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Ocean Color and River Data Reveal Fluvial Influence in Coastal Waters

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A critical yet poorly quantified aspect of the Earth system is the influence of river-borne constituents on coastal biogeochemical dynamics. Coastal waters contain some of the most productive ecosystems on Earth and are sites of intense downward particle fluxes and organic accumulation. Also, in many parts of the world, coastal ecosystems are experiencing unfavorable changes in water quality, some of which can be linked directly to the transport of water-borne constituents from land. These include the well-publicized, increasing frequency of hypoxia events in the Gulf of Mexico [*Goolsby*, 2000], harmful algal blooms [*Smayda*, 1992], diminished water quality, and changes in marine biodiversity [*Radach et al.*, 1990].

In light of global and local issues arising from the interaction of land and coastal ocean waters, a better understanding of the spatial extent to which riverine discharge influences coastal ecosystems is needed. Recently, a time series of satellite ocean color data was used to investigate the spatial extent and nature of riverine influence on coastal waters. In doing so, the ability of the Sea-viewing Wide Field-of-View Sensor (SeaWiFS) was used to provide spatial and temporal coverage over vast areas and multi-annual time scales [*McClain et al.*, 1998]. It is widely known that water-leaving radiance spectra change in response to varying concentrations of dissolved and suspended constituents such as sediment, colored dissolved organic matter (CDOM), and phytoplankton pigments. Thus, a first-order understanding of the land's influence on coastal waters can be obtained through careful examination of the extent to which the delivery of water and its associated constituents is correlated to the time-varying spectral signature of neighboring coastal waters.

For several large rivers in North and South America, we observed high correlations between the time series of river discharge and ocean color radiance data at pixels located near the mouth of the river. Spatial maps of these correlations for the Mississippi and Orinoco rivers are shown in Figures 1 and 2. The magnitude and sign of the correlation contains information about the delivery and fate of terrigeneous materials in the ocean. High negative correlation between the discharge and radiance in a blue band (for example, 443-nm band; Figure 1a) is associated with the presence of light-absorbing substances such as phytoplankton pigments, biogenic detritus, and CDOM. High positive correlation at longer

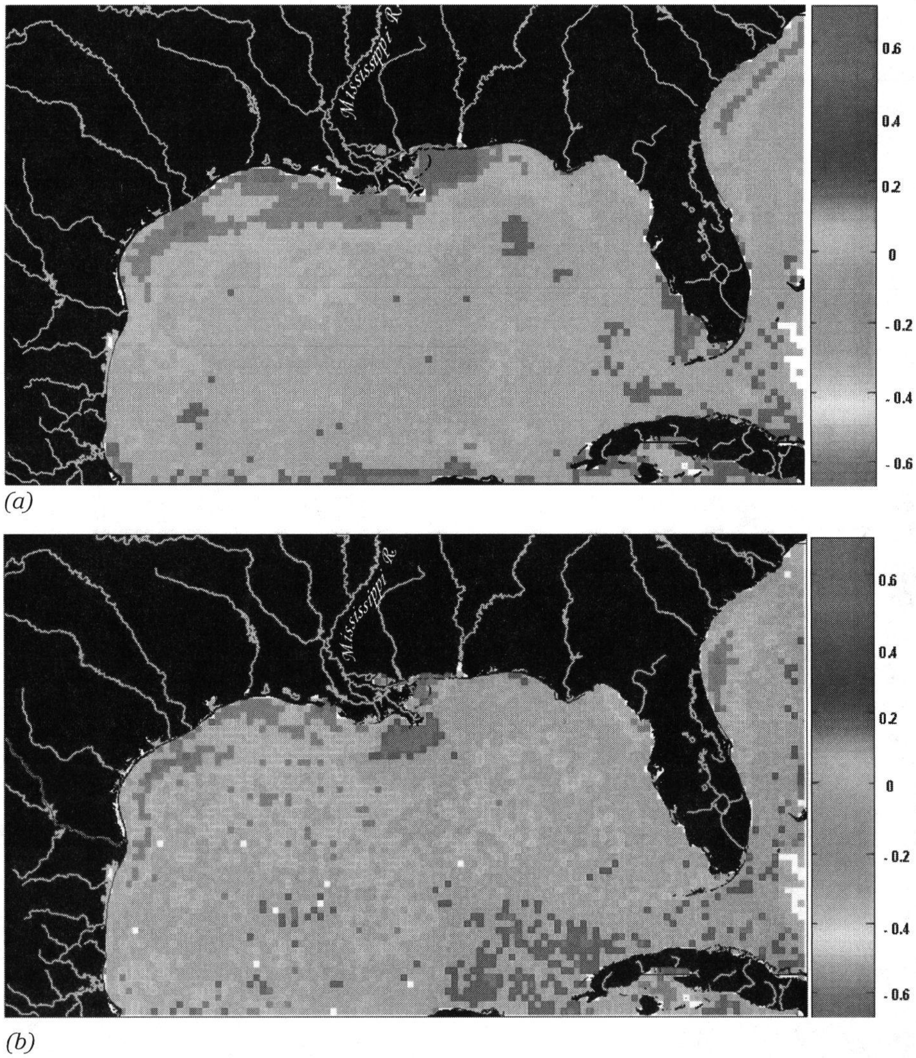

Fig. 1. Spatially mapped correlation coefficients between the Mississippi River discharge at Vicksburg and normalized water-leaving radiances in SeaWiFS bands. Correlations were computed from time series of monthly averaged data between September 1997 and October 2000. (a) Negative correlations between the discharge and the 443-nm band suggest that the Mississippi River is the source of organic matter absorbing in this blue band. (b) Positive correlations between the discharge and the 555-nm band suggest that light-scattering particles, presumably sediments, are concentrated near the mouth of the river. Original color image appears at the back of this volume.

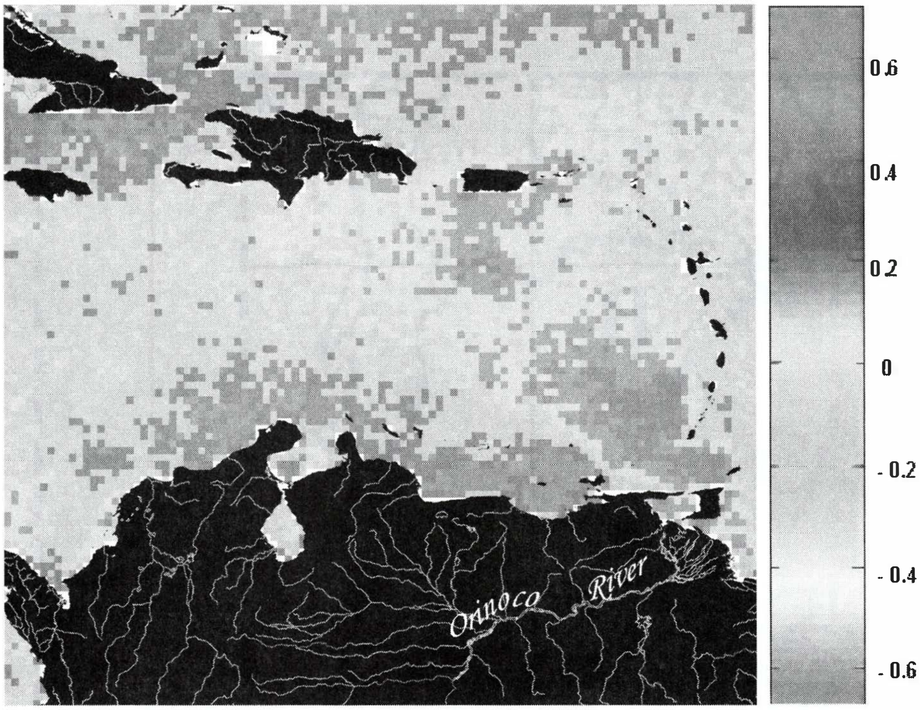

Fig. 2. Spatially mapped correlation coefficients between the Orinoco River climatological discharge and the 443-nm normalized water-leaving radiance from SeaWiFS for monthly averaged data between September 1997 and October 2000. The area of high negative correlation is believed to be the area influenced by the Orinoco River. The adjacent region of high positive correlation west of the plume is an area where upwelling-induced phytoplankton blooms are out of phase with the Orinoco discharge. Original color image appears at the back of this volume.

wavelengths (for example, 555-nm; Figure 1b) is associated with the enhanced backscattering properties of suspended sediments. These maps were generated using discharge data for the Orinoco and Mississippi rivers and SeaWiFS ocean color imagery of the adjacent coastal waters.

Daily discharge data for the Mississippi (September 1, 1997 to October 31, 2000) were obtained from the U.S. Geological Survey gauging station at Vicksburg, Mississippi, and averaged to obtain a 38-month time series of monthly average discharge values. Because contemporary discharge data were not available for the Orinoco, the climatology of monthly discharge values available from the University of New Hampshire's Global Composite Runoff Data Archive (http://www. watsys.unh.edu) was used. A corresponding set of monthly averaged global SeaWiFS data (Reprocessing #3) for the same period was obtained from the NASA Goddard Distributed Active Archive Center (http://daac.gsfc.nasa.gov). The SeaWiFS data sets were the normalized water-leaving radiances (nLw) in visible bands, spatially averaged within 9 x 9 km^2 bins, and temporally averaged over monthly intervals.

Data for the Gulf of Mexico and western Caribbean were extracted from the global SeaWiFS images, and the correlation coefficient was computed for each bin (pixel) between the monthly average SeaWiFS radiances and the monthly discharge at the mouth of the river. Results for two of the bands, 443-nm and 555-nm, are displayed in Figures 1 and 2. In Figures 3 and 4, graphs A, B, C, and D illustrate the coherence between monthly discharge data and scaled time series of the average radiances within boxes of 8 x 8 pixels (72 x 72 km^2) at the corresponding locations shown on the map.

Correlation maps for different spectral bands reveal information about the spatial distribution and quality of certain riverine constituents. For example, backscattering of light at 555 nm is known to vary proportionally in response to varying loads of suspended particles. Therefore, we believe the distinctive patch of highly correlated pixels in Figure 1b directly at the mouth of the Mississippi River indicates the spatial extent of suspended sediment in the Mississippi River plume. Graph A in Figure 3 clearly shows the coherence between the Mississippi River discharge and the 555-nm radiance data within that patch. The size of the patch makes intuitive sense, as the flux of mineral particles thought to be responsible for this phenomenon would likely settle out of the water column a relatively short distance from the point of discharge.

Riverine discharge typically delivers dissolved and particulate organic matter that absorbs light at blue wavelengths. Thus, as the flux of light-absorbing materials to the coastal waters increases in response to increasing discharge, the radiance at 443 nm decreases as less light exits the water column. This gives rise to the region of high negative correlation seen in Figure 1a. Graph B shows the coherence between the Mississippi discharge and the reciprocal of the 443-nm radiance within that region. Particulate and dissolved components contributing to this phenomenon include dissolved CDOM, phytoplankton pigments, and biotic detritus. Globally, rivers annually deliver an estimated 0.4 gt carbon to the coastal ocean [*Meybeck*, 1982], and the near-term sink for this carbon—whether the atmosphere, ocean, or sediments—is not known.

From the much larger spatial extent of the high-correlation region in Figure 1a compared with that of Figure 1b, we infer that organic matter that absorbs light at 443 nm is carried farther from the river mouth. In contrast, the denser sediment, which tends to backscatter light at 555 nm, is not carried as far. An alternative interpretation, however, is that some of these pixels are actually influenced by discharge from adjacent rivers. They appear to be correlated to the Mississippi discharge if the hydrographs of adjacent rivers were highly correlated. However, we found that the discharges from the smaller rivers draining into the northern Gulf of Mexico (Figure 1a) were not highly correlated ($r < 0.45$) to the Mississippi discharge, presumably because of the much larger drainage basin of the Mississippi and time delays in runoff routing. Regardless of whether a particular pixel is correlated to one or to more than one hydrograph, we believe that the correlation is a useful index of fluvial influence in coastal regions.

The optical influence of the Orinoco's plume and its effect on the ecology and biogeochemistry of the Western Caribbean have been studied in detail [*Müller-Karger et al.*, 1989; *Bonilla et al.*, 1993; *Blough et al.*, 1993]. Figure 2 shows the impressive areal extent to which the Orinoco's discharge is correlated to the 443-nm water-leaving radiance in this region. The apparent plume subtended by pixels of high negative correlation indicates a large area where light-absorbing constituents co-vary with the Orinoco River discharge, which is presumably the source of these constituents. The time series of the Orinoco's climatological discharge and the reciprocal of the 443-nm radiance at location C (Figure 4) are plotted in graph C.

A region of high positive correlation lying just west of the apparent plume is also notable in Figure 2. This is a region of seasonal coastal upwelling, which typically peaks early in the year and stimulates phytoplankton growth, hence reducing the water-leaving radiance at 443 nm. The high positive correlation is the result of this cycle being out of phase with the Orinoco's discharge, which peaks in August and is minimal at the time of the upwelling. The seasonal cycles of the 443-nm radiance in this upwelling area and the Orinoco hydrograph are illustrated in graph D. Their apparent relationship reminds us that caution must be exercised when drawing inferences about cause and effect strictly from statistical correlations. Any seasonally varying phenomenon that induces a seasonal pattern in the radiance would likely show some correlation with a local hydrograph that also responds to seasonal forcing.

Similar correlation analyses have been run for the coastal waters at the mouths of the Amazon and several of the large rivers of North America. Each analysis demonstrates distributions of correlated radiance values proximal to

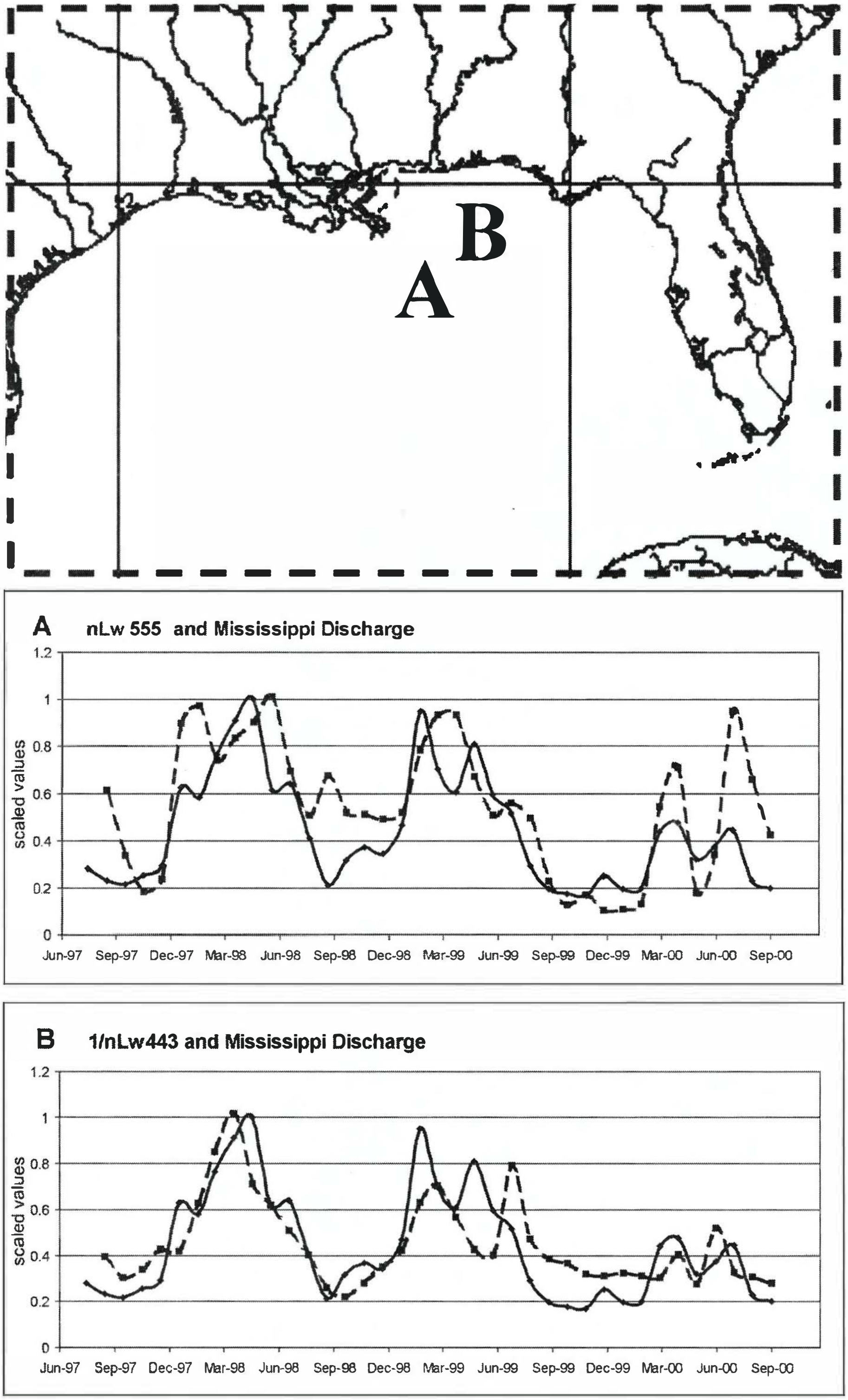

Fig. 3. Area of interest in the northern Gulf of Mexico. The region outlined shows the locations of Figures 1a and 1b. The graphs below illustrate the coherence between the time series of monthly average river discharge and water-leaving radiance data from SeaWiFS for the period September 1997 to October 2000. In each graph, the satellite data have been averaged over boxes of size 8 x 8 pixels (72 x 72 km^2) at locations indicated on the map. Where radiance and discharge are negatively correlated, the reciprocal of radiance is plotted (Graph B).

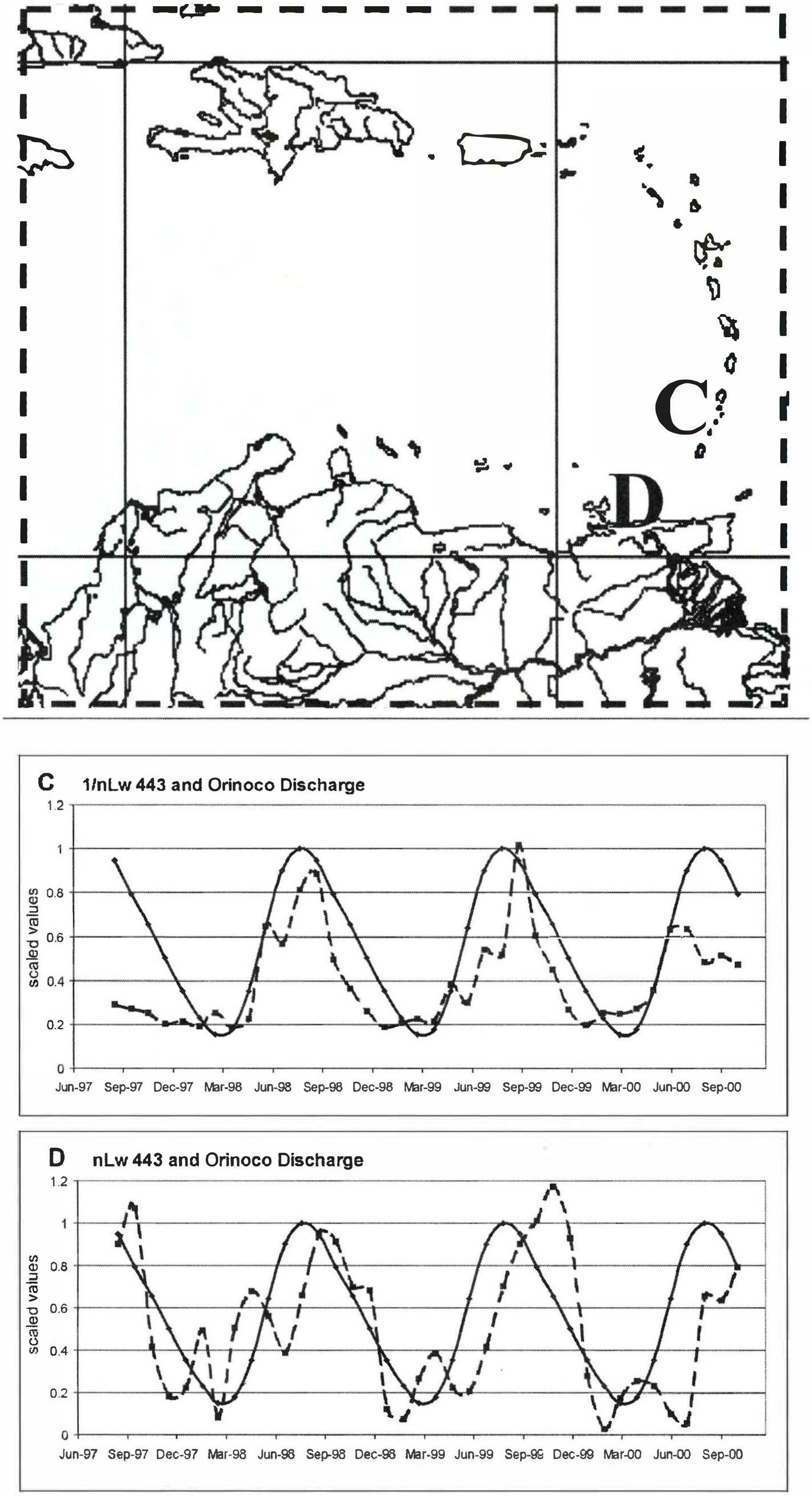

Fig. 4. Area of interest in the Western Caribbean. The region outlined shows the location of Figure 2. The graphs below illustrate the coherence between the time series of monthly average river discharge and water-leaving radiance data from SeaWiFS for the period September 1997 to October 2000. In each graph, the satellite data have been averaged over boxes of size 8 x 8 pixels (72 x 72 km^2) at locations indicated on the map. Where radiance and discharge are negatively correlated, the reciprocal of radiance is plotted (Graph C).

the river's point of discharge and indicates that, by using these methods, we can begin to characterize the spatial extent and nature of riverine influence in coastal waters. We have run several correlation analyses in which radiance data lagged the discharge by one or more months. Preliminary results are promising and may contain information about the movement and persistence of sediment plumes and the delayed response of phytoplankton growth stimulated by the delivery of riverine nutrients.

Research along these lines will continue, as we intend to document the relationship between the riverine delivery of constituents and any corresponding optical variability in the neighboring coastal ocean on a continental scale. The main goal of our research is to examine and model the land-ocean linkage to understand whether terrestrially-based biogeochemical processes are coherently coupled to the variability in the optical characteristics of neighboring coastal waters. This research augments efforts to develop site-specific algorithms for retrieving concentrations of chlorophyll, sediment, and dissolved organic carbon in coastal waters.

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Authors

Joseph E. Salisbury, Janet W. Campbell, L. David Meeker, and *Charles Vörösmarty*
For additional information, contact Joseph E. Salisbury, Ocean Processes Analysis Laboratory, University of New Hampshire, Durham, USA; E-mail: joe.salisbury@unh.edu

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Students Explore History of the Göttingen Institute of Geophysics

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The Institute of Geophysics at the University of Göttingen, Germany, has a long tradition that began long before its official founding in January 1898. Its history goes back to at least 1756, to the work on geophysical problems by Tobias Meyer, Carl-Friedrich Gauß, and Wilhelm Weber. At the beginning of the 20th century, the first director of the institute, Emil Wiechert, established a seismological working group that was a worldwide leader in this type of research for the next 10 to 12 years. In those golden years of seismology at Göttingen, famous students and co-workers of Wiechert such as G. H. Angenheister, L. Geiger, B. Gutenberg, L. Mintrop, and K. Zoeppritz made fundamental discoveries.

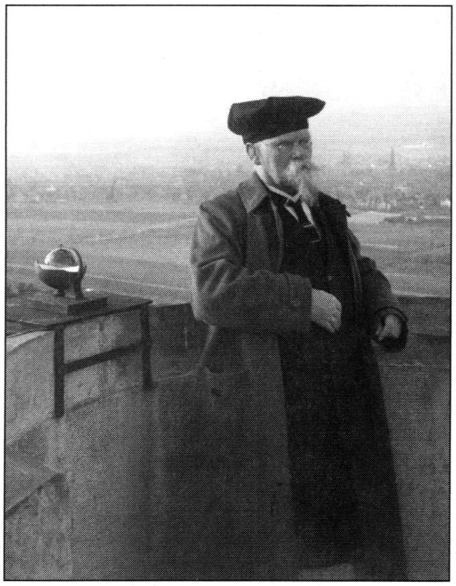
A seminar during the summer term 2000 provided an opportunity for undergraduate and graduate students of the Seismology Group at Göttingen to explore this interesting era in the history of their institute, and their work is presented on the institute's Web site. The participants in this history seminar benefitted in several ways. First, they had to read original and fundamental papers on their subject. Second, by sharing their findings in a lecture, they had to plan a clear presentation of the subject. Third, for a written summary in a foreign language, which was English, they had to extract the main points from the literature. In this way, scientific writing and citing was learned. Fourth, the articles had to be encoded in HTML for presentation on the World Wide Web. All of these activities gave the students a taste of the ways in which contemporary research is presented. By publishing the seminar results on the Web, no page charges are required and worldwide distribution is guaranteed.

In 1896, Wiechert had already presented his idea on a metallic core of the Earth underneath a stony mantle, which was based on astronomical observations and considerations about the Earth's average density. He soon realized that seismological research is best suited for exploring the Earth's deep interior. A focused summary of the discovery of the core and its physical state, including the role of Göttingen, can be found in *Brush* [1980]. Wiechert's theoretical contributions to seismology and his invention of new seismographs continually stimulated the group and attracted motivated students. His first assistant, Wilhelm Schlüter, addressed the question of whether far-field displacements due to earthquakes are tilt- or wave-type oscillations. Schlüter developed a klinograph and compared the measurements with recordings using a horizontal pendulum from 1899 to 1900, which led him to exclude tilt as an explanation for earthquake waves.

The construction of the famous Wiechert seismographs (1901–1903) and the opening of the earthquake observatory (GTT) in 1903 made possible the accurate recording of seismic waves and quantitative interpretations. The main achievement of the Wiechert seismographs was an exact measurement technique based on a clearly expressed theory [*Wiechert*, 1903]. Ground displacements were recorded continuously on smoked paper. By using critically damped instruments of different natural frequencies, a wide frequency band of about 0.01–2 Hz of displacements was covered with magnifications of 20–2000.

Those recordings were the basis of numerous discoveries and also prompted further theoretical efforts to explain the fine details of the observations. Seismic bulletins were produced beginning in 1903. Needing a unique and simple nomenclature for the different seismic phases, Georg von dem Borne and Wiechert defined abbreviations such as *P* and *S* for compressional ("primae") and shear ("secondae") waves, as well as *i* for impetuous ("impetus") and *e* for emergent ("emersio") waveforms. In 1906 and 1907, Karl Zoeppritz used the relatively precise arrival times for teleseismic travel-time curves (Zoeppritz tables) with which one-dimensional Earth models were constructed. In 1907, Gustav Herglotz, a mathematician at Göttingen, used Abel's integral equation to solve the problem of inverting travel times to derive velocity-depth functions. In the following years, Wiechert and his colleagues calculated improved Earth models based on the Zoeppritz tables by applying the Herglotz-Wiechert inversion.

In 1906, Gustav H. Angenheister discovered the attenuation of seismic surface waves along global wave paths. Later, in 1929, he became Wiechert's successor as director of the institute. Karl Zoeppritz derived formulas to calculate the reflected, refracted, and converted amplitudes for the wave propagation across elastic discontinuities between 1906 and 1907; these were the well-known Zoeppritz equations. Ludwig Geiger, a Swiss physicist, invented an inversion method to determine the location of an epicenter from *P*-wave arrivals in 1910 that is now known as the Geiger method. Ludger Mintrop came to Göttingen in 1908. He and Wiechert developed portable seismographs with amplifications of up to 50,000, and they experimented with active seismic sources. Later, Mintrop got a patent on the "examination of rock layers" using seismic head waves, now also called Mintrop waves.



Emil Wiechert (1861–1928) on the roof of the Göttingen Institute of Geophysics circa 1922. In the background lies the city of Göttingen and besides Wiechert there is a glass ball to measure the daily amount of sunshine. This instrument is still in use. Photo courtesy of Institute of Geophysics, Göttingen.

Beno Gutenberg published his results on the depth to the core-mantle boundary in 1913. His value of 2900 km is within 0.3% of the one obtained from modern seismological Earth models, and the outcome of all following investigations was within Gutenberg's error bars (also see *Brush* [1980]).

During and after World War I, the seismological activities declined. However, due to Wiechert's and Angenheister's efforts, the Institute of Geophysics at Göttingen continued to contribute important seismological findings.

The participating students' efforts in placing this material on the World Wide Web can be seen at www.uni-geophys.gwdg.de/~eifel/Seismo_HTML/history.html. The site begins with a general introduction on the history of the Institute for Geophysics that emphasizes seismology. Detailed biographies of the most important seismologists who worked at Göttingen before World War I under institute director Emil Wiechert then follow.

The extended biographies on Ludwig Geiger and Gustav H. Angenheister have been submitted to the handbook on earthquake and engineering seismology of the International Association of Seismology and Physics of the Earth's Interior. Comprehensive bibliographies of Angenheister, Geiger, and Wiechert are also available on the Web site.

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