Evidence May Indicate Recent Warming of Shallow Slope Bottom Water Off New Jersey Shore

Thermal data from boreholes on land have been used to infer recent changes in land-surface temperatures, since these surface temperature changes propagate downward into the Earth and leave a measurable record [e.g., Pollack and Chapman, 1993]. The temperature history of bottom water offshore New Jersey has been estimated using thermal data from the upper 150 m of sediment below the seafloor, and the results are surprising. The data appear to indicate a large temperature rise, on the order of 6-10°C, followed by a temperature decrease, all during the last 50-150 years and within a restricted area.

Data were collected during Ocean Drilling Program (ODP) Leg 150 (Figure 1) [Mountain et al., 1994], with the idea that shelf and slope waters might vary in temperature on decadal to centennial time-scales, and that such variations should be recorded in subseafloor sediments. Like Earth’s surface on land, the seafloor acts as a low-pass filter. High-frequency temperature variations are filtered out in the shallowest sediments and longer-period variations penetrate to greater depths. Given typical oceanic sediment properties, seasonal signals penetrate to depths of a few meters below the seafloor (mbsf), while centennial signals may penetrate several tens to over a hundred meters.

Thermal diffusion reduces the amplitude of these signals as they propagate, so longer-term variations must be relatively larger to be preserved. Given depth limitations and typical sampling intervals of ODP piston coring (100-150 mbsf and 10 m, respectively), as well as uncertainties about in situ temperature and thermal conductivity determinations, it was anticipated that bottom water temperature variations on the order of 14°C within the last several hundred years might be observable during this study. We are not able to explain our observations with confidence in terms of directly observed oceanographic or geological processes. We have prepared this report to make others aware of our findings, to solicit ideas as to what these observations may indicate, and to suggest that additional investigation of temperature changes in shallow bottom water may be worthwhile. A more detailed discussion of data collection, processing, interpretation, and modeling methods can be found at Web site http://emerald.ucsc.edu/~afisher.

In situ sediment temperatures were measured at ODP Sites 902 and 903 (Figure 1), on the slope of the U.S. eastern continental shelf (see Miller et al., 1994, Mountain et al., 1994, and references therein). Site 902 was drilled in 802 m of water, while Site 903 was drilled 4.4 km upslope in 453 m of water. Both sites were located on the edges of submarine canyons (Figure 1). Surface waters in this region are dominated by shelf, slope, and Gulf Stream sources. The main thermocline is seasonally stable at depths <400 m and Gulf Stream eddies ("warm core rings") are common. Surface sediments grade from silt to clay (up slope to down slope). Since the early Holocene there has been little river discharge.
Sediment temperatures were measured on recovered cores using the needle-probe method [Von Herzen and Maxwell, 1959]. Temperature data were collected at subseafloor depth spacing of 0.5-9.5 m, while thermal conductivity data were collected every 0.5-1.0 m.

Initial interpretations of all APC tool measurements [Mountain et al., 1994] have been reprocessed. Some sediment temperatures were significantly revised and others that were unreliable due to tool motion in the sediment were rejected. Temperature data were processed with a range of reasonable thermal conductivity values, and the resulting differences in temperatures indicate minimal uncertainties. Corer depth errors result from uncertainty in the depth of the drill string (21 m) and incomplete corer stroke and recovery.

Figure 2 shows estimated in situ temperatures from the most reliable deployments plotted versus cumulative thermal resistance. The thermal resistance can be understood as sub-seafloor depth corrected for differences in thermal conductivity [e.g., Davis, 1988]. If the thermal regime is at steady state and is purely conductive, this plot should yield a straight line. This is the case for Site 902 (Figure 2a).

The seven deepest measurements at nearby Site 903 indicate similar steady-state, conductive conditions (Figure 2b). However, the shallowest six measurements document a negative thermal gradient. The magnitude and consistency of this departure from steady-state, conductive conditions is striking. Extrapolation of the deep thermal gradients from Sites 902 and 903 to the seafloor suggests regional bottom water temperatures around 4.5°C, somewhat cooler than the lowest value measured during ODP Leg 150. The shallowest measurement at Site 903 provides only an upper bound on in situ temperature because of probe motion during deployment (Figure 2b).

Possible causes of the observed thermal structure at Site 903 include recent sediment slumping or fluid flow within the sediments. To explain the Site 903 thermal profile by sediment slumping, the upper 80 mbsf would need to have moved from higher on the slope quite recently, becoming thermally homogenized while preserving complete internal sediment and geochemical structure. There is no sedimentological or structural evidence for such extensive mass wasting at this site, only minor slumping near the seafloor [Mountain et al., 1994; Christensen et al., 1996].

Geochemical profiles are highly sensitive to fluid flow (more so than thermal profiles), but pore fluids squeezed from the upper 160 mbsf of sediments at Site 903 indicate dominantly diffusive and reactive conditions [Mountain et al., 1994; Hicks et al., 1996]. There is no geochemical evidence for transient lateral fluid flow (which under extreme conditions may cause a negative geothermal gradient) or for pervasive vertical fluid flow. The latter process would tend to reduce the thermal gradient but not make it negative. While we cannot completely eliminate the possibility that some combination of these mechanisms is responsible for the unusual thermal structure at Site 903, the observational evidence is inconsistent with these explanations.

If the observed thermal structure at Site 903 resulted from changes in bottom water temperatures, the general scenario is as follows: steady-state heat flow was initially 45 mW/m² with a bottom water temperature near 4.5°C. Bottom water temperature increased rapidly and generated the negative thermal gradient above 80 mbsf. The bottom water temperature subsequently decreased back towards the present value.

To estimate the time-temperature history of bottom water at Site 903, we analyzed the sediment temperature and thermal conductivity data using an inverse model [Wang, 1992]. The model estimates the temperature versus time history at an upper boundary of a conductive system. The time-series is constrained to be bounded and smooth, and the model incorporates a multilayer thermal...
was discovered that large variations in sea­
ation, and all sediment temperatures were
allowing large changes during the simula­
tion of 2.0°C. The temporal variation in bot­
ture during the time of the simulation was
tested with several dozen simulations and it
observed sediment temperatures. Two exam­
ple results are compared to the estimated sed­
iments in Figure 3.

In Case A, the mean bottom water tempera­
ture of about 5.5°C until 150 years before present (ybp), followed by a rapid warming to 11.3°C (peaking around 25 ybp), and a subsequent cooling (Figure 3b).

The match to subsurface sediment tempera­
tures is only fair, however, with a poor match
at the two inflection points (above and below
the negative thermal gradient; Figure 3a).

In Case B, lower uncertainties (0.1 °C) were
applied to the inflection points and the deepest
three measurements. The model results provide
a better fit to the observations but require even
larger variations in bottom water temperature,
from 4°C to 15°C over the last 80 ybp.

In general, the best fit to the data was
achieved when small uncertainties were
placed on the estimated temperatures and
when the bottom water temperature was
allowed to vary over a wide range. When
uncertainties were increased and/or the vari­
ations in bottom-water temperatures were
assigned uncertainties of 0.5°C. The resulting
inverse solution includes a bottom water
temperature range over the last 85 years. Observations
were made at individual locations.
Possibly it was the shift of the thermocline,
with sharp vertical and lateral gradients in
water temperatures at the depth of the
seafloor crossing Site 903. These gradients
would need to be quite sharp, as the lateral
offset between Sites 903 and 902 is only about
4 km, and there is no apparent change in bot­
tom water temperature at Site 902. Another
possibility is that variations in bottom water
temperatures reflect migration of a channel
for cross-shelf transport, whereby warm, sedi­
ment-laden bottom water flowed for some
years across Site 903, but there is no evidence that any of these processes occurred at
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and upper slope where variations in bottom water temperatures have been recorded on decadal timescales. It may be worthwhile to collect additional sediment temperatures within the upper 100 mbsf in these settings to test the idea that subsurface temperatures along continental margins and in marginal seas can be used to estimate changes during the past. If significant changes in bottom water temperatures are found to occur over spatially restricted areas, this could have implications for estimating short-term climate and/or ocean current variability.

**Acknowledgments**

This study of sediment temperatures and changes in bottom water temperatures along the New Jersey margin would not have been possible without the support of the co-chief scientists Greg Mountain and Ken Miller and the ODP Leg 150 scientific party. John Compton provided an early assessment of pore water profiles at Sites 902 and 903. This work was supported by NSF grants OCE-9416735 [later transferred to UCSC as OCE-9501637 (AF) and OCE-9415301 (RVH)]. Marlene Noble and Ken Drinkwater provided thoughtful reviews.

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**References**


**Measurements Show the Need for a Rapid Response to Space Weather Disturbances**

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"Storms" in space may significantly damage power grids and other sensitive technological systems. The onset of storm effects is related to the spread of disturbances in the near-Earth space environment. Studies are showing that disturbances spread more rapidly than previously thought. Knowing how to rapidly help determine how fast disturbances must be taken to protect such systems when a storm appears imminent.

The source of energy for space weather disturbances is the continuous stream of plasma directed outward from the Sun called the solar wind. The magnetosphere is the region of space that is shielded from the solar wind by the Earth's magnetic field. The portion of the magnetosphere lying at latitudes of 100-600 km is the ionosphere. Space weather effects are more readily observed there by ground-based instruments than in the outer reaches of the magnetosphere. An important manifestation of the coupling between the solar wind and magnetosphere is the circulation, or convection, of ionospheric plasma at high latitudes.

Storm-type disturbances often occur when the coupling between the solar wind and the magnetosphere across their boundary changes from weak to strong. The disturbances manifest themselves in several ways. More intense electrical current flows along magnetic field lines between the magnetosphere and ionosphere, stronger electric fields and plasma convection occur in the high-latitude ionosphere, and auroral precipitation intensifies and extends to lower latitudes. Determining how rapidly the magnetosphere-ionosphere components respond to the solar wind is analogous to meteorological efforts to determine the strength of storms. Climate research will need to identify the sign of the IMF (magnetic field) to determine the coupling between the solar wind and the magnetosphere.

**Response to Space Weather Disturbances**

Measurements show the need for a rapid response to space weather disturbances.

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