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A perspective on the fundamental quality of GPS radio occultation data

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Abstract

Radio Occultation (RO) is a promising source of observation for weather and climate applications. However, the uncertainties in processing and retrieving RO data may weaken the overall confidence in the data and discourage their use. This study assesses the fundamental quality of RO data, by modeling the "raw" measurement, phase path, through a ray tracing method without the nuisance of retrieval errors. The comparison of phase measurements with the European Center for Medium-Range Weather Forecasts (ECMWF) data made in the observation space shows that the RO measurement is of sufficient accuracy to uncover regional-scale systematic errors in ECMWF's operational analysis and the 45 year reanalysis (ERA40), and to clearly depict the error growth of short-term ERA40 forecasts. In the southern hemispheric stratosphere, in particular, the RO measurement served as a robust reference against which both of the two analyses were significantly biased in opposite directions even though they were produced by the same center using virtually the same set of data. The measurement and ECMWF analyses showed a close agreement in the standard deviation. This confirms the high accuracy of the RO measurement and also indicates that the main problem of the ECMWF analyses lies in their systematic error.

1 Introduction

Comprehending the state of the climate and monitoring its change are challenging (e.g., Folland et al., 2001; Randel et al., 2004; Seidel et al., 2004), mainly due to the lack of reference-quality observations (GCOS, 2011). Compared to a relatively dense global network of surface observations, information on the atmosphere above the surface is inconsistent or lacking. For instance, analysis of upper air data sets during the satellite era did not show any warming that corresponds to the rapid surface warming (Folland et al., 2001), and follow-up studies to reconcile the enigma by producing independent data sets revealed a pronounced spread in the assessed long-term temperature trends (e.g., Seidel et al., 2004). The discrepancies among the trends, even those estimated from the same data source but processed by different groups (e.g., Thorne et al., 2005; Haimberger et al., 2008; Xu and Powell, 2011; Thompson et al., 2012), stem from time-varying systematic errors in the data records (Sherwood et al., 2005; Thorne et al., 2007; IPCC, 2007).

Meanwhile, contemporary Numerical Weather Prediction (NWP) models equipped with state-of-the-art data assimilation techniques have advanced to a level considered indispensable for many research applications. In addition to their importance in weather analysis and forecasting, the NWP models are crucial for climate studies. A reliable simulation of present-day climate is a prerequisite for establishing faith in future climate projections; NWP data can play an important role in assessing, understanding, and reducing the uncertainties in climate models (e.g., Phillips et al., 2004; Rodwell and Palmer, 2007; Palmer and Weisheimer, 2011). This relates to the concept of a unified framework for weather and climate prediction (e.g. Hurrell et al., 2009; Senior et al., 2011; Brown et al., 2012).

The atmospheric reanalysis projects led by NWP centers (e.g., Kalnay et al., 1996; Kanamitsu et al., 2002; Uppala et al., 2005; Onogi et al., 2007; Saha et al., 2010; Dee et al., 2011; Ebita et al., 2011; Compo et al., 2011) provide data sets useful for a broad range of applications by synthesizing observations from diverse sources and a priori knowledge through data assimilation techniques. The reanalysis products are particularly valuable where observations are insufficient in number and accuracy in providing a good estimate of atmospheric states. The reanalysis products are also useful for the homogenization of historical radiosonde observations (Haimberger, 2007; Haimberger et al., 2012) by detecting and adjusting artificial breaks in the time series that are caused by changes in instruments, observational practices, site relocation, and so on (Lanzante et al., 2003; Seidel et al., 2004; Sherwood et al., 2008; Randel and Wu, 2006; Mears et al., 2006). Satellite data records are also prone to non-physical changes due to orbital drift or decay, inter-satellite instrumental biases, and drifts in instrumental calibration (Wentz and Schabel, 1998; Christy et al., 2003; Mears and

Wentz, 2005). However, reanalysis products are susceptible to the deficiencies of the observations, showing in some cases very obvious and unphysical time-varying biases (Trenberth et al., 2001; Marshall, 2003; Bengtsson et al., 2004; Sterl, 2004; Renwick, 2004; Karl et al., 2006; Graversen et al., 2008; Reichler and Kim, 2008; Thorne and Vose, 2010; Screen and Simmonds, 2011).

Today, operational NWP centers apply bias corrections for satellite data judging against the model's own state at the time of assimilation (Dee and Uppala, 2009). Because not all satellite platforms possess an obvious systematic error that is discrete and exceeds the model's uncertainty, the bias detection may at times become ambiguous. The model-based bias correction can be a chicken-and-egg problem, where biased observations lead to a biased analysis which in turn agrees with the bias in the observations, and vice versa. NWP and reanalysis products are also known to have greater uncertainties in regions where satellite observations predominate, compared to regions with plentiful radiosonde observations (e.g., Langland et al., 2008). This underscores the importance of bias-free observations that can counteract the model's systematic error and act as anchor points for the bias correction.

The issues pertaining to the bias correction also indicate that observations are not so useful in identifying and correcting the model's systematic error, unless they are unbiased. Instead, the general trend is quite the opposite in that the observational biases tend to be corrected while using NWP data as the reference. Nonetheless, NWP data are far from perfect. Besides the bias leaking from observations, NWP models themselves produce considerable systematic errors due to shortcomings in the governing equations, numerics, surface forcing, and parameterizations of unresolved physical processes (Saha, 1992; Larson et al., 2001; Trenberth and Stepaniak, 2002; Danforth et al., 2007; Mass et al., 2008; Wee et al., 2012). The presence of large biases in the assimilating model causes spurious shifts and other artifacts in the analysis, even if all assimilated observations are unbiased and correctly represented by the assimilation system (Kobayashi et al., 2009). Unless adequately addressed, the systematic error in NWP data reduces the effectiveness of the bias correction, leading to an underutilization of observations. It also negatively affects the model-based homogenization of climate data records and has the risk of misrepresenting the climate change signal that the observations are bearing. NWP models and reanalyses drive changes in the climate models that are going to be used for future projections of climate change (Folland et al., 2001). Observations underpin all areas of numerical modeling, weather analysis and forecasting, and climate monitoring and projections that are closely relevant to each other. Thus, the availability of high-quality observations is of the utmost importance, carrying broad socioeconomic implications.

Recently, Global Positioning System (GPS) Radio Occultation (RO) (Melbourne et al., 1994; Ware et al., 1996; Kursinski et al., 1997; Anthes et al., 2008) has been receiving a great deal of attention as a promising source of data for both weather and climate applications. The primary observable of RO is the phase path of GPS signals received by an accurate receiver onboard a Low-Earth Orbiting (LEO) satellite. By analyzing the time-frequency content in the occulted signals, a profile of the ray's bending angle and subsequent profiles of atmospheric refractivity, pressure, and temperature can be derived. In past decades, numerous studies have demonstrated the unique strengths of GPS RO, which include high accuracy and vertical resolution, global coverage, all-weather capability, and calibration-free aptitude (e.g., Kursinski et al., 1997; Hajj et al., 2002; Wickert et al., 2004; Kuo et al., 2004). The data are accepted as an operationally reliable source of information by NWP centers worldwide (Poli et al., 2010), and have shown clear positive impacts on weather forecasting (e.g., Healy, 2008; Buontempo et al., 2008; Cucurull and Derber, 2008; Aparicio et al., 2009; Rennie, 2010) and merits in atmospheric reanalysis projects (Saha et al., 2010; Dee et al., 2011). In particular, RO data are assimilated without any bias correction. RO data offer a great potential for weather and climate research (e.g., Kursinski et al., 1997; Anthes et al., 2000; Hajj et al., 2000; Ladstädter et al., 2011), and are recognized as a promising contribution to the climate data record (GCOS, 2007, 2010).

GPS RO offers a hierarchy of data products following the various steps of data processing. The data close to raw measurement are simple (largely random) in the error structure, but are difficult to model or interpret. On the contrary, higher-level data (e.g., temperature and moisture) are more complicated (dispersed and vertically correlated) in their error, but have close geophysical relevance. RO data are subject to various sources of error, ranging from phase noises to the assumption of spherically symmetric atmosphere. Differing choices on how to cope with the error sources can result in different solutions. For instance, bending angles differ depending on the method used to estimate them. Along the same line, intercomparisons of RO data sets processed by different centers worldwide (Ho et al., 2009, 2012; Steiner et al., 2013) showed that inter-center difference increases rapidly with heights above 25 km. The elevated disparity at high altitudes is attributed to different noise regularization approaches employed by the centers (Steiner et al., 2013) and the influence of a priori on the retrieved parameters is particularly concerning. Therefore, RO data are not completely free from the structural uncertainty, which refers to errors that arise as a result of subjective choices made in the processing of observations (Thorne et al., 2005). Although small compared to other observing systems (Hajj et al., 2004; Schreiner et al., 2007), the uncertainty in the derived data poses questions on the true quality of RO data (Wee et al., 2010; Gorbunov et al., 2011; Wee and Kuo, 2013). This may impede data users from building strong confidence in the technique as noted by GCOS (2007) and Hartmann et al. (2013). An important distinction though is that while the structural uncertainty in other observing systems stems from biased measurements and is thus largely inevitable, the retrieval uncertainty in RO is avoidable by using unprocessed "raw" data (Wee et al., 2010). In this study, we assess the intrinsic worth of RO data related to weather and climate, negating the processing-induced uncertainties by modeling L1 and L2 phase measurements directly and compare them with NWP analyses in the observation space.

2 Methodology

The GPS RO data used in this study are obtained from CHAllenging Minisatellite Payload (CHAMP) and Satélite de Aplicaciones Cientificas-C (SAC-C) missions during a four-month period, May–August 2002, and processed by the Data Analysis and Archive Center (CDAAC) of the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) at the University Corporation for Atmospheric Research (UCAR). The CDAAC data processing algorithms and procedures are described by Kuo et al. (2004) and Schreiner et al. (2011). The data types used here are atmospheric excess phases measured at two GPS L-band frequencies, f_1=1.57542 GHz (L1) and f_2=1.2276 GHz (L2). The excess phase $\Delta\Phi$ can be expressed as follows:

$$\Delta\Phi + \rho = \int_{\mathrm{GPS}}^{\mathrm{LEO}} n\mathrm{d}s = \int_{\mathrm{GPS}}^{\mathrm{LEO}} \left\{1 + 10^{-6}\left(k_1\frac{p}{T} + k_2\frac{p_\mathrm{w}}{T^2} - k_3\frac{n_\mathrm{e}}{f^2}\right)\right\}\mathrm{d}s \tag{1}$$

where ρ is the range between the transmitter (GPS) and the receiver (LEO); n the refractive index in the atmosphere, along the ray path ds, including both neutral atmospheric and ionospheric effects; T temperature in K; p (total) pressure in hPa; p_w water vapor pressure in hPa; n_e electron number per cubic meter; f GPS carrier frequency in Hz; and, k_1, k_2, and k_3 are coefficients.

Provided the appropriate atmospheric refractive index, the inverse operators of standard RO data processing algorithms that derives profiles of the ray's bending angle, refractive index, temperature, and pressure from measured time series of excess phase can be used to model the excess phases (e.g., Wee and Kuo, 2013). However, the methods of geometrical optics and wave optics are all based on the assumption of spherical symmetry in the refractive index and thus are unable to take into account horizontal inhomogeneity in the atmosphere, which is a major source error in modeling the measurement. The ray tracing method (e.g., Kirchengast, 1998; Healy, 2001; Zou et al., 2004; Poli and Joiner, 2004) can precisely model the phase measurements fully accounting for the horizontal atmospheric variations.

The main obstacle in using ray tracers is computational cost, especially when rays are traced along the full range of GPS–LEO radio links just as the measurements are made in real life. The factors responsible for the high cost are as follows: first, the long GPS–LEO distance along which rays travel, requiring ray equations be integrated; second, demands on extracting and storing all necessary information are needed to describe time-varying observing geometry that changes from one epoch to another in three full dimensions; and last, the ray shooting, which is multiple iterative end-to-end tracing of a ray for each epoch to realize the observed GPS–LEO link (Wee et al., 2010). Standard ray tracing methods approximate a ray path as connected straight lines. In general, the refractive index either in the neutral atmosphere or in the ionosphere is strongly stratified. Consequently, a ray seldom travels along a straight line. Accordingly, the straight-line ray tracing (SLRT) has to divide a segment of a ray path into smaller pieces in order to achieve an acceptable level of accuracy as the ray bends more and more. In addition, unless the step size for the integration is small enough, the phase path modeled with the SLRT underestimates the actual measurements as the result of approximating the curved ray paths with straight lines. That is because straight lines are always shorter than curves in their length.

In the region where the vertical gradient of refractive index is significant, the straight-line approximation of ray paths often limits the step size to be shorter than a few hundred meters, which is exceedingly smaller than the typical horizontal resolution of refractive index offered by contemporary global NWP models. The restriction due to the straight-line approximation is most notable near ray's tangent points. Therefore, it is impractical to use the SLRT in operational or real-time settings. The SLRT is necessary for the media that have a sharp optical contrast, which causes immediate changes in the ray's direction. Seismic ray tracing to explore the Earth's internal structure might be one such example since the lithosphere can have layers that are discontinuous in the density. However, the refractive index in the atmosphere varies continuously and rather slowly. Based on the fact, Wee et al. (2010) developed a rigorous ray tracing that can cut down the computational cost drastically, without compromising the accuracy of the solution. In the Curved Ray Tracing (CRT), the Frenet–Serret formula (Born and Wolf, 1964) is used to parameterize curved ray paths with a series of osculating circles. This allows CRT to use a step size considerably longer than that of SLRT, leading to a remarkable cost reduction. This in turn allowed us to perform ray tracings for a large number of occultation events. In this study, convergence tolerance of one millimeter was used for ray shootings.

Ray tracing requires knowledge of the horizontal structure in the atmosphere along the ray path. In this study, the refractive index from the Earth's surface up to the height of GPS satellites (~ 27 000 km) was made available. The operational analysis and the 45 year reanalysis (known as ERA40) (Uppala et al., 2005) of the European Center for Medium-Range Weather Forecasts (ECMWF) (OP and RA hereafter) provided the refractive index in the lower neutral atmosphere. The OP used here was a reduced-resolution version, T106 in spherical harmonics (1.125° at the Equator), of the original data (T511) on 26 constant pressure levels from surface to 1 hPa (~ 48 km). The resolution of RA was T159 (0.75°) on 60 model levels with its top at 0.1 hPa (~ 65 km). Both OP and RA were available every 6 h. The neutral atmosphere above the top of the ECMWF data and up to 200 km was extended with an empirical model, MSIS (Mass Spectrometer and Incoherent Scatter Radar) (Hedin, 1991; Picone et al., 2002). The International Reference Ionosphere (IRI) (Bilitza, 2001) and the Russian Standard Model of Ionosphere (SMI) (Chasovitin et al., 1998) were used to provide the electron density in ionosphere and plasmasphere. These models furnished a complete description of the refractive index along a GPS–LEO link. Readers are referred to Wee et al. (2010) for more details.

The entire RO events available from CHAMP and SAC-C during May–August 2002 were simulated with CRT, where the L1 and L2 phases of 50 Hz sampling rate were individually modeled. After applying a quality control that discarded a few faulty occultations (e.g., corrupted by unfixable cycle slips, too noisy with insufficient signal-to-noise ratio, physically unrealistic or highly suspicious in the quality when compared to the model, or too short in the height range), 36 512 occultation events (23 563 CHAMP and 18 846 SAC-C) were used. In this study, the measured and modeled phases were compared in the neutral atmospheric excess phase for which the first-order ionospheric effects were eliminated via the so-called ionosphere-free linear combination. Although the ionospheric effect in the modeled phase to be removed eventually, the ionospheric and plasmaspheric models used enabled a realistic simulation of ray paths, e.g. the difference in the routes taken by the L1 and L2 rays due to the ionosphere. This in turn improved the accuracy of the modeled phase. While the imperfect linear combination introduced systematic errors due to large-scale ionospheric residuals (Wee et al., 2010; Mannucci et al., 2011), the modeled and measured phases that had undergone the same ionospheric correction were consistent and very similar to each other (Wee et al., 2010). In order to suppress measurement noise, a low-pass filter, fourth-order Butterworth filter (Butterworth, 1930), with a cut-off period of one-third of a second (∼ 1 km in height) was applied to the ionosphere-corrected phase.

There are a few reasons that the particular period, May–August 2002, was chosen for this study. First of all, the ECMWF started operationally assimilating GPS RO data on 12 December 2006 (Healy, 2007) and ERA40 did not make use of RO data (Uppala et al., 2005). Therefore, RO data were independent of the ECMWF data during that period. At that time, RO was a relatively new technique and thus had a short span as a climate record. RO technique has been evolving rapidly over time in both instrumental and algorithmic perspectives, and hence the data collected during the pioneering days may be less reliable containing a higher level of random (but not systematic) errors. Also, the number of occultation events observed during the early period, before the launch of the six-satellite COSMIC in 2006, was small. In 2002, two RO missions, CHAMP and SAC-C, were operating. These two missions provided an excellent opportunity to cross validate the RO data. That year was also scientifically significant because the Stratospheric Sudden Warming (SSW) that occurs about every other year in the Northern Hemisphere had been observed only once in the Southern Hemisphere in September 2002 (Gerber et al., 2012). The extreme flow conditions in the austral stratosphere during the period exposed a computational instability of the ECMWF forecast model that had not been seen previously in either test or operational use (Simmons et al., 2005). The analysis period of ERA40 also ended in September 2002. The unusual atmospheric conditions that preceded and perhaps preconditioned the SSW offered a good testing environment for the NWP system. For instance, as early as the beginning of 2002, ERA40 forecasts already showed a distinct degradation in the fit to radiosonde data, e.g. at 200 hPa (Uppala et al., 2005). Manney et al. (2005) found that during the period some global analyses could differ ∼ 20 K in the temperature from radiosonde observations.

3 Results

Figure 1 compares phase measurements at 25 km during a two-month period, June–July 2002, with the corresponding simulations made with the CRT in which neutral atmospheric refractivity is derived mainly from either OP or RA. The departure of OP from observation (M–O) (Fig. 1a) shows a distinct pattern of negative differences over the interior of the East Antarctica, whereas RA (Fig. 1b) shows structured positive differences over the large area around the Ross Ice Shelf. The wavelengths of GPS signals (∼ 19 cm for L1 and ∼ 24 cm for L2) are too long to interfere with cloud droplets, hydrometeors, and aerosols. In addition, RO is not affected by the thermal radiation from the Earth's surface, differently from other satellite sensing techniques. Therefore, RO has no particular reason to cause such regional-scale systematic differences. Otherwise, OP and RA are expected to be similar in the M–O. NWP data, on the contrary, are known to possess organized large-scale systematic errors, e.g. the climatic error of operational ECMWF forecasts as shown by Jung et al. (2005). Langland et al. (2008) related the regional error to the irregular distribution of in situ and satellite observations. As can be inferred from Eq. (1), the excess phase in the stratosphere inversely relates to the temperature.

The latitudinal scatter plots of the M–O (Fig. 1c and d) indicate that the difference between OP and RA is significant and most notable over the high southern latitudes.

This is consistent with findings of previous studies (Newman et al., 2000; Marshall, 2002; Sterl, 2004; Bromwich and Fogt, 2004; Betts et al., 2006); namely, global analyses differ the most in data-void areas, signaling their uncertainty there. As Langland et al. (2008) noted, the actual uncertainty in those analyses might be even larger than the differences among them, because NWP centers apply similar methods of data assimilation to shared sets of observations. In this context, a noteworthy detail in Fig. 1c and d is that the large departures (M–O) near the South Pole ($> 2\,\%$) are opposite in their sign, despite both OP and RA are produced by the same NWP center (i.e., ECMWF) using virtually identical observations. While the disparity may relate to the difference in the assimilation method (three- versus four-dimensional scheme for OP and RA, respectively), it is a good example of fundamental difficulties that contemporary NWPs are facing. The difference between OP and RA does not itself inform which is at fault. It is thus worthwhile to see if the phase measurement is accurate enough to serve as a reference against which their relative trustworthiness can be reconciled.

Data from CHAMP and SAC-C are largely independent from each other, especially in the phase path. This permits a robust cross-validation in which RO data are separated into CHAMP and SAC-C data, and then their departures from a common model are compared to each other in search of consistency. The two scatter plots of O–M for OP at 25 km (Fig. 2a and b) are quite similar. Especially, zonal mean of the O–M and samples' spread from the mean do not show any notable difference. Therefore, the model's behavior is consistent, meaning that OP is responsible for the large O–M. This can be confirmed by examining collocated RO pairs. There were 819 pairs closely distanced, within 2 h in time and 300 km in distance. The paired deviations from RA are highly correlated, where the correlation coefficients are 0.89 at both 25 km and 12 km (Fig. 2c and d). The deviations aggregate densely at small-magnitude ends (i.e., near the origin of the coordinates) and along the line of $y = x$. The root-mean-square distance perpendicular to $y = x$ is very small: 0.296 and 0.087 % at 25 and 12 km, respectively. The high correlation represents NWP error, shared by the pairs. Indeed, this is a well-accepted way to characterize spatial error correlation in NWP data (Hollingsworth and Lönnberg, 1986; Kuo et al., 2004; Desroziers et al., 2005).

Figure 3a and b compares OP and RA in the systematic difference and standard deviation from RO data. The statistics are stratified into three latitude bands: Northern Hemisphere (NH), Southern Hemisphere (SH), and tropics (TR). The TR is defined as the area between 30° S and 30° N. In tropospheric heights, the analyses are close to RO and each other in the mean. However, their systematic differences from RO increase rapidly above 15 km and diverge into opposite directions. At the height of 40 km, OP and RA are radically different from each other in all latitudes. As backed by the results presented thus far, both OP and RA are significantly biased, and RO data are able to quantify their systematic errors. In the data-rich NH, OP and RA deviate less from each other and RA stays almost unbiased up to 30 km. This indicates that the data assimilation systems rely heavily on conventional observations, at least in defining the model's mean states. The M–O shows large-scale undulations in the stratosphere. In the SH, the standard deviation of RA also shows a trace of the oscillation. Many previous studies have reported the oscillatory vertical structure over the Antarctica in the temperatures of RA (e.g., Randel et al., 2004; Uppala et al., 2005; Manney et al., 2005) and OP (Gobiet et al., 2005; Parrondo et al., 2007). Our study finds that the oscillation is pervasive without being confined in the SH. This again proves that the phase measurements are precise enough to capture the artifact in the analyses that might be too subtle for other approaches.

In the standard deviation, OP generally agrees better with RO than RA, in particular in the stratosphere of the SH. The exception is the lower altitude below 22 km of the SH, where the vertical resolution of the specific OP used in this study seems too coarse to properly model the strong thermal gradient associated with the intense polar vortex during the period. In the NH and TR, both analyses show remarkable agreements with RO in the standard deviation, less than 0.2 % at 8 km and increases to 0.6–0.7 % at 30 km. This indicates that ECMWF analyses as well as RO data are very accurate in this measure. The higher standard deviations in the upper stratosphere are a combination of NWP error and measurement noise (Wee and Kuo, 2013). In the tropical lower troposphere, measurement error that arises from difficulties in reliably tracking GPS signals passing through the optically complex atmosphere also contributes to the increasing standard deviation. No comparison is made in the lowest 2 km because the voltage signal-to-noise ratio drops below a threshold (50 V/V) in most cases. Needless to say, the complex atmospheric structure is also challenging for NWP systems to properly represent. The phase measurements are accurate and clearly discern the growth of prediction error with the forecast range (Fig. 3c–e). The standard deviation of RA forecasts from RO data increases monotonically with the lead-time in all latitudes and is most pronounced in the SH. The forecast error also increases rapidly in the upper troposphere and lower stratosphere. These areas signify the places that the ECMWF data need greater improvement.

4 Conclusions

The modeling of the excess phase with a ray tracing method provided an excellent opportunity to assess the quality of underived RO data. The value of the RO measurement is attested by a transparent and straightforward comparison with corresponding ECMWF data without the involvement of RO retrieval uncertainties. It is concluded that the RO measurement is highly accurate in terms of both random and systematic errors so that it can reveal errors in the ECMWF data, and is thus well qualified as a reference-quality observation. The results obtained from this study can serve as a benchmark for studies striving to reduce the uncertainty of derived RO data products.

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analysis (111.0), and ERA40 analysis (117.2) and forecasts (121.2) are available at the Data Support Section (DSS) of UCAR (http://rda.ucar.edu/datasets/).

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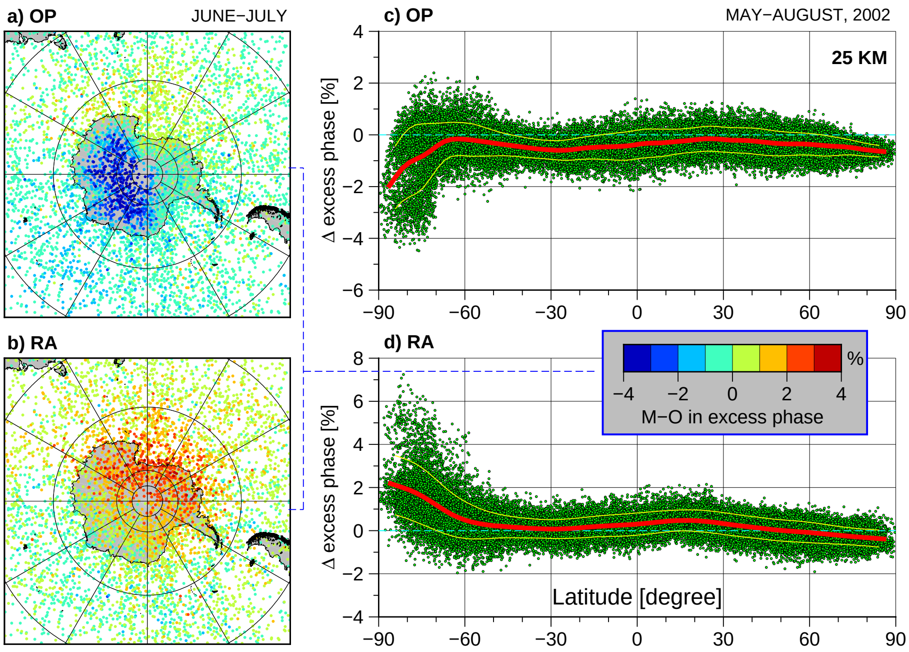

Figure 1. The percentage departure of ECMWF analyses from RO data in the excess phase at the height of 25 km over the high southern latitudes for June–July 2002: **(a)** operational (denoted OP) and **(b)** ERA40 (denoted RA) analyses. The latitudinal scatters of analyses minus RO (M–O) are shown for analyses of **(c)** OP and **(d)** RA, but for a four month the period, May–August in 2002. The red solid curve is a piecewise second-order least-square fit and yellow curve indicates the envelop of one standard deviation.

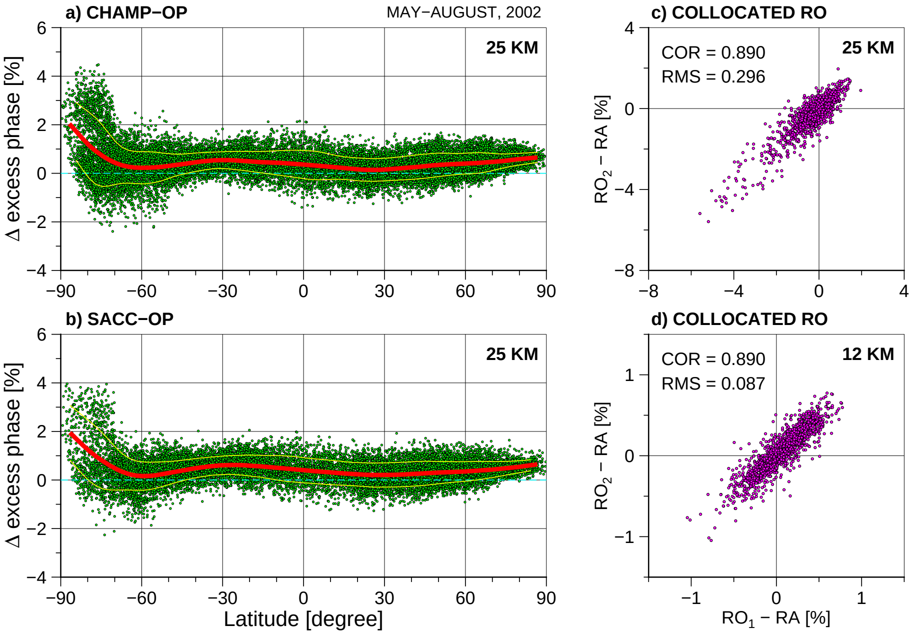

Figure 2. **(a)** and **(b)** are the same as in Fig. 1c and d, except for the deviation of RO data, **(a)** CHAMP and **(b)** SAC-C, from the operational analysis. Note that O–M is shown here, in contrast to the M–O shown in Fig. 1. This is following the convention that the data shared in the comparison are always taken as the reference. Scatter plots of RO data versus collocated RO data in terms of their deviation from ERA40 analysis at **(c)** 25 km and **(d)** 12 km. The criteria for the collocation are less than 2 h in time and closer than 300 km in the great circle distance. Note that the scatters are mirror symmetric with respect to $y = x$ as result of swapping the values of x and y in each pair. The correlation coefficient and perpendicular root-mean-square distance from $y = x$ are denoted as COR and RMS, respectively.

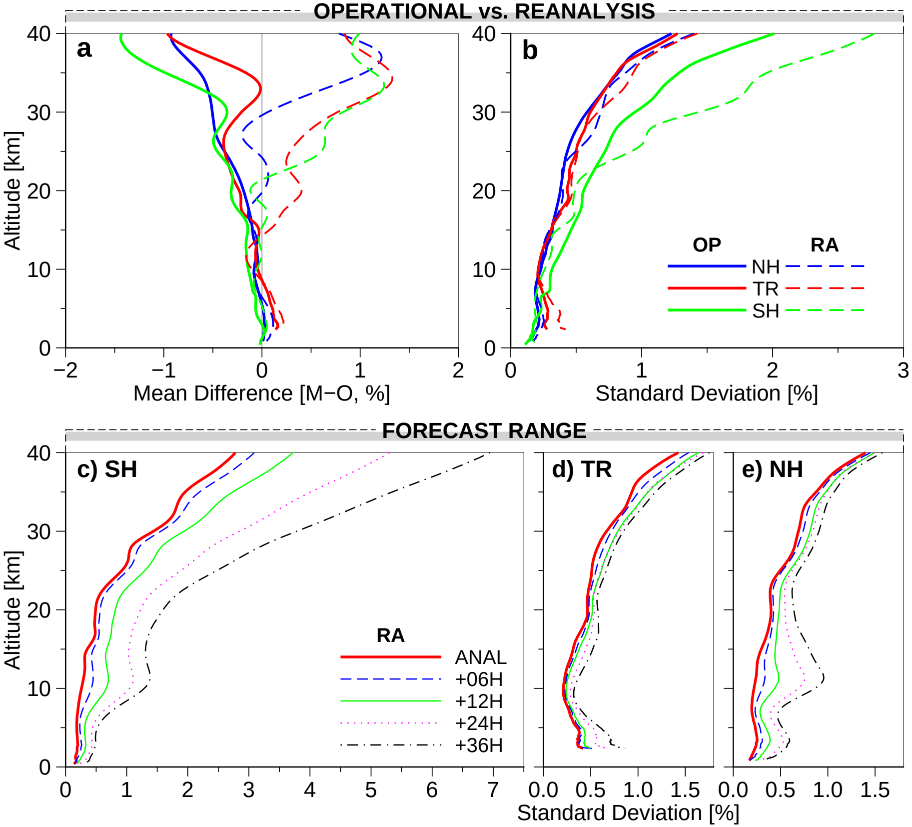

Figure 3. The **(a)** systematic difference and **(b)** standard deviation of the operational (solid) and ERA40 (dashed) analyses from RO data in three latitude bands. The standard deviation of ERA40 data from RO data for different forecast ranges over **(c)** southern latitudes, **(d)** tropics, and **(e)** northern latitudes. The SH and NH are south and north of the tropical zone defined as 30° S–30° N.