Seismology readily detects signals from natural sources such as ocean storms, bolides, tornados, and glacier calving. A new era of research has recently opened up at the interface of solid Earth geophysics, glaciology, oceanography, and atmospheric science, with high potential for transformative science and societal relevance. This multidisciplinary topic of how processes in the ocean and atmosphere couple into seismic waves in the solid Earth and how these can be used to monitor the global environment is one of the high-priority Seismological Grand Challenges.

There is great interest in understanding the coupling mechanisms between ocean waves and seismic waves over broad frequency ranges because it enables seismic monitoring of ocean processes and, in turn, the coupling of oceanic and atmospheric energy into the solid Earth provides a novel source for exploring Earth’s interior. Earth’s long-period “hum,” or continuous excitation of the planet’s free oscillations at periods of hundreds of seconds, was discovered just ten years ago in high-quality continuous records from the Global Seismographic Network (GSN) accumulated
over several decades. It has now been established that the primary sources of the hum are related to mid-latitude winter storms generating strong ocean waves that couple to the ocean floor via nonlinear mechanisms that are still poorly understood.

The ocean wave origin of the shorter-period “microseism” (between about 4 and 30 s) background was demonstrated in the 1950s, but for decades this ubiquitous signal was widely treated as troublesome noise. In fact, the microseism is a unique global integrator of storm energy spanning the world’s ocean. Seismologists and collaborators are now working to elucidate the relationship between Earth’s seismic background excitation across hum and microseism periods to ocean wave and atmospheric processes. This research is of interest to a large, multidisciplinary community, with applications ranging from the study of Earth structure, to effects on floating sea ice, to coastal oceanography (e.g., the effects of long-period ocean waves [infragravity waves] in harbors).

Seismology is providing a new and valuable integrative window into climate change at scales not otherwise accessible. Global warming affects broad-scale atmospheric circulation patterns, resulting in changes to storm duration and intensity. The microseismic and hum noise both track large ocean storms and their wave interactions with coastlines. Monitoring changes in wave activity and identifying whether changes have occurred in the wave system over the past century, especially in the southern ocean, may be reliably determined from archived seismograms from stations near the coast. It was also recently discovered that seismic methods can detect layering and mixing in the water column itself. Images with unprecedented horizontal resolution of oceanic structure can be used to derive quantitative estimates of internal wave energy and turbulent mixing that can help illuminate thermohaline circulation, which plays a key role in climate and natural sequestration of atmospheric carbon.

Seismologists and glaciologists are now collaborating in efforts to track how polar ice sheets are affected by global warming. Glacial earthquakes, resulting from the sudden (tens of seconds) movement of very large volumes (cubic kilometers) of ice, largely escaped attention until recently because they do not generate the short period (1–10 s) seismic waves visible at large distances that are used for standard earthquake
detection and location algorithms. Glacial sources that involve floating ice systems, such as calving, excite tsunami-like ocean waves that can be detected with seismometers deployed both on land and on floating ice, and offer additional new opportunities for monitoring key processes associated with the stability of tidewater glaciers and ice shelves.

Seismic sources within the solid Earth generate waves that propagate not only through the ground but also through the ocean (e.g., tsunami and T-phases), atmosphere (e.g., infrasound generated by volcanic eruptions and earthquakes), and even the ionosphere, where remote sensing using GPS and radar technologies hold potential for new ways to characterize the sources of large earthquakes. An explosion or disturbance near Earth’s surface produces both seismic and infrasound energy, the latter being best observed on microbarographs or, at high frequencies, by microphones. Atmospheric phenomena including tornados, meteorite impacts, and lightning strikes can be monitored by collocated seismic and infrasound sensors, providing new constraints on these processes and their global occurrence. It may also be viable to combine seismic and infrasound monitoring to detect and quantify wildfires using similar strategies to those used for volcanic eruptions. Seismic recordings can also sense changes in atmospheric pressure that causes ground tilt such as the rare “Morning Glory” cloud formations observed in Los Angeles and Australia. Combining seismic and infrasound recordings can help elucidate the way in which sound waves propagate through the atmosphere, and therefore provide a better understanding of atmospheric structure and its variation with time at spatial and temporal scales inaccessible by other means.

Cryoseismology

Cryoseismic research involves quantitative studies of ice processes that in many cases are known or suspected to show sensitivity to climate change. For example, high-quality seismographic networks can be deployed to study ice shelf stability/disintegration, which has been discovered to sometimes occur catastrophically. Recent research topics also include tectonic evolution of west Antarctica and the history of ice cap changes; studies of tidally modulated stick-slip motion of ice streams in west Antarctica; seismic and ocean acoustic observations of the collisions and break-up of Earth’s largest ice shelves and icebergs; remote detection of glacial calving via sea swell “mini-tsunamis” using broadband seismometers deployed atop giant tabular icebergs, and study of a newly observed class of remotely detectable slow glacial earthquakes from major tidewater outlet glaciers in Greenland. In each application, seismology can uniquely contribute to the quantification of the sources and structures involved in the dynamic polar environments.

Example of novel glaciological signals studied with seismology. Seismically identified and located long-period glacial events detected with the GSN are associated with major outlet glaciers in Greenland, showing seasonality and annual variability. (Image from G. Ekström, M. Nettles and V.C. Tsai, 2006. Seasonality and increasing frequency of Greenland glacial earthquakes, Science, 311(5768):1756–1758, doi:10.1126/science.1122112. Reprinted with permission from AAAS.)
**Seismic Imaging of Ocean Structure**

During routine seismic profiling of subseafloor structure off the Grand Banks on R/V Ewing, data collected to reveal structure within the sediments was found to also resolve variations in water temperature and salinity within the ocean itself. Thermohaline fine structure is usually mapped by lowering and raising instruments that measure water properties directly, but this slow process limits the volume of ocean that can be sampled and has constrained horizontal resolution. By tuning the processing of the seismic reflection records to emphasize ocean structure, boundaries between water masses can be rapidly mapped, revealing layers as thin as 5 m with unprecedented lateral resolution. The deeper, rounded structures in this image represent kilometer-scale eddies that are thought to play a major role in mixing within the water column. Seismic reflection techniques provide an ideal complement to traditional methods of probing the ocean, offering a way to rapidly illuminate large volumes, thus providing the possibility of 3D and 4D (time-lapse) imaging of the complex oceanic structures involved in oceanic mixing and transport. (Image courtesy of S. Holbrook.)

**KEY QUESTIONS AND ISSUES**

- How are Earth’s normal modes excited by phenomena in the atmosphere and ocean?
- How do ocean wave and other seismic background noise variations track climate change?
- Are models of thermohaline circulation consistent with seismic images of oceanic internal structure?
- How can seismic and infrasound data best be used to study tornadic storm systems and tornado touch downs?
- How can bounds be placed on the energy budgets and other physical properties of bolide impacts, glacial calving, volcanic eruptions, and other sources jointly observed by seismic and atmospheric monitoring?
- What conditions lead to ice-shelf collapse and can we monitor them in advance?
- What is the nature of friction and the role of fluids at the base of glaciers?

**SEISMOLOGICAL APPROACHES AND REQUIREMENTS TO MAKE PROGRESS**

- Sustain global and continuous observations of very broadband seismic signals on land and on the seafloor to evaluate mechanisms of hum and microseism excitation, coupled with wave height measurements with improved resolution in time and space.
- Increase the number of collocated infrasound and seismic stations.
- Make more hydroacoustic and infrasound data sources openly available for basic research.
- Develop an authoritative catalog and methodology for estimating size, duration, and other physical properties of non-earthquake seismic events.
- Install greater numbers of permanent broadband seismic networks in polar regions for long-term observations.
- Acquire large numbers of low-temperature-capable portable broadband seismic and geodetic instruments for temporary deployments in polar regions for experiments around ice-shelves, glacial streams, near glacier outlets, and in other cryospheric systems.