Chapter 1
Oceans from Space, a Once-a-Decade Review of Progress: Satellite Oceanography in a Changing World

Jim F. R. Gower

1.1 Introduction

At the first Oceans from Space conference in Venice in 1980, we celebrated NASA's launch of two ocean satellites, Seasat and Nimbus 7, which showed the amazing capabilities of the new images and measurements from space. We saw that altimetry could measure currents and waves, that ocean color could measure surface chlorophyll and plankton blooms, that SAR could measure waves and ocean fronts, that scatterometers could measure surface wind, and that microwaves could map ice and measure sea surface temperatures through cloud. We looked forward to the launch of NOSS, the planned US National Ocean Satellite System, which would "operationalize" satellite oceanography, and which as a result would be much more expensive.

At the second conference in 1990, we were a sadder but wiser group, NOSS had failed to appear, the CZCS had eventually died, and we were seeing gaps in our data time series. At the same time, we had become uncomfortably aware that global climate change was likely upon us, and that we needed continuing time series of exactly these types of data.

By 2000 we were again happier, celebrating the new strengths of the global ocean satellite community. MODIS had been launched, the ERS satellites marked the start of ESA's major role in global earth observation. Japan had a brief success with ADEOS, Russia had contributed radar satellites, and Topex/Poseidon had collected a significant time series of altimetric data.

Today in 2010, we can continue to rejoice in our new data sources, but we now have no remaining doubt of the dangers inherent in allowing un-checked growth in carbon dioxide concentration in the earth's atmosphere. We see the need for global, stable, long-term time series of ocean satellite data to show us the changes that are occurring. Happily, we now have more satellites and a much greater capability

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for transmitting and processing data. This capability takes us beyond the problem often talked about in the 1980s of "Drinking from a Fire-Hose." I was never sure that the analogy made the problem of handling large data flow seem serious. Drinking from a fire-hose might be slightly messy, but one would never need to go thirsty.

1.2 Ocean Satellites Showing a Changing World

Climate change is giving us all something to think about. It has huge social, economic and ethical implications. Scientifically though, it is fascinating. It keeps me from retiring, and I am sure I am not alone in this. At the 2000 conference I said I would like to stay working long enough to see the world agree that human-induced climate change is happening, and to start to do something serious about it. I can now see that this fails to give me any well-defined retirement date. A consensus has been reached, but there will always be hold-outs. Action will be expensive and will benefit some people more than others. Wind farms are being built, and there are rumours that coal-fired power stations are being closed, though many more are being built. Today in Canada, we stress that the coal we are exporting is "metallurgical" (i.e. needed for steel production) and therefore in some sense "greener" than coal being burned for generation of electricity. We are having a harder time excusing our tar sands, but exports of this relatively "high carbon" oil continue to increase. It seems that the effects of climate change need to be much more strongly felt, by many more people, before serious and concerted action occurs.

Ocean satellites are providing a number of time series that demonstrate the problems we are facing. I have my favorites and maybe you do too. I would like to present a few here, and to suggest that we might consider awarding a Venice prize for the chosen "best". Some time series are longer than others and some, though short, already have fascinating implications.

1.3 The Keeling Curve: Origin of All Climate Change Time Series

For this conference I should emphasize ocean satellite data, but I need to start where recent, human-induced climate change begins, at the Keeling curve. This is a fascinating and frightening time series,[1] showing the CO_2 concentrations in the atmosphere as measured on Mauna Loa in Hawaii. Figure 1.1 shows the monthly averages, starting in 1957, curving upwards.

At the start of the series, values were near 315 parts per million (ppm), and we have now reached 390. The agreed pre-industrial concentration is 280, so the

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[1] Available at http://scrippsco2.ucsd.edu/data/atmospheric_co2.html

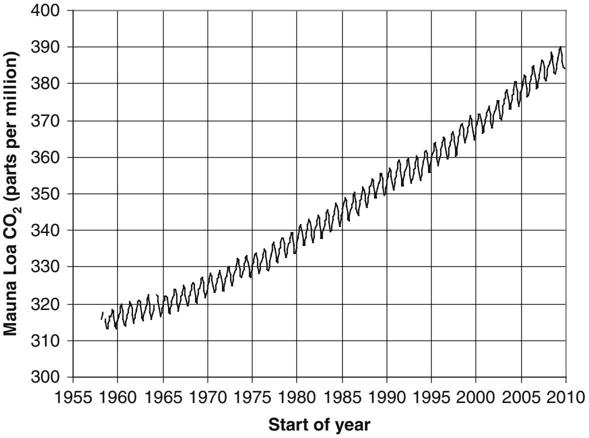

Fig. 1.1 The keeling curve: monthly averages of carbon dioxide in the northern hemisphere atmosphere, measured on Mauna Loa, Hawaii (20°N)

much-feared doubling refers to 560. The proposed world target of 350 ppm[2] was passed in about 1988 with no sign of slowing down.

When the annual cycle is removed, the curve shows a continuing and near-constant acceleration in CO_2 concentration, in spite of the stated aim of almost all national governments to reduce rates of emission. A good fit to the (12-month averaged) Keeling data between 1957 and 2009 is

$$CO_2(\text{ppm}) = 297 + 0.011(\text{year} - 1919)^2 \tag{1.1}$$

If this trend of the past 50 years continues into the future, the world will get to 410 ppm by 2020, the possible date of the next Venice conference, and we will see doubling of the pre-industrial value by 2073.

If the best fit, constant acceleration, curve of equation (1.1) is subtracted from the Keeling data, the residual differences show peaks in CO_2 concentrations which correlate with El-Nino (Fig. 1.2). They also show a single peak at 1990 which the Keeling research group at Scripps were unable to explain (Keeling et al., 1995).

At present, the Keeling curve continues its acceleration, even though the world entered a major economic recession in 2007, which would be expected to reduce emissions. A recent analysis predicted that the recession would change the present growth rate in emissions from their average rise of about 2.5% per year, to a drop of 3% for 2009. Such a drop is only by about 0.11 ppm in 1 year. It would need to continue for several years before it would be evident, given the variability shown in Fig. 1.2.

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[2] See http://www.350.org

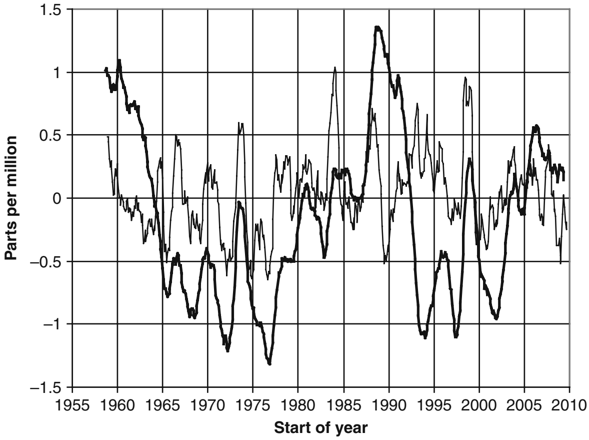

Fig. 1.2 Residual differences in carbon dioxide concentration between the keeling curve and the constant acceleration equation (1.1) (*heavy line*), compared with the Multi-variate El-Nino Index (Wolter and Timlin, 1998) (*light line*)

Figure 1.1 also shows a small but regular annual cycle. In May of every year the world breaks the "all-time" record for carbon dioxide concentration. Between then and October, plant growth on land in the northern hemisphere reduces the monthly averages.

The amplitude of this annual cycle has increased by about 20% over the 50 years (Fig. 1.3), suggesting that annual plant growth on land has measurably increased. Perhaps, here we are seeing a benefit from the increased levels of CO_2 in the atmosphere, though it seems doubtful that this will balance the associated losses.

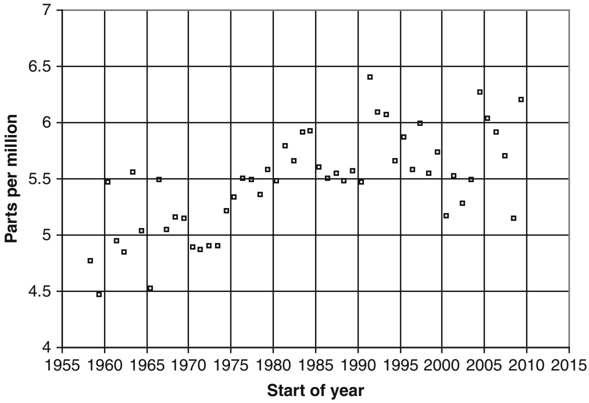

Fig. 1.3 Amounts of the annual draw-down evident in Fig. 1.1, from the northern spring (AMJ) to fall (SON) in each year. The data suggest that the amount of the drop is growing, probably indicating increased land productivity in a higher-CO_2 world

1.4 Ocean Colour and a Change in Global Productivity

As oceanographers, we need to ask what the ocean has contributed to this change. Has global ocean productivity (or biomass, as we effectively measure it) increased? If the total increase of ocean productivity is as large as that on land, then presumably the Keeling curve would not show an increase in its annual cycle amplitude, as the northern summer decrease would be offset by an increase in total productivity of the southern ocean.

The time series we have for this is poor, to say the least. It has been suggested that the average biomass deduced from the entire CZCS mission (1978–1986) was less than that more recently deduced by SeaWiFS for 1997–2004 (Antoine et al., 2005). Changes within the SeaWiFS data time series have also been reported (Gregg et al., 2005; Behrenfeld et al., 2006), and shown to be strongly affected by the El-Nino/La-Nina in 1997–1999. If these data are plotted as time series (Fig. 1.4), they lack the impressive impact of a multi-point plot, but they can be important nonetheless. The patterns of change seem related to an increase in area of oligotrophic waters in ocean basin gyres (Polovina, 2008).

In determining any trend in biomass, we come up against the continuing problem of providing long-term, stable, "climate quality" time series of global ocean optical data. Ocean color has already experienced the 10-year gap between CZCS and SeaWiFS. In an open letter to the ocean optics community Siegel et al. (2008) stated "It appears likely that the ocean biology and biogeochemistry communities will (again) face a multi-year gap in our climate data records." A problem which I would summarize in verse as:

We've needed one more SeaWiFS for many, many years
Instead we've bought 2 MODISs, a MERIS and a VIIRS

I should stress that both MODIS and MERIS have brought their own scientific and operational successes, but they were not designed as simple, stable instruments.

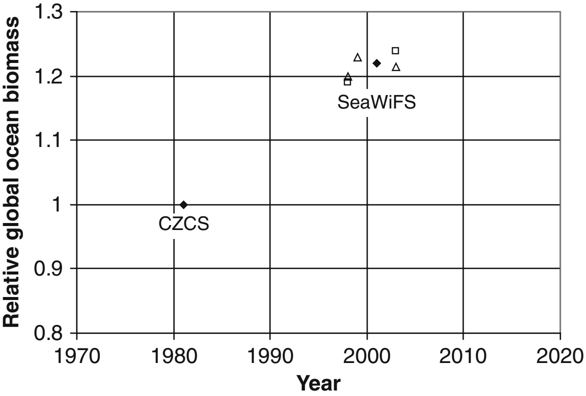

Fig. 1.4 Relative change in global ocean biomass from CZCS and SeaWiFS. *Filled diamonds*: Antoine et al. (2005). *Open squares*: Gregg et al. (2005). *Open triangles*: Behrenfeld et al. (2006)

It is possible that clever calibration may allow them to successfully continue the SeaWiFS time series. It is even possible that SeaWiFS may rise from the dead, and operate for a few more years (G. Feldman, personal communication).

1.5 Sea Surface Temperature (SST)

The Reynolds time series is based on ship and buoy data, using satellite data in data-sparse areas. This is only partly a "satellite" data time series and is becoming less so as surface data sources such as Argo, increase in density. Figure 1.5 shows the Hadley SST data series, in which the long-term warming trend is very clear, with short-term increases at the 1972 and 1997 El-Nino events, and a recent slight interruption of the steady warming, which is being made much of by warming skeptics ("cooling since 1998"), but which in fact looks typical of the variability in the record.

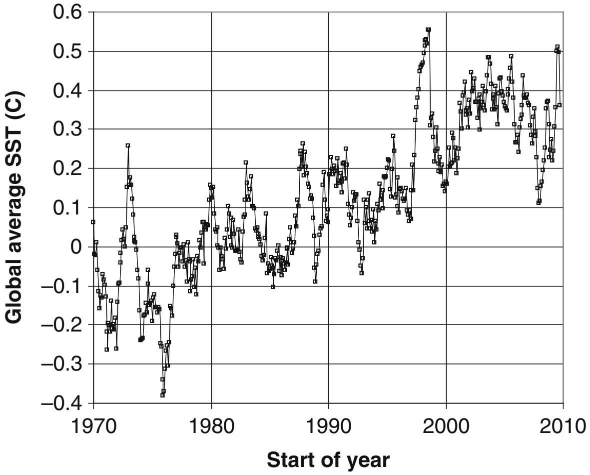

Fig. 1.5 Time series of global SST provided by the Hadley Centre, UK. Data show a warming trend of 0.014°C/year, with increases of about 0.3°C during the 1972 and 1997 El Ninos, but a smaller signal from the 1982 event

1.6 Polar Sea Ice Cover

The US National Snow and Ice Data Center (NSIDC) provides an archive of Arctic ice cover data based on satellite microwave radiometer observations of polar ice.[3] Figure 1.6 shows the anomaly time series deduced for each month by subtracting a fixed annual cycle. From the late 1970s to about the year 2000, the measured total ice areas oscillated with the seasons between about 5 and 15 million km^2. In Fig. 1.6, a slow drop of about 1 million km^2 is evident over this period, accelerating

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[3] Available at ftp://sidads.colorado.edu/DATASETS/NOAA/G02135/

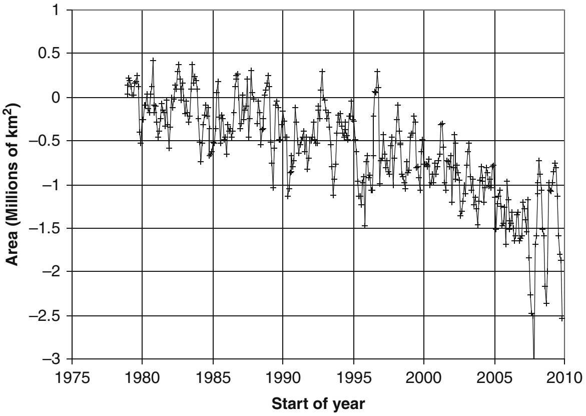

Fig. 1.6 Arctic sea ice area anomaly time series from the US National Snow and Ice Data Center, based on satellite microwave radiometer data, subtracting a fixed annual cycle for all years

after 2000, but recovering after 2007. The minimum in September 2007 represented a loss of almost half the usual late summer ice cover. In the three most recent years it appears that the annual cycle has changed to one with a larger amplitude. This may be related to the loss of multi-year ice in 2007. It is definitely a time series to watch.

1.7 The GRACE Satellite and Melting Ice Caps

The sea-ice loss in Fig. 1.6 is significant for northern navigation and Arctic warming, but will not affect sea level rise. Altimeter surveys of Greenland and Antarctica are attempting to show the mass loss from these two major ice caps.

Gravity measurements from GRACE (Gravity Recovery And Climate Experiment) suggest that these data can also provide useful time series. Recent data seem to show not only mass loss due to ice melting on Greenland and Antarctica, but an acceleration in this loss as shown in Fig. 1.7 (Velicogna, 2009). The short time series show average melt rates between 2002 and 2009 of 230 ± 33 Gt/year for Greenland and 143 ± 73 Gt/year for Antarctica, giving a total melt rate of 370 ± 80 Gt/year, equivalent to a sea level rise rate of 1.1 ± 0.2 mm/year.

The data also show apparent accelerations of 30 ± 11 Gt/year^2 for Greenland and 26 ± 14 Gt/year^2 for Antarctica. These imply melt rates in 2003 of 140 and 100, for a total of 240 Gt/year, or a sea level rise of 0.7 mm/year, increasing to melt rates in 2008 of 290 and 250, for a total of 540 Gt/year, or a sea level rise of 1.6 mm/year.

The time series in Fig. 1.7 are short, and we might hope to see significantly longer series at Venice 2020. Sadly, GRACE is due to die before then. It consists of a pair of satellites about 200 km apart, whose exact separation is precisely measured to show the effects of small changes in earth's gravity. For sensitivity, it is in a low orbit and needs frequent boosts to counteract atmospheric drag. It was designed for

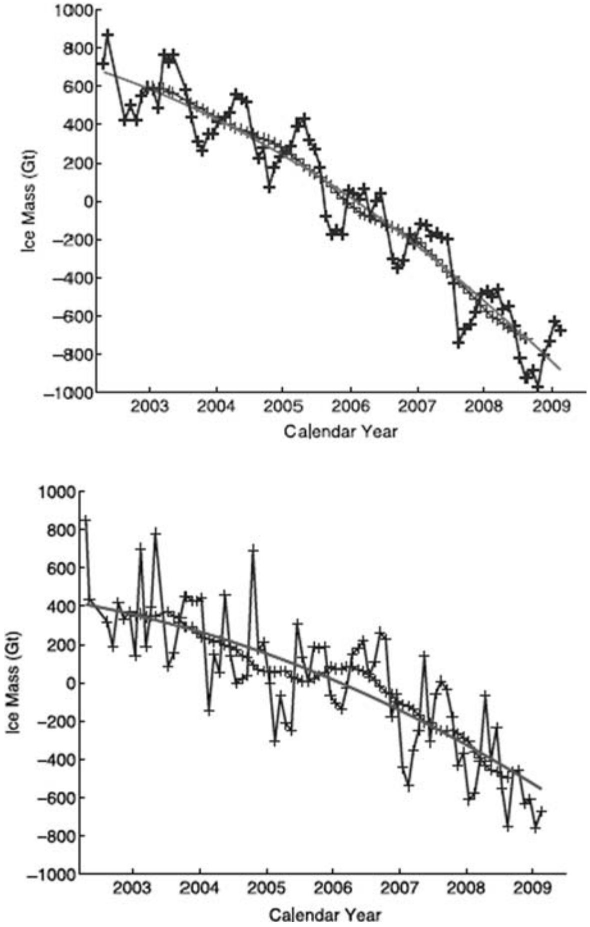

Fig. 1.7 Ice mass loss from Greenland (*top*) and Antartica (*bottom*) seen by the Gravity Recovery and Climate Experiment, GRACE (Velicogna, 2009). Each *plot* shows points, the result of smoothing by a 13 month window, and a quadratic fit

a 5-year life, is now in a 2-year extension, and will eventually run out of the fuel needed to keep it aloft.

1.8 Satellite Altimetry and Global Sea Level Rise

One of the most fascinating time series, especially for people living near a coast, is of global sea level measured by the Topex/Poseidon and Jason satellite altimeters (Leuliette et al., 2004). The data[4] (Fig. 1.8) show a very clear and relatively constant rate of increase of 3.1 ± 0.4 mm/year with an rms noise level on the individual points of only a few millimeters, much lower than is possible from shore-based tide gauges.

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[4] Available from http://sealevel.colorado.edu/results.php

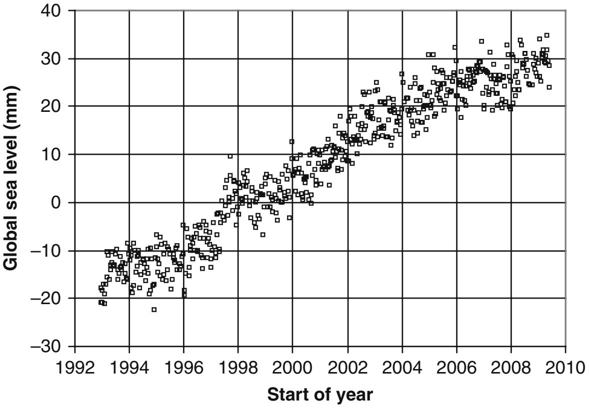

Fig. 1.8 The time series of global average sea surface height, based on 10-day repeat coverage of the Topex/Poseidon and Jason altimetry satellites, showing an average global rise rate of 3.1 mm/year

The series shows a peak of about a centimeter at the time of the 1997/98 El-Nino and a slower rise rate since the end of 2006. Sea surface heights are linked to the global sea surface temperature shown in Fig. 1.5 through the expansion of near-surface sea water. The 0.3°C average temperature increase associated with the 1997 El-Nino is equivalent to 7 mm of sea level rise if applied to the top 100 m of the ocean surface. The dip in temperatures between 2005 and 2009 explains some of the recent slowing in rise rate in Fig. 1.8. We note that GRACE data suggest that we should see an acceleration in global sea level rise. As yet there is no indication of this in the altimetry (Fig. 1.8), if anything the rise seems to have slowed since 2006. These observations need to be reconciled.

It is worth remembering that the global significance of plots like Figs. 1.5, 1.6 and 1.8 means that they will be inspected by many non-scientists who are more used to looking at time series of company share prices, indicating investment value. To such people, it is the recent trend which has special importance. Hence, they focus on “recent cooling” in Fig. 1.5 and “slow down” in Fig. 1.8. I’m not sure how they would interpret Fig. 1.6. Certainly, something in the Arctic has changed. Climate scientists have higher tolerance for “short-term fluctuations.” Maybe this sometimes leads them to make bad investment decisions? Figure 1.8 is a relatively short time series, which will have lengthened significantly by the time of Venice 2020, either confirming the slow down, continuing the steady upward trend, or showing acceleration.

1.9 Venice Acqua Alta

And so we return to Venice. Any city close to sea level needs to take global sea level rise very seriously. At the first two conferences in Venice (1980 and 1990), I was not aware of any flooding from the sea. In 2000, we saw the problem. Tides in the Mediterranean are small and are often ignored by boaters. In Marseilles, for example, the tide range is only about 20 cm. In Venice at the head of the Adriatic, tides are larger, but the range is still less than a metre. The phenomenon of “acqua alta” or high water in Venice is related more to winds blowing up the Adriatic, piling water in a “surge” which can be at least a metre higher. Lower barometric pressure associated with a storm will also raise the level by up to 30 cm, 10 cm for each 10 mb drop in pressure.

Venice also has to take seriously any drop in the level of the land on which the city is built. Since 1930, the area surrounding Venice has sunk about 20 cm due to the extraction of arterial water. Thanks partly to scientific work by the ISDGM (Instituto per lo Studio della Dinamica delle Grandi Masse, now ISMAR, Istituto di Scienze Marine), the host institute of these conferences, this extraction has now been halted, but the loss of height remains (Carbognin and Gatto, personal communication[5]).

Floods have affected Venice throughout recorded history. Today, a tide of 90 cm above the standard Venice reference will start to cover St Mark’s Square, but will cause few other problems. A tide of 110 cm will put 12% of the surface area of Venice under water. When this level is expected, forecast warnings are sounded (Fig. 1.9). At 130 cm, 70% of the city is flooded, and at 150 cm this rises to 96%. The floods do not usually last long, dropping as the high tide passes. The water is usually clear and drains away with relatively little damage, unlike a river flood,

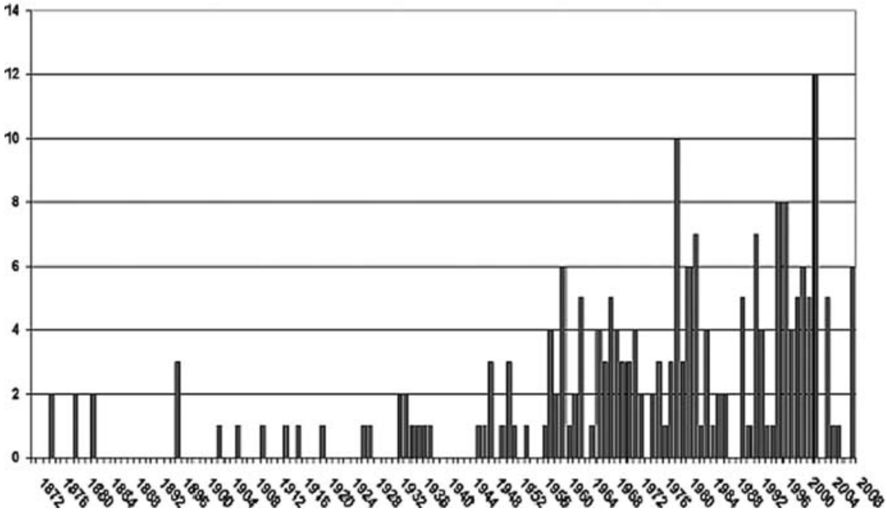

Fig. 1.9 The number of times in each year that water level at the Venice tide station has exceeded 110 cm, the level at which an alarm is sounded[6]

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[5] See http://iahs.info/redbooks/a151/iahs_151_0321.pdf

[6] Data from www.comune.venezia.it/maree

which may bring mud and debris. I remember watching a small fish swim by the meeting hall in 2000. An added problem of the high water is that boats cannot pass under some bridges. Tourists now come to witness “acqua alta”, but the city suffers.

The highest “acqua alta” in recent times was on 4 November 1966, reaching a level of 194 cm, enough to flood the entire city and do extensive damage. Since then people are more prepared, but levels have never come within 30 cm of this record. Recent highs were 156 cm on 1 December 2008, 147 cm on 16 November 2002 and 144 cm on 6 November 2000. Most extreme highs occur in November and December, but on 16 April 1936, water reached 136 cm. I see there will be a full moon at 12:21 UT on Wednesday 28 April 2010, during our conference. We must hope the barometer stays high and the winds light.

The project MOSE[7] is now underway, installing rising gates to block the gaps in the chain of offshore islands which include the Venice Lido. This is a huge and expensive project which has already faced delays and budget over-runs. It is now proceeding slowly and is due to be completed in about 2014.

1.10 Conclusions

What can we conclude? First, let us be selfish and conclude that we should all live long and scientifically productive lives, which will let us see how this dangerous adventure of the human race turns out. I hope we will all be here again at Oceans from Space, Venice 2020. For this, both Venice and ourselves need to survive. The extra 10 years will give us an improved perspective, and maybe the Keeling curve will have slowed. If not, the sea level rise may indeed have accelerated, and MOSE may well have already been proven inadequate.

At the 2000 conference I said I hoped to see humanity’s first contact with intelligent life elsewhere in the universe. This may seem a strange dream, yet it is reasonably rational. To many specialists the mystery is why another civilization has not already contacted us. Maybe global warming tends to wipe out intelligent life? Maybe we’ll see.

On a more down-to-earth note, we certainly conclude that the work covered by this conference is important, and that its importance is growing. We hope that governments will appreciate the need for improved monitoring of the global marine environment, and more importantly that they will act on the need to reduce emissions of carbon dioxide. I look for a significant reduction in the rise rate of the Keeling curve below the constant acceleration shown in Fig. 1.1 and Equation (1.1). I’m less sure how we hope to reduce the actual level to 350 ppm.[8]

Finally, let me also ask once again for any ideas on “best ocean satellite-based time series.” There must be others. I’m working on statistics of bright blooms

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[7] See http://en.wikipedia.org/wiki/MOSE_project

[8] As suggested by www.350.org

detected by the MCI index of MERIS. Can we show that blooms are changing or increasing in frequency (see, for example, Barale et al., 2008)? What other trends are apparent? Winds, waves, coral bleaching? Please point out candidates.

Acknowledgements Thanks to the Institute of Ocean Sciences (IOS) of the Canadian Department of Fisheries and Oceans and the Canadian Space Agency for continuing research support, to the Canadian Federal Government whose rules allow me to work past the age of 65, to Eric Lindstrom of NASA who recommended that I include GRACE results, and to my colleague Stephanie King who recommended that I leave out the "silly poem" (see Ocean Colour) and who helped prepare figures. Thanks also to colleagues at IOS and to V. Barale, JRC EC, Ispra (I), for useful comments and discussions.

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