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All-sky assimilation of microwave humidity sounders

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All-sky assimilation of microwave humidity sounders

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Satellite radiance observations give dense, frequent, global coverage of the atmosphere but they are difficult to use in cloudy areas. In the last decade ECMWF has pioneered the assimilation of cloud and precipitation-affected satellite observations in operational numerical weather forecasting. The implementation of Cycle 40r3 of the Integrated Forecasting System (IFS) will mark a milestone in this development: for the first time all the main humidity-sensitive microwave instruments will go through the 'all-sky' assimilation path, which allows us to exploit water vapour information in cloudy areas and to directly assimilate cloud and precipitation (see Box A).

All-sky assimilation of microwave imager observations, sensitive mainly to the lower troposphere, has been operational since 2009 (*Bauer et al.*, 2010). The new addition is the microwave humidity sounding channels at 183 GHz which are a core capability of the European and US polar-orbiting operational meteorological satellites. These channels were previously assimilated using the 'clear-sky' method: in other words, all cloud-affected observations had to be discarded. All-sky assimilation allows a more complete use of the data, particularly in the winter storm tracks.

The direct information content of microwave humidity sounders is humidity, cloud and precipitation, but when they are used inside any four-dimensional variational data assimilation system (hereafter referred to as 4D-Var) they also provide information on wind and temperature. Particularly in the mid-latitude upper troposphere, strong humidity and cloud gradients offer a chance to infer wind and mass information from the moisture fields. Indeed, the latest upgrade has its main benefit in the wind and geopotential forecasts, which are significantly improved out to at least day 4. We can see the microwave humidity observations as an important part of the observing system, improving the large-scale analysis of wind and mass and benefitting forecast scores into the medium range.

Though it is good that forecasts are being improved, it is important to know why it is happening. It could be that we now have better geographical coverage of upper-tropospheric water vapour in dynamically interesting cloudy regions. The assimilation of cloud and precipitation could itself be benefitting the forecasts. More crucially, we need to know if we are directly inferring winds from the humidity, cloud and precipitation fields or whether the benefit comes through some more subtle aspect of the data assimilation system. All-sky assimilation may be beginning to derive information that has historically come from cloud motion vectors. The more we understand the all-sky assimilation, the more we will know how best to use satellite observations in the future – whether as atmospheric motion vectors, clear-sky or all-sky radiances. In this article we make a start on investigating these questions.

Microwave humidity sounding around 183 GHz

Figure 1 shows the observations from the microwave humidity sounder (MHS) on the European Metop-B satellite. These are the observations available in the 00 UTC assimilation window on 15 August 2013, during the southern hemisphere winter where synoptic activity in the southern storm track is at its height.

Figure 1a shows MHS channel 3 (at 183±1 GHz), sensitive to upper-tropospheric humidity, cloud ice and frozen precipitation. In the absence of cloud or precipitation, low relative humidity corresponds to a high observed brightness temperature and vice-versa. The climatological subtropical high pressure regions are marked by high brightness temperatures indicating a very dry free-troposphere. In the mid-latitudes and in the inter-tropical convergence zone (ITCZ) there is much higher relative humidity and the brightness temperatures are relatively low. Also, in the mid-latitudes there is great variability and a mixture of dry and moist air masses. The great hope of humidity sounding is that the movement, position and water amounts of these air masses can be used to infer information on the wind fields and ultimately on the large-scale synoptic structures of the atmosphere (e.g. *Andersson et al.*, 1994, *Allen et al.*, 2014). Where the wind is aligned with a gradient in humidity, the model's humidity advection term should allow a 4D-Var assimilation system to infer information on the wind fields. Additionally, the effect of the continuity equation on the water vapour amounts can provide information on the convergence and divergence of the winds.

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The all-sky brightness temperatures in Figure 1a include cloudy and precipitating scenes. These are hard to distinguish, at least in a global view. At the microwave frequencies used by MHS, cloud ice and frozen precipitation cause scattering, which reduces brightness temperatures. High relative humidity also reduces brightness temperatures: without additional information it is hard to distinguish cloudy or deep-convective areas from those which just have high relative humidity.

Figure 1b shows MHS channel 5 (at 190 GHz), which peaks lower in the atmosphere, sometimes low enough to observe the surface. Again humidity is the main factor controlling the observed brightness temperature, but cloud and precipitation are more easily distinguished against the warmer clear-sky background: spots of localised low brightness temperature (the dark blue colours) indicate deep-convective systems or broader areas of thick ice cloud, for example in the ITCZ and in mid-latitude frontal zones.

Clear-sky and all-sky assimilation

A

When doing clear-sky assimilation there is no attempt to model the effect of cloud or precipitation. At the observation location, an assimilation system can only improve the fit to clear-sky observations by modifying the water vapour and temperature fields (though as explained in the main text, a 4D-Var system will have the possibility of doing this by adjusting the surrounding dynamical fields). Cloud-affected observations are discarded because cloud would otherwise be aliased into spurious water vapour or temperature increments, leading to degradation of the forecasts. Drawbacks of this technique are:

- Cloud detection may not remove all cloud-affected observations and the forecasts may be degraded anyway.
- The quality control is asymmetric: if cloud-affected observations are removed, the remaining observations are representative only of cloud-free areas. In the case of humidity observations this will lead to a dry bias.
- Observations have to be discarded in the most meteorologically interesting areas, such as frontal systems and mid-latitude storm tracks.

All-sky assimilation uses an observation operator capable of simulating the effect of cloud and precipitation. At the location of the observation, the assimilation system can adjust water vapour, temperature, cloud or precipitation to fit the observation better. No cloud screening is applied and all observations, whether clear, cloudy or precipitating, are assimilated in the same way using the same observation operator.

Three key components in an all-sky approach are:

- In a 4D-Var system, there must be a tangent linear and adjoint representation of the moist physical processes in order to make use of cloud and precipitation information coming from the all-sky radiances. These key pieces of the system were put in place at ECMWF by the Physical Aspects Section in the middle of the last decade (see *Janiskova & Lopez,* 2012).
- There must be an observation operator capable of representing cloud and precipitation effects on the observed radiances. To use cloudy microwave observations we have had to develop radiative transfer models that can represent the scattering of radiation from rain and frozen particles. At the same time, these models need to be fast enough to be used in an operational NWP system. A key recent development leading to the use of microwave humidity channels in the 183 GHz range has been better modelling of the scattering from frozen particles using non-spherical particle models, for example snowflakes (*Geer & Bauer,* 2014).
- The quality of first-guess cloud and precipitation is still much worse than humidity and temperature. In fact, it could be argued that at the smaller scales, and particularly when it comes to convection, cloud and precipitation are not even representable by current models – in other words, the model cannot be expected to supply a precise location, timing and intensity for cloud and precipitation. In all-sky assimilation this is addressed as a 'representivity error' by applying smaller observation errors in clear-sky areas and larger observation errors in cloud and precipitation (*Geer & Bauer,* 2011). For relatively high-spatial-resolution instruments like microwave imagers (resolutions down to 10 km) the observations are also averaged together (superobbed) onto an 80 km spatial scale to help remove small-scale cloud and precipitation variability. Microwave humidity sounders have relatively large spatial scales (40 to 60 km) and are not superobbed.

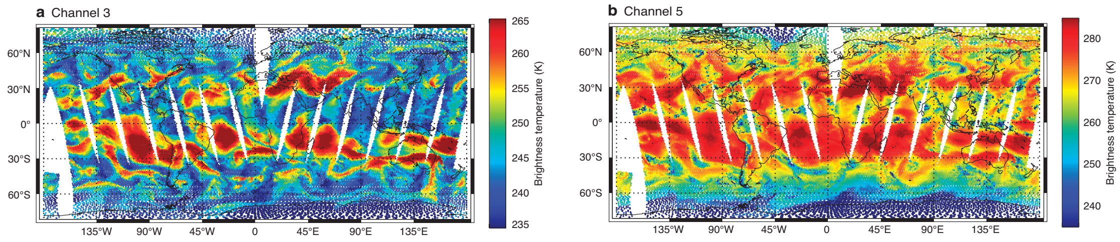

Figure 1 Observed brightness temperatures from Metop-B MHS in the 00 UTC assimilation window on 15 August 2013: (a) Channel 3, at 183±1 GHz, sensitive to upper-tropospheric humidity, cloud ice and frozen precipitation; (b) Channel 5, at 190 GHz, sensitive to mid-tropospheric humidity, cloud ice and frozen precipitation. High brightness temperatures correspond to low humidity; low brightness temperatures correspond to high humidity, cloud ice or frozen precipitation (typically deep convection).

Single cycle example

To illustrate the effect of assimilating microwave humidity channels in all-sky conditions, we can perform a single-cycle assimilation experiment and compare the increments generated by the all-sky observations on their own to those from the full observing system (including all-sky humidity observations). In the all-sky-only experiment we will assimilate humidity data from five microwave humidity sounders on various satellites (i.e. MHS on Metop-A, Metop-B, NOAA-18, NOAA-19 and SSMIS on DMSP-F17). The experiment is performed for the 00 UTC assimilation window on 15 August 2013, the same date as the observations we examined in the last section.

Figure 2 shows the normalised all-sky first-guess departures (first-guess departure divided by observation error) corresponding to the observations from MHS channels 3 and 5 in Figure 1. This is a fundamental quantity in the data assimilation system because, when squared, it gives the contribution of that observation to the 4D-Var cost function. In other words, the normalised first-guess departure is a guide to the influence of that observation in the data assimilation, though its ultimate effect in the analysis is also controlled by the background error term. The largest normalised departures are in the mid-latitude storm tracks and in the ITCZ: hence these are the areas where we might expect to have greatest influence on the analysis.

Only active observations are shown, so it is clear that in the lower-peaking channels the quality control removes a lot of data. We cannot yet assimilate these observations over high orography, sea-ice or at high latitudes. Here, there is too much influence from surface emission, which is difficult to model over land, snow and ice surfaces. We also have to remove the ‘cold air outbreak’ regions where a systematic lack of supercooled cloud liquid water in the forecast model causes a difficult-to-correct bias between model and observations. Overall, we might expect the upper-tropospheric channel to have the greatest impact on the data assimilation because it has a much greater geographical coverage.

Looking closely at the departures in the tropics, there are many positive and negative regions corresponding to displacements in the position of large convective systems in the ITCZ. It is still very hard for the model to simulate these features in the right place and at the right time, even in the 12-hour first-guess forecast. In the mid-latitudes, we can see elongated regions of negative and positive departures with a width of the order 100 to 300 km and lengths up to 1000 km. These correspond to displacements and intensity variations in mid- and upper-tropospheric humidity and in the cloud fields. This is the information we hope will lead back to the wind fields and ultimately to improvements in the analysis of the large-scale synoptic situation.

One of the key advantages of the all-sky approach is simply its enhanced coverage in meteorologically interesting areas. Figure 3 shows the number of MHS channel 3 observations that can be assimilated in this analysis using either a clear-sky or an all-sky approach. In either case, coverage is lowest in the northern hemisphere, mainly because high altitude land surfaces need to be discarded. But polewards of 50°S, across the southern hemisphere storm tracks, the all-sky technique provides at least double the number of observations. In the clear-sky technique, cloud screening removes a majority of observations in the winter high latitudes.

On its own, the all-sky humidity sounder assimilation can generate mid-tropospheric increments that replicate a substantial portion of those from the full observing system. Figures 4 and 5 show the humidity and wind increments 9 hours into the assimilation window. The humidity increments resemble the normalised departures from Figure 2 in terms of their size and morphology, though they cannot be compared quantitatively because the satellite observations are valid at different times

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through the assimilation window and are sensitive to a broad layer of humidity, not just a single model level. However, we do know that the analysis fits the all-sky observations much better than the first guess and that this fit is very similar whether the full observing system is used or just the all-sky water vapour data (not shown). So these humidity increments are being generated specifically to fit the all-sky observations. The morphology of the wind increments is qualitatively consistent too, on similar 100–400 km scales, and in similar areas of the globe: these wind increments will be associated with displacements, stretching and compression of the humidity field to make it fit the observations.

It is surprising how well the all-sky-only increments resemble those from the full observing system. There are plenty of other areas – stratosphere and lower troposphere included – where the all-sky-only assimilation does not replicate the full system. But all-sky assimilation on its own can generate mid- and upper-tropospheric wind increments that are reasonably consistent with those from the full observing system.

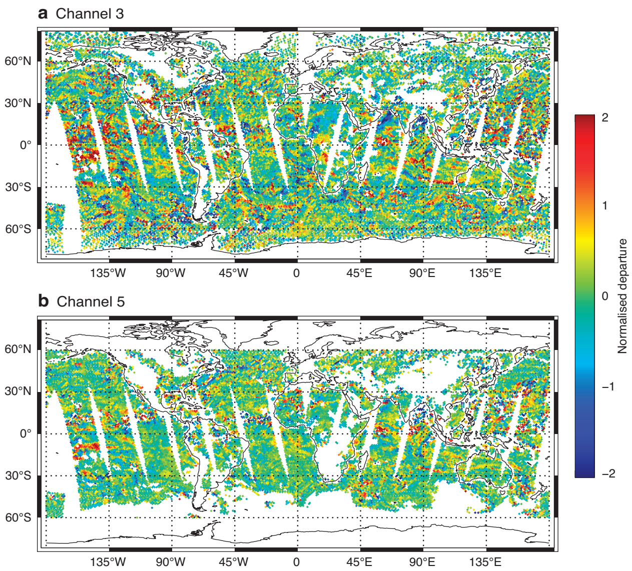

Figure 2 Normalised, bias corrected first-guess departures from Metop-B MHS in the 00 UTC assimilation window on 15 August 2013: (a) Channel 3, sensitive to the upper troposphere; (b) Channel 5, sensitive to the mid or lower troposphere. Normalised first-guess departures are computed as the observation minus the first guess divided by the observation error. Squared, these would give the observation's weight in the 4D-Var cost function; as they are, they retain information on the direction in which the analysis should move: either moistening or drying the model.

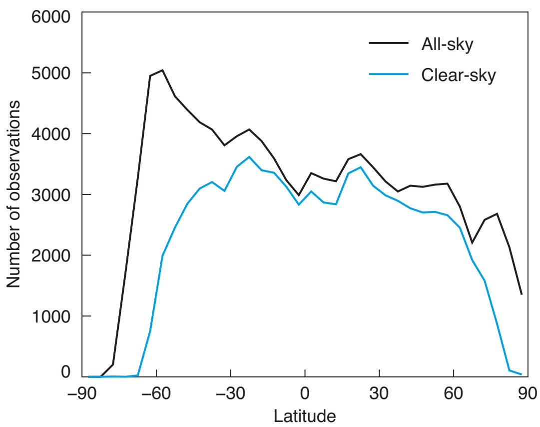

Figure 3 Number of MHS channel 3 observations actively assimilated, per 5° latitude bin, in 00 UTC assimilation window on 15 August 2013 for the all-sky approach and if clear-sky quality control is applied to remove cloudy scenes.

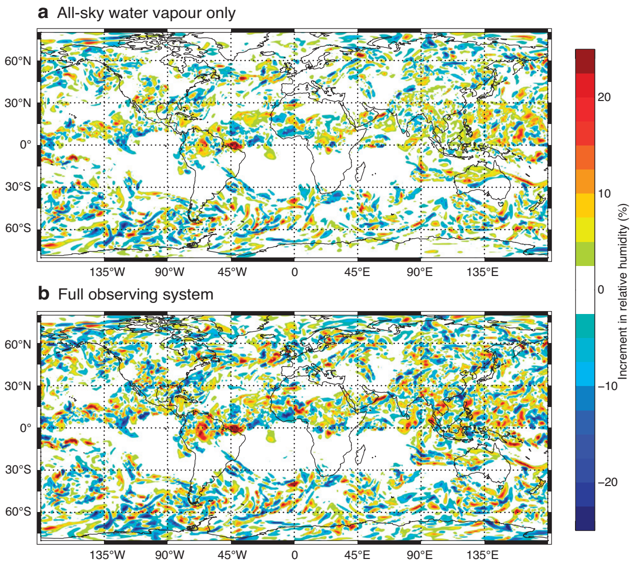

Figure 4 Increments in relative humidity on model level 95 (the closest level to 500 hPa) at 06 UTC on 15 August 2013: (a) assimilating only the all-sky microwave humidity observations; (b) assimilating the full observing system, including all-sky humidity channels. The first guess is identical in both cases and is created using the full observing system. Correlation between panels (a) and (b) is 72%.

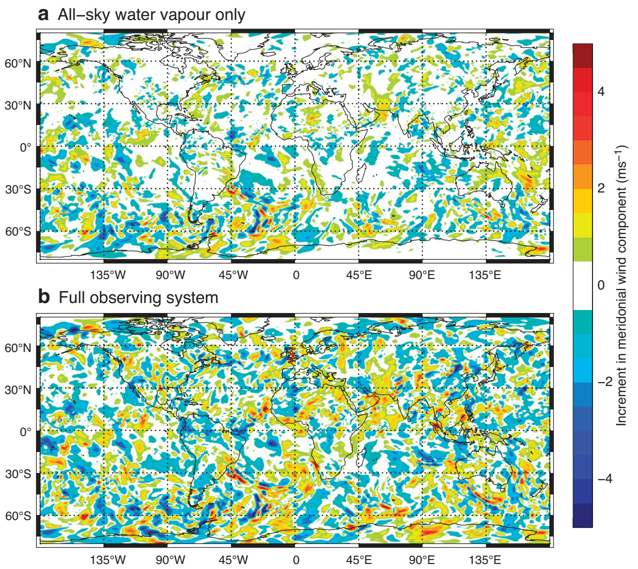

Figure 5 Increments in meridional wind component on model level 95 (the closest level to 500 hPa) at 06 UTC on 15 August 2013: (a) assimilating only the all-sky microwave humidity observations; (b) assimilating the full observing system, including all-sky humidity channels. The first guess is identical in both cases and is created using the full observing system. Correlation between panels (a) and (b) is 58%. Increments in the zonal wind component show qualitatively similar patterns.

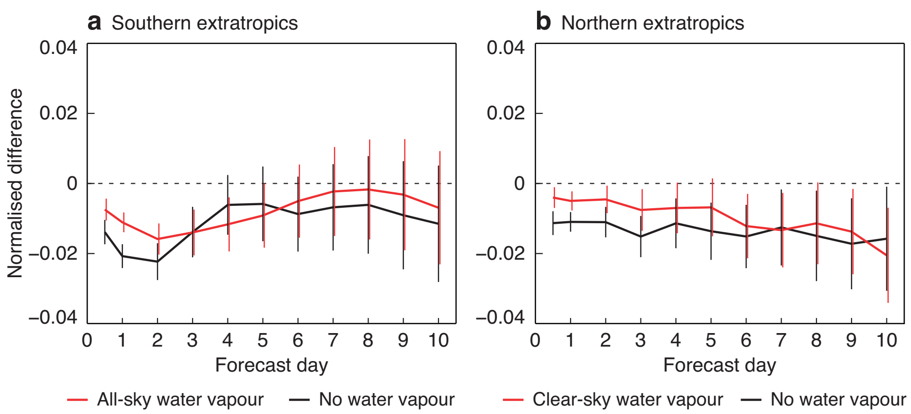

Figure 6 Normalised change in root-mean-square geopotential error at 500 hPa between the assimilation of clear-sky or all-sky microwave water vapour sounding observations and the otherwise full observing system in the (a) southern and (b) northern extratropics, based on a maximum of 236 forecasts from summer (August/September 2013) and winter (January/February 2014) experiments. Error bars indicate the 95% confidence range; verification is against own analysis.

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Forecast scores and observation fits

Assimilating the all-sky observations on their own is an unrealistic scenario. What really matters is whether the new technique can improve forecasts in the context of the full observing system: we need to know the incremental benefit of adding all-sky assimilation of microwave humidity sounders.

Adding clear-sky or all-sky assimilation to the otherwise full observing system improves standard 500 hPa geopotential height forecast scores out to at least day 4 (Figure 6). Beyond day 4, even though the error bars suggest there is impact, we should be cautious on these scores given the relatively short duration of these experiments (a combined total of around four months). At shorter ranges, the all-sky assimilation significantly outperforms the clear-sky assimilation and brings the total improvement from water vapour sounding channels to around 2% in forecast scores. This may sound small, but the improvement in ECMWF forecast scores over the last 10 or 20 years amounts to only around a percent annually. In the full observing system, there is a substantial amount of often overlapping information. New techniques and new instruments typically fill small gaps or add just a little more precision to what is already a very good analysis.

For the 48-hour forecast there is over 10% reduction in the wind errors in the upper troposphere in the southern mid-latitudes when the all-sky observations are added to the otherwise full observing system (Figure 7). Clear-sky assimilation of the same data gives impact in similar places, but in general it is less (not shown).

First-guess fits to assimilated observations confirm the short-range forecast scores (Figure 8). Clear-sky assimilation of microwave water vapour channels is beneficial to temperatures and winds, represented by AMSU-A observations and conventional wind data (Figures 8a and 8b respectively). Compared to clear-sky, all-sky improves the quality of wind fits to conventional observations between 50 hPa and 250 hPa. Temperature-sounding AMSU-A data is better fitted across channels spanning the troposphere (channels 5 to 9) and to a lesser extent the stratosphere (channels 10 to 14). Interestingly it is the relative humidity fits that see least benefit from the move to all-sky assimilation. Channels 11 and 12 of HIRS (Figure 8c) are infrared channels that are sensitive to mid- and upper-tropospheric humidity in a very similar way to the microwave humidity sounding channels at 183 GHz. Clear-sky assimilation already brings substantial improvements in upper-tropospheric humidity; all-sky improves the situation by a smaller margin. However, it is likely the wind and temperature improvements that are most important in improving forecast quality. In other words, the all-sky assimilation seems to have particular benefits to the dynamical fields that cannot be so easily obtained from the clear-sky approach.

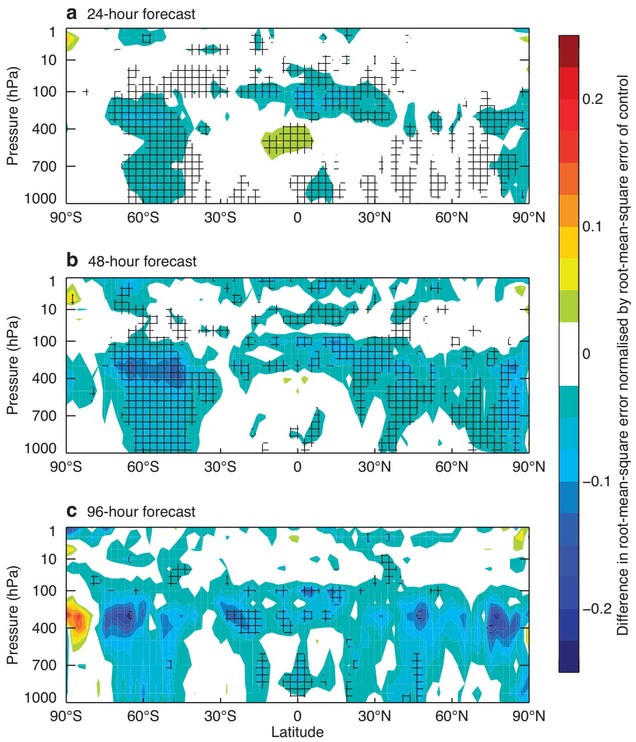

Figure 7 Normalised change in root-mean-square vector wind error for (a) 24-hour, (b) 48-hour and (c) 96-hour forecasts when all-sky microwave water vapour assimilation is added to an otherwise complete global observing system, based on a maximum of 236 forecasts from summer (August/ September 2013) and winter (January/ February 2014) experiments. Cross-hatching indicates statistical significance at 95%; verification is against own analysis.

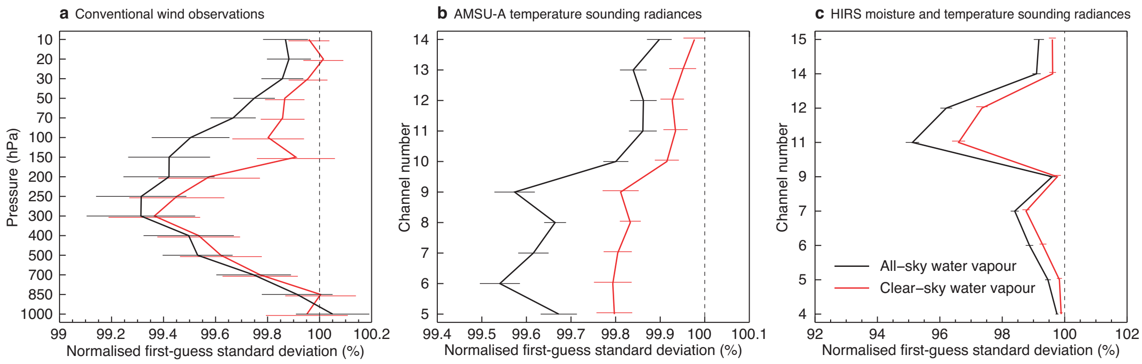

Figure 8 Normalised standard deviation of first-guess departures for: (a) conventional meridional and zonal winds from aircraft, profilers, pilot balloons and radiosondes; (b) temperature-sensitive AMSU-A observations (combining instruments on seven different European and US polar orbiting satellites); (c) HIRS infrared observations, with channels 11 and 12 sensitive to upper-tropospheric water vapour (on the Metop-A satellite). The departures are normalised by the results of the full observing system excluding microwave humidity observations, so that 100% corresponds to the full observing system experiment. The area is global and the period is a combination of August/September 2013 and January/February 2014.

Impact in the absence of other observations

To further understand how the all-sky assimilation benefits the forecasts, the single-cycle, single-observing system experiments were repeated twice-daily over a period of 16 days. This is a framework in which the first guess is always of the highest possible quality, coming from the full observing system, and the background errors are correctly specified. These experiments answer the question "what would happen if for 12 hours we lost all observations except...". In this set of experiments we have two reference points: (a) the quality of forecasts when no observations are assimilated and (b) the quality of forecasts when all observations are assimilated. We can create a metric that puts these points at 0% and 100% impact respectively. If forecast quality were degraded compared to the no data case, this 'impact' would be a negative number.

Figure 9 shows the impact of assimilating only clear-sky microwave humidity channels. Mid- and upper-tropospheric humidity errors are reduced by 50% to 80% of that generated by the full observing system. As we saw in the fits to observations (Figure 8) clear-sky assimilation benefits the wind and temperature fields too. In Figure 9, the reduction in wind errors is largest at 400 hPa, roughly consistent with the fit to conventional wind observations in Figure 8. In the absence of other observations, clear-sky water vapour assimilation can replicate about 40% of the impact of the full observing system in these upper-tropospheric winds.

The impact of all-sky humidity assimilation in the full observing system is shown in Figure 10. In much of the tropics and northern hemisphere, impact is similar to clear-sky, and in the relative humidity, it is even a little less. Only in the mid-latitude southern hemisphere is the impact substantially larger. Here, all-sky humidity observations can reproduce up to around 60% of the impact of the full observing system on winds in the upper troposphere and 40% in temperature. The impact is greater also around the tropopause, for example in tropical winds at 100 hPa and in extending the zone of impact in the mid-latitudes up a little – perhaps from 300 hPa to 200 hPa. In terms of latitude, the region where all-sky produces most benefit is from 30°S to 70°S – exactly the zone where all-sky assimilation is able to add substantially more observations in these examples (Figure 3). These experiments are for the southern hemisphere winter, but in the northern hemisphere winter, more impact occurs in the northern storm tracks (not shown) and this is also reflected in the score improvements in northern latitudes in Figure 7, which combines results from August/September 2013 and January/February 2014.

A minor issue is the degradation of forecast quality in the Antarctic at low levels in the microwave humidity assimilation. Partly, the issue is that this is a non-existent part of the atmosphere; ground levels are as high as 3,000 m and surface pressure can be at around 600 hPa to 700 hPa. Even at levels where this may represent a true degradation in forecasts, it may simply be that the fact that we do not assimilate microwave humidity observations in these areas and the unconstrained assimilation system is making spurious increments. In the full observing system, other observations, such as the microwave temperature sounders, can constrain these areas.

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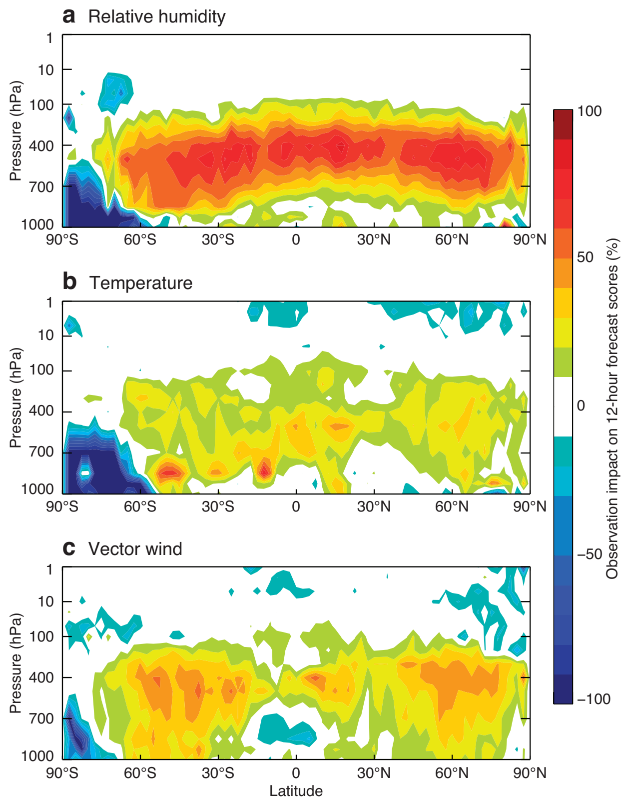

Figure 9 Percentage reduction of 12-hour forecast error in (a) relative humidity, (b) temperature and (c) wind when only clear-sky microwave water vapour sounding channels are assimilated, based on the period 15–31 August 2013. The assimilation is not cycled; the first guess comes from a full-observing system experiment. The quality of a forecast from the first guess (i.e. without any data assimilation) defines 0%; the quality of a forecast based on an analysis with the full observing system defines the 100% level. Clear-sky microwave assimilation can on its own replicate about 70% of the impact of the full observing system on mid- and upper-tropospheric relative humidity.

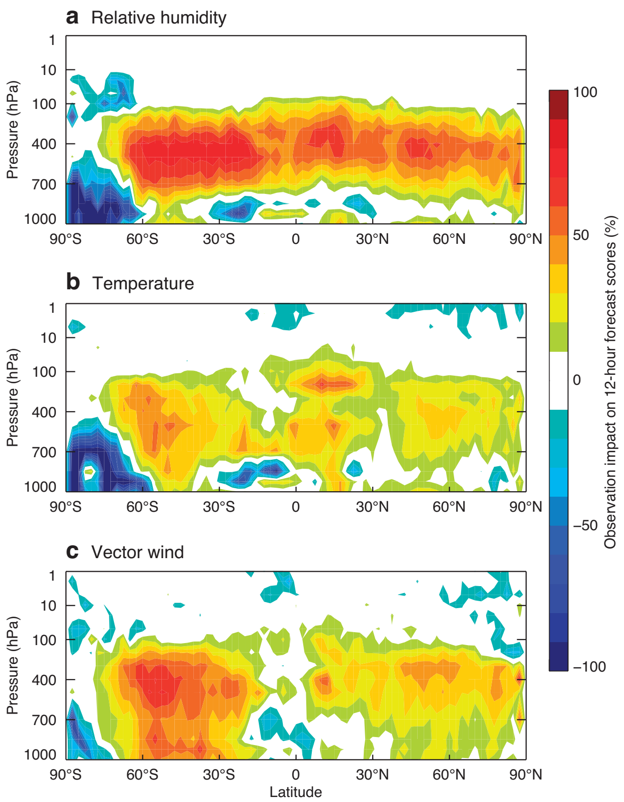

Figure 10 As Figure 9 but for all-sky assimilation of the microwave water vapour sounding observations. All-sky is comparable to clear-sky in the tropics and northern hemisphere but it is substantially better in the southern hemisphere, particularly in reducing temperature and wind errors.

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Looking at the southern hemisphere extratropics where the all-sky observations have greatest impact in this experiment, Figure 11 shows the impact on the 12-hour and 72-hour forecasts. As a reference point, this figure includes the impact of all the microwave temperature sounders, which are probably the single most important group of observations in our system. These can replicate around 50% to 60% of the full observing system's impact on temperature and wind fields, with benefits not just in the mid and upper troposphere but in the lower troposphere and stratosphere too. All-sky assimilation maintains its advantage over the clear-sky assimilation at least out to 72 hours, and brings the impact towards that of the microwave temperature sounding observations.

An important question is whether the benefits of all-sky assimilation come through constraining the water vapour fields in the presence of clouds or through the cloud fields themselves. A crude way to test this is to turn off the adjoint and tangent linear sensitivity to cloud and precipitation in the observation operator used in 4D-Var. Having done this, the assimilation system can only directly improve the fit to all-sky observations by changing the moisture fields at the observation location. The assimilation system is prevented from directly adjusting clouds and precipitation to fit the observations (though this may be a natural secondary result of improving the humidity). Figure 11 shows that turning off the cloud and precipitation sensitivity in the minimisation has relatively little impact. It looks like the majority of impact in going from clear-sky to all-sky assimilation is coming from a better constraint on relative humidity in the presence of cloud, rather than directly through the sensitivity to cloud and precipitation. Nevertheless, the cloud and precipitation sensitivity is clearly beneficial.

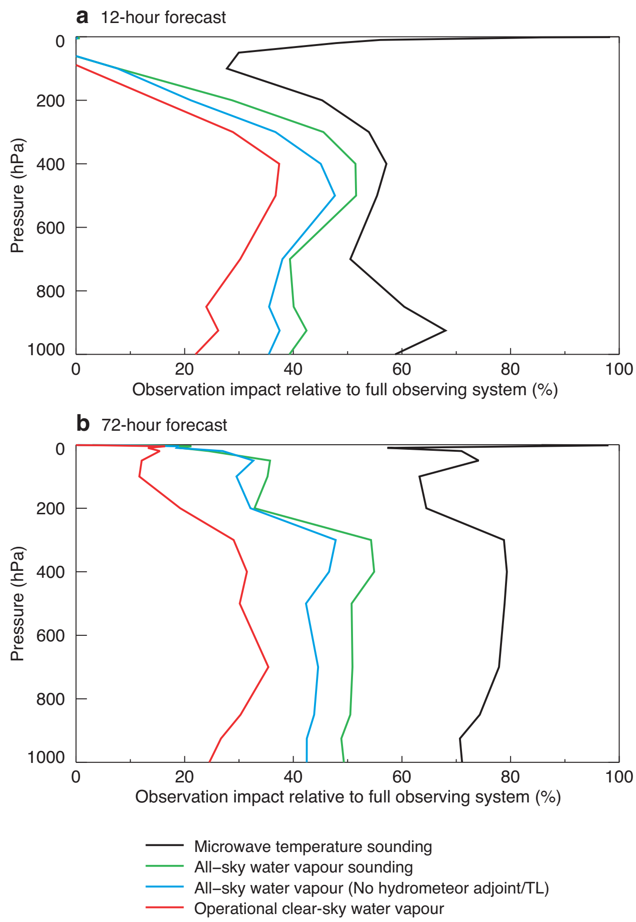

Figure 11 Southern hemisphere extratropical error reduction in vector wind error for (a) 12-hour and (b) 72-hour forecasts for different observing systems as a percentage of the impact from the full observing system. Results are given for microwave temperature sounders (AMSU-A, ATMS), all-sky water vapour sounders (MHS, SSMIS), all-sky water vapour sounders with adjoint and tangent linear (TL) sensitivity to hydrometeors (cloud and precipitation) turned off, and operational clear-sky water vapour sounders (just MHS).

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Summary

Clear-sky assimilation of microwave humidity sounders improves forecasts, but all-sky assimilation is better, particularly in the extratropics. Mid-latitude wind fields are improved in the analysis and in shorter-range forecasts. It is important to understand how this is achieved, whether through the 4D-Var tracing effect or in combination with other mechanisms. Perhaps improved humidity fields lead to improved modelling of the radiative or latent heating of the atmosphere, or perhaps dynamical information could be inferred through the background error correlations between humidity and temperature (ECMWF does not model correlations between humidity and wind). We hope to perform some more detailed tests on the system to better understand these and other possibilities, but there is evidence in the current experiments to suggest the tracing effect is most important.

All-sky humidity first-guess departures highlight regions where humidity and cloud need to be increased or decreased. These regions are prevalent in the winter storm tracks, where there are strong humidity gradients in the mid and upper troposphere and relatively large errors in the position and intensity of humidity features. In the absence of other observations, all-sky assimilation can create wind increments in these regions that substantially resemble those from the full observing system. Given that the forecast model in 4D-Var maintains the meteorological consistency of wind, temperature and moisture, wind increments must be contributing to the adjustment of the relative humidity and clouds through advection, convergence and divergence. The wind increments are also bound through the model to be consistent with adjustments to the large-scale synoptic structures, which is potentially the mechanism that can benefit longer-range forecasts.

It is the winter storm tracks where all-sky assimilation has the greatest ability to fill the gaps left by clear-sky assimilation. These are also the regions where the humidity tracing effect is likely to be largest, due to the strong humidity gradients, and where the humidity observations may be most beneficial to dynamical forecasts. In the context of the full observing system, the greatest impact on short-range wind forecasts is in the expected areas: in the upper troposphere in the storm-track regions. These characteristics are all consistent with a 4D-Var assimilation system that is adapting dynamical fields to better fit humidity, cloud and precipitation features in the observations.

Further reading

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