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Blending information from infrared radiances with ultraviolet data in the operational ozone analysis

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On 15 November 2011, ECMWF implemented the operational assimilation of ozone-sensitive infrared (IR/O_3 hereafter) radiances from three sounders, namely AIRS, IASI and HIRS (acronyms and abbreviations not defined in the text are listed in Table 1). This represents a major milestone in exploiting infrared sounders and analysing ozone.

In the past, NWP systems have relied operationally upon ozone products retrieved from BUV (Backscatter Ultra Violet) sensors, such as SBUV (Solar Backscatter Ultra Violet), and TOMS (Total Ozone Mapping Spectrometer) to constrain the analysis of ozone. However, a limitation of this data is that it requires sunlight and this leaves half of the globe unobserved daily. Also at high latitudes very few observations can be used throughout the entire winter season. A further limitation of BUV data is that, while it has good sensitivity to ozone near the altitude of maximum concentration (approximately 10–20 hPa), it is almost blind to important ozone variations at lower levels (e.g. in the upper troposphere and lower stratosphere).

Given the obvious limitations of BUV data, a number of studies have demonstrated that substantial improvements can be achieved by assimilating ozone profiles retrieved from limb-viewing infrared (IR) or microwave (MW) instruments (such as MIPAS or MLS) that have been carried as demonstration missions on research satellites. These sensors successfully operate in the absence of sunlight and provide (by virtue of their limb-viewing geometry) highly-detailed vertical information on the ozone concentration from the upper troposphere to the upper stratosphere. However, this data cannot be regarded as a long-term solution for operational NWP as at present there are no definite plans to deploy any limb-viewing ozone-sensitive instruments (either MW or IR) in the foreseeable future.

For this reason the exploitation of IR/O_3 radiances measured by nadir viewing sensors on operational satellites (such as IASI and HIRS) represents an appealing and arguably necessary supplement to the established BUV data. While nadir sounding IR/O_3 observations cannot offer detailed vertical information on ozone, they do provide complementary sensitivity to the ozone concentration at lower levels in the atmosphere (mostly the upper troposphere) and they have no sampling restrictions related to the presence of sunlight. The operational provision of these sensors is guaranteed for the foreseeable future and there is an extensive historical archive of data to support climate reanalysis studies.

Han & McNally (2010) (Han & McNally hereafter) presented an initial assessment of the potential impact of assimilating IR/O_3 radiances from IASI within a simplified version of the ECMWF system. Their study compared independent, unassimilated MLS ozone retrievals with the ozone analyses obtained from three experiments:

- Baseline, with no assimilated ozone data.
- Control in which only BUV ozone products were assimilated.
- Experiment that used only IASI IR/O_3 radiances.

Results showed that, with respect to the baseline, the assimilation of IASI IR/O_3 radiances could significantly improve the fit of the ozone analyses to the independent MLS ozone profiles. Indeed, in some areas the fit was comparable or better than that obtained from the BUV data. Han & McNally showed that the IR/O_3 radiances are most sensitive in the upper troposphere – lower stratosphere region, as opposed to the BUV data that can constrain the ozone field in the middle stratosphere. This would suggest that the two data types (IR and BUV) could be used synergistically and provide complementary information to the ozone assimilation system. This article documents the efforts to establish an optimal blend of these two very different sources of ozone information with a view to a combined assimilation system that is operationally robust.

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Instruments	
AIRS	Advanced InfraRed Sounder
GOME-2	Second generation Global Ozone Monitoring Experiment
HIRS	High-resolution Infrared Radiation Sounder
IASI	Infrared Atmospheric Sounding Interferometer
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding
MLS	Microwave Limb Sounder
OMI	Ozone Monitoring Instrument
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Chartography
SEVIRI	Spinning Enhanced Visible Infra-Red Imager
Satellites	
ENVISAT	Environmental Satellite
MetOp-A	Meteorological Operational Satellite-A
MSG	Meteosat Second Generation
Space agencies	
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration

Table 1 Acronyms and abbreviations not defined in the text.

Details of the IR/O_3 channels

At the time the study was conducted, ECMWF received near-real time data from five IR sounders on LEO (Low Earth Orbit) satellites that carried ozone-sensitive channels: AIRS on board the NASA Aqua satellite, IASI on board the EUMETSAT MetOp-A platform, and three HIRS sensors on board the NOAA-17, NOAA-19 and the EUMETSAT MetOp-A satellites. Additional IR/O_3 radiances were available from geostationary instruments, such as the MSG-9 SEVIRI, but the impact of this data is not assessed here.

AIRS and IASI have a very high spectral resolution (0.5–2 cm^{-1} and 0.5 cm^{-1} respectively) and could potentially provide many hundreds of ozone-sensitive channels. However, in this study the channels assimilated are limited to those used by Han & McNally and these are listed in Table 2. The HIRS instrument has only one channel that is strongly sensitive to ozone – channel 9. It should be noted that all of the IR/O_3 sensors carry other channels – primarily designed for temperature sounding – that have a weak, but collectively important sensitivity to ozone (*Jackson & Saunders*, 2002).

The IR radiances are assimilated directly inside the ECMWF four-dimensional data assimilation system (4D-Var). During the assimilation, observed radiances are compared to values simulated from the background estimate of ozone (from the short-range forecast) using the RTTOV (Radiative Transfer for TOVS) radiative transfer model. The difference between observations and simulations is then minimized by adjusting the ozone concentration appropriately. Before the assimilation, the observations are screened and rejected if they are contaminated by clouds and have any systematic errors (biases) removed adaptively by the variational bias correction system (VarBC).

AIRS	IASI	HIRS
1012, 1019, 1024, 1030, 1038, 1048, 1069, 1079, 1082, 1088, 1090, 1092, 1104, 1111, 1115, 1116, 1119, 1120, 1123	1479, 1509, 1513, 1521, 1536, 1574, 1578, 1579, 1585, 1587, 1626, 1639, 1643, 1652, 1658, 1671	9

Table 2 The AIRS, IASI, and HIRS assimilated channel numbers in the O_3 band. Channels that were used as an anchor to VarBC are in red.

The impact of IR/O_3 radiances

Experiments were run to assess the impact of assimilating the IR/O_3 channels in addition to the BUV ozone data using Cy36r4 of the ECMWF analysis and forecasting system (operational from November 2010 until May 2011) at a reduced horizontal resolution of T511 (roughly corresponding to grid spacing of 40 km).

- *CTRL.* Control used all observations that were assimilated in ECMWF operations at the time of this study. For ozone this includes total column ozone from the Aura OMI and ENVISAT SCIAMACHY instruments, as well as partial columns retrieved from NOAA-17 and NOAA-18 SBUV/2.
- *Exp/IR.* Experiment that additionally assimilates the IR/O_3 channels listed in Table 2.

Changes to the ozone field when the IR/O_3 radiances are assimilated are verified by comparing the resulting ozone analyses with independent (un-assimilated) observations from sondes and ozone profiles from the Aura MLS.

Figure 1 shows a June/July comparison of the ozone analyses with the ozone sonde profiles from the World Ozone and Ultraviolet Radiation Data Centre (WOUDC). The root-mean-square fit to the sondes are averaged over five latitudinal bands. It can be seen that when IR/O_3 radiances are assimilated, the ozone analyses show an improved agreement with ozone sondes in the troposphere and at most stratospheric levels compared to the CTRL. Particularly noticeable is the improved fit at mid and high latitudes in the southern hemisphere for this period where sunlight is limited. However, these comparisons also reveal a slightly degraded fit in the lower stratosphere between 50 and 100 hPa. This region of the atmosphere is something of a null space in between the altitudes where the IR and BUV data are most sensitive. Sonde comparisons for February/March have been carried out and show largely similar features.

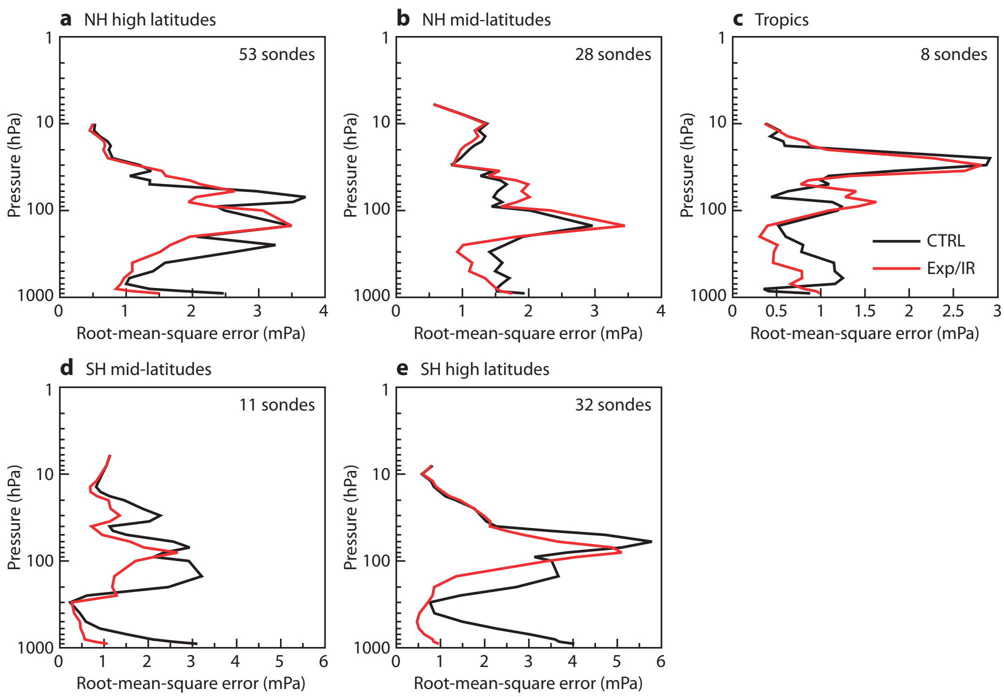

Figure 1 Root-mean-square fit of the Exp/IR and CTRL mean ozone analyses and ozone sondes averaged over five latitudinal bands: (a) northern hemisphere high latitudes (90°–60°N), (b) northern hemisphere mid-latitudes (60°–30°N), (c) tropics (30°N–30°S), (d) southern hemisphere mid-latitudes (30°–60°S) and (e) southern hemisphere high latitudes (60°–90°S). The comparisons were computed by averaging over the two-month long period June/July 2010. The number of ascents included in the average can be found in the top right corner of each panel.

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Figure 2 shows the comparison of the ozone analyses with MLS ozone retrievals. Zonally-averaged cross sections are shown of the mean difference between the MLS retrievals and the co-located ozone analysis for two periods. The MLS differences also confirm the improvements of the ozone analyses in the upper troposphere–lower stratosphere when the IR/O_3 radiances are assimilated. Most striking is the substantial improvement at high southern latitudes during June/July (again where there is no sunlight). However, the MLS comparisons also show the same signal as the ozone sondes, namely a slight degradation in the lower stratosphere.

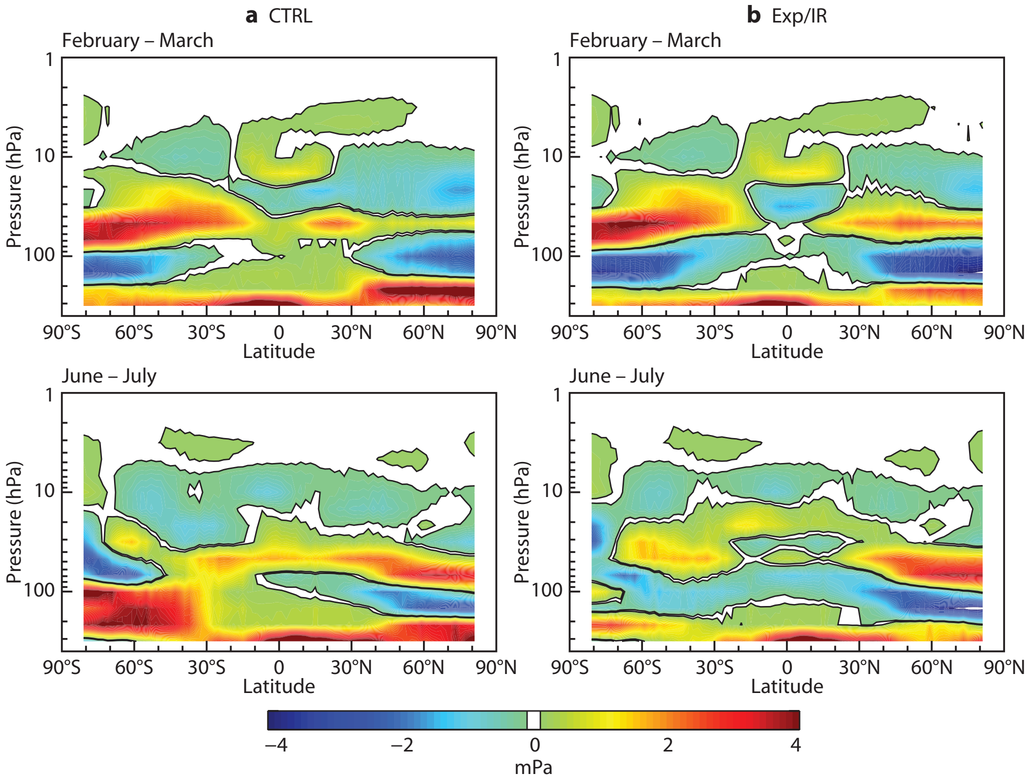

Figure 2 Mean difference between the MLS (version 2.2) ozone profiles and the co-located ozone analyses computed for (a) CTRL and (b) Exp/IR averaged over February/March (top panels) and June/July (bottom panels) 2010.

How can IR/O_3 radiances degrade ozone in the lower stratosphere?

The occasional slight degradation of the analyzed ozone above the upper troposphere–lower stratosphere (UTLS) is believed to be a consequence of the limited vertical resolution of the ozone information provided by nadir-viewing IR sounders. While it has been shown by Han & McNally that the radiances have a maximum sensitivity to ozone changes in the UTLS, they have a reduced residual sensitivity to the atmosphere above and below. In the absence of any external information (either from the background error constraints or other vertically-resolved observations) the vertical structure of the analysis increments reflects this broad layer sensitivity. If the background is (for example) significantly deficient in ozone in the region of the UTLS, assimilation of the IR/O_3 radiances will add ozone in this region, but also (albeit to a much lesser extent) in the layers above and below. There is thus the potential to degrade the analysis if the background happens to have a surplus of ozone above the UTLS.

Two possible solutions to this problem have been investigated.

One solution involves the additional assimilation of high vertical resolution ozone profiles from ENVISAT MIPAS. Figure 3 shows zonal-mean differences between the MLS ozone analyses from three experiments:

- ***CTRL.*** Control described previously using only BUV ozone data.
- ***Exp/IR.*** Experiment using BUV data plus IR/O_3 radiances.
- ***Exp/MIPAS.*** Experiment that uses BUV data plus a combination of IR/O_3 radiances and MIPAS ozone retrievals.

Comparison with the MLS shows that using the vertically resolved MIPAS information, the assimilation retains the benefit of the IR/O_3 radiances (in the UTLS) with little or no degradation of the ozone analysis at levels above.

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The supplementary assimilation of MIPAS ozone profiles is clearly an effective constraint upon the assimilation to prevent the spreading of increments from IR/O_3 radiances to the levels above. However, it can only be regarded as a temporary solution – possible only in periods when these research satellite data are actually available and so it makes sense to pursue other alternatives.

The second approach offers an attractive longer-term solution based on an optimised assimilation of the operational SBUV data (which could also be applied to other operational BUV sensors such as the EUMETSAT/MetOp GOME-2 retrievals). ECMWF currently assimilates ozone derived from the SBUV in the form of 6 thick ozone layers, obtained by merging 21 much finer layers provided in the original product – the vertical aggregation being done to reduce the adverse impact of observation error correlations between layers that could not be taken into account. Possible ways of accounting for this correlation in the near future are under investigation. Meanwhile, however, it is interesting to study how a sub-optimal use of the full 21 level SBUV products (without explicit account of vertical correlations) would influence the ozone analysis.

Figures 4 and 5 show the comparisons between three ozone analyses and the MLS ozone profiles and ozone sondes.

- ***CTRL.*** Control which uses the usual 6-layer averaged SBUV data.
- ***Exp/IR.*** Experiment that additionally assimilates IR/O_3 radiances.
- ***Exp/SBUV$^{(21)}$.*** Experiment that also uses IR/O_3 radiances, but the SBUV data is assimilated on the original 21 layers (with no modifications to the analysis to take into account vertical correlations).

Comparison with the sondes and MLS suggest that even this very naive use of the 21-level SBUV product helps prevent adverse spreading of the IR/O_3 radiance increments.

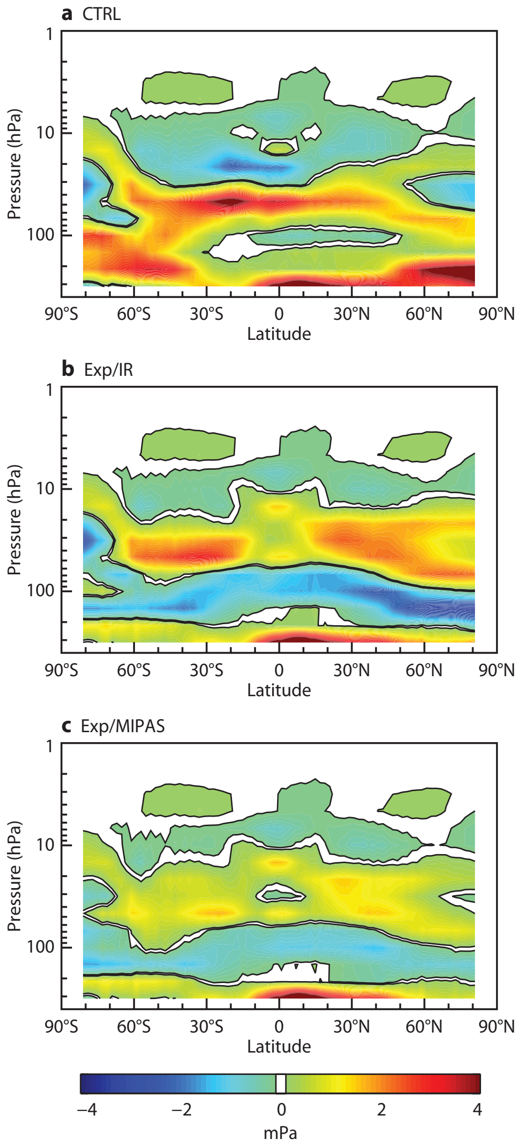

Figure 3 Mean difference between the MLS (version 2.2) ozone profiles and the co-located ozone analyses for (a) CTRL, (b) Exp/IR and (c) Exp/MIPAS. The mean residuals were computed for August to September 2011.

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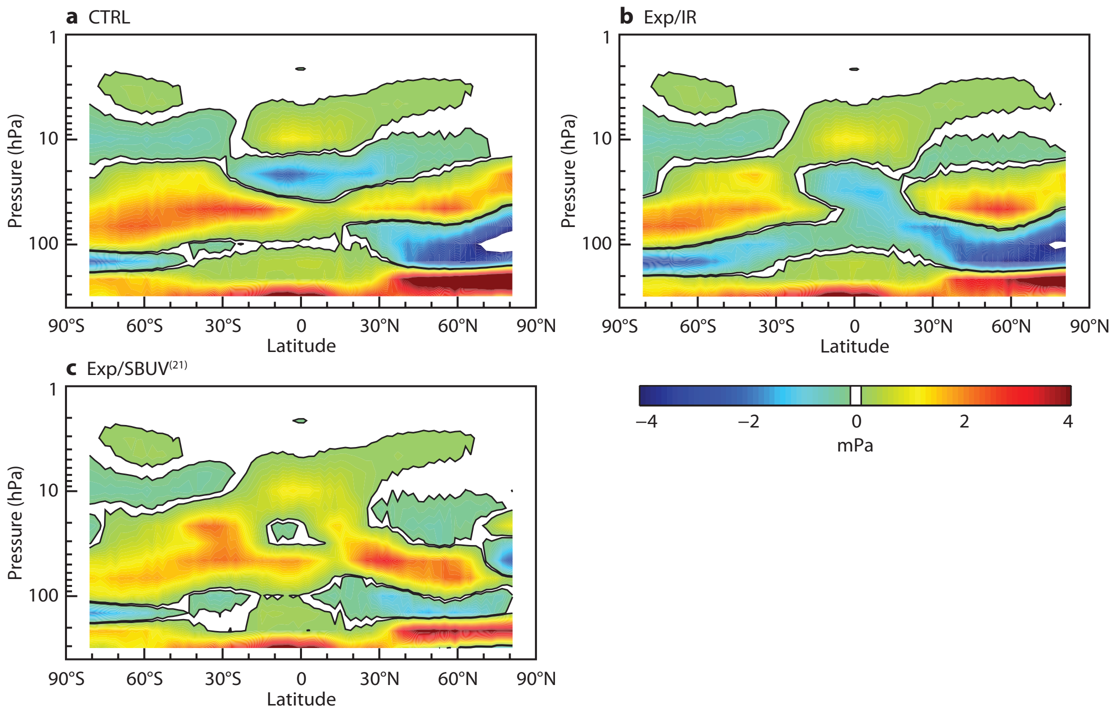

Figure 4 As Figure 3, but for (a) CTRL, (b) Exp/IR and (c) Exp/SBUV(21). The mean residuals were computed for March 2011.

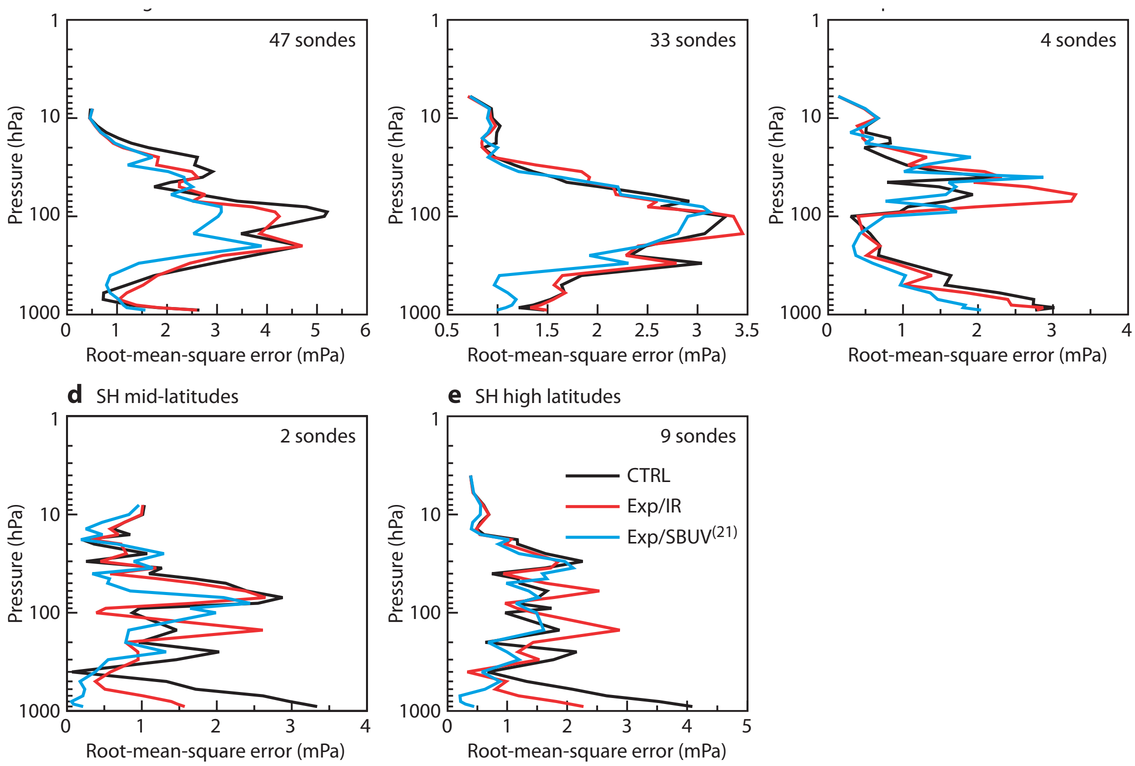

Figure 5 Root-mean-square fit of the CTRL, Exp/IR and Exp/SBUV(21) mean ozone analyses and ozone sondes averaged over five latitudinal bands for March 2011: (a) northern hemisphere high latitudes (90°–60°N), (b) northern hemisphere mid-latitudes (60°–30°N), (c) tropics (30°N–30°S), (d) southern hemisphere mid-latitudes (30°–60°S) and (e) southern hemisphere high latitudes (60°–90°S). The number of ascents included in the average can be found in the top right corner of each panel.

Time stability of ozone in the IR/O_3 radiance assimilation system

We now investigate the longer-term stability of the assimilation system that makes additional use of IR/O_3 radiances. It is known that systematic errors in the ECMWF ozone model can, over time, lead to a drift in the adaptively calculated bias corrections (VarBC) applied to the ozone observations. If unconstrained, this can lead to a corresponding drift in the ozone analysis – which can very quickly develop unrealistic mean ozone states. This drift in bias correction is seen very clearly in a set of previous experiments where only column BUV ozone is assimilated – the data being adaptively bias corrected every analysis cycle against the assimilating model. Figure 6 shows that the corrections drift very quickly and within 30 days can reach values in excess of 20 DU. In the context of this study, the solution adopted was to anchor the analysis mean state against drift by assimilating one observation type (SBUV) with no bias correction and adaptively correcting all other ozone observations to this constrained mean state.

In developing a prototype system to assimilate IR/O_3 radiances, Han & McNally addressed the problem of drift by using one channel without correction (channel 1585 from IASI) to anchor the bias correction process. This worked successfully in the short experiments carried out in the aforementioned study – where IR/O_3 radiances were the only ozone information assimilated. However, in this context (with a view towards an operational implementation) we must test the longer-term ability of this IASI channel and its corresponding AIRS one (channel 1088) to anchor the ozone analysis – particularly when IR/O_3 radiances are used in combination with BUV ozone observations. These alternatives for anchoring the ozone analysis against drift have been tested in a pair of parallel assimilations that have been run over a full calendar year:

- ***CTRL.*** Control that uses all available BUV data (SBUV, OMI and SCIAMACHY) – anchored by the SBUV data being assimilated without bias correction.
- ***Exp/IR.*** Experiment that additionally assimilates IR/O_3 radiances, but applies VarBC adaptive bias corrections to all BUV data (including SBUV) and uses two uncorrected IR/O_3 channels to anchor the system.

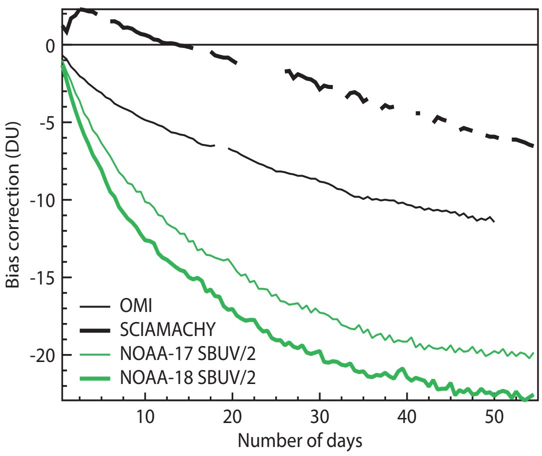

Figure 6 Evolution of the global bias correction applied to four ozone products assimilated in a low-resolution version of the ECMWF system that did not use IR/O_3. The thin and thick black lines refer to OMI and SCIAMACHY total column ozone, respectively. The thin and the thick green lines refer to the bottom layer (1013–16 hPa) of NOAA-17 and NOAA-18 SBUV/2, respectively.

To display the time evolution of ozone in these experiments in a concise way, ozone changes are now integrated in the vertical and presented in terms of total column values. Figure 7 shows a time series of the difference between the zonally-averaged total column ozone from the Exp/IR and CTRL analyses. It is clear that the assimilation of the IR/O_3 channels initially increases the analyzed column ozone at all latitudes (typically just 1–2 DU in the first month), but this increase continues to grow steadily in time, such that in less than a year the column differences have reached values as large as 30 DU.

To assess the realism of these significant changes to the mean column ozone, we again compare the analyses to the MLS. Integrated columns from the experiment and control analyses are computed over vertical domain of the MLS between 0.1 and 215 hPa and collocated to the MLS locations. In Figure 8 yellow to red colours show areas where the MLS has higher column ozone values than the analyses; the green to purple colours are where MLS has lower values. Initially the increase in ozone concentration at lower levels from the assimilation of IR/O_3 radiances (reported in previous sections) provides a marked improvement in the fit of total column ozone to MLS in the southern hemisphere and tropics compared to the control. But it is clear that the column ozone continues to increase and is far in excess of the control and the values measured by the MLS suggesting that the IR/O_3 system has drifted to an unrealistic state. An examination of the adaptive bias corrections computed for the BUV instruments within the IR/O_3 system shows the characteristic inflation to very large negative values. Consequently, we must conclude that the use of just two IR/O_3 channels is insufficient to anchor the ozone column as a whole against longer-term drifting due to model error.

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The obvious solution is to reinstate the assimilation of uncorrected SBUV as an additional anchor when the IR/O_3 radiances are assimilated. While it was impractical to re-run the full one-year experiment, short additional periods (capturing the periods when the drift was most pronounced) have been tested and confirm the effectiveness of the combined IR and SBUV anchor.

An experiment run between May 2011 and September 2011 is shown in Figure 9. Up until the 12 July this used only the two IR/O_3 channels as an anchor and the characteristic drift in the ozone analysis relative to the CTRL can clearly be seen (Figure 9a). However, after this date the SBUV anchor was reinstated in addition to the IR/O_3 channels, causing the drift to stop and revert backwards to lower ozone values. Following the change, comparison with the MLS column data (Figures 9b and 9c) shows the ozone analysis to be stable and in significantly better agreement with the MLS than the control ozone analysis.

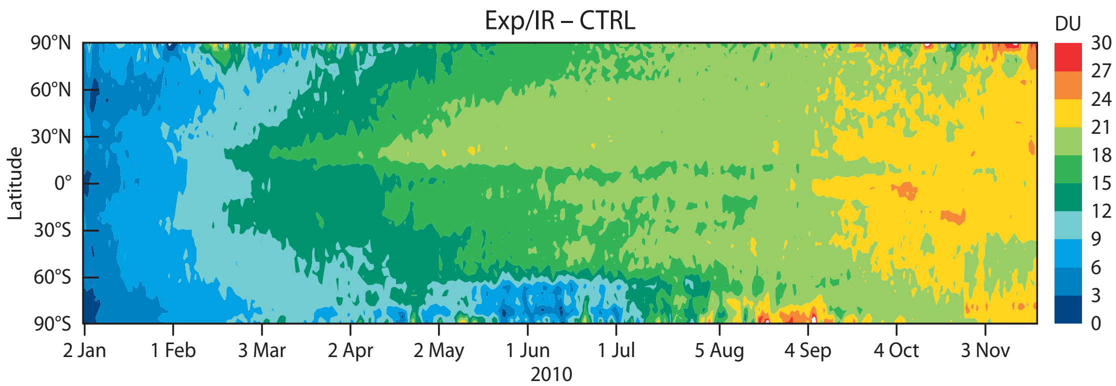

Figure 7 Hovmöller plot of the total column ozone residuals between the CTRL and Exp/IR experiments. Units are DU.

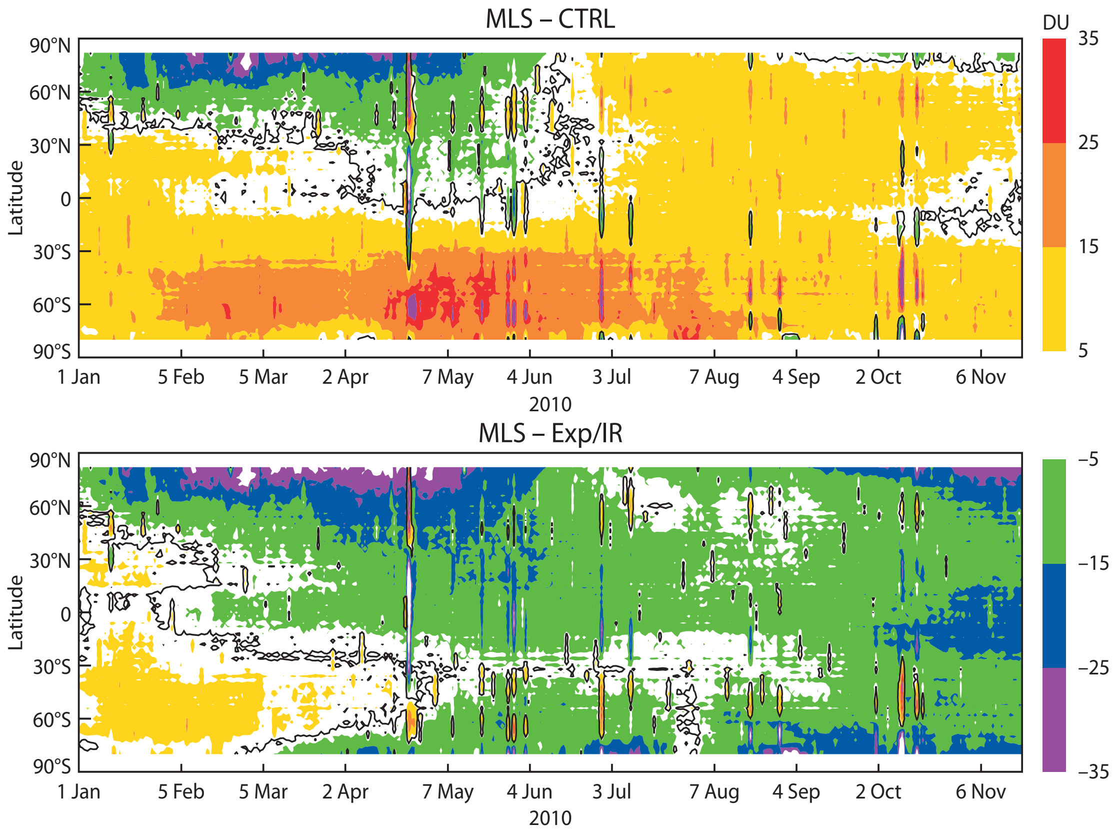

Figure 8 Hovmöller plots of the integrated column ozone difference between the MLS version 2.2 ozone profiles and co-located ozone analyses from CTRL (top) and Exp/IR (bottom), computed between 0.1 and 215 hPa. The black contour line shows the zero difference line. Data are in DU.

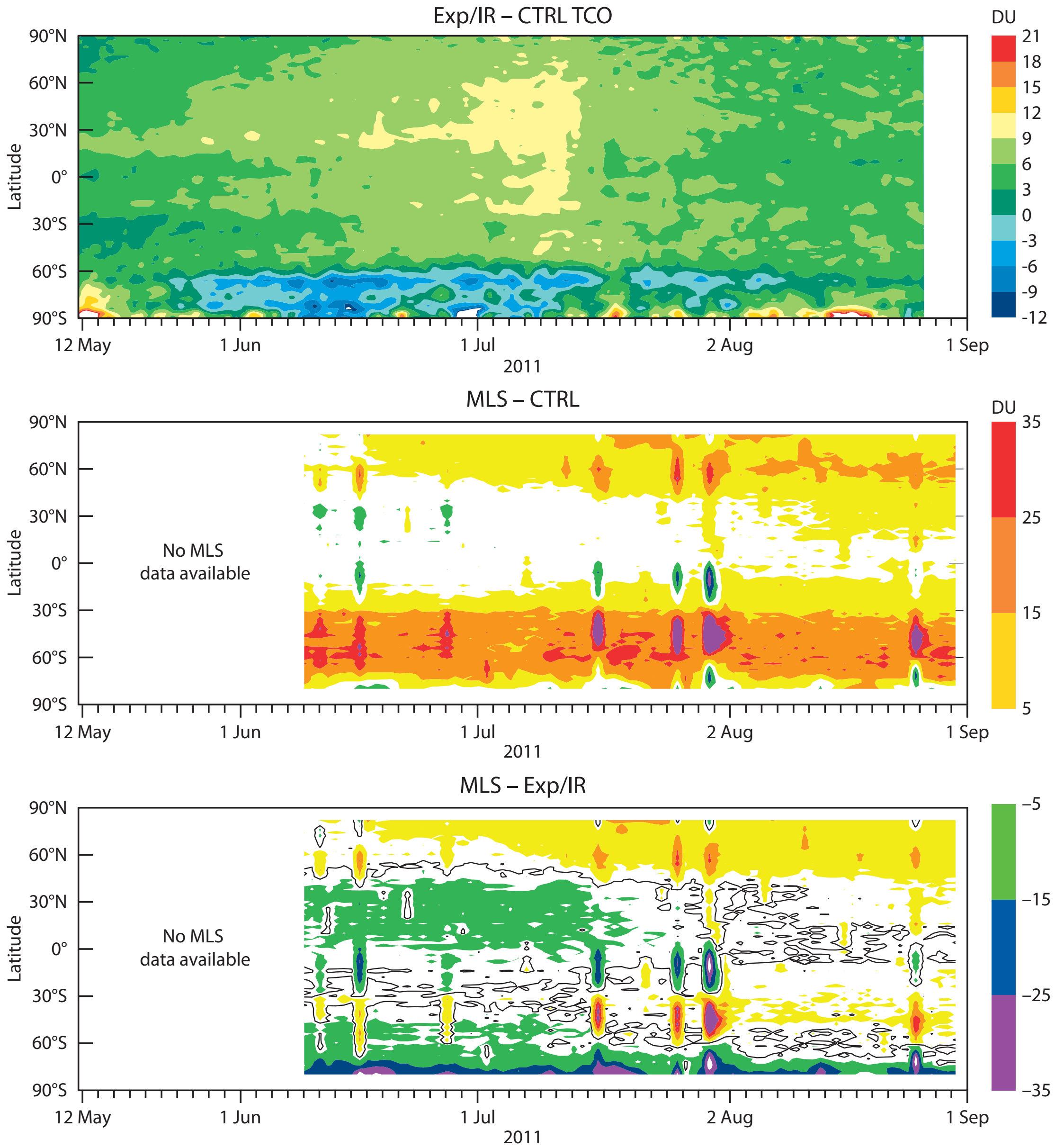

Figure 9 As for Figure 7 (top panel) and Figure 8 (middle and bottom panels), but when the ozone bias correction of the Exp/IR experiment was anchored to two IR/O_3 channels until 12 July, and to the additional SBUV ozone data afterwards. Note that MLS data was unavailable during the first part of the period.

Overview

This study has shown that IR/O_3 radiances from AIRS, IASI and HIRS can be successfully used to complement the existing BUV ozone data – providing additional information in the absence of sunlight and in the UTLS. The combined IR plus BUV ozone analyses agree significantly better with independent ozone information from sondes and the Aura MLS compared to an ozone analysis based on BUV data alone. As expected the main benefits are seen at altitudes below the ozone maximum in the region of the UTLS – particularly at high latitudes in the wintertime (when sunlight is limited).

Some vertical spreading of the analysis increments due to the IR/O_3 radiances can occasionally cause a slight degradation of ozone above the UTLS. This is not considered a severe problem and can be tolerated in view of the greater benefits brought by the radiance data. However, it has been shown that this spreading can be effectively constrained by providing the analysis with vertically-resolved ozone information above the UTLS from either MIPAS profiles – or indeed the operationally available SBUV used on its original 21 layers.

Longer-running experiments (in this and previous studies) have shown that the ozone analysis needs to be anchored to avoid model drift adversely affecting the VarBC bias corrections. Results clearly indicate that the use of just two IR/O_3 anchor channels is insufficient to stabilize the analysis in the longer term and these must be supplemented by anchoring information from the assimilation of uncorrected SBUV.

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Further reading

Han, **W.** & **A.P. McNally**, 2010. The 4D-Var assimilation of ozone-sensitive infrared radiances measured by IASI. *Q. J. R. Meteorol. Soc*, **136**, 2025–2037.

Jackson, **D.** & **R. Saunders**, 2002. Ozone data assimilation: preliminary system. *Technical Report 394*, Met Office.

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