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Assimilating satellite data along a slanted path

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Over the last two decades satellite radiances have come to have the greatest impact on forecasts compared to other types of observations used in numerical weather prediction (NWP). The satellite data are used to determine the initial conditions at the start of a forecast. However, their assimilation into forecast models has traditionally neglected the fact that, most of the time, satellite instruments view the Earth at an angle and therefore sound an atmospheric column that slants through the atmosphere. Data assimilation systems have instead essentially assumed that satellite instruments sense vertical profiles of the atmosphere, only taking into account the increased path length to determine to which vertical layers the radiances relate. With the upgrade of ECMWF's Integrated Forecasting System (IFS) in November 2016 (IFS Cycle 43r1), ECMWF became the first NWP centre to fully take the slanted viewing geometry into account in its operational system. The change has led to improvements in the assimilation of satellite radiances. This has resulted in improved forecast performance that is statistically significant in the short range, particularly in the stratosphere and at higher latitudes. This article gives an overview of what has changed and how forecasts have improved. The interested reader is referred to *Bormann* (2017) for further details.

Satellite viewing geometry

Close to 80% of the observations currently assimilated in the IFS come from passive sounding instruments on satellites, which measure radiation emitted naturally and do not actively transmit their own signals. These observations also have the largest impact on forecasts. The measurements are made by so-called nadir sounders. The viewing geometry of such sounders is illustrated schematically in Figure 1. Despite their name, most of the time nadir sounders do not look directly downwards towards Earth but view the Earth at an angle, as determined by the satellite's zenith angle (Figure 1). Cross-track scanners, for instance, scan the Earth at different viewing angles, with zenith angles varying between 0° (viewing directly downwards, i.e. a nadir view) to 50–60° either side from the nadir.

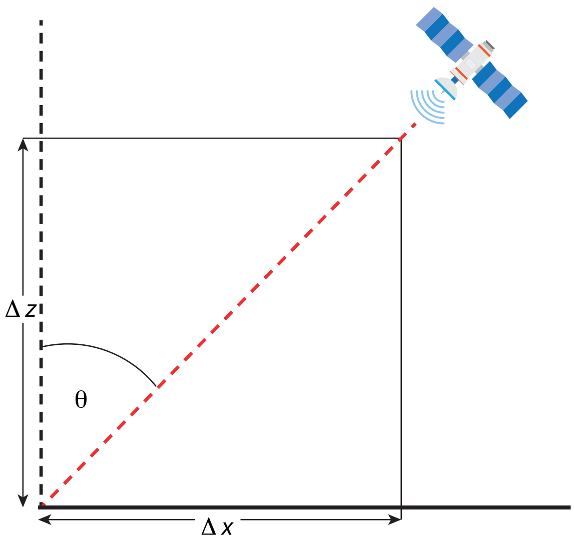

Figure 1 Schematic diagram of the satellite viewing geometry. The dashed black line represents the profile used until recently to describe the atmosphere for radiative transfer calculations in the ECMWF data assimilation system; the red dashed line shows the profile used in slant-path radiative transfer calculations. The angle θ is the satellite zenith angle.

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When the satellite instrument views the atmosphere at a zenith angle greater than 0° (see dashed red line in Figure 1), two effects occur: first, the viewing path through the atmosphere gets longer compared to the nadir view. This affects the position of the layers in the vertical to which a particular channel is sensitive. This effect has always been taken into account in radiative transfer models such as RTTOV (Box A) by appropriately scaling the optical depth of the atmosphere. Second, the atmospheric column sounded by the satellite instrument slants through the atmosphere. This effect has so far been ignored in data assimilation at NWP centres. Instead, the observed radiances from the slanted column have been compared with model equivalents (simulated radiances derived from a short-range forecast) calculated from a single vertical column (represented by the dashed black line in Figure 1). The vertical column's location is based on the geo-location information provided with the data, that is, the position where the instrument's view intersects the Earth's geoid (the surface corresponding to mean sea level). For a channel that senses the atmosphere at higher levels, this means that the model information is extracted in the wrong place. The displacement is most relevant for larger zenith angles and for channels that are mostly sensitive to higher layers of the atmosphere. For example, for a channel primarily sensitive to temperature in the lower stratosphere, at around 16 km, and viewing the Earth with a zenith angle of 60°, the displacement will be around 28 km. Such a channel will also have some sensitivity to levels even higher in the stratosphere, and for these levels the displacements will be even larger.

Radiative transfer model **A**

The purpose of a radiative transfer model is to determine what kind of radiances would be measured given a particular state of the atmosphere. The radiative transfer model can thus be used to simulate the radiances associated with the modelled state of the atmosphere in a short-range forecast. The data assimilation system compares the observed radiances with the simulated model equivalents and makes adjustments to the model atmosphere to better match the observations provided. A highly accurate radiative transfer model is important in order to make reliable adjustments. The radiative transfer model used at ECMWF is RTTOV, which has been developed by the EUMETSAT NWP SAF. RTTOV stands for Radiative Transfer for TOVS (TIROS Operational Vertical Sounder). TIROS refers to the US Television Infrared Observation Satellite programme.

The displacement error can be avoided by making better use of the model atmosphere when we interpolate the model fields to the observation locations. Instead of interpolating to the dashed black line in Figure 1, we can interpolate to the dashed red line and then pass the resulting slanted profile of model information to the radiative transfer model. During the assimilation, the adjustments of model variables can then also be applied to the slanted column rather than the vertical column. These changes were implemented operationally in IFS Cycle 43r1 on 22 November 2016. The slant-path calculations are performed for all sounding radiances used in our clear-sky system. The calculations require knowledge of the satellite's zenith and azimuth angles, which together describe the orientation of the slanted atmospheric column in a three-dimensional atmosphere. This information is usually provided with the observations. The technical framework used is based on earlier developments for two-dimensional observation operators for limb-viewing instruments, such as radio occultation or passive infrared limb radiances (*Healy et al.*, 2007, *Bormann et al.*, 2007). The effect and the size of the displacement in the slant-path case are roughly similar to those encountered from radiosonde drift, which should be taken into account for some sondes in the IFS from Cycle 45r1 onwards.

Better calculations of model equivalents

Taking the slanting viewing geometry into account leads to better simulations of the satellite observations from the model background (a short-range forecast). Figure 2 shows the standard deviation of the difference between observations and model equivalents as a function of the scan position for a particular channel of the Advanced Technology Microwave Sounder (ATMS). The channel is primarily sensitive to temperature around the tropopause. With the previous approach (black line in Figure 2), larger differences between the observations and the model equivalents are apparent for larger zenith angles. This can be attributed to the displacement errors inherent in the previous approach. The feature is very significantly reduced when we take the slant-path effect into account (red line in Figure 2). The influence of the slanted viewing path is particularly noticeable for this instrument as it is a cross-track scanner with a particularly wide swath, leading to some of the largest zenith angles at the swath edges. There has been a trend towards wider swaths for newer cross-track scanning instruments. This makes it increasingly important to take the slant-path effect into account.

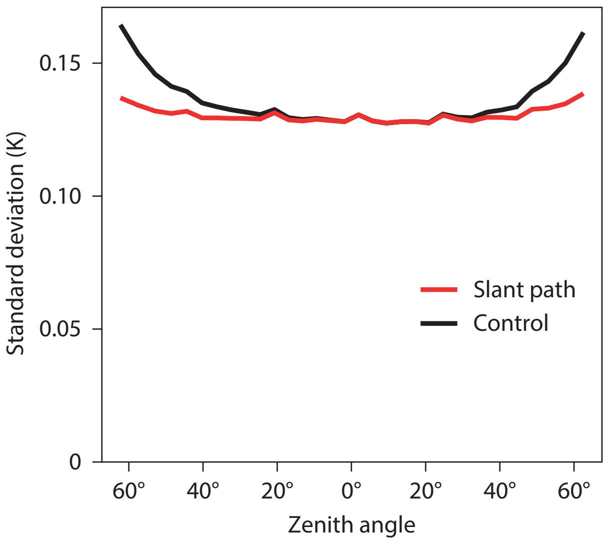

Figure 2 Standard deviations of the differences between observations and model equivalents (observations minus short-range forecast) for ATMS channel 9 as a function of scan-position (labelled here by zenith angle on the x-axis). The previous approach ('Control') leads to larger differences for higher zenith angles compared to when the slant-path effect is taken into account ('Slant path'). The statistics are based on observations after 3x3 averaging, and the same atmospheric background fields were used for the Slant-path and the Control calculations. Data cover a 1-month period in January/February 2015, over sea, after screening for clouds.

Figure 3 shows the global overall effect of modelling the slanted viewing geometry for a range of instruments and channels. Note that these statistics include all zenith angles. The effect is of course stronger for observations with large zenith angles. The microwave instrument ATMS and the hyperspectral Cross-track Infrared Sounder (CrIS) benefit the most from the slant-path modelling. Relative reductions in the standard deviations of the differences between observations and model equivalents reach nearly 8% and about 2% globally for ATMS and CrIS, respectively. Aside from the relatively wide swath for these instruments, this is also a reflection of lower noise in the observations, so that the displacement errors are relatively more important compared to the instrument noise. While in absolute terms the effect is larger the higher the channel peaks in the atmosphere, this is not necessarily apparent in these relative statistics. This is because instrument noise and errors in the short-range forecasts, which also contribute to the differences between observations and model equivalents, tend to be higher for temperature channels sounding the higher stratosphere. Some effect is also clearly visible for humidity-sounding channels sounding the upper troposphere (e.g. ATMS channels 18–22).

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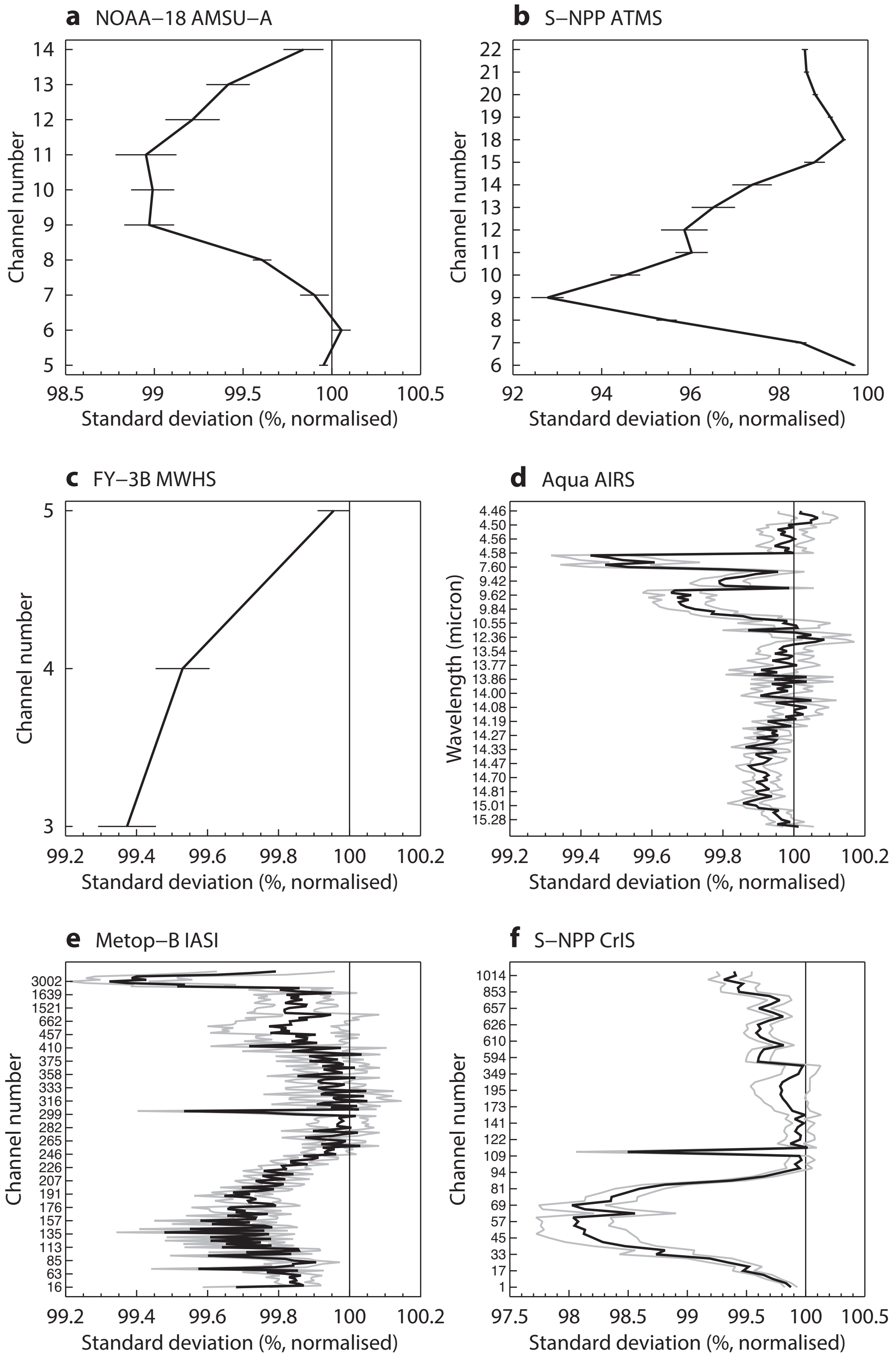

Figure 3 Improvements from slant-path calculations for a range of satellite instruments. The plots show the standard deviations of differences between observations and model equivalents, calculated with the slant-path effect included, normalised by the values obtained using the previous approach. Values under 100% therefore show a reduction in the displacement error in the calculations of the model equivalents. The atmospheric background is the same for both calculations and is taken from a 1-month period in January/February 2015. Statistics are shown for (a) the Advanced Microwave Sounding Unit (AMSU)-A on board the NOAA-18 satellite, (b) ATMS on board the Suomi-National Polar Partnership (S-NPP) satellite, (c) the Microwave Humidity Sounder (MWHS) on board the Feng-Yun-3B satellite, (d) the Atmospheric Infra-Red Sounder (AIRS) on board the Aqua satellite, (e) the Infrared Atmospheric Sounding Interferometer (IASI) on board Metop-B, and (f) CrIS on S-NPP.

For temperature-sounding channels, the effect is largest over mid- and higher latitudes. This can be seen in Figure 4a, which shows the differences between the previous and the new approach for an ATMS channel peaking around the tropopause. The reason is that the spatial gradients along the viewing direction tend to be particularly large for temperature in these regions. By contrast, for humidity sounding channels sounding the upper troposphere, the reduction in standard deviation is most noticeable around the mid-latitude storm tracks (Figure 4b).

Better forecasts

Assimilation experiments show that accounting for the slant-path effect improves forecast quality. Two experiments were conducted: a 'Control' experiment in which the slant-path effect is neglected, similar to the operational configuration before Cycle 43r1, and a 'Slant path' experiment, in which the slant-path effect is taken into account for all sounder radiances that are not treated in the all-sky assimilation. Radiances treated in all-sky are currently not considered since the treatment of viewing angles is more complex in cloudy conditions, and the interpolation to the slant path may also introduce undesirable smoothing of cloud details. This means the majority of microwave humidity sounders, with the exception of MWHS and ATMS, are excluded from the slant-path treatment. The experiments used ECMWF's 12-hour 4D-Var assimilation system, with a model resolution of TCo639 (16 km), an incremental analysis resolution of TL255 (80 km), and 137 levels in the vertical. Two four-month periods were considered: 2 June – 30 September 2014 and 2 December 2014 – 31 March 2015.

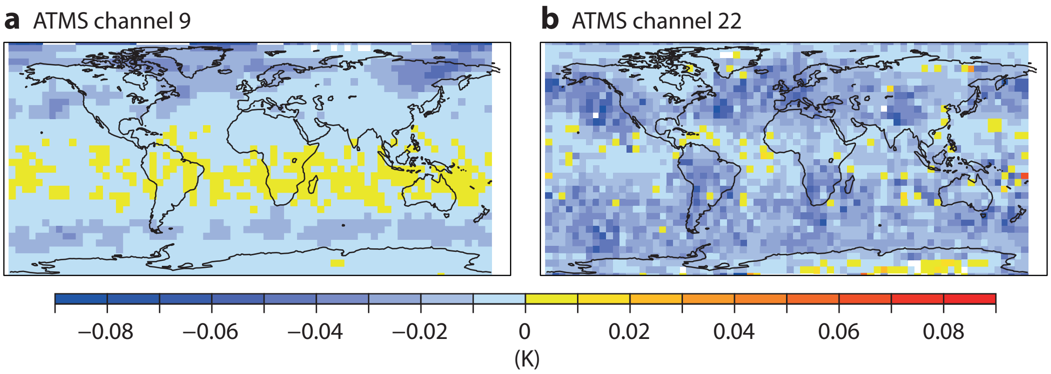

Figure 4 Geographical distribution of improvements in observation modelling. The maps show the change in the standard deviation of differences between observations and model equivalents when introducing the slant-path calculations for (a) ATMS channel 9, a channel primarily sensitive to temperature around the tropopause, and (b) ATMS channel 22, the uppermost tropospheric humidity-sounding channel of ATMS. Negative values (blue) show a closer agreement between model equivalents and observations when using slant-path calculations. For both channels, the statistics are based on observations after 3x3 averaging, and the same atmospheric background fields were used for the slant-path and the previous calculations. Data cover a one-month period in January/February 2015 after cloud screening.

The most notable effect in the assimilation experiments is that overall the analysis makes smaller adjustments to the background. The size of the analysis increments (i.e. the difference between the background and the analysis) is reduced by up to around 10% for higher latitudes and higher levels. This is illustrated in Figure 5a, which shows zonal (east–west) means of the relative change in the size of the analysis increments for wind. Other variables show a very similar pattern. As we did not change the observation errors in these experiments, the reduction in the analysis increments is an expected effect of the smaller differences between observations and model equivalents for the sounder radiances shown earlier. It could be argued that the reduction in the displacement error apparent from the previous section means that the assumed observation error used in these experiments should be reduced accordingly for the observations concerned. This would give them more weight and would most likely alter the size of the analysis increments. This has not been pursued here since the uncertainty in the assumed observation errors is probably larger than the error reduction obtained with the slant-path modification. However, taking the slanted path of satellite soundings into account may well make it possible to use a reduced observation error in the future, for instance for ATMS.

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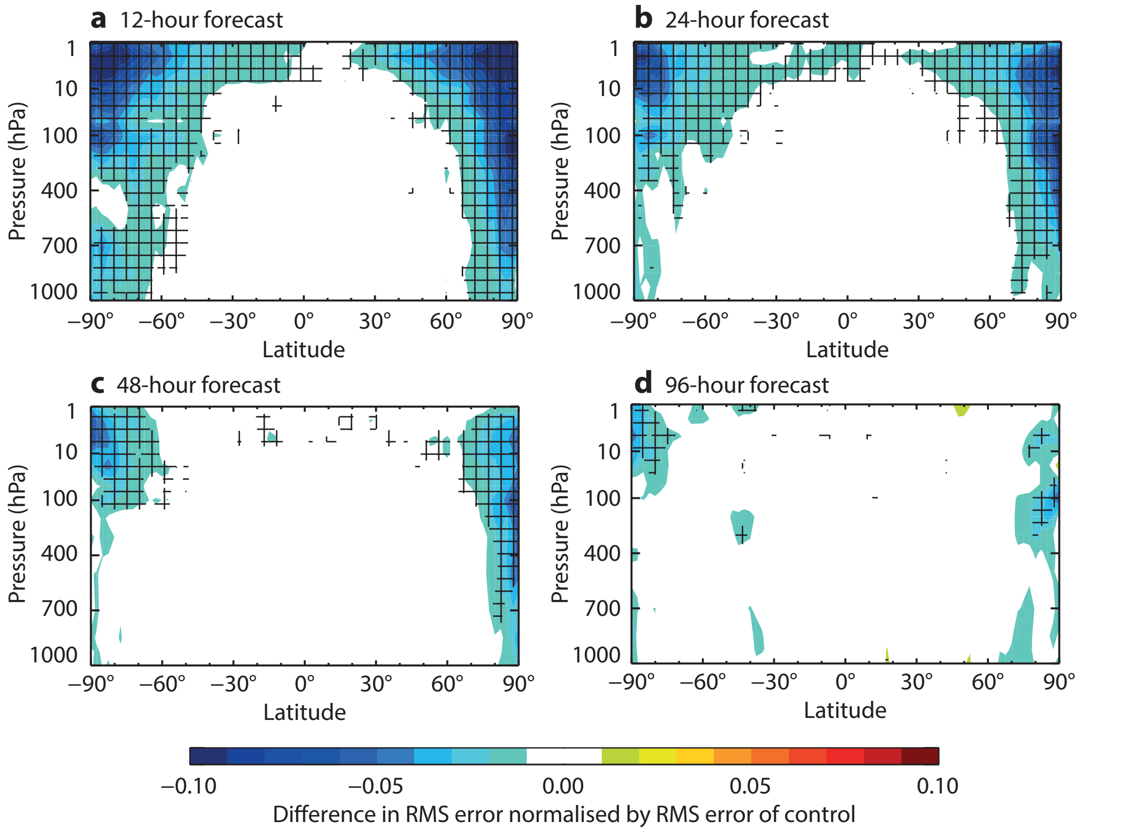

Figure 5 Better short-range forecasts and reduced increments. The panels show the relative change in the zonal mean root-mean-square vector wind error when the slant-path calculations are used in the assimilation for forecast ranges of (a) 12 hours, (b) 24 hours, (c) 48 hours and (d) 96 hours. The 12-hour forecast range also provides a measure of the change in the size of the analysis increments. Statistics are based on forecasts for a total of eight months over the two seasons considered, and each experiment was verified against its own analyses.

The reduced analysis increments lead to some statistically significant reductions in the size of forecast errors up to day 3, especially at high latitudes and in the stratosphere (Figure 5b–c). These improvements can be found in all geophysical variables. The reductions in forecast error beyond day 1 are, however, mostly small and generally less than 1% when averaged over the extra-tropics in the troposphere.

Outlook

Taking the slant-path geometry better into account is an example of the better use that can be made of the full three-dimensional model information that is available to us in an NWP system. Through this work, we improve the ability of the observations to identify and correct errors in short-range forecasts by eliminating a source of error arising from an unnecessary simplification in the interpretation of the full model information. Similar benefits were previously demonstrated in the limb-viewing context (*Healy et al.*, 2007; a, 2007), where taking horizontal structure into account also reduced the errors inherent in the assimilation of these observations. Making better use of the full spatial information will become even more important as spatial model resolution increases and uncertainties in observations and short-range forecasts are reduced. For example, changes to be implemented as part of IFS Cycle 45r1 will account for radiosonde drift. For satellite radiances, we intend to investigate how we can better take the extent of the spatial footprint into account: with nominal spatial model resolutions well below the footprint size of satellite radiances, simple interpolations of model variables to a single location (or a slanted line of sight) are likely not to be optimal and explicit modelling of the spatial footprint may be beneficial. Such an approach is expected to be particularly beneficial when assimilating cloud- and rain-affected observations from microwave imagers since it offers ways to better capture sub-footprint size model cloud variability. In addition, three-dimensional effects around clouds can play a significant role, and local three-dimensional radiative transfer calculations may offer benefits in certain situations. These developments will further improve the realism with which we can simulate observations and hence improve our interpretation and use of observations to specify the initial conditions at the start of a forecast.

Further reading

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