Report from the 10th SPARC data assimilation workshop and the 2014 SPARC Reanalysis Intercomparison Project (S-RIP) workshop in Washington DC, USA

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The 10th SPARC data assimilation (SPARC-DA) workshop and the 2014 SPARC Reanalysis Intercomparison Project (S-RIP) workshop were held together at the National Oceanographic and Atmospheric Administration (NOAA) Center for Weather and Climate Prediction (NCWCP) in College Park (Maryland, USA), close to Washington DC, for 5 days between September 8 and 12, 2014. Days 1 and 2 were dedicated to scientific presentations and discussion related to the SPARC-DA activities, Days 4 and 5 were dedicated to discussion on the progress of the S-RIP and Day 3 was to a joint session of both activities with scientific presentations. The 10th SPARC-DA workshop was one of regular series[1] started in 2002 and had around 25 participants, while the 2014 S-RIP workshop was the first one after the planning meeting in 2013 (Fujiwara and Jackson, 2013) and had also around 30 participants. Around 45 participants attended the joint workshop on Day 3.

The S-RIP activity emerged after discussions held in 8th and 9th SPARC-DA workshops. Therefore, it is natural to share the location and the week of both workshops and to have a one-day joint workshop. Moreover, many people involved only in one of these two activities were happy to have a one day joint meeting to follow the scientific talks about using and creating reanalysis data products.

This article summarizes the presentations during the SPARC DA and joint DA-S-RIP workshops on Days 1-3 and briefly notes the discussion during the S-RIP workshop as well as the discussion concerning the organization of the next workshop.

Observation requirements and exploitation of new observations for stratosphere-troposphere data assimilation

P. Bhartia (invited) presented the capabilities and potential applications of the Ozone Mapping and Profiler Suite (OMPS) Limb Profiler (LP) launched in October 2011 for the study of atmospheric chemistry and dynamics. The OMPS LP measures limb scattered radiances and solar irradiances between 275nm and 1050nm. The sensor employs three vertical slits separated horizontally to

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[1] Visit http://www.sparc-climate.org/activities/data-assimilation/ to access reports of previous meetings

provide wider cross-track coverage. Ozone profiles are retrieved between the cloud top altitude and 60km between 84S-84S during daylight with around 2km of vertical resolution. The instrument also provides profiles of aerosols extinctions at 5 wavelengths from the cloud top altitude to 35km. OMPS LP version 2 Ozone data agree well with observations from the Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACEFTS), the Microwave Limb Sounder (MLS) and ozonesondes and are supposed to show even better agreement with the release of the version 2.5 in 2015. The end of the presentation highlighted the potential use of data assimilation of LP data along with total ozone provided by the Nadir Mapper (NM) and the Cross-track Infrared Sounder (CrIS), also onboard OMPS. This would allow getting a good ozone analysis thanks to the good vertical resolution of LP in the stratosphere, the sensitivity of NM in the troposphere and the sensitivity of CrIS in the Upper Troposphere and Lower Stratosphere (UTLS).

L. Coy discussed several improvements realized in the second release (planned in early 2015) of the Modern Era Retrospective analysis for Research and Applications (MERRA-2), a reanalysis covering the period 1979-2015. The tuning of the gravity wave parameterization has been improved and allows a much better model representation of the Quasi Biennial Oscillation (QBO) than in the model used in the first MERRA release. The MERRA-2 also benefits from upgrade of the orographic gravity wave scheme to allow better representation of gravity waves over Southern Hemisphere islands. Other improvements come from new assimilated observations. Temperature profiles measured by MLS are now assimilated from 2004, once MLS data became available. This allows reducing the high temperature bias in the mesosphere seen in MERRA. For example, during the period of the Stratospheric Sudden Warming in 2010 (see Figure 1), MERRA-2 shows a lower stratopause and a cooler mesosphere than MERRA. It turns out that the zonal wind in MERRA-2 is stronger in the mesosphere than MERRA.

Troposphere / stratosphere / mesosphere interactions: Stratosphere & Troposphere

A. Lang (invited) presented an overview and the current status of the SPARC Stratosphere Network for the Assessment of Predictability (SNAP) activity (Charlton-Perez and Jackson, 2012). The goal of SNAP is to understand the role of the stratosphere in numerical weather predictions. Several case studies have been defined and are analysed with different Numerical Weather Prediction (NWP) systems involved in SNAP. She showed results of predictability for the Northern hemisphere (NH) SSW in early 2013. All the models failed to predict the warming 15 days in advance, and had a huge spread of zonal wind at 10 hPa and 60N (60 m/s after 15 days). However, all models basically can simulate the SSW if initialised 10 days in advance. By focusing on the "best" and "worst" ensemble members, she showed that all models struggle to simulate the amplification of wave-2 structure in the stratosphere, while amplification of wave-2 in the troposphere as well as amplification of wave-1 in both regions was relatively well resolved by the models.

G. Manney studied the effect of SSW on the composition of the upper troposphere and lower stratosphere using meteorological analysis and satellite data. It was shown that 6 SSWs have occurred in the past decade. Moreover, during SSW years, disturbances of the polar vortex lead to very early chlorine activation and substantial ozone loss in December-January. These disturbances were accompanied by changes in the patterns of upper tropospheric jets and the increased occurrence of multiple tropopauses.

J. de Grandpre evaluated the ozone predictability of the operational Environment Canada Chemical Data Assimilation (EC-CDA) system. Several numerical experiments were conducted using different ozone datasets, namely, data from MLS, the Global Ozone Monitoring Experiment-2 (GOME 2) and the Solar Backscatter Ultraviolet Radiometer (SBUV) instruments. The experiments have been evaluated on their skill to forecast the ozone anomaly correlation. When the coupling between the modelled ozone and radiation is considered, the system showed a better temperature forecast in the stratosphere in the case of MLS ozone assimilation. When assimilating GOME-2 in place of MLS, the gain in predictability is half a day after ten days of predictions. In the case of SBUV assimilation in place of GOME-2, the loss in predictability is greater than one day. Finally, removing the ozone *a priori* profile from the SBUV retrieval using the averaging kernels did not show significant improvements of the forecast skill.

Using the coupled whole-atmosphere/ionosphere model of NOAA's Integrated Dynamics in Earth's Atmosphere (IDEA), **H. Wang** made the first "weather forecast" (with this kind of model) for the January 2009 SSW. He used data assimilation up to 80 km altitude (the model upper boundary is around 600 km), with Incremental Analysis Update (IAU) and without digital filtering to allow accurate representation of tides. IDEA successfully predicts both the time and amplitude of the peak warming in the polar cap, with the 10 day forecast being superior to the standard NOAA NWP model (GFS). The observed impact of this SSW on the ionosphere includes enhanced (reduced) vertical drift velocity from the product between of the electric and magnetic field around 08-10Z (10-14 Z), and IDEA seems to do a good job of representing this. The drift velocity changes (and associated changes in ionospheric total electron content) is related to changes in lower thermospheric tides. The forecast of the semidiurnal, westward propagating, zonal wave number 2 (SW2) tide in zonal wind also shows an increase in the amplitude and a phase shift to earlier hours in the equatorial dynamo region during and after the peak warming, before recovering to their prior values about 15 days later. The SW2 amplitude and phase changes are shown to be likely due to changes in the stratospheric circulation and associated stratospheric ozone changes.

R. Ménard presented results from a study group on the added value of upper-tropospheric and stratospheric chemical data assimilation. While such chemical data assimilation systems are more and more mature and despite the high number of observations available in these regions, few applications of these analyses have been found. This group, supported by the International Space Science Institute (ISSI) in Bern (Switzerland), is based on assimilators and potential users. Potential products are a reanalysis of methane and CFCs to make their linearized chemical scheme to be used by climate model (see also the talk of Q. Errera summarised below).

Troposphere / stratosphere / mesosphere interactions: Upper Atmosphere

J. McCormack (invited) discussed the recent progress of the Naval Research Laboratory (NRL) NWP systems at high altitude. It showed that assimilation of radiances of Special Sensor Microwave Imager/Sounder (SSMIS) was able to constrain mesospheric temperature nearly as well as profile assimilation of MLS and SABER. The presentation also showed how a new linearized water vapour photochemical scheme significantly improved the water vapour analysis in the stratosphere and mesosphere, which reduced model temperature biases through a better representation of infrared radiation and enabled assimilation of additional radiance observations from the Infrared

Atmospheric Sounding Interferometer (IASI). Last but not least, many scientists are concerned by the lack of plans for new limb sounders, but J. McCormack also mentioned the lack of plans for future upper atmospheric radiance sounder like SSMIS.

D. Jackson presented the extension of the Met Office Unified Model (UM) to the thermosphere, with the aim of improved space weather forecasts in the long term. Development to extend the UM is to focus on two areas. The first area concerns the extension of the model lid up to 120-140km to have a better coupling between the lower and the upper atmosphere and to enable assessment of the UM tidal climatology against meteor radar and other observations. Initial UM simulations with UM lids at 100 km and 120 km are promising, but show issues with the tuning of the model non-orographic gravity waves scheme and with model stability. The second area focuses on the improvement of the dynamical core of UM above 120km. Idealised tests show that the representation of acoustic waves are challenging in this region.

V. Yudin discussed data analysis and whole atmosphere predictions calculated with the chemistry-climate model WACCM (Whole Atmosphere Community Climate Model). He highlighted the need for profile assimilation to reproduce vertical structures of observed ozone laminas and severe ozone losses as, for example, during the Arctic winter 2011. Yudin also presented results from a new version of WACCM with the lid extended from 140km to 500km. Using observations from the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) and Global Positioning System (GPS) Total Electron Content (TEC), he evaluated WACCM simulations where the dynamics was specified by meteorological analysis in the lower atmosphere. As shown, this simulation is able to reproduce several observed features like the tidal variability in the ionosphere-thermosphere during various SSW events between 2006 and 2013.

DA Methods

K. Hoppel explored the background forecast error covariances of the middle atmosphere the NRL NWP system. Forecast error covariances were estimated using two methods: (1) forecast field differences at 24 and 48 hours and (2) a random observation denial method. A rapid increase in error variance in the mesosphere was observed, along with unexpectedly large horizontal correlation patterns. The breakdown of geostrophic correlation at small scales (< 1000 km) was also observed in the mesosphere. By performing a spectral decomposition of analysis errors, the predictability limit as a function of resolution was inferred (see Figure 2). The skill-resolution was found to decrease with increasing altitude, reaching a values of around 6 degrees (wavenumber 30) in the upper mesosphere for temperature, and similar values for vorticity and divergence.

Data assimilation products in support of SPARC activities

M. Hegglin (invited) discussed the value of data assimilation products for the IGAC/SPARC Chemistry Climate Model Initiative (CCMI). Two examples using the Canadian Middle Atmosphere Model (CMAM) nudged to ERA-Interim reanalysis were discussed. The first one presented a study on stratospheric ozone between 1960 and 2010 (Shepherd et al., 2014). Thanks to model simulations using evolving and fixed amounts of ozone depleting substances, several remaining questions about observed ozone trends could be answered and the onset of ozone recovery identified. In the second example (Hegglin et al., 2014), the CMAM simulation is used as a transfer function between different satellite water vapour datasets in order to remove biases between the instruments and to create a

long-term (mid-1980 - 2010) water vapour record in the stratosphere. A negative trend is found in lower/mid stratospheric water vapour, implying that the positive trend observed in the balloon observations over Boulder (USA) is not globally representative. In the upper stratosphere, the water vapour trend is positive. The difference in sign between the trend in the lower and upper stratosphere is attributed to changes in the Brewer-Dobson circulation (BDC). Altogether, these two examples highlighted the high quality of ERA-Interim reanalysis, but also revealed an inhomogeneity at the time GPS Radio Occultation observations started to be fed into the assimilation system.

S. Chabrillat presented the Near Real Time (NRT) ozone analyses delivered by the European project MACC (Monitoring Atmospheric Composition and Climate). Due to NRT constraints, the system assimilates the NRT MLS ozone observations delivered 3 hours after measuring time and not the scientific MLS ozone data delivered around four days later. Due to the differences between these MLS datasets, the latter providing a better product, ozone fields from MACC are found to be of lower quality than those expected if the system could afford a four day delay (Lefever et al., 2014).

K. Wargan investigated the occurrence of Tropopause Inversion Layer (TIL) in the Goddard Earth Observing System (GEOS) version 5. Past studies showed that TIL was well represented in models but was erased in meteorological analysis by coarse assimilated data. GEOS-5 and more recent NWP systems exhibit the TIL correctly and numerical experiments performed with GEOS-5 demonstrated that the TIL is indeed erased if low spectral resolution data, such as from the Advanced Microwave Sounding Unit A (AMSU-A), are assimilated exclusively. It was shown that the use of hyperspectral radiance data and conventional observations in GEOS-5 is critical for reproducing the feature. In fact full data assimilation with GEOS-5 leads to a TIL that is sharper (and closer to radiosonde observations) than the model-only simulation.

Using different NWP reanalyses, **J. Xu** has compared the stratospheric temperature trend against radiosondes, satellite microwave radiances and model simulations between 1979 and 2005 from the Coupled Model Intercomparison Project (CMIP) phase 3 and 5. He also compared the spread of the trend based on the variability inside these different datasets. It revealed that reanalyses overestimate the tropospheric warming and underestimate the stratospheric cooling observed by the radiosondes. The inter-variability between the different reanalyses is also much higher than the one present in the different radiosonde datasets.

Another trend evaluation was done using different reanalyses, by **T. Iwasaki,** on the comparison of the evolution of the polar cold air mass (PCAM) in the troposphere. PCAM is defined by the quantity of air mass below 280K potential temperature and is a good indicator of the life stage of the polar cold air from generation to disappearance. In the northern hemispheric winter time, all reanalyses show a negative trend of PCAM which is on average 5% over 50 years. This quantity seems to be sensitive to the climate change. In the SH winter time, the trend in PCAM is less consistent between the different reanalyses, probably because of sparse surface and radiosonde data available for the assimilation procedure.

C. Long presented preliminary test results from assimilation of Stratospheric Sounding Unit (SSU) and AMSU radiances into the National Center for Environmental Prediction (NCEP) Global Forecast System (GFS). The tests were being conducted to address issues in the Climate Forecast System Reanalysis (CFSR) during the transition from the SSU to the AMSU radiances in October 1998. Issues with the CFSR associated to radiance assimilation in the stratosphere included: breaking up the

reanalysis into six streams, bias correction of SSU Channel 3, and not assimilating AMSU Channel 14. Other reanalyses handled this transition in different ways from switching immediately over from the SSU to AMSU in 1998 to assimilating both for an extended period of time. The greatest temperature impacts from this transition occurred above 10 hPa. The test runs showed that transitioning immediately from the SSU to the AMSU resulted in warmer temperatures above 2 hPa and cooler temperatures between 10 and 2 hPa. Assimilating both SSU and AMSU radiances reduced the respective warming and cooling by half.

Joint SPARC-DA/S-RIP workshop

Q. Errera presented a first effort in producing a chemical reanalysis of the stratospheric composition based on assimilation of MLS and the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS), for the period between 2007 and 2012. This study uses Belgian Assimilation System for Chemical ObsErvations (BASCOE) where 13 chemical species are assimilated: O_3, H_2O, CH_4, N_2O, HNO_3, NO_2, N_2O_5, $ClONO_2$, HCl, ClO CFC11, and CFC12. While the reanalysis agrees relatively well with independent observations, several issues were pointed out, in particular "zigzags" in the CH_4 profile in the lower tropical stratosphere coming from the observations as well as time inconsistency due to time inconsistency in the observing systems.

C. Kobayashi evaluated the BDC in the Japanese 55-years Reanalysis (JRA-55) family, i.e., JRA-55, JRA-55C (which assimilated conventional observations only, Kobayashi et al., 2014), and JRA-55AMIP (with the same forecast model as in the JRA-55 and JRA-55C without data assimilation). She showed that seasonal variations of the JRA-55 BDC compare well with those from ERA-Interim which was not the case of the previous JRA-25 product. However, the time series of troposphere/stratosphere mass exchange are different; the mass exchange increased in JRA-55, and decreased in ERA-Interim. The BDC in JRA-55AMIP data was found to be weaker than that in JRA-55 and JRA-55C data. Model experiments suggested that improving the gravity wave parameterization to allow the forecast model to produce QBO spontaneously may result in strengthening the BDC.

Z. Lawrence showed a comparison between MERRA and ERA-Interim based on diagnostics related to the formation of polar stratospheric clouds (PSCs), chlorine activation and the destruction of stratospheric ozone. Temperature in the winter hemispheric polar vortex is usually lower in MERRA than in ERA-Interim in the early years (before 2002) and *vice versa* in the later years. This is due to differences in the assimilated observing systems used in both reanalyses. MERRA also exhibits larger regions of cold air while ERA-Interim exhibits more cold days and larger polar vortices. Will the choice of MERRA or ERA-Interim strongly influence polar processing studies? In the early years, the answer is yes.

S. Das presented a comparison of in-situ observations (radiosondes and rocketsondes) against different reanalyses (MERRA, ERA-40, ERA-Interim and NCEP-II) over Thumba (8.5°N, 76.5°E), India. Features like the QBO and the tropical easterly jet from the reanalyses compared well with observations. The zonal winds are also in good agreement up to 30km. For the meridional wind, the agreement is only good below the tropopause.

B. Legras made a comparison of the BDC in several reanalysis (ERA-Interim, MERRA and JRA-55) based on age of air calculations. Compared to previous generations of reanalysis (e.g. ERA-40), the

agreement with observations is much better. However, there is still a maximum disagreement of 1 year in the Northern Hemisphere between reanalyses and it is not clear how to reduce it.

Representing the SPARC Temperature Trend Activity, **D. Seidel** discussed satellite observations of stratospheric temperature and presented preliminary results of an intercomparison of climate data records (CDRs) from meteorological sounders including MSU (Microwave Sounding Unit) channel 4, 3 channels of SSU, and 4 channels of AMSU spanning 1979-present. Despite recent revisions of SSU CDRs motivated by an earlier study (Thompson et al., 2012), differences remain between of 2 versions of SSU data and among 3 versions of MSU data. Empirical orthogonal function analyses revealed significant vertical and latitudinal structure to the main patterns of stratospheric temperature variability. The polar regions account for a very high fraction of interannual variability. For some channels, volcanic signals are evident. Long-term trends do not appear to account for much of the variability.

Recently, Thompson et al. (2012) documented the differences of temperature trends estimated from different datasets and called for re-investigation of the SSU that operated between 1978 and 2007. This was done by **C.-Z. Zou** who presented the recalibration and re-adjustment of the level 1c of SSU data affected by a space view anomaly. The revised SSU temperature trends are shown in Figure 3.

The end of the session saw four presentations about the recent updates done, respectively, by the different reanalysis centres. **S. Pawson** discussed that status of MERRA-2 at NASA. The MERRA-2 is ongoing and is expected to be released in February 2015. Compared to MERRA, the new version will benefit from modern radiance data types, update of SSU, temperature and ozone profiles from MLS (from 2004) and model improvements (see also the contribution of L. Coy above). **D. Tan** discussed the future ECMWF reanalysis that is supposed to replace ERA-Interim. This reanalysis will benefit from reprocessed observations and a later (better) model version and is expected to deliver, among others, better representation of SSWs. **C. Long** discussed the status of the four NOAA reanalysis efforts: NCEP/NCAR, NCEP/DOE, NCEP/CFSR, and ESRL/20CR. NOAA has just begun plans to create a new reanalysis as part of its next version of the Climate Forecast System. The new reanalysis would be generated in the 2018-2020 timeframe. A new version of the 20CR and a replacement of the NCEP/NCAR reanalyses are also in the early planning stage. **Y. Harada** presented some aspects of the new JRA-55 reanalysis w.r.t. the older JRA-25 version performed at the Japanese Meteorological Agency (JMA). In particular, it is found that JRA-55 reduced the cold bias in the stratosphere and significantly improved temporal consistency from JRA-25. Also in the stratosphere, the consistency of the atmospheric flow is improved from the point of view of momentum budget. As discussed above, JMA also has produced two other reanalyses, JRA-55C and JRA-55AMIP whose data will also be available soon for scientific use.

Seven posters were also presented during the workshop. **S. Chabrillat** compared Chemistry Transport Model (CTM) simulations driven by two different reanalyses: MERRA and ERA-Interim. **Y-H Kim** compared equatorial stratospheric waves between ERA-Interim, MERRA, JRA-55 and CFSR and their QBO momentum budget. **C. Long** displayed two posters comparing the same four reanalyses in the stratosphere focused on the temperature (poster 1) and the zonal wind (poster 2). **T. Sakazaki** compared the temperature tides in the stratosphere between the same four reanalyses as well as NOAA 20CR. To the four before mentioned reanalyses, **S.W. Son** added NCEP-NCAR, NCEP-DOE, JRA-25 and ERA-40 and evaluate their consistency of momentum diagnostics. Finally, **M. Taguchi**

compared interannual variation in northern stratospheric winter using the same eight reanalyses as well as NCEP 20CR.

Report from the S-RIP workshop

The planning meeting of the S-RIP was held in April-May 2013 (Fujiwara and Jackson, 2013). There, it was decided that annual S-RIP workshops will be held until 2018 when the full report is published in the SPARC report series. The main purpose of the annual S-RIP workshops is to discuss the progress and current issues for each chapter of the planned S-RIP report. On Day 3, **Masatomo Fujiwara** presented the S-RIP overview and Chapter 1 (Introduction), and **David Tan** presented the progress of Chapter 2 (Description of the Reanalysis Systems). On Day 4, **Craig Long** discussed Chapter 3 (Climatology and Interannual Variability of Dynamical Variables), **Sean Davis** and **Michaela Hegglin** discussed Chapter 4 (Climatology and Interannual Variability of Ozone and Water Vapour), **Thomas Birner** and **Beatriz Monge-Sanz** discussed Chapter 5 (Brewer–Dobson Circulation), **Edwin Gerber** discussed Chapter 6 (Stratosphere–Troposphere Coupling), **Gloria Manney** and **Cameron Homeyer** discussed Chapter 7 (Extratropical Upper Troposphere and Lower Stratosphere), and **Jonathon Wright**, on behalf of the chapter leads S. Tegtmeier and K. Krüger, discussed Chapter 8 (Tropical Tropopause Layer). On Day 5, **James Anstey** discussed Chapter 9 (Quasi-Biennial Oscillation and Tropical Variability), **Michelle Santee** discussed Chapter 10 (Polar Processes), and **Diane Pendlebury** and **Lynn Harvey** discussed Chapter 11 (Upper Stratosphere and Lower Mesosphere). The rapporteurs were assigned for each chapter, and they made brief, summary presentations at the end of the workshop.

In 2015, it is planned that the S-RIP "Interim" Report will be completed and published that covers the "basic" chapters, Chapters 1-4. Discussion was made for the actual procedures and some editorial details for the report. Also, it was agreed that by mid-2015, the zeroth-order draft will be prepared for the "advanced" chapters, Chapters 5-11.

Discussion and next workshop

David Jackson officially stepped down as chair of the SPARC-DA and co-lead of the S-RIP in April 2014. Quentin Errera is going to replace him at the SPARC-DA. Before the workshop, M. Fujiwara, the other S-RIP co-lead, proposed a potential candidate to the chapter leads and reanalysis-centre representatives for the S-RIP. At the workshop, it was agreed by all the participants that David Tan of ECMWF becomes the new S-RIP co-lead.

It was also agreed that we will have the next SPARC DA workshop and the next S-RIP workshop jointly in fall 2015. We will consider a good coordination with other SPARC-related workshops.

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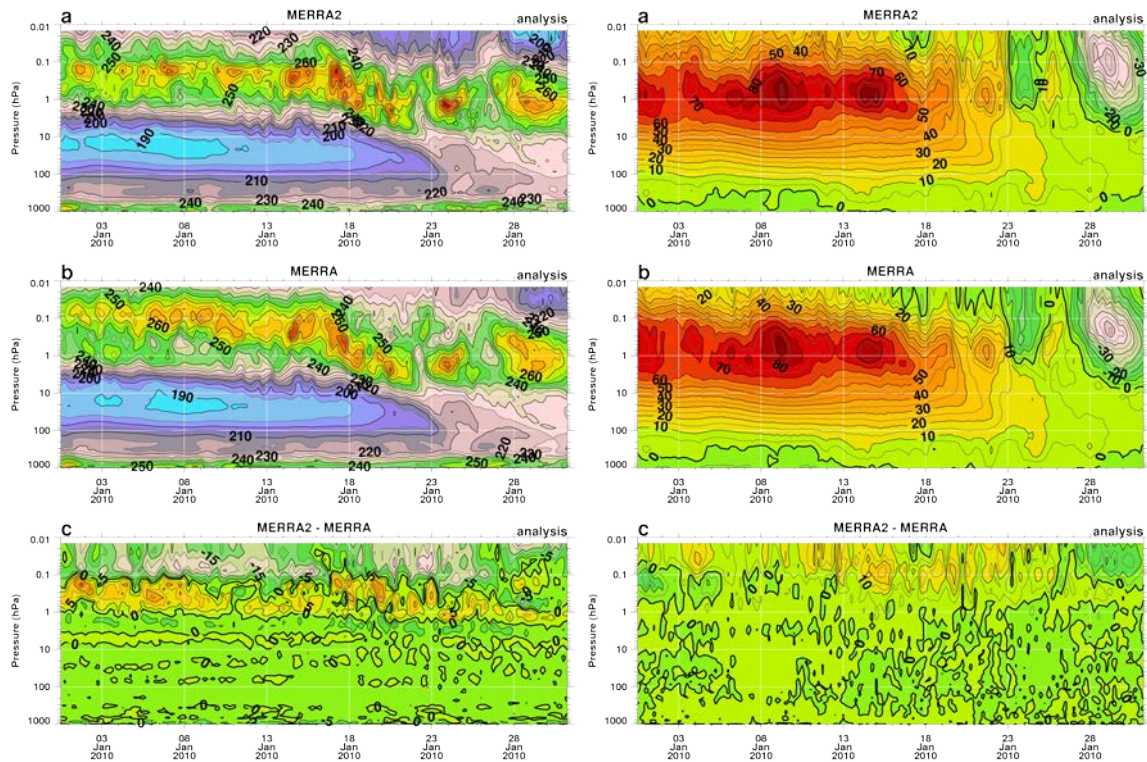
Figures

Figure 1: Time series of mean temperature between 60°N-90°N (left) and zonal wind at 60°N (right) analysis from MERRA-2 (top), MERRA-1 (middle) and their differences (bottom) in January 2010 when a Stratospheric Sudden Warming occurred. (Provided by Lawrence Coy.)
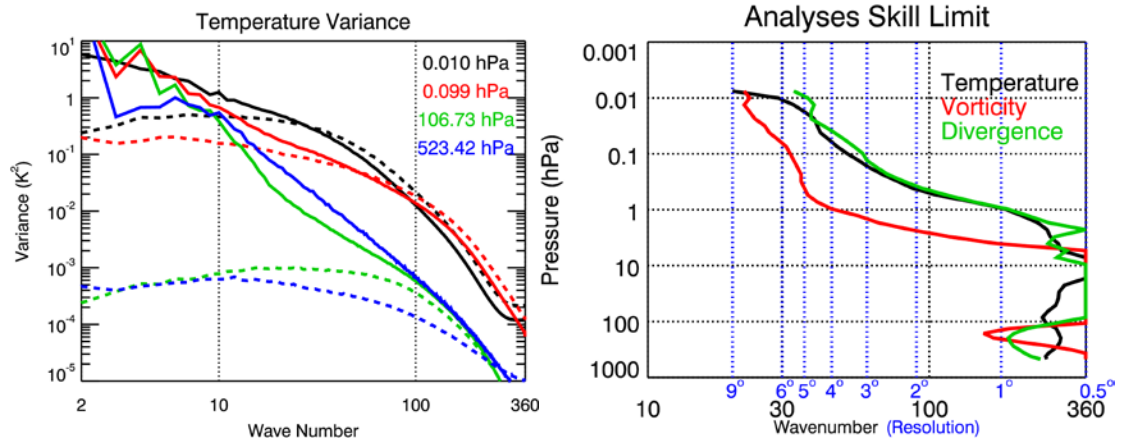
Figure 2: (left) Average power spectra for temperature forecast (solid line) and temperature analysis error (dashed lines) for several pressure levels. (right) Limit of predictability, defined as the wavenumber where the error variance exceeds the forecast variance. Analysis errors for Temperature (black), vorticity (red) and divergence (green) were estimated as the difference between two December 2011 analysis produced from a random-observation denial experiment. (Provided by Karl Hoppel.)
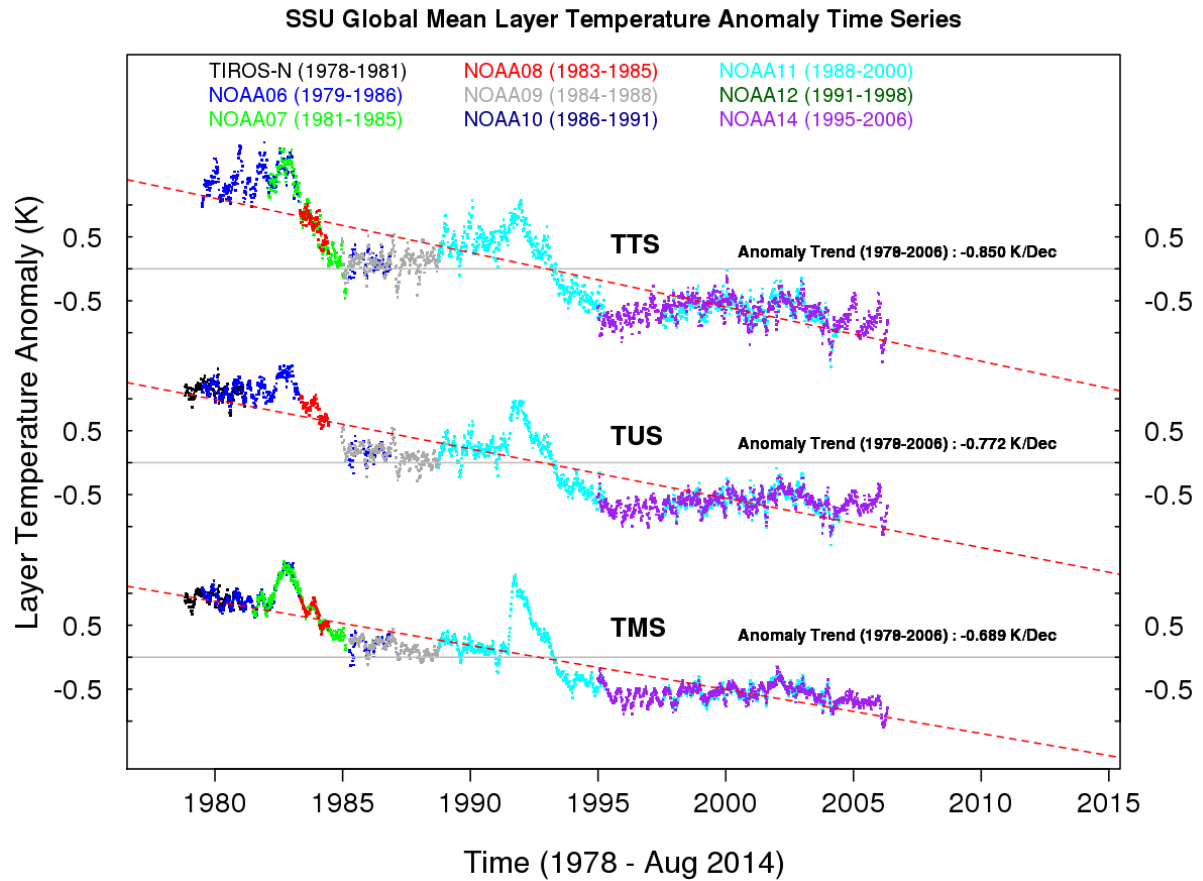
Figure3: SSU global mean anomaly time series and trends for layer temperatures of mid-stratosphere (TMS, channel 1), upper-stratosphere (TUS, channel 2), and top-stratosphere (TTS, channel 3) after recalibration and adjustment of multiple instrument drifting effects of the level 1c radiances (Provided by Cheng-Zhi Zou).