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Reintroducing the analysis of humidity in the stratosphere

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An analysis of humidity in the stratosphere to help determine the initial conditions of weather forecasts was introduced in 1999 but removed again a few months later because of excessively high stratospheric humidity, which resulted in significant systematic forecast errors. We have now developed a new way of analysing humidity in the stratosphere, which improves forecasts. It will be introduced in the second half of this year in Cycle 50r1 of ECMWF's Integrated Forecasting System (IFS). The work described here is part of the Copernicus Atmosphere Monitoring Service (CAMS) EvOlution project (CAMEO) funded by the EU.

It is widely recognised that properly initialising the humidity field in numerical weather prediction is crucial for a realistic representation of the hydrological cycle, convection, precipitation, and clouds. Additionally, it is important to note that water vapour is a long-lived tracer in the stratosphere, influencing atmospheric radiative processes and directly affecting the stratospheric temperature profile, as well as the shape and strength of the tropopause. Consequently, an accurate analysis of the stratosphere's humidity field is important for controlling and reducing systematic errors in the IFS. However, experience at ECMWF illustrates that analysing humidity in the stratosphere can present challenges. The ECMWF operational analyses produced from 12 October 1999 to April 2000 using IFS Cycle 21r4, which permitted stratospheric humidity increments, revealed increased moisture in the lower stratosphere at high and mid-latitudes, leading to significant systematic forecast errors (Jakob et al., 2000). To address this systematic model drift, stratospheric humidity increments were disabled in the subsequent IFS Cycle 22r1 by zeroing background errors above the tropopause. Essentially, the stratospheric humidity analysis is only derived from the short-range forecast of the preceding analysis, except in regions of supersaturation caused by a temperature drop from the analysis. As a result, the stratospheric humidity primarily evolves according to the model's dynamics and the parametrization of physical processes, remaining largely independent of observations.

Bland et al. (2021) examined the biases in IFS forecasts for the lower stratosphere and their underlying causes. Their research reveals that humidity levels in the lowermost stratosphere are significantly overestimated: they reach up to 150% of the observed values compared to various independent data sources, including radiosondes, satellite limb sounders, lidar, and aircraft measurements. The moist bias in the lower stratosphere is also identified as the root cause of an increasing cold bias in temperature forecasts, with a cooling rate of –0.2 K per day. This cold bias results from excessive longwave radiative cooling due to the moist bias. These systematic errors are also discussed in Polichtchouk et al. (2021). This article describes the investigation into reintroducing the humidity analysis in the stratosphere and how this change addresses the warm and cold bias issues in IFS forecasts for the lower stratosphere.

Humidity assimilation in 4D-Var

Starting with IFS Cycle 26r3 (October 2003), the ECMWF 4D-Var assimilation system incorporates a pseudo-relative humidity control variable, defined as the humidity mixing ratio scaled by the saturation mixing ratio of the background. The primary advantage of this approach is that the error statistics for this control variable closely resemble those of a Gaussian distribution and are, therefore, more suitable for 4D-Var. The 4D-Var system adjusts the values of pseudo-relative humidity using various observations, which mainly concern the troposphere. These include radiosonde humidity profiles, GNSS-RO bending angles, and radiances from satellite microwave and infrared sounders. Radiosonde humidity data are not assimilated above the model-diagnosed tropopause (typically between 300 hPa and 100 hPa; see box for an explanation). Despite the absence of radiosonde humidity data above the tropopause, 4D-Var is still able to produce useful analysis increments in the lower stratosphere due to the spatial structure of the vertical correlations and the standard deviation of the background errors used in the analysis update. Additionally, humidity-sensitive channels from satellite-based radiometers, which peak in sensitivity within the upper troposphere, often exhibit an extended tail of sensitivity that reaches into the stratosphere, where humidity values are two orders of magnitude smaller than those in the troposphere. In summary, multiple pathways within the 4D-Var analysis can alter the lower stratospheric humidity field, even when it is not directly observed.

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The tropopause **A**

In addition to its association with a minimum temperature and a sharp change in static stability, the tropopause level (hygropause) is linked to the model level at which the specific humidity exceeds 3 mg kg−1 and the specific humidity two model levels below is greater than 5 mg kg−1, when examining model levels from 70 hPa down to 500 hPa.

So, what has changed since the mid-2000s that has made the reintroduction of stratospheric humidity analysis feasible? One factor is that 4D-Var has benefited from the introduction of ensemble-based techniques for uncertainty estimation through the Ensemble of Data Assimilations (EDA); progressive improvements in the fidelity of the IFS model, including refinements to its physical parametrizations; and concomitant increases in both vertical and horizontal resolution. EDA-derived covariances have drastically improved the situation compared to the mid-2000s, as they provide sharper and more localised error estimates than the previously used method (see Bonavita et al., 2016). Furthermore, the increase in the number of vertical levels in the IFS (60 in IFS Cycle 21r4 versus 137 in the current IFS Cycle 49r1), with a more than proportional increase around the tropopause, has also enhanced the data assimilation (DA) system's ability to represent sharp error structures, thus yielding more localised analysis increments. The combination of these enhancements in DA and the model is already sufficient, as demonstrated in the next section, to significantly improve the situation regarding the systematic errors of the analysis and forecast in the lower stratosphere. As anticipated, incorporating additional humidity observations with sufficient vertical resolution to resolve the tropopause enhances the accuracy and fidelity of the resulting analyses.

Humidity data assimilation in the stratosphere

Beyond retaining the stratospheric humidity increments produced by 4D-Var, we assimilate two additional types of observations sensitive to stratospheric humidity in the experiments discussed here. One source is the EOS-Aura Microwave Limb Sounder (MLS) moisture retrievals, which have a vertical resolution of approximately 3–5 km. The second additional source of stratospheric humidity information involves extending the vertical usage of the humidity observations from RS41-type sondes up to 60 hPa, as they are recognised for accurately measuring humidity across a wide range of atmospheric conditions. This will provide relevant measurements even when MLS data are no longer available, which is anticipated for mid-2026. Because of the limited availability of MLS data, they will not be assimilated in IFS Cycle 50r1, but the benefits of enabling stratospheric humidity increments are preserved even without MLS data.

Figure 1 presents zonal average plots of the mean forecast change in relative humidity (left) and temperature (right) between an experiment incorporating stratospheric humidity analysis using MLS and sonde humidity observations and a control. The primary direct effect of assimilation is the significant drying of the lower stratosphere, as illustrated on the left-hand side of Figure 1, alongside the corresponding moistening below the tropopause. Both effects mitigate the known systematic deficiencies of the IFS. A secondary, more indirect effect is observed on the right-hand side of Figure 1. Due to radiative effects, the temperature of the lower stratosphere becomes warmer, while the area under the tropopause cools, with this effect growing as the forecast time increases. Again, these changes significantly reduce the known IFS analysis and forecast biases. Additionally, the changes in the humidity field and those in the temperature field strengthen and sharpen the tropopause. This is also a step in the right direction, as a weak and diffuse tropopause is another well-documented systematic deficiency of ECMWF analyses and forecasts (see for example Krüger et al., 2024). Figure 2 displays the normalised change in forecast root-mean-square error (RMSE) of relative humidity (left-hand side) and temperature (right-hand side) from the stratospheric humidity analysis experiment, compared to the control and verified against its own analysis. Reintroducing the analysis of stratospheric humidity evidently improves forecasts across all lead times. The enhancements are more pronounced in the Upper Troposphere Lower Stratosphere (UTLS) layer, but there are indications that they propagate into the troposphere with increasing lead time. This is very encouraging because the interaction between tropospheric and stratospheric dynamics is intermittent, and these results suggest that the improved characterisation of the tropopause may lead to a better representation of the troposphere–stratosphere interaction.

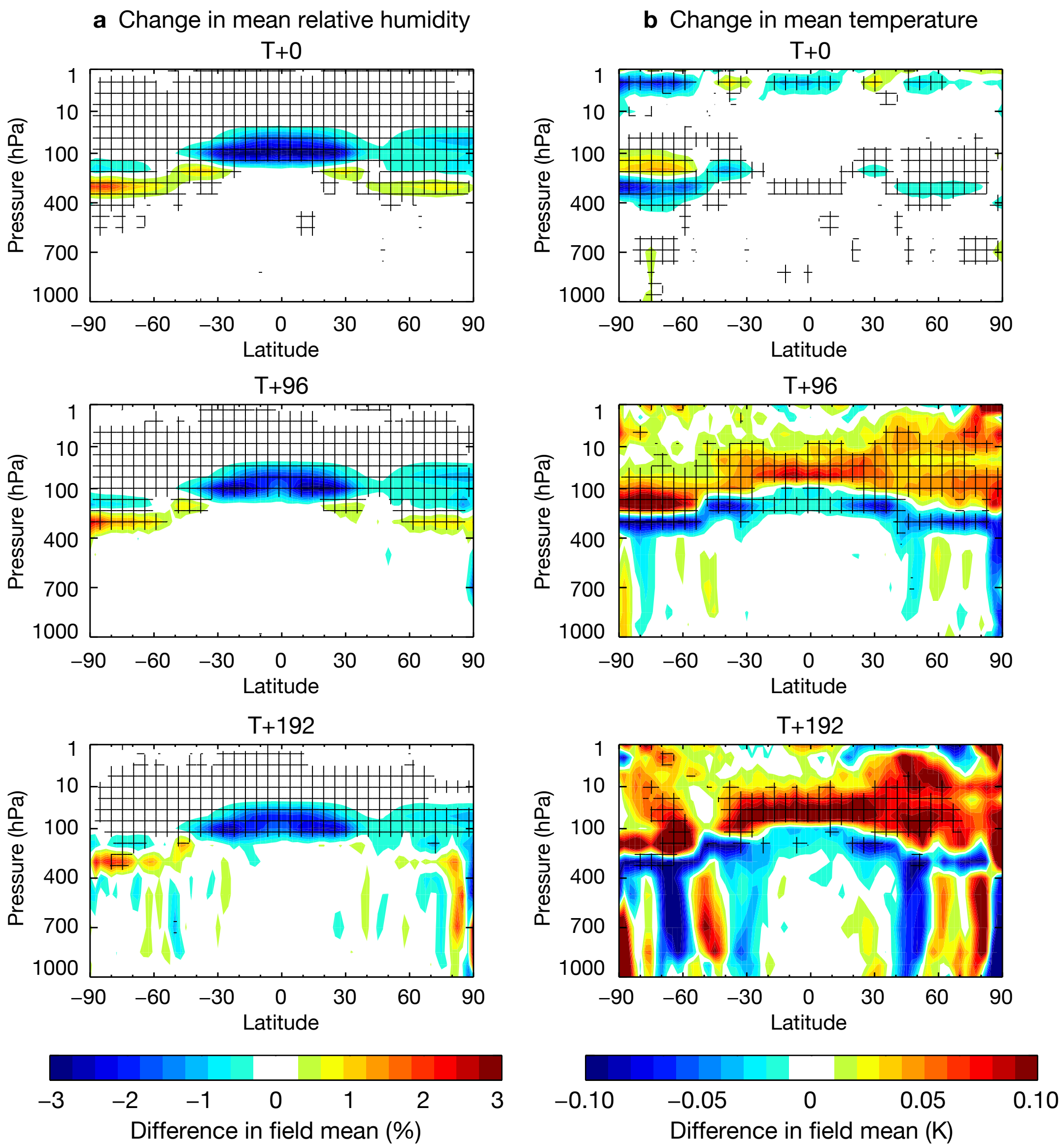

Figure 1 Change in (a) the forecast mean relative humidity and (b) the forecast mean temperature in a stratospheric humidity analysis experiment compared to the control over two and a half months of experimentation (13 December 2020 to 28 February 2021) at forecast times of 0, 96 and 192 hours. Areas marked with cross-hatching are statistically significant at the 95% level.

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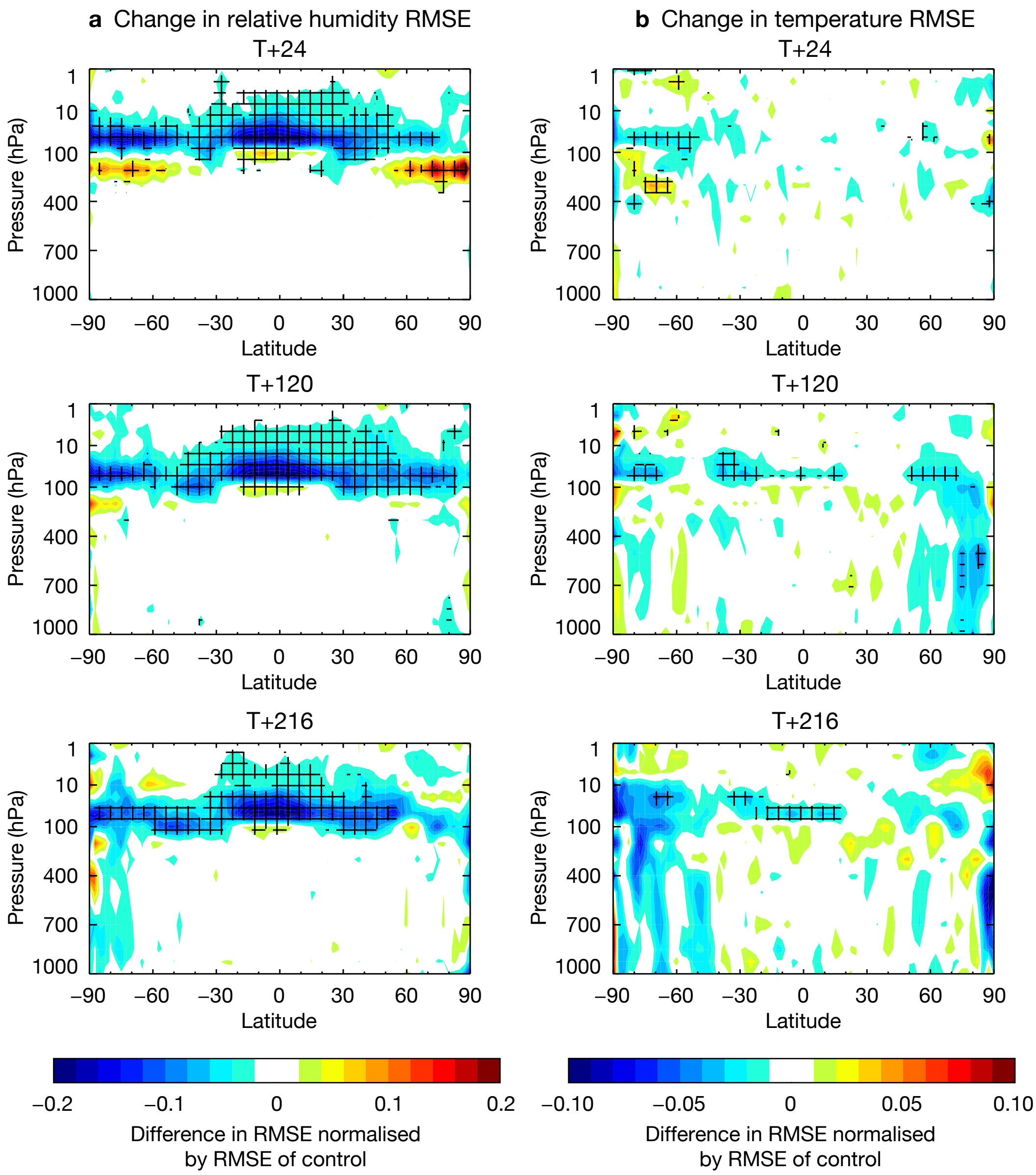

Figure 2 Normalised change in root-mean-square error (RMSE), in the stratospheric humidity analysis experiment compared to the control, of (a) relative humidity forecasts and (b) temperature forecasts, verified against own analysis, over three months of experimentation (3 December 2020 to 27 February 2021), at forecast times of 24, 120 and 216 hours. Areas marked with cross-hatching are statistically significant at the 95% level. Blue cross-hatched areas indicate a significant reduction in forecast error and hence an improvement in forecast quality.

Future directions

The results presented here clearly demonstrate the benefits of reintroducing the analysis of stratospheric humidity in the ECMWF operational assimilation cycle after a hiatus of over 20 years. This will be one of the main contributions to the upcoming IFS Cycle 50r1. They also highlight the importance of limb sounding observations that are sensitive to humidity and possess sufficient vertical resolution to resolve the tropopause, such as the proposed Changing-Atmosphere Infra-Red Tomography Explorer (CAIRT). If implemented, with high vertical resolution and the capability to measure key atmospheric components like water vapour, ozone, and aerosols, CAIRT would provide invaluable data to enhance climate models, improve weather forecasting, and deepen our understanding of atmospheric processes in the UTLS.

Humidity, like other trace gases, functions as a long-lived tracer in the stratosphere. Accurate initialisation directly influences extended-range predictability through wind-tracing effects and indirectly through radiative effects in the model and the observation operators of nadir-sounding satellite instruments. Therefore, enhancing the accuracy of initial conditions for trace gases in the stratosphere can substantially improve forecast skill in the medium and extended range. Current efforts aim to unlock this potential in future IFS operational cycles.

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Further reading

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