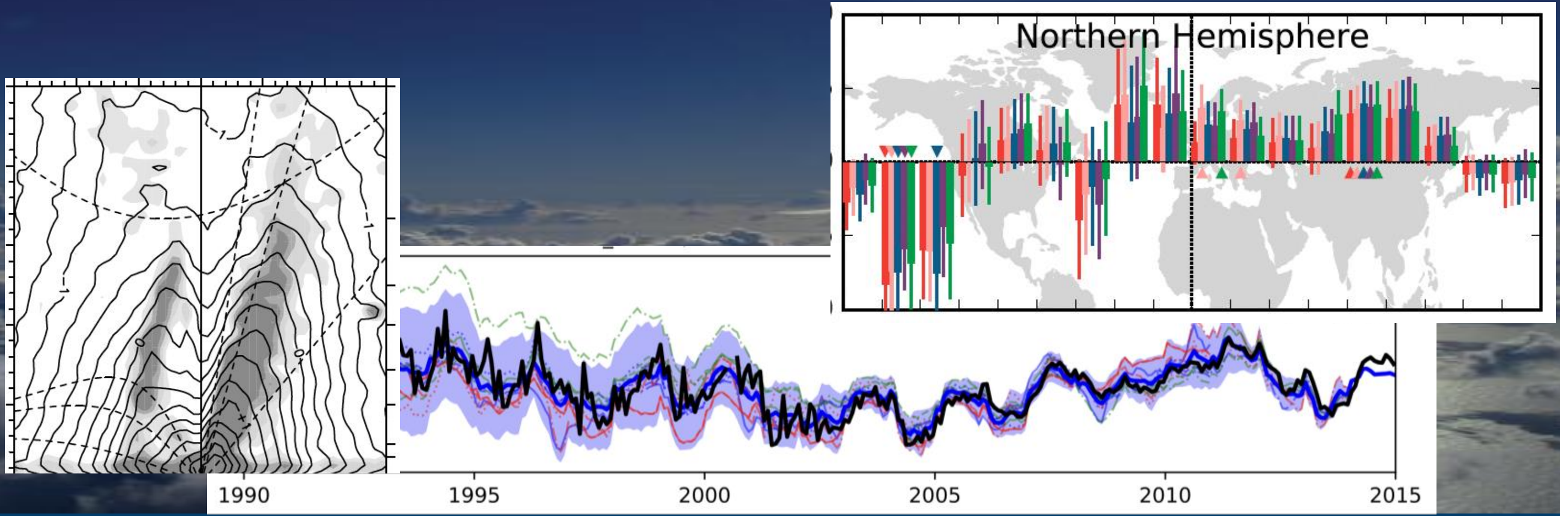


EVALUATION OF PROCESSES, INTER-ANNUAL VARIABILITY, AND TRENDS IN GLOBAL ATMOSPHERIC REANALYSES

A (MOSTLY) STRATOSPHERIC AND USER PERSPECTIVE!

06 SEPTEMBER 2023 I MICHAELA I. HEGGLIN

RESEARCH CENTRE JULICH | UNIVERSITY OF READING

ACKNOWLEDGMENT TO MY GROUP AND THE SPARC S-RIP COMMUNITY

Mitglied der Helmholtz-Gemeinschaft

University of Reading

JÜLICH Forschungszentrum

INTENDED LEARNING OUTCOMES

- **Knowing** different approaches to the evaluation of reanalyses.
- **Understanding** potential pitfalls in the evaluation (and use) of reanalyses.
- **Appreciation** of the value of user-driven evaluation of reanalyses in collaboration with reanalysis centres (cross-fertiliziation between communities).

OUTLINE

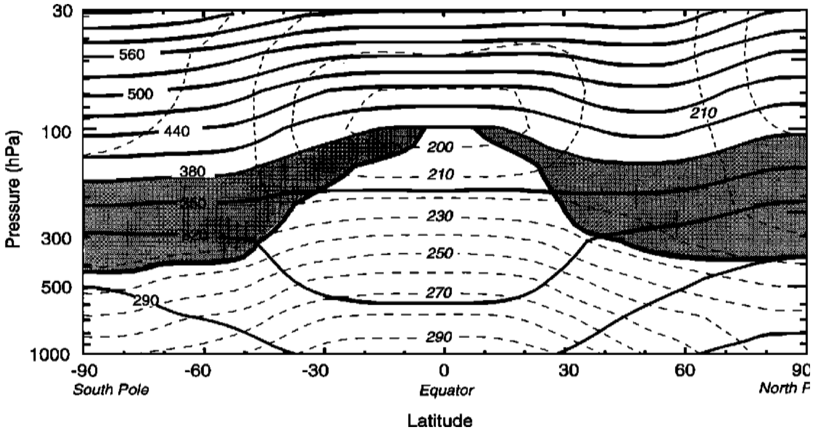
- The stratosphere and its role in weather and climate
- WCRP SPARC and reanalyses
- Evaluation of global atmospheric reanalyses
    - Climatology and natural modes of variability (seasonality, QBO, ...)
    - Processes
    - Trends
- Key points and conclusions

THE STRATOSPHERE

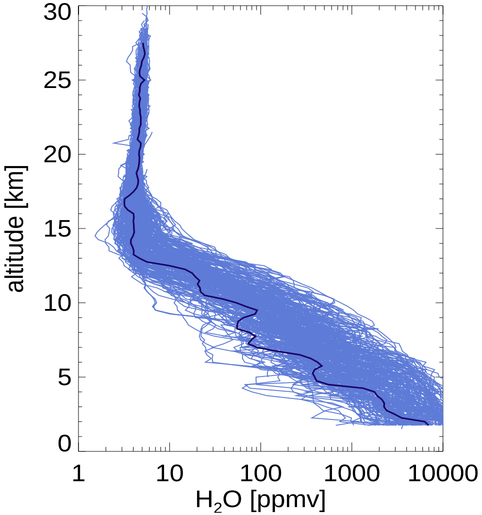
- The stratosphere lies **between 10 and 50 km**, is highly stratified/stable, and dry.
- This is in stark contrast to the troposphere **– the weather layer –** where temperature decreases with altitude and convective processes lead to turbulent mixing.
- The stratosphere hosts the **ozone layer**, which absorbs UV and is fundamental to life on Earth.

Source: NASA (Space Shuttle Endeavour)

Holton et al., *Reviews Geophys.* 1991

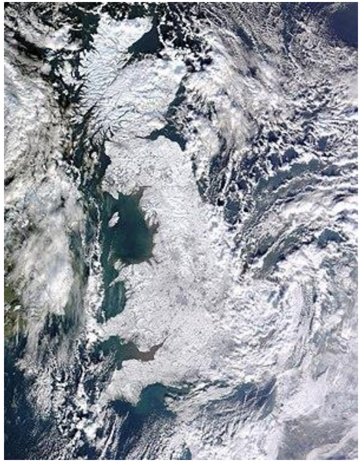


NOAA FPH Hilo balloon data



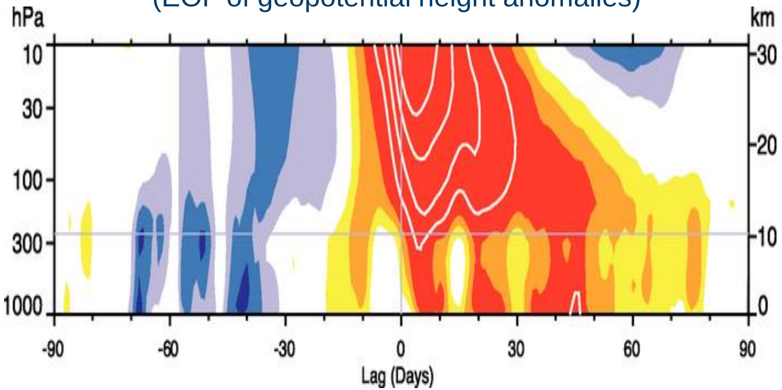
ITS ROLE IN WEATHER AND CLIMATE

- While the stratosphere is not directly involved in the development of daily weather, **stratospheric conditions impose constraints** on weather and climate variability (similar to SSTs, sea-ice cover, or soil moisture).
- **Stratosphere-troposphere coupling**, which affects weather patterns, is connected to the propagation of synoptic and planetary-scale Rossby waves as well as gravity waves.

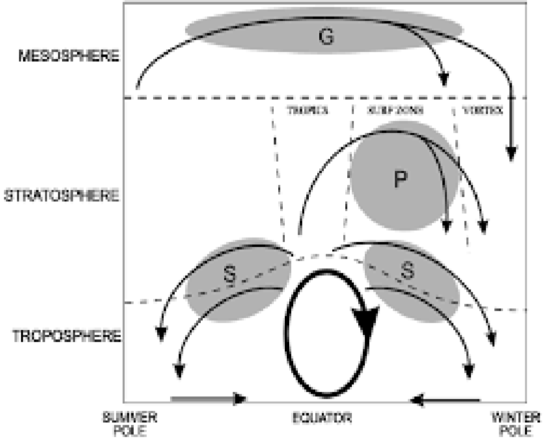


Satellite imagery
2009/2010 winter

Baldwin & Dunkerton, *Science* 2001
(EOF of geopotential height anomalies)



Plumb, *J. Met. Soc. Japan* 2002



ITS REPRESENTATION IN REANALYSES

- Given the realisation of the **importance of the stratosphere for weather and climate prediction**, reanalysis (and NWP) models now incorporate much more realistic representations of the stratosphere compared to ~20 years ago (e.g., with upper boundaries around 0.1 hPa instead of the stratopause).
- **Observations of temperature, wind,** and **chemical composition** (e.g., ozone) are used for assimilation in the stratosphere.
- Reanalyses ultimately offer the opportunity to study the state of the stratosphere and the processes which help improve **weather forecasts** and **modelling of climate change**, including **interactions between the stratosphere and troposphere**.
- But, **how well are reanalyses reflecting the real atmosphere** in terms of processes, variability and trends?

THE TRICKY TASK OF EVALUATING REANALYSES

University of Reading

- Many **observations** available for the evaluation of reanalyses are already being used in the data assimilation system, rendering the evaluation not independent.
  - Need to search for independent datasets, mostly in-situ data which may not be representative.
- Reanalyses have different temporal and spatial resolutions than many observational datasets, making direct comparisons challenging.
- Observations have their own **biases and inaccuracies**.
- Over time, observational networks change, and measurement techniques evolve. This can introduce inhomogeneities in both observational climate data records and reanalyses.
  - This leads to difficulties in establishing the long-term stability of reanalyses and trend analyses.
- Not all important meteorological features can be directly evaluated against observations (e.g. gravity waves).
- Due to these challenges, researchers work on improving observational networks, addressing data quality issues, and developing advanced validation techniques to better assess the accuracy of reanalyses.

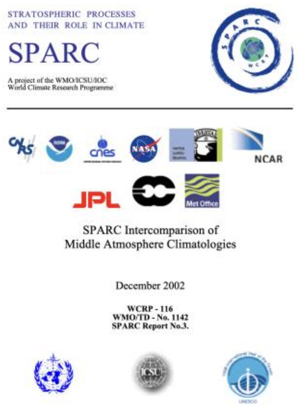
OUTLINE

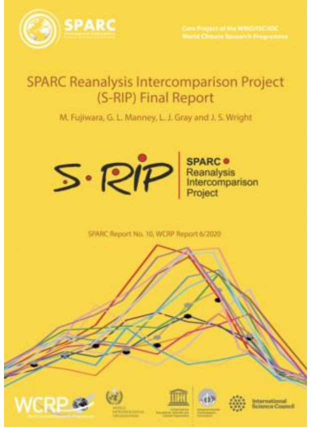
University of Reading

- The stratosphere and its role in weather and climate
- WCRP SPARC and reanalyses
- Evaluation of global atmospheric reanalyses
  - Climatology and natural modes of variability (seasonality, QBO, ...)
  - Processes
  - Trends
- Key points and conclusions

EVALUATION OF REANALYSES IN WCRP SPARC

- **SPARC** (Stratosphere-troposphere Processes And their Role in Climate) is a core project of the World Climate Research Programme (**WCRP**).
  - Coordinates international assessments of stratospheric observations and models.
- **First SPARC report** on a reanalysis intercomparison: Randel et al. (SPARC no. 3, 2002).
- **Second SPARC report:** SPARC Reanalysis Intercomparison Project (S-RIP, 2022).





- **First SPARC report** (SPARC no. 3, Randel et al., 2002)
  - **10 authors & 7 contributors** (incl. Adrian Simmons)
  - **109 pages**
  - **4 reanalyses** (UKMO, NCEP, ERA15, ERA40)
  - **Only limited observations available for comparisons**
- **Second SPARC report** (S-RIP)
  - **> 100 authors**
  - **635 pages**
  - **16 reanalyses** (ERA-40, ERA-I, ERA5, ERA-20, ERA-CM, CERA-20C, JRA-25, JRA-55, JRA-55C, JRA-55AMIP, MERRA, MERRA-2, NCEP-NCAR R1 & R2, CFSR, 20CR)
  - **More and better observations available**

OVERVIEW OF S-RIP

- S-RIP started in 2013 for focused intercomparison of atmospheric reanalyses with the overall goals:
  - to foster communication between SPARC-related researchers and reanalysis centres
  - to better understand the differences among current reanalysis products and their underlying causes
  - to provide guidance to reanalysis users by documenting the results of this reanalysis intercomparison
  - to contribute to future reanalysis improvements
- **Phase 1** completed with publication of the S-RIP Final Report in January 2022 and completion of Phase 1 journal special issue

- **Phase 2** planning began in 2022 and is continuing

List of new reanalysis systems considered:

- JRA-3Q
- CRA-40
- R21C
- CORe
- CAFE60

Chemical reanalyses:

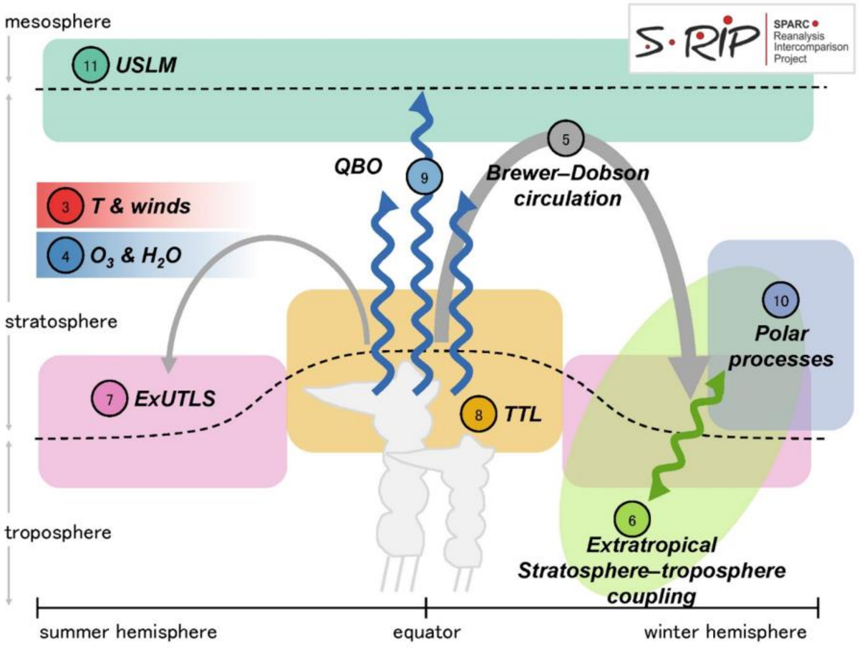
- CAMS-EAC4
- BRAM2
- M2_SCREAM
- TCR2
- R21C-CHEM

The S-RIP Planning Meeting (Met Office, UK, 2013)

S-RIP 2018 Chapter-lead Meeting (NWRA, Boulder, USA)

S-RIP REPORT: CONTENT AND STRUCTURE

Co-leads: M. Fujiwara, G. Manney, L. Gray
Report Editors: M. Fujiwara, G. Manney, L. Gray, J. Wright



- ACP/ESSD special issue on the S-RIP (>50 papers)
- S-RIP (https://www.sparc-climate.org/sparc-report-no-10/)

	Chapter Title	Chapter Co-leads
1	Introduction	M. Fujiwara, G. Manney, L. Gray
2	Description of the Reanalysis Systems	J. Wright, M. Fujiwara, C. Long
3	Overview of Temperature and Winds	C. Long, M. Fujiwara
4	Overview of Ozone and Water Vapour	S. Davis, M. Hegglin
5	Brewer-Dobson Circulation	B. Monge-Sanz, T. Birner
6	Extratropical Stratosphere-Troposphere Coupling	E. Gerber, P. Martineau
7	Extratropical Upper Troposphere and Lower Stratosphere (UTLS)	C. Homeyer, G. Manney
8	Tropical Tropopause Layer	S. Tegtmeier, K. Krüger
9	Quasi-Biennial Oscillation (QBO)	J. Anstey, L. Gray
10	Polar Processes	M. Santee, A. Lambert, G. Manney
11	Upper Stratosphere and Lower Mesosphere	L. Harvey, J. Knox
12	Synthesis Summary	M. Fujiwara, G. Manney, L. Gray, J. Wright

S-RIP PHASE 2: PLANS / GOALS

University of Reading

- Evaluation of **newer reanalyses** (e.g., full evaluation of ERA5; initial evaluation of CRA-40 and JRA-3Q)
- Evaluation of reanalyses of **atmospheric chemistry and composition**, including those focused on both air quality applications and stratospheric/UTLS chemistry and transport.
- More extensive examination of **stratosphere-troposphere coupling**, including tropical processes.
- Evaluation of reanalysis representation of **dynamical processes** in the troposphere as well as the middle atmosphere; e.g., Rossby-wave breaking, blocking, baroclinic storms, more detailed teleconnection (e.g., with ENSO and MJO) studies, etc.
- Analysis / comparison of **extreme weather events** (cold, heat, winds, precipitation) and their links to large-scale dynamics and stratospheric influence.
- More complete analysis of **SH processes**, especially aspects of stratosphere-troposphere coupling and links to extreme weather events.
- In addressing these topics, SRIP-2 will also build **online infrastructure** for maintaining **systematic documentation** and **evaluation of future reanalyses** as they are released to the public.

OUTLINE

- The stratosphere and its role in weather and climate
- WCRP SPARC and reanalyses
- Evaluation of global atmospheric reanalyses
  - Climatology and natural modes of variability (seasonality, QBO, ...)
  - Processes
  - Trends
- Key points and conclusions

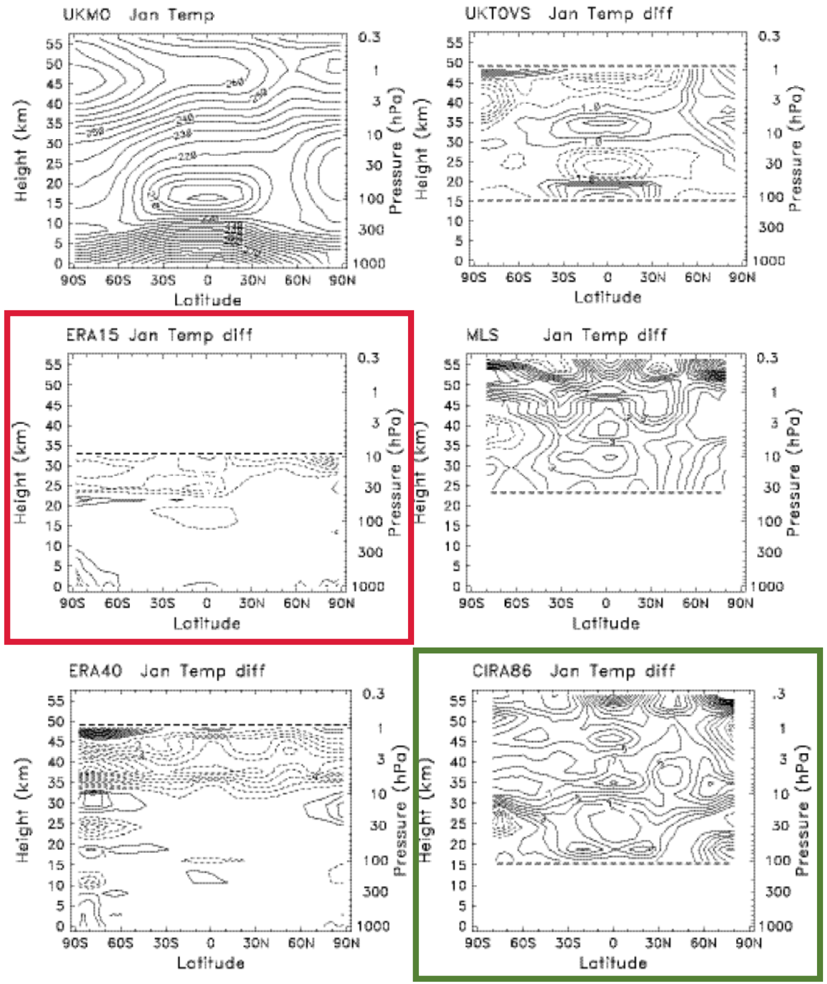
SPARC Report No. 3 (Randel et al., 2002)

MIDDLE ATMOSPHERE TEMPERATURE

1992-1997
1992-1993
1960s

Climatologies

- Zonal mean climatologies represent ‘first shot’ at evaluation of reanalyses.
- Observational constraints were poor, thus often an arbitrary reference was chosen.
  - CIRA86 is a mixture of radiosondes/assimilation.
  - The different datasets cover different time periods.
- CIRA86’s warm bias is explained by cooling in the lower stratosphere between the 1960s and 1990s.
- Differences (1K-contours) are largest at upper levels and in polar regions.
  - Due to boundary conditions / sparser observations.

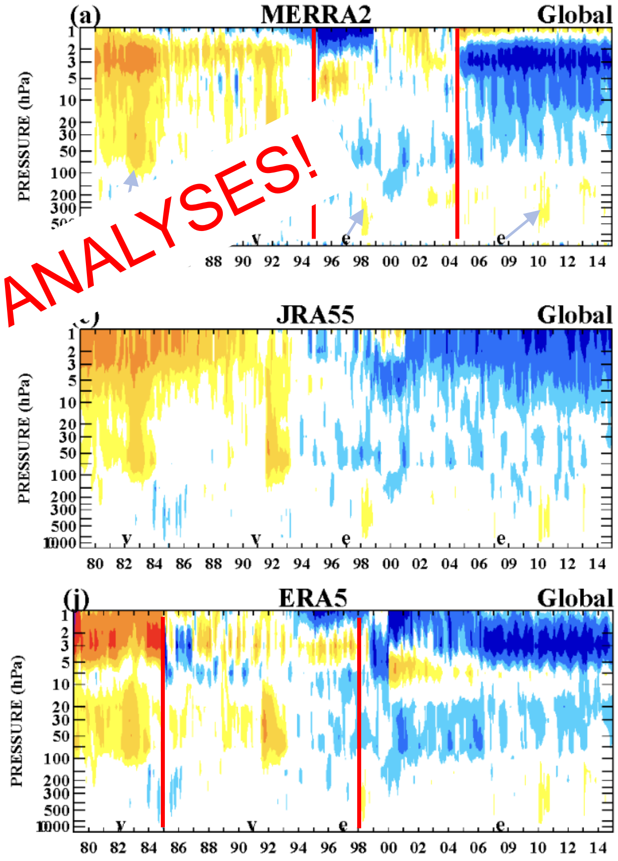


TEMPERATURE TIMESERIES

TIME-PRESSURE EVOLUTION OF GLOBAL MEAN ANOMALIES

- Illustrates how well the various reanalyses were able to transition between satellites and other data sources.
- Reveals several climatic features:
  - El Niño events (1998 and 2010)
  - Volcanic eruptions El Chichón (1982) and M… (1991)
  - Long-term cooling (combination ozo… …imate change)
- Major improvements over fir… …tion reanalyses.
- Still, discontinuities ar…
  - MERRA-2: 1995 (… from NOAA-11 to NOAA-14 SSU channel 3 radiance…), 2004 (assimilation of Aura-MLS)
  - ERA-5: 1985 (transition from NOAA-7 SSU to NOAA-9 SSU); August 1998 (transition from TOVS to ATOVS)
  - JRA-55: better handling of transitions through bias-correction.

IMPLICATIONS FOR TREND ANALYSES!



JÜLICH Forschungszentrum

(updated from Davis, Hegglin et al., *ACP* 2017)

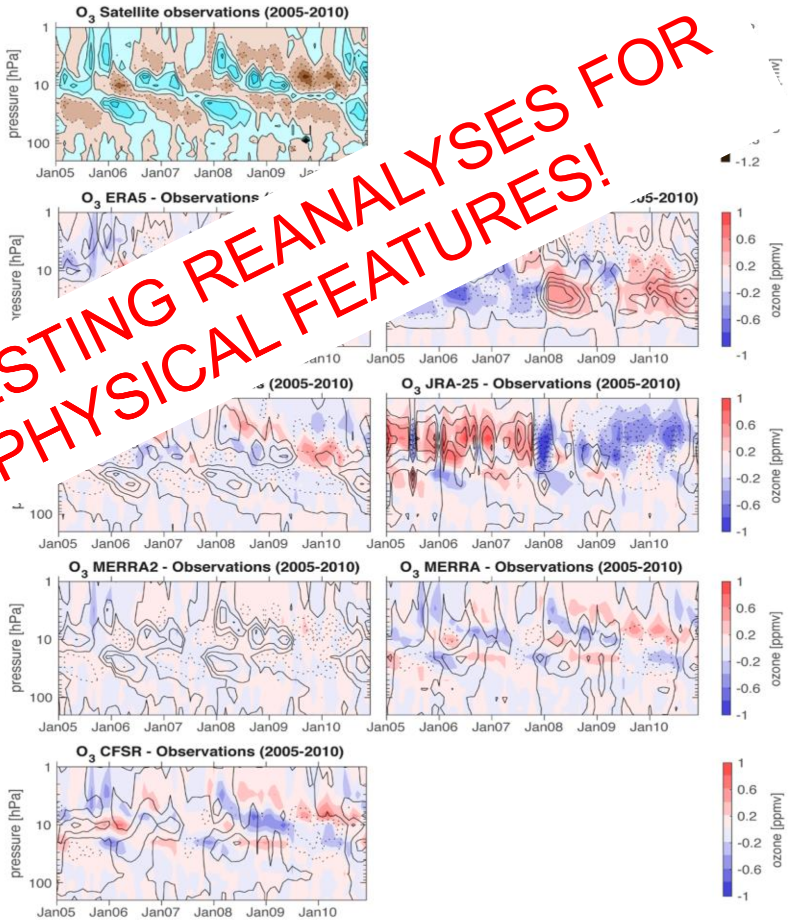
QUASI-BIENNIAL OSCILLATION

The QBO is one of the dominant influences on the interannual variability in tropical ozone

QBO-induced ozone anomalies (2005-2010) in satellite observations (top left panel, positive anomalies in green, SPARC Data Initiative; Hegglin et al., *ESSD* 2021), along with differences from reanalyses:

- Geophysical feature evident in downwar… anomalies.
- Newer reanalyses perform … differences from the o…
- Substantial diff… …alyses, partly related to many … …zone datasets assimilated.

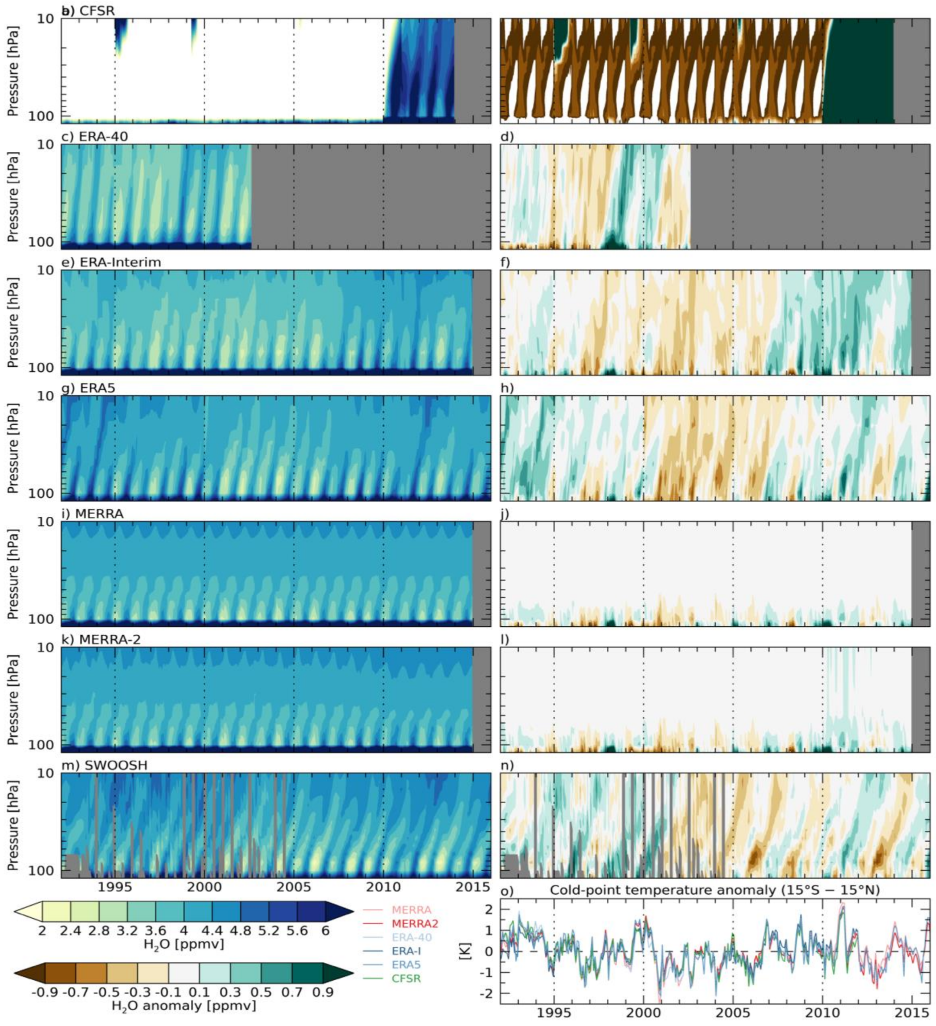
REVEALS VALUE OF TESTING REANALYSES FOR OBSERVED GEOPHYSICAL FEATURES!



THE TROPICAL H_2O TAPE RECORDER

The tropical tape recorder is one of the dominant influences on the interannual variability in tropical water vapour and reflects anomalies in cold-point temperature at the tropical tropopause

- Again, substantial differences between reanalyses, related to differences in the representation of stratospheric water vapour.
- MERRA-2 shows basically no internannual variability due to the relaxation to climatology.
- Drastic improvements in ERA-series, partially due to including a more realistic methane oxidation.



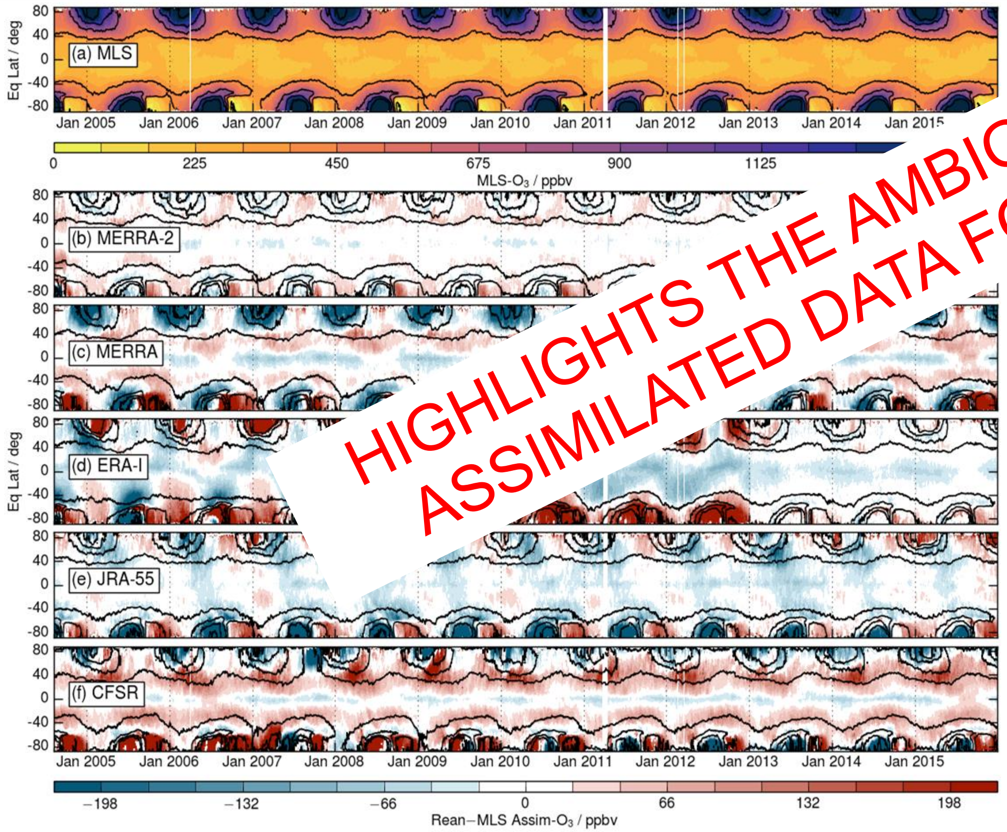
OUTLINE

- The stratosphere and its role in weather and climate
- WCRP SPARC and reanalyses
- Evaluation of global atmospheric reanalyses
  - Climatology and natural modes of variability (seasonality, QBO, ...)
  - Processes
  - Trends
- Key points and conclusions

University of Reading

ANTARCTIC OZONE HOLE

Interannual variability (2005-2015)



HIGHLIGHTS THE AMBIGUITY OF USING ASSIMILATED DATA FOR VALIDATION!

Time se… …ne at 390K in eq… …imates (top), and … reanalysis from Aura-MLS.

- …ny reanalyses underestimate ozone hole area and persistence
- Better agreement in later years, when more ozone observations are assimilated.

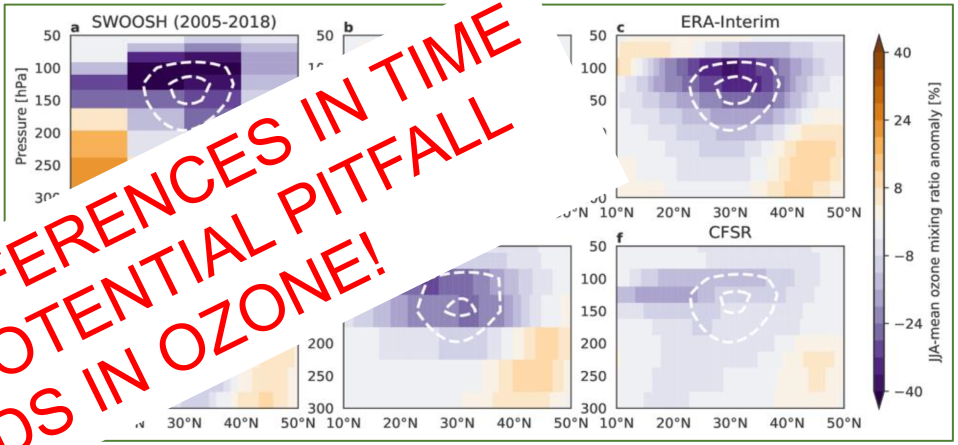
- MERRA-2 assimilates MLS ozone throughout the Aura mission.
- ERA-Interim assimilated MLS ozone in 2008, and after the second half of 2009, but in late 2009 through 2012, assimilated a near-real-time product that was not recommended for scientific use.

University of Reading

ASIAN SUMMER MONSOON

Climatological evaluation
(Reanalyses 1980-2010 / SWOOSH 2005-2018)

Latitude-pressure distributions of normalized anomalies in JJA mean ozone (30–120E) relative to zonal-mean values.



PRELIMINARY, BUT DIFFERENCES IN TIME PERIODS LEAD TO POTENTIAL PITFALL DUE TO TRENDS IN OZONE!

- Shows the impact of the strong co... transport within the Asian su... ozone at upper tropos...
- Also shows the di... downward t... ...g in the vicinity...
- Reveals un... ...vective transport in most rean...
- Reveals also t... ...pospheric ozone chemistry is not represented in reanalyses.

For Phase 2: We will extend monsoon-related evaluations to include:

- Trends and variability in a comprehensive set of dynamical fields, which will help assess the robustness of trends in area and intensity reported in the literature.
- Trends and variability in Asian monsoon composition from chemical reanalyses.

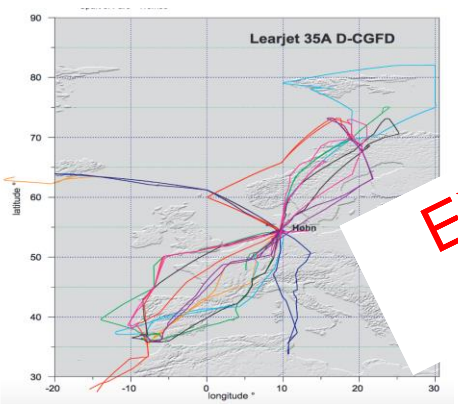
ROSSBY-WAVE BREAKING

University of Reading

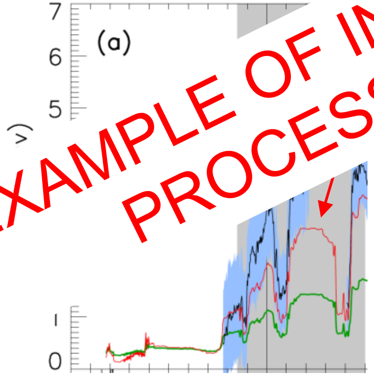
Cannot be directly observed, thus must be evaluated indirectly

- Rossby waves are important to drive stratospheric circulation and cross-tropop…
- Observations form the SPURT aircraft campaign (2001-2003) reveal sm… …nerated by troposphere-to-stratosphere transport that cannot be resolved by lo… …s.
- However, using the reverse-domain filling technique makes t… …rated by Rossby wave breaking visible and thus can be used for validation of … …s fields.

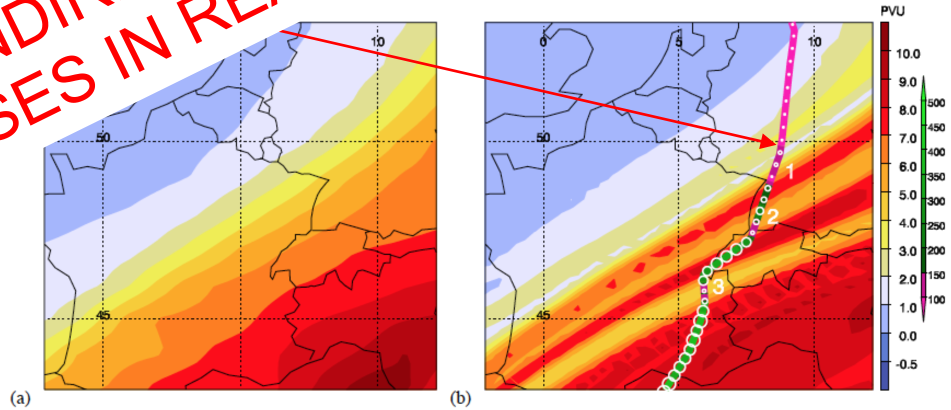
EXAMPLE OF INDIRECT VALIDATION OF PROCESSES IN REANALYSES



Engel et al., *ACP* 2006



Hegglin et al., *ACP* 2004



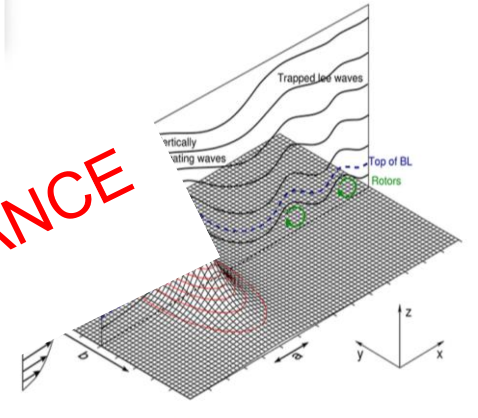
JÜLICH Forschungszentrum

MOUNTAIN WAVES

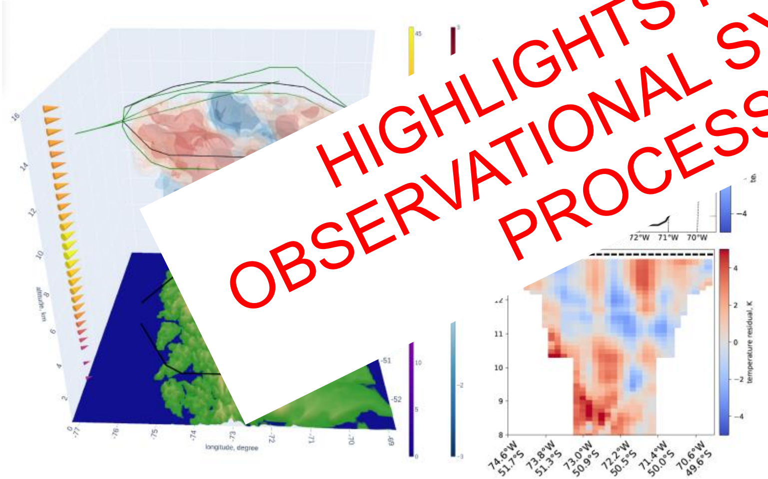
New observations for gravity waves are on the horizon …

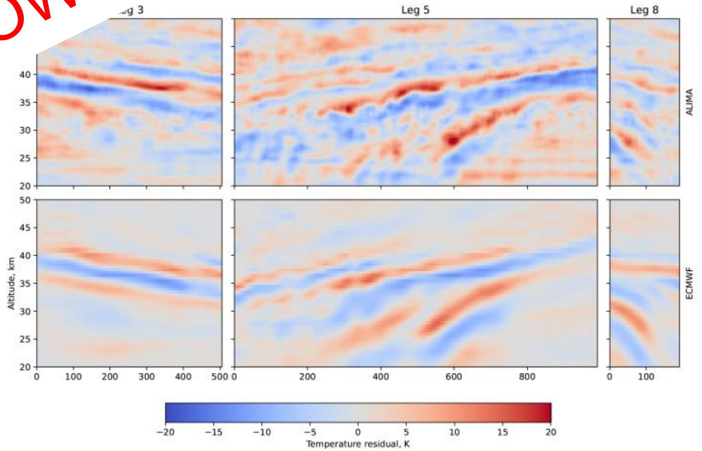
- Gravity waves (GW) are harmonic wind and temperature perturbati… propagating in the atmosphere.
- Important for middle atmosphere circulation and respon…
- New 3D-observations from GLORIA (CAIRT EE11… ALIMA can be used to evaluate GW represen…

HIGHLIGHTS IMPROVEMENTS IN OBSERVATIONAL SYSTEMS TO ENHANCE PROCESS KNOWLEDGE



M. Texeira, Frontiers in Physics, 2014





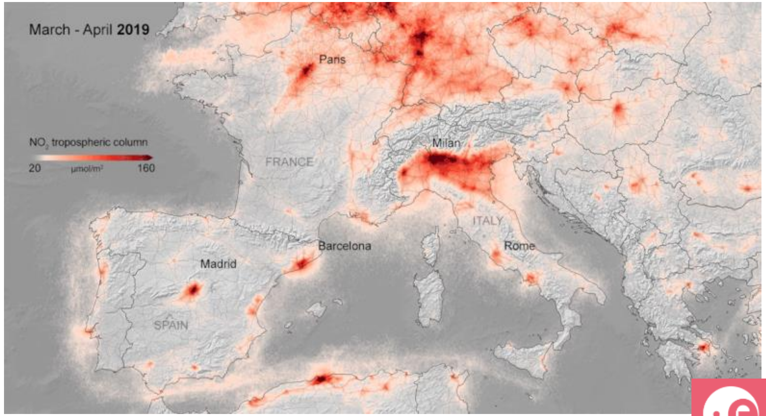
(courtesy Peter Preusse; Rapp et al., *BAMS* 2021)

PROCESS STUDIES IN UNCHARTERED TERRITORIES

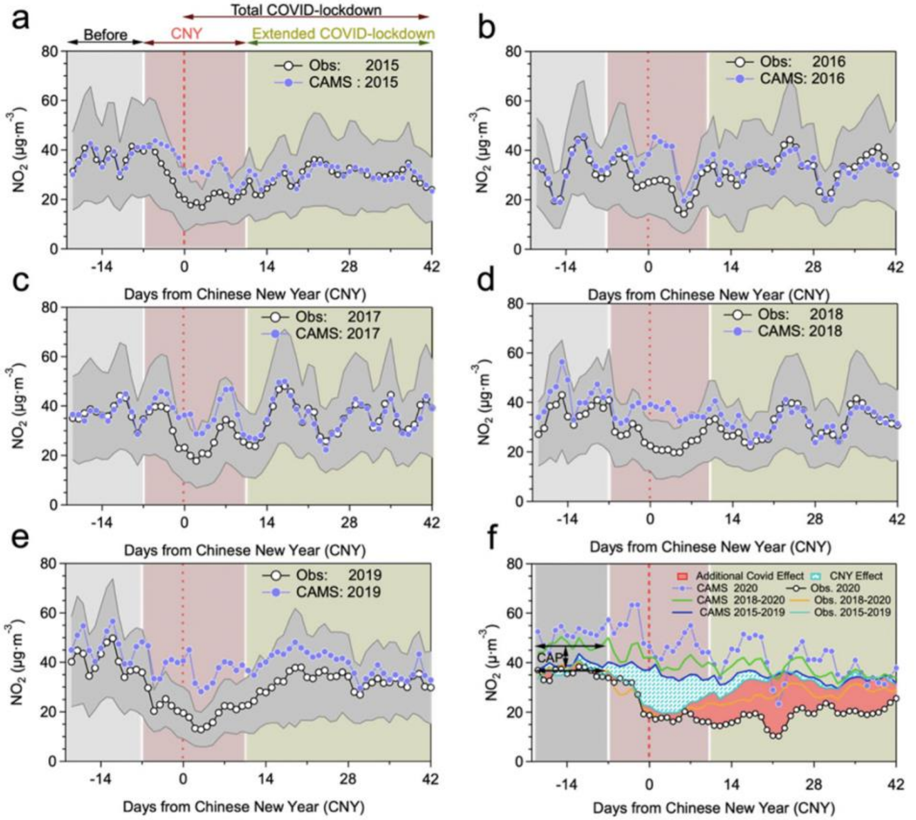
A unique experiment of air pollution during the Covid-19 lockdown

Shen, Hegglin et al., npj Climate and Atmospheric Science 2022

- CAMS is found to compare extremely well against observations, except it does not account for the Chinese New Year emissions reductions.
- An ML-based method helps disentangle reductions due to Covid-19 lockdown, impact of the Chinese Clean Air Plan, and meteorology.



Copernicus Sentinel-5P (TROPOMI observations)



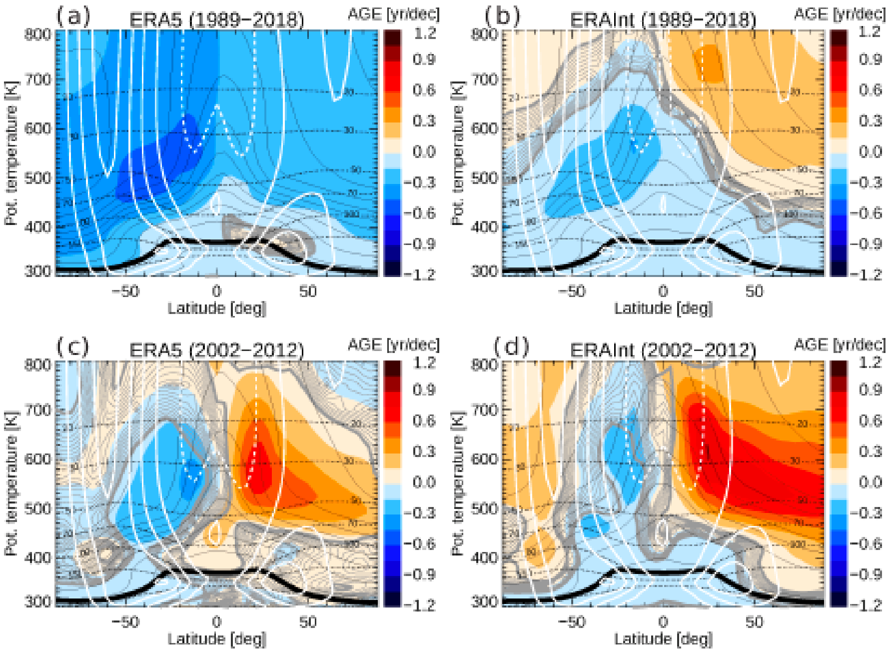
OUTLINE

- The stratosphere and its role in weather and climate
- WCRP SPARC and reanalyses
- Evaluation of global atmospheric reanalyses
  - Climatology and natural modes of variability (seasonality, QBO, ...)
  - Processes
  - Trends
- Key points and conclusions

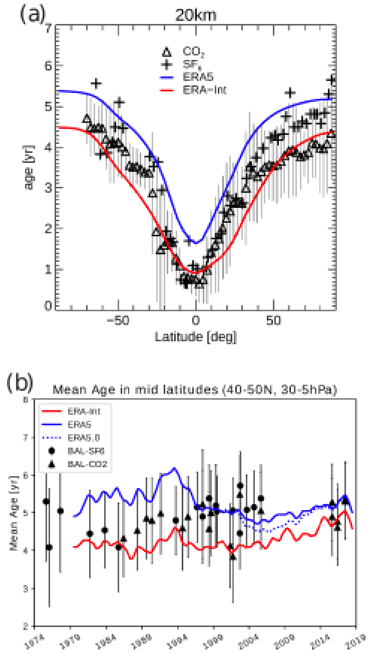
TRENDS IN MEAN AGE OF AIR IN REANALYSES

University of Reading

Indirect comparisons using reanalyses to drive chemistry transport and chemistry climate models



- Age of air in ERA5 is significantly older than in ERA-Interim (i.e., BDC is slower).
- Geophysica aircraft observations in NH LS suggest a high-bias for ERA5 mean age.
- Trend over 1989–2018 in ERA5 shows globally decreasing age.
- Trends over different time periods can differ strongly!



Ploeger et al., *ACP* 2021

- **Reanalysis trends in mean age of air show differences even if from the same centre.**

WATER VAPOUR TRENDS FROM WV_CCI

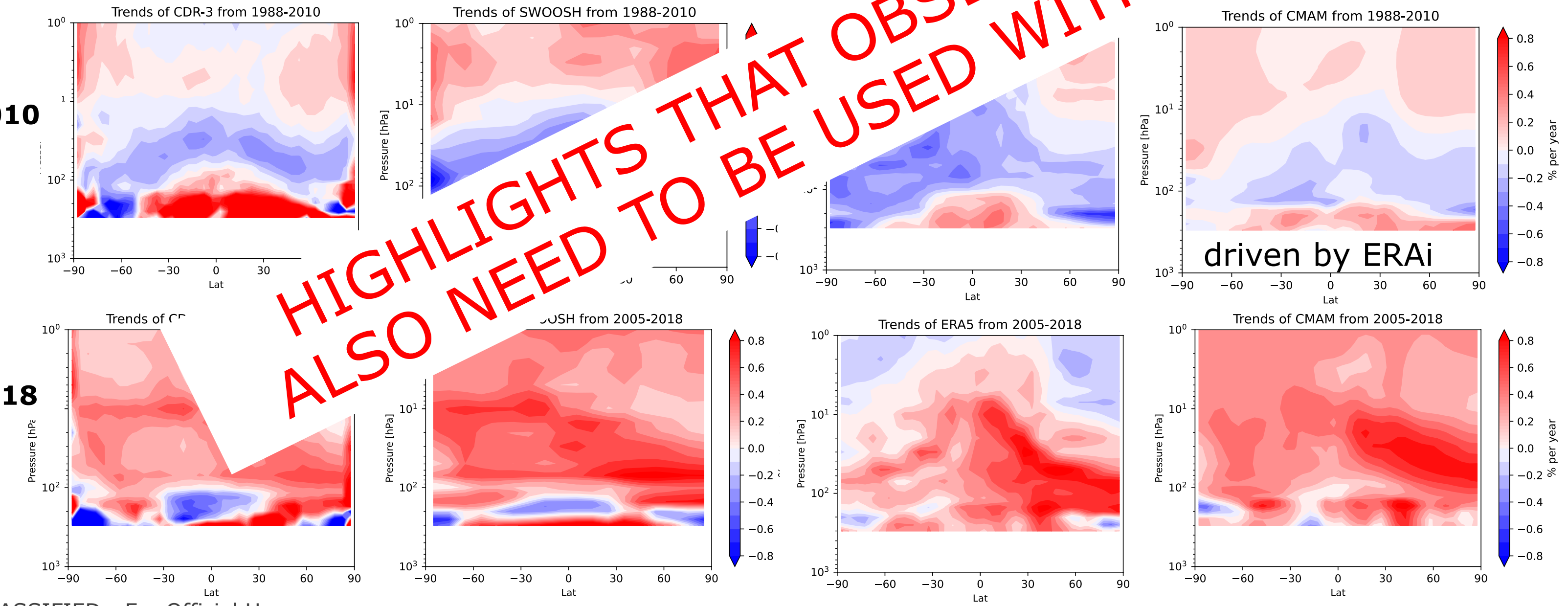
Ye et al., in pr...

- ERA5 and CMAM (nudged to ERAi) show a vertical structure in the change ... tent with the observations (ERA5 though only during the first time period).
- However, WV_cci (Hegglin et al., *Nature Geoscience* 2014) and SWO... the magnitude of the changes, thus provide only a weak observational const...

HIGHLIGHTS THAT OBSERVATIONS ALSO NEED TO BE USED WITH CARE!

1988-2010

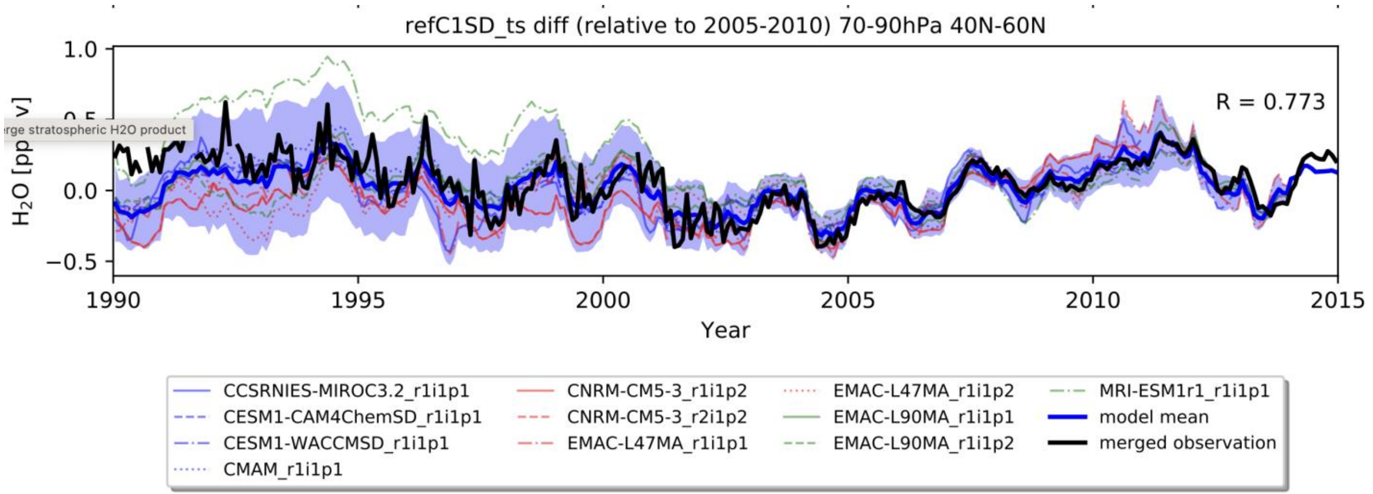
2005-2018



WATER VAPOUR TRENDS FROM WV_CCI

Ye et al., in prep.

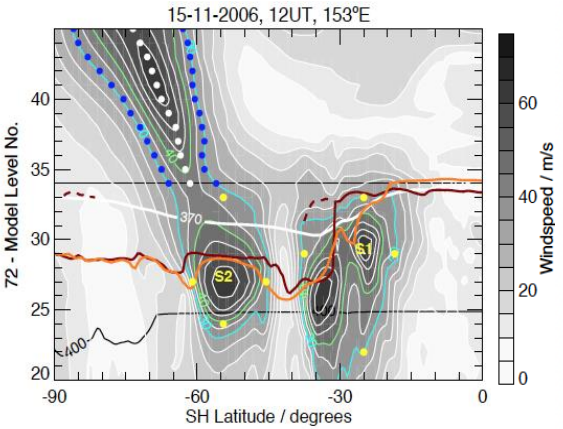
- Overall, chemistry-climate models nudged to different reanalyses are performing well in representing anomalies in water vapour also at mid-latitudes.
- Some larger differences for MRI-ESM1 (driven by JRA-product) and especially during the early time period when observations are scarce.
- However, evaluation does not yield information on whether the ESM or the reanalyses has issues.

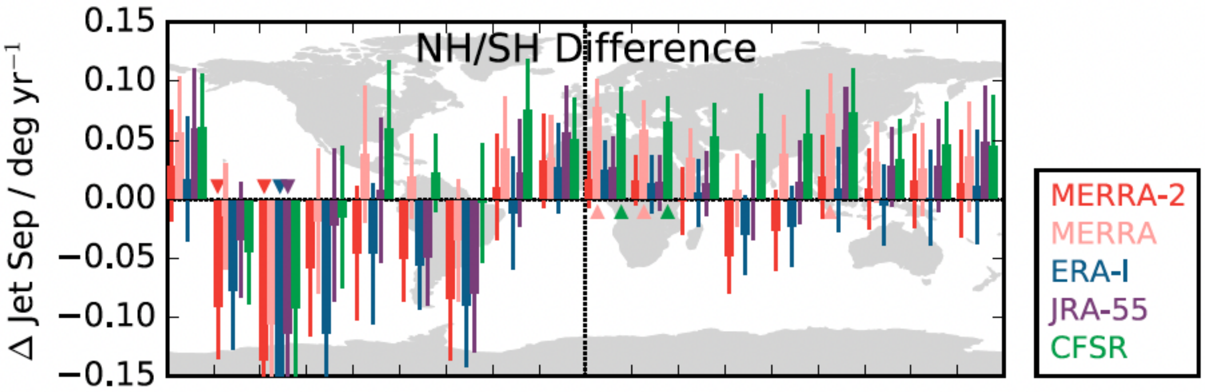


TRENDS IN TROPICAL HADLEY CELL WIDTH

Associated jet changes are expected to lead to changes in regional weather patterns and climate impacts

- **JETPAC** is used to identify jet location (lat,lon,p), windspeed, and whether subtropical or polar jet.
- Jet trends show strong seasonal and regional variations, that are not statistically significant on a zonal mean or annual mean basis.
- Importantly, statistical significance alone does not mean much, it is the robustness across reanalyses that yields confidence in derived trends.



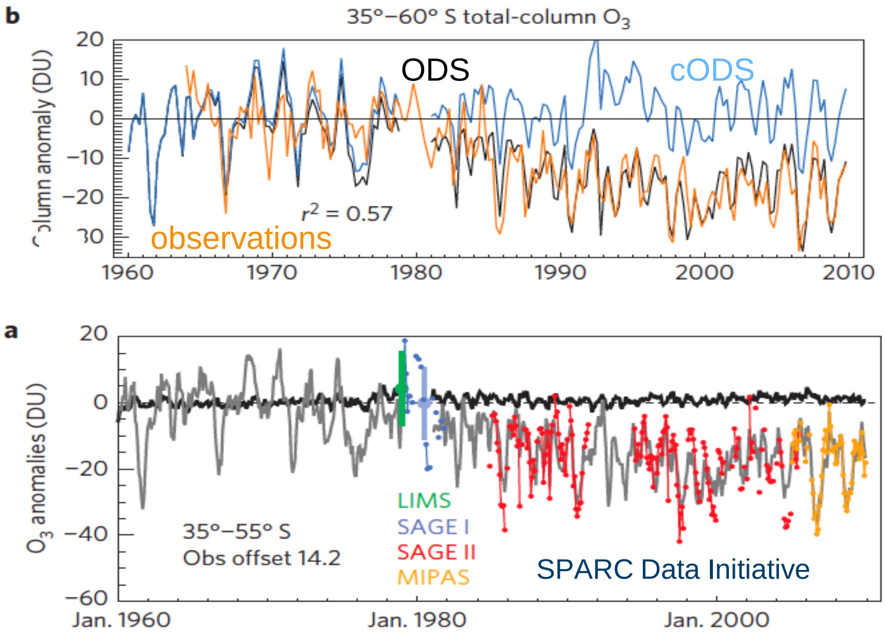


Manney, Hegglin et al., *ACP 2011; J. Clim 2014, J. Clim 2018*

ATTRIBUTION OF OZONE CHANGES TO ODS AND CLIMATE CHANGE

Shepherd, Plummer, Scinocca, Hegglin et al., *Nature Geoscience, 2014*

- **CMAM (nudged to ERAi) SH total column ozone** follows ground-based observations near-perfectly.
- **CMAM stratospheric partial column ozone** follows SPARC Data Initiative observations (Hegglin et al, *ESSD* 2020) near-perfectly.
- **Implies that ERA-interim shows a correct Brewer-Dobson circulation and transport processes.**



OUTLINE

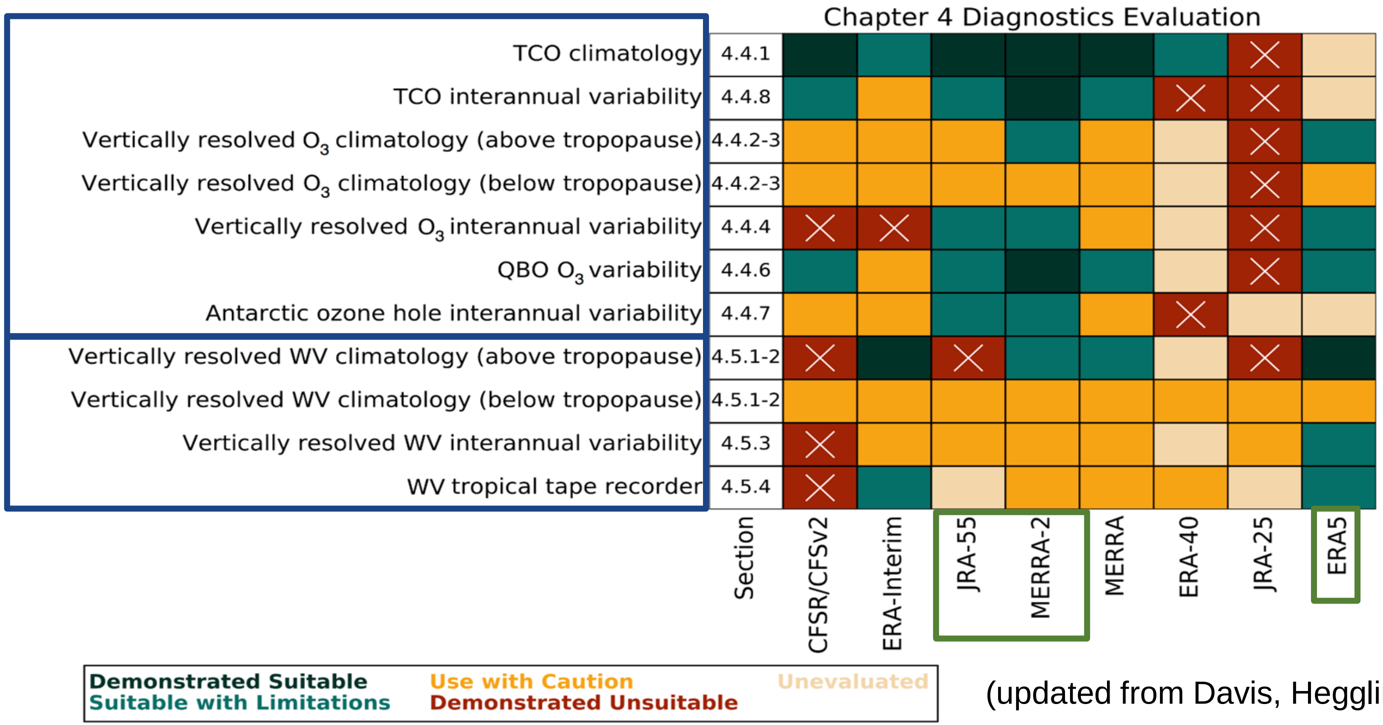
- The stratosphere and its role in weather and climate
- WCRP SPARC and reanalyses
- Evaluation of global atmospheric reanalyses
  - Climatology and natural modes of variability (seasonality, QBO, ...)
  - Processes
  - Trends
- Key points and conclusions

University of Reading

S-RIP EVALUATION TABLES

Reanalyses evaluations using different metrics

- The newer reanalyses perform much better across most of the ozone metrics, and ERA-5 (as exception) also in the water vapour metrics.



(updated from Davis, Hegglin et al., *ACP* 2017)

S-RIP KEY FINDINGS

University of Reading

- Coordinated intercomparison
- Systematic documentation
- Guidance and recommendations for users and producers

- Long-term datasets for both dynamics and composition are essential for reanalysis production and evaluation, as well as for the scientific studies that rely on reanalyses.

- **More recent reanalyses typically outperform earlier products**
- NCEP-NCAR R1 and NCEP-DOE R2 are unsuitable for many diagnostics and should generally not be used.
- Conventional-input and pre-satellite reanalyses are useful for many diagnostics but should be carefully validated against full-input satellite era products.
- **Studies relying on reanalysis products should use multiple reanalyses whenever possible.**
- **All reanalyses show discontinuities (especially CFSR); trends and climate shifts identified in reanalysis products should be carefully validated and justified.**
- Reanalysis products on model levels should be used for all studies when sharp vertical gradients or fine-scale vertical features are involved.
- Several quantities, such as tendency terms, are handled and reported differently by different reanalyses.
- ***Homogenized and continuing data records are essential for reanalysis production and evaluation.***

KEY CONCLUSIONS

- **Accurate representation of the stratosphere** in reanalysis datasets is essential for advancing our understanding of Earth's climate system and can help improve weather prediction capabilities.

- **WCRP SPARC** has coordinated international collaborations to carry out comprehensive evaluations of reanalyses; the projects involved both scientific users and reanalysis producers and provided valuable recommendations for both users and producers.

- **The evaluation of reanalyses** from the end-user perspective is complementary to the quality-control at reanalysis centres, provides additional human effort, and ultimately offers valuable insight and feedback to the reanalysis producers.

THANK YOU FOR YOUR ATTENTION!