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

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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 timescales, 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 1-4°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

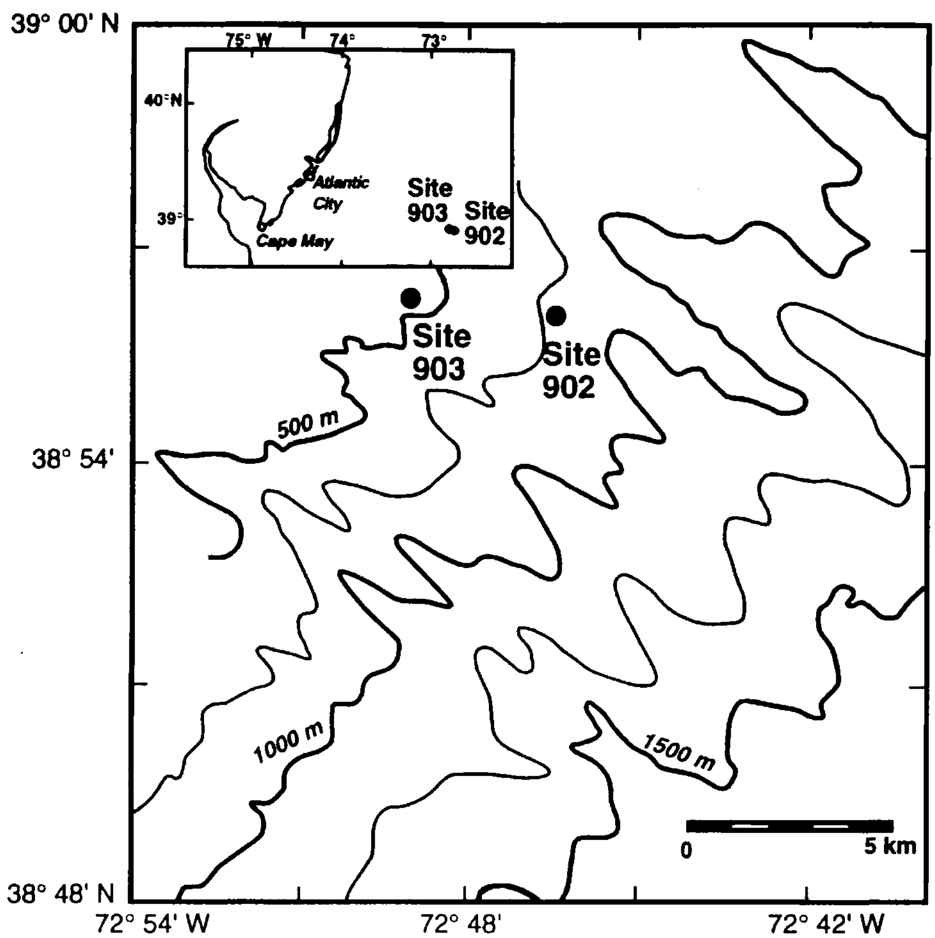

Fig. 1. Site map showing locations of ODP Sites 902 and 903 and local bathymetry, with depth contours in meters (modified from Miller et al., 1994; Mountain et al., 1994).

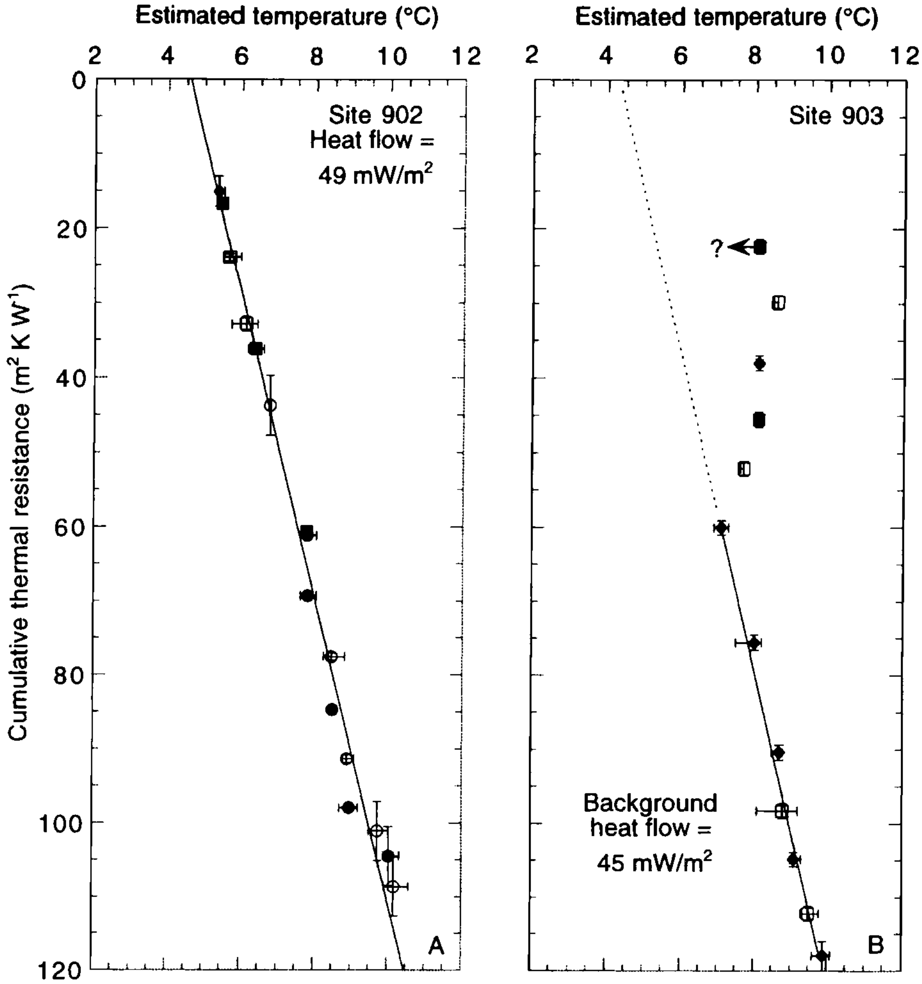

Fig. 2. In situ sediment temperatures versus cumulative thermal resistance (depth corrected for differences in thermal conductivity) determined from data collected during ODP Leg 150. Horizontal bars indicate ranges in temperatures estimated with a range of reasonable sediment thermal conductivities. Vertical bars indicate depth uncertainties. a) Site 902. Filled symbols are from data collected with APC Tool #12, and open symbols are from data collected with APC Tool #18. Diamonds are from Hole 902A, squares are from Hole 902C, and circles are from Hole 902D. Solid line is a least-squares best fit to all data. b) Site 903. All data are from Hole 903A, diamonds are from APC Tool #12, filled squares are from Tool #17, and open squares are from Tool #18. Dashed line is projection of deep gradient to the seafloor.

deposited due to the rise in sea level. Most modern sedimentation is hemipelagic, with some resuspended riverine mud and shelf sediments, and downslope transport is limited [*Miller et al.*, 1994].

Sediment temperatures were measured during ODP Leg 150 using the Advanced Piston Coring (APC) temperature shoe (APC tool), which is composed of a power supply, data logger, and temperature sensor fit within a sediment coring shoe. Precruise calibration of these tools provided absolute accuracy of greater than or equal to 0.006°C over a range of 0-30°C. The tool is run as part of regular coring operations, but after the coring assembly is fired into the sediments, it is left in place for 8-10 minutes to allow partial thermal equilibration of the sensor. Data were processed using conventional methods to extrapolate the recorded temperatures to equilibrium values following tool insertion [*Horai and Von Herzen*, 1985], and sediment thermal conductivities 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 (≥1 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 subseafloor 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), but 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±0.2 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 sedimentary 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; *McHugh 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/m^2 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

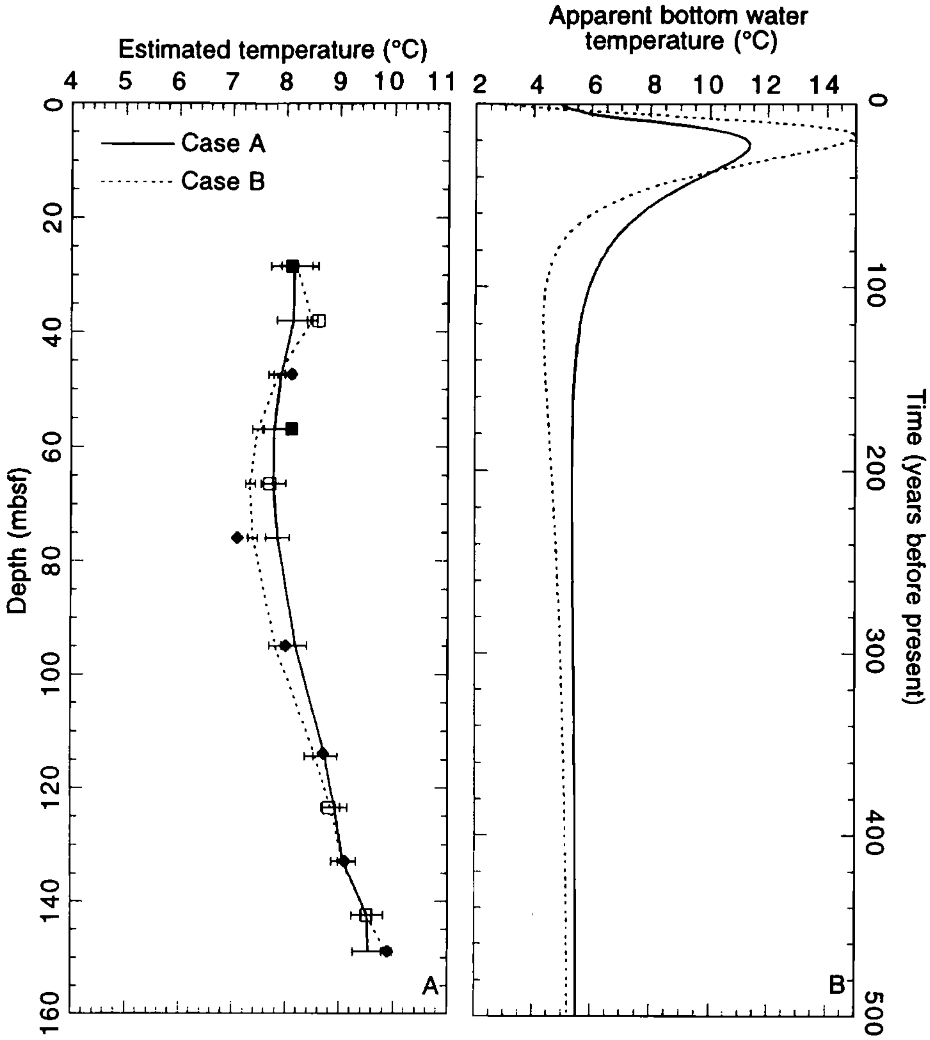

Fig. 3. Selected results of inverse models [Wang, 1992] using data constraints from Site 903 to estimate the recent history of bottom water temperatures. a) Comparison of model results with subseafloor observations. Symbols are as in Figure 1. Horizontal error bars around model results indicate the standard deviations of estimated in situ temperatures. Uncertainties in measured temperatures and measurement depths are not shown. Cases are described in the article. b) Apparent bottom water temperature histories for the same two cases are shown in panel a.

conductivity structure as well as uncertainties in both thermal conductivities and temperatures [*Wang*, 1992].

The model was used to estimate the last 2000 years of seafloor temperatures at Site 903. The constraints on the model were 12 subseafloor temperatures (Figure 2b), and a 12-layer thermal conductivity structure based on available measurements [*Mountain et al.*, 1994]. A range of numerical parameters was tested with several dozen simulations and it was discovered that large variations in seafloor temperatures were required to match the observed sediment temperatures. Two example results are compared to the estimated sediment temperatures in Figure 3.

In Case A, the mean bottom water temperature during the time of the simulation was assumed to be 4.0°C with a standard deviation of 2.0°C. The temporal variation in bottom water temperatures was set to 8.0°C, allowing large changes during the simulation, and all sediment temperatures were assigned uncertainties of 0.5°C. The resulting inverse solution includes a bottom water temperature 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 subseafloor sediment temperatures 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 variations in bottom-water temperatures were reduced, a less variable temperature-time record was generated, but the fit to the subseafloor data was poorer.

If the shallowest data point at Site 903 is omitted, a reasonably good fit to the remaining data also can be obtained with a model comprising an initial bottom water temperature of 4.5°C and a sudden increase of 8-10°C about 50-100 ybp. A subsequent decrease in bottom water temperature is then required to be consistent with present-day bottom water temperatures.

An examination of NOAA hydrographic data in the National Oceanographic Data Center's World Oceanographic Atlas (using the online GOODbase search engine) revealed that there are no direct observations of water column temperatures below 400 m water depth from within 10 km of Site 903 (38.938°N, 72.817°W) prior to 1970, and no data deeper than 200 m prior to 1959. The available hydrographic data from within 10 km of Site 903 also show no consistent trends during this time.

Data from 400-500 m water depth between 30°N and 45°N show an enormous temperature range over the last 85 years. Observations from 400 m made during 1912-1940 within several degrees of Site 903 include many values above 10°C. Temperatures above 15°C at 400 m water depth are found at latitudes >37 N and are common at latitudes <35 N, but temperatures at 400 m depth at 38-40°N are generally 5-8°C. The historical data are inconsistent, however, and observations of high temperatures in 1 year are commonly followed by much lower temperatures several years later. In addition, measurements made early in the century vary in quality, and few repeat measurements were made at individual locations.

The seafloor topography around Site 903 is irregular (Figure 1), and if bottom water temperatures varied in this area over the last 50-150 years, it could indicate local processes. Perhaps there was a shift in 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 bottom 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, sediment-laden bottom water flowed for some years across Site 903, and then this channel was abandoned. At present we have no evidence that any of these processes occurred at Site 903, but the lack of a suitable alternative explanation leaves recent changes in bottom water temperatures as one option.

We are hopeful that other scientists working in this area may have data that will support or refute the hypothesis that bottom water temperatures at Site 903 have changed by as much as 6-10°C over the last 50-150 years. If other data from near Site 903 are not available, perhaps there are reliable records from similar settings along the continental shelf 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 subseafloor temperatures along continental margins and in marginal seas can be used to estimate changes during the recent past. If significant changes in bottom water temperatures are found to occur over spatially restricted areas, this could have implications for estimates of short-term climate and/or ocean current variability.

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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 just how rapidly will help determine how fast steps 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 altitudes of 100-600 km is the ionosphere. Space weather effects are more readily observed there by groundbased 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 track storm systems. However, terrestrial storm systems evolve over periods of days while the timescales for magnetospheric disturbances are much smaller, perhaps hours or even minutes.

The shielding effectiveness of the Earth's magnetic field depends in large part on the orientation of the interplanetary magnetic field (IMF) carried by the solar wind plasma. When the IMF has a component that is antiparallel to the terrestrial field at the magnetospheric boundary (a condition called southward IMF or B_Z-), the coupling of plasma and energy between the solar wind and magnetosphere is enhanced in comparison to northward (B_Z+) IMF. The strongest coupling, accompanied by major geomagnetic disturbances, occurs when the solar wind plasma is very dense and energized and the IMF is dominated by B_Z-.

For B_Z- the plasma convection in the high-latitude ionosphere usually conforms to a two-cell pattern in which the plasma flows from noon to midnight, or antisunward, in the polar cap and returns to the dayside via sunward drifts at lower latitudes along the dawn and dusk flanks.

For strong B_Z+ the range of possible patterns is more varied but all include sunward flow at noon. Changes in the sign of B_Z can be expected to cause reconfigurations of the global convection pattern.

Owing to the difficulty of making simultaneous measurements over such a large region, the manner in which the pattern reconfigures is still unclear. Most studies have relied on effects observed at scattered locations to infer the onset and evolution of the pattern reconfiguration. These have tended to conclude that the pattern reconfigures on timescales of tens of minutes and that the onset of a response is delayed by increasing amounts

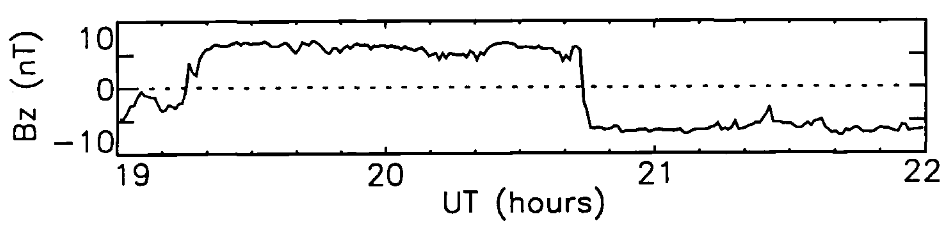

Fig. 1. Interplanetary magnetic field z-component data recorded at the position of the Wind satellite, November 24, 1996, 1900-2200 UT.