ARISE
Atmospheric dynamics Research
InfraStructure in Europe

Roadmap on the use of ARISE data for weather and climate monitoring in Europe

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[1] Dissemination level: **PU** = Public, **PP** = Restricted to other programme participants (including the EC), **RE** = Restricted to a group specified by the consortium (including the EC), **CO** = Confidential, only for members of the consortium (including the EC)

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Deliverable abstract

This report summarizes the current abilities of the ARISE network, focussing on the use of ARISE data for weather and climate monitoring in Europe, now, and within the next 10 to 20 years. Based on this outcome, and future needs, a roadmap is proposed to enlighten the ARISE impact and implementation for weather and climate monitoring including potential areas of work.

ARISE has clearly demonstrated that it has the potential to fill important gaps for numerical weather prediction to improve modelling of weather and climate. Potential is shown that ARISE techniques can provide accurate measurements where GCMs do not typically assimilate data. High-quality unbiased observations are of great importance. Idealized experiments have indicated that global coverage of stratospheric observations results in a larger forecast skill improvement compared to regional nudging.

Key actions are proposed towards the implementation of ARISE for weather and climate monitoring in the next 10 to 20 years. Assimilation of new observations requires a long pathway. Therefore, different steps are listed that lead to both short- and long-term impacts.

Short-term: develop methods to allow ARISE measurements to be used by weather and climate prediction centres, making the first pathway to assimilation without the need of developing costly assimilation routines or new model (parts).

- Assess and understand weather and climate models
- Pathway to assimilation: ensemble forecasts calibration
- Extract and use gravity wave observations

Long-term: important steps that require more time and which results are hardly noticeable in the beginning. Being on the roadmap of other project, being part of and contribute to the weather and climate community is the key element to guarantee long-term existence.

- **Developing a user community**
- Working towards a service for whole atmosphere models
- Developing understanding of coupling between stratosphere and troposphere

Deliverable Review

	Coordinator			**Work Package Leader**		
	Answer	**Comments**	**Type***	**Answer**	**Comments**	**Type***
1. Is the deliverable in accordance with						
(i) the Description of Work?	☐ Yes ☐ No		☐ M ☐ m ☐ a	☐ Yes ☐ No		☐ M ☐ m ☐ a
(ii) the international State of the Art?	☐ Yes ☐ No		☐ M ☐ m ☐ a	☐ Yes ☐ No		☐ M ☐ m ☐ a
2. Is the quality of the deliverable in a status						
(i) that allows it to be sent to European Commission?	☐ Yes ☐ No		☐ M ☐ m ☐ a	☐ Yes ☐ No		☐ M ☐ m ☐ a
(ii) that needs improvement of the writing by the originator of the deliverable?	☐ Yes ☐ No		☐ M ☐ m ☐ a	☐ Yes ☐ No		☐ M ☐ m ☐ a
(iii) that needs further work by the Partners responsible for the deliverable?	☐ Yes ☐ No		☐ M ☐ m ☐ a	☐ Yes ☐ No		☐ M ☐ m ☐ a

* Type of comments: M = Major comment; m = minor comment; a = advice

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1 - Introduction

This report summarizes the current abilities of the ARISE network, focussing on the use of ARISE data for weather and climate monitoring in Europe, now, and within the next 10 to 20 years. Based on this outcome, and future needs, a roadmap is proposed to enlighten the ARISE impact and implementation for weather and climate monitoring including potential areas of work.

Major limitations in weather and climate monitoring

Weather and climate monitoring are based on forecasting models, on both global and regional scales. In order to perform regional monitoring, a global model is required to obtain the general circulation. The response of the global climate system is simulated by General Circulation Models (GCMs), advanced numerical models describing the physical state of the atmosphere and/or ocean. In general, weather forecasting models have to deal with three main disadvantages. First two are due to its limited temporal and spatial resolution, resulting in parameterization and feedback mechanisms of different processes. And thirdly, weather forecasting models are constrained by a varying range of scattered atmospheric observations.

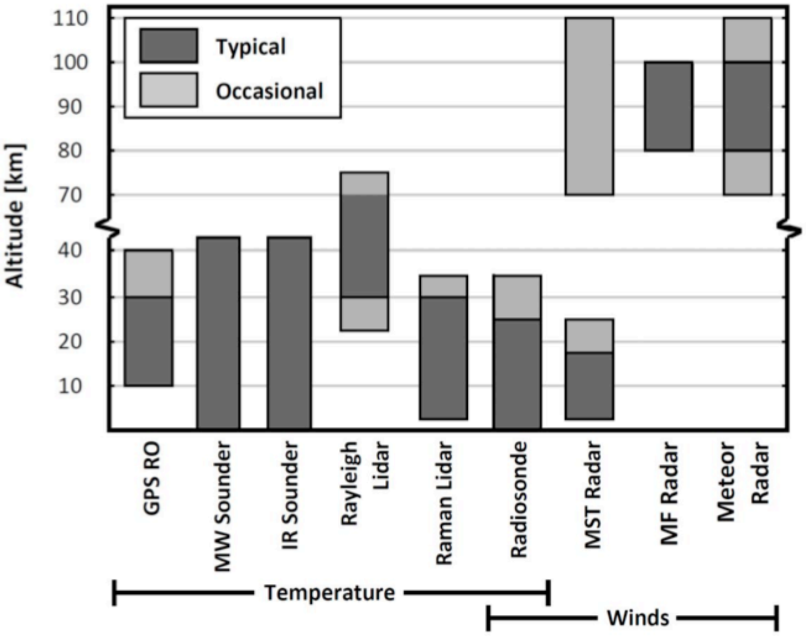

Figure 1 - Altitude coverage of typical wind and temperature measurements; lidar, and radar measurements above approximately 15km, are not assimilated into NWP models at present.

Limited atmospheric observations

Concentrating on the middle atmosphere, the measurements commonly assimilated into NWP models are all discussed in detail in Technical Report 5.1 (TR5.1), alongside those used for `research', rather than in an operational mode. TR5.1 highlights a dearth of measurements in the upper stratosphere and lower mesosphere, illustrated in Figure 1. Only temperature lidars provide sporadic measurements between 40 and 70 km. Below 40 km, satellite- based Infrared and Microwave sounder instruments, and GPS Radio Occultation (RO), provide temperature observations with global coverage but coarse resolution in either vertical (microwave sounder) or horizontal (infrared and RO) direction. Wind observations remain sparse, with radiosondes and radar wind profilers offering `point' coverage up to approximately 25 km. However, models are not constrained in the upper stratosphere and beyond, because of a general absence of middle atmospheric observations. There are currently no measurements of winds between 25 – 80km, or temperatures above 40km, suitable for constraining NWP models. Therefore, the representation of the middle atmosphere in weather and climate models is still in its infancy. The most recent fifth Coupled Model Intercomparison Project (CMIP5; *Charlton-Perez et al.*, [2013]) indicates that more than half of the examined climate models fully represented the stratosphere with consequent biases in the representation of stratospheric climate and variability for those that did not. On the other hand, very few weather or climate models represent the mesosphere.

Many forecast centres around the world now run standard models extending above the stratopause, with significant stratospheric resolution. The need for improved measurement of the stratosphere, for model initialisation, is highlighted by interviews conducted with staff at NWP organisations: Biases in satellite temperature data can increase significantly above 35 km, and noisy GPS measurements at similar altitudes can not be used for their calibration. Comparisons with experimental data sets suggest that there can be considerable biases in upper stratosphere winds and temperatures (TR5.1 and D5.3).

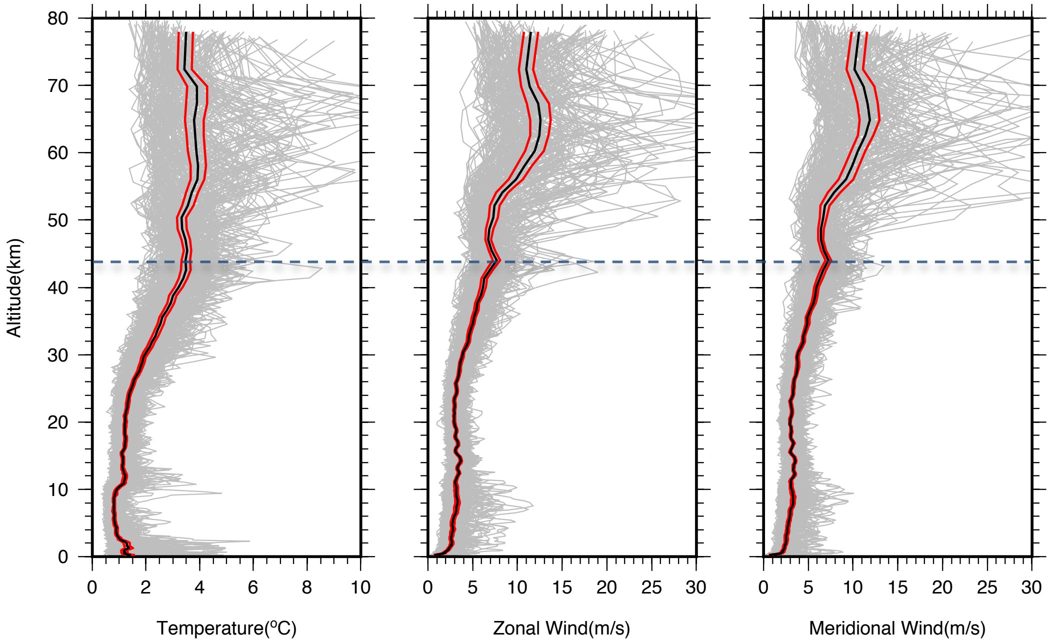

Figure 2 - One year of daily analysis spread at IS46, Russia, at midnight (gray), with mean spread per level (black) and 95% confidence intervals (red). Horizontal dashed line (~44km) indicates the assimilation limit.

An error analysis of the combined model and assimilated observation error of the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecast System (IFS), based on ensemble spread, reveals the lack of upper atmospheric observations. Figure 2 shows one year of ensemble spread, an approximation for the best-estimate error variance, at IS46, Russia, with the mean spread indicating the average combined model error per model level. The best-estimate error variance in Figure 2 clearly indicates the altitude limit of assimilated observations (approx. 44 km), noticeable by the flattening of the temperature error and the nod in the wind variance. Above this altitude the error represents the combined model and climatology error.

Gravity wave parameterization

The atmosphere is a dynamic medium with variability over a huge range of time scales and spatial scales ranging from thousands of kilometres to tens of meters. Planetary scale Rossby waves and smaller-scale gravity waves are particular important both because they can transfer momentum from one part of the atmosphere to another, playing an important role in determining local weather and climate. The climate and variability of Earth's middle atmosphere, comprising the stratosphere and mesosphere, is to a large extent controlled by the upward propagation and breaking of planetary and gravity waves.

Gravity waves are a particular problem for stratosphere resolving models: Coarse temporal and spatial modal resolution means that gravity waves can rarely be resolved directly. At present, parameterization of gravity waves assumes global invariance and is not based on observational constraints. This is mainly due to the limited availability of gravity wave observations, but also because of the gravity wave schemes are currently used to tune the GCM (see TR5.1). For instance, the link between the generation of gravity waves by tropical convection and regular oscillations of stratospheric and mesospheric winds such as the Quasi-Biannual Oscillation well established in theory and represented in some models has almost no observational constraint.

A key example of the variability of the middle atmosphere, critical to the coupling between the troposphere and stratosphere, are Sudden Stratospheric Warmings (SSWs; see D5.2 and 5.3). In winter, the stratospheric polar vortex can get disturbed due to momentum transfer from tropospheric planetary waves breaking into the stratosphere. This momentum dump results in a change of the stratospheric wind direction and velocity, inducing a temperature increase. That the stratosphere influences tropospheric weather has been well demonstrated with modelling studies, and is increasingly widely accepted; *Gerber et al.* [2009], for example, used ensemble runs of a GCM to show that the latitude of the tropospheric jet stream is affected by both the onset and duration of SSWs. Other studies have examined the prediction of the onset of sudden warmings [e.g., *Sun et al.*, 2012], though as TR5.1 concluded, it is the prediction of SSW duration that forecasting centres are particularly keen to improve, since that parameter has greater uncertainty then SSW onset, in current NWP models. Correctly predicting the evolution SSW can lead to improvements in tropospheric weather forecasts on weekly timescales [*Tripathi et al.*, 2014].

Potential of ARISE data

Two particular roles for the ARISE network, that emerged from discussions with NWP centres (ECMWF, Met Office, KNMI), are to constrain biases in existing satellite observations, and provide additional high-resolution measurements to test and improve model parameterization schemes (particularly for gravity waves). Filling the gap in middle atmosphere (upper stratosphere and mesosphere) and gravity wave observations are two of the key objectives of ARISE. Adding this missing information will improve the accuracy of the initial stratospheric state and thereby short and medium-range weather forecasting.

2 - State-of-the-Art

ARISE measurements result in local observations of temperature by Rayleigh lidar, GRIPS OH*-airglow spectrograph, and of wind by ground-based microwave wind radiometer (WIRA), complemented by wide-range continuous infrasound recordings. In this Chapter, a brief overview of the added high quality ARISE observations are listed, mainly used for NWP verification studies. A full description of all the ARISE products and achievements can be found in the other deliverables.

High quality observations filling the gap

Temperature and wind observations

Lidar, WIRA, and OH airglow result in direct values of wind or temperature that can be compared to NWP output. Because (high-resolution) regional models tend to be limited in altitude, these local observations are compared with GCM's, reaching up to the mesopause.

ARISE observations are compared with the ECMWF Integrated forecast System (IFS) High-Resolution model (HRES) analysis from 2006 onwards. Statistics based on long time- series provide useful first-order estimates of similarities and differences depending on ranges of altitude and seasons. However, comparisons between coarse-resolution output of GCMs with high- resolution measurements showing local variability is challenging. While some of the observed discrepancies could be associated with unresolved physics and parameterisation in the GCM, others are related to differences in the spatial and temporal sampling. Generally, ECMWF and lidar and WIRA are in good agreement up to the stratopause and even up to 50 km, except during the recovery after a SSW (see D3.3 chapter 4). The comparison between Rayleigh lidar at OHP and ECMWF temperatures shows large systematic differences above 50 km Differences with airglow temperature observations, and upper lidar and WIRA observations, are larger due to the known lack of middle atmospheric assimilated data. However, if the model physics were perfect, the upper atmosphere that is driven from below would follow much better the observations. Important for the observed differences in wind by WIRA is to keep in mind that, from the stratosphere, winds are derived from the temperature following the thermal-wind relation.

The comparison of airglow and lidar temperature at the altitude of the airglow layer indicates a positive bias of the lidar. This altitude range corresponds to the top of the profile and the lidar temperature may be biased by the initialisation of the pressure profile at the top for the downward integration of the temperature profile. In order to better understand the impact of the initialisation process in the lidar temperature profile, a solution is to use GRIPS temperature observations to start the lidar initialisation. This may also impact the Brunt-Väisäla frequency computed from the lidar profile and used for the computation of the potential energy of gravity waves form airglow data. At OHP, differences between modelled and measured temperature profiles may reach 10 to 20°C above 60 km. These differences are particularly large during the winter months with Sudden Stratospheric Warmings (SSWs). Spectral analyses also provide information on the representation of large-scale atmospheric structures (~2-20 day periods). At OHP, comparisons between spectra of temperature profiles reveal the lack of representation of planetary waves in the models.

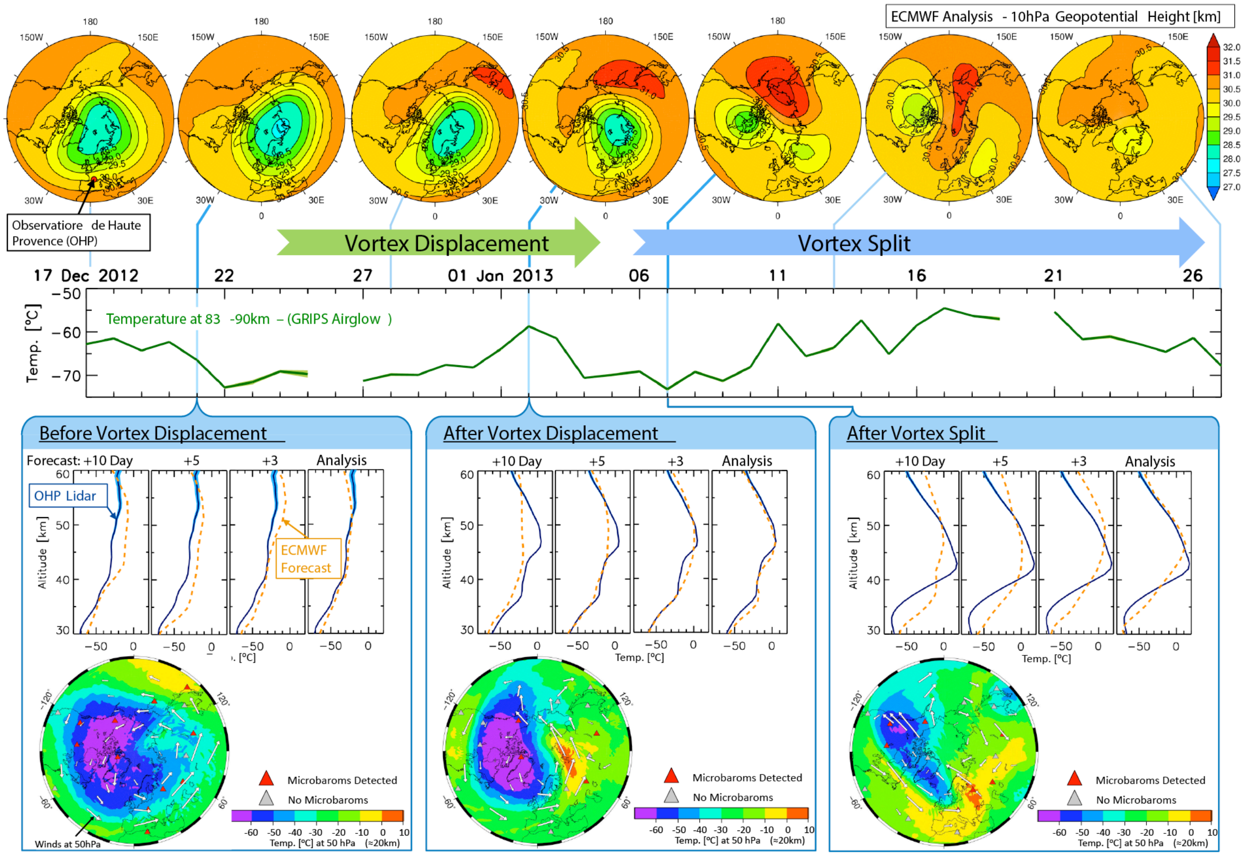

Figure 3 - ARISE observations of the Winter 2012/13 SSWs compared with ECMWF analysis and forecasts. Figure modified from *Lee et al.* [2013].

Major SSWs present a challenge for weather forecasting [*Smets and Evers*, 2014]. ARISE measurements can provide valuable information on atmospheric dynamics before and during such events as shown in Figure 3. Collocating ARISE measurements helps to better describe the interaction between atmospheric layers from the ground to the mesosphere and the influence of large-scale waves on the atmospheric dynamics, achieved by the Haute-Provence Observatory (OHP, 44°N, 6°E) in summer 2012 field campaign (D3.1 and D3.2). Comparing ARISE observations of the Winter 2012/13 SSWs with forecasts reveals: Cooling around the mesopause proceeded both major SSWs, difficultly in forecasting vortex positions after the vortex split, and changes in polar vortex winds substantial altered infrasound propagation. Before vortex displacement, strong westerly winds of the polar vortex carry microbaroms to most stations while temperature profiles over OHP, from later forecasts, are similar to lidar observations. After vortex displacement temperature profiles from forecasts out to seven days are consistent with OHP lidar observations, and the analysis replicates the temperature structure at all altitudes. Changes in polar vortex winds alter microbarom propagation, with only four stations measuring microbaroms. After vortex split, forecasts struggle to replicate the temperature profile at all altitudes, and the upper stratosphere is poorly represented in the analysis (attributed to poor forecasting of split-vortex positions). Weakening of vortex winds again alters patterns of microbarom detection. A global signature of the SSW can be obtained using infrasound, using infrasonic ambient noise: microbaroms [*Evers and Sigmund*, 2009]. Microbaroms are dominant and permanent sources of infrasound signals resulting from the non-linear interaction of ocean waves. No direct observations of wind and temperature are obtained yet, but a clear infrasonic signature is observed with clear differences compared to the ECMWF analysis [*Smets and Evers*, 2014].

Infrasound recordings in the 0.1 to 4 Hz band can be used as input of inversion procedures to delineate the vertical structure of the wind. As infrasound is measured worldwide, this allows for a remote sensing technique that can be applied globally. Deliverable D3.4 provides an overview of studies focusing on the sensitivity of infrasound to the upper atmosphere in order to derive wind field updates as shown in Figure 4. It is found that the inversion results are in line with comparisons with independent techniques such as lidar and WIRA and ECMWF analysis [*Assink et al.*, 2014b; D3.4]. A validation of vertical wind and temperature profiles from ECMWF analysis in the western Mediterranean is performed using volcanic infrasound from Mt. Etna. The near-continuous, high activity of Mt. Etna is useful for acoustic remote sensing studies, as the volcanoes allow us to study propagation along well-defined propagation paths with a time resolution ranging from hours to years. Using infrasonic trace velocity distributions and a simplified inversion procedure it is shown that the effective sound speed during some equinox periods may be significantly underestimated. Future inversion studies could focus on the retrieval of small-scale structure using infrasound data, which could then directly be compared with lidar and WIRA observations and be used to further constrain gravity wave parameterization schemes.

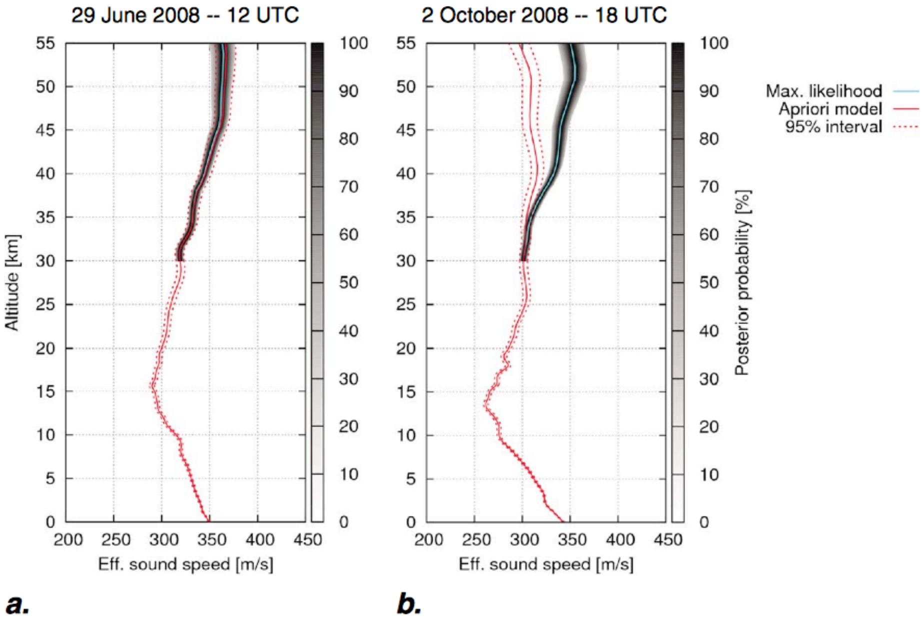

Figure 4 - Two example effective sound speed inversions for (a) 29 June 2008 and (b) 2 October 2008. In both cases, the a priori model is represented by the red curve; the dashed lines indicate the intrinsic uncertainty in the model due to unmodeled small-scale structure. The dark patched areas correspond to the a posteriori model distribution, which is the statistical distribution obtained by combining a priori information on the effective sound speed profiles with measured infrasonic trace velocities. The maximum likelihood model is indicated by the cyan line. While the a priori and a posteriori model distributions correspond well in the summer case, the fall equinox case shows that the effective sound speed is underestimated by about 30 m s−1 at 50 km. Figure from *Assink et al.* [2014] and D3.4.

Beside an infrasound inversion routine, a trace gas inversion scheme has been developed that can be implemented within a chemical assimilation system to provide daily initial wind fields (see D3.4). The potential for chemical inversion was demonstrated by assessing the global potential to restore distorted initial wind fields in terms of forecast skill.

Planetary and gravity waves

The 3 techniques provide spatial and temporal characteristics of gravity and planetary waves with different sensitivity at different altitudes. The combination of information provided by these instruments is contributing to improving global wave climatology in relation with specific geophysical phenomena like thunderstorms, jet stream, and sudden stratospheric warmings described by D3.2 and D3.3.

The stability of the atmosphere is based on the vertical temperature gradient and can be represented by Brunt-Väisäla frequency (*N*). *N* is the angular frequency at which a vertically displaced parcel oscillates within a statically stable environment, and is required to convert gravity wave induced temperature fluctuations to potential energy. Figure 3 compares the Brunt-Väisäla frequency derived from ECMWF analysis and lidar. Below 60 km altitude, temporal trends of *N* from lidar and ECMWF analysis are consistent and do not show any significant difference, while at higher altitudes, the variability of lidar data appears much stronger. However, during the major sudden stratospheric warming (SSW) of 2013 (from 12 to 19 January) lidar data shows a peak in *N* between 30 and 40 km that is not observed in the analysis, probably due to the lack of resolved GW's. The combination of lidar and airglow observations, with auxiliary data (GPS radio-occultation, radiosondes) can be used to reconstruct vertical profiles of potential energy from the surface to the mesopause, useful to follow the activity of planetary waves from the middle atmosphere to the mesopause which is of importance for SSWs (see D3.2).

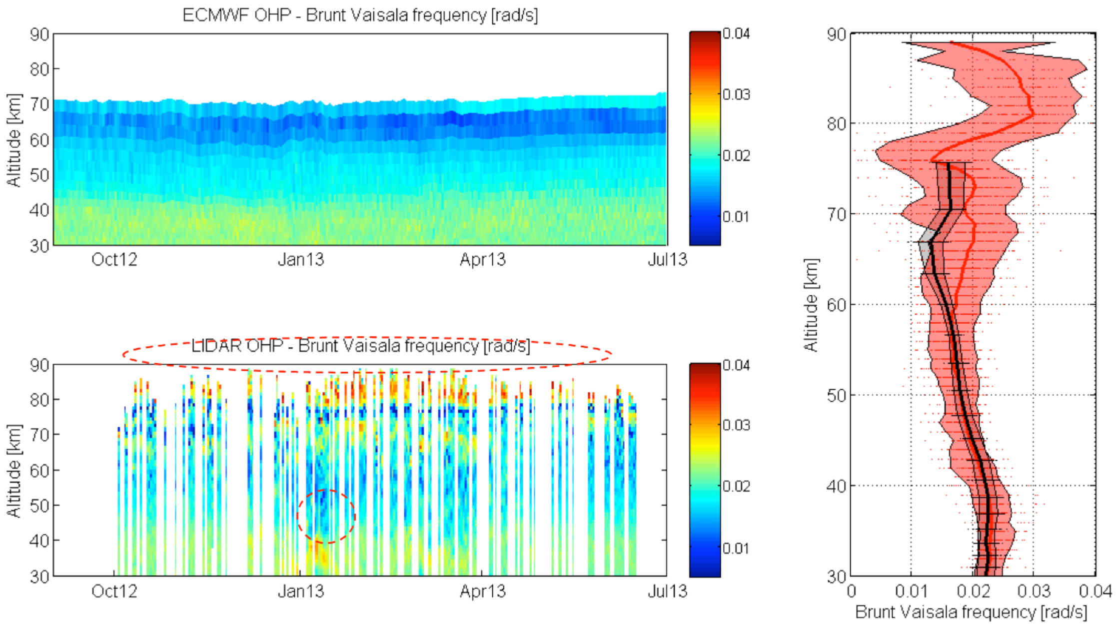

Figure 5 – (left) Brunt Väisäla frequency estimated from ECMWF analysis temperature and lidar measurements at OHP from October 2012 to June 2013. (right) Comparison between analysis (black dots) and lidar (red dots); median (bold lines) and 95% confidence intervals (filled area) are shown. Figure from D3.3.

Most gravity waves are too small to be explicitly resolved by NWP models; instead parameterizations are used to simulate the drag on the mean flow caused by wave breaking. However, the paucity of measurements means that NWP parameterization schemes are often tuned to produce more realistic temperature structures near the tropopause, or to improve representation of winds, rather than to replicate the actual deposition of gravity wave momentum.

Infrasound observations can be used to measure small-scale gravity waves that are not observed by other techniques. Observations and modelling of convection induced gravity waves in the tropics by infrasound are presented in TR5.5 and D5.3. Measurements made by infrasound microbarometer arrays, demonstrated for the Ivory Coast infrasound stations, can be used to detect gravity waves in a range under-sampled by conventional techniques. This improved resolution provides a long-term data set of gravity waves at parameterization scales, which is likely to be a useful additional tool for constraining gravity wave parameterisations in climate models.

Climatology of gravity wave occurrence and gravity wave parameters show a seasonal variability throughout the whole atmosphere, regardless of geographical location and/or the used measurement devices. In other words, all presented studies emphasize a seasonal variation of gravity waves throughout the atmosphere. It is necessary to cover this seasonal variation in climate and weather models. Given wind filtering conditions and source distribution a deeper understanding of (not only) the seasonal variation, can be obtained by performing more height-resolved studies including more wind-field measurements.

Satellite intercomparison and long-term trend estimates

As identified by TR5.1, a difficulty of satellite trend analysis and intercomparison is the presence of sensor related biases or time drifts during the life of the satellite. The latter is very important for to take into account for atmospheric thermal tide analysis. Therefore, an independent, long-term, data source is required. Airglow and especially lidar have a long-term record of observations, suitable as measure for intercomparison studies or as a reference for tidal amplitude and phase when satellite data is used for trend studies in the stratosphere (see TR5.8, TR5.9, and D3.3).

The ARISE network provides data for the monitoring of the long-term variability and trend of temperature and wind in relation with global climate change. The major challenges that have to be faced with atmospheric observations before a trend estimate can be derived are seasonality and solar forcing (solar cycle). Both the observation technique and altitude as the trend estimation methodology are of importance. Potential long-term trends are best to detect in the upper atmosphere, more precise in the mesopause, due to the smaller heat capacity of the rarified air. This reduces external influences affecting the trend estimate, for example, solar cycle variability. Two different methodologies to deal with seasonality and solar forcing are either, complicated, multiple linear regressions, and treating (sub-) annual variations separately per season or month without actual decomposing the data series. Examples illustrate how difficult it is to estimate a trend, using either of the two methods, whose form is not known (linear or not) in a system, namely the atmosphere, which is not fully understood. Discrimination from solar or larger scale dynamical influences of airglow data is currently not possible due to the length of the data series.

The temperature trend derived from Rayleigh lidar observations during the last 30 years indicates a mean cooling of 1 to 3K/decade, up to 3 times larger in winter than in summer (D3.3). The smaller winter trend may be reduced by the increase of SSW occurrence since 2000. Therefore, is very important to consider possible changes in the meridional circulation when we interpret the long-term evolution of the middle atmosphere temperature.

Idealized experiments of potential contribution of ARISE measurements

The potential contribution of ARISE measurements on numerical weather prediction are examined by a series of idealized experiments, presented in Deliverables D5.2 and D5.3.

Deliverable D5.2 focuses on the impact of high-resolution measurements on the upper stratosphere – the region of great opportunity for ARISE techniques. The experiments use an idealized general circulation model (specifically the HADGEM2 Met Office Unified Model - UM), to investigate the onset and evolution of stratospheric sudden warmings (SSW). Comparison with re-analysis data shows that the model simulates the frequency of the stratospheric warmings seen in nature (approximately 6 per decade), and also captures the variability of those events (ranging from no warmings to six, every half decade). Extensive investigations have shown that, whilst this version of the model can be used to perform the perturbation experiments needed to investigate the sensitivity of the models, it has not been specifically tailored to that task, and the latest model version will be more suitable for more detailed experiments.

D5.3 confirms that stratospheric conditions are important for tropospheric forecasts, resulting from idealised forecasts. Stratospheric nudging reduces the ensemble spread for the nudged ensemble, resulting in improved tropospheric synoptic-scale predictability by 1-2 days (see Figure 6). The skill over different regions varied; there was a two-day improvement in forecast skill when considering all mid- and polar-latitudes, but only one day considering Europe only. A better representation of the upper stratosphere did not give an improvement in synoptic scale skill. This is attributed to the teleconnection times between the upper stratosphere and the surface. Improving estimates of initial conditions above 40km could potentially give additional skill at the tropopause. Measurements made by infrasound microbarometer arrays can be used to detect gravity waves in a range under-sampled by conventional techniques. Gravity wave parameters detected with infrasound station IS17, in Ivory Coast, are presented here. The wave source is thought to be tropical convective. The propagation direction, momentum flux, vertical and horizontal wavenumbers, and the intrinsic frequency of the waves vary with season, as the tropical convergence zone shifts to different latitudes. The strongest momentum fluxes are recorded in mid to late spring and autumn, when the convergence zone is at similar latitudes to the microbarometer. These measurements could be a useful additional tool for constraining gravity wave parameterisations in climate models.

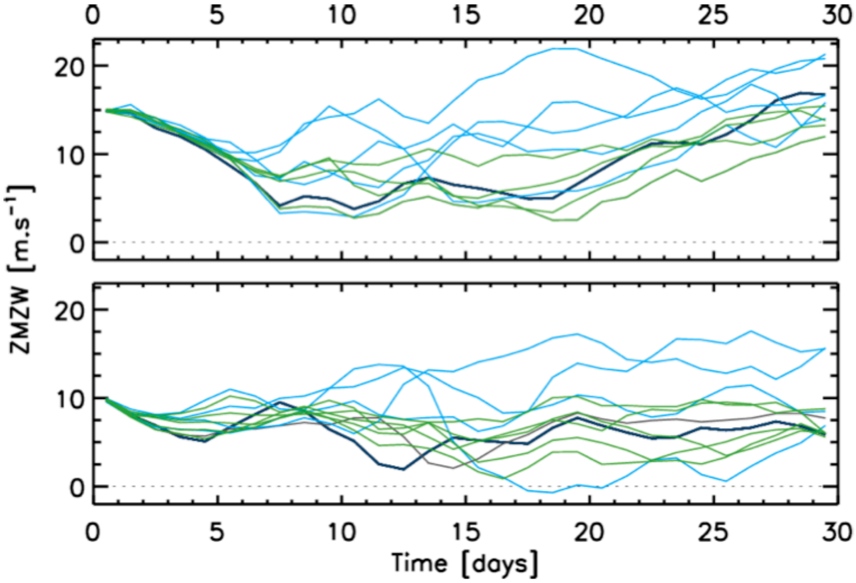

Figure 6 - ZMZW of two SSW cases from the control run (thick dark line), and their 30 day ensemble forecasts (light blue) with upper-stratosphere nudged ensemble (green lines), for the lower troposphere (100hPa). Stratospheric nudging reduces the ensemble spread for the nudged ensemble, indicating enhanced predictability at these altitudes. Figure from D5.3.

3 - Results and Analysis

In this Chapter the impact of the ARISE state-of-the-art is evaluated, stating future needs to propose a roadmap emphasizing the impact and implementation of ARISE for weather and climate monitoring in the next 10 to 20 years.

ARISE impact for weather and climate modelling

ARISE techniques clearly provide valuable information in the range where NWP lacks of observations, demonstrated by multiple comparison and modelling studies based on ECMWF specifications discussed in Chapter 2. Potential is shown that ARISE techniques can provide accurate measurements where GCMs do not typically assimilate data. Differences are consistent between the different techniques, indicating similar model variability, and are largest in the altitude range where few to no data are assimilated. The ARISE OHP campaign has demonstrated the seasonality of the model variability, highlighting significant loss of predictability in the decay phase of a SSW, with even preliminary SSW signals of mesospheric cooling. All techniques show potential providing gravity wave observations, in a broad temporal and spatial range, allowing the recovery of useful information of, e.g., seasonality, geographic and spatial variation, launch spectrum, and fine-scale atmospheric perturbations, which is parameterized in current GCM. Although these studies are still in an early stage, there is a lot of opportunity to validate or even improve GW parameterization schemes.

High-quality unbiased observations are of great importance for NWP. A large variance is not a limitation, as long as it is known. Therefore, zero biased observations for lidar, with some issues in the top levels, and infrasound, due to perturbations in the frequency-response of wind-noise-reduction pipe systems [*Assink et al.*, 2014c], should be ensured.

Additional stratospheric observations have a significant added value for long-term forecast, demonstrated by idealized experiments nudging the stratosphere. However, modelling studies indicate that regional stratospheric nudging, for example Europe, results in only a marginal improvements compared with adding global middle atmospheric observations. However, comparison of high-resolution local observations with coarse-resolution GCMs is challenging, but assimilation would likely be even problematic. Adding a coarse set of local high-resolution observations to a GCM does not guarantee an improved analysis or forecasts skill, but in worst case even destabilizes the model due to physical and numerical boundaries.

Figure 7 shows a schematic of the current position and future direction of ARISE for weather and climate monitoring. In the ARISE project, the basis towards NWP is formed, assessing the model variability and model bias estimation and preliminary achievements in GW parameter estimation. Although ARISE shows great potential towards NWP, the first impact is rather limited. Actual use the data for weather and climate monitoring takes a long pathway where both ARISE and NWP finally should meet, existing of many small steps. Direct assimilation of new observations is extremely costly, and risk full, for operational weather centres, requiring clear prove of the benefits. Therefore, different steps and aspects that meet the needs of weather and climate monitoring are proposed, aimed to being part of the community of weather and climate monitoring.

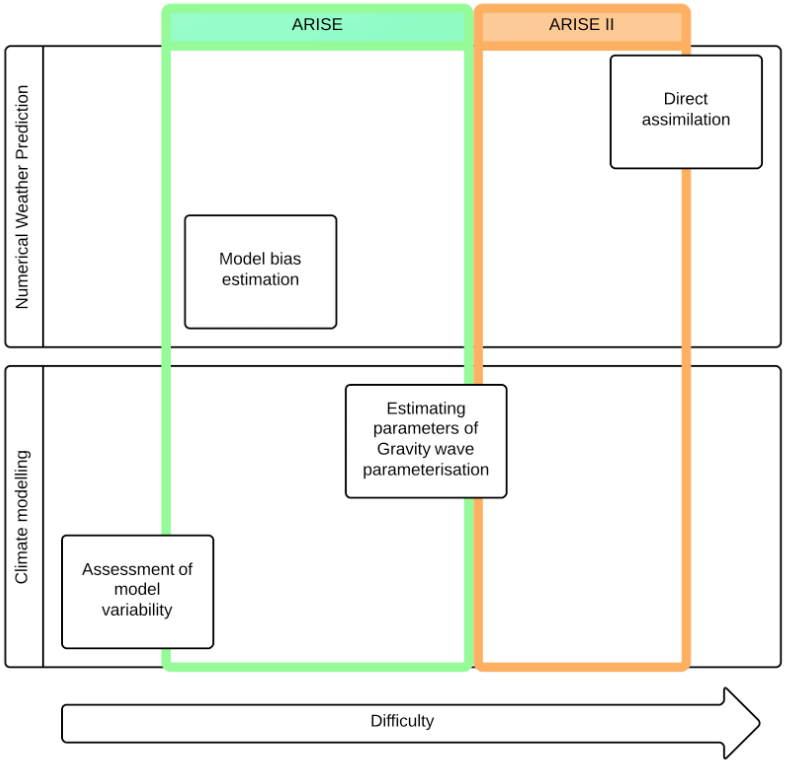

Figure 7 – Schematic of current position and future direction of ARISE for weather and climate monitoring. Difficulty, on the horizontal axis, is similar to time, while the vertical axis indicates the impact.

Developing a user community

Get the attention of the weather and climate community. Scientifically, this requires some effort in meeting their jargon and methodologies to, for example, express achievements in synoptic-scale predictability or forecast skill score. NWP is very sensitive to direct comparisons with observations due to the known physical and numerical limitations of the model. However, comparisons are still of great added value. Therefore, a more subtle, or indirect, approach of presenting to outcome using the correct jargon often works better.

In addition to the science questions, it is critical to develop a broader and well engaged user community. Who from outside the ARISE community is interested and what service do they require? This meets the goal of « ARISE as a service ». This needs further and deeper collaboration with, for example, Met Office, KNMI, ECMWF, WMO, and other weather services and climate modelling institutions.

Potential areas of work

Assess and understand weather and climate models

How can we develop ARISE to be relevant and useful for routine assessment of weather forecasting and climate models? Related to the adapted jargon and methodologies and the above stated sensitivity for direct comparisons between models and observations. In addition, this requires further development and testing of methods and discussion, in cooperation with our (potential) user and link-up with other systems, e.g., World Meteorological Organization (WMO) Global Climate Observing System (GCOS, see http://www.wmo.int/pages/prog/gcos/).

Developing pathway to assimilation: ensemble forecast calibration

Can we develop tools to make ARISE measurements (particularly infrasound) ready for assimilation by models? At this stage, infrasound is the best candidate for future assimilation due to the continuous global coverage and sensitivity to the large general (stratospheric) circulations beside small-scale fluctuations, of great value for GCM. Although this advantage, yet several steps are needed along the pathway to assimilation.

A first step along the pathway to assimilation is using ARISE measurements to constrain ensemble predictions. For users of ensemble weather forecasts, a key metric of forecast success is its ability to effectively predict the uncertainty of a given weather condition happening at some point in the future. While more than 10 weather forecasting centres now produce routine medium-range ensemble forecasts making the best and most effective use of these products remains a challenge. Although some authors have shown that a forecast constructed from more than one numerical model generally produces more skilful forecasts than the best model, methods to effectively calibrate and condition this ‘multi-model ensemble’ are still in their infancy. The measurements of the stratosphere made by ARISE provide a detailed and independent measure that can be used to examine the ensemble forecasts produced by one or more routine forecast models. This task will develop and investigate methods that can be used to down weight models and ensemble members, which are not consistent with the independent ARISE measurements, and produce a better calibrated and potentially more skilful weather forecast.

Extracting and testing gravity wave parameters

ARISE has shown that the network can provide measurements of a part of the gravity wave spectrum that is poorly sampled by other measurement techniques. This helps to provide novel constraints on the spatial and temporal distribution of gravity waves in the atmosphere. Important is to provide on-going climatologies of gravity wave parameters and test these in state-of-the-art model GW schemes, proving its impact. This requires more development and understanding/testing of stochastic GW schemes. Also the impact of modifications of GW parameterization schemes with respect to model tweaking has to be clarified, as these schemes are widely used as overall GCM modification and tweak tools. A valuable product will be deriving a seasonally and latitudinally varying gravity wave (GW) climatology from ARISE measurements.

Working towards a service for whole atmosphere models

« ARISE as a service » can become a critical service for the coming generation of whole atmosphere forecasting models (WAM), which incorporate upper atmospheric physics. Related to the needs of a user community, this requires specific understanding of this user community and the rapid development path of these models. In many European countries there is a growing interest in the potentially far ranging impacts of space weather on our technologically sophisticated societies. As part of this interest, several routine centres including KNMI and the Met Office are developing whole atmosphere models. Given the relative paucity of observational data in the upper stratosphere and above, it is likely that ARISE measurements will have a significant role to play in the development of these models towards routine capability. Therefore, it is worth the investment looking at the ways in which measurements from the ARISE network can be directly assimilated into these new (near) future numerical models or how potential new ARISE techniques should be added to fulfil the needs of NWP towards future WAMs. Important to investigate is the required global coverage of the networks with respect to GCM, as demonstrated by the impact of regional observations in the idealized experiments.

Developing understanding of coupling between stratosphere and troposphere

An urgent need of NWP is develop a greater and more detailed understanding of the dynamical coupling between the stratosphere and the troposphere. For ARISE this would involve further well-designed idealized experiments to explore dynamics. Beside this need, it is of great importance for the network itself. Understanding how atmospheric variability affects the ability of the ARISE network to detect atmospheric extreme events. One of the core functions of the routine ARISE network will be the detection of extreme events in the Earth system. One potential challenge in this regard is in assessing how natural atmospheric variability affects the ability of the network to detect these extreme weather events.

4 - Conclusions

ARISE has clearly demonstrated that it has the potential to fill important gaps for numerical weather prediction to improve modelling of weather and climate. Potential is shown that ARISE techniques can provide accurate measurements where GCMs do not typically assimilate data. High-quality unbiased observations are of great importance. Idealized experiments have indicated that global coverage of stratospheric observations results in a larger forecast skill improvement compared to regional nudging.

Key actions are proposed towards the implementation of ARISE for weather and climate monitoring in the next 10 to 20 years. Assimilation of new observations requires a long pathway. Therefore, different steps are listed that lead to both short- and long-term impacts.

Short-term: develop methods to allow ARISE measurements to be used by weather and climate prediction centres, making the first pathway to assimilation without the need of developing costly assimilation routines or new model (parts).

- Assess and understand weather and climate models
- Pathway to assimilation: ensemble forecasts calibration
- Extract and use gravity wave observations

Long-term: important steps that require more time and which results are hardly noticeable in the beginning. Being on the roadmap of other project, being part of and contribute to the weather and climate community is the key element to guarantee long-term existence.

- **Developing a user community**
- Working towards a service for whole atmosphere models
- Developing understanding of coupling between stratosphere and troposphere

5 - Bibliography

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