ENHANCING THE USE OF HYPERSPECTRAL RADIANCES IN THE WATER VAPOUR ABSORPTION BAND AT ECMWF

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Abstract

Only a handful of hyperspectral water vapour channels (HWVC) of Atmospheric Infrared Sounder (AIRS) and Infrared Atmospheric Sounding Interferometer (IASI) are actively used in the 4D-Var assimilation system of the European Centre for Medium-range Weather Forecasts. Two approaches are presented with the aim at making the assimilation of HWVC more aggressive. The first approach is to modify the determination of cloud flags towards better accounting for atmospheric humidity properties in the presence of cloud. This approach is found to introduce moist analysis increments immediately above cloud top. The second approach is to reduce sensitivity to stratospheric humidity errors while selecting HWVC to be assimilated. The two approaches are found to improve consistency between analysis and independent humidity-sensitive observations. As a result, the number of actively assimilated HWVC can be considerably increased.

INTRODUCTION

Hyperspectral infrared sounders provide radiance data on thousands of channels with large parts of observing spectra falling within the main water vapour absorption band between 1100–2100 cm^{-1}. While numerical weather prediction (NWP) implementations make extensive use of infrared sounders in the long-wave CO_2 absorption band, hyperspectral water vapour channels (hereafter HWVC) constitute a minority in operationally-assimilated channels. This is demonstrated in Fig. 1 for the case of the operational assimilation of Atmospheric Infrared Sounder (AIRS; McNally et al., 2006) and Infrared Atmospheric Sounding Interferometer (IASI; Collard and McNally, 2009) radiances in the 4D-Var system of the European Centre for Medium-range Weather Forecasts (ECMWF). For reasons that are not fully understood, the high spectral resolution of advanced sounders has not yet been successfully converted into vertical resolution in humidity analysis using HWVC.

This report characterizes the role of HWVC in the currently-operational setup of the ECMWF 4D-Var system. The impact is assessed in terms of removing all HWVC from the system on the one hand, and by adding new HWVC into the system on the other. Two approaches to improve the treatment of HWVC are then introduced and discussed. In the end, the impact of HWVC is re-assessed in a modified assimilation system.

IMPACT OF HWVC IN THE ECMWF 4D-VAR SYSTEM

The currently operational setup of the ECMWF 4D-Var system includes assimilation of seven and ten HWVC of AIRS and Metop-A IASI, respectively. HWVC are assimilated assuming a diagonal observation error covariance matrix, and observation error standard deviations are set to either 1.5 K (for AIRS) or 2.0 K (for IASI). Observations are bias-corrected using a variational technique with a standard set of eight predictors to account for scan-angle and air-mass dependent components of the bias. Only clear channels over open sea are assimilated.

The impact of HWVC in the ECMWF 4D-Var system is assessed by running a set of assimilation experiments, in which the number of assimilated HWVC is varied as described in Table 1. Each run consists

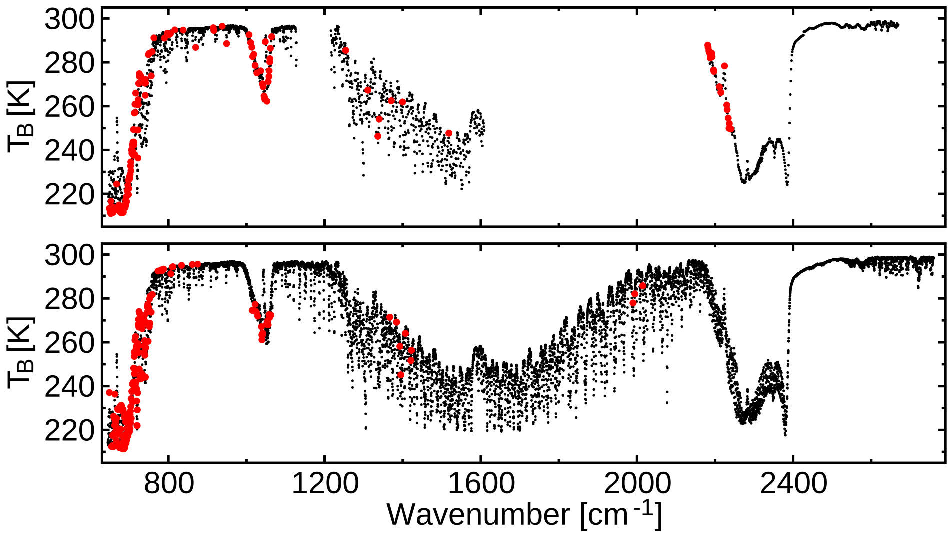

Figure 1: **Simulated brightness temperature spectra (black dots) for AIRS (top) and IASI (bottom) in a tropical reference atmosphere. Actively assimilated channels in the ECMWF 4D-Var system are highlighted in red.**

Run	Number of HWVC	
	AIRS	IASI
Denial	0	0
Control	7	10
Adding I	18	25
Adding II	30	40
Re-assess I	18	25
Re-assess II	24	35

Table 1: **Number of HWVC in different runs of the impact assessment.**

of two 50-day time periods covering both summer and winter seasons. Horizontal resolution is set to T511 (roughly corresponding to grid spacing of 40 km) and the vertical discretization to 91 model levels. IASI channels to be added on top of the operationally-assimilated ones are chosen following the ranking as documented in the information content -based study of Collard (2007). In the case of AIRS, similar ranking is unavailable; the additional AIRS channels are chosen with the aim at maintaining the similarity with the IASI channel selection, as determined by visual assessment of channel weighting functions. Temperature jacobians for the used channels in a tropical reference atmosphere are shown in Fig. 2.

Figure 3 gives an indication of the impact of HWVC on the humidity analysis in the northern hemispheric summer. The scores are shown in terms of Observation minus Analysis departure (OmAd) statistics on humidity-sensitive channels of the High-resolution Infrared Radiation Sounder (HIRS) and Microwave Humidity Sounder (MHS), both onboard the Metop-A satellite. Mean OmAd (left panels) is shown for non-bias-corrected data and it is given relative to the control run, whereas OmAd standard deviation (right panels) is normalized by the control run. Removing all HWVC from the assimilation system (red lines) systematically decreases the uncorrected OmAd on all verifying channels, implying drying that is consistent in all verification domains. In contrast, adding new HWVC on top of the control run (black lines) is found to increase the mean OmAd, suggesting an increase in the water vapour content of model atmosphere. This effect is the largest on upper-tropospheric-sensitive channels such as HIRS-12 and MHS-3. However, introducing another set of additional HWVC (orange lines) leads to further moistening only on lower-tropospheric-sensitive channels in the extratropics (top and bottom panels).

Taking all HWVC out of the assimilation system increases the OmAd standard deviation in all verification domains, indicating a considerable degradation in the quality of humidity analysis. Nevertheless, adding

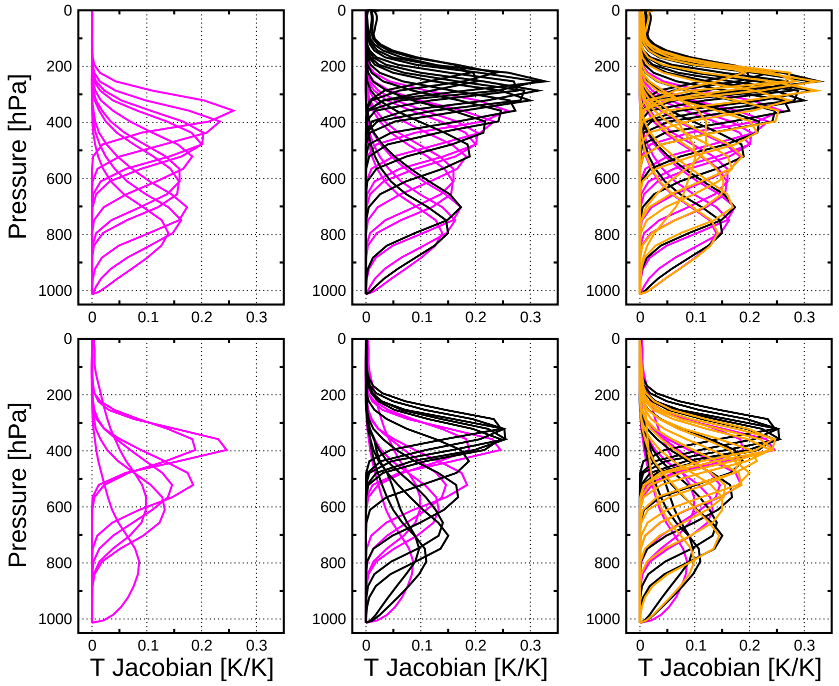

Figure 2: **Tropical temperature jacobians of IASI (top) and AIRS (bottom) HWVC assimilated in the Control (left), Adding I (middle), and Adding II (right) runs of the impact assessment. Different colours indicate channels that are added at each step of the assessment.**

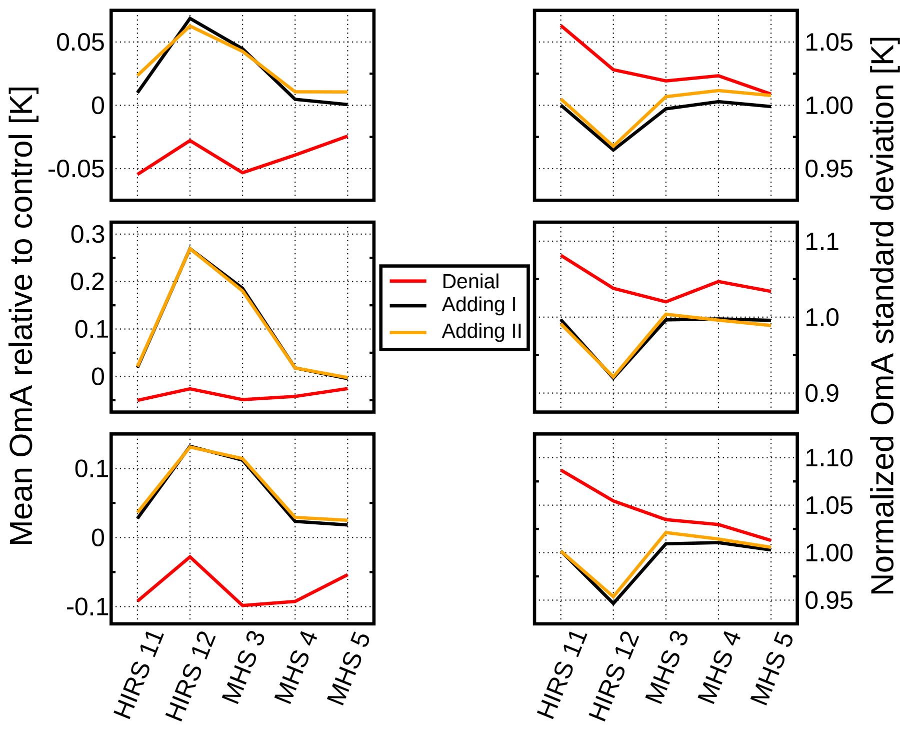

Figure 3: **Mean uncorrected OmAd (left panels) and standard deviation of OmAd (right panels) on humidity-sensitive channels of HIRS and MHS onboard the Metop-A satellite. Red, black and orange lines are for the Denial, Adding I, and Adding II runs, respectively. Means are shown relative to the Control, whereas standard deviations are normalized by the Control. Top, middle and bottom panels show scores in the northern extratropics, tropics, and southern extratropics, respectively.**

new HWVC on top of the operationally-assimilated ones does not generally improve the fit to collocated sounders, except in the case of the high-peaking HIRS channel. Otherwise, the impact from adding new HWVC is neutral in the tropics (middle panels) and slightly negative in the extratropics.

It is summarized that while removing all HWVC from the assimilation system has a characteristic signature on the humidity analysis, the impact from adding new HWVC on top of the operationally-assimilated ones is similarly consistent between the tropics and extratropics. The denial runs make a strong case to conclude that it is highly beneficial to actively assimilate some HWVC, but it remains challenging to get further benefit from increasing the number of HWVC in the system. Behaviour of OmAd standard deviation on the upper-tropospheric-sensitive HIRS channel is exceptional: this is the only suggestion of systematically improved performance when new HWVC are added to the system. This can be understood as a consequence of insufficient vertical coverage in the operationally-assimilated subset of HWVC. Left panels of Fig. 2 suggest that the operationally-assimilated HWVC have very little sensitivity to atmosphere above 300 hPa. This is greatly enhanced in the first set of additional HWVC, shown in the middle panels of Fig. 2. Further additional HWVC (right panels in Fig. 2) do not similarly enhance the vertical coverage (although they could be expected to enhance the vertical resolution), and therefore little improvement is gained in the OmAd statistics from these.

It remains to be noted that differences between OmAd statistics of HIRS and MHS data are attributed to different sampling by the two instruments over land and sea ice, as well as to different sensitivity to cloud contamination between infrared and microwave regimes.

IMPROVING THE CONDITIONS FOR USING HWVC

In the following, two approaches are presented for improved treatment of HWVC in the ECMWF 4D-Var system. The first is related to the determination of cloud flags, while the second relates to accounting for sensitivity to stratospheric humidity errors in the selection procedure for additional HWVC.

The determination of HWVC cloud flags

Cloud-contaminated HWVC data are not assimilated in the operational setup of the ECMWF 4D-Var system. The cloud detection is based on background departure data in the primary (long-wave) CO_2 absorption band. The cloud detection scheme was originally developed for the assimilation AIRS (McNally and Watts, 2003) and it has later been modified for the assimilation of other hyperspectral radiances.

In principle, the cloud detection scheme could as such be applied in the water vapour absorption band similarly as it is applied in the long-wave CO_2 band. In practice this is not done, because humidity-sensitive background departures vary considerably (with respect to typical cloud radiative effect) even in clear conditions, making it difficult to distinguish between cloud-contaminated and clear channels. Instead, HWVC are diagnosed clear or cloudy by comparing lower tails of their weighting functions, as computed from the background atmospheric profiles, with an estimate of cloud top height; the latter is obtained as output from the cloud detection in the long-wave CO_2 band. This approach for determining the HWVC cloud flags is called the cross-band cloud detection.

The cross-band cloud detection relies on background profiles in determining whether or not the weighting function of a HWVC hits the underlying cloud. This is potentially risky, because background humidity error introduces a vertical shift in the weighting function. This issue is illustrated in Fig. 4. In this particular case, the diagnosed cloud top height is at 720 hPa. The cloud flag on the HWVC now depends on background humidity: in case of a moist background error (blue line), the weighting function will not penetrate deeply enough, implying *an excess risk of missing a cloud* (because the channel senses lower atmospheric layers than what the background profile implies). In the opposite case, the background is too dry, and the weighting function (red line) penetrates too deeply, introducing *an excess risk of a false alarm* (because radiation emitted from within the cloud does not reach the satellite, even though the weighting function hits the cloud).

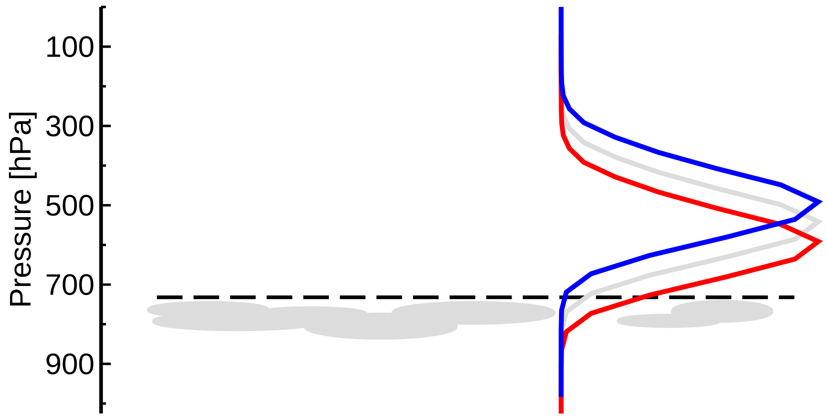

Figure 4: **Schematic illustrating the effect of background humidity error on the determination of HWVC cloud flags. Temperature jacobians are shown in a case without a background humidity error (gray line) and for either moist (blue) or dry (red) background errors. The dashed black line represents a cloud top height estimate.**

Traditionally, cloud detection (in NWP applications) is tuned such that the risk of missing a cloud is minimized even if it means increasing the risk of making a false alarm. If such a conservative approach was taken in the context of HWVC cloud flag determination, one would try and minimize the excess risk of missing a cloud in the presence of a moist background error. This could be achieved by determining the cloud flags using a modified background profile, in which the amount of humidity is artificially decreased. However, it turns out that there is more benefit from doing exactly the opposite.

It can be argued that presence of cloud requires a state of saturation with respect to either liquid water or ice. On the other hand, there is a physically-based constraint preventing background humidity from considerably exceeding the saturation. This means that presence of cloud excludes the possibility of a moist background error, providing us with protection against the excess risk of missing a cloud.

Taking this argument one step further allows one to minimize the excess risk of making a false alarm. Presence of cloud means presence of saturation, and therefore it is most useful to determine the HWVC cloud flags under the assumption that the humidity profile is saturated. In other words, weighting functions used in the cloud detection are computed from a modified background profile, in which relative humidity is artificially set to 100%. This modification will make the assimilation of HWVC increasingly aggressive, but only immediately above cloud top, and only in those cases where the background profile is too dry. In essence, this provides us with protection against the excess risk of making a false alarm. When the concept of saturated HWVC cloud flags is tested in the framework of ECMWF 4D-Var, systematic cooling and moistening are found in the marine stratocumulus regions of Eastern Pacific and Atlantic Oceans (see Fig. 5). This is associated with improved fit to collocated MHS radiance data, not only in these regions but also in averaged scores computed over large verification domains (not shown).

Accounting for the sensitivity to stratospheric humidity errors

In NWP applications, stratospheric humidity is relatively poorly known and it has little importance. In the context of assimilation of HWVC, this is potentially an issue. As illustrated in the middle panel of Fig. 6, many upper-tropospheric-peaking HWVC show some dependence on stratospheric humidity. The risk involved here is that stratospheric humidity errors introduce non-zero background departures, that can lead to spurious analysis increments in the upper troposphere.

It is straightforward to reduce the stratospheric sensitivity by modifying the selection of HWVC that are assimilated. Our approach, in this work, is to remove those HWVC that show stratospheric sensitivity in their weighting functions. The removed channels are replaced by new channels such that the total

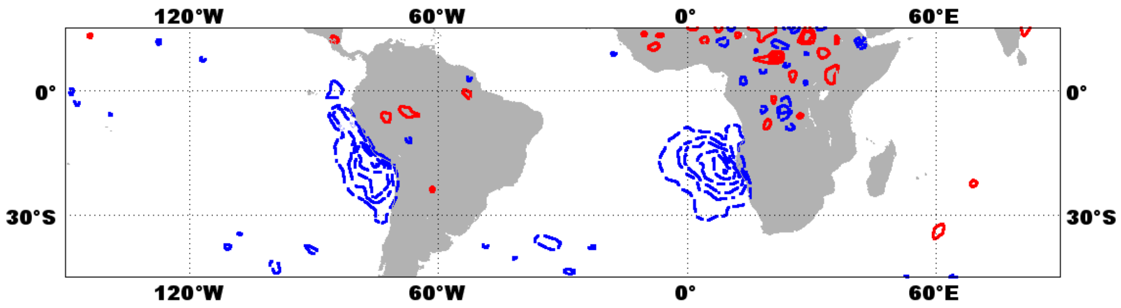

Figure 5: **Impact of assuming a saturated humidity profile during the determination of HWVC cloud flags on mean 925 hPa temperature analysis. Contour interval is 0.1 K. Dashed blue contours indicate cooling.**

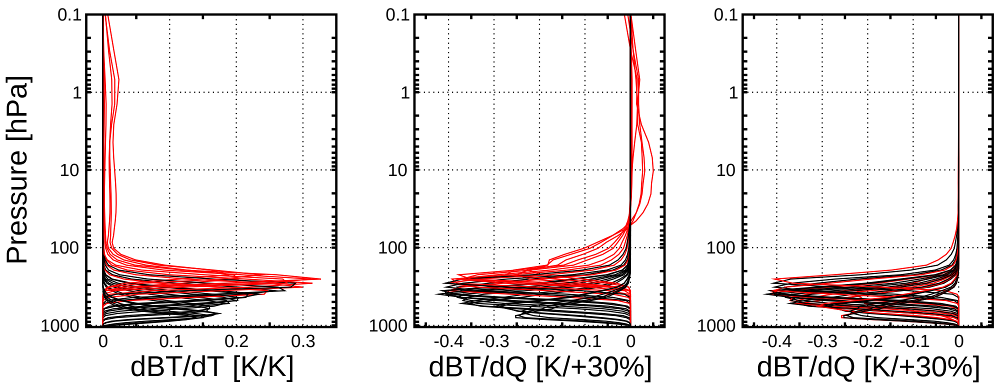

Figure 6: **Temperature (left) and humidity (middle) jacobians in the selection of 25 most information-containing IASI HWVC. Humidity jacobians in an alternative selection of 25 HWVC (right panel). Black lines show those channels that are included in both selections.**

number of HWVC remains the same. Temperature and humidity jacobians of HWVC included in the original information-content-based list of 25 IASI channels are shown in Fig. 6 (left and middle panels), together with humidity jacobians of channels included in the alternative list (right panel).

In the alternative channel lists, there are fewer channels constraining the upper-tropospheric humidity, but those remaining are free from the distracting effect of stratospheric humidity errors. On the other hand, channels that are chosen to compensate for the removed ones enhance the lower-tropospheric humidity analysis. Experiments carried out with the modified channel lists suggest systematic moistening in northern polar tropopause and drying in the tropical tropopause (not shown). Although these patterns are weak in magnitude, radiosonde humidity data suggest that they act towards improved fit in terms of mean background departure.

RE-ASSESSING THE IMPACT OF HWVC

It was found earlier that adding new HWVC on top of the operationally-assimilated ones does not generally improve the analysis fit to independent humidity-sensitive radiances, except in the case of the upper-tropospheric-sensitive HIRS channel. The two approaches to improve the conditions for assimilating HWVC show weak indications of improved consistency when tested in isolation from each other. It is worth re-running some of the earlier experiments in the modified setup of the assimilation system, in which the concept of saturated HWVC cloud flags is used together with alternative channel selections reducing the sensitivity to stratospheric humidity errors.

As listed in Table 1, two additional experiments are run (“Re-assess I” and “Re-assess II”). Right panels of Fig. 7 show the normalized OmAd standard deviation on the collocated HIRS and MHS channels in

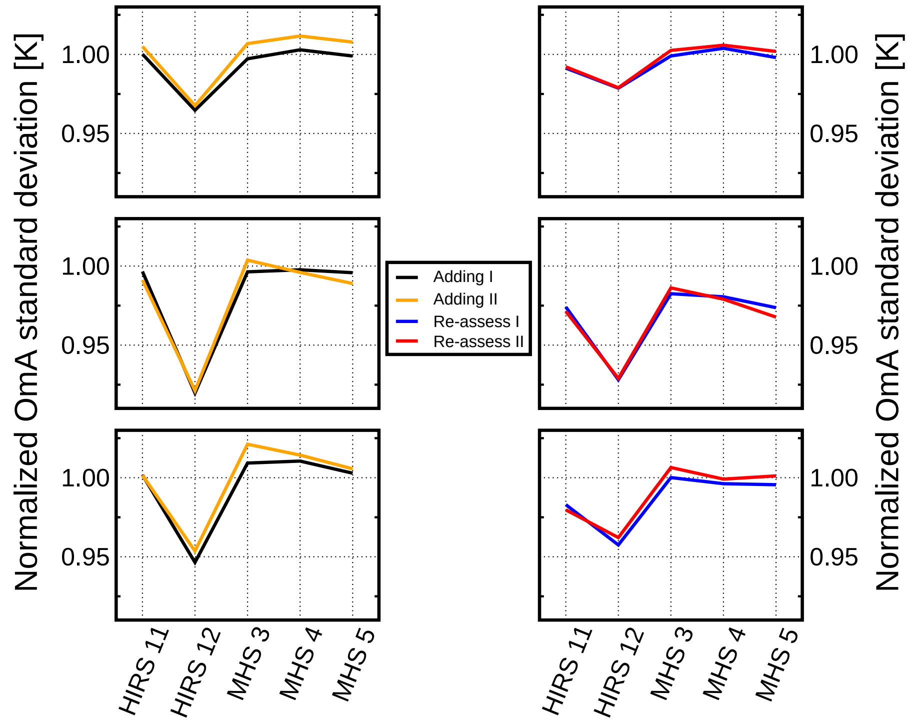

Figure 7: **OmAd standard deviation, as normalized by the control run, on humidity-sensitive channels of HIRS and MHS onboard the Metop-A satellite. Black, orange, blue, and red lines refer to the Adding I, Adding II, Re-assess I, and Re-assess II runs, respectively. Top, middle and bottom panels show scores in the northern extratropics, tropics, and southern extratropics, respectively.**

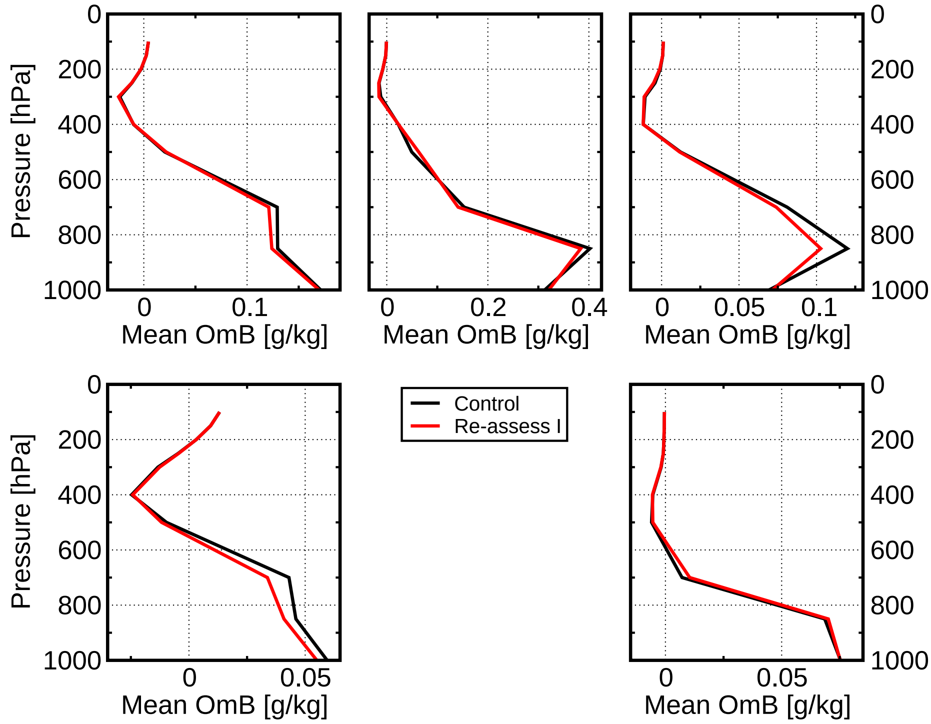

Figure 8: **Mean OmB departure for radiosonde specific humidity in the Control (black) and Re-assess I (red) runs in (clockwise from the bottom left panel) the northern polar region, northern extratropics, tropics, southern extratropics, and southern polar region.**

these runs. As compared with the initial impact assessment (left panels of Fig. 7), the positive impact on the fit to HIRS-12 channel is slightly reduced in magnitude. In contrast, the fit to the lower-tropospheric-sensitive HIRS channel is improved consistently in all verification domains. Similarly, in terms of the analysis fit to collocated MHS data, the new experiment runs consistently outperform the initial runs. In particular, all HIRS and MHS channels now show improved analysis fit from the first additional channel set in the tropics. In the extratropics, though, there is still little benefit from the additional channels.

The beneficial impact from the additional HWVC in the “Re-assess I” runs is also found in background fit to radiosonde specific humidity. This is demonstrated in Fig. 8. In both the northern (top left) and southern extratropics (top right), as well as in the northern polar regions (bottom left), the newly added HWVC help to reduce the dry bias present in the lower-troposphere of model background.

CONCLUSIONS

The characteristic signature of HWVC in the ECMWF 4D-Var system is consistent between different verification domains. Degraded consistency between analysis and humidity-sensitive radiance data in denial experiments underscores the important role of HWVC in the humidity analysis. However, adding new HWVC on top of those currently assimilated in operations is found to make little difference.

It is found useful to assume a saturated humidity profile while determining HWVC cloud flags. In contrast to the previous approach, where background humidity profile is used, the new approach provides protection against excess risk of making a false alarm in the presence of a dry background error. This makes the use of HWVC increasingly aggressive and leads to moist analysis increments immediately above cloud tops. The assimilation of HWVC is also found to benefit from channel selection procedures where sensitivity to stratospheric humidity errors is minimized.

When the reference assimilation system is modified in response to the two approaches to improved use of HWVC, adding HWVC on top of operationally-assimilated ones is found to improve consistency with humidity-sensitive HIRS channels in all verification domains, and with MHS channels in tropics. Additionally, new HWVC are found to improve background fit to radiosonde humidity in both the northern and southern extratropics. In the modified setup of the ECMWF 4D-Var system, the number of actively used HWVC can safely be increased by a factor of 2.5.

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