INTRODUCTION

Accurate weather forecasts depend on having a good description of the current atmospheric state. This is known as an analysis, where an earlier forecast is combined with new observations in the process of data assimilation. Satellite data contributes a great deal of this information but until recently its use has been limited to clear-sky areas. However, microwave imager radiances have been assimilated at ECMWF for several years under all-sky conditions, bringing information mainly on the vertical columns of water vapour and liquid water. All-sky assimilation uses the same observation operator in clear, cloudy and precipitating situations. This means that the analysed cloud and precipitation fields must be directly modified in order to fit the observations, in conjunction with the usual humidity and temperature adjustments. Thus, radiance observations that would previously have been discarded due to cloud contamination can now be assimilated, and the universal coverage means that sampling biases (e.g. from observing only clear-sky situations) are avoided. The all-sky approach is now being extended to use information from microwave sounders such as AMSU-A, hopefully to bring additional information on temperature as well as cloud.

INFORMATION CONTENT OF AMSU-A

The Advanced Microwave Sounding Unit-A (AMSU-A, Robel, 2009) is a 15 channel microwave radiometer for atmospheric temperature sounding that has been flown on NOAA satellites from NOAA-15 onwards and on Metop-A. It is the main observational constraint for global weather forecasting along with the advanced infrared sounders AIRS and IASI. There are 12 channels in the 60 GHz oxygen band with weighting functions peaking from the surface to 40 km. Table 1 gives the specifications of channels relevant to the troposphere. There are also three imaging channels sensitive to water vapour, cloud and precipitation at 24, 31 and 89 GHz. The instrument is a cross-track scanner, covering a swath of width 2343 km on the earth’s surface. The swath is composed of thirty step-scanned observations with an effective field of view (EFOV) of 50 km by 50 km at nadir and 140 km by 80 km at the edge of the swath (Bennartz, 2000). Channel 5 is the lowest channel operationally assimilated at ECMWF; channels 3 and 4 would bring new temperature information if assimilated.

Figure 1 explores the influence of cloud and precipitation on AMSU-A temperature-sounding channels. The left column shows bias-corrected first guess (FG) departures of AMSU-A observations for a single day, with cloud and precipitation included in the observation operator. With a range of ±20 K, departures are largest in channel 3, which has the greatest sensitivity to cloud and precipitation and the surface. The typical size of departures decreases rapidly as we move to the channels that are sensitive to higher atmospheric levels, becoming e.g. ±3 K in channel 5. Patches of spatially homogeneous departures are found in high latitude regions and are indicative of bias in the observation operator or in the forecast model, and in practice these areas would be screened out of the assimilation. The generally negative departures in the Arctic Ocean and the Ross Sea are the result of poor estimates of the surface emissivity of sea-ice. The areas of positive departures around Antarctica are the ‘cold-sector’ bias which
Table 1: Channel specifications of the AMSU-A instrument, ignoring purely stratospheric channels. Polarisation is either vertical (v) or horizontal (h).

<table>
<thead>
<tr>
<th>Number</th>
<th>Frequency [GHz]</th>
<th>Polarisation</th>
<th>NEΔT (specified) [K]</th>
<th>Peak of weighting function at nadir [km]</th>
<th>Surface to space transmittance at nadir [0-1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>23.8</td>
<td>v</td>
<td>0.3</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>31.4</td>
<td>v</td>
<td>0.3</td>
<td>0</td>
<td>0.94</td>
</tr>
<tr>
<td>3</td>
<td>50.3</td>
<td>v</td>
<td>0.4</td>
<td>0</td>
<td>0.67</td>
</tr>
<tr>
<td>4</td>
<td>52.8</td>
<td>v</td>
<td>0.25</td>
<td>1</td>
<td>0.31</td>
</tr>
<tr>
<td>5</td>
<td>53.596±0.115</td>
<td>h</td>
<td>0.25</td>
<td>4</td>
<td>0.12</td>
</tr>
<tr>
<td>6</td>
<td>54.4</td>
<td>h</td>
<td>0.25</td>
<td>7</td>
<td>0.02</td>
</tr>
<tr>
<td>7</td>
<td>54.94</td>
<td>v</td>
<td>0.25</td>
<td>10</td>
<td>0.00</td>
</tr>
<tr>
<td>8</td>
<td>55.5</td>
<td>v</td>
<td>0.25</td>
<td>14</td>
<td>0.00</td>
</tr>
<tr>
<td>15</td>
<td>89.0</td>
<td>v</td>
<td>0.5</td>
<td>0</td>
<td>N/A</td>
</tr>
</tbody>
</table>

has been a longstanding issue in assimilating all-sky microwave imager observations at ECMWF (e.g. Geer et al., 2009). Channels 4 and 5 show similar biases to those in channel 3. Channel 6 does not have these problems, because it has little sensitivity below 3 km. There are no other obvious biases, but the size of departures is largest in cloudy and/or precipitating regions, as would be expected given the forecast model’s difficulty in placing clouds and precipitation with exactly the right timing, location and intensity (Geer and Bauer, 2011). For example, an S-shaped band of tropical convection in the central Pacific is associated with relatively large departures, particularly in channel 5.

The right column of Fig. 1 shows the radiative effect of hydrometeors, ΔT_{cld}. This can be computed assuming the brightness temperature T is the sum of a clear-sky part T_{clr} and a modification coming from cloud or precipitation, ΔT_{cld}:

\[ T = T_{clr} + ΔT_{cld} \quad (1) \]

The brightness temperature in the absence of hydrometeors, T_{clr}, is a routine by-product of the RTTOV-SCATT radiative transfer model (see e.g. Geer et al., 2009). Areas of non-zero ‘cloud’ effect indicate the presence of radiatively important hydrometeors. The effect of hydrometeors is typically to increase brightness temperatures in channel 3 but to decrease them in channel 6. Channel 3 is similar to the 19 and 37 GHz channels used in microwave imagers, where clouds and precipitation are warm emitters over a radiatively cold ocean surface. In channel 6, cloud and precipitation in the lower troposphere are irrelevant, and the brightness temperature is the atmospheric temperature in the region of the channel’s upper-tropospheric / lower-stratospheric weighting function, modified by the effect of hydrometeors in deep convective systems. Here, hydrometeors reduce the brightness temperature by moving the weighting function to higher levels where the temperature is colder, and through scattering from frozen particles. Channels 4 and 5 show a mix of behaviours: there are brightness temperature (TB) increases from midlatitude cloud and precipitation, and TB decreases from tropical deep convection.

The Mie soft sphere approach used to compute snow scattering properties in RTTOV-SCATT is known to be unreliable (Petty and Huang, 2010) and we already screen out deep-convective regions in the all-sky assimilation of microwave imagers due to an obvious problem of excess-scattering or excess falling snow coming from the model (Geer and Bauer, 2010). Even if these problems were fixed, we would still not have any microphysical information on which to predict the habits of frozen precipitation or their size distributions, so it would be difficult to do accurate radiative transfer in such regions. Hence, we will not attempt to assimilate AMSU-A observations in tropical deep-convective regions. Since deep convection provides the only visible radiative impact from hydrometeors in AMSU-A channel 6 (Fig. 1h), there is probably no point in applying the all-sky approach to this channel.

In channel 5, there is a strong effect from deep convection, but also some influence from midlatitude cloud, though rarely more than 0.5 K and hence of similar order to the specified instrument noise of 0.25 K (Tab. 1). Outside of deep-convective regions, there is little difference in channel 5 FG departures whether the effect of cloud is included or not (not shown). It is not immediately obvious that the all-sky approach will bring any benefit to channel 5 assimilation, given that it is also quite computationally
Figure 1: (Left column) FG departures in brightness temperature [K]; (right column) effect of hydrometeors [K], computed as the difference between cloudy and clear FG. Sample is all Metop-A AMSU-A observations for 5th February 2010, but to reduce the size of the image file, they have been subsampled in longitude and latitude to one per 1° by 1° box. Sample is restricted to ocean and sea-ice surfaces.
costly. In contrast, it is easy to see that cloud radiative transfer is necessary for a successful simulation of channel 3 and 4 radiances (Figs. 1d). Hence, the all-sky approach could bring most benefit to AMSU-A channels 3 and 4, since they are not actively assimilated in the clear-sky approach and they are strongly sensitive to liquid water cloud.

METHOD

Technical Details

Microwave imager radiances are assimilated operationally in all-sky conditions (Bauer et al., 2010; Geer et al., 2010; Geer and Bauer, 2011) using multiple-scattering radiative transfer from RTTOV-SCATT (Bauer et al., 2006). The all-sky approach has novel features to enable cloud and precipitation-affected assimilation:

- Observation errors are assigned as a function of symmetric cloud amount;
- Observations are superobbed to give them a broader resolution, one that is more representative of the model’s effective resolution for cloud and precipitation;
- Situations with large hydrometeor-related biases must be screened out. Examples are the ‘excess scattering’ bias in deep convection, and the ‘cold sector’ bias in high latitude cold-air outbreaks discussed in the previous section.

The all-sky path omits some important parts of the clear-sky framework, of which the most relevant are:

- Each clear-sky observation uses a skin-temperature sink variable to account for errors in the prescribed sea-surface temperatures (these come from OSTIA, Stark et al., 2007).
- The thinning algorithm selects observations with the smallest FG departures, in order to remove cloud-contamination.

The all-sky microwave imager assimilation works successfully without a skin temperature sink variable, and active thinning for cloud would be inappropriate, so there is no plan to incorporate these in the all-sky framework.

In order to use the all-sky approach for microwave sounder channels we need to solve a number of problems. First, the ‘symmetric cloud amount’ is used for screening out scattering situations and for the prescription of observation error. For imagers, we rely on the polarisation difference at 37 GHz as a measure of cloud amount. Unfortunately, sounders such as AMSU-A measure only one polarisation. For the observation error formulation, we instead use a liquid water path retrieval (Grody et al., 2001). Scattering situations are screened out using the ‘cloud delta’ \( \Delta T_{\text{cld}} \), Eq. 1). Second, nadir scan positions see more cloud than the extreme positions, because (a) their weighting functions are lower in the atmosphere and (b) zenith and polarisation effects mean surface emissivity increases slightly away from nadir, making the ocean surface relatively warmer and the clouds less visible. Hence, the observation error formulation needs to vary with scan position to account for the varying sensitivity to cloud.

Experiments

Table 2 lists the main experiments in this study. They are based on cycle 37R3 of the ECMWF operational NWP system, but with a slightly reduced horizontal resolution of T799 (roughly 25 km). Experiments start on 7 February 2011 and run to 21 March. The full operational observing system is used including polar orbiting satellite measurements (AMSR-E, SSMIS, HIRS, AMSU-A, AMSU-B, MHS, AIRS,
<table>
<thead>
<tr>
<th>Experiment name</th>
<th>Additional AMSU-A usage</th>
<th>Geographical coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>All-sky channel 4</td>
<td>4</td>
<td>40°N to 40°S</td>
</tr>
<tr>
<td>All-sky channel 3+4</td>
<td>3,4</td>
<td>40°N to 40°S</td>
</tr>
<tr>
<td>All-sky channel 5</td>
<td>5</td>
<td>90°N to 60°S</td>
</tr>
</tbody>
</table>

Table 2: Experimental configuration. AMSU-A in all-sky is used over ice-free ocean surfaces only.

IASI TBs, QuikSCAT wind), geostationary radiances and wind vectors (SATO-B-uv), radiosonde temperature, specific humidity and wind measurements (TEMP-T, TEMP-q and TEMP-uv), surface pressure data (SYNOP-Ps) and aircraft temperature reports (AIREP-T).

On top of the normal observing system, we add all-sky AMSU-A channels 3 and 4, channel 4 alone or channel 5 from NOAA-15, NOAA-18, NOAA-19 and Metop-A (but ignoring Aqua). The first two cases are limited to the range 40°N to 40°S to avoid residual cold-sector bias. Early experiments showed that the bias was being aliased into the temperature and wind fields and causing forecast degradation. In the latter case, all-sky channel 5 replaces clear-sky channel 5 over the oceans and follows the same geographical range and screening criteria, e.g., 90°N to 60°S with sea-ice screened out. Here, clear-sky channel 5 continues to be assimilated in the usual way over land.

RESULTS

Figure 2 shows the normalised in vector wind RMS error forecast scores compared to the Control. See Geer et al. (2010) for details of how these scores are computed. Even for a purely statistical viewpoint, there are few significant differences, and with such a short experimental period (43 days), even these should be treated with caution because we have not covered a full range of seasons or weather patterns. Nevertheless, all-sky AMSU-A assimilation for channel 3+4 or channel 5 appears to degrade scores more than it improves them, whereas channel 4 alone has a more neutral impact.

The fits to other observations in the analysis and at FG provide another way of assessing the AMSU-A all-sky assimilation. Figure 3 shows radiosonde temperature FG and analysis departure standard deviations, normalised by the Control standard deviation. All-sky AMSU-A channel 5 degrades the radiosonde analysis fit by nearly 1% and the FG fit by around 0.1%. The channel 3+4 and channel 4 experiments do not affect the analysis fit so much, but they still just slightly degrade the fit to radiosondes. Other data types show similar results, such as AIREP temperatures, AIRS and IASI (not shown).

The channel-4 only assimilation appears the most promising, with hints of tropical improvement. Including channel 3 or channel 5 degrades analysis fits to other instruments sensitive to temperature in the lower troposphere, by up to 1%, and there are some indications that forecast scores are negatively affected too. For channel 3, the problems is likely that it has a high sensitivity to hydrometeors and a relatively low sensitivity to temperature. Hence, cloud errors may be contaminating the analysis - either via uncorrected biases or just the ‘noise’ from poorly-located cloud features.

The picture is more complicated for channel 5. Clear-sky AMSU-A assimilation is already very highly-tuned, and also crucial to forecast performance, so it is perhaps not unexpected that replacing over-ocean channel 5 with an imperfect experimental system causes a slight degradation of the scores. However, even in the worst case (NH days 3-7), the forecast degradations are only 1 - 2% and are barely significant, so this does not invalidate the all-sky approach.
Figure 2: Effect of assimilating different AMSU-A channels through the all-sky route. Normalised difference in RMS vector wind forecast error between experiment and control, using own-analyses as the reference.
Figure 3: Standard deviation of (a) analysis and (b) FG departures from assimilated radiosonde temperature observations. Standard deviations have been normalised by the control values.

CONCLUSION

The all-sky assimilation framework at ECMWF has been extended to work with temperature-sounding radiances from AMSU-A. This framework is computationally expensive so it will not be applied to stratospheric channels. Its benefit is also very limited for mid- and upper-tropospheric channels (e.g. channels 5 and 6) because we cannot yet accurately model radiative transfer when there are large amounts of frozen hydrometeors in deep convection. For operational implementation, we are concentrating our efforts on the most promising candidate, AMSU-A channel 4, which is strongly affected by water cloud and is not yet assimilated at ECMWF. In longer experiments with channel 4 (not shown here), there are indications of minor (order 0.5%) improvements in wind forecast scores around days 2-4 in the southern hemisphere and tropics, although there are corresponding minor degradations in the northern hemisphere. Channel 4 also brings up to a 3% improvement in fits to microwave imagers, suggesting improvements to the analysed and forecast cloud fields.

ACKNOWLEDGEMENTS

Alan Geer was funded by the EUMETSAT fellowship programme and NWP-SAF. Philippe Lopez, Bill Bell, Anne Fouilloux, Deborah Salmond, Niels Bormann, Tony McNally, Sabatino DiMichele, Mohamed Dahoui, Jan Haseler, Paul Dando, Gabor Radnoti, Steve English and Jean-Noël Thépaut are thanked for their help in this work.

References


