from GNSS path-delay, but additionally with MWHS-1 and MWHS-2 sensors. Background errors are inferred from a lower-resolution Ensemble of Data Aassimilations [?, EDA,]]bonavita2015, giving a hybrid ensemble-variational approach. Correlations are a mix of climatology and errors of the day determined from the ensemble, while the variances are completely determined by the errors of the day. The only moist control variable is relative humidity, and since July 2017 the background error variances have come from the ensemble like other variables, rather than from the symmetric normalisation function of [H_m ~al.(2002)H_m, Andersson, Beljaars, Lopez, Mahfouf, Simmons and Thepaut]. The use of tangent linear and adjoint models for large-scale and convective cloud and precipitation in the 4D-Var minimisation [Janiskov and Lopez(2013)] mean it is possible to assimilate cloud and precipitation without cloud and precipitation control variables, as long as it is determined by the dynamical and humidity initial conditions. As illustrated by [Bauer ~al.(2010)Bauer, Geer, Lopez and Salmond] and [Geer ~al.(2014)Geer, Baordo, Bormann and English] the generalised (or '4D-Var') tracing effect can infer changes to these initial conditions in order to better fit observed cloud and precipitation. The forecast model has prognostic variables for cloud water, cloud ice, large-scale rain and large-scale snow. Additionally, convective rain and snow are diagnosed from a mass-flux scheme. However, for hydrometeor assimilation, the tangent-linear and adjoint representations of these variables are based on simpler diagnostic parametrisations [Tompkins and Janiskov 2004), Lopez and Moreau(2005)].

Figure 1: Normalised change in NH RMSE in 500 hPa geopotential height coming from the addition of GMI, AMSR2, SSMIS F-17 and four MHS instruments in an ECMWF system representative of the operational configuration in mid-2015. Confidence bars indicate the 95% confidence interval. See [Geer ~al.(2017)Geer, Baordo, Bormann, English, Kazumori, Lawrence, Lean, Lonitz and Lupu] for more details.

Microwave humidity sounding and imaging radiances are assimilated in all-sky conditions, i.e. in clear-sky, cloudy and precipitating scenes. Three microwave imagers (AMSR2, GMI and F-17 SSMIS) are assimilated at frequencies from 19 GHz to 90 GHz, over oceans only [?, e.g.]]bauer2010,kazumori2016,lean2017. Nine instruments with humidity sounding channels around 183 GHz are assimilated, including 4 MHS, 2 SSMIS and the individual sensors GMI, SAPHIR and MWHS-2 [?]]geer2014b,lawrence2016,chambon2017allsky. These are all polar orbiters except GMI and SAPHIR which are in inclined orbits, giving coverage up to latitudes of ±69° and ±28° respectively. The humidity sounding channels are assimilated over ocean, land, snow-covered land and sea-ice [?, e.g.]]baordo2016. Together these microwave instruments are sensitive to moisture in different layers in the troposphere, plus rain (mainly at lower frequencies), cloud liquid water (particularly in window frequencies from 37 GHz to 90 GHz), large frozen hydrometeors in deep convection (mainly at 183 GHz) and there is also a minor sensitivity to cloud ice. The novel 118 GHz channels of MWHS-2 are assimilated in all-sky conditions with sensitivity to cloud and temperature, though with little impact compared to that of other frequencies. Overall, all-sky microwave observations are one of the most significant parts of the observing system at ECMWF. Their impact on day-5 forecasts is at least 3% (Fig. 0) and as of September 2016, all-sky instruments gave 18% of short-range forecast impact [?, more if remaining clear-sky humidity sounding instruments are included,]]geer2017a.

The successful assimilation of all-sky radiances has been supported by many developments beyond the assimilation methodology. Both the forecast model and the observation operator (RTTOV, Sec. 2.8) have been developed over the last ten years within the constraint of the all-sky FG departures. For example, the observation operator has had successive upgrades to improve its physical representation of the radiative transfer and hence improve consistency between simulated and observed all-sky brightness temperatures [?, e.g.]]geer2009a,geer2014a. Further, it was necessary to develop situation-dependent observation error models to inflate the observation errors in cloudy conditions [?, e.g.]]geer2010b,geer2011. These are ‘symmetric’ models in that they inflate the errors whether the cloud is present in the model or in the observations.

The use of cloudy infrared observations is less developed: IASI, AIRS, CrIS and Meteosat SEVIRI radiances are assimilated above overcast clouds [McNally(2009), Lupu and McNally(2012)] though only for a limited number of scenes; still the bulk of forecast impact derived from infrared radiances comes from temperature-sounding channels in locations where the weighting function does not include any cloud. Finally, the NEXRAD combined gauge and radar rainfall accumulations are assimilated over the United States [Lopez(2011)] with the main impact being on the local precipitation; global forecast impact measured in terms of forecast sensitivity to observation impact [?, e.g. FSOI,]]langland2004 is small.

2.3 Japan Meteorological Agency

JMA operates global and mesoscale NWP systems [JMA(2013)]. In the global NWP system, the analysis system uses an incremental 4D-Var approach [Courtier ~al.(1994)Courtier, Thàaut and Hollingsworth] to produce initial conditions for the Global Spectral Model (GSM). The horizontal resolution of JMA GSM is about 20 km and that of the model used in the inner-loop of incremental 4D-Var is about 55 km. The global analysis uses a 6 hourly assimilation cycle with a long cut off time (11 hr. 50 min. for 00, 12 UTC and 7 hr. 50 min. for 06, 18 UTC) to allow maximum use of observational data. These analyses maintain the quality of the global data assimilation system. The cycle analyses produce first guess (FG) fields for 6 hourly early analyses with a short cut-off time (2 hr. 20 min.) which prepare initial fields for 11 day forecasts (12 UTC initials) and 84 hour forecasts (00, 06, 18 UTC initials). The forecasts are used not only for weather guidance but also for applications such as driving force for an ocean wave forecast model and a volcanic ash tracer model. The control variables in the 4D-Var are the relative vorticity, unbalanced divergence, unbalanced temperature, surface pressure, and logarithm of specific humidity in spectral space on model layers. The background error covariance matrix is static and computed statistically [?, NMC method;]]parrish1992.

In the global analysis, clear-sky satellite radiance data are assimilated [Okamoto ~al.(2005)Okamoto, Kazumori and Owada] along with the rest of the global observing system (Tab. 0). Additionally, tropical cyclone (TC) bogus profile data of wind vectors and surface pressure, which are empirically derived from geostationary and polar-orbiting satellite imagery, are assimilated to obtain observation information in cloudy and rainy situations in the presence of TC in the NW Pacific [JMA(2013)].

The mesoscale NWP system is operated every three hours using lateral boundary conditions given by the global forecasts. The analysis system is a non-hydrostatic based 4D-Var [?, JNoVA; â€œJMA Non-hydrostatic modelâ€ based Variational Analysis Data Assimilation,]]honda2005 and its horizontal resolution is 5 km, with the resolution of the inner-loop model being 15 km. It produces initial fields for 39 hour forecasts by the Meso-scale Model (MSM) to assist in better forecasting weather phenomena, with emphasis on high impact events. The control variables of the mesoscale analysis are the two horizontal wind components, potential temperature, surface pressure, and pseudo relative humidity (i.e. specific humidity divided by saturated specific humidity of the FG). The background error covariance matrix is estimated using the NMC method. In the minimisation, in place of a TL model used in many other systems, the simplified nonlinear inner-loop model is run at every iteration to provide a nonlinear update to the cost function. An adjoint forecast model (including large-scale clouds) is still required, but it uses the trajectory that is being updated every iteration.

The mesoscale system assimilates conventional observational data, plus microwave radiances and Clear Sky Radiance (CSR) data from Himawari-8 [Kazumori(2014), Kazumori(2016)]. Retrieved precipitation data from microwave radiances [?, GMI, AMSR2 and SSMIS,]]sato2004 are assimilated as well. Moreover, retrieved hourly precipitation data from ground-based radar data are assimilated in rainy conditions [Koizumi ~al.(2005)Koizumi, Ishikawa and Tsuyuki]. Furthermore, relative humidity profiles retrieved from ground-based radar and space-based radar [?, Dual-frequency Precipitation Radar, DPR, on GPM core satellite,]]ikuta2011,ikuta2016 are assimilated in rainy conditions.

2.4 NCEP

NCEP operates the Global Forecast Model (GFS) with a resolution of T1534 (approx. 13km) out to a forecast time of 10 days which then continues at T574 (approx. 34km) to 16 days. Four forecast runs are performed per day. Analyses are calculated at T574 using the Gridpoint Statistical Interpolation [Kleist ~al.(2009)Kleist, Parrish, Derber, Treadon, Wu and Lord] in its hybrid 4D-EnVar extension [Wang and Lei(2014), Kleist and Ide(2015)]. The hybrid background error covariance is derived from an 80 member ensemble analyzed using the ensemble square-root filter [?, EnSRF;]]whitaker2002ensemble. Most of the major instruments on polar-orbiting satellites listed in Tab. 0 are assimilated at NCEP with the exception of SAPHIR and the microwave imagers. For geostationary platforms, humidity-sounding infrared channels from the GOES-15 sounder and SEVIRI on Meteosat 10 are assimilated in clear skies. All conventional data listed is used apart from GNSS path delay.

The capability of all-sky microwave radiance assimilation in the GSI has been developed at NCEP, and the assimilation of cloudy radiances from the AMSU-A microwave radiometer for ocean scenes has been operational since May 12, 2016 [Zhu ~al.(2016)Zhu, Liu, Mahajan, Thomas, Groff, van Delst, Collard, Kleist, Treadon and Derber]. The same implementation included an upgrade of the data assimilation system from Hybrid 3D-Var (which has been operational since May 2012) to Hybrid 4D-EnVar. In these frameworks, the background error covariance includes static and ensemble contributions, currently with an 87.5% weight given to the ensemble part and 12.5% to the static term. For the ensemble part, the cloud water background error variance and the cross-covariances among cloud water and other variables are extracted implicitly from the ensemble forecasts, while currently there is no cross-covariance between cloud water and other variables specified in the static term. This approach is followed in order to reduce the need for development and maintenance of the tangent-linear and adjoint of the forecast model and its physics processes. Further development and research are required to determine the best combination of static, ensemble and linearized physics background constraints to be used.

In the GFS model, cloud water (the sum of the cloud liquid water and cloud ice) is a prognostic variable. The model moist physics includes a cloud microphysics parametrization [Zhao and Carr(1997), Sundqvist ~al.(1989)Sundqvist, Berge and Kristjansson, Moorthi ~al.(2001)Moorthi, Pan and Caplan] and parametrizations for deep and shallow cumulus convection [Han and Pan(2011)]. Clouds due to convection are only considered through detraining the convective cloud water to the grid scale cloud water near the convective cloud tops, thus the cloud condensate in the convective plume is not included in the total condensate of the forecast model output, and the convective cloud is not available for use in data assimilation. Investigation on the impact of including convective clouds in all-sky radiance assimilation is underway. Also, cloud output from the GFS does not currently include precipitation (rain and snow) information.

Normalized relative humidity and cloud water are used as the humidity and cloud control variables, respectively. Due to the lack of precipitation and snow information from the GFS model, only AMSU-A radiances affected by non-precipitating clouds are assimilated, in addition to radiances from cloud-free scenes. The symmetric observation error method [Geer and Bauer(2011), Geer ~al.(2012)Geer, Bauer and English] is adopted for modelling AMSU-A observation errors as a function of cloud water amount. Additional situation-dependent observation error inflation is applied based on the physically based factors on which it is assumed the observation error (through primarily CRTM) is dependent. Moreover, in the variational radiance bias correction scheme [Zhu ~al.(2014)Zhu, Derber, Collard, Dee, Treadon, Gayno and Jung, Zhu ~al.(2014)Zhu, Derber, Collard, Dee, Treadon, Gayno, Jung, Groff, Liu, van Delst, Liu and Kleist], only a selected data sample of AMSU-A radiances, where clouds retrieved from the observation and those from the FG are consistent, are used to derive the bias correction coefficients and the coefficients are then applied to all used AMSU-A radiances. This effectively removes the bias from the radiances while preserving the cloud signal in the observation for the radiance data with mismatched cloud information. By excluding the precipitating scenes, this is not a technically complete 'all-sky' approach but it still makes sense to refer to it as 'all-sky', given that it uses all the typical tools of an all-sky approach. The assimilation of AMSU-A radiances using the all-sky technique improves the temperature and relative humidity at 850 hPa off the west of the continents as well as reducing a known bias in stratus. A comparison of the mean relative humidity at 850 hPa against the ECMWF analysis is provided in Fig. 1, which indicates that the clear-sky analysis is too wet in these regions while the all-sky analysis is much closer to ECMWF.

Figure 2: Averaged relative humidity analysis (%) for the ECMWF analysis (top panel), the difference between clear-sky NCEP analysis and ECMWF (middle panel), and the difference between all-sky NCEP analysis and ECMWF (bottom panel) at 850 hPa for the period from Oct. 27 to Dec. 1, 2013.

2.5 Met Office

The Met Office produces operational forecasts by running the Unified Model (UM) on a global domain and over a local area – UK High Resolution model (UKV) – centred on the UK. The global model grid length at midlatitutes is about 10 km and it has 70 levels with a lid at about 80 km. The UM dynamical core is based on a semi-implicit semi-Lagrangian discretization on a latitude-longitude C-grid and a height-based vertical coordinate [Davies ~al.(2005)Davies, Cullen, Malcolm, Mawson, Staniforth, White and Wood], recently improved [Wood ~al.(2014)Wood, Staniforth, White, Allen, Diamantakis, Gross, Melvin, Smith, Vosper, Zerroukat and Thuburn, Walters ~al.(2016)Walters, Brooks, Boutle, Melvin, Stratton, Vosper, Wells, Williams, Wood, Allen, Bushell, Copsey, Earnshaw, Edwards, Gross, Hardiman, Harris, Heming, Klingaman, Levine, Manners, Martin, Milton, Mittermaier, Morcrette, Riddick, Roberts, Sanchez, Selwood, Stirling, Smith, Suri, Tennant, Vidale, Wilkinson, Willett, Woolnough and Xavier] to make it more scalable (i.e. faster to run when using more computing nodes), numerically more accurate and computationally more robust. Global initial conditions for prediction are generated using hybrid 4D-Var [Clayton ~al.(2013)Clayton, Lorenc and Barker], where climatological covariances are blended with flow-dependent covariances generated from MOGREPS-G, the global component of the Met Office Global and Regional Ensemble Prediction System, currently composed of 44 20-km-resolution perturbed members that are updated twice a day at 00 UTC and 12 UTC. Analyses are generated every six hours and forecasts up to six-days' lead time are produced twice a day (at 0000 and 1200 UTC). The assimilated observations are detailed in Tabs. 0 and 1, noting that GMI data is not yet used but additionally MWHS-1 and MWHS-2 microwave humidity sounders are assimilated, in clear-sky conditions.

The UKV model [Tang ~al.(2013)Tang, Lean and Bornemann] is convection-permitting [?, e.g.]]clark2016convection with a 1.5-km horizontal resolution grid over the UK and a 4-km resolution over an outer domain, recently extended in all directions to improve the spin up of convection over the UK. It operates over 70 levels, with a lid at about 40 km. The UKV model generates up to T+12 forecasts at every hour from initial conditions estimated using 4D-Var, with up to a T+54 hour lead time four times a day (at 0000 UTC, 0600, UTC, 1200 UTC and 1800 UTC) and twice a day (at 0300 and 1500 UTC) up to a T+120 hour lead time. The operational data assimilation scheme is 4D-Var with a one-hourly time window, with covariances from a climatology of T+6 minus T+3 forecast differences. The system assimilates the conventional observations listed in Table 0 plus satellite radiances (in clear-skies only) from the AIRS, IASI and CrIS infrared sounders, the MHS and ATMS microwave sounders and the humidity-sounding channels of SEVIRI.

The variational method to estimate the initial conditions for prediction makes use of a set of control variables, which are assumed mutually uncorrelated. The control variables used at the Met Office include a single moist variable [Ingleby ~al.(2013)Ingleby, Lorenc, Ngan, Rawlins and Jackson] defined, following [H_m ~al.(2002)H_m, Andersson, Beljaars, Lopez, Mahfouf, Simmons and Thepaut], as a total (i.e. vapour plus cloud) relative humidity increment normalized by the standard deviation of the total relative humidity increment distribution conditioned on the average between forecast and analysis total relative humidity. A parameter transform then determines total water increments at initial time from the control vector at each iteration in the variational minimization procedure.

A linear "perturbation forecast" (PF) model is used at the Met Office to evolve the initial increments in time. As the two moisture prognostic variables represent water vapour and cloud increments, at initial time the cloud water increments are diagnosed as proportional to the total water and temperature data assimilation increments, assuming that no latent heat release takes place. The PF model also employs a moist physics scheme [Stiller and Ballard(2009)] to diagnose and evolve vapour and cloud water (and diagnose precipitation) increments so as to parametrize latent heat release. The scheme does not distinguish between liquid and frozen phases. Furthermore, the PF model operating within the global configuration of the Met Office operational data assimilation system includes a linear convection scheme [Stiller(2009)] to diagnose the potential temperature, moisture and precipitation increments due to subsidence and mass-flux perturbations from the nonlinear scheme's convective available potential energy (CAPE) closure relationship.

Finally, the UM and the observation operator need increments to vapour, cloud liquid and frozen water. This means that in order to calculate the predicted observations from the updated model state as well as the initial state for the nonlinear model, it is necessary to make use of a moisture incrementing operator, which distributes the total water increments into increments of vapour and cloud liquid and frozen fields. This operator has been recently redesigned (see section 3.4) to be better suited for prediction of cloud-affected observations.

2.6 Météo France

Météo-France operates several numerical weather prediction systems providing both global forecasts with the ARPEGE model up to 4 days ahead and regional forecasts with the AROME non-hydrostatic model up to 36-hours ahead. While ARPEGE predictions are performed on a stretched and tilted grid of 7.5 km resolution over Europe and 37 km resolution at the antipodes, AROME predictions are performed at 1.3 km resolution over Western Europe and 2.5km resolution over five domains in the Tropics covering the French Overseas territories. Both deterministic and ensemble forecasts are computed with ARPEGE and AROME over Europe. The ARPEGE model is initialised using 6h-cycle 4D-Var analysis while the AROME model over Western Europe uses a 1 h-cycle 3D-Var system [Brousseau ~al.(2016)Brousseau, Seity, Ricard and Làer] and ARPEGE for its lateral boundary conditions. In both systems, all the main observing systems listed in Tab. 0 are assimilated, in clear sky conditions only regarding the satellite radiances. A unique feature of the AROME prediction system is that it assimilates radar reflectivities in all-sky conditions every hour using a Bayesian framework [?, referred as 1D-Bay+3D/4D-Var,]]caumont2010 which is an alternative to both 1D-Var+3D/4D-Var [?, e.g.]]bauer2006a and direct assimilation techniques [?, e.g.]]bauer2010. This method was inspired by the GPROF algorithm [?, e.g.]]kummerow2001 which retrieves rainfall and snow profiles from space-based passive microwave observations. The term 'all-sky' is appropriate since both the non-precipitation and precipitation-affected reflectivities are assimilated, and this helps avoid a biased analysis, just as for radiance assimilation. The method was successfully implemented operationally at Météo-France in 2010 and proved to be a robust method for improving short-term precipitation forecasts at mesoscale [Wattrelot ~al.(2014)Wattrelot, Caumont and Mahfouf].

2.7 DWD

The German Weather Service (DWD) operates both a global numerical forecasting system and a limited area model at convection resolving scale along with corresponding ensembles. The global system has been fundamentally updated during the last years with the introduction of the new Icosahedral Non-hydrostatic ICON model [Zangl ~al.(2015)Zangl, Reinert, Ripodas and Baldauf] in January 2015 running on an icosahedral grid at about 13 km resolution and 90 sigma-z levels up to 75 km globally providing forecasts to 120 hours. In the same run, forecasts are computed on a 6.5 km grid covering Europe with a two-way nesting. For data assimilation, an EnVar system has been introduced in January 2016 based on a 40 member LETKF [Hunt ~al.(2007)Hunt, Kostelich and Szunyogh] at 40 km resolution providing covariances to a 3-hourly 13 km variational analysis (with weights of 70% for flow-dependent LETKF and 30% for climatological covariances). This EnVar approach could be labelled as hybrid 3D-EnVar. The moist control variables in the ensemble part (LETKF) are specific water vapour as well as specific cloud liquid water and cloud ice, whereas the 3D-Var uses a generalized humidity variable involving a transformation function at near zero humidity to ensure positive humidity values during analysis. Satellite radiances from MW (AMSU-A, ATMS) and IR sounders (IASI, HIRS) on polar orbiting satellites are assimilated along with radio occultation data and the standard set of conventional observations (Tab. 0). Currently, satellite data are only assimilated in clear-sky conditions and with a focus mostly on temperature sensitive channels. The upgrade of the analysis to use humidity-sensitive satellite data, and further, to all-sky assimilation, had been left until after the introduction of the new ICON model. The new model involved completely new numerics and physical parametrizations, and hence a very different behaviour of the humidity analysis. With the successful introduction of ICON, this upgrade is now under way: all major flying humidity sensitive MW sounders and imagers (see list in Table 0) have been technically implemented. Currently they are being tested for the assimilation and their all-sky implementation will be addressed as soon as each group of instruments goes operational during the current and the next years.

On the convective scale, the non-hydrostatic COSMO model [Baldauf ~al.(2011)Baldauf, Seifert, Forstner, Majewski, Raschendorfer and Reinhardt] at 2.8 km resolution covers Germany and parts of adjacent countries. The assimilation is based on the same LETKF approach with currently 40 members and is implemented as a 4D-LETKF system called KENDA [?, Kilometre-scale Ensemble Data Assimilation;]]schraff2016, operational since March 2017. It calculates the observation innovations at the observation time during the hourly assimilation window. The moist control variables are specific water vapour as well as specific cloud liquid water and cloud ice and cross correlations between all variables are based on the ensemble. The current configuration of KENDA does not yet operationally assimilate satellite data, but it includes latent heat nudging for the assimilation of radar derived rain rates [Stephan ~al.(2008)Stephan, Klink and Schraff] from the German and European networks. All-sky assimilation of satellite data is not yet included, but in development (Sec. 3.6).

2.8 Radiative transfer models

A comparison of RTTOV and CRTM fast radiative transfer models

Features	CRTM-2.3	RTTOV-11
Interface	Unified Interface for all sensors and conditions	Separate interfaces for IR and MW sensors under all-sky (RTTOV-SCATT for MW)
Cloud Types	Six types: water, ice, rain, snow, hail, graupel	
Four types: cloud water, ice, rain, snow (MW)		
Six types: 2 stratus, 3 cumulus, 1 cirrus (IR)		
Total Cloud Cover		
Fractional Cloud	Four cloud overlapping schemes available	

Two-column radiance calculation	Hydrometeor weighted average overlap (MW)
Streams method/Maximum-random overlap (IR)	
RT Solver	Thermal emission for clear-sky and non-precipitating clouds
Advanced Adding and Doubling scheme	Delta-Eddington Approximation (MW)
Single-stream RTE with scaling of cloud optical thickness to account for the scattering effect (IR)	
Hydrometeor Optical Properties for MW	All hydrometeors - sphere; modified gamma
Mie solution	
Constant density for each hydrometeor type	
LUT for bulk mass extinction and scattering coefficient,	Cloud water/ice - sphere; gamma

<table>
<tr><td>and Legendre phase function coefficients, as a function of frequency, temperature, hydrometeor type, and effective radius</td><td></td></tr>
<tr><td colspan="2">Rain - sphere; Marshall-Palmer</td></tr>
<tr><td colspan="2">Snow - sector; Field</td></tr>
<tr><td colspan="2">Mie solution (sphere); DDA (non-spherical)</td></tr>
<tr><td colspan="2">Constant density for each hydrometeor type</td></tr>
<tr><td colspan="2">LUT for volume extinction coefficient, single scattering albedo, and average asymmetry, as a function of frequency, temperature, hydrometeor type, and hydrometeor water content</td></tr>
<tr><td>Hydrometeor Optical Properties for IR</td><td>Similar to MW except for cloud ice</td></tr>
<tr><td colspan="2">Cloud ice - hexagonal columns; gamma</td></tr>
<tr><td colspan="2">Mie solution - sphere</td></tr>
<tr><td>FDTD/GO - non-spherical</td><td>Water clouds - sphere; modified gamma</td></tr>
<tr><td colspan="2">Ice clouds - ensemble</td></tr>
</table>

of shapes & PSDs
Mie solution - sphere
Baran database - function of IWC & temperature

For all-sky radiance assimilation at the NWP centers participating in this study, accurate and fast simulation of radiative transfer in the presence of clouds and precipitation is provided by either CRTM or RTTOV. These radiative transfer models (RTMs) contain functions to compute atmospheric gaseous absorption, scattering and emission for hydrometeor and aerosol particles, surface emissivity and reflectivity, radiative transfer solvers, and ultimately provide satellite sensor radiances and Jacobians. It is noted that CRTM has unified interfaces for all sensor types and conditions, whereas RTTOV has separate interfaces for Infrared (IR) and Microwave (MW, known as RTTOV-SCATT) sensors under all-sky conditions. Both CRTM and RTTOV are highly modularized;Table 2.8 compares their all-sky related features.

At the core of the RTMs are solvers of the radiative transfer equation. Under multiple-scattering conditions, relatively complex solvers are required. In CRTM, the advanced doubling-adding (ADA) method [Liu and Weng(2006)] is used for all sensor types. The ADA method employs Gaussian quadrature to calculate radiative transfer for specific up-welling and down-welling zenith directions, and uses Legendre polynomial expansion to represent the scattering phase function. In RTTOV, the delta-Eddington approach is used for the microwave, forming the core of RTTOV-SCATT [Bauer ~al.(2006)Bauer, Moreau, Chevallier and O'Keeffe]. This approximates the radiance vector and phase function to the first order so that only the calculation at the viewing (satellite zenith) angle is required. For IR sensors in RTTOV, the normal approach keeps the radiative transfer equations in the same form as for clear-sky conditions but with a scaling of the cloud optical thickness to account for scattering as proposed by [Chou ~al.(1999)Chou, Lee, Tsay and Fu]. A discrete ordinates solver has been made available for the IR in RTTOV v12, but is unlikely to be fast enough for operational use.

In all-sky assimilation, the small-scale variability of cloud and precipitation must be carefully considered in order to obtain accurate simulations of sensor radiances. At microwave frequencies, the non-linear dependence of radiance on hydrometeor amount causes a "beam-filling effect" in satellite observations [Kummerow(1998)]. Even when two fields of view contain the same mass of hydrometers, variations in fractional cloud coverage can result in large differences in observed radiances. To better handle situations with fractional cloudiness, the cloudy simulation for infrared sensors in RTTOV can use either a simple gray cloud method (defined by cloud fraction and cloud-top pressure) or a multiple-column approach sometimes (confusingly) referred to as the streams method [Amorati and Rizzi(2002)]. In this approach, cloud is assigned to the columns using maximum-random cloud overlap to account for partially cloudy conditions. In the microwave, the partially cloudy column is handled by splitting the column into two: clear and overcast (two-column calculation), and the total cloud cover is calculated by the hydrometeor weighted average cloud overlap scheme [Geer ~al.(2009)Geer, Bauer and O'Dell], which is a reasonable assumption due to the semi-transparency of clouds in this spectral range. The total radiance is then calculated as the sum of the radiances from the clear and overcast columns weighted by the total clear cover and total cloud cover, respectively. Until recently, CRTM did not handle partially cloudy scenes, and made the assumption that cloudy columns are overcast. However, a two-column calculation similar to RTTOV-SCATT has been developed in CRTM, which will be available in the next release (2.3).

In all-sky applications, the optical properties of hydrometers can be calculated from the Lorenz-Mie solution for a single spherical particle. For non-spherical particles, a combination of techniques such as discrete dipole approximation (DDA), finite difference time domain (FDTD) algorithm, T-matrix method, and geometric optics (GO) are available to obtain the optical properties for randomly oriented single particle as described in [Yang ~al.(2005)Yang, Wei, Huang, Baum, Hu, Kattawar, Mishchenko and Fu] and [Liu(2008)]. The bulk optical properties of a specific hydrometeor type to be used in the RTMs can then be computed by integrating the optical property of a single particle over its particle size distribution (PSD). In practice, the single hydrometeor type can be replaced by an ensemble of hydrometeor types (habit distribution) in the integration to obtain the bulk optical properties for a distribution with a mixture of habits.

For computational efficiency, a pre-calculated look-up table (LUT) stores the bulk optical properties as a function of hydrometeor type, frequency, temperature, plus either the effective particle size (in CRTM) or water content (in RTTOV). This difference is explained by noting that CRTM tabulates the mass extinction coefficient [m^2 kg^{-1}] [?, e.g.]]hong2007,yang2013 and the volume extinction coefficient [m^{-1}] is obtained by multiplying by the hydrometeor water content (density). For microwave scattering in RTTOV, LUTs contain the volume extinction coefficient directly, with dependence on hydrometeor water content [?, e.g.]]geer2014a. An explicit dependence on effective particle size is likely useful for accurate simulations in the IR but has not yet been examined in depth for the microwave. In CRTM, additional Legendre phase coefficients are used to reconstruct the phase function required for the ADA scheme [Liu and Weng(2006)]. For RTTOV IR scattering, various ice cloud optical property parameterizations are available [Saunders ~al.(2012)Saunders, Hocking, Rayer, Matricardi, Geer, Bormann, Brunel, Karbou and Aires] including one based on an ensemble model of six habits (hexagonal column, six-branch bullet rosette, and 4 hexagonal ice aggregates with 3 to 10 elements) for ice cloud [Baran and Labonnote(2007), Baran ~al.(2011)Baran, Bodas-Salcedo, Cotton and Lee].

3 Future developments by operational centre

3.1 ECMWF

Given the good results with all-sky assimilation so far, ECMWF will continue to develop it further, moving towards more challenging areas such as low-frequency (e.g. 10 GHz) microwave imaging channels, microwave temperature-sounding instruments (AMSU-A, ATMS) and IR radiances.

Figure 3: Histogram of brightness temperatures from TMI 10 GHz vertically polarised channel covering August 2013 for model (red) and observations (black, superobbed; blue, raw data) with a binning of 5 K. The sample is over ocean, excluding any potential land-contaminated scenes.

The assimilation of 10 GHz channels over ocean exposes limitations in the forward modelling for microwave imagers. In clear-sky conditions there is strong sensitivity to the surface emissivity and sea-surface temperature; systematic errors in FG departures suggest the modelling is not yet accurate enough. Further, all-sky assimilation uses superobservations (superobs) which can cause land contamination close to coastlines and islands, particularly at low frequencies. The main atmospheric signal is from heavy rain, and comparisons between model and observations also reveal systematic errors (Fig. 2, in the range between roughly 190 K and 230 K). This may come from limitations of the current modelling of sub-grid precipitation variability. The forecast model assumes convective rain shafts occupy only a small fraction of the field of view (5%) and the effective cloud fraction in RTTOV-SCATT [Geer ~al.(2009)Geer, Bauer and O'Dell] is often similar. Given that observed brightness temperatures are typically much warmer than simulations in precipitating areas, this may suggest the convective fraction is too small. However, another explanation may be the 'projection' effect: microwave imagers observe at a zenith angle of around 53° and the real observed beam often travels through the vertically-oriented convection shafts; if properly modelled this projection effect would also boost simulated brightness temperatures [?, e.g.]]bauer1998. Further, as the model resolution has increased the simulations have started to represent a smaller area than the superob (which represents scales around 80 km, compared to an effective model resolution around 30-40 km, i.e. 3-4 times the grid spacing). As a result, the very highest brightness temperatures are now overly-frequent in the model simulated data compared to superobs (see Fig. 2, range above 240 K; now the raw data agrees better with the model simulations). To address all these issues, the all-sky superobbing framework will be complemented by 'super-modelling', where the simulated observation is the average of simulations from multiple model grid points enclosed in the superob area. This will match the scales of the superob and the model equivalent and will support the introduction of slant-path multiple independent columns in the observation operator, to better simulate surface and atmospheric inhomogeneity, including the projection effect.

The assimilation of microwave temperature-sounding channels (e.g. from AMSU-A) was not successful in early experiments at ECMWF [Geer ~al.(2012)Geer, Bauer and English], partly due to the poor quality of scattering simulations at the time, at the 50 GHz frequencies of these instruments. Further, the separation of temperature background errors (of order 0.1 K in brightness temperature space) from cloud and precipitation background errors (up to order 50 K) is challenging and it requires accurate modelling of background and observation errors to avoid cloud signals being aliased into temperature fields and degrading the dynamical initial conditions. Now that scattering simulations have been improved [Geer and Baordo(2014)] and with increasingly sophisticated background error modelling from the EDA, AMSU-A assimilation is being tested again. Initial tests of moving AMSU-A assimilation from the clear sky system (where cloudy radiances are detected and screened out) to the all-sky system have revealed mixed results. Small improvements to short range temperature forecasts were seen in the troposphere (around 0.5%) while there were degradations of up to 0.2% in the stratosphere. The clear sky assimilation of AMSU-A radiances has been finely tuned for the past 15 years at ECMWF and hence simply moving the assimilation to the relatively immature all-sky system was always likely to lead to mixed results. Further work is required to understand and eradicate the degradations before the all-sky assimilation of AMSU-A channels can be recommended for operational implementation. Future work is planned to also test and implement the all-sky assimilation of ATMS radiances.

Figure 4: Impact of adding all-sky IR water vapour sounding channels into the otherwise full observing system, measured in terms of the standard deviation of FG departures from AMSU-A radiances, normalised by the standard deviations in the control experiment. Confidence bars indicate the 95% confidence interval.

The extension of all-sky assimilation to the infrared has been investigated since [Chevallier and Kelly(2002)] and [Chevallier ~al.(2004)Chevallier, Lopez, Tompkins, Janiskov and Moreau] showed the quality of model-simulated all-sky IR radiances and identified the IR water vapour sounding channels (at wavelengths around 6.3 μm) as good candidates for assimilation. These channels have similar characteristics to the microwave humidity sounding channels which have been assimilated successfully in all-sky. Increasing relative humidity and increasing cloud optical thickness drive radiances in similar ways, giving a relatively smooth dependence on atmospheric water in both its vapour and condensed forms. [Matricardi(2005)] extended

RTTOV to model the effect of cloud including scattering and cloud overlap as described in Sec. 2.8. The assimilation framework has been extended to hyperspectral sounders [Migliorini ~al.(2014)Migliorini, Geer, Matricardi and English] and a symmetric observation error model has been investigated [Okamoto ~al.(2014)Okamoto, McNally and Bell]. One issue blocking operational use has been the RTTOV IR multiple independent column scheme, which can use up to around 100 columns for each observation, with a computational cost and memory usage that is currently unaffordable for operational forecasting. To allow testing of upper-tropospheric moisture channels, a simplified two-column cloud-overlap scheme has been introduced, like that of [Geer ~al.(2009)Geer, Bauer and O'Dell] in the microwave, but with the effective cloud fraction taken as the maximum cloud fraction in the mid and upper-troposphere. This is not appropriate for window channels but it gives good results for the upper-tropospheric water vapour channels. Figure 3 illustrates the results of a month-long proof of concept experiment in which HIRS channels 11 and 12 were assimilated in all-sky conditions from two satellites (Metop-A and NOAA-19) in the context of the full global observing system except for HIRS. Despite using fixed observation errors (of 6 K and 4 K for channels 11 and 12) and using the new simplified two-column overlap approach, there were significant improvements in fits to other observations, including the tropospheric temperature channels of AMSU-A, as shown in the figure. However, further development is needed.

In related areas, ECMWF is planning to directly assimilate reflectivities from cloud radar and lidar from the future EarthCARE mission, developing beyond the experimental 1D+4D-Var framework of [Janiskov ~al.(2012)Janiskov Lopez and Bauer]. The assimilation of rain gauge observations has been demonstrated experimentally [Lopez(2013)] but is not planned for operational assimilation. Lightning assimilation is also in development [Lopez(2016)]. These developments may not have a big immediate impact on global forecasts, due to limited global coverage, but they should give a large indirect benefit by identifying deficiencies in, and subsequently helping to improve, the forecast model.

3.2 Japan Meteorological Agency

JMA has been working on all-sky MW and IR radiance assimilation. All-sky MW assimilation has been developed using the global data assimilation system including a 4D-Var method and RTTOV-SCATT. Cloud liquid water, cloud ice water, cloud fraction, rain and snow profiles are not control variables but are provided by the JMA global model. All-sky MW observations from AMSR2, SSMIS and GMI are pre-processed and assimilated with 4D-Var. For example, they are averaged to match the model resolution used in the inner-loop minimisation, and thinned in 150 km by 150 km boxes. Situation dependent observation errors are set using a symmetric cloud amount parameter based on [Geer and Bauer(2011)].

Figure 5: Impact of all-sky assimilation on tropical cyclone forecasts at JMA, illustrated by Hurricane Jimena in 2015 Eastern Pacific. (a) The tropical cyclone track predictions (Red: all-sky, Blue: clear-sky, Black: observed track). The numbers in the panel indicate the day. (b) Predicted and observed central pressures and (c) maximum wind speed of the tropical cyclone.

Impacts of all-sky MW radiance assimilation were compared with those of clear-sky radiance assimilation using the JMA global NWP system as of March 2016. Analysis and FG fits to other satellite observations demonstrated improved water vapour, temperature and wind in the troposphere, especially in cloudy and rainy areas (not shown). Remarkable impacts of all-sky MW radiance assimilation were seen in Tropical Cyclone (TC) analyses and forecasts (Fig. 4). All-sky MW radiance assimilation enhanced the increase and concentration of TCWV under cloudy situations, leading to a better representation of rapid intensification through the data assimilation cycle. In addition to these direct impacts, all-sky MW radiance assimilation improved the tropospheric wind field through the 4D-Var tracing effect. This resulted in better mid-latitude atmospheric circulation and improved TC track prediction. However, there were several negative impacts. One was a negative bias in mean temperature in the lower troposphere in marine stratocumulus areas where the diurnal variation of cloud liquid water is underestimated. Similar issues have been seen in the ECMWF model [Kazumori ~al.(2016)Kazumori, Geer and English]. Further degradations were a decrease in TCWV around light rain areas in the tropics, responding to excessive light rain predictions in the forecast model. Because these degradations are associated with global model biases in cloud and precipitation processes, this indicates that the success of all-sky radiance assimilation is much more dependent on accuracy of those processes than clear-sky radiance assimilation. Several improvements in the moist physics scheme of JMA GSM have been performed [WGNE(2016)].

IR all-sky radiance assimilation is also under development based on similar approaches to the MW all-sky assimilation. A situation dependent observation error model is built as a linear function of a symmetric cloud effect parameter calculated from observation and FG departures from clear-sky FG [Okamoto(2017)]. The parameter is also used to define the cloud-dependent criteria for FG departure QC: if the cloud effect is predicted to be large, samples with large FG departure, which would be rejected in the traditional static FG departure QC, can pass the QC. Creating superobs by spatially averaging pixels is also done in the same way as in MW all-sky radiance assimilation, but with the addition of careful elimination of highly inhomogeneous scenes. This homogeneous QC is important for IR radiances because of the strong sensitivity of IR radiances to cloud. Unacceptably inhomogeneous super-obs are identified when the standard deviation calculated from original pixel radiances exceeds a certain threshold that varies with the superob size.

JMA has been developing all-sky IR radiance assimilation for Advanced Himawari Imager

(AHI) onboard JMA's geostationary satellite Himawari-8. AHI's water vapour channels have been selected for the assimilation at the initial stage of development because the PDFs of their FG departures are close to Gaussian distributions. By contrast, the PDFs for window and CO2 bands are skewed and depart from Gaussian distribution probably because of a significant underestimation of cloud effect in the FG [Okamoto(2017)]. Observation parameters such as thinning distance and the maximum and minimum values in the observation error model are estimated based on a diagnosis following [Desroziers ~al.(2005)Desroziers, Berre, Chapnik and Poli]. Aiming at the operational assimilation of all-sky IR radiances, the impact of these preprocessing strategies is being assessed using JMA's NWP systems.

3.3 NCEP

Since the implementation of all-sky AMSU-A radiance assimilation in the GSI, progress has been made on extending all-sky radiance assimilation to ATMS. ATMS has 22 channels, combining most of the channels from AMSU-A and Microwave Humidity Sounder (MHS). Effort has been focused on additional quality control procedures due to the unique ATMS features and for MHS-like channels. In addition, testing of the use of advanced non-linear quality control [Purser(2011)] is underway using ATMS.

For infrared sensors, there are three broad strategies being followed in multiple research projects, to investigate the best way to use cloudy radiances: direct assimilation of cloudy radiances; cloud clearing and simple modelling of the clouds' radiative effect with a thin grey cloud model.

The first of these [Bi ~al.(2016)Bi, Collard, Liu, Jung and Derber] follows the approach of [Migliorini ~al.(2014)Migliorini, Geer, Matricardi and English] where cloudy radiances are assimilated, but only for water vapour channels - the thinking being that any resultant aliasing of the cloud signal into other state variables would primarily affect humidity rather than temperature. The development of this capability has necessitated improvements to the CRTM: in particular the inclusion of a way of allowing for fractional cloud in the CRTM radiative transfer calculation. An observation error model has been adopted that uses a 'cloud-effect' observation error covariance model analogous to that used for the microwave [Okamoto ~al.(2014)Okamoto, McNally and Bell].

The investigation of the assimilation of cloud-cleared radiances was prompted by initial encouraging results assimilating AIRS cloud cleared radiances [LeMarshall ~al.(2008)LeMarshall, Jung, Goldberg, Barnet, Wolf, Derber, Treadon and Lord]. That study used an AIRS cloud cleared radiance product with the initial guess provided from AMSU-A retrievals. In the current study [Liu ~al.(2015)Liu, Collard and Derber] the NWP model field itself is used as a FG. The accuracy of the cloud cleared radiances produced and their sensitivity to the NWP initial guess has been investigated by using nearby clear pixels as truth. It was found that the influence of the FG increases as the peak of the Jacobian is deeper in the atmosphere, but that useful information from the observations themselves is present in at least a subset of channels. Initial forecast impact experiments have found a small positive impact from using these data.

Finally, investigations are underway on the use of a simple grey cloud model defined through the cloud top pressure and effective cloud fraction using the methodology of [McNally(2009)] and following the approaches of ECMWF and other centres.

Assimilation of the microwave imagers AMSR2 and GMI is being explored in the hybrid 4D-EnVar GSI-based system of the NASA Global Modeling and Assimilation Office (GMAO). In GMAO GEOS, all-sky GPM Microwave Imager (GMI) radiance data assimilation increased lower tropospheric moisture near the Tropics in the analysis. Forecast impact experiments demonstrated improvements in 5-day forecasts of lower tropospheric humidity and temperature globally [Kim ~al.(2016)Kim, Jin, McCarty, Todling, Gelaro and Gu].

The investigations above have built upon improvements to the CRTM. The one-column radiance calculation currently used in operations has been extended into two columns to handle partially cloudy scenes. Total cloud cover can be calculated from one of the four cloud overlapping schemes: maximum, random, maximum-random, and hydrometeor weighted averaged overlap based on input cloud fraction and/or cloud content profiles [van Delst ~al.(2016)van Delst, Liu and Bi]. Going to two columns has greatly reduced the biases in innovations observed in cloudy infrared assimilation [Bi ~al.(2016)Bi, Collard, Liu, Jung and Derber] and is expected to also have an impact on all-sky MW assimilation [Liu ~al.(2015)Liu, Collard, Sun, Zhu, van Delst, Groff and Derber].

To prepare for the assimilation of radiance affected by precipitation, the microwave brightness temperatures calculated under scattering conditions in CRTM have been validated against those calculated from RTTOV and observations from MW sensors [Liu ~al.(2015)Liu, Collard, Sun, Zhu, van Delst, Groff and Derber]. Large biases in simulated brightness temperatures were found in surface sensitive channels under scattering conditions. It was found that the off-diagonal terms of the surface reflectivity matrix are zero so that no diffuse radiation is reflected at the surface towards the sensor view angle. To correct the situation required temporarily reintroducing the reflection correction [Deblonde and English(2001)] — more properly only to be used in two-stream models — until a bidirectional reflectance distribution function (BRDF) model can be implemented.

A cloud optical property table which is more consistent with the model cloud microphysics is being developed, covering spectral range from visible to microwave.

3.4 Met Office

The Met Office aims to assimilate cloud-affected satellite radiances in a gradual manner, starting with non-precipitating scenes observed by lower peaking channels from microwave sounders such as ATOVS AMSU-A channel 4 and 5 (in the global model) and MHS channel 3, 4 and 5 (both in the global and in the UKV model). Cloud-affected radiances from other temperature and humidity sounders will be considered for assimilation later on (see Tab. 1). Initial efforts were devoted to improving the existing moisture incrementing operator, discussed in section 2.5, which allows the total water data-assimilation-derived increments to be transformed into moisture increments for water in all phases. The main characteristics of the new moisture incrementing operator [Migliorini ~al.(2017)Migliorini, Lorenc and Bell] are that it is a linear function of the model's state increments; its increments are consistent with the liquid and frozen cloud fractions prescribed by the cloud scheme used in the prognostic model; it is statistically trained in order to fit the cloud liquid and frozen water perturbations prescribed by the ensemble prediction system.

At the same time, a new functionality was added to the operational observation processing system to allow inflating the observation error standard deviation of a given instrument channel as a function of the cloud amount present in the field of view of the instrument. Following [Geer and Bauer(2011)], the inflation factor is applied when cloud is either detected by the observations or when it is present in the forecast within the instrument field of view. Work is under way so as to determine suitable thresholds for inclusion of cloud-affected observations into the set of data to be assimilated, which are not detrimental to the state estimation process.

3.5 Météo France

All-sky assimilation of both microwave and infrared observations are under study at Météo-France with a two-step strategy corresponding to short term and longer term plans.

In the short term, the lack of tangent-linear and adjoint of the convection scheme for the ARPEGE model and the convection-resolving AROME model prevents Météo-France from testing a fully direct all-sky assimilation methodology like the one developed at ECMWF. Hence, different methods are being studied. In the longer term, work is ongoing to develop a new data assimilation system based on an EnVar methodology [Desroziers ~al.(2014)Desroziers, Camino and Berre, Desroziers ~al.(2016)Desroziers, Arbogast and Berre] in which condensed variables could be included in the control vector [Michel ~al.(2011)Michel, Aulignàand Montmerle]. These latter developments would then allow testing direct assimilation of cloudy and rainy radiances both in ARPEGE and AROME while fully avoiding the need of TL/AD of the convection schemes.

Regarding microwave observations, research is ongoing to capitalize on the experience gained from the successful operational all-sky assimilation of radar reflectivities within the AROME model. The 1D-Bay+3D/4D-Var technique retrieves atmospheric profiles from cloudy and rainy radiances, only using a forward observation operator and model profiles within the vicinity of each observation. Hence, it avoids the complexity of 1D-Var methods requiring the linearisation of the observation operator and specific background covariance errors for the relevant condensed variables. This method has the common point with 1D-Var+3D/4D-Var to assimilate pseudo-profiles of humidity as new observations even though they have some information content related to the FG, but on a less contaminated basis than 1D-Var (as the FG comes from the vicinity of the observations). Hence, it is likely that the 1D-Bay+3D/4D-Var technique will require a dedicated modelling of observation errors. Indeed, [Geer ~al.(2017)Geer, Baordo, Bormann, English, Kazumori, Lawrence, Lean, Lonitz and Lupu] explains that when moving from 1D-Var+4D-Var to direct all-sky assimilation, ECMWF forecast errors worsened and recovered only with a proper modelling of observation errors [Geer and Bauer(2011)]. Therefore, it is likely that 1D-Bay+3D/4D-Var assimilation with an adapted observation error model may have some potential for improving both global and regional forecasts as well.

[Guerbette ~al.(2016)Guerbette, Mahfouf and Plu] showcased the feasibility of the 1D-Bay step for SAPHIR radiances from the Megha-Tropiques satellite and the ALADIN limited area model over the Indian ocean [Faure ~al.(2008)Faure, Westrelin and Roy]. Research is now ongoing in order to adapt the 1D-Bay step to both the ARPEGE and the AROME models and move forward toward data assimilation testing.

Preliminary tests of infrared cloudy radiance assimilation have already been performed at Météo-France in the convective scale AROME model context. [Martinet ~al.(2013)Martinet, Fourrià Guidard, Rabier, Montmerle and Brunel] have shown that the hyperspectral IASI sounder has the potential to retrieve cloud microphysical variables, specifically liquid and ice water contents. This study was done in a 1D-Var framework using an advanced radiative transfer model including profiles for liquid-water content, ice water content and cloud fraction to simulate cloud-affected radiances as background equivalents with AROME fields. A similar approach to that of [Michel ~al.(2011)Michel, Aulignàand Montmerle] was chosen for the determination of forecast AROME errors of cloud liquid and cloud ice water, allowing couplings with errors of temperature and unbalanced specific humidity, the temperature being univariate.

In the context of an observing simulation system experiment, an improvement of temperature and ice-water content above the cloud top was found for opaque clouds. For low clouds, information on temperature, humidity, liquid-water content and ice-water content can be extracted with cloudy radiances through the entire atmospheric column.

The persistence of the cloud information brought by the analysis of cloud variables during a 3-h forecast has then been evaluated by using 1D-Var retrievals to initialize 3-h forecasts performed of the one-dimensional model AROME 1D [Martinet ~al.(2014)Martinet, Fourrià Bouteloup, Bazile and Rabier]. This study showed that the NWP model successfully retained information when cloud variables were included in the control vector of the assimilation. A significant reduction of the forecast error of liquid water content, ice water content, temperature and humidity was also found.

However, even though these latter results were encouraging, they were obtained in a simplified and favourable framework. Considering the future evolution of Météo-France models, the chosen current approach for cloudy IASI radiance assimilation is to work directly in the operational ARPEGE system. An ongoing study aims at determining the observations suitable for assimilation, using collocated imager information and avoiding large mismatches between observations and background simulations. Once this required step before assimilation will be achieved, the 1D-Bay+4D-Var assimilation will be tested for the assimilation of cloudy infrared radiances with an appropriate observation error modelling.

3.6 DWD

The development of all-sky assimilation at DWD has so far been pursued in the framework of the LETKF system KENDA, as the global model and analysis system was in the process of being completely reshaped. However, the developments especially on the use of IR radiances are also being done in view of transferring the approach to the global system. For the high-resolution KENDA, the aim is to provide forecasters with predictions evolving seamlessly from current observations. Therefore, a major development focus is the inclusion of cloud- and rain-sensitive observations, not to only analyse the dynamic variables and humidity, but also the cloud variables themselves (specific cloud water and cloud ice that are part of the control vector) exploiting the cross-covariances provided by the ensemble. Data available at high frequency from geostationary satellites and radar are used in (at least) hourly analysis updates.

For the all-sky assimilation of IR water-vapour radiances from SEVIRI, an observation error scaling based on a cloud impact parameter derived from the both the observations and the FG is used. This follows work by [Harnisch ~al.(2016)Harnisch, Weissmann and Peri ~nez] from the cooperation of DWD and University of Munich (LMU) within the HErZ framework [Weissmann ~al.(2014)Weissmann, Gober, Hohenegger, Janjic, Keller, Ohlwein, Seifert, Tromel, Ulbrich, Wapler, Bollmeyer and Deneke]. The dynamic error estimate as a function of the cloud impact parameter leads to substantially more Gaussian FG departures and is related to the methods proposed by [Geer and Bauer(2011)] and [Okamoto ~al.(2014)Okamoto, McNally and Bell]. This work is being adapted to an operational context looking into time (seasonal) dependence of a brightness temperature threshold used in the cloud impact parameter. Also, bias correction issues and its dependence on scene type (clear sky and different cloud regimes) are being investigated.

In order to make use of the information from additional channels including the near-infrared and visible (VIS) range, the assimilation of cloud retrievals based on multiple-channel radiances has been studied. This is done especially with a view to better analyse low level cloud situations, which are difficult to sense with IR radiation but which are very important for many forecasting scenarios and emerging applications e.g. supporting renewable energy production. In the scheme studied, cloud top heights derived from SEVIRI radiances (using software from Nowcasting Satellite Application Facility, NWC-SAF) are combined with radiosonde information for quality assurance and to specify observation errors based on data reliability. The cloud information is assimilated as pseudo-observations in the form of cloud-top height and 100% humidities in cloudy areas and zero cloud cover at three heights in cloud free areas. In single observation experiments with wintertime low stratus the LETKF is able to improve cloud variables and also produces physically consistent adjustments of the temperature profiles through the cross-correlations [Schomburg ~al.(2015)Schomburg, Schraff and Potthast]. Full experiments using the SEVIRI cloud top heights additionally to conventional data show the ability of the scheme to enhance cloud cover in areas where the run using only conventional data has too little cloud and to suppress clouds in areas with too high cloud cover. This information is retained in the subsequent free forecasts for a period of 12-24h (see Fig. 5 and Fig. 6).

Figure 6: Cloud cover (in percent) over the COSMO model domain for 13 Nov 2011 12 UTC. Left: Observation (NWC-SAF cloud retrieval); Middle: 1 h forecast from KENDA run with only conventional data; right: 1h forecast from KENDA run with assimilation of cloud retrievals additionally to conventional data.

Figure 7: Example of the time evolution of correlation of cloud cover between the forecast and the cloud cover retrievals for a 24h forecast run starting on 13 Nov 2011 6 UTC. Forecast based on KENDA assimilation using only conventional data (black curve) and conventional data and cloud retrievals (grey curve).

As an alternative approach to exploit the visible range, the assimilation of VIS radiances (or reflectances) themselves is being pursued. A fast forward model simulating the top of atmosphere reflectance has been developed within HErZ [Scheck ~al.(2016)Scheck, Frerebeau, Buras-Schnell and Mayer] and has been applied to assimilate the $0.6\mu m$ SEVIRI VIS channel reflectances in KENDA. The main model parameters influencing the forward calculations are the model cloud water and ice which are also part of the control vector in KENDA. Initial case studies yield very encouraging results with more realistic cloud cover through the direct analysis of the cloud variables. Moreover, an improvement in humidity is seen in comparison to ground-based GPS data. This work is currently being pursued in the operational context at DWD.

To complement these satellite oriented developments, the assimilation of slant delay GPS data and radar volume data is being pursued. A 3-D forward operator for radar reflectivities has been developed and implemented in KENDA. Assimilation studies show promising performance in significantly improving very short range precipitation forecasts [Bick ~al.(2016)Bick, C., S. and Wapler]. Despite the method being still in an experimental implementation phase, results are competitive compared with the currently operational latent heat nudging.

4 Discussions

4.1 Data assimilation

A fully-specified cloud and precipitation assimilation system might be expected to have these features: (i) Hydrometeor control variables; (ii) Full modelling of the error covariances between hydrometeors and other variables; (iii) A way to link a change in the control variables to a change in cloud and precipitation at observation time, either implicitly through ensemble covariances (e.g. in 4D-EnVar or LETKF) or explicitly through a tangent-linear forecast model and/or incrementing operator (e.g. in 4D-Var). However, some of the benefit of all-sky assimilation should be achievable in less complex systems, allowing NWP centres to develop the capability progressively, as seen in Tab. 2.1. For example, separate hydrometeor control variables have not yet been necessary in the 4D-Var systems of ECMWF and JMA. This suggests that, apart from perhaps a short period at the beginning of the assimilation window, the hydrometeor fields can be determined from the initial dynamical and humidity fields, at least as far as they are predictable at all. At the Met Office cloud liquid and frozen water (as well as vapour) have been included in a single total moisture control variable, and a moisture incrementing operator acting as a strong constraint can separate this into its components. However for nowcasting and short-range forecasting, it is probably important to initialise the hydrometeors separately, and many of the expected benefits come from doing so.

The influence of cloud and precipitation on the dynamical error covariances, and the covariances between errors in these variables, might need to be addressed with cloud-dependent covariance modelling, or cloud balance operators [?, e.g.]]montmerle2010,caron2010,michel2011. However, in practice, some of these balances may be implicitly represented through the tangent-linear and adjoint moist physics models at centres which use them. Further, ensemble-derived covariances are in use at most centres and may also help capture the effects of moist processes on the background errors.

The third feature, the need for TL/adjoint moist physics or equivalently time-covariances from an ensemble, might also be avoided during initial developments. The 1D-Var+4D-Var approach used originally at ECMWF [?, e.g.]]bauer2006a retrieved water vapour from cloud-affected radiances and assimilated that as a pseudo-observation. This was sub-optimal due to its 'recycling' of background information [?]]geer2010b. However, the 1D-Bay+3D/4D-Var approach being explored by Météo-France [Caumont ~al.(2010)Caumont, Ducrocq, Wattrelot, Jaubert and Pradier-Vabre, Guerbette ~al.(2016)Guerbette, Mahfouf and Plu] may be able to avoid this, and hence use cloudy observations more optimally, while not needing a TL/adjoint moist physics model.

In an initial all-sky implementation, it may even be possible to treat the cloud and precipitation information as noise rather than signal, as in [?]their Fig. 17]geer2014a: the TL/adjoint moist physics could be turned off without major damage to the quality of all-sky MHS analyses in a simplified system in which no other observations were assimilated. However, it remains to be seen whether this would work in a higher-quality data assimilation system. This aproach reduces all-sky assimilation to simply the use of a cloud- and precipitation-capable observation operator, plus an observation error model to boost errors in cloudy areas. The benefits of this possible approach are as a replacement for traditional cloud screening, but with more symmetric (i.e. unbiased) sampling and the ability to extract information from observations that would previously have been discarded. The large reduction in humidity biases at NCEP (Fig. 1) illustrates the advantage of using a more symmetric sample of observations. The work summarised in this paper shows there is great benefit from assimilating cloud and precipitation itself, but there is also benefit simply using the first mechanism from the introduction, 'mass and wind in the presence of cloud'.

Particularly for all-sky infrared assimilation, the addition of high-level cloud in a window or low-peaking channel can move the Jacobian of the observation operator from near the surface to the tropopause. This causes high non-linearity and further, the issue of the Jacobian may be a particularly important for data assimilation schemes that require vertical localisation, such as the LETKF. In these schemes, any observation needs to be assigned to a height level and the vertical localisation distance is often less than the height of the troposphere. An obvious idea is to determine the vertical location from the Jacobian of the radiative transfer operator. However, if the FG is cloud free and the observation strongly affected by a high cloud, the observation may be assigned to the wrong height level with no chance of influencing the correct part of the atmosphere. Therefore, the vertical assignment and localisation should take into account both observation and FG information, possibly from the whole FG ensemble. In variational schemes, or in the variational components of EnVAR systems, this issue does not occur explicitly, but a mismatch of the location of the Jacobian between the FG and observation implicitly leads to non-linear effects, potentially impacting the convergence. However, experience at ECMWF with all-sky microwave assimilation is that the incremental 4D-Var formulation deals with the non-linearities sufficiently well [Bauer ~al.(2010)Bauer, Geer, Lopez and Salmond]. In practice, also a strong observational constraint from many other assimilated observations must help reduce such non-linearity and convergence issues. However, successful operational assimilation of all-sky infrared window-channel radiances will be challenging.

4.2 Observation error modelling

A common theme is the use of a situation-dependent observation error model following [?]hereafter GB2011]geer2011. The need for some observation error inflation has been widely recognised when assimilating cloud-affected radiances [?, e.g.]]deblonde2007,zhang2016. To the knowledge of the authors, no operational-quality experiments have successfully demonstrated the use of 'small' observation errors, i.e. errors similar to those used in clear-sky assimilation. Apart from anything else, the quality control mechanisms used in most systems would throw out any observation with a combination of a large (e.g. 50 K) departure and small observation error (e.g. 3 K). However, for infrared assimilation at Météo France, a strategy is being tested that would keep only the scenes where model and observations agree, which would allow the use of 'small' observation errors, albeit at the cost of losing many scenes.

The errors that lead to large all-sky FG departures are thought to be dominated by representivity errors, rather than background errors. For example [Harnisch ~al.(2016)Harnisch, Weissmann and Peri ~nez] found the standard deviation of all-sky departures to be up to three times larger than ensemble-derived background errors mapped into radiance space, and similar results have been found in unpublished studies at ECMWF. Some of the missing error may come from limitations of current ensembles such as insufficient spread or too few members, and this question deserves more research. However, the missing errors are most likely attributed to representivity and are therefore part of the observation error. Fundamentally, they come from the lack of predictability of cloud and precipitation, particularly on smaller (e.g. sub 100 km) scales.

The GB2011 approach, though successful, is just an empirical climatological model for all-sky observation errors. It is worth investigating if there is a more optimal or correct way to describe the observation error. One possible criticism of GB2011 is apparent when FG departure errors are resolved over 2 dimensions, i.e. separately by cloud in model and cloud in observations [?]their Fig. 3]chambon2014. Where the model and the observations agree, on the diagonal of this two-dimensional error distribution, the GB2011 model still gives large errors. It might be hoped that by reducing the error on the diagonal, the FG could be better constrained where the departures are small. [Minamide and Zhang(2017)] have proposed an alternative adaptive observation error inflation (AOEI) that scales the observation error variances as a function of the FG departure. This gives more flow-dependent and generally smaller observation errors, which could help extract more information from the observations. In particular it gives much smaller observation errors where the FG and observations agree. However, this could potentially violate the Bayes Theorem underlying data assimilation by introducing conditional probability into a term (that representing the observation error) which is supposed to be unconditional. Indeed it needs to be investigated whether the basic GB2011 itself might be in violation, so this is an issue that likely affects all such observation error models.

Another option may be to rely on Variational Quality Control [?, VarQC,]]jarvinen1997 which also is a way of downweighting observations as a function of the departure, though it is different from AOEI in a number of ways, including that it downweights observations according to the evolving analysis departure. Note that GB2011 presented their results both with and without VarQC and for them it was necessary to use both VarQC and observation error inflation.

The need for observation error inflation may also come in part because of the neglect of observation error correlations. [Bormann ~al.(2011)Bormann, Geer and Bauer] showed that in cloudy areas, all-sky observation errors have strong inter-channel correlations. These are not currently being modelled in any centre’s all-sky assimilation framework. The representation of inter-channel error correlation has proved a breakthrough in extracting more information from clear-sky hyperspectral IR radiances [Weston ~al.(2014)Weston, Bell and Eyre, Bormann ~al.(2016)Bormann, Bonavita, Dragani, Eresmaa, Matricardi and McNally]. It might prove equally useful in all-sky assimilation.

4.3 Radiative transfer developments

For all-sky microwave simulations at operational centres, the current state-of-the-art and minimum baseline is a radiative transfer model with a solver for scattering and the ability to simulate the effect of all hydrometeors in the forecast model, including convective hydrometeors. A representation of sub-grid cloud and precipitation (i.e. cloud overlap and variations in hydrometeor water contents) is required, and frozen hydrometeor scattering properties must be represented using non-spherical particles. However, the solver need not be overly computationally demanding: there are no plans to supersede the delta-Eddington approach in RTTOV-SCATT, because the largest remaining systematic errors are thought to be in other parts of the radiative transfer problem [?, see]]bennartz2011. Representations of sub-grid variability and of particle scattering are the main candidates for improvement.

The two-column effective cloud fraction approach of [Geer ~al.(2009)Geer, Bauer and O'Dell] is showing its limitations at low microwave frequencies (e.g. 10 GHz); these frequencies also expose the assumption of a horizontally homogeneous atmosphere that is made inside each column. The next step is to add more independent columns to better represent the sub-grid heterogeneity, and the columns must be slanted to better represent the projection effect, i.e. the side view of clouds and precipitation. An ultimate goal would be to treat the problem in full 3D, but that would be unaffordable in operational systems for many years.

The second issue in the microwave is the representation of particle scattering properties. A problem is that most forecast models do not represent the full microphysical variability of hydrometeors in the atmosphere, and yet knowledge of these properties is essential. These properties, such as particle shape and size distribution, are assumed a-priori, often by choosing assumptions that bring models and observations into closer agreement but require compromises across different frequencies and different weather regimes [?, e.g.]]geer2014b,guerbette2016. There are rapid advances being made in understanding the size distributions and habits of frozen particles and in modelling their optical properties [?, e.g.]]eriksson2015,kuo2016,olson2016, bringing for example a variety of new databases for aggregates and graupel, which should be incorporated into CRTM and RTTOV-SCATT. Currently RTTOV-SCATT only has a 'cloud ice' and 'snow' hydrometeor to represent frozen particles so it would be useful to add at least one more type, such as graupel.

Because all-sky infrared is not yet operational, a minimum baseline configuration has not yet been established. CRTM has available a multi-stream solver, and it can now represent cloud overlap with a two-column approach. In contrast, RTTOV uses a parametrisation of scattering [Chou ~al.(1999)Chou, Lee, Tsay and Fu] rather than a multi-stream solver, but represents cloud overlap using O(100) independent columns. Both these approaches may face performance problems in an operational context: ECMWF found that 100 columns was too many, and derived a simple two-column approach instead. However, a two-column approach is only appropriate for simple overlap situations in the infrared, for example for upper-troposphere humidity channels. IR window channels are sensitive to the cloud fraction in any visible cloud layer, of which there may be many, which implies a need for at least 3 carefully chosen columns [?, or alternatively, a cloud inhomogeneity screening,]]okamoto2017. The choice of scattering models (e.g. cloud particle shapes and size distributions) in CRTM and RTTOV will also likely have to be refined as all-sky data assimilation increasingly confronts models and IR observations.

The visible is expected to see rapid development and its potential has been described in Sec. 3.6. To support this the [Scheck ~al.(2016)Scheck, Frerebeau, Buras-Schnell and Mayer] visible forward model will be incorporated into RTTOV over the next few years. As for other frequencies, visible wavelengths are strongly influenced by cloud overlap features that are represented in forecast models, but only at the sub-grid scale within the cloud physics subroutines. Care has to be taken to apply the same cloud overlap diagnosis and assumptions within the interface to the radiative transfer. For example the reflectance histograms of SEVIRI observations and COSMO model equivalents are only consistent if an additional sub-grid scale cloud fraction is diagnosed from the grid scale humidity (as done in the cloud physics) and taken into account within the sub-columns treated within the VIS forward operator [Scheck ~al.(2017)Scheck, Weissmann and Mayer]. As at other frequencies, difficulties come from the lack of essential microphysical properties, such as size distributions, in the cloud representation of current forecast models.

The correct handling of the details of cloud and precipitation parameters is important to all-sky assimilation in all spectral ranges. Otherwise, there can be substantial situation dependent biases that have to be dealt with before assimilating the data - see also Sec. 4.5. The issues may be that: (i) the model represents something (such as cloud overlap or convective precipitation fluxes) but work needs to be done to ensure this information is available to the radiative transfer operator - see also Sec. 4.4; (ii) assumptions (such as size distributions) are made separately in the forecast model and the radiative transfer, but may be inconsistent; (iii) potentially important details (such as particle orientation) are not known or represented anywhere. In principle it would be good to ensure that microphysical and sub-grid assumptions are more consistent across the observational operator and forecast model (including not just the moist physics but the modelling of radiative heating and cooling). This would greatly support the inference of model biases from the all-sky observations (mechanism 4 from the introduction). However, this may conflict with the objective of achieving unbiased FG departures, which currently requires some independent tuning of microphysical assumptions [?, e.g.]]geer2014a.

The long-term hope is to directly predict more microphysical quantities in the forecast model and to use those properties in the observation operator. Research is needed to decide what additional degrees of freedom should be added to the observation operator (e.g. additional moments of the size distribution; degree of riming, particle orientation). Most operational forecast models currently only predict single moments (e.g. mixing ratio) from a handful of hydrometeors. At a few centres two-moment schemes (predicting e.g. hydrometeor mass and number of particles) have been developed [?, e.g.]for ICON and COSMO at DWD]seifert2006, but are not yet necessarily operationally used due to the high computational cost. To assimilate this information, the parameter estimation approach could also be considered. Here the assimilation system can be set up to modify the assumptions being made in the forecast model [?, e.g. the shape of the dependence of cloud fraction on relative humidity,]]norris2007assimilation helping retain the information throughout the subsequent forecast. Moving forward in this direction will require further great investment in improved representation of microphysics. It may drive global models towards representing microphysical processes more explicitly, and at smaller, convection-permitting scales.

One final issue has been illustrated by the difficulty of coupling multi-stream solvers in CRTM with an adequate model of the surface interaction. A BRDF model was required, but not available. The BRDF need not be of high angular resolution, it simply needs to model the surface reflection and emission in the streams being used in the atmospheric solver. More generally, all-sky atmospheric data assimilation also relies on developments in modelling the surface, over ocean, sea-ice and land; it will be important to continue developing the interface between a scattering atmosphere and the surface.

4.4 Cloud and precipitation modelling

To simulate all-sky radiances accurately, a necessary first step is that all atmospheric hydrometeor fields are available to the observation operator, but surprisingly this is not always the case. For example, one technical reason why NCEP started all-sky assimilation in non-precipitating cloudy areas was because the precipitation forecast fields were not easily available in their system. In the context of climate monitoring, [Rysman ~al.(2016)Rysman, Berthou, Claud, Drobinski, Chaboureau and Delanoe] have illustrated the very large biases that result from simulating precipitation-affected microwave brightness temperatures without access to the vertical profiles of convective precipitation. Investigators wishing to simulate all-sky radiances offline using archived ECMWF forecast fields cannot do this, because the convective fluxes are not archived (another issue is that not every model timestep is stored). As forecasting centres move further towards assimilating cloud and precipitation, they must make sure that hydrometeor variables, particularly convective hydrometeors and their sub-grid-scale cloud fractions (see also Sec. 4.3) are respected as much a part of the atmospheric state as the basic dynamical variables, so that full details are made available to observation operators and potentially large but avoidable biases are prevented; these variables must also be stored in forecast archives to enable offline computations of all-sky radiances.

Systematic situation dependent forecast errors are also an important source of bias in all-sky assimilation. Reduction of the model biases in terms of cloud and precipitation representation is crucial for all-sky assimilation, as has been seen at ECMWF and JMA. For example, the two different forecast models share similar systematic errors, such as a lack of cloud liquid water in stratocumulus regions [?, e.g]]kazumori2016. It is not usually possible to let the observations correct systematic model errors that have short timescales; even if this does not create spurious budgets, during the forecast the model will typically revert quickly to its climatological biases. Hence it is good to continue using the information from all-sky observations to diagnose and help fix systematic errors in the forecast models themselves, and possibly in future this could be done by parameter estimation.

As mentioned in the discussion on radiative transfer modelling, all-sky assimilation will become increasingly demanding in terms of the detailed microphysical information required from forecast models. Although the systematic errors in 10 GHz simulations at ECMWF (Fig. 2) are at least partly due to limitations of the observation operator, they also point to issues with the representation of convective precipitation inside the mass-flux convection scheme, with potentially inaccurate assumptions like the 5% coverage of convective cores within a grid-box. A possible issue and a common problem between ECMWF, NCEP, and likely any model using a mass-flux scheme, is that convection schemes do not fully represent convective cloud: they represent detrainment from convection, by adding a source term to the large-scale cloud scheme, but they do not represent cloud within the convective cores, just the mass fluxes of precipitation particles. These issues might well be solved by making better assumptions in the radiative transfer, but an alternative is being developed at Météo France: a fully prognostic convection scheme [Guààу and Piriou(2016)]. Increased sophistication in the microphysics is also being demonstrated, for example by [Morrison and Milbrandt(2015)], who are able to prognose four different properties of frozen particles, including rime mass and volume. [Vià~al.(2016)Vià Pinty, Berthet and Leriche] describe a quasi two-moment microphysics scheme that uses a prognostic aerosol population to determine cloud condensation nuclei (CCN) availability and its impact on the cloud particles, and also represents aspects of the aggregation and riming processes. At DWD, a two-moment scheme has been implemented in both ICON and COSMO models [Seifert and Beheng(2006)] and the effect of aerosol assumptions on cloud properties (and their downstream effects) have been investigated: aerosol assumptions do have significant effects on model radiation fields [Seifert ~al.(2012)Seifert, Kohler and Beheng]. The influence of the DWD two-moment scheme is being studied in conjunction with the radar forward operator; similar studies would be useful for all-sky assimilation of radiances.

4.5 Bias correction

Clear-sky observations are always corrected for bias, typically using a variational bias correction approach [?, e.g]]derber1998,dee2004,zhu2014a. All-sky assimilation usually inherits the clear-sky bias correction model, which is typically based on a constant offset, some geophysical predictors (e.g. geopotential layer thicknesses, surface temperature) and a scan-bias model. The question is how to correct biases that are a function of cloud amount. [Geer and Bauer(2010), Geer and Bauer(2011)] showed that using either the observed or the model cloud amount as a bias predictor will identify a spurious 'sampling' bias. They suggested instead the symmetric (i.e. average) cloud amount, which was used successfully as a predictor for rain-rate biases [Lopez(2011)]. Further, bias correction can be based on the subset of observations where the model and observed cloud amounts agree [Zhu ~al.(2014)Zhu, Derber, Collard, Dee, Treadon, Gayno, Jung, Groff, Liu, van Delst, Liu and Kleist, Chambon ~al.(2014)Chambon, Zhang, Hou, Zupanski and Cheung] and, for complex biases, binned as a function of symmetric cloud amount [Harnisch ~al.(2016)Harnisch, Weissmann and Peri ~nez].

At ECMWF, good results have been achieved without adding a cloud-related bias correction for all-sky radiances. The importance of cloud-related biases has been judged by their size relative to the assigned observation error. By this measure the most important biases remain in regions of stratocumulus and shallow convection, where the assigned observation error is relatively low. These are complex situation-dependent systematic errors, likely due to the forecast model cloud schemes (Sec. 4.4). Biases are addressed in one of three ways: (i) if the bias is too large to assimilate, the observations are removed by a targeted screening [Lonitz and Geer(2015)]; (ii) if assimilation in the presence of bias is not problematic, the data remains active [Lonitz and Geer(2017)]; (iii) if possible, biases are fixed at source by improving the physical representation in the observation operator [?, e.g.]]geer2009a,geer2014a or in the forecast model (for example a problem of excess liquid water in fronts).

The experimental [Chambon ~al.(2014)Chambon, Zhang, Hou, Zupanski and Cheung] and [Harnisch ~al.(2016)Harnisch, Weissmann and Peri ~nez] bias corrections addressed biases that were acknowledged to be large and potentially better corrected at source. However, bias corrections using symmetric cloud or precipitation as a predictor have been successful in some operational contexts [?, e.g.]]lopez2011. Hence, there is currently a diversity of approaches to cloud bias correction, but it is always important to investigate and deal with systematic errors in all-sky assimilation.

4.6 Verification

A final common experience is the difficulty of using forecast verification to validate the addition of all-sky assimilation. When activating all-sky assimilation, forecast scores computed against own-analysis usually show apparent degradations in humidity or temperature RMS errors, when verification against observations shows clear and consistent improvements [?, e.g.]recent experience at JMA]geer2010c,kazumori2016,geer2017a,chambon2017allsky. This is a particular issue for all-sky assimilation of microwave imagers, which has strong impacts on the moisture fields at low levels in the tropics. The effects may partly be associated with uncorrected systematic errors between model and observations (as caused by forecast model or observation operator bias). When not corrected by bias correction, these can introduce large systematic increments. Also, it is possible that adding all-sky radiance observations introduces small structures or patterns in analysed temperature and humidity fields that are retained during the time integration of the forecast model, leading to an increase in apparent random errors. The discrepancy between verification using own-analysis or observational references is typically found in shorter-range forecasts where the analysis error and forecast error are similar in magnitude, whereas for longer range forecasts, the forecast error is much larger and the choice of reference is less important. However, in the tropics, the growth of forecast model error is not as large as in the mid-latitudes, and some apparent degradations can remain even in 10 day forecasts (these are not changes in the forecast, but instead are changes in variability of the analysis reference). Hence, analysis-based forecast verification methods must be improved, and more use made of observationally-based verification, particularly for the tropics.

Finally, cloud and precipitation variables are one of the main targets of all-sky assimilation, but verification methods are not yet fully developed for these parameters. Given the difficulty of predicting the exact location of precipitation, fuzzy verification measures such as the Fractions Skill Score [?, FSS;]]roberts2008 will be necessary. For example, the impact of all-sky SAPHIR and MHS assimilation on tropical precipitation has been demonstrated robustly using FSS with newly-developed statistical significance testing [Chambon and Geer(2017)].

5 Conclusion

This article has surveyed developments in all-sky assimilation at operational centres where it is already used, or should be within the next few years. All-sky assimilation aims to improve satellite data utilisation in the presence of cloud, to improve forecasts by inferring initial conditions from observed cloud and precipitation, and finally to initialise the cloud and precipitation fields themselves, particularly for nowcasting and short-range forecasting. Further, by confronting models and observations, this will help to improve the representation of cloud and precipitation in forecast models, as well as to develop better observation operators. These aims are already being achieved in operational systems. Current research also gives examples of the beneficial impact of all-sky assimilation on tropical cyclone forecasts, and of cloud assimilation on cloud-cover forecasts in short-range forecasting.

The most extensively used all-sky observations are those from microwave humidity sounders and imagers, which have a relatively smooth sensitivity to water vapour and hydrometeors. To further develop the use of these observations, it will be necessary to improve representations of cloud overlap, slant-path radiative transfer, and hydrometeor scattering properties. Moreover, all-sky assimilation relies on high-quality clear-sky modelling, so further improvements are needed in surface emissivity modelling over ocean, land and sea-ice. These developments will help extend the useful frequency range down to 10 GHz, for heavy rain, and up into the 200 GHz to 700 GHz range, for the future Ice Cloud Imager (ICI). Temperature-sensitive humidity sounding observations are less used, and mixed results have been seen at ECMWF. However, NCEP has good results from operational assimilation of AMSU-A in non-convective situations. The challenge of all-sky assimilation of temperature channels is the separation of temperature and cloud signals. Incorrectly aliasing a cloud error into the temperature field can damage the dynamical forecast; hence increased sophistication in data assimilation, particularly in modelling background and observation errors, may be necessary.

All-sky infrared assimilation is still not operational, but many centres are looking to activate the water-vapour sounding channels around 6.3 μm. In contrast the window and temperature-sounding channels present similar challenges to the microwave temperature channels, but with stronger nonlinearity of the cloud sensitivity. For infrared observation operators, a balance needs to be found between sophistication (multiple-stream solvers and multiple-column treatments of cloud overlap) and operational performance. Further, the potential of visible channels is becoming apparent, with the development of fast modelling for visible radiances. Visible observations could complement other frequencies particularly with their information on low cloud. The visible channels also offer the potential of very high spatial resolution, to support storm-scale assimilation, as well as to provide information on sub-grid heterogeneity for assimilation on coarser scales.

Surveying the data assimilation tools for all-sky assimilation, there is a mix of variational and ensemble techniques being used, but it is key to have either TL/adjoint moist physics, or ensemble covariances, to represent the link between the control variables and the hydrometeor profile at the observation time and location. Nevertheless, it is possible for operational forecasting centres to build gradually towards all-sky assimilation, even if they do not yet possess all the tools. For example, just the adoption of all-sky observation operators and observation error models could allow a more balanced observational sampling and a progressive use of increasingly cloud-affected data.

One near-universal aspect of all-sky assimilation is the use of error inflation in cloudy situations. This accounts for error of representivity linked to the lack of predictability of cloud and precipitation at small scales (e.g. less than 100 km). There could be great benefits from developing the error inflation models further, making them more situation-dependent, and accounting for correlated observation error. It would also be necessary to continue checking that what we currently model as representivity error is not simply a lack of spread in the ensembles that represent background error.

A general issue in any all-sky assimilation implementation is the presence of complex situation-dependent systematic errors. These show up as regional or situation-dependent biases between observations and their model equivalents and have different sources: they may result from underlying approximations and inaccuracies in the observation operator as well as in the forecast model. A third source of bias is the interfacing of the model simulation to the radiative transfer observation operator: the model may represent something (e.g. convective fluxes or sub-grid hydrometeor fraction) that should be passed to the observation operator but is not; assumptions may be made separately and inconsistently in model and radiative transfer (though sometimes this is a deliberate choice that helps reduce systematic error); or assumptions may be needed but not represented in models (e.g. riming, particle size distributions). If possible it is good to correct these biases at source, rather than with bias correction, but viable cloud bias correction schemes have been devised and applied operationally. A final possibility is to exclude observations when an unbiased FG cannot be computed. For the future, parameter estimation may be a possibility. Whatever strategy is used, good results from all-sky assimilation are contingent on careful diagnosis and treatment of such biases.

As all-sky assimilation develops, it will require increased sophistication in cloud and precipitation modelling within forecast models. The great sensitivity of observations to microphysical details such as particle habit and size distributions will encourage (and help support) the development of better microphysical representations in the forecast models. The inflated size of observation errors has allowed some of the finer microphysical details to be neglected initially. However, the errors of the comparison between model and observations will come down as initial conditions improve, more all-sky observations are assimilated, and forecasts become more accurate.

Although many challenges remain, it is a realistic possibility to expect most satellite radiances to be assimilated in all-sky conditions in the future.

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Appendix

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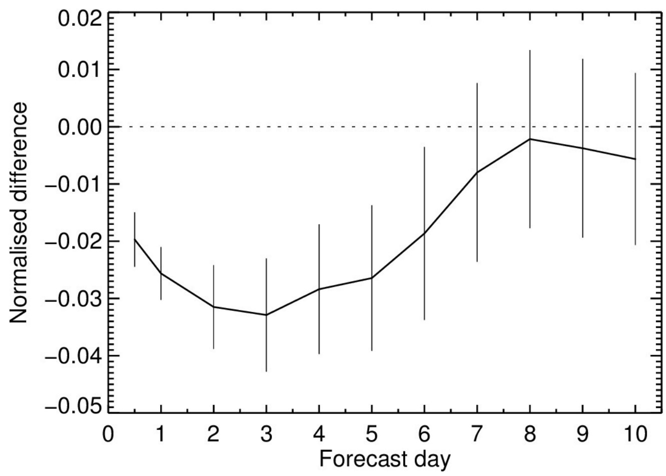

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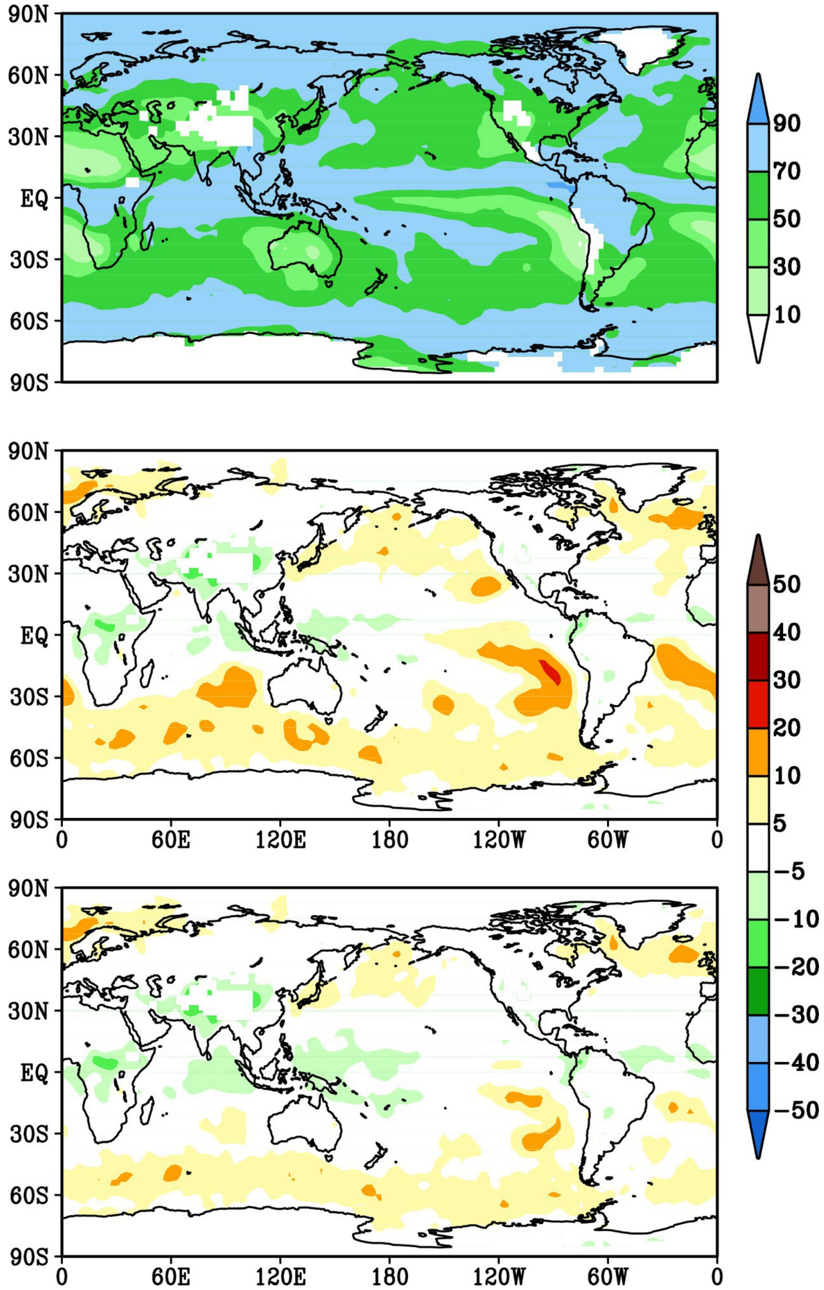
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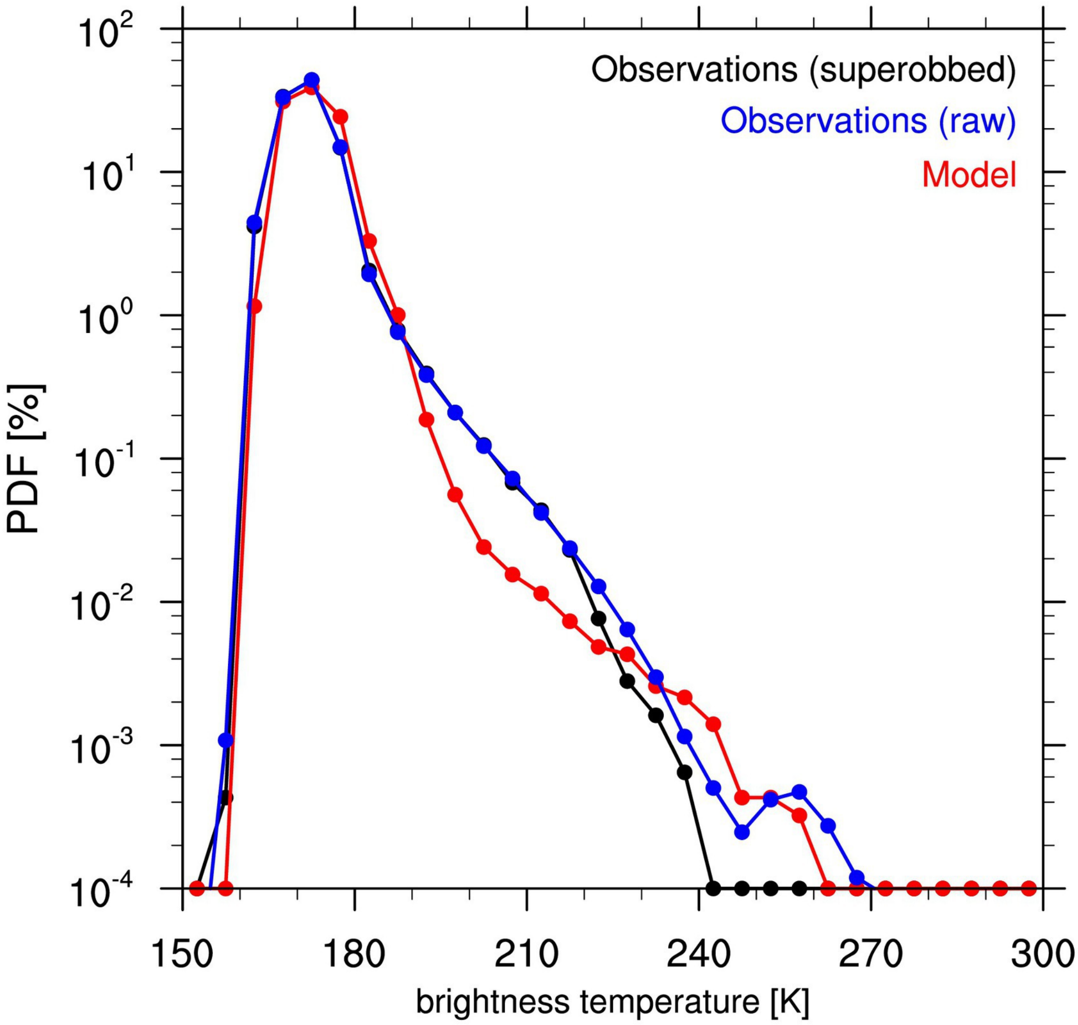

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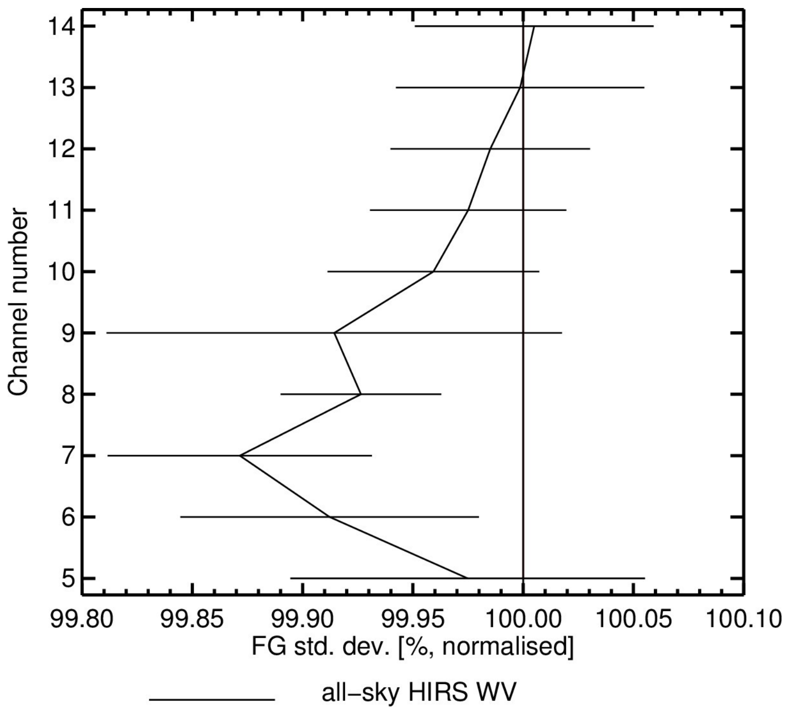
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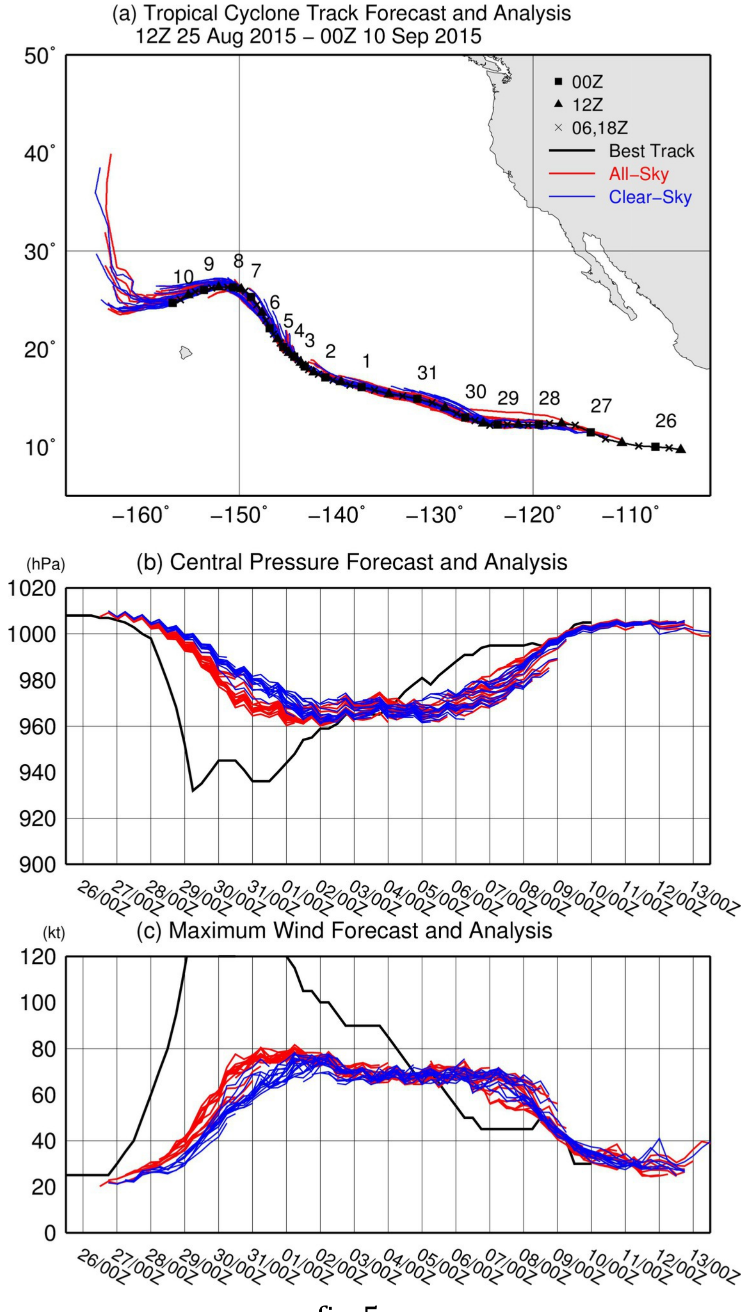
(a) Tropical Cyclone Track Forecast and Analysis
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(c) Maximum Wind Forecast and Analysis
(kt)

fig_5.eps

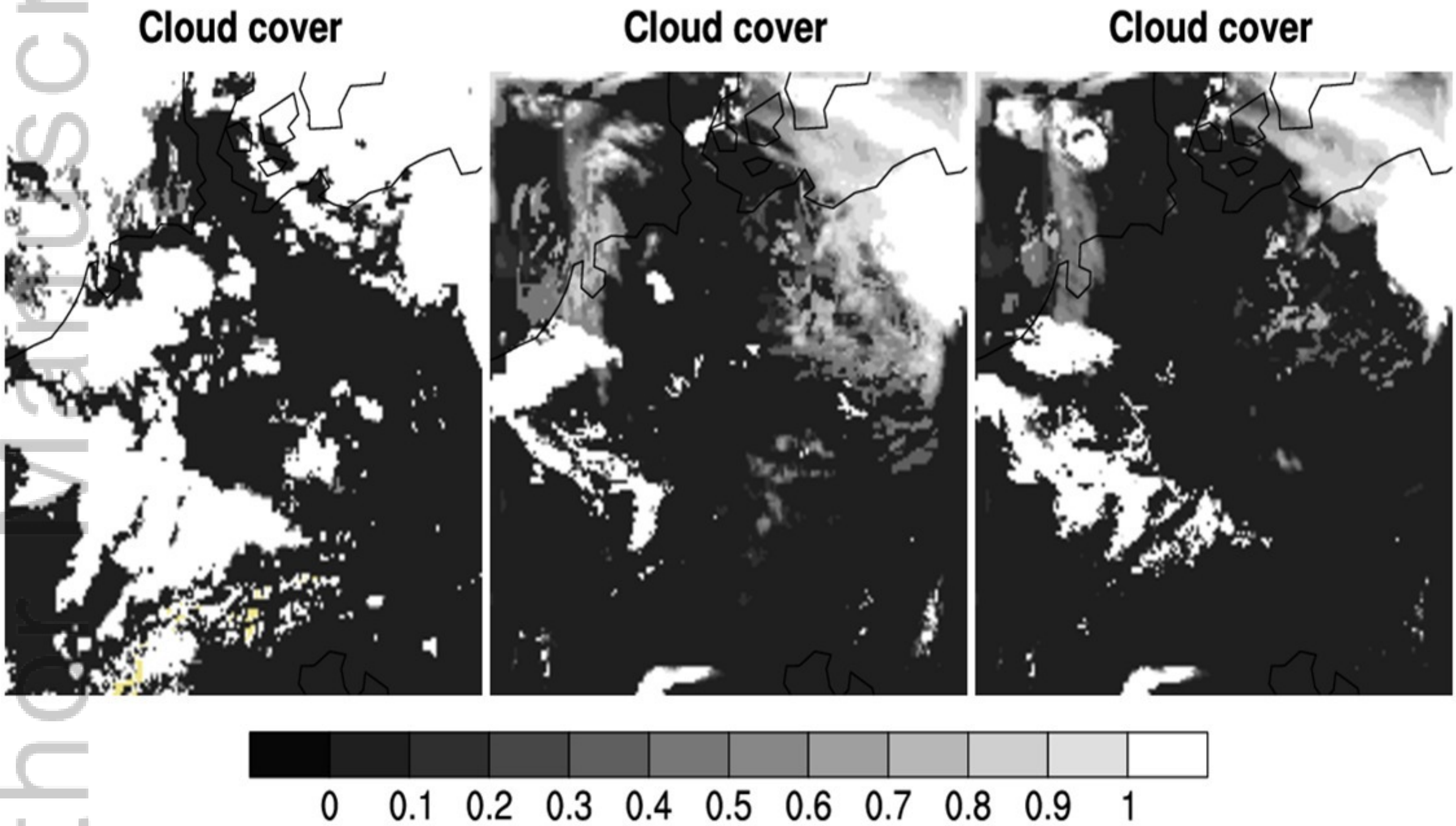
Cloud cover
Cloud cover
Cloud cover
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

fig_6.jpg

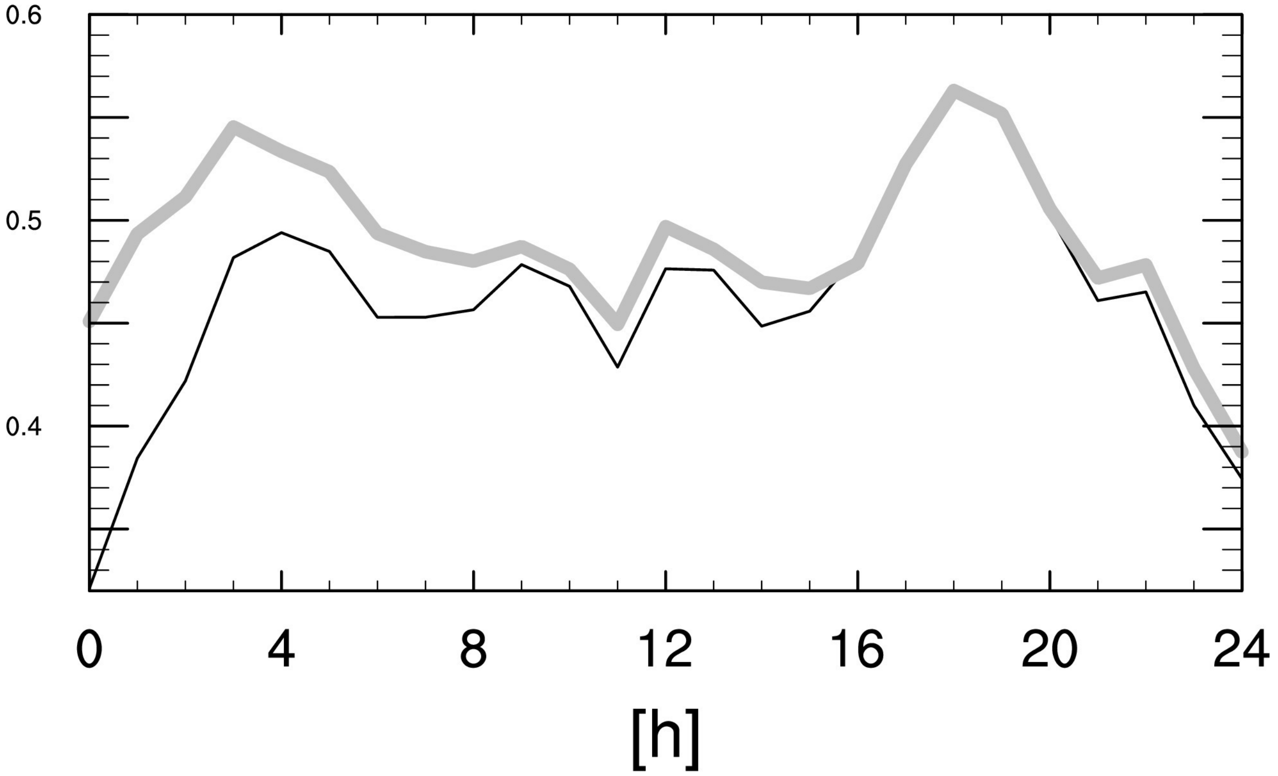

fig_7.eps

All-sky satellite data assimilation at operational weather forecasting centres

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This article reviews developments towards assimilating cloud and precipitation-affected satellite radiances at operational forecasting centres. Satellite data assimilation is moving beyond 'clear-sky' towards assimilating all observations directly as radiances, whether they are clear, cloudy or precipitating. This is known as the 'all-sky' approach and it improves global forecasts, and can improve the analysis and shorter-range forecast of otherwise poorly-observed weather phenomena as diverse as tropical cyclones and wintertime low cloud.