Stratospheric and Mesospheric Data Assimilation

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Abstract

Many weather forecast centers now use global models with lid heights in the middle mesosphere in order to simulate the stratosphere and better assimilate nadir radiance measurements. However, assimilation of data from the stratosphere and mesosphere poses new challenges. In order to understand the behaviour of such assimilation systems it is necessary to consider the dynamics of this region. In this work, we consider how the dynamics of the middle atmosphere impact the data assimilation problem.

1. Introduction

The middle atmosphere refers to the stratosphere and mesosphere and extends from roughly 10 to 80 km above the Earth's surface. Temperature increases with height in the stratosphere due to the absorption of ultraviolet radiation by ozone and decreases with height in the mesosphere as the ozone concentration drops off. There are various reasons for wanting to simulate or estimate the state of the stratosphere. For instance, one may want to study stratospheric ozone loss or dynamic events such as stratospheric sudden warmings (SSWs), or increase predictive skill of extended range (10 days to seasonal) forecasts, or simply assimilate nadir satellite observations. Figure 1 shows the normalized weighting functions from the Advanced Microwave Sounding Unit (AMSU)-A instrument. Several channels (12-14) exhibit sensitivity to stratospheric temperature. In order to assimilate these channels, a model would need a good background forecast up to 0.1 hPa, so its sponge layer should begin above this level. This then implies a model lid in the middle mesosphere. For this reason, many operational weather forecasting centers (e.g. ECMWF, Met Office and GMAO) use forecast models with lid heights at 0.01 hPa (roughly 80 km). Thus the stratosphere and even the lower mesosphere are now part of the weather forecasting domain. In order to understand how the forecasting and assimilation systems respond to perturbations such as analysis increments, it is necessary to understand a little about middle atmosphere dynamics. A very brief introduction is given here, but more detailed accounts are available in textbooks (e.g. Andrews et al. 1987, Vallis 2006) and articles (e.g. Shepherd 2000, 2002, 2007; McLandress 1998; Smith 2004).

The stratosphere is statically stable and the climatological winds are to a first approximation zonal. If we consider the two-dimensional, steady, geostrophic and hydrostatic equations, in the absence of a momentum source the atmosphere would be in radiative equilibrium balance with outgoing terrestrial radiation balancing incoming solar radiation. This means a cold dark winter pole and a warm sunlit summer pole. Through thermal wind balance, zonal winds increase with height. However, radiative-equilibrium temperature calculations yield temperatures that are far too cold near the winter pole, and zonal winds speeds that are much too strong. To demonstrate that the assumption of no momentum

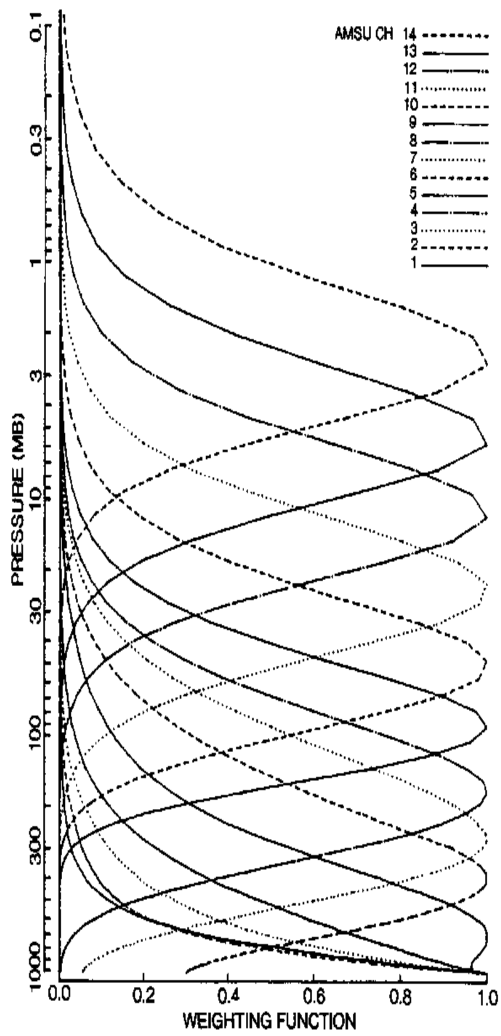

Figure 1: Normalized AMSU-A weighting functions. Figure source is unknown.

source is inaccurate, McLandress (1998) added a simple Rayleigh friction term to simulate a forcing term which is linearly proportional to wind and which increases with height. The resultant temperatures and zonal wind speeds were then brought closer to observations. The conclusion is that some kind of momentum source is needed to explain the observed zonal mean temperatures and winds, as was first hypothesized by Leovy (1964).

The origin of this momentum source is breaking waves, which exert a drag on the zonal mean flow and drive a mean meridional circulation. In the winter stratosphere large-scale quasi-stationary planetary waves forced by topography and land-sea contracts are able to propagate vertically where they increase in amplitude as density decreases. Eventually they break, impart their momentum to the zonal mean flow, exerting a drag on the wintertime westerlies. This creates poleward motion through a Coriolis torque and by continuity, descent (and warming through adiabatic compression) over the winter pole. Thus, waves drive this thermally-indirect circulation, called the Brewer-Dobson circulation. The Brewer-Dobson circulation is important not only for explaining stratospheric temperature distributions, but also for transporting constituents, as is apparent in the accumulation of ozone over the winter pole in Figure 2. The conditions for vertical propagation of quasi-stationary Rossby waves (see Andrews et al. 1987, chapter 4.5 or Vallis 2006, chapter 13.3) in the case of a constant wind (U) are that U>0 (eastward) and U remains below a critical value (U_c). Thus these waves cannot propagate into the stratosphere in summer when zonal winds are easterly. Furthermore, in the winter when they can propagate vertically, large scale waves (wavenumbers 1 to 3) are favoured because the critical wind speed (U_c) decreases rapidly with increasing wavenumber. Thus the winter stratosphere is dominated by waves having large horizontal scales. Due to the absence of vertically propagating quasi-stationary Rossby waves in easterlies, the summer stratosphere is characterized by temperatures closer to radiative equilibrium.

The stratospheric jets also act to filter much smaller-scale waves (i.e.,gravity waves) which propagate up to the mesosphere. In winter when stratospheric winds are westerly and increasing with height, gravity waves with eastward phase speeds may reach their critical level (where the zonal phase velocity equals the zonal wind) in the stratosphere. This removal or “filtering” of eastward propagating waves at their critical levels leads to predominantly westward propagating gravity waves reaching the mesosphere. When those waves break in the mesosphere they create a net westward drag force. Similarly, in the summer hemisphere, easterly winds filter westward propagating gravity waves at their critical levels, so that gravity waves which break in the mesosphere create a net eastward drag. In the mesosphere, the deceleration of the westerlies in the winter hemisphere and deceleration of the easterlies in the summer hemisphere create poleward motion in the winter hemisphere, but equatorward motion in the summer hemisphere. By continuity, there is descent over the winter pole and ascent over the summer pole. Thus gravity waves drive a pole-to-pole circulation in the mesosphere.

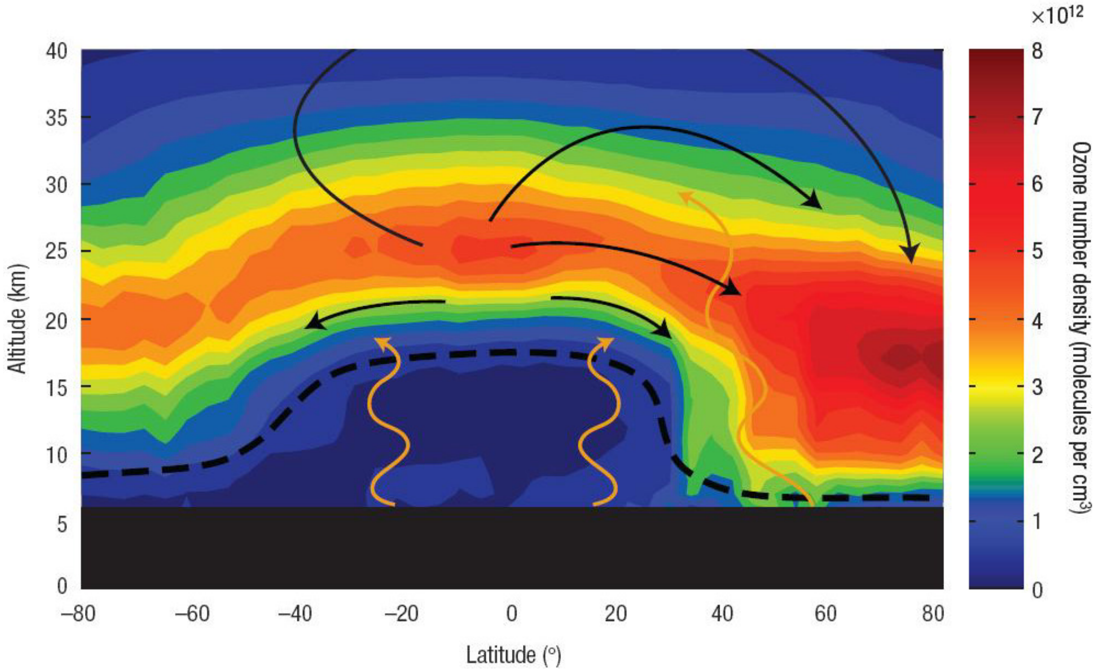

Figure 2: Cartoon of the Brewer-Dobson circulation. Meridonal circulation is indicated by black arrows. The tropopause is indicated by a heavy dashed line. The ozone distribution for March 2004 from OSIRIS is shown in colours with values indicated by a colour bar on the right. From Shaw and Shepherd (2008).

2. Impact of middle atmosphere dynamics on data assimilation

The fact that the middle atmosphere is largely driven by waves propagating up from the troposphere has implications for data assimilation. The fundamental difference in stratospheric dynamics between winter and summer also impacts interpretation of data assimilation results and inputs (such as covariances). Finally, the importance of gravity waves to the mesospheric circulation means that these signals (which are frequently treated as noise in the troposphere) might need to be better simulated or estimated. In this section, we explore how middle atmosphere dynamics impact inputs and results of data assimilation systems.

2.1 Vertically propagating waves

Figure 3 shows that by changing only the strength of an externally applied filter in a 3D-variational (3D-Var) system, systematic impacts on mesospheric temperatures are seen. Specifically, the stronger the filter, the colder the global mean mesopause temperature. A difference of 20 K at 90 km is seen between experiments. These results were surprising because the system employed the Canadian Middle Atmosphere Model (CMAM) (Scinocca et al. 2008) which extends to about 95 km but the observations were inserted only below about 45 km. Thus the filters were targeting imbalance arising from increments below 45 km. Yet below 45 km, the temperature profile averaged over all coincident measurement locations was virtually identical regardless of the filter employed. This is because the averaging over all profiles smoothes whatever degree of noise is present in the profiles with different filters. However, the waves defined by the increments in the troposphere (whether real or spurious) propagate up to the mesosphere where they break and create a drag, which the model converts to a heating. Thus a strong filter results in fewer waves reaching the mesosphere. This was confirmed by comparing the temperature variance of time series of analyses from the various experiments. The stronger the filter, the smaller the variance. Thus resolved waves in the troposphere and stratosphere can propagate up to the mesosphere and impact the zonal mean (or global mean) flow. The implication is that tropospheric tuning of data assimilation systems can have large impacts on mesospheric analyses. On the other hand, the sensitivity of the mesosphere can also be used to tune assimilation parameters (such as filter strength, as in Sankey et al. 2007).

Nezlin et al. (2009) demonstrated that even without observations above 45 km, large scales (up to wavenumber 10) in the mesosphere could be improved. They also showed that the quality of mesospheric analyses was sensitive to the accuracy of observations taken below 45 km. Both of these facts attest to the vertical propagation of information. (Here we use the term "information" to describe that part of the true atmospheric signal that a given model can resolve.) Since the middle atmosphere is largely forced by upward propagating waves, information and errors propagate vertically in data assimilation systems. Nezlin et al. (2009) obtained theoretical results in the context of a perfect model assumption, but Xu et al. (2011a,b) demonstrated that CMAM-Data Assimilation System (DAS) mesospheric winds compare well to independent measurements on long time scales. This confirms that vertical propagation of information from the troposphere to the mesosphere actually occurs in assimilation systems.

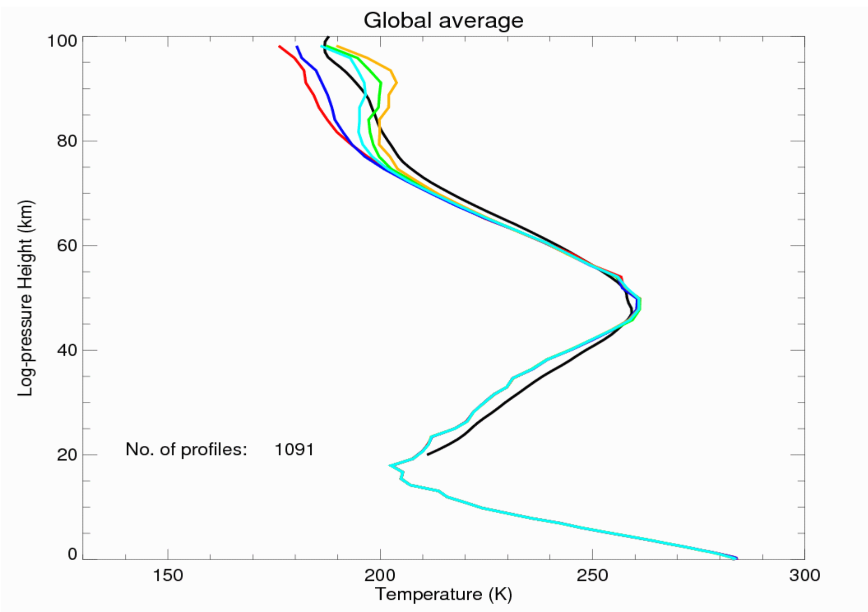

Figure 3: Average of CMAM-DAS temperature profiles sampled at SABER locations during 25 January 2002. The temperatures are from analyses obtained from assimilation experiments which were identical except for the externally applied filter. In all cases, observations were assimilated below 45 km only. The colours are black (SABER data), cyan (DF with 12-h cutoff), yellow (DF with 6-h cutoff), green (IAU with 6-h cutoff), blue (IAU with 4-h cutoff), and red (IAU with constant coefficients). Filter strength increases as follows: yellow-green-cyan-blue-red. From Sankey et al. (2007).

Since not all waves will be correctly analysed (because the observing system can define only certain spatial scales), and some waves are forced by parameterization schemes which are imperfect (e.g. deep convection), we should expect errors in the meridional circulation. Errors in the forcing of a meridional circulation should then lead to latitudinally varying biases. Thus, we should expect bias in stratospheric forecasts. Since observations (such as those from nadir sounders) also have bias and require a pre-assimilation bias-correction procedure, the challenge is to separate these two sources of bias. Moreover, observation bias correction schemes often rely on an assumption of unbiased forecasts—which is clearly invalid in the stratosphere. Dee and Uppala (2009) note that improvement in stratospheric bias of ERA-interim over ERA-40 was achieved through the introduction of variational bias correction (Derber and Wu 1998). In this procedure, bias correction parameters are added to the control vector so that all observations—including those which are not corrected such as radiosondes--are used to determine their values. This then forces a consistency among observations which are being bias corrected (e.g. the same instrument on different platforms). Of course, even with variational bias correction, the bias so-determined could be due to either a bias in observations or observation operators or to a bias in the model forecast. Since the bias correction is applied to the observation, only the former type of bias is desired. Thus care must be taken to ensure that the recovered bias is truly due to the observations. To some extent, the anchoring of the assimilation system by uncorrected observations (such as radiosondes) reduces the likelihood that model bias will be detected. However, in the upper stratosphere and mesosphere where few uncorrected observations exist, the danger of correcting for model bias is considerable. Thus Dee and Uppala (2009) chose to leave the top peaking channel (SSU channel 3 or AMSU-A channel 14) uncorrected in the ERA-interim, in order to anchor the system. This resulted in a reduced warm bias near the model top. Since a warm bias had independently been attributed to the model forecast (McNally 2004) the results were positive. Variational bias correction has thus proven to be a valuable tool for reanalyses as well as operational assimilation systems. However, the problem of separating model and measurement bias in the upper stratosphere remains. Leaving a certain instrument uncorrected still creates difficulty when it is present on multiple platforms, or when the observing system changes (e.g. when the top peaking channel changed from SSU ch. 3 to AMSU-A ch. 14). Furthermore, whatever bias exists in the uncorrected measurement will appear in the analyses.

In summary, the fact that the middle atmosphere is driven by vertically propagating waves has important implications for data assimilation systems.

- Tropospheric waves (whether correctly simulated or not) impact zonal mean fields in stratosphere and mesosphere. This means that apparently random signals (e.g. waves) can produce nonlocal systematic errors (e.g. a zonal mean bias)
- Since not all waves are correctly simulated, we should expect bias (errors in zonal mean) in the mesosphere and stratosphere. This has implications for observation bias corrections schemes that assume background forecast is unbiased
- Mesospheric analyses are sensitive to errors in tropospheric analyses. On the other hand, perhaps we can use this sensitivity to help choose assimilation parameters in troposphere.
- Information propagates up (through resolved waves during the forecast step). Some of large scales in mesosphere can be improved even with no mesospheric observations if tropospheric wave forcing is captured and the middle atmosphere is well modelled.

2.2 Polar dynamics

The winter polar stratosphere is dominated by westerly winds that increase with height and define a polar vortex (polar night jet). In the Northern Hemisphere this vortex is occasionally disrupted by stratospheric sudden warmings (SSW) events during which temperatures can rise dramatically (by 50 K in one week) at 10 hPa. Simultaneously, the climatological westerly winds weaken and may even become easterly. Mesospheric coolings can also occur in conjunction with stratospheric warmings. Since SSW events are driven by planetary waves propagating up from the troposphere, such events involve vertical coupling from the troposphere to the mesosphere. Baldwin and Dunkerton (2001) showed that the dominant mode of slowly varying wintertime variability called the Northern Annular Mode (or NAM) has a spatial structure which is similar from the surface to over 50 km, thus indicating a coupling of the troposphere and stratosphere. (At the surface the pattern is called the Arctic Oscillation or AO.) The NAM pattern at 10 hPa is a disk of similarly signed values around the pole with oppositely signed values in a ring or annulus around this. A strong projection of the geopotential height onto this pattern indicates the relative strength of the polar vortex. A strongly positive projection indicates a stronger than normal polar vortex, while a strongly negative projection indicates a weaker than normal vortex. Moreover, when time series of strongly positive or negative NAM events are composited, vertical structure becomes apparent. Specifically, a large stratospheric event, such as a SSW, will appear at 10 hPa about ten days prior to its appearance at the surface. And once the NAM signal appears in the troposphere (300 hPa), the same sign of the NAM index persists in the troposphere for around 60 days. During this time, the troposphere is characterized by a certain climatology. For instance, during a strong vortex event, cool winds would flow over eastern Canada, North Atlantic storms would bring rain and mild temperatures to northern Europe and drought conditions would prevail in the Mediterranean (Thompson and Wallace 2001). Thus, the stratospheric modulation of tropospheric climate suggests a predictive skill which can be exploited on the week to seasonal timescales (e.g. Douville 2009). Charlton et al. (2004,2005b) also showed that stratospheric initial conditions can impact tropospheric forecast skill on the 10-15 day timescale. Various mechanisms have been proposed to explain the stratospheric modulation of tropospheric climate on the week to seasonal timescale (Charlton et al. 2005a) but there is no consensus as to which is the most important one.

Recently, an even shorter timescale influence of the stratosphere on tropospheric forecasts was seen when the Canadian Meteorological Centre raised the lid of its operational forecast model from 10 to 0.1 hPa. A 75% reduction in 5-day forecast scores against radiosondes in the northern hemisphere was seen for geopotential height in winter at 10 hPa. Even in the troposphere, a 5-10% reduction was seen, and this level of improvement is comparable to that obtained with the “High Top” system between 3D-Var and 4D-Var (Charron et al. 2011). Because numerous changes to the model were introduced at the same time, and some of these (such as the new radiation scheme) were not connected to the raising of the model lid, it is not clear that improvement in tropospheric forecast skill was due to the better modeling of the stratosphere. However, it is clear that most (over 80%) of the improvement in forecast skill (of both stratosphere and troposphere) is achieved without new measurements in the upper stratosphere (AMSUA ch. 11-14 and GPSRO between 30-40 km). This makes sense because information propagates vertically, so that a good depiction of tropospheric waves combined with a good modeling of the stratosphere can lead to an improved upper stratospheric analysis. Additional results showed that the improvement was greatest in the winter (of both hemispheres). Thus improvement depended more on season (when the stratosphere was dynamically active) than on hemisphere (or observation distribution). Furthermore the extra observations in the upper stratosphere were beneficial in winter but not in summer. These results are understandable in the context of middle atmosphere dynamics. Just as tropospheric observations are most useful when dynamic activity (such as baroclinic wave development) is occurring, stratospheric observations are most useful when the stratosphere is dynamically active (in winter). Unanswered questions arising from Charron et al. (2011) are: why does there appear to be a downward propagation of skill from the stratosphere to the troposphere as a function of forecast day? Also, is this improvement due to an improved stratospheric depiction, or some other model change?

2.3 Gravity waves in the mesosphere

Earlier we noted that breaking (small-scale) gravity waves are important for driving the mesospheric meridional circulation. They are also surmised to be an important source of heating in the mesospause region (Lűbken et al. 2002). Thus although gravity waves are often considered as noise which must be filtered from the tropospheric data assimilation systems, in the mesosphere they are ubiquitous and are part of the signal. The two orders of magnitude increase with height in forecast error variance seen in Figure 4 (bottom left panel) largely reflects the increasing amplitude of gravity waves from the stratosphere to the mesosphere. As a result, spurious increments in the mesosphere can be produced (top left panel) when the variances are combined with small but nonzero correlations in the wings of the weighting function. Setting such tiny correlations (which are due to statistical noise) to exactly zero removes much of the spurious mesospheric increment (dashed lines in top left panel). In fact,

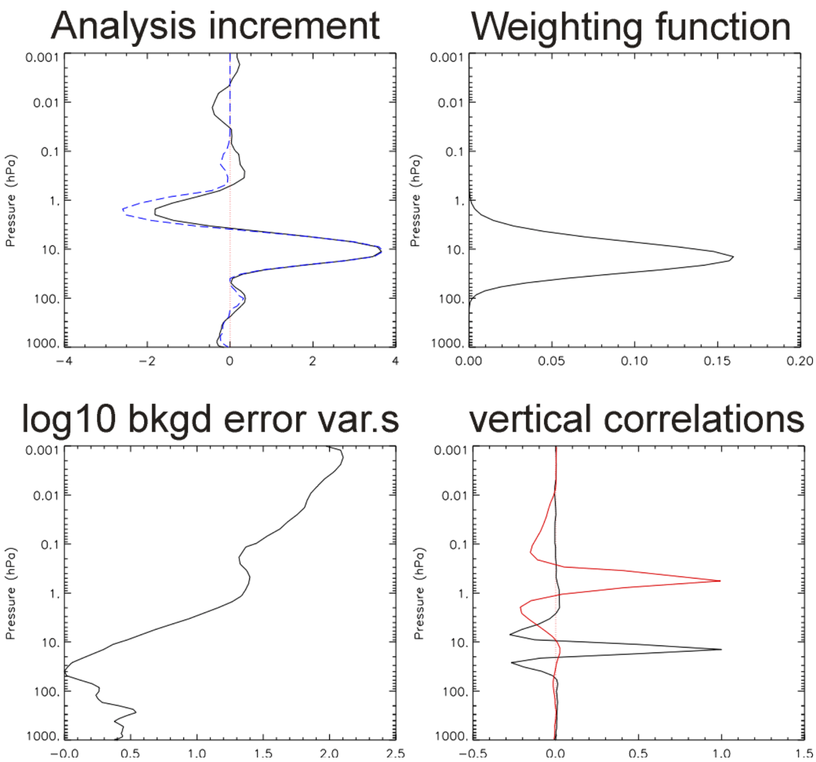

Figure 4: A 1-D assimilation of AMSU channel 11. Top left: Temperature analysis increments obtained when vertical correlations are unmodified (solid) or modified so that near zero values are exactly zero (dashed). Top right: weighting function for AMSU-A channel 11. Bottom left: log10 of temperature background error variance used with the CMAM-DAS. Bottom right: Two sample vertical correlation functions. From Polavarapu et al. (2005).

removing such spurious increments in the mesosphere is imperative when an assimilation system assimilates no mesospheric observations which might otherwise be able to damp such errors. In the mesosphere, such spurious increments may be persistent (because of the presence of model and/or observation biases) and can actually lead to physically nonsensical results after only a few weeks of assimilation. Thus information propagated to the mesosphere through background error covariances is not necessarily desirable. Similarly, erroneous small scale vertical structures in background error covariances cannot be damped by measurements if the observing system is lacking in detailed vertical information. This is the case in the upper stratosphere where nadir temperature sounders are the dominant source of information.

Gravity wave drag (GWD) schemes can also propagate information from the troposphere and stratosphere to the mesosphere. GWD schemes parameterize the processes of gravity wave generation in the troposphere, vertical propagation and nonlinear saturation. The output of such a scheme is a drag or forcing term for the momentum equations. GWD schemes are needed in climate models because their coarse horizontal resolutions lead to insufficient forcing of the meridional circulation and insufficient downwelling (and warming) over the winter pole (as well as insufficient upwelling and cooling over the summer pole). Thus, without a GWD scheme, climate models can suffer from the “cold pole” problem, which is particularly evident in the southern hemisphere where there are fewer forced planetary waves.

GWD schemes can also vertically propagate information in data assimilation systems (Ren et al. 2008). Observations are used to define winds in the troposphere and stratosphere which filter resolved gravity waves which might otherwise reach the mesosphere. Similarly, the parameterized impact of subgrid scale gravity waves in GWD schemes produce a force on the mesospheric flow. The benefit of a GWD scheme on mesospheric analyses was demonstrated by Ren et al. (2011). Background or 6-h forecasts were closer to independent observations of mesospheric temperature (from SABER retrievals) when a GWD scheme was used. The benefit was quite large if no mesospheric observations were assimilated, but still apparent even if they were assimilated. Since mesospheric analyses obtained with a model using a GWD but with no mesospheric observations were close to independent measurements, it is evident that GWD is able to propagate useful information to the mesosphere. At ECMWF, the same GWD scheme used in Ren et al. (2011) was implemented operationally, and shown to improve the bias in temperature at the stratopause at the winter pole in 5-day forecasts (Orr et al., 2010).

3. Issues is middle atmosphere data assimilation

The challenges in stratospheric and mesospheric data assimilation include:

- The observing system does not include much vertical information, nor wind measurements.
- Bias can seem to come from random errors (Dissipating waves impact zonal mean flow.)
- Both models and observations are biased
- Gravity waves are part of the signal
- Information and errors propagate vertically

Information can be propagated vertically in data assimilation systems through covariances, vertically propagating waves, and gravity wave drag schemes. As a result, very large scales in the mesosphere can be improved even without assimilating any mesospheric measurements.

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