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High Water Blues: The Climate Science behind Sea Level Rise and its Policy Implications – 2005 update

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► **To cite this version:**

Valentin Bellassen, B. Chameides. High Water Blues: The Climate Science behind Sea Level Rise and its Policy Implications – 2005 update. [Research Report] auto-saisine. 2005, 27 p. hal-01190165

HAL Id: hal-01190165

<https://hal.science/hal-01190165>

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High Water Blues



THE CLIMATE SCIENCE BEHIND SEA LEVEL RISE
AND ITS POLICY IMPLICATIONS

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ENVIRONMENTAL DEFENSE

finding the ways that work

High Water Blues

THE CLIMATE SCIENCE BEHIND SEA LEVEL RISE
AND ITS POLICY IMPLICATIONS

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ENVIRONMENTAL DEFENSE

finding the ways that work

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Executive summary

There is broad consensus that human emissions of greenhouse gases—principally carbon dioxide, but also methane and nitrous oxide—contribute to global warming. Because of water’s high capacity for heat retention, the warming effect is not nearly as clear in the atmosphere as it is in the oceans, which have warmed by approximately 0.5°C (0.9°F) over the past 65 years.¹ Warming seas translate into numerous negative impacts, including coral reef bleaching, fish stock depletion, Gulf Stream disruption, stronger hurricanes, and, of course, a rising sea level.

In order to better understand the challenges presented by sea level rise, in this study we review recent scientific publications and seek both to explain the phenomenon and to predict future effects. In order to gauge the potential benefits of a climate stewardship policy, we illustrate a range of possible impacts below one meter of sea level rise for selected sites both in the United States and worldwide, with three different scenarios for the 21st century in the background. The three scenarios are based on potential greenhouse gas concentrations that would result of three different types of climate policies.

Introduction

The Cape Hatteras Lighthouse, the tallest brick lighthouse in the United States, was built on a cape on the North Carolina Outer Banks in 1870, 1,500 feet from the sea. Little did the original builders know that, just over a century later, only 160 feet would remain between the lighthouse and the sea, despite protective measures to reduce the rate of beach erosion. Finally, the National Park Service realized that it needed to take action if this historical landmark was to be preserved, and in 1999, with more than \$10 million from Congress, the lighthouse was moved 2,900 feet inland.²

It is certain that most structures on the U.S. coast will not receive such

attention and money, let alone those in developing countries. In 1990, 200 million people were living in coastal flood plains worldwide, most of them in the developing world.³ This figure keeps rising, as do sea level.

Whether we respond to sea level rise by cutting greenhouse gas emissions or by engineering retreats from encroaching waters, we all face a complex set of hard choices. These choices will be dictated by many factors, including geography, technology, resources, politics, cultural acceptance, and economic considerations. The following report is intended to shed light on the problem so that such choices can be made with a plain understanding of the science.

Observed sea level rise and its causes

Sea level rise, past and present

Ocean levels have risen over the past century. Based on global tide gauge data, the rate of rise averaged between one to two millimeters (mm) per year during the 20th century.⁴ Therefore, over the past century, the oceans have risen between 10 to 20 cm (approximately four to eight inches).

There is compelling geologic and archaeological data demonstrating that the rate of increase in sea level over the past 100 years represents a significant acceleration over that of the previous 3,000 years. Such studies find an average rate of rise of 0.1 to 0.2 mm/yr over the previous three millennia, or ten times less than the estimated rate for the 20th century.⁵

Over the last decade (1993–2003), sea level has also been measured by satellite, with data showing an estimated rise of 2.8 mm per year.⁶ It is not yet entirely established whether the discrepancy between longer-term tide gauge and more recent satellite data is due to differences between the two methods or to a recent increase in the rate of sea level rise. Though there is no strong evidence from tide gauge data that sea level rise has accelerated during the past few decades,⁷ satellite imagery has in the long run the potential to give much more accurate estimates, since it is neither sensitive to subsidence (tide gauges move up or down with the coastline) nor subject to limited data points (it can cover the entire surface of the world).

Main causes of sea level rise

The two major causes of sea level rise are oceanic thermal expansion (as ocean water warms, its volume increases) and

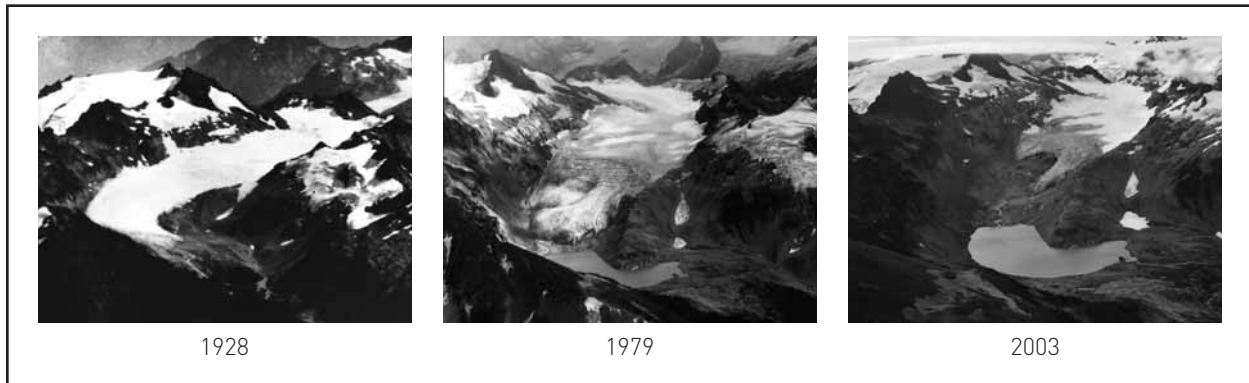
glacial melting. Tide gauge measurements fall within the range expected from oceanic thermal expansion models, as well as analysis of retreating glaciers and other lesser factors. Together, thermal expansion and glacial melting are responsible for 95% of the rise in sea levels.⁸ However, significant uncertainties remain, and scientific debate continues regarding the relative importance of various factors.⁹

The last ice age occurred more than 10,000 years ago, and the slow rise in global temperature since then explains the slow pace of sea level rise over the past millennia. However, recovery from the ice age and other natural factors cannot explain the rate of rise over the past century, which is ten times higher than previous rates. As for global temperature, it can only be explained if human-produced greenhouse gas emissions are factored into the models.¹⁰

Global and relative sea level rise

Although sea level rise is a global phenomenon, levels are not rising evenly all around the world. We distinguish between two types of sea level rise: *global* and *relative*. *Global* sea level rise is analogous to water in a bathtub: Adding water raises the level. The oceans, however, are not bathtubs with rigid porcelain walls. The “walls” are not vertical but, for the most part, nearly horizontal as a result of the sedimentary processes that determine land gradients near the sea. In addition, the “floor” is not immobile. The crust of the Earth can undergo significant vertical movements (as glacial rebound, or even on human timescales as with earthquakes) that can cause water to engulf or retreat

FIGURE 1
South Cascade Glacier, Washington



Photos: Courtesy of Edward G. Josberger, Ph.D., U.S. Geological Survey, Washington Water Science Center

from a coast. Finally, the oceans are not surrounded by rigid bedrock, but by mobile and dynamic sediments of both a geological nature (sand or mud, for example) and of biological origins (marshes, mangroves, coral reefs). Sediment dynamics are critical to the response of shorelines to rising sea levels.

Because of these complicating local effects, it is necessary to define the second type of sea level change: *relative* sea level rise. This refers to changes in sea level observed at a particular coastline due to changes in the land surface underlying that coastline, including sedimentary changes. To predict a new coastline position, one must consider both global and relative factors and, ideally, many other data, such as relief, rock types, sediment characteristics, wave energies and so on.

Other human activities are locally enhancing vulnerability to rising sea levels

Although the human influence on sea level is most often spoken of in terms of global warming, we also affect relative sea levels in profound ways apart from the greenhouse effect. Indeed, it seems that human activities are systematically biased to *raise* sea level

and not to lower it. Two general categories can be defined: (1) human-induced land subsidence and (2) human-induced sedimentation impacts.¹¹

Human-induced land subsidence:

Humans create land subsidence most notably by withdrawing oil, gas and water and by draining wetlands for land reclamation. This can create surface depressions, proportionally increasing sea level.

Human-induced sedimentation

impacts: When human activities affect river systems, catchment areas and deltas, sediment supply processes are disturbed and consequently lower the coast's floor. Embankments along river channels keep sediment from adjacent land. The construction of dams and reservoirs in upper river areas for flood protection, power supply and irrigation can choke off downstream sediment. For example, as a result of such activities, relative sea level is rising in the Mississippi River delta by as much as one meter per 100 years.¹²

Sand and coral-reef mining, as well as the removal of other natural buffers to sea level rise, can interrupt alongshore sediment transport and cause additional

erosion. Clear-cutting of mangroves and their replacement by brackish water aquaculture systems and wetland rice patties can have similar effects.

Addressing skeptics' claims about sea level rise

Below are samples of skeptics' claims—selected from articles and Internet postings - contrasted with information from peer-reviewed literature and reports from the Intergovernmental Panel on Climate Change (IPCC). Compared with other aspects of climate change, skeptics do not address sea level rise extensively, perhaps because it is often considered as the clearest impact of global warming.

Iain Murray, senior fellow at the Competitive Enterprise Institute, writes: "First and foremost, people assert we know a lot about glaciers, but we don't. We know next to nothing about glacial activity, but what we do know suggests there are as many expanding glaciers as there are shrinking ones (this even happens with two glaciers within a few miles of each other) and that there is no universal trend either way."¹³ While it is true that, because of local climate peculiarities a few glaciers are growing in New Zealand and southern Scandinavia, the studies documenting the general trend based on the 300 glaciers measured so far, show that the average mass balance of glaciers worldwide has been negative since records were first kept.¹⁴ J. Oerlemans found that 142 of the 144 glaciers on which he compiled length data between 1900 and 1980 had been retreating over this period.¹⁵

Moreover, the journal *Science* recently documented a new and promising method of measuring glacial mass balances more comprehensively by aerial photography. And while the study is

limited to Alaskan and West Canadian glaciers, it also shows that, despite a few local peculiarities such as glacial advances, the overall volume change in Alaska's glaciers amounted to a 96 km³/year decrease in the 1990s (the equivalent of a global rise in sea level of roughly 0.3 mm/year, and this only from Alaskan glaciers).¹⁶

Dr. Nils-Axel Mörner, another skeptic, claims: "In the last 300 years, sea level has been oscillating close to the present with peak rates in the period 1890–1930.... Satellite altimetry indicates virtually no changes in the last decade."¹⁷ Although it is not clear which data Dr. Mörner draws his conclusion from, it can be assumed from a table he presents that he only considers data from Europe, particularly the North Sea. This could explain his failure to note any important rise in sea level, as this region undergoes a lesser rise than the average (although still significantly larger in the 20th century than before), possibly because of glacial rebound.¹⁸ As mentioned earlier however, the global trend, free from local variations, clearly shows a rise of 1–2 mm/year in the last century. Moreover, the IPCC review for altimetry data indicates 1.4–3.1 mm/year in the late 1990s,¹⁹ and the most recent study (and the only one to date over a complete decade) points out to a rate of 2.8 mm/year.²⁰

Finally, Dr. Roy Spencer asks, "if someone living within 30 feet of sea level has to contend with the possibility of a giant wave suddenly destroying his house and drowning his family, how much will he worry about an inch of sea level rise every ten years due to global warming?"²¹ Storms surges, like most extreme weather events, occur at different amplitudes and with different returning times. The milder the surge, the smaller the returning time, which means that small storms occur more

often than big ones. The problem with even a few inches of sea level rise is that storm surges start from a higher point; therefore smaller, more frequent, and relatively benign storms could do more damage on a frequent basis. For example,

the CLIMB report concluded that in the Boston metropolitan area, a local sea level rise of one foot (forecast to occur by 2050) would produce a level of flooding every 16 years that is currently reached only every 100 years.²²

Consequences of sea level rise: now, in a century, and in a millennium

General impacts of global sea level rise

In assessing the general impacts of rising seas, it should be noted that the world's coastlines, like the world's climate, have enjoyed relative stability for thousands of years following the end of the last ice-age cycle that terminated 10,000 years ago. Thus most coastal landforms have had time to achieve relatively stationary configurations, although changes are continually taking place due to such short-lived disturbances as earthquakes and storms.²³

Accordingly, the main impacts of sea level rise come from both the sheer increase in sea level and the accelerated pace of the increase. Higher seas would inundate dry land, erode coastline, increase damage from storm surges and increase salinity of coastal water bodies, no matter the pace of the rise. However, important coastal ecosystems, such as wetlands or mangroves, that can usually adapt to sea level rise through landward migration or sedimentation are at risk when the pace of the rise is too fast for them to keep

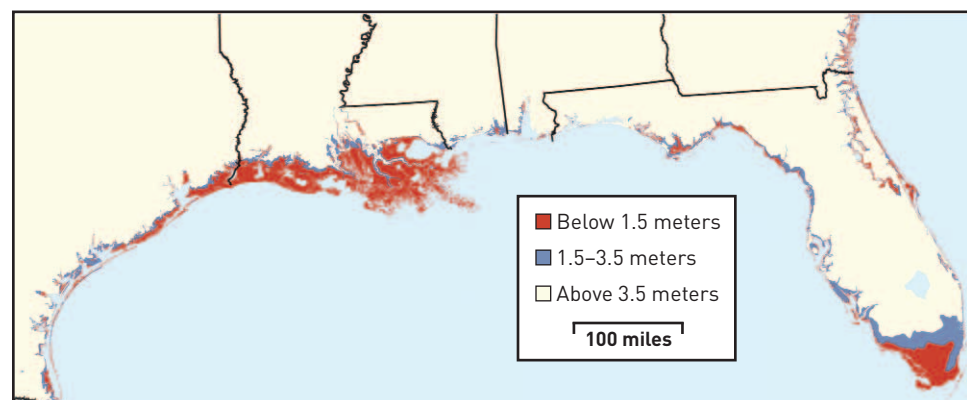
up or when coastal development blocks them from migrating inland.²⁴

Inundation: It is easily appreciated that a global sea level rise will lead to increased marine submergence of low-lying coastal areas, generally referred to as inundation. High and low tides will advance landward accordingly.²⁵ The new high and low tides will lead to increased erosion as near-shore waves break farther inland. As an illustration, EPA published maps of low lands for the entire Atlantic Coast (see an example for the Gulf Coast in Figure 2). It finds that 57,638.6 km² of land (22,254.4 square miles, or the area of Massachusetts and Maryland combined) are less than 1.3 m (4 feet) high.²⁶

Coastline erosion: Erosion amplifies inundation, leading to even greater land loss. The magnitude of erosion accompanying a sea level rise is generally determined by an equation called the "Brunn Rule."²⁷ To summarize, this rule states that for the beach to keep

FIGURE 2

EPA predictions for the impacts of sea level rise on the Gulf Coast



The sea level is already 0.2m higher than the map's benchmark, which therefore means that the land in red is below 1.3 meters in elevation based on the current sea level.

Source: Titus and Richman. 2001

its equilibrium profile while the sea level rises, the erosion of the emerged part of the beach feeds the immersed part.²⁸ This translates into a shoreline retreat of the order of 150 times the amount of sea level rise. Thereby, in addition to inundation, a one-foot sea level rise would cause beaches to retreat about 150 feet landward due to erosion.²⁹

Wetlands loss: The loss of coastal ecosystems such as wetlands is a widely observed consequence of sea level rise. In Louisiana, 908,450 acres of marsh had already been lost between 1932 and 1990—28% of the original marsh.³⁰ However, as mentioned earlier, the impact of sea level rise on wetlands is intensified by human-induced sedimentation and land development that prevents wetlands from moving landward. It is important to bear in mind that wetlands are not only valued by conservationists and birdwatchers: Their average yearly value in the U.S. as fisheries, recreation areas, flood barriers and salinity balance providers has been estimated at \$3–13 million per square kilometer (\$7.7–33.7 million per square mile).³¹

Storm surges: The main effect of sea level rise on storm surges is easy to understand: If surges start from a higher point, they will travel further inland. Based on this reasoning, Wu et al. have computed that in Cape May County, New Jersey, a sea level rise of 60 cm (two feet) would increase the area at very high flood risk by 33%. However, they conclude that additional factors, such as intensity build-up (disproportionate increase in wind-driven wave height with sea level height) or the disappearance of wetland buffers could inflate the figures by as much as 50%.³²

Increased salinity: A rising sea level also tends to increase salinity of near-shore

water bodies. This disrupts the natural salt gradient that is the fount of wetlands' rich biodiversity.³³ EPA also worries that further changes in salinity could pollute water reservoirs of coastal cities.³⁴

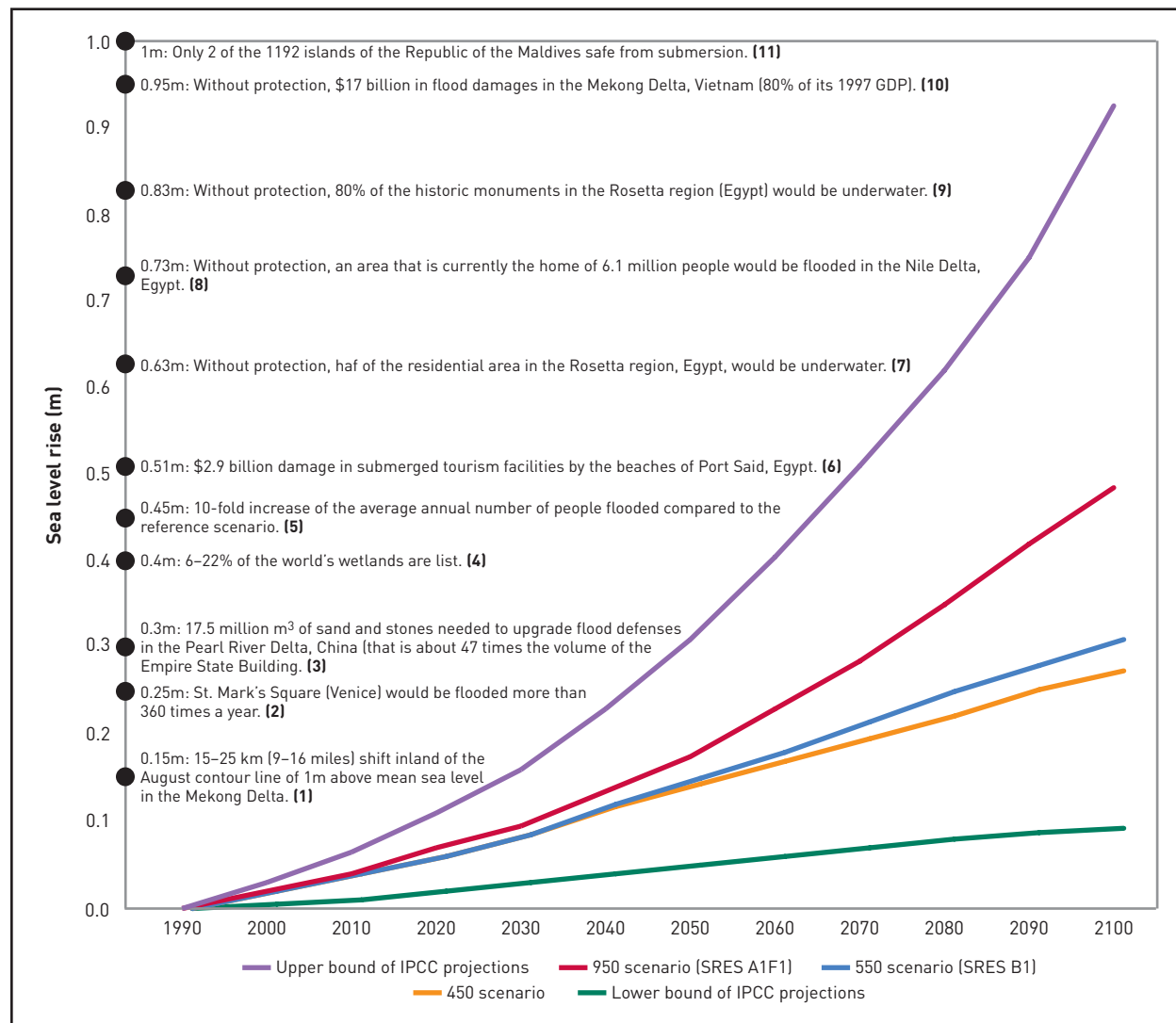
Projecting sea level rise in the 21st century

The IPCC has published forecasts of future sea level rise using a variety of assumptions about future global warming and the physical processes leading to sea level increases. The most recent projections for the next century are shown in Figure 3. These projections reflect the range of possible sea level increases due to the various uncertainties, as explained below.

The projections were made using different models and different future emissions scenarios from the Special Report on Emissions Scenarios (SRES). The 450 ppm and 550 ppm curves are the best estimates of sea level rise for a scenario where CO₂ concentration is stabilized at respectively 450 ppm and 550 ppm by 2100.³⁵ Both of these scenarios would require the implementation of an international framework for worldwide greenhouse gas emission reductions, most realistically starting within the next decade, since past that timeline reduction rates become prohibitively costly.³⁶ The 950 ppm curve is the best estimate of sea level rise for the most fossil-fuel intensive IPCC scenario (SRES A1F1), where CO₂ concentration reaches 950 ppm in 2100 and keeps increasing.³⁷ (All the scenarios include similar assumptions of concentrations of other greenhouse gases such as methane and nitrous oxide, but for clarity further references will be to CO₂ concentrations because it is, the most important greenhouse gas.)

The surrounding thick curves represent the uncertainty associated with

FIGURE 3
Impacts of global sea level rise on selected coasts and islands worldwide



See Appendix 1 for detailed legend (indicated by bold numbers in parentheses)

these projections: They show the entire range of projections by all seven models used by the IPCC for all the 35 SRES scenarios. The emission scenarios are run on models of sea level rise that take into account both the thermal expansion of seawater as it warms and the thinning of mountain glaciers on land.

A large part of this range comes from the diversity of emissions scenarios (CO₂ concentrations of 450 to 950 ppm in 2100) in which uncertainty about the amount of human-produced emissions

comes from different projections concerning population growth, the development and implementation of technology, climate policy and so on. The remaining uncertainty reflects the range of assumptions about climate sensitivity and ice melt parameters. The forecasts suggest that by 2100 thermal expansion will contribute about 60% to sea level rise, while the remaining 40% will result mainly from glacial, ice cap, and Greenland ice sheet melting.³⁸

TABLE 1
Threshold concentrations and the associated sea level rise

Process	Threshold (CO ₂ concentration)	Eventual sea level rise	Likely time scale
Thermal expansion ⁴¹	540 ppm/1080 ppm	0.5–2 m/1–4 m (1.5–6.5 feet/3–13 feet)	1,000 years
Greenland ice cap melting ⁴²	450–550 ppm	7 m (23 feet)	1,000 years
West Antarctica ice cap melting ⁴³	550 ppm or higher	5 m (16 feet)	1,000 years

An important point to consider when reviewing Figure 3 is that the central value of the IPCC projections (0.48 m) represents about two to four times the rate experienced over the past century (1–2 mm/yr). Thus the rate of land loss and increase in storm surges experienced in the past will not be an adequate guide to the losses that will be suffered and the adjustments that will be required in the future. Also, the amount of sea level rise in 2100 shows only the tip of the iceberg: The full extent of the process will take several centuries to unfold.

Titus and Naryanan have developed an innovative probabilistic model of sea level rise based on warming oceans and melting ice caps that treats model uncertainties as a probability distribution, as gauged by 20 climate experts.³⁹ Among their more notable conclusions: There is a 1% chance that global warming will raise sea level by one meter (3.2 feet) in the next 100 years and four meters (13 feet) in the next 200 years. Moreover, the recent increased rate of warming in the Arctic region is likely to lead to sea level increases on the high end of the IPCC estimates, which would be close to one meter in 2100.⁴⁰

Emissions today are a commitment to sea level rise for centuries

The timeline of most studies on sea level rise is 2100 at latest. However, this timeline only shows the tip of the iceberg, and most of the extent of sea level

rise will unfold only centuries after 2100. This delay is due to the inertia of both the ocean and the polar ice caps, in which warmth diffuses slowly. Table 1 shows the full extent of these processes.

Because these processes are complex and take place over long periods of time, there is necessarily some uncertainty associated with the concentration threshold and the timeline. Indeed, a number of recent studies documenting accelerated melting, especially in Alaska, Greenland and Antarctica, hint at a timeline that could be reduced to a few centuries.⁴⁴

What is certain, however, is that the decisions we make or fail to make within the next decade regarding target levels for greenhouse gas concentrations will commit us to different degrees of sea level rise for centuries to come. This commitment mechanism is laid out in a simplified way in Figure 4. This figure gives only an idea, and not a precise projection, of the eventual consequences of the three scenarios already discussed in Figure 3. Indeed, other processes affecting sea level rise, such as changed accumulation, temperate glacial melting or further Antarctic melting are not accounted for. The resulting projection is conservative, since such factors are likely to translate into additional increased sea level rise.

It also renders the uncertainty associated with such remote projections: A stabilization of CO₂ concentrations at 450 ppm is forecast to increase sea level by slightly less than 0.5–2 m (which is the figure for 540 ppm) because of

FIGURE 4
Consequences of today's decisions on sea level rise in a millennium

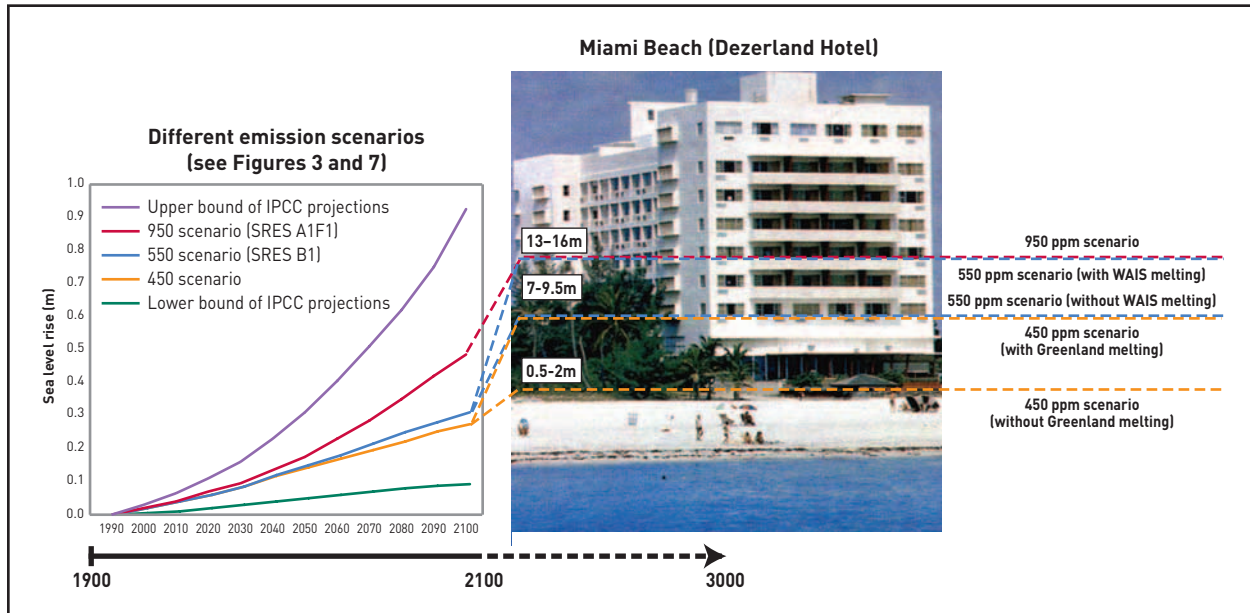


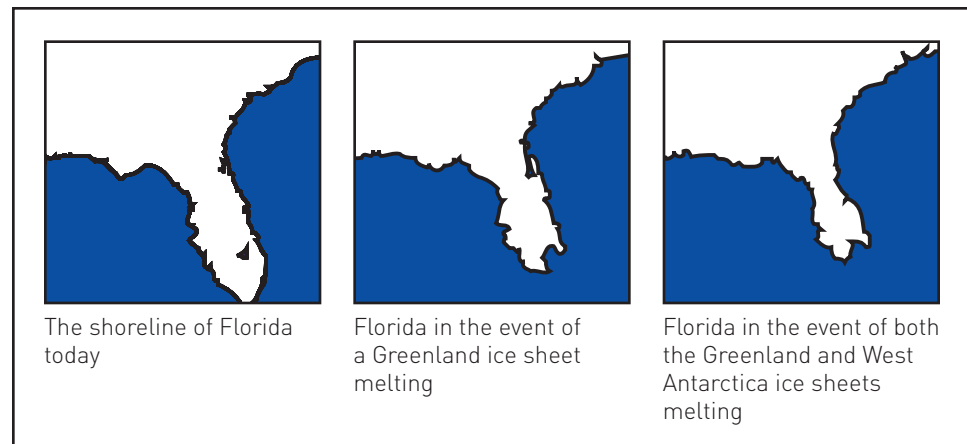
Photo: www.travelbase.com

thermal expansion, but uncertainty remains as to whether it will lead to a complete melting of the Greenland ice sheets. A stabilization at 550 ppm is very likely to trigger this melting, leading to a sea level of at least seven more meters (thereby up to 7.5–9 m from the current level because of thermal expansion). However, the fate of the West Antarctica Ice Sheet (WAIS) would remain uncertain.

Finally, the last scenario would not only involve a melting of the WAIS, but the rise from thermal expansion would more likely be around 1–4 m. Adding up numbers, this leads to 13–16 m (43–52 feet) above the current level.

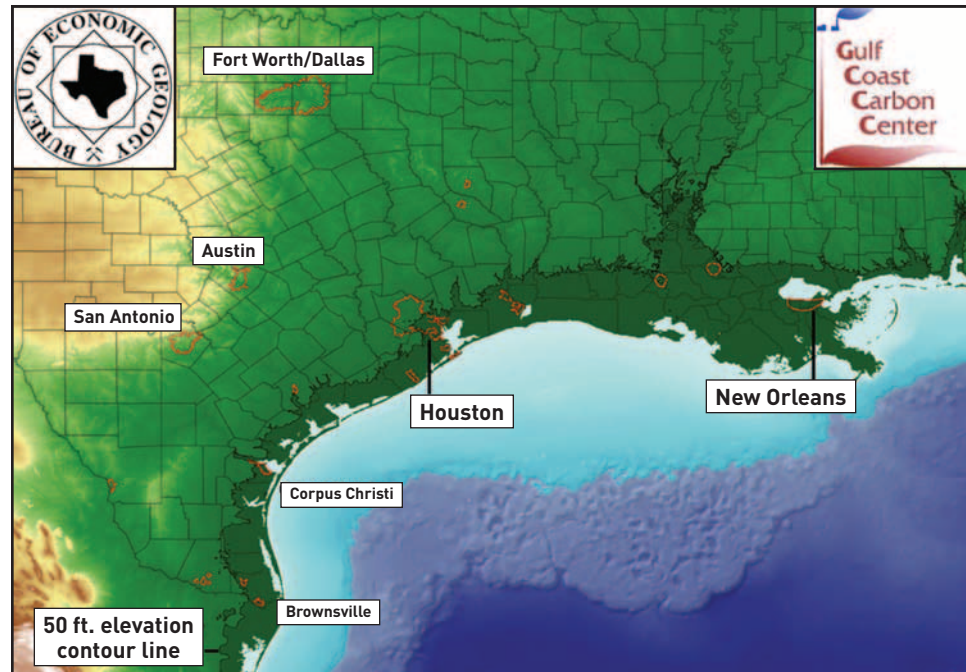
Following the same logic, Dr. Richard B. Alley of the University of Pennsylvania presented the following maps at a congressional briefing in 2004

FIGURE 5
Potential coastline retreat as a result of ice sheets melting Florida



Courtesy of Byron R. Parizek, Ph.D., Pennsylvania State University

FIGURE 6
Potential coastline retreat as a result of ice sheets melting the Gulf Coast



Another study by the Gulf Coast Carbon Center and the Bureau of Economic Geology displays the map of the Gulf Coast, featuring the 15.2 m (50 feet) elevation line, which is the order of altitude that the sea is likely to reach if both Greenland and West Antarctica ice sheets were to melt entirely.

(see Figure 5).⁴⁵ These maps model the impact of the melting of the Greenland Ice Sheet and the WAIS on the shoreline of Florida.

Regional impacts of sea level rise superimposed on IPCC projections

Abbreviated summaries of the consequences of sea level rise on selected coastlines and islands are presented in Figures 3 and 7. Figure 3 focuses on global impacts while Figure 7 is restricted to the United States.

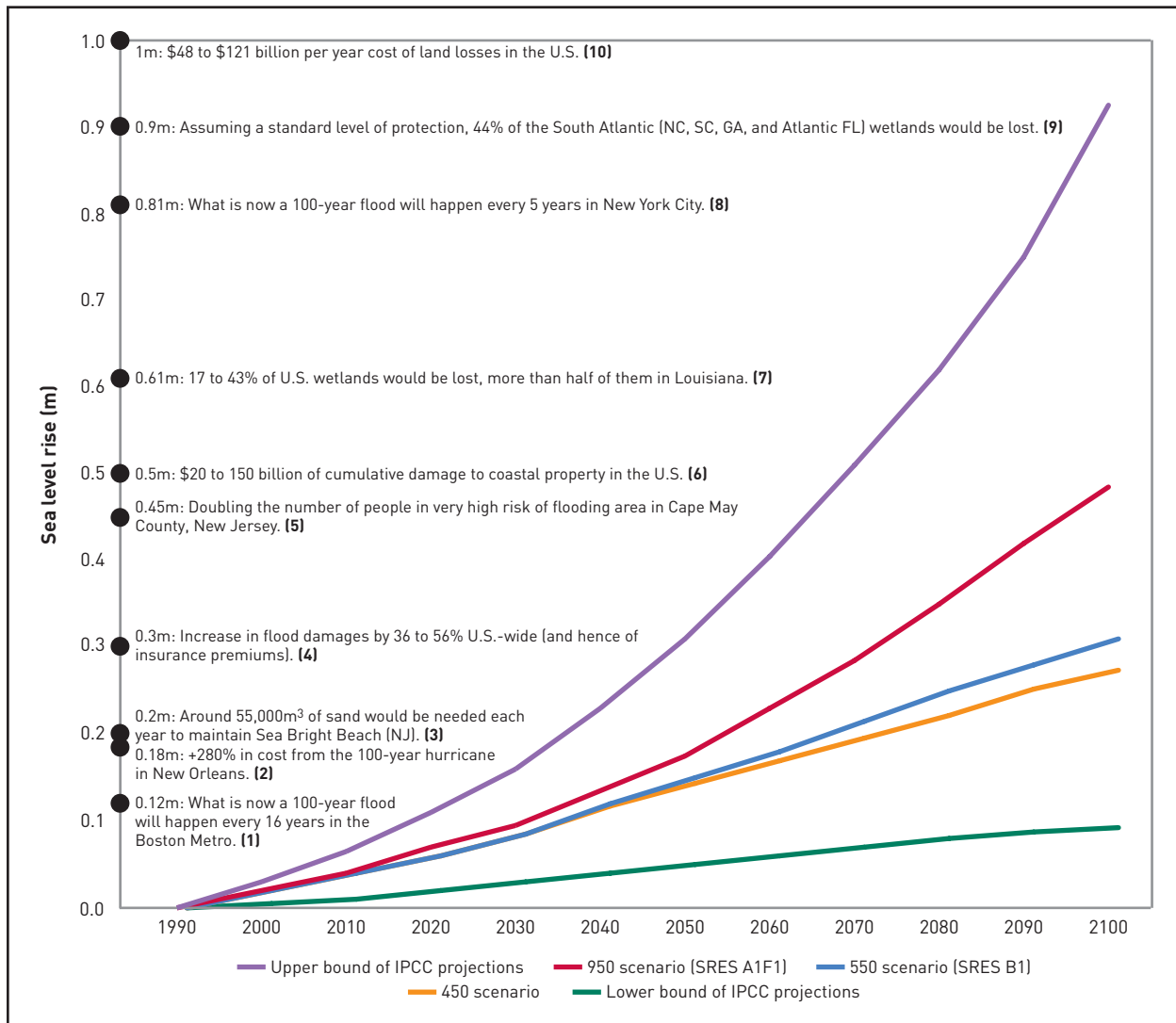
The figures superimpose captions for impacts at various locations on top of the three scenarios discussed previously (stabilization at 450 ppm by 2100, stabilization at 550 ppm by 2100 or unrestrained emissions reaching 950 ppm in 2100 and still growing). The range of the IPCC

projections based on 35 scenarios (including these three) put in seven different climate models is also outlined in order to give an idea of the uncertainty associated with these projections.

The impacts are keyed to the global sea level rise so that it is meaningful to compare them to one another. However, since most local studies assess the impacts resulting from local sea level rises, a conversion was usually needed. It consisted in subtracting the amount of subsidence expected by 2100 in the locality from the sea level rise figure given in the study. Indeed, relative sea level rise is mainly the result of global sea level rise and local subsidence. Both the original figure and the local subsidence rate are given in the legend each time the conversion is applied.

On a few occasions, a close location or a regional average was taken as a

FIGURE 7
Impacts of global sea level rise on selected sites in the U.S.



See Appendix 2 for detailed legend (indicated by bold numbers in parentheses)

proxy for subsidence at the study’s site. And when the estimate for subsidence was given as a range, the lower bound was retained. This is meant to be conservative, since it requires a more important contribution from the global sea level to reach the “impact threshold” locally. All these specific variables are noted in the legend when needed.

Finally, one should bear in mind that these figures are only intended to give an idea of the different timeframes and the kinds of sea level rise impacts that

can be expected from different climate policies. There is necessarily some uncertainty associated with such impact predictions and we opted, whenever it applied, for conservative rather than alarmist estimates.

Effects of sea level rise on small island nations

Small island nations, many of which are only a few meters above sea level, may be facing annihilation due to the in-

evitability of significant sea level rise, as shown in Figure 3. Thus they deserve special attention in any report on sea level rise impacts. Among the most vulnerable of these islands are the Pacific Ocean's Marshall Islands, Kiribati, Tuvalu, Tonga, Line Islands, Federated States of Micronesia, and Cook Islands; the Caribbean island nations of Antigua and Nevis; and, in the Indian ocean, the Maldives.

Pernetta offers an excellent authoritative summary of the climatic horizon for small island nations, taking into account geology, demography, economics, oceanography, social traditions, and marine and island biology, among other subjects.⁴⁶ Below are some salient points and a brief synopsis.

In general, population levels, growth rates and densities are very high. Cultural, and especially linguistic, diversity is enormous—for example, more than one third of the world's languages are spoken in four island countries in Melanesia. Accelerated emigration due to climatic or environmental degradation would weaken the elements of the traditional cultures, which is why the issues of equity and human rights have been raised at the United Nations with regard to these islands.⁴⁷ Even though these states account for less than 1% of global greenhouse gas emissions and are among the poorest countries on Earth, they are the most vulnerable to climate change, mainly because of sea level rise.⁴⁸

Among the impacts that small islands will face due to sea level rise and climatic warming are: (1) increased coastal erosion; (2) changes in aquifer volumes with increased saline intrusion; (3) greater demand for air conditioning and hence energy consumption and fossil fuel

importation; (4) coral reef deterioration resulting from sea level rise accompanied by thermal stress; (5) social instability related to inter-island migration; (6) loss of income through negative impacts on tourist resort location; and (7) increased vulnerability of human settlements because of increasing size.

Policies and practices that will exacerbate these problems include: (1) coral reef mining; (2) land reclamation; (3) construction of harbors, jetties, and breakwaters; (4) over-use of aquifer resources; (5) lack of in-country data covering physical and biological resources; (6) shortage of labor power; and (7) inadequate disposal of sewage and toxic chemicals. The failure to adequately address current environmental problems will leave the islands more vulnerable to future climatic and sea level changes.

Climate change will affect rainfall, wind and monsoon patterns. Upwelling zones in the ocean may shift, affecting fisheries. Storms and droughts may increase in number and intensity. Evapo-transpiration rates may change. General weather-related changes may lead to impacts on agricultural crops, natural vegetation and the growing season.⁴⁹

Finally, it is interesting to note that since marine resources provide the bulk of small island income, if the people of island nations can continue to occupy their islands through adaptation, their nations may remain economically viable. However, protection measures must be carefully analyzed. Dikes, for example, are infeasible because of coral atoll porosity. Thus, the islands would most likely have to elevate.⁵⁰

How can future sea level rise hazards be addressed?

Climate stewardship, sooner rather than later

There are two major ways to address the sea level rise issue: tackle causes or mitigate consequences. Figure 3, 4, and 7 show how different concentrations of greenhouse gases would lead to greater or lesser impacts. Indeed, cutting greenhouse gas emissions and stabilizing concentrations is probably the most efficient and cheapest way to address sea level rise.⁵¹ As discussed by O'Neill and Oppenheimer, this solution requires fast action. They show, for example, that if industrialized nations put off absolute emissions reductions until 2020, it could foreclose on the possibility of stabilizing concentrations at 450 ppm in 2100, because the costs would become unrealistically high as the cuts would be unfeasibly steep.⁵²

Possible local response strategies

Even if the political difficulties of responsible climate stewardship were solved and greenhouse gas concentrations were on course to be stabilized at a reasonable level by 2100, sea level would continue to rise due to past emissions. Therefore, the solution to sea level rise encompasses both global climate stewardship and local response strategies. These fall into three categories: *retreat*, *accommodate* and *protect*.⁵³

As described in IPCC reports, *retreat* strategies emphasize abandonment of coastal lands and the resettlement of inhabitants. This policy would further entail preventing development in coastal areas and withdrawing government subsidies and protections for coastal development. In the states of Maine, Massachusetts, Rhode Island

and South Carolina, for example, state legislation exists to explicitly limit how land can be developed that is vulnerable to sea level rise.⁵⁴

Accommodation stresses the conservation of ecosystems with continued occupancy and adaptive management. This strategy would employ advance planning, modification of land-use and building codes, ecosystem protection, and hazard insurance.

Protection involves the defense of vulnerable areas, populations, and economic activities. Hard structural options include dikes, levees, seawalls and saltwater intrusion barriers. Soft options include periodic beach nourishment, dune restoration, wetlands creation, drift replenishment and afforestation. In the Netherlands, for example, dikes are built with extra elevation in order to allow for sea level rise. Similarly, in San Francisco, reclaimed land has to be of a certain elevation.⁵⁵

Not all of these options are feasible for all regions. For example, heavily populated areas, island nations like Japan and seaside tourist centers have little choice but to protect. In many countries, the scarcity of technology and a dearth of personnel will limit the choice of accommodation options. Retreat and resettlement options will involve questions of international refugees and related disputes as well as issues of cultural traditions: To what extent will various communities be willing to resettle? How will changed or lost access to traditional fishing and hunting sites be tolerated?

Above all, economic considerations will determine the feasibility of various options. A comparison of different strategies is very clearly laid out in the recent study on the Boston metropolitan

area.⁵⁶ In many countries, merely maintaining existing shorelines could require substantial funding relative to GNP.⁵⁷

The literature on costs usually divides them into three categories: (1) capital costs of protective measures, (2) annual

costs of forgone land services and (3) the costs associated with increased flood and storm frequencies. The literature estimating the costs of protection has been reviewed by R. Tol in 2002⁵⁸ and will not be reviewed here.

Conclusion

Of all the forces of nature, the oceans inspire the deepest respect and awe. From the dawn of human civilization, the oceans have been associated with countless myths, gods and tales of adventure and exploration. That this powerful force is being fundamentally transformed by another force—that of human industry and resultant global warming—to the extent that we see threatening changes in sea levels, ocean's acidity, coastal configurations, sea surface temperatures, and storm activity, strikes a deep chord.

The comparative irreversibility of sea level rise—it would continue for centuries even if global warming were

slowed or stopped—means that it constitutes one of the gravest of the many threats we face from global warming. Because of greenhouse gas emissions and the overall environmental degradation of our coasts, we are jeopardizing our complex relationship with the very oceans that have economically and culturally sustained and nourished humanity's development throughout the ages. The only rational response is to prevent, to the greatest extent possible, dangerously high levels of greenhouse gas accumulation in the atmosphere, and thereby avoid the bleakest consequences of sea level rise.

Detailed legend of Figure 3

- (1)** Local subsidence conservatively estimated at 5 cm/century: The rate given for the overall local sea level is around 1.75–2.56 mm/year, which leaves out 0.5–1 mm/year of subsidence when the average global rate for sea level is subtracted. R. Wassmann *et al.*, “Sea Level Rise Affecting the Vietnamese Mekong Delta: Water Elevation in the Flood Season and Implications for Rice Production,” *Climatic Change* 66, pp. 89–107 (2004).
- (2)** Based on the given average rate of subsidence between 1900 and 1970, local subsidence was estimated at around 5 cm/century. As a benchmark, it is interesting to know that in the beginning of the twentieth century, St Mark’s Square was only flooded five to seven times a year. E. Penning-Rowsell, P. Winchester and J. Gardiner, “New Approaches to Sustainable Hazard Management for Venice,” *The Geographical Journal* 164, pp. 1–18 (1998).
- (3)** No local subsidence. Z. Huang, Y. Zong and W. Zhang, “Coastal Inundation Due to Sea Level Rise in the Pearl River Delta, China,” *Natural Hazards* 33, pp. 247–264 (2004).
- (4)** This figure represents the amount of wetland losses caused strictly by sea level rise. When other human influences are added, the losses could add up to 70% of total by 2080. R. J. Nicholls, F. M. J. Hoozemans and M. Marchand, “Increasing Flood Risk and Wetland Losses Due to Global Sea-Level Rise: Regional and Global Analyses,” *Global Environmental Change* 9, pp. 69–87 (1999).
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Detailed legend of Figure 7

(1) Local subsidence rate is 18 cm/century. The 16-year figure is an average over the 50 years surrounding the date at which sea level rise will reach 30 cm in the Boston metropolitan area.

P. Kirshen et al., “Climate’s Long-term Impacts on Metro Boston (CLIMB) Final Report” (2004): http://www.tufts.edu/tie/climb/CLIMB_FV1-8_10pdf.pdf.

(2) Local subsidence rate is 20 cm/century. The original estimate was for a local sea level rise of 0.38 cm by 2050.

B. Good et al., “Coast 2050: Toward a Sustainable Coastal Louisiana,” *Report by the Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority* (1998) <http://www.coast2050.gov/2050reports.htm>.

(3) Local subsidence rate is assessed to be around 14 cm/century on average. The amount of sand given is the average of the 60 years surrounding the date when local sea level rise reaches 34 cm (2050 in the original article). To give an idea of the volume, 55,000 m³ is more than twice the Lincoln Memorial’s Reflecting Pool in Washington DC.

V. Gornitz, S. Couch and E. K. Hartig, “Impacts of Sea Level Rise in the New York City Metropolitan Area,” *Global and Planetary Change* 32, pp. 61–88 (2002).

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(5) Local subsidence rate is assessed to be between 10 and 25 cm/century. A somewhat conservative figure of 15 cm/century is retained for the calculation from the local 60 cm impact forecast in the article.

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(8) Local subsidence rate is assessed to be around 14 cm/century. This was subtracted to the local rise of 0.95m scenario that corresponds to this impact prediction.

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J. G. Titus et al., “Greenhouse Effect and Sea Level Rise: The Cost of Holding Back the Sea,” *Coastal Management* 19, pp. 171–204 (1991).

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