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Tidal effects on stratospheric temperature series derived from successive advanced microwave sounding units

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Stratospheric temperature series derived from the Advanced Microwave Sounding Unit (AMSU) on board successive NOAA satellites reveal, during periods of overlap, some bias and drifts. Part of the reason for these discrepancies could be atmospheric tides as the orbits of these satellites drifted, inducing large changes in the actual times of measurement. NOAA 15 and 16, which exhibit a long period of overlap, allow deriving diurnal tides that can correct such temperature drifts. The characteristics of the derived diurnal tides during summer periods are in good agreement with those calculated with the Global Scale Wave Model, indicating that most of the observed drifts are likely due to the atmospheric tides. Cooling can be biased by a factor of 2, if times of measurement are not considered. When diurnal tides are considered, trends derived from temperature lidar series are in good agreement with AMSU series. Future adjustments of temperature time series based on successive AMSU instruments will require considering corrections associated with the local times of measurement.

Key Words: satellite; temperature; stratosphere; tides

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1. Introduction

According to observations, the stratosphere has cooled over the last decades (Randel et al., 2009). Chemistry climate model intercomparisons (Shine et al., 2003; Austin et al., 2009) indicate that the upper stratospheric trends were driven by ozone depletion and the increase in carbon dioxide, while feedback contributions including increases in stratospheric water vapour (Solomon et al., 2010), cloud occurrence (Wylie et al., 2005) and dynamical changes (Angot et al., 2012) are not well quantified. The agreement between models and observed temperatures trends showed improvement as of the last assessment (Austin et al., 2009); models have introduced interactive ozone chemistry and included a slightly colder climatology, yet large differences both between models and between models and observations still persist. Trend analyses are standard diagnostics for evaluating stratospheric climate model performance (Powell et al., 2013). Observations of stratospheric temperature trends have been regularly assessed as part of the World Meteorological Organisation/United Nations Environment Programme (WMO/UNEP) Scientific Assessments on Ozone Depletion (WMO, 2007) and the Intergovernmental Panel on Climate Change (IPCC) assessment of climate changes (IPCC, 2007). Several different research experiments providing atmospheric temperature have operated on board satellites. However, because their objectives, lifetime and the techniques involved are so different, the time continuity over more than a decade has been difficult to keep. Estimates of global past temperature trends in the middle and upper stratosphere rely primarily on a single dataset derived from the successive operational Stratospheric Sounding Unit (SSU) instruments. The derived series exhibit substantial uncertainties including change of the vertical weighting functions due to atmospheric CO2 changes (Shine et al., 2008b), radiometric drifts and atmospheric tides (Nash and Forrester, 1986). Essentially, there are two SSU datasets available for the research community: the first was produced by Nash and colleagues (Nash and Browncombe, 1982; Nash and Forrester, 1986; Nash, 1988; Nash and Edge, 1989), and extensively used for several years as it was the only available SSU analysis (even though details of data processing are largely unknown); and a second, recently released SSU analysis from the National Oceanic and Atmospheric Administration (NOAA) Center for Satellite Applications and Research (Wang et al., 2012). The latter takes into account the aforementioned uncertainties and corrects for the limb effect due to varying angles–of–view of...
The purpose of this study is to estimate instrument calibration differences by taking into account tidal effects for the purpose of correcting series from these effects. The AMSU measurements are described in section 2, while section 3 describes tidal corrections and the remaining calibration difference. Impact on trends is discussed in section 4. Finally, discussions about the methodology and the impact on a future strategy are included in section 5.

2. AMSU description

This study focuses on the stratosphere temperature monitoring by using the temperature data from AMSU-A. This spectrometer is a cross-scanning microwave instrument that is composed of 15 channels between 50 and 58 GHz in the oxygen band, allowing the observation of the temperature structure of the atmosphere from the surface to around 50 km. More specifically, six channels (from 9 to 14) sound the stratosphere with vertical weighting functions with half-width of around 10 km (Karbou et al., 2005). The weighting functions for these channels are centred approximately at 18, 20, 25, 30, 35 and 40 km, respectively. The AMSU instrument has been collecting observations on board several successive NOAA polar-orbiting satellites (NOAA-15 through to -19, starting in 1998, 2000, 2002, 2005 and 2009 respectively), National Aeronautics and Space Administration Earth Observing System (NASA EOS-Aqua) satellite (since May 2002), and Metop (Metop-A in 2006 and Metop-B launched in 2012). In principle, it consists of quite homogeneous data as the same instrument is used; however, the same instrument on different platforms may yield slightly different measurements when overlapping the same position at the same time; this issue will be discussed further on. Given a ‘target’ area, two overpasses per day are generally available, thus zonal means using both ascending and descending passes are calculated for several latitudinal bands ranging from 80° S to 80° N. Only measurements of the near-nadir field-of-view tracking position are taken to avoid limb effects that affect the effective centre of the weighting function (Goldberg et al., 2001). The superposition of temperature measurements from the successive AMSU instruments shows consistent monthly-mean zonal-mean temperature series with similar interannual variability and agreements better than 1 K (Figure 1). Such differences are small; however, they induce uncertainties on trend calculations. Fortunately, the AMSU series exhibit several overlapping periods. When temperatures obtained for the same period from different AMSU instruments are compared, systematic differences can be noted (Figure 2(a) for 10° N to 10° S latitude band). At some levels (channels 12 and 13, Figure 2(c) and (d), respectively) and for some coupled AMSU, drifts can also be observed with the largest amplitudes for data series corresponding to the upper altitude levels. NOAA-15 and NOAA-16 AMSU-A, which provide the longest period of operation and a long overlapping period, show obvious drifts for channels 12 and 13 (AMSU channel 14 on NOAA-15 failed in October 2000). Such drifts are assumed
to be associated with atmospheric tides since orbit drifts induce changes of the times of measurement (Figure 3). This has already been reported for the Microwave Sounding Unit (MSU) series on successive NOAA satellites (Mears et al., 2002) with mean effects in the troposphere of a few tenths of a degree, with however large regional effects related to orography and convection.

Recently, Zou and Wang (2011) performed AMSU inter-calibration, adjusting all AMSU measurements with respect to those collected by that on NOAA-15 using the Simultaneous Nadir Overpass (SNO) method (Cao et al., 2004). The new, inter-calibrated data, named ‘AMSU IMICA’ (Integrated Microwave Inter-Calibration Approach) is currently available (as of January 2014) through NOAA’s National Climatic Record Center Climate Data Record Program site at http://www.ncdc.noaa.gov/cdr/operationalcdrs.html. This dataset takes into account and corrects biases found in the pre-launch AMSU observations, including: relatively stable inter-satellite biases between most satellite pairs, instrumental drifts, sun-heating-induced instrument temperature variability in radiances, and scene temperature dependency in biases due to inaccurate calibration nonlinearity. NOAA also made available the full operational AMSU data along with data with limb-correction following Goldberg et al. (2001). When using only near-nadir data to construct the time series, the range of temperature differences between NOAA-13 and NOAA-16 from both IMICA and operational AMSU are basically unchanged (Figure 4), whereas using all fields-of-view to calculate monthly means yields temperature differences smaller for IMICA than for limb-corrected AMSU, within however the same order of magnitude and same sign of slope (not shown). This indicates that the diurnal cycle component present in the data is not completely removed in the IMICA data series, as the SNO method uses matched pairs that are geographically and temporally close, and thus free from the effects of the diurnal drift.

3. Quantification of tidal effects

AMSU data from NOAA-15 and NOAA-16 provide a good opportunity to investigate the source of the differences and the possibility to correct them as both provide the longest period of operation and a long overlapping period since January 2001. Channel 13 was chosen, as the temperature differences are...
obtained for the longest period while both instruments on NOAA 15 and 16 are in operation simultaneously over a long period (decade). Drifts evolve in the opposite direction, and in mid-2008 both satellites presented measurements at nearly the same time of day. Data obtained during this specific period can be used to calculate temperature differences that can be associated with instrumental differences, as temperature anomalies induced by atmospheric tides are similar. Small but robust values around 0.08 K are derived (Table 1), with AMSU temperature on NOAA-15 being slightly warmer than temperature from NOAA-16. These estimates were obtained by first constructing monthly mean temperatures for nine latitude bands (80 to 60^\circ N and S, 60 to 45^\circ N and S, 45 to 30^\circ N and S, 30 to 15^\circ N and S, and 15^\circ S to 15^\circ N). Then, the mean temperature differences were calculated for each latitude band (Table 1). Except for the southern high latitudes, where the variability is large, the temperature differences are similar. Such results are expected since the same instrument is used for measurements in all latitude bands. The temperature evolution reveals monotonic drifts as a function of time (Figure 5) with varying amplitude according to the latitude bands. This systematic difference is in good agreement with that of about −0.08 K inferred by the bias adjustment scheme used in the ERA-Interim data assimilation system (Simmons et al., 2014), which does not show strong sensitivity to orbital drift. In the summer stratosphere, the main tidal mode is a 24 h oscillation (Keckhut et al., 1996). The diurnal tides exhibit a seasonal cycle with amplitudes that increase with latitude, and the amplitude of the semi-diurnal mode increases too (Keckhut et al., 1996), leading to a tidal behaviour that is more complex at high latitudes. This simple tidal model explains the appearance of an annual oscillation in the temperature difference between AMSU instruments. Here, only diurnal tide is considered and only summer data for each respective hemisphere (June, July, August and December, January, February respectively for Northern and Southern Hemispheres) are used to derive a tidal correction. Temperature anomalies at a given time t, and at an altitude z induced by tides \text{tide}(t, z) can be expressed as:

\[ \text{tide}(t, z) = a(z) \cdot \cos((2\pi t/24) - \phi(z)), \]

with \(a(z)\) and \(\phi(z)\) being respectively the amplitude of the tide and phase (time of the maximum). It can be also expressed as:

\[ \text{tide}(t, z) = a_1(z) \cdot \sin(2\pi t) + a_2(z) \cdot \cos(2\pi t), \]

with \(a_1(z)\) and \(a_2(z)\) being the amplitude of two out-of-phase functions.

The amplitude and phase of the tides can be calculated from \(a_1(z)\) and \(a_2(z)\):

\[ a(z) = \sqrt{a_1^2(z) + a_2^2(z)} \text{ and } \phi(z) = \text{arctan} \left( \frac{a_1(z)}{a_2(z)} \right). \]

While the large-scale temperature change over the diurnal scale is negligible (that is the case during summer months), the difference between two collocated temperature measurements obtained at different times \(t_1\) and \(t_2\) can be deduced from Eq. (2) and expressed as follows:

\[ \Delta T(z) = a_1(z) \cdot \sin(2\pi (t_2 - t_1)) + a_2(z) \cdot \cos(2\pi (t_2 - t_1)). \]

Since the time difference is known (Figure 3), a least-square fit was applied on the difference temperature series in summer (except for the equatorial band where all the data are considered) and parameters \(a_1\) and \(a_2\) were calculated for each altitude level \(z\) amplitude and phase were calculated using Eq. (3) and reported in Table 1.

In addition to a drift, a seasonal cycle is clearly visible that is due to the seasonal evolution of the tidal amplitude. Phase values are similar to previous estimates with lidar (Keckhut et al., 1996), while amplitudes are smaller probably because of vertical smoothing caused by the large vertical weighting function of AMSU. The tidal characteristics derived from both instruments have been compared with the Global Scale Wave Model (GSMW: Hagan et al., 1999) developed by Hagan to study tides (1998) which provided zonal estimates. There is an even better agreement with the values derived here with AMSU series than with the lidar, maybe because the vertical resolutions are similar. The amplitudes show differences smaller than 10% in most of the latitude bands except for the Southern Hemisphere where differences increase up to 50%. As the amplitude estimates depend on vertical resolution, the phase is a more valuable parameter to qualify the agreement.

Phases agree within 2–3 h except for high southern latitudes where large differences are observed. However, we note that these values agree with recent lidar observations performed at Dumont D’Urville (David et al., 2012). A detailed view of the tide behaviour reveals that there is a strong gradient of the phase from 1000 to 2000 h (solar time) around the peak of the weighting function of channel 13 (for more detail, visit http://www.hao.ucar.edu/modeling/gswm/gswm.html); for the tidal generator associated with a more recent version of

\[ (\text{AMSU channel 13 are reported). NOAA-16}) retrieved from AMSU operational (black) and IMICA (red) analyses \]

\[ \text{NOAA-15 minus NOAA-16) (black) and NOAA-16 (blue). Differences between IMICA and operational data \]

\[ \text{atmospheric tides are similar. Small but robust values around } \]

\[ \text{instrumental differences, as temperature anomalies induced by } \]

\[ \text{tides } \text{tide}(t, z) \text{ can be expressed as:} \]

\[ \text{tide}(t, z) = a(z) \cdot \cos((2\pi t/24) - \phi(z)), \]

\[ \text{tide}(t, z) = a_1(z) \cdot \sin(2\pi t) + a_2(z) \cdot \cos(2\pi t), \]

\[ a(z) = \sqrt{a_1^2(z) + a_2^2(z)} \text{ and } \phi(z) = \text{arctan} \left( \frac{a_1(z)}{a_2(z)} \right). \]

\[ \Delta T(z) = a_1(z) \cdot \sin(2\pi (t_2 - t_1)) + a_2(z) \cdot \cos(2\pi (t_2 - t_1)). \]

\[ (\text{AMSU tidal amplitude and phase estimates (upgrade from Hagan et al., 1999).}) \]

\[ \text{Latitude domain} \]

\[ \text{(a) N15, N16} \]

\[ \text{AMSU tidal} \]

\[ \text{amplitude (K)} \]

\[ 60–80^\circ \text{N} \]

\[ 0.29 \]

\[ 14.1 \]

\[ 0.26 \]

\[ 13.5 \]

\[ -0.052 \]

\[ 45–60^\circ \text{N} \]

\[ 0.21 \]

\[ 17.3 \]

\[ 0.28 \]

\[ 20.0 \]

\[ -0.076 \]

\[ 30–45^\circ \text{N} \]

\[ 0.20 \]

\[ 17.8 \]

\[ 0.31 \]

\[ 21.7 \]

\[ -0.088 \]

\[ 15–30^\circ \text{N} \]

\[ 0.32 \]

\[ 21.4 \]

\[ 0.30 \]

\[ 20.1 \]

\[ -0.089 \]

\[ 15^\circ \text{S–15}^\circ \text{N} \]

\[ 0.20 \]

\[ 22.6 \]

\[ 0.73 \]

\[ 16.0 \]

\[ -0.084 \]

\[ 15–30^\circ \text{S} \]

\[ 0.49 \]

\[ 22.4 \]

\[ 0.28 \]

\[ 19.2 \]

\[ -0.067 \]

\[ 30–45^\circ \text{S} \]

\[ 0.60 \]

\[ 17.7 \]

\[ 0.32 \]

\[ 22.2 \]

\[ -0.070 \]

\[ 45–60^\circ \text{S} \]

\[ 0.21 \]

\[ 17.1 \]

\[ 0.28 \]

\[ 18.6 \]

\[ -0.074 \]

\[ 60–80^\circ \text{S} \]

\[ 0.60 \]

\[ 20.8 \]

\[ 0.27 \]

\[ 11.2 \]

\[ -0.155 \]

\[ \text{All} \]

\[ -- \]

\[ -- \]

\[ -- \]

\[ -- \]

\[ -0.084 \]
a good correlation is observed while some differences due to tides are superimposed. When this effect is corrected with the derived tidal model (Table 1), the correlation increases considerably (Figure 6) and a regression coefficient is derived with a slope of 1.

AMSU series have been also compared with temperature lidar series. Few sites within the international Network for the Detection of Atmospheric Composition Change (NDACC) provide decadal series (Keckhut et al., 2004, 2011). The lidar operating on Table Mountain, California, is the only NDACC site that can provide a sufficiently large time sampling during summer months to correctly trap the interannual variability (Leblanc et al., 1998).

AMSU summer data are selected to compare raw and tidal corrected temperature data with those derived by the Table Mountain Facility (TMF) lidar. The corresponding altitude between lidar and AMSU channel 13 has been determined following the same method as that developed by Funatsu et al. (2008). Raw AMSU temperature series show differences on tendencies (around 15%) with lidar time evolution for both instruments on board NOAA 15 and 16 (Figure 7). The NOAA-15 temperature dataset shows reduced tendencies (around 15%) with lidar time evolution for both instruments on board NOAA-15 and NOAA-16 satellites show that the differences can be reduced (Figure 6). The tidal correction is applied on data series at mid to high latitudes long-term drifts are removed (Figure 5), but differences still exhibit a seasonal oscillation associated with the tidal seasonal cycle and the semi-diurnal mode. This analysis can be extended to other channels. However, channel 12, with weighting function peaking at a lower altitude, is expected to be less influenced by tidal effects because tidal amplitudes are smaller. Channel 14 also exhibits large drifts (Figure 2) but the overlapping period is relatively short because channel 14 on NOAA-15 failed by the end of October 2000, and AMSU on NOAA-17 failed in 2003; thus the longest overlapping series are those of NOAA-16 and NOAA-18 from mid-2005.

4. Effects on trend estimates

When both temperature series (NOAA 15 and 16) are compared, a good correlation is observed while some differences due to tides are superimposed. When this effect is corrected with the derived tidal model (Table 1), the correlation increases considerably (Figure 6) and a regression coefficient is derived with a slope of 1.

AMSU series have been also compared with temperature lidar series. Few sites within the international Network for the Detection of Atmospheric Composition Change (NDACC) provide decadal series (Keckhut et al., 2004, 2011). The lidar operating on Table Mountain, California, is the only NDACC site that can provide a sufficiently large time sampling during summer months to correctly trap the interannual variability (Leblanc et al., 1998).

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5. Discussion and conclusions

Drifts of the orbits for the instruments in space are a key issue for stratospheric temperature analysis due to atmospheric tides.
It is not easy to disentangle the contributions of atmospheric tides from the instrument drift to explain observed temperature drifts between two simultaneous instruments in space on different orbits.

In this study, in assuming that atmospheric tides are the main reason for observed temperature drift between measurements by AMSU on NOAA 15 and 16, diurnal tides are derived for summer months. These compare well with simulated tides, showing that most of the observed temperature drifts may be due to tides. The impact on temperature trend estimates is large and the observed trend induced by tidal effects is of the same order. Such a correction was possible for summer data when the diurnal mode dominates. An extension to other months will require deriving both diurnal and semi-diurnal components. With only two measurement series, an unequivocal tidal solution cannot be derived accurately. However, based on the good agreement found here between models and AMSU observations, we conclude that tidal model estimates can probably be used instead, with a small rescaling.

These corrections on successive instruments over several decades also presuppose that atmospheric tides are stable with time. Such a methodology is limited by two factors. First, atmospheric tides due to ozone and water vapour can have their own variability and potential trends due to climate change and emission of ozone-depleting substances. Second, tides are waves that propagate vertically and depend on temperature and wind fields that also exhibit a large variability and long-term trends. Characteristics of atmospheric tides in such a variable atmosphere are still not well known. However, a sensitivity study shows that long-term changes of tide amplitudes due to expected atmospheric changes remain smaller than 10% (Morel et al., 2004). Only non-migrating tides are considered in this study; however, migrating tide should also contribute, mainly if data are investigated over longitudes.

In most cases, the temperature monitoring is ensured by a succession of instruments, due to their operational status for weather forecasting and temperature monitoring (identified as sentinel instruments), using overlap periods. AMSUs on NOAA 15 and 16 exhibit an unexpectedly long lifetime. However while the instruments are similar, if their times of measurement are different some bias due to tides is superimposed on instrumental bias, as was demonstrated by using AMSU IMICA data (which eliminated most instrument and scene biases). On some platforms, like Metop, the orbit is maintained. However, tidal corrections are still required to separate both effects. If overlap periods do not exist, adjustment and time continuity could be ensured with a ground-based lidar network (Keckhut et al., 2011), and tide corrections should also be considered (Keckhut et al., 1996).

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centre (http://www.icare.univ-lille1.fr) with the assistance of the IPSL expert centre ESPRI. NDACC data used in this work are created by NASA-JPL and are archived in the NOAA database at http://www.ndsc.ncep.noaa.gov/. The AMSU IMICA and limb-corrected operational AMSU data used in this study were acquired from NOAA’s National Climate Data Center (http://www.ncdc.noaa.gov). AMSU IMICA was originally developed by Cheng Zhi Zou and colleagues at NOAA though

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