Long-Term Strategy for NDACC Water Vapor Measurements

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19 January 2022

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1 Executive Summary

This document provides the scientific foundation for a long-term strategy for water vapor measurements within the Network for the Detection of Atmospheric Composition Change and other networks. The strategy encompasses the water vapor observing capabilities as a whole and does not consider just one instrument. Each of the instruments within the network has its own strengths and weaknesses, and no single instrument can do everything. This strategy aims at making the best use of each instrument within a network and to provide data that best match the scientific needs identified as part of this effort.

The strategy provides (i) guidance for instrument operators on observation frequency and data handling, (ii) guidance for network operators to allocate resources, and (iii) scientific justification for funding managers to support atmospheric research in the field of water vapor.

2 Background

2.1 NDACC

The Network for the Detection of Atmospheric Composition Change (NDACC) was formed in the late 1980's as the Network for the Detection of Stratospheric Change in response to the emerging threat on the global ozone layer. While the NDACC remains committed to monitoring changes in the stratosphere with an emphasis on the long-term evolution of the ozone layer, its priorities have broadened considerably to encompass issues such as the detection of trends in overall atmospheric composition, understanding their impacts on the stratosphere and troposphere, and establishing links between climate change and changes in atmospheric composition. The principles of NDACC on consistent, standardized, and long-term measurements apply to these expanded observations.

Within NDACC, water vapor is currently measured with one in situ and three types of remote sensing instruments: Balloon borne frost point hygrometer (stratosphere and troposphere), Raman lidar (troposphere and lowermost stratosphere), microwave radiometer (upper stratosphere and mesosphere), and FTIR (Fourier Transform Infrared) spectrometer (troposphere). Other remote sensing techniques such as Differential Absorption Lidar (DIAL) may be included as official NDACC instrumentation in the future and are covered by the considerations here. The addition of in situ measurements by balloon-borne water vapor sondes complements the existing suite of water vapor remote sensors. Of current water vapor sondes, cryogenic frost point hygrometers have the demonstrated ability to measure water vapor profiles from the surface to the middle stratosphere, the altitude ceiling of meteorological balloons. Other water vapor sondes, including Lyman-alpha hygrometers and thermoelectric-cooled frost point hygrometers, are not able to make full profile measurements during daytime but may be considered in the future.

Many satellites provide global observations of tropospheric water vapor from space with their respective vertical and horizontal resolution. Only a small number of satellites observe stratospheric and mesospheric water vapor, and only one (Aura/MLS) provides daily global coverage. This instrument is expected to end observations within the next few years. Water vapor observations within NDACC will need to fill some of the gaps that will be created by the end of this instrument. The consistency and homogeneity of NDACC water vapor observations will become even more essential.

2.2 Task

In order to better address the network's atmospheric composition and climate coupling goals, the NDACC steering committee has requested that a long-term strategy for water vapor measurements within the network be developed. Such a strategy would not be limited to any single measurement capability, but would include water vapor sondes, lidars, microwave radiometers, and FTIRs. Representatives from the respective NDACC Instrument Working Groups listed below are engaged in this effort together with scientists from within the NDACC Science Team and those representing other international measurement activities.

Lidar: Thierry Leblanc, JPL & Wolfgang Steinbrecht, DWD

Microwave: Alexander Haefele, Meteoswiss & Gerald Nedoluha, NRL

FTIR: Emmanuel Mahieu, Univ. Liege & Jim Hannigan, NCAR

Sondes: Holger Vömel, NCAR & Dale Hurst, CIRES (representing frost point hygrometers)

Incorporation of the full suite of NDACC water vapor measurement capabilities into this strategy will be an iterative process. Thus, the initial strategy formulation focuses on the utilization of water vapor sondes, both independently and as a critical adjunct (both long-term and periodic) to scheduled measurements by the other instruments at NDACC sites. In addition, this strategy will also incorporate the possibility of leveraging other measurement activities conducted by various international institutions and agencies independent from NDACC.

To enhance the value of the overall network, inter-comparisons of different instruments and validations of different techniques are vital for establishing comprehensive long-term data series.

2.3 Expected Outcome

This document is expected to help network managers in optimizing the resources allocated within the respective network operations, to guide in possible future collaborative efforts with the various NDACC Cooperating Networks and other international measurement campaigns, and to provide a scientific basis for atmospheric research managers in their prioritization of resource allocations. A focus on inter-comparison and validation observations is expected to support the confidence in all techniques given their different vertical and temporal resolution as well as their different uncertainty estimates.

3 Challenges

Water vapor is the most important greenhouse gas in the Earth's atmosphere and the carrier of latent heat in the lower/middle troposphere. It directly and indirectly participates in numerous chemical processes affecting other greenhouse gases and stratospheric ozone. It is integral to all cloud formation and growth processes and plays a pivotal role in determining the Earth's radiation budget and atmospheric circulation patterns (Figure 1). Thus, observations of water vapor are key to addressing multiple scientific foci.

No measurement technology covers the entire vertical range from the surface to the mesosphere, and each technology has its strengths and weaknesses. The vertical and temporal resolutions of each technology vary dramatically; thus, it is a challenge for any station to provide comprehensive observations throughout the atmospheric column.

An ideal observational strategy needs to consider instrumental limitations associated with an individual measurement capability by fully utilizing the synergistic strengths afforded by a multi-technique network. This strategy will provide an optimal balance for providing the data required to study the multitude of processes in which water vapor plays a key role in our atmosphere.

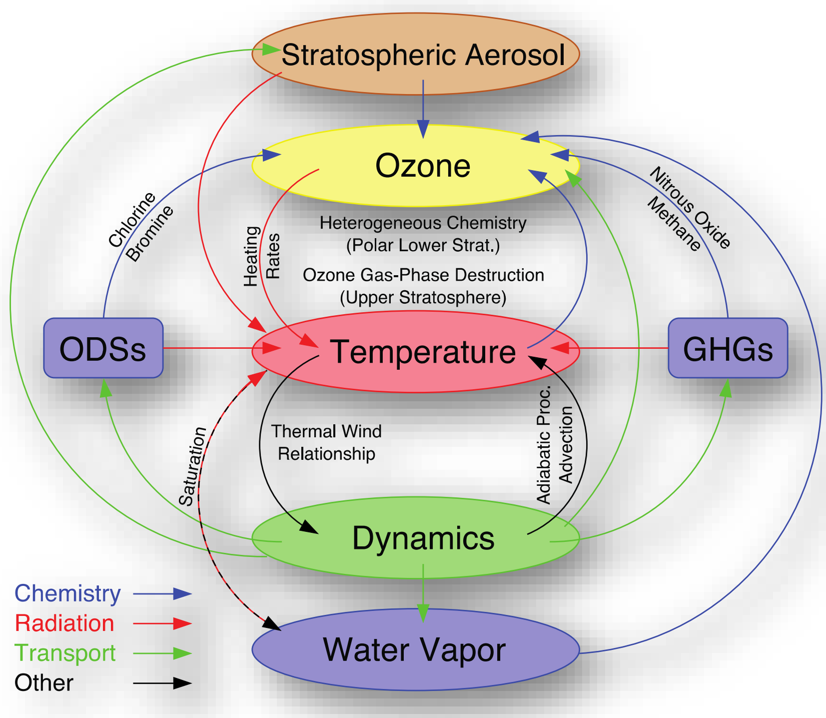

Figure 1. The interrelationships between atmospheric temperature, dynamics and key constituents. Water vapor is prominently connected with temperature and dynamical processes that impact ozone-depleting substances and greenhouse gases.

3.1 Climate Research

Long-term changes in atmospheric composition are expected to have significant impacts on weather and climate. Variations in water vapor play a central role by altering precipitation, atmospheric dynamics, and atmospheric radiative properties.

In the lower and middle troposphere, water vapor abundances are highly variable and can change by one or more orders of magnitude on very short time scales. Insufficient understanding of the links between clouds, circulation, and climate sensitivity has been identified as one of the grand challenges in climate research (http://www.wcrp-climate.org/grand-challenges). Tropospheric water vapor is central to several processes that influence the coupling between clouds and circulation, two important determinants of climate sensitivity. One example is the impact that water mixing processes in the lower troposphere have on the extent of low altitude clouds that influence climate. Another example is the effect that moist convection has on the diurnal cycle of cloud cover and thus on large-scale tropospheric heating and circulation. Observations of tropospheric moisture pathways from source (surface evaporation) to sink (precipitation) could be used to diagnose the respective performance of models. While the direct observation of these pathways is nearly impossible, isotopic ratios of water vapor may provide good proxies for the various moisture pathways and their relative importance to the global water cycle.

The tropopause transition layer (TTL), in particular the tropical TTL, controls most of the water vapor budget of the global stratosphere. Small changes in tropical tropopause temperatures lead to significant changes in stratospheric water vapor on local seasonal scales [Mote et al., 1996] and globally on longer timescales [e.g. Dessler et al., 2014]. These changes mask the slow long-term increase in middle atmospheric water vapor away from the tropical tropopause that results from the oxidation of increasing anthropogenic methane emissions. Water vapor in the TTL itself plays an important role in the radiative balance of our atmosphere; water vapor changes in the tropical TTL contribute significantly to temperature changes near the Earth's surface [Solomon et al., 2010]. Therefore, long-term observations in this region are of high importance for the understanding of the entire stratospheric water vapor budget. This strategy envisions an expansion of long-term NDACC water vapor measurements within the tropics, in particular at the altitudes of the tropical TTL.

3.2 Lower Tropospheric Water Vapor

As already mentioned, the variability of lower tropospheric water vapor is very large. With frontal systems, water vapor concentrations can change one or two orders of magnitude in a few hours. Thus, measuring lower tropospheric water vapor abundances is essential for estimating the amount of possible precipitation, i.e., the precipitable water column. A number of ground-based remote sensing instruments are capable of making such measurements, e.g., tropospheric microwave profilers, lidars, Global Navigation Satellite System (GNSS) receivers, and Fourier Transform Infrared spectrometers. In addition, essential to the observing system are high-quality, high vertical resolution observations by in situ sondes that provide data for the validation and better characterization of remote sensing instruments.

Monitoring long-term changes of tropospheric water vapor requires observations with high frequency, high stability and the ability to reliably measure over a wide concentration range to adequately sample the large atmospheric variability. Thus, an optimal cost-effective strategy needs to be developed to augment existing NDACC measurements.

Observations of different water vapor isotopes in the troposphere as well as in the stratosphere may be used as proxies for the various water pathways. Isotope monitoring will be an important contribution to the WCRP Grand Challenge "clouds, circulation, and climate sensitivity" and may help to assess the abilities of climate models to correctly capture key aspects like the low cloud feedback or changes in circulation and precipitation patterns.

3.3 Upper Tropospheric and Lower Stratospheric Water Vapor

The concentration and the variability of water vapor drop off rapidly from the upper troposphere into the lowermost stratosphere. These regions are largely free of clouds and are most important for the radiative balance of the atmosphere. Water vapor in this region is difficult to measure due to the need for high vertical resolution and high sensitivity at low mixing ratios. This region is particularly difficult to measure when there are underlying clouds that cannot be penetrated by lidar systems and which pose the risk for contamination of balloon sondes that ascend through layers of saturated air. Methods to routinely monitor this altitude region without these limitations need to be developed and implemented to avoid biasing observations to cloud free conditions.

3.4 Upper Stratospheric and Mesospheric Water Vapor

The water vapor mixing ratio increases with altitude in the middle and upper stratosphere due to the oxidation of methane and hydrogen. In the upper mesosphere, the water vapor mixing ratio decreases with altitude due to photo-dissociation by Lyman-alpha radiation. Away from polar regions, the lower mesosphere has little variability as almost all of the CH_4 and H_2 have been oxidized, thus making it an ideal region for long-term trend detection.

The upper stratosphere and mesosphere can only be probed by remote sensing instruments. So far, it has been challenging to construct continuous profiles from the surface to the mesosphere with confidence because of the vertical gap between the lowest measurement altitudes of the upper stratospheric and mesospheric remote sensors and the highest altitudes of the in situ instruments and remote sensors observing the troposphere and lower stratosphere (Figure 2). Furthermore, this gap precludes simple evaluations of biases and drifts between instruments measuring below and above it because there is no vertical overlap in their data.

4 Current NDACC Observational Capabilities

A comprehensive overview of ground-based remote sensing and in situ methods for monitoring atmospheric water vapor can be found in Kämpfer (2013).

Each instrument has its own strengths and limitations. The measurements made by each type of instrument differ broadly in their vertical and temporal resolutions, as well as in the altitude ranges they cover. Figure 2 provides a rough comparison for the vertical extent of the different observing systems. Individual lidar and profiler systems may be different from this estimate, and the vertical extent in balloon soundings depends strongly on the atmospheric conditions under which these measurements are made.

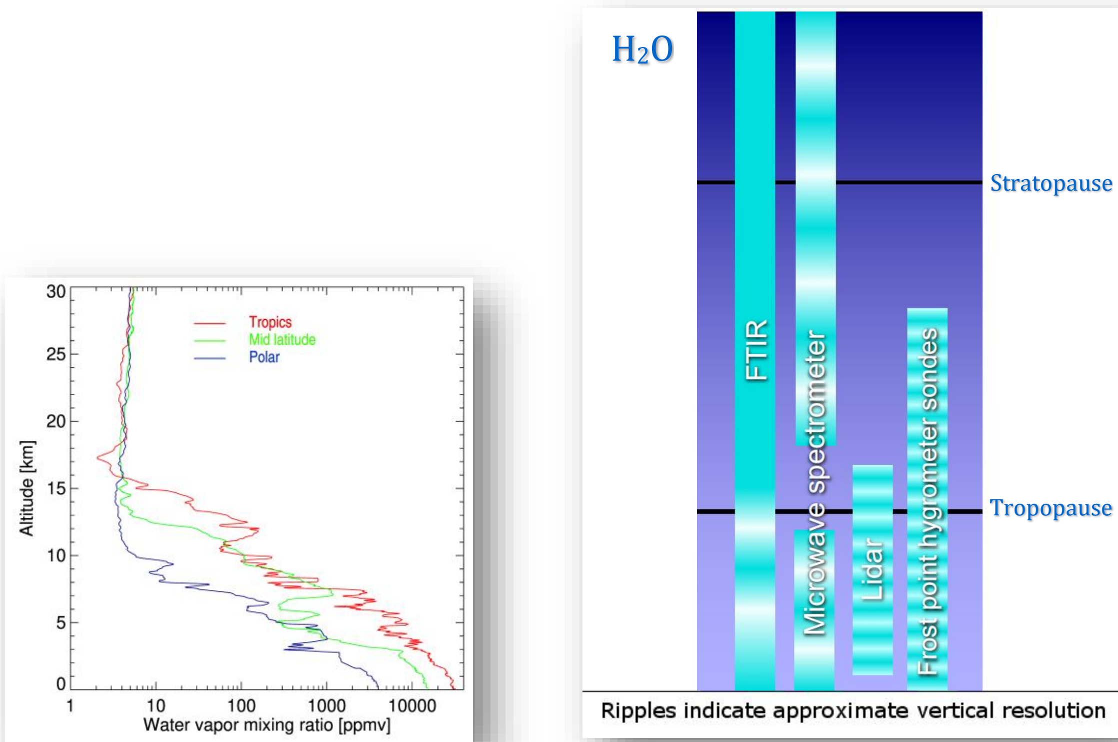

Figure 2: Left: Typical water vapor profiles for polar, mid latitude, and tropical regions obtained by frost point hygrometers. Right: Vertical ranges of measurement coverages for frost point hygrometers, lidars, microwave radiometers, and FTIR. Frost point hygrometers and lidars have high vertical resolution, microwave radiometers an intermediate resolution and FTIR only coarse resolution in the troposphere. All instrument types can provide an estimate for the total water vapor column.

4.1 Frost Point Hygrometers

Small and lightweight frost point hygrometers carried by weather balloons provide in situ vertical profile measurements at 10 to 100 m resolution from the surface to the middle stratosphere. The technique relies on accurate measurements of the frost point temperature by a calibrated thermistor embedded in a chilled mirror. The mirror is continually cooled by a cryogenic liquid and intermittently heated by a proportional-integral-derivative (P-I-D) controller to initially grow and subsequently maintain a stable layer of frost. The partial pressure of water vapor immediately above the stable frost layer is calculated directly from the measured frost point temperature. Relative humidity and mixing ratio values are determined from coincident measurements of the ambient temperature and pressure, respectively. Measurement accuracy and precision in the stratosphere are estimated to be better than 10% respectively [Vömel et al., 2007; Hurst et al., 2011b, Vömel et al., 2016; Hall et al., 2016].

4.2 Lidar

When using the water vapor Raman lidar technique, light emitted by a laser, typically at 532 or 355 nm, into the atmosphere is backscattered by atmospheric nitrogen with a spectral shift of 2330 cm^{-1} and by water vapor with a shift of 3654 cm^{-1}, and then collected in two different receiver channels. After common lidar signal corrections, the ratio of the corrected signals at the two wavelengths is proportional to the water vapor mixing ratio [Melfi et al., 1969]. The typical altitude range reached is 10 km given sufficient integration time (e.g., 2 hours), and in some cases 15-20 km. Vertical resolution of the retrieved water vapor profiles ranges from a few meters in the lower troposphere to a 2-3 km in the upper troposphere/lower stratosphere (UTLS). Calibration is typically done using external measurements (e.g., radiosonde, total precipitable water) or in some cases, internally. For measurements above 10 km, the lidar receiver needs to be carefully designed to avoid contamination of the water vapor backscatter signal by fluorescence. This has become an issue of recent concern with the extreme increase in wildfires and resulting emission of large amounts of (possibly biogenic) aerosol in the UTLS region, which strongly contaminate the water vapor Raman signal in that altitude region. Only one system currently measures the broadband fluorescence spectrum in the Raman spectral region of the lidar and is capable of subtracting the aerosol influence in order to calculate the pure water vapor Raman signal. This new challenge will require additional attention by the Raman lidar community.

Eight water vapor Raman lidars are currently affiliated with NDACC. Another lidar technique can be also used to measure water vapor, namely Differential Absorption Lidar (DIAL) [Schotland, 1966]. However, instrument stability and cost have been among the limiting factors in developing a NDACC-qualified water vapor DIAL and no such system is currently affiliated with NDACC.

4.3 FTIR

FTIR (Fourier Transform Infrared) spectrometers within the NDACC observe broadband, high-resolution infrared spectra of the direct incoming solar radiation. Data obtained using this technique are only representative of clear sky daytimes. The entire mid-IR spectrum from 750-4500cm^{-1}, which contains numerous spectral features of H_2O, is recorded and stored for each instrument/site. Water vapor is routinely retrieved, as it is required in subsequent retrievals of other species. The current standard Infrared Working Group (IRWG) data files include an associated H_2O profile that represents the best estimate of the water vapor at the time of the measurement of a target gas. Inclusion of H_2O as targeted species would be straightforward and historical data can be processed to create time series from the initiation of the observational record. The current state-of-the-art FTIR retrievals of water vapor including retrieval of pairs of {$H_2{}^{16}O$, $HD^{16}O/H_2{}^{16}O$} are done within the MUSICA project [Schneider et al., 2012]. These data allow investigating lower/middle tropospheric water pathways. The data product would be coarse profiles, where for $H_2{}^{16}O$ roughly three layers in the troposphere (lower, middle, and middle/upper troposphere) can be distinguished almost independently. For

{$H_2{}^{16}O$, $HD^{16}O/H_2{}^{16}O$} pairs the sensitivity is limited to the lower and middle troposphere. This work would be a starting point for an IRWG-wide H_2O data product.

4.4 Microwave Profiler

Water vapor profiles in the atmosphere can be retrieved from spectral measurements by microwave radiometers. These instruments observe the pressure broadened emission lines of rotational transitions by water vapor at specific frequencies in the microwave part of the spectrum. Transitions of water vapor that are used for remote sensing of the atmosphere are located e.g. at 22.235 GHz, 183.310 GHz, 448.001 GHz and at 556.936 GHz. However, not all of these lines can be observed from the ground as the line strength at some frequencies is too high to allow instruments to look through the troposphere where most water vapor resides; hence, the 22.235 GHz transition is used almost exclusively for ground-based observations [Kämpfer et al., 2013].

4.5 Geographic distribution

Figure 3 shows the geographic distribution of currently active NDACC stations measuring water vapor. Twenty-five stations operate FTIR instruments, 9 stations operate lidar, 6 stations operate stratospheric and mesospheric microwave radiometers, and another 6 stations launch frostpoint soundings.

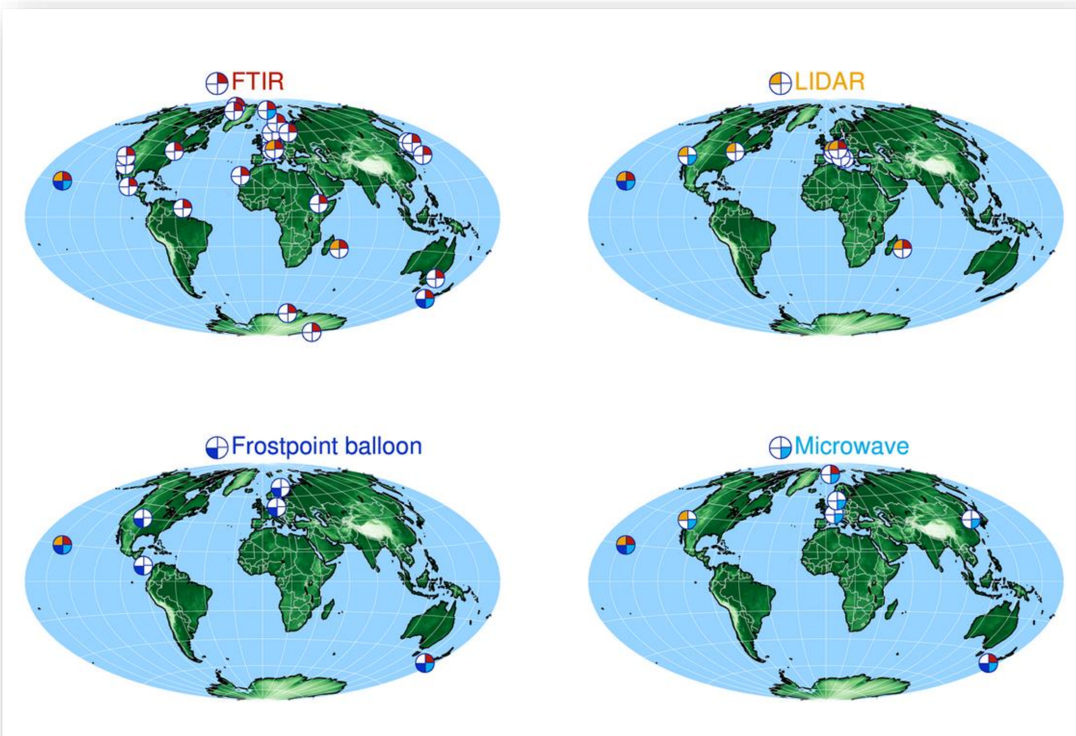

Figure 3. Geographic distribution of NDACC water vapor observing systems. Stations with multiple instruments are shown in the respective panels and instrument colors.

Observing capabilities are unevenly distributed. The highest density of stations using all instrument types is found in Europe, followed by North America.

Lauder, New Zealand, is the only southern hemispheric station, which can observe the entire column between the surface and the mesosphere. In and near Africa, the stations at Addis Ababa, Ethiopia, and Izaña, Canary Islands, operate an FTIR spectrometer, and the station at La Reunion operates both an FTIR spectrometer and a lidar. NDACC water vapor observations in the Southern Hemisphere are otherwise sparse and non-existent in the Western Pacific.

The combined site of Mauna Loa and Hilo, HI, is the only station that operates all four systems. Lauder operates an FTIR spectrometer and a microwave radiometer and launches frostpoint soundings. La Reunion operates an FTIR spectrometer and a lidar, Table Mountain operates a microwave spectrometer and a lidar, and Ny Ålesund operates and FTIR spectrometer and a microwave radiometer. Other stations such as Lindenberg have a combination of these instruments, not all of which are affiliated with NDACC.

The upper troposphere and lower to middle stratosphere are only poorly sampled within NDACC. In the tropics, the only station monitoring upper-tropospheric and lower-stratospheric water vapor is at Costa Rica.

4.6 Operational Radiosondes

Capacitive polymer humidity sensors have been used for water vapor measurements on board radiosondes for several decades with varying success. Heated humidity sensors avoid solar heating and contamination biases by design, thereby avoiding the largest sources of measurement error. They are suited for measuring the water vapor profile and integrated column from the surface to somewhere in the upper troposphere. At cold temperatures, the sensor response time slows dramatically reducing the vertical resolution of profile measurements in the UTLS. Well-tested algorithms are applied to correct for the time lag in response.

Currently, only Vaisala is employing this type of humidity sensor operationally on their RS41 radiosonde, but other manufacturers are beginning to introduce heated humidity sensors as well. A statistically robust inter-comparison of the Vaisala RS41 sensor to other higher quality humidity sensors is currently underway and the stability and fidelity of the calibration is being evaluated. Validations of heated humidity sensors of other manufacturers has yet to take place.

5 Strategic Considerations

The focus of NDACC is to monitor atmospheric composition for the purpose of detecting and understanding long-term changes and their impacts. Although many of the water vapor data provided by NDACC will be useful as input for operational Numerical Weather Prediction (NWP) systems, it is envisioned that the main goal of this NDACC observational strategy is to construct data records that are useful for understanding the long-term evolution of the ozone layer and for climate studies.

The considerations described below refer to the challenges described above.

5.1 Instrument Calibration

Time series spanning decades require that the instruments maintain a stable calibration and that possible drifts in calibration be kept to a minimum. Each measurement technology has specific calibration requirements and the methods to verify calibration stability should be documented and be as consistent across the network as is technically feasible. Where similar technologies use different calibration methods, these should be compared and their equivalence evaluated and documented.

Despite best efforts, experience has shown that the calibration and the performance of instruments may drift due to factors not understood at the time. This may be due to aging of components, changes in manufacturing, changes in operating procedures, or numerous other possibilities, all requiring further research to characterize artifacts. Therefore, ongoing work is required to routinely verify the stability of the calibration. This may require using traveling standards or instrument inter-comparison campaigns, which are discussed in more detail below, or site-specific calibration validation activities.

5.2 Uncertainty Documentation

The proper interpretation of any observation requires an estimate of its uncertainty. The methods used to determine uncertainty estimates for each instrument must be documented and published for reference. Uncertainty estimates themselves should be validated in inter-comparisons and changes in instrumentation must be reflected in the documentation of its uncertainty and assessed for possible impacts on the long-term stability of the measurement record.

5.3 Raw, Metadata, and Processing Stability

Raw data and all metadata associated with an observation must be archived over the long term to allow future reprocessing. If the data processing of any instrument changes, the entire data set should be reprocessed using the updated processing software. No unique definition for raw data and metadata can be provided here. What constitutes raw data and essential metadata needs to be decided by the representatives of each instrument family. Archiving of raw data, metadata and processing software must ensure that no artifacts in the long-term data set will be created due to changes in processing. Depending on the instrument type, raw data and metadata may be centrally archived and processed, but long-term storage of raw data and metadata at the measurement site is paramount.

5.4 Instrument Inter-comparisons

Inter-comparisons of water vapor instruments verify that their respective observations agree to within their stated measurement uncertainties. These inter-comparisons are an essential element for the evaluation and validation of satellite observations.

Assessments of water vapor observations between the upper troposphere and mesosphere have also taken place in the past in the framework of SPARC [e.g., Kley et al., 2000] and more focused on satellite observations [Russell et al., 2016]. These activities constitute a substantial research effort and are an essential element for a heterogeneous observing system. Comparisons between ground-based microwave remote sensing instruments and satellites have been recently conducted by Nedoluha et al. [2017] and Weaver et al. [2019], which allow an assessment of the consistency of instruments that cannot easily be co-located.

Several comparisons between different ground-based remote sensing and in situ observations have taken place [e.g., Vömel et al., 2007; Hurst et al., 2011a; Leblanc et al., 2011; Hall et al., 2016; Ortega et al., 2019]. To maintain a high level of confidence in all observations and in their trend estimates, these inter-comparisons must be conducted at regular intervals. This allows early detection of instrumental biases and other possible artifacts, which may limit the value of the overall data set.

The frequency of instrument inter-comparisons and the modes of such activities depend critically on the available resources.

Depending on the stability of the measurement technology and the stability of a specific instrument, the time between inter-comparisons may be as short as a few years or as long as a decade. Less frequent inter-comparisons carry the risk that significant parts of a data set may be drawn into question, particularly if previously unknown problems are identified that require additional research.

In some cases, satellite measurements that have shown to be suitable relative transfer standards may be used to evaluate the consistency of data records. However, this practice should be avoided if at all possible since satellite observations themselves often rely on NDACC and other data sets for validation.

Stratospheric and mesospheric microwave radiometers cannot be compared to other types of NDACC instruments, since they do not share a measurement overlap region. Therefore, microwave radiometers often depend on satellite data for routine cross validation. Nevertheless, a traveling standard microwave radiometer would provide better validation. In particular, with the expected reduction of stratospheric and mesospheric water vapor observations by satellites, a traveling standard may become essential.

Lidar and balloon borne in situ instruments have been compared in a number of inter-comparison experiments, such as AWEX-G (Whiteman et al., 2006) or MOHAVE (Leblanc et al., 2011) and have proven to be extremely valuable. However, these campaigns are often limited to NDACC stations and the range of atmospheric conditions that can be measured there. The tropical regions are under-sampled by NDACC water vapor measurements and only a few inter-comparison observations between balloon and aircraft borne instruments have taken place in these regions.

FTIR observations may be better validated with respect to other remote sensing observations due to limited vertical resolution, requiring a larger number of coincident observations to reduce random variability between the techniques. High quality operational radiosondes, such as those launched at GRUAN stations, may also be used for inter-comparisons with FTIR observations of water vapor.

Inter-comparisons should preferably be conducted as blind experiments and follow the NDACC protocol for instrument intercomparisons (NDACC, 2017). The goals of the specific experiment, which are defined in the planning phase, should determine whether data may be shared during the campaign or only afterwards. Data sharing during a campaign allows investigators an early evaluation of instrument performance and an opportunity to rectify instrumental problems. On the other hand, data sharing only after the campaign has been completed provides a true evaluation of the performance of each participating instrument.

The goals of potential inter-comparison experiments must be determined by first weighing the benefits and drawbacks of these opposing views, then specifying how the experiment is to be conducted. All participants need to agree to the rules of the inter-comparison before it begins. In fully blind inter-comparisons, where data are shared only after the completion of the campaign, an impartial referee should be appointed. This referee will have access to all data as soon as they are available, but will keep these confidential. Early inspection of the data and intervention by the referee may help prevent easily rectifiable problems in a data set.

During the campaign preparation, participants may also agree on a mixed approach, in which one phase of the campaign is semi blind and a second is fully blind. This allows new developments and instruments that have been re-located for the purpose of the campaign to be tested prior to entering the fully blind phase of the campaign.

The outcomes of inter-comparison experiments and the lessons learned must be documented in the peer-reviewed literature. Any changes to operational routines and data processing as a result of these activities should be documented and the impact on the long-term data series should be discussed.

If these inter-comparisons identify the need for significant changes to an instrument or even the need to replace an instrument, proper change management should be followed to minimize the impact on the long-term data series. This is discussed in the following section.

5.5 Change Management

It is likely that there will be some changes in instrumentation over multi-decadal periods of atmospheric water vapor monitoring, through instrument modification or outright replacement. A strategy of change management must be developed and followed to ensure that such changes do not introduce biases into measurement records. Strategies should include side-by-side comparisons of the old and new instruments for an adequate period pf time that considers diurnal to seasonal changes in atmospheric composition and environmental conditions that affect instrument performance. Some approaches may include comparisons to a third instrument that has proven steady over daily to annual time scales. If the instrument change occurs at multiple sites, care must be taken to perform change management studies at one or more sites in different climate regions rather than extrapolate results from comparisons at one site or at sites within a single climate region.

5.6 Traveling Standards

With the exception of balloon sondes, most water vapor instruments are not suitable as traveling standards since the absolute values of the measurements are likely to change slightly during relocation. While there is no guarantee that measurements from satellites are latitudinally consistent, satellite-based measurements in the stratosphere and mesosphere, where precise collocation is not crucial, are likely to provide the best travelling standard (e.g., Haefele et al., 2009). Some, but likely not all instrument groups may require traveling standards. These standards should be considered as the best available instrument within that group of instruments and should receive special attention to maintain the status as traveling standard. A review of its operations by a respective group of experts may be required.

5.7 Synergistic considerations

Synergies through redundant observations by different techniques should be exploited. For instance, a record of water vapor profiles can be significantly enhanced with a record of collocated integrated water vapor column from another technique (e.g., Hicks-Jalali et al. 2020; Bernet et al., 2020). Thus, it should be a design goal to combine different techniques at single sites and to make use of these collocated datasets when analyzing the data.

5.8 Observation Frequency, Schedule, and Data Latency

The optimal frequency of observations for each instrument type is highly dependent on the desired minimum detection limit for trends in various regions of the atmosphere (i.e., can a trend of X% be detected in Y years?) and the locations of instruments [Whiteman et al., 2011]. Depending on the atmospheric region, instruments with higher random uncertainty may be acceptable, if the atmospheric variability is large as well. For all instruments, the absence of drifts (trends in their systematic errors) is essential, since these may lead to false identification of atmospheric changes.

The nearly exponential decrease of water vapor with altitude may cause distortions when deriving statistical moments of layer averages and may be a potential source of discrepancy when comparing multiple datasets. Recommendations for the computation of statistical indicators such as long-term and layer-averaged means need to be provided and should be consistently applied across all instrument specific data sets.

Satellite operators benefit from having access to preliminary data with a latency of two to three days.

5.9 Geographic Distribution

The distribution of water vapor observations within NDACC is discussed in Section 4.5 and should be periodically reviewed within the framework of the network's science goals. Weaknesses need to be identified and addressed. As indicated in section 3.1, due to the high importance of the tropics and regions of the subtropical jet in determining the global distribution of water vapor, an increase in the number of tropical and subtropical sites may be desired, in particular for observations of tropospheric and lowermost stratospheric water vapor.

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7 Acronyms

AIRS	Atmospheric Infrared Sounder
AWEX-G	AIRS Water Vapor Experiment–Ground
CIRES	Cooperative Institute for Research in Environmental Sciences at the University of Colorado
DIAL	Differential Absorption Lidar
DWD	Deutscher Wetterdienst
FTIR	Fourier Transform Infrared
GCOS	Global Climate Observing System
GHGs	Greenhouse Gases
GNSS	Global Navigation Satellite System
GRUAN	GCOS Reference Upper Air Network
IRWG	Infrared Working Group
JPL	Jet Propulsion Laboratory
MOHAVE	Measurements of Humidity in the Atmosphere and Validation Experiments
MUSICA	MUlti-platform remote Sensing of Isotopologues for investigating the Cycle of Atmospheric water
NCAR	National Center for Atmospheric Research
NDACC	Network for the Detection of Atmospheric Composition Change
NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Research Laboratory
NWP	Numerical Weather Prediction
ODS	Ozone Depleting Substances
SPARC	Stratosphere-troposphere Processes And their Role in Climate
TTL	Tropopause Transition Layer
UTLS	Upper Troposphere/Lower Stratosphere
WCRP	World Climate Research Programme