CATASTROPHE MODELING FORUM

Changing Climatic Dynamics and Catastrophe Model Projections

Tuesday – Wednesday, October 16-17, 2007

The Down Town Association, NYC

SUMMARY OF FIRST WORKSHOP

Sponsored by:

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PART ONE
SUMMARY REPORT

Introduction

Global climate change holds the potential to confound our current understanding of the causes and connectivity of extreme weather events across the globe. Asking *What is predictable? What are the key uncertainties?* and *What does "probabilistic event attribution" tell us about potential liabilities*, the Catastrophe Modeling Forum (CMF) has brought together leading climate scientists, catastrophe modelers, and insurers, reinsurers and insurance brokers from around the world. The aim of this interdisciplinary forum is to provide guidance on climate change and how it impacts catastrophe models and associated insurance sector premiums, practices and policies. The CMF also addresses communications issues that pertain to the "CAT" modeling community, the insurance sector, financial analysts, regulators, rating agencies, and perceptions of the general public.

The CMF was developed by the Center for Health and the Global Environment at Harvard Medical School, The Insurance Information Institute, Lloyd's America and American International Group (AIG). The primary sponsors are Lloyd's America, and AIG, with additional support from ACE Ltd, Marsh, Inc., Allstate, Travelers, and Guy Carpenter. The first workshop of the CMF was held in New York City, October 16 and 17, 2007 and a second CMF workshop will be held in NYC, June 11-12, 2008.

The CMF grew out of discussions regarding climate change risk that took place among AIG, Lloyd's and the Insurance Information Institute following an I.I.I. conference on Hurricane Risk in the Northeast in (July 2007).

Leading scientific bodies (e.g., the Intergovernmental Panel on Climate Change and the world's leading National Academies of Sciences) have reached consensus that climate change, including observed increases in sea surface and land temperatures, melting of glaciers and sea ice, retreat of mountain glaciers, sea level rise, and more, is already occurring and that it is likely caused by human activities including the combustion of fossil fuel and tropical deforestation. The IPCC reports on different scenarios of the modeled impacts of climate change, scenarios that vary depending on the amount by which greenhouse gas emissions, and their concentrations in the atmosphere, are assumed to rise. The modeled impacts include increases in the frequency and severity of weather-related catastrophes of all types.

While there has been a sharp rise in insured property/casualty (P&C) losses from natural catastrophes (NatCats) over the past two decades and the insured losses from 2004/2005 include 7 of the 10 most expensive hurricanes in U.S. history, totaling $81 billion, a significant portion of the increase in losses is attributed to an increase in property values, as well as growth in high risk areas. Over the last couple of decades, Atlantic and Pacific storms accounted for nearly half of the NatCat losses.

The potential impact of climate change on the intensity and frequency of weather-related catastrophic events, together with the increase in property values and insurance penetration in vulnerable areas, led AIG and Lloyd's to propose that I.I.I. and the Harvard Center for Health and the Global Environment convene a forum where leading climate scientists and representatives of catastrophe modeling companies and the insurance industries could meet to discuss how to incorporate climate change risk into the catastrophe models.

The primary aim of the CMF is to stimulate discussion on how to most effectively include climate change risks in the cat modeling process. This ultimately might lead to the integration of dynamic models (those based on the interaction of atmospheric and oceanic conditions) with statistical models, to better identify trends and emerging patterns, and to improve projections, risk analysis, and communication of these issues to regulators, rating agencies, and the public. The integration draws upon on-going research efforts to improve *regional* forecasts.

The First CMF Workshop

The first CMF workshop involved approximately 40 participants, and the structure was a series of panels with presentations by the scientists and modelers. The opening talk and subsequent panel addressed the main findings of the latest report of the Intergovernmental Panel on Climate Change (2007) and the science behind climate modeling. The consensus IPCC report clearly projected that extreme events, including heat waves, droughts, floods, would increase with climate change. For tropical cyclones (TCs) there is the likelihood that intense hurricanes will be more frequent, accompanied by a decrease in weaker ones.

Among the chief findings

There has already been a shift to heavy precipitation events, including well-documented changes in the U.S., and an increased frequency and intensity of heat waves (with warmer nights). For the U.S., flooding disasters led to $8 billion in losses from 1990 through 1998, while heat was the leading cause of weather-related deaths, responsible for more than 3,400 fatalities between 1999 and 2003. There has been an observed increase in weak tornadoes in both the U.S. and Europe, though this could be the result of better monitoring.

Warm surface temperatures and larger gradients between high and low pressure regions could intensify windstorms. Worldwide windstorms account for the bulk of insured losses. High latitude westerly winds have increased in both hemispheres; south to a greater extent than north. There are uncertainties in models and scenarios, the largest having to do with human responses.

Focus on tropical cyclones

Given the central role of Atlantic tropical cyclones (TCs) in the P&C insurance sector, the CMF first focused on the trends in the frequency, intensity and tracks of TCs. The frequency and intensity of TCs correlate with increased sea surface temperatures (storms form only when SSTs exceed 26.5°C), but are influenced by changes in modes of natural variability (e.g., El Niño, the North Atlantic Oscillation).

While average SST has increased globally, the increases in the tropical Atlantic now reach the West coast of Africa, extending the area of potential storm genesis. A calm atmosphere, meaning minimal wind shear, is another condition allowing TCs to intensify. There is increased predictability on decadal scales when natural oscillations are included, namely the Pacific Decadal Oscillation, the North Atlantic Oscillation and the Atlantic Multi-decadal Oscillation, though the existence of the last cycle in the records is disputed.

The view from the modelers

The general approach is to examine historical data and the stochasticity (random nature) of events, with "smoothing" of trends and specification of the ranges of uncertainty. Key issues related to TCs are storm genesis-storm tracks, upper level winds (jet stream), landfall projections, and contrasts between low pressure/high pressure regions. Insurers noted that there were two very strong hurricanes in 2007, both as potential of being as severe as Katrina, but that they took southern tracks, striking unpopulated areas. Integrating the physics that form the basis of dynamical models (chiefly energy fluxes) with historical trends was considered crucial to improving projections. But models, it was noted, are constrained to observed frequencies and not the major outliers that can have the greatest societal impact.

From the climate modelers

The priorities for climate models is to forecast multi-decadal and multi-century responses to different greenhouse gas emission scenarios, using fully coupled Earth System Models (atmosphere, ocean, carbon cycle, etc.). They do not specifically addresses current risk trends. However, new "probability analyses" and attribution could inform insurers. Heat waves, for example, such as Europe's in summer 2003 (that was six standard deviations from the norm) are now 2-4 times more likely with climate change.

In this context, liability issues were addressed, noting the U.S. Supreme Court decision in April, 2007 designating CO_2 as a pollutant under the Clean Air Act. It was noted that the aggregate emissions from 4-5 of the largest U.S. coal fire plants was a measurable percentage of the total greenhouse effect.

Paleoclimatic tales

Glaciers ("that do not lie") have melted very quickly in the past two decades, and there is an accelerating decay of Arctic summer ice. Antarctica and the Southern Ocean Climate System have warmed up faster than any other region of the globe, and the rate of sea level rise is also speeding up. Additionally, ice core records demonstrate that rapid climate change can happen within just the span of a few years, and there are increasing signs of instability in the ice that could make such a shift more possible.

Paleotempestology can be used to study storms in past eras as revealed in the geologic record. This field is called upon to search for analogues of today's conditions and for potential triggers for Rapid Climate Change Events; some of which have been small (1°C shift); others large jumps (5-20°C). This information can be linked with ice core records and potentially reveal precursors of rapid shifts in climate, such as changes in Earth's ice cover and albedo (i.e., reflectivity; now ~30% overall).

Today's signs of instability include: changing rates of warming; increasing weather volatility; more major outliers; and increasing Southern and Northern Hemispheric Westerly winds. The last have direct implications for wind shear and storm tracks, and the ice core records reveal that increased storminess occurs during periods of accelerated (phase-state) transitions.

Varying time horizons

Adaptations by the insurance sector, itself, were addressed, in terms of the continuous changes in products, and pricing, and how companies position themselves. While underwriters are interested in the near term as a consequence of typical (re)insurance contract durations of 1 year, strategists are interested in the long term. Some (re)insurers noted that although 12-month contracts are the main guidepost, it was in their companies' best interests to not move in and out of markets.

Related Models

The Princeton Ocean Model (POM) was presented. It is a three-dimensional numerical ocean model that includes a surface wave model and an inundation capability, as well as the surface gravity wave (waves down to 30 meters). The POM has been used to trace ocean thermal anomalies.

In addition, the University of Reading and Willis have formed a long term partnership in the U.K. that includes leading international scientific institutions. Their aim is to evaluate climate and weather, earthquake and terrorism risks. Using a tracking methodology they are advancing methods to integrate results of climate models with catastrophe models and are facilitating focused, multi-disciplinary research with the insurance industry as the end user. Combining computer power is an added benefit of this collaboration.

Research needs

The following research needs were identified:

- Improved databases and data quality.
- Understanding correlations across perils.

- Integration of regional with global models.
- Shorter-term (< 10 years) climate projections of risk.
- Stochastic models of TCs, from "birth to death," generated for 1000s of years of synthetic TCs.
- An open source Catastrophe Risk Model was proposed to accelerate development of risk models.
    - They could include: Hazards, Exposures and Damages; probabilities, location, magnitude and duration of storms; exposure, including location, construction, age and building code; damages, included physical damages and repair costs; and insured losses, in terms of coverage.
- There is the ongoing need to share research among scientists, society, business, governments and NGOs through appropriate forums, such as this. The Lighthill Risk Network – a community of expertise for today's risk society – was suggested as a possible host for these activities.

Public policy implications

A set of principles exists that many insurers and insurance brokers have signed on to: www.Climatewise.org.uk. There are also strategy questions about the future of the insurance industry. Some insurers and insurance brokers are becoming increasingly active in advocating public policies that can facilitate the clean energy transition (i.e., primary mitigation of climate change) as well national legislation to limit greenhouse gas emissions from human activities.

Future directions

Other perils the CMF will discuss, at the next forum in June 2008, include: drought, heat waves, wildfires, coastal and inland floods, winter storms, and windstorms. Droughts affect more people than any other NatCat and result in losses of $6-$8 billion annually. Documented changes in Earth's hydrological cycle raise the potential to increase aridity in several parts of the globe.

At the next forum in June, the CMF will also address underlying and emerging issues, including: the role of deep ocean warming in replenishing surface water after storms; the impacts of ocean warming on the modes of natural variability; the occurrence of Atlantic TCs in new regions (Europe and Brazil); the non-linear affects of sea level rise on storm surges and inland wave "fetch;" and changes in the Pacific Ocean affecting storms in Asia.

In the future, if additional forums are held, the CMF will consider the biological responses to climate change (e.g., the spread of forest pests, crop and animal diseases, floods and mold, and coral bleaching), which can increase vulnerabilities to damages from NatCats. The CMF will develop its work against the background of differing time horizons for P&C (0-5 years) *vs.* those for Life & Health, D&O insurance, and Asset Management.
Finally, the CMF will address ways of mitigating risks of a changing climate, including building codes; land use/development planning; care for wetlands and estuaries (which improve resilience, coping and adaptation); and emergency planning..

Conclusion

The CMF was formed to consider the changing nature of risks related to climate change and natural catastrophes. There is the need for better observational data; a coordinated catalog of storms; integration of regional and global models; shorter term (< 10 year) climate risk projections; an understanding of correlation across perils; a matrix of time scales for different lines of business; and an on-going network for the vetting and disseminating relevant information. Insurers are now determining how best to complement risk management and risk transfer with risk reduction. The insurance sector shares with the public health community the "precautionary principle," and can play a pivotal role in reducing harm through its practices and policies, and promotion of sound public policies that facilitate the transition to the low carbon economy.

PART TWO
PAPERS AND PRESENTATIONS
(presented in alphabetical order)

Concept Note: modelling and understanding trends in extreme weather risk

CAT Modelling Forum, October, 2007

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Background

Increased public awareness of the global change issue has fuelled unprecedented interest in the possible role of human influence on climate in observed instances of extreme weather. At the same time, the risk modelling community is increasingly aware of the dangers of relying on historical statistics and assumed stationarity. Inclusion of empirical trends in risk models is also dangerous unless we understand the origins of these trends: for example, the lack of any explosive volcanic eruptions since 1992 may have contributed to increased heatwave risk in the current decade. Attribution of all of the change (if any) in heatwave risk since the 1970s to human influence on climate, and naïve extrapolation of this change into the future, might therefore be highly misleading. Understanding the origins of trends in weather risk requires physically-based climate modelling.

The challenge we face is that the current WCRP-identified priorities for climate modelling experiments fall into two categories, neither of which is necessarily optimal for assessing the origins and magnitude of current trends in extreme weather risk. These are:

1. Centennial-timescale integrations of fully coupled coarse-resolution Earth System Models (ESMs). These are designed to inform policy, such as emission reduction strategies, and hence focus on relatively long time-frames and hence coarse spatial resolution. Nominal resolution can be improved locally with nested regional models, but experience suggests that if phenomena such as the storm track are not adequately resolved by the driving global model, this may lead to misleadingly large and acutely model-dependent trends in weather risk due to, for example, a single-grid-box shift in the location of maximum winds.
2. Decadal climate forecasting experiments with intermediate-resolution coupled Atmosphere-Ocean models (AOGCMs) initialised using assimilation of "ocean weather" data. In principle, this approach should provide the most accurate possible forecast of climate trends over the coming decade, but assimilation methods are still under development for coupled models, and the high cost of data assimilation limits the resolution of these experiments to date. Although it would be possible in principle, no attempt has been made to date to incorporate model uncertainty into decadal forecasting experiments.

Both multi-century ESM simulations and decadal climate forecasts with AOGCMs are technically very challenging and are hence restricted to a handful of major climate modelling centres, competing with other research and operational activities for supercomputing resources. This limits both the size of ensembles that are possible and the scope for exploring model uncertainty through the use of multiple models or perturbed versions of individual models. We suggest there may be scope for a much simpler set of experiments focussing explicitly on quantifying and understanding recent and near-future trends in weather risk. This note highlights some of the requirements for this new set, and provides an example of one possible design, in the hope of stimulating debate about how this gap might be filled.

Requirements

In order of increasing stringency, we have identified three potential beneficiaries of a coordinated set of modelling experiments focussing on trends in current weather risks.

1. Academic studies of the origins of current risks and attribution of risk to specific external drivers of climate change. These can be posed essentially as "what if" type questions, and hence do not necessarily need to simulate current risks accurately to address the question of how risks are affected by external factors in the context of a particular climate model. Clearly, the greater the realism of the model and the more comprehensive the treatment of model uncertainty, the greater the impact any attribution statement will have.
2. Qualitative studies of current risk trends for scenario planning in CAT modelling. These studies require information on the sign and overall magnitude of potential trends in risk, but do not necessarily require the risks to be accurately simulated within an actual CAT model.
3. Quantitative information on current risks trends for input into CAT models. This is the most demanding requirement, because it requires not only that current risks are simulated adequately, but that we have a full understanding of how information generated by a climate model interfaces with CAT models.

The aim of this concept note is to stimulate discussion of what the best experimental design(s) might be to address these three requirements. The crucial common factor in this is that none of 1-3 necessarily require a fully coupled atmosphere-ocean modelling design, since there is no evidence that deep ocean dynamics play any role at all in decadal extreme weather trends. This removes the need for multi-century spin-up integrations to obtain a stable base climate, or for ocean data assimilation to nudge the base climate towards observations. An atmosphere-only modelling design, either driven with sea surface temperatures or coupled to a simple ocean mixed-layer model, can hence be run at much higher resolution, or large ensemble size, than any fully coupled design. We present here a sample experimental design that was primarily motivated by requirement (1), to provide a context for discussion, but the precise design or designs best suited to requirements (2) and (3) remain open for discussion.

Sample experimental design

Our methodology is driven by interest in relatively extreme (20-year to 100+ year return time) events. Understanding trends in this class of risks without relying heavily on statistical extrapolation requires hundreds to thousands of years of simulation. It also requires relatively high spatial resolution in order to simulate the relevant meteorological phenomena (the storm track, blocking, etc.) with sufficient realism for quantitative conclusions to be drawn.

Our essential concept is derived from "probabilistic event attribution" as presented in Allen (2003), explored in more detail in Stone and Allen (2005), and initially applied by Stott et al (2004). Under a project funded by the UK Natural Environment Research Council, with additional support from the NOAA/DoE International

Detection and Attribution Group, WWF International, the UK Department of the Environment, Food and Rural Affairs and the Tyndall Centre, we have developed a model-based approach to the problem detailed in Pall (2007). The approach draws directly on the concept of "paired ensembles" often used for predictability studies in seasonal forecasting. It makes use of distributed computing resources, which allow the generation of thousand member ensembles but limit individual simulation segment lengths to 1-2 years; however, the approach equally could be implemented through continuous simulations if supercomputing resources became available. In summary:

1. We generate a large ensemble of approximately one- to two-year duration simulations with a forecast-resolution atmospheric general circulation model driven by observed sea surface temperatures (SSTs) and sea-ice over a recent, well observed period: Pall (2007) focussed on the year 2000 to explore flood risk in the UK. Ensemble members are initialised with random perturbations on the initial atmospheric state but are otherwise identical, although an obvious generalisation of this approach would be to allow for uncertainty in model physics by perturbing parameters or including a number of different models. In order to examine explicitly the statistics of relatively rare (>100-year return time) events, the ensemble size must be of order 1,000 members. It is clearly desirable to repeat this exercise simulating recent years in the observed historical record in order to validate and calibrate the model.
2. We modify the boundary conditions of the ensemble in order to simulate conditions that might obtain either
    a. For the same simulation period but in the absence of a particular external driver of climate, such as anthropogenic greenhouse gas increase or explosive volcanism (this allows us to isolate different drivers' contributions to current risks: the attribution problem).
    b. For the late 20^{th} century (to support interpretation of the historical record and provide for calibration of model output against the historical record).
    c. For the next two decades (to assess how risks are changing).
3. Setting up these modified ensembles involves altering atmospheric composition (trivially), but more importantly modifying the SSTs imposed on the model to remove the (spatially- and seasonally-varying) pattern of change between the baseline period and the period in question. For the late 20^{th} century (perturbed ensemble b) we can use newly-developed high-resolution reconstructions from actual SST observations. For the "non-industrial present" (perturbed ensemble a) and the "next two decades" (perturbed ensemble c), we derive these patterns of SST change from a conventional "optimal fingerprinting" analysis of coupled model simulations of centennial climate change, allowing for uncertainty in the magnitude of the response through the optimal fingerprinting procedure, and allowing for uncertainty in the pattern of the response by using results from a range of coupled climate models. We argued in Allen et al (2000) that these pattern-based approaches can be used to predict future trends in large-scale temperatures over the coming decades, provided the origins of those trends are understood. Sea ice cover is modified to retain consistency with the modified sea surface temperatures, but no change is made to land-cover or soil moisture, which are assumed to equilibrate rapidly with the atmospheric conditions (the validity of this assumption would depend on the precise phenomena under investigation). A number of possible sets of modified boundary conditions must be generated,

attempting to span current uncertainty in both pattern and magnitude of the greenhouse-induced warming to date.

This design focuses on trends in risk interpreting "all other things being equal" very strictly: we are addressing the question of how the risk of weather events has changed and is changing due to specific external factors, assuming all other factors, including inter-annual fluctuations in sea-surface temperatures, evolve exactly as observed. Hence we subtract (ensemble a) or add on (ensemble c) the signal of greenhouse-induced warming from observed sea-surface temperatures leaving in whatever other patterns of variability may be present naturally. It would clearly be possible to extend this approach to allow for modification of the state of El Niño and so forth.

A number of possible generalisations of this approach naturally present themselves. Instead of prescribing sea surface temperatures, for example, we could prescribe an ocean heat flux convergence field in a slab or mixed-layer model. This might improve the simulation of variability in some atmospheric variables, but would also require ensemble members to be several years' rather than a single year's duration. With the participation of modelling centres it may be possible to run complete simulations covering the full period of interest on supercomputers.

Distributed computing

Our interest in the statistics of 100+ return-time events requires a baseline ensemble of several thousand members, and perturbed ensembles of comparable size to allow for uncertainty in the perturbations (this is particularly important for the "late 2020s" experiment). Even approximate simulation of storm-track and blocking statistics appears to requires a horizontal resolution of ~80km in the vicinity of the UK. Ensembles of this size with a model of this resolution would represent a significant commitment even for a major modelling centre, but can also be achieved using distributed computing, at significantly lower cost: see http://attribution.cpdn.org. If a number of large organisations were to collaborate on implementing such an experiment, it might well be possible to achieve it using "idle time" on existing desk-top computers rather than with dedicated supercomputing. With volunteers from the public providing free computing resources, output would have to be made publicly available, but this should be a requirement whether or distributed computing is used. Along with the possible provision of additional supercomputing resources, a key benefit of collaboration would be the possibility to include of a number of different climate models in the experiment allowing a much needed estimate of the robustness of results.

References

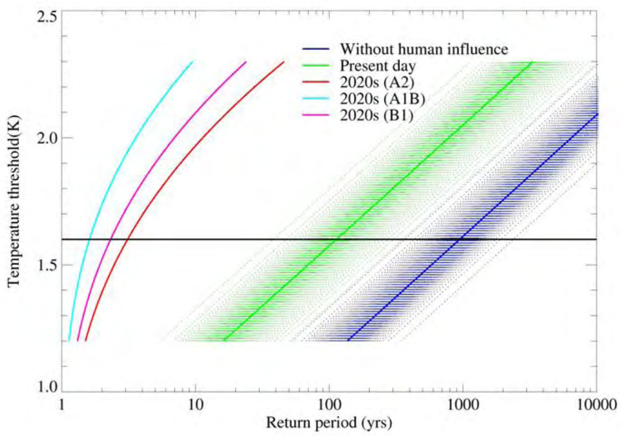
Myles Allen *et al*, Quantifying the uncertainty in forecasts of anthropogenic climate change, *Nature*, **407**:617-620 (2000)

Myles Allen, Liability for Climate Change, *Nature*, **421**:891-892 (2003)

Pardeep Pall, PhD Thesis, University of Oxford, Department of Physics (2007)

Dáithí A. Stone & Myles R. Allen, The End-to-End Attribution Problem: From Emissions to Impacts, *Climatic Change* **71**:303-04 (2005)

Peter A. Stott, D.A. Stone, & M.R. Allen, Human Contribution to the European Heatwave of 2003, *Nature***,** **432**:610-613 (2004)



An example: change in risk of European summer (JJA-average) temperature anomalies exceeding a range of temperature thresholds. Heavy green line shows the best-estimate of the risk under present-day conditions, with light green lines showing the range of uncertainty in these return periods. Heavy blue line shows the best-estimate of the risk under conditions similar to present-day except with human influence (the impact of increased greenhouse gas levels and sulphate aerosols) removed, with light blue lines showing the range of uncertainty. Coloured lines show best-estimate of this risk in the 2020s under three different scenarios for future emissions. Black horizontal line shows the temperature threshold exceeded in summer 2003. Data from Stott et al (2004).

Understanding and predicting current weather risk trends

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With thanks to:

Peter Stott & Doug Smith, The Met Office

Gregor Leckebusch, Freie Universität Berlin

Steve Jewson and Celine Herweijer, RMS

climateprediction.net

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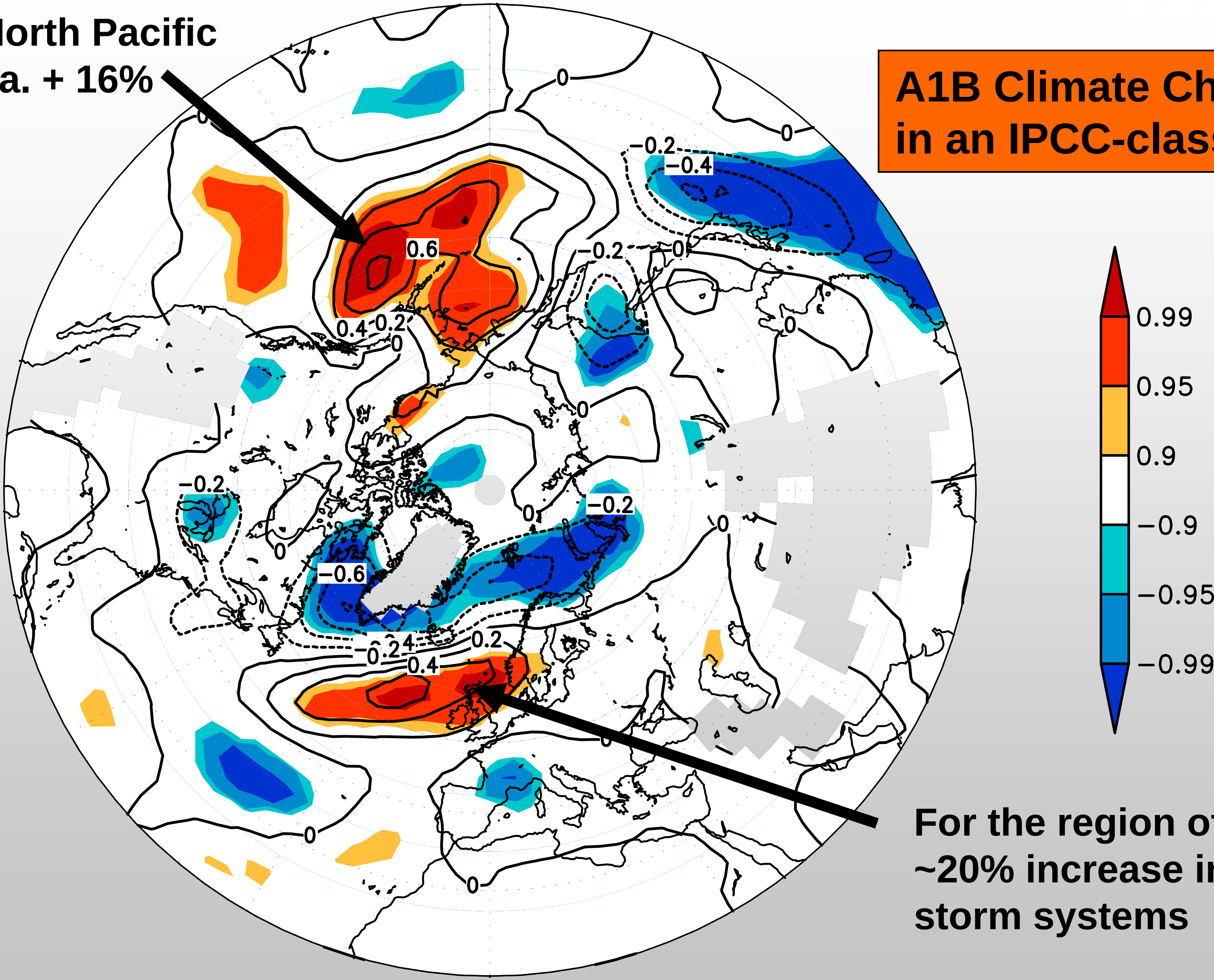
A problem, and an opportunity

- Priorities for major climate modelling centres are:
  1. Forecasting the multi-century response to different emission scenarios using fully coupled Earth System Models (atmosphere, ocean, carbon cycle etc.)
  2. Decadal forecasting using coupled atmosphere-ocean models initialised with ocean data assimiliation.
- Neither specifically addresses current risk trends:
  1. Requirement of multi-century integrations limits global resolution. Nesting regional models provides detail, but changes still dependent on global model.
  2. Demands of initialisation limits resolution, and current methods still experimental and contending with coupled model drift.

Example: Changes in intense storm frequency in models by ~2080

Freie Universität Berlin

North Pacific
ca. + 16%

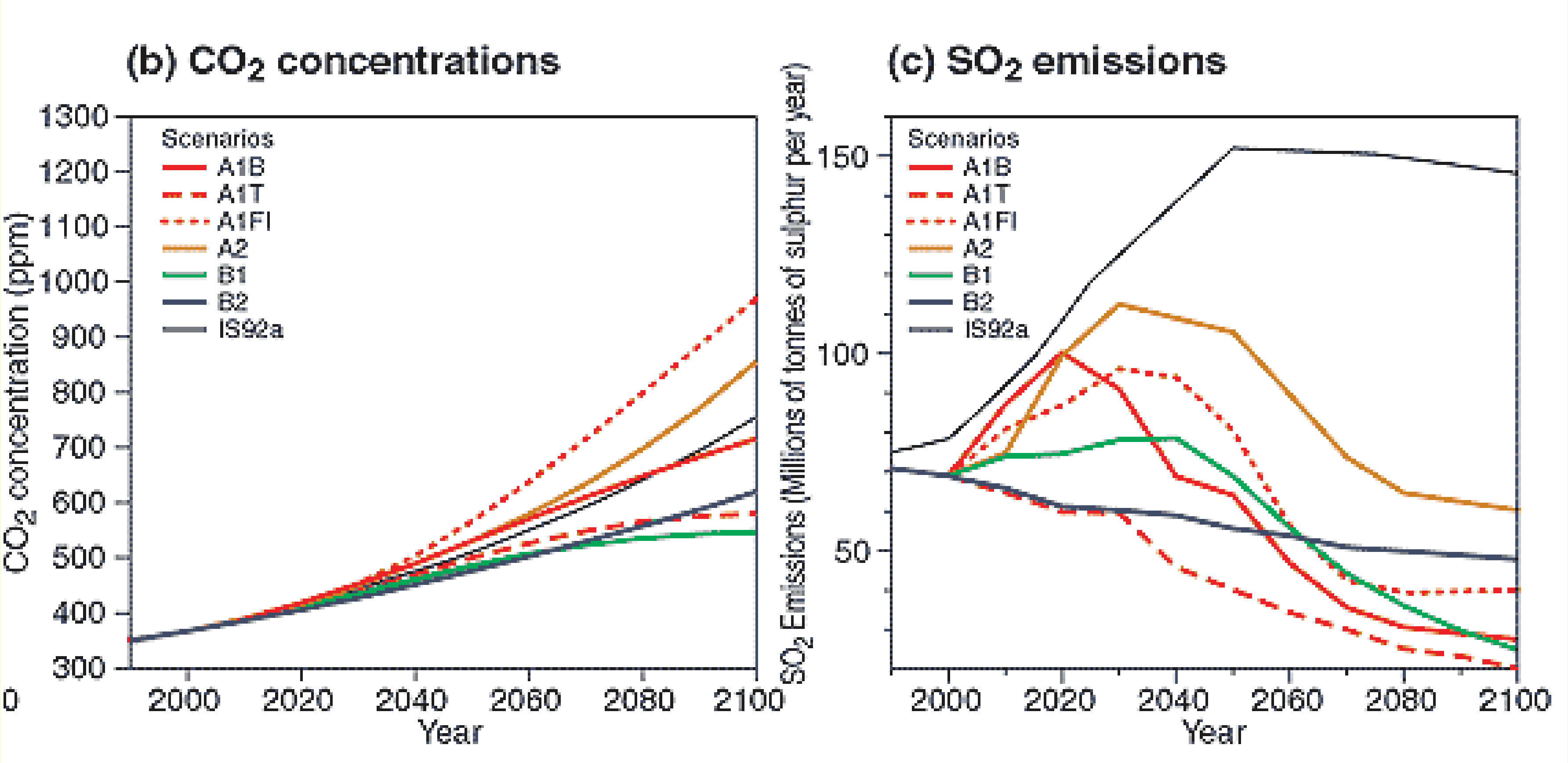


A1B Climate Change Signal in an IPCC-class ensemble

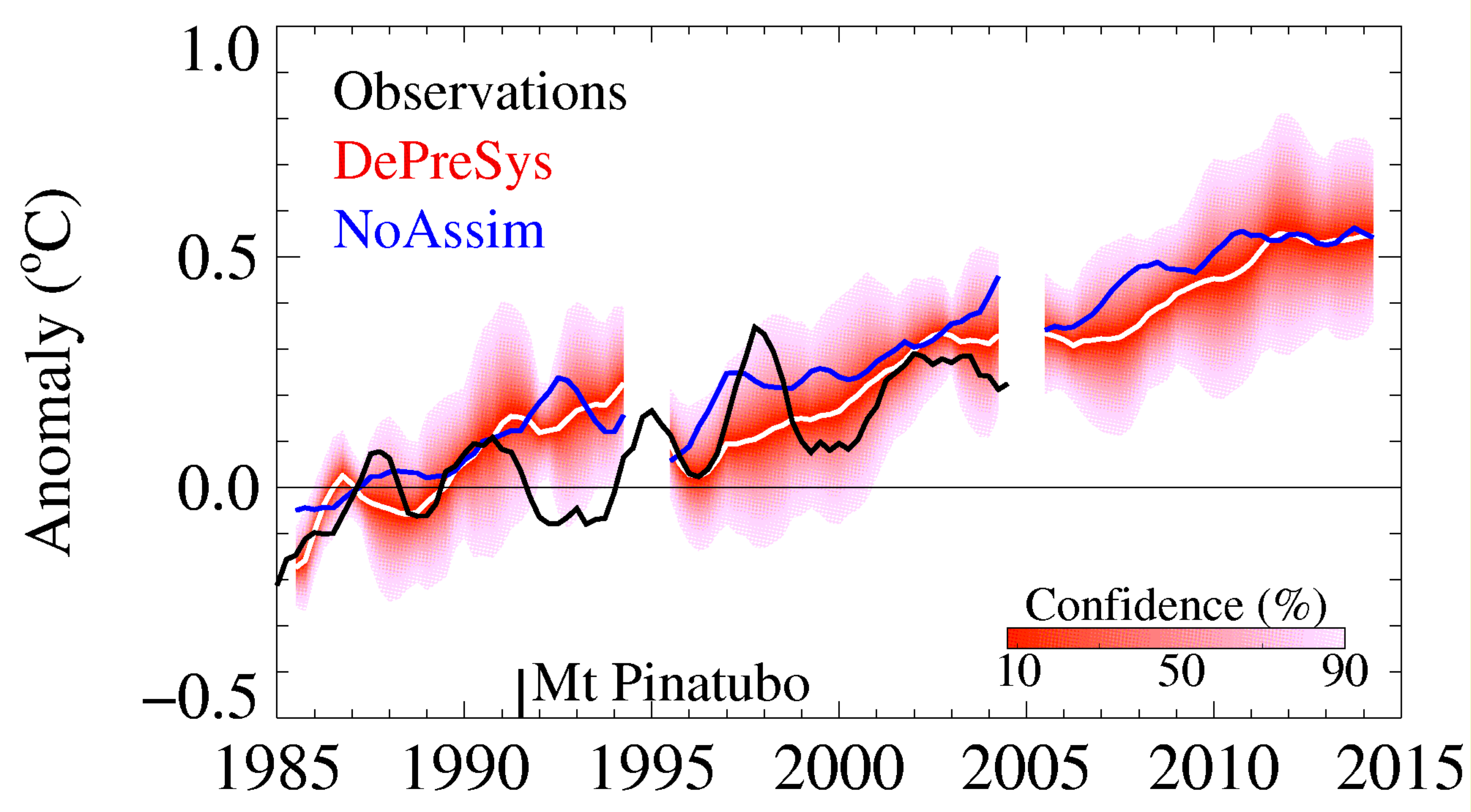
For the region of e.g. Scotland: ~20% increase in strong storm systems

But interpolating back from 2080 is problematic: the balance of drivers is changing.

Modellers focus on 2080 to increase the signal-to-noise ratio: for 2020 better to use a larger ensemble



Decadal forecasts of global temperature with ocean initialisation (Doug Smith et al, Science, 2007)



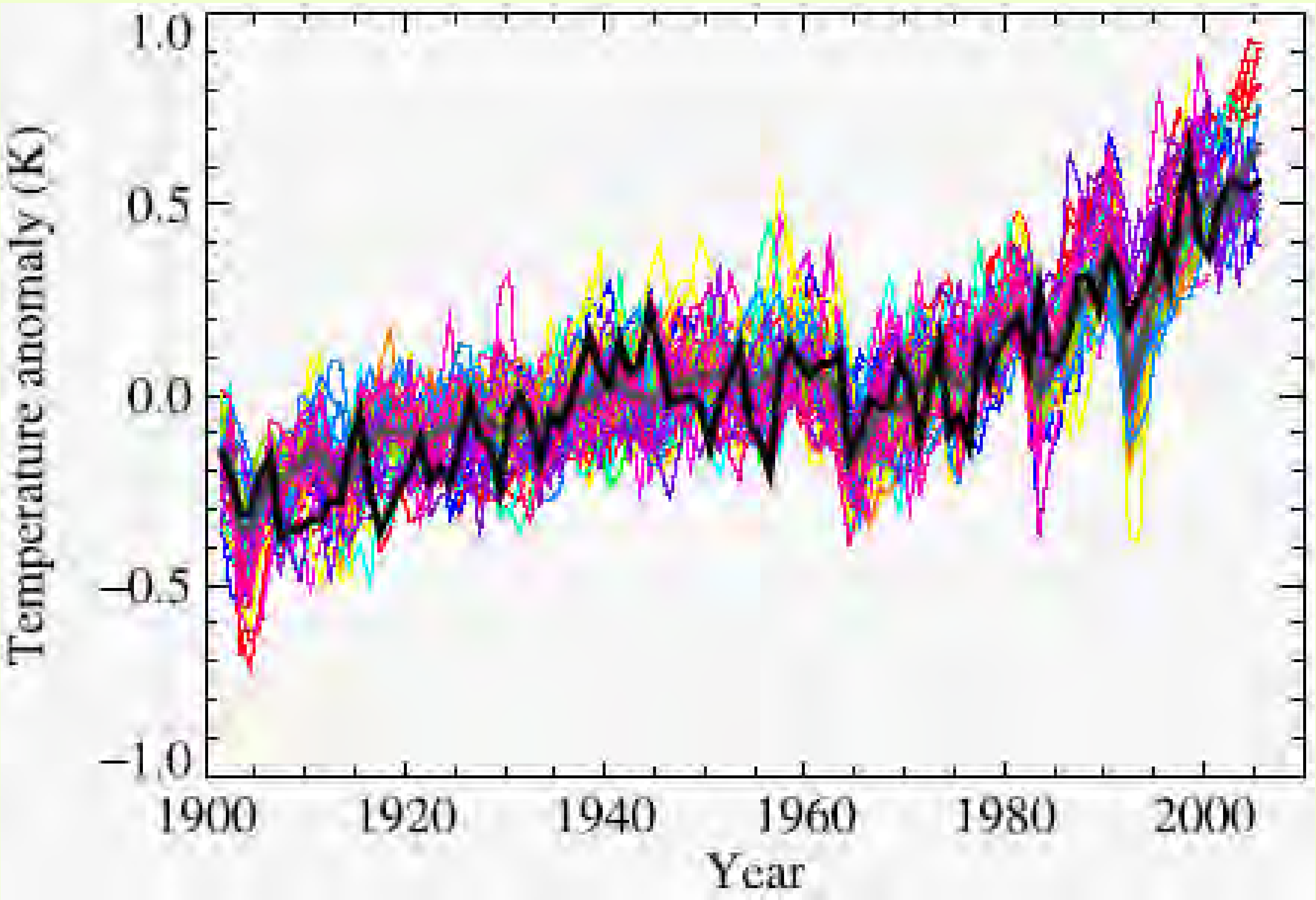
climate*prediction*.net

Oxford University

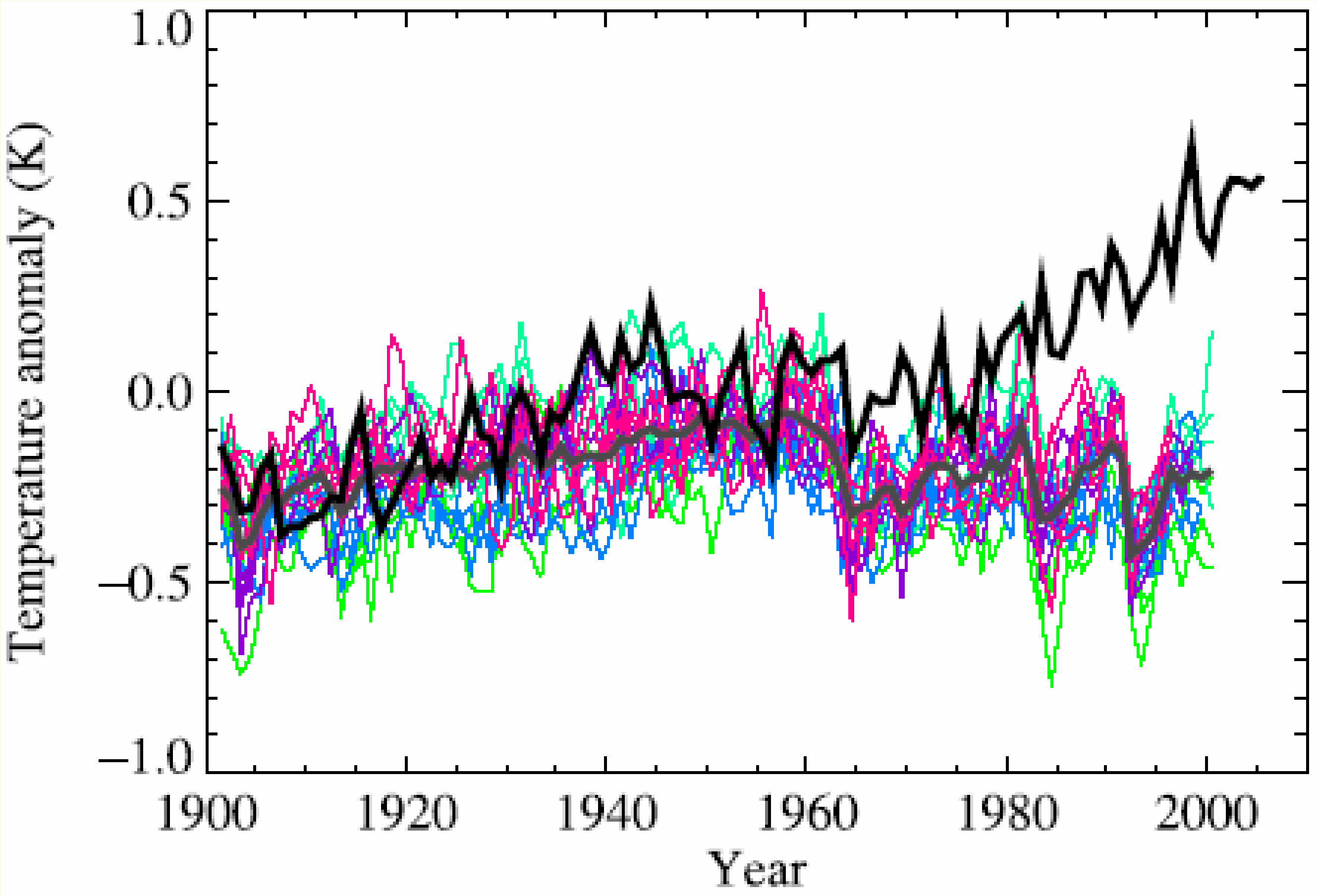
Why understanding trends in risk is more important than decadal prediction

- **Even with very careful "initialisation" with observed climate, coupled models show little skill from initial conditions for variables that matter after 1-2 years.**
- **Skill emerges again from changing boundary conditions (e.g. rising GHG levels) after ~10 years (sooner if a volcano erupts).**
- **Best estimate of 2027 climate may be today's climate plus 20 years of the estimated trend (allowing for uncertainty), not the end state of a 20-year coupled model forecast.**

Understanding trends, not just extrapolating them:
observed global temperatures & model responses to human and natural influences



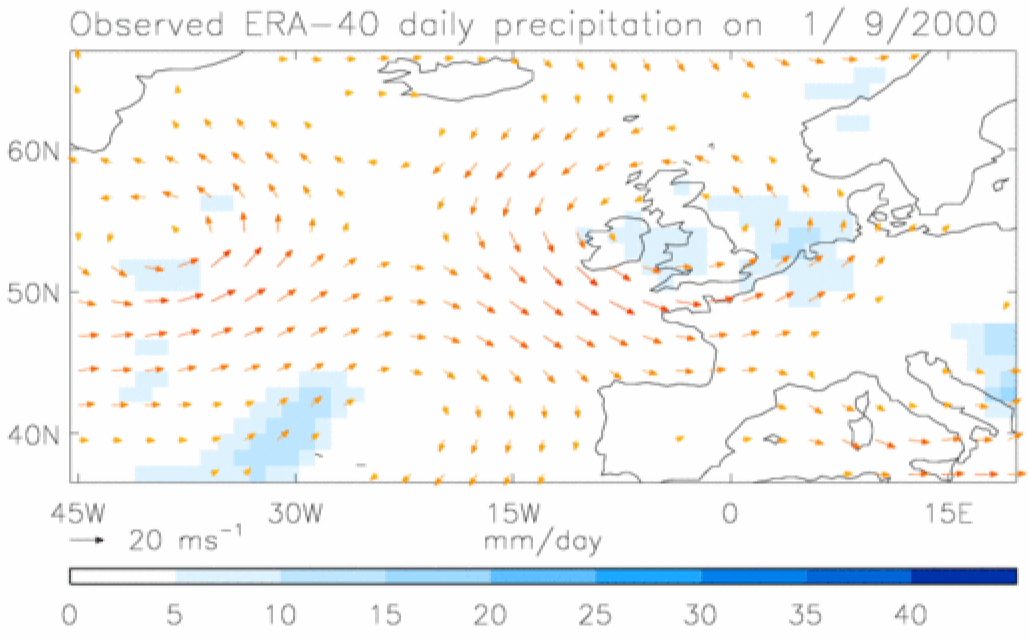
Understanding trends, not just extrapolating them:
observed global temperatures & model responses to natural influences alone

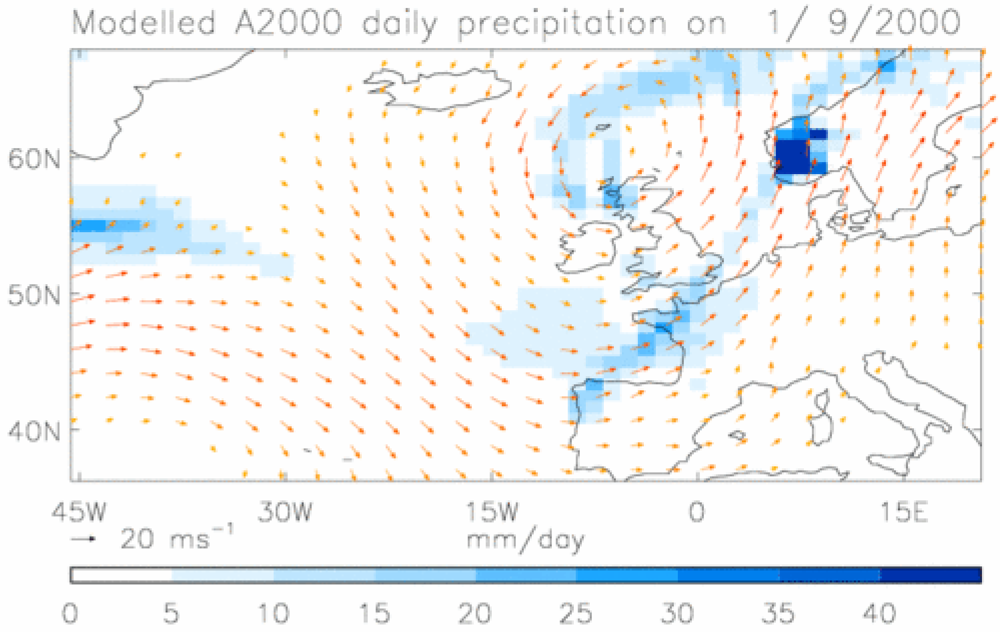


Oxford University

The climate*prediction*.net seasonal attribution experiment (Pall et al, 2007)

- **Aim: to quantify the role of increased greenhouse gases in precipitation that caused 2000 floods in UK.**
- **Challenge: relatively unlikely event even given 2000 climate drivers and sea surface temperatures (SSTs).**
- **Approach: large (multi-thousand-member) ensemble simulation of April 2000 – March 2001 using forecast-resolution global model (80km resolution near UK).**
- **Identical “non-industrial” ensemble removing the influence of increased greenhouse gases, including attributable SST change.**
- **Use several coupled models for SST signal to allow for uncertainty in magnitude and pattern of change.**

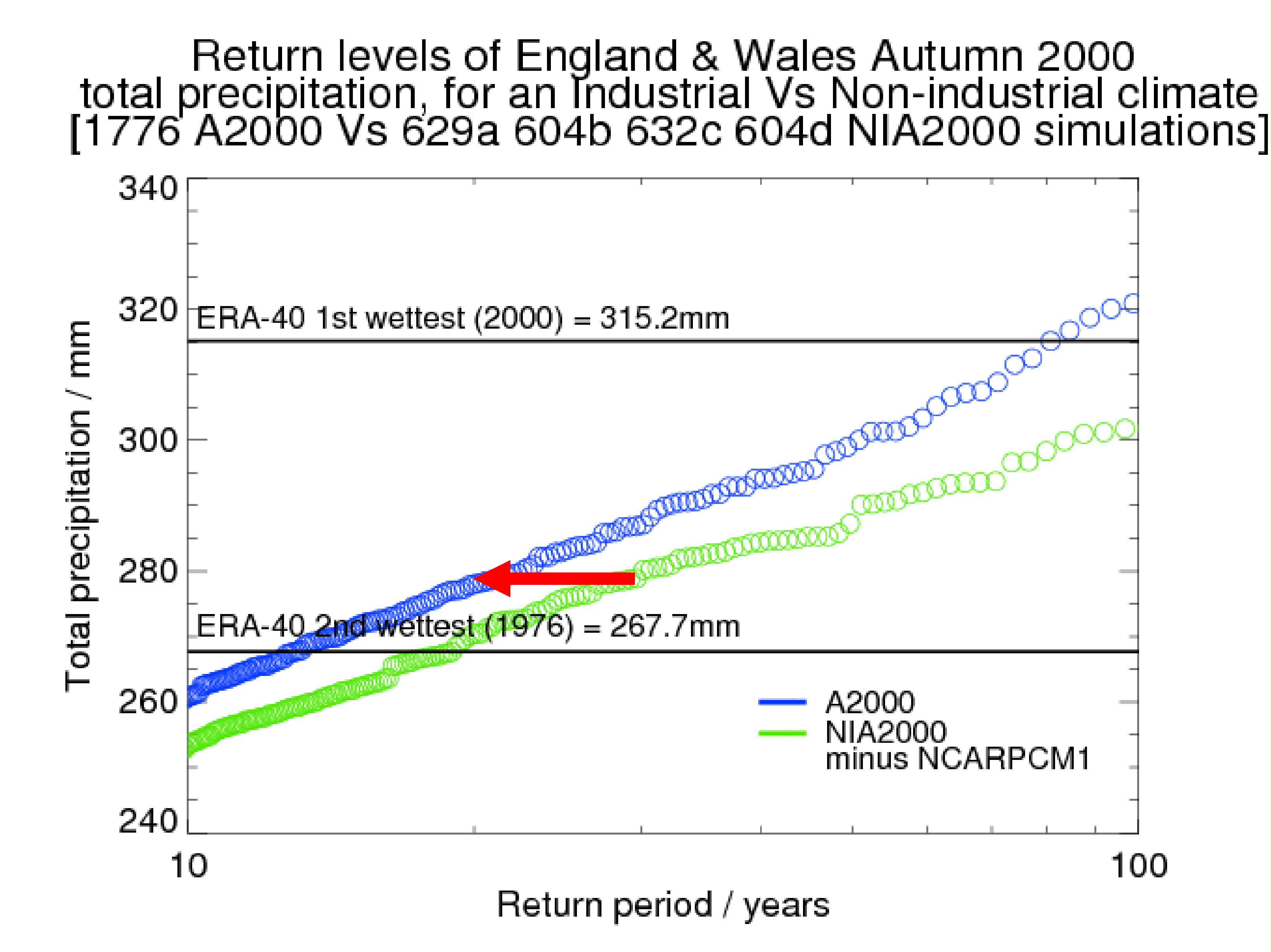




Autumn 2000 in the ERA-40 reanalysis…

…and in one of the wetter members of our ensemble.

Return-times after removing estimated signal of greenhouse warming



Implications of Pall et al study

- **Early studies with coarse-resolution driving models gave diametrically opposing conclusions regarding the anthropogenic contribution to UK flood risk.**
- **Large ensemble simulations with higher-resolution models give modest but still significant anthropogenic increase in flood risk: more credible.**
- **We need large ensembles to capture events of interest, and we need relatively high resolution to simulate them realistically.**
- **But these can be atmosphere-only simulations and hence do not need to compete for conventional super-computing resources (Pall et al was done on a volunteer network of personal computers).**

Conclusions

- **"General purpose" multi-century runs of "climate resolution" (300km grid) models are difficult to use directly for studying extreme weather.**
- **New "decadal forecast" runs face problems of drift and limited ensemble sizes for exploring extremes.**
- **The runs you need are simple, in principle:**
  - **Simulate the current decade hundreds to thousands of times with a set of forecast-resolution atmospheric models.**
  - **Perturb the models to simulate current conditions without specific drivers: to understand how drivers contribute to risk.**
  - **Perturb the models to simulate the 2020s using estimated anthropogenic trends in atmospheric composition and sea surface temperatures, allowing for uncertainty.**
  - **Natural extensions to simulate the impact of a volcano etc.**

Predictability and Prediction of North Atlantic Hurricane Activity and Risk on Subseasonal to Decadal Timescales

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Georgia Institute of Technology
Climate Forecast Applications Network (CFAN)

The risk of increased hurricane activity is arguably the greatest near term risk associated with global warming. The challenge to scientists is to assess this future risk in the face of incomplete data, imperfect models, and incomplete understanding. It has been hypothesized that as tropical sea surface temperature (SST) increases owing to global warming, tropical cyclone (TC) intensity, number, size, precipitation, season length, and tornadic activity could increase and tracks could be altered. Assessing these hypotheses and projecting future risk requires assessment of the available data, models, and physical understanding and integrating them into a statistically robust, plausible probabilistic projection of risk.

Predictability of TCs on weekly to monthly timescales has been demonstrated by high-resolution (50 km or less) global ensemble simulations and by "predicting the predictors" methodology. This predictability on subseasonal timescales provides confidence in the capability of high-resolution numerical models to capture TC genesis, intensification and tracking. TCs that originate from easterly waves show greater predictability than cyclones forming *in situ*. Additionally, TCs with small horizontal size that are currently not resolved well by models are also difficult to predict. Improved predictability may be achieved by reassessment and refinement of the traditional genesis factors.

Seasonal and interannual prediction using coupled climate models depends on the predictability of ENSO, which may vary with climate state. There is little predictability of seasonal Atlantic TC activity prior to late May owing to the springtime predictability barrier of ENSO. The increasing resolution and ensemble size of coupled climate models used in seasonal climate prediction, combined with predicting the predictors strategy, shows great promise for improved June 1 seasonal predictions of TC activity. Predictability on decadal timescales arises from the general predictability and persistence of multidecadal modes such as the Atlantic Multidecadal Oscillation (AMO) and the Interdecadal Pacific Oscillation, IPO (or Pacific Decadal Oscillation, PDO). Decadal scale projections of future TC activity must integrate in some way the climate model projections of externally forced century-scale climate change with what is known about natural modes of climate variability and their future changes.

Below is our assessment of the predictability and predictions of North Atlantic (NATL) TCs out to 2025, which integrates physical understanding, climate model projections, and analysis of the data record. During the next 10-20 years, the tropical SST is expected to increase by 1^{o}F owing to external forcing by greenhouse gases. The AMO is expected to remain in the warm phase, the IPO/PDO is expected to be in the negative phase (with greater frequency of La Nina), and the NAO is expected to be in a negative phase during the initial portion of this period before shifting to a more predominantly positive phase. A key element of the analyzed impact of these variations on NATL TC activity is consideration of the combined impact of AMO, NAO and ENSO on TC characteristics and landfall locations, in combination with global warming.

Hurricane intensity. Since wind damage is roughly proportional to the cube of wind speed and storm surge as well depends on wind speed, hurricane intensity is a critical metric for catastrophe modeling. Assessments of the average hurricane intensity increase for a 1^{o}F (0.5^{o}C) SST increase range from 6% (Webster et al. global observational analysis), 2% (high resolution climate models), and 2.7% (Emanuel) and 5.3% (Holland) from potential intensity theory. The observed value is almost certainly too high (owing to problems with the intensity data sets) and the climate model value is almost certainly too low, and hence we bound the expected average increase by 3-5%. This would suggest an increase between 9–15% in average wind damage. This increase in average intensity is associated with a change in the intensity distribution. This change in the intensity distribution was noted by Webster et al., but questions about the quality of the intensity data outside the NATL led us to examine changes in the intensity distribution. The intensity data during the periods 1970-1982 and 1983-1994 (cool phase of the AMO) are similar, lending credibility to the intensity data back to 1970. The intensity distribution in the current active phase (since 1995) compared with the early part of the data record shows a shift in the intensity distribution with substantially more category 4 hurricanes, consistent with the findings of Webster et al. Owing to uncertainties in the historical intensity data before 1970, the impact of natural variability on TC intensity cannot be convincingly established or separated from the global warming signal, although there is the perception of the warm phase of the AMO being associated with more major hurricanes. In summary, virtually all TC researchers expect an increase in TC intensity with increasing SST; the (often heated) debate is over the magnitude of the increase and whether it can be detected in the data record given the uncertainties.

Hurricane genesis and frequency. Total NATL TC frequency is an important indicator of our understanding of TC genesis and is also loosely associated with the number of landfalling TCs. Observations show a substantial increase (nominally 40-50%) in the number of TCs during the current active period since 1995, when compared with any other period in the historical data record. However, the dataset of NATL TC numbers (HURDAT) is plagued by inconsistencies in storm classification and by missed storms prior to 1970; current estimates of annual undercounting in the early part of the record range from 1-6, although these uncertainty estimates have not closely examined the issue of spurious inclusion of subtropical and extratropical storms in the database. This issue is the subject of intense debate within the TC community and the HURDAT data set is being reanalyzed. Arguments for believing that the HURDAT data set is generally credible (or at least useful) in terms of annual TC counts, is the decadal scale correlation with SST and the (relatively) consistent relationship of TC counts with ENSO. While the factors controlling TC genesis are generally understood, our understanding of what controls basin average TC counts and the TC counts in an individual year is poor. The NATL basin is the only basin globally that has shown an increase in TC count in recent decades. The two highest-resolution climate model simulations to date have shown an overall decrease in TC numbers outside the North Atlantic in a warmer world, while showing the NATL TC counts to remain approximately the same or increase by 30%. Analysis of the historical data record suggests an increase of about 4 TCs per 0.5^{o}C increase in SST. The key issue is to understand why the NATL TC counts would increase with global warming, while the TC counts in other basins decrease. Part of the reason is likely to be associated with the relatively cool temperatures of the North Atlantic MDR in comparison with the Pacific and Indian Oceans. During the early part of the 20th century, average tropical NATL SST was 26.5-27^{o}C, close to the climatological threshold for the onset of tropical cyclogenesis. Not only are average SSTs increasing, but the area of the NATL warm pool has extended significantly over the past century, with summertime temperatures above 28^{o}C now extending to the African coast. It is hypothesized here that owing to the relative coolness of the NATL tropical SSTs, the NATL has not yet saturated in terms of the number of TCs, whereas the other basins have and their numbers are declining with warming in concert with an increase in storm duration and intensity.

Season length. With the expansion of the North Atlantic warm pool both spatially and temporally, TCs can be expected to form outside the climatological Main Development Region (MDR) and during the early and later periods of the hurricane season and even outside of the traditional hurricane season. There is some indication from the data that average NATL TC season length has increased by about 50 days over the last 100 years. Successful analysis of season length data depends critically on filtering subtropical and extratropical storms from the HURDAT dataset, which is problematic particularly prior to 1950. The importance of season length as a metric arises from the perspective of seasonal TC projections, deployment of resources such as hurricane hunters, and also from macroeconomic considerations (e.g. tourism and its infrastructure).

Hurricane size. Storm surge and the geographic extent of hurricane damage have a substantial dependence on horizontal size of the storm. There has been very little research on hurricane size, and this is arguably a key metric for catastrophe modeling. Our analysis of TC size for U.S. landfalling TCs using ROCI (radius of closed isobar) and DOT (distance of tornadoes from TC center) since 1955 indicates a statistically significant increase (32% and 13% respectively ROCI and DOT) for Gulf landfalling TCs in the current active period (since 1995) when compared with period of previous elevated activity (1955-1964). The controls on hurricane size are not well understood, but our preliminary research indicates a link with mid tropospheric humidity, which is expected to increase with global warming.

U.S. landfall frequency; One of the most puzzling issues in analysis of the historical data record of NATL TCs is the lack of any trend in the number of U.S. landfalls, given the increase in total number of NATL TCs. During the recent active period, the proportion of U.S. landfalls (and also those striking the Caribbean and Central America) to total NATL TCs has been lower than historical values, and this has led to speculations that the total number of NATL TCs particularly prior to 1970 may have been significantly undercounted (Landsea). While this may be true, there are two alternative arguments that can be used to explain the lack of trend in U.S. landfalls and in particular the relative low proportion of U.S. landfalls. The frequency of U.S. landfalls shows low frequency variability that reflects the influence of the AMO, with more landfalls during the warm phase. The eastward extension of the North Atlantic Warm Pool has resulted in increased genesis in the eastern region of the tropical NATL, which has been associated with a greater number of TCs taking a track northward in the NATL and avoiding landfall. In the coming decades, with the projected predominance of the negative phase of the PDO and hence more frequent La Nina, and with at least some negative NAO years anticipated, it is expected that the number of U.S. landfalls could increase significantly in the next two decades.

U.S. landfall location: In exploring the predictability of landfall location, we tend to focus our attention on predictors with a seasonal scale influence on the steering behaviors in the NATL, including ENSO and NAO. In the last 80 years all portions of the US coast have become populated enough where it is believed we have captured all landfalling TCs. Combinations of seasonal drivers can also provide improved insights into landfall location probabilities. We are also just beginning to understand how these seasonal level influences behave in the presence of one or more multidecadal scale factors such as the AMO and PDO. The increased number of landfalls during the warm phase of the AMO is associated predominantly with an increase in Gulf landfalls. Coupled climate models used for seasonal forecasts have the potential to provide probabilistic projections of landfall locations if the model resolution is sufficient.

Hurricane induced tornadoes: Damage from hurricane-induced tornadoes has been estimated at 10% of total U.S. landfall damages. As hurricane intensity and size increases, the number of hurricane-induced tornadoes also increases. Tornado damage is greatest in the right front quadrant of the TC, and hence there are more tornadoes striking land in Gulf landfalls than in Atlantic landfalls. There is a credible dataset of U.S. tornadoes back to 1955. Prior to 1995 when the Doppler network was installed, undercounting has been estimated to range from a factor of 2-3. During the active period since 1995, there has been a very large increase (factor of 7) in the annual average number of hurricane induced tornadoes and average number of tornadoes per storm, largely driven by the 2004 and 2005 seasons. While a statistically significant trend cannot be determined for this data set, the probability of the very large tornadic activity caused by multiple TCs during the consecutive years 2004 and 2005 arising solely from natural variability is very low. With projected increases in both TC size and intensity, combined with increasing numbers of Gulf landfalls, the frequency of tornadoes induced by landfalling TCs, along with the associated damage, is expected to increase.

Research needs. It is proposed that new metrics (TC size and TC-induced tornadoes) be included in catatstrophe modeling (and possibly season length). Seasonal TC forecasts (starting in May or June) have substantial potential for improvement using high-resolution coupled atmosphere/ocean climate models in combination. The approach of integrating relationships derived from historical data, physical understanding, and climate model projections should be a focus of research activities to project the future risk of hurricane catastrophes in a warmer world.

Recent relevant publications, presentations and testimony from GT/CFAN:

Webster et al. (2005) Changes in Tropical Cyclone Frequency, Duration, and Intensity in a Warming Environment. *Science.* *http://www.sciencemag.org/cgi/content/full/309/5742/1844*

Hoyos et al. (2006) Deconvolution of the Factors Contributing to Increase in Global Hurricane Intensity. *Science.* *http://curry.eas.gatech.edu/currydoc/Hoyos_Science312.pdf*

Curry (2006) Congressional testimony on "Global Warming and Hurricanes" *http://www.cleartheair.org/documents/CurryCongressionalTestimony.pdf*

Curry et al. (2006) Mixing Politics and Science in Testing the Hypothesis that Greenhouse Warming is Causing a Global Increase in Hurricane Intensity. *Bull. Amer. Meteorol. Soc.* *http://curry.eas.gatech.edu/currydoc/Curry_BAMS87.pdf*

Curry and Webster (2007, in press) Potential Increased Hurricane Activity in a Greenhouse Warmed World. In *Sudden and Disruptive Climate Change*, M. MacCracken, ed., *http://www.eas.gatech.edu/static/pdf/Maccracken_chapter.pdf*

Curry (2007) Congressional testimony on "Dangerous Climate Change" *http://www.eas.gatech.edu/static/pdf/Curry_Energy.pdf*

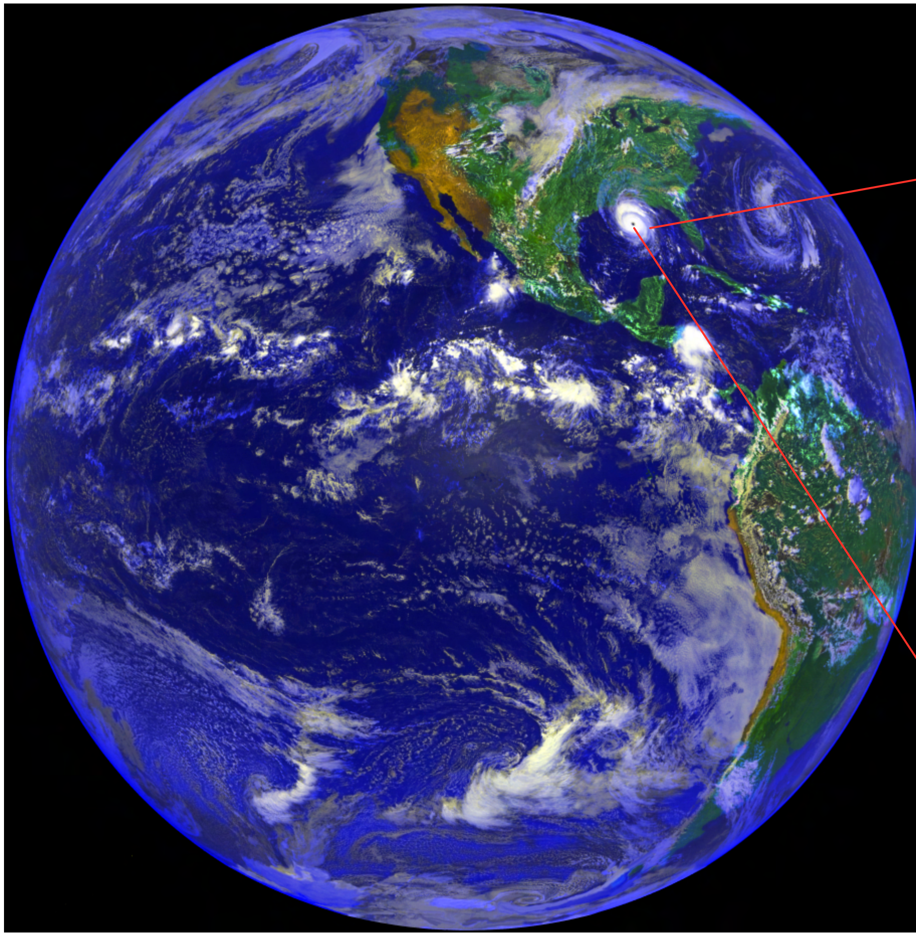
Webster (2007) Interactions between climate and tropical cyclones. AGU Charney Lecture *http://webster.eas.gatech.edu/Presentations/Webster.2007.CharneyLecture.AGU.pdf*

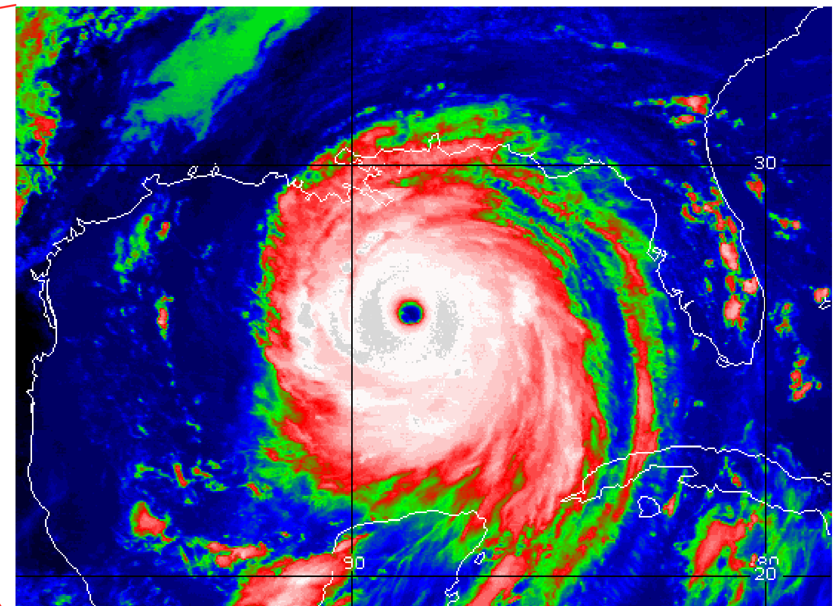
Holland and Webster, (2007) Heightened tropical cyclone activity in the North Atlantic: natural variability or climate trend? *Phil. Trans. Roy. Soc. A* *http://webster.eas.gatech.edu/Papers/Webster2007a.pdf*

Belanger et al. (2007, in review) Recent Increase in Tornadoes Spawned by U.S. Landfalling Tropical Cyclones. *J. Appl. Meteorol. Climatol.* (manuscript available upon request)

Webster et al. (2007, to be submitted) Expanding tropical warm pools and their impact on global climate.

Predictability and Predictions of N. Atlantic Hurricane Activity: Weeks to Decades



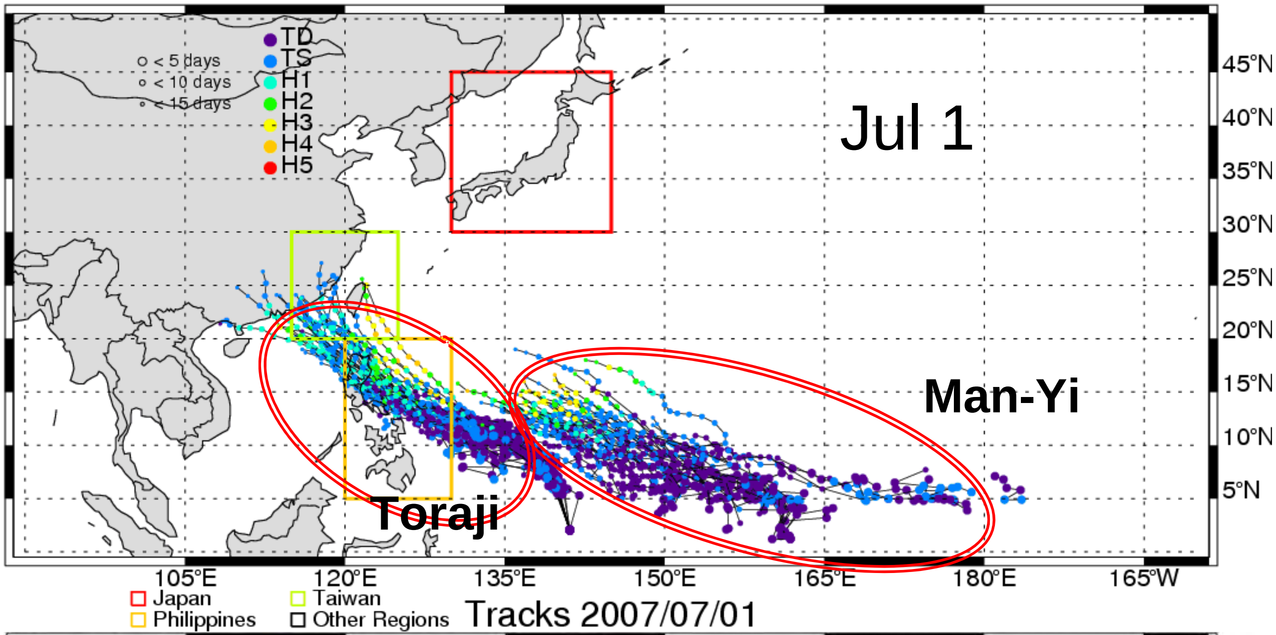


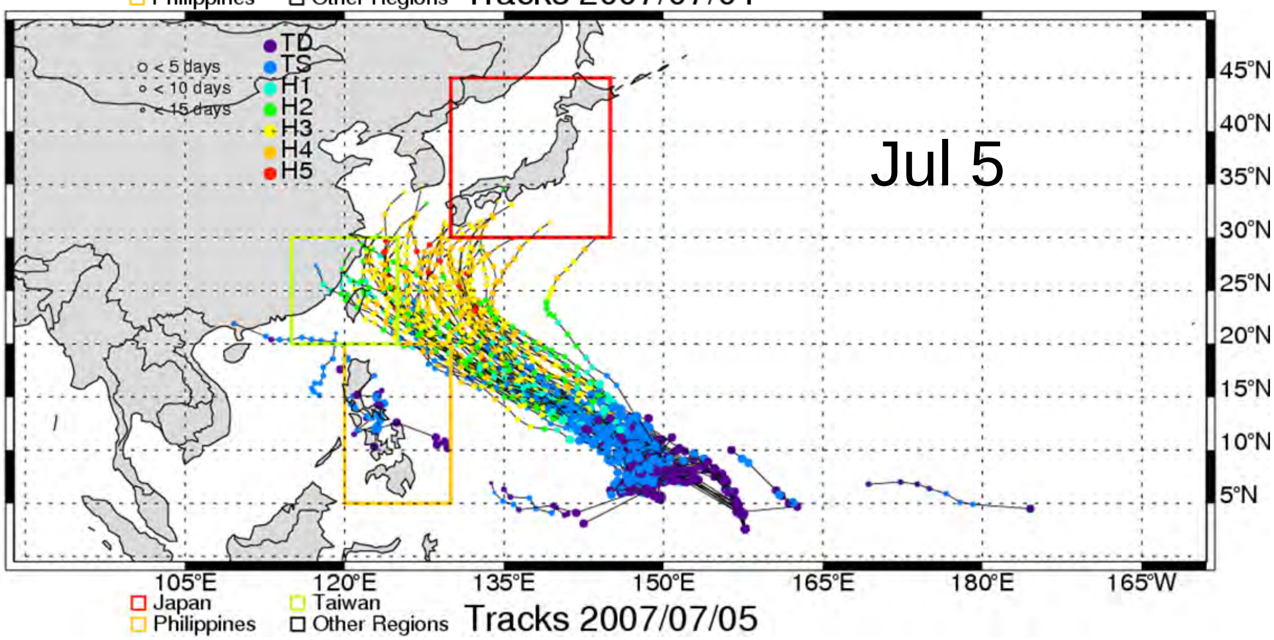
Judith A. Curry

Cat. Modeling Forum
October 16, 2007

CFAN
Georgia Tech

ECMWF EPS Forecasts (55 km)





Model

Observation

System ID 6/26

2 separate TCs 7/1

Man Yi named 7/7

Cat 4 ID 7/1

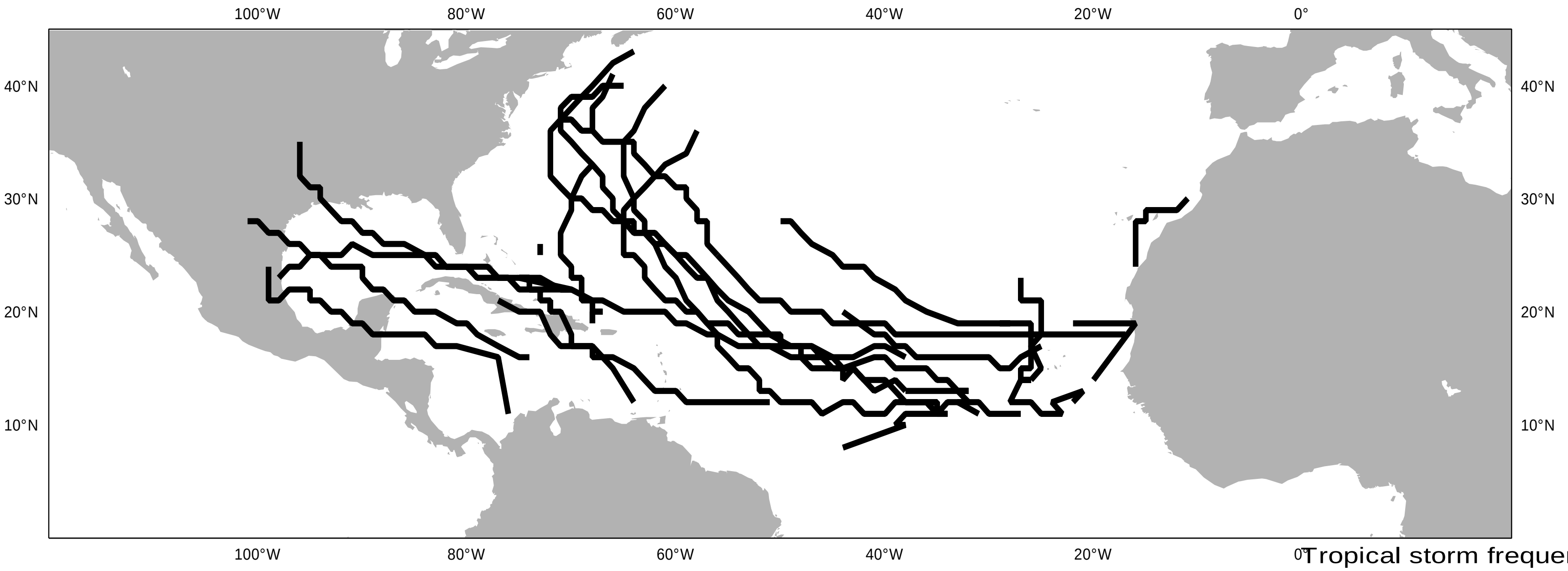
Reaches Cat 4 7/13

Japan landfall 7/5

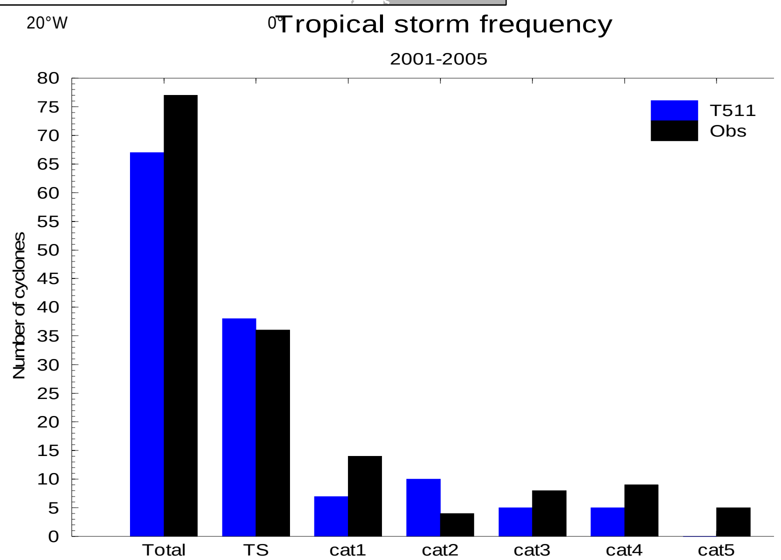
Japan landfall 7/14

ECMWF Seasonal Forecast

(2005 hindcast - T511 ~40 km, starting 6/1)



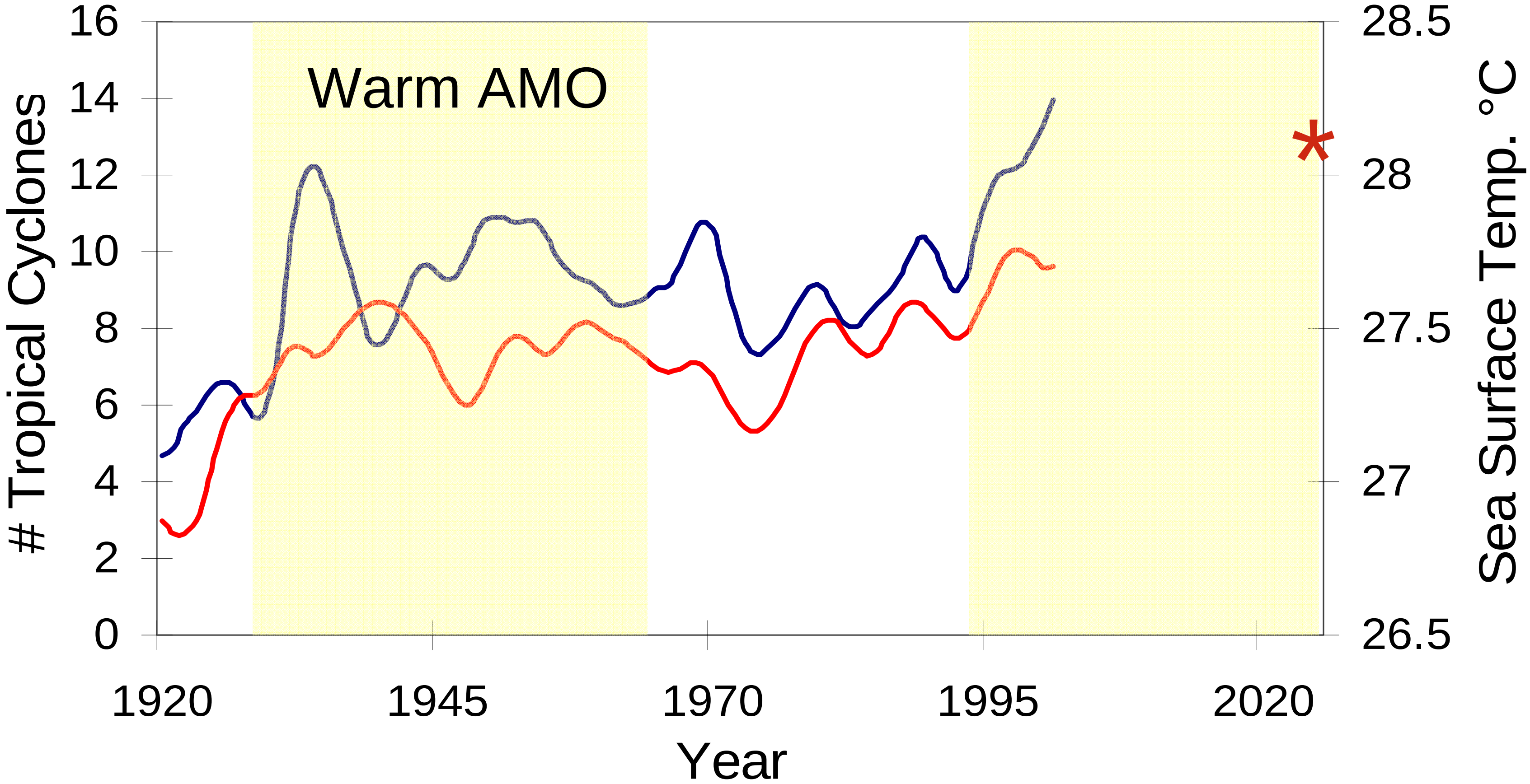
Operational coupled ocean/atm model
7 month ensemble sims (40 members)
Resolution T159 (125 km)



Courtesy F. Vitart

N. Atlantic Tropical Cyclones & SST

Decadal scale variations: 9 yr Hamming filter



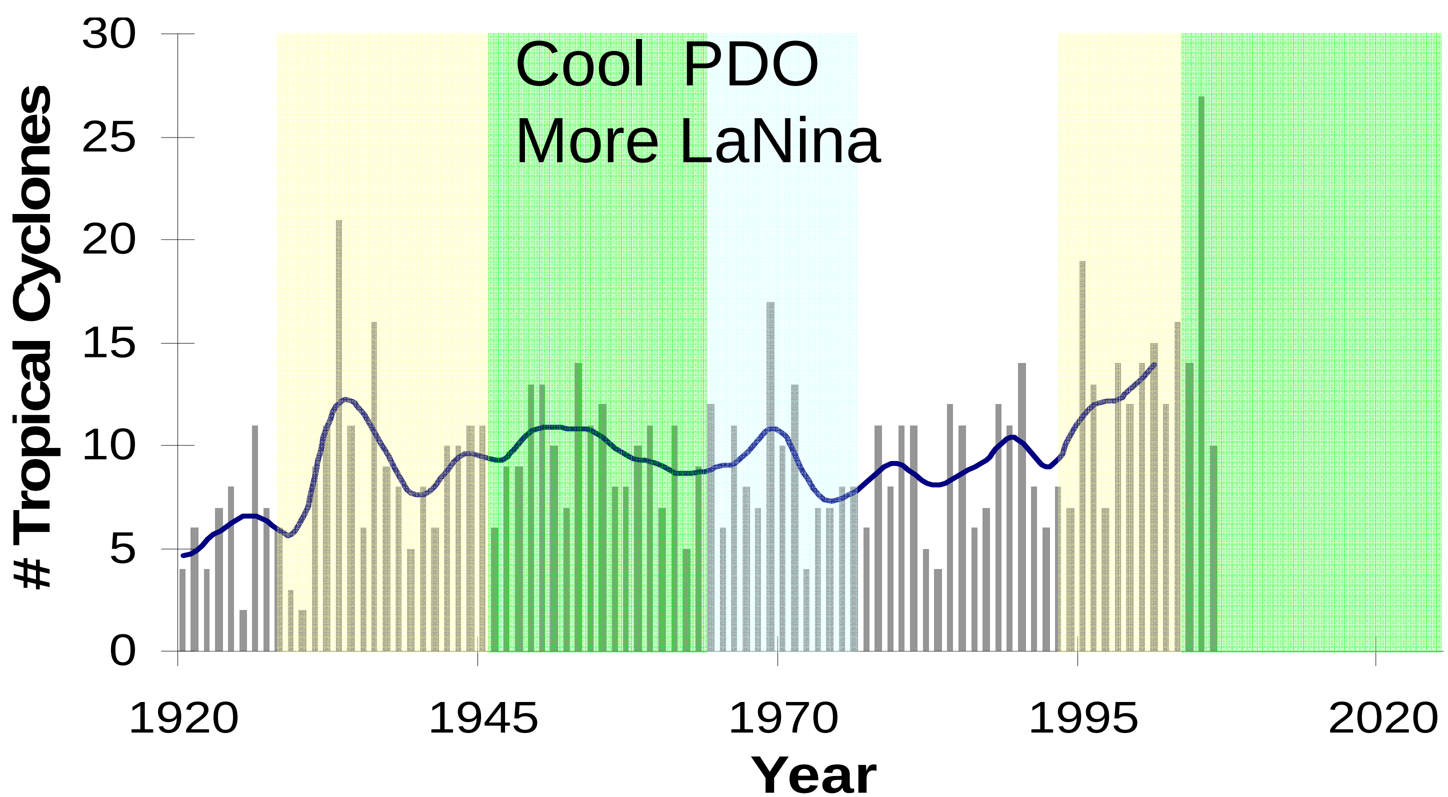
Current warm phase of AMO expected to extend to 2025+

1ºF warming by 2025 expected from AGW

Figure Courtesy: M. Jelinek

N. Atlantic Tropical Cyclones:

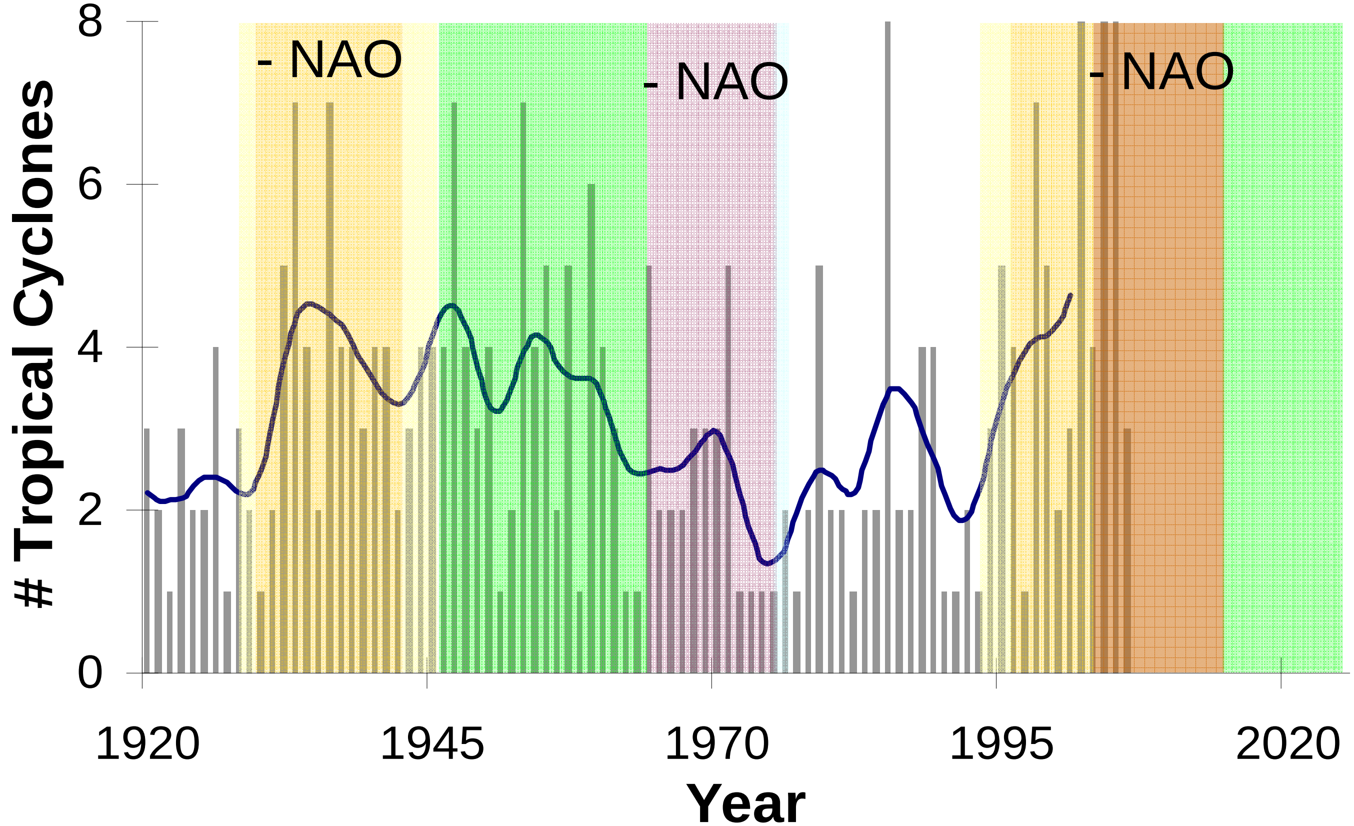
Decadal modes of variability: AMO & PDO



Currently transitioning to cool PDO

Figure Courtesy: M. Jelinek

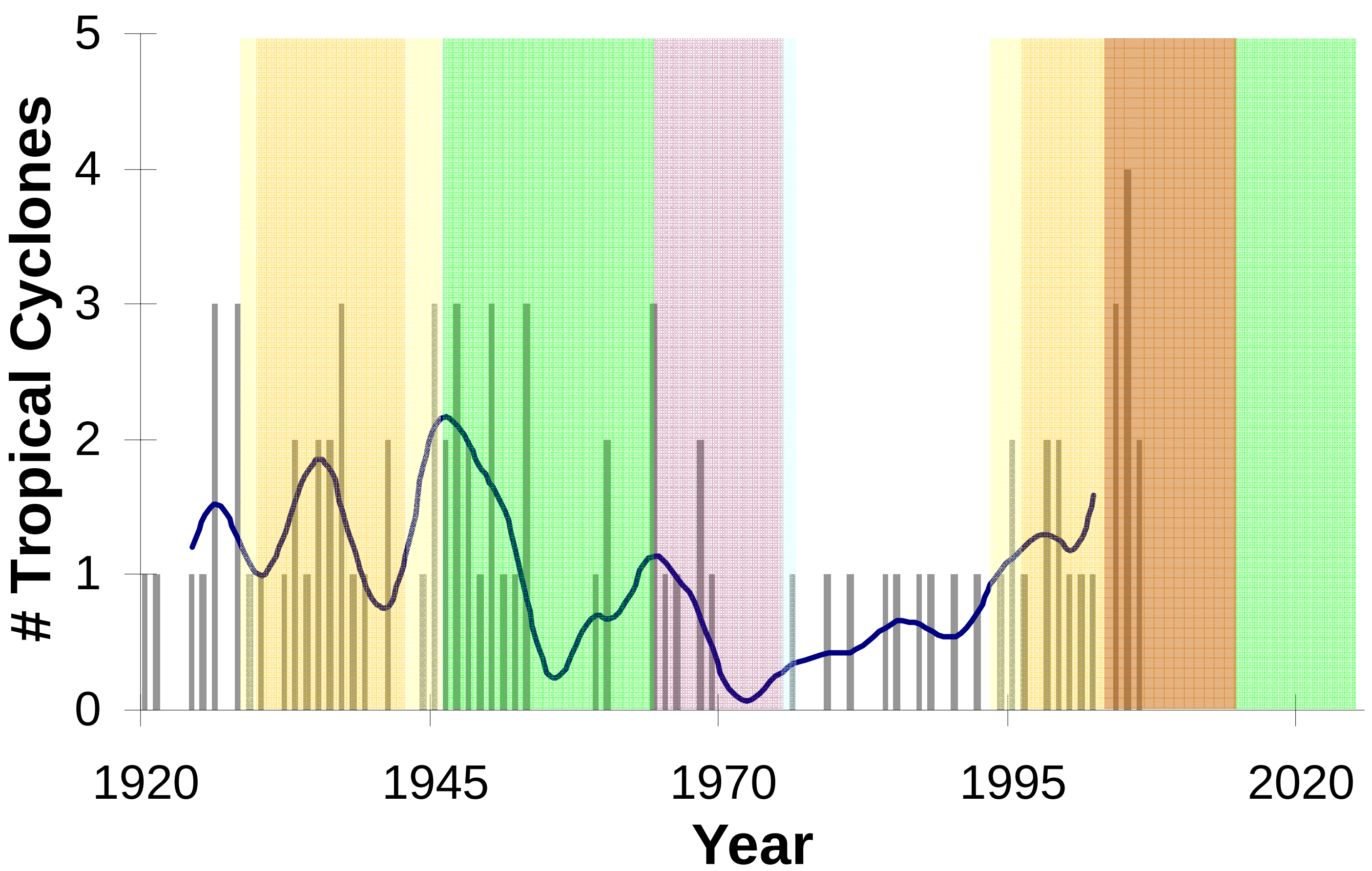
U.S. Landfalling TCs



Landfall probability increases with neg. NAO, esp with warm AMO, cool PDO

Figure Courtesy: M. Jelinek

FL Peninsula Landfalling TCs

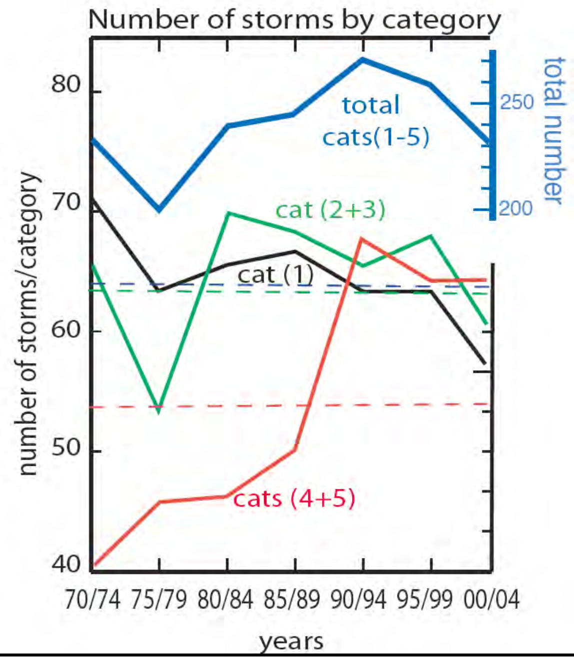


Elevated while neg. NAO (warm AMO, cool PDO)

Figure Courtesy: M. Jelinek

TC intensity → 1°F SST increase

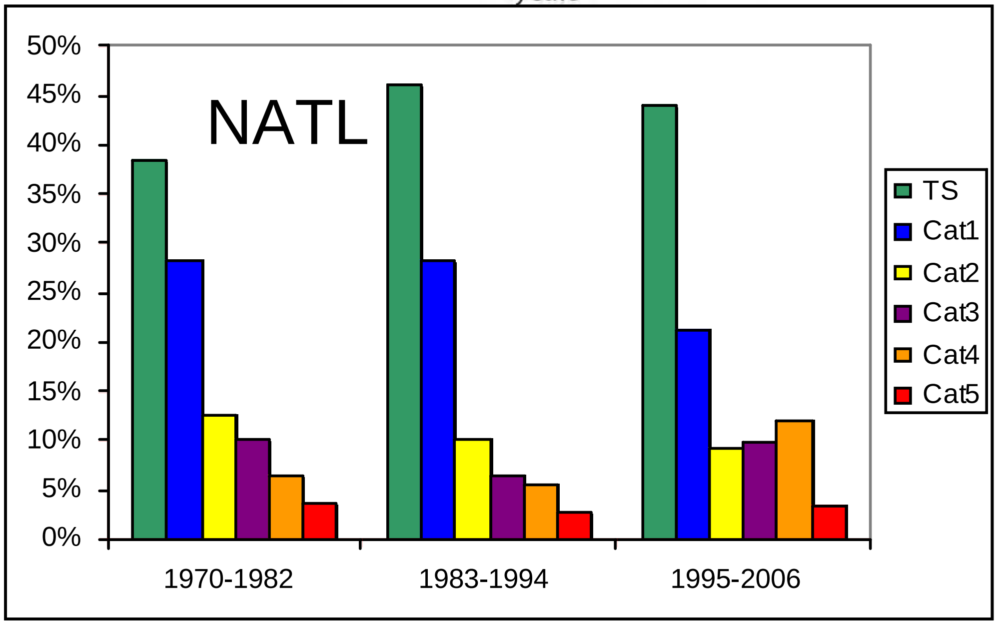
Webster et al. obs:	+6.0%
Climate models:	
Knutsen/Tuleya (2004):	+2.0%
Oouchi et al. (2006):	+2.1%
Potential intensity theory:	
Emanuel	+2.7%
Holland	+5.3%



Likely avg intensity increase:
3-5%

Avg wind damage increase:
min. 9-15%

Intensity distribution shift:
more cat 4-5

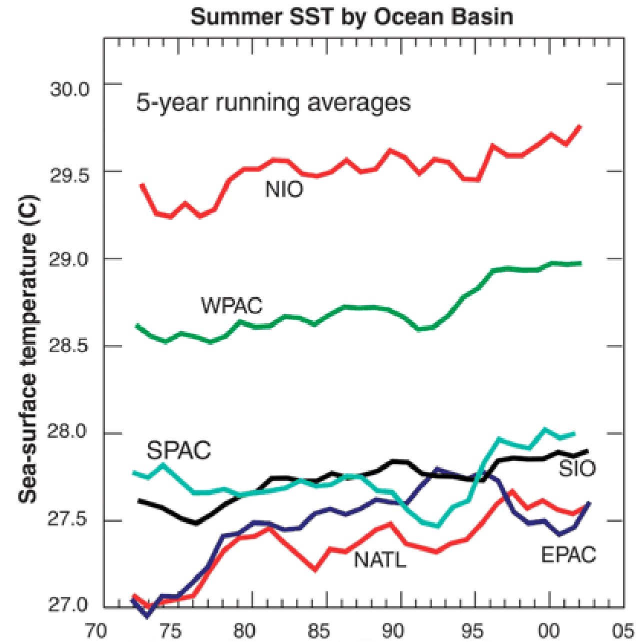


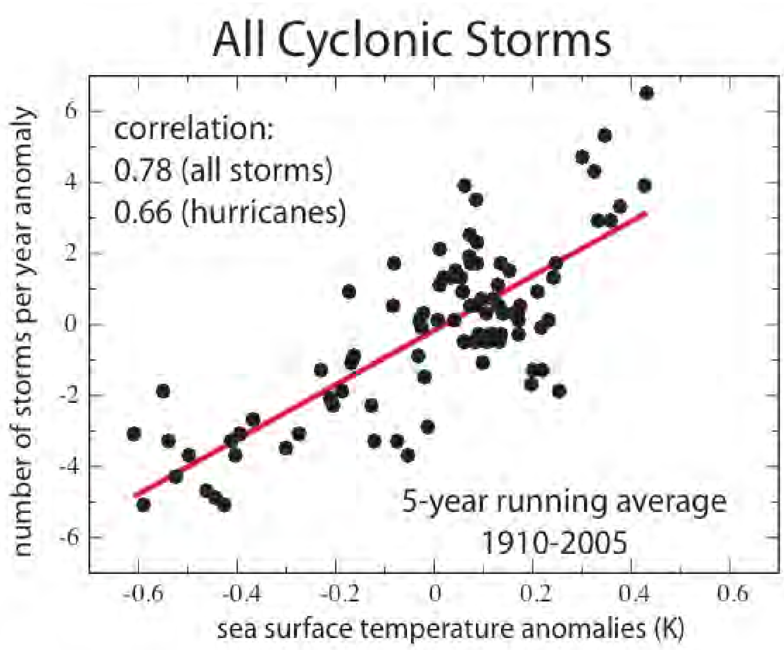
NATL TC frequency → 1°F SST increase

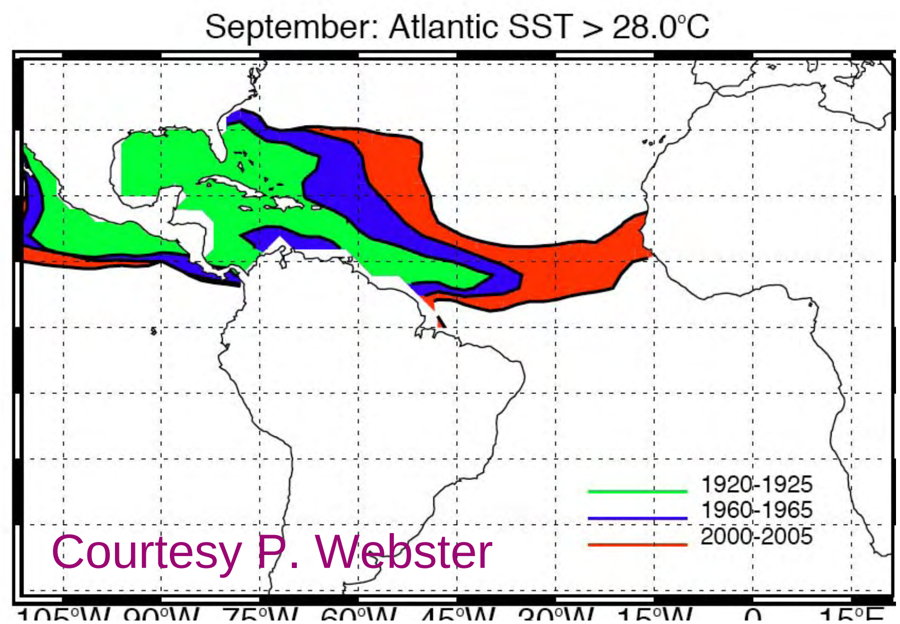
Climate models suggest zero to small increase in #TC

Data suggest +5 TCs
- NATL SSTs relatively cool

Expanding NATL warm pool
- Extends genesis region, season
- Reduces wind shear







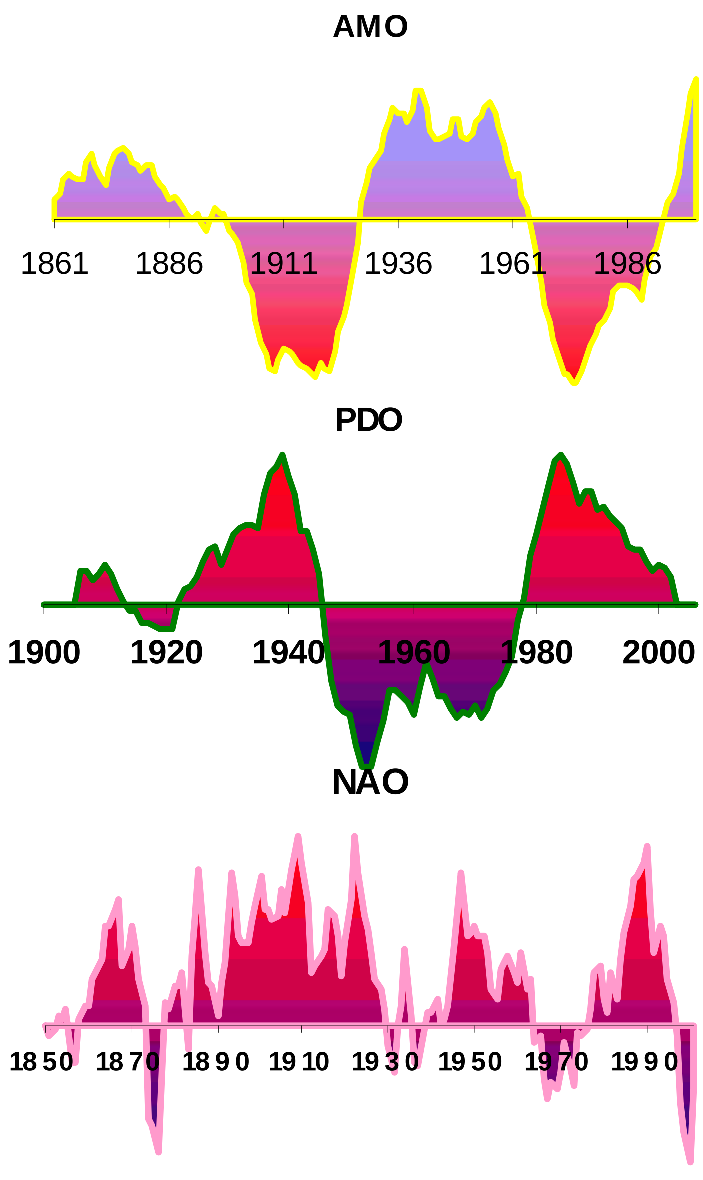
Summary: NATL TC predictability

- Subseasonal (weeks) predictability from ensemble prediction system with ~50 km resolution
- Seasonal (months) predictability (after mid May) using atm/oce ensemble prediction system
- Predictability gap on annual/interannual timescales owing to ENSO springtime "predictability barrier"
- Predictability on decadal scales using AMO, PDO, NAO
- Near term impacts of global warming on NATL TC activity bounded by combining models, observations, theory

Candidate metrics:

- TC size, TC-induced tornadoes, TC season length

Time series of climate regimes



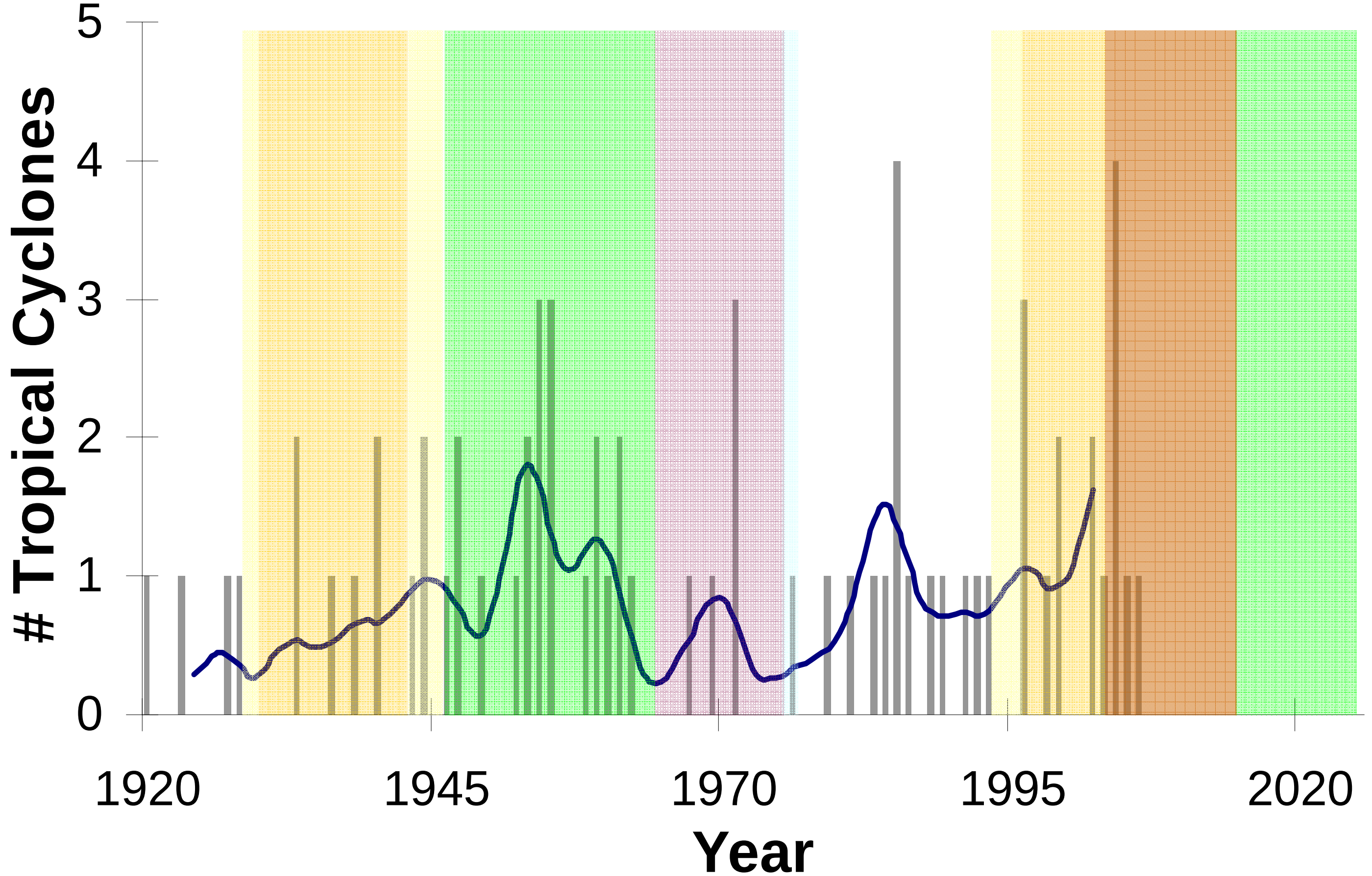
AMO: All months

PDO: Oct-Mar

NAO: May-June

Figure Courtesy: M. Jelinek

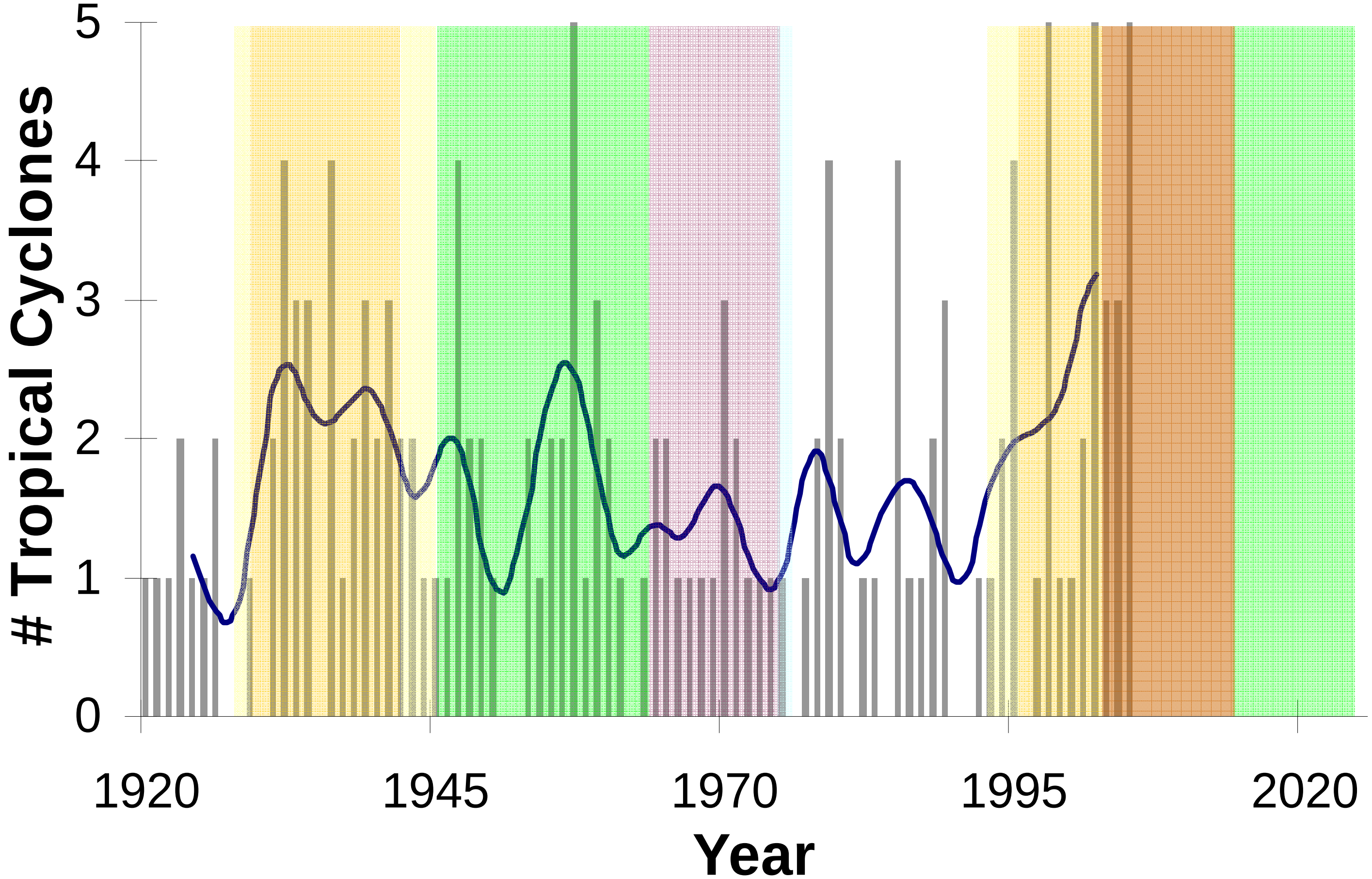
Atlantic Coast Landfalling TCs



Likely increase during pos. NAO (warm AMO, neg. PDO)

Figure Courtesy: M. Jelinek

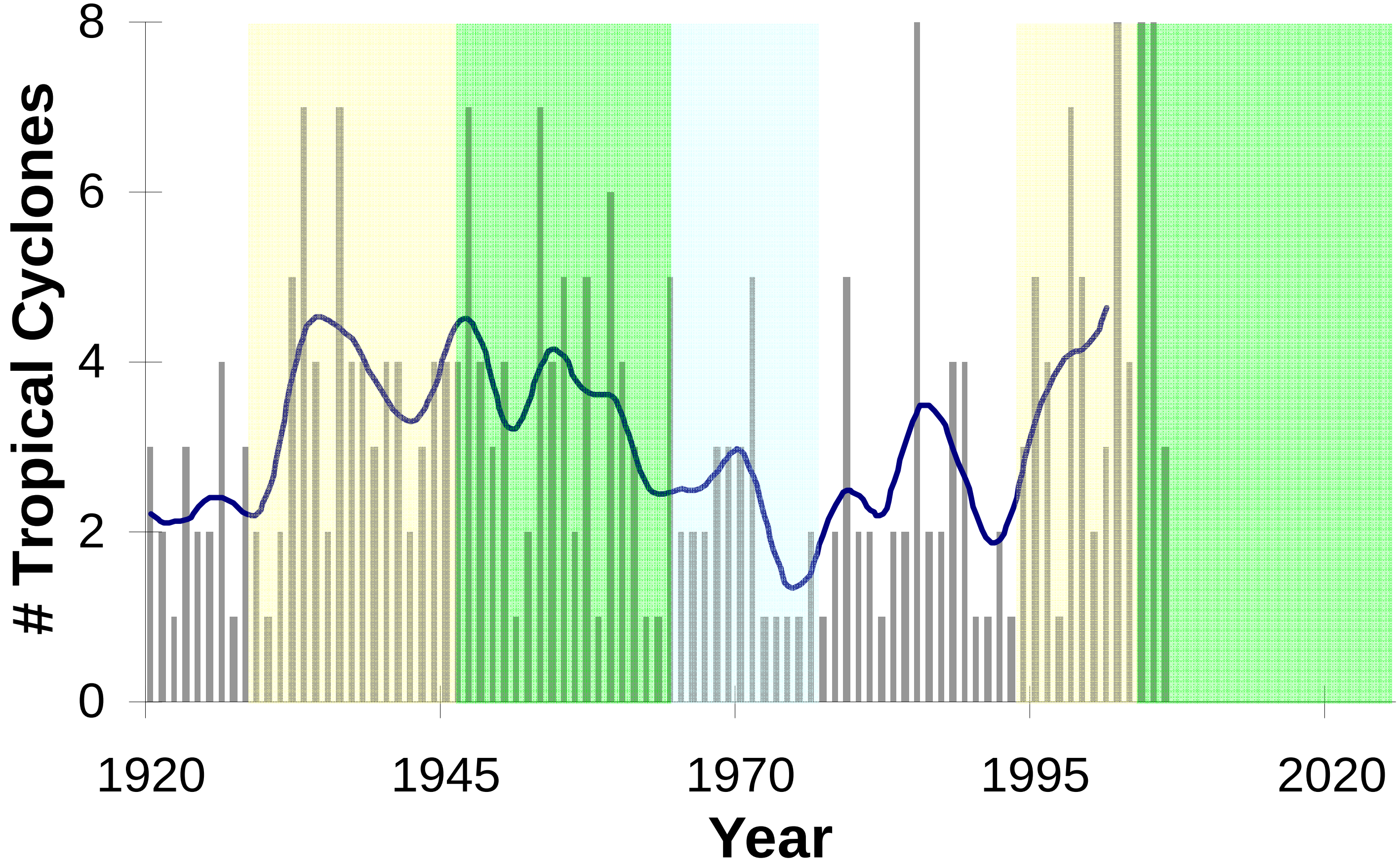
Gulf Coast Landfalling TCs



Elevated with neg. NAO, warm AMO

Figure Courtesy: M. Jelinek

N. Atlantic US Landfalling TCs



More landfalls in warm AMO, cool PDO

Figure Courtesy: M. Jelinek

Catastrophe Modeling Forum:
Changing Climatic Dynamics and Catastrophe Model Projections

October 16, 2007
New York City

James B. Elsner
Florida State University
Climatek, Inc.

Topic 1: Global warming, Atlantic hurricanes, and insured losses

Increases in Atlantic hurricane activity during the past decade are related to increases in tropical Atlantic warmth. A debate concerns the attribution of these increases with some suggesting a natural atmospheric/oceanic cycle called the Atlantic Multidecadal Oscillation (AMO) and others suggesting climate change. Leading atmospheric scientists in academia and government are found on both sides of this issue. The large correlation between late summer/early fall Atlantic sea surface temperature (SST) and global near-surface air temperature together with lagged values of global temperature predicting SST but not the other way around argues in favor of the climate change hypothesis. However the positive influence of climate change on Atlantic hurricane activity is limited to the connection with Atlantic SST possibly as a consequence of increased atmospheric thermodynamic stability and/or wind shear from greater warmth.

The return period of a Katrina-like hurricane is 21 years for the Gulf coast of the United States (Texas through Alabama) and 14 years for the entire coast. Hurricane Katrina might be a harbinger of things to come in a warmer world as the observed and modeled consequence of climate change on hurricane intensity appears to start at Katrina's observed near-coastal intensity of 71 m/s. The annual probabilities for hurricanes weaker than Katrina do not change between globally warm and globally cool years. However, for hurricanes stronger than Katrina the increase in the 100-year return intensity from cold to warm years is 11%.

Coastal hurricanes generate huge financial losses for the insurance industry. The relative infrequency of severe coastal hurricanes implies that empirical probability estimates of the next big loss will be unreliable. Hurricane climate science has advanced to the point where hurricane activity can be predicted several months and even several years in advance with some skill using probability models. Similar models can be used to forecast the expected and maximum annual aggregated insured loss prior to the start of the hurricane season. From year to year the effect of climate change on insured losses will be minor relative to El Niño, the North Atlantic Oscillation, and random SST fluctuations, but averaged over several years the effect could be significant.

Topic 2: A 5 year model of Atlantic hurricanes

Hurricanes cause drastic social problems as well as generate huge economic losses. A reliable forecast of the level of hurricane activity covering the next several seasons has the potential to mitigate against such losses through improvements in preparedness and insurance mechanisms. We develop a statistical model to predict North Atlantic hurricane activity out to five years. The algorithm has two components, a time series model to forecast average hurricane-season Atlantic sea surface temperature (SST), and a regression model to forecast the hurricane rate given the predicted SST value. The algorithm uses Monte Carlo sampling to generate distributions for the predicted SST and model coefficients. For a given forecast year, a predicted hurricane count is conditional on a sampled predicted value of Atlantic SST. Thus forecasts are samples of hurricane counts for each future year. Model skill is evaluated over the period (1997--2005) and compared against climatology, persistence, and other seasonal forecasts issued during this time period. Results indicate that the algorithm will likely improve on earlier efforts and perhaps carry enough skill to be useful in the long-term management of hurricane risk.

Topic 3: Data models

Traditionally tropical cyclones are analyzed as a passive response to climate forcing: the hurricane as a product of its environment. A warm ocean provides sustenance, a calm atmosphere nurturing, and a subtropical high pressure cell forward direction. An increase in oceanic heat will raise a hurricane's potential intensity, yet an increase in shearing winds could counter by dispersing the heat in a fledgling storm. This perspective is useful for identifying the mechanisms responsible for making some seasons active while others inactive. In this regard it was argued that data modeling is superior to data analysis (trend lines, etc) as it avoids cherry-picking the evidence and provides a framework for making use of older, less reliable data.

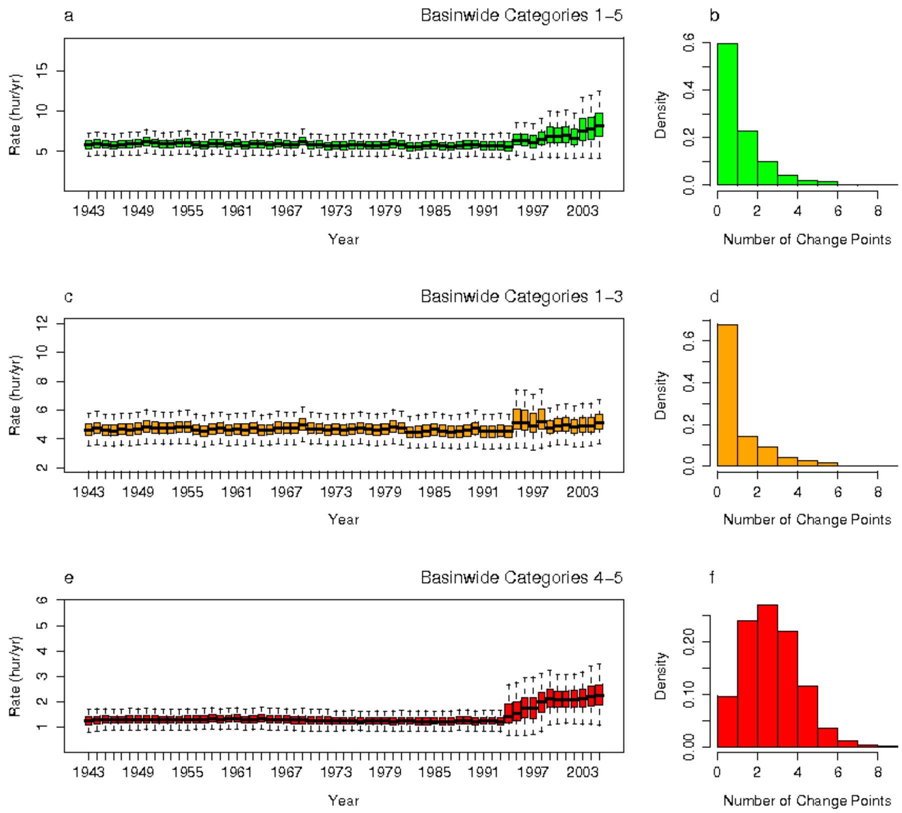
For example, a Poisson distribution is useful for modeling tropical storm counts over time. The benefit of this approach is that it provides a context that is consistent with the nature of underlying physical processes, analogous to the way the laws of physics provide a context for studying meteorology. It was shown that smoothing (filtering) the count data introduces low frequency patterns that may not be significant and that a data model of Atlantic hurricanes indicates a recent upswing in the number of strongest hurricanes with little multidecadal variation. The figure shows annual hurricane rates using a data model of basin-wide Atlantic hurricane counts. Results are shown for different categories of hurricane intensity. Note that for each year the model provides a distribution on the estimated annual rate as indicated by a box plot. The model also provides a distribution for the number of rate changes over the 63-year period (1943-2005). Note the absence of a multidecadal pattern.

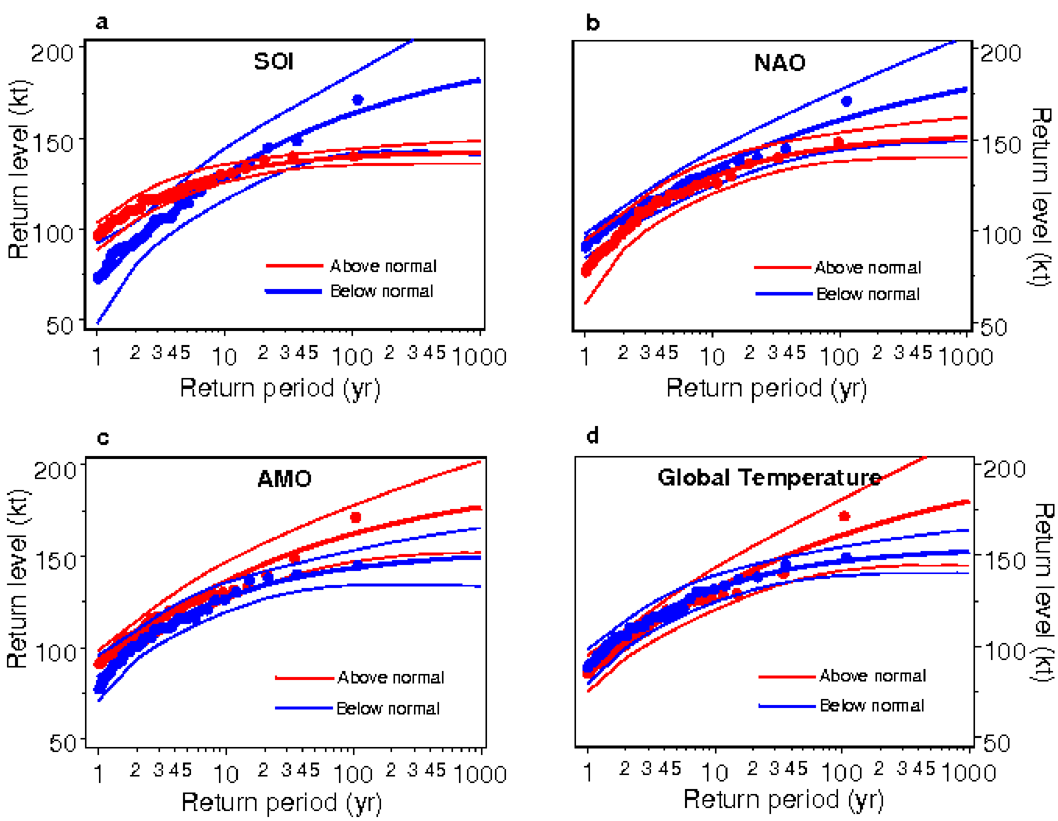
Although the question of whether we can ascribe a change in tropical cyclone intensity to anthropogenic climate change (attribution) is still open, it is argued based on data models for extreme winds that the difference in U.S. hurricane intensity between globally warm and cool years is consistent in sign and magnitude with theory and simulations. In this regard it is noted that the discrepancy between numerical model results and observations is likely due to a reliance on data analysis rather than data models.

Topic 4: Limitation of risk models in a changing climate

Hurricane risk models used by the insurance industry rely on a catalog of storms that represent the historical data in some way or another. While useful for estimating aggregate portfolio losses from a hypothetical worse case scenario, these catalogs are not easily suited for anticipating losses based on a changing climate. At the core of the catalog is a set of synthetic storms and a way to assign a probability to each. But each synthetic storm in the catalog is a composite of size, track, and intensity so it is difficult to estimate risk at a particular point location. Additionally, it is important to consider how climate influences hurricane risk, but it is not obvious how to condition the multidimensional storm event on climate. Perhaps most importantly, the assigned return rates are empirically driven in that the rates are not connected parametrically to a theoretical distribution. This leads to lower confidence in the estimated rates.

We propose an alternative approach for anticipating losses that produces predict expected wind speed distributions at any location. The parametric distributions which give tighter confidence intervals can be naturally conditioned on pre-season climate variables. More importantly this approach could allow the reinsurance industry to examine which coastal regions are most sensitive to the changing climate. For example, with increasing Atlantic sea-surface temperatures is it realistic to expect that the risk of hurricane damage will increase everywhere? The answer to this question has implications for insurance rates and societal vulnerability.


a
Basinwide Categories 1–5
Rate (hur/yr)
Year
b
Density
Number of Change Points
c
Basinwide Categories 1–3
Rate (hur/yr)
Year
d
Density
Number of Change Points
e
Basinwide Categories 4–5
Rate (hur/yr)
Year
f
Density
Number of Change Points
1943 1949 1955 1961 1967 1973 1979 1985 1991 1997 2003


a
SOI
Return level (kt)
Return period (yr)
Above normal
Below normal
b
NAO
Return level (kt)
Return period (yr)
Above normal
Below normal
c
AMO
Return level (kt)
Return period (yr)
Above normal
Below normal
d
Global Temperature
Return level (kt)
Return period (yr)
Above normal
Below normal

Anticipating the Hurricane Peril in the United States

Catastrophe Modeling Forum
October 16-17, 2007
New York City

James B. Elsner
Florida State University
Climatek, Inc

Support: NSF, RPI

Take Home Points

Hurricane activity responds to variations in climate. On the seasonal time scale, and to a first order, a warm ocean fuels hurricanes, a calm atmosphere allows them to intensify and the position and strength of the subtropical high paves the tracks.

Theory and evidence supports a connection between climate change and Atlantic hurricanes through oceanic warmth.

Observations and models agree on the magnitude of the effect. Inhibiting factors include the possibility of greater wind shear and atmospheric stability. Evidence is ambiguous in other tropical cyclone basins.

The next generation of hurricane risk models should make use of this new science & technology.

- Problem:

  Today's hurricane risk models are based on a large set of hypothetical storms (catalogue) generated from historical data and based on random sampling, but it is difficult to condition the large amount of sampling on climate variability & climate change.

- Solutions:

  Expert elicitation: panel of experts determine short-term (next 5 yr) activity.

  - Pros: easy, cheap, no need to scrap the catalogue.
  - Cons: who/how many experts, lack of coherency, basin-wide activity rather than landfall activity, uncertainty quantification.

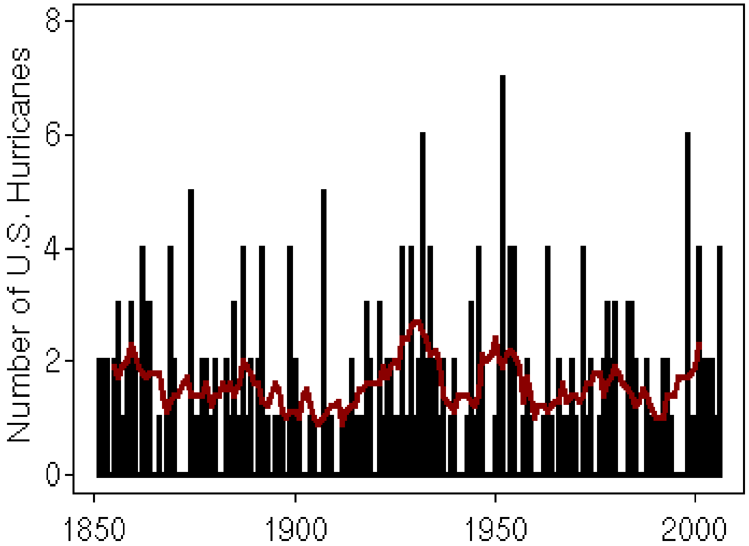
  Numerical models: Capable of resolving hurricanes.

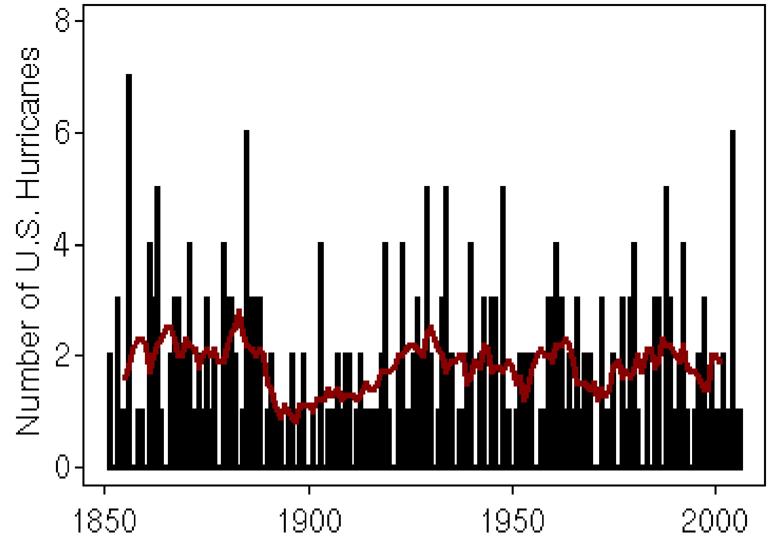
  - Pros: directly predict number, intensity hurricanes under various climate scenarios.
  - Cons: expensive, resolution too low for seasonal or multi-year forecasts.

  Data models: theoretical statistical distributions for activity (frequency, intensity, etc).

  - Pros: easy, cheap, climate conditioning on the distributional parameters, Bayesian methods can incorporate less precise data, uncertainty is easily included.
  - Cons: statistically sophisticated.

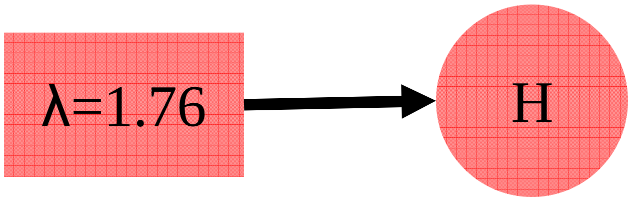
Data Models vs Data Analysis

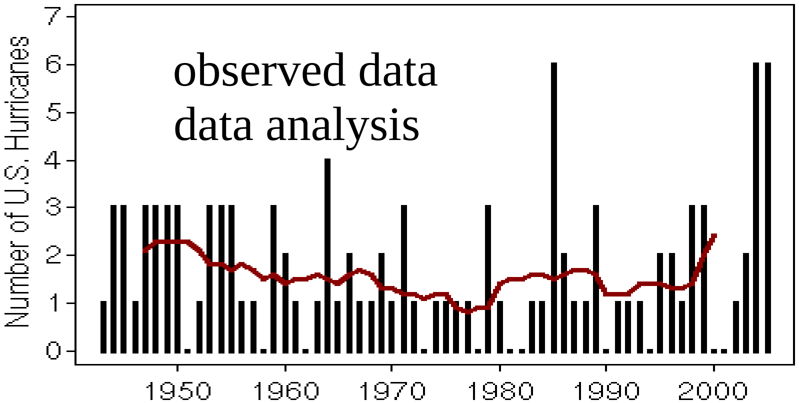


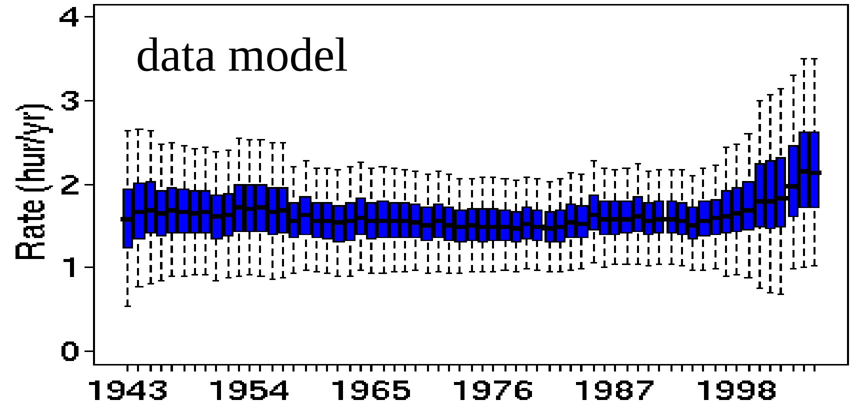


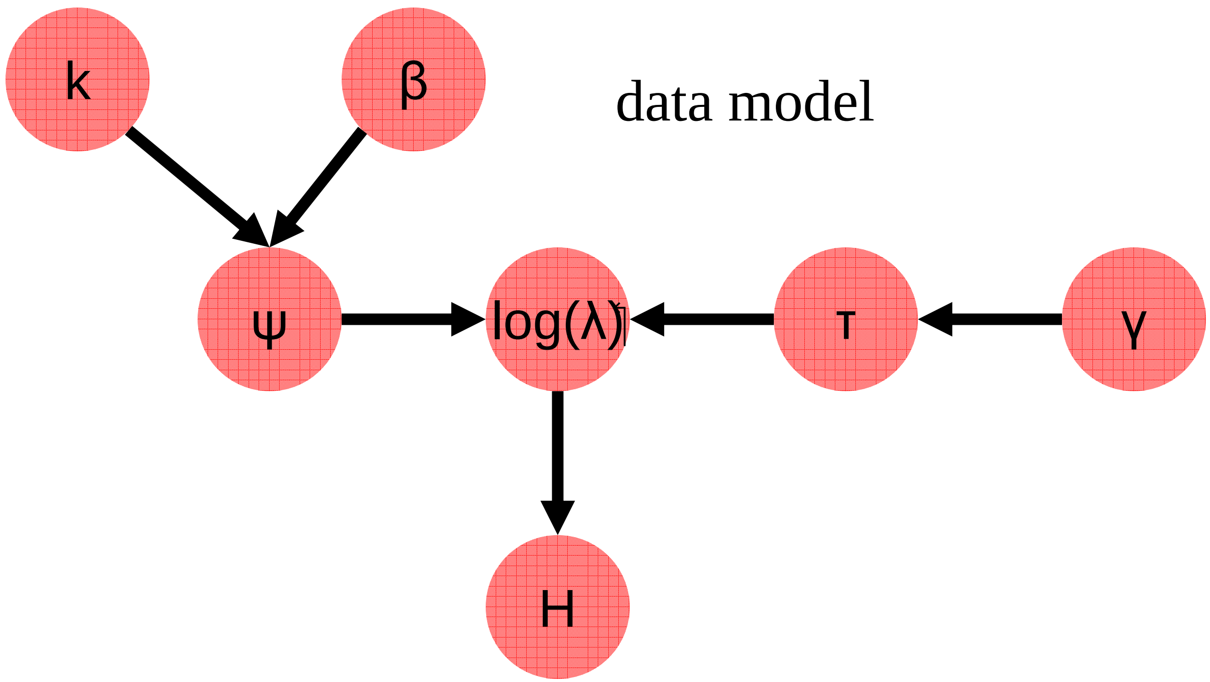
data analysis
(fooled by randomness)

data model



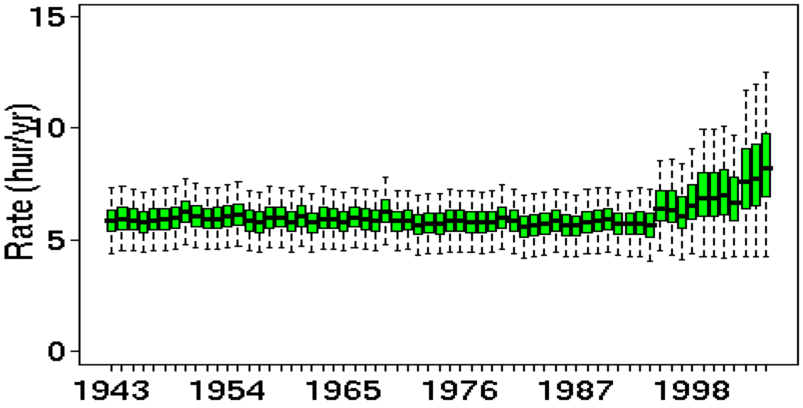

observed data
data analysis
Number of U.S. Hurricanes
0
1
2
3
4
5
6
7
1950
1960
1970
1980
1990
2000


data model
Rate (hur/yr)
0
1
2
3
4
1943
1954
1965
1976
1987
1998

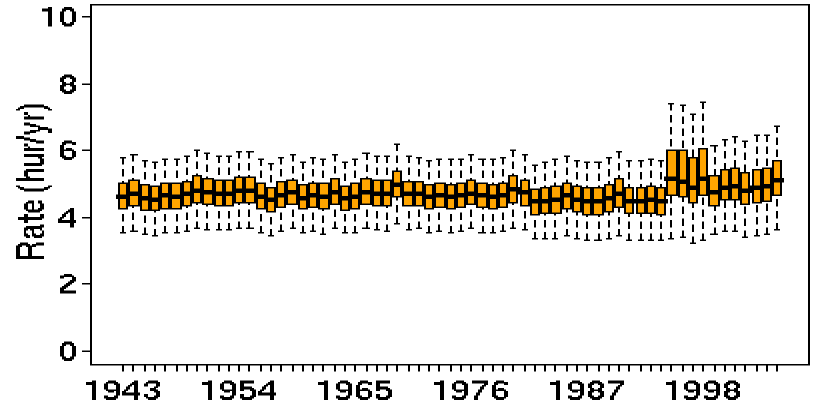

k
β
ψ
log(λ)
τ
γ
H

data model

Basin wide, Cat 1-5

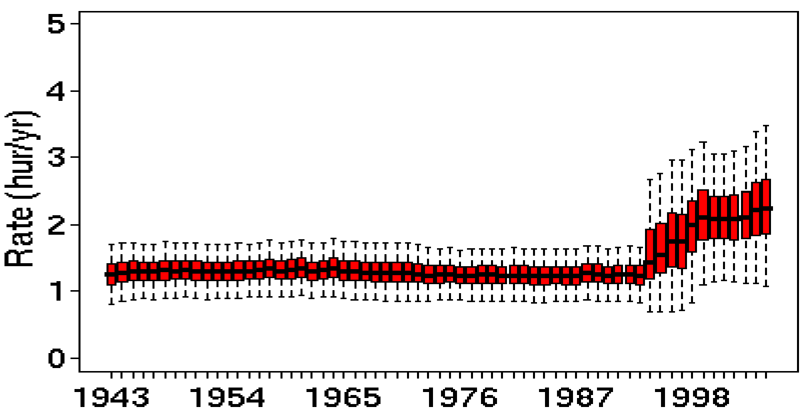


Basin wide, Cat 1-3

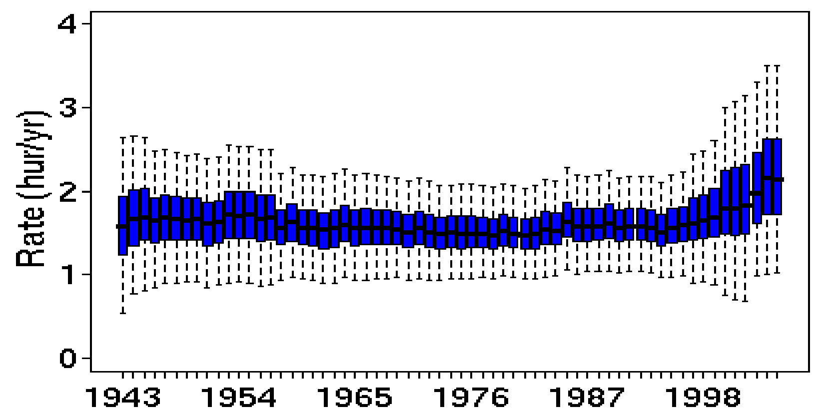


Note the lack of decadal variation. Why?

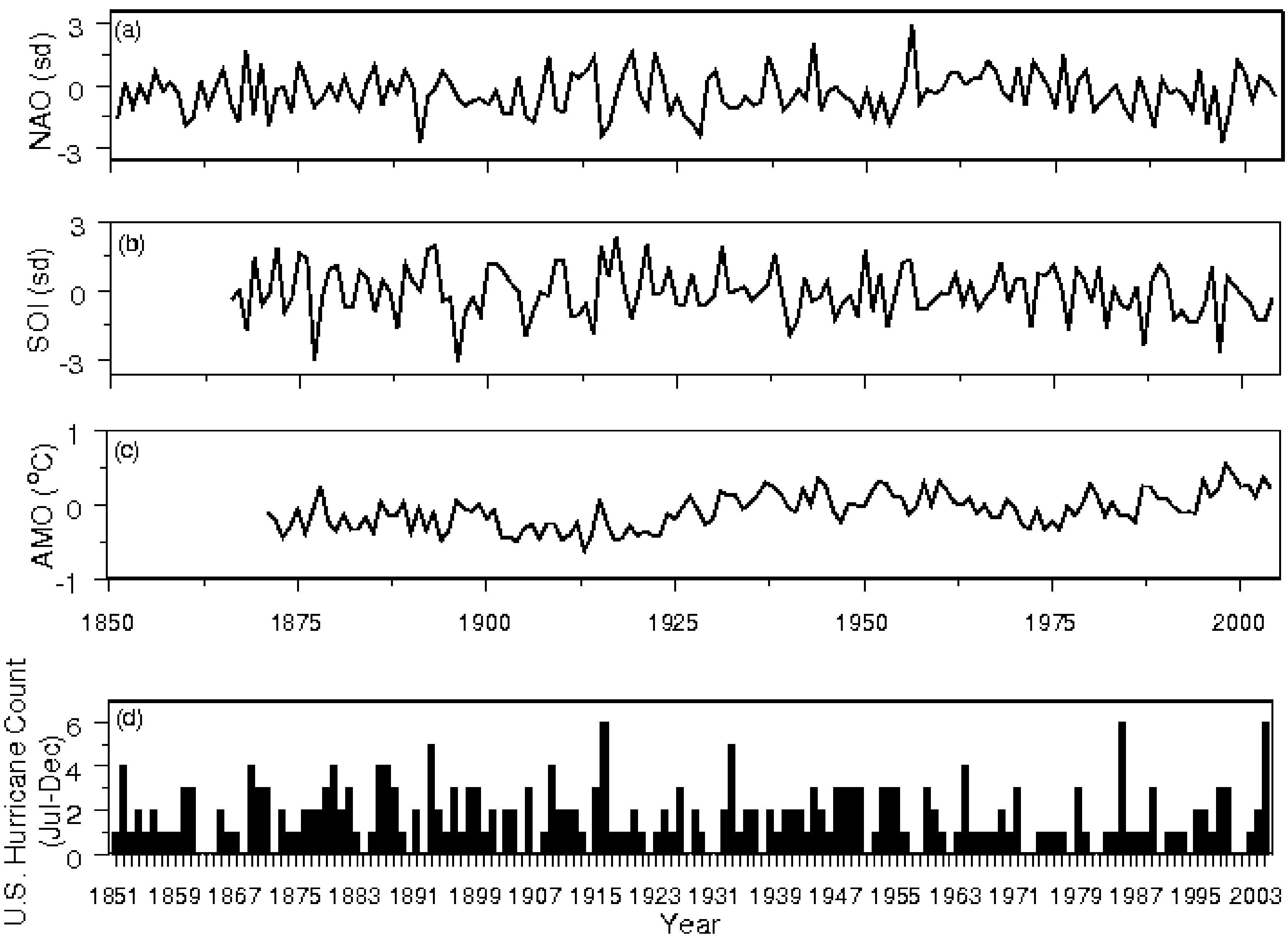
Basin wide, Cat 4-5

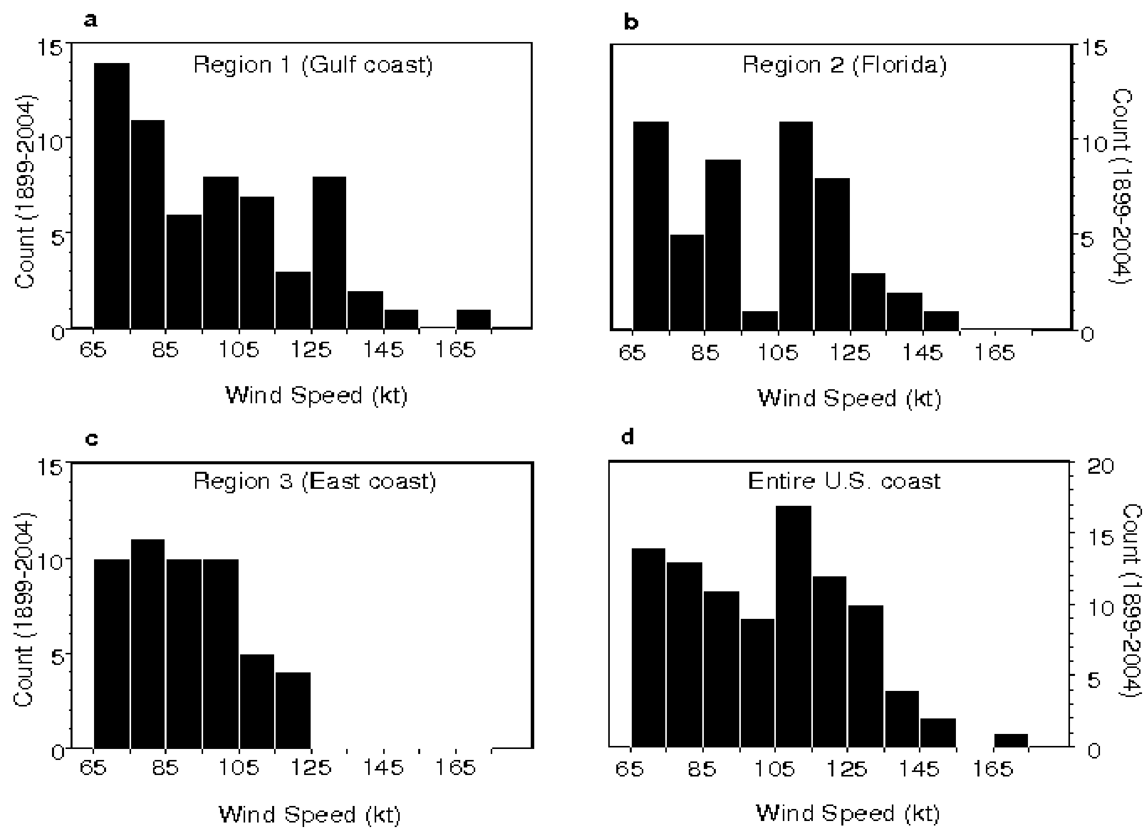


U.S. Landfalls, Cat 1-5

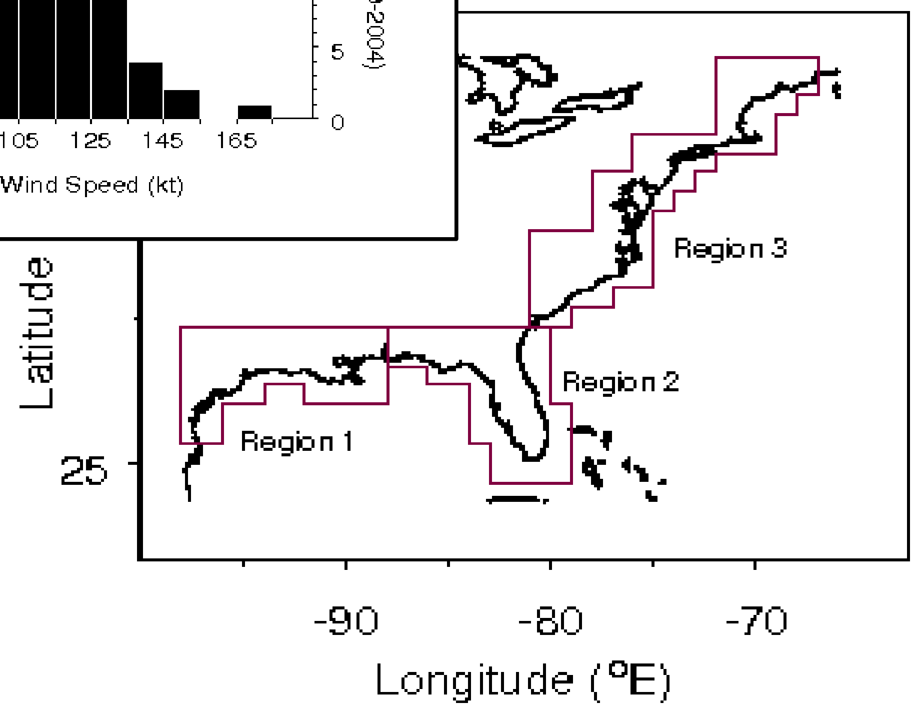


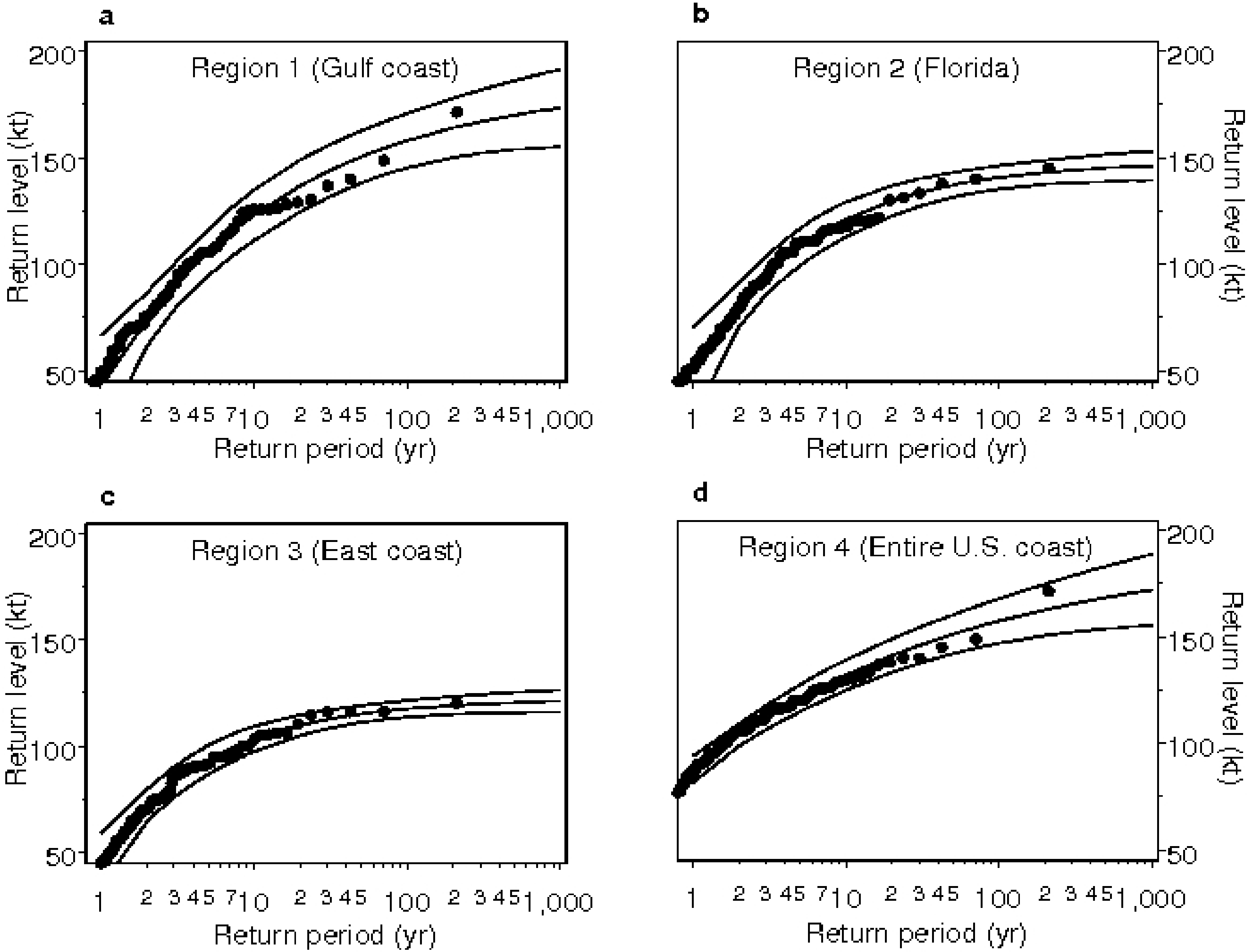
May-June values

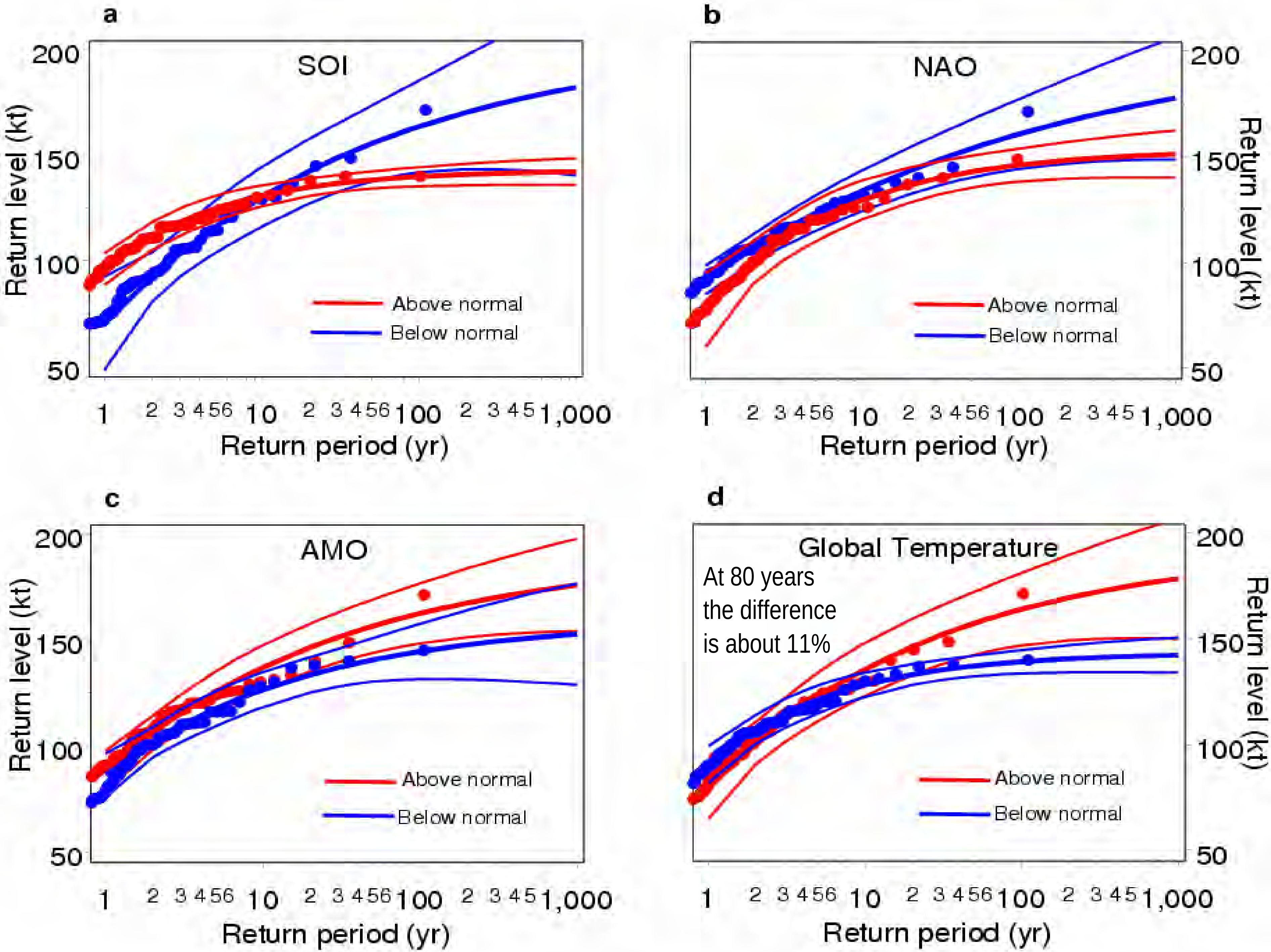




Too few strong storms to make meaningful empirical estimates of changes. But data models are useful.



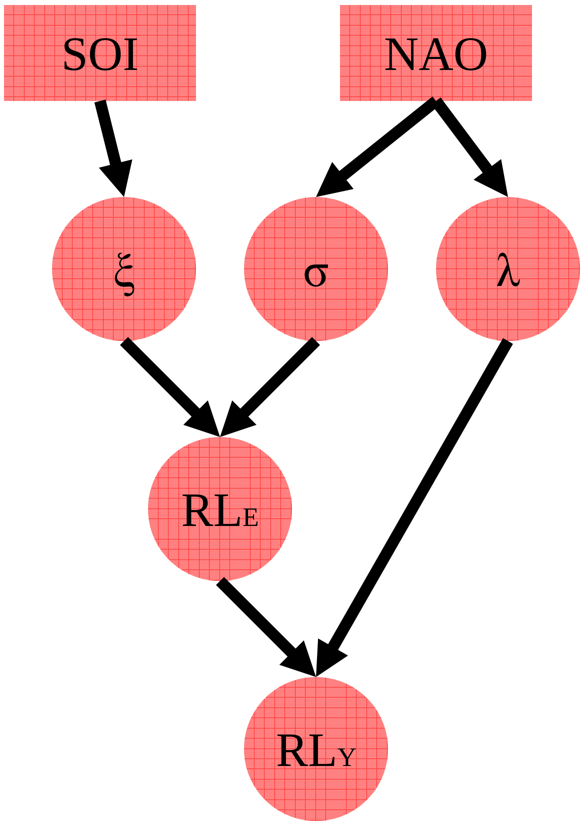

a
Region 1 (Gulf coast)
b
Region 2 (Florida)
c
Region 3 (East coast)
d
Region 4 (Entire U.S. coast)
Return level (kt)
Return period (yr)
50
100
150
200
1
2 3 45 7
10
100
1,000

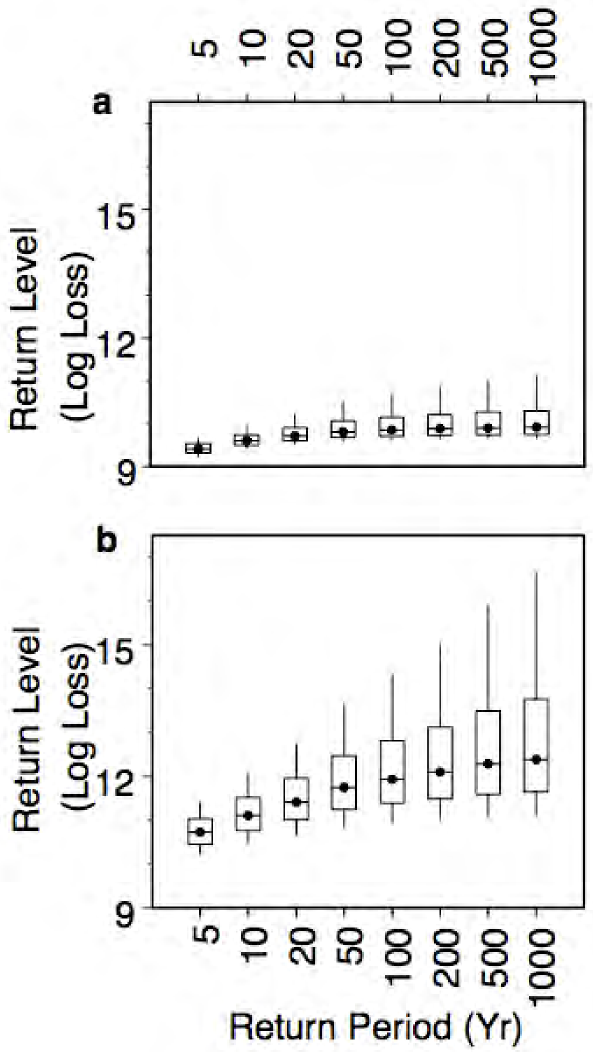


a
SOI
Return level (kt)
Return period (yr)
Above normal
Below normal
b
NAO
c
AMO
d
Global Temperature
At 80 years
the difference
is about 11%

Data Models for Insured Losses

Combining a model for frequency with a model for intensity and applying it to normalized insured loss data aggregated over the entire U.S. coast produces a model that can be used to predict the maximum possible loss before the season begins.





Summary

Evidence indicates that the North Atlantic basin is responding to climate change with stronger and perhaps more frequent hurricanes. No conclusive evidence exists elsewhere.

Continued ocean warming will likely lead to stronger hurricanes threatening the US. From year to year the warming effect will be minor relative to the NAO, ENSO, and SST fluctuations, but averaged over many years (>20), the warming effect will be significant.

Climate conditions before the season provide clues as to the nature of the season and to the probability of catastrophic losses. This year? Above normal NAO (Oct06-Jan07) indicated a lower probability of a catastrophic loss.

New research in the coming months and years will continue to shed light on some of the issues mentioned here. Advances in the field of paleotempestology. Incorporation of proxy and historical records into models of risk assessment. New, more flexible, risk assessment tools based on parametric and Bayesian statistics.

More Information

Google hurricane climate

http://garnet.fsu.edu/~jelsner/www

jelsner@fsu.edu

Hurricane Risk: Present and Future

Catastrophe Modeling Forum, New York, 16 October 2007

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1. Introduction

It has been understood for some time (e.g. Palmén, 1948) that tropical cyclones respond to climate change on a variety of time scales. Empirical studies (e.g. Gray, 1968) have established that tropical cyclone activity is sensitive to a variety of environmental conditions, including the magnitude of the shear of the horizontal wind through the depth of the troposphere, sea surface temperature, low level vorticity, and the humidity of the lower and middle troposphere. Theory has so far established only a bound on the maximum winds speed of tropical cyclones (Emanuel, 1987), though empirically, this bound has been shown to provide the relevant scaling for the actual peak wind speed of real storms (Emanuel, 2000). This bound, referred to as the “potential intensity”, is a function of the sea surface temperature and the profile of temperature through the troposphere and lower stratosphere (Bister and Emanuel, 2002); it is a far more physically-based quantity than sea surface temperature (SST).

While there has been some advance in the theory of tropical cyclone intensity, the question of frequency is more vexing. About 90 tropical cyclones develop each year around the globe, with a standard deviation of 10; at present, we lack a theory that predicts even the order of magnitude of this number. Although there has been little progress in developing a theory governing the rates of occurrence of tropical cyclones, a number of empirical indices have been developed, beginning with that of Gray (1979). Recently, the author and David Nolan (Emanuel and Nolan, 2004) incorporated potential intensity in an empirical index of the frequency of tropical cyclone genesis, called the Genesis Potential Index (*GPI*). This index was fitted to the annual cycle of genesis in each hemisphere, and to the spatial distributions of storms each month of the year, as described in some detail in Camargo et al. (2007), who also showed that the *GPI* captures some of the dependence of genesis rates on El Niño/Southern Oscillation (ENSO). The high power with which the potential intensity enters this empirical index suggest that it plays an important role in the frequency as well as intensity of tropical cyclones, but it must be stressed that a good theoretical understanding of the environmental control of storm frequency is lacking.

While theory is still deficient, there has been some progress in using climate models to simulate the effects of climate change on tropical cyclone activity, as reviewed in section 4. At present, global models are too coarse to resolve the inner cores of intense tropical cyclones, and their ability to simulate the full intensity of such storms is therefore seriously compromised. Yet this approach is beginning to yield interesting and possibly useful insights into the effect of climate change on storm activity.

In this essay, I will review evidence from the instrumental record of changing tropical cyclone activity, including a discussion of various problems with the tropical cyclone data itself, and also briefly review the budding new field of paleotempestology. Section 4 describes the debate over attribution. The fifth section presents some results of a new method of estimating hurricane risk for global gridded data, such as contained in the output of global climate simulations. A summary is provided in section 6.

2. Tropical cyclone variability in the instrumental record

Beginning shortly after WWII, aircraft have surveyed tropical cyclones in the North Atlantic and western North Pacific, though aircraft reconnaissance in the latter basin ended in 1987. During the 1960s, earth-orbiting satellites began to image some tropical cyclones, and by about 1970 it can be safely assumed that hardly any events were missed. Before the aircraft reconnaissance era, tropical cyclone counts depended on observations from ships, islands and coastal locations. Detection rates were reasonably high only in the North Atlantic, owing to dense shipping, but even here, the precise rate of detection remains controversial (Holland and Webster, 2007; Landsea, 2007). Estimates of the intensity of storms as measured, for example, by their maximum surface wind speeds, are dubious prior to about 1958, and some would say, prior to 1970 in the Atlantic and western North Pacific. Elsewhere, there are only very spotty estimates prior to the satellite era. Satellite-based estimates of intensity commenced in the 1970s and have improved along with the spatial resolution of satellite imagery, but the accuracy of such estimates is still debated. Intensity estimates based on aircraft measurements are prone to a variety of biases owing to changing instrumentation and means of inferring wind from central pressure, as described in the online supplement to Emanuel (2005)[1]. Some indication of the nature of these problems is evident in Figure 1, which shows a variety of estimates of tropical cyclone power dissipation in the western North Pacific since 1949. (The power dissipation is defined as the integral over the life of each storm of its maximum surface wind speed cubed, also accumulated over each year; see Emanuel, 2005. This should be thought of as a measure of the total amount of energy released by hurricanes over their lifetimes.)

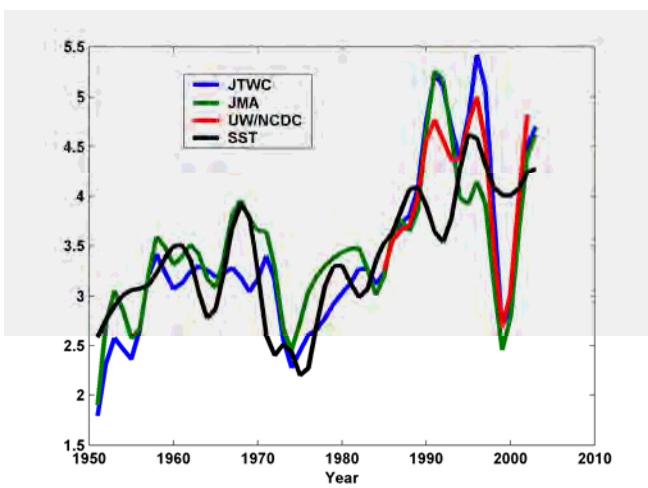

Figure 1. Power dissipation (colored curves) in the western North Pacific according to data from the U.S. Navy Joint Typhoon Warning Center as adjusted by Emanuel, 2005 (blue); unadjusted data from the Japanese Meteorological Agency (green), and re-analyzed satellite data from Kossin et al. (2007) (red). The black curve represents a scaled July-October sea surface temperature in the tropical western North Pacific region. All quantities have been smoothed using a 1-3-4-3-1 filter.

[1] The online supplement is available at ftp://texmex.mit.edu/pub/emanuel/PAPERS/NATURE03906_suppl.pdf

Note that the adjusted estimate from the Joint Typhoon Warning Center agrees well with the unadjusted estimate from the Japanese Meteorological Agency and that both are well correlated with sea surface temperature prior to the cessation of aircraft reconnaissance in 1987; after that time, there is much more divergence in the estimates and less correlation with SST. There is a general upward trend in SST and tropical cyclone power dissipation, but there are also prominent decadal fluctuations in both. The general upward trend in power dissipation was pointed out by the author (Emanuel, 2005) and is consistent with the finding by Webster et al. (2005) that the global incidence of intense tropical cyclones is generally trending upward.

In the North Atlantic, tropical cyclone records extend back to 1851, but are considered less reliable early in the period, and intensity estimates are increasingly dubious as one proceeds back in time from 1970. (A discussion of the sources or error may be found in the online supplement to Emanuel, 2005[3] and in Emanuel, 2007). A vigorous debate has ensued over the quality of the wind data (Emanuel 2005; Landsea, 2005; Landsea et al., 2006), and even the annual frequency of storms is open to question prior to 1970 (Holland, 2007; Holland and Webster, 2007; Landsea, 2007). Similar questions have been raised about the veracity and interpretation of the record of storms in the western North Pacific (Chan, 2006).

Here, on the premise that storms were more likely to be detected near the time of their maximum intensity, we define a “storm maximum power dissipation” as the product of the storm lifetime maximum wind speed cubed and its duration, summed over all the storms in a given year. Figure 2 compares this quantity to the sea surface temperature of the tropical Atlantic in July through October, going back to 1870. Except for the period 1939-1945, the correspondence between power dissipation and SST is remarkable, even early in the period. Since 1970, the r^2 between the two series is 0.86.

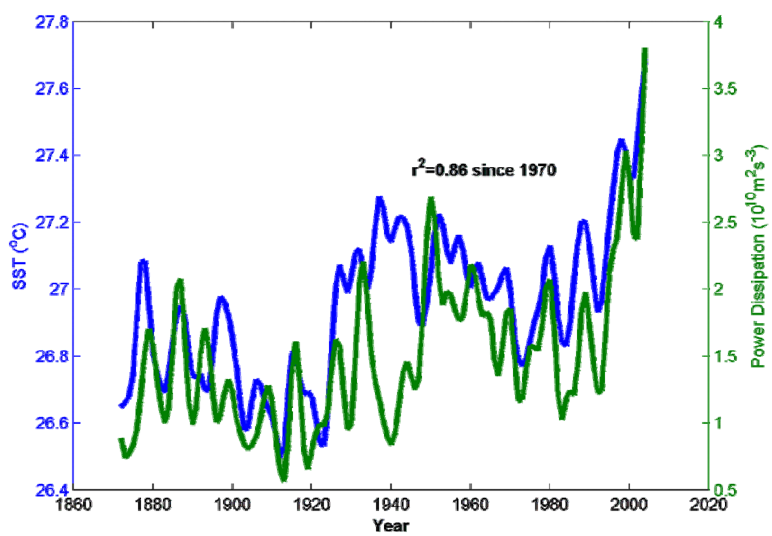

Figure 2. Storm lifetime maximum power dissipation in the North Atlantic according to data from the NOAA National Hurricane Center as adjusted by Emanuel, 2005 (green). The blue curve represents August-October sea surface temperature in the tropical North Atlantic, from 20-60 W and from 6 to 18 N. Both quantities have been smoothed using a 1-3-4-3-1 filter. The sea surface temperature is the HADSST1 data from the United Kingdom Meteorological Office Hadley Center.

The very low power dissipation during WWII may reflect a dearth of observations owing to enforced radio silence on ships during the war. In the Atlantic, variations in the power dissipation reflect variations in numbers of storms to a large degree (Emanuel 2007). While some have argued that the number of Atlantic storms may have been grossly underestimated prior to the aircraft and/or satellite eras (Landsea, 2007), statistical analyses of the likelihood of ships encountering storms suggest that the counts are good to 1 or 2 storms per year back to 1900 (Chang and Guo, 2007), and it is also possible to overestimate storm counts owing to multiple counting of the same event encountered infrequently. In addition, Holland and Webster (2007) point out that the large increases during the 1930s and 1990s both occurred during periods when measurement techniques were relatively stable; the advent of aircraft reconnaissance in the 1940s and the introduction of satellites during the 1960s were not accompanied by obvious increases in reported activity. Even with fairly liberal estimates of storm undercounts in the early part of the Atlantic record, the correlation with tropical Atlantic SST remains remarkably high (Mann et al., 2007).

3. Paleotempestology

A number of remarkable efforts are underway to extend tropical cyclone climatology into the geological past by analyzing paleo proxies for strong wind storms. One technique looks at storm surge-generated overwash deposits in near-shore marshes and ponds; this was pioneered by Liu and Fearn (1993) and has been followed up with analyses of such deposits in various places around the western rim of the North Atlantic (Liu and Fearn, 2000; Donnelly and co-authors, 2001; Donnelly and co-authors, 2001; Donnelly, 2005; Donnelly and Woodruff, 2007). Another technique makes use of dunes of sand, shells and other debris produced along beaches by storm surges (Nott and Hayne, 2001; Nott, 2003). Very recently, new techniques have been perfected that makes use of the anomalous oxygen isotope content of hurricane rainfall (Lawrence and Gedzelman, 1996) as recorded in tree rings (Miller et al., 2006) and speleothems (Frappier et al., 2007). Collectively, these methods are beginning to reveal variability of tropical cyclone activity on centennial to millennial time scales. For example, the recent work of Donnelly and Woodruff (2007), analyzing overwash deposits near Puerto Rico, reveals centennial variability of Atlantic tropical cyclones that is highly correlated with proxies recording long-term variability of ENSO; the same record shows a pronounced upswing over the last century that may reflect a global warming signal. The interested reader is directed to reviews by Nott (2004), Liu (2007), and Frappier et al. (2007).

4. Attribution

The North Atlantic is the only basin with a reasonably long time series of tropical cyclone records, and it is clear from Figure 2 that there is variability on a broad spectrum of time scales. Some of the shorter time scale variability is associated with El Niño/Southern Oscillation (ENSO), known to have a strong effect on Atlantic hurricanes (Gray, 1984). It is also clear from inspection of Figure 2 that both SST and tropical cyclone power have see-sawed up and down on a multi-decadal time scale over the past century or so in the Atlantic.

Mestas-Nuñez and Enfield (1999) detrended the time series of sea surface temperature and detected a “mode” of variability on time scales of many decades that has maximum amplitude in the North Atlantic; this was later identified as a prominent cause of both SST and Atlantic tropical cyclone variability on multi-decadal time scales (Goldenberg et al., 2001) and christened the “Atlantic Multi-Decadal Oscillation”, or “AMO” (Kerr, 2000). What began as a mathematical analysis ended up as a mode, even though there are only two troughs and one peak in the time series. It turns out that the time series of the amplitude of this “mode” is barely distinguishable from the detrended time series of August-October tropical North Atlantic SST. We can ask the somewhat more direct question: What caused the tropical North Atlantic SST (and hurricane power) to see-saw as it did during the 20th century, as evident in Figure 2?

Figure 3 provides one clue. This compares the 10-year running averages of the August-October SST of the so-called “Main Development Region” (MDR) of the tropical North Atlantic (between Africa and the eastern Caribbean) with the northern hemisphere mean surface temperature (including land). The excellent correspondence between the two time series would seem to imply that on decadal time scales, over the last 100 years or so, the tropical North Atlantic is simply co-varying with the rest of the northern hemisphere. Occam’s Razor would lead one to suspect that variations of the two series have a common cause, though it has been suggested that the North Atlantic might be forcing the rest of the hemisphere (Zhang et al., 2007).

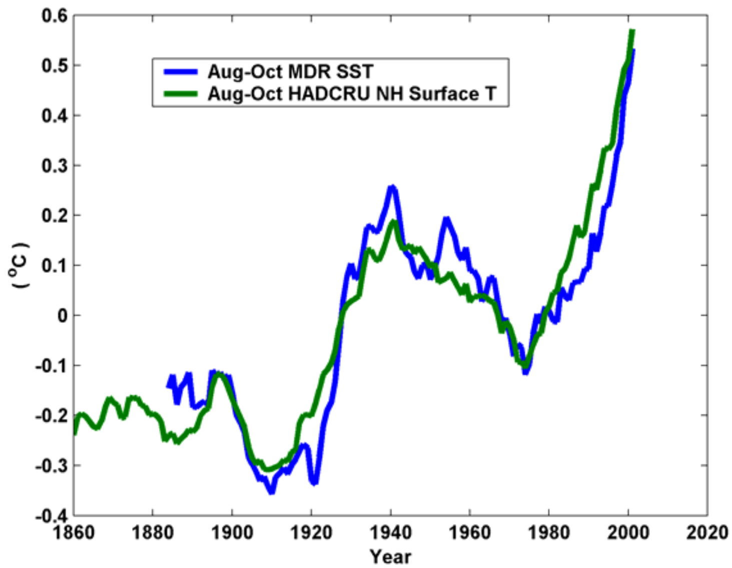

Figure 3. Ten-year running averages of the Atlantic Main Development Region (MDR) SST (blue) and the northern hemispheric surface temperature (green), both averaged over August-October. The long-term mean has been subtracted in both cases. The United Kingdom Meteorological Office Hadley Center supplies the SST data (HADSST1) and the northern hemispheric surface temperature (HADCRU).

The decadal variability in the northern hemispheric surface temperature has been addressed in a number of studies, as summarized in the most recent report of the Intergovernmental Panel on Climate Change (IPCC, 2007). In contrast to Mestas-Nuñez and Enfield (1999), Goldenberg et al. (2001) and others, the IPCC report attributes most of the decadal variability to time-varying radiative forcing associated principally with varying solar radiation, major volcanic eruptions, and anthropogenic sulfate aerosols and greenhouse gases. This also helps explain the overall trend, which was disregarded in the mathematical analyses. In particular, the warming of the last 30 years or so is attributed mostly to increasing greenhouse gas concentrations, while the cooling from around 1950 to around 1980 is ascribed, in part, to increasing concentrations of anthropogenic sulfate aerosols, a kind of air pollution that produces a haze that reflects sunlight back to space. Mann and Emanuel (2006) pointed out that the cooling of the northern hemisphere relative to the globe from about 1955 to 1980, evident in Figure 3, is most easily explained by the concentration of sulfate aerosols in the northern hemisphere. While there is still a great deal of uncertainty about the magnitude of the radiative forcing due to sulfate aerosols, the time series of sulfate concentration is strongly correlated with the difference between global and northern hemisphere surface temperature (Mann and Emanuel, 2006). The important influence of anthropogenic effects in the time history of SST is also emphasized in the work of Hoyos et al. (2006), Trenberth and Shea (2006), Santer et al. (2006), Elsner (2006) and Elsner et al. (2006). The author (Emanuel 2007) emphasizes that the thermodynamic control on tropical cyclone activity is exercised not through SST but through potential intensity, which in the North Atlantic has increased by 10% over the past 30 years. This increase, which is greater than predicted by simple climate models for the observed increase in SST, can be traced to increasing greenhouse gases, decreasing surface wind speed in the Tropics, and also to decreasing lower stratospheric temperature (Emanuel 2007).

Thus there are two school of thought about the decadal variability of tropical North Atlantic SST and tropical cyclone activity. The first holds that the multidecadal variability is mostly attributable to natural oscillations of the ocean-atmosphere system (Goldenberg et al., 2001), while the second attributes it to time-varying radiative forcing, some of which is natural. These two schools are not mutually exclusive, as the response to time-varying radiative forcing can be greatly modified by natural modes of the system.

5. Assessing present and future hurricane risk

Currently, there are three main approaches to assessing hurricane risk. The first, and most commonly used, is to make an assessment based on the statistics of historical storms. Jim Elsner has done excellent work on this technique and will describe this approach during the forum. A second technique is to manufacture large numbers of synthetic storms based whose main statistical attributes are also based on those of historical events (Casson and Coles, 2000; Vickery et al., 2000).

A third approach, which I will briefly describe here, derives hurricane climatologies directly from the large-scale climate of current analyses or global climate models and was developed by the author and his colleagues (Emanuel 2006; Emanuel et al., 2006); this has recently been extended to account for varying genesis rates (Emanuel et al., 2008). Using certain key statistics from the output of climate models, this technique synthesizes very large numbers (~10^4) of tropical cyclones using a 3-step process. In the first step, the climate state is "seeded" with a large number of candidate tropical cyclones, consisting of warm-core vortices whose maximum wind speed is only 12 m/s. These candidate storms then move according to a "beta-and-advection" model (Marks, 1992), which postulates that tropical cyclones move with a weighted vertical mean large-scale flow in which they are embedded, plus a correction owing to an effect due to the curvature of the earth; here the large-scale flow is taken as the climate model-simulated flow. Finally, in the third step, the storm's intensity evolution is simulated using a deterministic, coupled ocean-atmosphere tropical cyclone computer model which achieves very high spatial resolution in the critical central core region. In practice, most of the seeds die a natural death owing to small potential intensity, large wind shear, and/or low humidity in the middle troposphere. We show that the climatology of the survivors is in good accord with observed tropical cyclone climatology. For example, Figure 4 compares the simulated to observed rates of formation of tropical cyclone around the world.

The beauty of this technique is that it does not rely in any way on hurricane history, which is short and contains many flaws. Thus it can be applied not only to analyses of the present climate but to future climates as simulated by global climate models. We have also shown that it nicely captures the year-to-year variability of Atlantic hurricanes over the past 27 years (Figure 5), so that if a good seasonal forecast of the climate state can be made, we could make a pretty good seasonal forecast of hurricanes. As presented in Emanuel et al. (2008), we have applied the technique to estimate future hurricane activity using the output of global climate models under IPCC scenario A1b, in which atmospheric CO_2 concentrations continue to increase to 720 ppm by 2100, after which they are held constant. On the whole, this technique suggests increased hurricane risk in the Atlantic and western North Pacific regions, but decreased risk in the southern hemisphere.

6. Summary

Tropical cyclones respond to climate change in a number of ways. Their level of activity appears be controlled primarily by four factors: potential intensity, vertical shear of the horizontal environmental wind, low-level vorticity, and the humidity a few kilometers above the surface. Records of tropical cyclones are best and longest in the North Atlantic, are somewhat less reliable in the

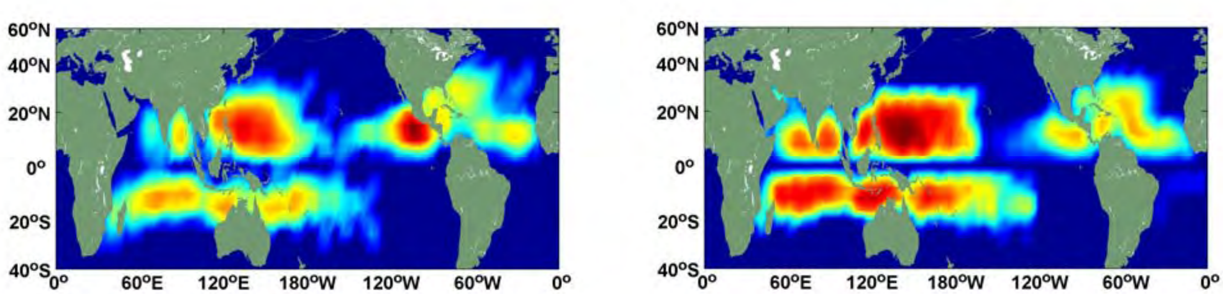

Figure 4. Observed (left) and simulated (right) annual frequencies of tropical cyclone development. The simulations use a random seeding technique in which very weak fledgling storms are randomly distributed and space and time, while a sophisticated computer model of hurricanes determines which develop and which die.

western North Pacific, and are dubious elsewhere, particularly before the satellite era. In the North Atlantic region, tropical cyclone power is highly correlated with tropical sea surface temperature during hurricane season, on time scales of a few years and longer. The tropical North Atlantic sea surface temperature is in turn highly correlated with northern hemisphere surface temperature, at least during hurricane season, on time scales of a decade and longer. The weight of available evidence suggests that multidecadal variability of hurricane season tropical Atlantic SST and northern hemispheric surface temperature, evident in Figure 3, is controlled mostly by time-varying radiative forcing owing to solar variability, major volcanic eruptions, and anthropogenic sulfate aerosols and greenhouse gases, though the response to this forcing may be modulated by natural modes of variability. The increase in potential intensity of about 10% in the North Atlantic over the last 30 years was driven by increasing greenhouse gas forcing, declining lower stratospheric temperature, and decreasing surface wind speed (Emanuel 2007); this increase is consistent with the ~60% increase in tropical cyclone power dissipation during this time. There is no persuasive evidence for the existence of “cycles” of Atlantic hurricane activity.

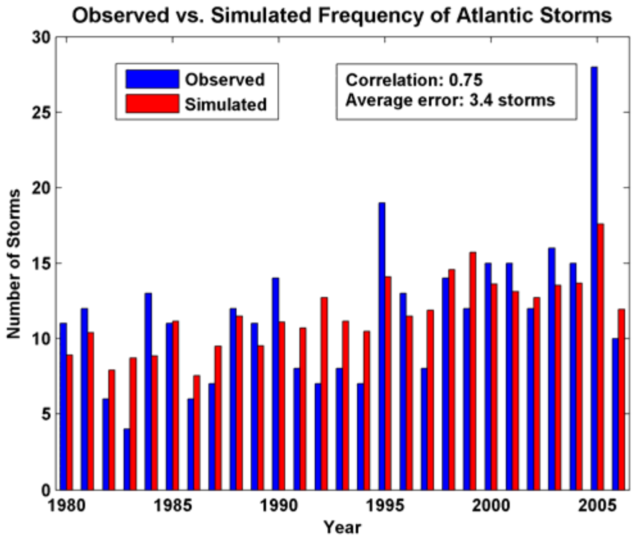

Figure 5. Observed (blue) versus simulated (red) annual number of tropical storms and hurricanes in the Atlantic, from 1980 through 2006. The correlation between the observed and simulated numbers is 0.75, while the average error is 3.4 storms.

The authors and his colleagues have developed a new technique for assessing hurricane risk around the world which does not rely in any way on the statistics of historical hurricanes, except as a means of evaluating how well the technique does. We are able to simulate the observed spatial, seasonal, and interannual variability of hurricanes in the present climate, and the technique is easily applied to future climates simulated by global climate models. This suggests that hurricane risk should increase, owing to global warming, in the Atlantic and western North Pacific, but decrease elsewhere. The technique is valuable for quantifying hurricane risk in the present climate, including differentiating between El Niño and La Niña years. It can easily produce tens of thousands of events in any area of interest. We are currently applying it to a variety of problems involving the assessment of hurricane risk around the world.

References

Bister, M. and K. A. Emanuel, 2002: Low frequency variability of tropical cyclone potential intensity, 1: Interannual to interdecadel variability. *J. Geophys. Res.*, **107** (4801), doi:10.1029/2001JD000776

Camargo, S. J., K. Emanuel and A. H. Sobel, 2007: Use of a genesis potential index to diagnose ENSO effects on tropical cyclone genesis. *J. Climate*, in press

Casson, E. and S. Coles, 2000: Simulation and extremal analysis of hurricane events. *Appl. Stat.*, **49**, 227-245

Chan, J. C. L., 2006: Comments on “Changes in tropical cyclone number, duration, and intensity in a warming environment". *Science*, **311**, 1713

Chang, E. K. M. and Y. Guo, 2007: Is the number of North Atlantic tropical cyclones significantly underestimated prior to the availability of satellite observations? *Geophys. Res. Lett* , , **34** (L14801), doi:10.1029/2007GL030169

Donnelly, J. P., 2005: Evidence of past intense tropical cyclones from backbarrier salt pond sediments: a case study from Isla de Culebrita, Puerto Rico, USA. *J. Coastal Res.*, **I42**, 201-210

Donnelly, J. P. and co-authors, 2001: 700 yr sedimentary record of intensehurricane landfalls in southern New England. *Geo. Soc Am. Bull.*, **113**, 714-727

______, 2001: Sedimentary evidence of intense hurricane strikes from New Jersey. *Geology*, **29**, 615-618

Donnelly, J. P. and J. D. Woodruff, 2007: Intense hurricane activity over the past 5,000 years controlled by El Niño and the West African monsoon. *Nature*, **447**, 465-468

Elsner, J. B., 2006: Evidence in support of the climate change-Atlantic hurricane hypothesis. *Geophys. Res. Lett.*, **33**, L16705, doi:10.1029/2006GL026869

Elsner, J. B., A. A. Tsonis and T. H. Jagger, 2006: High-frequency variability in hurricane power dissipation and its relationship to global temperature. *Bull. Amer. Meteor. Soc.*, **87**, 763-768

Emanuel , K., 2005: Meteorology: Emanuel replies. *Nature*, **438** (7071), E13

______, 2006: Climate and tropical cyclone activity: A new model downscaling approach. *J. Climate*, **19**, 4797-4802

______, 2007: Environmental factors affecting tropical cyclone power dissipation. *J. Climate*, In press

Emanuel, K. and D. Nolan, 2004: Tropical cyclone activity and global climate. 26th Conference on Hurricanes and Tropical Meteorology, Miami, Amer. Meteor. Soc.

Emanuel , K., R. Sundararajan and J. Williams, 2008: Hurricanes and global warming: Results from downscaling IPCC AR4 simulations. *Bull. Amer. Meteor. Soc.*, submitted

Emanuel, K. A., 1987: The dependence of hurricane intensity on climate. *Nature*, **326**, 483-485.

______, 2000: A statistical analysis of tropical cyclone intensity. *Mon. Wea. Rev.*, **128**, 1139-1152

______, 2005: Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, **436**, 686-688

Emanuel, K. A., S. Ravela, E. Vivant and C. Risi, 2006: A statistical-deterministic approach to hurricane risk assessment. *Bull. Amer. Meteor. Soc.*, **19**, 299-314

Frappier, A. B., T. R. Knutson, K.-B. Liu and K. Emanuel 2007: Perspective: coordinating paleoclimate research on tropical cyclones with hurricane-climate theory and modelling. *Tellus A*, **59**, 529-527

Frappier, A. B., D. Sahagian, S. J. Carpenter, L. A. González and B. R. Frappier, 2007: Stalagmite stable isotope record of recent tropical cyclone events. *Geology*, **35**, 111-114

Goldenberg, S. B., C. W. Landsea, A. M. Mestas-Nuñez and W. M. Gray, 2001: The recent increase in Atlantic hurricane activity: Causes and implications. *Science*, **293**, 474-479

Gray, W. M., 1968: Global view of the origin of tropical disturbances and storms. *Mon. Wea. Rev.*, **96**, 669-700

______, 1979: Hurricanes: Their formation, structure, and likely role in the tropical circulation. In *Meteorology over the tropical oceans*. D. B. Shaw, Roy. Meteor. Soc.**,** 155-218

______, 1984: Atlantic seasonal hurricane frequency. Part I: El Niño and 30 mb quasi-biennial oscillation influences. *Mon. Wea. Rev.*, **112**, 1649-1668

Holland, G. J., 2007: Misuse of landfall as a proxy for Atlantic tropical cyclone activity. *EOS*, In press

Holland, G. J. and P. J. Webster, 2007: Heightened tropical cyclone activity in the North Atlantic: Natural variability or climate trend? *Phil. Trans. Roy. Soc.*, doi:10.1098/rsta.2007.2083

Hoyos, C. D., P. A. Agudelo, P. J. Webster and J. A. Curry, 2006: Deconvolution of the factors contributing to the increase in global hurricane intensity. *Science*, **312**, 94-97

IPCC, 2007: IPCC WG1 AR4 Report. World Meteorological Organization, Geneva, pp.

Kerr, R. A., 2000: A North Atlantic climate pacemaker for the centuries. *Science*, **288**, 1984-1985

Landsea, C. W., 2005: Meteorology: Hurricanes and global warming. *Nature*, **438** (7071), E11-E12

______, 2007: Counting Atlantic tropical cyclones back to 1900. *EOS*, **88**, 197-200

Landsea, C. W., B. A. Harper, K. Hoarau and J. A. Knaff, 2006: Can we detect trends in extreme tropical cyclones? *Science*, **313**, 452-454

Lawrence, J. R. and S. D. Gedzelman, 1996: Low stable isotope ratios of tropical cyclone rains. *Geophys. Res. Lett.*, **23**, 527-530

Liu, K.-B., 2007: Paleotempestology. In *Encyclopedia of Quaternary Science*. S. Elias. Amsterdam, Elsevier**,** 1978-1986

Liu, K.-B. and M. L. Fearn, 1993: Lake-sediment record of late Holocene hurricane activities from coastal Alabama. *Geology*, **21**, 793-796

______, 2000: Reconstruction of prehistoric landfall frequencies of catastrophic hurricanes in northwestern Florida from lake sediment records. *Quat. Res.*, **54**, 238-245

Mann, M. E. and K. A. Emanuel, 2006: Atlantic hurricane trends linked to climate change. *EOS*, **87**, 233-244

Mann, M. E., K. A. Emanuel , G. J. Holland and P. J. Webster, 2007: Atlantic tropical cyclones revisited. *EOS*, **88**, 349-350

Marks, D. G., 1992: The beta and advection model for hurricane track forecasting. Natl. Meteor. Center, Camp Springs, Maryland, 89 pp.

Mestas-Nuñez, A. M. and D. B. Enfield, 1999: Rotated global modes of non-ENSO sea surface temperature variability. *J. Climate*, **12**, 2734-2746

Miller, D. L., C. I. Mora, H. D. Grissino-Mayer, C. J. Mock, M. E. Uhle and Z. Sharp, 2006: Tree-ring isotope records of tropical cyclone activity. *Proc. Natl. Acad. Sci.*, **103**, 14294-14297

Nott, J. F., 2003: Intensity of prehistoric tropical cyclones. *J. Geophys. Res.*, **108**, doi:10.1029/2002JD002726

______, 2004: Palaeotempestology: The study of prehistoric tropical cyclones – a review and implications for hazard assessment. *Environ Int.*, **30**, 433-447

Nott, J. F. and M. Hayne, 2001: High frequency of 'super-cyclones' along the Great Barrier Reef over the past 5,000 years. *Nature*, **413**, 508-512

Palmén, E., 1948: On the formation and structure of tropical hurricanes. *Geophysica*, **3**, 26-39

Santer, B. D. and co-authors, 2006: Forced and unforced ocean temperature changes in Atlantic and Pacific tropical cyclogenesis regions *Proc. Natl. Acad. Sci.*, **103**, 13905-13910

Trenberth, K. E. and D. J. Shea, 2006: Atlantic hurricanes and natural variability in 2005. *Geophys. Res. Lett.*, **33**, L12704, doi:10.1029/2006GL026894

Vickery, P. J., P. F. Skerjl and L. A. Twisdale, 2000: Simulation of hurricane risk in the U. S. using empirical track model. *J. Struct. Eng.*, **126**, 1222-1237

Webster, P. J., G. J. Holland, J. A. Curry and H.-R. Chang, 2005: Changes in tropical cyclone number, duration and intensity in a warming environment. *Science*, **309**, 1844-1846

Zhang, R., T. L. Delworth and I. M. Held, 2007: Can the Atlantic Ocean drive the observed multidecadal variability in Northern Hemisphere mean temperature? *Geophys. Res. Lett* , , **34** (L02709), doi:10.1029/2006GL028683

Catastrophe Modeling in an Environment of Climate Change

By Dr. Jayanta Guin, Senior Vice President, AIR Worldwide Corporation

Introduction

The Earth's climate is changing. Indeed the consensus today among most scientists is that "...warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level."[1] While there is uncertainty in the magnitude and rate at which warming will occur and debate over its precise causes, it is clear that the consequences of a warmer climate will have profound societal impacts worldwide.

Since the advent of catastrophe modeling, which is used to support risk management decision-making in general and insurance and reinsurance pricing in particular, the focus has been on assessing risk at the current or near term. Modelers do this by leveraging the long-term historical record to perform tens of thousands of simulations of what may occur this or next year. Things become more complicated, however, if the current risk environment is distinctly different from what it has been historically.

In assessing the risk from weather-related phenomena, such as tropical and extratropical cyclones, severe thunderstorms, and floods, it is critically important to develop an understanding of the impact of a warmed climate on these natural hazards. Catastrophe models incorporate the frequency and severity characteristics of the modeled peril as of today's climate regime. Therefore, basic questions for the modeler to answer are: (1) does the historical record of the peril—the most dependable portion of which is usually 50 to 150 years long—have a signature that is clearly distinguishable from what we are experiencing today, and; (2) how is the signature going to change in the future if the earth continues to warm?

Thus the nature of the peril must be understood on two time scales: the near term, or what is the influence of climate change today; and the long term, or what will be the nature of the peril fifty or a hundred years from now. This is obviously a nontrivial task. One of the many major challenges for the catastrophe modeler in deciphering the puzzle is how to interpret the historical data, which may be contaminated by underreporting, population biases and changes in the technology used in recording measurements.

The clear separation of time scales is important because it has profound implications for the practical application of catastrophe modeling results, the conclusions drawn and appropriate mitigation strategies to adopt. Should a homeowner's insurance premium reflect current hurricane risk in the Atlantic or what the risk will be in 2050? Few would

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[1] Intergovernmental Panel on Climate Change. The complete IPCC Summary for Policymakers released in 2007 is available at http://www.ipcc.ch/.

suggest the latter. Making matters more complex, for each of the two time scales we need to understand not only the influence of climate on an individual peril, but also its impact on the correlation between perils.

From a global insurance loss perspective, the most important perils are tropical cyclones in the Atlantic and Northwest Pacific, extratropical cyclones over Europe, floods and severe thunderstorms. Questions like “Is severe thunderstorm activity over the US correlated with Atlantic hurricanes?” and “Are European extratropical cyclones correlated with Atlantic hurricanes?” become quite relevant to the discussion. Although some recent studies suggest some degree of correlation between these perils, the limitations of the historical data and the current state of science make it difficult to incorporate these correlations. The Earth’s atmosphere and oceans make up a very complex, dynamic environmental system, with several known teleconnections[2], and it would be reasonable to assume that a warmer future is likely to alter existing climate relationships and correlations. Continued research into these correlations as they exist today and how they may change going forward will be critical to understanding the nature of the risk.

Influence of climate on Atlantic hurricanes

In recent years, the influence of climate change on Atlantic hurricanes has received a lot of attention in the scientific community. Following the very active 2004 and 2005 hurricane seasons, the topic became the focus of attention of the insurance industry and, indeed, of the population at large.

So what do we currently know with a high degree of certainty? We know that:

1. Basinwide tropical cyclone activity in the Atlantic has been higher than the long-term climatological average since 1995.
2. There are problems with the historical data in terms of completeness and technological changes. (The data challenges are perhaps more severe in other ocean basins and are most apparent in the early part of the 20th century.)
3. Certain climate factors influence tropical cyclone activity from both a meteorological and physical point of view, among them sea surface temperatures (SSTs), El Niño Southern Oscillation, North Atlantic Oscillation and the Saharan Air Layer.
4. Predictive models on a seasonal scale have been around for about twenty years, and although the forecasts have improved over the years, uncertainty in the forecasts remains quite high.

Since 1995, tropical cyclone activity in the Atlantic basin has been elevated over the long-term average. Scientists at the National Oceanic and Atmospheric Administration

[2] A *teleconnection* is a known relationship between two distinct climate mechanisms supported by the historical record and a physical understanding of the environment. For example, the ENSO cycle (more commonly known as the El Niño / La Niña cycle) which is a periodic warming and cooling of the Pacific Ocean has been shown to influence wind shear in the Atlantic, and can therefore modulate tropical activity well away from the origin of the ENSO signal.

(NOAA) have linked this above-average activity to elevated sea surface temperatures (SSTs) which, they say, are in turn linked to the positive (warm) phase of the Atlantic Multidecadal Oscillation (AMO) (Goldenberg et al 2001), a naturally occurring cycle that oscillates over periods of decades.

In fact, a number of climate signals other than elevated SSTs affect hurricane activity and storm track, and these may dominate and even counter their impact. In 2006, for example, the onset of El Niño conditions produced increased wind shear in the Atlantic, which had a mitigating effect on hurricane activity despite the presence of anomalously warm Atlantic sea surface temperatures.

There are other complexities. For example, scientists also credited the Saharan Air Layer (SAL) for the low rate of storm formation in 2006. Storms over Africa's Sahara Desert can carry significant amounts of dry, dusty air westward over the Atlantic Ocean, depriving incipient tropical cyclones the moisture and heat they need to develop.

Nevertheless, the consensus at NOAA is that the current warm phase is likely to continue "for years to come." Therefore, it might seem reasonable to assume that hurricane losses along the US. Gulf and East Coasts will be similarly elevated and that catastrophe models should adjust accordingly. However, significant caveats apply to this argument. In 2000, 2001 and 2006—all years in which SSTs have been warmer than the long term average—no hurricanes made landfall in the US. In two other years—1997 and 2002 (and thus far in 2007)—only one tropical cyclone made landfall as a hurricane, which is below the long term average.

The primary focus to date of scientific investigation into climatological influences on tropical cyclones has been on basinwide activity. Making the leap from increased hurricane activity in the Atlantic to increased landfall activity and, ultimately, to the effect on insured losses requires significant additional research. The correlation between landfalling hurricane numbers and SST is very weak and models that do not recognize this fact are likely to understate the uncertainty in their risk estimates.

Sources of uncertainty

Although there has been a substantial body of recent research in projecting the impact of a warmer climate on tropical cyclone frequency and intensity, there is as yet no clear consensus. In its latest report the IPCC states:

> Based on a range of models, it is *likely* that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and more heavy precipitation associated with ongoing increases of tropical SSTs. There is less confidence in projections of a global decrease in numbers of tropical cyclones.

However, a careful evaluation of the competing theories highlights the uncertainty in that conclusion. The uncertainty arises from broadly two sources: the assumptions required in dynamical climate models and the quality of the historical Atlantic hurricane data.

Studies based on the output from dynamical climate models have concluded that the *frequency* of tropical cyclones will likely remain constant (Knutson 2004) or even decrease as a result of increasing wind shear in the main development region of the Atlantic (Vecchi and Soden 2007), while some of the same models also predict an increase in the *intensity* of Atlantic hurricanes later in the century (Knutson 2004). Increases in vertical wind shear combined with a warming ocean are competing factors for tropical cyclone development, and their interaction is not fully understood, especially under conditions of a future climate regime.

Several studies based on analysis of historical hurricane data in the Atlantic have concluded that hurricanes are likely to be more intense in the future. Emanuel (2005) demonstrates a strong correlation in the destructive power of hurricanes with Atlantic sea surface temperatures. However other scientists (Landsea 2006 and 2007) argue this conclusion is at least partly an artifact of shortcomings in the widely accepted HURDAT database. As discussed above, there are questions on the completeness of HURDAT (Figure 1) and the accuracy of the intensity measurements of the earlier storms.

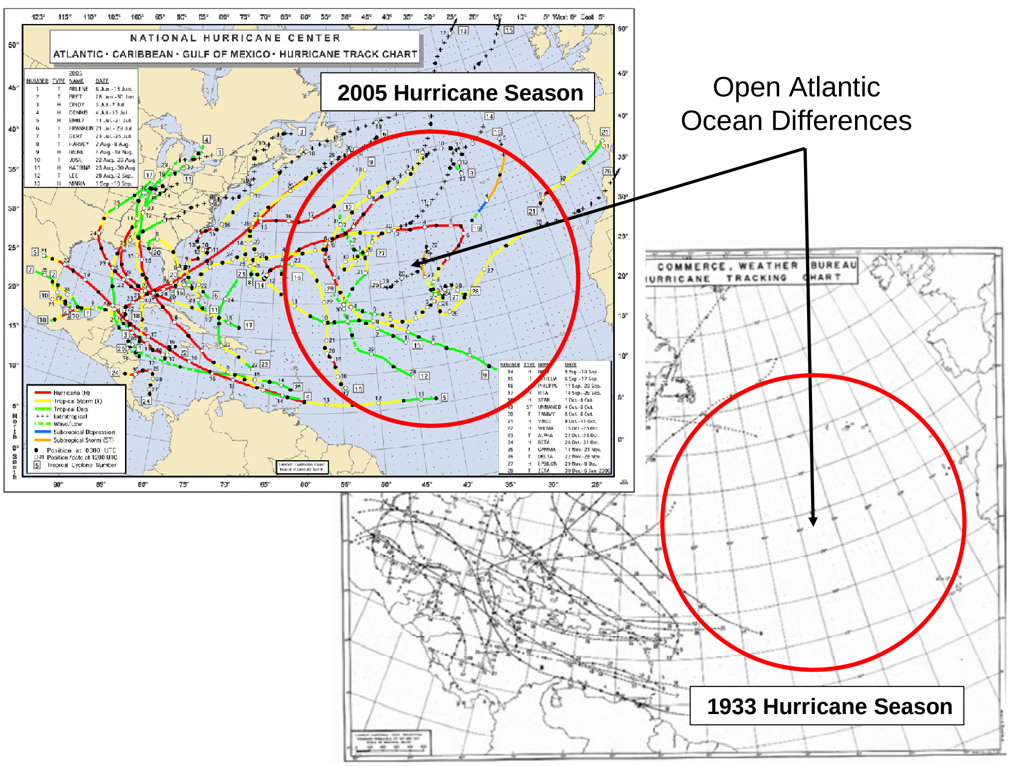


Figure 1. Apparent stark differences in tropical cyclone frequency in the open Atlantic between the first and second half of the century suggest the possibility of underreporting (Landsea, 2007)

In addition, the primary driver (or "forcing") upon which theories regarding climate change are based revolve around the release of greenhouse gases. Most of the release, in the form of carbon dioxide emissions, has occurred over the last few decades—a timeframe that makes it exceedingly difficult to quantify the impacts even if the data is relatively accurate.

What does the historical data tell us?

Since climate change is expected to alter the frequency of storms in the Atlantic basin, as well as the number of hurricanes that impact the US, it is useful to examine the historical record and look for trends in hurricane frequency that may already have appeared. The period since 1900 is sufficiently long to include past decadal fluctuations in hurricane activity, shorter El Niños and La Niñas, and a range of other climate signals of varying duration, all of which can provide insight on how climate signals, in general, and SSTs, in particular, affect tropical cyclone activity in the Atlantic.

Activity in the Atlantic

Tropical cyclone frequency data in the Atlantic basin over the period 1900-2006 shows a clear upward trend. A linear trend line fitted to this data set has a positive upward slope with a slope coefficient that differs significantly from zero. This would suggest an increase in Atlantic storm frequency during this period. However, some scientists (Landsea 2007) believe that Atlantic basin data prior to the advent of aircraft reconnaissance and satellites is likely missing some basin storms, since without direct or remote sensing many are likely to have gone undetected. Such limitations on the historical data make it difficult to reach firm conclusions about trends in Atlantic storm frequency.

Activity along the US Coast

The number of hurricanes and major hurricanes (SS category 3 and greater) that make landfall in the US over the period 1900-2006 are shown in Figure 3. The data shows no clear trend and a linear trend line fitted to this data set has a slope coefficient which is very small and close to zero, signaling no increase in the landfall frequency during this period. Furthermore, historical data on landfall frequency is likely to be much more robust than basinwide data.

Another way to examine the presence of a trend is to compute moving averages of the landfall frequency over periods of several years. In addition to revealing trends in the hurricane frequency, these moving averages will help answer questions such as (1) How does the landfall frequency during the current warm period that started in 1995 compare to the landfall frequency that has been observed during periods of similar lengths in the past, and (2) How does landfall frequency observed since 1970, when a global warming trend may have emerged, compare to the frequency observed earlier in the century for periods of similar length. In other words, is there anything unusual about landfall frequency during the current active period that started in 1995 or the frequency during the last 35 year period when the global warming effect may have set in? The 12-year and 35-year moving averages shown in Figure 2 (all landfalling hurricanes) and Figure 3 landfalling major hurricanes) clearly demonstrate a lack of trend in the two data series. Moreover, the frequency of hurricanes and major hurricanes during the last 12-year or 35-year periods, although high, are not unusual compared to the hurricane frequency during periods of similar lengths in the past.

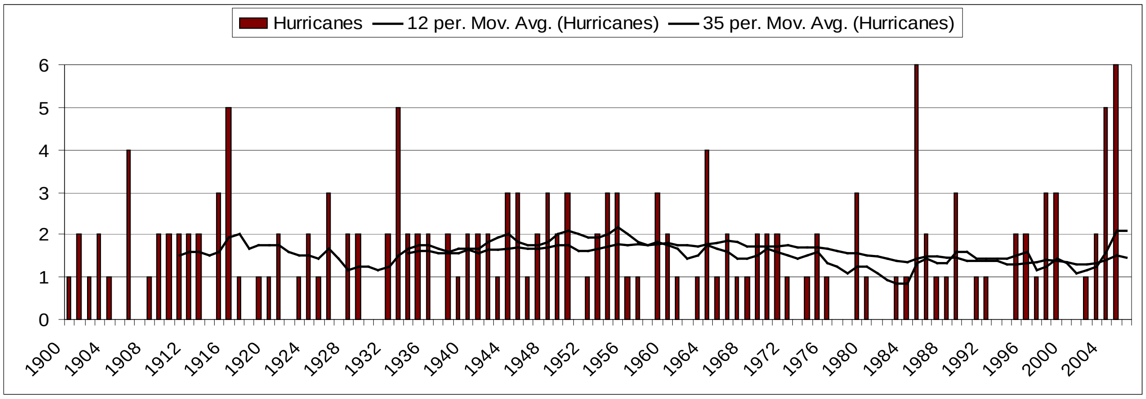


Figure 2. Annual Frequency of Landfalling Hurricanes in the US

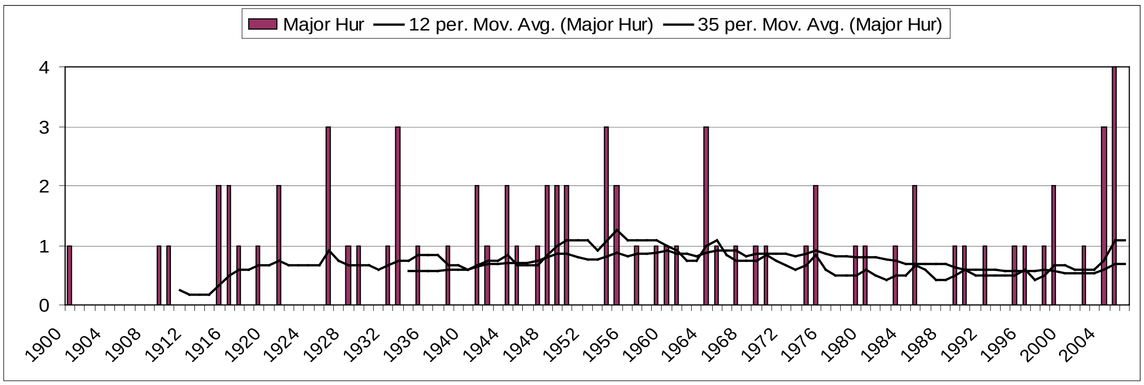


Figure 3. Annual Frequency of Landfalling Major (≥Cat 3) Hurricanes in the US

Given that the Atlantic storm frequency shows a clear up-ward trend while the trend is not present in the US landfall frequency, there are two possible arguments that could be made. If the relationship between basin activity and landfalling activity has not changed in the past century, then reverse inference would support the idea of an incomplete dataset in the Atlantic, especially in the early part of the last century.

On the other hand, if one assumes that the Atlantic dataset is fairly complete and the underreporting is not severe, then it implies that some physical mechanisms that underlie the relationship between basin activity and landfalling activity have changed over the course of the last century. Theories that could possibly explain this change include an eastward shift in the genesis locations of storms, thereby increasing the probability that storms will recurve in the open Atlantic, or changes in the circulation patterns that steer storms across the Atlantic. These are areas that require further research.

AIR's approach to addressing the current (warmed) climate in the face of uncertainty

Over the course of the last two years, AIR scientists have undertaken extensive analyses of the link between elevated SSTs in the Atlantic and regional landfall frequency. The research has also included a critical evaluation of the historical data and its quality.

As a result of this research, AIR released a near-term catalog of stochastic storms in 2006 and an updated version in 2007 (AIR 2007, Dailey et al 2007). The approach used to develop the near-term catalog— which represents potentially increased hurricane risk over the next several years— explicitly quantifies the uncertainty in the estimates of near-term risk. AIR has provided the near-term catalog to clients as a supplement to, rather than a replacement for, the standard catalog, which is based on more than 100 years of historical data and 20 years of research.

AIR's updated near-term catalog is conditioned not on point forecasts of SSTs, which are highly uncertain, but rather on scientists' projections that sea-surface temperatures are likely to remain elevated for the next several years. There is more certainty in stating that SSTs will be warmer than average over the next several years than in stating they will be warmer by a specific number of degrees. One advantage of this approach is that the inclusion of one additional season of hurricane landfall experience will not significantly change estimates of near-term risk, lending stability to model results and, at least in theory, insurance pricing.

AIR is committed to bringing not only advanced science, but also robust and reliable models to market. In doing so, the meteorologists and climate scientists at AIR have resisted the temptation to push the state of the science beyond the implicit limitations of the data that supports it. The AIR US hurricane model provides two credible views of potential hurricane activity and by doing so captures, in essence, model uncertainty. By providing two credible estimates of the hurricane risk today, AIR is providing clients with more information and an expanded toolset to aid risk management decisions. The underlying uncertainty in developing a near-term view is clearly borne out by the lack of landfalling hurricanes in the US in 2006 and thus far in 2007.

The Importance of Time Scale

The most dire scenarios of climate change are those projected well into the future (> 50 years). Policymakers and society as a whole must begin to grapple with the implications and develop effective mitigation strategies based on sound science.

In order to attempt to assess some of the implications for the insurance industry, the Association of British Insurers (ABI 2005) commissioned a study in which the financial risks under certain future (year 2080) climate scenarios defined by ABI were quantified. AIR was provided with a range of scenarios for increases in intensity of tropical cyclones in the Atlantic and the Northwest Pacific, and changes in frequency of the extreme extratropical cyclones impacting western Europe.

Using the probabilistic loss estimation models AIR has developed, the impact on losses to the insured industry were quantified as shown in the tables below. The study did serve to highlight the highly nonlinear relationship between damage to property and wind speed. Consider the median scenario of 6% increase in wind speed for tropical cyclones in the

Atlantic by year 2080 which results in an increase of about 70% in financial risk at the 1% annual exceedance probability (EP) level (100 year return period).

Scenario	Increase in windspeed	Annual average insured loss	Insured loss with chance of occurring once every 100 years	Insured loss with chance of occurring once every 250 years
Lower-bound sensitivity analysis	4%	+2.5	+27	+42
Potential impact of climate change[a]	6%	+4.0	+41 (+ Δ70%)	+62 (+ Δ75%)
Upper-bound sensitivity analysis	9%	+6.5	+68	+98

Figure 4. Results of sensitivity testing of impact of increased US hurricane intensity as performed for ABI by AIR. ABI assumed a 6% increase in wind speeds, resulting in a 70-75% increase in insured loses (Incremental losses in bn USD).

Scenario	Increase in windspeed	Annual average insured loss	Insured loss with chance of occurring once every 100 years	Insured loss with chance of occurring once every 250 years
Lower-bound sensitivity analysis	4%	+1.0	+7	+9
Potential impact of climate change[a]	6%	+1.5	+10 (+ Δ67%)	+14 (+ Δ70%)
Upper-bound sensitivity analysis	9%	+2.5	+17	+25

Figure 5. Results of sensitivity testing of impact of increased Japan typhoon intensity as performed for ABI by AIR. ABI assumed a 6% increase in wind speeds, resulting in a 67-70% increase in insured loses (Incremental losses in bn USD).

Scenario	Frequency increase in top 5% of storms	Annual average insured loss	Insured loss with chance of occurring once every 100 years	Insured loss with chance of occurring once every 250 years
Potential impact of climate change[a]	20%	+0.5	+2.0 (+ Δ5%)	+2.5 (+ Δ5%)

a. The impact of climate change on the majority of less intense storms was not modelled, because quantitative information about the changes is still limited.

Figure 6. Results of sensitivity testing of impact of increased European extratropical cyclone frequency as performed for ABI by AIR. ABI assumed a 20% increase in frequency of the most severe storms, resulting in a 5% increase in insured loses (Incremental losses in bn USD).

Just how useful are such studies? For most businesses, planning cycles revolve around a much shorter time frame (< 10 years), so in any discussion of the impact of climate change, it is essential that the time horizon be made explicit. Furthermore, for insurers it is equally important to consider other factors that are driving their risk profiles, again in order to put the issue of climate change in the appropriate perspective.

Consider again the ABI study. Let's assume that the future climate scenario of a 6% increase in hurricane wind speeds is realistic, there are no other feedback loops that alter hurricane climatology and the modeling of its impact on insured loss is accurate as well. If we further assume the increased financial loss (70% at 1% EP, Figure 4) follows a process that has a constant annual rate of increase, it is equivalent to roughly 0.7% increase in insured losses each year. How does an 0.7% annual increase compare with other risk factors?

There are two, less uncertain risk drivers that the insurance industry is currently facing. The most important is the increase in the number and value of insured properties in areas of high hazard. AIR estimates that, currently, 38% of the total exposure in Gulf and East Coast states is located in coastal counties, which accounts for 16% of the total value of properties in the US (Figure 7). Further, AIR estimates that the value of properties in coastal areas of the United States has roughly doubled over the last decade and there is, as yet, no sign that the rate of growth is slowing. That translates directly to a doubling every ten years (~7.0% annual rate) in insured losses *exclusive of any effect of climate change*.

State	Coastal ($B)	Total ($B)	Percent Coastal
Alabama	75.9	631.3	12%
Connecticut	404.9	641.3	63%
Delaware	46.4	140.1	33%
Florida	1,937.4	2,443.5	79%
Georgia	73.0	1,235.7	6%
Louisiana	209.3	551.7	38%
Maine	117.2	202.4	58%
Maryland	12.1	853.6	1%
Massachusetts	662.4	1,223.0	54%
Mississippi	44.7	331.4	13%
New Hampshire	45.6	196.0	23%
New Jersey	505.8	1,504.8	34%
New York	1,901.6	3,123.6	61%
North Carolina	105.3	1,189.3	9%
Rhode Island	43.8	156.6	28%
S. Carolina	148.8	581.2	26%
Texas	740.0	2,895.3	26%
Virginia	129.7	1,140.2	11%
All Above States	7,203.7	19,041.1	38%
All Above States as % of Total U.S.	7,203.7	43,665.6	16%

Figure 7. AIR estimates that fully 38% of the total property value in Gulf and East Coast states is located in coastal counties, which accounts for 16% of the total value of properties in the U.S.

The second risk driver is the quality and granularity of data that insurers capture about the properties they insure, including accurate replacement values and other construction characteristics. In 2005 analysis of client data performed in 2005, AIR found significant and widespread undervaluation of the properties in insurers' portfolios. A property's replacement value is the full cost to replace the building in the event of a total loss. Since catastrophe models estimate loss by applying vulnerability functions to the replacement value before applying insurance policy terms and conditions, accurate replacement values are essential for obtaining accurate catastrophe loss estimates. If a property's replacement value is understated by 25 percent, for example, the estimated ground up loss will be understated by that much. Which means that companies will be managing to a much lower level of risk than their true risk.

The inaccuracy in loss estimates as a result of poor data quality is at least, if not more, than 0.7%. This is not to say that an 0.7% increase in risk as a result of a warming climate should be ignored, but rather to underscore the importance of addressing issues that are less uncertain and *more manageable*.

Conclusion

We are at a critical juncture in the field of risk modeling given that it is almost certain that the Earth's climate is warming. All stakeholders in the risk transfer chain need to be aware of the consequences of climate change. But at the same time we need to be objective in our analysis and recognize the uncertainties associated with current risk projections.

While the larger scientific community is advancing the state of knowledge on the impact of climate change, the catastrophe modeler needs to incorporate clearly established findings into the models to reflect risk in the *current* climate regime. AIR will continue to integrate advanced physics-based models with data-driven statistical models to develop unbiased estimates of risk.

Should new modeling approaches and science support the existence of a trend in the intensity or frequency of atmospheric perils that impact the built environment, then the catastrophe modeler can confidently incorporate this trend. However, it is important to point out that such an approach would have to be approached holistically, by accounting for mitigative factors, such as advances in the wind resistivity of structures and the enforcement of improved building codes.

Perhaps most importantly, the explicit quantification of the uncertainty in risk estimates will be critical to informed and effective risk-management decisions.

Acknowledgements

The author would like to thank Dr. Peter Dailey, Dr. Greta Ljung and Beverly Porter for their contributions to this paper.

References

2007 IPCC Summary for Policymakers (http://www.ipcc.ch/). The full report is expected to be released later this year.

AIR Worldwide, 2005: "The Coastline at Risk," (http://www.air-worldwide.com/_public/NewsData/000797/The_Coastline_at_Risk-AIR_Worldwide.pdf), AIR white paper.

AIR Worldwide, 2005: Exposure Data Quality, (http://www.air-worldwide.com/_public/NewsData/000829/AIR_Data_Quality.pdf), AIR white paper.

AIR Worldwide, 2007: "Near-term Hurricane Risk in the US: The 2007 Update to the AIR New-term US Hurricane Risk," AIR white paper.

Dailey, P., Ljung, G, Zuba, G, and Guin, J, 2007,"On the Relationship between North Atlantic Sea Surface Temperatures and U.S. Hurricane Landfall Risk", submitted to the *Journal of Applied Meteorology and Climatology*.

Emanuel, K., 2005: Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, 436, 686-688. doi: 10.1038/nature03906.

Goldenberg, S.B., C.W. Landsea, A.M. Mestas-Nuñez, and W.M. Gray, 2001: The recent increase in Atlantic hurricane activity. Causes and implications. *Science*, 293, 474-479.

Knutson, T. K., and R. E. Tuleya, 2004: Impact of CO2-induced warming on simulated hurricane intensity and precipitation: Sensitivity to the choice of climate model and convective parameterization. *Journal of Climate*, 17(18), 3477-3495.

Landsea,C.W., B.A.Harper, K.Hoarau, and J.A.Knaff, 2006: Can we detect trends in extreme tropical cyclones? *Science*, 313, 452-454.

Landsea,C.W., 2007: Counting Atlantic tropical cyclones back to 1900. Eos 88, 197-202

ABI, 2005 “Financial Risks of Climate Change,” Association of British Insurers (ABI) Summary Report

Vecchi G. and J Soden, 2007. “Increased tropical Atlantic wind shear in model projections of global warming,” *Geophysical Research Letters*, Vol 34, 2007.

Catastrophe Modeling in an Environment of Climate Change





Jayanta Guin, Ph.D.

BETTER TECHNOLOGY
BETTER DATA
BETTER DECISIONS

AIR

CATASTROPHE MODELING FORUM

Changing Climatic Dynamics and Catastrophe Model Projections

Tuesday – Wednesday, October 16-17, 2007
New York City

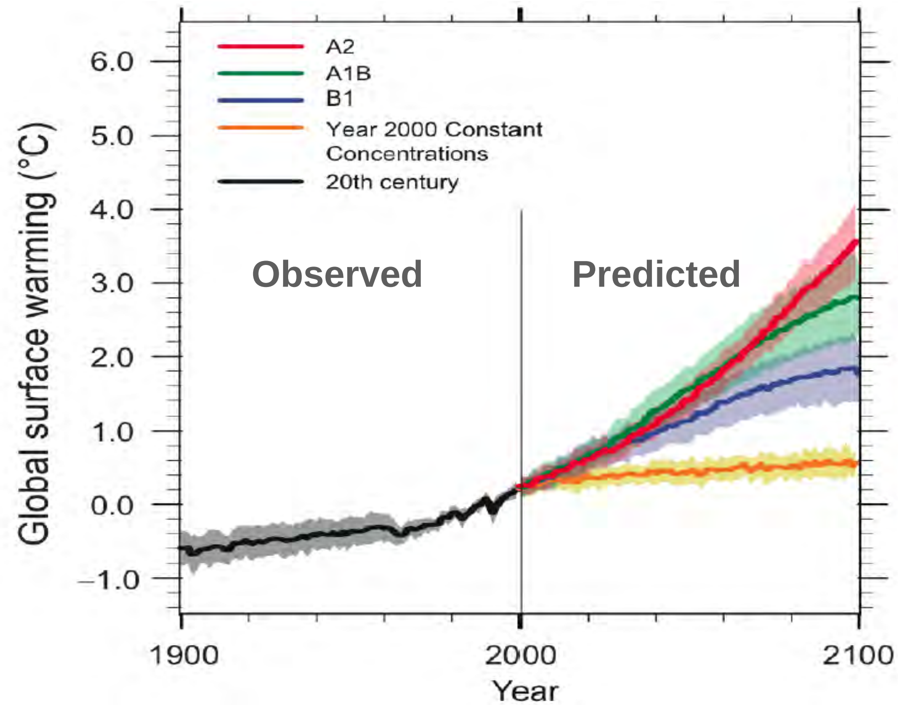
www.air-worldwide.com

Discussion Agenda

- Implications of climate change for catastrophe modeling
- What do we know about Atlantic hurricane activity
- Short-term climate fluctuations in Atlantic hurricane activity
- Quantifying financial impact of future climate scenarios
- Factors impacting the changing risk profile for the insurance industry

Important Considerations for Catastrophe Modeling under Atmospheric Warming

- Does the historical record for a particular peril reflect today's climate regime?
- Can the historical record be used to model the climatology of a peril in the future
- Current state of scientific understanding of the correlations across different perils e.g. TC, ETC, Severe Thunderstorm

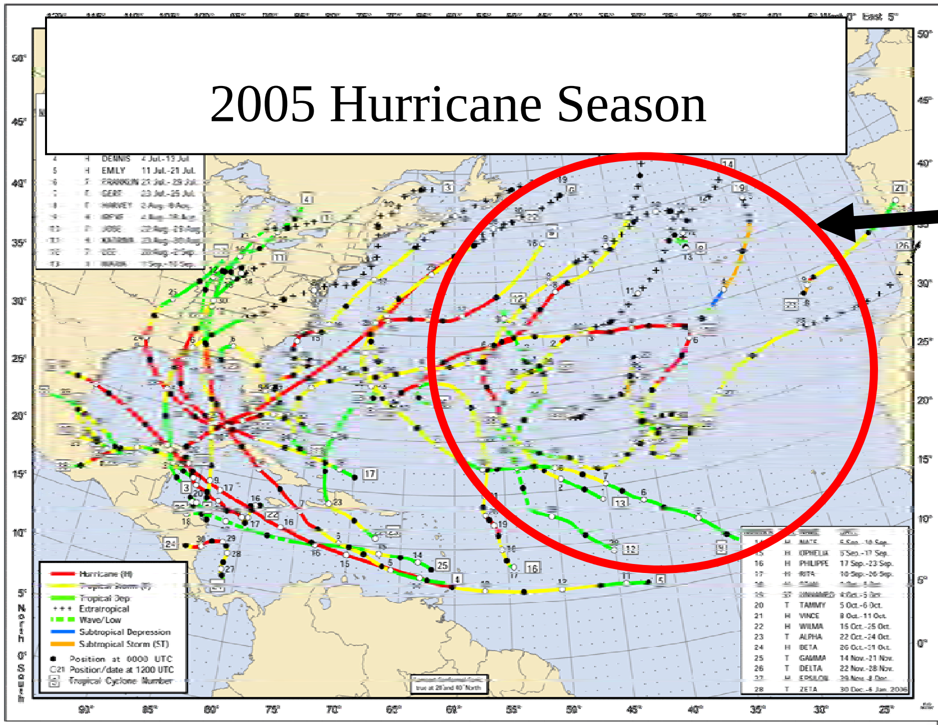


Source: Intergovernmental Panel on Climate Change (IPCC)

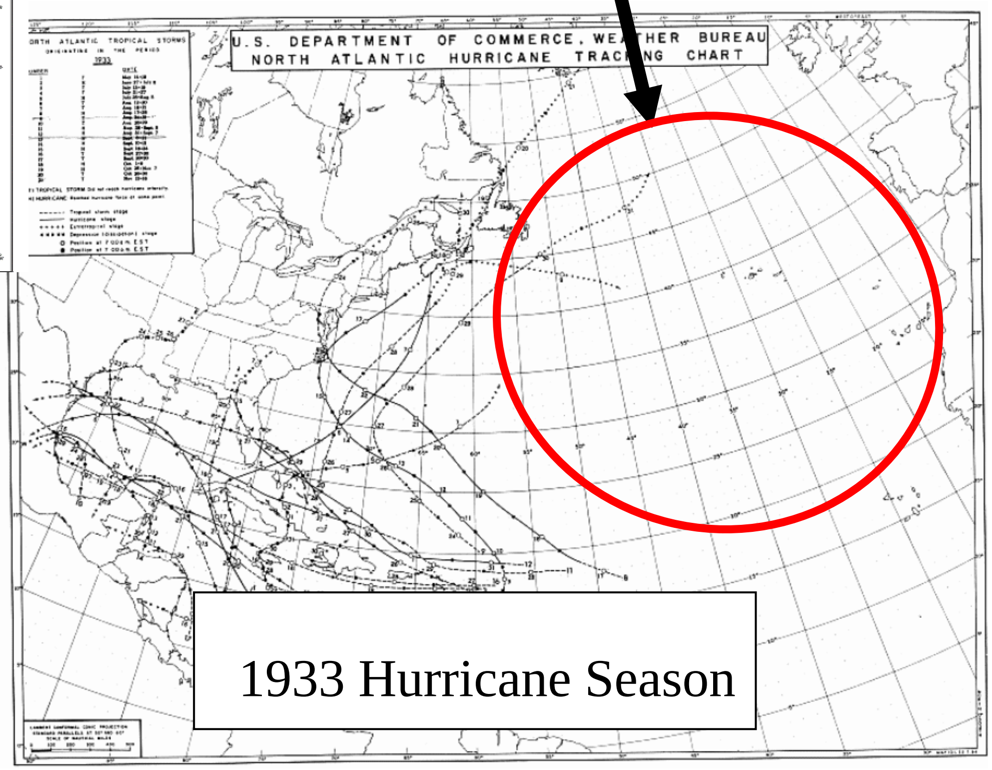
What do we Know About Atlantic Hurricane Activity

- We are in a regime of higher activity in the open Atlantic since 1995
- The correlation of landfalling activity in the US and basinwide activity is weak
- Short term forecasts (seasonal scale) of hurricane activity have high degree of uncertainty
- Several recent studies indicate that future hurricanes are likely to get more intense (e.g. Emanuel, 2005, Knutson, 2004)
- Some dynamical models indicate that under a warmer environment the frequency of Atlantic will remain unchanged or perhaps decrease (e.g. Knutson, 2004, Vechhi, 2007)
- However there are serious concerns about studies that are based on historical data because of the quality of basinwide data

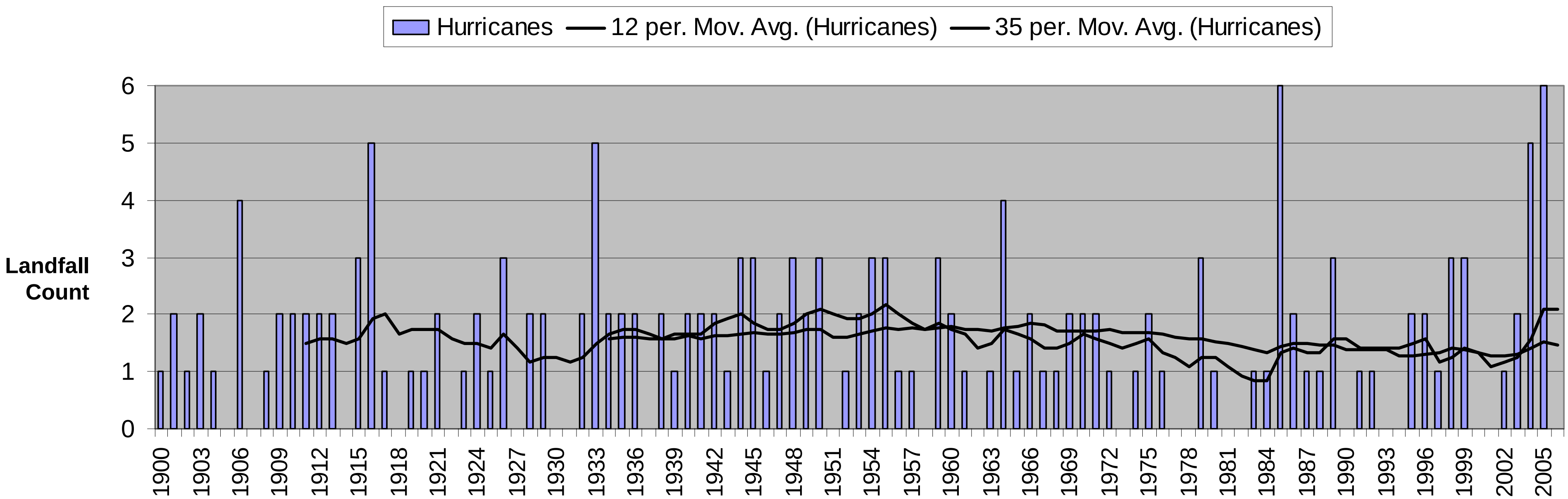
Stark Differences in TC Activity in the Open Atlantic (Landsea, 2007)



Open Atlantic
Ocean Differences

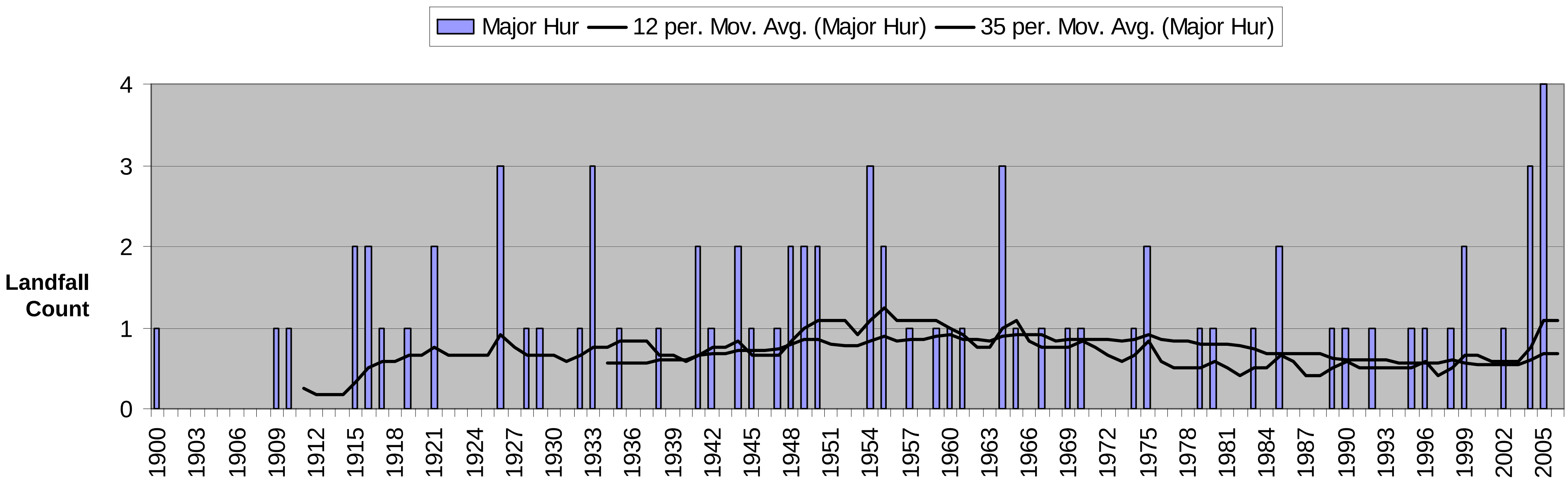


Variability in U.S. Hurricane Landfall Activity



Annual Frequency of Landfalling Hurricanes in the US

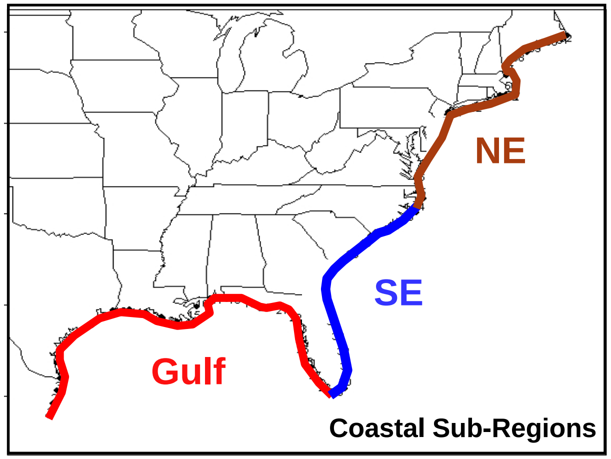
Variability in U.S. Major Hurricane Landfall Activity



Annual Frequency of Major Landfalling Hurricanes in the US

AIR Research Has Led to the Development of a Frequency Adjusted Near-term Catalog

Region	Coastal Segments	CAT	Index (Version 9.0)
Gulf Coast	01 - 28	1	1.05
		2	1.00
		3	1.00
		4	1.15
		5	1.15
Southeast Coast	29 - 44	1	1.15
		2	1.15
		3	1.30
		4	1.30
		5	1.30
Northeast Coast	45 - 62	1	1.01
		2	1.01
		3	1.02
		4	1.02
		5	1.00



- Refines estimates in data rich regions without over-stressing data in data sparse regions
- Does not depend on highly uncertain SST forecasts, assumes warm SST condition
- Does not assume that landfall proportion is constant in time or by region

Stress Tests Performed for the ABI Report using AIR Catastrophe Models

Weather Feature	Region	Stress-test[a]	Key References
Hurricane	US	Increased average wind-speed by 6%, with sensitivity tests for +4 to +9%	Third Assessment Report, Intergovernmental Panel on Climate Change, 2001, http://www.ipcc.ch Knutson and Tuleya (2004) Journal of Climate, 17(18): 3477–3495.
Typhoon	Japan	Increased average wind-speed by 6%, with sensitivity tests for +4 to +9%	
Windstorm	Europe	Increased frequency of storms that occur once every 20 years (or less) by 20%	Leckebusch and Ulbrich (2004) submitted to Global and Planetary Change. Kuzmina and others (2005) submitted to Geophysical Research Letters.

a. The stress-tests on tropical cyclones were applied to the entire distribution of all possible hurricanes and typhoons, whereas the stress-test on European windstorms was restricted to the extreme upper tail of the distribution of all possible storms. There may be an impact on less intense storms, but these are not considered here, because quantitative information about the changes is still limited. The stress-tests therefore severely underestimate the full potential impact of climate change on European windstorms – particularly, given that a considerable proportion of current insured losses result from more frequent but less intense storms.

Source: Association of British Insurers (ABI) Report (2005) on "Financial Risks of Climate Change"

ABI Estimated Impacts of Long-Term Climate Change on Insured Loss from U.S. Hurricanes

Scenario	Increase in windspeed	Annual average insured loss	Insured loss with chance of occurring once every 100 years	Insured loss with chance of occurring once every 250 years
Lower-bound sensitivity analysis	4%	+2.5	+27	+42
Potential impact of climate change[a]	6%	+4.0	+41 **(+70%)**	+62 **(+75%)**
Upper-bound sensitivity analysis	9%	+6.5	+68	+98

Source: ABI Report (2005) on "Financial Risks of Climate Change"

ABI Estimated Impacts of Long-Term Climate Change on Insured Loss from Japan Typhoons

Scenario	Increase in windspeed	Annual average insured loss	Insured loss with chance of occurring once every 100 years	Insured loss with chance of occurring once every 250 years
Lower-bound sensitivity analysis	4%	+1.0	+7	+9
Potential impact of climate change[a]	6%	+1.5	+10 **(+67%)**	+14 **(+70%)**
Upper-bound sensitivity analysis	9%	+2.5	+17	+25

Source: ABI Report (2005) on "Financial Risks of Climate Change"

ABI Estimated Impacts of Long-Term Climate Change on Insured Loss from European ETCs

Scenario	Frequency increase in top 5% of storms	Annual average insured loss	Insured loss with chance of occurring once every 100 years	Insured loss with chance of occurring once every 250 years
Potential impact of climate change[a]	20%	+0.5	+2.0 **(+5%)**	+2.5 **(+5%)**

a. The impact of climate change on the majority of less intense storms was not modelled, because quantitative information about the changes is still limited. **Note: ETC stands for Extra-tropical Cyclone.**

Source: ABI Report (2005) on "Financial Risks of Climate Change"

Primary Driver of Growing Catastrophe Losses Is Increase in Numbers and Values of Properties at Risk

Overall, 38% of the total exposure in Gulf and East Coast states is located in coastal counties, which accounts for 16% of the total value of properties in the U.S.

State	Coastal ($B)	Total ($B)	Percent Coastal
Alabama	75.9	631.3	12%
Connecticut	404.9	641.3	63%
Delaware	46.4	140.1	33%
Florida	1,937.4	2,443.5	79%
Georgia	73.0	1,235.7	6%
Louisiana	209.3	551.7	38%
Maine	117.2	202.4	58%
Maryland	12.1	853.6	1%
Massachusetts	662.4	1,223.0	54%
Mississippi	44.7	331.4	13%
New Hampshire	45.6	196.0	23%
New Jersey	505.8	1,504.8	34%
New York	1,901.6	3,123.6	61%
North Carolina	105.3	1,189.3	9%
Rhode Island	43.8	156.6	28%
S. Carolina	148.8	581.2	26%
Texas	740.0	2,895.3	26%
Virginia	129.7	1,140.2	11%
All Above States	7,203.7	19,041.1	38%
All Above States as % of Total U.S.	7,203.7	43,665.6	16%

AIR Analysis of Exposure Data Quality

- Nine out of ten commercial properties analyzed had replacement values less than the amount estimated using a standard engineering-based cost estimation process.
- Over 50 percent of companies analyzed lacked construction and/or occupancy information for more than a third of their policies.
- Accurate analysis of multiple-location policies requires an address for each location.
- To obtain accurate catastrophe loss estimates, the coverage limit should not be used as a proxy for the replacement value, particularly for policies covering only a share of the property.

Summary

- Long-term (> 50 years) climate projections pose several challenges to catastrophe modelers
  - Impact on frequency and severity of weather related phenomenon
  - Correlations across perils needs further research
- Shorter-term (< 10 years) climate conditioned estimates of risk are also uncertain
  - Estimated impact on U.S. hurricane losses are from 5 to 15%
- ABI estimates of the impact on extreme event losses are significant but not a primary driver of risk in the future
  - U.S. hurricane losses: 70 to 75%
  - European ETC wind losses: 67 to 70%
  - Japan typhoon losses: ~ 5%
- Growth in property exposures is the primary driver of increasing catastrophe losses
- Detailed exposure data used in catastrophe models severely underestimates replacement value which leads to risk underestimation

Tropical Cyclones: Research Directions and an SST-Landfall Analysis

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NASA Goddard Institute for Space Studies and Columbia University
Stephen Jewson
Risk Management Solutions

1 Introduction

Earth is warming to a degree unprecedented for thousands of years, due largely to industrial greenhouse-gas emissions (IPCC). The effects on human civilization, which is tuned to a climate that had been relatively stable over this period, will be disruptive. Agriculture in cold regions may well be enhanced by longer growing seasons, but other regions will become dryer and suffer. Low lying coastal regions will be encroached by incrementally rising sea level due to thermal expansion of the oceans. There is a poorly-quantified risk of meter-scale sea-level rise over a century if a significant fraction of the Greenland or Antarctic ice sheets break up.

Greenhouse warming may also be influencing the frequency and character of extreme meteorological events. Much attention has been focused on the evolution of tropical cyclones (TCs) in a warming climate. TCs draw their energy from the heat of the underlying ocean, so that, other factors equal, increasing sea-surface temperature (SST) increases TC intensity. The impact on TC formation is less clear. However, warm water is necessary for initial disturbances to grow, and so it is reasonable to look for relationships between SST and TC frequency. While data biases in the early historical record affect trend analysis, certain conclusions are clear:

- Tropical cyclone frequency shows no global trend, but it has increased in the North Atlantic, correlated with SST (Holland and Webster, 2007).
- The power dissipated TCs globally has increased (Emanuel, 2005), again closely correlated with SST, and a higher fraction of TCs are reaching the most intense categories (Webster et al., 2005).

Climatologists are interested in understanding the general relationship between TCs and climate. Coastal residents are interested in whether TCs hit close to home, and if so, with what frequency and intensity. Many factors affect regional landfall rates in addition to basin-wide TC frequency and intensity, including the geographic distribution of TC genesis and the shape of TC tracks. Genesis distribution and TC track shape could conceivably change in a warming climate, possibilities that have received less attention than frequency and intensity. The primary focus here is on TCs and secular climate change, but it is important to note that modes of large-scale climate variability such as El Nino/Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) have great influence on Atlantic TC formation and tracks (e.g., Elsner, 2003).

2 Analysis Tools

The tools to study TC-climate change include statistical analysis and modeling, based on historical TC data, and physical modeling, based on the underlying dynamics and thermodynamics. Global physical models, such as general circulation models (GCMs), are valuable for understanding the range of future environments in which TCs will form and propagate. In addition, observationally-derived statistical relationships between climate state and TC genesis can be extrapolated into the future using GCMs (Camargo et al., 2007). However, GCM representation of TCs is generally poor, due to insufficient resolution, a fact prohibiting their direct use in catastrophe risk assessment. More limited domain physical models have been used to study TCs at high resolution, revealing insight into the detailed mechanisms of cyclogenesis.

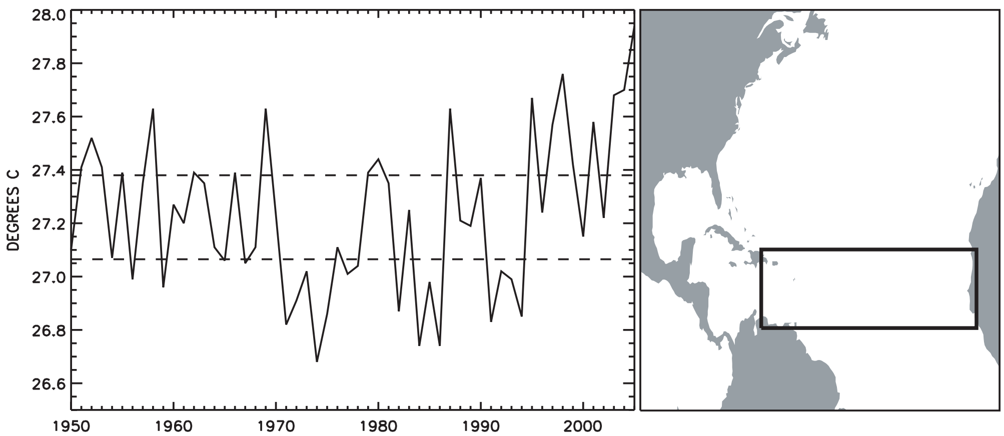

Figure 1: SST (left) averaged of July–September and the spatial region shown at right. The dashed lines indicate the thresholds for the hottest and coldest 19 years.

Statistical models are the work horses of hurricane catastrophe modeling. They represent TC formation and propagation with distributions or stochastic processes that are determined from, or constrained by, historical data. Statistical models are ultimately data limited; intense TCs are rare and their reliable observation from genesis to lysis began only in the era of routine aircraft reconnaissance (1940s) and satellites (1970s). Nonetheless, well built statistical models can be used to draw powerful inferences that are not obvious from casual plotting of time series. Some statistical models are build on historical landfall events (e.g., Jagger et al., 2001), for which event identification back to the 1800s is reliable, although intensities may be uncertain. Other statistical models are build on full TC track data (e.g., Vickery et al., 2000) from lysis to genesis, which has the advantage of exploiting the information in "near misses" for landfall rate estimation, but the disadvantage of requiring more complete data. Combined approaches are possible, for example a simple dynamical model run on a statistical track model (Emanuel et al., 2006). Statistical modeling to predict future TC behavior requires, of course, the assumption that the past is a guide to the future.

Here, we apply the statistical track model described and evaluated by Hall and Jewson (2007) to explore variation with SST of TC landfall rates along the North America coast. The model generates synthetic TCs from genesis through lysis. Intensity, however, is not included here. The model is primarily non-parametric, and is constructed by averaging and sampling historical tracks in a manner that has been optimized out-of-sample. Annual TC number is modeled by simple re-sampling of historical annual numbers. The data source is the NOAA HURDAT best-track data (Jarvinen et al., 1984) from 1950–2005. These TC data, comprising the best observational estimates of TC path and intensity, form the basis for many analyses of North Atlantic TCs.

3 SST-Landfall Results

In order to estimate the influence of SST on landfall the 56 years 1950–2005 were ranked by average Jul-Aug-Sep SST over the subtropical North Atlantic, using the UK Met Office Hadley Centre SST data (Rayner et al., 2003), as shown in Fig. 1. An upward trend is evident starting in the 1970s. The track model was separately constructed on the 19 hottest years, the 19 coldest years, and the full period, resulting in three model versions: hot, cold, and full. With each model version 1000 years of synthetic TCs were generated and their landfalls counted on the 39 coast segments shown in Fig. 2.

There are more TCs in the hot years than cold, 12.8 yr^{-1} versus 8.5 yr^{-1}, a difference which is highly significant compared to random sampling. The mean simulated landfall rates considered along the entire coast,

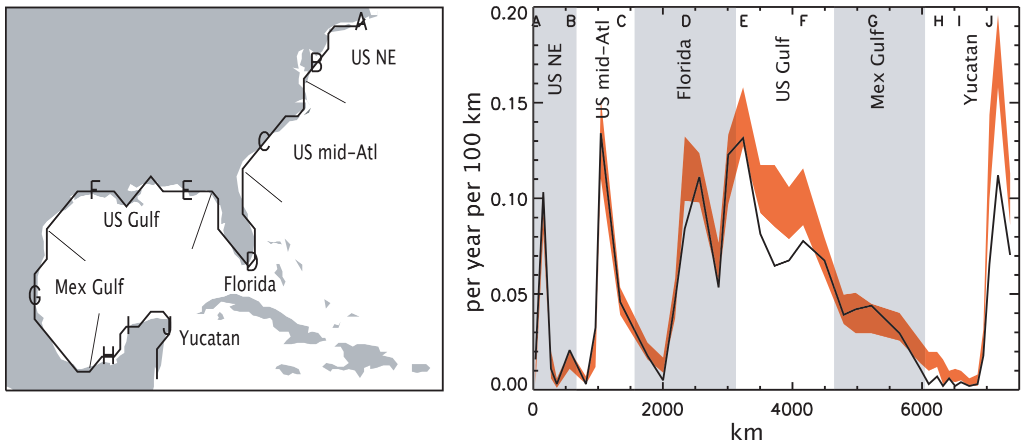

Figure 2: Segmented coastline (left) on which landfalls are counted. Probability derived from the synthetic TCs of at least one landfall per year per 100 km of segmented coastline for the full 1950-2005 period (black) and the 19 hot years (red). The spread for the hot-year probability is derived from analyzing all 18-year subsets of the 19 hot years.

4.7 yr^{-1} hot and 3.1^{-1} cold, are in the same proportion. In other words, the overall landfall fraction does not vary with SST in these simulations.

Table 1: Probabilities of at least 1 (P_1) and at least 2 (P_2) landfalls on the 6 coastline regions for the hot years and for all years, as labeled. Ranges on hot-year probabilities are obtained by modeling each of the 18-year subsets of the 19 hot years.

	US NE	US mid-Atl	Florida	US Gulf	Mex Gulf	Yucatan
P_1(hot)	0.17–0.21	0.29–0.36	0.59–0.65	0.80–0.84	0.34–0.42	0.49–0.56
P_1(all)	0.23	0.33	0.59	0.76	0.37	0.37
P_2(hot)	0.016–0.023	0.05–0.07	0.22–0.29	0.48–0.57	0.07–0.10	0.15–0.20
P_2(all)	0.029	0.06	0.22	0.42	0.08	0.08

There is, however, geographic structure in the landfall-SST relationship. Fig. 2 shows the simulated probability of at least one landfall per year per 100 km of segmented coast for the hot years (red) and for all years (black), plotted as a function of distance along the coast from New England to Yucatan. The increased hot-year risk is realized on Florida, the US Gulf Coast and Yucatan (Table 1). No increase is seen on the US Northeast and Mid-Atlantic coasts. This geographic structure is due to shifts with SST in the spatial distribution of TC genesis and the shapes of TC tracks. The simulated genesis distribution shifts southeastward from cold to hot SST, and there is a tendency for hot-year tracks to curve northeastward away from the mid-Atlantic coast sooner than in cold years. These results on regionalization of risk variation with SST are intriguing, but warrant corroboration by other techniques. Physical mechanisms relating genesis-site and track shape to SST have not been identified. It is possible that the track and genesis variations may be due to a projection of the SST time series on another mode of climate variability, such as ENSO or the NAO. We are presently exploring these issues.

4 Future Directions

Physical and statistical modeling will continue as valuable tools for the study of TCs. Combining the two is particularly compelling. In one approach a statistical track model is derived from large-scale observed environmental fields, such as mean wind (Emanuel, 2006), and evaluated against historical TCs. The model is then applied to a GCM's predictions of the large-scale fields and used to generate large numbers of synthetic tracks consistent with the GCM's climate. In this way GCM projections of future climate are "down-scaled" to the TC level. A possible physical-statistical combination that addresses current risk assessment is to generate a set of many time-evolved high-resolution TCs from a meso-scale model or a numerical weather forecast system. Such systems are crucial for real-time forecasting of particular TCs, but have biases in their TC climate. However, if the modeled TC set is sampled with probability weights derived from a statistical track analysis, one can exploit the detailed four-dimensional TC information and have a TC climate faithful to observations.

Observationally, the continued maintenance of the HURDAT archive, and similar archives from other ocean basins, is crucial, as is continued research to estimate the magnitude of biases in the pre-aircraft era. Ship logs may be useful in this respect. Risk modelers could make great use of a TC-size diagnostic (e.g., radius to maximum wind speed), if it were included in these data bases. Finally, the field of "paleotempestology"—the study of pre-historic TCs based on various paleo proxies, such as back-bay sediment washovers—should be encouraged. It will lead to improved estimation of long-term variability in the frequency of intense TCs.

5 References

Camargo, S. J., et al., 2007, *Tellus, A*, 59, 428–443.

Elsner, J. B., Tracking hurricanes, 2003, *Bull. Amer. Meteor. Soc.*, 84, 353–356.

Emanuel, K., 2005, *Nature*, 436, 686–688.

Emanuel, K., 2006, *J. Clim.*, 19, 4797–4802.

Hall, T. M., and S. Jewson, 2007, Tellus, A, 59, 486–498.

Holland, G. J., and P. J. Webster, 2007, *Phil. Trans. R. Soc. London, A*, doi:10.1098/rsta.2007.2083.

IPCC, 2007, Climate Change 2007: The Physical Basis, Cambridge University Press, Cambridge, UK.

Jagger, T., et al., 2001, *Appl. Stat.*, 40, 853–863.

Jarvinen, B. R., et al., 1984, *NOAA Tech. Memo., NWS NHC 22*.

Rayner, N. A., et al., 2003, *J. Geophys. Res.,* 108, doi:10.1029/2002JD002670.

Vickery, P. J., et al., 2000, *J. Struct. Engin.,* 126, 1222–1237.

Webster, P. J., et al., 2005, *Science*, 309, 1844–1846.

Statistical Modeling of Tropical Cyclone Tracks

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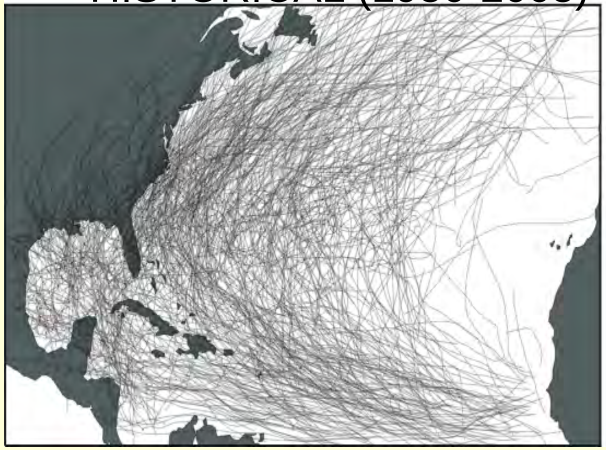
Risk Management Solutions

Statistical track model

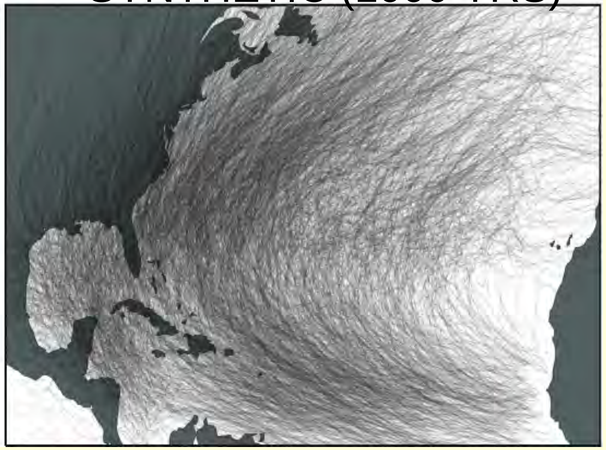
- Stochastic model of TCs birth to death.
- Generate 1000s of years of synthetic TCs.
- Historical TCs should look like subset of synthetic TCs.
- Compute regional landfall rates from synthetic set.

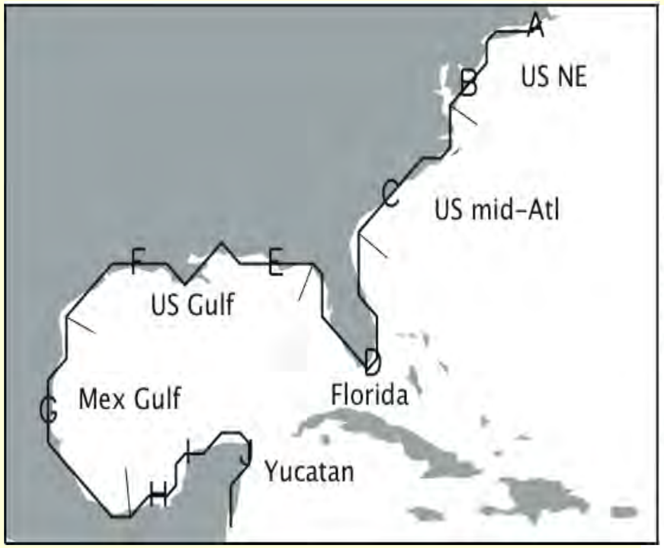
- Casson and Coles, *App. Stat.*, 2000.
- Vickery et al., *J. Struct. Engin.*, 2000.
- James and Mason, *J. Wtrwy, Engin.*., 2005.
- Emanuel et al., *Bull. Amer. Met. Soc.*, 2006.
- Hall and Jewson, *Tellus*, 2007.
- Hall and Jewson, *J. Appl. Met.*, 2007.

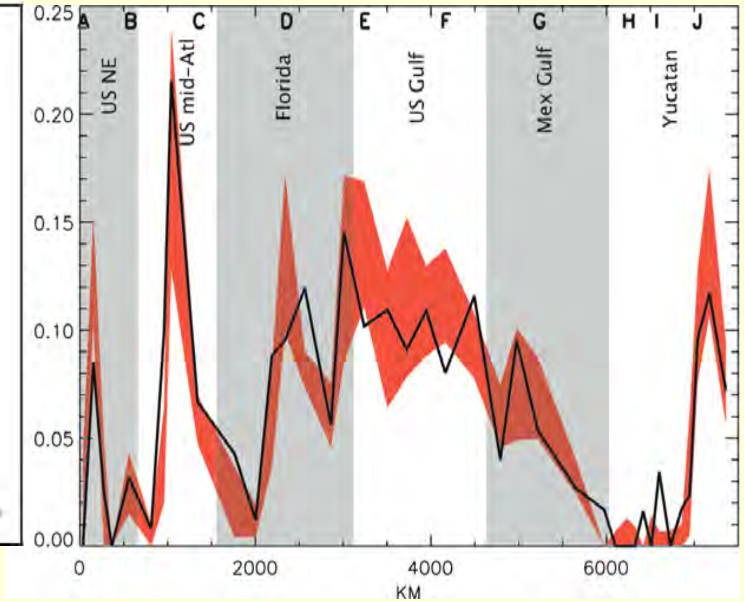
HISTORICAL (1950-2005)



SYNTHETIC (1000 YRS)

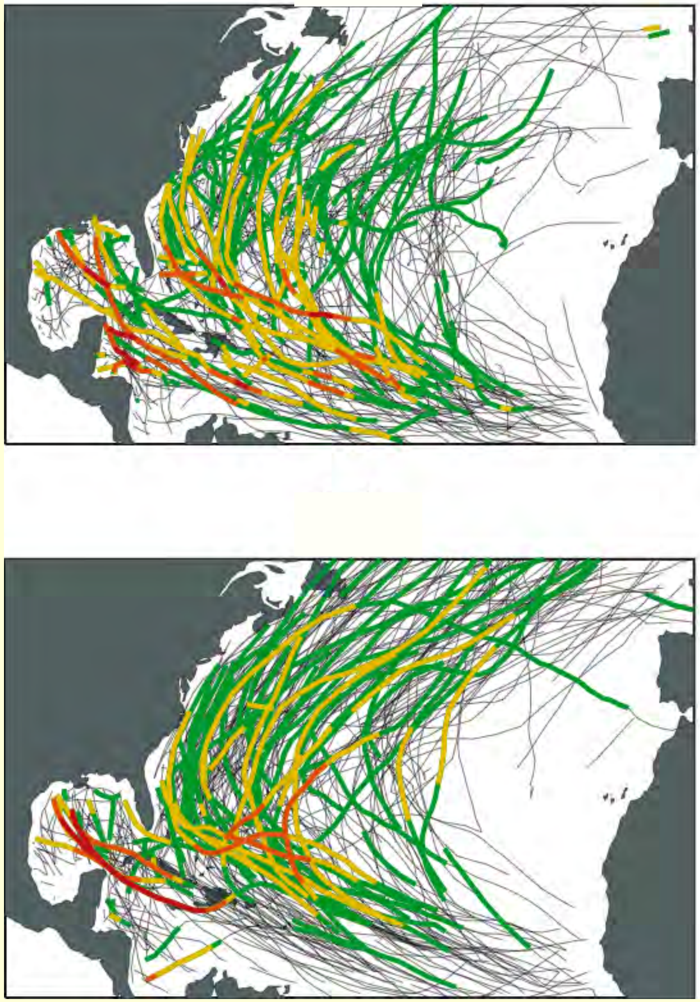


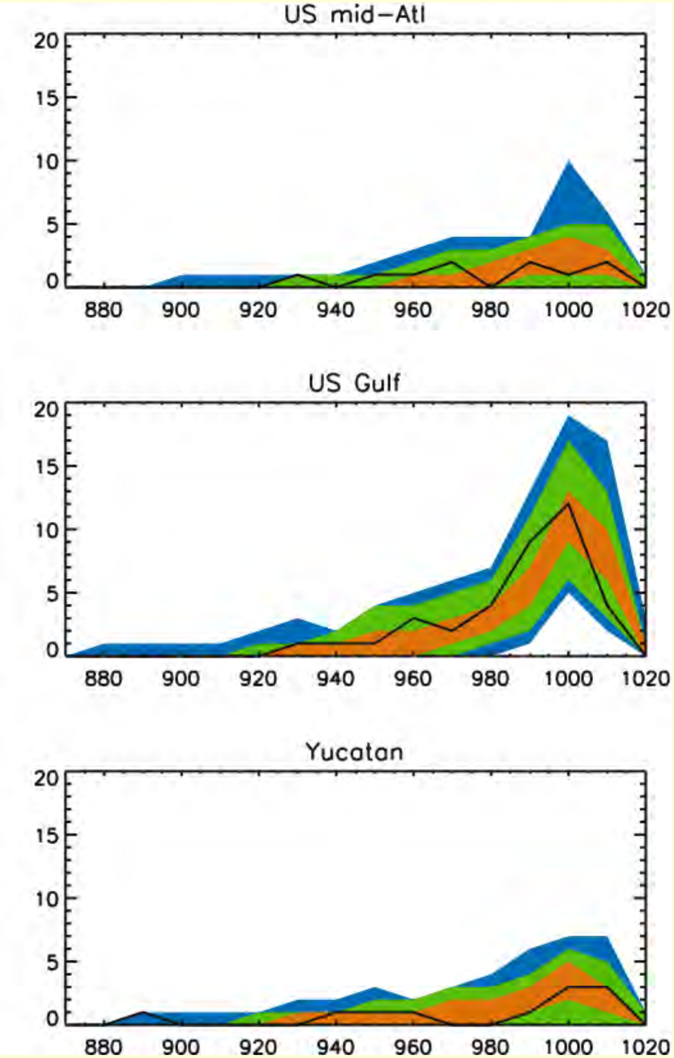


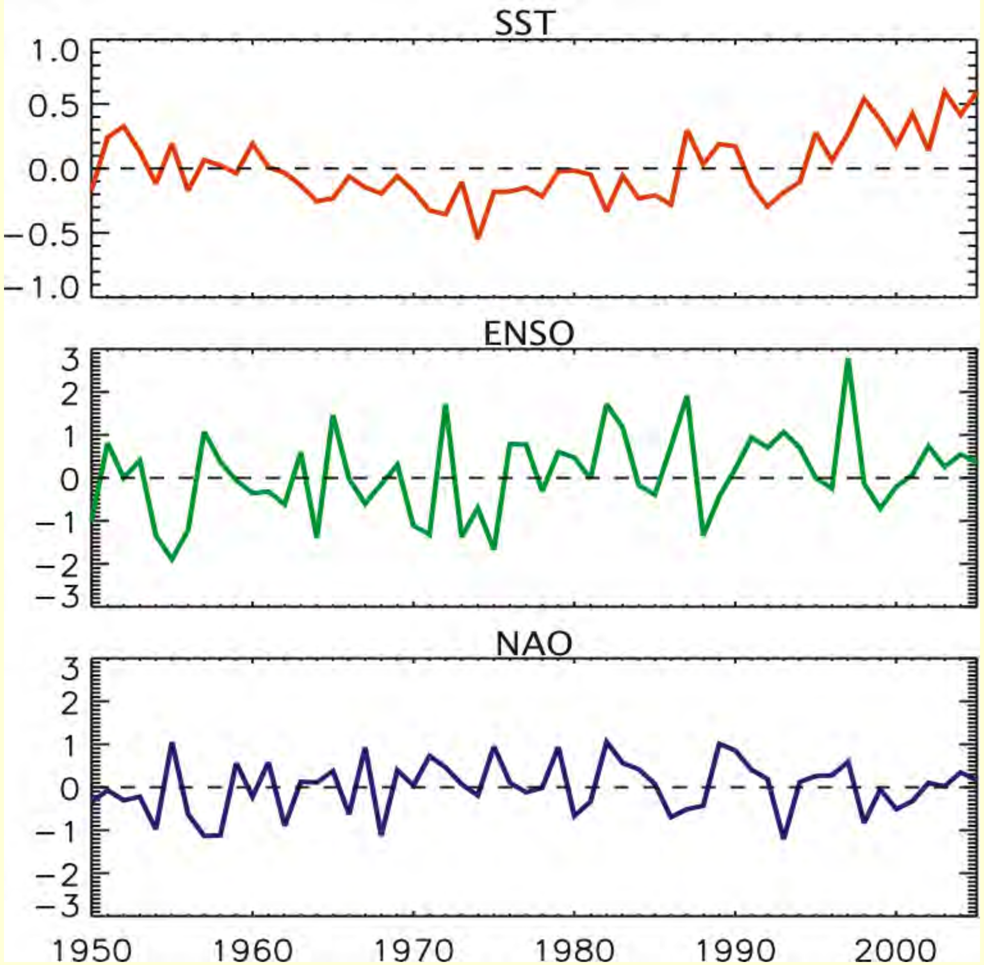


Central pressure (still under development):
"local" regression for p increments on previous increment
and total p drop. Local data kernel size optimized out-of-sample.

1979-2005







SST, ENSO, NAO known to influence TC formation, development, propagation.

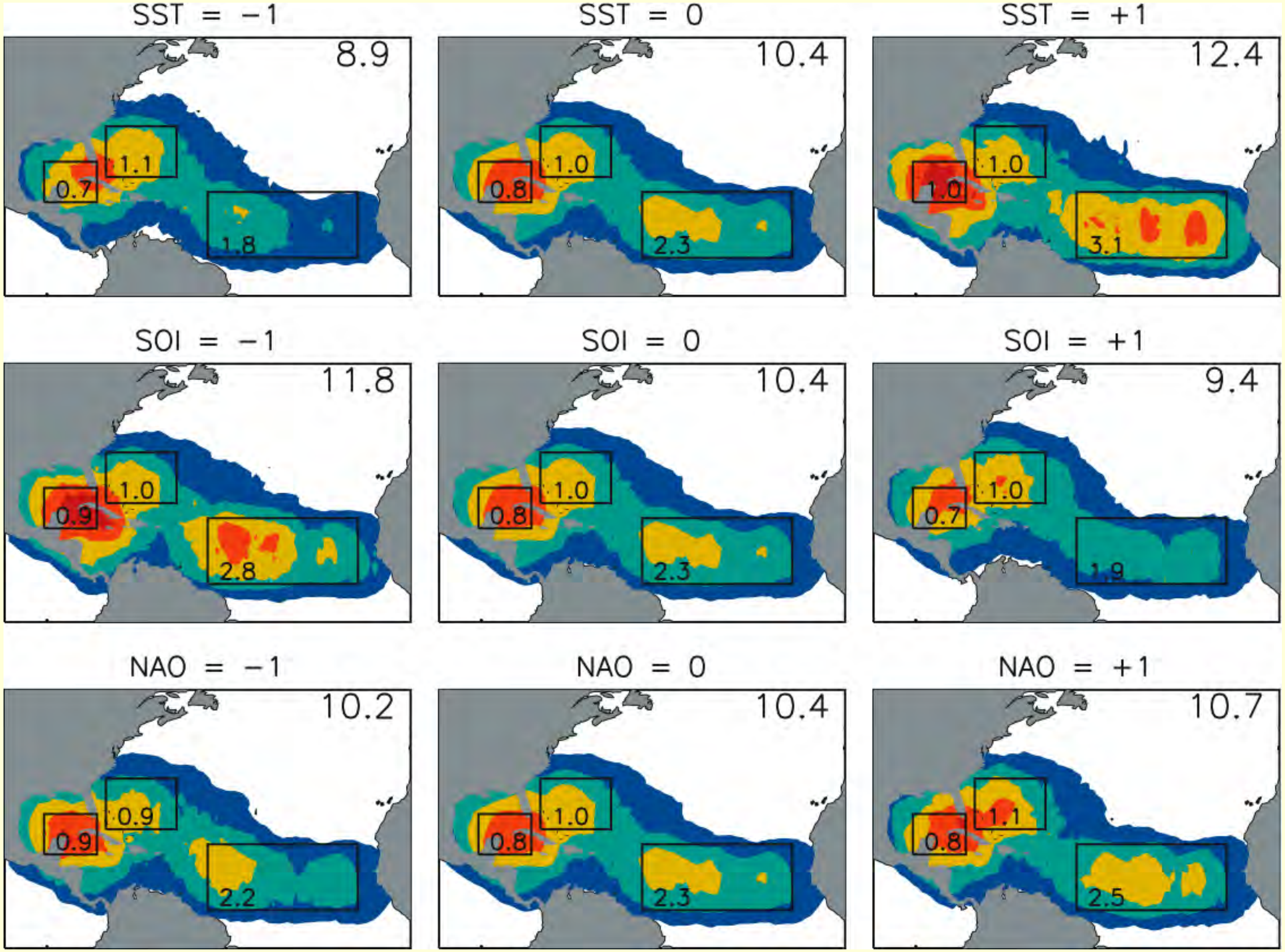
e.g., Elsner, *BAMS* (2003)
Emanuel, *Nature* (2005)

Various ways to introduce climate variables into track model:

1. Build model separately on data years above/below threshold.
2. Include local (i.e., spatially varying) regression of model components on climate variables (Poisson regression in the case of counts).

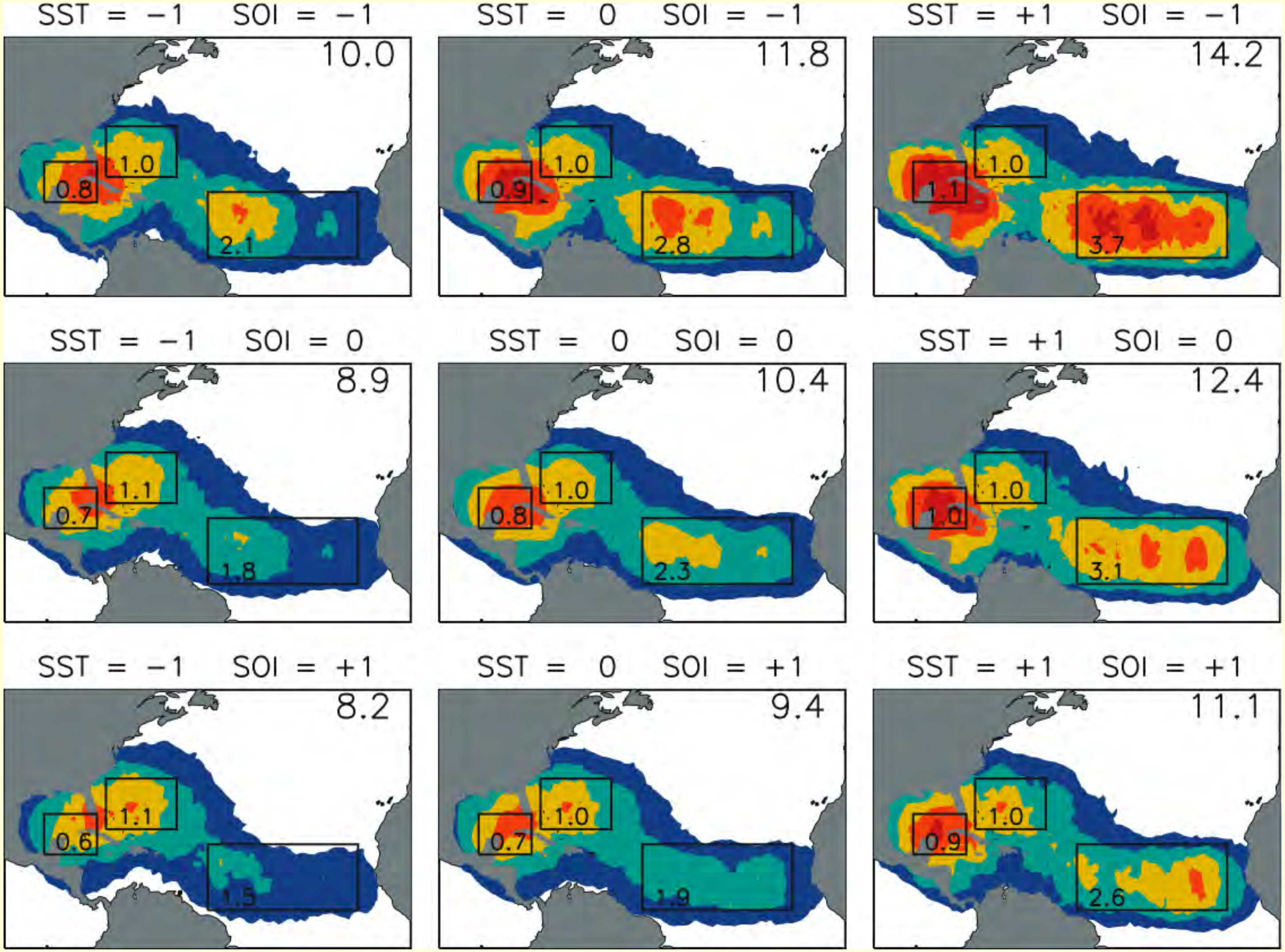
So far, have looked at genesis and track effects, but not intensity.

Genesis: mean rate as function of location and climate state (local Poisson regression)

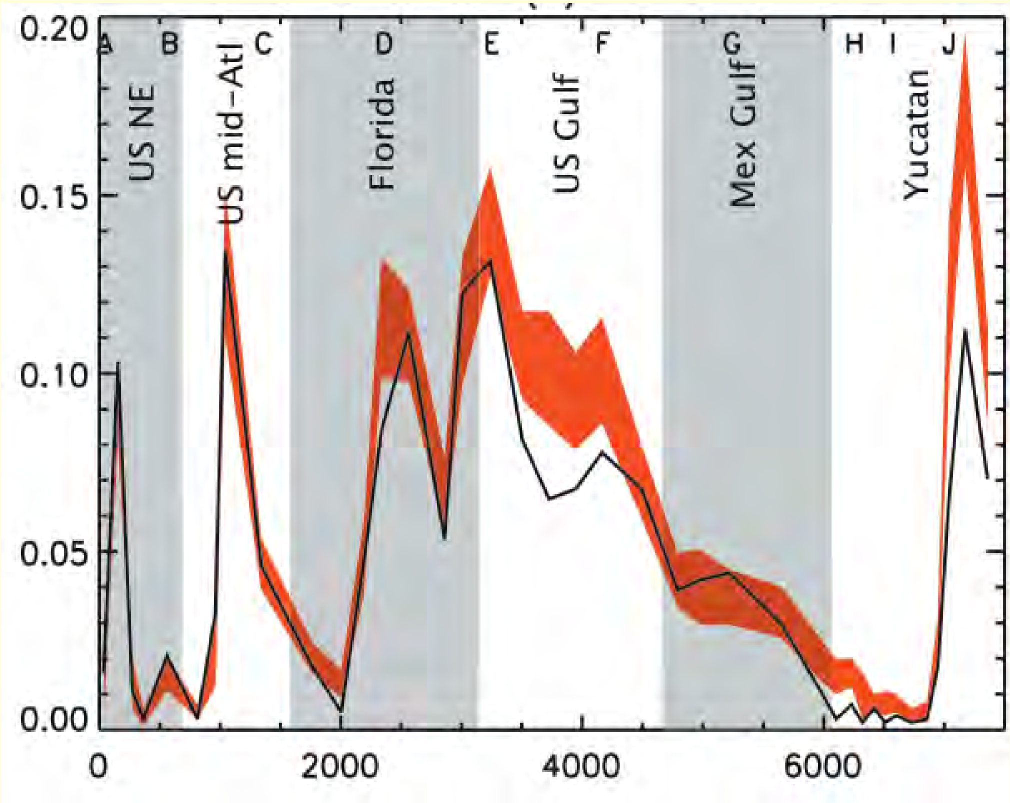


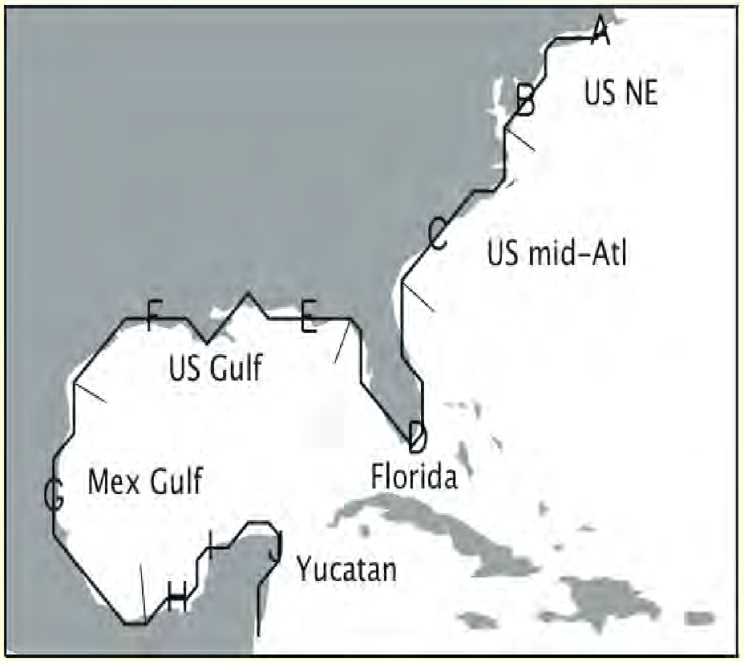
Note: 1. TC frequency increase with SST not uniform.
2. Decrease in SOI very similar to increase in SST.

Vary SST and ENSO simultaneously



Probability at least 1 landfall in a year per 100 km of gated coastline





Partition years into coldest 1/3 and hottest 1/3 and construct separate models.

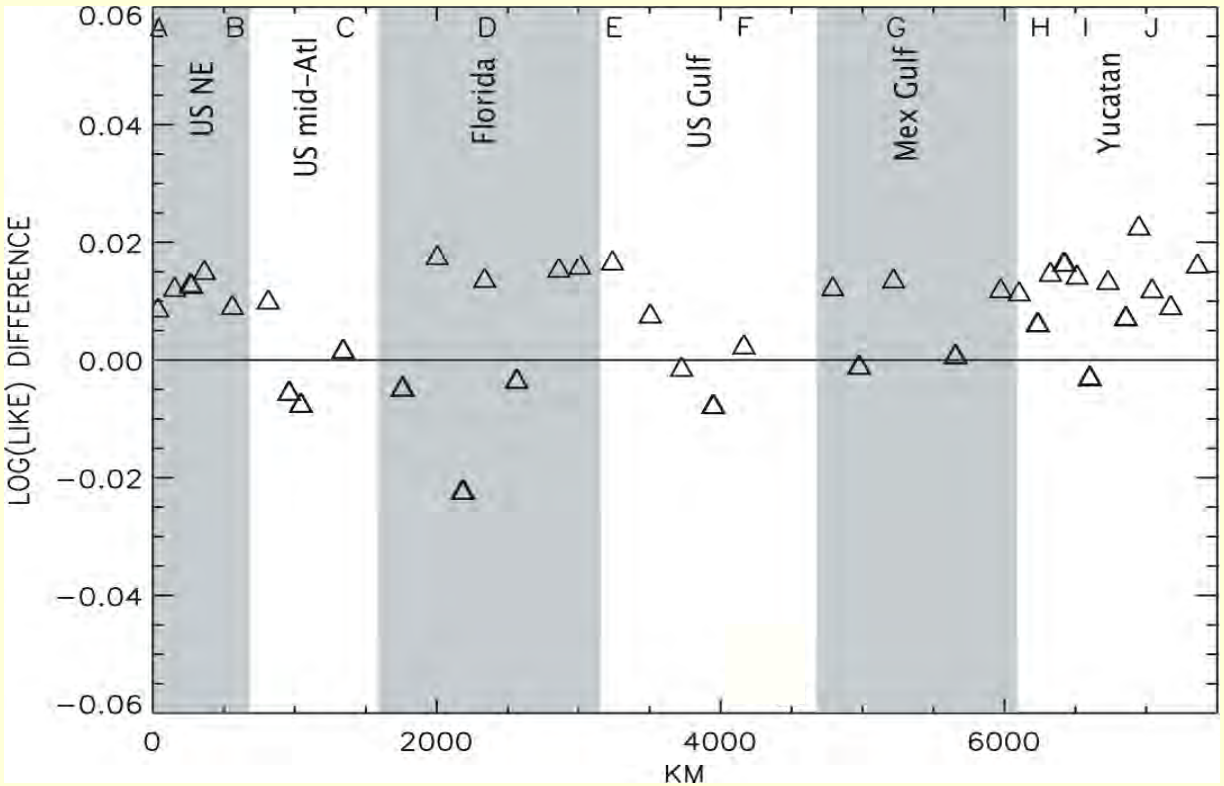
- Significant increase landfall risk with SST for Florida & Gulf & Yucatan.
- No significant change for US NE and mid-Atlantic.

Presently working verify this SST regionalization result with a model that Depends continuously on climate variables.

Use track model or historical landfall for estimating landfall rates?

- Track model: more bias, but less sampling error
- Local model: less bias, but more sampling error

Out-of-sample forecast landfall likelihood comparison: (Hall and Jewson, *JAMC*, 2007).



Track model does best on small scales, where historical landfalls are infrequent.
(Large reduction in sampling error dominates increase in bias.)

Mixed results on larger scales, where more historical landfalls.
(Modest reduction in sampling error comparable to increase in bias.)

Catastrophe Modeling for Climate Hazards: Challenges and Climate Change

By: Steve Jewson, Celine Herweijer and Shree Khare, Risk Management Solutions.

Introduction

Catastrophe Modeling is the science of making probabilistic predictions of financial risk due to natural and non-natural catastrophic events. Catastrophe (Cat) Modeling has developed almost exclusively in the private sector, driven by the needs of financial institutions such as insurers and reinsurers to understand and quantify their risk. It is currently both a hundreds of millions of dollars industry, and an innovative and exciting area of scientific research. From its start in earthquake modeling in the 1980's, it soon expanded to include hurricanes. It has now covers a wide range of perils, including winter storms, severe convective storms, floods and non-natural catastrophes such as terrorism and pandemic flu. Cat modeling companies today employ more PhDs than many academic departments, and hire dozens of academic consultants from a wide range of disciplines. In this short article, we describe cat modeling from the point of view of the world's leading cat modeling organization, Risk Management Solutions. We begin by reviewing the goals of cat modeling, describe the basic methodologies, and then discuss some of the particular challenges of modeling climate hazards. Finally, we discuss how climate change is relevant to cat modeling.

The current state of the art in cat modeling

The basic goal of cat modeling is to produce probabilistic predictions of future losses to property from catastrophic events, for both individual properties, of any type, and for portfolios of properties, however large. The basic structure of cat models takes an event-based approach to modeling. That is, the core of most cat models consists of a simulated set of events occurring with some specified annual rate. This approach is more or less essential in order to capture the details of the dependency structure between losses at different locations that is created by the physical structure of the catastrophic events themselves. Cat models are typically structured into various components, such as a rates module that simulates appropriate numbers of events over a specified length of time, a hazard module that simulates the events themselves, a vulnerability module that derives loss ratios from hazard values and engineering principles, and an exposure module that captures the exposed properties (Figure 1).

Figure 1: Typical components of a cat model – the example of flood.

To achieve their goals, cat modellers use a wide variety of tools designed to suit the particular task at hand. Most models use an appropriate combination of statistical and dynamical (derived from physical laws) modeling methods. The statistical modeling methods used include classical statistics, non-parametric statistics, and Bayesian statistics where appropriate. Methods such as Principle Component Analysis, time-series analysis, regression, kriging, Bayesian filtering, Bayesian networks, Bayesian decision theory, shrinkage and low-discrepancy simulation methods are commonly used. The dynamical modeling methods used typically include hydrological runoff models, computational fluid dynamics models, shallow-water equations, atmospheric boundary layer models, mesoscale atmospheric models, atmospheric general circulations models and coupled climate models. One of the most important skills in building a cat model is in the judicious use of these different modeling methodologies to answer the problem at hand, at the resolution being modelled.

Difficulties and Challenges in Weather Related Cat Modeling

To illustrate exactly where effort is being spent in the development of today's cat models, we now list 10 key challenges that we see in weather-related cat modeling (the effects of climate change will be discussed in the following section).

1) Accurate representation of uncertainty

Baysesian statistics can be used in a rather straightforward manner to quantify and understand the uncertainty around model parameters and the impact that has on losses. Some parameters are well estimated, and others are rather poorly estimated. Some affect losses at short return periods, while others affect losses at longer return periods. Additional challenges include how to quantify hazard uncertainty, and even more challenging is the quantification of uncertainty driven by model choice. To address such issues, cat modeling is starting to move in the same direction as climate modeling, with multiple models and multiple versions of models being developed.

2) Modeling loss amplification

Cat modeling started as a local calculation: given a certain wind speed at a location, it was assumed that the distribution of possible losses for a building at that location could be calculated. In recent years, and especially following hurricane Katrina in 2005, it has become abundantly clear that the total loss from very large catastrophic events can only be modelled by considering a number of additional factors, such as demand surge, risk and cost associated with evacuation, sociological factors and risk and costs associated with political interference in the insurance process. These factors can only be modelled using combinations of economic and sociological modeling.

3) Data

Relative to what cat modellers would ideally like, the network of surface observing stations is not necessarily adequate, the principle problem being geographic coverage. Another problem is consistency, even within a single country, wind speed measurements may be taken in many different ways. One challenge is therefore to combine measurements in such a way as to make the best use of what is available. One response to the lack of data is that cat modellers themselves are now setting up their own networks of measuring stations to supplement those available from government agencies and universities.

4) Extracting information from loss data

Whereas surface weather observations during extreme events are typically very sparse, observations of loss, almost by definition, are often very extensive. If used correctly, loss observations can be a mine of information. In development of cat models, loss data could be exploited by formulating and solving a filtering / data assimilation problem with non-linear and unknown transfer functions. In the next decade, significant efforts will put forth into trying to decode this information to tell us more about the detailed structure of wind fields, especially for smaller wind events such as tornadoes.

5) Understanding and predicting decadal and interdecadal variability

The occurrence rates and intensities of many weather-related perils vary on multi-year to decadal multi-decadal timescales. Driven by the needs of their clients, cat modellers today are primarily interested in quantifying risk in the next 1-5 years. In academic realms of atmospheric science / geophysical fluid dynamics, the emphasis is on understanding and modeling of the phenomena. In cat modeling, the emphasis is on trying to produce a reasonable prediction, whatever the current level of understanding. This is particularly difficult in two instances: prediction of tropical Atlantic sea surface temperatures which influence hurricanes, and north Atlantic circulation patterns which are related to storm activity over Europe.

6) Avoiding overfitted models

In cat modeling, the emphasis is on prediction. In order to make accurate predictions, it is necessary to ensure that statistical models are not overfitted to observations. Early generation cat models were overfitted, and thus represented historical data very well but had poor forecasting performance. The danger of overfitting is very high in cat models, because of their large numbers of parameters, and the small amounts of available data. There is a current trend, therefore, towards models that are built very rigorously to avoid overfitting in statistical components. Such methods are computationally intensive, and have only recently become feasible.

7) Modeling the infinite variety of building types

No two buildings are the same in every detail. This makes the modeling of building vulnerability difficult. State of the art cat modeling of the vulnerability of buildings combines both empirical data from past catastrophic events with engineering and physical models of the performance of buildings and building components under different forms of stress. The challenges in this are in trying to extract the most information from empirical data, without oversmoothing, and in building physical models of building performance that are consistent with real data and represent the observed variability between different building types accurately.

8) Modeling the correlations between perils

At some level, hurricane and winter storm activity are not entirely independent. In current day cat models, it is a challenge to understand and model such weak correlations.

9) Modeling at sufficient resolution

Ideally, cat models would capture the effect of kerb stones on flood waters and adjacent buildings on local wind speeds. Currently, that level of detail is a long way off. The challenge, then, is to model at sufficient resolution to capture the most important factors that determine flood depths and wind speeds at individual locations, even if many details must be ignored.

10) Modeling turbulent processes in the atmospheric boundary layer and other weather-related perils

Atmospheric boundary layer flows are turbulent, in part arising from the interaction of air flows over the rough earth surface. Appropriate parameterization of such turbulent flows using statistical and physical models is a challenge. While the focus of the discussion above has been on loss due to wind, weather-related perils can generate loss from rain, snow, freeze and hail. The challenge is to build accurate models of these additional perils, and quantify the relative contributions to a given loss.

The Effects of Climate Change

Anthropogenic climate change means that for some climate perils, and for some regions, the frequency and/or intensity of events is changing the hazard. For catastrophe modelling, this means that so-called statistical stationarity will not necessarily give the best representation of the real-time risk. As such, leading catastrophe modelling firms today look for where clear long-term trends in climate signals can be observed, and determine how best to adjust the models from the long-term baseline. Methodology differs from peril to peril in accordance with the observed trends in the relevant datasets of principal climatic drivers for a particular peril (e.g. precipitation and temperature for flood; storm tracks, temperature and wind for winterstorms; hurricane activity, sea surface temperatures and wind shear for hurricanes). Adjustment or no adjustment, each climate peril model in each region is considered individually, and a comprehensive literature review and data analysis is involved. This process is repeated whenever models are updated.

Using Catastrophe Models to explore Climate Change in 2020 and Beyond

Whilst the traditional users of cat models – insurers - are primarily focused on the 1-5yr timeframes of underwriting, a surge in the demand to understand climate change impacts in decades to come, has highlighted the potential to use cat models as a tool to explore risk and the financial value of adaptation on these longer timescales. This drive for longer-term risk assessment has come from public policymakers, planners, investors and corporate risk managers. The insurance industry itself, on the heels of nearing disclosure requirements around climate change, and a growing realisation that 20 year plus timeframes do impact upon investment decisions and long-term business sustainability, are also showing interest in such longer term risk analysis.

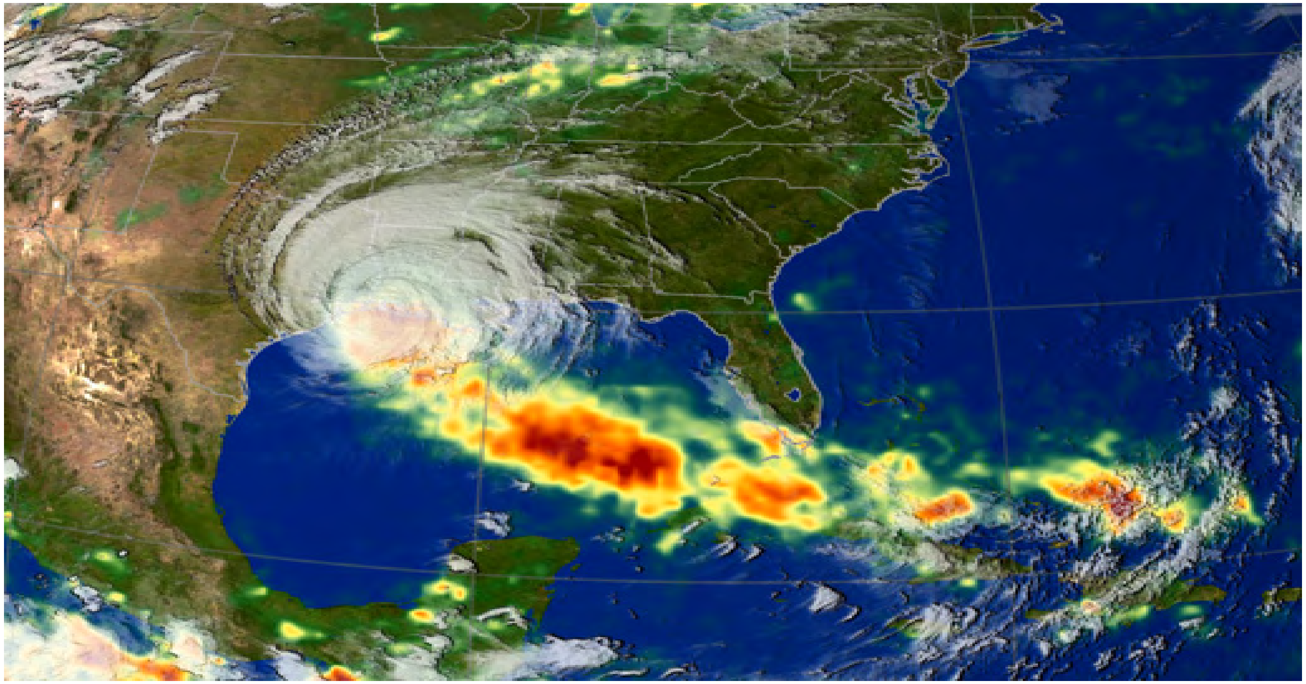
Climate models of different resolution are used by academics worldwide to explore the range and uncertainty of changes in mean and extreme climate over the coming century and longer. Whilst there are clear limitations in these models (forcing uncertainty, model inadequacy, model uncertainty, theoretical limitations), their value lies in understanding the ramifications of the broadest changes both for society and for spurring effective climate change policymaking aimed at mitigating rising greenhouse gases.

The science of linking climate models together with impact models is relatively young, yet already in high demand given the value of the output to increasingly aware decision making. Catastrophe models can be viewed as one such impact model, and academics and cat modelers are increasingly working together to achieve this.

By adjusting the stochastic event set and hazard module to represent the range of projections from climate models, we have a window into what future risk and associated losses may be. The output of a climate model is translated into the output of a cat model, enabling us to address different questions than a climate model can address. This can be achieved through stress testing the cat models with different scenarios, or by incorporating probabilistic climate model output. The granularity of the cat models can be used to explore impacts to particular geographies and infrastructure types. Vulnerability modifiers can be applied to investigate the most effective ways of minimizing future risk given future hazard. However, the limitations of interpreting climate model output for 2020 and beyond apply, as do the limitations of cat models outlined above. Nevertheless, there is a clear value to communicating climate change impacts in the language that risk managers across finance and government use to analyse risk today – cat modelling.

With growing demand for such output there are clearly many exciting opportunities for partnership between the insurance and cat modelling community and the climate modelling community.   Building climate change into cat models can be achieved in a myriad of ways. Determining which is best, is where the challenge lies.

Catastrophe Modeling for Climate Hazards: Fundamental Challenges and Climate Change



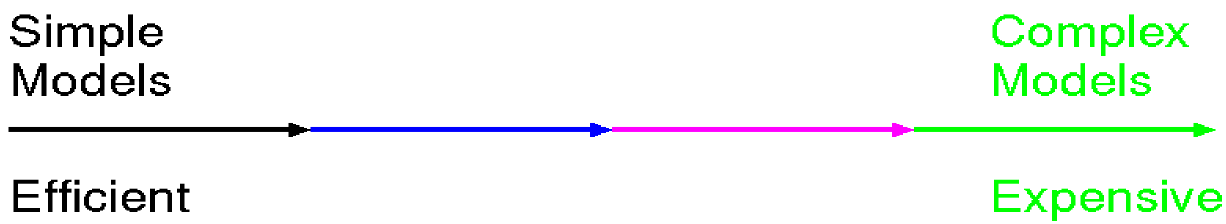
Dr Shree Khare – Senior Catastrophe Risk Modeler

Dr Celine Herweijer – Principal Scientist, Future Climate

Risk Management Solutions Ltd., London, UK

Challenges in Weather-Related Cat Modeling

❑ **Challenge #1 – Develop accurate model components that are feasible – choose appropriately from spectrum of models:**

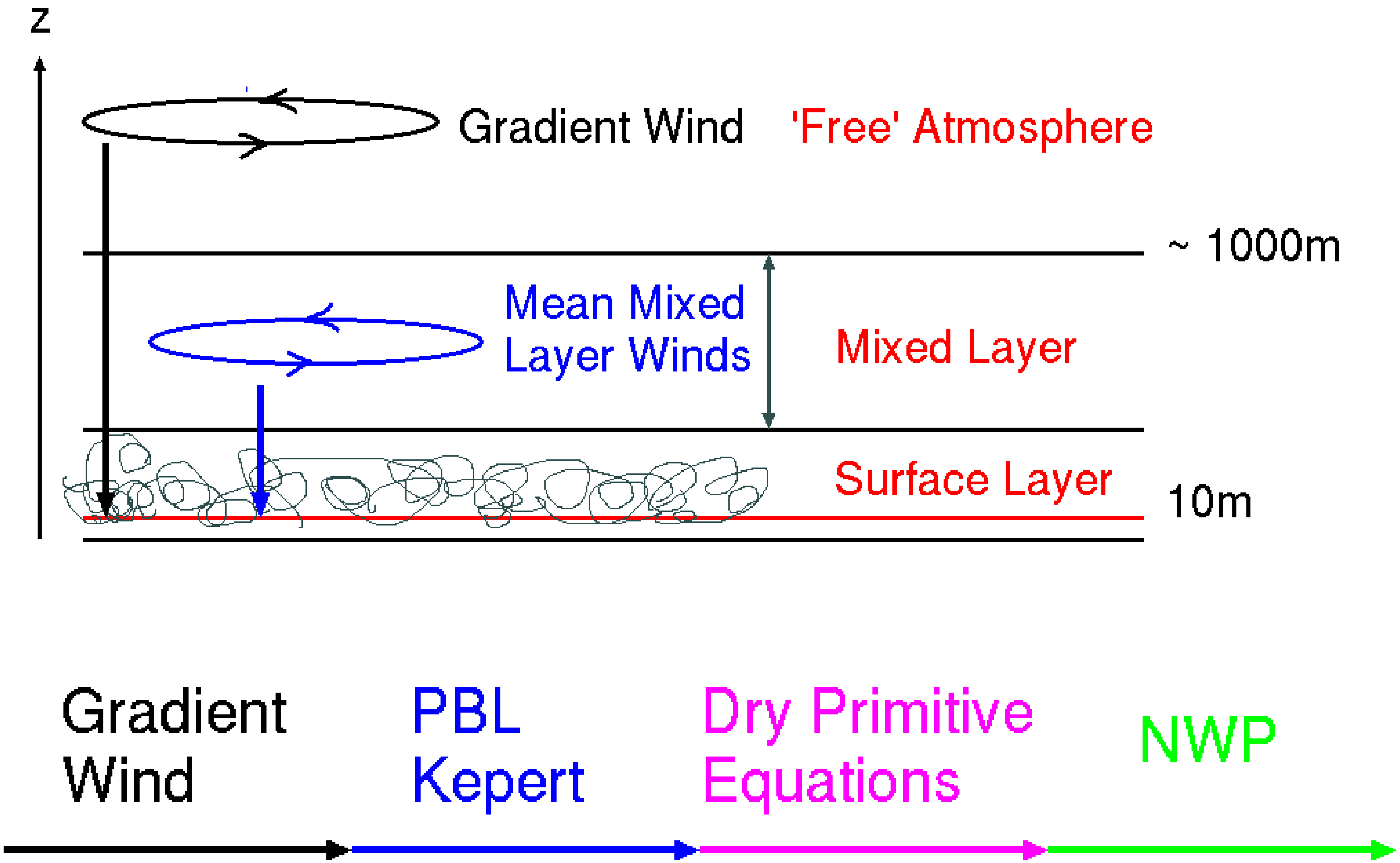


- **Modelling hurricane winds - millions of simulations needed!**
- **Example from hurricane rate prediction**

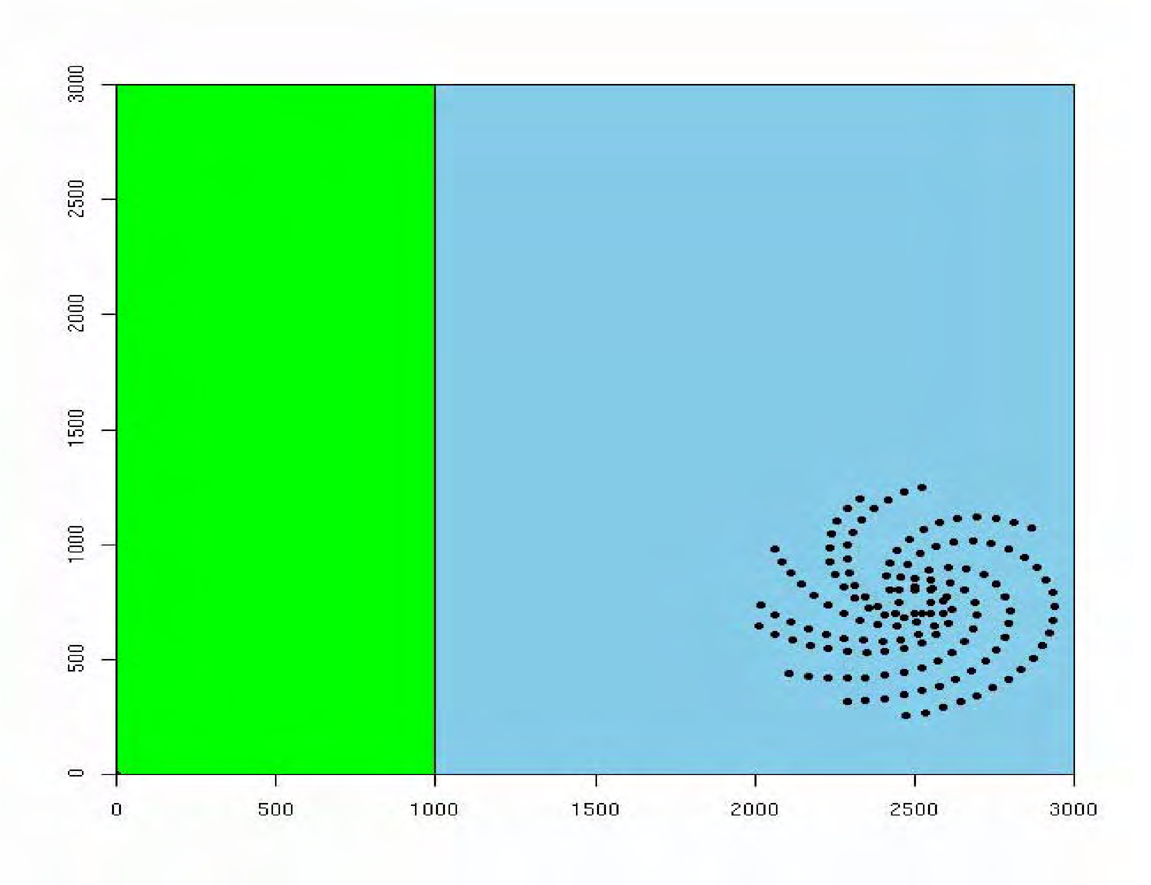
❑ **Challenge #2: Dealing with annual to inter-decadal climatic variability**

- **NAO, El Nino, AMO**, ...

Hurricane Wind Modeling



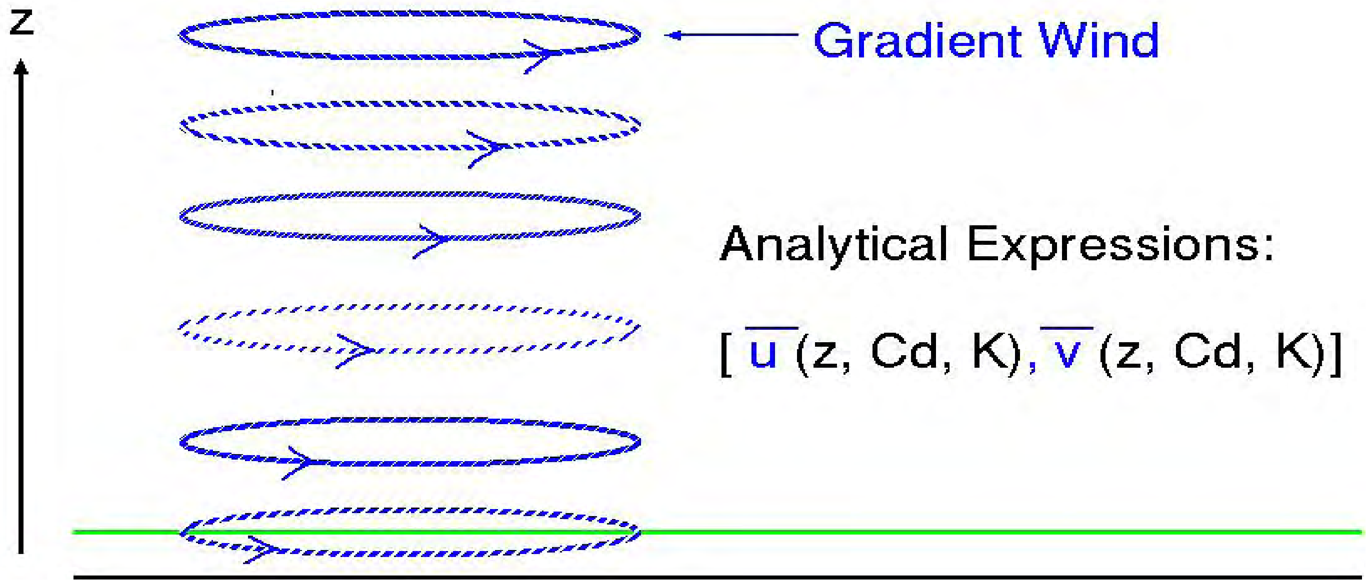
Planetary Boundary Layer Models



$$\frac{\partial \overline{u}}{\partial t} + \overline{u}\frac{\partial \overline{u}}{\partial r} + \frac{\overline{v}}{r}\frac{\partial \overline{u}}{\partial \theta} - \frac{\overline{v}^2}{r} - f\,\overline{v} = -\frac{1}{\rho_o}\frac{\partial p}{\partial r} - \frac{F(c,\overline{u})}{H}$$

$$\frac{\partial \overline{v}}{\partial t} + \overline{u}\frac{\partial \overline{v}}{\partial r} + \frac{\overline{v}}{r}\frac{\partial \overline{v}}{\partial \theta} + \frac{\overline{u}\,\overline{v}}{r} + f\,\overline{u} = -\frac{F(c,\overline{v})}{H}$$

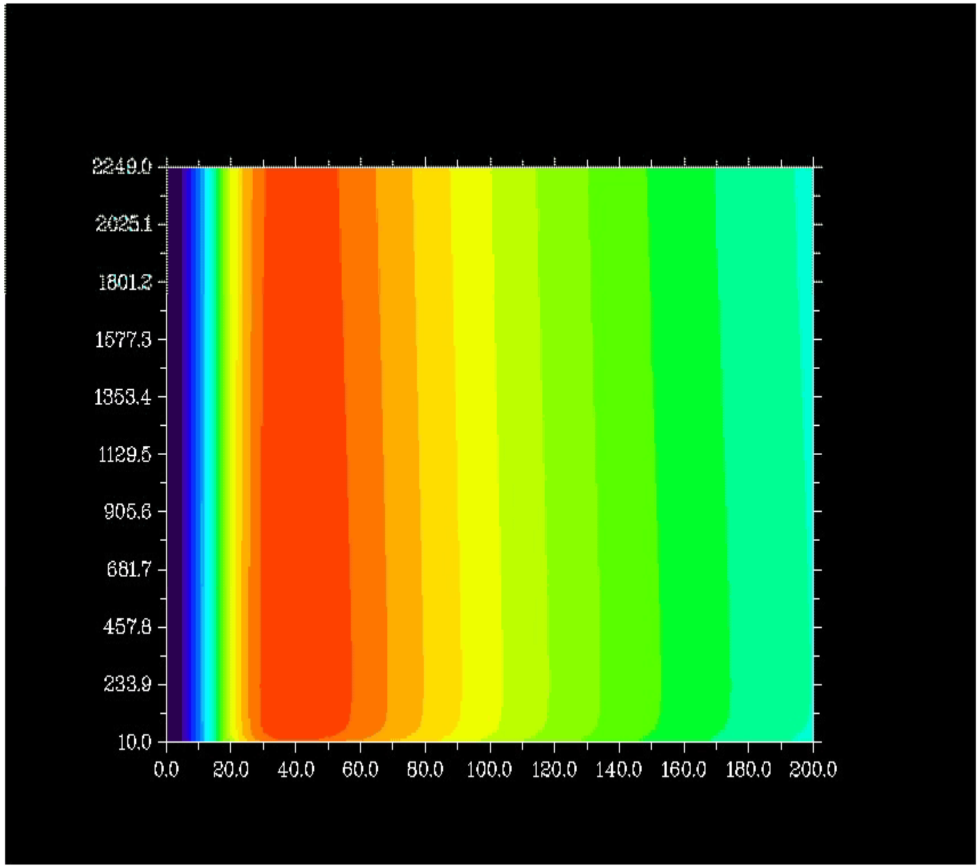
Kepert Linear Boundary Layer Model



$$\bar{u}\frac{\partial \bar{u}}{\partial r} + \frac{\bar{v}}{r}\frac{\partial \bar{u}}{\partial \theta} + \bar{w}\frac{\partial \bar{u}}{\partial z} - \frac{\bar{v}^2}{r} - f\bar{v} = -\frac{1}{\rho_o}\frac{\partial p}{\partial r} + K\frac{\partial^2 \bar{u}}{\partial z^2}$$

$$\bar{u}\frac{\partial \bar{v}}{\partial r} + \frac{\bar{v}}{r}\frac{\partial \bar{v}}{\partial \theta} + \bar{w}\frac{\partial \bar{v}}{\partial z} + \frac{\bar{u}\bar{v}}{r} + f\bar{u} = K\frac{\partial^2 \bar{v}}{\partial z^2}$$

‘Dry’ Primitive Equations Model



$$\frac{du}{dt} = fv - \theta\frac{\partial \pi}{\partial x} - g\left(1 - \frac{z^*}{z_t}\right)\frac{\partial z_s}{\partial x} + K_h \nabla^4 u + \left(\frac{z_t}{z_t - z_s}\right)^2 \frac{\partial}{\partial z^*}\left(K_v \frac{\partial u}{\partial z^*}\right)$$

$$\frac{dv}{dt} = -fu - \theta\frac{\partial \pi}{\partial y} - g\left(1 - \frac{z^*}{z_t}\right)\frac{\partial z_s}{\partial y} + K_h \nabla^4 v + \left(\frac{z_t}{z_t - z_s}\right)^2 \frac{\partial}{\partial z^*}\left(K_v \frac{\partial u}{\partial z^*}\right)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w^*}{\partial z^*} = \frac{u}{z_t - z_s}\frac{\partial z_s}{\partial x} + \frac{v}{z_t - z_s}\frac{\partial z_s}{\partial y}$$

$$\frac{d\theta}{dt} = K_h \nabla^4 v + \left(\frac{z_t}{z_t - z_s}\right)^2 \frac{\partial}{\partial z^*}\left(K_v \frac{\partial \theta}{\partial z^*}\right)$$

$$\frac{\partial \pi}{\partial z^*} = -\left(1 - \frac{z_s}{z_t}\right)\frac{g}{\theta}$$

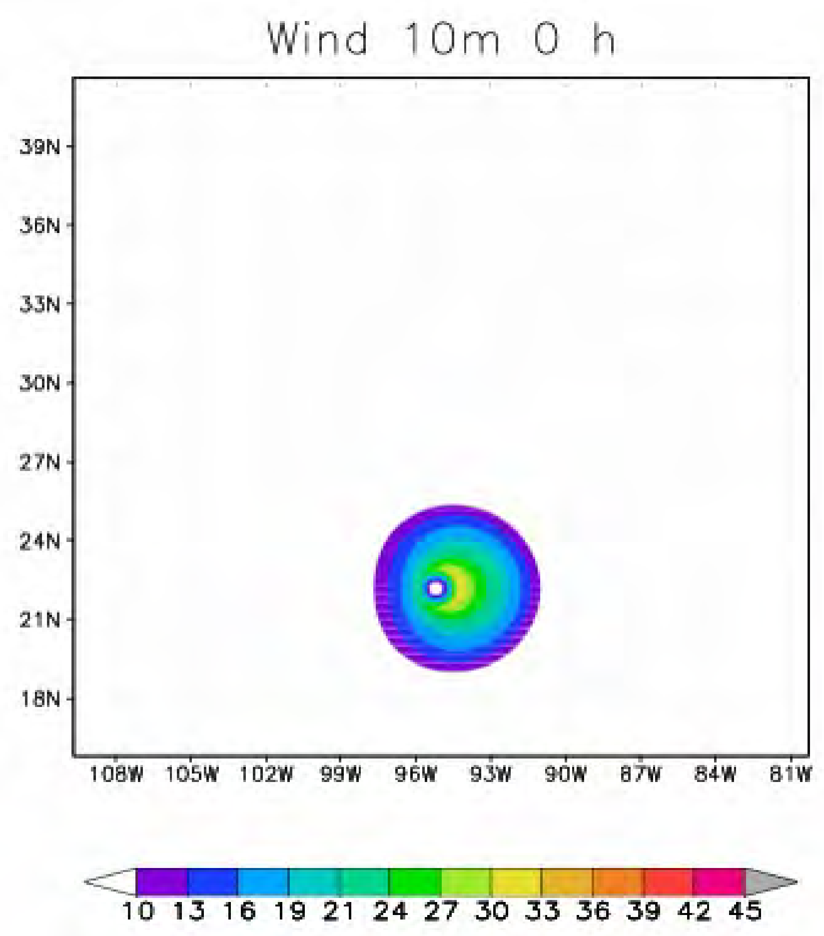
$$\frac{d}{dt} \equiv \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w^*\frac{\partial}{\partial z^*}$$

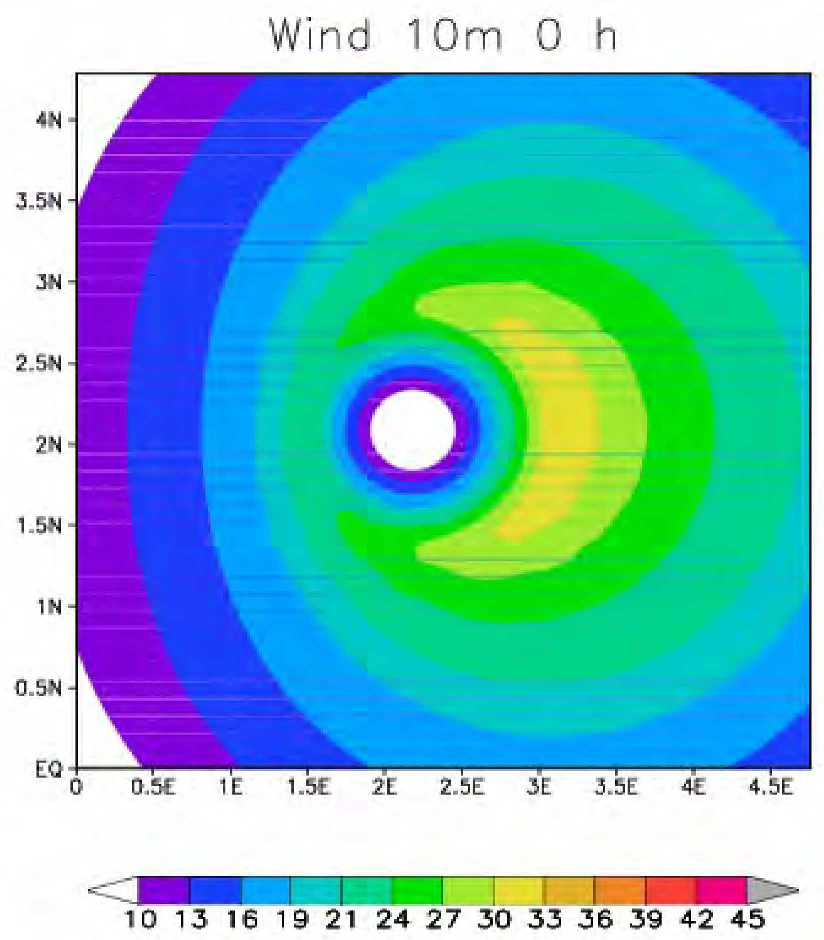
$$\pi = C_p\left(\frac{p}{p_o}\right)^{R/C_p}$$

$$w = \left(1 - \frac{z_s}{z_t}\right)w^* + \left(1 - \frac{z^*}{z_t}\right)\left(u\frac{\partial z_s}{\partial x} + v\frac{\partial z_s}{\partial y}\right)$$

Dry primitive equations model being developed in-house at RMS

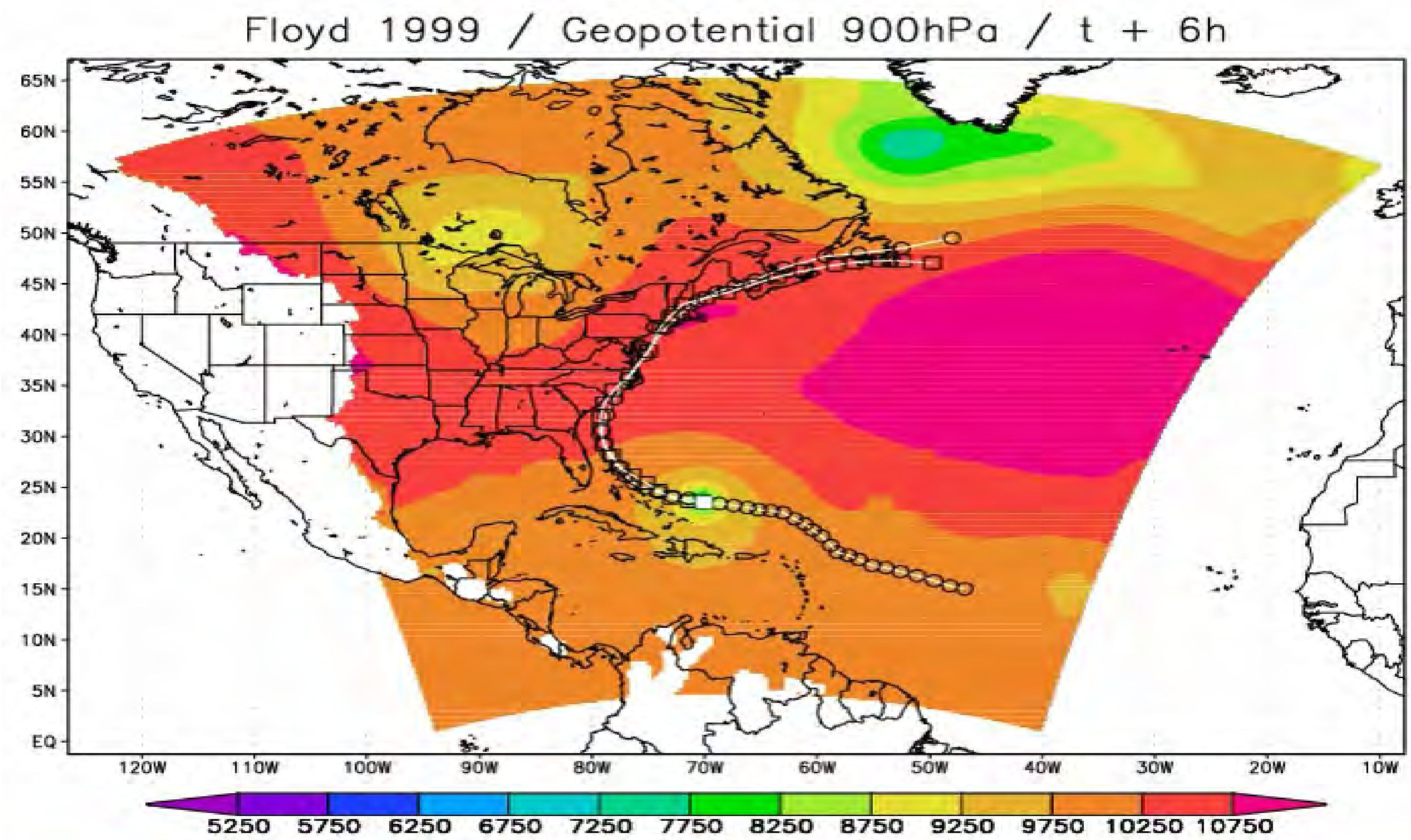
Numerical Weather Prediction Models





- ❑ Simulation using Weather Research and Forecasting Model

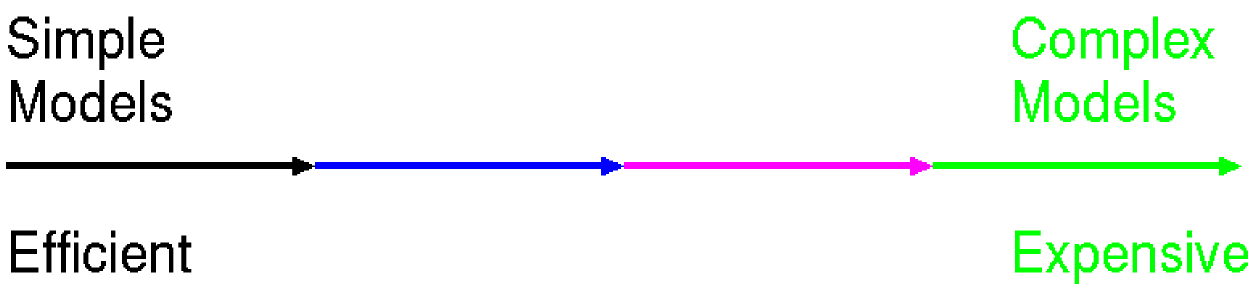
Modeling Transitioning Storms



- Simulation using Weather Research and Forecasting Model

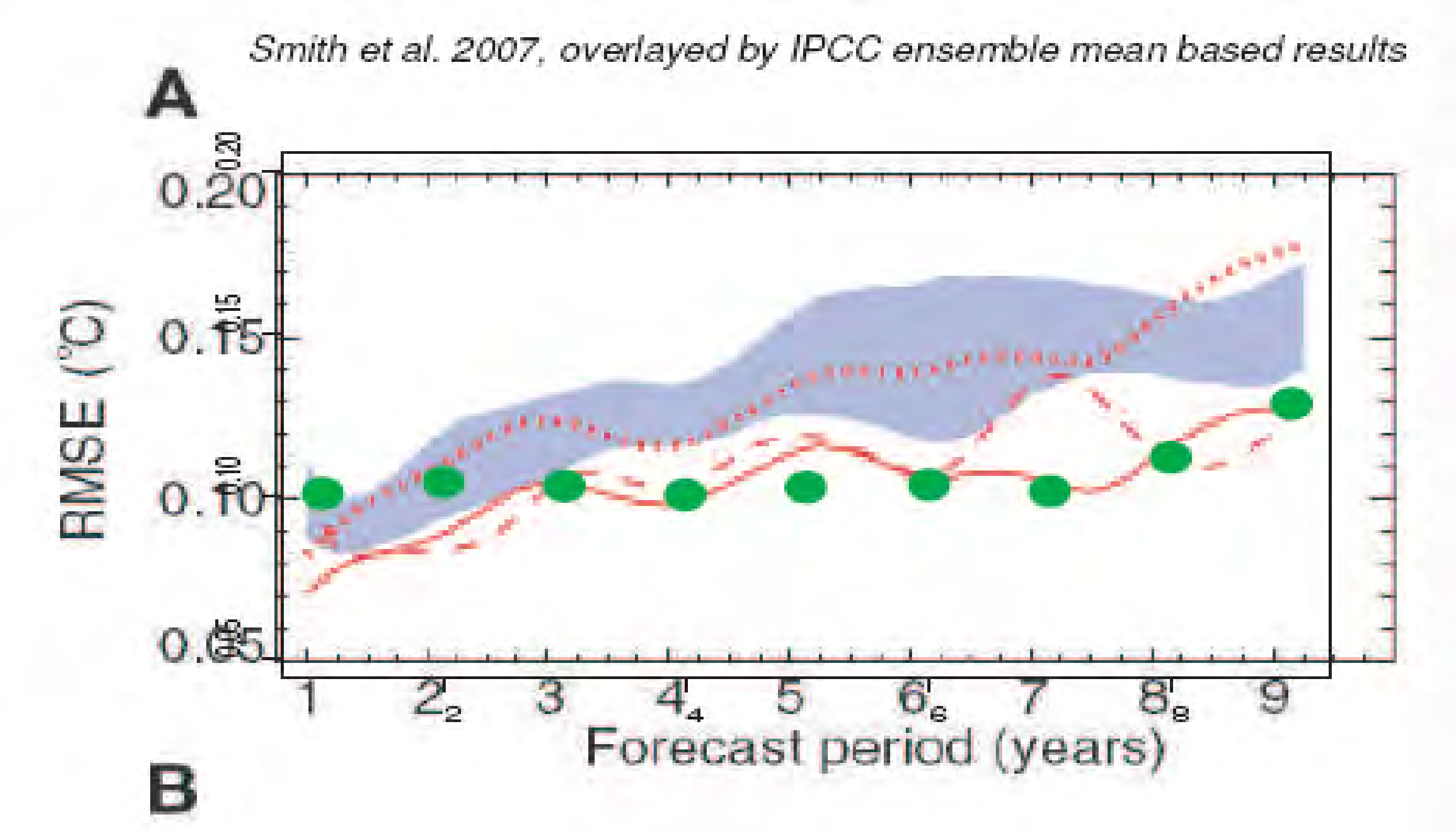
Remarks

- We need: Accurate model components that are feasible
- *Challenge* to make appropriate use of model hierarchy
- Models are **extremely** sensitive to small component changes!
- Must use data to perform model selection/validation
- Hurricane wind field data sources: H*Wind, Buoy, Metar, C-Man, FCMP, Texas Tech …
- A striking example from a recent Science paper …



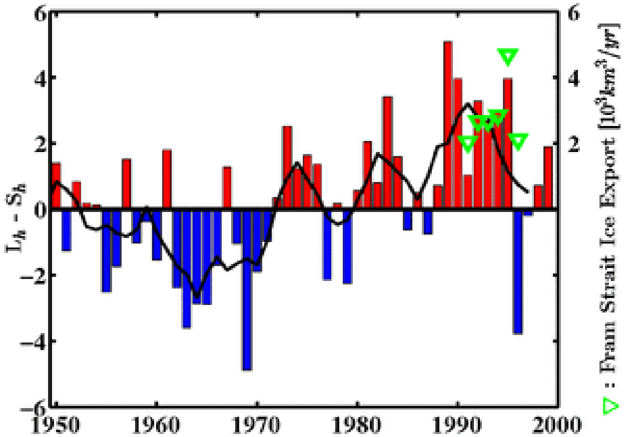
ST Prediction: Simple vs. Complex Methods

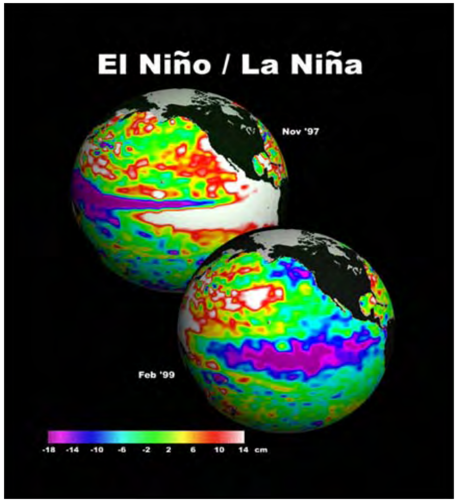
- **"Improved Surface Temperature Prediction for the Coming Decade from a Global Climate Model" by: Smith et al., 2007, Science**

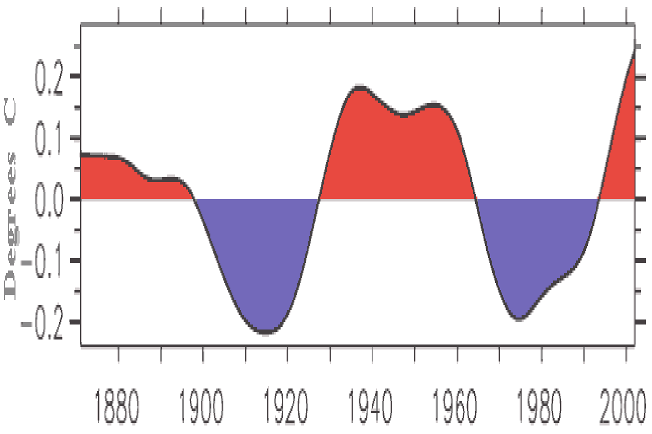


Annual to Inter-Decadal Variability

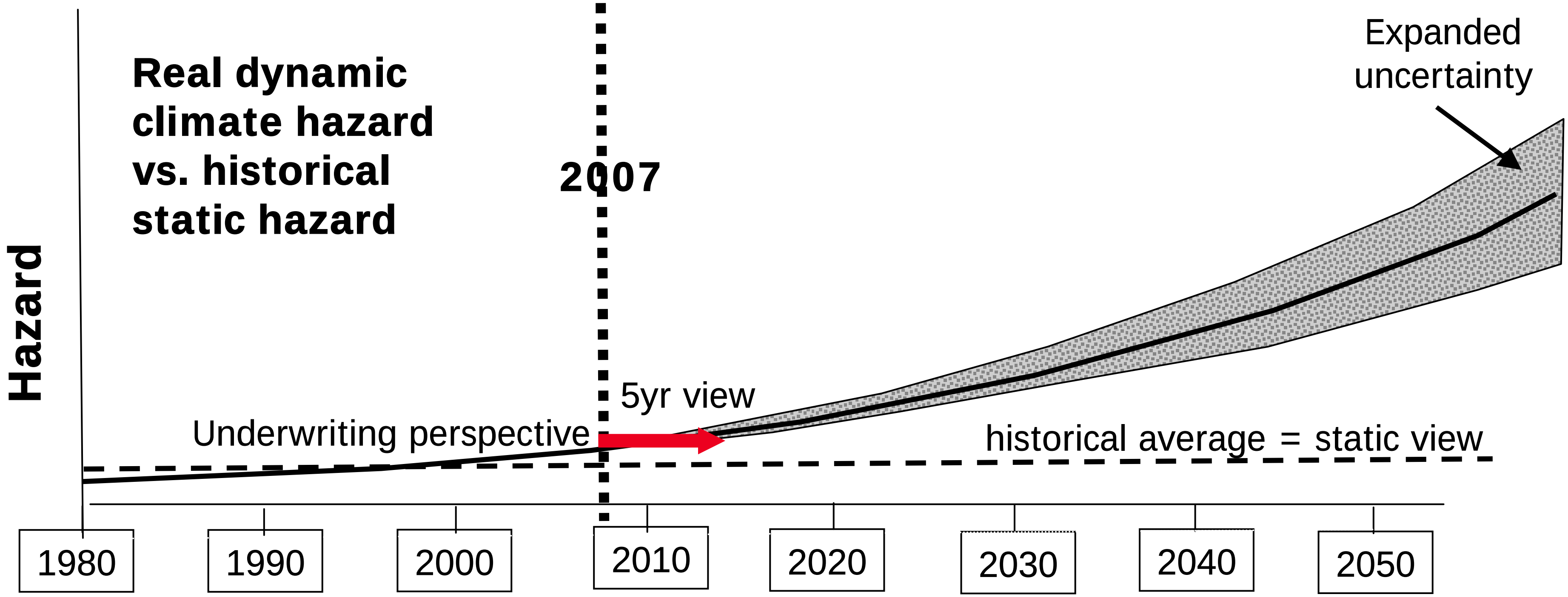
- *Challenge*: Accounting for NAO, El Nino and AMO
- Requirement: <u>Predictability on time-scales of interest</u>
- Uncertainty driven by such variability presents exciting opportunities for players in the marketplace
- RMS is making extensive efforts to incorporate such variability: Particularly in <u>Hurricane Rate Prediction</u> – Annual Expert Elicitation







The Insurance Perspective: How are climate trends incorporated into RMS models?

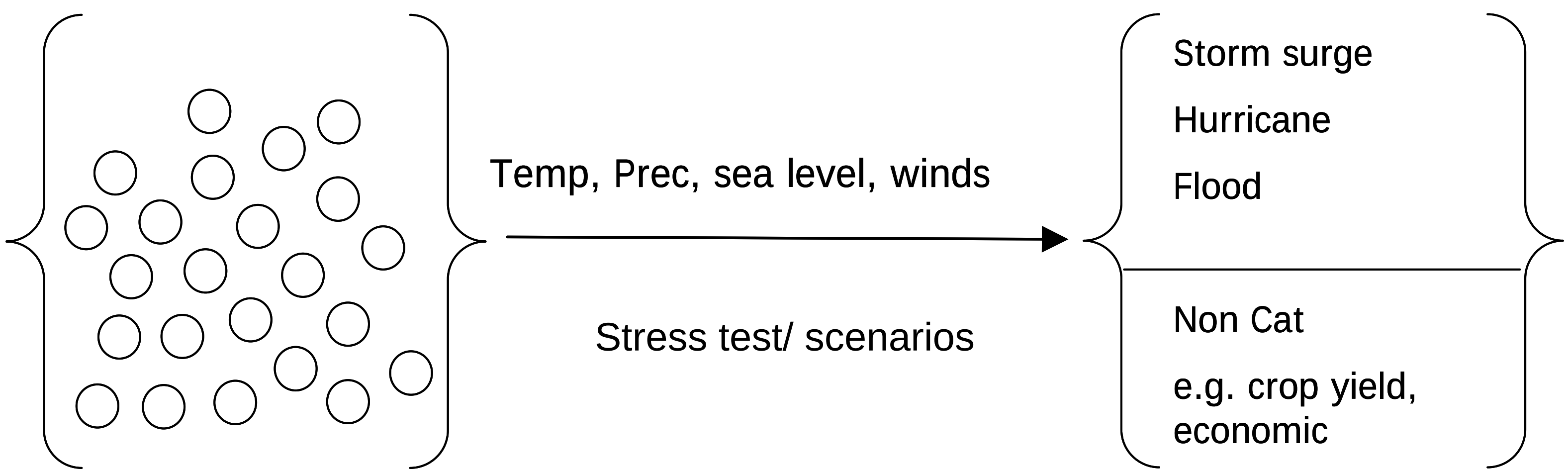


- **For the 5-yr Risk Horizon:** For each peril and region, RMS is investigating whether a climate trend is already occurring and how best to adjust from the long-term baseline
- e.g. U.S. HU activity rates 2007-2011; Germany FL, UK FL '08; other climate perils to follow…

Coupling Climate Models and Cat/Impact Models

- ‘future climate condition’ RMS cat/impact models to explore risk and value of adaptation in 2020 and beyond

Climate models: Impact models:

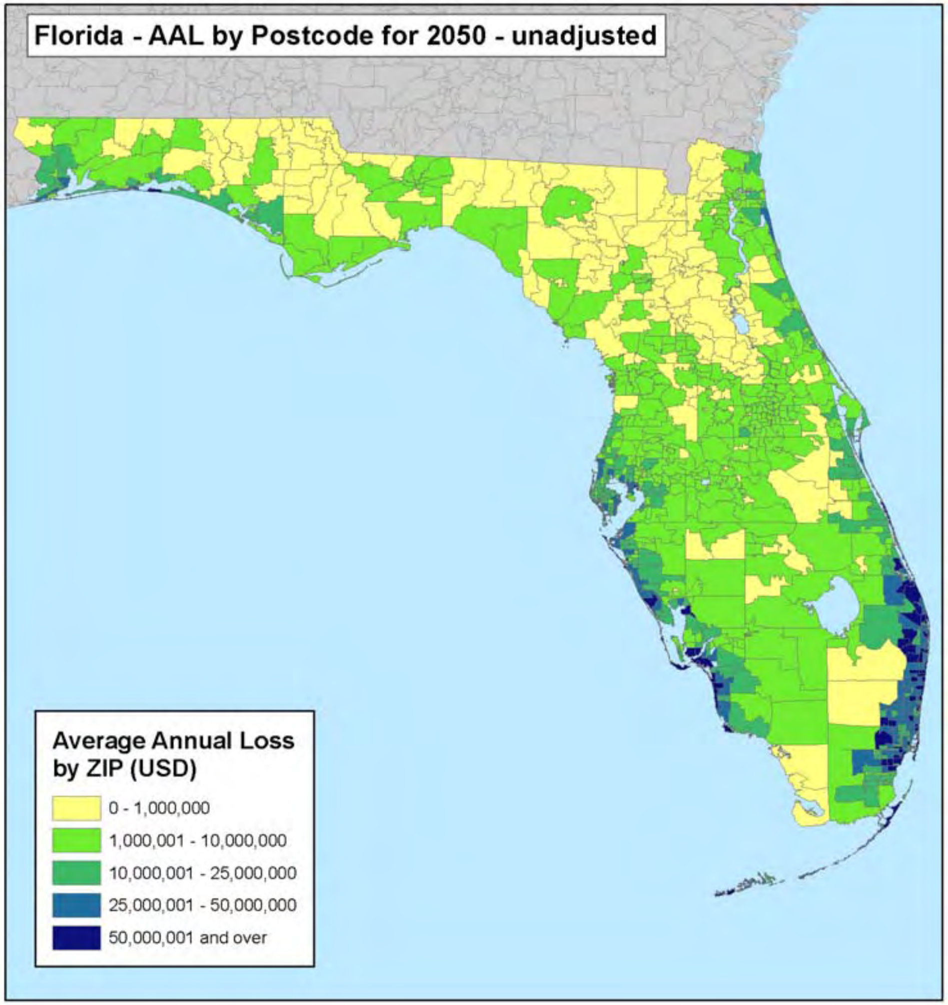


Ideal case: need large ensemble size, multiple models and high resolution

→ Use to explore future risk costs

e.g. Scenarios for Future Hurricane Losses in FL in 2050

- ❑ INPUT: 2050's HU activity rates and 0.5m of sea level rise
- ❑ Can investigate:
  - – How much could future losses could rise?
  - – How do exposure growth projections influence future losses?
  - – Where should adaptation be focused?
  - – Which adaptation measures work best?:
    - Risk-driven land use policy
    - Different ways of increasing infrastructure resilience



Going Forward: How Best to ‘Condition’ Cat Models for 2020?

- Want to know how risk of extreme events changes, not best prediction for 2020
- What Cat Modelers need from climate modeling community:
  - large ensembles (100’s-1000’s) of simulations to quantify trends in risk of events in the tail (1/20 – 1/100+yr events)
  - high spatial (forecast) resolution to simulate the relevant meteorological phenomena with sufficient realism
- How could this be achieved? (see accompanying Allen et al. note)

✗ decadal forecasting and multi-century runs of fully coupled coarse resolution models ✗

✓ derived from probabilistic event attribution approach - baseline ensemble (forecast resoln. AGCMs; 1000+members) for current decade, & perturbed ensembles to simulate the 2020s using estimated anthropogenic trends in atmospheric composition and SSTs, allowing for uncertainty. Distributed computing power. ✓

Catastrophe Modeling Forum

New York, October 16-17, 2007

Dennis E. Kuzak
Senior Vice President, EQECAT, Inc

Key Insurance Perils

- Peak Perils
  - US Hurricane
  - California Earthquake
  - Europe Winterstorm
  - Japan Earthquake
- Off-Peak Perils (e.g.)
  - Japan Typhoon
  - Tornado & Hail
  - Floods
- Secondary Perils
  - Storm surge
  - Coastal flooding
  - Inland flooding
  - Tsunami
  - Fire following earthquake

Modeling Methodology

- General Approach
  - Historical data
  - Stochastic event set incorporating “smoothing” and uncertainty parameters
  - Models constrained to observed frequencies
  - Subject to the “Black Swan”
- Earthquake vs Wind Perils
  - Plate tectonic theory leads to use of geologic evidence in extending historical data
  - Long term (5 million years) earthquake slip rates appear constant
  - No global meterological analogy-what is the upper bound of storm frequencies and severities?

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Climatology Research Topics

- Historical Data
  - “paleo- meterological” investigations (sand depositions, tree rings, ice- cryosphere)
- Hurricane Landfall probabilities
  - Storm genesis-storm tracks
  - Upper level winds (jet stream)
  - Low pressure/High pressure regions
- Correlation between regions
  - Europe Winter storm vs Atlantic Hurricane
  - Atlantic Hurricane vs Western Pacific Typhoon

Modeling Challenges from Climate Change

- Consensus science unlikely
- Use of multiple models of frequency and severity
- Volatility vs trend line (one year vs 50 year view)
- Alternate loss models- frequency and severity sensitivity options

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Observational Evidence of Changes in the Frequency and Severity of Extreme Weather and Climate Events

Catastrophe Modeling Forum
Changing Climatic Dynamics and Catastrophe Model Projections
New York City, October 16-17, 2007

Jay H. Lawrimore, Climate Monitoring Branch
NOAA's National Climatic Data Center

Instrumental observations collected from the late 19th century to the present, and proxy sources covering the centuries before instrumental records, are essential for understanding past changes in the frequency and intensity of extreme weather and climate. They are also important to understanding how extremes may change in the future as the Earth's climate continues to warm under the influence of increasing greenhouse gas concentrations.

Weather and climate extremes affect societies, economies, and the environment in every nation of the world. Within the U.S. alone there were 70 weather-related disasters that caused overall damages exceeding $1 billion dollars from 1980-2006 (Lott and Ross, 2006).

Included among some of the most damaging extremes are those related to heavy precipitation, drought, wildfires, heat waves, tornadoes, and snow and ice storms.

Extreme Precipitation

- Precipitation amounts have increased in the U.S. and in many mid- and high latitude land areas of the world since 1900 (Lawrimore and Levinson, 2007)

- In many parts of the world, precipitation falling during extreme precipitation episodes has increased at a faster rate than for precipitation as a whole. In the U.S., total precipitation increased by 6-7% in the 20th century, while the amount of precipitation falling in the heaviest 1% of rain events increased by 20% (Groisman et al., 2004)

- Enhanced rainfall rates increase the risk of runoff and flooding, but the implementation of mitigation practices, changes in land use, and increasing settlement in flood-prone areas complicate the detection of trends in flooding (Trenberth et al., 2003).

Drought

- There is evidence that the incidence of severe drought has increased globally in the past 30 years (Dai et al., 2004).

- While there are regional differences and multi-decadal variations in the frequency and severity of drought in the U.S., there has been no observed increase in drought for the nation as a whole in the 20th century (NCDC, 2007).

- Recent increases in drought severity and expanse in the western U.S. have resulted in widespread impacts. In addition to billions of dollars of losses and other impacts within sectors that include agriculture, energy, and tourism, the number of acres burned by wildfire in the U.S. has reached new record highs in each of the past three years (NCDC, 2007).

- Proxy sources of precipitation provide evidence that droughts more severe than the Dust Bowl droughts of the 1930s have occurred many times in the past 1000 years (Woodhouse and Overpeck, 1998). This indicates that events more severe and wide-ranging than the worst droughts of the 20th century could recur in the future even without the influence of a warming climate.

Heat Waves

- While the global temperature has risen at a rate slightly higher than 1°F/Century since 1900, the rate of increase has been approximately three times faster since the 1970s (Menne and Peterson, 2007).

- The rise in the mean temperature of the Earth has shifted the distribution of temperature and made the occurrence of once rare heat extremes more common (Peterson et al. 2007).

- A heatwave as severe as the European heat wave of 2003 occurring in the U.S. in the month of August would likely result in more than 1000 excess deaths in New York City alone (Kalkstein et al., 2007).

Extratropical Storms

- A pole-ward shift in the Atlantic and Pacific storm tracks has been observed. Several studies have identified a decrease in the frequency of extra-tropical cyclones in the mid-latitudes while finding an increase in frequency in high-latitude regions (e.g., Wang et al. 2006).

- There has been a northward shift in snowstorm occurrence in the U.S. since 1900, with upward trends occurring in the Northeast and Upper Midwest, while trends in the Southeast and Midwest have been negative (Changnon et al., 2006).

- The increase in the total number of tornadoes in the U.S. over the past 50 to 60 years can be attributed mostly to improving observing technologies and reporting practices. There is no evidence that the frequency of very strong to violent tornadoes has increased (Gleason and Bell, 2005).

References

Changnon, S.A., D. Changnon, and T. Karl, 2006: Temporal and spatial characteristics of snowstorms in the contiguous United States., *Journal of Applied Meteorology and Climatology*, **45**, 1141-1155.

Dai, A., K.E. Trenberth, and T. Qian, 2004: A global dataset of Palmer Drought Severity Index for 1870–2002: Relationship with Soil Moisture and Effects of Surface Warming. *Journal of hydrometeorology,* **5** (6) 1117-1130.

Gleason, K.L. and G.D. Bell, 2007: U.S. Climate. *State of the Climate in 2004*, A. Arguez, Ed., *Bulletin of the American Meteorological Society*, **86**(6), S47-S52.

Groisman, P.Y., R.W. Knight, T.R. Karl, D.R. Easterling, B. Sun, J.H. Lawrimore, 2004: Contemporary changes of the hydrological cycle over the contiguous United States, trends derived from in situ observations. *Journal of hydrometeorology,* **5** (1) 64-85.

Kalkstein, L.S., J.S. Greene, D.M. Mills, A.D. Perrin, J.P. Samenow, and J. Cohen, 2007: The development of analog European heat waves for U.S. cities to analyze impacts on heat-related mortality, *Bulletin of the American Meteorological Society,* accepted.

Lawrimore, J.H., and D. H. Levinson, 2007: Global Precipitation. *State of the Climate in 2006*, A. Arguez, Ed., *Bulletin of the American Meteorological Society*, **88**(6), S14-S15.

Lott, N., and T. Ross, 2006: Tracking billion-dollar U.S. weather disasters. (Nowcast news and notes—conference notebook). *Bulletin of the American Meteorological Society,* **87** (5), 557-559.

Menne, M.J. and T.C. Peterson, 2007: Global Temperature. *State of the Climate in 2006*, A. Arguez, Ed., *Bulletin of the American Meteorological Society*, **88**(6), S14-S15.

NCDC, 2007: *Climate of 2006 in Historical Perspective*. Available from the National Climatic Data Center [http://www.ncdc.noaa.gov/oa/climate/research/2006/ann/ann06.html]

Peterson, T.C. X. Zhang, M. Brunet India, J.L. Vazquez Aguirre, 2007: Changes in North American extremes derived from daily weather data. *Proceedings of the National Academy of Science*, submitted.

Trenberth, K.E., A. Dai, R.M. Rasmussen, and D.B. Parsons, 2003: The Changing Character of Precipitation. *Bulletin of the American Meteorological Society*, **84**(9), 1205-1217.

Wang, X.L., V.R. Swail, and F.W. Zwiers, 2006: Climatology and changes of extratropical storm tracks and cyclone activity. Comparison of ERA-40 with NCEP/NCAR reanalysis for 1958-2001. *Journal of Climate*, 19, 3145-3166.

Woodhouse, C.A. and J.T. Overpeck, 1998: 2000 Years of drought variability in the central United States. *Bulletin of the American Meteorological Society*, **79** (12), 2693-2714.

Observed Trends in Climate Extremes

Jay Lawrimore
NOAA's National Climatic Data Center

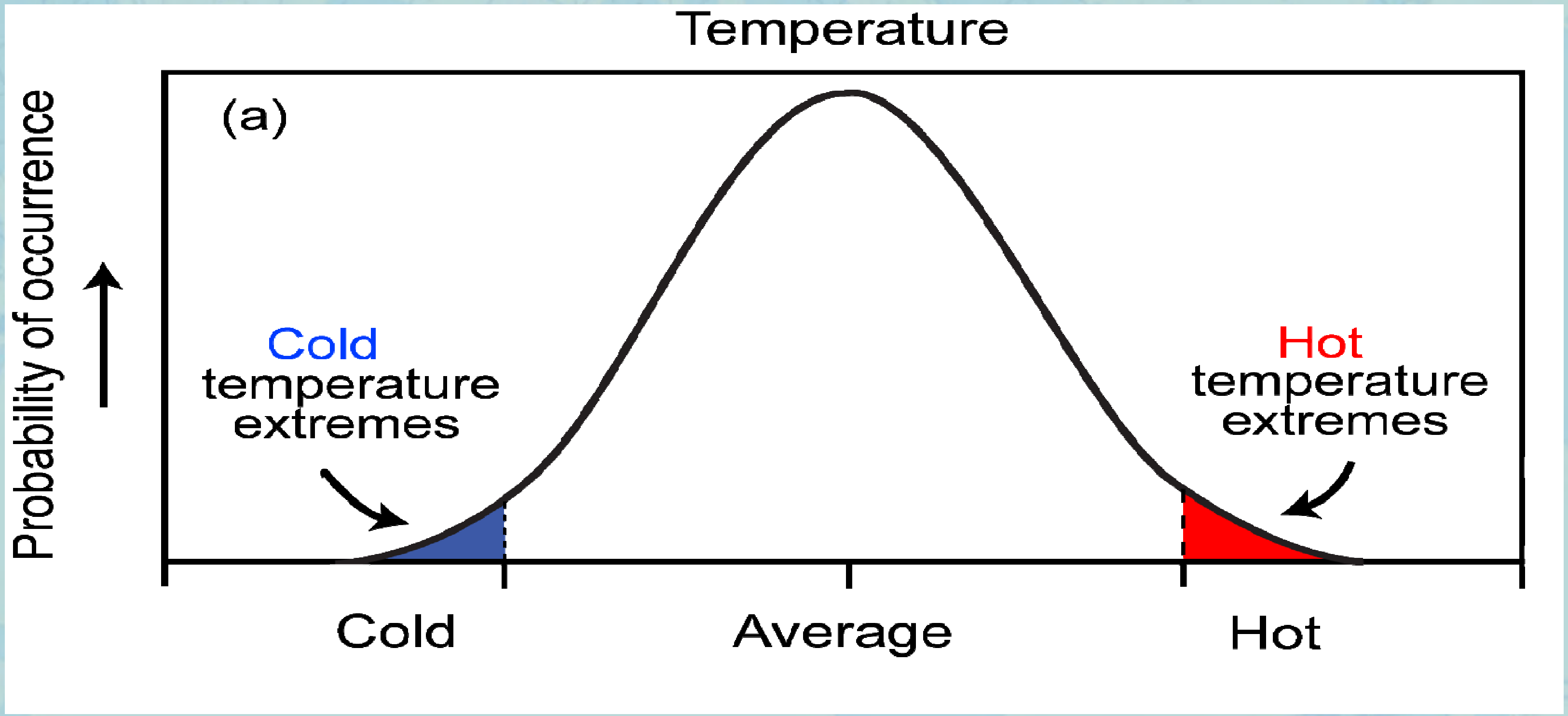
Overview

- Heat waves
- Heavy Precipitation
- Drought
- Wildfires
- Tornadoes

Mean Changes in Temperature

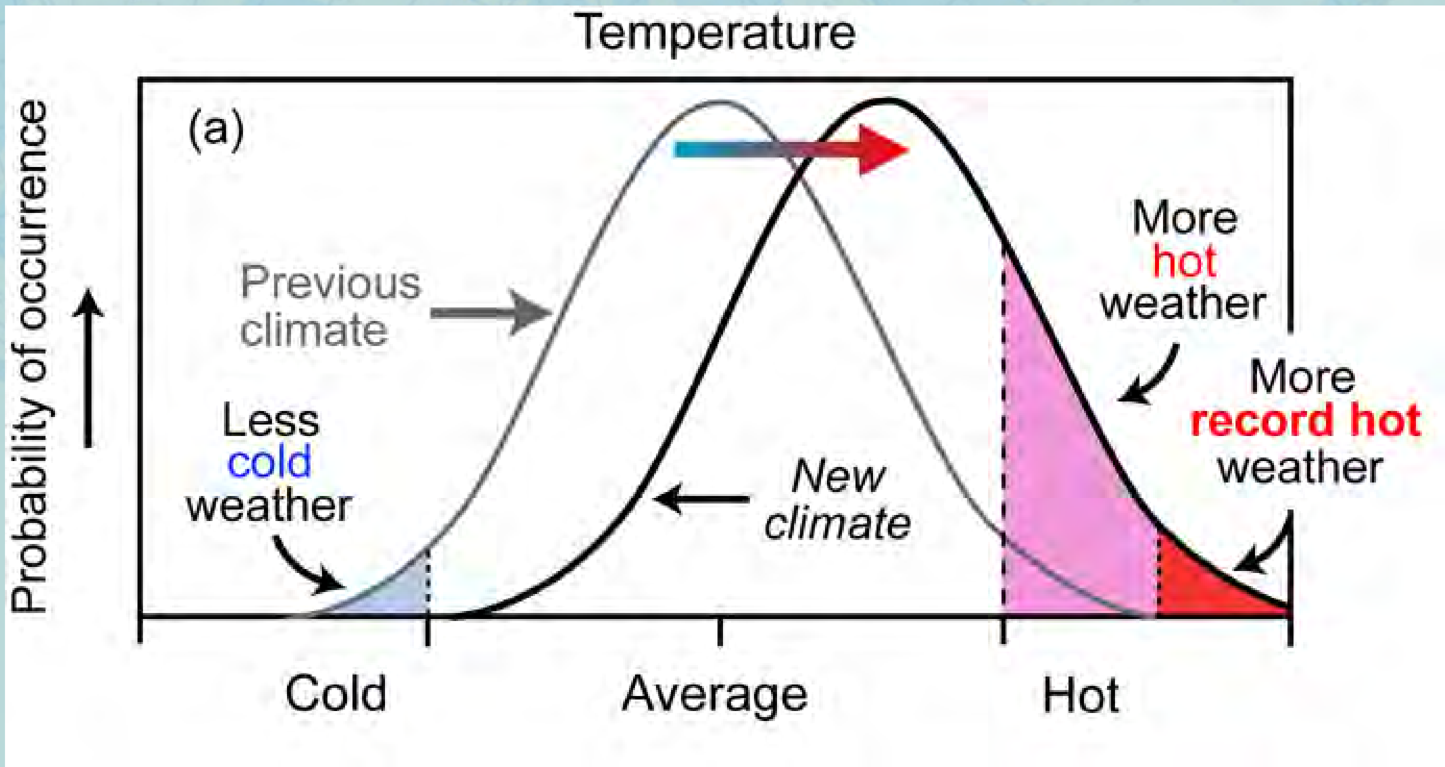
- Global and U.S. Mean Temperature rose approximately 1˚F during the 20th century and the rate of increase has been approximately 3 times higher in the past 30 years.

Normal Distribution of Temperatures



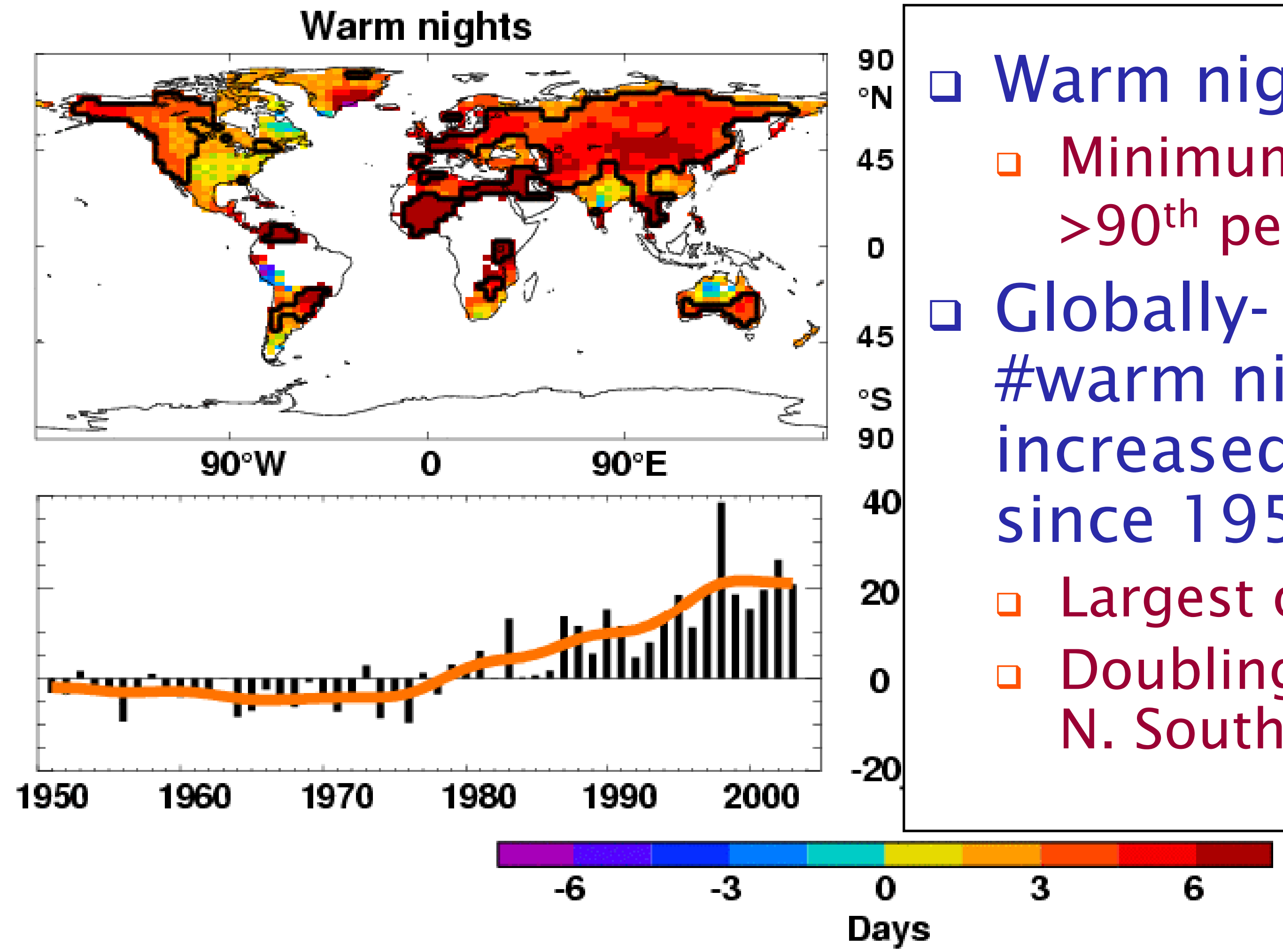
Few really hot or cold days: But the extremes impact people more than mean temperature

As Mean Temperature Increases - *Extremes Become More Common*



Observed and Projected changes –
Less cold weather, More hot weather

Affect of Warming on Temperature Extremes



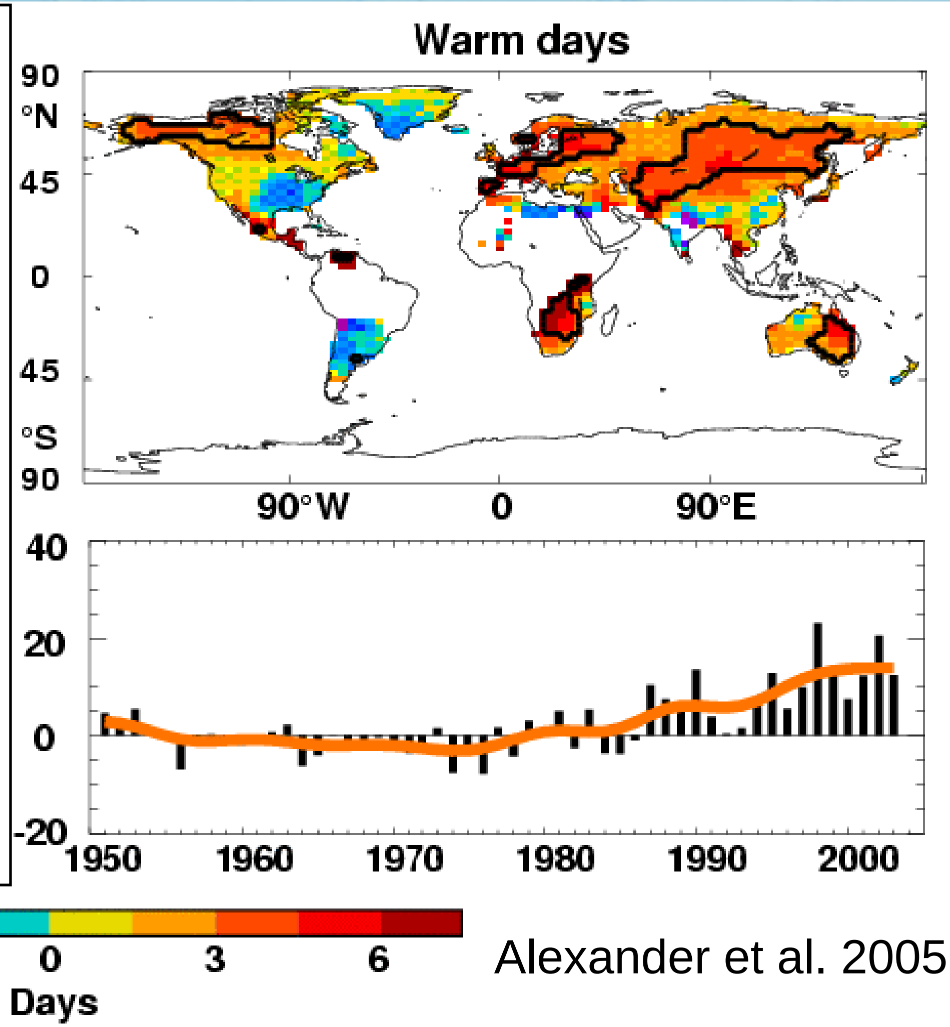
- Warm nights
  - Minimum daily temp >90th percentile
- Globally- Annual #warm nights increased ~25 days since 1951
  - Largest over Eurasia
  - Doubling over N. Africa, N. South Am.

Alexander et al. 2005

- 1951-2003; At least 40 yrs of data required
- 74% of sampled land area showed an increase in warm nights

Affect of Warming on Temperature Extremes

- Warm days
  - Maximum daily temp >90th percentile
- Increasing trend not as large as #warm nights
- Larger areas of decreasing trends



Alexander et al. 2005

- 1951-2003; At least 40 yrs of data required
- Black lines enclose regions where trends significant at 5% level

Why should we care about extreme heat?

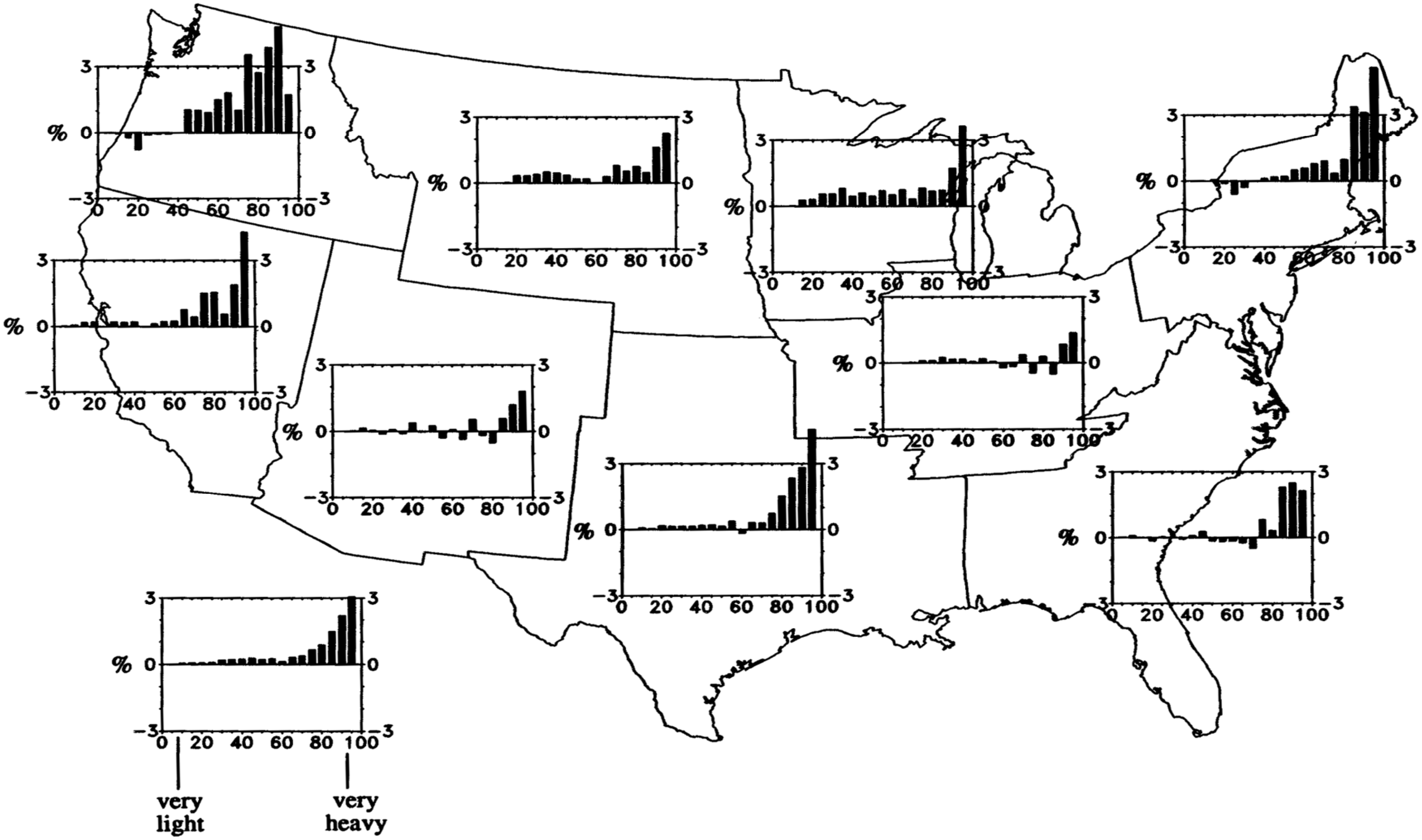
- Heat is the leading cause of weather-related deaths in the United States, responsible for more than 3,400 fatalities between 1999 and 2003.
  - Kalkstein and Greene, 2007, which was released September 6, 2007 and available from http://www.as.miami.edu/geography/Climatology/Heat-Mortality_Report_FINAL.PDF
- If a heatwave as severe as the European heatwave of 2003 struck the U.S. in August, the number of excess deaths in New York City alone would exceed 1000.
  - From Kalkstein *et al.* (2007) to be published in the December issue of the *Bulletin of the American Meteorological Society, which is available from:*
    - *http://www.as.miami.edu/geography/Climatology/BAMS_website.pdf*

Precipitation

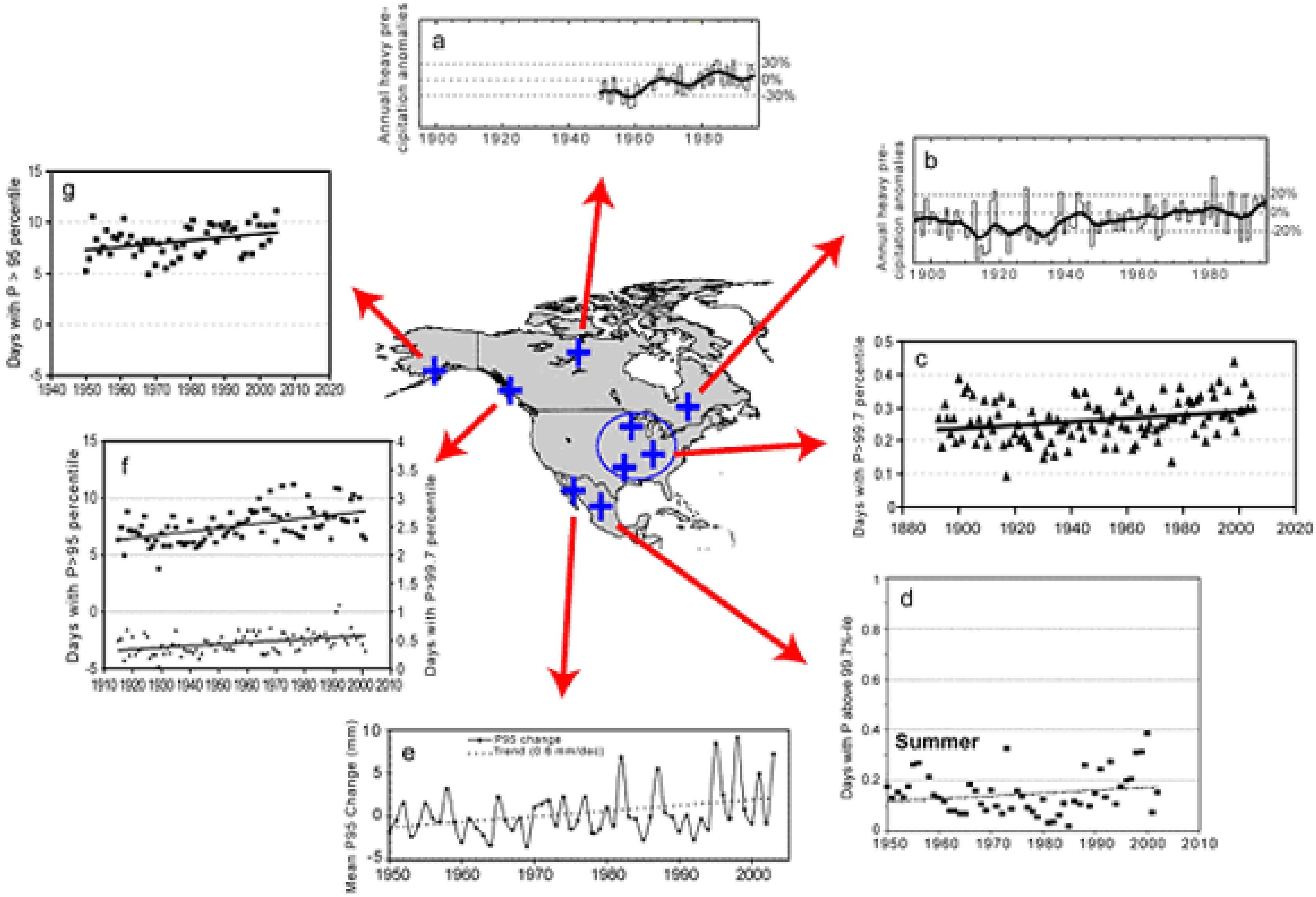
- Precipitation has increased in mid- and high latitudes of the Northern Hemisphere
- As the atmosphere has warmed it can hold more moisture (approximately 4% more for every degree of warming)
- This warmer and moister atmosphere provides the fuel for stronger storms
- Heavy and Extreme Precipitation events are increasing faster than precipitation as a whole

Precipitation Trends (% / Century) for Various Categories (Percentiles) of Precipitation Intensity

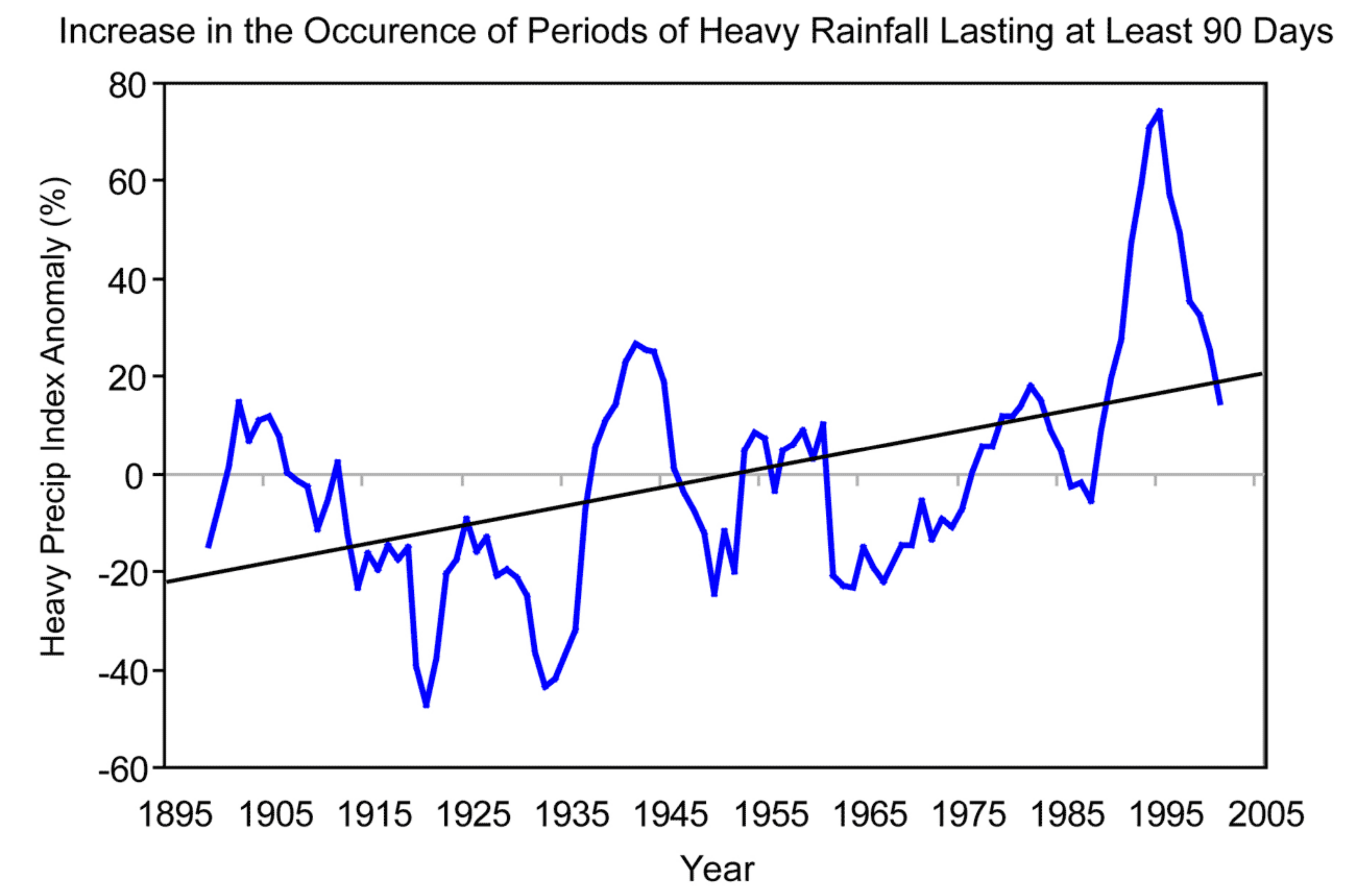
ANNUAL



Regions of N. America where Heavy and Very Heavy Precipitation has Increased



Persistent Heavy Rains



Costs of Flooding

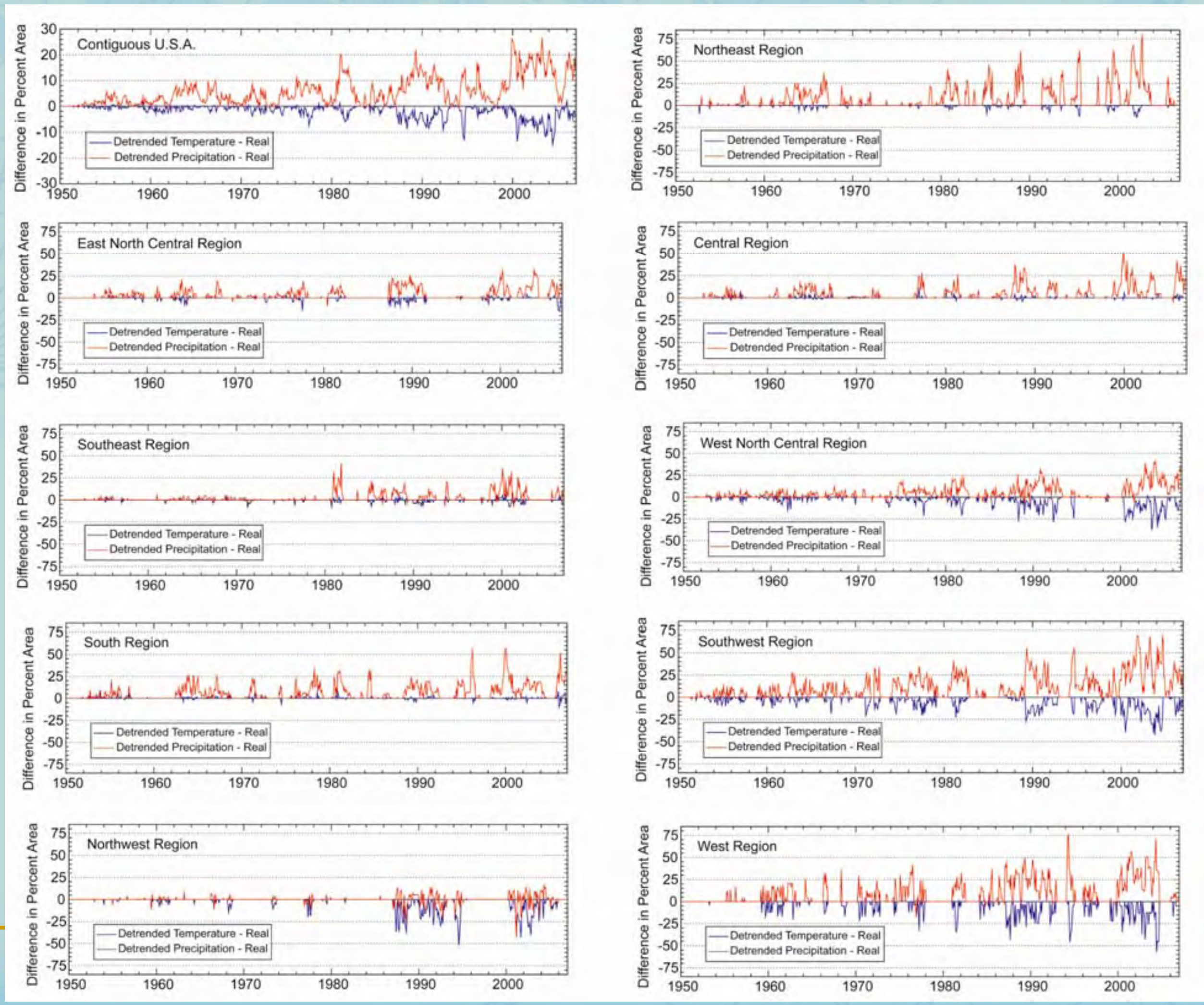
- Eight Billion Dollar Flooding Disasters in the U.S. from 1990 through 1998
  - Some due to months of heavy rainfall
    - Midwest, Summer 1993
    - California, Jan-Mar 1995
  - Some due to heavy rainfall over days
    - Texas, October 1994
    - Pacific NW, February 1996

Drought

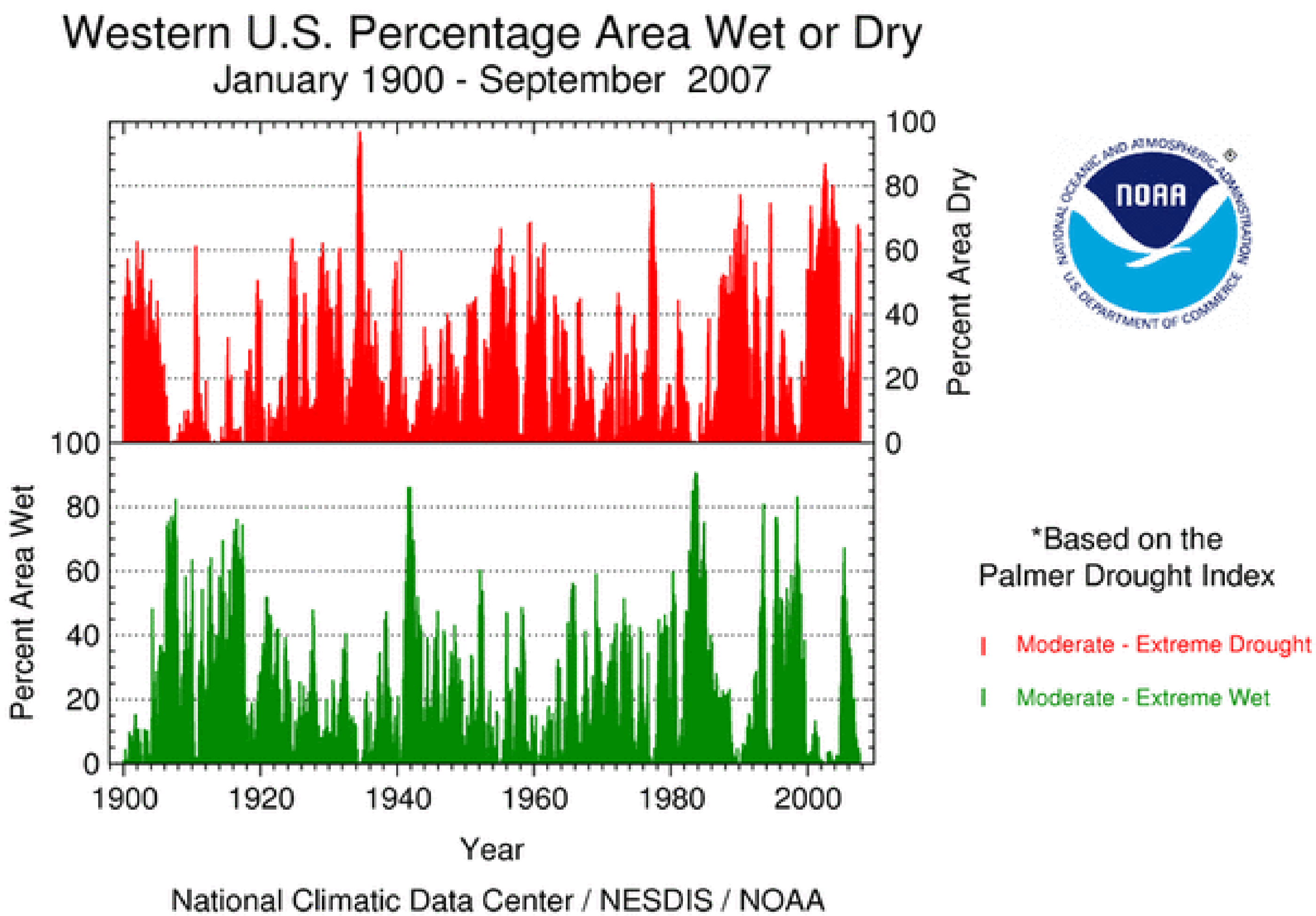
- In the U.S. drought affects more people than any other natural hazard and it is one of the most costly, with direct losses that average between $6-8 Billion each year
  - Federal Emergency Management Agency, 1995: *National Mitigation Strategy: Partnerships for Building Safer Communities*. Washington, D.C.

- Drought has plagued the Western U.S. for the last 8 to 9 years.
- Drought has covered at least half of the contiguous U.S. in 3 of the past 8 years.
- Warming temperatures are exacerbating naturally occurring droughts.

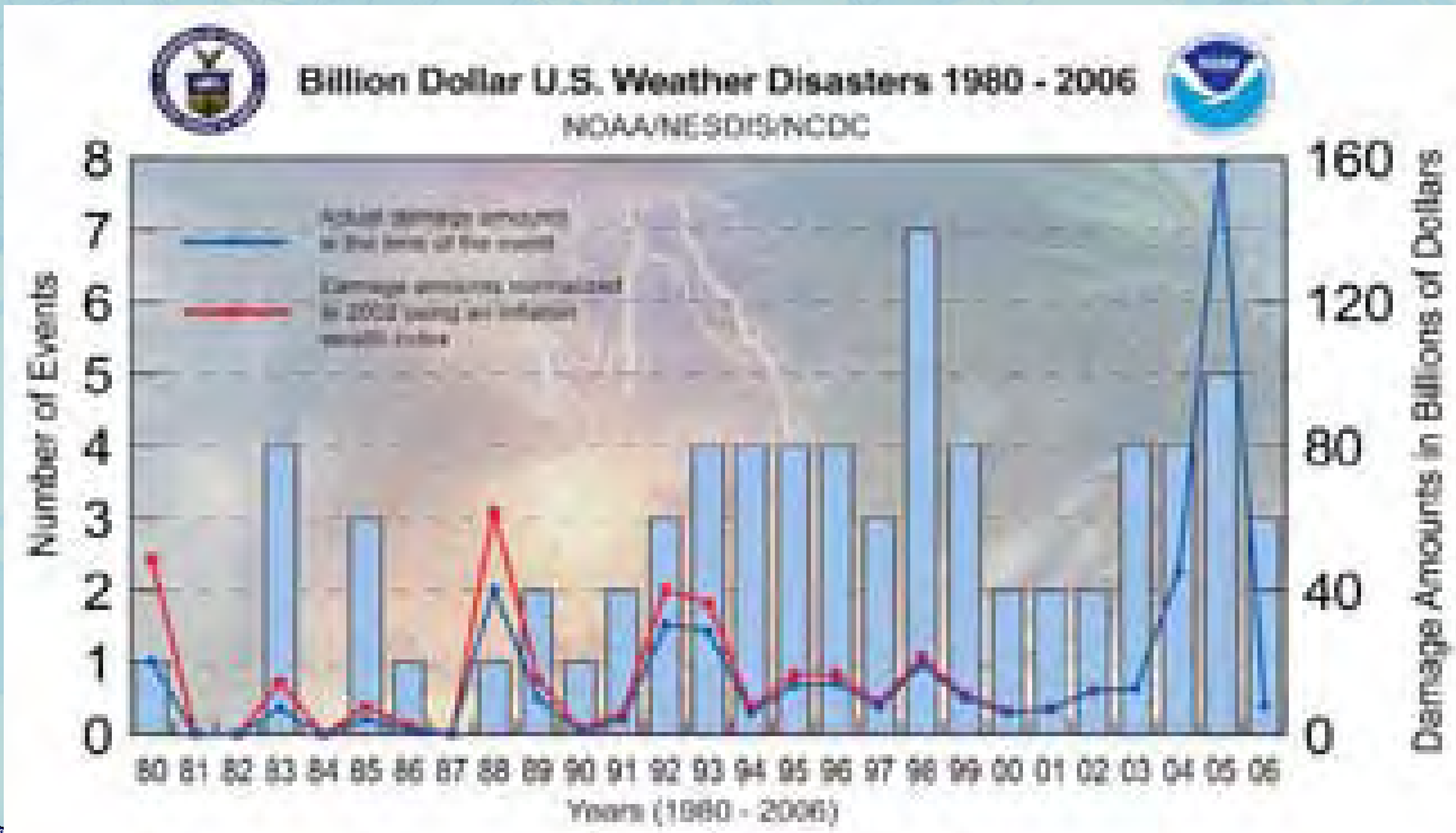
Increasing Temps=> More Widespread Droughts



Drought and Extreme Wetness – Western U.S.



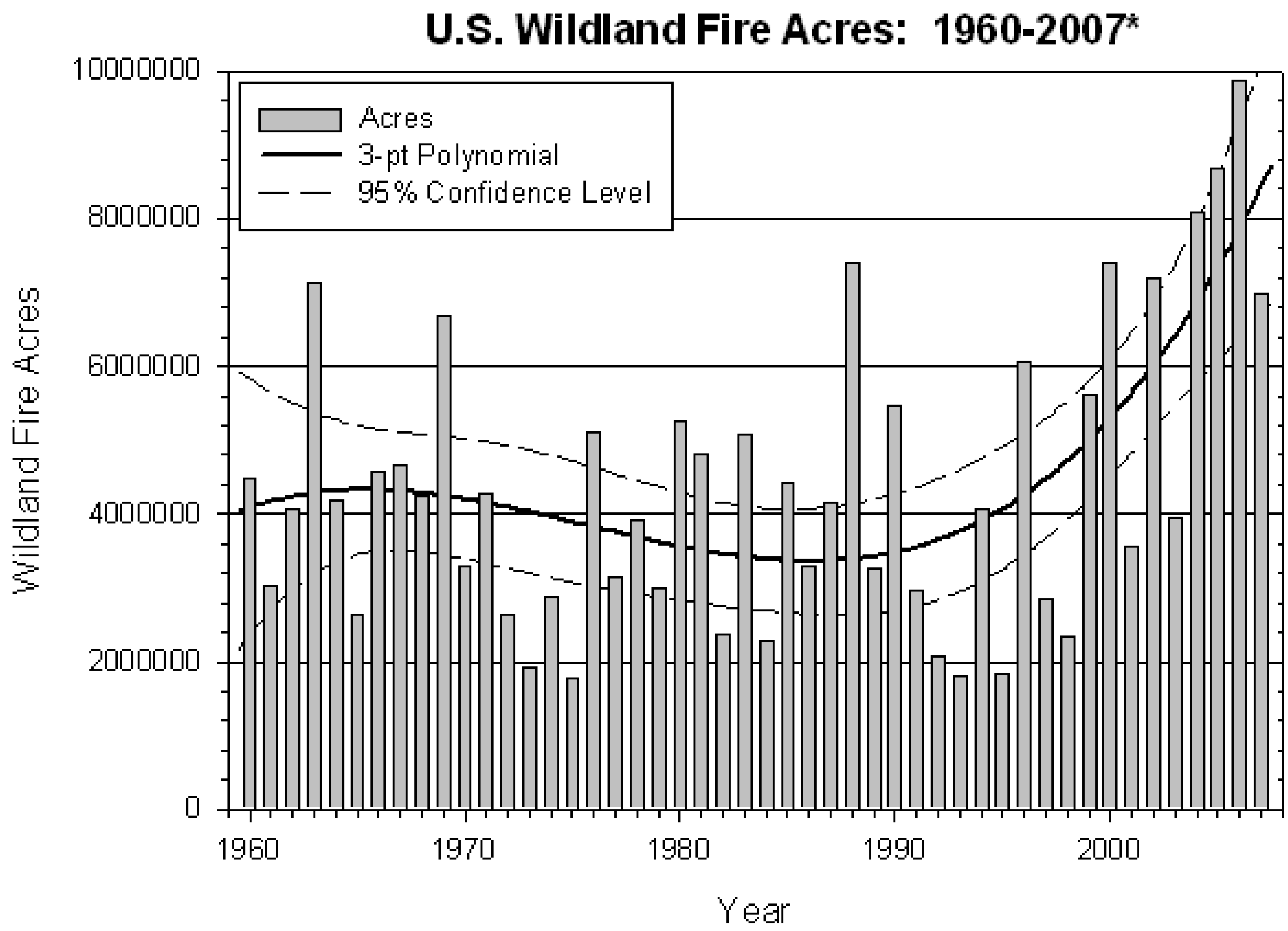
Most costly disasters often attributable to drought



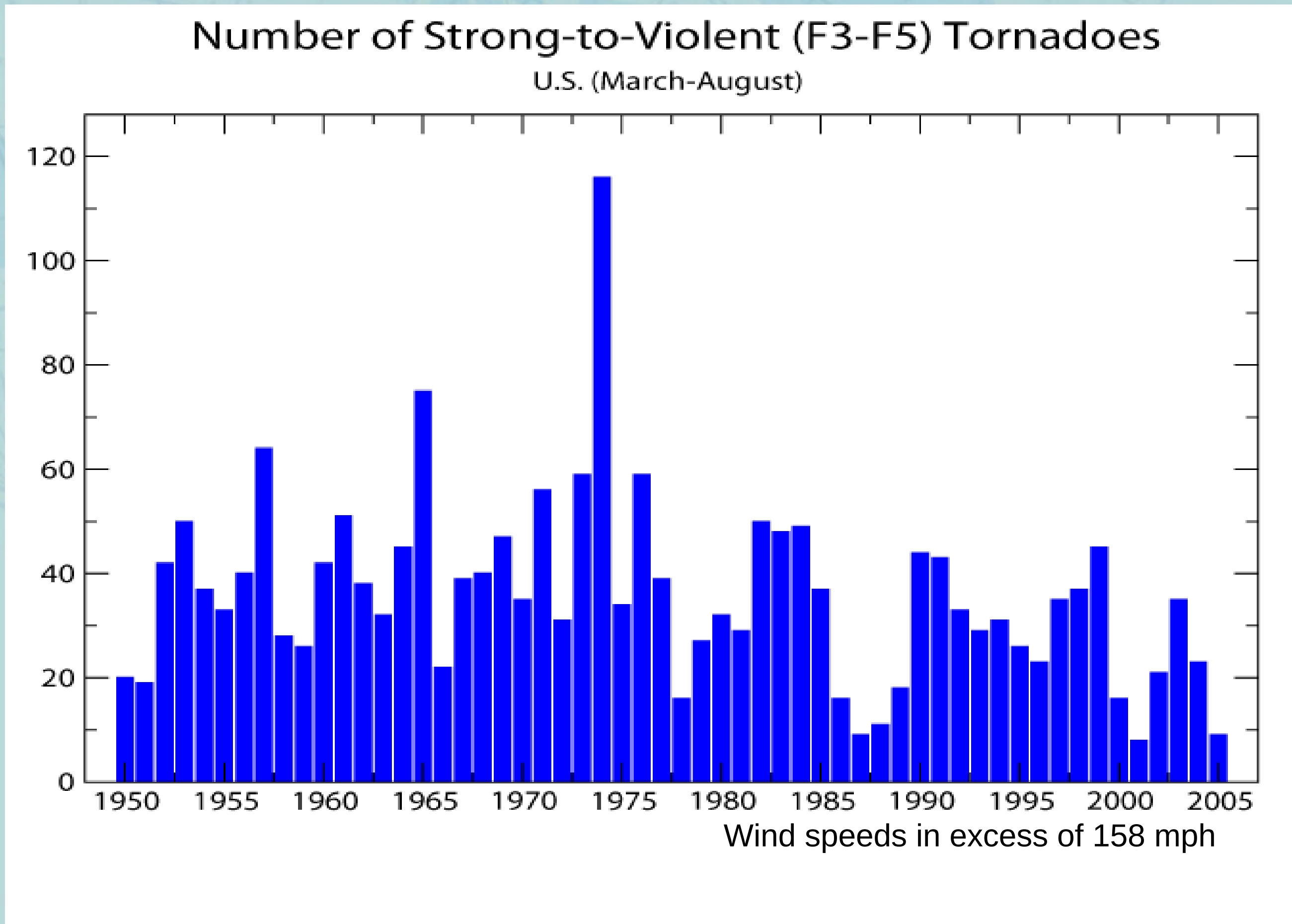
Wildfires

- Increasing incidence of drought is making wildfire seasons more active in the U.S.
  - Winter 2005/2006: More than 1 million acres burned in Texas alone
  - More than 8 million acres burned in the contiguous U.S. in each of the past 4 years.

U.S. Acreage Burned 1960-2007*



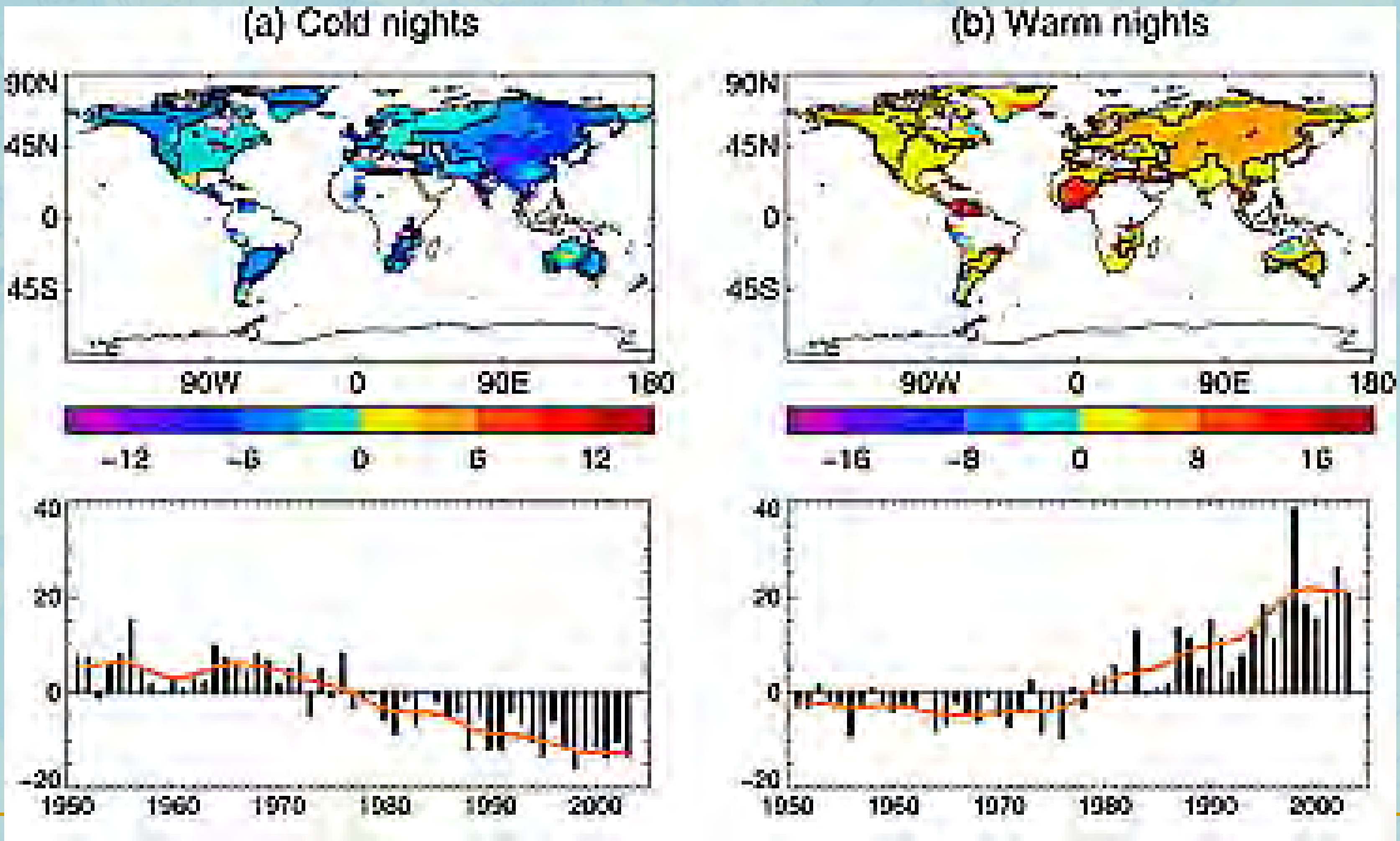
Very Strong to Violent Tornadoes



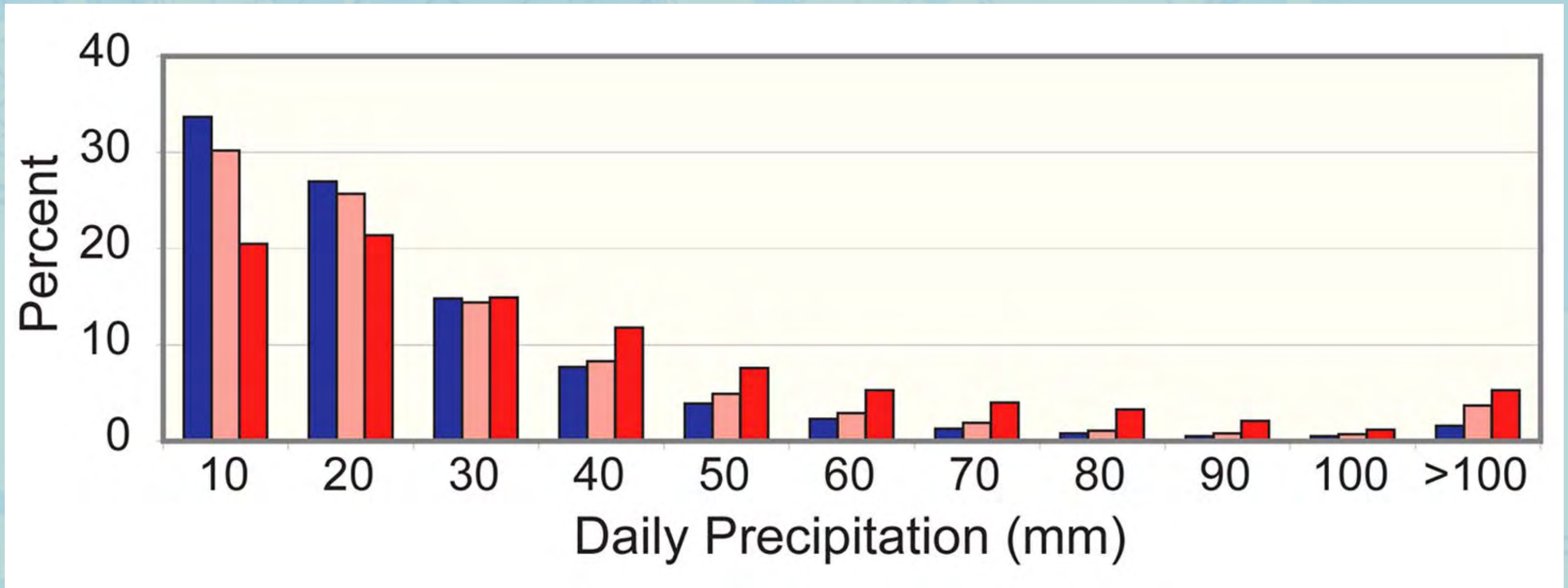
- F3-F5 Tornadoes: Less likely to have been missed in earlier decades
- Decreasing trend in F3 to F5 tornadoes

Questions?

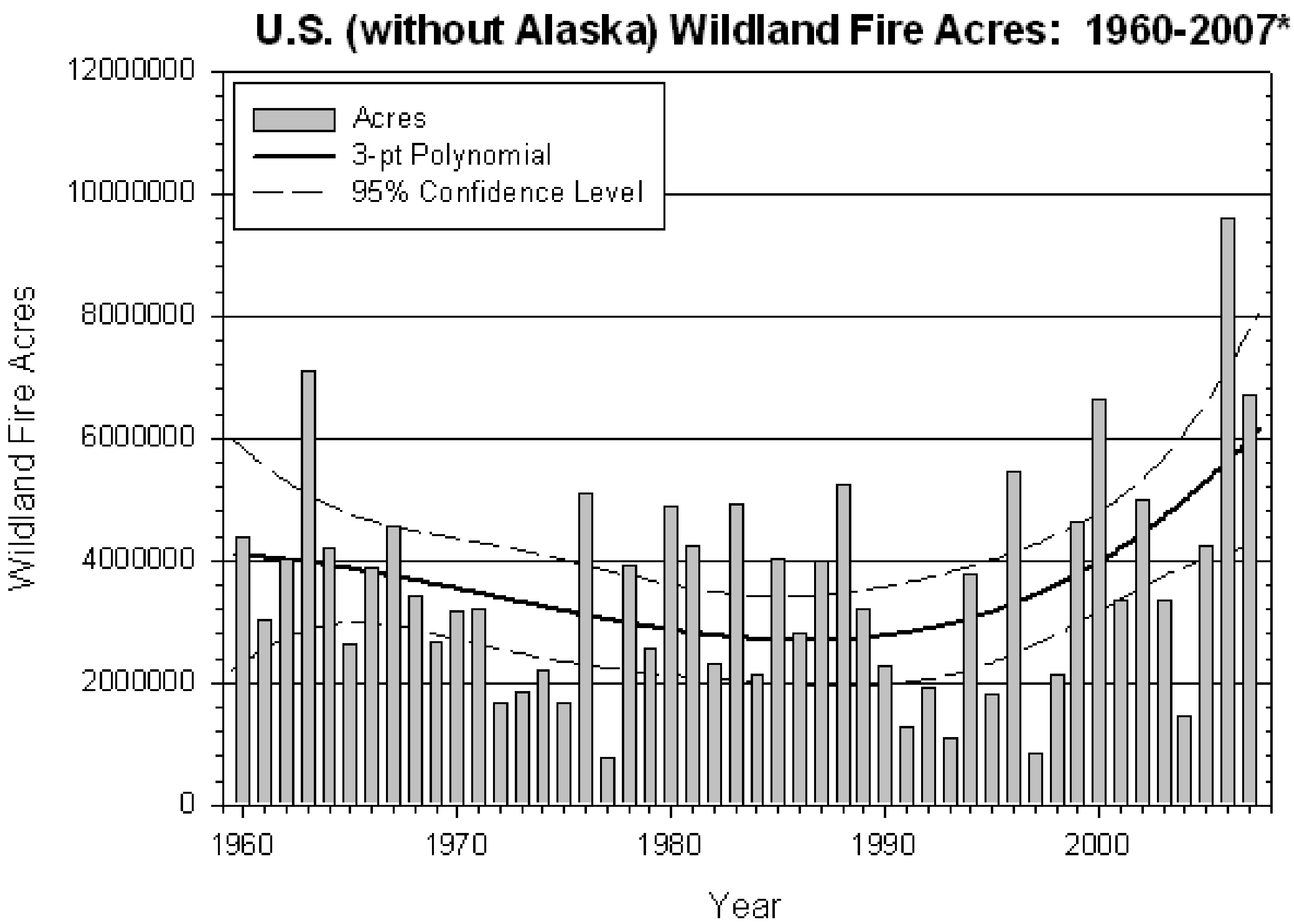
Number Warm Nights Increasing
Number Cold Days Decreasing



Heavier precipitation falls in warmer climates



Contiguous U.S. Acreage Burned 1960-2007*



Ice and Climate Change

Paul Andrew Mayewski
Director, Climate Change Institute
University of Maine

Ice is a sensitive "first responder and agent of climate change" and it also provides a "robust archive of past climate change".

Although the climate system is not yet fully understood, it is realized that the role of the hydrologic cycle, and more specifically the role of the cryosphere (water in the form of snow and ice) is a key ingredient.

Ice (and snow) as a "first responder and agent of climate change":

The cryosphere is comprised of ice sheets, ice caps, mountain glaciers, sea ice, permafrost, and snow cover. These cryospheric components fluctuate in size over time, from days to thousands of years, in response to climate forcing, largely depending on their size, and in turn can have time varying impacts on climate. For example, large ice sheets play an active role in long-term climate change (thousands to tens of thousands of years) and while ice sheet build up may take many millennia, significant ice sheet disintegration can be accomplished in small fractions of build-up time resulting in dramatic changes in sea level. Sea-ice and snow significantly impact Earth's albedo and heat exchange between the ocean-atmosphere and the land-atmosphere, respectively. Further, the presence of large ice covered areas (ice sheets, sea-ice, snow cover) dramatically modifies atmospheric circulation. In the atmosphere ice is present in the form of clouds, dramatically affecting Earth's energy balance (shortwave, longwave, and latent heat).

Ice as a "robust archive of past climate change":

Earth's physical and chemical climate has experienced dramatic change in the past on scales sufficient to disrupt the course of human civilization and ecosystems. Remarkably some of these changes can be initiated in a few years – "abrupt climate change events". In the last few decades, and to a lesser extent centuries, humans have introduced hitherto unsurpassed chemical and physical environmental changes. The direct observational basis for understanding past, modern, and future climate and the resultant impact of and on humans is founded on barely 100 years of instrumental record length for the Northern Hemisphere and significantly less for the Southern Hemisphere.

Indirect observations of physical and chemical climate developed from ice cores, glacier fluctuations, lake, and ocean sediments coupled with studies documenting characteristics of past humans and ecosystems offer a robust environmental setting to understand past climate, assess the impact of humans on modern climate, and predict future climate. These studies provide the only evidence of pre-instrumental era climate and therefore provide our only robust evidence for assessing modern environmental change and analogs for predicting potential range and speed of change in addition to assessing regions of greatest potential sensitivity to change.

Some key questions related to ice and future climates:

Records of past climate and modern observations of the change in extent of ice masses provide lessons relevant to understanding the following questions regarding future change in climate:

(1) Why is the temperature response to anthropogenic source increase in greenhouse gases lagging rise in greenhouse gases? If we find out why we will know when the BIG change will come. We know that the ocean, notably the Southern Ocean, is capable of buffering vast amounts of heat, and that aerosols (sulfates, dusts, etc) are effective agents of regional to global scale cooling. Dramatic examples of sulfate aerosol forcing from the past include the multi-decadal long cooling that accompanied the Toba volcanic eruption ~72,000 years ago and periods of widespread starvation associated with volcanic events during the First Millennium in Europe.

We know less about another potential cause for lagged response to greenhouse gas rise, the underpinning for modern climate, notably the current state of natural climate variability. To understand modern temperature change requires models that include both natural and human forcing of temperature. Reconstruction of past variability in atmospheric circulation calibrated with instrumented records of modern atmospheric circulation reveals that this part of the climate system is still largely within the range of variability of the last 2000 years. Exceptions include features like the Icelandic Low that is beginning to display change outside this range, but other atmospheric circulation systems may be slower to respond. Major changes in temperature over the pre-anthropogenic impacted portion of the past 2000 years are usually preceded by change in atmospheric circulation and the temperature changes are more localized. This suggests that modern climate change is not evolving as it did in the past (anthropogenic forcing is “overpowering” natural climate change) and that there are changes to be expected beyond those thus far observed related to atmospheric circulation since temperature and atmospheric circulation are closely coupled. Significant warming (cooling) in the past is characterized by contraction (expansion) of the polar cells and attendant poleward (equatorward) migration of lower latitude climate as noted in records of past change from Antarctica, the Arctic, and Asia with consequent impacts on zonal and meridional winds, moisture delivery, and distribution of heat. Understanding the current state of atmospheric circulation, natural and humanly forced contributions (as done for temperature), is critical to predicting changes in moisture availability for regions sensitive to drought such as Asia (half of Earth’s population), Africa, the Middle East, and Australia, to flooding such as monsoon regions and in temperature for regions particularly sensitive to increased heat stress such as the Arctic, Europe, and North America and to cooling such as northern Europe (in response to possible decrease in North Atlantic thermohaline circulation).

(2) What is the potential range and timing of the next abrupt change in climate and where is the most likely region for such an event to occur? The natural range in magnitude and initiation speed for abrupt climate change events is startling. The largest naturally occurring abrupt change events occur during the periods of glacial climate and the region of maximum response is in the North Atlantic, with changes on the order of >10^{o}C in less than 2-10 years plus accompanying massive changes in storm intensity and precipitation. However, even the more subdued events (temperature change <2^{o}C) of the last few thousand years, since ice sheets dwindled to their modern state, are sufficient to have caused disruptions to civilizations and ecosystems. Classic examples include massive disruption of the Norse (AD1400) in Greenland due to minor cooling and of the Mayan (AD900) in Latin America and

Akkadian (4200 years ago) civilizations in the Middle East due to potentially small changes in atmospheric circulation leading to declines in moisture transport and drought.

Examples of massive declines in Arctic sea ice releasing ocean trapped heat and terrestrial ice melt contributing to changes in thermohaline circulation are documented in the past. Triggers (possibly changes in solar output) for these past, naturally forced, abrupt climate change events are significantly smaller than estimates for future forcing by greenhouse gases. Antarctica is poised for change and exhibits some of the most impressive warming on the planet. In the past 2000 years major abrupt climate change events are evidenced first in the Antarctic followed by change in the North Atlantic, likely due to geographic differences between the hemispheres. Dramatic change in the Antarctic will result in global scale responses through changes in the production of Antarctic deep bottom water, sea level, ocean heat release, albedo, and dramatic changes in atmospheric circulation over Antarctica and the Southern Ocean with impacts extending into equatorial regions.

(3) How much and how fast could sea level rise in response to warming over Greenland and Antarctica? Observations from just two east coast Greenland outlet glaciers account for ~10% of the annual global sea level rise over the past 5 years. Monitoring of other Greenland outlet glaciers implies even greater contributions. Modeled Antarctic ice sheet response to IPCC projected warming over the next century suggests a potential sea level rise of ~20 feet over the next 2000 years, but there is no reason to assume the rise will be linear based upon understanding of past changes and considering that the projected temperature was last attained over Antarctica ~40 million years ago at a time close to formation of the ice sheet. These models and the Antarctic glaciological community provide a far less conservative view of impending sea level rise than the IPCC.

(4) How much has the chemistry of the atmosphere changed in response to human activity? We have robust records for several greenhouse gases but what about acids, trace elements, and others? Ice core derived histories of change in the chemistry of the atmosphere reveal that rates and magnitudes of acid rain, toxic metals (eg. lead, copper, mercury, bismuth, arsenic, cadmium), radionuclides, organic acids, and obviously humanly engineered chemicals far exceed natural background levels. Many of these introduce significant health risks to humans and ecosystems that add to the health risks associated with warming.

LLOYD'S

CLIMATE CHANGE

INTEGRATING DATA AND KNOWLEDGE INTO MODELS

17 October 2007

Trevor Maynard

ClimateWise

Reducing the Risk for Tomorrow

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ClimateWise is...

a group of leading companies and organisations in the insurance industry. Each of us is committed to taking action on climate change and to reporting publicly on our own performance.

We will: lead the way in analysing and reducing risks; support climate awareness amongst our customers; incorporate climate change into our investment strategies; inform and engage in public policy debate; and reduce the environmental impact of our businesses.

Statement from HRH Prince of Wales

"This is just the beginning of the process of real change. Time is a luxury we do not have and I urge companies both at home and internationally to sign the ClimateWise principles and take the necessary action."

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Prudential
QBE European Operations
RJ Kiln
RMS
Standard Life
UNUM
XL

1 Lead in risk analysis

- Support and undertake research on climate change to inform our business strategies and help to protect our customers' and other stakeholders' interests.
- Support more accurate national and regional forecasting of future weather and catastrophe patterns affected by changes in the earth's climate.
- Use research and improve data quality to inform levels of pricing, capital and reserves to match changing risks.
- Evaluate the risks associated with new technologies for tackling climate change so that new insurance products can be considered in parallel with technological developments.
- Share our research with scientists, society, business, governments and NGOs through an appropriate forum.

2 Inform public policy making

- Work with policy makers nationally and internationally to help them develop and maintain an economy that is resilient to climate risk.
- Promote and actively engage in public debate on climate change and the need for action.
- Support work to set and achieve national and global emissions reduction targets.
- Support Government action, including regulation, that will enhance the resilience and reduce the environmental impact of infrastructure and communities.
- Work effectively with emergency services and others in the event of a major climate-related disaster.

3 Support climate awareness amongst our customers

- Inform our customers of climate risk and provide support and tools so that they can assess their own levels of risk.
- Encourage our customers to adapt to climate change and reduce their greenhouse gas emissions through insurance products and services.
- Increase the proportion of repairs that are carried out in a sustainable way through dialogue with suppliers and developers and manage waste material appropriately.
- Consider how we can use our expertise to assist the developing world to understand and respond to climate change.

4 Incorporate climate change into our investment strategies

- Consider the implications of climate change for company performance and shareholder value, and incorporate this information into our investment decision-making process.
- Encourage appropriate disclosure on climate change from the companies in which we invest.
- Encourage improvements in the energy-efficiency and climate resilience of our investment property portfolio.
- Communicate our investment beliefs and strategy on climate change to our customers and shareholders.
- Share our assessment of the impacts of climate change with our pension fund trustees.

5 Reduce the environmental impact of our business

- Encourage our suppliers to improve the sustainability of their products and services.
- Measure and seek to reduce the environmental impact of the internal operations and physical assets under our control.
- Disclose our direct emissions of greenhouse gases using a globally recognised standard.
- Engage our employees on our commitment to address climate change, helping them to play their role in meeting this commitment in the workplace and encouraging them to make climate-informed choices outside work.

6 Report and be accountable

- Recognise at Company Board level that climate risk has significant social and economic impacts and incorporate it into our business strategy and planning.
- Publish a statement as part of our annual reporting detailing the actions that have been taken on these principles.

www.climatewise.org.uk

1 Lead in risk analysis

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www.lighthillrisknetwork.org

"An appropriate forum"

An Ocean Model for Hurricane Risk Assessment

George Mellor
Atmospheric and Oceanic Sciences Program
Princeton University, Princeton, N.J.

October, 2007

It is proposed that a three-dimensional ocean model that includes surge, wind generated waves and inundation processes can develop information useful to catastrophe models.

The Princeton Ocean Model

The Princeton Ocean model (POM)* is a well established numerical model used by over 3000 researchers, institutions and government entities throughout the world. For example, the Department of the Interior has used POM as part of its Oil Spill Risk Assessment program.

It is a three-dimensional model with a free surface and thus can simulate tides and wind-driven storm surge. It has an embedded turbulence closure sub-model which permits oceanic response to momentum, heat and salinity surface flux. Recently, an inundation capability has been added to the model and applied to test cases. Further, a wave model has been fully coupled to POM, a capability not found in any other three-dimensional ocean model. Waves not only represent a hazard unto themselves, but also can add to coastal sea level elevation and surge.

Hurricanes

An attribute of hurricanes is that they are well organized storms and by stipulating a few parameters (e.g., path, central pressure, core radius) an entire surface wind field can be provided by well documented and surprisingly simple, algebraic models. Thus, a member of an ensemble of hindcast hurricanes can be prescribed without the need for a full three-dimensional atmospheric model (which, of course, is necessary for the forecast of a newborn hurricane's path and intensity).

Risk Assessment

Our vision is to do studies of hurricane damage at major population centers along the U.S. East Coast and Gulf of Mexico coasts. POM has already been applied to Katrina and Wilma before the recent inundation and surface wave enhancements had been added to the model. For a given population center many hurricane scenarios (land fall, direction, intensity and radius) can be specified whence the model will simulate surge and inundation and wave intensity. In consultation with damage experts, this information must then be translated into parameters useful to the insurance industry and to strategies useful, for example, for evacuation and possibly for mitigation (artificial reefs?).

First Step

Before the above program can commence, model simulative skill has to be established. Thus, named hurricanes will be simulated and surge heights and inundation incursions compared with available data, perhaps some of it anecdotal data. Gathering this data may be most difficult element of the project but it should be pursued.

Investigators

There are established ocean researchers that can help to make the project work in varying roles. Prof. George Mellor and Dr. Leo Oey are at Princeton University (at which there is an operational POM model of the Gulf of Mexico) and are associated with NOAA's Geophysical Fluid Dynamics Laboratory (where POM is the ocean component of the GFDL operational hurricane model). Prof. Alan Blumberg and Dr. Robert Abel are at Stevens Institute of Technology (at which there is an operational POM model of New York and New Jersey waters). Prof. Huijie Xue is at the University of Maine (at which there is an operational POM model of the Gulf of Maine) and Prof. Chris Mooers of the University of Miami (at which there is a operational POM model of the Florida Straits). These are all ocean people and may need to be augmented by other experts in other fields such as Prof. Kerry Emanuel of M.I.T.

* www.aos.princeton.edu/WWWPUBLIC/htdocs.pom/

Discussion Points

Richard J. Murnane
Risk Prediction Initiative
Bermuda Institute of Ocean Sciences

Overview

Catastrophe (cat) models provide insurers, planners and emergency managers with valuable insights on the probability of natural disasters and their subsequent impacts. The models represent an amalgam of a huge amount of scientific, engineering, financial, and economic knowledge. Nonetheless, a complete cat model simulates many phenomena that are partly, or wholly, unknown. I manage a program, the Risk Prediction Initiative (RPI), that is a science-business partnership based at the Bermuda Institute of Ocean Sciences. The RPI is supported by a number of companies active in the catastrophe reinsurance industry. Part of RPI's mission is to support scientific research that will benefit its sponsors by allowing them to better understand and manage their exposure to risk. This research can, in part, be used to improve cat models. Below I address the questions posed to forum participants by discussing a number of research projects supported by RPI and note other topics of interest to RPI sponsors. In addition, I touch on some ongoing and emerging efforts to develop open-source risk models that, I believe, offer a possible avenue for addressing a number of concerns related to climate change and variability.

RPI research and topics of interest

The RPI was formed in 1994, and soon after that, RPI sponsors decided to focus on tropical cyclones, particularly those in the Atlantic basin, as they threaten the largest insurance market, which is the United States, and represent one of the biggest risks to property catastrophe markets. At the same time, the RPI chose to focus on the impact of natural climate variability because on business time scales the range of natural variability was expected to be far more important to hurricane losses than any expected variability related to potential anthropogenic climate change. In recent years sponsor interest in anthropogenic climate change has grown because of a series of published papers, changes in cat modeling approaches, and recent hurricane seasons with record-breaking events.

To date most research supported by RPI has not been directed towards understanding anthropogenic climate change, however, it happens that much of it is related to understanding how climate change will alter hurricane activity. (For this paper, hurricane activity is a generic term that accounts for a variety of changes in hurricanes including, but not limited to, intensity, size, track, frequency, genesis location, and landfall.) The research programs are supported by three different groups: 1) Benchmark development, 2) Forecasting, and 3) Emerging markets. Below I describe selected research supported by each group related to the questions posed to forum participants. This is followed by a summary of other hazards related to climate that interest RPI sponsors.

<u>Benchmark Development</u>. This research group has supported two main efforts. The first is the development of records of prehistoric hurricane landfall. The records are derived mainly by analyzing sediment cores collected from coastal lakes and marshes. Layers in the cores are produced as storm surge associated with hurricanes washes over coastal barriers depositing sand and marine organisms. The ages of these layers are dated using a variety of methods. Cores

collected by RPI-sponsored scientists reproduce the historical record of landfalls and analyses of the prehistoric layers suggest millennial-scale variability in hurricane landfall rates. The cause for this is unknown.

A second effort is related to the extension and refinement of best-track data on hurricanes. These data provide the foundation for all hurricane cat models and include the location and wind speed at six-hour intervals between the formation and dissipation of a tropical cyclone. The RPI has supported both the analysis of archival records and research on the reanalysis of the best-track data set. In addition, RPI helped organize and led an international workshop on the reanalysis of best-track data for the western North Pacific.

Forecasting. This group is interested in understanding how climate variations influence hurricane activity and how hurricanes might influence climate. This knowledge can then be used to improve seasonal and interannual forecasts of tropical cyclones. Current projects include an effort to develop hybrid season forecast schemes that couple statistical and dynamical models.

Emerging Markets. This group focuses on research that could be used for developing new models in areas and hazards not covered by existing cat models. Current research includes the development of techniques that use satellite observations for developing internally consistent data sets and the analysis of these data.

Other hazards of interest. The main way that RPI is involved with hazards other than hurricanes is through the support and development of science-business workshops. RPI sponsors choose the workshop topics on the basis of their business relevance. Workshop participants include leaders in the field of interest. Among the hazards covered in past workshops are wildfires, European wind storms, and a variety of modes of climate variability such as the El Niño-Southern Oscillation, the North Atlantic Oscillation, and the Madden Julian Oscillation. All of these hazards and climate modes are likely to be sensitive to changes in climate.

Open-source risk models

There are a number of ongoing efforts to develop open-source catastrophe risk models that could complement the current generation of cat models. Most of these open-source efforts are in the seismic community and include specific projects such as OpenSHA, a seismic hazard model, and OpenSEES, an effort to develop seismic engineering algorithms, AGORA, and GEMS. In the hurricane world, the State of Florida has supported the development of a public model, the Florida International University Public Hurricane Loss Projection Model (PHLPM). This model is fully documented but the source code is not publicly available. An energetic group could reproduce the model from the detailed documentation. These nascent efforts at open source are promising, mainly because they could provide a variety of alternative hazard models and a venue for regions outside of traditional insurance markets to develop exposure data bases.

The future?

With sufficient resources, it should be possible to combine the output from complex coupled climate models with different climate change scenarios to catastrophe risk models. The combination of climate and cat models could provide a means of converting the typical output from climate models (e.g., more frequent intense precipitation events, more intense storms, etc.) into estimates of dollar losses that improve decisions involving cost-benefit analyses.

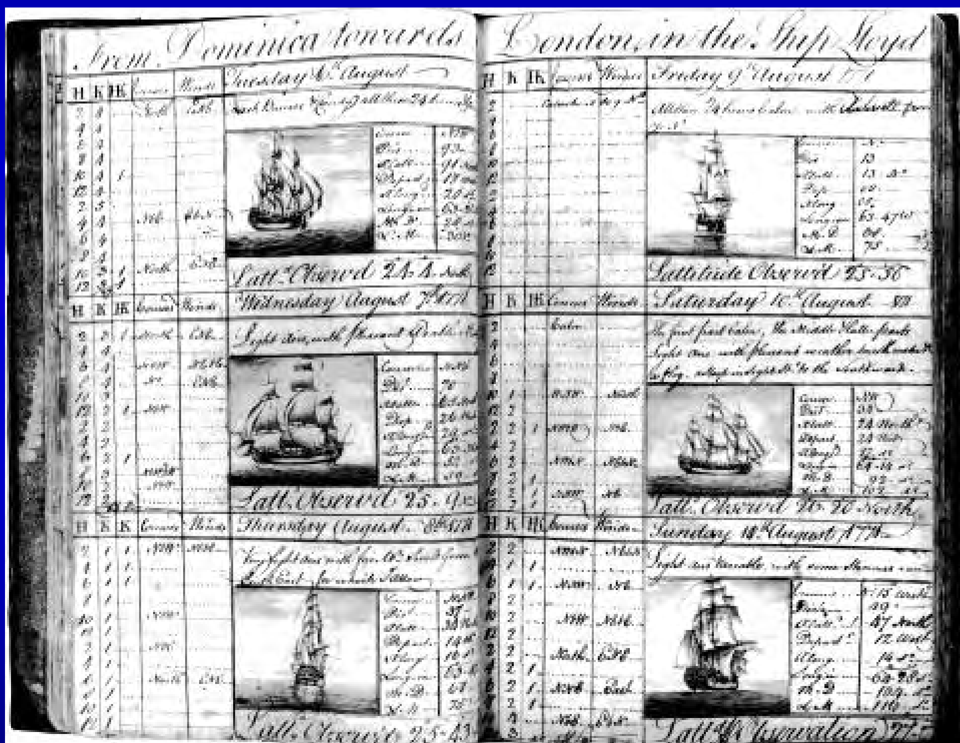
New Directions in Catastrophe Risk Models

Catastrophe Modeling Forum
October 16-17, 2007

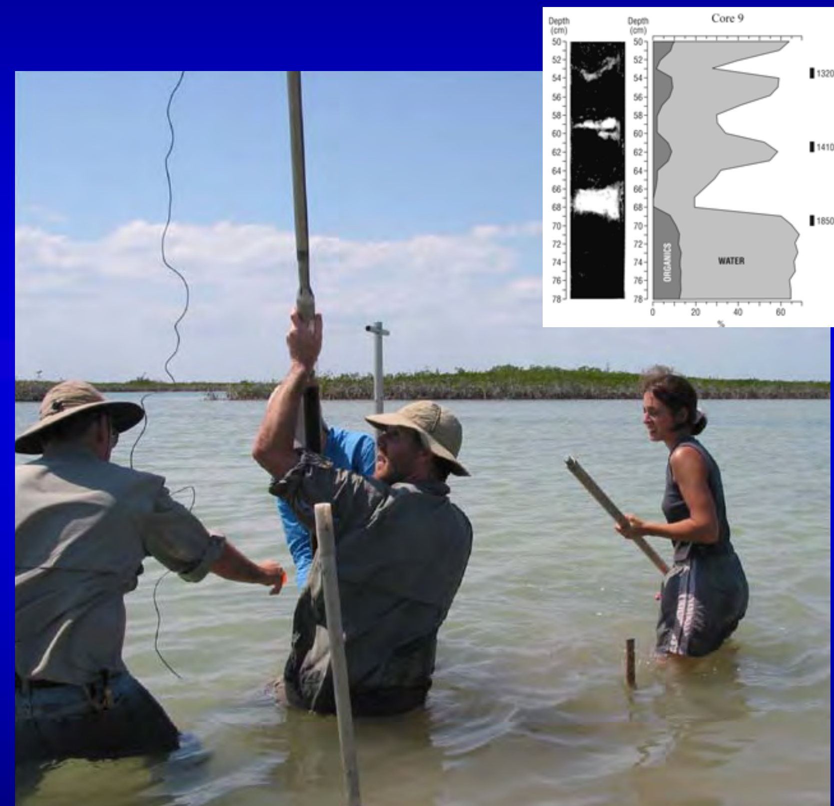
Richard J. Murnane
Risk Prediction Initiative
Bermuda Institute of Ocean Sciences

RPI Research

- Extending and improving the historic record



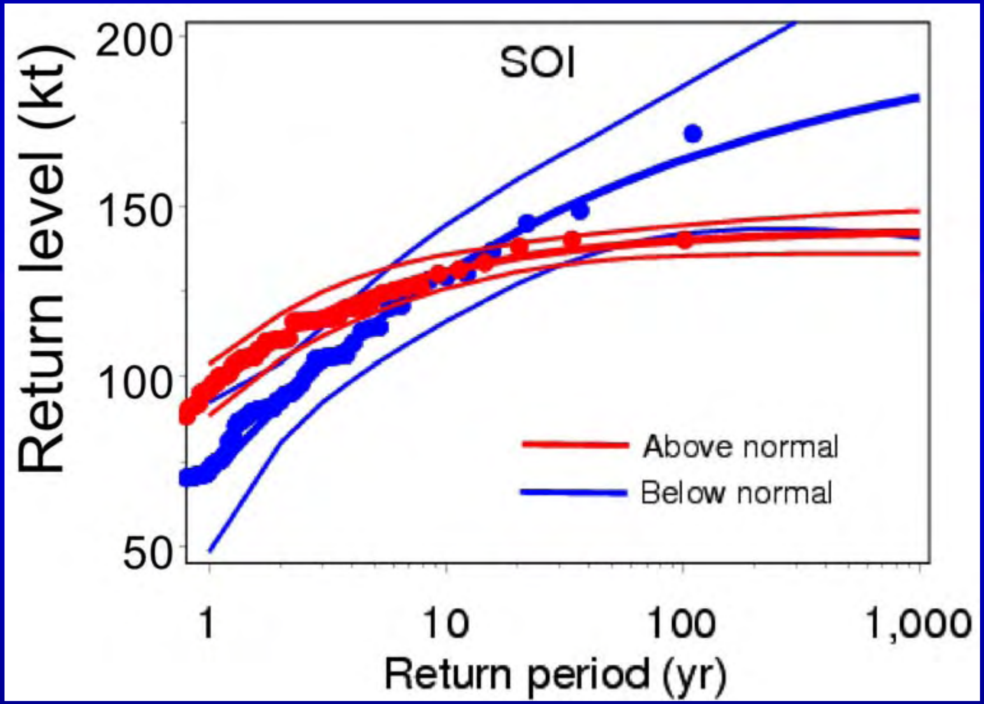
Pages from the logbook of the merchant vessel *Lloyd* for August 1771. The *Lloyd* sailed regularly between England and the Caribbean region. (Garcia et al., 2004)



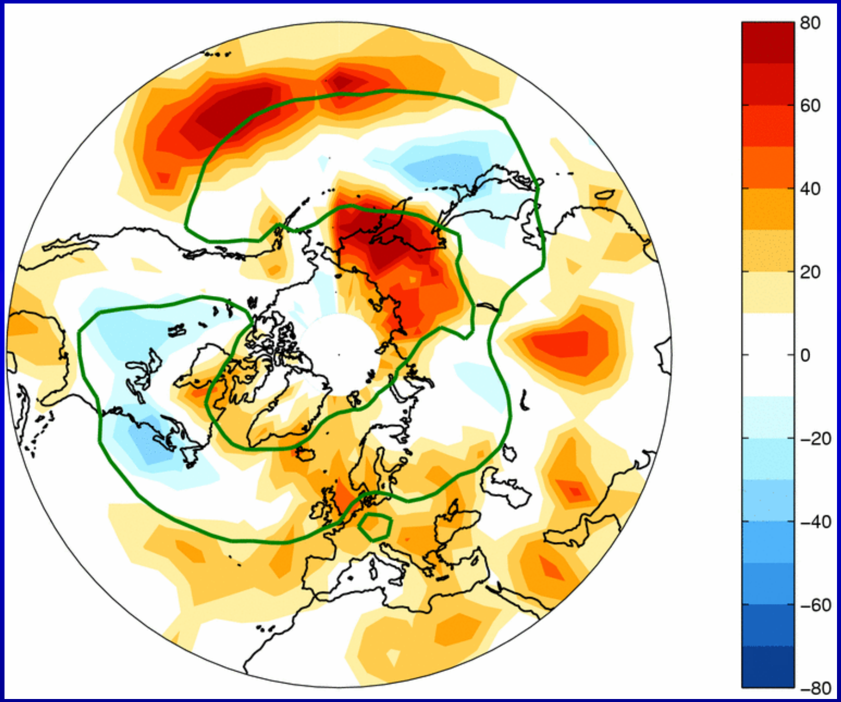
Collecting cores to develop records of prehistoric hurricane landfall. Inset: sample core and analysis results. (photo: J. Tierney)

RPI Research

- Understanding the impact of climate on extreme events



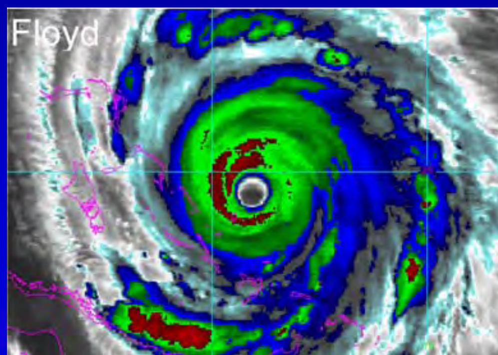
Relation between landfalling hurricane wind speed and return period as function of Southern Oscillation Index (SOI). (Jagger and Elsner, 2006)

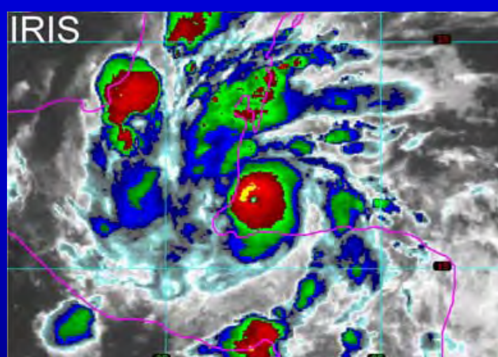


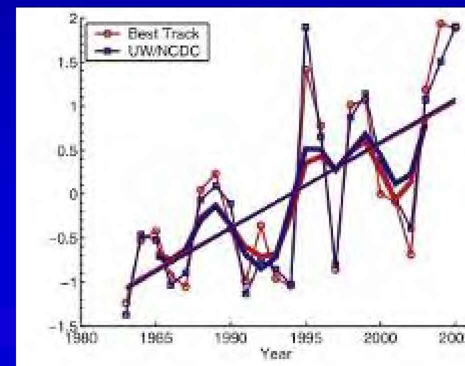
Regions of overdispersion (clustering) and underdispersion of European wind storms. (Stephenson et al., 2004)

RPI Research

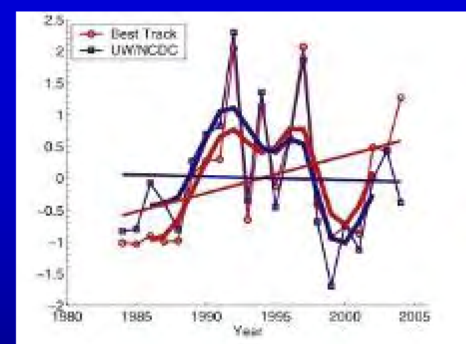
- Promoting development of new sources of hazard data







Atlantic

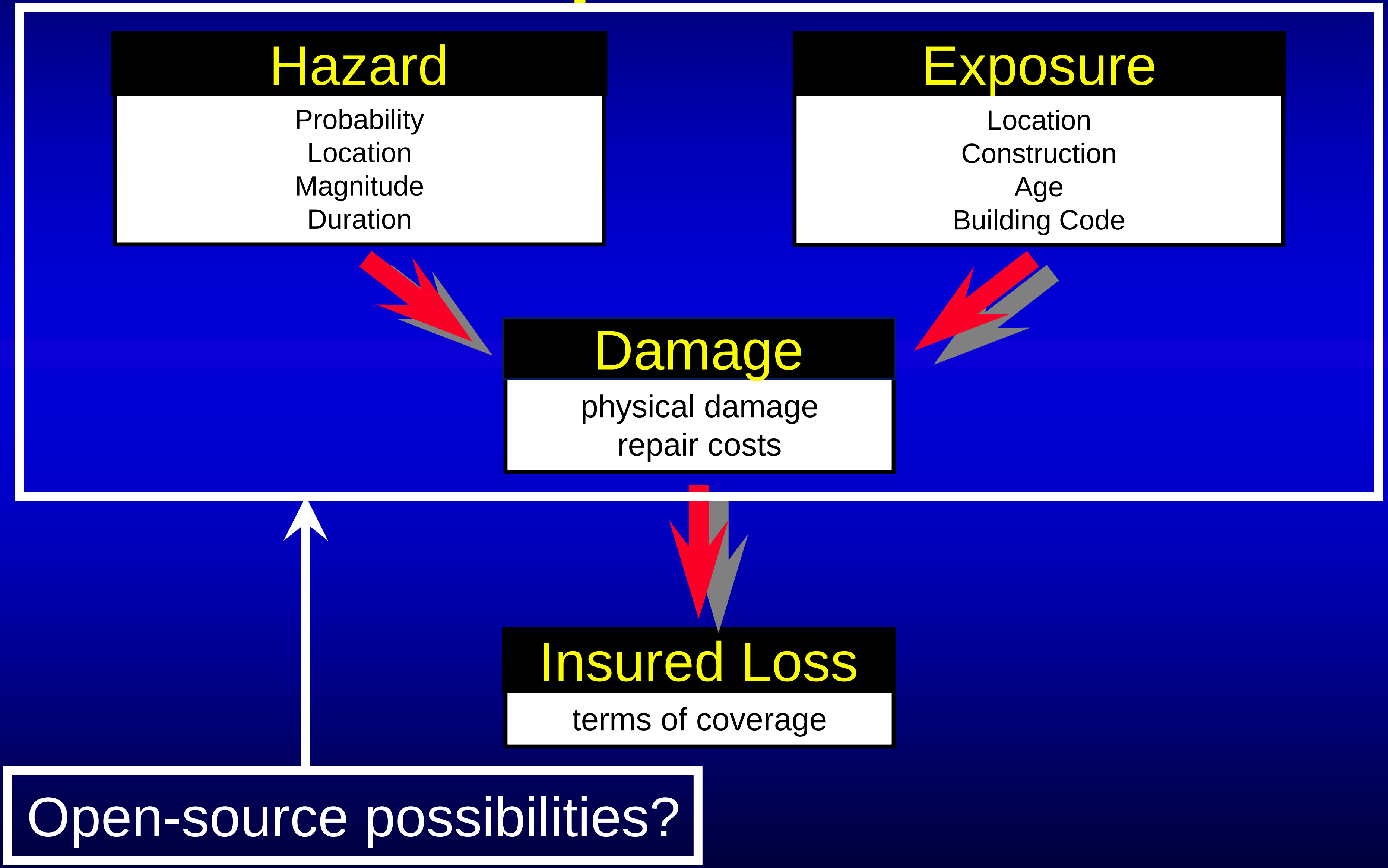


Global

Satellite images provide underexploited information regarding size parameters and maximum winds.

Analysis of satellite data provides homogeneous set of best-track data

(Open Source?) Catastrophe Risk Model



Benefits Of An Open-Source Risk Model

- Accelerate development of risk models
- Enhance liquidity of alternative risk products
- Rationalize insurance regulation
- Promote financing of natural catastrophes in developing countries
- Broaden pool of scientific and engineering talent that could contribute to cat model development

Integrating Climate And Risk Models

- Serious issues related to resolution of hazard, beyond temperature and precipitation extremems, to date most work mainly on hurricanes
- Sea level rise considered at some level, but not for flooding/storm surge issues
- Perhaps best (only?) way to account for impact of changes in climate modes on extreme event frequency, magnitude, location, etc….
- Would this make climate simulations easier to integrate into policy decisions?

Climate Change: Impacts and Implications on the Science of Catastrophe Modeling

D. Rind
NASA/GISS

The latest IPCC report continues the trend of envisioning a warming world with a variety of hydrologic responses, depending on latitude and location. The magnitude of the warming is currently unknown, due both to uncertainty in climate sensitivity and to the uncertain future of greenhouse gas concentration changes. These uncertainties are less important for the next few decades, whose climate change is strongly governed by the warming that is already built into the system from past greenhouse gas concentration increases. From that perspective, unless something drastic happens, the near-future warming can be anticipated to some extent.

When it comes to how climate change will affect severe events, even in the near-term, there is less that can be said with confidence. Our understanding of the dynamics of severe storms is not fully developed for the current climate, at least partly because of the smaller scales and extreme conditions that apply. We're not sure how extreme weather events have changed over the historical record, nor can we tell how they would be altered by even small changes in climate.

With this as context, there are a few things IPCC WGI has concluded about severe events. With regard to historical changes since 1950, heat waves have increased, as have the number of warm nights (while cold nights have decreased). The area affected by droughts appears to have grown, with precipitation over land having decreased marginally. Heavy precipitation events have increased in a number of regions. Tropical storm and hurricane frequencies and intensities appear to have increased since the 1970s, although the attribution of such changes to global warming is still being debated. Changes in tornadoes and severe thunderstorms are difficult to assess, given their scattered nature and the improvements that have occurred in the observing systems.

As to future predictions, IPCC WGI has the following to say: "*The type, frequency and intensity of extreme events are expected to change as Earth's climate changes, and these changes could occur even with relatively small mean climate changes*". A number of the projected changes are similar to those already observed to be happening: increase in heat waves and reduced cold air outbreaks, some increase in summer dryness and winter flooding at mid-to-high latitudes, more intense rainfall interspersed with longer drier periods, Others are more uncertain, such as the suggestion of an increase in more intense hurricanes, and a decrease in weaker ones. With respect to more severe local storms, tornados and severe thunderstorms, IPCC does not offer an opinion, although with more energy available, at least some increase in severe thunderstorms would seem likely.

IPCC WGII has discussed present and potential future impacts. Currently, the hydrologic impacts include increased runoff and earlier spring peak in glacial and snow-fed rivers, followed by water shortages later in the season. In addition, warming of lakes and rivers is occurring, with effects on thermal structure and water quality. At high northern latitudes there have been increases in glacial lakes, increased instability in permafrost regions, and effects on ecosystems, including predators high on the food chain (e.g., polar bears). From the biological standpoint, there has been an earlier timing of spring events (leaf-unfolding, bird migration, egg-laying), poleward and upward shifts in ranges of plant and animal species, shifts in the range of algal, plant and fish abundance in high latitude oceans and lakes, and rapid changes and earlier migration of fish in rivers.

Additional changes are occurring which may have at least some climate change component. These include altered agriculture and forestry management at Northern Hemisphere higher latitudes (earlier spring planting, disturbances), human health issues (heat-related mortality, infectious diseases, allergies), human activities in the Arctic and lower-elevation alpine areas, and sea level rise (along with human development) helping to produce coastal wetland/mangrove loss and coastal flooding damage. While some of these effects are undoubtedly related to the warming climate, differentiating them from other natural and anthropogenic influences is not straightforward; often the best one can say is that they are changing in the direction expected in a warming climate.

Projected impacts again include ‘more of the same’ aspects. Water runoff and availability is expected to increase at high latitudes and in some wet tropical regions, while decreasing in some mid-latitude dry regions and the dry subtropics. There is the threat that ecosystems will be overwhelmed by a combination of climate change and associated disturbances (e.g., flooding, drought, wildfire, insects, ocean acidification), as well as other global change drivers (e.g., land-use change, pollution, over-exploitation of resources). IPCC WGII estimates that ~20-30% of the plant and animal species assessed so far are at increased risk of extinction when (if) warming reaches 1.5-2.5°C. Such warming would also cause major changes in ecosystems and species ranges with predominantly negative effects on biodiversity and ecosystem goods and services (e.g., food and water supply). Progressive acidification of oceans will have negative impacts on corals and their dependent species. Crops may increase at high latitudes until temperature warms more than 1-3°C; at lower latitudes crops should decrease. However, globally commercial timber productivity could rise modestly with climate change in short-to-medium term

Continued coastal erosion and negative impacts on salt marshes and mangroves will be occurring, with many millions of people affected by flooding by 2080. The magnitude of sea level rise is also associating with potential melting in polar ice sheet regions, something IPCC did not feel component to project. One can expect increases in malnutrition, diarrhea, cardio-respiratory diseases (from increased low level ozone), and altered infectious disease vectors. The elderly population will be particularly at risk from heat waves, while there will be fewer cold-related illnesses.

To be useful, projections of impacts in specific regions are necessary. IPCC WGI often shows predictions from the average of some 20 different models, and suggests that this average may be more accurate than predictions from any individual model. However, there is no proof that this is the case for climate change assessments. The aspect of the climate system that most affects changes in atmospheric dynamical properties and extreme events relates to future changes in temperature gradients, and in this regard the models show strong disagreement among themselves. Low latitude and high latitude climate sensitivity differ greatly from one model to another, on the order of a factor of two. The ratio of the high latitude response to the global average response varies from factors of 1.3x to 4x in the models used for the IPCC assessment. What's more, the pattern of sea surface temperature change (as exemplified by ENSO events) differs greatly among the models, and this pattern is highly influential in forcing regional climate anomalies. Without knowing changes in latitudinal and longitudinal temperature gradients, many aspects of severe weather (and even mean regional changes) cannot be determined.

The historical record does not provide a firm indication of either low or high latitude climate sensitivity, due to problems in the observing record, the large natural variability at high latitudes, and the fact that we are entering a 'no-analog' situation with increasing greenhouse gases. And past may not be prologue; there are potential nonlinearities in the climate system, and thresholds that may be breached (e.g., ice melts abruptly when temperatures exceed the freezing point). The same is likely to be true for biological systems.

It is not clear when our modeling capabilities and observational record length will improve sufficiently to provide more confident assessments of extreme events. The primary reasons for the modeling disagreements relate to uncertain cloud cover parameterizations as well as some cyrospheric (sea ice and snow cover) issues, and improvement in our understanding of these aspects is slow. IPCC projections are plausible, but the actual course of events, especially on regional levels where all impacts are really felt, may well differ from expectations. A sensible course of action would be to build resiliency into whatever systems may be at risk, and update that capability as observations continue to accumulate. As IPCC concluded, extreme events are very likely going to change, and we would do well to give ourselves leeway when (as) the unexpected arises.

Climate Change: Impacts and Implications on the Science of Catastrophe Modeling

D. Rind
NASA/GISS

General Understanding (or lack thereof) concerning the Likelihood of Changes in Severe Climate Events

From the IPCC perspective

…And a personal view

Multi-Model Averages and Assessed Ranges for Surface Warming

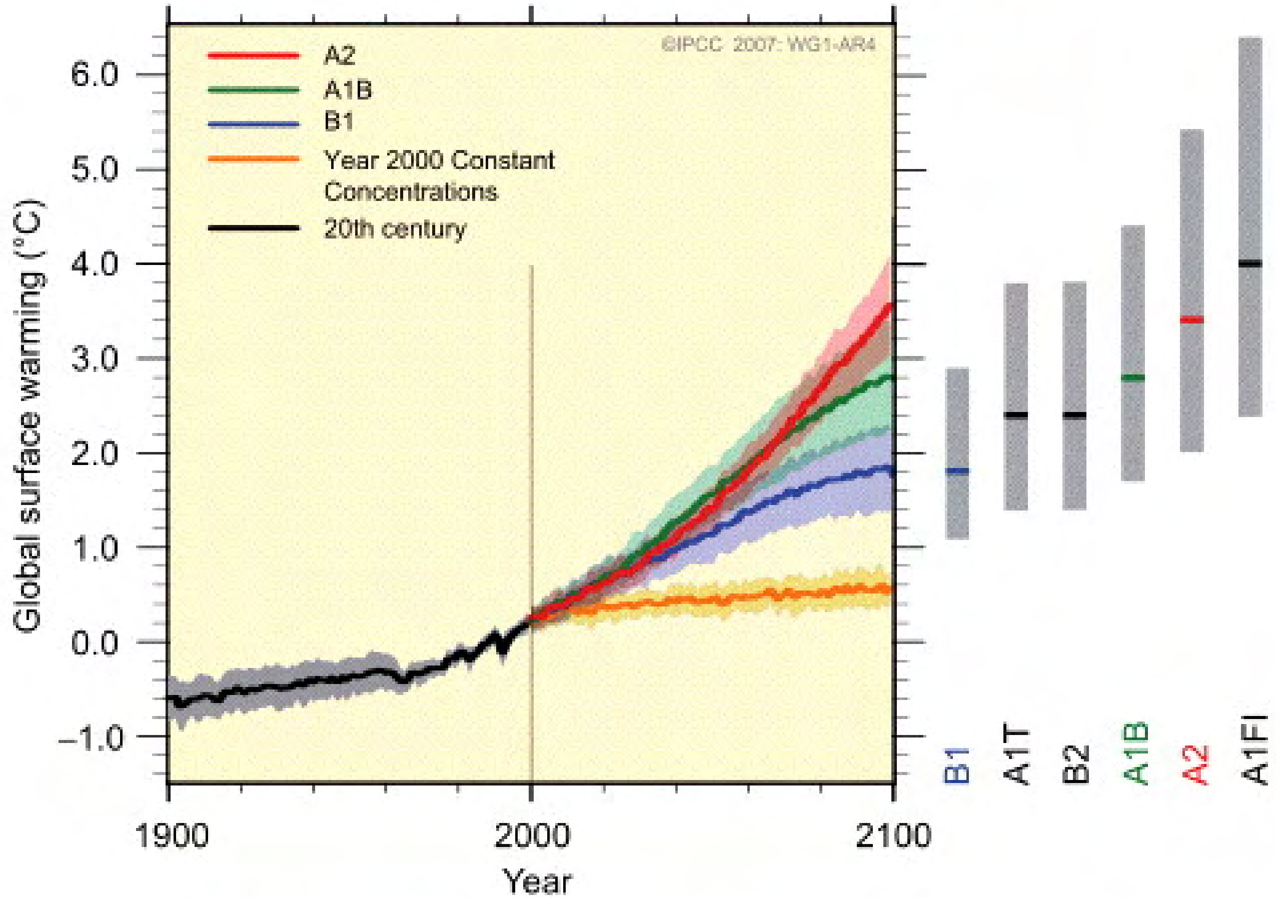


Figure SPM.5. *Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the ±1 standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the* ***likely*** *range assessed for the six SRES marker scenarios. The assessment of the best estimate and* ***likely*** *ranges in the grey bars includes the AOGCMs in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints. {Figures 10.4 and 10.29}*

Projections of Surface Temperatures

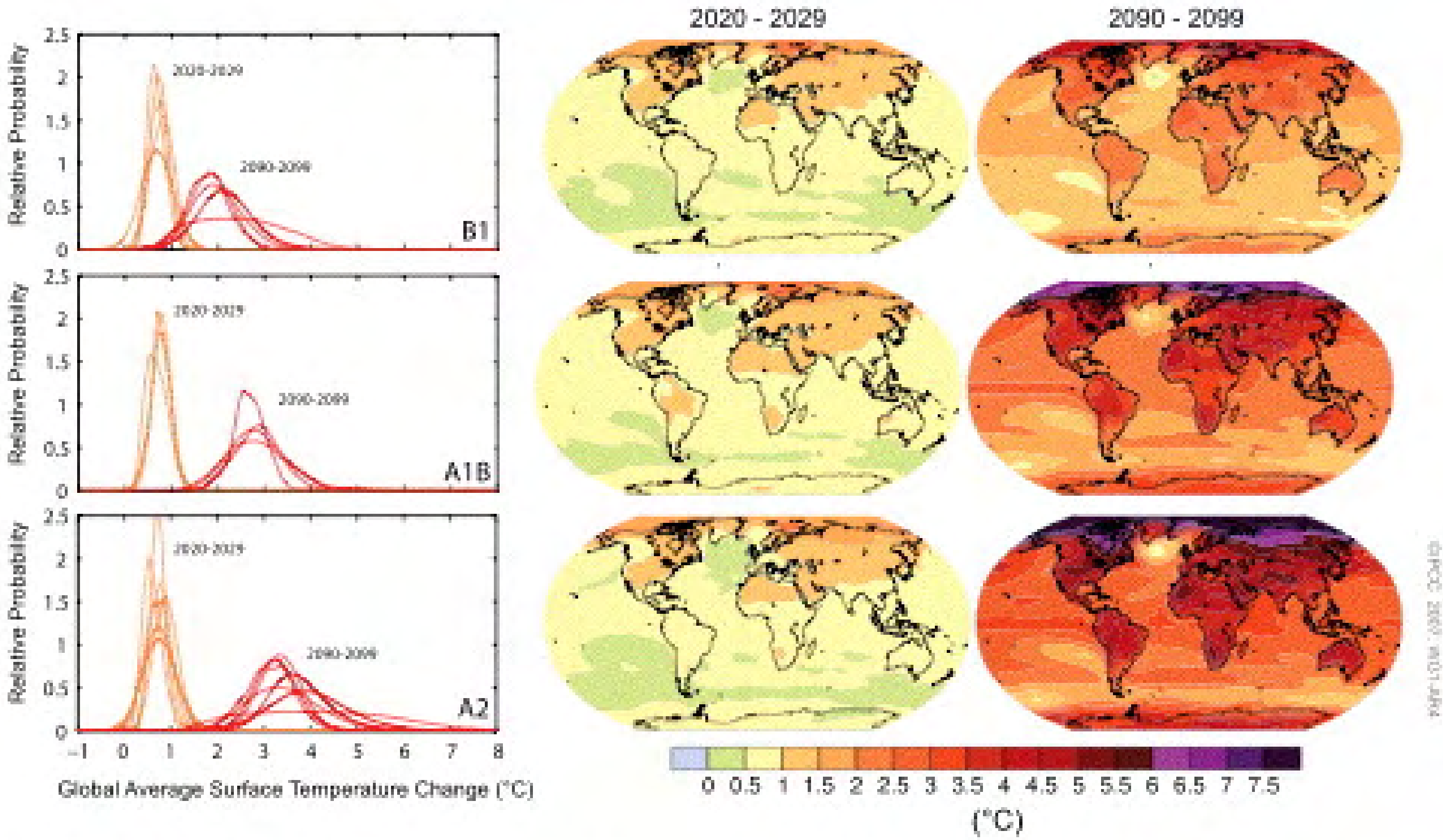


Figure SPM.6. *Projected surface temperature changes for the early and late 21st century relative to the period 1980–1999. The central and right panels show the AOGCM multi-model average projections for the B1 (top), A1B (middle) and A2 (bottom) SRES scenarios averaged over the decades 2020– 2029 (centre) and 2090–2099 (right). The left panels show corresponding uncertainties as the relative probabilities of estimated global average warming from several different AOGCM and Earth System Model of Intermediate Complexity studies for the same periods. Some studies present results only for a subset of the SRES scenarios, or for various model versions. Therefore the difference in the number of curves shown in the left-hand panels is due only to differences in the availability of results. (Figures 10.8 and 10.28)*

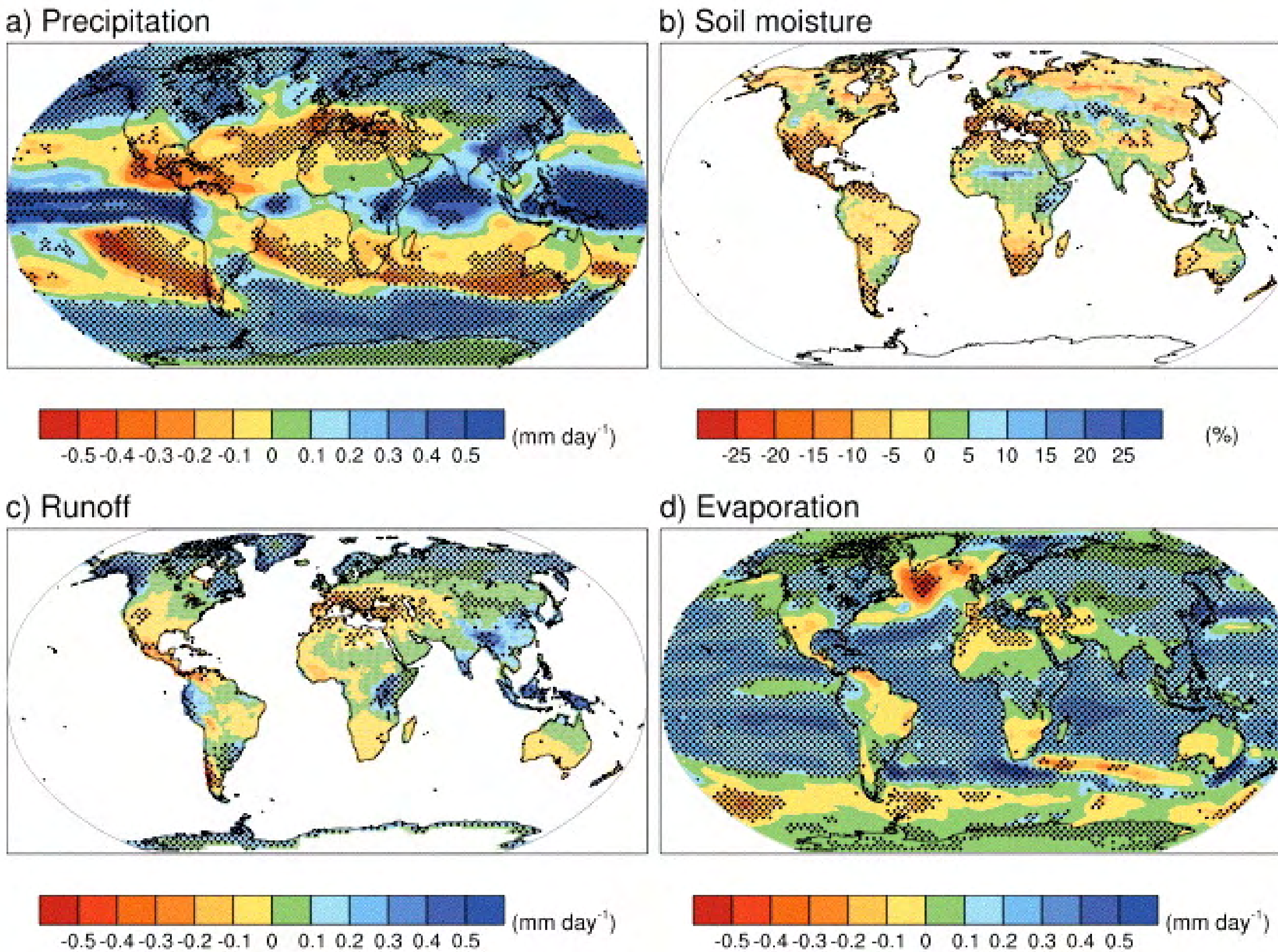
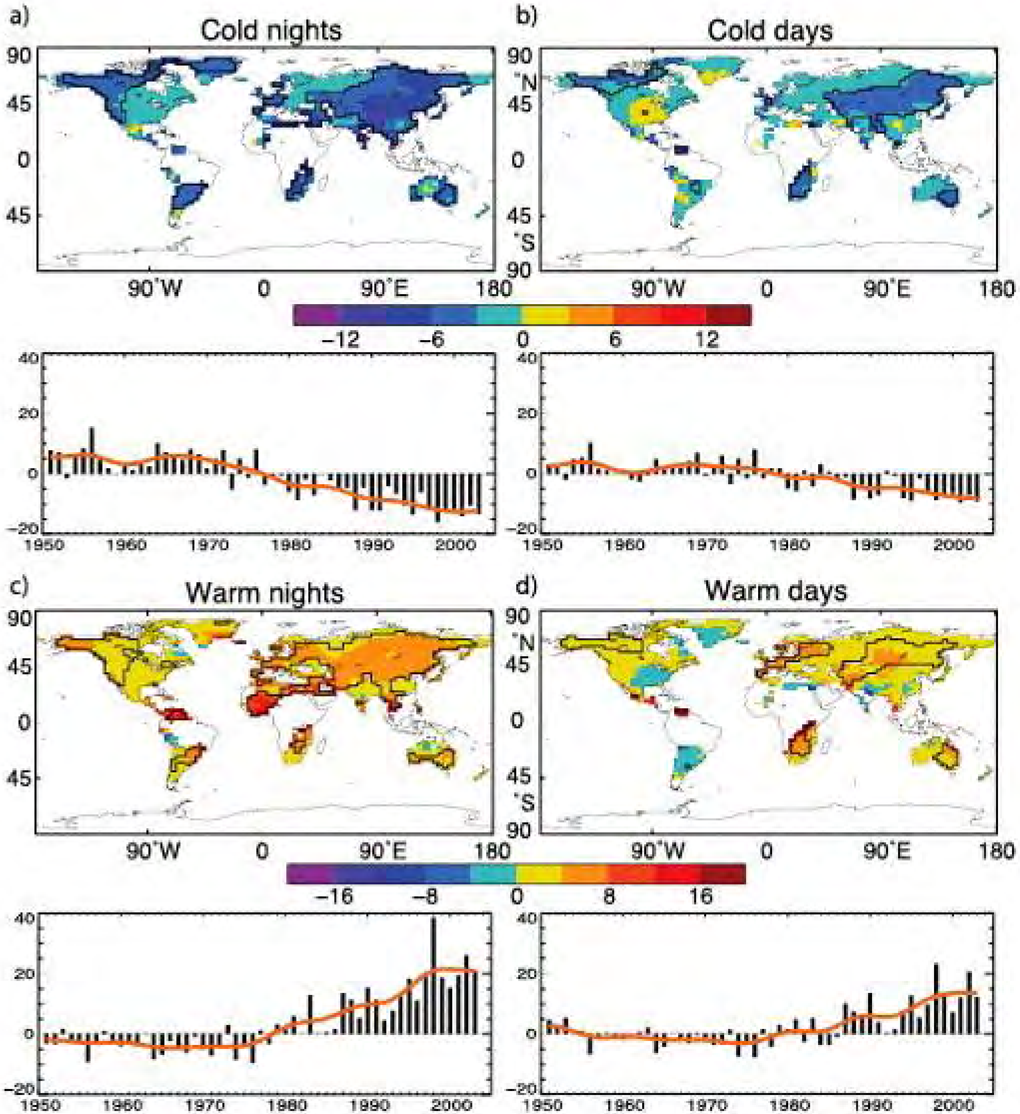


Figure 10.12. *Multi-model mean changes in (a) precipitation (mm day^{-1}), (b) soil moisture content (%), (c) runoff (mm day^{-1}) and (d) evaporation (mm day^{-1}). To indicate consistency in the sign of change, regions are stippled where at least 80% of models agree on the sign of the mean change. Changes are annual means for the SRES A1B scenario for the period 2080 to 2099 relative to 1980 to 1999. Soil moisture and runoff changes are shown at land points with valid data from at least 10 models. Details of the method and results for individual models can be found in the Supplementary Material for this chapter.*

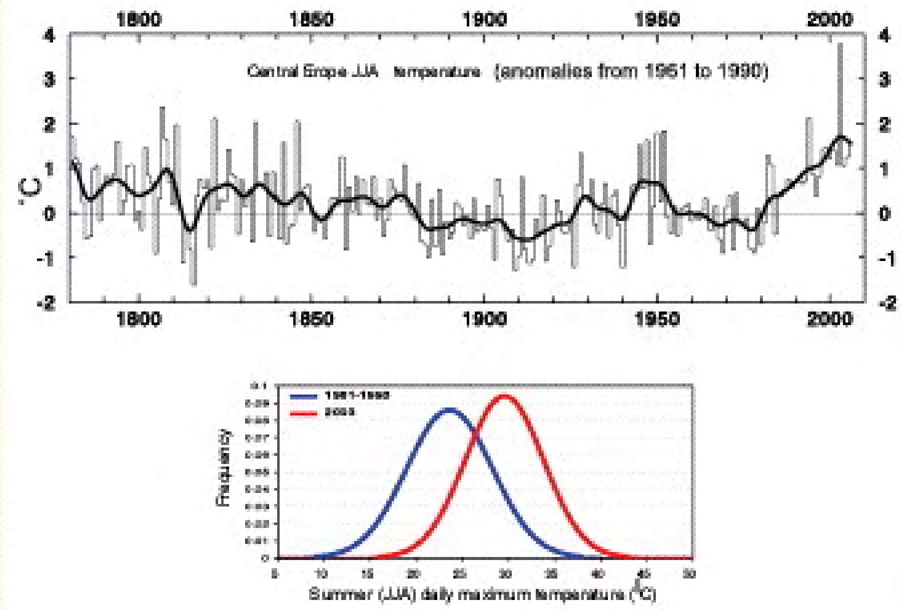
Frequently Asked Question 3.3: Has there been a Change in Extreme Events like Heat Waves, Droughts, Floods and Hurricanes?

Since 1950, the number of heat waves has increased and widespread increases have occurred in the numbers of warm nights. The extent of regions affected by droughts has also increased as precipitation over land has marginally decreased while evaporation has increased due to warmer conditions. Generally, numbers of heavy daily precipitation events that lead to flooding have increased, but not everywhere. Tropical storm and hurricane frequencies vary considerably from year to year, but evidence suggests substantial increases in intensity and duration since the 1970s. In the extratropics, variations in tracks and intensity of storms reflect variations in major features of the atmospheric circulation, such as the North Atlantic Oscillation.

- Observed increase in weak tornados in both the US and Europe may well be the result of better monitoring
- Changes in frequency of such events associated with severe thunderstorms cannot be determined - phenomenon is localized, observing network is scattered, and remote sensing can’t delineate severe events



FAQ 3.3, Figure 1. *Observed trends (days per decade) for 1951 to 2003 in the frequency of extreme temperatures, defined based on 1961 to 1990 values, as maps for the 10th percentile: (a) cold nights and (b) cold days; and 90th percentile: (c) warm nights and (d) warm days. Trends were calculated only for grid boxes that had at least 40 years of data during this period and had data until at least 1999. Black lines enclose regions where trends are significant at the 5% level. Below each map are the global annual time series of anomalies (with respect to 1961 to 1990). The red line shows decadal variations. Trends are significant at the 5% level for all the global indices shown. Adapted from Alexander et al. (2006).*



Box 3.6, Figure 2. *Long time series of JJA temperature anomalies in Central Europe relative to the 1961 to 1990 mean (top). The smooth curve shows decadal variations (see Appendix 3.A). In the summer of 2003, the value of 3.8°C far exceeded the next largest anomaly of 2.4°C in 1807, and the highly smoothed Gaussian distribution (bottom) of maximum temperatures (red) compared with normal (blue) at Basel, Switzerland (Beniston and Diaz, 2004) shows how the whole distribution shifted.*

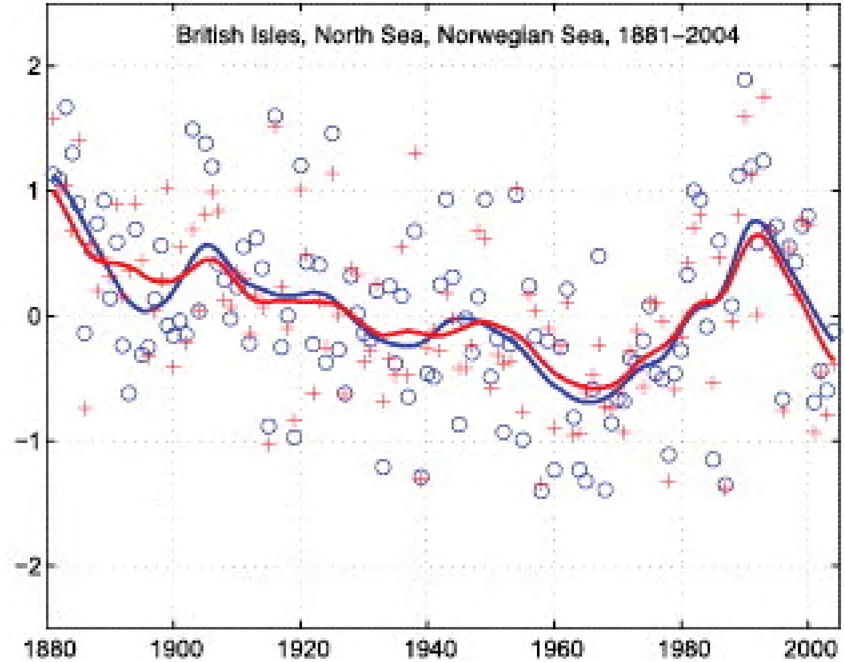


Figure 3.41. *Storm index for the British Isles, North Sea and Norwegian Sea, 1881 to 2004. Blue circles are 95th percentiles and red crosses 99th percentiles of standardised geostrophic winds averaged over 10 sets of triangles of stations. The smoothed curves are a decadal filter (updated from Alexandersson et al., 2000).*

Extratropical storms influenced by atmospheric circulation patterns

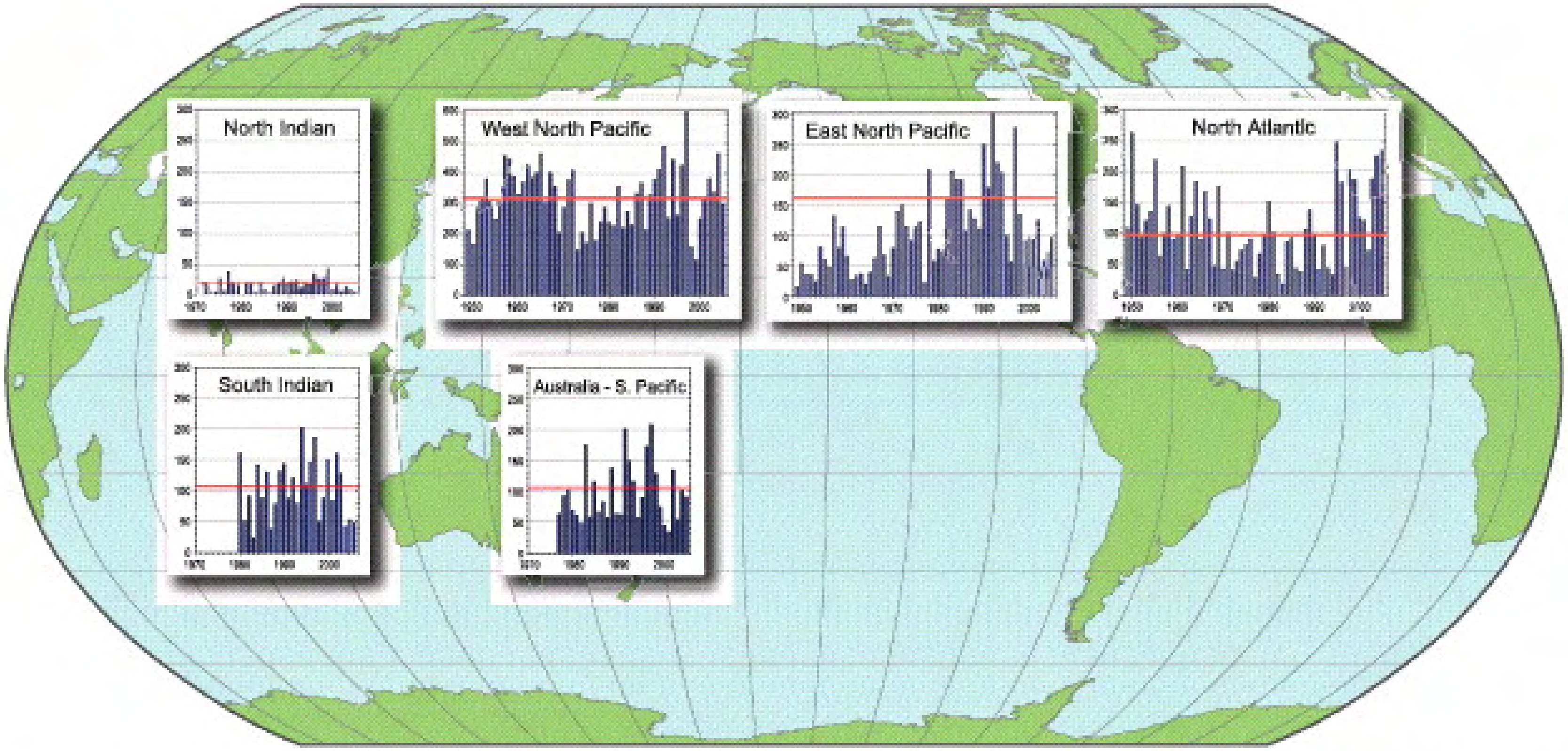


Figure 3.40. *Seasonal values of the ACE index for the North Indian, South Indian, West North Pacific, East North Pacific, North Atlantic and combined Australian-South Pacific regions. The vertical scale in the West North Pacific is twice as large as that of other basins. The SH values are those for the season from July the year before to June of the year plotted. The timeline runs from 1948 or 1970 through 2005 in the NH and through June 2006 in the SH. The ACE index accounts for the combined strength and duration of tropical storms and hurricanes during a given season by computing the sum of squares of the six-hour maximum sustained surface winds in knots while the storm is above tropical storm intensity. Adapted and updated from Levinson (2005).*

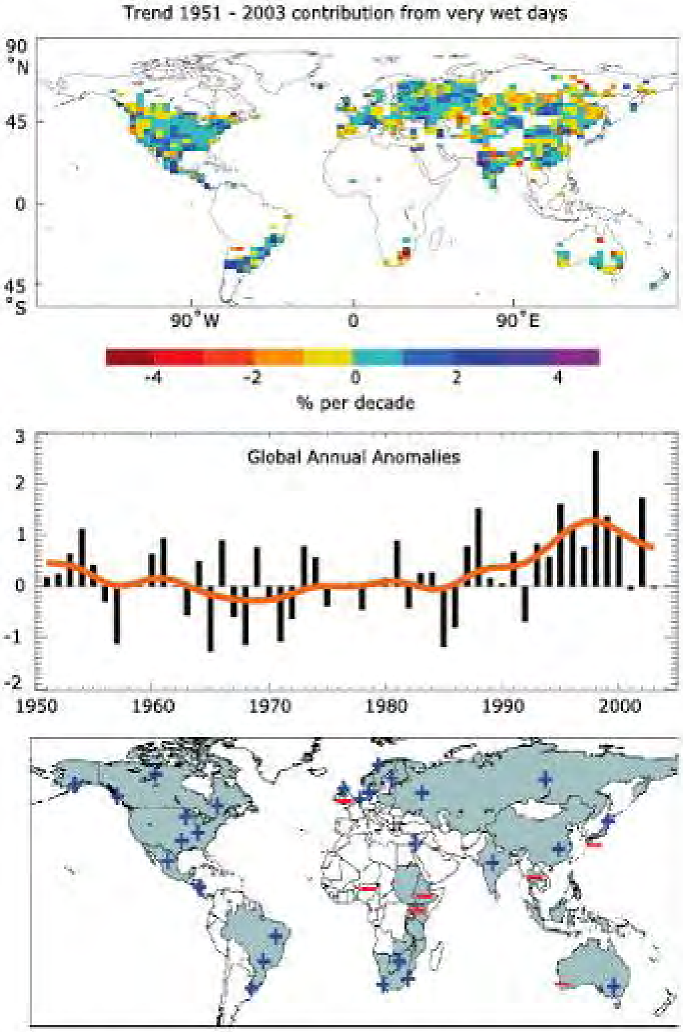
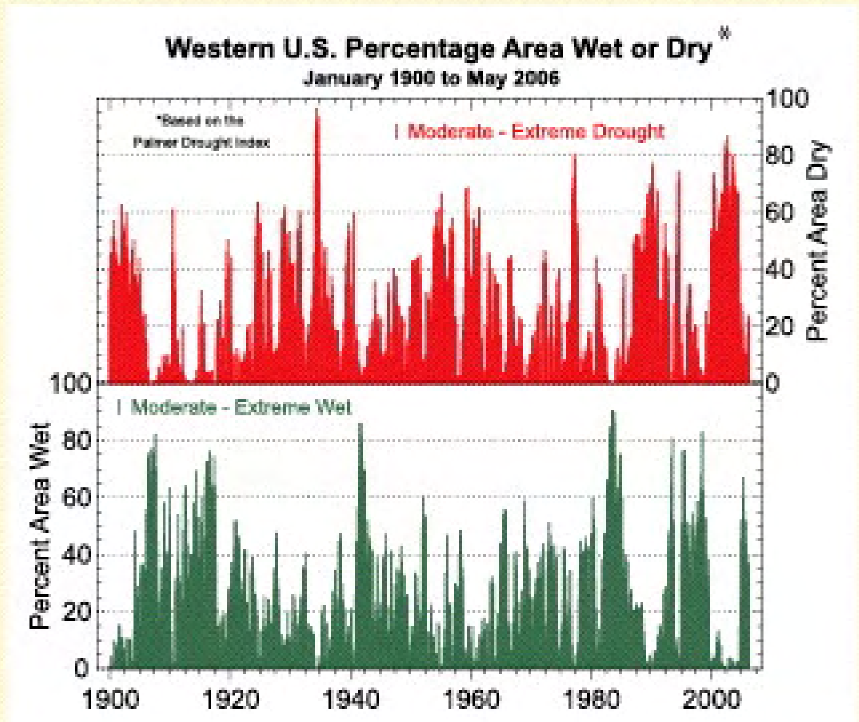


Figure 3.39. (Top) Observed trends (% per decade) for 1951 to 2003 in the contribution to total annual precipitation from very wet days (95th percentile). Trends were only calculated for grid boxes where both the total and the 95th percentile had at least 40 years of data during this period and had data until at least 1999. (Middle) Anomalies (%) of the global annual time series (with respect to 1961 to 1990) defined as the percentage change of contributions of very wet days from the base period average (22.5%). The smooth red curve shows decadal variations (see Appendix 3.A). From Alexander et al. (2006). (Bottom) Regions where disproportionate changes in heavy and very heavy precipitation during the past decades were documented as either an increase (+) or decrease (–) compared to the change in the annual and/or seasonal precipitation (updated from Groisman et al., 2005). Thresholds used to define "heavy" and "very heavy" precipitation vary by season and region. However, changes in heavy precipitation frequencies are always greater than changes in precipitation totals and, in some regions, an increase in heavy and/or very heavy precipitation occurred while no change or even a decrease in precipitation totals was observed.



Box 3.6, Figure 1. *Percentage of the USA west of the Rocky Mountains (the 11 states west of and including Montana to New Mexico) that was dry (top) or wet (bottom), based on the Palmer Drought Severity Index for classes of moderate to extreme drought or wet. From NOAA, NCDC.*

Frequently Asked Question 10.1: Are Extreme Events, like Heat Waves, Droughts or Floods, Expected to Change as the Earth’s Climate Changes?

Yes, the type, frequency and intensity of extreme events are expected to change as Earth’s climate changes,and these changes could occur even with relatively small mean climate changes. Changes in some types of extreme events have already been observed, for example, increases in the frequency and intensity of heat waves and heavy precipitation events.

- Increase in heat waves lasting several days or a week
- Reduced diurnal temperature range
- Fewer frost days and cold air outbreaks
- Some increase in summer dryness and winter wetness at mid-to-high latitudes
- More intense rainfall interspersed with longer dry periods
- Both wet and dry extremes increase
- Perhaps an increase in more intense hurricanes and a decrease in weaker ones.

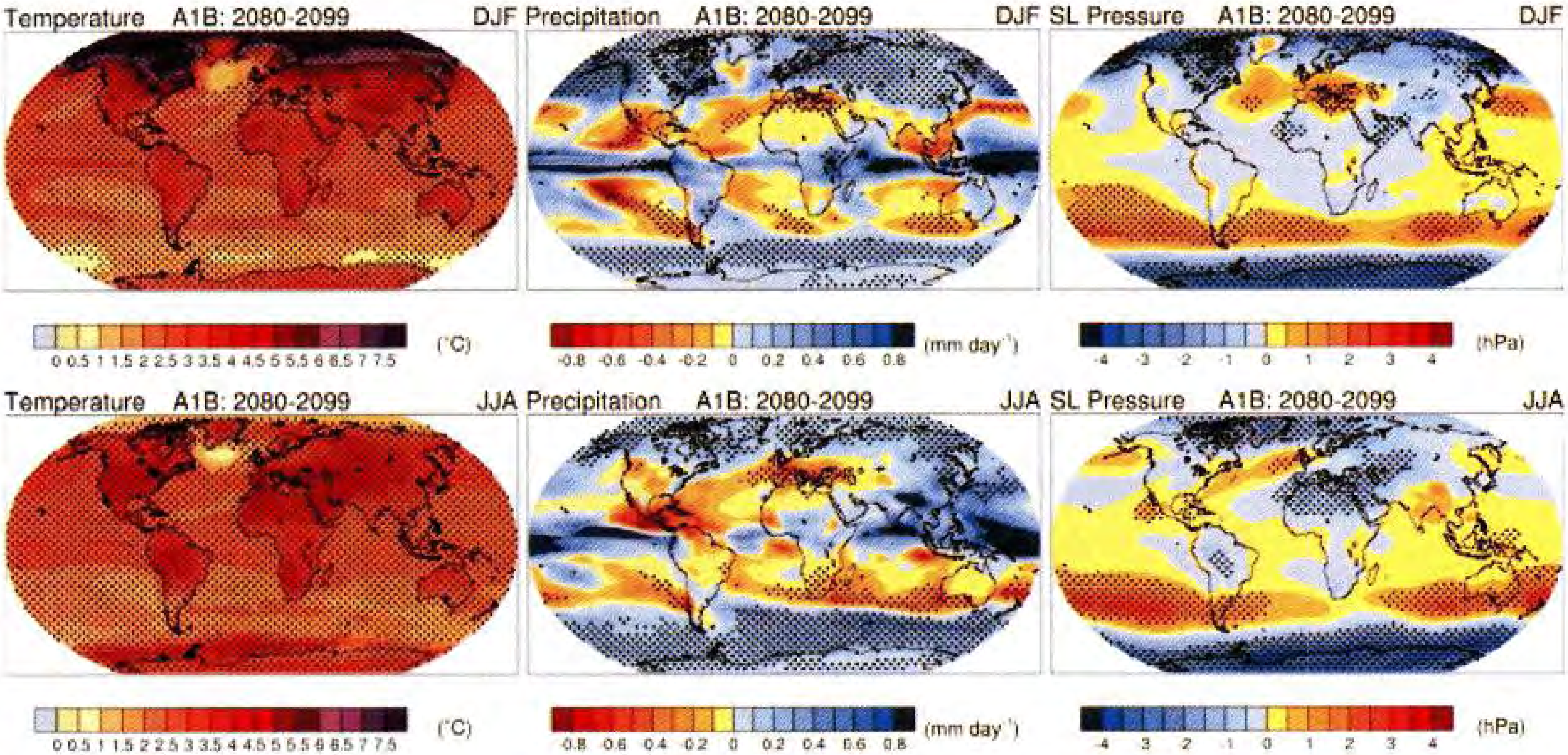


Figure 10.9. *Multi-model mean changes in surface air temperature (°C, left), precipitation (mm day^{-1}, middle) and sea level pressure (hPa, right) for boreal winter (DJF, top) and summer (JJA, bottom). Changes are given for the SRES A1B scenario, for the period 2080 to 2099 relative to 1980 to 1999. Stippling denotes areas where the magnitude of the multi-model ensemble mean exceeds the inter-model standard deviation. Results for individual models can be seen in the Supplementary Material for this chapter.*

IPCC, WG1, 2007

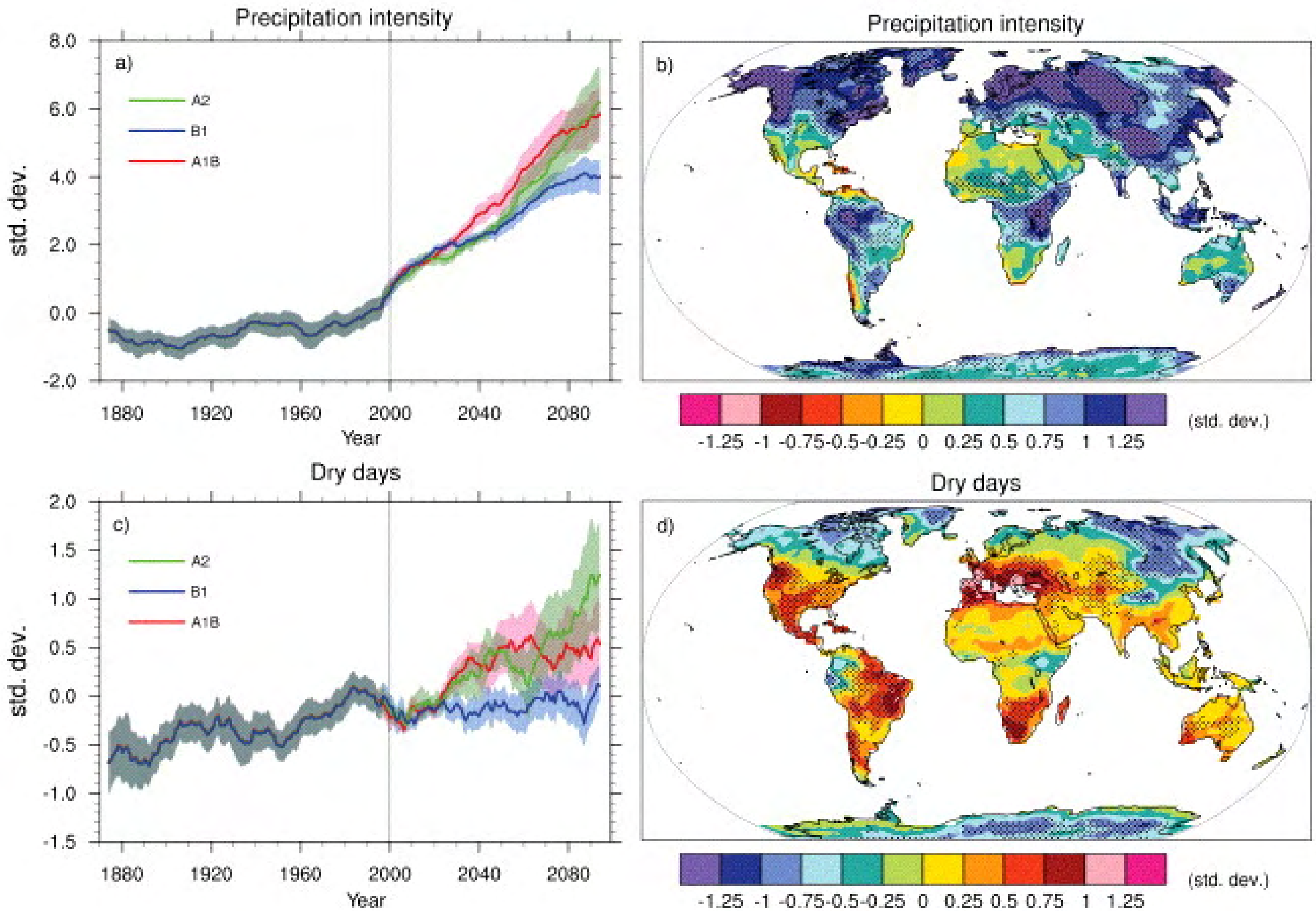


Figure 10.18. *Changes in extremes based on multi-model simulations from nine global coupled climate models, adapted from Tebaldi et al. (2006). (a) Globally averaged changes in precipitation intensity (defined as the annual total precipitation divided by the number of wet days) for a low (SRES B1), middle (SRES A1B) and high (SRES A2) scenario. (b) Changes in spatial patterns of simulated precipitation intensity between two 20-year means (2080–2099 minus 1980–1999) for the A1B scenario. (c) Globally averaged changes in dry days (defined as the annual maximum number of consecutive dry days). (d) Changes in spatial patterns of simulated dry days between two 20-year means (2080–2099 minus 1980–1999) for the A1B scenario. Solid lines in (a) and (c) are the 10-year smoothed multi-model ensemble means; the envelope indicates the ensemble mean standard deviation. Stippling in (b) and (d) denotes areas where at least five of the nine models concur in determining that the change is statistically significant. Extreme indices are calculated only over land following Frich et al. (2002). Each model's time series was centred on its 1980 to 1999 average and normalised (rescaled) by its standard deviation computed (after de-trending) over the period 1960 to 2099. The models were then aggregated into an ensemble average, both at the global and at the grid-box level. Thus, changes are given in units of standard deviations.*

Impacts (IPCC WGII)

(Occurring now)

- **Hydrology**:
  - Increased runoff and earlier spring peak in glacial and snow-fed rivers; then subsequently water shortages
  - Warming of lakes and rivers, with effects on thermal structure and water quality
- **Polar**:
  - Increase in glacial lakes
  - Increased instability in permafrost regions
  - Effects on ecosystems, including predators high on the food chain
- **Biology:**
  - Earlier timing of spring events (leaf-unfolding, bird migration, egg-laying)
  - Poleward and upward shift in ranges of plant and animal species
  - Shifts in range of algal, plant and fish abundance in high latitude oceans, lakes
  - Rapid changes and earlier migration of fish in rivers

Possible climate-related occurrences (now)

- Agriculture and forestry management at NH higher latitudes (earlier spring planting, disturbances)
- Human health (heat-related mortality, infectious diseases, allergies)
- Human activities in the Arctic and lower-elevation alpine areas
- Sea level rise and human development with coastal wetland/mangrove loss and coastal flooding damage
- Arctic wildlife, traditional indigenous ways of life

Changes in physical and biological systems and surface temperature 1970-2004

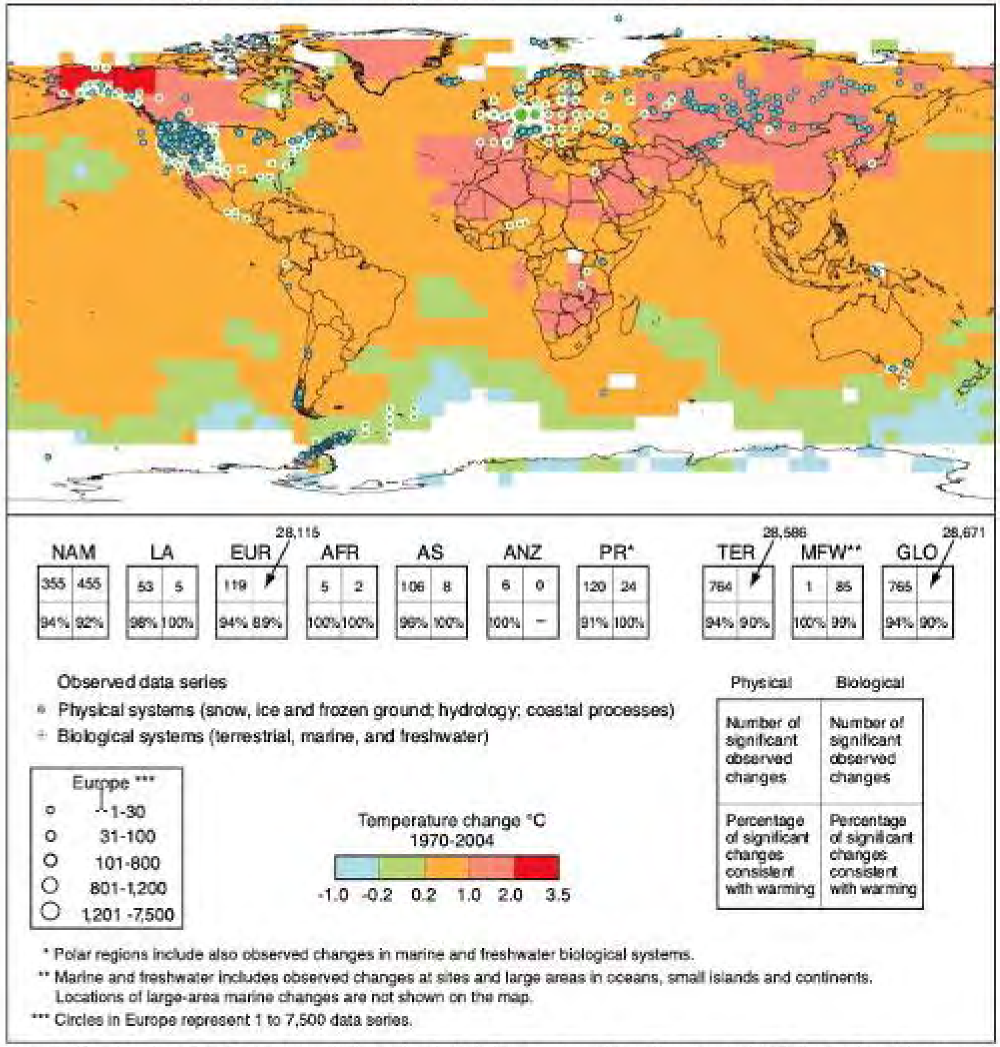


Figure SPM.1. *Locations of significant changes in data series of physical systems (snow, ice and frozen ground; hydrology; and coastal processes) and biological systems (terrestrial, marine, and freshwater biological systems), are shown together with surface air temperature changes over the period 1970-2004. A subset of about 29,000 data series was selected from about 80,000 data series from 577 studies. These met the following criteria: (1) ending in 1990 or later; (2) spanning a period of at least 20 years; and (3) showing a significant change in either direction, as assessed in individual studies. These data series are from about 75 studies (of which about 70 are new since the Third Assessment) and contain about 29,000 data series, of which about 28,000 are from European studies. White areas do not contain sufficient observational climate data to estimate a temperature trend. The 2 x 2 boxes show the total number of data series with significant changes (top row) and the percentage of those consistent with warming (bottom row) for (i) continental regions: North America (NAM), Latin America (LA), Europe (EUR), Africa (AFR), Asia (AS), Australia and New Zealand (ANZ), and Polar Regions (PR) and (ii) global-scale: Terrestrial (TER), Marine and Freshwater (MFW), and Global (GLO). The numbers of studies from the seven regional boxes (NAM, …, PR) do not add up to the global (GLO) totals because numbers from regions except Polar do not include the numbers related to Marine and Freshwater (MFW) systems. Locations of large-area marine changes are not shown on the map. [Working Group II Fourth Assessment F1.8, F1.9; Working Group I Fourth Assessment F3.9b].*

Projected Impacts

- Water runoff and availability: +10 to +40% at high latitudes and some wet tropical regions; -10 to -30% for some mid-latitude dry regions and dry subtropics (by 2050). Demand (population), vulnerability (exposure, sensitivity, adaptive capacity - wealth) may be more important for availability.
- Ecosystems will likely be overwhelmed by combination of climate change and associated disturbances (e.g., flooding, drought, wildfire, insects, ocean acidification), as well as other global change drivers (e.g., land-use change, pollution, over-exploitation of resources). ~20-30% of plant and animal species assessed so far at increased risk of extinction for warming of 1.5-2.5°C (but may be worse than this - species change faster than biomes; extremes more important than means; rate of change of great importance); impacts on biodiversity and species ranges with predominantly negative effects on biodiversity and ecosystem goods and services (e.g., food and water supply)
- Progressive acidification of oceans will have negative impacts on corals and their dependent species
- Crops may increase at high latitudes until temp warms more than 1-3°C; at lower latitudes crops should decrease. General distinction at <1°C or >1°C. Also a function of duration, climate extremes, CO_2 fertilization, adaptation.
- Sea level rise: Continued coastal erosion and negative impacts on salt marshes and mangroves, with many millions of people affected by flooding by 2080; adaptation (protection, accommodation, retreat) helps; rise continues >1000 years
- Increases in malnutrition, diarrhea, cardio-respiratory diseases (ozone), altered infectious disease vectors
- Elderly population at risk from heat waves, fewer cold-related illnesses

Population in danger of water stress

(Arnell, 2006)

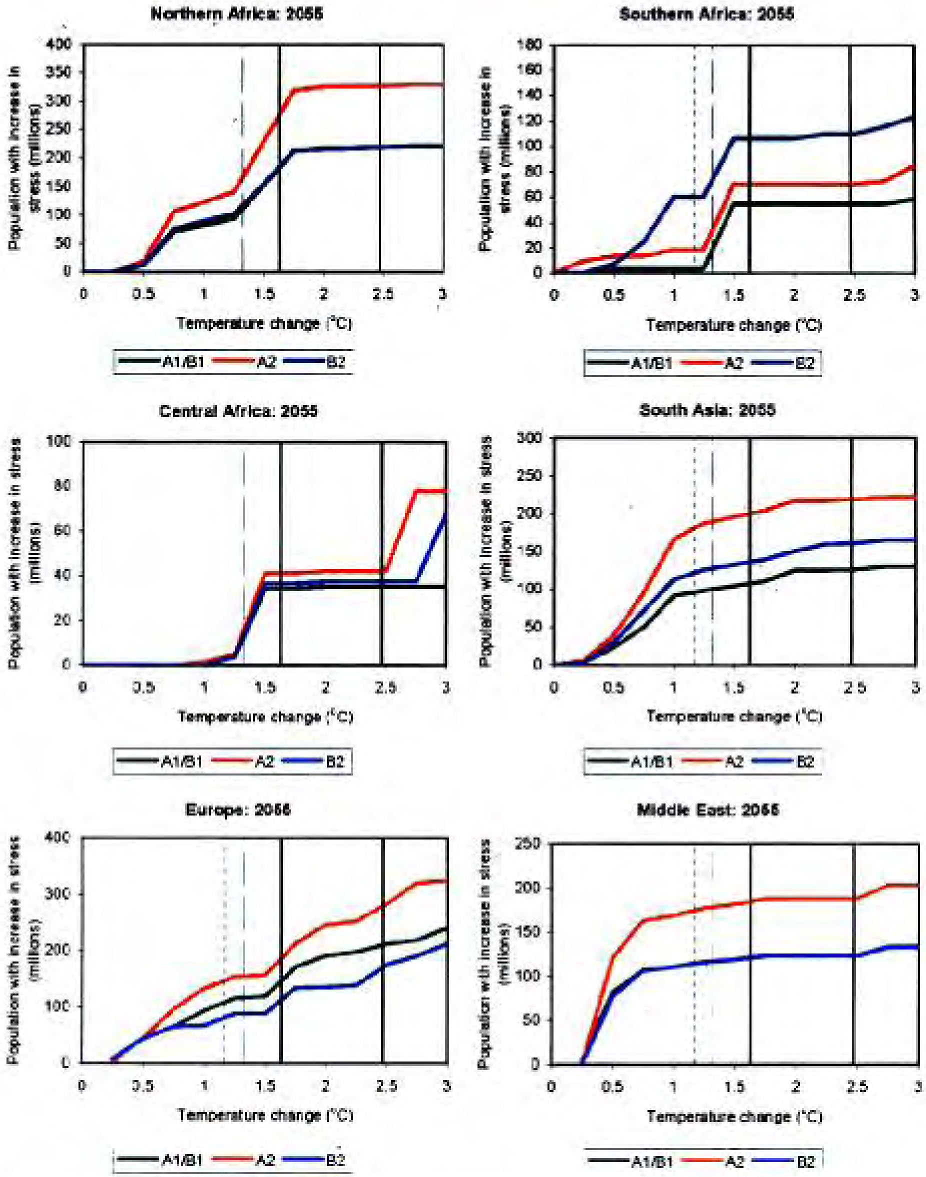


Figure 17.7 Numbers of people living in watersheds with an increasing water stress, by region, in 2055, with different amounts of global temperature change relative to 1961–1990. Changes in temperature and rainfall derived from HadCM3.

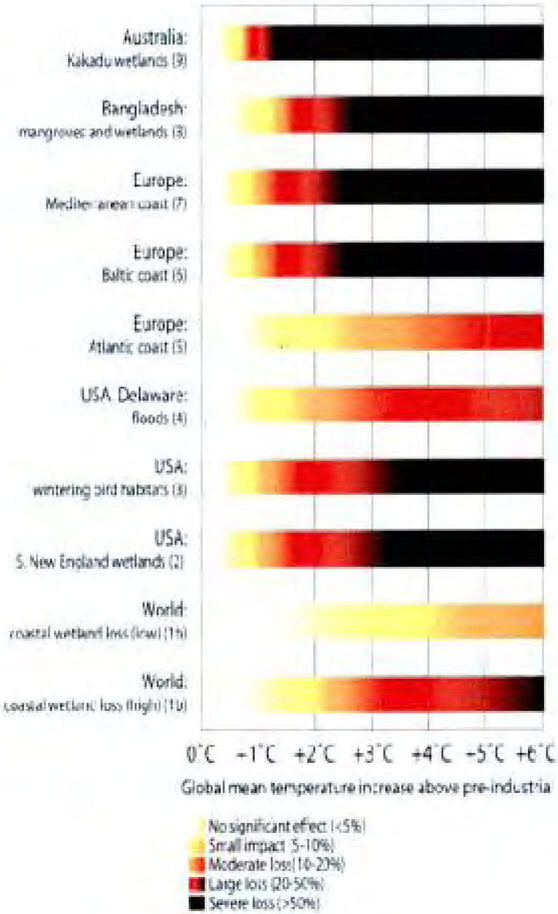


Figure 18.1 Impacts on Coastal Wetlands

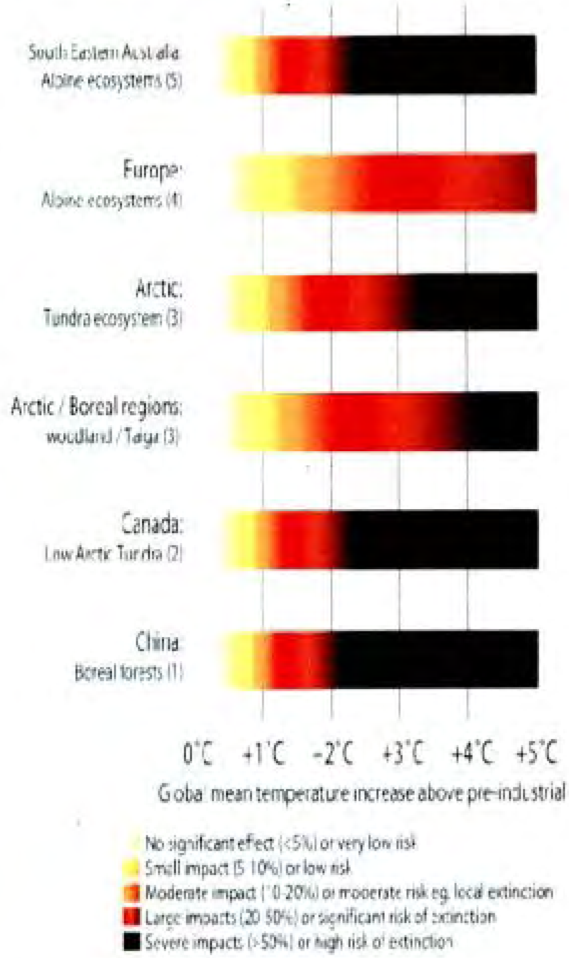


Figure 18.4 Impacts on ecosystems

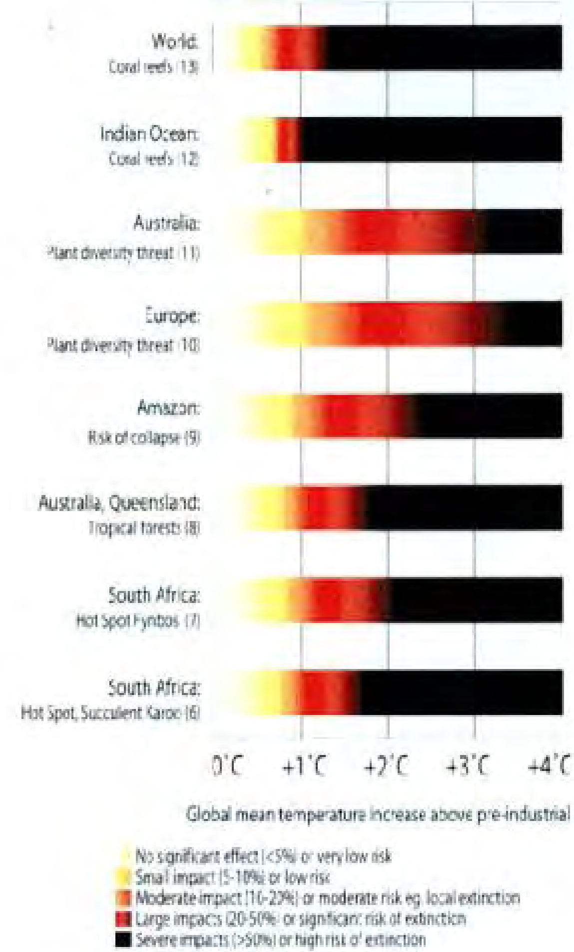
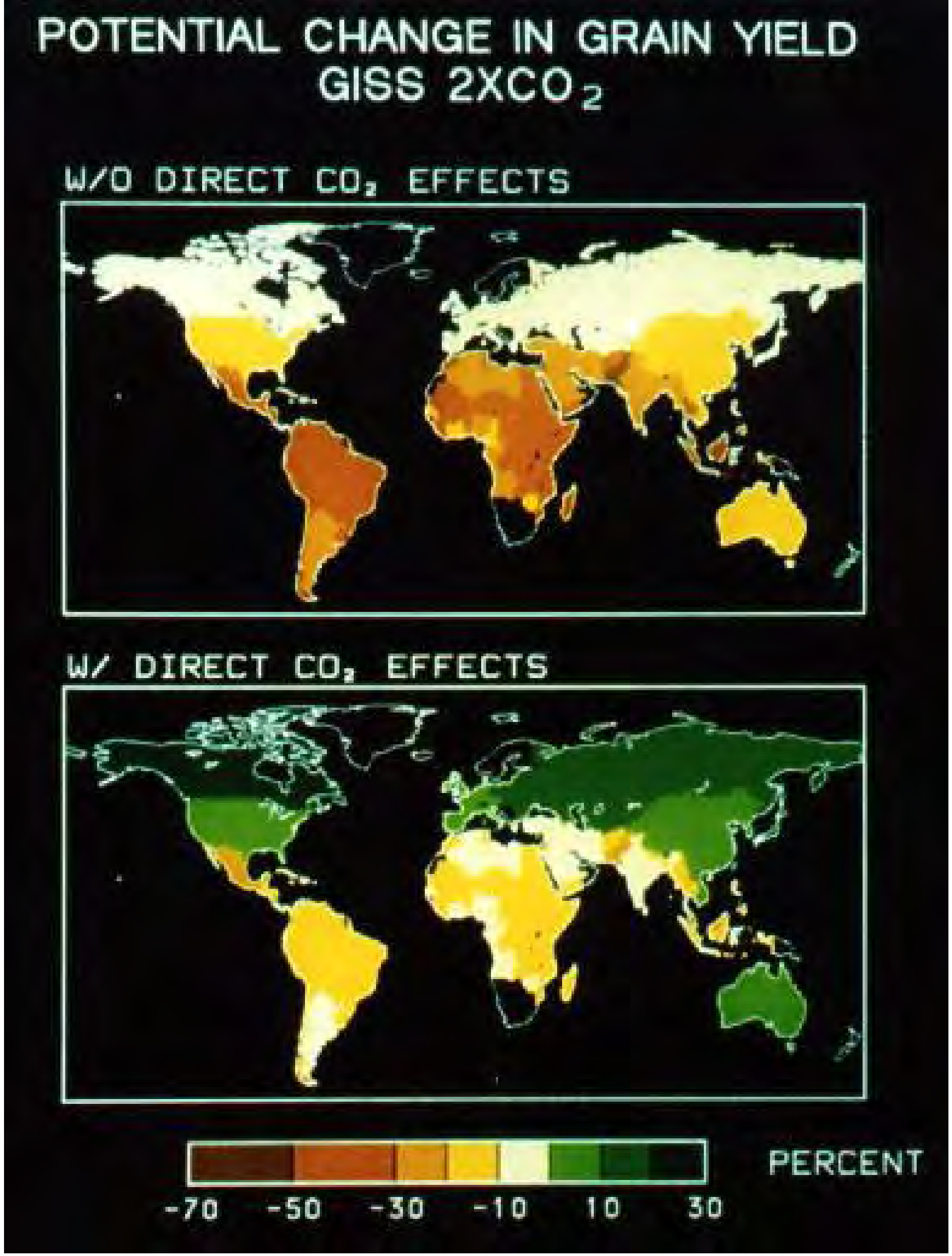


Figure 18.5 Impacts on ecosystems (continued)

Coastal Wetlands

Ecosystems

Hare (2006)



Rosenzweig and Parry (1992)

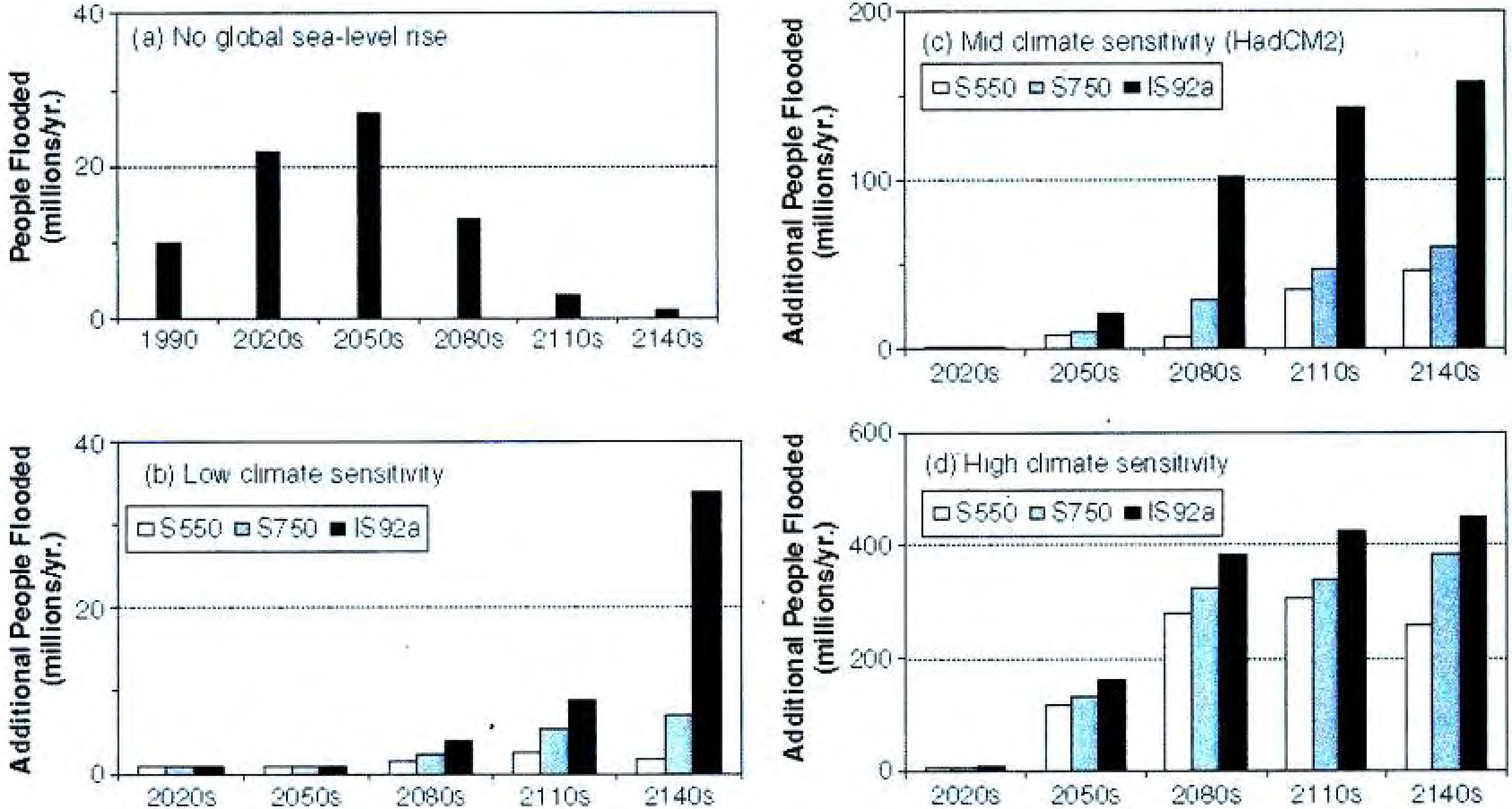


Figure 20.3 Coastal flooding under the IPCC 'S' Stabilisation experiments from 1990 to the 2140s, which compares unmitigated (IS92a) impacts with those under the S750 and S550 stabilisation scenarios. (a) People flooded/year without any global sea-level rise; (b) Additional people flooded/year due to sea-level rise assuming low climate sensitivity; (c) as (b) for mid climate sensitivity (HadCM2); (d) as (b) for high climate sensitivity. Note the varying scale of the y axis. (Reprinted from Nicholls and Lowe (2004) with permission from Elsevier).

Nicholls and Lowe, 2006

Impacts at Δ Global Mean Temp

(R. Warren, in "Avoiding Dangerous Climate Change" 2006)

- 1°C: world ocean and arctic ecosystems damaged
- 1.5°C: Greenland ice sheet melting starts; ecosystems damaged in many regions
- 2°C: Agricultural yields fall, 1-3 billion experience water stress, sea level rise displaces millions, malaria risks spread, Arctic ecosystems collapse, extinctions take off , 97% of coral reefs gone, global ecosystems lose 5-66% of their extent;
- 2-3°C: Amazon and other forests and grasslands collapse, adding to CO2 increase
- 3°C: Millions at risk to water stress, flood, hunger, dengue and malaria increase, few ecosystems can adapt, losing 7-74% of extent
- 4°C: whole regions forced out of agriculture (Australia), thermohaline circulation could collapse, West Antarctic Ice Sheet melting may begin, increases in extreme weather, 60% loss of tundra

A Personal Perspective

- Atmospheric Dynamics are Initiated by gradients in temperature (or energy)
  - Latitudinal/Longitudinal Temperature Gradients for Extratropical Storms
  - Vertical Energy Gradients for localized Severe Storms
  - The vertical gradients are affected by the latitudinal gradients
- Unfortunately, we don’t know how these temperature gradients will change

BACK IN 1979…

- CHARNEY REPORT: ~1.5-4.5°C FOR $2XCO_2$
- FOLLOW UP ASSESSMENT (SMAGORINSKY ET AL., 1982): SAME RANGE
- NOT NOTICED - BUT FACTOR OF 2 UNCERTAINTY FOR BOTH LOW AND HIGH LATITUDE RESPONSES*

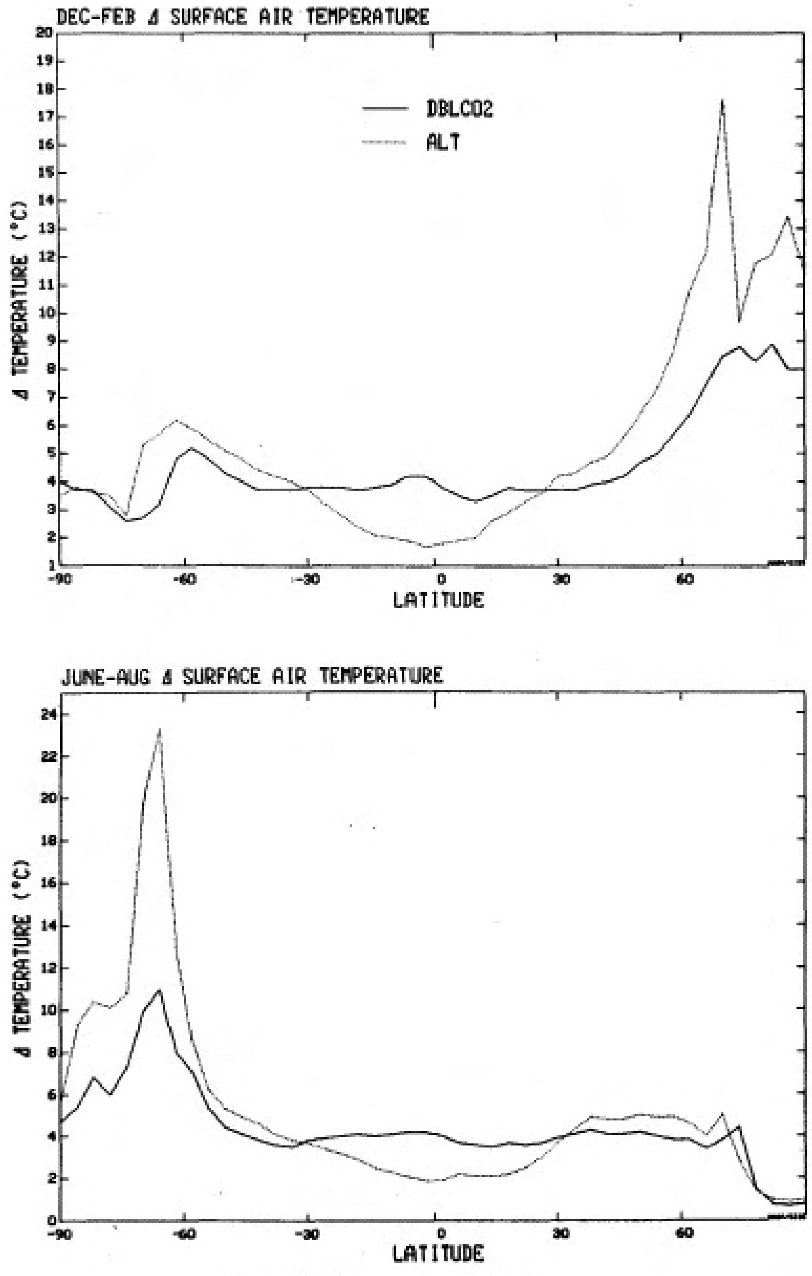
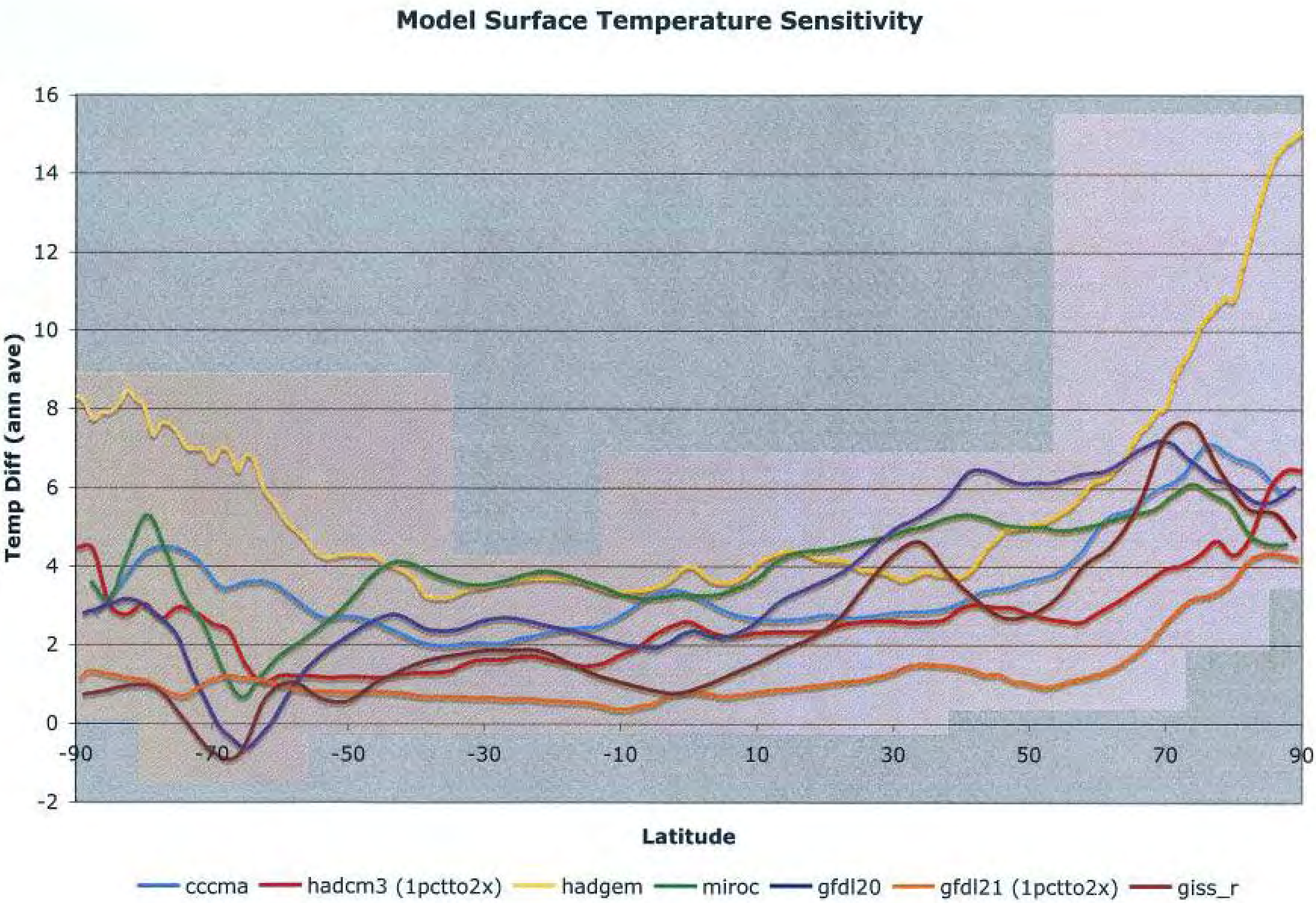


FIG. 2. As in Fig. 1, except for surface air temperature.

RIND
J.Atmos.Sci.
(1987)

WHAT HAS CHANGED SINCE?

- RANGE PRETTY MUCH STILL THE SAME (LOWER PROBABILITY FOR <2°C)
- LOW LATITUDE AND HIGH LATITUDE SENSITIVITY - IN GENERAL STILL A FACTOR OF TWO DIFFERENCE (BOTH EQUILIBRIUM AND TRANSIENT)*
- AR4 MODELS:
  – 50% PROB TROPICS>+2°C FOR A1B SCENARIO AT 2100
  – HIGH LAT N.H .FACTOR OF 4 IN ΔT FOR 2100
  – HIGH LAT AMPLIFICATION RELATIVE TO GLOBAL TEMP CHANGE VARIES FROM 1.3 - 4X



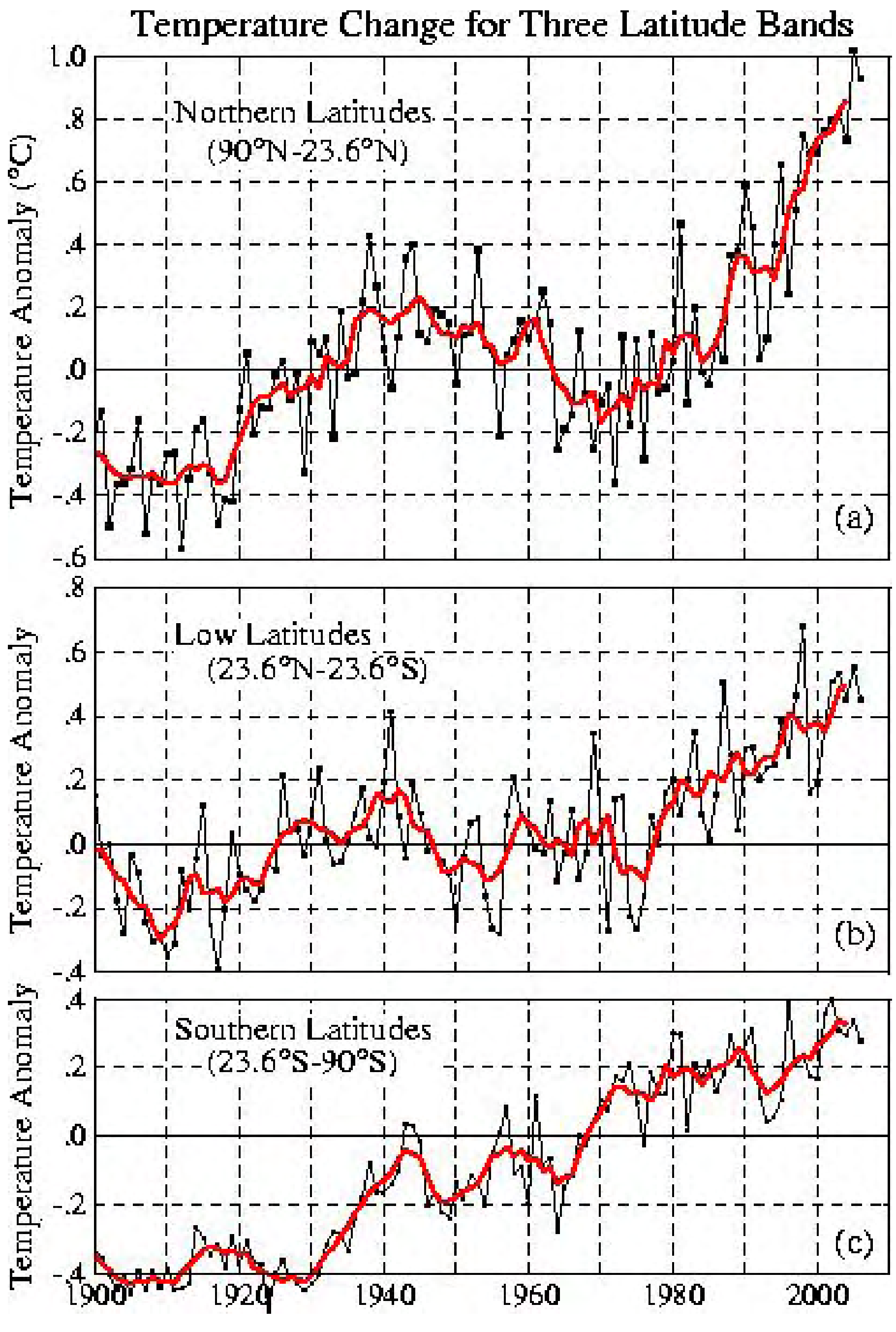
Data from AR4 Lawrence Livermore website (courtesy J. Alltop)

WHY THE DIFFERENT GCM TROPICAL SENSITIVITIES?

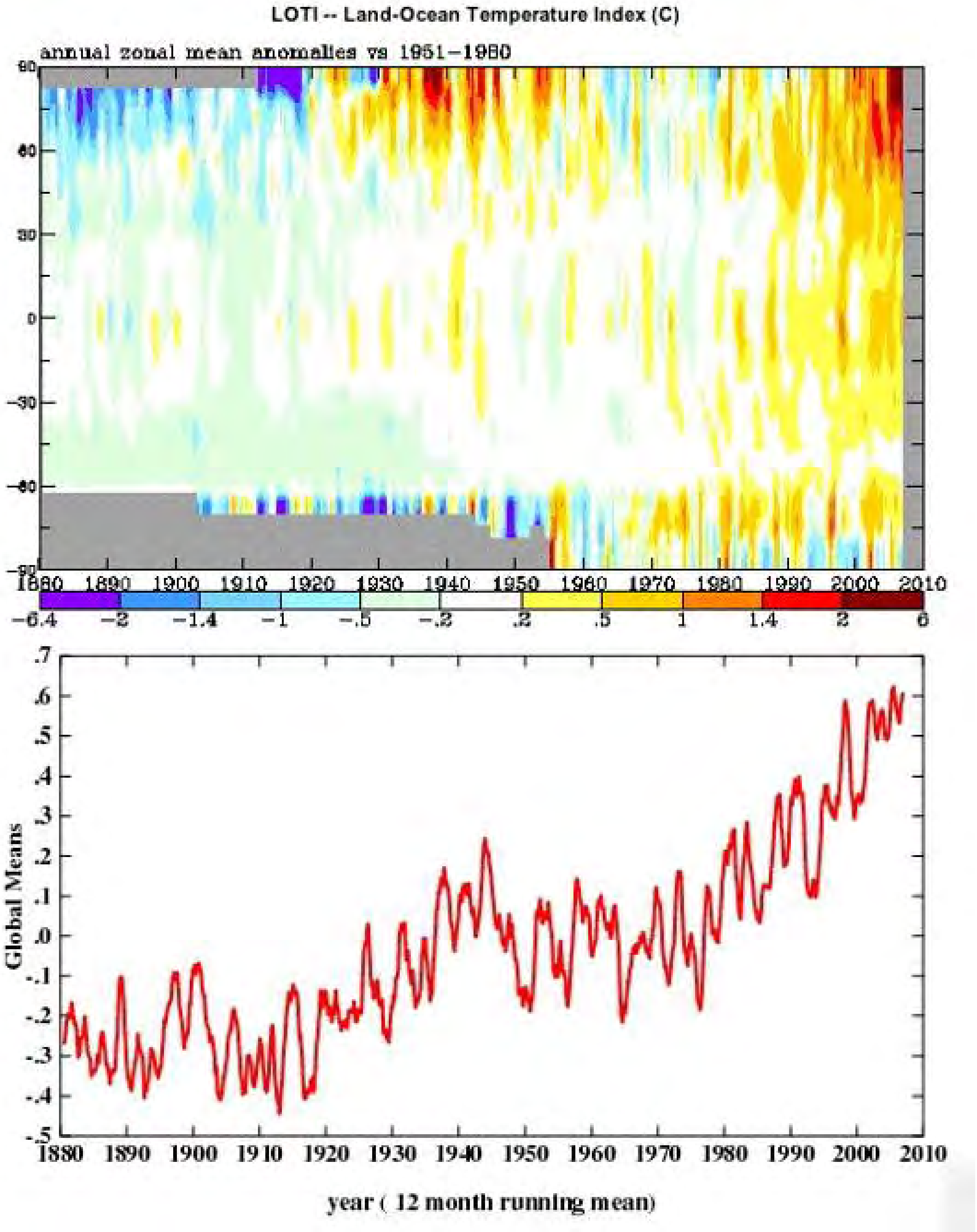
- NOT WATER VAPOR - AND NO EVIDENCE THIS FEEDBACK IS WRONG
- LOW CLOUDS = f(STABILITY, SHALLOW CONVECTION, PRECIP, CAPPING INVERSION HT; REMOTE DYNAMICS - DEEP CONVECTION AND SUBSIDENCE)
  - CHANGES DOMINANT IN EAST AND WEST PACIFIC*
- HIGH CLOUDS =f(TROPICAL DEEP CONV, MICROPHYSICS FOR CRF, AREAL COVERAGE ; CLOUD TOP TEMP)
  - CHANGES DOMINANT IN CENTRAL PACIFIC, INDIAN OCEAN*
- DYNAMICAL CHANGES (WALKER, HADLEY CIRCULATION) AFFECT CLOUDS AND MAYBE Cloud Radiative Forcing

DOES THE HISTORICAL CLIMATE HELP? TROPICS

- TROPICS 2/3 OF EXTRATROPICS (TRUE FOR 100 YRS AND LAST 25 YRS)*
- TROPICAL DATA UNCERTAIN (ESPECIALLY BACK 100 YEARS)
- TROPICAL RESPONSE TIMES FASTER (SMALLER MIXED LAYER DEPTHS)
- MORE FREQUENT EL NINOS MIGHT BE OBSCURING RECORD
- RECORD IS INCONSISTENT*



http://data.giss.nasa.gov/gistemp/



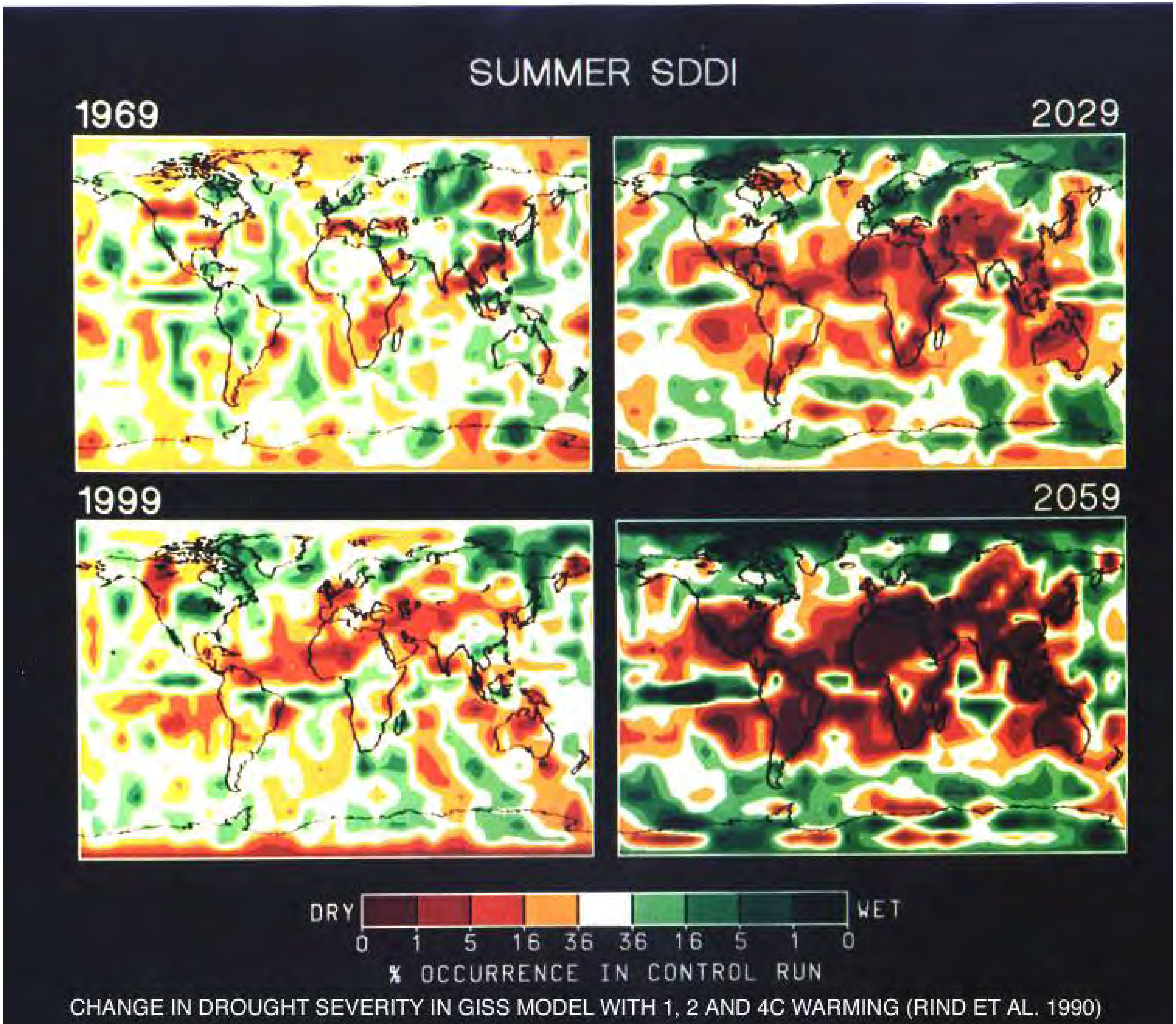
http://data.giss.nasa.gov/cgi-bin/cdrar/do_LTmapE.py

IMPACTS RELATED TO TROPICAL UNCERTAINTY

- LARGER THE TROPICAL TEMPERATURE CHANGE, GREATER THE LIKELIHOOD OF SEVERE NEGATIVE EFFECTS ON HUMAN HEALTH, AGRICULTURE, ECOSYSTEMS (IPCC, 2001)
- GREATER THE WARMING, LARGER THE INCREASE IN POTENTIAL EVAPOTRANSPIRATION AND PROBABILITY OF DROUGHT*
  - ABSOLUTE VALUES OF RESULTS DEPENDS UPON POT EVAP SENSITIVITY TO TEMPERATURE
  - RESULTS CONSISTENT WITH AGRICULTURAL MODELS WHEN NOT USING CO2 FERTILIZATION*
  - SIGN OF PRECIP CHANGE OVER TROPICAL LAND INCONSISTENT IN AR4 MODELS

0°

+1°



+2°

Rind et al.
J. Geophys.
Res. 1990

+4°

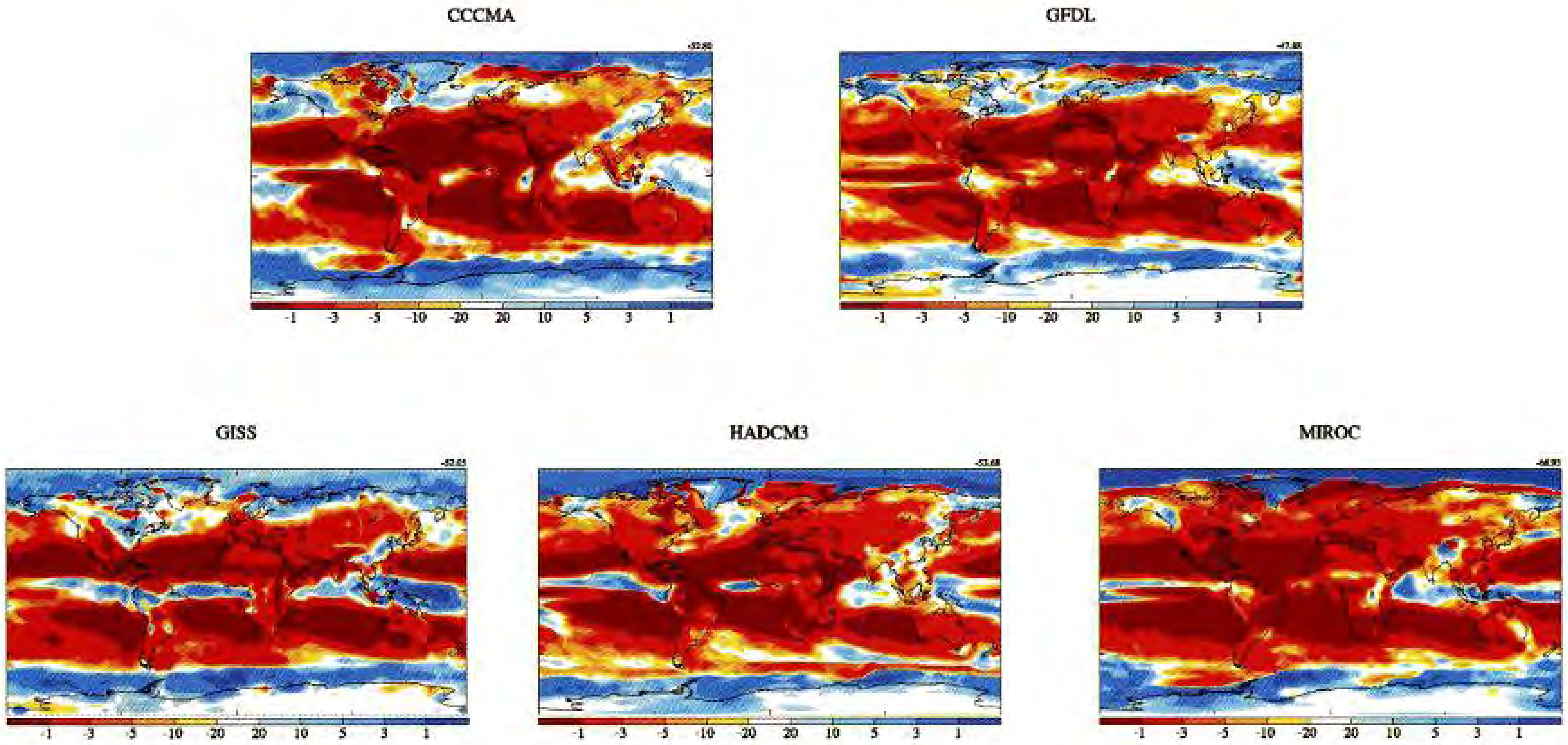
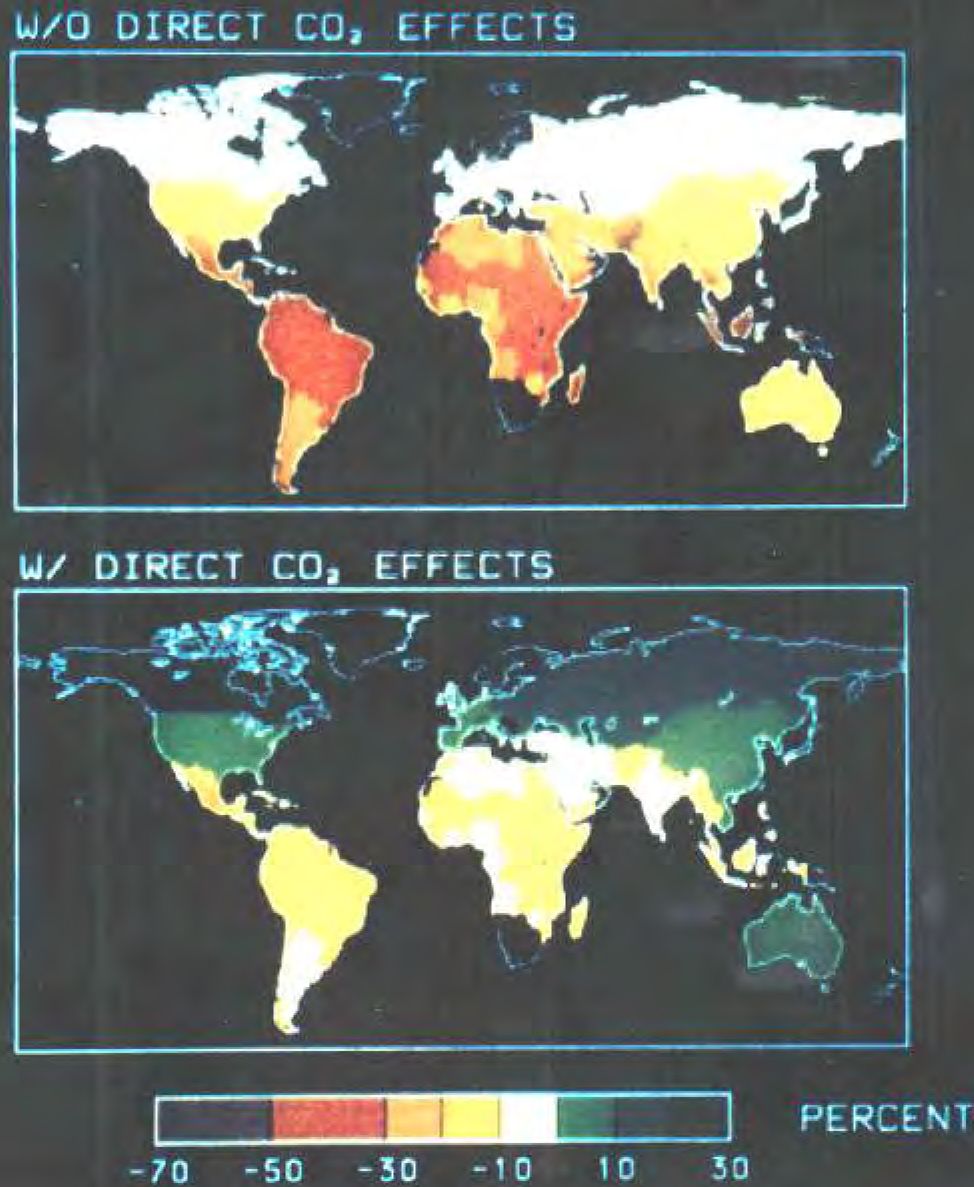


Figure 2 - This figure shows the % occurrence of future SDDI values in control run. 30-year average from 2071 to 2100 is shown. Dry and wet condition are negative and positive respectively.

(courtesy J. Alltop)

POTENTIAL CHANGE IN GRAIN YIELD GISS $2XCO_2$

Without the optimistic assumption of full CO2 fertilization (bottom) even the U.S. suffers from the effect of water stress on agricultural production (top), but 3rd World countries are most affected.



Source: Rosenzweig and Parry 1992

WHY THE DIFFERENT GCM HIGH LATITUDE SENSITIVY?

- CRYOSPHERE : SNOW AND SEA ICE (ABOUT 50%-50%)
- SNOW SURF ALBEDO=f(MELT, AGING, IMPURITIES) CHANGE WITH TEMP VARIES BY 3X
- SEA ICE SIMULATIONS POOR - f(ATM, OCEAN CIRCULATION)
- CHANGE = f(SEA ICE THICKNESS IN NH)*
- ALSO f(LOW CLOUDS, WATER VAPOR: DOWNWARD LW FLUX; ATM & OCEAN HEAT TRANSPORT)

DOES THE HISTORICAL RECORD HELP? POLAR

- OVER PAST 25 YEARS, REGION >65N HAS WARMED 1°C, 3X TROPICS
- HIGH SOUTHERN LATITUDES HAVE LITTLE CHANGE (ZONALLY-AVERAGED)
- HIGH LAT MORE VARIABLE - RUSSIAN DATA SHOW LITTLE TREND OVER LAST 100 YRS*
- AO/NAO INFLUENCE - MAYBE NOT GLOBAL WARMING RELATED*
- CURRENT TREND COULD ACCELERATE - PASS CRITICAL MELTING POINTS

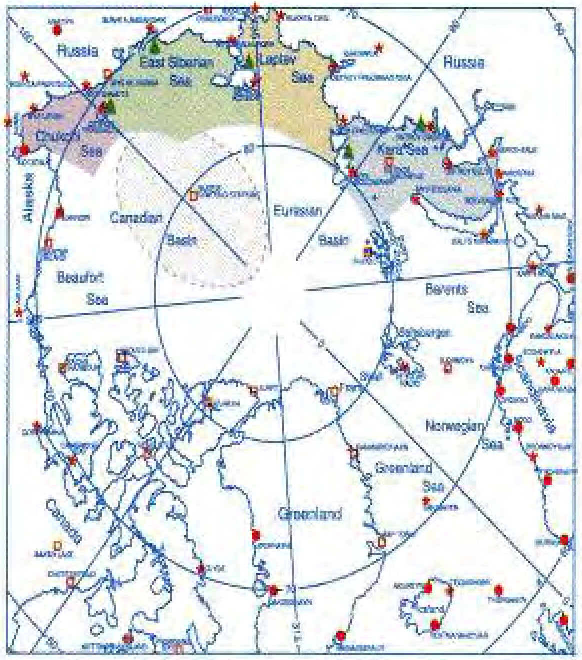


Figure 1. Locations of surface-air temperature and ice observations. Red circles show stations with length of observations L ≥ 100 years, red stars represent stations with 65 ≤ L < 100, and red squares indicate stations with L < 65. The red cross-hatched oval denotes the region represented by data from the manned drifting stations and IABP drifting buoys. Colors denote regions used for analysis of observed ice extent. Green triangles denote stations where the fast-ice thickness data were collected.

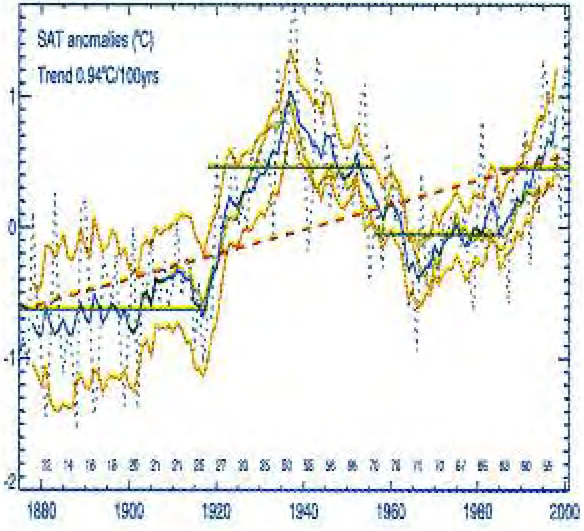


Figure 2. Composite time series of surface air temperatur anomalies (°C) relative to 1961–90 for the region polewar of 62°N. The plot displays the annual means (dashed blue) six-year running means (solid blue), 95% significance leve (yellow), trend (dashed red), means for positive an negative LFO phases (horizontal green), and six-yea running means using the 24 longest (century plus) records Numbers at the bottom of the panel denote the number o stations used for averaging.

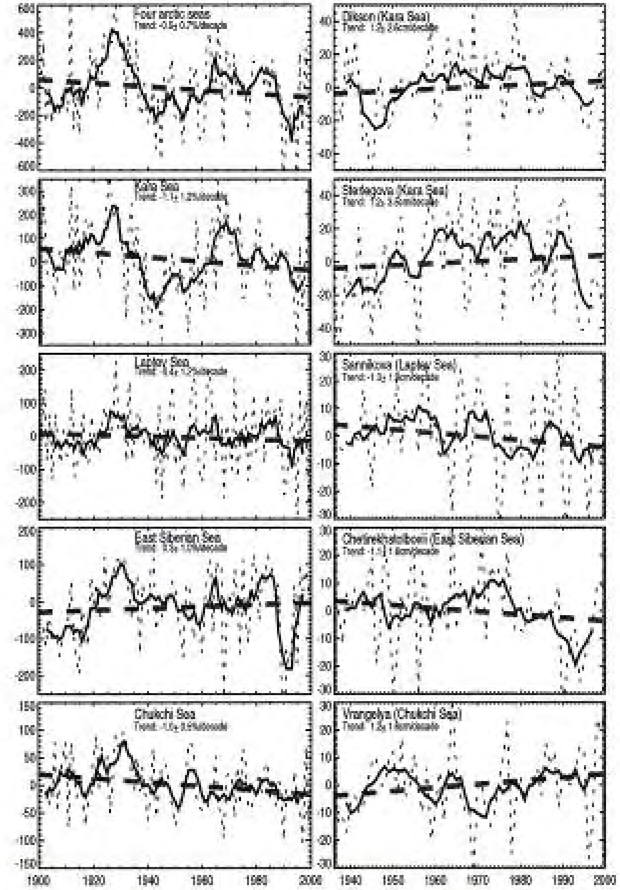
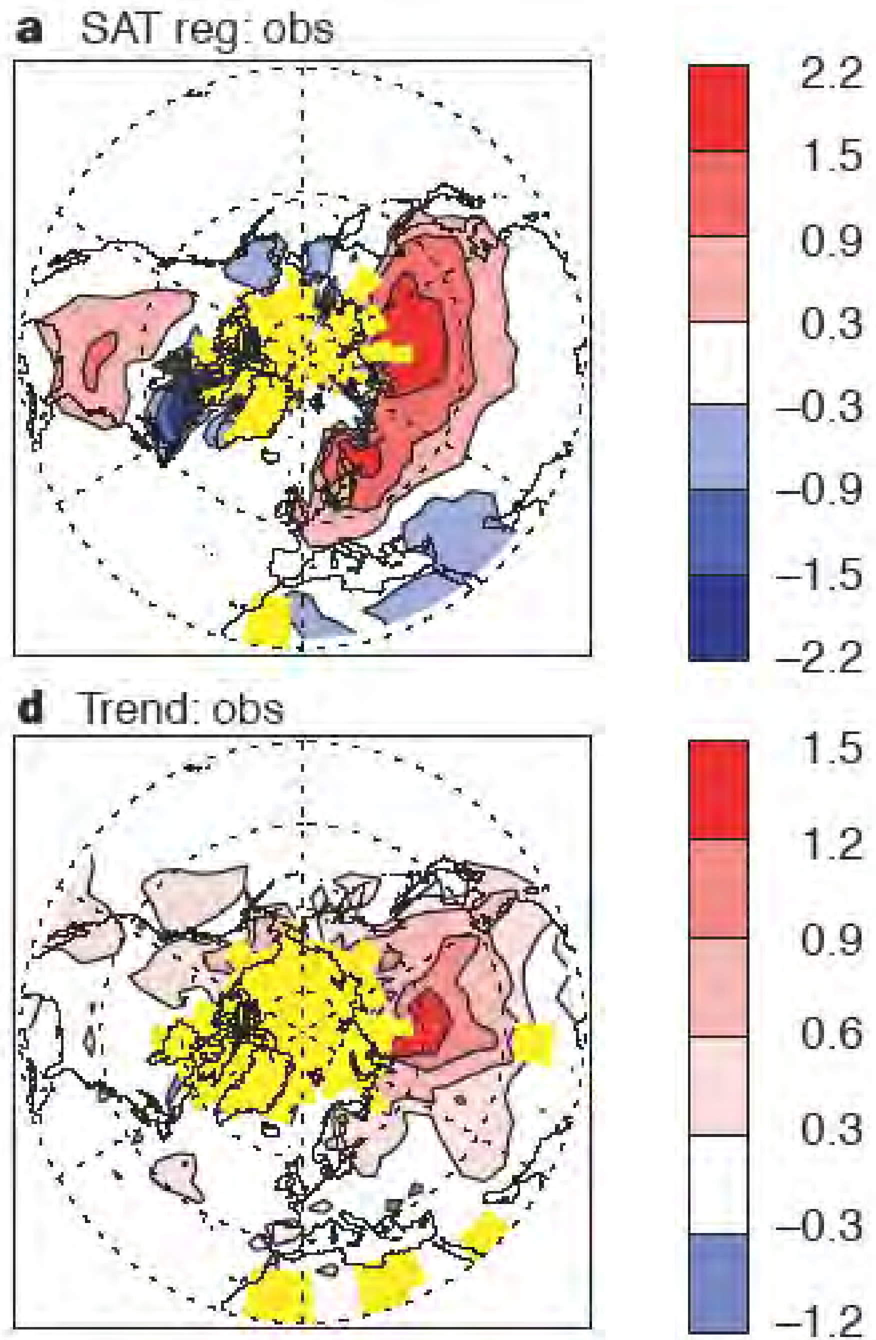


Figure 4. (Left) Time series of August ice-extent anomalies (×1000 km^2) in four arctic seas. (Right) Time series of annual maximum fast-ice thickness anomalies (cm) at five locations. The plot shows annual means (dotted), six-year running means (solid), and linear trends at the quoted 95% level (dashed).

POLYAKOV ET AL., GRL, 2002

REGRESSION OF AO INDEX ON SURFACE AIR TEMP

LINEAR TREND



SHINDELL ET AL., NATURE, 1999

IMPACTS RELATED TO HIGH LATITUDE UNCERTAINTY

- MAGNITUDE OF MELTING OF POLAR ICE SHEETS AND SEA LEVEL RISE
- FUTURE OF SEA ICE AND POLAR SHIPPING LANES
- FUTURE OF HIGH LATITUDE MAMMALS AND INDIGINOUS LIFE STYLES
- POTENTIAL FOR CHANGES IN OCEAN CIRCULATION INITIATED FROM POLAR LATITUDES

REGIONAL EFFECTS OF TROPICAL/HIGH LATITUDE SENSITIVITY

- REGIONAL INFLUENCES OFTEN ASSOCIATED WITH LONGITUDE-SPECIFIC SST CHANGES
- NEED TO FORECAST HOW DIFFERENT REGIONS WILL WARM RELATIVE TO OTHERS AT THE SAME LATITUDE
- REGIONAL DIFFERENTIATION CAN AFFECT CLIMATE CHANGE IN LOCATIONS FAR REMOVED
- HERE TOO ATMOSPHERIC DYNAMICS MORE A FUNCTION OF TEMPERATURE GRADIENTS THAN ABSOLUTE TEMPERATURE
  - WHAT WE HAVE LEARNED ABOUT TELECONNECTIONS WILL BE APPLICABLE TO SOME EXTENT IN THE FUTURE AS WELL
- WE WILL TAKE A ‘WORLD TOUR’, STARTING AT LOW LATITUDES AND PROGRESSING POLEWARD

TROPICAL OCEANS

- PATTERN OF WARMING AFFECTED BY CLOUDS: LOW CLOUDS IN EASTERN AND WESTERN PACIFIC, HIGH CLOUDS IN CENTRAL PACIFIC AND INDIAN OCEAN (IN MODELS)
- PATTERN AFFECTED BY OCEAN DYNAMICS AND ATM DYNAMICS
  - 80% OF MODELS IN AR4 FORECAST QUASI-PERMANENT EL NINO BACKGROUND STATE (20% LA-NINA LIKE)
  - NO AGREEMENT ON CHANGES IN FREQUENCY/PHASE
  - ENSOS AFFECT INDIAN OCEAN AND ATLANTIC TEMPERATURES VIA ATMOSPHERIC BRIDGES (LATENT HEAT FLUX EFFECTS)
- PROJECTIONS FOR YEARS 2000-2050 SHOW STANDARD DEVIATION AMONG MODELS 40% OF PROJECTED TRENDS IN EASTERN PACIFIC AND SOUTH ATLANTIC, ABOUT 25% IN INDIAN OCEAN AND NORTH ATLANTIC
  - 60% OF AR4 MODELS HAD INDIAN OCEAN WARMING >2°C, 40% HAD IT LESS*
  - 50% HAD WARMING IN N.ATL. AND S. ATL. >2°C, 50% <2°C (LOW CLOUD COVER EFFECTS)

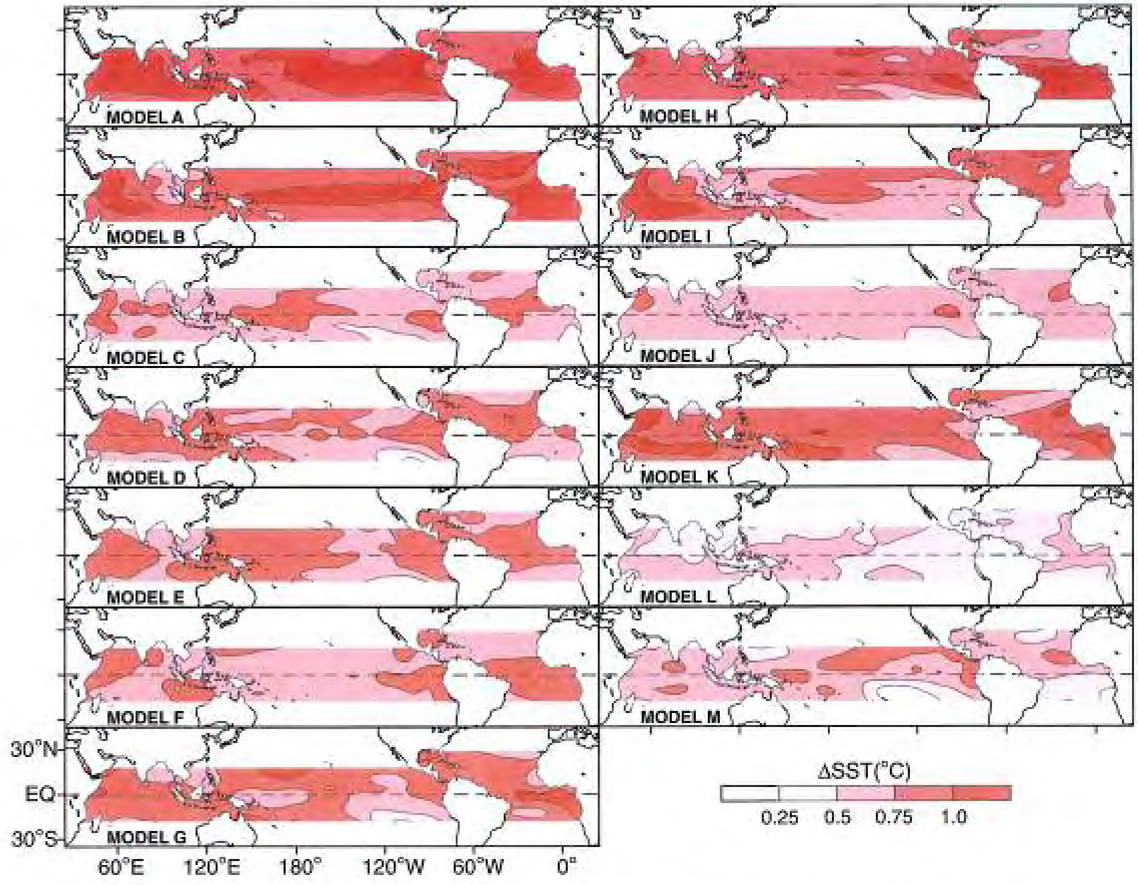


Fig. 2 The 13 coupled climate model projections of tropical SST change used to construct Fig. 1a, b. Using the nomenclature of the repository at PCMDI (Program for Model Intercomparison and Diagnosis, http://www-pcmdi.llnl.gov) the climate models are as follows: CCCMA CGCM3.1, CNRM CM3, CSIRO MK3.0, GFDL CM2.0, GFDL CM2.1, GISS MODEL E_R, IMNCM3.0, IPSL CM4, MIROC3.2_medres, MPI_ECHAM5, NCAR CCSM3.0, NCAR PCM1, and UKMO HADCM3. The particular choices of models and of emissions scenario are only intended to be illustrative of the variety of SST patterns projected by state-of-the-art coupled climate models. Therefore, we have not labeled the individual plots with the source model names

Barsugli et al., Clim Dyn, 2006

NORTHERN AUSTRALIA/INDONESIA/ WESTERN TROPICAL SOUTH AMERICAN

- DEPENDS ON BACKGROUND STATE AND ENSO VARIABILITY (DRIER TO THE WEST, WETTER TO THE EAST IF WARM EASTERN PACIFIC SSTS)
- MULTI-MODEL PRECIPITATION PREDICTION: STANDARD DEVIATION AMONG MODELS EXCEEDS FORECAST CHANGE*

INDIA

- WARMER INDIAN OCEAN WATERS LEAD TO GREATER MONSOON RAINFALL
- INDIAN OCEAN DIPOLE OR ZONAL MODE: + PHASE COLDER IN SE, WARMER IN CENTRAL AND WESTERN TROPICAL INDIAN OCEAN -> GREATER MONSOON RAINFALL
- EL NINO HAS CONFLICTING INFLUENCES
  - WARMS INDIAN OCEAN
  - HELPS PRODUCE DIPOLE (MAYBE OCEANIC BRIDGE)
  - ROSSBY WAVE PATTERN (FROM REDUCED RAINFALL IN TROPCAL WEST PACIFIC) WITH SUBSIDENCE OVER INDIA
- AR4 MODELS SHOW OVERALL INCREASE IN PRECIP FOR ASIAN MONSOON, BUT INTER-MODEL STAND DEV> MEAN CHANGE

BRAZIL

- DROUGHT IN NORDESTE WHEN N. ATLANTIC WARMS MORE THAN S. ATLANTIC (ITCZ FORCED NORTHWARD)
- EL NINO HELPS PRODUCE THIS WITH REDUCED NE TRADES IN ATLANTIC
- UNCERTAINTY IN CLOUD AND SST PREDICTION
- NORDESTE PRECIP CHANGE IN MODELS < STAND DEV AMONG MODELS

AFRICA

- FOR SAHEL, WESTERN AFRICA: GREATER WARMING SOUTH OF EQUATOR PRODUCES DRYING (LIKE FROM 1960S-1990S)
- EL NINOS HAVE CONFLICTING INFLUENCE
  - AS NOTED, TEND TO WARM N. ATL.
  - AFFECT ON LONGITUDINAL (WALKER) CELLS PRODUCES SUBSIDENCE IN THIS REGION (WINS OUT)
  - ALSO PRODUCE DRYING IN ZIMBABWE
- OTHER OCEANS HAVE INFLUENCE
  - WARMING IN SOUTHERN INDIAN OCEAN, S. ATL.
  - COOLING IN NORTH PACIFIC, N. ATL.
- MULTI-MODEL PREDICTION OF SOME PRECIP INCREASE IN SW PORTION OF AFRICAN MONSOON, BUT STD.DEV > MEAN CHANGE

TROPICAL STORM IMPACT REGION, ESP. N. ATLANTIC

- REDUCED LAPSE RATE WITH WARMING FAVORS REDUCED FREQUENCY
- GREATER SSTS FAVOR STRONGER STORMS
- WIND SHEAR CHANGE MAY BE DECISIVE
  - ON MONTHLY AVERAGE, MODELS DON'T SHOW MUCH CHANGE
  - DEPENDS IN N. ATL. ON ENSO (+ PHASE OR WARM MEAN STATE MEANS STRONGER SHEAR AND FEWER HURRICANES)
- WESTERN AFR MONSOON AND EASTERLY WAVES AFFECTED BY ENSO PHASE AND S.ATL/N ATL. WARMING

MID-LATITUDES, ESP. NORTH AMERICA

- TROPICAL FORCING NOT DOMINANT - ONLY 15 TO 20% OF VARIANCE IN MOST SENSTIVE REGIONS ARE SST FORCED
- MODELS SHOW SLIGHT POLEWARD HADLEY CELL EXPANSION (STABILITY EFFECT, BUT EXTRATROPICA LAT GRADIENT UNCERTAINTY REDUCES CONFIDENCE)
- GREAT PLAINS DROUGHTS FROM:
  - LA NINA EFFECT, (PARTICULARLY IN WINTER)
  - WEST PACIFIC/INDIAN OCEAN WARMING
  - MECHANISM UNCERTAIN: STATIONARY WAVE TRAIN OR TRANSIENT EDDY MOMENTUM TRANSPORTS?
- POLEWARD STORM TRACK SHIFT AFFECTED BY ENSO UNCERTAINTY (MOVES POLEWARD DESPITE ENSO-LIKE BACKGROUND STATE) AND HIGH LAT AMPLIFICATION
- REDUCED HIGH LATITUDE SEA ICE MAY LEAD TO RIDGING AND DECREASED WESTERN NORTH AMERICA PRECIP IN WINTER
- NO CONSENSUS ON DROUGHTS OR SOIL MOISTURE CHANGE AT MID-LAT IN AR4 MODELS

JAPAN, ALASKA, WESTERN CANADA

- NORTH PACIFIC INDEX (NPI) - ALEUTIAN LOW REGION SLP
  - RELATED TO TEMP AND PRECIP IN THESE REGIONS (PROXY FOR PNA TELECONNECTION PATTERN)
  - AFFECTED BY SSTS
    - IN TROPICAL INDIAN OCEAN/W. PACIFIC
    - ENSO PERTURBATIONS IN EAST PACIFIC
- MODELS PREDICT MORE NEGATIVE INDEX (LOWER SLP) FROM TROPICAL WARMING

EUROPE, N. ASIA

- NAO (SLP DIFFERENCE BETWEEN PORTUGAL AND ICELAND)
  - RELATED TO WARM, WET WINTERS OVER N. EUROPE AND SIBERIA
- VARIATIONS IN PHASE POTENTIALLY THE RESULT OF
  - SST GRADIENT IN TROP WEST PACIFIC
  - INDIAN OCEAN TEMPS
  - TROPICAL EAST PACIFIC
  - ATLANTIC SSTS, VIA CONVECTION OVER AMAZON/CARRIBEAN SEA
- PROJECTIONS OF SOMEWHAT MORE POSITIVE PHASE, MAYBE EASTWARD SHIFT

MIDDLE/HIGH NORTHERN LATITUDES

- NORTHERN ANNULAR MODE (NAM; ALSO ARCTIC OSCILLATION, AO)
  - SIMILAR POTENTIAL INFLUENCES AS FOR NAO
  - ENSO AFFECT UNCERTAIN (MAY BE TOO FAR SOUTH)
  - INDIAN OCEAN AND W. PACIFIC EFFECTS MAY BE OUT OF PHASE
- AFFECTED BY ZONAL-AVERAGE LATITUDINAL TEMPERATURE GRADIENT CHANGES DISCUSSED EARLIER
- MORE MODELS THAN NOT PROJECT MORE POSITIVE PHASE
  - ABSOLUTE MAGNITUDE OF CHANGE NOT LARGE

S. AUSTRALIA, NEW ZEALAND, ANTARCTICA

- SOUTHERN ANNULAR MODE (SAM)
  - POSITIVE PHASE ASSOCIATED WITH WARMER CONDITIONS IN ANTARCTIC PENINSULA, COOLER OVER ANTARCTICA
  - SOUTHWARD SHIFT OF STORM TRACKS REDUCED PRECIP IN S. AUST, NEW ZEALAND
- ASSOCIATED WITH GREENHOUSE WARMING AND OZONE DEPLETION
- ASSOCIATION WITH ENSO UNCERTAIN
  - ENSO INFLUENCE NOT ZONALLY SYMMETRIC: HIGHER PRESSURE IN EAST PACIFIC, LOWER IN WEDDELL SEA
    - DIPOLE RESPONSE FROM STAND OR TRAN WAVES
  - STRONG NATURAL VARIABILITY
- MODELS PROJECT INCREASE IN + PHASE (INDEPENDENT OF STRAT OZONE CHANGES)

SOUTHERN OCEAN SEA ICE

- CURRENTLY STRONG REDUCTIONS IN SOUTHERN BELLINGSHAUSEN/ ANTARCTIC PENINSULA REGIONS (SEA ICE DURATION 85 DAYS SHORTER)
- CURRENTLY STRONG INCREASES IN ROSS SEA (SEA ICE DURATION 60 DAYS LONGER)
- MORE POSITIVE SAM INFLUENCE ON SEA ICE ADVECTION, POSSIBLY INTERACTING WITH LA NINA OCCURRENCES
- MODELS PROJECT REDUCED SEA ICE OVERALL BUT OCEAN HEAT UPWELLING RESPONSE UNCERTAIN
- MIGHT HAVE NEGATIVE FEEDBACK REGIONALLY - REDUCED SEA ICE REDUCES BAROCLINICITY, MORE NEGATIVE SAM

ARCTIC SEA ICE

- CURRENTLY DECREASING MORE RAPIDLY THAN IN GCMS
- AFFECTED BY MORE POSITIVE NAO
  - ADVECTS SEA ICE OUT THROUGH FRAM STRAIT
  - ADVECTS OCEAN HEAT INTO ARCTIC THROUGH FRAM STRAIT AND BARRENTS SEA
- LAST DECADE NAO NO LONGER POSITIVE
  - BUT OTHER HELPFUL ADVECTIVE SLP PATTERNS AROSE (LOW PRESSURE OVER CENTRAL ARCTIC; HIGH PRESSURE IN CANADIAN ARCTIC WITH LOW OVER SIBERIA)
- POSITIVE FEEDBACKS FROM INCREASED VERTICAL OCEAN HEAT FLUXES THROUGH THINNER ICE, AND SEA ICE ALBEDO CHANGE
- MODELS PROJECT CONTINUED DECREASES, MOSTLY THERMODYNAMIC
- POSITIVE FEEDBACK POSSIBLE, AT LEAST AT LOW LEVELS - GREATER INSTABILITY WHEN SEA ICE REMOVED, LOWER SLP, MORE ADVECTIVE LOSS
  - MAY DEPEND ON LOCATION OF SEA ICE CHANGE

GREENLAND ICE SHEET

- RAPID GLACIAL LOSS AND SURFACE MELTING IN LAST DECADE
- MUCH VARIABILITY - LOSS TURNED AROUND LAST YEAR
- UNCERTAIN PHYSICS
  - DOES SUMMER MELTING REACH ICE SHEET BED AND ACCELERATE MOTION?
  - IS THE BASE FROZEN TO THE BED?
- MODELS DON’T HAVE THE RESOLUTION OR EMBEDDED PHYSICS
- MODELS PREDICT SNOW ACCUMULATION TO THE NORTH, SMALL + SEA LEVEL CONTRIBUTION (VERY UNCERTAIN)

WEST ANTARCTIC ICE SHEET

- GLACIERS DRAINING TO AMUNDSEN SEA ARE ACCELERATING
  - OCEAN WARMING MAY BE THE CAUSE
- ON ANTARCTIC PENINSULA, COLLAPSE OF PORTIONS OF LARSEN ICE SHELF, WITH ACCELERATED ICE STREAMS
- IN BOTH REGIONS, PART OF THE LOSS HAS BEEN COMPENSATED FOR BY INCREASED SNOWFALL
- MODELS PREDICT MASS GAIN FOR ANTARCTICA - CURRENTLY LOSING MASS

NORTH ATLANTIC DEEP WATER

- MOST MODELS PREDICT DECREASE
  - WARMING OF WATERS REDUCES SURFACE DENSITY
  - ALSO FRESHENING =f(INCREASED RAINFALL, INCREASED RIVER RUNOFF INTO ARCTIC AND FRESHWATER FLUX INTO N. ATL.)
  - CURRENTLY APPARENT FRESHENING - BUT INCREASED SEA ICE MELT HELPING OUT
- REDUCTION WOULD SLOW CO_2 UPTAKE
- COULD INCREASE LAT TEMP GRADIENT OVER N. ATLANTIC

SOUTHERN OCEAN

- POSITIVE SAM WOULD STRENGTHEN HIGH LATITUDE DEACON CELL
  - STRONGER AND MORE SOUTHWARD ZONAL WINDS PRODUCE GREATER DIVERGENCE AND UPWELLING TO THE SOUTH, DOWNWELLING TO THE NORTH
- ON SOUTH SIDE WOULD BRING UP MORE (NATURAL) CO_2, ON NORTH SIDE WOULD SEQUESTER MORE (ANTHROPOGENIC) CO_2
- CURRENTLY CO_2 SOURCE; MORE POSITIVE SAM WOULD MAKE IT MORE OF A SOURCE

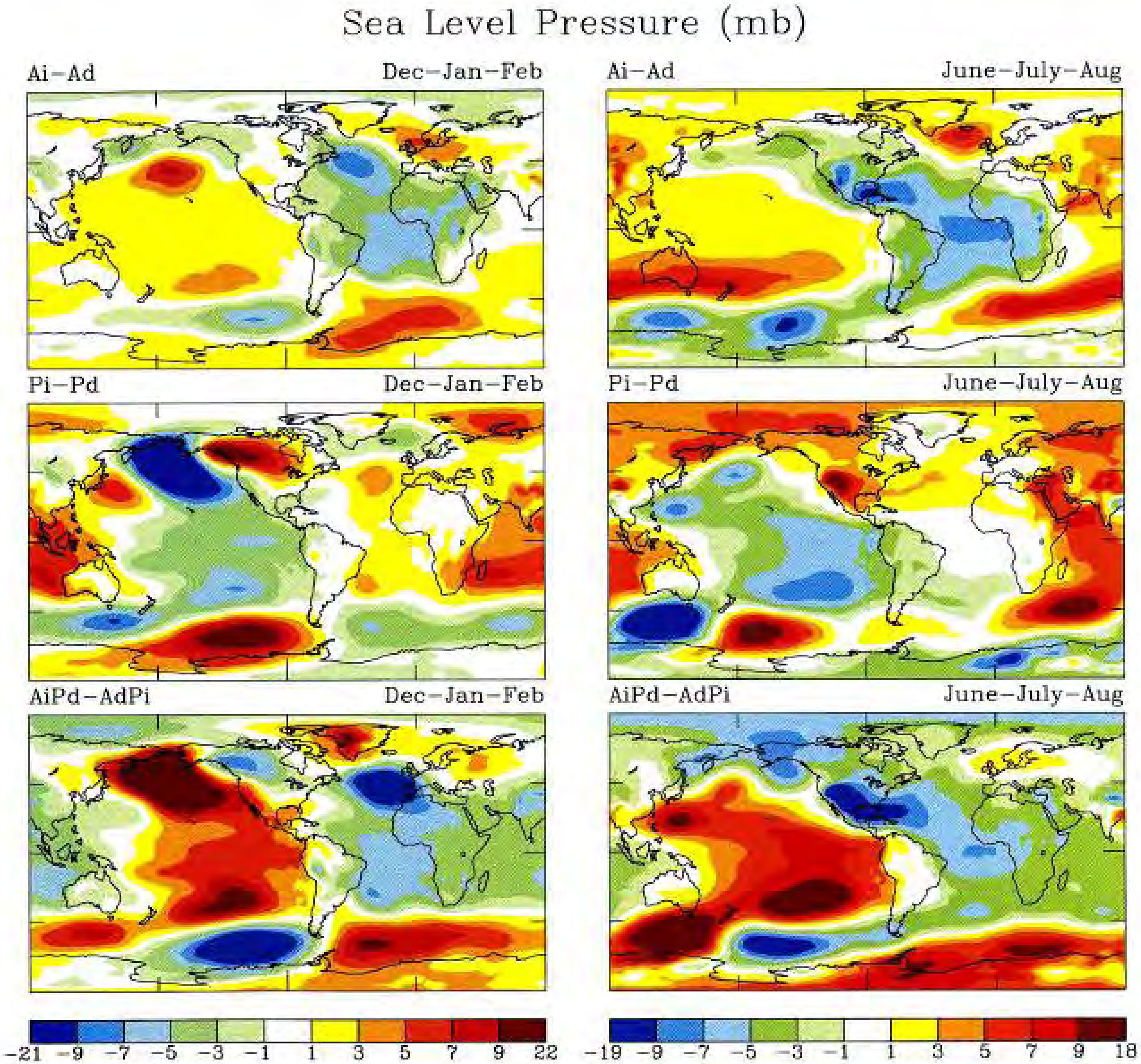
HIGH LATITUDE PEATLANDS (E.G., WESTERN SIBERIA)

- TAKE UP CO_2, RELEASE METHANE
- IF IT WARMS AND DRIES, WILL RELEASE CO_2, BUT SHUT DOWN METHANE OUTGASSING
- IF IT WARMS AND GETS WETTER, CURRENT EFFECTS WOULD BOTH GET STRONGER
- CO_2 EFFECT WINS OUT ON 500 YEAR TIME-SCALE
  - IF IT GETS A LOT WARMER, METHANE RESPONSE WILL GO UP

OCEAN BASIN TEMP GRAD

- WITH REDUCED NADW, N. ATL. SST GRADIENT COULD INCREASE
- WERE LA NINA-LIKE STATE TO BECOME MORE PERMANENT, N. PACIFIC SST GRADIENT COULD DECREASE STRONGLY
- GRADIENTS IN ONE OCEAN BASIN PRODUCE SIMILAR EXTRATROPICAL IMPACTS TO GRADIENTS OF THE OPPOSITE NATURE IN THE OTHER OCEAN BASIN (LONGITUDINAL CELL EFFECT)*
- RESULT COULD BE VERY STRONG IMPACT ON EXTRATROPICS
- NH LAT GRADIENT CHANGE COULD BE VERY DIFFERENT FROM THAT IN SH (SEA ICE RESPONSE VERY DIFFERENT)
  - AFFECTS CROSS-HEMISPHERIC RESPONSES

Rind et al., JGR 2001

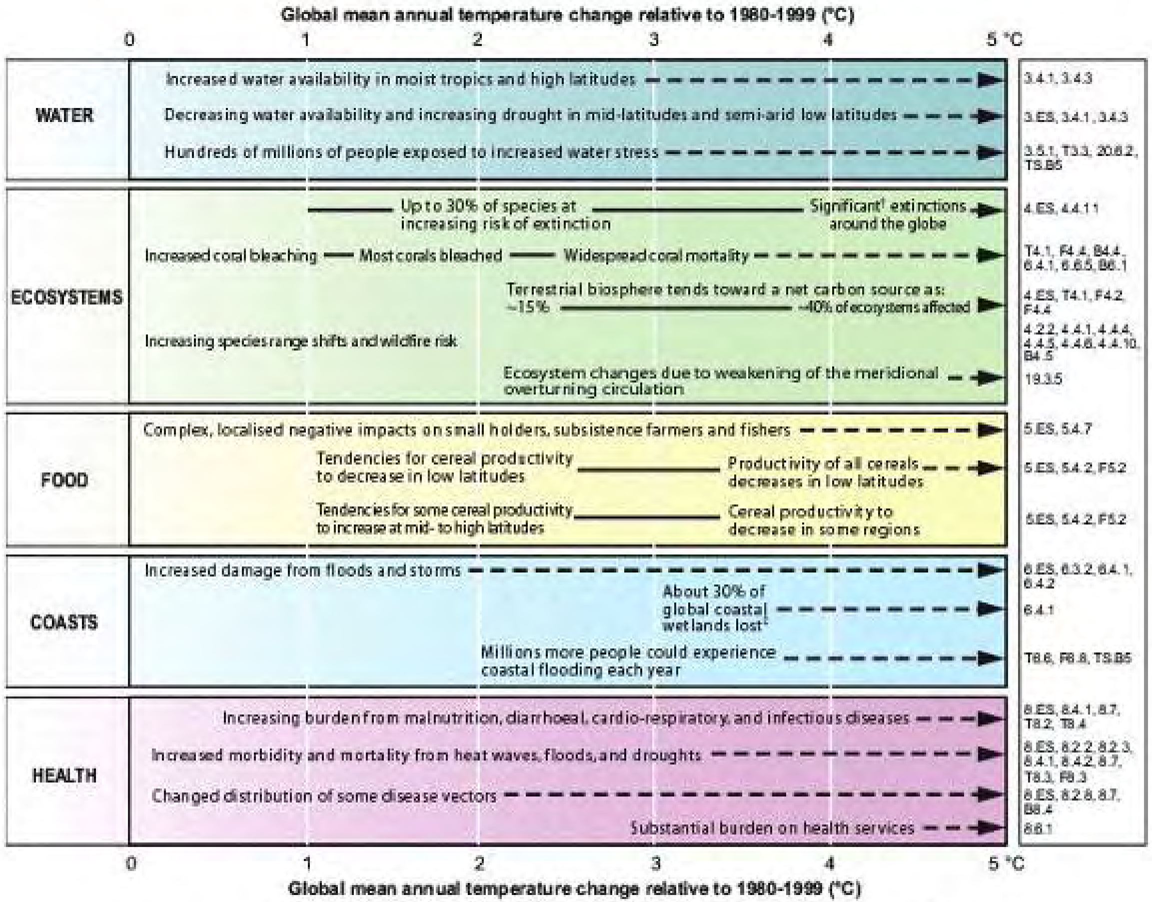


CONCLUDING REMARKS

- PAST 25 YEARS: NO IMPROVEMENT IN ASSESSMENT OF HIGH AND LOW LATITUDE SENSITIVITY
- BETTER ASSESSMENT OF REASONS WHY NOT
- ADDITIONAL OBSERVATIONAL PROGRAMS AND STUDIES UNDERWAY
  - CLOUDSAT AND CALIPSO FOR CLOUD OBSERVATIONS
  - ARM AND GCCS FOR MODELING
  - IPY FOR POLAR STUDIES
  - MORE MODELING GROUPS, FINER RESOLUTION
- WHEN WILL WE KNOW A LOT MORE?
- WHAT DOES SOCIETY DO IF IT’S NOT QUICK ENOUGH?

Key impacts as a function of increasing global average temperature change

(Impacts will vary by extent of adaptation, rate of temperature change, and socio-economic pathway)



† Significant is defined here as more than 40%.

‡ Based on average rate of sea level rise of 4.2 mm/year from 2000 to 2080.

Figure SPM.2. *Illustrative examples of global impacts projected for climate changes (and sea level and atmospheric carbon dioxide where relevant) associated with different amounts of increase in global average surface temperature in the 21st century [T20.8]. The black lines link impacts, dotted arrows indicate impacts continuing with increasing temperature. Entries are placed so that the left-hand side of the text indicates the approximate onset of a given impact. Quantitative entries for water stress and flooding represent the additional impacts of climate change relative to the conditions projected across the range of Special Report on Emissions Scenarios (SRES) scenarios A1FI, A2, B1 and B2 (see Endbox 3). Adaptation to climate change is not included in these estimations. All entries are from published studies recorded in the chapters of the Assessment. Sources are given in the right-hand column of the Table. Confidence levels for all statements are high.*

The use of high-resolution global climate models for climate risk assessment

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Work supported by Willis Analytics, London, UK: Matthew Foote, Kirsten Mitchell-Wallace, Taro Hosoe, Claire Crerar

Catastrophe modelling is traditionally based on statistical (stochastic) models, which use synthetic event-sets to project the incidence of destructive weather events, such as tropical cyclones, windstorms and floods.

Climate science, on the other hand, uses dynamical models of the earth's climate system to simulate past, present and future climate conditions, using observational data to validate simulations.

The aim of this research is to begin to integrate dynamical modelling, or at least the results from dynamical modelling, into the stochastic modelling approach, so that catastrophe modelling can benefit from increased understanding of the dynamical climate- in terms of natural climate variability and anthropogenic climate change- and how these changes may alter risk associated with destructive weather events.

Research currently being undertaken within the Willis Research Network uses high-resolution, global climate models to simulate tropical cyclones in a global climate context. This allows an assessment to be made of changes in cyclone activity, in terms of their tracks, intensity and frequency, in relation to different modes of climate variability, such as the phase of the El Niño-Southern Oscillation, and climate change. Analysis will focus on parameters of concern to the insurance industry – tracks will be considered in terms of landfall location, and intensity in terms of maximum wind speed and precipitation along the storm path.

1. Introduction to global climate modelling

Global climate models, known as General Circulation Models (GCMs), are a test lab for climate scientists. They are used to explore important processes and to test hypotheses concerning the nature of the climate system, to understand past climate conditions and to predict the future of the earth's climate.

As stated in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), Atmosphere-Ocean GCMs remain the primary source of information on the range of possible future climates. A clearer picture of regional climate is emerging due to improvement in model resolution, the simulation of processes of importance for regional change and the expanding set of available simulations.

GCMs essentially consist of extensive computer codes based on fundamental mathematical equations of motion, thermodynamics and radiative transfer. These equations govern the:

- flow of the atmosphere and oceans,
- exchange of heat between the surface and the atmosphere,
- release of latent heat energy by condensation during cloud and precipitation formation,
- absorption of sunshine and emission of thermal radiation.

The earth's atmosphere and oceans are represented by a three dimensional grid giving a three dimensional view of the global atmospheric and oceanic circulation.

As climate research becomes increasingly relevant to industry and non-academic stakeholders, climate research output needs to become tailored to the end user. The compatibility of climate research output with catastrophe modelling is a clear example of this demand. This paper will introduce an example of a climate research area of great interest to the insurance industry. The aim will be to generate output information which can be easily incorporated into catastrophe modelling.

2. High-resolution global climate models and computational demands

UK climate scientists at the Climate division of the National Centre for Atmospheric Science (NCAS-Climate), based at the University of Reading, and the UK Met Office have developed the High Resolution Global Environmental Model, HiGEM, of the atmosphere and ocean systems. This model, based on the weather forecasting model of the UK Met Office, has a 90km grid resolution. Until recently global climate models have been unable to simulate individual weather events. However, at this spatial resolution global climate models are beginning to simulate weather systems and extreme weather events. HiGEM performs as well as, if not better than, any other model on the international scene. This allows the study of catastrophic weather events, such as tropical storms, in a global context.

Development of HiGEM led to the development of the Nihon-UK Global Environmental Model, NUGEM, which has a 60km grid resolution. This very-high resolution model was developed through the UK-Japan Climate Collaboration (UJCC). Because of its complexity and resolution, running the model is computationally very demanding and requires computing power only available on the world's most powerful supercomputers. The UJCC team, based in Yokohama, Japan, has access to the Earth Simulator super-computer - able to perform 40 teraflops (equivalent to the computing power of several thousand standard home pcs).

The power of the Earth Simulator has allowed simulation of the global climate with much finer resolution than ever before. This is leading to a major advance in the fidelity of simulations of the global environment, improving our understanding of the mechanisms of climate variability and change on time scales of days to centuries. With finer resolution, we will be able to predict, with more confidence, how extreme weather events may change in under in future climate conditions - information which will be of paramount interest to the insurance industry.

3. Tracking tropical cyclones in GCMs

The IPCC-AR4 states that GCMs with less than 100km resolution cannot accurately simulate tropical cyclone (TC) intensities. However, given sufficient horizontal resolution, models are increasingly capable of reproducing the detailed structure of circulation, track and intensity typical of TCs (e.g. Oouchi et al., 2006).

The damage and insured loss associated with TCs can vary significantly from one season to the next as a consequence of changes in frequency, intensity, and landfall (storm path). In order to gain statistical information concerning the frequency, severity and location of TC activity from global climate modelling, simulated TCs will be extracted from model data output using a novel TC identification and powerful tracking methodology. This method has been developed at the University of Reading (Thorncroft and Hodges, 2001, Hodges et al., 2003, Bengtsson et al. 2006, Bengtsson et al. 2007) and is able to calculate the full life-cycle of the TC, including their transformation into extra-tropical cyclones, an important aspect of cyclone activity for the insurance industry.

The technique is used to diagnose the three-dimensional vorticity structure of TC:

1) Tropical vortices are identified as maxima (over a predefined threshold) in the 850hPa relative vorticity field in a region extending from the equator to the extra-tropics.
2) For TCs, cyclogenesis (defined by first identification) must occur 0-30º (0-20º) latitude over ocean (land).
3) Vortices with lifetimes of >2 days are extracted and these tracks are referenced to the vorticity field through the atmosphere to obtain the vertical vorticity structure.
4) The vertical vorticity structure of the vortices is used to identify those with a warm core structure, crucial to the intensification of tropical storms.

From the simulated TC tracks and basic wind, precipitation, and pressure fields, properties can be referenced to a specific storm - low level vorticity (used to identify the intensity of the storm), maximum near-surface wind speed, minimum pressure (steepest descent). It is this impact relevant data, such as landfall, maximum winds and associated intense precipitation which lead to damage and loss of life, and therefore most applicable to catastrophe modelling. Precipitation data will also be important for predicting the risk of landslides and flooding.

Simulated tracks data and TC properties are compared with re-analysis data (from 40 years of European Centre for Medium-range Weather Forecasting (ECMWF) Re-Analysis, ERA40

(Uppala et al., 2005)) and observational "best track" data (best estimates of the TC locations and intensities at 6-hourly intervals produced by the international warning centres (Klotzbach, 2006)), to ascertain the ability of the model to reproduce the path, frequency and intensity of TCs.

4. The influence of climate variability on tropical cyclones

Isolating potentially predictable aspects TC activity requires an understanding the relationship between TCs and different modes of climate variability.

The relationship between TCs and ENSO is important in terms of annual variability. As the year to year variability is of great importance to the insurance industry, a major element of this research will be to identify any relationship between the phase of ENSO and the mean TC path, frequency, severity. Identification of an ENSO-TC relationship will help to provide an element of annual forecasting skill.

Improved resolution in both the ocean and the atmosphere is necessary to produce realistic ENSO variability. HiGEM has improved resolution in both, producing a much more realistic simulation of ENSO variability than previous models.

To begin assessing any relationship, simulated TC tracks from HiGEM data will be separated into those occurring in El Nino, La Nina and "neutral" conditions. In order to do this a method may be adopted similar to that used by Camargo et al. (2007). This method uses a probabilistic cluster analysis of TC tracks. This method is based on assessment of large-scale atmospheric/oceanic conditions in relation to TC "types" in terms of genesis and track. From this data we can begin to look at how ENSO influences TC activity.

Similar analysis may also be undertaken for other important modes of natural variability, such as the influence of Madden Julian Oscillation (MJO) activity on western Pacific TCs and the influence of decadal variability in the Atlantic Ocean. It is very important for the insurance industry to understand how different climate forcing phenomena may change risk.

Similar analysis will also be applied to climate sensitivity experiments used to assess how climate change may influence TC activity and impact:

(i) Annually increasing CO_2 concentrations.

(ii) Positive sea surface temperature anomalies.

Understanding and identifying modes of natural variability, such as ENSO and the MJO, and their impact on, say, tropical cyclone activity, is also very important in terms of assessing the potential impact of climate change. By being able to identify the influence of natural variability, we will improve out ability to identify any climate change signals- changes occurring outside the range of natural variability.

It will also be beneficial to assess the change in ENSO variability associated with simulated climate change, and using results from the above research assess the impact these changes may have on tropical cyclone activity.

6. Conclusions

If we can begin to understand how TC risk may change with different modes of climate variability (whether natural variability or CO_2-induced climate change) and there is an element of predictability of that mode of variability, then we can begin to suggest how TC risk may change in the near future. The aim is not to predict how cyclone risk will change with projected climate change. It is to better understand the importance of global climate variability for the risk, on a background trend of global warming; this will be important for the time-scales of interest to the insurance industry.

Climate research on the Earth Simulator applicable to the insurance industry, particularly to catastrophe modelling, will be part of an on-going assessment of the ability of high-resolution models to capture extreme weather events. Probabilistic results from the model analysis will allow more confident assessments of future impacts of climate -related catastrophe by building on firm scientific foundations, especially relating to high impact weather, to form an important tool for risk management.

References

Bengtsson, L., Hodges, K. I. and Roeckner, E. 2006. Storm tracks and climate change. *J. Clim.* **19**, 3518-3543.
Bengtsson, L., Hodges, K. I. and Esch, M. 2007. Tropical cyclones in a T159 resolution global climate model. *Tellus* **59A**, 396-416.
Bengtsson, L., Hodges, K. I., Esch, M., Keenlyside, N., Komblush, L., Luo, J. J., and Yamagata, T. 2007. How many tropical cyclones change in a warmer climate. *Tellus*, in press.
Camargo, S. J., Robsertson, A. W., Gaffney, S. J., Smith, P., and Ghil, M. 2007. Cluster analysis of typhoon track. Part II: Large-scale circulation and ENSO. *J. Climate*. **20**, 3654-3676.
Hodges, K. I., Hoskins, B. J., Boyle J. and Thorncroft, C. 2003. A comparison of recent re-analysis datasets using objective feature tracking: storm tracks and tropical easterly waves. *Mon. Weather Rev*. **113**, 2012-2037.
Klotzbach, P. J. 2006. Trends in global tropical cyclone activity over the past twenty years (1986-2005), 2006. *Geophys. Res. Lett*. **33**, doi:10.1029/2006GL025881.
Oouchi, K., Yoshimura, J., Yoshimura, H., Mizuta, R., and co-authors. 2006. Tropical cyclone climatology in a global-warming climate as simulated in a 20 km-mesh global atmospheric model: frequency and wind intensity analysis. *J. Meteorol. Soc. Japan*. **84**, 259-276.
Onogi, K., Koide, H., Sakamoto, M., Kobayashi, S., Tsutsui, J., and co-authors. 2005. Japanese 25-yr re-analysis project- progress and status. *Q. J. R. Meteorol. Soc*. **131**, 3259-3268.
Thorncroft, C., and Hodges, K. 2001. African easterly wave variability and its relationship to atlantic tropical cyclone activity. *J. Clim*. **14**, 1166-1179.
Uppala, S. M., Kallberg, P. W., Simmons, A. J., Andrae, U., Bechtold, V. Da Costa, and co-authors. 2005. The ERA40 Re-analysis . *Q. J. R. Meteorol. Soc*. **131**, 2961-3012.

The use of high-resolution global climate models for climate risk assessment

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Supported by Willis Analytics: Matthew Foote, Kirsten Mitchell-Wallace, Taro Hosoe, Claire Crerar

Content

1) Introduction to the Willis Research Network
2) Two-way communication between academic researchers / catastrophe modellers / Willis Clients
3) The use of high-resolution global climate modelling to simulate weather/extreme events in a global climate context
4) Initial focus- driven by insurance industry interests – Western Pacific Typhoon
5) Use of a tracking methodology
6) Aim to integrate results into catastrophe modelling

The Willis Research Network (WRN)

- A **major long term partnership** between leading international scientific institutions and Willis.
- To evaluate the **frequency, severity and impact of catastrophes** such as hurricanes, earthquakes, floods and terrorism.
- Coordinated by Willis Analytics - to **focus research** and activities of the network towards the **needs of its clients and the international insurance and reinsurance market**.
- Encourages **focused, multi-disciplinary research** keeping in mind the insurance industry as the end user.

Willis Research Network – Cornerstone members

Consists of seven **cornerstone** members: leading academic institutions across the earth sciences, engineering and mathematics. Each cornerstone member is represented by a leading Professor supported by a Willis Research Fellow.

Around this cornerstone group Willis supports an **international** network of experts and institutions that bring specialist or local knowledge of hazards or the human environment.

University	Departments	WRN Leader	Disciplinary Focus
Reading	Meteorology	Professor Julia Slingo	Regional Weather Systems, Global Atmospheric Modelling, Data Assimilation, Weather Events
Exeter	Mathematics	Professor David Stephenson	Climate Change & Weather Regimes, Climate Analysis, Statistical Verification, Extreme Events
Imperial	Civil Engineering, Geotechnics	Professor Julian Bommer	Ground Motion Prediction, Seismic Hazard Assessment, Building Codes, Earthquake Loss Est.
Durham	Geography, Institute of Hazard & Risk Research	Professor Stuart Lane	Earth Processes, Flood Modelling, Landslides, Hazards of Technology and Infrastructure.
Bristol	Geography	Professor Paul Bates	Flood Modelling,, Volcanology, Remote Sensing, Spatial Modelling, Climate Change
Bristol	Civil Engineering	Professor Colin Taylor	Hydrology & Water Management, Earthquake Engineering, Coastal Engineering, Soil Mechanics
Cambridge	Architecture	Professor Robin Spence	Building Stock Vulnerability, Structures & Risk, Loss Estimation, Remote Sensing
City	GIS	Professor Jonathan Raper	Geographic Information Systems, Multi-Dimensional Surface Modelling, Geo Visualisation

Research themes

Walker INSTITUTE

- **Uncertainty**: quantifying and explaining modelling uncertainty
- **Exposure Data**: understanding impact on model results and exploiting new sources
- **Interpretation**: Increasing sophisticated interpretation of model results
- **Hazards**: Peril specific research across flood, storm, earthquake and accumulation themes and balanced assessment of emerging concerns
- **Correlation and Seriality**: Multi-peril models and correlations between events and hazards
- **Climate Change & Climate Variability**: the impact of climate change on extreme events and model outputs
- **Communication**: new means of communicating, illustrating and describing loss estimation

Willis

Resolution of global models used in the IPCC Assessment Reports

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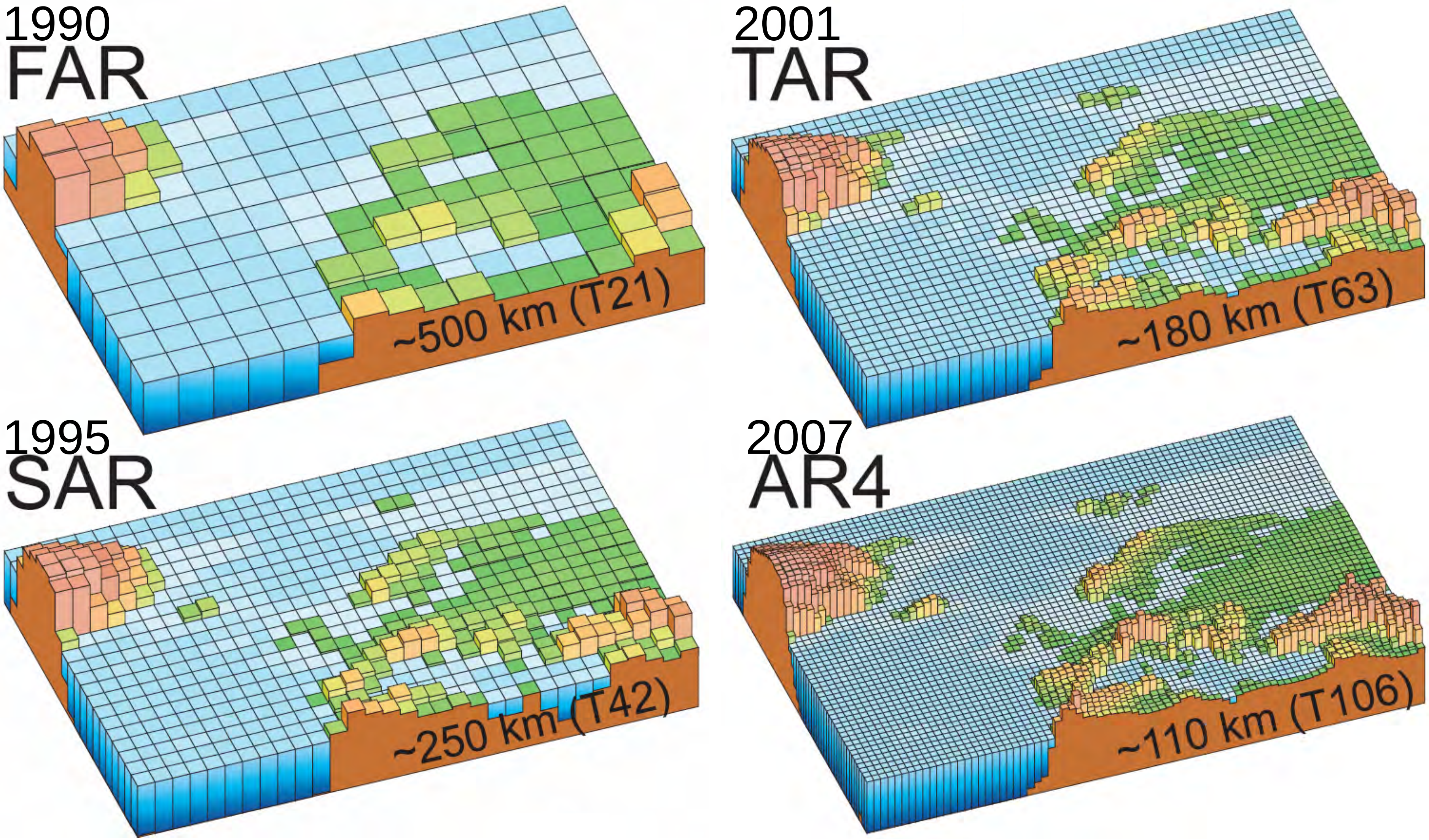
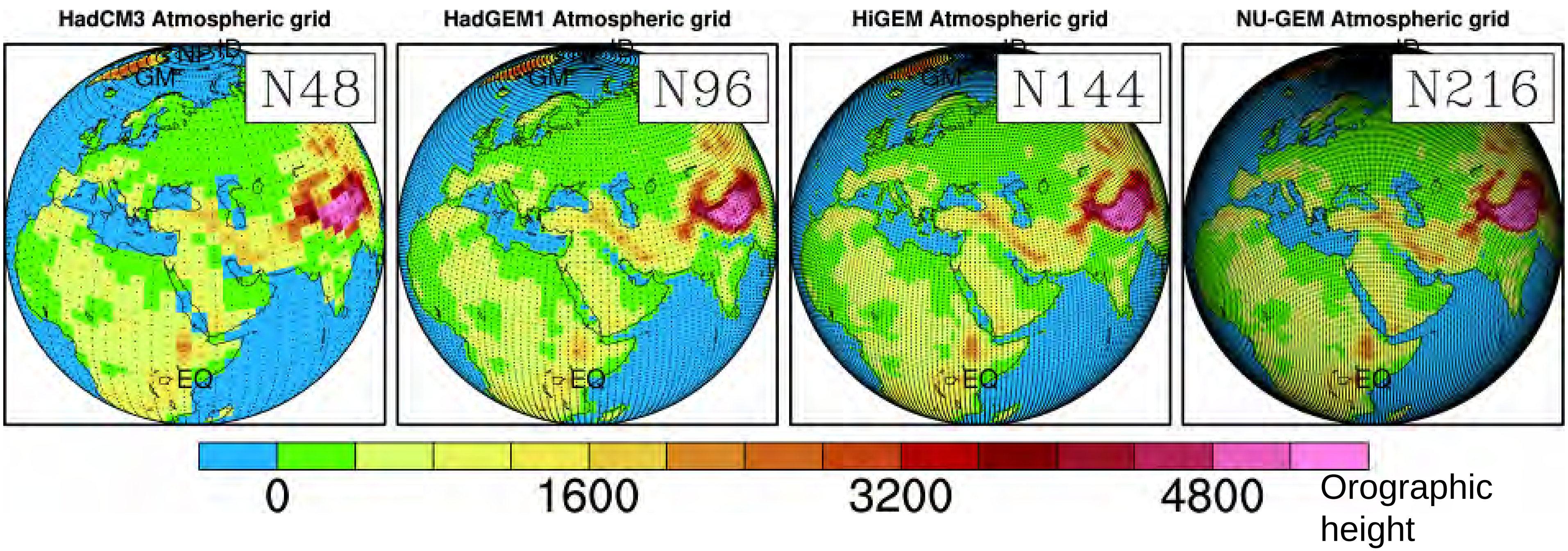


High resolution global climate models

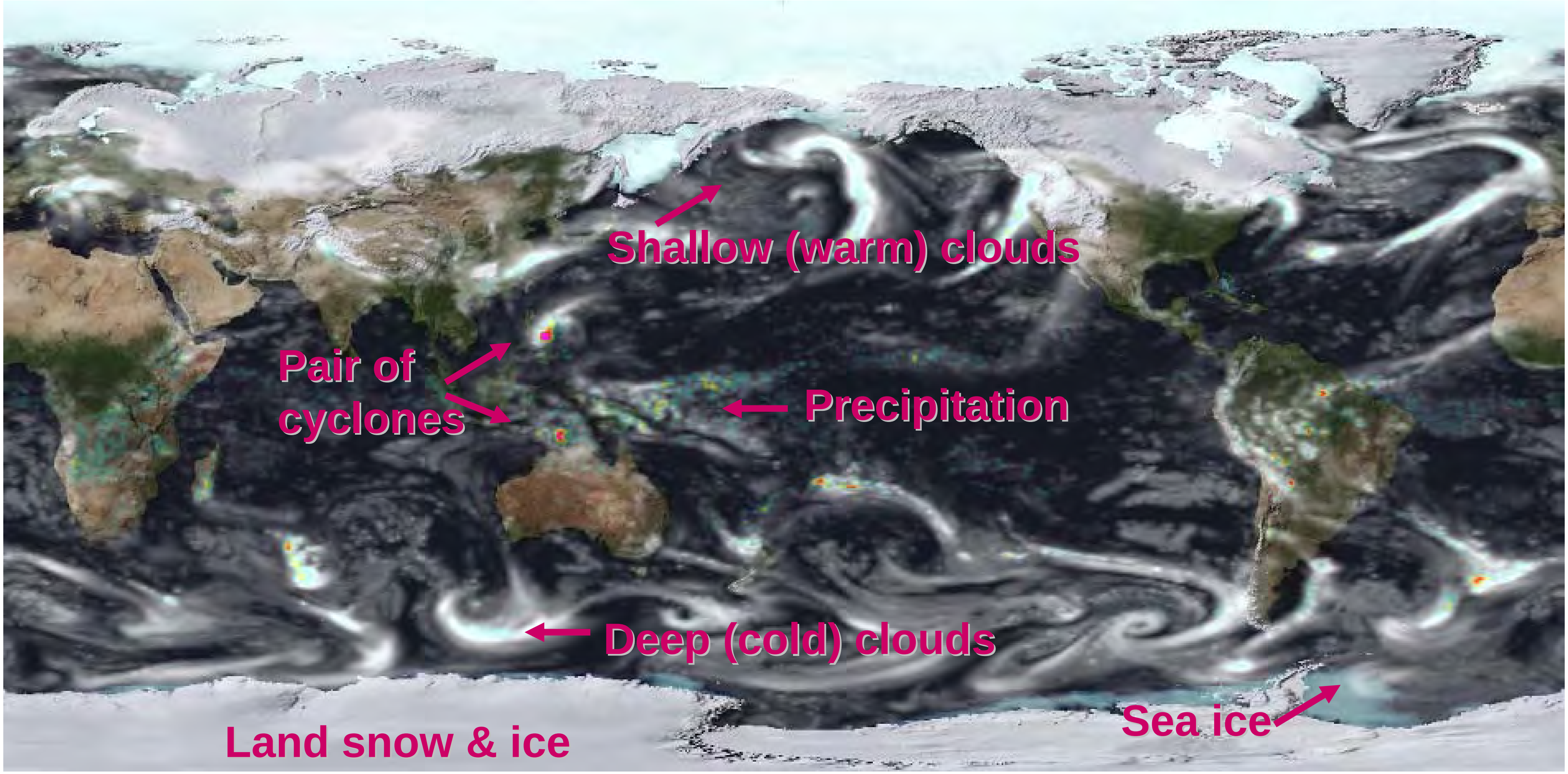
270km | 135km | 90km | 60km



60km grid model = comparable to the resolution of the Met Office weather forecast models a few years ago

We can start to simulate weather events in global climate context

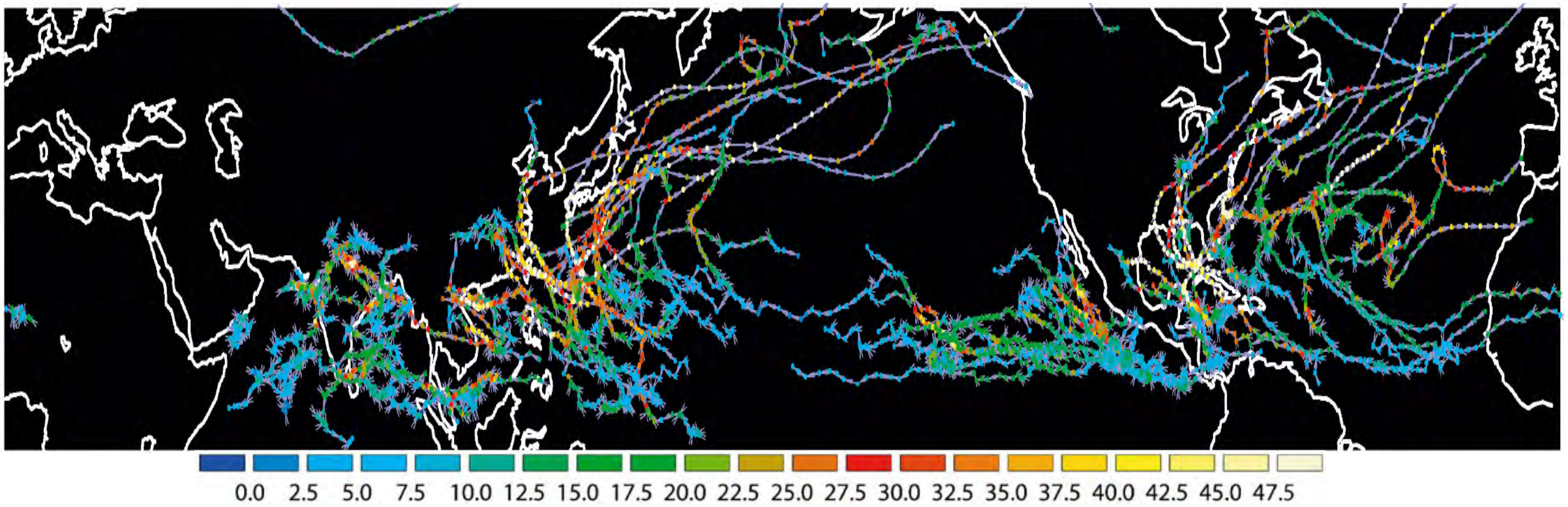
…can now simulate tropical cyclones

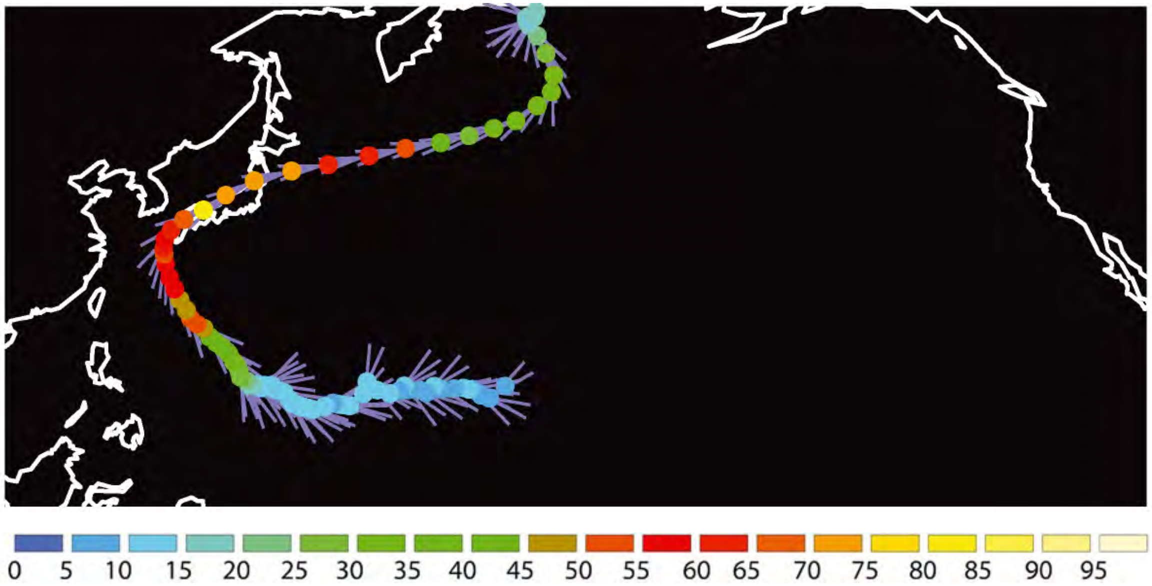


NUGAM 60km model simulation snapshot
visualisation produced by NASA Earth Observatory

QuickTime™ and a
H.264 decompressor
are needed to see this picture.

Cyclone tracking





Intensity of tropical cyclones in global climate models

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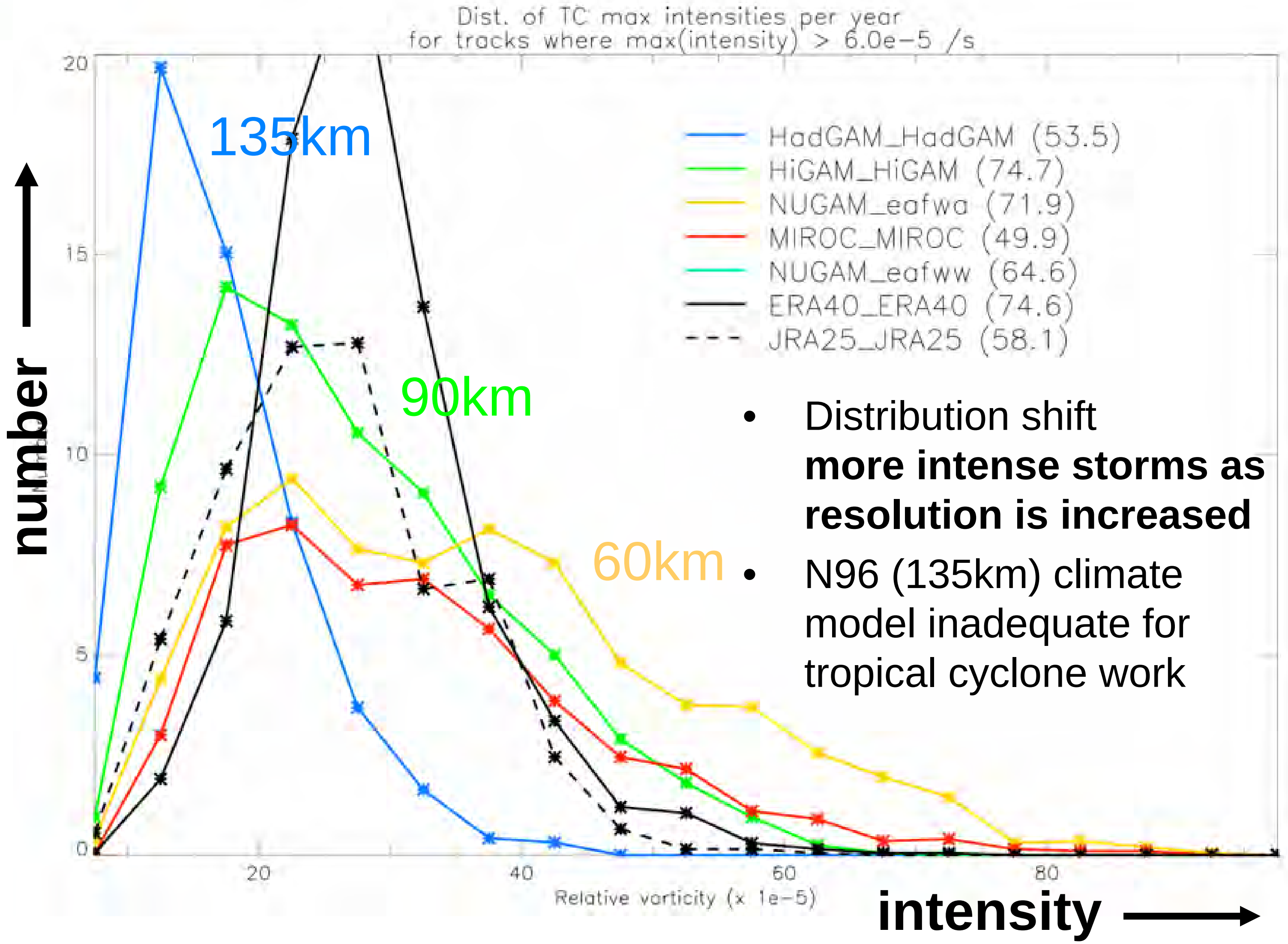

- Distribution shift **more intense storms as resolution is increased**
- N96 (135km) climate model inadequate for tropical cyclone work

How does this help the catastrophe modelling and insurance industry?

We need to concentrate on parameters of importance to the insurance industry:
-Use tracks to determine landfall
-Maximum near-surface wind speed
-Precipitation output may be used to assist the modelling of flood associated with landfalling TC

- Use good science to back up Catastrophe Models and their output

- Allow insures and their clients to be better informed about climate change and how it may affect their business

- Inform academics about the insurance industry and allow future research to be more tailored for the end user

PART III
Attendee List

CATASTROPHE MODELING FORUM

Changing Climatic Dynamics and Catastrophe Model Projections

Tuesday – Wednesday, October 16-17, 2007

The Down Town Association, NYC

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