Commentary

Sea level is rising: Do we know why?

Mark F. Meier*† and John M. Wahr‡

*INSTAAR and Department of Geological Sciences and ‡CIRES and Department of Physics, University of Colorado, Boulder, CO 80309

The gradual rise of sea level is one of the most troubling aspects of global change, especially because it is likely to accelerate in the future as global warming progresses. Understanding the linkage between warming climate and sea-level rise therefore is important and has been the subject of much study (e.g., refs. 1–5). Two processes are involved: an increase of the mass of water in the oceans (the eustatic component), derived largely from the melting of ice on land, and an increase of the volume of the ocean without change in mass (the steric component), largely caused by the thermal expansion of ocean water. Neither of these components is understood fully, and observations are not sufficient yet to develop a precise assessment of the causes of present-day sea-level rise let alone a projection of future rise. In fact many of the analyses produce conflicting results. The article by Munk (6) in this issue of PNAS enlightens and sharpens our understanding of the enigma before us by examining a number of geophysical constraints on the process.

Societal and economic impacts of sea-level rise are evident already, and the consequences of continued rise are substantial (2). Beach erosion and shoreline retreat affect valuable real estate in developed nations and the livelihood of many waterfront communities in developing countries. Shoreline retreat may pinch out coastal wetlands against developed areas, or the wetlands may be harmed irreversibly if the rate of sea-level rise exceeds the rate at which the biota can adapt. Rising sea level can influence the rate of salt-water incursion into coastal aquifers, expansion of the salt-water wedge in estuaries, and the probability of damage from storm surges along coastlines. More than 100 million people live within 1 m of the mean sea level (7), and the problem is especially urgent and serious for the low-lying small island nations of the world.

Most published values for global sea-level rise are based on tide-gage data provided by the Permanent Service for Sea Level, adjusted in various ways to account for the nonrepresentative sampling of gage locations and local rates of uplift or depression of the land caused by the ongoing postglacial rebound (also called glacial isostatic adjustment). These adjusted observations and the estimated component causes of sea-level change during the 20th century were summarized in the scientific assessments of the Intergovernmental Panel on Climate Change (IPCC; refs. 4 and 5; Table 1). The problem of understanding current sea-level rise is obvious from these numbers: the central value of the "observed" rise is twice the central value of the sum of the estimated components, and the central value of the sum of the components is less than the minimum estimate of the observed rise. An additional complication is that the tide-gage observations show no statistically valid acceleration during the 20th century (8), but observations of ocean warming (and thus thermal expansion of ocean water) and glacier wastage (causing transfer of water from land to sea) clearly implies acceleration during the 20th century (5, 9, 10). To resolve these contradictions, we can investigate the measurement of global sea level, the observations of the climate-related processes that may affect sea level, and the "signature" of eustatic or steric changes of the ocean on the rotation of the Earth.

Table 1. Summary of IPCC estimates of the rate of sea-level rise in the 20th century

Component	IPCC 1996 (4) low/mid/high	IPCC 2001 (5) min/central/max
Thermal expansion	2/4/7	3/5/7
Glaciers	2/3.5/5	2/3/4
Greenland	−4/0/4	0/0.5/1*
Antarctica	−14/0/14	−2/−1/0*
Other eustatic	−5/0.5/7	−11/−0.5/10
Totals	−19/8/37	−8/7/22
Estimated from observations	10/18/25	10/15/20

Units are cm/cy following ref. 6.

*An additional eustatic contribution of 0/2.5/5 caused by long-term adjustment of the Greenland and Antarctic ice sheets (undifferentiated) since the last ice age, based on modeling, is included in ''Other eustatic.''

Traditionally, sea-level trends are calculated from tide-gage data. These gages are along coastlines, and whether they are representative of changes over the global ocean has been questioned recently. Cabanes *et al.* (11) suggest that the global pattern of sea-level rise measured by satellite altimetry 1993–1998 matches the calculated thermal expansion based on a recent summary of ocean temperature data (12) and note that when the longer-term global pattern of expansion is sampled at tide-gage locations, the resultant "average" overestimates the real global average. Can this overestimate be a resolution to the contradiction, as the "unexplained" difference between observed sea-level rise and the sum of the estimated components would shrink to a small value? Unfortunately, at least two nagging difficulties remain: the satellite data were taken over a relatively short period, and the sea-level change record shows significant fluctuations at decadal and multidecadal scales such that the agreement between the satellite data and steric expansion calculations may not be representative at a century-long time scale, and the Cabanes *et al.* analysis leaves little room for eustatic contributions of which there is good evidence (see below). In comparison to steric change caused by warming, the steric effect of change in the salinity structure is very small and can be discounted.

Munk (6) adds Earth rotation and other geodynamic results to examine the quantitative contributions of steric and eustatic sources of sea-level rise. He takes the "historic" sea-level rate of rise to be 18 cm per century (cm/cy), a value somewhat higher than the IPCC 2001 central value (Table 1) but less than that suggested by

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†To whom reprint requests should be addressed at: INSTAAR, University of Colorado, UCB 450, 1560 30th Street, Boulder, CO 80309-0450. E-mail: mark.meier@colorado.edu.

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some other authors (e.g., refs. 2 and 7). He then adds an average contribution of 3 cm caused by greenhouse warming during 1950–2000 (one could argue that this is actually included in the historic rise) and subtracts a value for a eustatic contribution of 6 cm attributed to the IPCC (5) to give a residual rise to be explained of 12 cm to the end of the century, which cannot be accounted for by steric expansion only; the heat content of ocean water would have to be far greater than that measured and modeled. Nor does he indicate that it could be accounted for by additional eustatic sources; this would imply a far larger "attrition of the polar ice sheets" than that estimated by the IPCC and conflicts with astronomic evidence (see below) as well.

Astronomical observations of Earth rotation offer insight into the steric/eustatic dilemma. Based on study of ancient eclipses, the length of day (lod) has increased by 1.7 milliseconds per century (ms/cy) over the last 2,000–3,000 years (13). However, this result is beset somewhat with large error limits. Lunar ranging indicates that tidal friction is causing a change of +2.3 ms/cy, which leaves a −0.6 ms/cy change in lod to be explained. The Peltier (14) and Lambeck and Johnson (15) geodynamic models of postglacial rebound are consistent with a secular change in lod of this order caused by the poleward movement of the Earth's mantle after deglaciation. Direct measurement of changes in the Earth's moment of inertia obtained from geodetic satellites suggests a change in lod of −0.38 to −0.6 ms/cy over the last 2–3 decades. Munk notes this "triple accord" but points out that it leaves essentially no room for a eustatic contribution and wonders if the accord could be a "cruel accident."

A major problem with this apparent accord is circularity: geodynamic models are tuned to be consistent with astronomic results. Also, Munk points out that the decadal variability in lod may mask century-long variability, and century-long values may be different from those expected over millennia. In fact, long-term smoothing of the eclipse data shows an apparent variability at a period of many centuries, with amplitude that could easily mask the −0.6 ms/cy component determined over a 100-year time scale. This apparent long-term variability could simply be the result of noise in the eclipse data; its presence does add an element of caution in attaching significance to the agreement between these three variables. The accord may be more apparent than real, but it is useful to give it further study.

Movement of the rotational pole (polar wander) gives insight into the source and amount of a eustatic contribution. The Antarctic ice sheet is nearly symmetric about the rotational pole. If changes in the ice sheet are similarly symmetric, they could have an important effect on lod while providing only a small contribution to polar wander. The Greenland ice sheet is sufficiently off-axis that it could have an effect on wander. Munk calculates that a 10-cm eustatic rise in sea level derived from Greenland would cause a movement of the pole of ≈10 m/cy toward the North Atlantic, approximately what is observed. However, the Peltier and Lambeck geodynamic models (14, 15) suggest a motion of about the same amount and direction caused by postglacial rebound with *no* change in sea level. Thus a Greenland contribution of this magnitude does not seem to be supported by polar-wander calculations if the rebound models are correct. Here again, we note that polar-wander calculations have been used as constraints when constructing the rebound models. Furthermore, models have shown that the steady mass redistribution associated with imperfectly compensated tectonic motion could well be a sizable fraction of the observed drift (16–18).

It might be tempting to consider some of Munk's arguments, and those from Cabanes *et al.* (11) and others as well, as implying that present-day sea-level rise is overestimated significantly by the tide-gage record and that the actual rise is almost entirely steric. However, a different analysis of geodynamic results (15) suggests the existence of an appreciable eustatic component. Recent glaciological studies suggest that small glaciers and the Greenland ice sheet are contributing water to the ocean at a rate that is even larger than that estimated by the IPCC in 2001 (5). These compilations indicate that the average rate of sea-level rise caused by small glacier wastage for the period 1961–1998 was 2.5–3.0 cm/cy but has been accelerating markedly in recent years (9, 10, 19). However, one problem has been the scarcity of data from the huge glaciers of south-central and southeast Alaska (Fig. 1). This problem has been solved in the last few years by use of repeated laser altimetry from a small aircraft by Echelmeyer and coworkers (20, 21).

Incorporating these glaciological data into a global synthesis suggests that the eustatic contribution by small glaciers since about 1988 is close to 5 cm/cy (M.F.M., unpublished compilation), which is more than the maximum value listed by the IPCC 2001 (5). Recent studies of the Greenland ice sheet by remote sensing also suggest a significant eustatic contribution of ≈1.3 cm/cy (22), slightly higher than the IPCC maximum value for the 20th century (5). Although this Greenland result is from observations over a short period (since 1993), measurements of change since a 1954 traverse of North Greenland suggest a larger rate of thinning (23) at least in northwest Greenland. The Alaska and Greenland contributions suggest a current influence on the Earth's rotation rate (lod) of −0.12 and −0.08 ms/cy, respectively, and a contribution to polar wander of 1.8 and 4.5 m/cy. Perhaps the Earth-rotation signature of this ice wastage will be detectable in the near future. There is no evidence known to us that *growth* of the Antarctic ice sheet is anywhere near large enough to cancel out the current eustatic contributions by small glaciers and the Greenland ice sheet. Also, there are a number of terrestrial processes such as ground-water depletion, land-use changes, and reservoir construction that have some effect on sea level. The IPCC 2001 study points out that these terrestrial

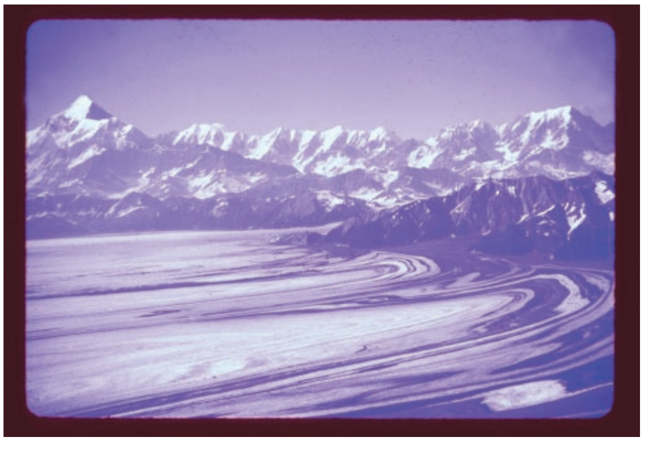

Fig. 1. The Malaspina Glacier (a small portion shown here), with an area of ≈5,000 km (2), and the equally large Bering Glacier now are known to be major sources of runoff to the ocean causing sea-level rise. These and nearby glaciers in southern Alaska and adjacent Canada now supply about as much glacial runoff as all the other glaciers in the world, exclusive of the two major ice sheets. Many previous analyses underestimated this contribution because of the lack of quality meteorological and glaciological data from the area. (Credit: U.S. Geological Survey/photo by Austin Post.)

effects might be appreciable and assigns very wide error limits; however, values near these extremes require the juxtaposition of very unlikely circumstances.

The important question is this: do we understand the causes of sea-level rise in the 20th century well enough to make confident projections for its course in the 21st century? Clearly, we still have a problem here. Munk has invoked some powerful arguments to clarify the issue, but as he states, the enigma is not resolved yet. Further study of both the steric and eustatic components of sea-level rise is needed. We eagerly await results from the gravity satellite GRACE that has just been launched and other new measurements in the fields of satellite geodesy, oceanography, glaciology, geodynamics, and climate change. It is interesting that such a seemingly simple problem such as understanding current sea-level rise can involve such a wide range of geophysical sciences.

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