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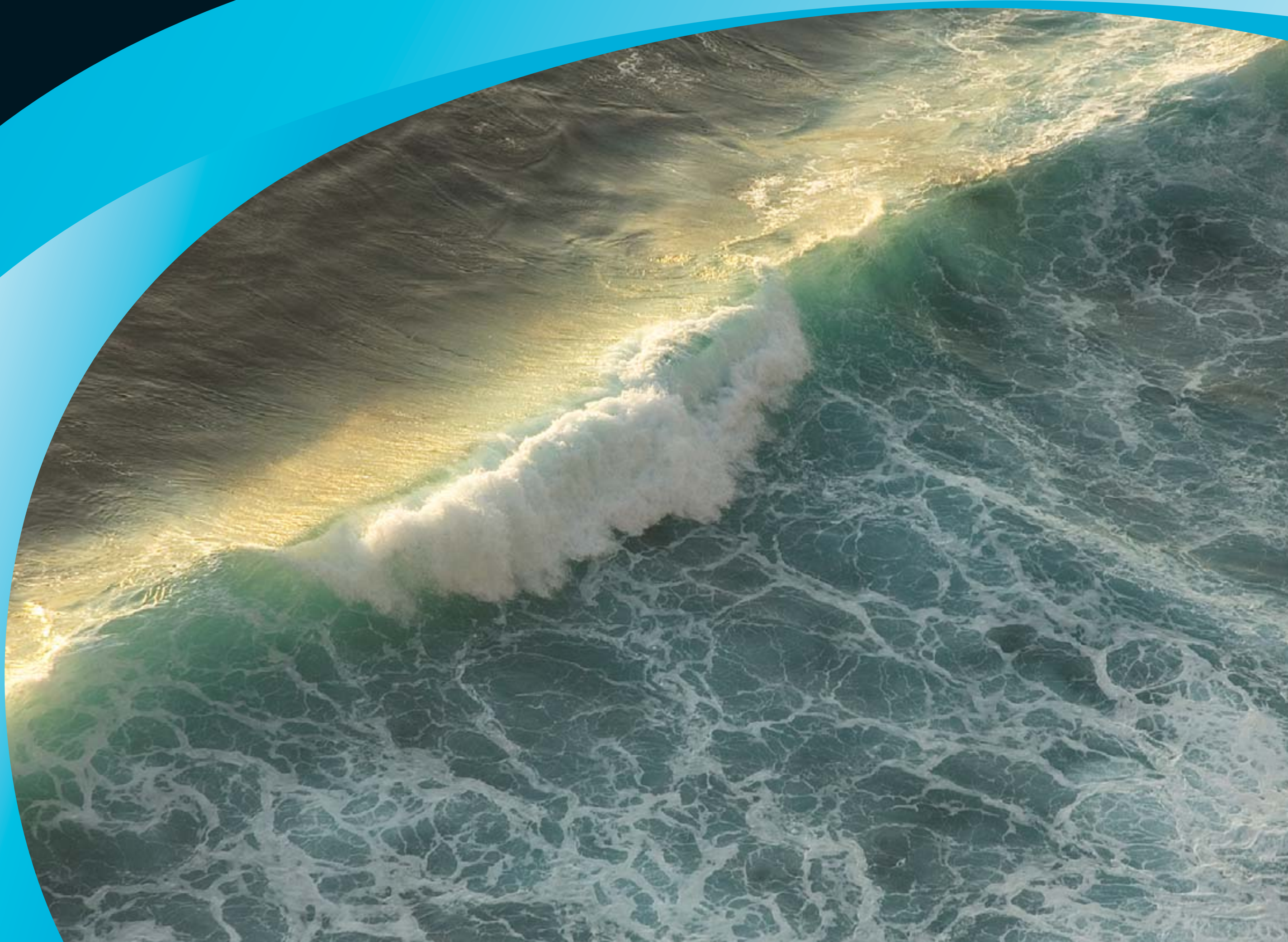
The 2008 Lloyd's Register Educational Trust Lecture

Risk-Informed Investments in Oceanic and Atmospheric Research

Dr Richard W. Spinrad
Assistant Administrator, Office of Oceanic and Atmospheric Research
National Oceanic and Atmospheric Administration

Date: Tuesday 29 April 2008
Venue: 2 Savoy Place, London WC2R 0BL



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Risk-Informed Investments in Oceanic and Atmospheric Research

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Abstract

In the decades and century to come, mankind will experience - and thus benefit and potentially suffer from - dramatic changes in the nature of the world's oceans and atmosphere, and their impacts on society. Therefore, investment strategies to protect human health and safety, sustain viable ecosystems, provide national security, and enhance economic development are inextricably tied to understanding society's impact on the oceans and the oceans' impact on society. Understanding the interactions of the ocean with the atmosphere and land are critical for reducing uncertainty in forecasting climate change, predicting severe storms, and sustainably managing ecosystems. This lecture will show that the risk associated with decision-making increases when scientific research is lacking. Scientific discovery directly informs a risk-management strategy that maximises economic and societal benefits. Further, the lecture will demonstrate that risk-management principles must be applied to research investment strategies to create a balanced research portfolio prioritising research objectives, identifying high risk/high impact research, and ensuring investments in breakthrough technologies outpace potential adverse impacts. In other words, oceanic and atmospheric research have extraordinary implications to risk-informed decision-making from a local to global scale.

Introduction

I am honoured to speak to this distinguished audience tonight about a subject for which I have great interest, and from which I believe society could benefit considerably. I am also most grateful to the sponsors, Lloyd's Register Educational Trust and The Royal Academy of Engineering for inviting me over to this side of the 'pond' to discuss this important set of issues.

On a personal note - and as a scientist standing before this august audience of engineers - I hope that through this discourse I might dispel the notions of the famous German mathematician, David Hilbert, who stated “One hears a lot of talk about the hostility between scientists and engineers. I don't believe in any such thing. In fact I am quite certain it is untrue…There cannot possibly be anything in it because neither side has anything to do with the other.”

Quite significantly, the relationship between risk, decision-making, and information about the nature and variability of our environment is becoming dramatically more evident of late. Over the last ten years, the world has suffered an increasing number of natural disasters affecting more than 2.5 billion people, killing 478,100 people, and causing economic losses of about US$690 billion (Figure 1).[1] From a risk-management perspective, the growing world population and associated infrastructure increase global human vulnerability to natural hazards. This is particularly true for coastal areas where population growth is strongest, and exposure to hazards such as floods, tropical cyclones and tsunamis is greater.

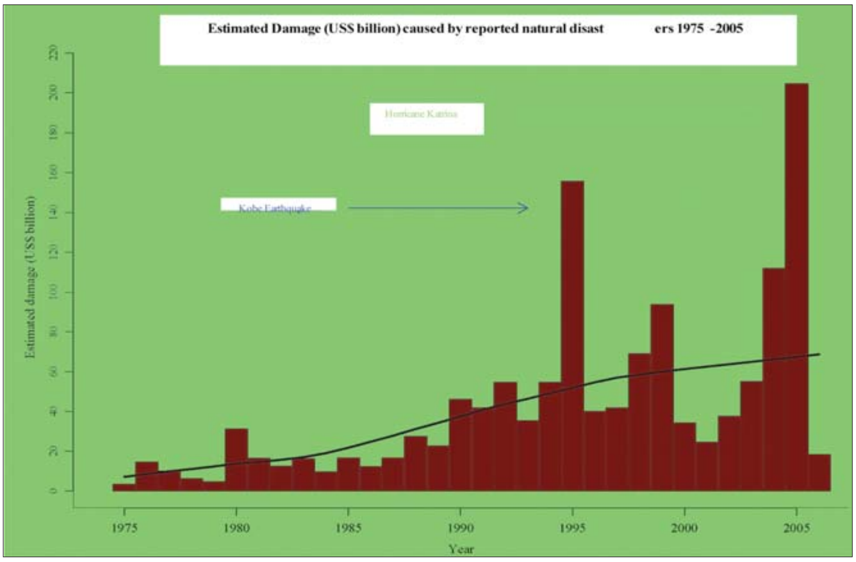

Figure 1. Source: EM –DAT: The OFDA/CRED International Disaster Database – www.em–dat.net – Université Catholique de Louvain, Brussels – Belgium

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[1] *Sálvano Briceño, Director, United Nations, Inter-Agency Secretariat of the International Strategy of Disaster Reduction UN/ISDR.*

Two recent and unforgettable examples that contributed dramatically to the total number of people affected by natural disasters include the Indian Ocean tsunami of Boxing Day, 2004, and Hurricane Katrina in the U.S. Gulf Coast in August of 2005 (Figure 2). The tsunami, one of the most devastating natural disasters in recorded history left 273,636 people dead (220,153 in Indonesia alone), 7,253 people missing, 1.5 million displaced and over half a million homeless[2]. In terms of economic costs, the impact on coastal fishing communities - some of the poorest people in the region - has been devastating, with high losses of income earners (fishermen) as well as the means for surviving fishermen to earn income, their boats and fishing gear[3]. Just the expenses of recovery costs have exceeded US$7 billion among all the contributors worldwide[4]. Hurricane Katrina resulted in 1,330 dead - 80 percent of those were in New Orleans and 68 percent were in nursing homes[5]. As of February 17, 2006, there were still 2,096 people from the coastal areas of the Gulf of Mexico reported missing. Katrina's extraordinary force and structure, impacting nearly 93,000 square miles across 138 parishes and counties, devastated far more residential property than had any other recent hurricane, and destroyed or made uninhabitable an estimated 300,000 homes. But as is typical with most hurricanes and typhoons the damage was not limited to that caused by the initial winds and rain; storm surge cresting up to 27 feet dealt a ferocious blow to homes, businesses, and property on the coast and for many miles inland. Approximately 80 percent of the city of New Orleans was flooded. Again, the economic costs were astronomical: total costs are expected to exceed US$100 billion[6]. Insurance companies have paid an estimated US$41.1

Figure 2. Hurricane Katrina, August 28, 2005. Credit: NOAA

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[2] *International Red Cross.*

[3] *Staff Writer. "Indian Ocean Tsunamis Devastate Fisherfolk." UK Agricultural Biodiversity Coalition.*

[4] *US Agency for International Development.*

[5] *Federal Response to Katrina - Lessons Learned. February 2006. White House, www.whitehouse.gov/reports/katrina-lessons-learned.pdf*

[6] *Federal Response to Katrina - Lessons Learned. February 2006. White House, www.whitehouse.gov/reports/katrina-lessons-learned.pdf*

billion on 1.7 million claims for damage to homes, businesses and vehicles in six American states from Hurricane Katrina, the largest loss in the history of the insurance industry[7]. The economic risks and consequences were also realised by some major sectors. Hurricane Katrina forced the evacuation of more than 75 percent of the Gulf's 819 manned oil platforms[8]. By one estimate, even two days before landfall, the hurricane had already caused the oil industry to reduce Gulf of Mexico oil production by more than a third[9].

It is most essential that we also discuss the trends for these risks since our capacity to forecast these events is obviously critical. While policy and planning at the national, regional and local levels, may address factors of exposure, what about natural variability (including that which might be in response to anthropogenic forcing)? Well, the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (FAR)[10] confirms the unequivocal warming of the climate system as being *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations. This means many natural systems are being affected by regional climate changes. Regional changes include a *very likely* increase in frequency of hot extremes, heat waves, and heavy precipitation; and unmitigated climate change would, in the long term, be *likely* to exceed the capacity of natural, managed, and human systems to adapt.

Probably the most common and publicly understood hazards associated with oceanic and atmospheric threats are hurricanes, tsunamis, tornadoes and severe storms. Less understood is the hazard associated with climate change. While the scientific community understands the criticality of climate change, the global public is widely divergent in its comprehension and level of awareness of the potential hazards associated with a changing climate. Collectively, we are only beginning to comprehend the scientific and social implications of sea level rise, warming of the ocean, atmosphere and land temperatures, changes in ocean currents, ocean acidification, variability in weather patterns and extreme events. Complicating the issue of accurately predicting the frequency, magnitude and location of natural hazards is the ability to quantify the consequences as related to the value of human lives, ecosystems and property. Uncertainties lie in our ability to measure, quantify and forecast or predict all aspects of these risks including social behavior and adaptation. As responsible stewards of research investments, we must focus on decreasing uncertainty in the forecast of natural hazards by risk-informed investments in research.

So, the fundamental questions are whether research into these and other environmental phenomena may help reduce what are clearly significant risks associated with the forecasting of natural hazards and how such risk implications might be used to prioritise oceanographic and atmospheric research investments.

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[7] *Insurance Information Institute, www.iii.org/media/facts/statsbyissue/hurricanes/*

[8] *Federal Response to Katrina - Lessons Learned. February 2006. White House, www.whitehouse.gov/reports/katrina-lessons-learned.pdf*

[9] *Federal Response to Katrina - Lessons Learned. February 2006. White House, www.whitehouse.gov/reports/katrina-lessons-learned.pdf*

[10] *www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf*

Risk assessment for research investment: reducing uncertainty through research

Investment strategies to protect human health and safety, sustain viable ecosystems, provide national security, and enhance economic development are inextricably tied to understanding society's impact on the oceans and the oceans' impact on society. Scientific discovery directly informs a risk-management strategy that maximises economic and societal benefits.

Forecast Uncertainty: Oceanic and Atmospheric Examples

A critical component of the nature of environmental forecasting is the uncertainty in the predictions. Let's discuss a few general concepts and how we might consider the uncertainties in oceanic and atmospheric hazards in the context of global and regional or local impacts and different perspectives on acceptable risk.

• Conducting a Risk Assessment

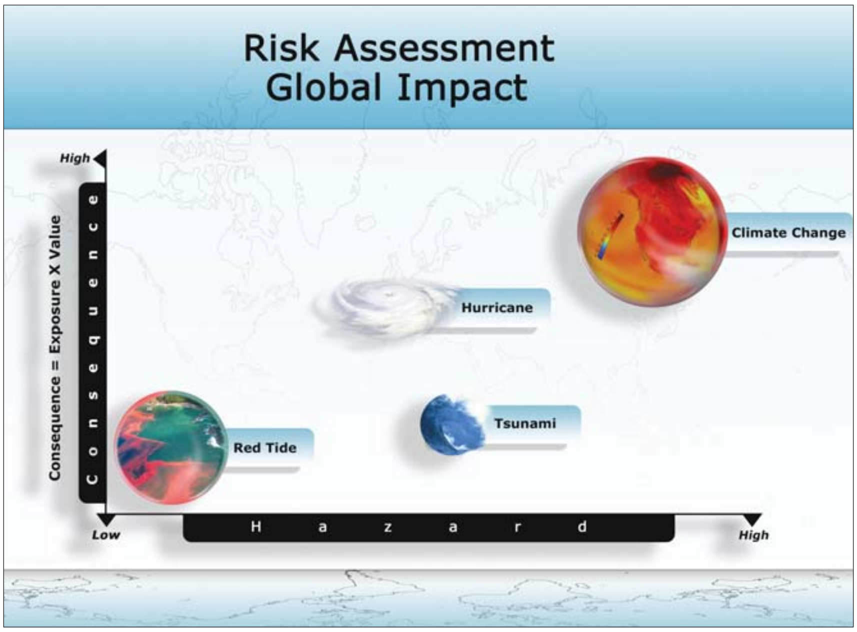

Figure 3. Risk assessment in oceanic hazards. Credit: NOAA

Figure 3 is a conceptual plot of the global probability of a hazard occurring, versus the consequences if it does occur; it helps us formulate how one might compare natural hazards in a risk assessment framework. The size of the hazard representation depicts the relative uncertainty of our ability to either forecast the hazard or quantify its consequences. Our ability to forecast or predict the frequency, location and magnitude of the hazardous event may be limited by the accuracy or availability of the data, our scientific understanding of the phenomena or technical limitations in modelling the phenomena. Uncertainty also lies in our ability to accurately describe the vulnerabilities to an event, such as an ecosystem's adaptive response to ocean acidification, the changing demographics of population densities, or how society values a resource. Further complicating the issue are the individual perspectives that may dictate whether a consequence is at an acceptable level.

Uncertainty in Science and Social Response

Looking at this proposed assessment, let's focus on climate first. We might all agree, based on the IPCC FAR, that climate change is inevitable and the consequences on a global scale could be extreme. Further, we might also agree that there is a high level of uncertainty in our ability to forecast what will happen. Outputs from the IPCC indicate that global surface warming by the year 2100 may vary from somewhat less than 1°C to over 4°C, depending on future emissions scenarios, population growth, economic development, life style choices, technological change, and availability of energy alternatives (Figure 4). Uncertainty in the modelling of these scenarios was reduced by using ensemble results such that for each scenario the range of forecast in temperatures was less than 1°C per scenario[11]. Few would disagree, at least in the scientific community, that we can improve the forecast with better science (climate models and observations), access to more powerful supercomputers, and improved understanding of emission scenarios and thereby begin to lower the risks associated with climate change.

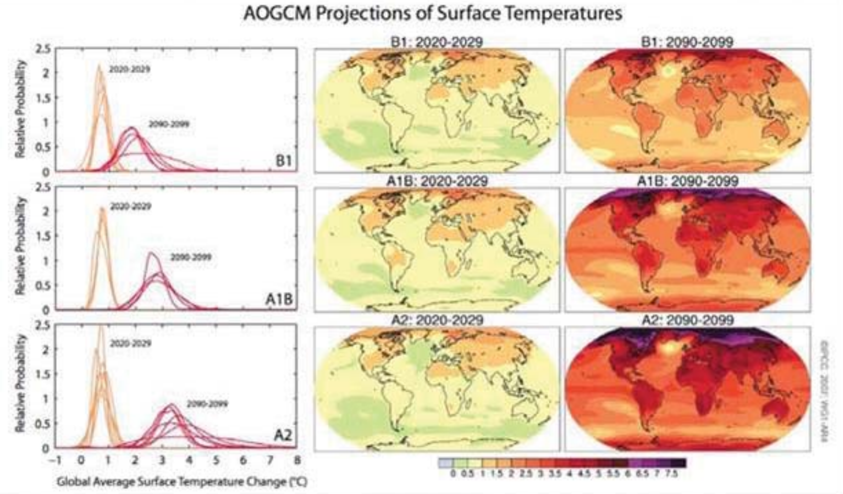

Figure 4.

***Left panel**: Solid lines are multi-model global averages of surface warming (relative to 1980-1999) for the Special Report on Emissions Scenarios (SRES) A2, A1B and B1, shown as continuations of the 20th century simulations. The orange line is for the experiment where concentrations were held constant at year 2000 values. The bars in the middle of the figure indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios at 2090-2099 relative to 1980-1999. The assessment of the best estimate and likely ranges in the bars includes the Atmosphere-Ocean General Circulation Models (AOGCMs) in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints.*

***Right panels**: Projected surface temperature changes for the early and late 21st century relative to the period 1980-1999. The panels show the multi-AOGCM average projections for the A2 (top), A1B (middle) and B1 (bottom) SRES scenarios averaged over decades 2020-2029 (left) and 2090-2099 (right). {WGI 10.4, 10.8, Figures 10.28, 10.29, SPM} Source: IPCC*

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[11] *"Understanding and Responding to Climate Change", NAS report, http://dels.nas.edu/basc/Climate-HIGH.pdf*

Further, current climate science and the evidence that we are approaching tipping points, such as the Arctic ice melt, are telling us the decision to invest cannot wait. Dire consequences may require urgent response. The real issues then, may be the willingness of society to invest in high risk/high pay-off research (high pay-off in terms of dramatically reducing the consequences), the commitment to a meaningful level of investment, and our effectiveness to balance our investment in social/political research, scientific research and development of technological solutions.

So to wrap up this point, even if we all agree that the hazard will occur and has high consequences, reducing uncertainty will not only require scientific research to improve our modeling forecasts, but also social or political research to correctly forecast the world's behavior to the crisis.

• Perspective and Reason for Investment Not Just Driven by Consequences/Uncertainty

Now let's move to tsunamis. I might argue that our forecasting capability is really pretty good (that is, after the detection of a 'tsunamigenic' event, such as an earthquake or deep ocean mudslide). We could improve our warning time and our warning systems on a global basis, but still relative to climate or even hurricanes we have a fairly certain capability. You might argue on a global scale that both the consequences are moderate and the likelihood of the hazard is also low to medium. Now the risk assessment gets personal.

This assessment might change dependent upon where you live. If you are in an area that has a low probability of a tsunami striking (say Northampton), the consequence is low. However, in areas where it is high or even a rare occurrence, the consequences can have not only local, but globally devastating impacts to society. The discussion of the Indian Ocean tsunami at the beginning of the lecture, demonstrated that point.

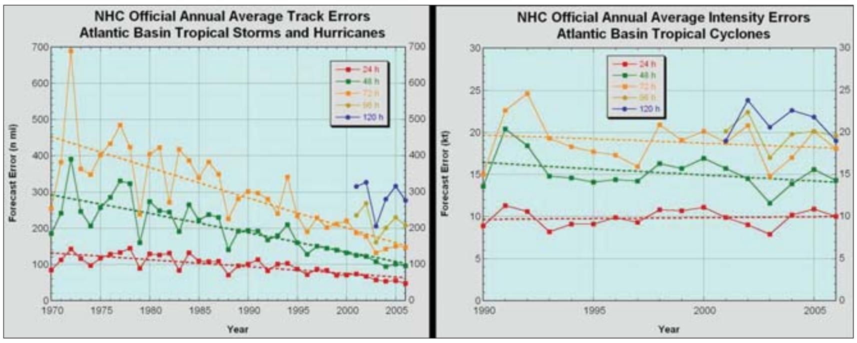

Figure 5. NOAA's research has significantly improved track forecasts over the last 30 years, while additional research is needed to improve forecasts of hurricane intensity. Source: NOAA's National Hurricane Center (NHC)

Our reasons for investing or not investing in research and warning systems may be based on humanitarian response or trickle effects to global economy rather than absolute consequence. Regarding hurricanes, we have less certainty about our ability to forecast than tsunamis, but relative to climate we are more certain. Previous research has resulted in great improvements in tracking hurricanes, but more research is needed to improve forecasting intensity and structure (Figure 5). While globally the consequences may not be as dire, both the likelihood of occurrence on United States' shores and the consequences to our highly populated coastlines, has compelled us to invest in this research as a priority.

• High Uncertainty but Low Consequences (Red Tide) May Find Some More Willing to Invest than Others

As we just argued, even if the likelihood of a tsunami is moderate, the consequences have global impact and we may be more willing to invest our scarce research dollars for the good of society. However, one may not have the same perspective when assessing red tides (harmful algal blooms). Based on our current state of understanding, we can predict the transport of a red tide and when it might land, but we are relatively uncertain as to how to predict its origins (as reflected in the size of the bubble in Figure 3). However, since this affects few in a global sense, and we have the ability to warn beach goers in advance, we might decide not to invest much in this area. It doesn't mean we should not invest. Consider that a regional government, such as the state of Florida that relies heavily on tourism, might find the cost of investment worth the price. Consider also, that the research in one area might branch over to our success in another. The same circulation and transport modelling that helps us forecast red tides on local beaches will allow us to track contaminants from point sources.

• Tradeoffs Between Risk and Reducing Uncertainty

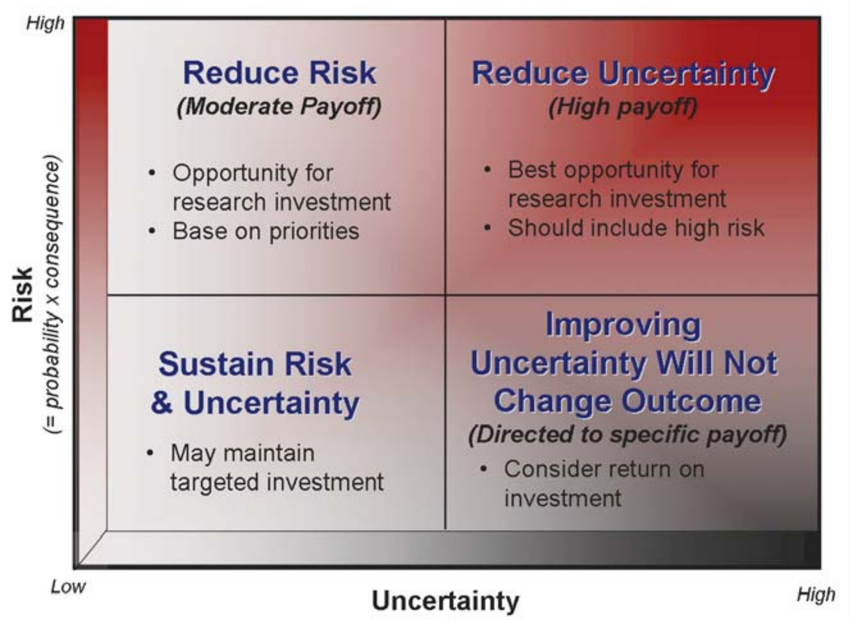

Figure 6. Risk and uncertainty in research investment. Credit: NOAA

Following our discussion of uncertainty above, let's look at it from another angle. If you look at the four quadrants reflecting high risk/high uncertainty, high risk/low uncertainty, low risk/high uncertainty, and low risk/low uncertainty you might question what your investment in research priorities might be (Figure 6). Risk as we define it here reflects the product of the probability of the hazard occurring and its consequences. For purposes of discussion, research investment can contribute to either, or both, in reducing uncertainty and reducing risk. We would, of course, want to prioritise our investments to those above the acceptable levels of risk and particularly target high risk-high uncertainty areas. Investment below the line is more subjective. If you can justify an incremental improvement to risk by an investment in reducing uncertainty, then you may fall in the lower right hand quadrant. Likewise, even though return on investment may not be that great, you may want to consider minimal or status quo funding for activities in the lower left quadrant.

Now let's take the same four hazards above and discuss in context of this graph (Figure 7). First a disclaimer, this exercise is simply intended to demonstrate the concept of conducting a risk assessment to inform investment decisions, not reflect actual decisions. Again, we may all agree on the location of climate change on this graph, but may be less convinced regarding the other three. If we look at it from the global perspective we described above and in context with each other, the argument may make some sense. Obviously, assuming the hazard falls in one quadrant is oversimplifying the phenomenon. Also, depending upon where we live, we may want to bias our investment. If others are investing in climate, we may want to focus on the incremental improvements to reducing the risk of red tides on our local beaches.

All this goes to say that a more quantitative approach would take some of the guess-work out of our assessment, but at the end of the day the decision to invest belongs to those who control the resources. That is why a transparent process for prioritisation that includes stakeholders is critical and can help inform the investment decision. Perhaps the most complicated part of this simple graph is defining the acceptable level of risk.

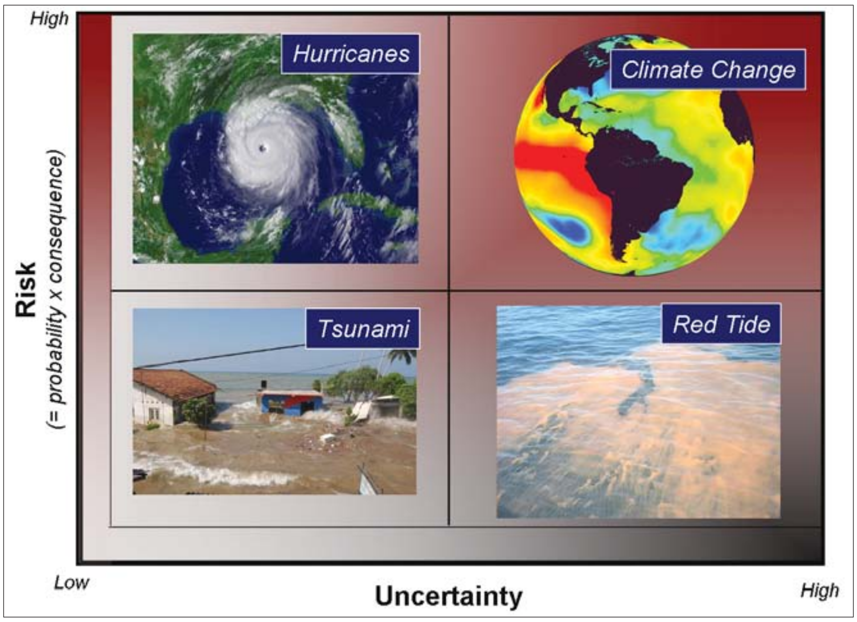

Figure 7. Risk and uncertainty in oceanic and atmospheric hazards research investment. Credit: NOAA

• Communicating Risk and Risk Tolerance

Perhaps the most cogent expression of risk association with environmental factors is reflected in the Stern Review Report's conclusion that *"Using the results from formal economic models, the Review estimates that if we don't act, the overall costs and risks of climate change will be equivalent to losing at least 5% of global GDP each year, now and forever. If a wider range of risks and impacts is taken into* *account, the estimates of damage could rise to 20% of GDP or more."*[12] Insurance and investment companies are fully engaged in understanding risk as it pertains to hazards. In fact, shortly after Hurricane Andrew's devastating impact on South Florida in 1992, the reinsurance industry developed new strategies for mitigating risk by distributing investments differently.

The insurance crisis that followed Katrina pushed the insurance industry to a new focus on quantifying risk. The consequences were too critical and costly. In Goldman Sachs' Strategic Portfolio, they are considering the new opportunities that will accompany climate change, including new growth in environmentally friendly companies and cap and trade commodities[13].
But having major corporate sectors engage in new thinking associated with risk analysis is insufficient. We must invoke a more public engagement in similar analyses. How does/should the general public interpret risk? As noted by Slovic[14], "… risk analysis is a political enterprise as well as a scientific one, and public perception of risk also plays a role in risk analysis."

• Russian Roulette

Put one bullet in a gun with six chambers. You have a one in six or 17 percent chance of losing. And losing is permanent. Would you play? Yet indeed if you look at the climate predictions for continental increases in temperature, which are much higher than the average we discussed previously, you must ask, what will the public accept and are we playing a similarly dangerous game? What is their risk tolerance? Dr. Alexander E. "Sandy" MacDonald, my Deputy Assistant Administrator, Presidential award recipient, and world-renowned scientist, has postulated that if atmospheric carbon dioxide (CO_2) levels double, the mean scenario estimates reveal that the continental temperatures will rise 5.5°C by 2100. If you look at the distribution about that mean, on the high end there is an approximately ten percent chance that continental temperatures will rise by more than 10°C and on the low end a ten percent chance it will be less than 3.8°C. The uncertainty in the range of these projected temperatures could be minimised with better research. Uncertainty also lies not only in the forecast, but in the implications of what that rise in temperature could be for agricultural production and food supply. A 10°C change is catastrophic. How do we communicate that message to the general public? Would explaining the odds help?

A recent article in *Engineer News Record*, points out the failures of engineers to communicate risk citing Katrina as an example. "Engineers are failing the public by not effectively communicating risk, the cost of protection and alternatives for mitigating natural disasters," said Robert Gilbert, University of Texas Professor at the closing plenary of the Annual Congress of the Geo-Institute of the American Society of Civil Engineers. In fact, the ASCE code of ethics, Canon 1, states, "Engineers shall hold paramount the safety, health and

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[12] www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm

[13] The Goldman Sachs Group, Inc. "Global Themes and Risks" October 2007 as presented at "Creating Knowledge-Based Partnerships." November 2, 2007, University of Delaware.

[14] Slovic, P. (1999). Trust, emotion, sex, politics, and science: Surveying the risk-assessment battlefield. Risk Analysis, 19(4), 689-701.

welfare of the public."[15] Scientists should consider the same code of ethics. Science must be prepared to provide tools that address uncertainty in a meaningful way to assist policy makers in weighing risks against public acceptance of risk, public risk-aversion, and including our natural tendency to discount future risk.

Without good scientific information, tradeoff decisions are made based on perception, political pressure, or perhaps media blitz. I have argued that the risk associated with decision making increases when uncertainty is large, as a result of insufficient scientific research. Without information, we make poor decisions and create inefficient or ineffective policy and may not be motivated to change behaviour. It is also important to remember the perspective of who makes the decisions and that risk tolerance is also subject to changing perspectives. Investments in research will enable us to quantify the hazards and society's exposure, and should focus on clearly communicating the risks and any associated uncertainty.

NOAA research initiatives focus on reducing future risk

The National Oceanic & Atmospheric Administration (NOAA) is reducing societal risk by applying management principles to research investment strategies. We create a balanced research portfolio prioritising research objectives, identifying high-risk/high-impact research, and ensuring investments in breakthrough technologies outpace potential adverse impacts. NOAA is working to reduce uncertainty in our forecasts of climate change and other natural hazards through investments in some exciting research.

Strategy NOAA is taking to insure research investments address highest risk hazards

NOAA is taking an activist strategy to ensure the limited resources available for research are providing the best value to society. NOAA research emphasises investment in preeminent science of value to society, undertaken within a culture of transparency. We strive to ensure that our research investment aligns with the organisation's highest mission priority areas. We are setting corporate performance measures for internal and external accountability. Our scientific reviews focus on evaluating our portfolio for relevance, quality and performance, all with attention to reducing uncertainty, both in our understanding of, and our ability to predict change in the oceanic and atmospheric environment.

While NOAA's research investment of more than US$500 million addresses an extraordinarily diverse portfolio of applications - from improving assessments of fisheries' stocks and extending warning times for tornadoes to building decadal forecasts of drought - some examples of our attention to relevance, performance and quality are demonstrated below.

• Relevance

The issue of relevance begs the question of "to what?" Specifically, with so much guidance and policy doctrine abounding, how does one determine the most appropriate context of relevance. As an agency with a specific set of

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[15] *Bergen, Angelle. Engineers Fail in their Duty To Keep Public Informed. Engineer News Record McGraw-Hill Construction, March 13, 2008.*

applications and operational objectives, NOAA is well-positioned to identify a prioritised set of mission-relevant requirements. These requirements are expressed in a corporate strategic plan and in annual programme/budget guidance documents. Alone, these documents are insufficient, so it is important to develop this doctrinal literature within a broader set of plans and strategies (much of which is developed by the expert "community of practice"), including the U.S. Ocean Research Priorities Plan, the U.S. Climate Change Science Program, the IPCC FAR, etc.

The relevance of our investment must also be in alignment with issues of national importance as expressed by public concern. We try to target highest return on investment (e.g. protecting coastal communities) or protecting critical resources that might not necessarily be represented by economic drivers (e.g. marine mammals). Additionally, the relevance of an investment must tolerate a balance in the portfolio of both basic and applied research and a portfolio that allows for a percentage of high-risk/high-payoff research to ensure we start today to answer tomorrow's problems. Some examples of the relevance of NOAA research are as follows:

- The Center of Excellence for Great Lakes and Human Health at NOAA's Great Lakes Environmental Research Lab focuses on understanding the inter-relationships between the Great Lakes ecosystem, water quality and human health. The Center employs a multidisciplinary approach to understand and forecast coastal-related human health impacts for natural resource and public policy decision-making, and develop tools to reduce human health risks associated with three research priority areas: beach closures, harmful algal blooms, and drinking water quality.

- Through a close collaboration between the academic community, private sector development and multiple federal agencies, NOAA is working toward the next generation of weather radars. Specifically, advancing the state of phased array radar, as developed in the military, will provide extraordinary new capabilities for improved severe weather forecasting (e.g., tornadoes), meteorological research, emergency management of landfalling hurricanes, flood forecasting and water use management, wildland fire detection and response, airborne chemical/biological weapons release, surface transportation, aviation, and aircraft/Unmanned Aircraft Systems surveillance over the homeland (both cooperative and non-cooperative).

- NOAA's Earth System Research Lab has developed a tool called CarbonTracker[16] (Figure 8), which is a system that calculates carbon dioxide

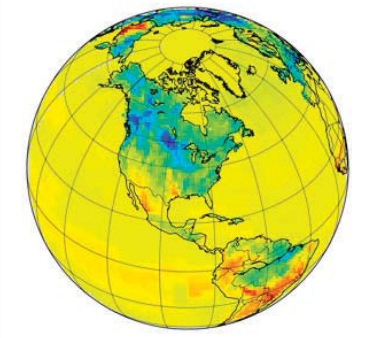

Figure 8. Snapshot of the surface uptake of CO2 across North America showing the strongest CO2 sinks (blue colors) in the East Coast forests, coniferous forests in Canada and the U.S. Midwest. Note that the largest carbon cycle component, the fossil fuel emissions, is not shown on this map. The figure represents a week in July of 2005 and illustrates one of the many products in CarbonTracker. Credit: NOAA

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[16] *www.esrl.noaa.gov/gmd/ccgg/carbontracker/*

uptake and release at the Earth's surface over time. It estimates the carbon dioxide exchange from an atmospheric point of view. CarbonTracker produces model predictions of atmospheric CO_2 mole fractions, to be compared with the observed atmospheric CO_2 mole fractions. The difference between them is attributed to differences in the sources and sinks used to make the prediction (the so-called 'first-guess') and the sources and sinks affecting the true atmospheric CO_2. Using numerical techniques, these differences are used to solve for a set of sources and sinks that most closely matches the observed CO_2 in the atmosphere. Policy makers, industry, scientists, and the public need CarbonTracker information to make informed decisions to limit greenhouse gas levels in the atmosphere.

• Quality

The quality of the research NOAA conducts and sponsors must be preeminent, with unquestioned credibility to ensure confidence in its application. Ultimately, the objectives of our research investment are to reduce uncertainty, constrain risk, define solutions, and aid decisions. A necessary component of such an effort is the quality of the communication of the scientific findings; the best research poorly communicated is of compromised quality. Uncertainty associated with findings must be clearly expressed in a manner that is meaningful for policy makers. Some examples of the quality of NOAA research are as follows:

- Some 120 NOAA scientists are among the hundreds of researchers in many fields around the world who have contributed to the scientific basis (and in several cases, held leadership positions) for the four Intergovernmental Panel on Climate Change assessment reports created since 1988. On October 12, 2007, the Norwegian Nobel Committee announced that the Nobel Peace Prize for 2007 was to be shared, in equal parts, between the Intergovernmental Panel on Climate Change and former U.S. Vice President Albert Arnold (Al) Gore Jr. for *"their efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change."*

- Dr. Isaac M Held, Senior Scientist at NOAA's Geophysical Fluid Dynamics Laboratory earned The Carl-Gustaf Rossby Research Medal, the highest award for atmospheric science of the American Meteorological Society, *"for fundamental insights into the dynamics of the Earth's climate through studies of idealised dynamical models and comprehensive climate simulations."*

- One of the most important measures of quality of research is its incorporation into the private sector as a formal part of a corporate business plan. NOAA's Pacific Marine Environmental Laboratory (PMEL) has long been recognised as a global leader in the development of tsunami detection technologies, and forecast methodologies. The quality of this research was codified in a formal licensing agreement between Science Applications International Corporation and PMEL for the commercial production of DART™ tsunami detection buoys.

• Performance

Measurement of research activity and results is critical to defending the investment and justifying growth in resources. Research must target results that reduce uncertainty, improve accuracy and are reliable. Improved forecasts, warning times and procedures for emergency preparedness, system reliability and repeatability (reduce false warnings) depend on efficient transfer of high quality research into applications and operations. Accuracy of results (trajectory, magnitude of event) can translate, through established metrics, into lives saved and property protected. Performance measures will necessarily take a variety of forms. We take seriously the need to set targets or goals for performance, for example improvements to hurricane intensity forecasts, longer warning times for tornadoes, and buoy reliability. We also recognise the need to apply long-standing research-specific metrics such as publication rates and other bibliometrics. No single performance measure is sufficient to characterise the overall performance portfolio. Some examples of the performance of NOAA research are as follows:

- Development and testing of new concepts for broadband data communications allowing access to real-time full ocean exploration from the newly designed NOAA Research Vessel, *R/V Okeanos Explorer* (Figures 9a and 9b) to a huge cadre of technical experts around the world. How many new discoveries will be made from this, the world's only dedicated ocean exploration ship?

Figure 9a. The freshly painted Okeanos Explorer is tied up after leaving dry dock. The ship received new stern and bow thrusters, handling, navigation and safety equipment in dry dock. Credit: NOAA

Figure 9b. Telepresence technology uses satellite technology and Internet2 to transmit data and video in real-time from remotely operated vehicles working at depth, to a shore-based hub, which then sends this data to a variety of receiving stations on shore. Credit: Paul Oberlander, Woods Hole Oceanographic Institute

- Consistent and reliable activity is one standard for assessing performance. Mauna Loa Observatory (MLO) is a premier atmospheric research facility that has been continuously monitoring and collecting data related to atmospheric change since the 1950s. The undisturbed air, remote location, and minimal influences of vegetation and human activity at MLO are ideal for monitoring constituents in the atmosphere that can cause climate change. The observatory is part of the NOAA Earth System Research Laboratory Global Monitoring Division.

- As the US agency responsible for delivering accurate weather predictions, NOAA recognises the need for improved track and intensity forecasts for hurricanes. Consequently, we have developed a research-oriented project on hurricane forecast improvement with clear performance metrics. The metrics are related to hurricane track and intensity improvements for 1, 2, 3, 4, and 5 day lead times, with a focus on rapid intensity change. The metrics seek to reduce forecast errors in hurricane track and intensity, increase the Probability of Detection and decrease the False Alarm Ratio of rapid intensification events.

Concluding thoughts

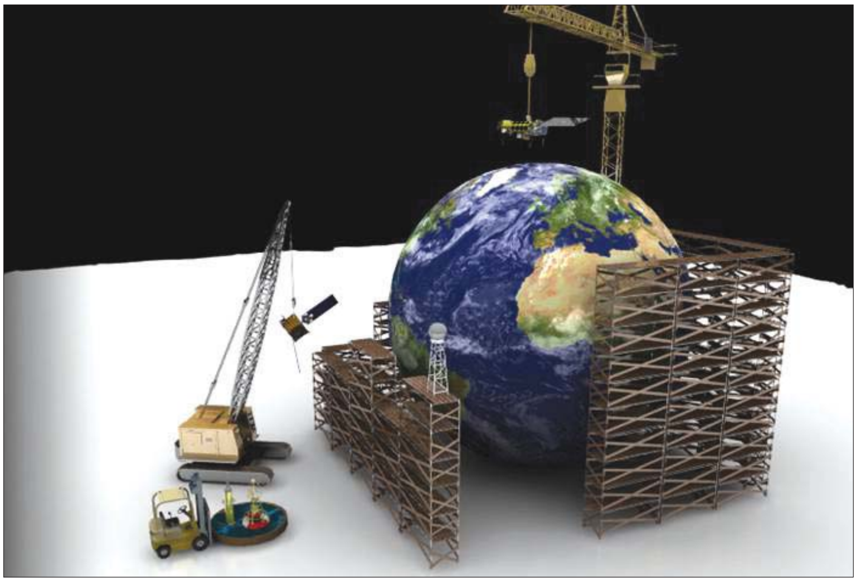

Figure 10. The Group on Earth Observations (GEO), an international partnership espousing the free exchange of Earth observational data, was established in July 2003 to begin development of the Global Earth Observation System of Systems (GEOSS). GEOSS builds on and adds value to existing Earth observation systems by coordinating their efforts, addressing critical gaps, supporting their interoperability, sharing information, reaching a common understanding of user requirements and improving delivery of information to users. Credit: NOAA

Our society's dependence on freely available and integrated information regarding the oceans, atmosphere and climate is becoming dramatically more relevant to key societal needs, from environmental stewardship, to security of all forms, including economic development (Figure 10). We can think of our investment in research in terms of mitigating risk, especially when hazards and our exposure to them, can be assessed in a quantitative manner. Our research investment priorities are facilitated by an assessment of where we can reduce uncertainty in the most credible (scientifically) manner and in the most meaningful (in terms of impact) way. Additionally, by assessing our research in terms of its relevance, quality and performance we are assured of an optimised investment portfolio.

"Unless man can make new and original adaptations to his environment as rapidly as his science can change the environment, our culture will perish."[17]

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[17] *On Becoming a Person: A therapist's view of psychotherapy, Carl Ransome Rogers, 1961.*

The Royal Academy of Engineering

As Britain's national academy for engineering, we bring together the country's most eminent engineers from all disciplines to promote excellence in the science, art and practice of engineering. Our strategic priorities are to enhance the UK's engineering capabilities, to celebrate excellence and inspire the next generation, and to lead debate by guiding informed thinking and influencing public policy.

The Academy's work programmes are driven by three strategic priorities, each of which provides a key contribution to a strong and vibrant engineering sector and to the health and wealth of society.

Enhancing national capabilities

As a priority, we encourage, support and facilitate links between academia and industry. Through targeted national and international programmes, we enhance – and reflect abroad – the UK's performance in the application of science, technology transfer, and the promotion and exploitation of innovation. We support high quality engineering research, encourage an interdisciplinary ethos, facilitate international exchange and provide a means of determining and disseminating best practice. In particular, our activities focus on complex and multidisciplinary areas of rapid development.

Recognising excellence and inspiring the next generation

Excellence breeds excellence. We celebrate engineering excellence and use it to inspire, support and challenge tomorrow's engineering leaders. We focus our initiatives to develop excellence and, through creative and collaborative activity, we demonstrate to the young, and those who influence them, the relevance of engineering to society.

Leading debate

Using the leadership and expertise of our Fellowship, we guide informed thinking, influence public policy making, provide a forum for the mutual exchange of ideas, and pursue effective engagement with society on matters within our competence. The Academy advocates progressive, forward-looking solutions based on impartial advice and quality foundations, and works to enhance appreciation of the positive role of engineering and its contribution to the economic strength of the nation.

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The Lloyd's Register Educational Trust, an independent charity wholly funded by the Lloyd's Register Group, was established in October 2004. Its principal purpose is to support advances in transportation, science, engineering and technology education, training and research worldwide for the benefit of all. It also funds work that enhances the safety of life and property at sea, on land and in the air. The Trust focuses on four categories:

- **Pre-university education:** through appropriate organisations, promotes careers in science, engineering and technology to young people, their parents and teachers.
- **University education:** through universities and colleges, provides undergraduate and post-graduate scholarships and awards at first degree/masters levels to students of proven ability.
- **Vocational training and professional development:** supports professional institutions, educational and training establishments working with people of all ages.
- **Research:** funds existing or new centres of excellence at institutes and universities.

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