**As a player in the effort to stem nuclear proliferation, both in France and internationally, CEA holds the brief, in France, for implementation of the surveillance activity instituted by the Comprehensive Nuclear Test Ban Treaty.** It is actively engaged in the building up of the International Monitoring System, which relies on a network carrying out the detection of seismic, hydroacoustic or infrasonic waves, and radionuclides, indicating a nuclear explosion. CEA expertise in terms of detection is being used to advantage for the purposes of environmental monitoring, and the investigation of atmospheric perturbations.
In the longer term, measurement of large-scale atmospheric waves may contribute to the description of the global dynamics of the atmosphere, and its impact on climate evolution.

# **Infrasound measurements** to unravel the **dynamics** of the **atmosphere**

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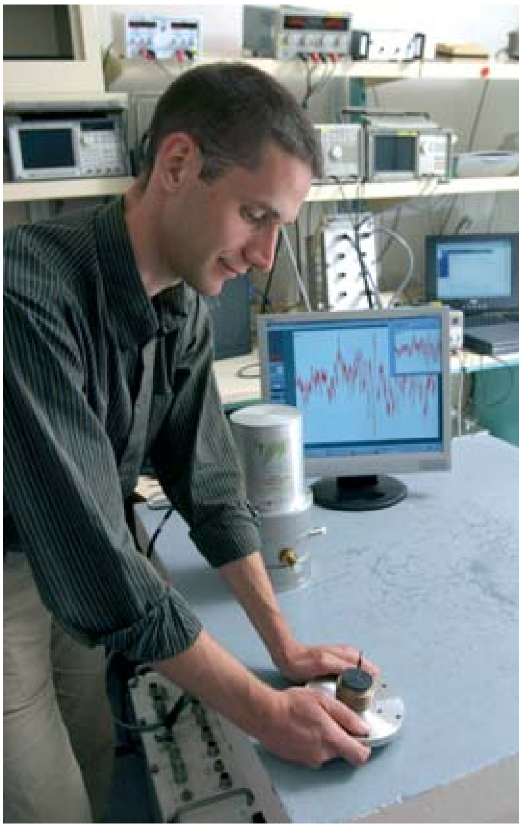
In the context of worldwide nuclear test monitoring, the international monitoring network, when deployed, will comprise 321 detection stations, spread around the world, including 60 infrasound stations, and 16 radionuclide analysis laboratories. CEA has the remit for the setting up of 25 stations, together with all associated analysis resources. One of these is the I33MG station, sited in Madagascar.

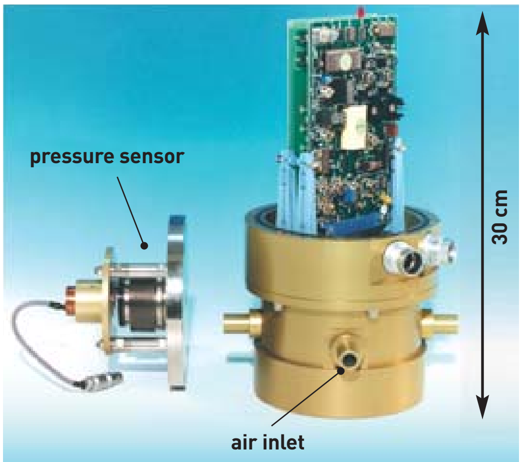
Airbursts, be they nuclear, chemical, or natural, generate inaudible acoustic waves, known as infrasonic waves, or **infrasound**, having **periods** ranging from a few tenths of a second to several minutes. Propagation of such waves takes place over long distances, owing to their propagation very weak attenuation, and the fact the various layers in the **atmosphere** set up particularly effective waveguide conditions. In the context of verification tools development, under the aegis of the Comprehensive Nuclear Test Ban Treaty (**CTBT**), a network of 60 stations, based on infrasound detection, is being incorporated into the International Monitoring System (IMS).

## A variety of infrasound sources

The expertise gained by the Analysis, Surveillance, Environment Department (DASE) of CEA's Military Applications Division, in the realm of infrasonics, is the outcome of over 40 years' systematic measurements and specific experiments carried out to detect atmospheric nuclear explosions, and identify them in the midst of perturbations of the atmospheric environment of natural origin. Drawing on this knowhow, DASE has taken an active part in the buildup of the International Monitoring System, for CTBT verification. Under its remit to detect nuclear explosions,



C. Dupont/CEA

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Microbarometer, as fitted to every component of an infrasound station. Technical specifications require, amongst other stipulations, a measurement noise lower than one ten-billionth of atmospheric pressure, i.e. a pressure variation corresponding to a rise in altitude of one tenth of a millimeter.

DASE has further been contributing to the specification and construction of sensors, the setting up of monitoring stations, and the development of original, operative methods, currently used by the international treaty organization. DASE hosts the National Data Center, which manages and operates the stations in the French national network, as also stations in other countries with which it has entered into collaboration. More than half of the stations in the international network have now been set up, and are sending their data continuously, in real time, to the International Data Center (IDC) of **CTBTO** (the Comprehensive Nuclear Test Ban Treaty Organization), in Vienna (Austria).

Pressure readings from each station are processed on a continuous basis, to search for **coherent** wave trains(1) in the acoustic background noise. By turning to advantage the **noncoherent** structure that is inherent to the nature of acoustic background noise, detection of low-amplitude coherent signals becomes feasible. Measurement of the differences in wave arrival times, from one sensor to another, allows its direction of propagation to be determined, along with trace velocity, together with its principal characteristics.

Systematic, detailed investigations of the infrasounds detected are being carried out for the purposes of validating detection and identification methods for such signals. Efforts are directed at achieving a better understanding of extant **empirical models** of the atmosphere, these being used to simulate the propagation of such waves, and improve localization accuracy. Conversely, since the characteristics of infrasounds propagating along the atmospheric waveguide, formed by the various layers in the atmosphere, depend on atmospheric conditions, these measurements are further used to validate, and improve empirical models for wind at altitude. Indeed, simulation accuracy relies, in part, on realistic **modeling** of daily and seasonal variabilities by such models. These may be further improved through complementary, direct or indirect point measurements of the atmosphere. Recent investigations of the low-frequency (lower than 0.05 **Hz**) component of atmospheric waves have further shown that the network is equally sensitive to **gravity waves** (with a period longer than 5 min), which contribute to global atmospheric circulation, for the Earth's atmosphere, opening up further prospects with regard to future climate-oriented investigations.

Among the main infrasound sources, one should accord specific consideration to:

- *permanent* or *repetitive reference point sources* (anthropic sources, active volcanoes, lightning…), which, taken as calibration sources, allow the system's functioning to be validated, and certain atmospheric parameters to be determined, such as wind profiles at altitude;
- *sources limited in space and time* (earthquakes, auroras), infrasounds from which, when measured, provide the means for accurate reconstruction of the source's extent, and to gain a better understanding of coupling mechanisms with the atmosphere;
- *permanent extended sources* (ocean swell, mountain waves), monitoring of which evidences the impact of atmospheric dynamics on propagation;
- *large-scale gravity waves* from the **troposphere** (storms, dynamic instabilities, wave interaction), interacting with the major atmospheric circulation currents.

Operated in continuous mode, this network enables the building up of a passive, high-performance system of environmental monitoring. It is also finding new applications, with the investigation of atmospheric circulation laws on a global scale (see Figure 1). This paper sets out to show, by way of a few examples, how the identification, and continuous measurement, on the scale of a human lifetime, of climate indicators at meteorological altitude (troposphere), and higher altitude

(1) Wave train: a series of waves, of finite spatial and temporal extent.

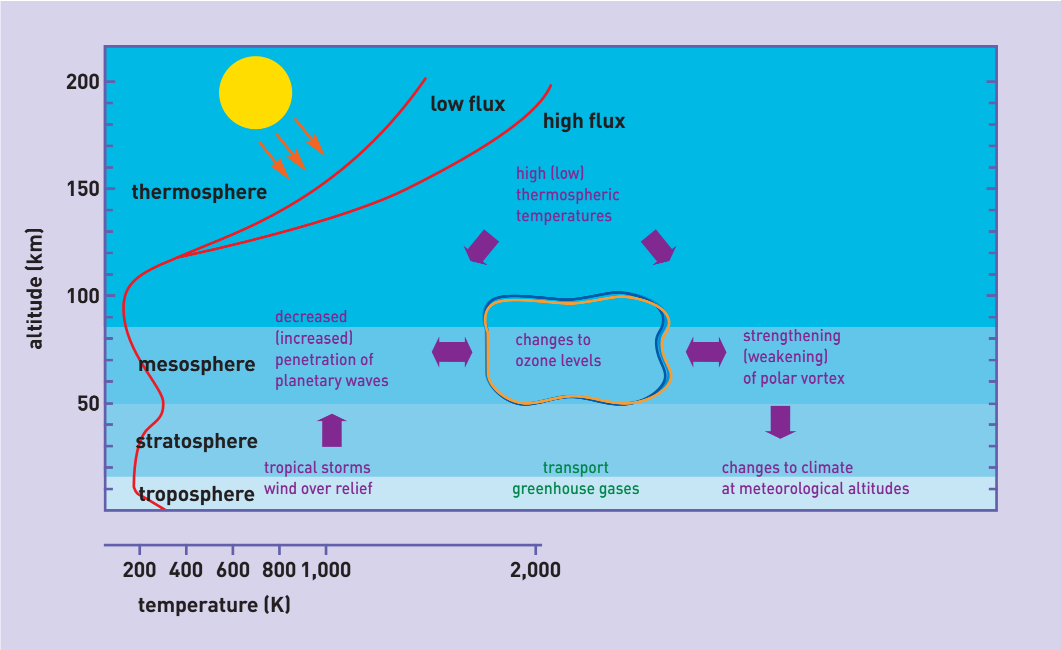


Figure 1.
Impact of the dynamics of the stratosphere on climate evolution. The stratosphere is a cold, stable environment, coupled with meteorological altitudes through the gravity waves (tropical storms, winds over high relief) propagating at these altitudes. Penetration of such waves into the stratosphere causes long-lasting changes in general circulation, these impacting back at meteorological altitudes, and affecting climate (taken from N. F. Arnold, 2000).

(**stratosphere**–**mesosphere**–**thermosphere**), together with monitoring of their evolution, can assist in enhancing our understanding of the physics of climate-related atmospheric processes.

## Infrasound imaging of natural processes

Earthquakes of a **magnitude** greater than 6, occurring in mountain areas, are sources of infrasounds, having periods that may be as long as 10 seconds or so. One mechanism leading to wave formation is the coupling of seismic waves with the atmosphere, as they propagate. Trace velocity values for such signals (several kilometers per second) are then compatible with the characteristics of the various seismic phases measured, reaching the station. Propagation of such seismic waves from the **epicenter** through mountain areas further contributes to generation of infrasounds, as they set the mountains vibrating. Once emitted, the waves generated are channeled along the various layers in the atmosphere, and may be detected several thousand kilometers away from the epicenter, under favorable propagation conditions.
The characteristics of such waves may be used to reconstruct the spatial extent of the regions where coupling occurs between the ground's vertical motions and the atmosphere. Knowing the time of origin and the coordinates for the epicenter, measurement of the waves' times of arrival and direction of propagation at a single station yields this localization. The azimuth(2) detected yields the direction of the source, while the propagation velocities of the seismic waves, and of the infrasounds allow constraints to be set as to distance. However, bearing in mind the directivity of the source, resulting from the orientation of the mountain ranges relative to the station, and the variability of propagation conditions, the reconstructed regions will vary as a rule, from one station to the next. Taking into account the uncertainties attaching to the measurements, and to the models of the atmosphere used, localization accuracy stands at a few tens of kilometers or so.
To take the example of the superficial earthquake of magnitude 7.9 that occurred on 3 November 2002 in Alaska (northwestern part of North America). This earthquake proved particularly spectacular, as it rup-

(2) Azimuth: the horizontal angle by which the direction of an object differs from the direction of the geographic North. This is measured in degrees, clockwise from the North.

(3) Strike-slip fault: near-vertical fault, along which one bedrock compartment slips horizontally, relative to the opposite compartment.

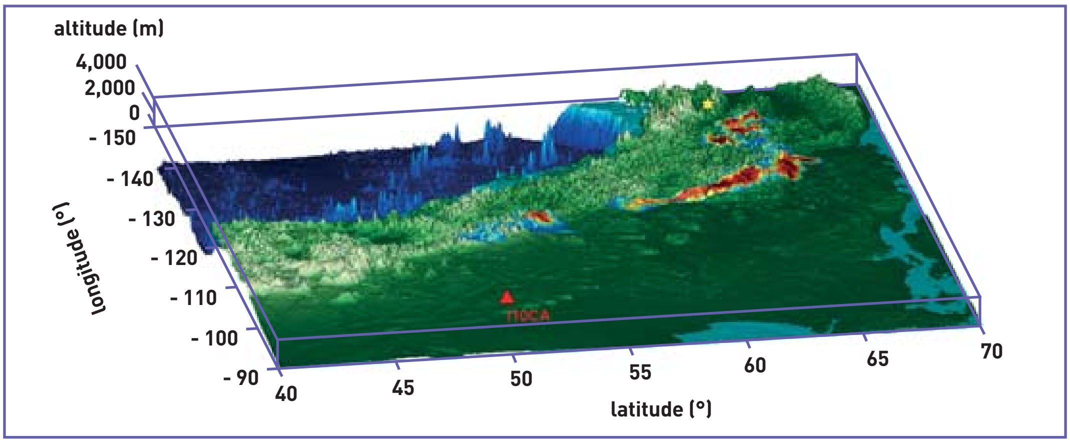


Figure 2.
Localization of regions of coupling between ground vertical motions and the atmosphere, during the earthquake that occurred in Alaska in November 2002, as effected from the infrasound station sited in Canada. The yellow star marks the epicenter, the red triangle the station. Densities of localization are shown, using a normalized color scale, from blue to red.


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At left, map showing the location of infrasound station I22FR (shown at center), set up in New Caledonia, relative to the active volcanoes in Vanuatu, detected constantly at the station. Right, the Yasur volcano. A microbarometer is positioned at the mouth of the crater, to measure the very small pressure variations around atmospheric pressure, in the infrasound band.

tured one of the largest strike-slip faults[3] in the world over more than 300 km. About 3,400 km from the epicenter, infrasounds originating in the Rocky Mountains were detected for nearly two hours by station I10CA, in Canada. Inversion of the measurements allowed the spatial distribution to be retrieved, for the coupling regions, over an area more than 2,000 km long (see Figure 2). Complementary investigations of some ten recent earthquakes, of magnitudes greater than 7, recorded in some cases by several stations, evidence a clear relationship between the amplitude of the measured signals and seismic magnitude, as also, systematically, a spreading out of the duration of infrasound signals, linked to the local, and regional topographical environment around the epicenter.

Such events allow our understanding to be enhanced, with regard to seismic–acoustic coupling mechanisms, by affording the opportunity to validate models of propagation velocity in the atmosphere, by matching localizations to expected coupling regions. The synergy between the IMS seismic and infrasound networks shows itself to advantage here, as it may lead to expanded cartography of the areas where seismic motions are largest, more particularly when the area subject to monitoring is poorly instrumented.

## Local atmospheric imaging

Known repetitive point sources of infrasounds, whether of artificial or natural origin, such as certain active volcanoes, may be used to evaluate temporal variations in prevailing wind fields in the upper layers of the atmosphere (stratosphere–mesosphere). Indeed, knowledge of the exact location of such sources, together with their regularity, makes it possible to investigate more precisely the variability of the environment through which these waves travel, and thus to validate, or even enhance, empirical models of the atmosphere. However, bearing in mind the relatively limited propagation distances of such waves (as a rule less than 1,000 km), these investigations may only be carried out on the basis of a restricted number of stations, thus concerning only a limited region of the world.

Volcanoes provide unique sources for the evaluation of IMS detection and localization capabilities, further affording opportunities for the investigation of the dynamics of the upper atmosphere. Indeed, the development of inverse measurement tools allows the continuous probing of winds in areas that remain inaccessible to operational observation means. Recent investigations were carried out on the active volcanoes in Vanuatu (former New Hebrides), for which the main effusive and eruptive phases are constantly detected, more than 600 km away, by station I22FR, set up in New Caledonia. These records show that infrasounds undergo, through the year, considerable deviations in azimuth. Variations exhibit a quasi-sinusoidal form, with a one-year period, the deviations in azimuth, relative to the initial axis of propagation, ranging up to 10°. Propagation simulation showed that the more precise atmospheric models do yield the cyclical, seasonal variations in azimuth, however they underestimate their amplitude, by several degrees. The development of inversion procedures brings a possibility of getting a step closer to **tomography** of the upper atmosphere.[4] Indeed, iterative adjustment of wind field vertical struc-

(4) Tomography of the upper atmosphere: this imaging technique allows, on the basis of infrasound recording and processing, certain parameters of the atmospheric environment to be retrieved.

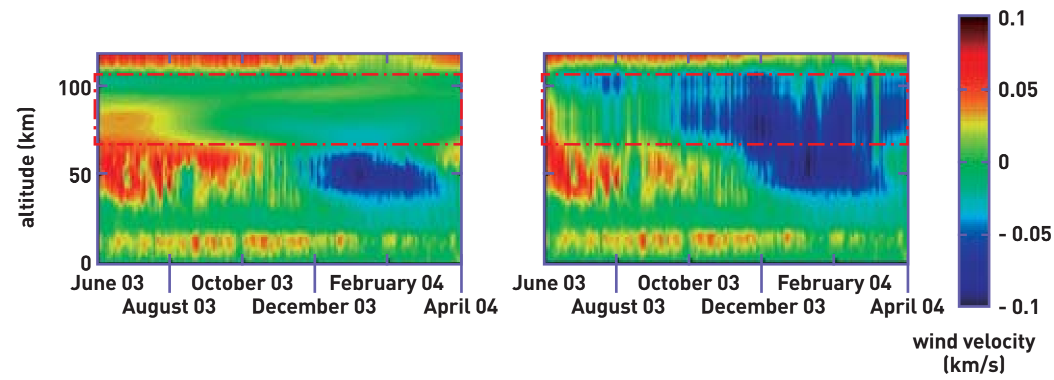


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Figure 3.
Tomography of zonal winds in the mesosphere and lower thermosphere, on the basis of continuous records of signals generated by active volcanoes in Vanuatu. At left, initial NRL–G2S wind model; right, corrected wind model. The red rectangle bounds the region being investigated, where winds are not well known. Bounded in altitude between 60 km and 100 km, this region was initially characterized by the HWM-93 empirical model. Wind velocities positive towards east.

ture, taking as a guide minimization of discrepancies, between observations and findings from simulations, makes it possible to evaluate the errors in atmospheric models. The findings from inversions show that, in the mesosphere, the velocity of winds transverse to propagation, controlling as it does azimuth deviation, is underestimated by 20 m/s on average, and that, to account for observations, introduction of a stochastic variability would be required, for winds above 60 km in altitude (see Figure 3). Such measurements are proving to be of importance for the description of jet[5] dynamics, and gravity waves, which are superimposed in the upper stratosphere and the mesosphere, over intervals that range from a few hours to several days.

## Investigation of the major atmospheric circulation currents

Ocean swell and mountain waves also provide sources of interest, since the infrasounds generated are constantly detected, all over the world, by a large number of stations. Continuous monitoring of such waves is thus particularly suitable, for the investigation of perturbations in the major atmospheric currents, onto which they are superimposed. With periods in the 5–8 s range, signals from swell exhibit an energy maximum close to that of 1-kiloton explosions, remaining restricted, however, to a limited portion of the latter's spectrum. Often located at the center of depressions, ocean swells result from the coupling with the atmosphere of continuous waves occurring on the ocean surface. A theoretical description of this production mechanism links the amplitude of the pressure signal to wave height and oscillation frequency. In favorable propagation conditions, strong swell is detected over all the stations in the international network.

Thus, for instance, station I34MN, set up in Mongolia, records in the months from December to February the North Atlantic swell, some 10,000 km away. At that time of year, in the Northern Hemisphere, prevailing westerly winds favor the propagation of these signals along the stratospheric waveguides. Superimposed onto the swell signal, waves with periods in the 20–50 s range are also often found. These waves originate in strong wind flows (with a velocity greater than 20–30 m/s), along an axis perpendicular to the axis of mountain ranges. Such winds generate **stationary waves**, causing **turbulence** at around 20–25 km altitude, and mountain waves at higher altitude. Subject to weak attenuation, such waves propagate over large distances, and, as for swell signals, their propagation is governed by wind dynamics in the stratosphere. Correlations between seasonal variations in amplitude for these waves, and that for zonal and meridional winds[6] in the assumed source region (between 1,500 m and 5,500 m in altitude) have clearly been evidenced.

Figure 4 shows the main directions for swell and mountain waves, as detected in Bolivia over an interval of 5 years. Detections are near-continuous, with marked cyclical annual variations. In the Southern Hemisphere, strong depressions move from west to east, along a circum-Antarctic belt through the year. In the North Atlantic, these generally originate off the United States East coast (Caribbean, or sometimes south of Greenland) and, following the Gulf Stream, cross the Atlantic before disappearing over the North Sea. The annual periodicity exhibited by detections is attributed to propagation effects, rather than to the source. Simulations account for such alternations through the appearance and disappearance of the stratospheric waveguides, with the seasonal inversions of zonal winds.

(5) Jet: a type of flow sheared from ambient air masses.

(6) Zonal winds, meridional winds: the former move along a parallel, whereas the latter move along a meridian, this being the locus of points having the same longitude.

Central component of infrasound station I34MN, set up in Mongolia. The sensor is positioned in an air pipe, at the center of an acoustic filtering system, attenuating the noise associated to local atmospheric disturbances. This station records the North Atlantic swell.

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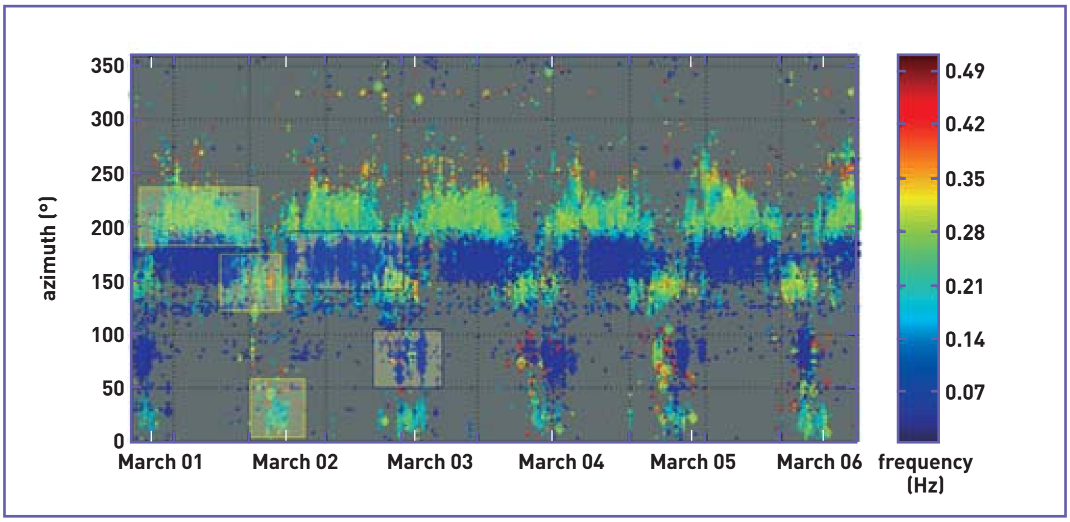


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Figure 4.
Detection of ocean swell and mountain waves at the I08BO station in Bolivia. Depending on the time of year, detections of swell (yellow rectangles) occur preferentially in certain directions: coming from the South Pacific (200–230°) during the southern Winter, from the South Atlantic (130–170°) and North Atlantic (10–30°) in the southern Summer. Exhibiting longer periods (about 20 s), mountain waves (blue rectangles) generated over the Andes follow the same seasonal alternations.

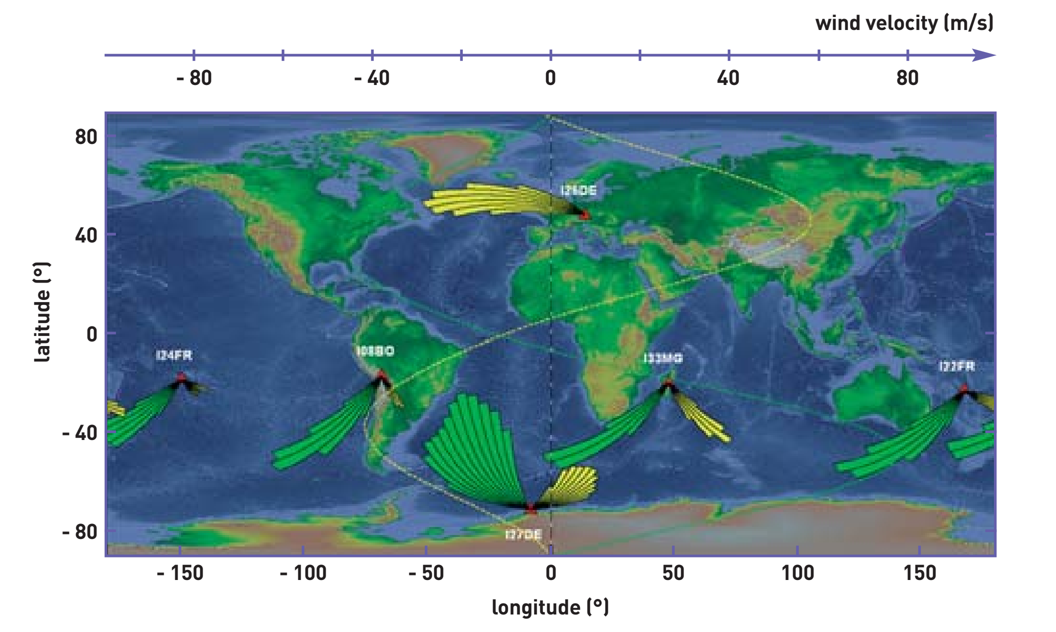


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Figure 5.
Global detection of ocean swell and seasonal azimuth distribution. Detections are correlated in the southern wintertime (yellow segments) and southern summertime (green segments) with zonal wind velocities, as characterized by the HWM-93 empirical model, in the stratosphere (dotted lines). Wind inversion, from one hemisphere to the other, is found in the detections. (D. Drob, Hulburt Center for Space Research, Naval Research Laboratory, Washington [DC] [United States], and L. Cerenna, German Federal Institute of Geosciences and Natural Resources, Hanover [Germany], took part in this investigation.)

From January to March, wind inversion at an altitude of 40 km is sufficiently large to trap the energy from the North Atlantic swell and channel it to the Bolivia station, along a stratospheric waveguide. Bearing in mind the considerable distances these waves travel, the simulation tools employed must have the ability to take in large variations in wind fields through the entire path. Recent investigations, using 3D raytracing simulation, taking into account an environment varying over time and space, have allowed empirical laws to be established, relating the amplitude of the signals recorded to wind velocity at 40–50 km altitude.

Such correlations are also confirmed on a global scale (see Figure 5). In a well-defined wind regime, it is found, at the same time, that variations in amplitude follow those for wind velocity at 40–60 km altitude. The empirical laws arrived at differ little from those worked out from campaigns of nuclear and chemical atmospheric tests. The advantage of using signals emitted by ocean swell – increasingly well described and modeled as this is, e.g. through the work of the US National Oceanic and Atmospheric Administration (**NOAA**) – for the purposes of providing information, on a permanent basis and for every point in the world, on the dynamics of the major stratospheric currents is thus apparent.

## Interaction between large-scale waves and climate

Atmospheric storms are another major source of infrasounds (some 2,000 storms may be counted at any time, over the Earth's surface). Stations sited at intermediate and low latitudes record such perturbations on a continuous basis. A number of source mechanisms have been identified. Thunder is produced by heating, and by the **electrostatic** forces in the storm. Infrasound frequencies are high, verging on audible frequency range. Such signals rarely propagate further than a distance of 200 km. Other waves, with periods from about 10 s to several tens of seconds, are generated by **convective** motions of the air masses. Meteorological disturbance fronts, and convective systems are also the source of larger-scale gravity waves. Monitoring gravity waves, having periods of several minutes, on a global scale and over an extended timespan, is of interest for the investigation of climate evolution. These large-scale waves, as indeed mountain waves – these being mainly generated in the troposphere at meteorological altitudes, in low- and intermediate-latitude areas – reach into the stratosphere, which is a region of great stability. A global circulation motion is set up, whereby air rises in the tropics, up to the stratosphere, moves to the poles in the stratosphere, then gradually sinks over the latter, influencing in turn the troposphere at high latitudes.

Planetary waves thus disrupt the polar vortices,(7) these being stratospheric wind systems, moving around the poles in wintertime, when the onset of the polar night accentuates the temperature differences between stratospheric air at intermediate latitudes, and at high latitudes. These winds insulate the polar stratosphere, pre-

(7) Vortex: a swirling motion, leaving a hollow center, which arises, under certain conditions, in a flowing fluid.

Signature of gravity waves, seen on noctilucent (luminous in nighttime) clouds, observed from an airplane at altitudes of around 90 km. Such waves affect the atmosphere as a whole, from ground level, where they are recorded at the infrasound stations from the IMS network, to altitudes up to about 200–300 km, where they are detected by **ionospheric** radars.

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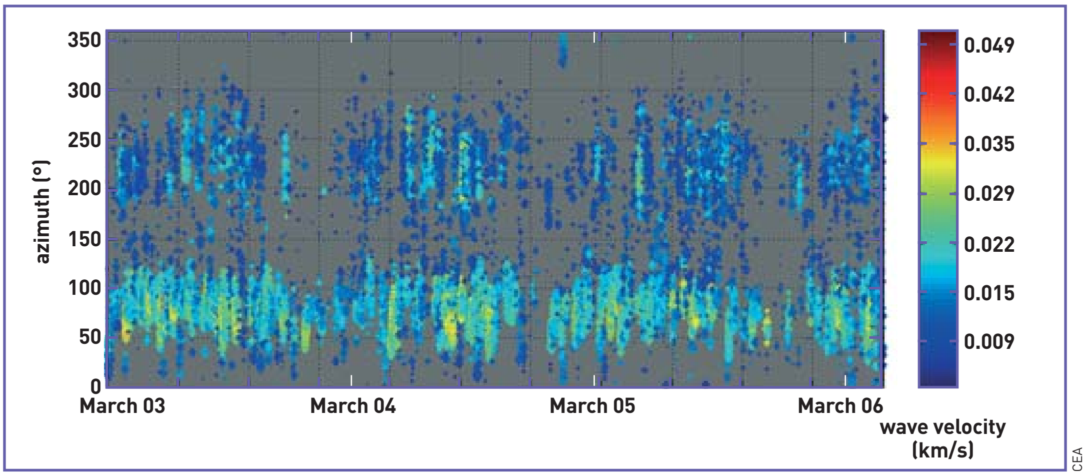


Figure 6. Detection of gravity waves at station I27DE (Antarctica), over an interval of three years. Colors code the trace velocity of waves measured through the station. (This station is run by the team led by M. Henger, from the German Federal Institute of Geosciences and Natural Resources, Hanover [Germany].)

venting the air and **ozone** from lower-latitude regions from entering it, causing a fall in ozone concentrations above the poles. This vortex breaks up under the action of planetary waves, especially in the Northern Hemisphere, where the presence of a number of continents favors the formation of mountain waves and atmospheric storms. Current climate warming, close to the Earth's surface, due to the impact of rising concentrations in **greenhouse gases** may slow down the motion of planetary waves (see Figure 1), causing a strengthening of the vortices, and ozone depletion above the poles.

Some of the IMS stations, sited in Antarctica, constantly record gravity waves, with characteristics exhibiting cyclical, seasonal fluctuations, but equally variations on a shorter timescale (see Figure 6). Two wave systems, distinguished by their azimuths, have been identified. The first one is a faster (25–40 m/s), quasi-permanent system, coming from an easterly direction (~ 80°). This is an itinerant wave system, caused by topographical features, moving at low altitude, which has already been observed during previous pressure measurement campaigns, carried out over several months in Antarctica by teams from the University of Sheffield (United Kingdom). The second one is a slower (10–15 m/s) system, coming from a westerly direction (~ 230–280°), active in wintertime (June–September). This wave system is controlled by the polar vortex, extending from the surface to the stratosphere. This vortex is stronger in winter, when temperatures are lowest. Identification of these two wave systems stands as validation of the effectiveness of the observation and data processing systems in the CTBT network.

## Expanding the potentials of the international monitoring network

With the deployment of the International Monitoring System, a number of natural, permanent infrasound sources have been identified, on a continental and global scale. In conjunction with the development of high-performance analytic and modeling tools, this network is opening up new horizons for environmental monitoring, but equally for the investigation of the atmosphere.

Since the waves being measured travel through the upper layers of the atmosphere, and propagate over long distances, continuous monitoring of these waves affords promising prospects, as regards measuring the characteristics of winds at altitude, which, thus far, were only known from local, point measurements. Description of the conditions for the generation of gravity waves, and the investigation of their interaction with the stratosphere, and influence on global convective motions are also of major interest, most emphatically with respect to a longer-term goal, namely to use infrasound measurements to achieve a more realistic description of the global dynamics of the atmosphere, with a view to investigate its effects on climate evolution.

Climate-related investigations will then reap the benefits of a major contribution, for instance in assisting verification of general laws of atmospheric circulation, and evidencing propagation anomalies, related to stratospheric warming processes. Full use of the synergy with other CTBTO technologies (**radionuclide** measurements), and complementary measurement systems (balloons, satellites, radar and lidar(8) measurement stations…) will further expand the potentials of this network.

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Military Applications Division
*CEA DAM Île-de-France Center*

(8) Radar, lidar: both based on the same functioning principle, these devices operate in distinct spectral regions: radio waves (2.7 mm–100 m) for radar, and **visible** light, the **ultraviolet** and **infrared** for lidar.

## FOR FURTHER INFORMATION

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