THE U.S. COMMISSION ON OCEAN POLICY

Testimony in San Pedro, California
18 April 2002

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Admiral Watkins invited me to say some words about Oceanography in the past, as it might have some bearing on the work of your commission concerning the next fifty years. At the opening ceremony of *EXPO 2000* in Lisbon, I was given five minutes to cover *Oceanography before Satellites*; I presented a biblical event thought to be associated with a Mediterranean tsunami (Figure 1). Admiral Watkins did not have in mind going quite this far back.

The millennium turnover has produced a frenzy of backward looks, including those sponsored by NSF[1], ONR[2] and IAPSO[3]. The beginnings of the past century were highlighted by the "expedition mode" of oceanography, of a few ships chasing the vast oceans. Successive measurements differed in space *and* time. We believed in a steady circulation consisting of a few major ocean currents, and any variability in this space-time sampling was ascribed to changes in space. This view came to a crashing halt in the 1960s with the discovery of the mesoscale variability: 99% of the ocean's kinetic energy is associated with mesoscale variability, only a small fraction with the mean currents. For 100 years we had ignored the mesoscale storms (the ocean weather). In the atmosphere, it was rather the other way around; weather came first, emphasis on climate developed later.

How oceanographers could ignore ocean weather for so long is a bit of a mystery; oceanographers don't like to occupy the same station twice (observations may not agree) and ship captains don't like to heave to in rough weather. The consequences were severe. My teacher, Harald Sverdrup, considered the highest calling of the physical oceanographers to be providing information to those who study life in the sea. In retrospect, physical charts of temperature, salinity, nutrients, and currents were so unrealistic that they could not possibly have been of any

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[1] Munk, W. (2000) Achievements in Physical Oceanography. *50 Years of Ocean Discovery, National Academic Pr*ess: 44-50, 90.
[2] Munk, W. (2000) National Priorities and the Creation of a Discipline. *The Oceanography Greats Colloquia Series*, Scripps Institution of Oceanography, La Jolla, Ca.
[3] Munk, W. (2002) The evolution of Physical Oceanography in the last 100 years. *Oceanography* **15**(1): 135-141. The Joint IAPSO/IABO Assembly 2001: *An Ocean Odyssey*, Mar del Plata, Argentina.

use to the biologists. Similarly, scientists could find experimental support for their favorite theory no matter what the theory claimed.

My chief message is associated with the word SAMPLING. Let me illustrate with reference to the global mean surface temperatures for the last fifty years (Figure 2). Anyone sampling the first twenty-five years would come to a different conclusion than the last twenty-five years. More importantly, within the stationary first half epoch, a person sampling at the times shown by the blue dots would deduce global cooling, whereas the red dots imply an accelerating global warming. This is not an argument for more and more data, but for *adequate* sampling (a well-defined finite strategy).

I would have preferred to remind you of the romantic exploits of Nansen and Shackelton, or of the father of the previous speaker[4]; *sampling* is such a dull word. Nevertheless, the concept is of immense importance. Most of the previous century could be called a "century of undersampling."

Satellites have revolutionized oceanography. This is not so much because of the instrument packages (remarkable as they are) but the ability to sample adequately, and to sample globally (two different things). Take the U.S.–French altimetry mission TOPEX/POSEIDON that sampled the topography of the sea surface at about 7 km intervals to an astonishing precision of one-inch (Figure 3). When you go over the list of accomplishments, you find that what really made the difference was the sampling. I consider this the most successful ocean experiment of all times[5]. Yet, when John Apel came to Scripps and Woods Hole in 1970 to look for advise and support for the SEASAT altimetry mission, he received neither. Like most seafaring people, oceanographers are conservative people and what is not done from ships (sailing ships preferably) is not oceanography.

Having said this, I must emphasize that remote sensing enhances, rather than diminishes, the need of shipboard observations. Sea-truth, if you wish. But it goes further. In the few instances I have worked on the combination of satellite sensing from above plus the interior ocean sensing, the combination gave more information than the sum of each alone, like 1+ 1 = 4. With regard to remote sensing, I will put in a plug for acoustics (my special interest). The atmosphere is an

[4] Jean-Michel Cousteau spoke about education in oceanography for young people.
[5] It was only the persistent effort of Carl Wunsch that kept the TOPEX/POSEIDON mission from being cancelled on numerous occasions.

excellent propagator of radio (and other electromagnetic) waves, but a poor propagator of sound. The oceans, on the other hand, are opaque to electromagnetic energy but transparent to sound. Whales have known this much longer than oceanographers. Under appropriate conditions, an "imploding" light bulb in the ocean sound channel can be heard at 1000 km. Acoustics has been the mainstay of anti-submarine warfare (ASW); it could play a major role in ocean monitoring, especially the deeper oceans. We have an abysmal record of monitoring the abyssal ocean (Figure 4). There is enough ignorance here to leave plenty of room for first-order surprises.

There have been a number of revolutions on my watch (a knowledgeable person in pre-revolution days would utterly fail a post-revolution freshman test). We have mentioned the mesoscale revolution; another is plate tectonics. My guess for the next two revolutions is (i) climate and (ii) combined biological/physical/chemical models of ocean processes.

Now, for the future. In my estimate, the first priority is the establishment and maintenance of an Ocean Observing System. Some ingredients that are essential to its dual goal of managing and sustaining ocean assets and of understanding ocean processes are outlined in Figure 5. I have spoken (too much so) of the dangers of inadequate sampling, and not enough about the benefits of adequate sampling. The astounding returns to our investment in TOPEX/POSEIDON is an indication of what is to come from a rationally designed observing system. To stop now would be turning back the clock.

In reference to Figure 5, the dual goal of combining operational requirements with the need for increased understanding will be difficult to meet and very expensive (NOT understanding is infinitely more expensive). I have no experience in what it takes to make a working partnership.

Perhaps the most difficult requirement is that of *sustained* observations. Long time series take a long time no matter how good the engineering is. Some important climate oscillations have time scales of a several decades and longer. By any precedent it will take a time series of four or five wiggles to understand and predict these oscillations (i.e. a century of observations). Neither government, nor Academia has a proven record of sustained observations. It requires a priesthood of dedicated disciples. Perhaps the uniformed officer corps of the former Coast & Geodetic Service[6] came closest to reward and respect observations of the highest quality.

[6] However, this must not prevent the adaptation of new technology (such as replacing the Kelvin Tide machine with digital computers).

Looking backwards, a small number of people have made a big difference. Three men: Ewing, Iselin, and Revelle dominated the immediate post-war era. Together they set national priorities for years to come. The U.S. oceanographic budget was upped by more than an order of magnitude. There has not been such a determined leadership until Admiral Watkins took a position on ocean policy. My community is looking to him and to this commission for daring leadership.

The Office of Naval Research has played a singular role in progress in oceanography over last fifty years; I owe my career to their generous support. Somehow, in the years to come, there must be a place for such enlightened leadership.

Figure 1. The Red Sea parted (a tsunami?), allowing Moses and the Israelites to escape the pursuing soldiers of the Pharaoh (Munk, W. (2000) Oceanography before, and after, the advent of Satellites. *Satellites, Oceanography and Society, ed.* David Halpern, Elsevier: 1-4).

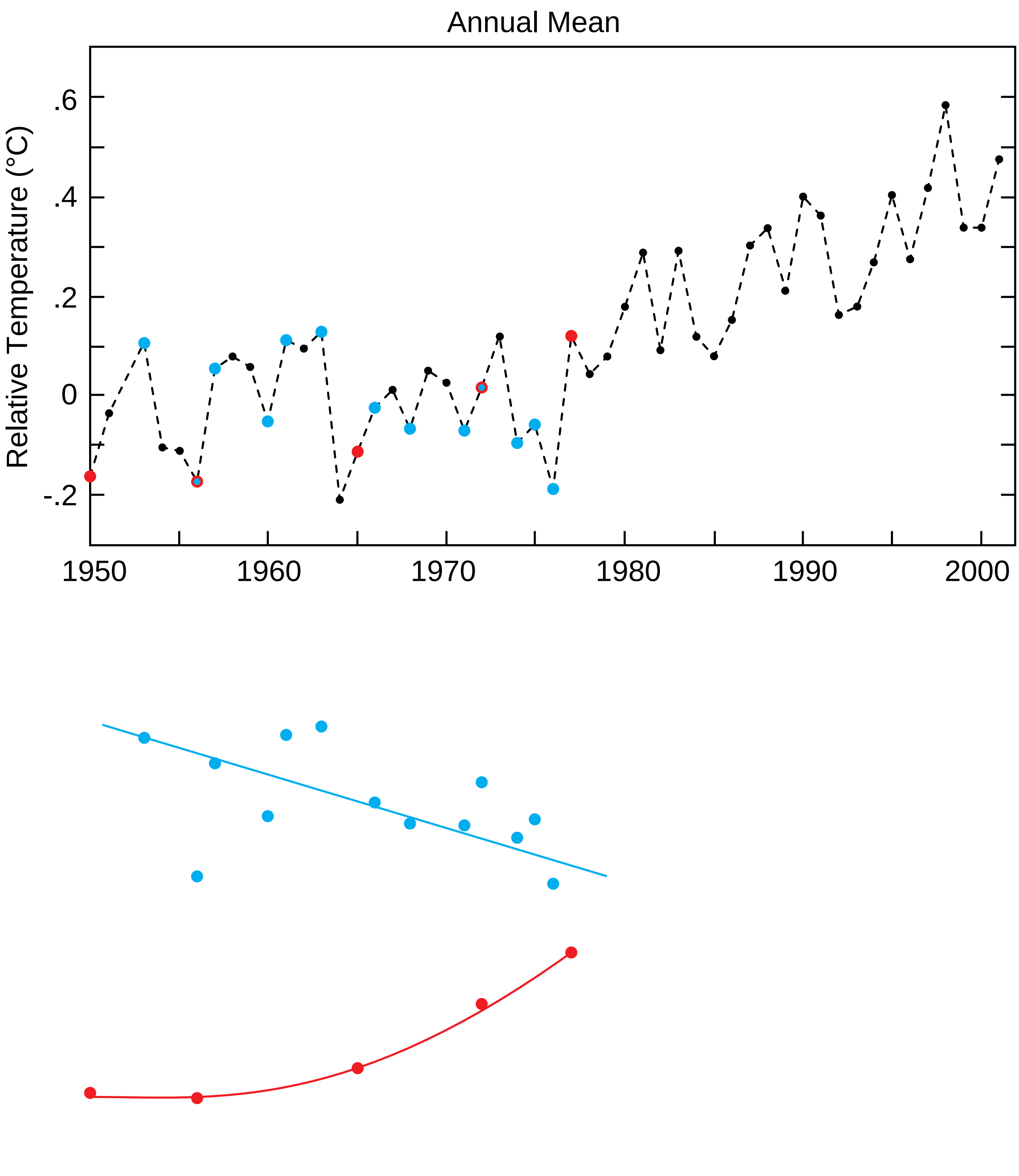

Figure 2. Fifty years of global sea surface temperatures. The time series is non-stationary, with a pronounced warming trend starting in 1975. Even in the stationary epoch prior to 1975, a ficticious cooling (warming) is observed when selectively (under) sampled at the times indicated by the blue (red) dots.

TOPEX POSEIDON HAS…

- solved global tidal problems
- major errors in mapped bathymetry
- first test of global circulation
- unexpected large variability
- trapped equatorial waves (El Nino)
- assimilation leading to forecasting
- ocean surface waves (prediction)
- ice sheet dynamics & mass balance
- sea level changes

see L-L Fu & Anny Cazenave(2001).
Satellite Altimetry and Earth Science.
Academic Press.

Figure 3.

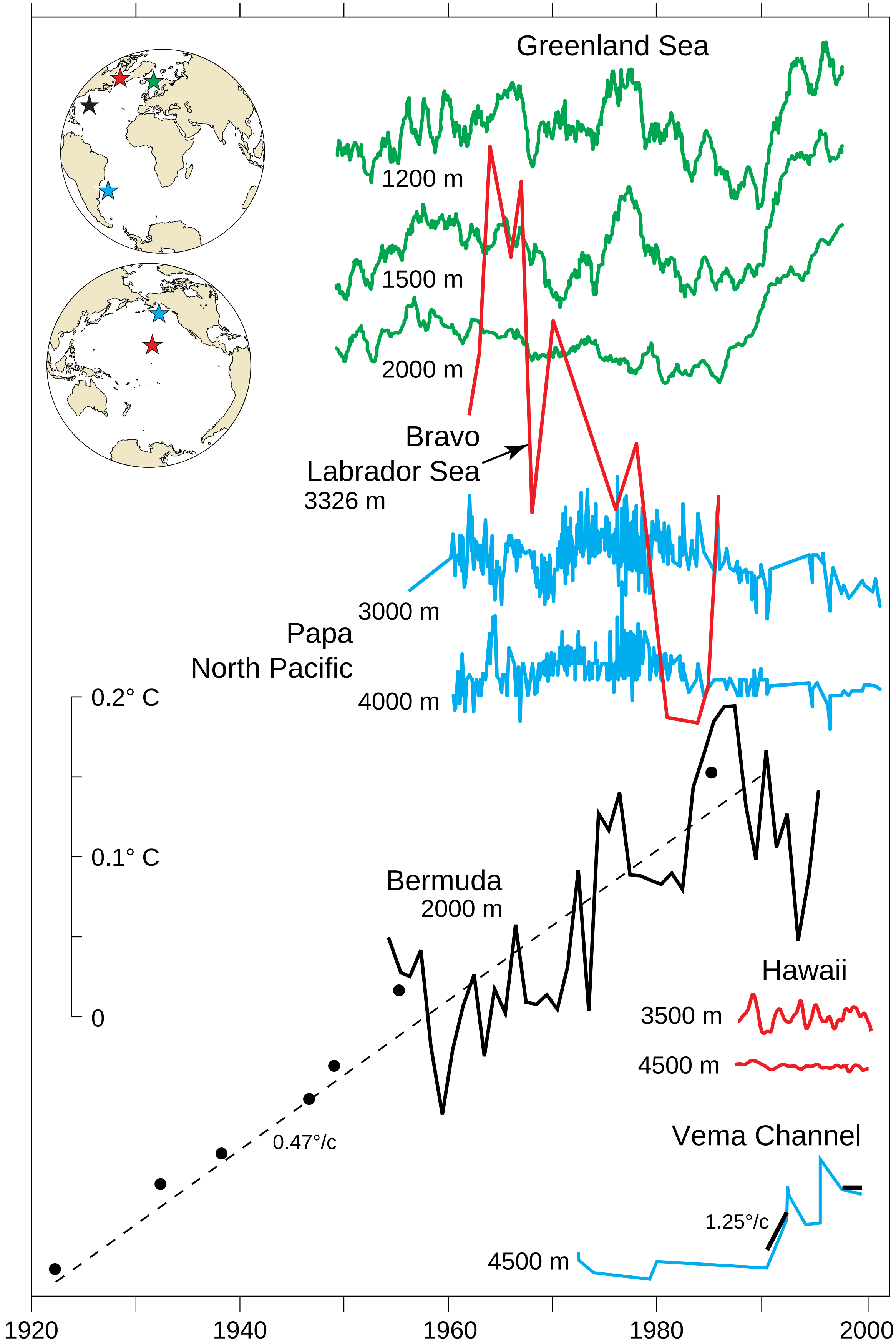

Figure 4. Potential temperature time series in the abyssal oceans. Greenland Sea (66°N, 2°E) from Østerus and Gammelsrød (1999); Labrador Sea "Bravo" (56°N, 52°W) from Lazier (1988); North Pacific "Papa" (50°N, 145°W) from Newton (2001); Bermuda (32°N, 65°W) from Joyce and Robbins (1996); Hawaii (21°N, 158°W) from Lukas and Santiago-Mandujano (1996); Vema Channel (30°S, 39°W) from Hogg and Zenk (1997), with rate of warming 1990-92 indicated.

OCEAN OBSERVING SYSTEM

- **ADEQUATELY SAMPLED**
Mesoscale resolving

- **GLOBAL**
Telecommunications

- **SUSTAINED**
Century (resolve decadals) Priesthood

- **DIVERSE PLATFORMS**
Ships, Satellites, Moorings, Drifters

- **DIVERSE SENSORS**
Flexible; include biological, chemical

- **PARTNERSHIP**
Government, University, Industry

- **DUAL GOAL**
Operations and "Understanding"
Daring; Tolerance for failure

Figure 5.