tors. Finally, it is possible to match any spacing of edge waves with the scale of some feature (from 3-m beach cusps to 30-km capes) by picking a certain wave period and mode. Therefore, the choice of edge wave modal number 3 by Dolan *et al.* (*1*) has no special meaning and would have extremely low energy relative to lower number modes. In order to invoke edge waves to explain this kind of shoreline response, it is necessary to demonstrate how such long waves were caused and how they can persist at the same wavelength through highly variable infragravity wave input.

We must conclude that the present configuration of the eastern shore of Virginia is the result of a regime of shoreline retreat responding to temporal and spatial variations in well-understood and documented coastal processes. Process variations result from reduced sediment supply, vertical tectonic movements, long-term changes in wave refraction over the continental shelf, and an apparent influence of late Pleistocene drainage systems, all operating in the ubiquitous presence of a rising sea level. More localized geomorphic responses within the system can be related to their time of onset and prevailing weather, local episodes of erosion and rapid retreat, local variations in sediment supply, and changes in inlet morphology and dynamics. The published works of many investigators establish the importance of these factors and influences to the coastal processes maintaining barrier shorelines during retreat. The recorded changes in the configuration of the eastern shore of Virginia suggest that a smoother shoreline configuration, rather than emerging cape-like features, can be anticipated in the future.

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The Rise of Global Mean Sea Level as an Indication of Climate Change

Abstract. *Rising mean sea level, it is proposed, is a significant indicator of global climate change. The principal factors that can have contributed to the observed increases of global mean sea level in recent decades are thermal expansion of the oceans and the discharge of polar ice sheets. Calculations indicate that thermal expansion cannot be the sole factor responsible for the observed rise in sea level over the last 40 years; significant discharges of polar ice must also be occurring. Global warming, due in some degree presumably to increasing atmospheric carbon dioxide, has been opposed by the extraction of heat necessary to melt the discharged ice. During the past 40 years more than 50,000 cubic kilometers of ice has been discharged and has melted, reducing the surface warming that might otherwise have occurred by as much as a factor of 2. The transfer of mass from the polar regions to a thin spherical shell covering all the oceans should have increased the earth's moment of inertia and correspondingly reduced the speed of rotation by about 1.5 parts in 10^8. This accounts for about three quarters of the observed fractional reduction in the earth's angular velocity since 1940. Monitoring of global mean sea level, ocean surface temperatures, and the earth's speed of rotation should be complemented by monitoring of the polar ice sheets, as is now possible by satellite altimetry. All parts of the puzzle need to be examined in order that a consistent picture emerge.*

The ocean is a logical domain in which to search for evidence of climate change such as may be caused by increasing concentrations of atmospheric CO_2. Because the oceans are so closely coupled to the atmosphere and because of the very large heat capacity of the oceans, any climate change of global proportions will necessarily be reflected in oceanic conditions.

The two most readily identifiable measures of globally integrated oceanic conditions are the mean temperature and the volume of the oceans as reflected by the global mean sea level. It is not now feasible to monitor closely the mean temperature of the oceans. Even mean surface temperatures cannot now be determined with sufficient accuracy to detect unambiguously interannual or decadal variations. Improvements in satellite measurements of ocean surface temperature may, in time, remedy the major sampling problems of obtaining valid mean surface temperatures, but for the moment only conjectures about variations in the mean temperature of the oceans are possible. On the other hand, evidence of changes in the mean thermal state of the oceans can be found in changes of global mean sea level and may also be inferred from changes in mean atmospheric surface temperatures. Modeling experiments (*1*) strongly indicate that, in the absence of any changes in the mean ocean surface temperature, global mean surface air temperatures would not vary either.

There is consensus (*2*) that during the period between 1890 and 1940 the mean surface air temperature of the Northern Hemisphere rose between about 0.3° and 0.6°C (Fig. 1A). One cannot be certain that these estimates applied to the entire globe, since the Southern Hemisphere is only poorly represented in available data. For the sake of argument, however, we will assume that the lowest of these values (0.3°C) applies to the entire earth and also is representative of the upper mixed layer of the ocean. Because the upper waters of the ocean are not wholly uncoupled from the deeper layers, we will also assume that any slowly

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evolving perturbation is distributed according to a profile suggested by Cess and Goldenberg (*3*). This profile consists of a temperature change at the surface that is constant through the uppermost 70 m and then falls off exponentially with depth with a scale height of about 367 m. On the basis of such a profile, we have estimated the change in sea level that would result from the thermal expansion of the ocean (Table 1). The calculated value of 24.0 mm, based on the most conservative estimate of the increase in mean surface temperature, accounts for more than half the actual sea level rise of about 45 mm during the same time period (1890 to 1940) reported by Fairbridge and Krebs (*4*) on the basis of tide gauge measurements (Fig. 1B).

According to Emery (*5*), the global mean sea level has risen over the most recent 40 years at an average rate of more than 3 mm per year. During this period, however, the global mean temperature appears to have decreased by about 0.2°C. This most recent and more rapid sea level rise cannot, therefore, be attributed to thermal expansion. One must look for a more likely cause. The only plausible explanation seems to be an increase in the discharge rate of the polar ice sheets.

The relationship among the changes in global mean surface temperature, global mean sea level, and the mass of discharged polar ice during any given interval may be expressed as

Table 1. Estimation of sea level rise due to a 0.3°C increase in surface temperature.

Ocean depth layer (m)	Coefficient of thermal expansion ($\times 10^6$)	ΔT (°C)	Increment of sea level rise (mm)
0– 70	257	0.3	5.4
70– 170	227	0.26	5.9
170– 370	192	0.17	6.4
370– 570	166	0.09	3.0
570– 770	147	0.05	1.4
770–1070	142	0.02	1.0
1070–1570	136	0.01	0.7
1570–2070	135	0.003	0.2
2070–3070	149	0.0002	0.03
Total sea level rise			24.0

$$\Delta H = \alpha_1 \Delta T_1 + \alpha_2 \Delta T_2 + \beta \Delta M \quad (1)$$

$$\Delta T_2 = -\gamma \Delta M \quad (2)$$

where ΔH is the change in the height of the mean sea level, ΔM is the change of oceanic mass due to an equal but opposite change in the mass of the polar ice sheets, ΔT_1 is the externally imposed change in mean surface temperature, and ΔT_2 is the change in the mean ocean surface temperature induced by the melting of the polar ice. The coefficients α_1, α_2, β, and γ are estimated as follows: $\alpha_1 = 80$ mm per degree Celsius, $\alpha_2 = 18$ mm per degree Celsius, $\beta = 2.7 \times 10^{-15}$ mm/kg, and $\gamma = 4.0 \times 10^{-18}$ °C/kg.

The calculations of values for α_1, α_2, and γ involve assumptions regarding the vertical profile of temperature change. The terms $\alpha_1 \Delta T_1$ and $\alpha_2 \Delta T_2$ represent thermal expansion and contraction effects, but they relate to temperature changes that occur over different time scales. In the calculation of α_1 (the coefficient expressing the rise in sea level due to thermal expansion), we have used the Cess-Goldenberg profile, which is appropriate to the time scale of CO_2 changes in the atmosphere—about 33 years. The calculations of α_2 and γ are based on a different profile of temperature change, more consistent with the apparently more rapid sea level rise of recent years. For these coefficients, which express the thermal effects of the discharged ice, we assume in the calculations a temperature perturbation confined to the upper 70 m of the ocean, there being less time for the less dense meltwater to mix with deeper, more saline waters. The coefficient γ is derived from the latent heat of fusion of ice and the specific heat required to warm the meltwater to the mean temperature of oceanic surface water. In the last term of Eq. 1, the mass added to the ocean, β is the ratio of the mean specific volume of seawater to the surface area of the oceans. From Eqs. 1 and 2, one can write

$$\Delta H = \alpha_1 \Delta T_1 + (\beta - \alpha_2 \gamma)\, \Delta M \quad (3)$$

Thus the dependence of ΔH on α_2 and γ appears only through their product, which is small compared to β in any case and much less sensitive to the distribution of temperature change than either α_2 or γ separately.

It is instructive to apply these relationships to the interval between 1890 and 1980, during which the sea level has increased by about 165 mm, and ΔT_1, according to Cess and Goldenberg, should have been about 0.4°C. From Eq. 3 we can calculate

$$\Delta M = \frac{\Delta H - \alpha_1 \Delta T_1}{\beta - \alpha_2 \gamma} = \frac{165 - 32}{2.6 \times 10^{-15}} = 51 \times 10^{15} \text{ kg}$$

and then, from Eq. 2

$$\Delta T_2 = -\gamma \Delta M = -0.2\text{°C}$$

Thus one should expect a net change in the surface mean temperature of $\Delta T_1 + \Delta T_2 = 0.2$°C. The negative feedback of the melting ice on the mean temperature reduces the observable

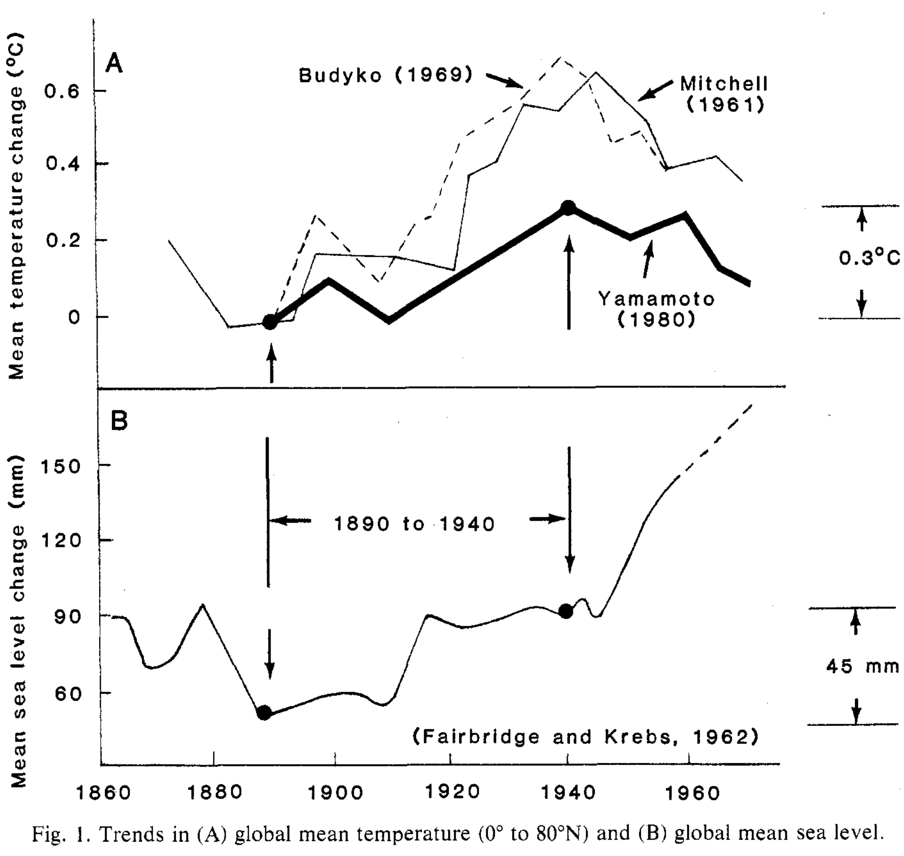

Fig. 1. Trends in (A) global mean temperature (0° to 80°N) and (B) global mean sea level.

change by about half. A different assumption regarding the vertical profile of induced mean temperature perturbations might have reduced the calculated negative feedback by a factor of 3 or 4. Nevertheless, it is in the right direction to contribute to the explanation of the relatively modest observed global warming.

The apparent consistency between sea level changes and the effective warming may be spurious. Our arguments included gross approximations. A very important link is the change in the volume of the polar ice sheets, for which credible estimates are not now available. It is possible, however, to acquire measurements of the polar ice sheets with sufficient accuracy to confirm their crucial role in global climate change. Satellite-borne radio altimeters, as demonstrated on GEOS-3 and Seasat (*6*), can now measure the surface elevation of ice sheets to within about 2 m. Since the ratio of the area of the West Antarctic ice sheet to that of the ocean is of the order of 1 to 200, a mean change in the thickness of the ice of 2 m corresponds to a sea level change of about 1 cm. Thus satellite altimetry is capable of supplying the important connecting link in an assessment of the relative roles of externally produced heating and ice melting in bringing about observed changes in sea level.

Another geophysical measurement that can contribute to our interpretation of these changes is the rate of rotation of the earth. The discharge and subsequent dispersion as meltwater of large quantities of polar ice is, in effect, a mass transfer away from the earth's axis of rotation and must change the earth's moment of inertia. This change should be reflected in the planet's rate of rotation. The magnitude of this effect can be estimated if one takes the difference in moment of inertia between a uniform layer of water, equivalent to a thin spherical shell, and a polar ice cap composed of the same mass of water circling the globe as an annulus at high latitude (*7*). This difference, divided by the nominal value for the earth's moment of inertia, provides an approximation for the fractional change in the earth's rate of rotation

$$\Delta \dot{m} = \frac{I_s - I_i}{I_e} \quad (4)$$

where $I_s = 2/3\Delta M r^2$, $I_i = \Delta M(r \cos \theta)^2$, $I_e = 8.04 \times 10^{37}$ kg-m^2 (the earth's moment of inertia), r is the radius of the earth, and θ is the mean latitude (taken to be 80°S) of the West Antarctic ice sheet, which is assumed to be the principal source of the discharged ice. The calculated value of the relative change in the earth's rate of rotation that one should expect during the last 40 years (during which most of this discharge is presumed to have occurred) is 1.5×10^{-8}. This accounts for about three quarters of the fractional reduction in the earth's angular velocity that has been observed during this period (*8*).

One can conclude from these considerations that global mean sea level, the earth's speed of rotation, and the masses of the polar ice sheets are important parameters for the detection and identification of global climate change. Each factor separately provides extremely important information, but the value of these factors taken together in allowing us to make credible assessments of the interactive behavior of sea level and global mean temperature would be especially great.

For the present it can only be stated as a reasonable hypothesis that the rapid rise in sea level over the past 40 years, and especially since 1970, is due primarily to the accelerated discharge of polar ice sheets. The extraction of latent heat as a consequence of the discharge and melting of more than 50,000 km^3 of ice over the past 40 years has significantly reduced the net sensible increase in global mean surface temperatures.

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Occultation by a Possible Third Satellite of Neptune

Abstract. *The 24 May 1981 close approach of Neptune to an uncataloged star was photoelectrically monitored from two observatories separated by 6 kilometers parallel to the occultation track. An 8.1-second drop in signal, recorded simultaneously at both sites, is interpreted as resulting from the passage of a third satellite of Neptune in front of the star. From the duration of the event, the derived minimum diameter for an object sharing Neptune's motion is 180 kilometers. If the object was in Neptune's equatorial plane and there are no significant errors in the prediction ephemeris, the object was located at a distance of 3 Neptune radii from Neptune's center.*

The occultation of a star by Neptune is an unusual event, occurring about once a year for stars that are sufficiently bright to permit their observation (*1*). Such events provide a unique opportunity to probe the space near Neptune for faint rings and satellites and to investigate the structure of Neptune's upper atmosphere. It was the observation of an occultation of a star by Uranus that revealed that planet's multiple ring system (*2*). Several groups have undertaken programs for observation of occultations by Neptune. Initial reports of three such events mention one partial secondary occultation at a distance of 1.5 Neptune radii (R_N) (*3*) but mention no other possible ring or satellite events (*4*).

On 24 May 1981 we observed the close approach of Neptune to a star with the 154-cm Catalina and the 1-m Mount Lemmon telescopes of the University of Arizona observatories. These telescopes are separated by 6 km (east-southeast to west-northwest) in a direction roughly aligned with the Neptune occultation track. The combined signals of Neptune and star were observed with identical dual-channel pulse counting photometers, which digitally recorded data at 10-msec intervals. Time signals from radio station WWV were digitized at the beginning and end of the data records. We used filters that gave wavelength coverage in the red channel of 845 to 930 nm at the 154-cm telescope and 770 to 930 nm at the 1-m telescope. The blue channel at both telescopes covered 450 to 500 nm.

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