

UNDERSTANDING MULTIDECADAL CLIMATE CHANGES

BY CHIH-PEI CHANG, MICHAEL GHIL, HUNG-CHI KUO, MOJIB LATIF, CHUNG-HSIUNG SUI, AND JOHN M. WALLACE

The 2012 National Taiwan University International Science Conference on Climate Change focused on two of the most difficult challenges in the study of climate change: 1) delineating the multidecadal and longer time scale variations in historical records that extend back only ~150 years, and 2) distinguishing between anthropogenically forced and natural variability. To address these issues, the organizers invited some of the world's leading experts in observational analysis, mathematical theory, and modeling to discuss issues related to the understanding of climate changes in recent decades. Consensus was formed from reviews of recent theoretical and observational research and related model simulations that have advanced our fundamental understanding of free (unforced) and forced climate variability. It is concluded that the full range of internal processes that contribute to free climate variability on multidecadal time scales needs to be considered as they could have important implications

THE NATIONAL TAIWAN UNIVERSITY INTERNATIONAL SCIENCE CONFERENCE ON CLIMATE CHANGE: MULTIDECADAL AND BEYOND

WHAT: More than 60 scientists met to review and discuss recent observational and theoretical research on natural and anthropogenic climate change with focuses on the multidecadal time scale and its possible relationship with longer scales.

WHEN: 17–21 September 2012

WHERE: Taipei, Taiwan

for estimates of climate sensitivity, in particular the extent to which the statistics of extreme weather events is changing in response to human-induced climate change.

The 23 invited reviews at the conference were presented in hour-long segments, each beginning with a lecture and followed by discussion. These reviews were augmented by 20 contributed oral and poster papers. A collection of the review papers is the basis of a forthcoming monograph entitled *Climate Change: Multidecadal and Beyond* (Chang et al. 2014). The highlights of the scientific presentations are summarized in the following sections.

ANTHROPOGENIC FORCING AND INTERNALLY GENERATED VARIABILITY.

Attribution of the causes of climate change may be approached by carefully inspecting model outputs from ensembles of “historical” and “future” climate simulations. If the number of ensemble members is sufficiently large, the ensemble mean response to a prescribed external (e.g., anthropogenic) forcing can be considered as a measure of the “forced”

AFFILIATIONS: CHANG—National Taiwan University, Taipei, Taiwan, and Naval Postgraduate School, Monterey, California; GHIL—École Normale Supérieure, Paris, France, and University of California, Los Angeles, Los Angeles, California; KUO AND SUI—National Taiwan University, Taipei, Taiwan; LATIF—Helmholtz Centre for Ocean Research, and Kiel University, Kiel, Germany; WALLACE—University of Washington, Seattle, Washington
CORRESPONDING AUTHOR: Chih-Pei Chang, Department of Atmospheric Sciences, National Taiwan University, Taipei 10617, Taiwan

E-mail: cpchang@nps.edu

DOI:10.1175/BAMS-D-13-00015.1

In final form 16 April 2013
©2014 American Meteorological Society

variability and the departures of the individual realizations from the ensemble mean response the “free” variability. For small incremental changes in the climate system, the simulated climate changes can be further divided into dynamically and thermodynamically induced signals (Fig. 1). That there exists a large amount of free climate variability in the climate models suggests that significant portions of the observed multidecadal variability in the climate record could be inherently stochastic—that is, attributable to sampling fluctuations associated with naturally occurring modes of variability. This is even true for ENSO, where coupled interactions enhance the variability at a distinct time scale, leading to a peak that stands out above the red background spectrum.

A case study of the 135-yr-long Darwin sea level pressure record serves as an example. The long-term trend over the full period is not statistically significant, yet multidecadal (20–60 yr) trends pass statistical significance tests when they are based on fits to autoregressive models or performed using bootstrap calculations. Thus, multidecadal records are too short to be useful for inferring longer-term centennial trends in Darwin pressure.

Regardless of the mechanisms that give rise to it, multidecadal climate variability modulates the rate of global-mean surface air temperature rise. Applying a “dynamical adjustment” to remove (or at least reduce) the contribution of these circulation changes to the global-mean temperature trend simplifies the space–time structure of the surface air temperature record and renders it more spatially and seasonally coherent. Results presented at the workshop suggested that the enhanced wintertime warming over high northern latitudes from 1965 to 2000 was mainly a reflection of unforced climate variability.

MULTIDECADAL- TO CENTURY-SCALE CLIMATE VARIATIONS. Analyses of observed climate records during the twentieth century, the last ice age, and the Holocene, in conjunction with climate modeling results, suggest that pronounced multidecadal to century-scale variability can be produced internally by a number of different mechanisms.

| | thermodynamically induced | dynamically induced |
|---------------|---|--|
| Forced | <i>radiative response to increasing GHG, solar, volcanoes</i> | ozone hole polar amplification heating gradients “robust responses” |
| Free | <i>response to AMO/AMV, PDO, ENSO</i> | COWL, NAO PNA, QBO, ENSO, TAV, PDO, AMO/AMV |

FIG. 1. Observed climate variations consist of forced and free components. The former is forced by variations of greenhouse gas (GHG), aerosol concentrations, or solar constant, and the latter arises internally either from the chaotic dynamics of individual climate system components or owing to coupled climate processes. For small incremental changes in the climate system, the two components can be further divided into thermodynamically induced and dynamically induced as listed in the matrix (adapted from Mike Wallace’s presentation at the National Taiwan University Climate Change Conference). Abbreviations: COWL, cold ocean–warm land pattern; NAO, North Atlantic Oscillation; PNA, Pacific–North American pattern; QBO: quasi-biennial oscillation; TAV, tropical Atlantic variability; PDO, Pacific decadal oscillation.

The observed sea surface temperature (SST) variations and proxy climate records in the Southern Ocean (50°–70°S) suggest the existence of pronounced global-scale centennial variations, with the most recent maxima around the mid-1870s and mid-1970s. In one climate model, these long time scale variations originate from the slow accumulation of North Atlantic Deep Water in the Weddell Sea at mid-depth, which destabilizes the water column from below and eventually stimulates deep convection there. The accumulation of heat during the quiescent regime and its subsequent release to the atmosphere during the convective regime acts as a recharge oscillator in that model.

The Atlantic meridional overturning circulation (AMOC) is another important source of global- and regional-scale multidecadal climate variability. Numerical simulations show that these variations are advected along interior pathways in the extratropical North Atlantic, reaching the subtropics several years later. Several independent fingerprints of AMOC variability were proposed at the meeting and new evidence was brought to light that the North Atlantic multidecadal SST mode known as the observed Atlantic multidecadal oscillation (AMO)—some scientists prefer the term Atlantic multidecadal variability (AMV) given the short length of the observation period—may be linked to AMOC variations. This view is contrary to recent

findings with the Met Office Hadley Centre Earth System Model, which indicate that the AMO/AMV is merely a response to the radiative forcing caused by time-varying aerosol loading in the twentieth-century record. It was pointed out that there are major discrepancies between these simulations and the observations that appear to be due, in large part, to unrealistically strong aerosol forcing in the model.

The AMOC fingerprints described at the meeting may be used for reconstructing AMOC variations in the past and monitoring AMOC variations in the future. Modeling studies indicate that the AMOC weakens most at northern high latitudes in response to increasing greenhouse gas concentrations. The simulated AMOC weakening under anthropogenic forcing cannot be distinguished from natural AMOC variability in the record extending through just the first few decades of the twenty-first century, but the free and forced variability should become separable toward the middle of the century. Analysis of the 350-yr-long central England historical temperature record is suggestive of pervasive multidecadal variability that climate models suggest could be associated with variations in the strength of the AMOC.

The recent decrease of Arctic sea ice has attracted widespread media attention. This decrease is superimposed by a rich spectrum of variability of the Arctic sea ice. Strong variations with time scales of 50–120 years have been reported. It was suggested that the AMOC might be capable of influencing Arctic sea ice on this time scale through the inflow of Atlantic Water into the Arctic Ocean. It should be kept in mind, however, that while Arctic sea ice exhibited a record low in the last decade, Antarctic sea ice featured a record high. The role of global-scale unforced variability needs to be quantified in this context.

MONSOON, TROPICAL CYCLONE, AND

EXTREME RAINFALL. Indian summer monsoon rainfall (ISMR) did not exhibit a secular trend in the 1871–2000 historical record and therefore has been considered to be one of the most stable elements in the climate system. However, with the inclusion of the 2001–11 data, the ISMR now displays a significant downward trend since ~1950. Whether this trend is due to greenhouse warming or to the rapid increase in the burden of aerosols over southern Asia during this period is under debate. Multidecadal variability is also apparent in the monsoon rainfall over East Asia.

Several of the presentations focused on variations in tropical cyclone (TC) activity in the western North Pacific (WNP), the Atlantic, and the

Southern Hemisphere. The results for the Southern Hemisphere show an abrupt increase in TC activity from the period 1976/77–1987/88 to the period 1988/89–2007/08. The increase is related to the more frequent occurrence of intense TCs in the southwestern Indian Ocean and northwestern Australian region. The number, intensity, tracks, and landfall locations of WNP TCs also exhibit strong decadal or multidecadal variations. When adjusted for likely missed TCs, the observational record does not show evidence of a significant secular trend in North Atlantic hurricane activity. In fact, none of these TC characteristics exhibits a significant centennial trend. Shorter-term variations in TC activity are closely related to the variability in the anomalous patterns of SST and vertical wind shear. Model projections of late twenty-first-century hurricane activity indicate an increase in the frequency of the strongest storms. The largest source of uncertainty in projecting changes in Atlantic hurricane frequency for the coming decades arises from the internal (i.e., unforced) variability of the climate system.

Analysis of trends in the frequency of occurrence of extreme rainfall in the Asian monsoon regions is complicated by the fact that trends in TC-related rainfall may be different from trends in local monsoon (non-TC) rainfall. Over most of the China summer monsoon region a decrease in WNP TC activity has affected estimates of trends in extreme rainfall since the midtwentieth century. When the TC-related rainfall is removed, the slight upward trend in the extreme rainfall becomes more prominent. A notable exception is Taiwan, where a dramatic increase of heavy rainfall due to TCs in the past decade has led to the widespread belief that global warming is the main culprit. However, detailed analysis of high-resolution data shows that the increases are due to the slower motion of modest-intensity TCs, local variations in TC tracks relative to the mesoscale high mountains, and stronger TC–monsoon interactions after the typhoon center exits land. Most of these changes are consistent with the recently observed multidecadal intensification of the tropical circulation over this region that is not believed to be a part of the anthropogenic global warming footprint.

MATHEMATICAL THEORY RELATING TO CLIMATE CHANGE.

Since the climate system may possess multiple equilibria, the stability of these equilibria and the transition dynamics between them matter. A systematic stability and transition theory for the oceanic thermohaline circulation has been developed. It is found that the transitions are

crucially determined by basin size and geometry, as well as by the thermal and salinity Rayleigh numbers. Numerical results across a hierarchy of models suggest that both jumps and continuous transitions between climate equilibria are possible. In particular, the jump transitions may be associated with hysteresis phenomena.

The presentations included a review of fluctuation-dissipation theory (FDT) from statistical mechanics. This theory and its various generalizations allow one to calculate a system's mean response to external forcing through the knowledge of appropriate correlation functions of its internal fluctuations. Such an approach may help one interpret the results derived from ensembles of numerical integrations with climate models.

The combined dynamics of low-frequency climate variability and forced climate change may be simplified by treating the faster processes as random noise, superimposed upon and interacting with the slower, nonlinear processes. Several presentations described how the theory of nonlinear, stochastically forced dynamical systems can provide insight into a wide range of time-varying climate phenomena.

An analysis based on observations and experiments with an atmospheric model coupled to a mixed layer ocean suggested that teleconnections are substantially stronger at multidecadal versus interannual time scales. In effect, the former is dominated by a global-scale "hypermode" that exhibits an equatorially symmetric structure reminiscent of ENSO.

The fact that climate variability involves such a wide range of time scales renders the separation of trends and cycles difficult. Several innovative spectral-analysis methods—including empirical mode decomposition, the multi-taper method, and singular spectrum analysis—are being more widely used to study the trend and cycles on different time scales in climate records. When applied properly, these methods behave like data-adaptive temporal filters and thus facilitate the differentiation between the century-long trends and multidecadal cycles. Their application to the historical record of global mean surface temperature and to several proxy records of local and regional temperatures substantiates the existence of human-induced global

warming over the past century and also highlights the role of AMV in modulating the rate of global warming.

CONCLUDING REMARKS. Most climate change meetings have tended to focus on the forced, thermodynamically induced variability of the climate system, as represented by the upper left box in Fig. 1. In contrast, this meeting featured scientists who think outside of that box. The climate response to external forcing—especially on regional scales—is strongly influenced by dynamical processes in both the ocean and the atmosphere. Moreover, the existence of strong natural multi-decadal to centennial variability makes the detection of anthropogenic climate change a challenge. The presentations at the workshop dealt with the full range of processes that contribute to forced and free (also referred to as unforced or internal) multi-decadal climate variability. This broader framing of climate change science is required for quantifying the societal risks of future climate change because the internal variability is so large that ignoring it may lead to false estimates of the climate's sensitivity to anthropogenic forcing. It is also required for properly assessing the extent to which today's weather, specifically the statistics of extreme weather events, is changing in response to human-induced climate change. Bringing together a critical mass of climate researchers with these broader scientific interests was intellectually stimulating and it served to catalyze a number of research collaborations that may bear fruit in the future.

ACKNOWLEDGMENTS. We thank Professor Chang-Shou Lin, Director of National Taiwan University Center for Advanced Study in Theoretical Sciences and Taida Institute for Mathematical Sciences, for initiating and hosting this conference.

REFERENCES

- Chang, C.-P., M. Ghil, M. Latif, and J. M. Wallace, Eds., 2014: *Climate Change: Multidecadal and Beyond*. World Scientific Series on Asia-Pacific Weather and Climate, Vol. 6, World Scientific, in press.