1 FINAL PUBLISHABLE SUMMARY REPORT

1.1 Executive summary

Recent studies have robustly demonstrated that variations in the circulation of the middle atmosphere influence weather and climate throughout the troposphere all the way to the Earth's surface. A key part of the coupling between the troposphere and stratosphere occurs through the propagation and breaking of planetary-scale Rossby waves and gravity waves. Limited observation of the middle atmosphere and these waves in particular limits the ability to faithfully reproduce the dynamics of the middle atmosphere in numerical weather prediction and climate models. Observations above the stratopause, where measurements are rare, could then provide crucial information for a better description of the atmosphere and more accurate longer-term weather forecasts, on timescales up to several weeks ahead.

The challenge of the ARISE project (http://arise-project.eu) was to combine complementary measurements to provide updated 3D images of the atmosphere and unresolved disturbances from the ground to the mesosphere with unprecedented spatio-temporal resolution. The considered time scales range from seconds for extreme events (volcanoes, thunderstorms, cyclones, avalanches, meteorites) to minutes or hours for gravity waves, days for planetary waves and up to tens of years for long term mean trend studies. The observations cover areas with very different climatic regimes, extending over Europe and outlying regions, including polar and equatorial regions.

The infrastructure integrates:

- the infrasound networks, part of the International Monitoring System (IMS) developed for verification of the Comprehensive Nuclear Test Ban Treaty (CTBT - http://www.ctbto.org/),
- the Network for the Detection of Atmospheric Composition Change (NDACC - http://ndacc-lidar.org) – using lidar (LIght Detection And Ranging),
- the Network for the Detection of Mesosphere Change (NDMC, http://wdc.dlr.de/ndmc), dedicated mainly but not only to airglow layer measurements in the mesosphere.

It will also include the complementary infrasound stations of various countries, specific infrasound stations located near volcanoes for volcanic source studies, ionospheric arrays to determine coupling with near Earth space and satellite observations.

The ARISE main objectives are the following:

- improving the representation of gravity and planetary waves in stratosphere-resolving climate models, crucial to estimating the impact of stratospheric climate forcing on the troposphere,
- monitoring climate-related phenomena such as severe weather, thunderstorms and sudden stratospheric warmings, over large time periods, in order to characterize their intensity and evolution over time in relation with climate change,
- providing a near-real time and continuous monitoring of natural hazards such as large volcanic eruptions, cyclones, avalanches, and meteorites.

The expected benefits are a better description of the atmosphere and an improved accuracy in short- and medium-range weather forecasts up to scales of weeks. The data will be used for monitoring the middle atmosphere dynamics, its long-term mean trends and also the evolution of extreme event characteristics with climate change. Furthermore, the benefits include civil applications related to monitoring of natural hazards. It concerns for example remote monitoring of volcanoes for civil aviation in case of ash injections in the atmosphere.

1.2 Summary description of project

The ARISE project aims to design a novel infrastructure integrating different atmospheric observation networks to better elucidate the 3D dynamics of the atmosphere from the ground to the mesosphere. The ARISE network includes stratospheric and mesospheric NDACC-lidars, mesospheric NDMC-airglow observations and IMS infrasound measurements complemented by additional radar and satellite measurements.

This first combination of information provided by these instruments will help to build a better view of global wave climatology in relation with specific geophysical phenomena like thunderstorms, jet stream, sudden stratospheric warming. These networks also provide data for the monitoring of the long-term variability and trend of temperature and wind in relation with global change of the climate.

ARISE was divided into five core Work Packages. The key results of each WP are summarised below.

- **WP2** described the ARISE observation network, starting from an assessment of the existing instrumentation of the different measurement technologies and ending with a proposed design as well as identified optimization tasks for the network in the future of ARISE. Furthermore very reasonable costs for optimizations of the infrastructure were estimated.
- **WP3** focused on developing advanced data products for end-users of the ARISE data service who are interested in meteorological, climatological and atmospheric science problems. Several advanced data products have been developed to document the climatology of temperature and winds and the knowledge on dynamics and gravity and planetary waves in the middle and upper atmosphere. Measurements performed during the 2012-2013 campaign at OHP emphasize the benefit of combining the 3 main observation techniques plus additional observations involved in ARISE. We summarize below the main scientific results obtained with these advanced data products.

  The comparison of ECMWF vertical profiles above OHP with Rayleigh lidar temperatures and microwave radiometer winds shows large systematic differences above 50 km with some improvements with the new L137 version compared to the previous L91 counterpart.

  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 and the use of airglow data to initialize the downward integration of the temperature profile will allow reducing this bias. As expected, improved detection capability of infrasound occurs for stratospheric downwind conditions from October 2012 to May 2013 with change of azimuth during the January 2013 SSW event.

  The potential energy Ep of gravity wave is a robust parameter to evaluate the wave activity from the surface to the lower thermosphere and to identify the regions where the momentum flux and the energy of these waves interact with the large-scale circulation. Ep can be estimated from the time or vertical fluctuations of the atmospheric density or temperature. In the scope of ARISE, Ep was estimated from Rayleigh lidar data in the stratosphere and mesosphere, airglow spectrometer data at the mesopause, temperature radio-occultation profiles in the UT-LS and radiosonde profiles in the troposphere. It allowed us to build climatology of this parameter at middle latitude around OHP, to identify the sources of enhanced gravity wave activity (thunderstorms, SSW) and to determine the altitude layers where most of the wave dissipation occurs.
- **WP4** of the ARISE project focused on the applications of the future infrastructure for the monitoring of extreme events. Different kinds of extreme events were taken into account during the ARISE Design Study Project (volcanic eruptions, earthquakes, snow avalanches, severe

weather, meteoroid entries and industrial explosions in Northern Europe) whose extent, energy and impact on civil security is extremely different. These span from snow avalanches, which have a dramatic impact on civil security but over extremely small areas and are detectable only with infrasound observation, to volcanic eruptions and severe weather that can effect transnational areas and affect the whole atmospheric profile and are thus detectable with all 3 ARISE observation networks.

The main objective of the WP4 was to define the benefit of ARISE technologies to improve the monitoring of these extreme events and provide advanced parameters specifically designed for this. During the first part of the project, the state of the art of available observations was analysed and future benefits deriving from the three ARISE technologies were carefully investigated, by highlighting benefits, limitations and impact of ARISE measurements.

Specific attention was given to volcanic eruptions. Volcanoes are prolific sources of infrasound and are commonly detected with infrasound arrays even at large distances (up to 10000 km) from the source. During the project the mutual effect between volcanic plumes and atmospheric dynamics was addressed, and the potentials of ARISE to assess atmospheric dispersal of volcanic ash was analysed. Moreover, volcanoes were used extensively ads infrasonic sources for atmospheric probing and to evaluate the monitoring network sensitivity in time and space.

During the course of the project advanced parameters for the different kinds of extreme events were defined. These are processed information, that are obtained from ARISE infrastructure and provide useful information to stakeholders and end users such as decision making and civil protection agencies.

Eventually a plan for the use of ARISE infrastructure to improve monitoring of extreme events in Europe was proposed. The ARISE network appears to be quite well developed to monitor most of the expected extreme events in Europe. The largest benefits are expected for monitoring volcanoes and severe weather, because for the nature itself of the process they produce large-scale effect in the atmosphere and are well detectable with the 3 ARISE technology in synergy. For volcanoes in particular ARISE could provide a warning system of ongoing volcanic activity, thus providing a significant improvement of the procedure for assessing atmospheric dispersal of volcanic ash worldwide. This is in particular relevant for distant non instrumented volcanoes.

- **WP5** work enable partners to elucidate the current interest of the ARISE network and ARISE data for weather and climate monitoring in Europe, now, and within the next 10 to 20 years. A roadmap was proposed to achieve the potential ARISE impact and implementation of ARISE services for weather and climate monitoring.

  ARISE has clearly demonstrated that it has the potential to fill important gaps for numerical weather prediction to improve modelling of weather and climate. ARISE techniques could 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.

  In the short-term, the consortium should develop methods to allow ARISE measurements to be used by weather and climate prediction centres, facilitating assimilation without the development of costly assimilation routines or new model (parts). In the long-term, the consortium should reinforce its contributions to the weather and climate community by developing the user community, working towards a service for whole atmosphere models and developing an understanding of coupling between the stratosphere and troposphere.

- **WP6** aimed to showcase and provide access to the synergistic use of data and products from complementary scientific fields in order to establish a unique atmospheric research and data platform in Europe, combining observations with theoretical and modelling studies, to elucidate the dynamics of the middle and upper atmosphere.

  Not to be confused with the ARISE project webpage (http://arise-project.eu), the ARISE data centre (http://andromeda.caf.dlr.de/arise) holds the infrastructure where most relevant scientific findings of the ARISE project are made freely accessible to the interested user. The scientific results obtained in the ARISE project are ranging from infrasound detections to observations of atmospheric dynamics and comparative studies. Outstanding scientific results are obtained by creating "value-added products" by combining observed or retrieved scientific outcomes from different disciplines.

  These complex results – as well as the "pure" observations obtained at measurement sites -- are made accessible to the public in an interactive way through the ARISE data centre.

  In order to successfully publish these findings and products, all necessary algorithms reflecting the scientist's know-how on handling and visualizing their specific observational data and products were re-implemented by the ARISE data centre team at DLR into a dedicated web server environment.

  Moreover, the ARISE data centre aimed at navigating the user through its variety of ARISE scientific data products ranging from infrasound detections to observations of atmospheric dynamics and comparative studies.

  Final results of this WP included the Final design of the ARISE Data Centre as implemented at DLR and a cost estimate for the long-term operation of the portal. Moreover, the ARISE data centre was successfully implemented by the DLR team in collaboration with scientists from all contributing institutions. Finally, the portal was successfully transferred to its new host, EMSC.

1.3 Main results

1.3.1 Design and optimization of the network

The ARISE observation monitoring network has been described and its performance assessed. Data policies and intellectual property issues for each station and network (infrasound, lidar and airglow) were addressed. For the different technologies, legal aspects and data harmonization procedure have been proposed and implemented in the ARISE data center.

Negotiations of new agreements with ECMWF and CTBTO were undertaken. The agreement with ECMWF served to define the use of their data in project context and for the project campaign location and duration as well as their requirements concerning services to be provided via the ARISE data portal. The one with CTBTO served to define the use of CTBT-IMS data by ARISE partners and to set-up a joint ARISE-CTBTO service for the monitoring of non-instrumented volcanoes.

New partners, stations and technologies relevant for the continuation of the project have been identified and proposed for a future design. This includes contacting, evaluating and inviting new contributions to the ARISE infrastructure as well as estimating potential costs. Final recommendations for the future observation network were given, supporting the project management and providing a solid basis for the development of the ARISE infrastructure.

Potential improvements of the ARISE infrastructure were proposed. Studies on detection performance using the ARISE observation network and planning measurement campaigns and instrumental setups at new observation sites were conducted. Significant improvements in the detection capability and source characterization procedure are expected. This can be achieved with an appropriate selection of complementary technologies, network configuration and instrumental technical innovations. Furthermore, the performance of the future ARISE observation network can significantly be improved by including new contributors and novel approaches.

Network optimization

Different studies were performed to highlight the network performance of the different ARISE technologies and optimize it by improving the observation technology or adding more stations and new sounding techniques.

For the **infrasound** technology, network performance simulations were conducted to evaluate the benefits of increasing the number of stations to optimize the infrasound network. **Figure 1** compares the European geographical coverage of the minimum detectable signal amplitude by one station, at a frequency of 0.8 Hz, in summer and winter, with and without adding specific stations to the operating IMS network. Benefits by increasing the number of stations are gradually shown from pure IMS network to experimental stations progressively added to the IMS network. The predicted network performance follows the general stratospheric wind circulation and provides here a good description of the global seasonal oscillation of the dominant zonal wind component. Clearly, incorporating ARISE partner stations and further contributors allows the European region to be better monitored with decreasing detection thresholds.

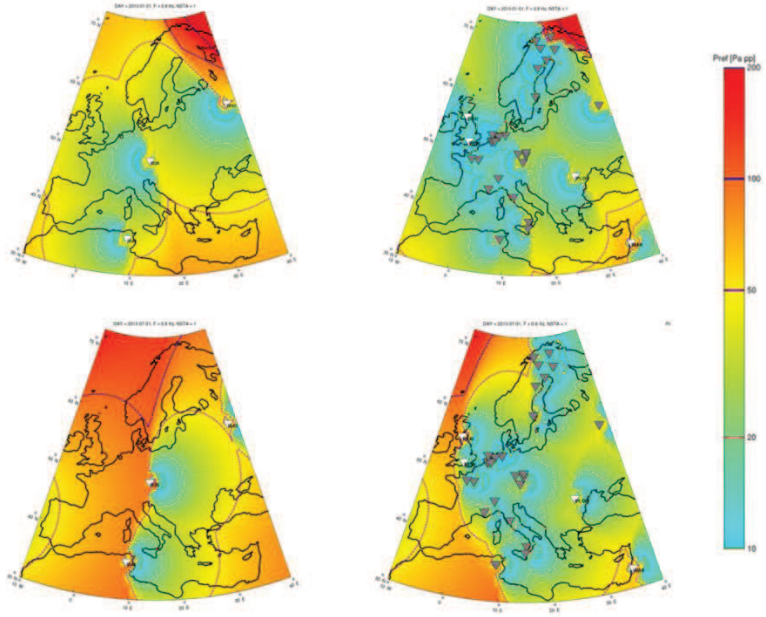

Figure 1. Incorporating ARISE partner stations and further contributors allows the European region to be better monitored with decreasing detection thresholds (shown by colour scale). This figure simulates the smallest detectable source amplitude in winter and summer at 0.8 Hz, considering one-station coverage. Simulations are carried out with the atmospheric conditions present on January 1st, 2013 (top) and July 1st, 2013 (bottom). The images on the left consider data from the IMS network only. On the right, national ARISE partner and associated partner facilities are integrated to the network. Grey and white triangles indicate the location of existing and added infrasound arrays, respectively. The colour maps the source amplitude at a reference distance of 1 km from the source in Pa peak-to-peak.

For **lidar** observations, a number of further instrumental sites and partners with existing lidar technology were identified for a potential extension of lidar facilities within the next stage of the project. Assessment of new lidar instrumentation was performed to establish further multi-technology sites. Furthermore technical developments concerning lidar and the corresponding partners responsible for the work in this field were identified.

- With the IAP Kühlungsborn, Germany, a partner was identified operating lidars at two different sites, Kühlungsborn and ALOMAR. The ALOMAR observatory was identified to be an ARISE multi-technology site and the IAP Kühlungsborn could provide lidar and also radar and further complementary instrumentation at ALOMAR. Lidar and additional complementary observations could be provided for the Kühlungsborn site as well as important expertise in technical developments like daytime capability and wind measurements.
- The DLR-IPA, Germany, was identified as another important partner for lidar measurements, especially in the field of technical development and with a prototype mobile lidar instrument, that could be established for the future ARISE project as campaign instrument and (in serial production) as low-cost alternative for establishing semi-permanent lidar sites in regions of interest for dynamics, volcanic, weather and climate studies.
- Further stations (NDACC and non-NDACC) and their station operators were identified, that could increase the observation coverage with lidar technology inside and outside of Europe, but for those stations upgrading, modifications or more regular operations are needed to fully participate to ARISE.

For **airglow** observations, contributions of OH spectrometers were assessed during the first project phase; some current and future ARISE partners will provide OH spectrometer observations to the next stage of the ARISE project (LATMOS, NTNU, NUIM). Since these observations provide only data at a single point in space, only limited conclusions concerning spatial characteristics can be drawn. This is explicitly relevant for studies of atmospheric waves, which by definition are periodic phenomena in time and space. Therefore the so-called imagers are a rapidly evolving instrument group in present airglow studies. These are sensitive camera systems, often optimized for the use in the infrared spectral region. Airglow imaging performed by some of the ARISE partners and at some of the future ARISE multi-technology sites, e.g. at ALOMAR observatory, was identified to be most relevant for the airglow part of future ARISE project.

Furthermore, **other technologies** already associated to ARISE or identified to be of relevance to the project, include radar, wind radiometer (WIRA) and ionospheric Doppler observations. The inclusion of radar as a new observation technique to be considered highlights a novel possibility to observe high altitude wind and temperature (above 70 km) by polar mesosphere summer/winter and meteor echoes. Furthermore a link to the EU-funded and ESFRI-established project EISCAT (3D) for ionospheric radar observations has been proposed. The experiences gained with WIRA on the different campaigns (Bern, Switzerland; Sodankylä, Finland; Haute-Provence, France; La Reunion, France) have proven that microwave Doppler wind radiometers can operate under most conditions encountered from polar to tropical latitudes. Thus, instruments like WIRA offer a high autarky and low operation costs. It is concluded, that a mobile, autarkic, cost-efficient instrument like the WIRA would be a highly useful complement to the ARISE instrumentation, especially at multi-technology measurement sites. Further plans also include the extension of the Doppler sounding network with the installation of a Doppler sounder at the Observatory Haute Provence, France. Additional ionospheric instrumentation could be developed and/or installed for observations of extreme events in Italy or at other ARISE multi-technology sites.

New contributing technology

Final investigations and decisions on the future ARISE network were considered relative to actual and new partners, stations, instruments and technologies within the project. New partners, that have been identified were added to the ARISE2 project along with new technologies, stations and instrument for the growing ARISE observation network; furthermore stations and partners not contributing available data due to data policy aspects and/or leaving the project were removed from the future network.

A prospective design of the future ARISE observation network in Europe is given in **Figure 2**. From a global perspective, international stations of the CTBT infrasound and NDACC lidar networks are participating/contributing to ARISE along with ionospheric stations in Argentina, South Africa and Taiwan, as well as wind radiometer currently installed at the lidar facility of in Reunion Island, a French island in the tropical Pacific. Further instrumentation will be prepared and installed within ARISE2 for existing and new multi-technology sites at Haute Provence, France; La Reunion, France; ALOMAR observatory, Norway and near IS17 station, Ivory Coast.

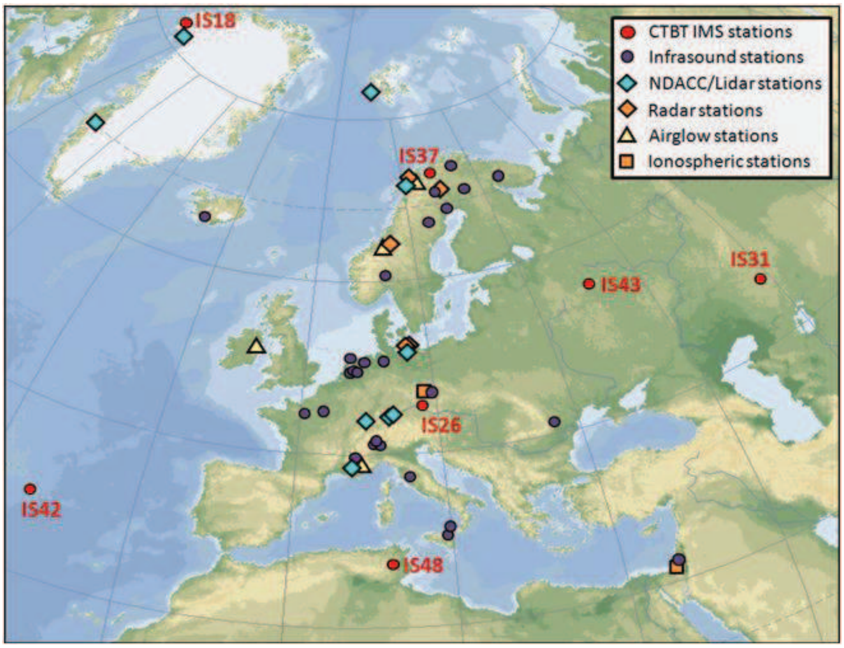

Figure 2. European part of the future ARISE2 observation network.

1.3.2 Promote data utilization for weather forecasting and climate models

To better initialize weather forecasting systems, a key challenge is to understand stratosphere-resolving climate models. ARISE objectives include the evaluation of the benefit of collocated measurements to improve our knowledge of the middle atmosphere dynamics and to create advanced dynamics products that will be used for the validation and improvement of weather forecast and climate numerical models. The inter-technology ARISE measurement campaigns provided high-resolution data of high quality that have been used to evaluated Numerical Weather Prediction (NWP) and climate models by characterizing the mean state of the middle atmosphere, gravity and planetary waves.

This work was successfully performed thanks to the OHP (Haute-Provence Observatory), where the different ARISE technologies were collocated to initiate the collaborative work. The OHP campaign provided the vertical structure of the wind and temperature from the ground to the mesosphere by using Lidar and mesospheric airglow observations, complemented by continuous infrasound measurements. Together with additional ground-based wind radar system, such complementary techniques help to better describe the interaction between atmospheric layers from the ground to the mesosphere and the influence of gravity and planetary waves on the atmospheric dynamics.

The analyses of the ARISE data allowed characterizing atmospheric perturbations in the middle atmosphere and their effects on the mean circulation. Such gravity waves cannot be resolved directly by current global circulation models due to their sub-grid scales and there is a lack of operational measurements especially in the altitude range between 40 and 80 km. The ARISE database provides novel observations on the spatial and temporal distribution of gravity wave characteristics at different ranges of altitudes and time of year, thus building a detailed understanding of large scale atmospheric disturbances through multiple independent and complementary observational platforms.

Climatology and comparison with ECMWF

Historical recordings available at NDACC lidar stations have been considered for evaluating ECMWF analyses at 40 km and above where very few observations are assimilated. Generally, ECMWF and lidar are in good agreement up to the stratopause. However, differences may reach an average of -20 K in the mesosphere above 65 km. This is expected since very little data is assimilated above 50 km altitude. However if the physics of the model were perfect, the upper atmosphere that is driven from below would agree much better with the observations. The vertical resolution of the ECMWF model was increased in 2013 from 91 levels (L91) to 137 levels (L137).

Figure 3 presents the monthly statistical distribution of the differences between the ECMWF temperature models and lidar observations during the OHP measurement campaign. Generally, ECMWF, NASA MERRA and lidar are in agreement up to the stratopause with a small, but systematic positive difference of ~3 K at ~35 km altitude. The median of the differences increases with altitude, predominantly above the stratopause region. The largest deviations noted in winter correspond to the time of the major SSW that occurred early January 2013. After the vernal equinox, the median and 95% intervals reduce by about a factor 2 due to the lack of stratospheric and mesospheric variability in this season.

The horizontal wind is another fundamental atmospheric parameter. However there is no wind data assimilated in NWP models above the top of radiosoundings (around 30 km). The wind is indirectly derived from temperature and pressure fields solving the primitive equations of the atmospheric dynamics. The new microwave radiometer WIRA operated at OHP by Bern University provided us a unique opportunity to validate the ECMWF zonal and meridional wind components.

Similar comparisons between ECMWF and WIRA observations have also shown that measurements and model values are in good agreement between 30 and 60 km. Above 60 km, the median of the difference falls outside of the instrumental error, and is thus considered statistically significant. Deviations as large as 30 m/s during the winter months were found.

Differences between models and measurements can be related to: (i) systematic problem in the model physics that drives the analysis fields away from available observations; (ii) temporal and spatial differences between instrument observations and model output; (iii) model failing to capture atmospheric variability in regions devoid of any measurements or the inherent smoothing of the data assimilation system in global circulation models; and (iv) systematic errors in the independent observations used for the comparison. In order to evaluate the lack of variability in the models, the spectral contents of both wind and temperature models and observations have been compared.

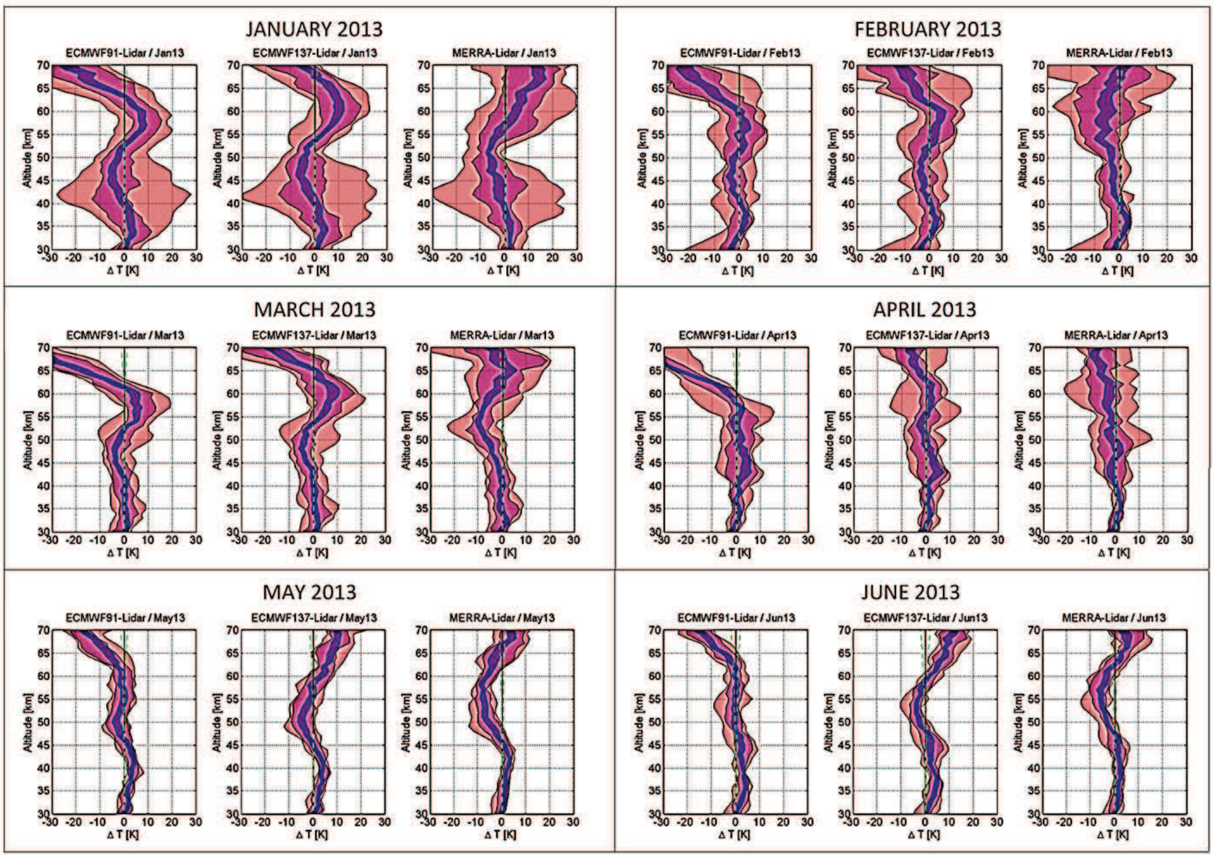

Figure 3. Distribution of the monthly difference between ECMWF (L91 and L137) and MERRA temperature models at 0h UTC and nightly averaged lidar measurements versus altitude at OHP from January to June 2013. Blue lines: standard error of the mean. Green dashed lines: instrumental error bars. The differences are significant when the blue lines fall outside of the green dashed lines. Purple and pink regions: 66% and 95% confidence intervals of the difference profiles (from Le Pichon et al., 2015).

The periodograms shown on **Figure 4** compare spectral amplitude of ECMWF, NASA MERRA re-analyses and the climate MPI-ESM-LR models with long-term lidar time series. A reasonable agreement in spectral amplitude is found down to 15-20 days for all models. Compared to the observations, the variability at shorter time-scales is lacking in both weather and climate models. The lower level of variability found in the free running MPI-ESM-LR model can partly be explained by its coarser resolution and the lack of data being assimilated.

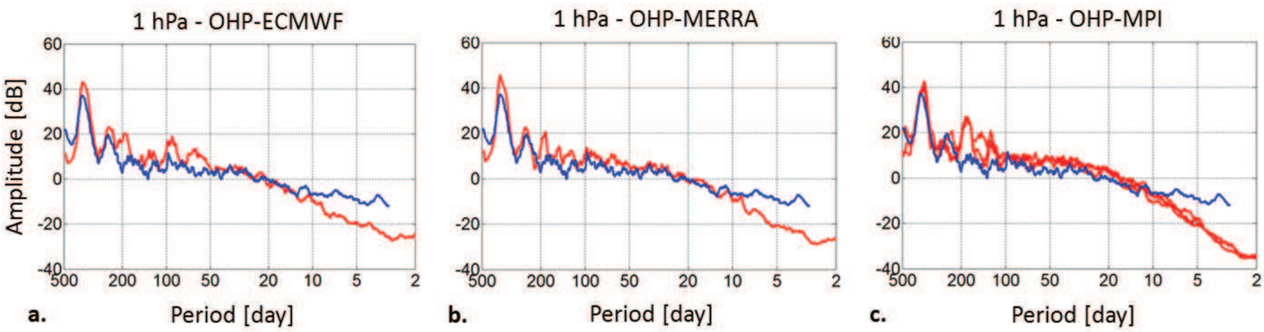

Figure 4. Comparison between lidar (blue) and model (red) periodograms at 1 hPa (~47 km) over OHP. (a): ECMWF (2003-2013). (b): MERRA (2003-2013). (c): MPI-ESM-LR (1991-2005), each line corresponds to one ensemble member (from Le Pichon et al., 2015).

The signal measured by the GRIPS instrument operated by DLR at OHP comes from the OH*-airglow layer with a peak height at OHP at ~86 km altitude. The airglow layer allows us to derive an accurate determination of the temperature near the mesopause. **Figure 5** (left) compares nocturnal mean airglow and lidar measurements integrated between 80 km and the top altitude of the profile that can vary. A generally satisfactory agreement is found between airglow and lidar measurements. However, differences can reach ~20 K during periods of 1-2 weeks at the end of February and the beginning of March. Possible reasons for this difference could be the height and the variability of the OH layer which need to be taken into account when calculating the averaged lidar temperature values. Other reasons may include the varying top of the lidar measurements that influences the averaged lidar temperature values or the initial values of the lidar temperature retrieval. These reasons could explain why the current atmospheric state is not well captured, leading to large differences, especially at the top of the lidar measurement. When OH-layer variability and form are taken into account, the temperature values of TIMED-SABER and GRIPS measurements agree very well (mean difference SABER - GRIPS: -0.4 K ± 6.3 K, **Figure 5**, right).

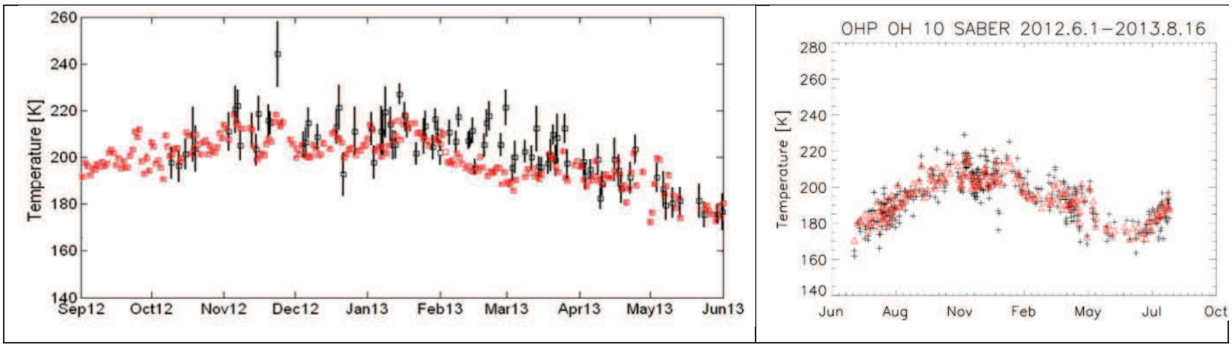

Figure 5. Left: Comparison between airglow (red squares) and lidar measurements (black vertical bars are errors integrated between 80 km and the highest available level) at OHP. Right: Comparison between TIMED-SABER (black) and GRIPS (red) temperature data in 2013.

Multi technology view of the middle atmosphere

One of the main objectives of the OHP campaign was to investigate the synergy between different collocated techniques for the characterization of specific dynamics events. The Sudden Stratospheric Warming (SSW) occurring in January 2013 event offered a good opportunity to test this synergy. Microbaroms in the Atlantic Ocean are dominant and permanent sources of infrasound signals period in the 0.1-1.0 Hz frequency band, resulting from the non-linear interaction of ocean waves. These signals have been well detected during the 2012-2013-measurement campaign at OHP. Comparing ECMWF wind and temperature models, lidar and wind radiometer observations with collocated infrasound measurements provides here additional continuous, directional and integrated information about the structure of the stratospheric waveguide from the source to the station.

Figure 6 presents on the same time basis the temporal evolution of lidar, airglow and infrasound observations to the L91 model. Microbarom detections are superimposed to the effective sound speed ratio above OHP site, defined as the ratio between the maximum of the along-path wind plus the adiabatic sound speed at 30-60 km altitude and the sound speed at the ground level, derived from ECMWF. Microbarom sources are predicted using a source model and operational ECMWF ocean wave models. The back azimuths of predicted microbarom sources with respect to the OHP array are superimposed. As expected, improved detection capability occurs downwind during the period from October 2012 to May 2013. Good agreement between the observed and predicted azimuths is found in a range of ~20°. Deviations from this trend are either related to short time-scale variability of the atmosphere (e.g. large-scale planetary waves, stratospheric warming effects), or can be explained by unresolved changes in the nature of the microbarom sources.

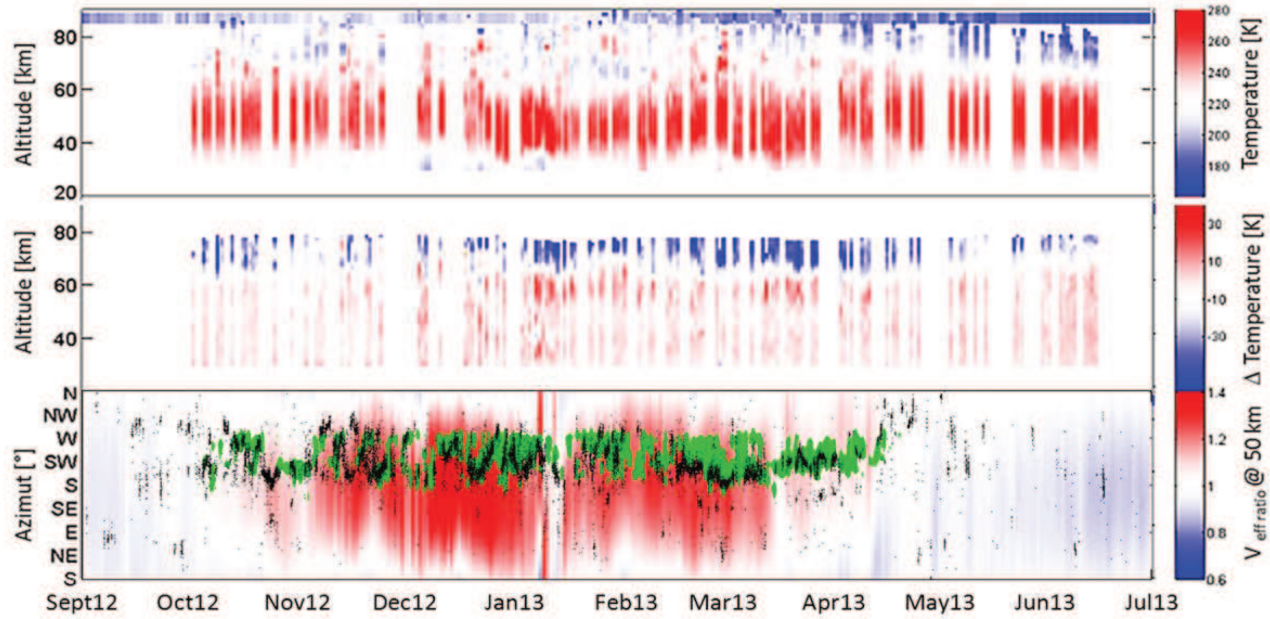

Figure 6. Multi-technology synthetic view of the OHP measurement campaign. Top: lidar and airglow. Middle: difference between L91 and lidar. Bottom: microbarom detections (black dots) and predicted signals (green regions) superimposed to the color-coded effective sound-speed ratio.

Some results obtained through these comparative measurement campaigns are:

- Systematic comparisons between ECMWF and lidar confirm differences as large as 20 K. In average, the temperature appears to be overestimated by ~5 K in the stratosphere and underestimated by ~10 K in the mesosphere. NDMC measurements at around 87 km height confirm the underestimation of atmospheric temperature by ECMWF in the upper part of the atmosphere.
- Comparisons with collocated infrasound measurements provide additional useful integrated information about the structure of the stratospheric waveguide. The effect of the major sudden stratospheric warming (SSW) which occurred in January 2013 can be seen in the strong decrease in the number of microbarom detections from the north Atlantic.
- Additional ground-based sounding technique for measuring the vertical structure of the wind fields was deployed at OHP by University of Bern, Switzerland. This system is a microwave Doppler-spectro-radiometer specifically designed for the measurement of middle atmospheric horizontal wind by observing ozone emission. As observed for the temperature, significant errors in the zonal wind model are noted between 40-60 km altitude. The mean flow of the zonal wind appears to be overestimated by ~40 m/s in the mesopause.
- We also clearly show that mesopause airglow measurements can constrain the temperature where uncertainties in the model are the largest.

Improving GCM models using innovative observations

Rayleigh lidar data provide accurate and altitude-resolved gravity wave (GW) energy profiles but are only available in about 10 locations in the world. A global view of the GW field can only be determined using satellite data. The GPS radio occultation (RO) temperature profiling technique, featuring high vertical resolution and global coverage, represents a powerful means for studying the sources and climatology of GWs. Operational since April 2006, COSMIC GPS RO system, provides 1500-2000 occultations per day with sampling density maximizing at mid-latitudes. The GPS RO temperature observations cover the altitude range between about 8 and 35 km, with the highest accuracy (< 0.5 K) in the lower stratosphere and a vertical resolution of 0.2-1.4 km.

Figure 7 shows a time series of GW potential energy retrieved through analysis of temperature perturbations (*Khaykin et al., 2015*). The potential energy of GW has been evaluated from the fluctuations in vertical temperature profiles using the two different techniques, GPS RO from 10 to 35 km and Rayleigh lidar above 30 km. This allows reconstructing the time evolution of GWs from the troposphere near their sources to the stratosphere and the mesosphere in the regions of their dissipation. The time of enhancement of GW energy estimated from MERRA meteorological reanalysis (white lines) is also in good agreement with the observations but the energy is about 5 times lower in the reanalysis because the model can only capture one part of the GW spectrum.

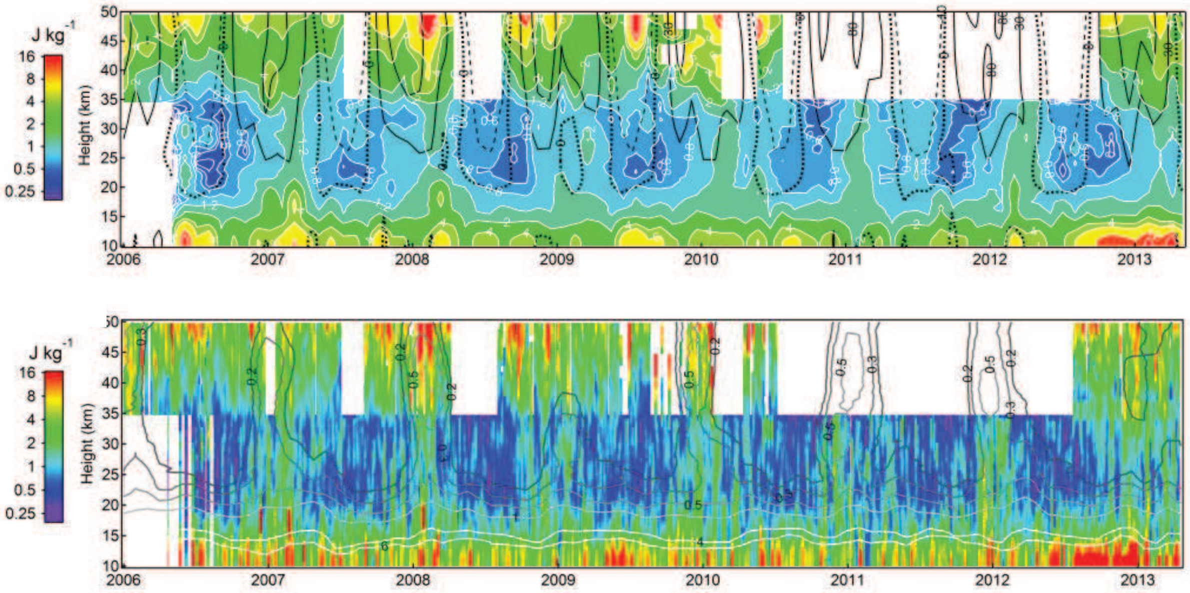

Figure 7. Combined time series of GW Ep from Rayleigh lidar at OHP and COSMIC (5° × 5° domain centered at OHP). White areas represent the missing data. a) Monthly-mean Ep (color map) and zonal wind (solid contours - westerly winds of 30 and 80 m/s, dotted contour - zero wind, dashed contour - easterly wind of 10 m/s). b) Weekly means of E_p from COSMIC and lidar (color map) and monthly means of MERRA Ep (from Khaykin et al., 2015).

Rayleigh lidar observation of the GW potential energy has been complemented upwards around 86 km using the high-frequency temperature observations made by the GRIPS spectrometer at OHP. The temporal resolution of the data accounts for 15 s; the data are therefore feasible for GW investigation in the upper mesosphere. As the middle atmosphere dynamics play in an important role in both tropospheric weather and climate, characterizing the spatio-temporal distribution of GWs in a broad range of altitude opens perspectives for new parameterization schemes in numerical weather prediction systems.

Inversion for wind field derivation/improvement

Radiosondes provide accurate wind and temperature profiles up to the lower stratosphere (near 30 km), but the information is limited to one location and the uncertainty in the measurements increases in the stratosphere. On a global scale, devices on weather satellites allow for the direct observation of temperature through radiance and indirect estimation of horizontal winds using the thermal wind relation up to an altitude of about 40 km. There is no direct wind observations assimilated in NWP models above 30 km. This may lead to large errors in horizontal wind fields - especially in the higher stratosphere – which may have an adverse impact on weather forecasts.

Infrasonic waves propagate in the atmosphere over large distances, in waveguides formed by temperature gradients and wind speed variations in the atmosphere. Ducting is especially efficient in the waveguide that forms between the ground and the stratopause, due to small absorption rates. Acoustic absorption, which is strongly dependent on the acoustic frequency, is higher for infrasonic waves propagating between the ground and the lower thermosphere, which leaves the thermospheric waveguide most efficient for the lowest infrasonic frequencies. The use of infrasound as a passive remote sensing technique allows for validation of vertical temperature and wind profiles using infrasound. The comparison between observations and predictions of the infrasound propagation allows identifying some biases in the wind fields provided by NWP and climatological models. Recently, studies have focused on the development of inverse methods to estimate upper atmospheric wind updates from infrasound data.

The near-continuous activity of Mt. Etna, the favorable locations of the available infrasound arrays and the good detection capability at the far-field infrasound array make Mt. Etna a good candidate for passive acoustic remote sensing and general circulation model validation studies of the stratosphere. A first-order update of the effective sound speed in the middle atmosphere using the observed trace velocity has been obtained by applying a Bayesian inversion formalism. Instead of a more rigorous inversion procedure that involves propagation paths, travel time and bearing deviations we seek the ensemble of effective sound speed updates that would likely explain the observed spread in trace velocities. While the infrasonic simulations during the summertime are in good agreement with the data, significant misfits near the equinox periods and during some anomalous wintertime periods were found. We suggested that infrasound observations can provide useful, additional information that could be considered in the validation of general circulation models.

Figure 8 shows example inversions during the summer (29 June 2008) and during the equinox period (2 October 2008). While the a priori and a posteriori model distributions essentially overlap for the summer case, the results for 2 October 2008 show that the effective sound speed is underestimated by at least 25 m/s at 50 km altitude. The dashed red lines indicate the estimated intrinsic uncertainty in the a priori model due to non-modeled small-scale structure (estimated from the gravity wave pdf and represented by the solid red line. The cyan and red lines represent the maximum likelihood and a priori models, respectively.

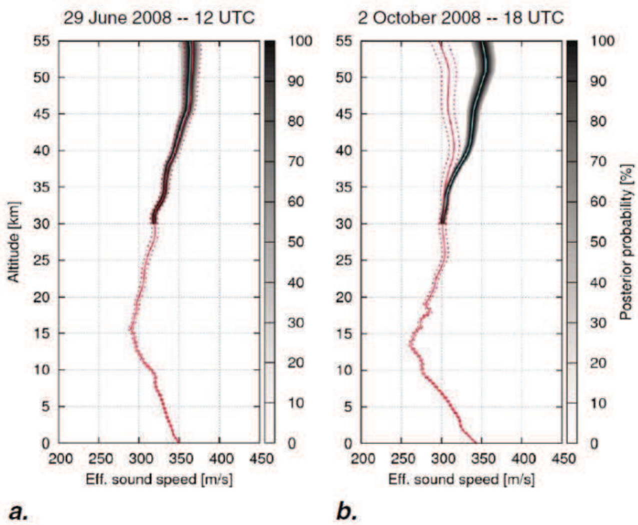

Figure 8. Two example effective sound speed inversions for 29 June 2008 (a) and 2 October 2008 (b). In both cases, the a-priori model is represented by the red curve; the dashed lines indicate the intrinsic uncertainty in the model due to non-modeled small-scale structure. The dark patched areas correspond to the a posteriori model distribution. 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 at 50 km.

1.3.3 Promote data use for better extreme events understanding and monitoring

ARISE investigated the potentials and benefits of the three ARISE technologies for monitoring extreme events. Six different kinds of extreme events were identified (volcanoes, earthquakes, avalanches, severe weather, meteors, ground truth industrial explosions) and further investigated during the project. ARISE studies focused on the occurrence of these extreme events in Europe, in relation to the geometry of each individual observation network, and highlighted the added-value of the synergy between the infrasound lidar and airglow technologies.

For each type extreme events, advanced data products were identified for potential used by to ARISE infrastructure end-users, such as civil security and decision making agencies and the scientific community. These advanced parameters are defined for non-scientific end-users and thus aim to provide the most critical information necessary to identify an extreme event and possibly to evaluate its effects. To achieve this task, several databases were created during the project including infrasonic source time functions of volcanoes and repeating industrial explosions in Europe. The ARISE network appears to be quite well developed to monitor most of the expected extreme events in Europe.

ARISE studies showed the potential of the infrasound technology to provide enhanced information on active volcanoes. Infrasound revealed to be extremely efficient both in providing real-time reliable source-term parameters from local observations, necessary for improved modelling ash dispersal in the atmosphere and also in monitoring activity from long-range (thousands of km) observations of unmonitored volcanoes. It was shown that infrasound observations can complete satellite detection of hazardous volcanic clouds, which is limited in time and can suffer significantly from the cloud cover which can persists over large areas, leading to a more efficient mitigation of the risk volcanic ash encounters. For this typical application, ARISE is a key infrastructure that can provide novel valuable information to the Volcanic Ash Advisory Centres (VAACs) of the International Civil Aviation Organisation for its potentials on infrasound monitoring of eruptive volcanoes.

Volcanic eruptions

In order to mitigate volcanic risk it is necessary to know when a volcanic eruption occurs, where it happens, how strong it is and how it evolves. Few volcanoes in the world are very well instrumented that provide a detailed eruptive chronology, many volcanoes are monitored with single seismic stations, that can provide information on when the eruption occurred, but most volcanoes potentially active worldwide are not monitored at all. The only way to know that an eruption has occurred is usually from satellites, and information can reach the research and monitoring community hours/days after the event originally occurred, thus strongly limiting a prompt and efficient response to decision making agencies.

Infrasound is an efficient monitoring system for explosive volcanoes. Short-range observations (< 10s km) can be used to reconstruct in detail the eruptive chronology and is currently used to provide near-real time notification of ongoing activity to civil protection authorities (Ulivieri et al., 2013). At larger source-to-receiver distances (> 100s km), infrasound observations showed to somehow match with the reported height of the eruptive column (e.g. Dabrowa et al., 2011) and in some specific cases infrasound could efficiently reconstruct the eruptive chronology for non-monitored volcanoes (e.g. Matoza et al., 2012). This suggests that infrasound observation, especially when combined with network sensitivity analyses (Tailpied et al., 2013), represents a significant tool for a future global volcano monitoring.

For volcanic eruptions, ARISE infrastructure can provide the origin time, the event location, the energy spectrum and the frequency. All of them can be derived from infrasound observations, both with local as well as far arrays (**Figure 9**), and reflect some key aspect of volcanic eruptions that are of major interest for civil security. ARISE can thus provide near-real time information on the source terms with a planned prototype notification system to the VAACs that will initially cover Europe but might be expanded according to the coverage of infrasound arrays worldwide.

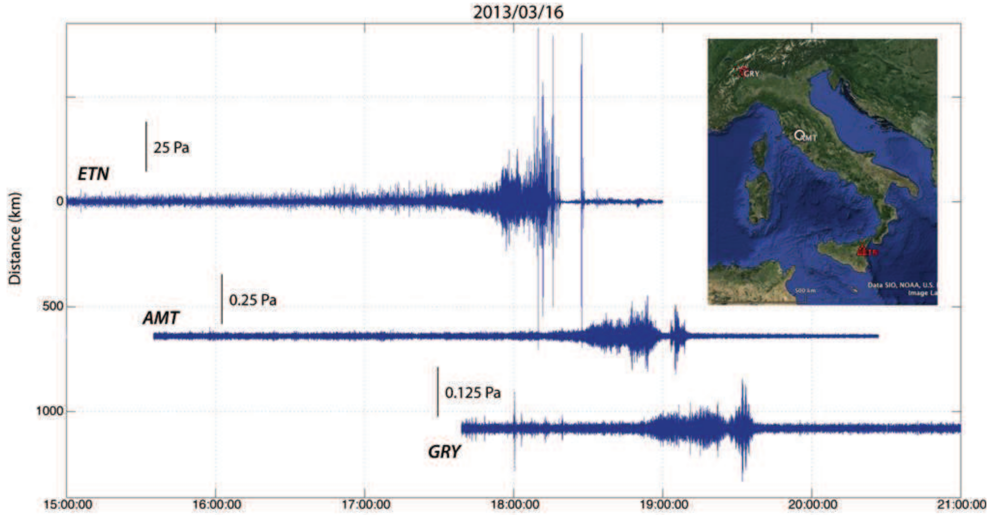

Figure 9. Infrasonic record of the March 16th, 2013, lava fountain from Etna at ETN array (5 km from the source) at AMT array (630 km form the source) and at GRY array (1080 km from the source).

Earthquakes

Earthquake can radiate infrasound, both at the epicenter by direct shaking of the ground (primary infrasound) or from secondary sources that radiate infrasound as a consequence of being shaken by seismic waves (secondary infrasound). During ARISE we showed how infrasound observation allow to derive the earthquake origin time, the radiant area, which is a proxy of the shake area, and the infrasonic amplitude (**Figure 10**). This is particularly useful to improve earthquake monitoring and understanding especially in poorly instrumented areas.

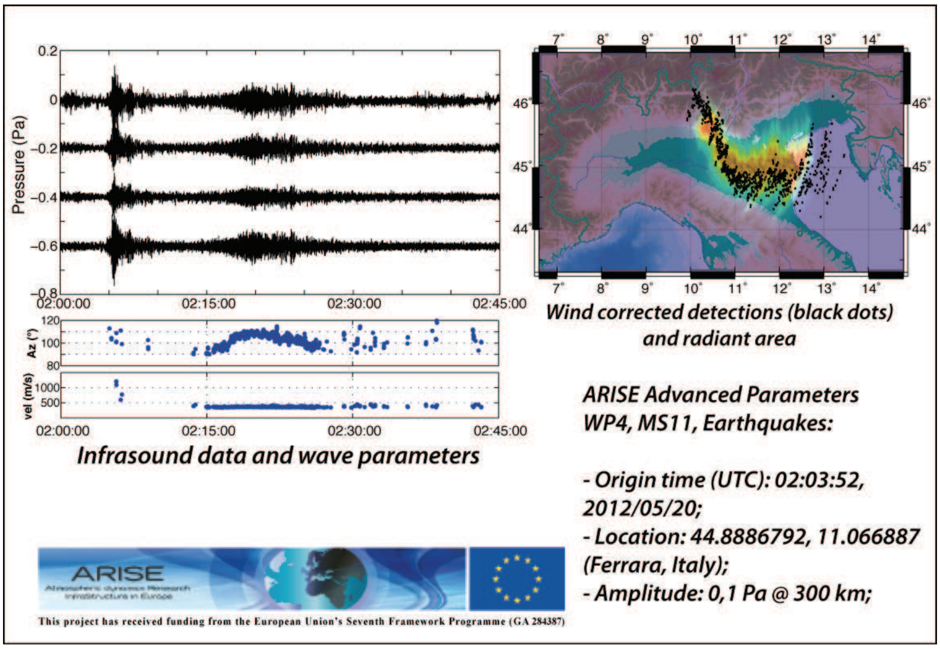

Figure 10. Advanced parameters derived from ARISE observations for the 2012 Ferrara earthquake.

Snow avalanches

Snow avalanches radiate infrasound as the snow volume accelerates downhill compressing the surrounding atmosphere. During ARISE we showed how snow avalanches can be identified with infrasound array observations, being wave parameters (e.g. back-azimuth and apparent velocity) reflecting a downhill moving source. During ARISE Infrasound array analysis was adapted to avalanche monitoring, in order to increase the reliability of automatic avalanche identification, and allowing extraction of information such as the origin time, the location, the run out distance and the front velocity. These are extremely useful both for the improvement of avalanche forecasting and for a proper risk management.

Severe weather

Different atmospheric processes of various scale are very well detected and monitored by the 3 ARISE technologies, spanning from thunders and sprites, that can happen around ARISE monitoring stations up to sudden stratospheric warming (SSW) events, that being among the largest and more significant atmospheric processes taken into account by ARISE, can affect areas at a sub-planetary scale. Severe weather can be detected and observed with the three ARISE observation technologies, both in terms of direct observation of the event or induced fluctuations in the upper atmosphere. In case of thunderstorms, infrasound can detect and locate thunders, thus being able to provide the duration and extend of the process, while LIDAR and Airglow observations can measure GWs generated by the extreme atmospheric convection associated to thunderstorm. The ARISE infrastructure can provide the event start time, the end time, its extension and event type (**Figure 11**).

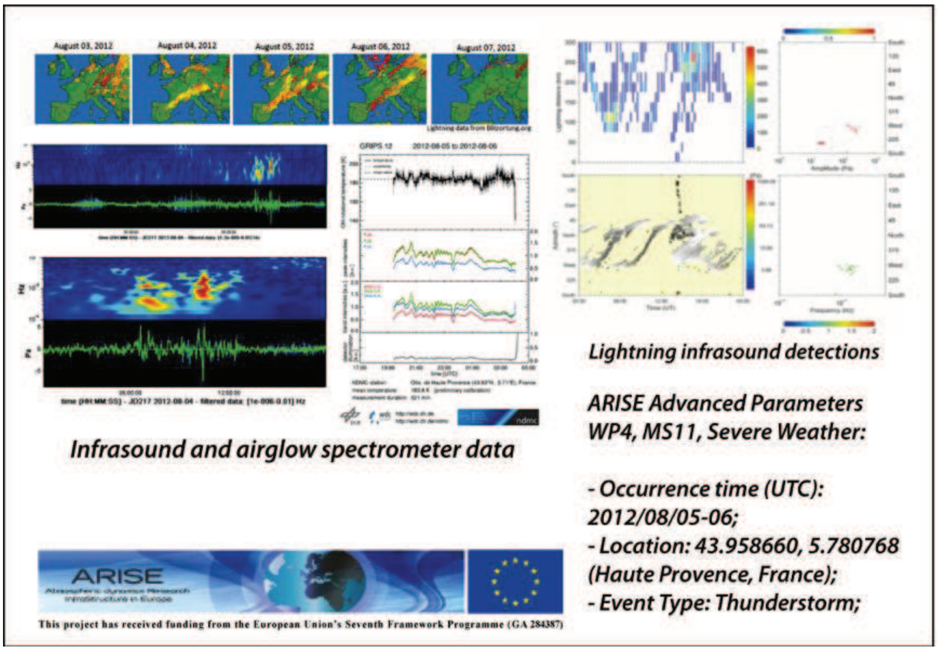

Figure 11. Advanced parameters derived from ARISE observations for a thunderstorm in southern France (Aug. 5-6, 2013).

Meteor entries

Meteoroids of various sizes continuously enter the Earth's atmosphere with speed of the order of tens of kilometres per second. When meteoroids larger than a few centimeters in size vaporize intensely in the atmosphere, the vapour dispersion lead to the formation of a cylindrical shock wave (blast wave), which is transformed into infrasound. Thanks to the low attenuation of infrasound in the atmosphere, infrasonic observations provide a unique ground-based method to detect and identify meteoroid entries. The study performed within ARISE showed how to derive for meteoroid entries information such as the origin time, the event location, the entry and radiant (**Figure 12**).

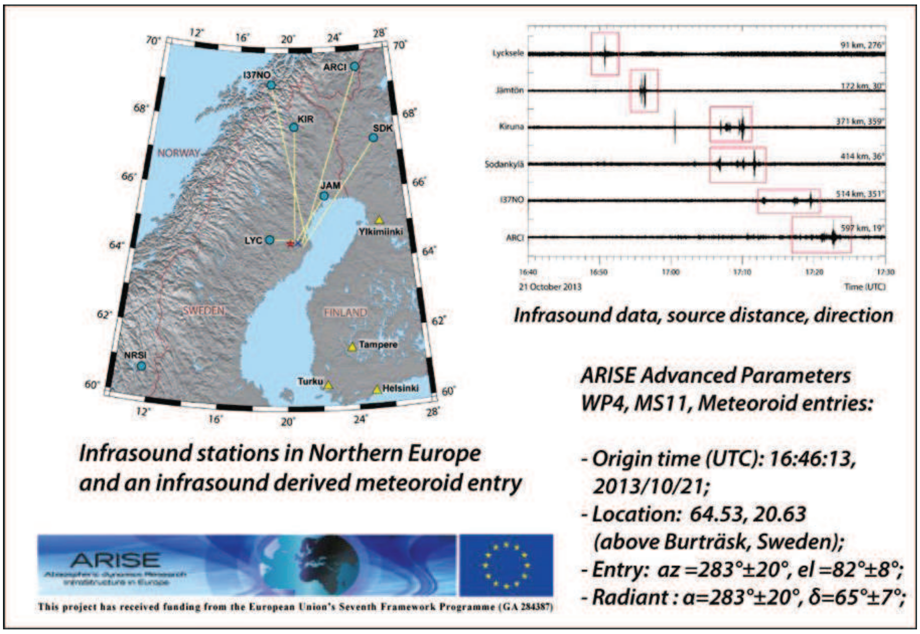

Figure 12. Advanced parameters derived from ARISE observation for a meteor entry that occurred in Sweden in Oct. 2013.

Events in the industrial belt

Explosive blasting is used almost globally as a means of extracting rock and minerals from quarries. Automatic or semi-automatic classification of such events has long been deemed essential. Infrasound is an excellent discriminant for determining that a small seismic event is surface or near-surface rather than at a significant depth, and so the observation of infrasound signals that are clearly associated with a set of seismic signals can assist greatly in event classification and/or discrimination. The seismic recording of industrial blasts therefore tells us exactly where an explosion took place and when it occurred (so-called Ground Truth information). Many quarries blast at least once per week, and sometimes as frequently as several times per day, and so provide us with vast numbers of events with which we can validate and calibrate our models of atmospheric specification for the prediction of infrasound arrivals. For ARISE industrial belt explosions, the primary parameters are the origin time, the latitude, longitude, depth, and seismic magnitude.

1.3.4 Data utilization for weather forecasting and climate models

ARISE project investigated the way in which the ARISE network could fill current and future data gaps for both numerical weather prediction and climate simulations. One of the most exciting results of ARISE is the progress made toward developing methods to **assimilate ARISE data in future weather forecasting models (ECMWF) to increase their accuracy from about 10 days today, to monthly and seasonal time scales.** ARISE work set the objectives for ARISE2 in this respect.

Review of missing data for trends investigations

Satellite platforms have been used for several decades to estimate temperature trends in the upper stratosphere and mesosphere. Whilst these instruments provide a broad spatial coverage, they do suffer from several drawbacks. Firstly, their spatial resolution is typically limited to scales between a few tens to hundreds of kilometres. Secondly, trend estimation relies on measurements made with different instruments, which have different systematic errors. In the lower stratosphere, measurements provided by satellites, GPS Radio Occultation, radiosonde, and radar winds are already assimilated into NWP models (**Figure 13).** Although they provide near-global coverage, the resolution of these measurements can be coarse. ARISE observations could help constrain the uncertainty in these measurements, and provide high-resolution information at measurement sites.

- ARISE project examined the need to fill gaps in the current observation network, to improve the measurement of middle-atmosphere temperatures. It focused on lidar and airglow observations, and proposed the following:
- At high latitudes (60-75°N) in the northern hemisphere, some NDACC lidar stations exist that should be included in a future infrastructure for dynamical studies and specifically for trend monitoring. These stations are: Thule, Greenland (76.53˚N, 68.74˚W); Ny Ålesund, Spitsbergen (78.9°N, 11.93˚E); Andøya, Norway (69.3˚N, 16.0˚E).
- At mid northern latitudes (40-60°N), the coverage is good for both networks.
- At tropical latitudes (±25°), long lidar series exist, except at latitudes close to the equator.
- At mid-northern latitudes (40-60°S) there is not much coverage due to the lack of continent to implement ground-based instruments.
- At high southern latitudes (60-75°S) there are some instruments, but instruments are difficult to maintain because of the remote locations.

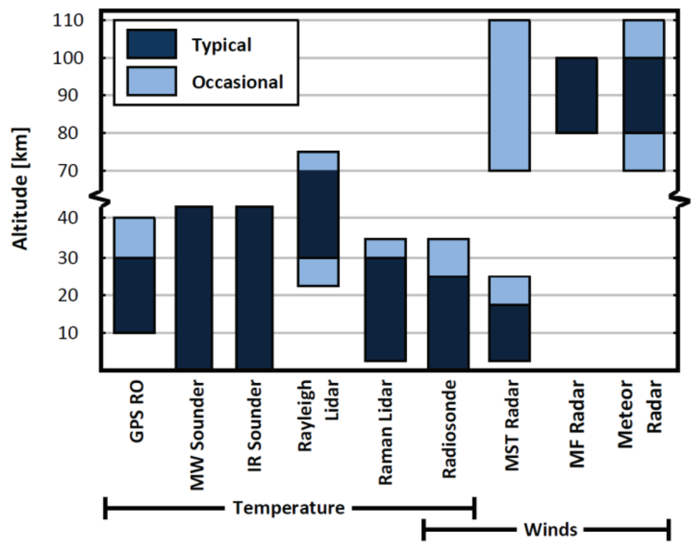

Figure 13: Typical and occasional altitude coverage of different measurement techniques currently assimilated into numerical weather prediction models.

Simulation of thunderstorms and their effects from surface to mesosphere

Studies were performed within ARISE to investigate the representation of convectively generated gravity waves in numerical weather predication models. High resolution WRF (Weather Research and Forecasting) model simulations were compared to in-situ observations made in the tropics, during strong tropical thunderstorms. The results suggest that the cold-pool outflow from the thunderstorm may be the leading factor in generating initial high-frequency pressure changes observed by the infrasound station (Costantino and Heinrich, 2013) though later peaks in pressure are not replicated. Gravity waves produced by thunderstorms propagate vertically into the stratosphere, mesosphere, and lower thermosphere (**Figure 14**). They form concentric rings in the mesosphere as observed by all-sky airglow layer imagers. Gravity waves are filtered by the background winds as they propagate upwards through the stratosphere. The cumulative effects of gravity wave activity may disturb the general atmospheric circulation.

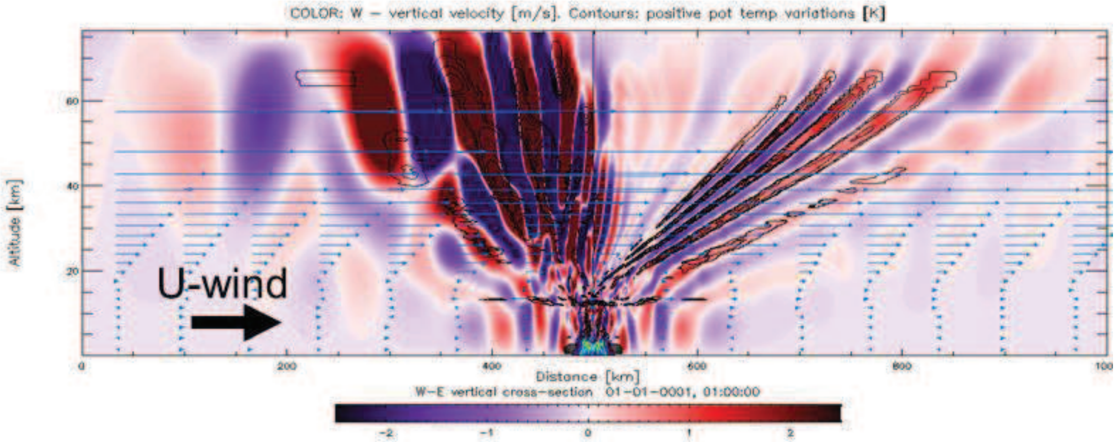

Figure 14: Gravity waves generated by a thunderstorm (in blue, at the bottom of the figure) for a vertically-sheared horizontal velocity. Vertical velocity is computed from ground to an altitude of 77 km. Black contours represent strong variations of the potential temperature. Simulations were performed by a regional meteorological model.

Impact of the stratosphere dynamics on numerical weather prediction

The experiments used an idealized general circulation model (specifically the HADGEM2 Met Office Unified Model - UM), to investigate the onset and evolution of stratospheric sudden warmings. Comparison with re-analysis data showed 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). **Figure 15** shows the ensembles of ZMZW (Zonal Mean Zonal Wind) in the upper troposphere, for un-nudged and nudged (upper stratosphere) forecasts. The ensemble spread of the latter is much smaller, because of the dynamics at this level are influenced by the stratosphere. The ensemble spread shown here, and the differences between the forecasts, is a realistic representation of different operational forecasts at these levels.

Stratospheric nudging reduces the ensemble spread for the nudged ensemble, resulting in improved tropospheric synoptic-scale predictability by 1-2 days. 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.

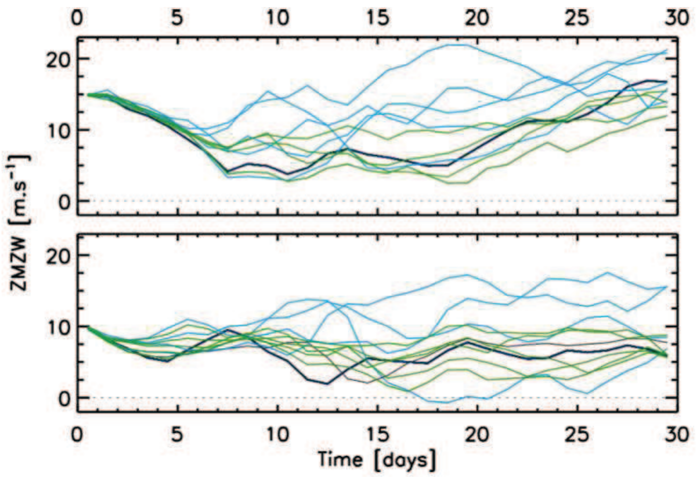

Figure 15. ZMZW (Zonal Mean Zonal Winds) of two SSW cases from the control run (thick dark line), and their 30 day ensemble forecasts (light blue) with upper-stratosphere nudged ensemble (green lines), for the lower troposphere (100 hPa).

Idealised experiments replicated the surface effects of SSWs reported in previous studies. **Figure 16** shows the pattern of surface temperature anomalies averaged over days 15-30 for 15 SSW cases. The negative NAM pattern is clear, with a warming over North America, and a cooling over Northern Europe. This pattern has been shown in previous studies, and illustrates the teleconnection between the stratosphere and lower troposphere, and indicates that idealized experiments give a realistic representation of the associated atmospheric dynamics.

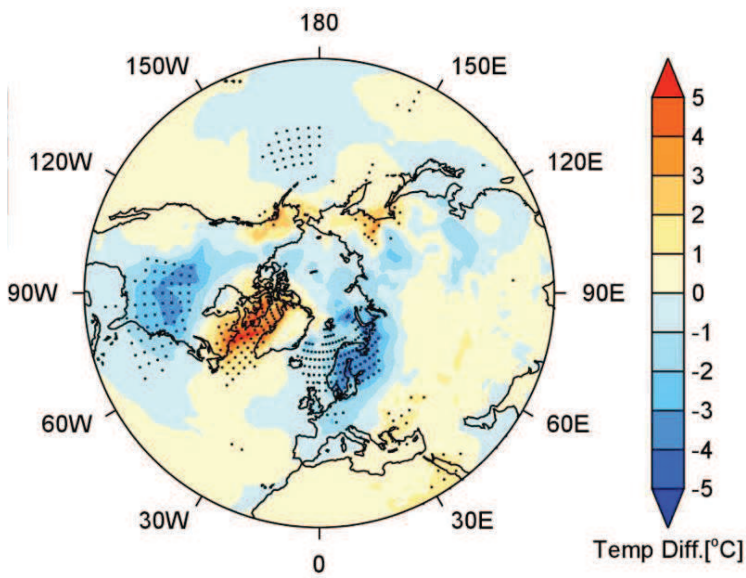

Figure 16. Surface temperature anomalies averaged over forecast days 15-30 for 15 SSW cases. The stippling indicates significance at the 95% confidence level.

The weather forecasting studies found that relaxation of either the whole stratosphere, or the upper-stratosphere only (simulating the effect of data assimilation at these altitudes) improved the representation of average surface temperature patterns, especially over eastern North America, and Northern Russia (**Figure 17**). Similar results were shown in studies looking at longer forecasts (out to 60 days), however our results are particularly useful because they demonstrate an impact on routine weather forecasting time-scales (out to 30 days).

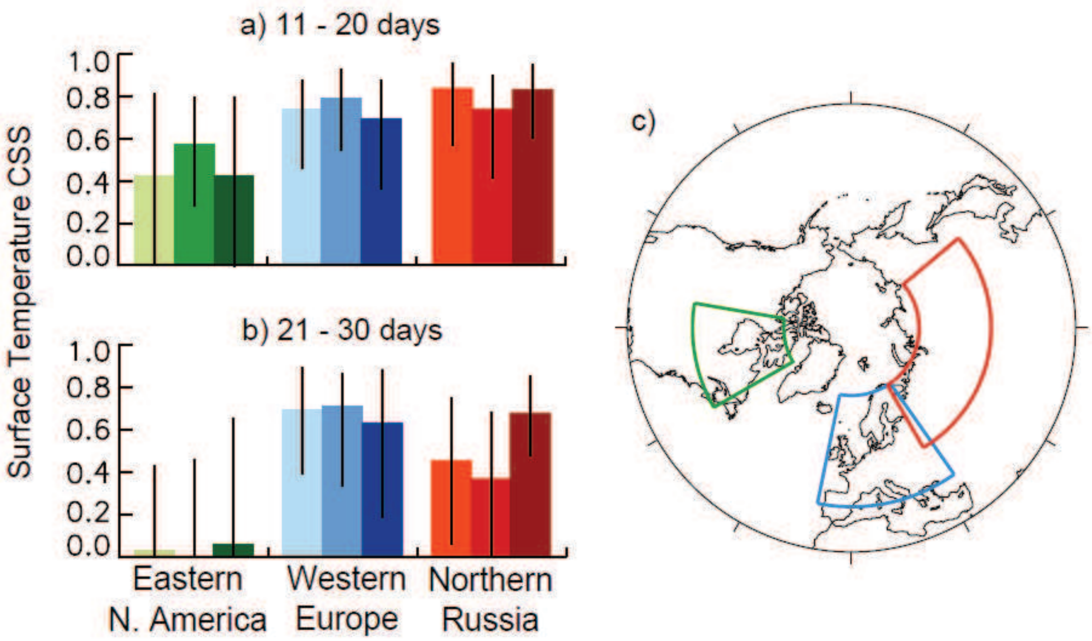

Figure 17. CSS (Correlation Skill Score) of surface temperature averaged over (a) days 11-20 and (b) 21-30; for eastern North America, Western Europe, and Northern Russia. The three boxes for each region give the CSS for (i) the control (light boxes), (ii) whole-stratosphere relaxed, (and (iii) upper-stratosphere relaxed (dark boxes) forecasts, from left to right. Black lines give the 95% confidence intervals, calculated with bootstrapping. The three analysis regions are highlighted in (c).

On the use of ARISE data for weather and climate monitoring in Europe.

The measurements provided by ARISE (lidar, OH airglow spectrograph, ground-based wind radiometer, complemented by continuous infrasound recordings), offered a unique opportunity to provide detailed information on upper atmospheric processes from seasonal to daily scales, and to better characterize atmospheric coupling processes from the ground to the upper mesosphere.

The Haute-Provence Observatory (OHP, 44°N, 6°E) field campaigns with collocated ARISE measurements, help 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. Comparing ARISE observations of the winter 2012/13 SSWs with forecasts reveals: Cooling around the mesopause preceeded both major SSWs, difficultly in forecasting vortex positions after the vortex split, and changes in polar vortex winds substantial altered infrasound propagation. A global signature of the SSW can be obtained using microbaroms [*Evers and Sigmund*, 2009], which 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].

ARISE measurements for constraint of gravity wave parameterisations

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. In addition, non-orographic gravity wave parameterisations used in NWP models are usually spatially and temporally invariant, and will not capture the seasonal behaviour.

Gravity wave measurements were analysed over 5 years in Ivory Coast, where the wave source is tropical convection. The results clearly demonstrated a seasonal trend in gravity wave propagation directions (Blanc et al., 2014) average momentum flux, intrinsic frequency, and vertical and horizontal wavenumbers. Particularly encouraging is the distribution of horizontal and vertical wavenumbers, and the intrinsic frequencies. The frequencies and gravity wavenumbers measured by the array show that the instrument resolves smaller scale waves than other techniques. Measurements at these scales are particularly valuable because they are at the scales parameterised in NWP models, where measurements have previously been lacking. Additionally, the ability to capture the intermittency of gravity waves means that gravity wave measurements made by these instruments have the potential to provide valuable information to the modelling community.

Figure 18 shows the typical horizontal and vertical scales measured by existing techniques (shown by the green shading) and gravity waves detected by the IS17 infrasound array (blue dots) in Ivory Coast. Results at IS17 show that horizontal and vertical wavenumber distributions both peak close to 20km; the distributions extend from approximately 3 km up to 400 km and 50 km for horizontal and vertical wavenumbers respectively. The dominant intrinsic frequencies have periods of around 10-20 minutes. This covers most of the region that cannot be seen by any of the other observation conventional techniques.

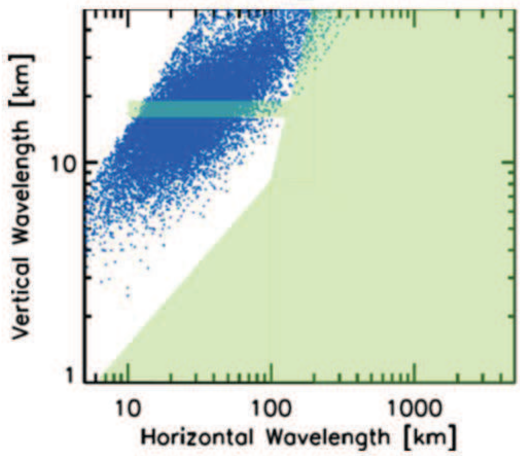

Figure 18: Gravity wave scales observed by the Ivory Coast infrasound station (blue dots), and typical observation ranges of other instruments (green shading). Five years of gravity wave data were used for this study.

Roadmap for the use of ARISE measurements for weather and climate monitoring

Figure 19 shows a schematic of the current position and future direction of ARISE. 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. In particular, the next step will be to develop a spatially and temporally varying climatology of the GW spectrum at the ground (from infrasound measurements) and in the stratosphere (from lidar measurements) and mesosphere (from meteor radar measurements). This climatology will be compared to outputs from the GW parameterisation of the HadGEM and IPSL-LMDz models, and to outputs of meteorological mesoscale models.

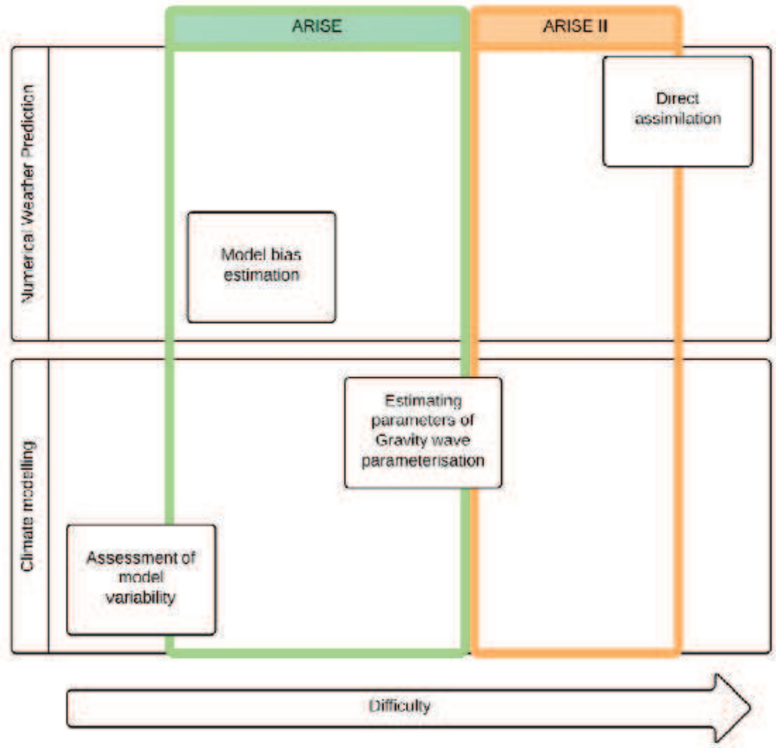

Figure 19. Schematic of current position and future direction of ARISE for weather and climate monitoring. Difficulty, on the horizontal axis, is similar to time, while the vertical axis indicates the impact.

1.3.5 ARISE data portal

The ARISE data portal (http://wdc.dlr.de/arise) is an infrastructure in which data and advanced data products developed during the ARISE project are made freely accessible to the interested user. This interactive and interoperable web portal covers all thematic fields of the ARISE infrastructure project (microbarometer mini-array observations, lidar observations, radar observations of the thermosphere and airglow observations).

At first, scientific observations of the state of the atmosphere covering all altitude levels from the ground to the thermosphere and targeting a multitude of observed parameters are accessible and visualized interactively. These datasets are obtained from many different scientific networks participating in the ARISE project and have been accessible to DLR. ARISE data providers handed over their specific research data sets in a multitude of file formats, database dumps or via access provided to their servers. In the latter case, the provider's servers are contacted by the ARISE Data Center "on demand" interoperably. The provided data sets cover a number of different scientific disciplines such as infrasound observation, LIDAR temperature retrieval or satellite based temperature observation of the middle and upper atmosphere.

Consequently strategies to handle and manage the diversity of ARISE data sets and formats were developed, tested, implemented and were harmonized in order to fit into the technical architecture of the ARISE Data Center.

Excellent scientific collaboration is demonstrated by combining observations and derived parameters from different scientific communities to “ARISE value-added products”, namely multi-sensor-intercomparison studies conducted at the OHP site (e.g. **Figure 20**).

All results are easily accessible (through different navigation strategies) to the research, forecasting and extreme-event monitoring communities.

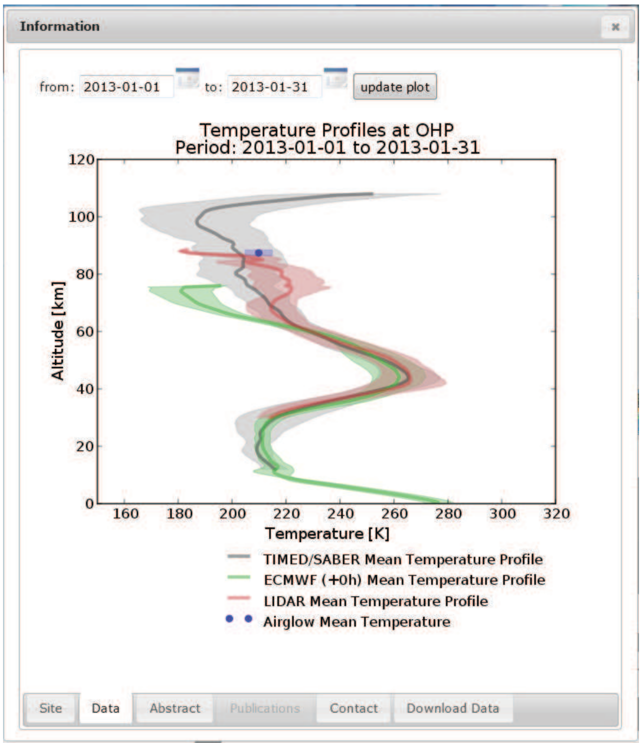

Figure 20: ARISE value-added product combining temperatures derived from meteorological analyses, LIDAR observations, TIMED/SABER satellite observations and airglow for a user-defined period.

In order to provide an accessibility to all data products, the ARISE Data Center portal supports two different navigation strategies allowing a thematic and a geographic approach. The thematic approach invites the user to select the atmospheric altitude region or process (e. g. thunderstorms); in the geographic approach, the user is invited to choose a measurement network and a measurement site as the starting point of the interactive navigation. In any case, he is subsequently guided towards matching ARISE data and value added products.

All ARISE products are equipped with appropriate metadata and are linked together in a so called “graph database”. This database type supports the logical interconnections between different items by linking certain aspects of datasets such as identical observation technologies or sites together. As a result, a tree-like interconnected structure arises (**Figure 21**).

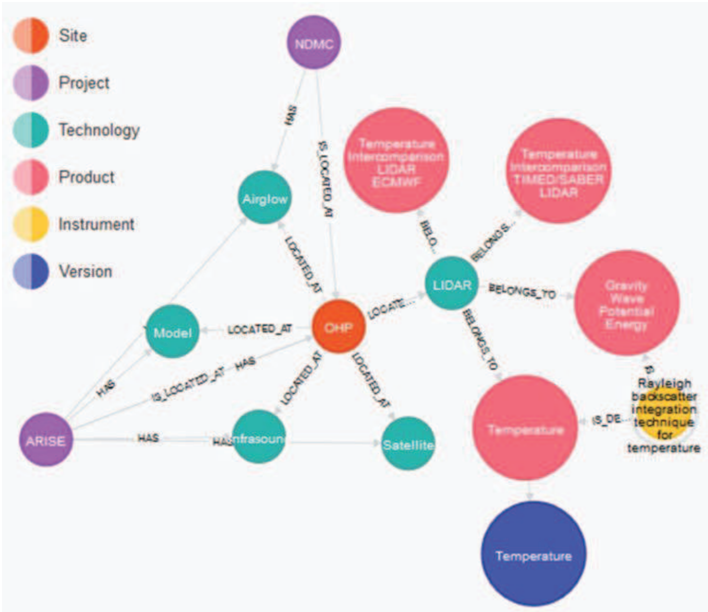

Figure 21: Graph database structure of ARISE products.

The product-specific metadata contains information on the owner (provider) of the product, the site (where the product was observed), the applied technology, scientific abstract, scientific publications and the URL of the visualization or download service. This URL can point to a service inside the DLR facility, but also to a service provided by any other ARISE partner interoperably (**Figure 22**). In the latter case the ARISE Data Center requests data from external partners, performs some post-processing and delivers the result to the user. By these means, an interoperability with ARISE partners was successfully established. Consequently there is no need to store all ARISE products at the ARISE Data Center.

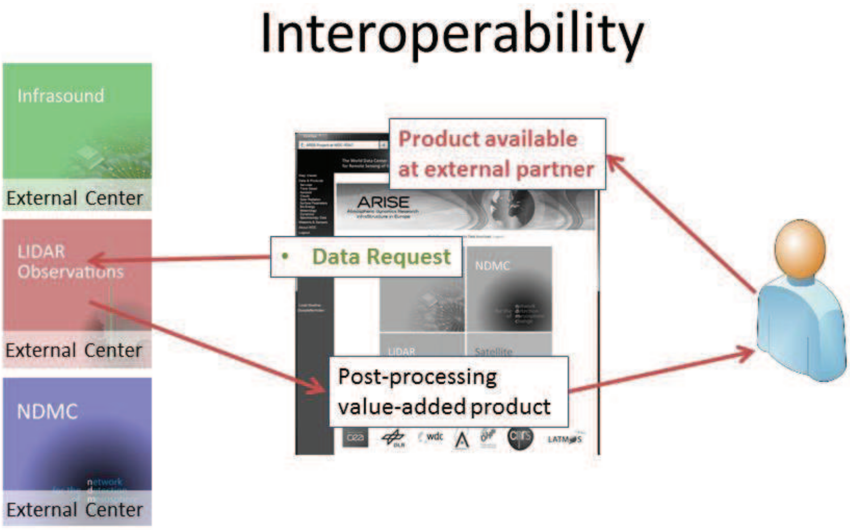

Figure 22: Interoperability between ARISE partners.

All algorithms of the ARISE products have been proposed by the responsible scientific group and have been adopted to run in the ARISE environment by DLR staff members. However, the responsible DLR staff members have a long working experience in the field of atmospheric sciences and therefore a profound understanding of the science-driven requirements.

All data and products accessible via the ARISE portal are available to the general public (open data policy). The most relevant parameters of the majority of products can be downloaded in JSON format

(Javascript Object Notification) which is an open, standard format. In order to reach the highest number of non-specialist end-users, there is a pedagogical side to the portal. Indeed, users of the data portal can click on links to obtain explanations, which are provided on the ARISE project website as shown in **Figure 23**.

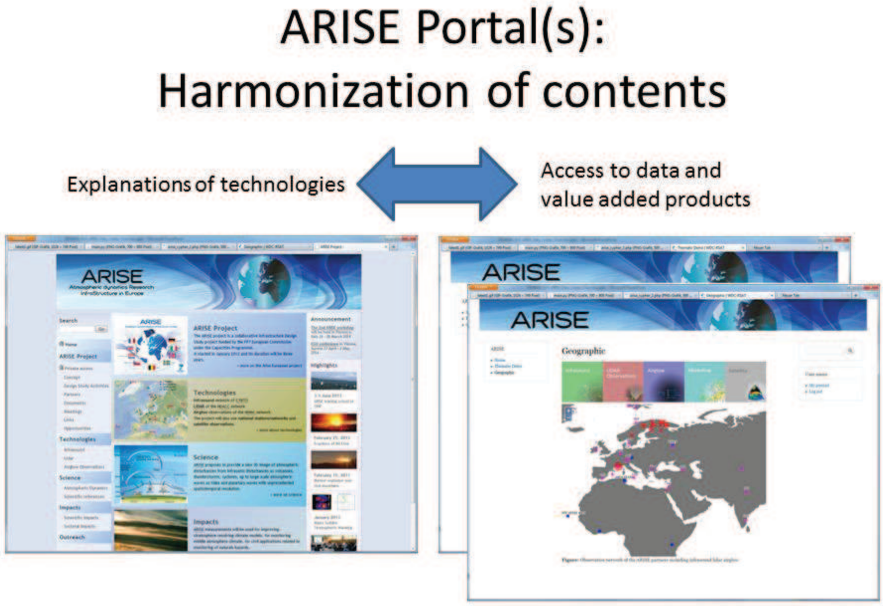

Figure 23: Harmonized content of ARISE project portal (left) and ARISE data center (right) allows pedagogical explanations for users.

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1.4 Expected final results and their potential impact and use

The ARISE data platform provides a wide variety of data and advanced data products to a large scientific community. These data are adapted for easy use in weather forecasting, remote volcano monitoring and climate monitoring and other applications which have shown a great need for such high-quality and ready-to-use data. ARISE has already a direct impact on operational or research studies related to infrasound propagation. It will also lead to the development of infrasound and lidar networks in the strategic areas to solve key problems in atmospheric dynamics and weather predictions.

The societal impact of ARISE is large as it covers important topics related both to

- **weather forecasting,**
- **climate change forecasting,**
- **warning and information notifications of natural and human-induced disasters.**

In addition, ARISE will contribute to the reinforcement of networks and to the development of models.

1.4.1 Improvements of atmospheric models

The stratospheric dynamical variability is controlled by small changes in the stratospheric mean state and it is therefore important to further understand biases between models and observations and seek to reduce them. Simulating realistic middle atmospheric variability remains a challenge for all models. The ARISE project has demonstrated that gravity waves can be measured in by infrasound, lidar, or airglow techniques Their analysis allows the recovery of useful information on fine-scale atmospheric perturbations. The next step is to develop in a climatological model an accurate parameterisation of gravity waves that is based both on ARISE observations and on regional meteorological simulations.

Several groups at operational modelling centres are actively developing general circulation models which calculate wind fields from the ground to a height of 120 km. ARISE contributes to the development of these models both by scoping out how the measurements made by the network can be used by models on an operational basis and by seeking to improve the parameterization of gravity waves which are necessary for these models**.**

Today, the amount of data produced by meteorological instruments outnumbers the assimilation capabilities of any current weather simulation. High Performance Computing (HPC) has become an essential tool in scientific and technological research for numerical simulations, as well as for industrial applications (http://www-hpc-cea.fr/). In this context, statistical methods for the HPC have been proposed by CEA within the call FETHPC1: HPC Core Technologies, Programming Environments and Algorithms for Extreme Parallelism and Extreme Data Applications.

1.4.2 Weather forecasting

Many companies depend on weather conditions and require reliable weather forecasts for production, planning or risk hedging. Increasing the reliability of longer-time-scale predictions will have great impacts on renewable energy production, maritime companies, tourism sectors, agriculture, etc.

Deterministic weather forecasting using operational meteorological models is typically only accurate on time-scales of 5 to 6 days in both the Northern and Southern Hemisphere. The fundamental limitations of deterministic forecasting stem from the chaotic nature of the atmosphere and the imperfect set of measurements available to observe it. Progress made over the past quarter-century in numerical weather prediction (NWP), has revealed that:

- the lack of stratospheric variability in the low-top models has an impact on stratosphere-troposphere coupling which do not produce long-lasting tropospheric impacts as seen in observations,
- improvement in forecast needs an accurate representation of the stratosphere and a more precise determination of the state through observations and data assimilation.

NWP models are based on the assimilation of observational data, which is much sparser in the middle atmosphere than in the troposphere. ARISE has the potential to fill gaps in the middle atmospheric measurement system and data transfer. These datasets start to be used as a benchmark for the validation of models. In the future, systematic measurements of gravity and planetary waves could be used for data parameterisation and assimilation in the models.

The main asset of ARISE is to provide high quality data including fine-scale structures and gravity waves parameterisation for improving the accuracy of the initial stratospheric state and thereby short and mid-range weather forecasting. This step will have immediate societal impact in Europe and other regions (for instance Africa) where accuracy in forecasting is still limited.

Major SSW events, which typically occur in roughly 6 out of every 10 years, can be followed by **cold weather that can affect Northern Europe for many weeks** (for instance in 2010 and 2013). It should be recalled that harsh winters or cold spells result in strong socio-economic impacts (in terms of energy demand, transport, industry and agriculture, emergency protection systems). Unfortunately**,** tropospheric forecasts by NWP models are unreliable beyond a few days under these circumstances. In addition, we still have little understanding of the strato-tropospheric coupling mechanism in spite of tremendous modelling work and the increasing power of supercomputers. ARISE has demonstrated that the three networks (infrasound, lidar and airglow stations) can monitor SSW events during their whole life (onset, mature stage, recovery). The future strategy is to thoroughly analyse observations and their differences with models. The complementary expertise of the ARISE community will help to better understand the physical mechanism at the origin of the stratosphere impact on the weather. **Relevant ARISE data will be then assimilated in NWP models with the objective of 10 to 20-days weather forecasts**.

1.4.3 Climate change

Climate change is probably the most challenging environmental issue the society will have to confront in the future. According to the Fifth Assessment Report from IPCC (Intergovernmental Panel Climate Change), the net damage costs of climate change (that are not priced) are likely to be "significant and to increase over time." Based on climate models, IPCC states for instance that extreme precipitation events will become more intense and more frequent in wet tropical regions or in Northern Europe that should suffer increased risk of inland flash floods.

ARISE observations and collaborative work deepens our understanding of the stratosphere-troposphere coupling. This understanding will help to better predict climatic effects of stratospheric changes due to the increase of greenhouse gases concentrations, to stratospheric ozone depletion and solar changes. **As the troposphere warms, a cooling in the middle atmosphere is expected** to be induced by greenhouse gases due to the direct emission toward space of the thermal infrared radiation. However the evolution is complex due to possible changes in the general atmospheric circulation that transports heat from the equator to the pole in the stratosphere and from the summer to the winter pole in the mesosphere. The progressive recovery of the stratospheric ozone layer is expected to have also an impact on the stratospheric temperature evolution.

Already, archived data as lidar data contribute to monitor the long-term stratospheric cooling at different latitudes. The infrasound data recorded during more than 10 years in some stations can also be used to monitor long-term mean trends of severe weather events. Thunderstorms might be more intense, but fewer in some countries in a future warmer climate. Statistics about their evolution will contribute to assess the climate change effects and to predict environmental impacts.

As regards modelling, the stratosphere is now represented in most current climate models, just as the ocean was introduced into climate models in the 1990s. The absence or the misrepresentation of gravity waves in these models hinders the representation of large-scale phenomena such as the Quasi Biannual Oscillation of winds. An expected result of ARISE is to introduce in a climate model an accurate gravity waves parameterisation based on ARISE data. **The combination of observations and climate simulations will make it possible to examine and predict changes in stratospheric and surface climate over the coming century.**

1.4.4 Severe weather

According to IPCC, global change has likely resulted in a higher frequency and intensity of heavy precipitation events in North America and Europe. Increase in intense tropical cyclone activity has been also observed in Atlantic (since 1970). Poor countries suffer disproportionately because they are more vulnerable to such disasters.

Severe weather (polar lows, severe storms, tornadoes and cyclones) represent a major hazard. The teams of ARISE consider **maintaining and further developing the ARISE database that is made up of a unique, detailed and independent dataset for continuous and long-term monitoring of the intensity and evolution of extreme weather events that are recorded routinely by infrasound, lidar or radar stations.**

In particular, infrasound stations are relevant to detect small-scale extreme weather events that are not simulated by current global models or are not observed in regions with few meteorological stations. In addition, it has been shown recently that flashes induced by thunderstorms can be tracked by an array of 4 microphones within the range of 50 to 100 km.

In the future, the characterisation of severe weather phenomena, and in particular their extent and their evolution, could be assimilated into existing meteorological models to improve the accuracy in short- and medium-range weather forecasts.

1.4.5 Infrasound volcano monitoring, volcanic ash characterization

Volcanic eruptions in Europe (Italy, Iceland) and Africa (Tanzania, Democratic Republic of Congo, Comoros, La Reunion) are powerful natural sources of potential disturbances in the different atmospheric layers. ARISE observations of volcanic eruptions are performed by short-range measurements with local small-aperture infrasound arrays as well as far field infrasound measurements. Signals from volcanic activity are now routinely recorded, and the ARISE project helps to build an appropriate database.

It is now planned to develop models providing reliability criteria deduced from propagation conditions. Eruptions are either effusive or explosive in their behaviour, the largest eruptions being sometimes accompanied by significant release of ash in the upper atmosphere. Studies are ongoing to determine the **type of eruption class, its intensity and estimate ash height from the characteristics of the detected infrasound signals and the maximum range for observing these signals**. Gravity waves (including those generated by volcanoes themselves) could be included in the simulation of propagation to improve their accuracy. With the future completion of the IMS infrasound network and the addition of local and regional networks, the infrasound technology becomes a reliable observation system to monitor volcanoes in near-real time at large distances. The CTBTO investigates this possibility and intends to provide information extracted from IMS infrasound data about the eruptions and ash injections. Obviously, this latter phenomenon is of great interest for civil aviation and may have large economic impacts.

The expected results of these developments are first to provide eruption notifications including quality criteria depending on propagation conditions. In a further stage, infrasound signal parameters characterizing the intensity of the eruptions and the amount of ash injected into the atmosphere, as well as ash height, will be explored. Such studies are strongly encouraged by several Volcanic Ash Advisory Centres (including VAAC Toulouse) and the International Airways Volcano Watch Operation Group. On one hand, they will help the scientific community to better understand the specificity of individual active volcanoes; on the other hand, they will contribute to volcano warning systems in Europe and worldwide.

1.4.6 Reinforcement of the ARISE station networks

So far, Earth's atmosphere is monitored within ARISE using infrasound, lidar and airglow measurements. In the future, teams of ARISE envisage to associate observations using a multitude of technologies including the IMS infrasound network, the NDACC lidar network, airglow spectrometers and imagers, satellites, ionospheric, MST and Meteor Radars. This combination offers a wide range of civil security applications that may possibly contribute to human welfare and safety and may mitigate economic damage. It also opens the doors to new scientific studies.

The IMS network represents a unique dataset of high quality homogeneous data that are uniformly distributed across the globe. The data are primarily used to serve the main objective of the CTBT to prevent any underground, underwater or atmospheric nuclear tests. Through its data portal, ARISE fosters dissemination of IMS infrasound data as well as regional infrasound data in Europe and Africa. The collaboration with CTBTO is beneficial to all parties:

- IMS data are used by universities and institutes work on the research and development of new processing algorithms and the enhancement of atmospheric models,
- the state-of-the art methodologies and the better knowledge of the atmosphere and its disturbances improve operational detection capability of the CTBTO and regional networks. Reducing biases and uncertainties in the models is essential in the context of the future verification of the CTBT. Improved atmospheric models are extremely helpful to reduce source location errors and to better characterize the source.

The NDACC network is composed of more than 70 high-quality, remote-sensing research stations for observing the stratosphere and upper troposphere. The concentration of chemical species (such as ozone) versus latitude and altitude is strongly related to the atmospheric dynamics through vertical and meridional transport and turbulent mixing. ARISE has the potential to provide to the NDACC community essential information on atmospheric processes for a correct interpretation of their observations.

The ARISE project allows to establish a win-win partnership between CTBTO, NDACC and other European partners by strengthening the relationship between the worlds of atmospheric observation, forecasting and research and by reinforcing the position of European countries in their efforts of development and maintenance of a dense network for monitoring the atmosphere. ARISE **helps to guarantee the longevity of such networks, which are useful for scientific and civil applications.**

1.4.7 Dissemination of results

ARISE led to the publication of **40 peer-reviewed scientific papers (including ARISE acknowledgments)** and **will continue to produce a vast array of scientific results and publications.** In addition, numerous research programs and papers focus on objectives relevant to ARISE.

The infrasound topic is a "young science" and has rapidly progressed thanks to the IMS infrasound network development. The number of papers dealing with infrasound increases, from a few per year in the nineties up to more than 50 per year in the last 5 years. The infrasound topic has appeared in at least 6 international conferences each year since 2010 (International Union of Geodesy and Geophysics, European Geophysical) Union, American Geophysical Union, Acoustical Society of America, CTBT Science and Technology, Infrasound Technological Workshop). In the past two years, around **15 abstracts related to ARISE have been presented in ARISE dedicated sessions at EGU general assembly.**

A **review book offering state-of-the-art atmospheric measurement techniques, edited by three ARISE partners, was published by Springer in 2010**. The number of chapter downloads was 1060 in 2011, 540 in 2012. **A drastic increase up to 6900 occurred in 2013 showing that the ARISE topics are relevant to an extremely large community**. This book is one of the top 25% most downloaded eBooks in the relevant Springer eBook Collection in 2013.

Following our original idea, a new Springer volume is in preparation which will offer both a state-of-the-art atmospheric ground-based measurements (including infrasound), opening perspectives on key issues and challenges for the future. This book will review recent technical and scientific advances in the field of infrasound. It will also address new perspectives on key issues and challenges for climate related studies and civil applications. This project has been well received by the editorial board of Springer. Researchers and students interested in a broad interdisciplinary field, encompassing academic disciplines of physics and recent technical and scientific developments, will benefit from a comprehensive content of both fundamental and applied topics.

1.4.8 Dissemination and networking with climate and weather modelling communities

The dynamics of the project should lead to the connection of ARISE with several ongoing or future international initiatives to further the development of understanding the impact of stratospheric disturbances on surface weather on various time scales. This collaboration is made possible through the participation of some ARISE partners to the SPARC project for several years (Stratosphere-troposphere Processes And their Role in Climate project). Thus, a close working relationship is envisaged with 2 international projects (SNAP and Dynvar) to ensure that our results and data products are widely disseminated amongst the stratospheric predictability community. The SNAP project (Stratospheric Network for the Assessment of Predictability) is a core project of the SPARC network which brings together scientists from around the world who work on stratospheric predictability. The DynVar project focuses on the representation and understanding of coupling between climate in the stratosphere and troposphere.

1.4.9 Dissemination and networking concerning atmospheric extreme events

The collaboration between the CTBTO and the international scientific community (including several partners of ARISE) takes the form of organizing the Science and Technology conference in Vienna every two years. Several ARISE partners participate very actively to this conference and disseminate information broadly, given their close collaboration and many shared interests and objectives with the CTBTO.

Severe weather (polar lows, severe storms, tornadoes and cyclones) represent a major hazard. The ARISE project aims at maintaining a unique dataset for continuous and long-term monitoring of extreme weather events that are recorded routinely by the ARISE network. The next step is to disseminate results to decision-makers and to citizens. For instance, it is planned to communicate more about cold wintertime periods following SSW events, which could introduce skepticism about climate change.

Finally, links with other international projects focusing on extreme events will be reinforced. ARISE partners are already involved in 3 other projects: HYMEX that focuses on the predictability and evolution of extreme weather events in the Mediterranean regions, TARANIS, a micro-satellite project that aims to study the magnetosphere-ionosphere-atmosphere coupling and TEA-IS that studies the effects of thunderstorms on the atmosphere-ionosphere system.

1.5 Address of the project public website and contact details

For additional information, please contact Elisabeth Blanc, Elisabeth.blanc@cea.fr or consult our website at http://arise-project.eu/.

The ARISE Consortium