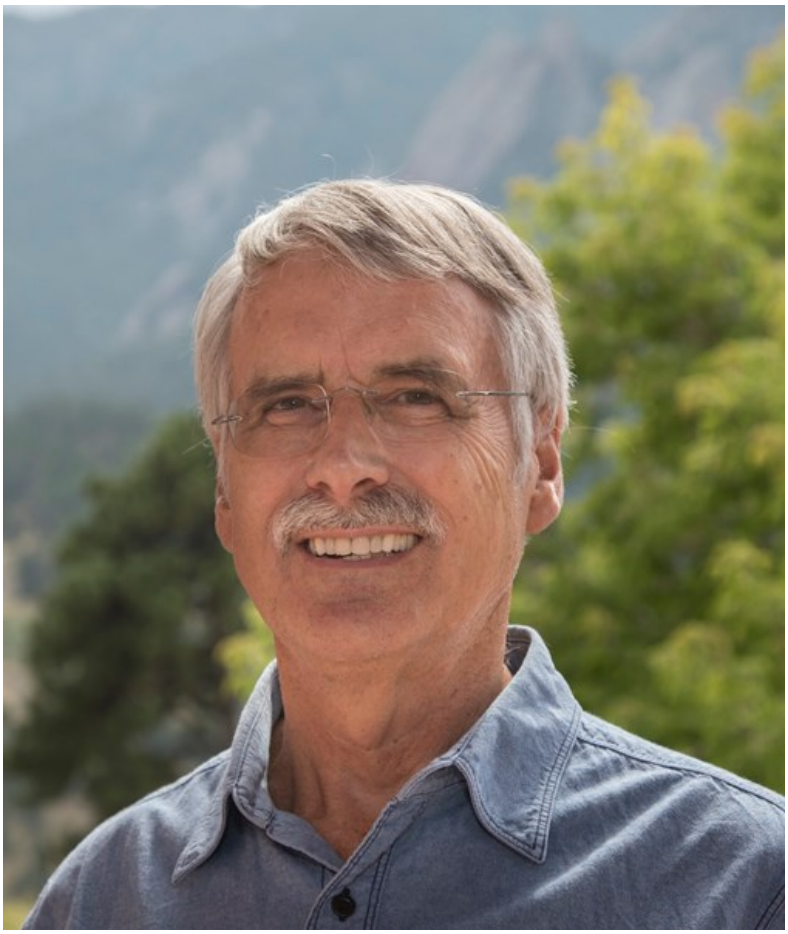
The 2022 AMS Kevin E. Trenberth Symposium

Climate Change: Global Water and Energy Cycles and Extremes



Kevin in Summer 2017, Table Mesa, Boulder, CO, USA

Monday, January 24th, 2022, Houston, Texas, USA

Join us in-person or virtually to celebrate Kevin's outstanding and prolific career of climate research, leadership and communication

Organized by James W. Hurrell, Aiguo Dai, Richard Anthes, and Thomas R. Karl

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A booklet for the 2022 AMS Kevin E. Trenberth Symposium, designed by A. Dai and J. W. Hurrell with materials from Kevin Trenberth, published by AMS, Boston, 2021. Available from https://annual.ametsoc.org/index.cfm/2022/program-events/conferences-and-symposia/kevin-e-trenberth-symposium/

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On top of NZ Meteorological Service building in Kelburn, Wellington
From the Evening Post, Wellington, 19 June 1977

A Brief Bio of Kevin E. Trenberth

Dr. Kevin E. Trenberth is a Distinguished Scholar at the National Center for Atmospheric Research, and an Honorary Academic, Department of Physics, University of Auckland, Auckland, New Zealand.

From Christchurch, New Zealand, his undergraduate degree was from the University of Canterbury in Christchurch, B.Sc. (HONS First Class) in 1966 in just three years. This is normally a four-year degree, equivalent to a Masters, but without a thesis. He majored in Applied Mathematics. After a short bout in the army (Vietnam war years) he took a job at the New Zealand Meteorological Service in Wellington. He was trained as a forecaster and performed some field studies related to the siting of a power station, before winning a New Zealand Government Research Fellowship in 1968 to study and obtain his Sc. D. in meteorology from Massachusetts Institute of Technology in 1972. He returned to New Zealand with his new wife.

In 1977, Kevin took a position as Associate Professor at the University of Illinois, in Champaign-Urbana, and was promoted to full Professor in 1982. In 1984 he took a research position at the National Center for Atmospheric Research in Boulder, Colorado, and remained as an Adjunct Professor at the University of Illinois for 3 years, while his Ph.D. students graduated. As a Senior Scientist at NCAR he became Head of the Climate Analysis Section in 1987, Deputy Director of the Climate and Global Dynamics Division from 1991-1995, and was appointed a Distinguished Scholar on retirement in 2020.

Kevin also served as Editor on *Monthly Weather Review* from 1981 to 1987 and helped initiate the *Journal of Climate*, where he was an Associate Editor from 1987 to 1995.

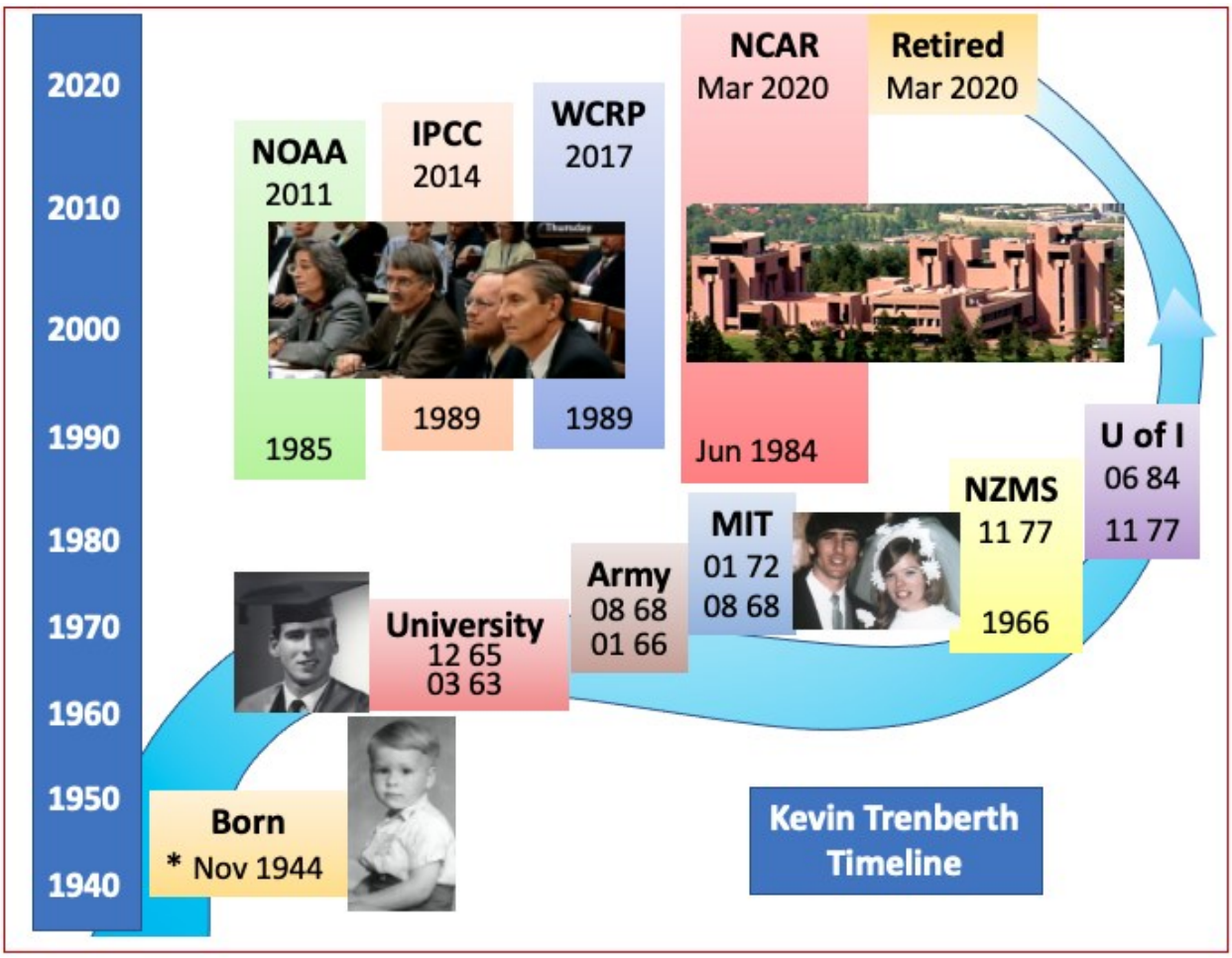
Kevin has extensively served the World Climate Research Programme (WCRP) in numerous ways from 1989 to 2018. Following on from membership in the U.S. TOGA (Tropical Oceans Global Atmosphere) Panel from its initiation in 1995, in 1989, he became a member of the International TOGA scientific steering group (SSG) until the end of the program in 1995. He then became the first co-Chair of the international SSG of the CLIVAR (Climate Variability and Predictability) Programme 1995-1999, and a member of the WCRP Joint Scientific Committee (JSC) 1999-2006. He was an Officer from 2003-2006 (executive committee). He then chaired the WCRP Observations and Assimilation Panel (WOAP) 2004-2010, and also served as a member of the WCRP Modeling Panel (WMP). In 2007 he was appointed to the GEWEX SSG, which, as chair 2010-2013, he led the revamping and renaming of it to Global Energy and Water Exchanges (GEWEX). He continued on the SSG for another year and served as co-chair of the Seventh International Scientific Conference on the Global Water and Energy Cycle, which was held in The Hague, The Netherlands, in July 2014. He was then recruited to become co-chair of CONCEPT-HEAT (Consistency between planetary energy balance and ocean heat storage) under CLIVAR until 2018, when he stepped down. He has also served on many U.S. national committees, especially in NOAA.

Kevin has been very prominent in most of the Intergovernmental Panel on Climate Change (IPCC) scientific assessments of Climate Change for Working Group I. In 1992 he was recruited to be the Convening Lead Author of Chapter 1 of the second scientific assessment report (SAR) of IPCC that came out in 1995. For the 2001 IPCC Third Assessment Report (TAR), he was recruited as a Lead Author, this time for the chapter on climate processes, and then as the Coordinating Lead Author (CLA) of Chapter 3 on observations of the atmosphere and the surface for the Fourth Assessment (AR4) that came out in 2007. He continued as a Review Editor for AR5. He was involved in the intergovernmental meetings that approved the reports and the Summary for Policy Makers for the SAR, TAR and AR4. He also had some involvement with the Working Group II reports. Accordingly, he shared the Nobel Peace Prize that went to IPCC and Al Gore in 2007.

He is a fellow of the American Meteorological Society (AMS), the American Association for Advancement of Science, the American Geophysical Union (AGU), and an honorary fellow of the Royal Society of New Zealand Te Apārangi. In 2000 he received the Jule G. Charney award from the AMS and in 2003 he was given the NCAR Distinguished Achievement Award. In 2013 he received the Prince Sultan Bin Abdulaziz International Prize for Water, joint with Aiguo Dai, and the AGU Climate Communication Prize, and in 2017 the AGU Revelle Medal.

Kevin edited a 788-page book *Climate System Modeling*, published in 1992 by Cambridge University Press. Another major book "*The changing flow of energy through the climate system*", Cambridge University Press, 336 pp, is out in December 2021 (in the UK). He has published **over 580 publications** plus 4 videos; including 71 books or book chapters, and **288 journal articles**, 16 reviewed contributions to *The Conversation*, and many other blogs. His research covers broad areas of climate science, with a focus on the global energy and water cycles, climate data analysis, ENSO, precipitation characteristics, extreme changes, and model evaluation. On the Web of Science, there are over 48,000 citations and an H index of 97 (97 publications have 97 or more citations). On Google Scholar, there are **>108,000 citations and an H index of 126** (or 85 since 2015). From 1996 until 2017 he ranked first in the number of highly cited papers published out of all 223,246 published environmental scientists. "Trenberth" is one of the most cited names in climate journals and conferences of our time.

He has given many invited scientific talks as well as appearing in a number of television and radio programs, and newspaper articles. In his spare time, he plays golf. Learn more about Kevin at https://www.cgd.ucar.edu/staff/trenbert/



Timeline: running vertically up the page; included is the long-term committee membership in NOAA, WCRP and IPCC committees or boards, while employed at NCAR. Small photos include Kevin at age 2, at 20 upon graduation from the University of Canterbury, and when married to Gail in 1970. The photo showing Congressional testimony in February 2007 includes Susan Solomon, Kevin, Richard Alley and Jerry Meehl. The NCAR Mesa Lab photo was taken from the west above NCAR in the front range.

The Role of MIT in Kevin's Life

At MIT starting in August 1968, Kevin took courses the first year, then was fortunate to go to NCAR for a computer work program in the summer of 1969. On return he passed the doctoral exams and set forth a thesis proposal to build a highly truncated spectral global atmospheric general circulation model to carry out numerical experiments related to sudden stratospheric warmings. The model was compatible with some simplified models pioneered by Professor Ed Lorenz. Prof. Lorenz then asked whether he could become Kevin's supervisor. Ed did not provide much advice for Kevin's thesis. As Kevin was quite shy and Lorenz was very introverted, he did not get to know Ed Lorenz until after graduation in January 1972. Later, the Lorenz's visited the Trenberth's in New Zealand and they often got together in Boulder during summers.

Kevin shared a house in Cambridge Mass. with 3 other students; one was engaged to be married to a girl with three roommates; one of whom, Gail, was to become Kevin's life-long mate. In April of 1969 Kevin proposed marriage to Gail and she accepted. The wedding was on March 21, 1970, almost a year later, in Norway and reception in Paris (actually South Paris) – both in Maine! Several fellow students drove the 150 or so miles from Cambridge, Massachusetts to attend in snowy conditions and covered Kevin's Mustang in fax weather maps.

The Green building of MIT is tall, but the floors were somewhat isolated from each other. The 16th floor, where Kevin's office was located, was the synoptic floor where the students with central interests in weather forecasting were located along with Professor Fred Sanders. Current weather maps received from a fax were displayed on the wall, and a contest was ongoing to forecast the weather in Boston 4 days in advance. The forecasts of temperature and precipitation were evaluated and those who beat Fred's score received a cigar at the end of the semester (Kevin received two). His room-mate most of the time was Richard Rosen. Others nearby included Lance Bosart, Bob Burpee, Steve Mudrick, Fred Zbar, John Brown, Steve Tracton and Bob Houze, and a bit later, Howie Bluestein. Bob Burpee was best man in Kevin's wedding and they played squash together frequently.

After Kevin returned to New Zealand in 1972, to simplify correspondence, Bob Burpee and he set up a rotating letter, which still goes to this day, over 47 years later. The idea was to write a letter with photographs, replace your old letter, and package it together with the rest and mail it on. It circulated at rates of 8 months to a year. In this way they were able to experience the trials and tribulations of growing families, a divorce, problems with aging parents, and politics. They had a reunion in Boulder after 30 years in 2003 (hosted by Gail and Kevin), a 35th anniversary in Boston in 2008, and a 40th anniversary in Seattle in 2013. Sadly, Bob Burpee died before the 35th anniversary.

In late 1977, Kevin and Gail, with a three-year old daughter, Annika, left New Zealand to go to Champaign-Urbana where Kevin became an Associate Professor, and later a full Professor, until 1984 when they moved to NCAR and Boulder, CO, also accompanied by an adopted daughter, Angela. They remained in Boulder, until Kevin retired in 2020 when he moved to New Zealand as the pandemic hit.

MIT reunions in 2003 in Boulder (30th, left), and 2013 in Seattle (40th, right) featuring Howie Bluestein, Lance Bosart, John Brown, Kevin Trenberth, Bob Burpee (left only), Fred Zbar, Steve Mudrick, Steve Tracton and Bob Houze (order in left panel).

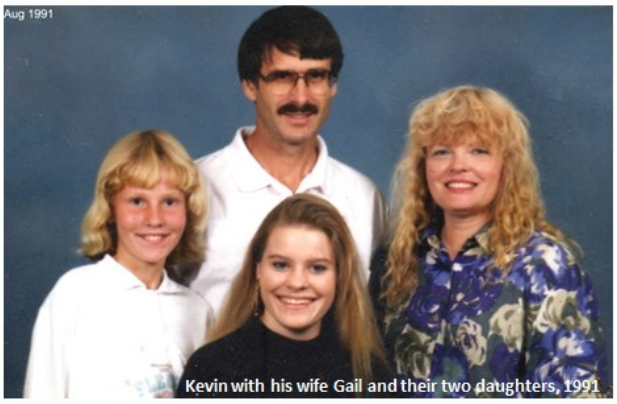
Kevin: Age 2, 1946

Kevin (in circle), 1962

The Trenberth Family , 1963

Graduation from U. of Canterbury , 1966

Gail Kevin, 16 Oct 1969

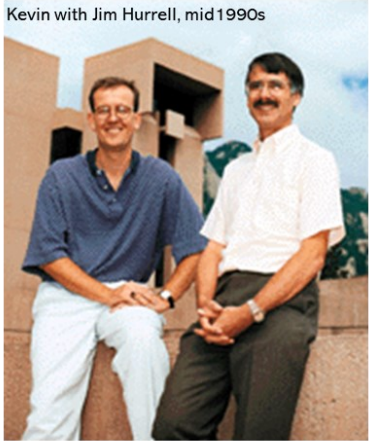


Kevin with his wife Gail and their two daughters, 1991

Kevin with Jim Hurrell (left) and Doug Kinnison (right), 2001, east of Boulder, CO
Bill Randel took the photo

2006, Bolder Boulder , which Kevin ran most years

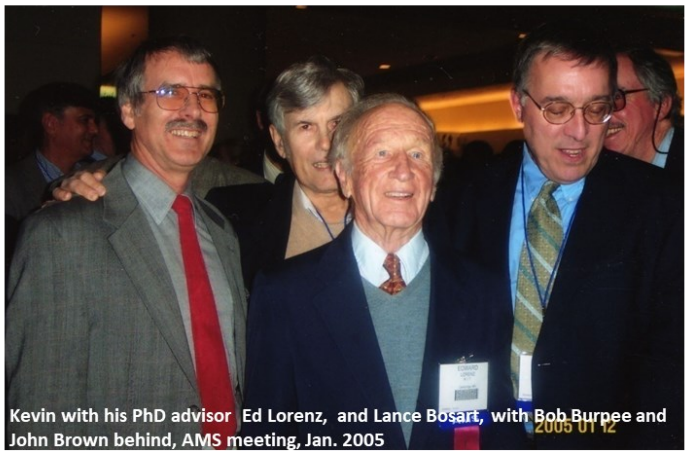
New Zealand army service medal



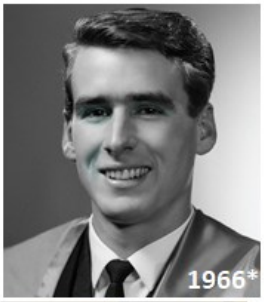
Kevin with Jim Hurrell, mid 1990s

NCAR Climate Analysis Section scientists, 2001
Aiguo Dai, Clara Deser, Kevin Trenberth, Rol Madden, Jim Hurrell, Jerry Meehl

Kevin protesting in Denver, May 2017



Kevin with his PhD advisor Ed Lorenz, and Lance Bosart, with Bob Burpee and John Brown behind, AMS meeting, Jan. 2005

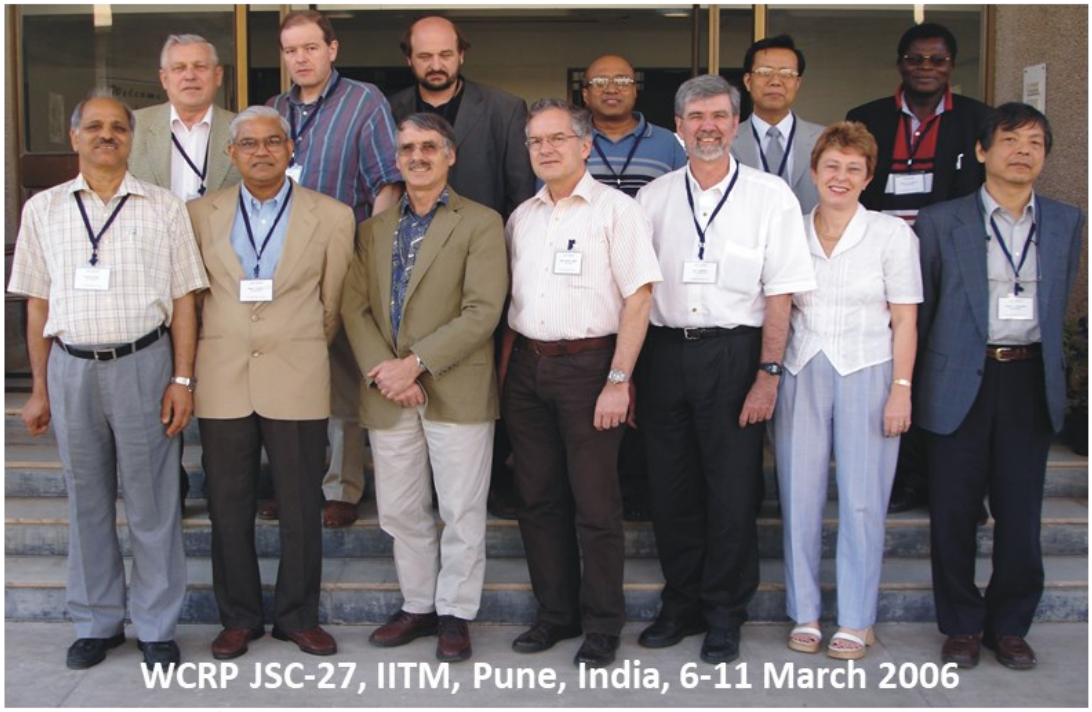


Kevin with his collaborators John Fasullo & Lijing Cheng

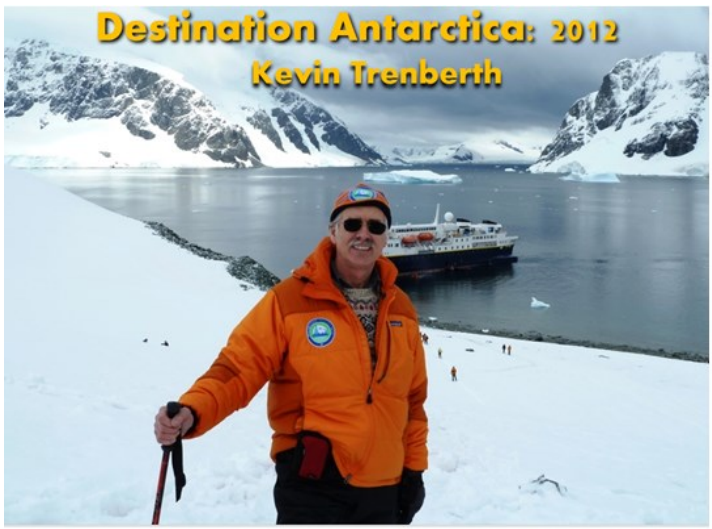
* From https://collection.canterburymuseum.com/objects/680341/film-negative-mr-trenberth-graduate

S. Solomon, K. Trenberth, R. Alley, G. Meeh (L to R) testify before a U.S. House Sci. & Tech. Committee in Feb. 2007

TOGA SSG meeting in Barbados July 1992, (left to right) Dave Halpern, Peter Webster, J. Shukla, Mark Cane (back), Kevin, Bob Knox (back) and Antonio Moura (from Brazil).



Kevin (front, 3rd from left) was on the JSC 1999-2006 and Executive Committee of WCRP, and chaired its Observation and Assimilation Panel from 2004-2010


Destination Antarctica: 2012
Kevin Trenberth


Kevin with Al Gore

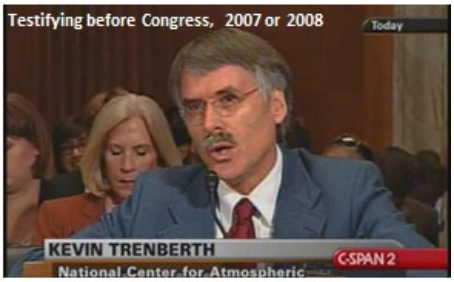

Thatcher visit to NCAR, Aug.3, 1990
John Gille, Kevin, Bill Mankin, John Firor


NIGHTLY NEWS
2014

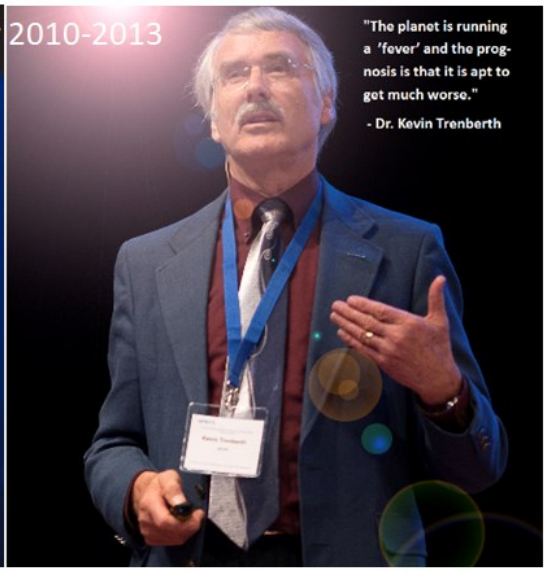

EXTREME WEATHER
BIG CHANGE COMING?
abc NEWS
2014
#ABCWorldNews


AGU Fellow
presentation by
Tim Killeen, 2007

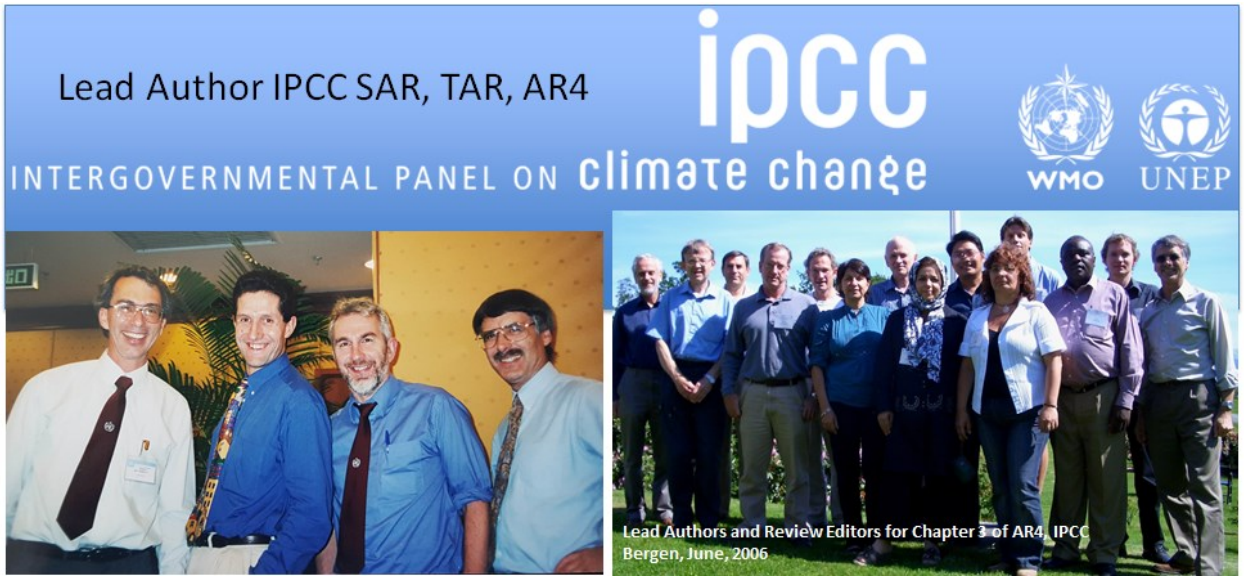

Big Freeze Reignites Climate Change Debate
PBS NEWSHOUR
2012
What's Causing Unusually Hot Temperatures in U.S.?
Kevin Trenberth


Testifying before Congress, 2007 or 2008
Today
KEVIN TRENBERTH
C-SPAN 2
National Center for Atmospheric


GEWEX SSG Chair 2010-2013
GEWEX
TRENDING
NOW:WATER


"The planet is running a 'fever' and the prognosis is that it is apt to get much worse."
- Dr. Kevin Trenberth


WMO
INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC)
Working Group I
UNEP


Lead Author IPCC SAR, TAR, AR4
ipcc
INTERGOVERNMENTAL PANEL ON climate change
WMO
UNEP
Lead Authors and Review Editors for Chapter 3 of AR4, IPCC
Bergen, June, 2006

Prince Sultan bin Abdulaziz International Prize for Water - 2012


Kevin with (L-R) Jim Hurrell, Guy Brasseur, Warren Washington & Jerry Meehl

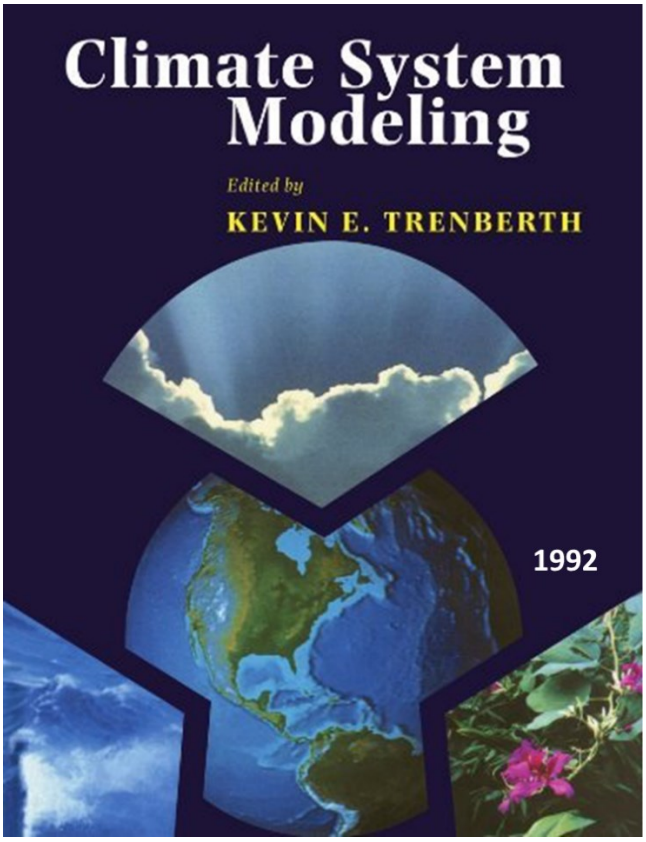
Roger Revelle Medal AGU, 2017

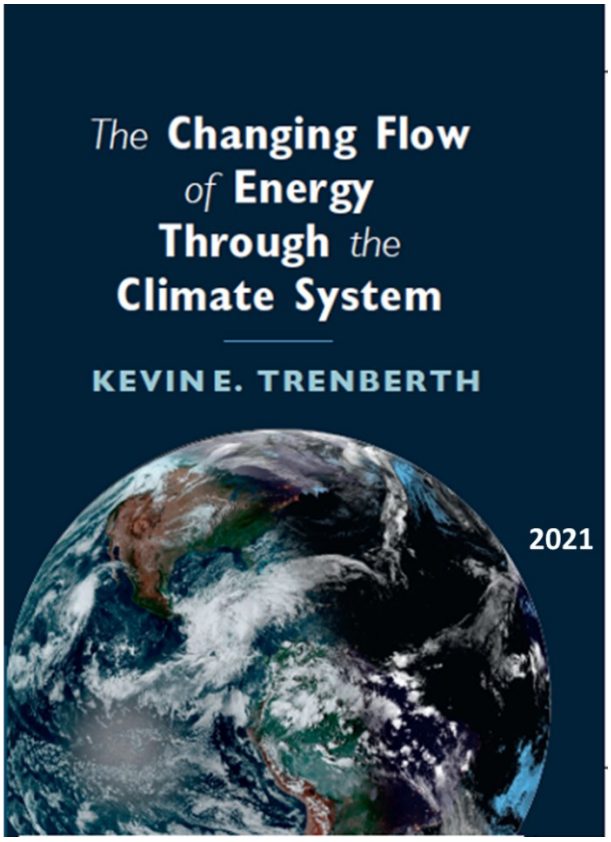
Jule Charney Award 2000

Kevin with Naomi Oreskes and Susan Hassol

AGU 2013 Climate Communication Prize

Kevin with Warren Washington, Dec. 2013





The Changing Flow of Energy Through the Climate System

Cambridge University Press, 2021

Hardback 978-1-108-83886-3 336 pp

Original price	Discount price (valid until 31 July 2022)
£69.99	£55.99
$89.99	$71.99

Paperback 978-1-108-97246-8

Original price	Discount price
£34.99	£27.99
$44.99	$35.99

For more information, and to order, visit: www.cambridge.org/9781108972468
and enter the code CFETCS21 at the checkout

Comments on Kevin's New Book:

The Changing Flow of Energy Through the Climate System

"The consequences of this extraordinary amount of additional heat energy are all around us, and they are spelled out in startling detail in "The Changing Flow of Energy Through the Climate System" – the disruption of the hydrological cycle which is evaporating much more water vapor from the oceans into the sky, where the warmer air holds more of it -- filling the atmospheric rivers that fuel stronger storms and more extreme downpours and floods. We're seeing deeper and longer droughts, increased water stress, declining crop yields, the spread of tropical diseases poleward, refugee crises and the resulting political instability in several regions. Concurrently, the excessive pollution is contributing to the melting and fracturing of the cryosphere, accelerating sea level rise, threatening coastal cities and freshwater aquifers; and increased outgassing of both CO2 and methane from thawing permafrost in the arctic.

Kevin Trenberth is one of the world's premier climate scientists, and along with his colleagues he has been warning us about this mounting crisis for decades. Kevin has an extraordinary ability to take the complicated scientific dynamics of global warming and communicate what's happening in a clear and compelling way. I have learned a great deal from him for many years, and I am grateful for Kevin's patience as a teacher and his ability to convey complexity in simple and understandable language. He's taught me about quite a few of the intricate ways that we humans are disrupting the balance of important ecological systems. And I highly value the way he not only informs, but also motivates action. "

Former Vice President **Al Gore**

'Authoritative, rigorous, well written, and nicely illustrated, Trenberth's book is a welcome addition to the non-specialist literature on climate change. It should be suitable as a possible textbook for graduate courses in climate change and climate dynamics, and appealing to the reader willing to invest the time and effort required to understand the scientific principles that determine how the climate system will respond to the buildup of greenhouse gases in the atmosphere.'

John Michael Wallace, University of Washington

'Nobody has contributed more to our understanding of climate change than Kevin Trenberth. In this book, Trenberth uses the concept of energy flows to explain, in accessible terms, how Earth's climate system operates and how it's being profoundly impacted by human-generated carbon emissions. Read this book to be informed about the basic science underlying the defining challenge of our time.'

Michael E. Mann, Distinguished Professor, Penn State University and author of *The New Climate War: The Fight to Take Back Our Planet*

'Trenberth is the world's greatest master-gatherer of climate data; he orders and translates it into beautifully rendered illustrations that can be followed by everyone. If you do not understand a figure, just go to his accompanying prose and you will. He understands every contour of the data. He teaches us through the lens of energetic reservoirs and fluxes among the various climate system components and how they are forced to move about, grow or shrink. What a treat it is. The wonderfully tinted illustrations in the book are taken and modified from the literature, and many have originated from his own work. The images have been shaped and perfected by decades of lectures he has given to all sorts and levels of audiences. The colorful illustrations are the bones of the book, but the flesh of the prose clearly explains just about every aspect under the great umbrella of climate science.'

Gerald R. North, Texas A&M University

'Kevin Trenberth has been the leader for many years in research on aspects of energy in the climate system based on observational data. He therefore has the perfect background to write a book on climate and climate change based on this perspective. The result is an illuminating discussion that should be of wide appeal.'

Brian Hoskins, The Grantham Institute for Climate Change, Imperial College London

Learn more about Kevin's new book on global energy flow at www.cambridge.org/9781108972468

Some Personal Reflections on Interactions with Kevin

*I first met Kevin at a National Research Council conference in Woods Hole in the early 1980s. I was director of NCAR's Atmospheric Analysis and Prediction Division at the time and over appropriate beverages in the evening on the lawn overlooking the harbor we discussed the possibility of Kevin moving to NCAR from the University of Illinois. I was impressed by his intellect and ability to explain climate science in an articulate, authoritative manner and encouraged him to join NCAR, which he did in 1984. We interacted in many ways over the next 35+ years when I was mostly in Administration and Kevin became the quintessential senior scientist, one of NCAR's very best. He was always my climate "go to" expert when I had questions about the science or various "theories" proposed by global warming deniers. His responses to complex climate questions were always direct, clear, and based on solid evidence. I have greatly appreciated our friendship and interactions! – **Rick Anthes**, 12/8/2021*

*Although it is easy to be inspired by Kevin's accomplishments, I would like to convey an example of how Kevin has helped my career. In 1989, Kevin was extremely busy with science articles, committee work, and more. He was asked by the newly developed IPCC to help lead the Observation Chapter for the First Assessment Report. Kevin recognized this would be a very important activity not only for climate scientists, but for all of human civilization. He called me and told me that he did not have adequate time to devote to this report, but urged me to consider taking this on. This enabled me to engage internationally with some of the world's leading climate scientists over the next several decades. This was definitely the most rewarding aspect of my professional career. I owe a debt of gratitude to Kevin. – **Tom Karl**, 12/7/2021*

*This symposium appropriately celebrates and honors Kevin's seminal contributions to climate research, his tireless efforts to communicate climate science, and his leadership of national and international science committees and activities. To me, however, Kevin is much more than an outstanding scientist and leader. He is a friend and a mentor. I have tried to emulate his high scientific and ethical standards, and his deep commitment to community service, throughout my professional career. Kevin guided me through the myriad of challenges early career scientists face, and he taught me how to do science at the highest levels. He also inspired me to focus on more than my personal research through professional service and leadership. Kevin set aside for me unlimited time, and he was (and is) deeply invested in my personal and professional success. I am forever grateful for our friendship and indebted to him for the guidance and advice he has so unselfishly given over the years. – **Jim Hurrell**, 12/9/2021.*

*I was very fortunate to have had Kevin as my postdoc supervisor and later as my mentor and colleague at NCAR. Kevin has always been very supportive of my work and career. I benefited greatly from his broad vision, prompt response, insightful comments, and excellent writing. He guided me to expand my research into precipitation characteristics, the global water cycle and model evaluation. He is sharp and always on top of things. Despite traveling a lot, he usually gave me constructive feedback the next day when I sent him something for comments. This high efficiency enabled us to produce many papers together. I really enjoyed working with him. I'm also grateful to him for sharing the Prince Sultan Bin Abdulaziz International Prize for Water with me. Thank you, Kevin, for all your support, guidance, and the enjoyable collaborations! I wish you and Gail all the best. – **Aiguo Dai**, 12/5/2021*

The life and times of Kevin Trenberth

A poem by Kevin, 11/18/2021

The year was 1944
At the end of World War two
When Kevin came upon this Earth
Head of the Trenberth crew.

New Zealand was quite remote
And they never had much stuff
But a carefree life, with lots of fun
It wasn't at all that tough.

Played rugby and did well in school
Mathematics at university,
Computers and meteorology
But not much adversity.

Off to America to seek his fortune
To MIT he was bound,
A doctorate resulted but so much more
A wife was what he found.

Back Down Under for a while
To spawn a lovely daughter.
Life was good, and they were poor
But never in hot water.

To Illinois they next did go
To teach and then expand.
To NCAR, Boulder and beyond
To explore this wondrous land.

For research of the climate world
Reanalyses were a need;
More and better data
Let complex analyses proceed.

El Niño and the WCRP
Gave an international stage
To expand horizons far afield
And cooperatively engage.

A climate scientist he became
Climate change was all the rage.
The IPCC played a role
And made Kevin come of age.

Water and energy are the key
To understand it all
How climate causes more extremes
And may lead to our downfall.

Kevin Trenberth Symposium Program[1]

Session 1: Climate Modeling: Advances and Challenges
8:30 AM - 10:00 AM, Monday, January 24, 2022
George R. Brown Convention Center - Grand Ballroom A
Chairs: ***Jim Hurrell***, *Colorado State Univ., Fort Collins, CO;*
Aiguo Dai, Univ. at Albany, Albany, NY

8:30-8:45 1.1 What Is Needed to Do Reliable Quantitative Climate Attribution on Recent Extreme Weather Events? (Invited Presentation)[$]

Tim Palmer, *Univ. of Oxford, Oxford, United kingdom*

8:45-9:00 1.2 The challenge of energy budget closure in Earth system Models[$]

Peter H. Lauritzen, *NCAR, Boulder, CO*

9:00-9:15 1.3 Sea Ice Retreat and Navigation: Implications from Climate Scenarios for Arctic Geopolitics[$]

Amanda H. Lynch, *Brown Univ., Providence, RI;*
and C. H. Norchi and X. Li

9:15-9:30 1.4 Understanding the global warming slowdown (or "hiatus") of the early 2000s (Invited Presentation)[$]

Gerald Allen Meehl, *NCAR, Boulder, CO*

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[1] Available online at https://ams.confex.com/ams/102ANNUAL/meetingapp.cgi/Program/1570
[$] indicates a remote presentation

9:30-9:45 1.5 The Legacy of Trenberth and Shea (2006): What is 'Signal' and What is 'Noise' in Atlantic Multidecadal Climate Variability? (Invited Presentation)[$]

***Amy C. Clement**, Univ. of Miami, Miami, FL; and*
M. Cane, J. Klavans, and L. Murphy Goes

9:45-10:00 1.6 Legacy Contributions of Kevin Trenberth to the World Climate Research Program (Invited Presentation)

***Ghassem R. Asrar**, Universities Space Research Association, Columbia, MD*

Session 2: Global Energy Budget

10:45 AM - 12:00 PM, Monday, January 24, 2022
George R. Brown Convention Center - Grand Ballroom A
*Chairs: **Aiguo Dai**, Univ. at Albany, Albany, NY*
Jim Hurrell, Colorado State Univ., Fort Collins, CO;

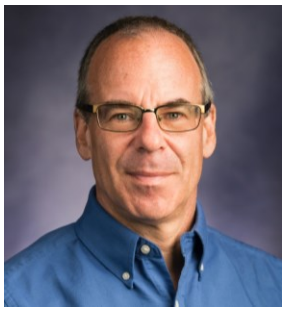
10:45-11:00 2.1 Perspectives on Oceans and Their Role in the Global Energy Budget and Water Cycle (Invited Presentation)[$]

***Lijing Cheng**, IAP/CAS, Beijing, China; and*
J. Abraham, Univ. of St. Thomas, St Paul, MN

11:00-11:15 2.2 The Earth energy imbalance - new advances and remaining challenges (Invited Presentation)[$]

***Karina von Schuckmann**, Mercator Ocean International, Toulouse, France*

11:15-11:30 **2.3** Evaluating 20-yr Trends in Earth's Energy Flows from Observations

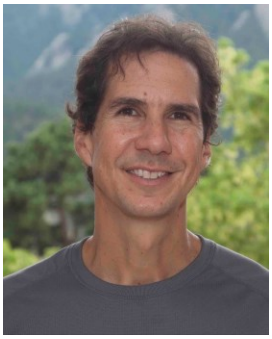


***Norman G. Loeb**, NASA Langley Res. Center, Hampton, VA; and M. Mayer, S. Kato, J. T. Fasullo, M. Balmaseda, and H. Zuo*

11:30-11:45 **2.4** The Role of Clouds in Modulating Meridional Heat Transport (Invited Presentation)

***Tristan S L'Ecuyer**, Univ. of Wisconsin-Madison, Madison, WI; and E. Nelson and E. McIlhattan*

11:45-12:00 **2.5** Wildfire's Emerging Influence on Earth's Energy Imbalance and ENSO (Invited Presentation)[$]



***John T. Fasullo**, NCAR, Boulder, CO*

Kevin Trenberth Symposium Luncheon

Monday, January 24, 2022
12:00 PM - 1:20 PM

12:45-1:00 If You See Something, Say Something: Climate Communication and You (Invited Presentation)[$]

***Susan J. Hassol**, Climate Communication, Asheville, NC*

Session 3: Climate Analysis: Observations and Reanalyses

1:30 PM - 3:00 PM, Monday, January 24, 2022
George R. Brown Convention Center - Grand Ballroom A
Chairs: ***Jim Hurrell***, *Colorado State Univ., Fort Collins, CO;*
Aiguo Dai, Univ. at Albany, Albany, NY

1:30-1:45 3.1 A Brief Tour of Kevin Trenberth's Prolific Contributions to Climate Analysis (Invited Presentation)[$]

Clara Deser, *NCAR, Boulder, CO*

1:45-2:00 3.2 The Sutcliffe-Trenberth Omega Equation

Lance F. Bosart, *University at Albany/SUNY, Albany, NY*

2:00-2:15 3.3 The Origin and Development of Atmospheric Reanalysis (Invited Presentation)[$]

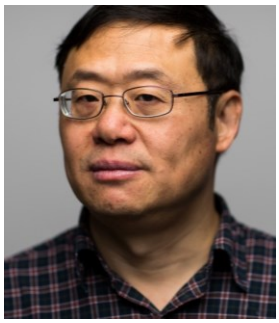
Adrian John Simmons, *ECMWF, Reading, U.K.*

2:15-2:30 3.4 Atlantic Tropical Cyclone Activity Downscaled from Climate Reanalyses Shows Increasing Risk through the Late Nineteenth and Twenty-First Centuries[$]

Kerry A. Emanuel, *MIT, Cambridge, MA*

2:30-2:45 3.5 Monitoring Tropospheric Temperature Changes from Satellite MSU/AMSU Observations: A Personal Perspective on Kevin Trenberth's Impact

***Qiang Fu**, University of Washington, Seattle, WA*



2:45-3:00 3.6 Kevin Trenberth, Community Engagement, and Lessons for All Who Follow (Invited Presentation)

***Jonathan T. Overpeck**, University of Michigan, Ann Arbor, MI*

Session 4: The Global Water Cycle

3:45 PM - 5:15 PM, Monday, January 24, 2022
George R. Brown Convention Center - Grand Ballroom A
*Chairs: **Aiguo Dai**, Univ. at Albany, Albany, NY*
Jim Hurrell, Colorado State Univ., Fort Collins, CO;

3:45-4:00 4.1 Kevin Trenberth's Role in Improving the Water Cycle in Climate Models (Invited Presentation)[$]

***Roy M. Rasmussen**, Boulder, CO*

4:00-4:15 4.2 Assessment of Land Surface and Atmospheric Model Mass Flux Using Water Balance Techniques and GRACE/GRACE-FO Data

***Benjamin Krichman**, The Univ. of Texas at Austin, Austin, TX; and S. Bettadpur, Z. L. Yang, and T. Pekker*

4:15-4:30 **4.3** Precipitation Observations: Variability and Consistency (Invited Presentation)[$]

***Maria Gehne**, NOAA, Boulder, CO*

4:30-4:45 **4.4** Global Precipitation Means and Variations: The New Version of GPCP[$]

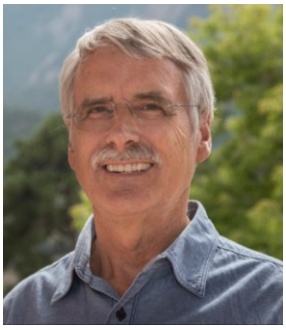
***Robert F. Adler**, Univ. of Maryland, College Park, MD; and G. Gu, G. J. Huffman, A. Behrangi, D. T. Bolvin, J. J. Wang, and E. J. Nelkin*

4:45-5:00 **4.5** A Recount of the Global Water Cycle Research Done by Trenberth and Dai (Invited Presentation)

***Aiguo Dai**, University at Albany, SUNY, Albany, NY*

5:00-5:15 **4.6** Reflections on My Role in the Development of Climate Science[$]

***Kevin E. Trenberth,** NCAR–UCAR, Auckland, New Zealand*



Kevin Trenberth Symposium Poster Session
5:15 PM - 6:00 PM, Monday-Thursday, January 24-27, 2022
*Chairs: **Aiguo Dai**, Univ. at Albany, Albany, NY*
Jim Hurrell, Colorado State Univ., Fort Collins, CO;

Poster # 1 Effects of Cloud Feedbacks on Marine Heat Waves

***Amanda Culp**, RSMAS, Miami, FL; and A. C. Clement*

Poster # 2 Assessing the Influence of the Background State and Climate Variability on Weather Extremes Using Initialized Ensembles in E3SM

*Xue Liu, Texas A&M Univ., College Station, TX; Texas A&M Univ., College Station, TX; Texas A&M Univ., College Station, TX; and **R. Saravanan**, P. Chang, D. Fu, C. M. Patricola, and T. A. O'Brien*

Poster # 3 The Observed State and the Climate Change Fate of the Global Precipitation Heat Engine

***George Duffy**, JPL, Los Angeles, CA; JPL, Pasadena, CA; and A. J. Heymsfield*

Poster # 4 Evaluation of NASA/GEWEX Surface Radiation Budget Fluxes through the Prism of Weather States

***Stephen J. Cox**, SSAI, Hampton, VA; and P. W. Stackhouse Jr., J. Mikovitz, and T. Zhang*

Poster # 5 Assessing the Vertical Velocity of the East Pacific ITCZ

***Lidia Huaman**, Texas A&M Univ., College Station, TX; and C. J. Schumacher and A. Sobel*

Poster # 6 Satellite Precipitation Evaluation over the U.S. Coastal Land–Water Using the Gauge-Corrected Multi-Radar/Multi-Sensor System Product

***Yike Xu**, The Univ. of Arizona, Tucson, AZ; and J. A. Arevalo, A. Ouyed, and X. Zeng*

Poster # 7 Objective Evaluation of Reanalysis-Derived Convective Profiles

***Carlos Mario Cuervo López**, Central Michigan Univ., Mount Pleasant, MI; and J. T. Allen*

Kevin Trenberth Symposium Virtual Poster Session
5:00 PM - 6:30 PM, Monday, January 24, 2022
George R. Brown Convention Center
Chairs: ***Aiguo Dai****, Univ. at Albany, Albany, NY*
Jim Hurrell, Colorado State Univ., Fort Collins, CO;

Poster # R9 Significant Reduction of the Southern Ocean Radiation Bias in a Climate Model

Hideaki Kawai*, MRI, Tsukuba, Japan; and S. Yukimoto, T. Koshiro, N. Oshima, T. Tanaka, H. Yoshimura, and R. Nagasawa*

Poster # R10 The Indian Summer Monsoon Active-Break Cycle from a New Perspective: Using Modern Reanalyses to Connect Large-Scale Circulation Regimes, Diabatic Heating, and Monsoon Intraseasonal Variability

David M. Straus*, George Mason Univ., Fairfax, VA*

Poster # R11 Variation Characteristics of Nonrainfall Water and Its Contribution to the Water Balance in China's Summer Monsoon Transition Zone

Wang Sheng*, Institute of Arid Meteorology, Lanzhou, China; and Q. Zhang Sr. and J. Zhao*

Poster # R12 Atmospheric Moisture Transports from Ocean to Land as a Function of Wind and Humidity Changes

Ambroise Dufour*, Shirshov Institute of Oceanology, Moscow, Russia; and S. Gulev*

Poster # R13 From Einstein to Trenberth and Beyond: Earth's Global Mean Energy Budget as the Solution of Four Radiative Transfer Constraint Equations

Miklos Zagoni*, Eotvos Lorand Univ., Budapest, Hungary*

Poster # R14 Toward Closing the Regional Energy Budget over Ocean in Integrating Satellite-Derived Energy Data Products

Seiji Kato*, NASA, Hampton, VA; and F. G. Rose, F. L. Chang, D. Painemal, W. L. Smith Jr., N. G. Loeb, J. T. Fasullo, K. E. Trenberth, P. H. Lauritzen, D. A. Rutan, and M. Satoh*

Poster # R15 How ENSO Canonical Patterns Change under Global Warming: Contrasting between 1985–2019 and 1950–84 Indicating No Changes Except for the Mean Climate

Yongxin Zhang*, NCAR, Boulder, CO*

Kevin Trenberth Symposium Abstracts[2]

1.1 - What Is Needed to Do Reliable Quantitative Climate Attribution on Recent Extreme Weather Events? (Invited Presentation)

Tim Palmer, Univ. of Oxford, Oxford, United Kingdom

Kevin Trenberth has argued persuasively that attribution studies should focus primarily on the thermodynamic aspects of extreme events, in order to assess the extent to which climate change contributes to such events' extremity. However, recent extreme events in British Columbia, Henan Province China, the Rhine Valley and New York, are so extreme that it seems inevitable that we must also consider how climate change can amplify the dynamical aspects of these events. The problem for CMIP class models is that these observed events are so extreme that they are literally out of range of such models. So what is needed to provide reliable quantitative estimates of the impact of climate change for such events? I argue that this is yet another example of the need for dedicated exascale computing resources so that climate models do not have to be run with parametrised deep convection (not to mention other key parametrisations). Current dedicated exascale computing is being planned for nuclear weapons simulation, so why not climate simulation as well? Ultimately we may need a "CERN for climate change" - something along the lines of CERN or ECMWF where both human and computing resources are pooled at the international level.

1.2 - The Challenge of Energy Budget Closure in Earth System Models

Peter H. Lauritzen, NCAR, Boulder, CO, USA

A closed total energy (TE) budget is of utmost importance in coupled climate system modeling. In the case of the atmosphere it involves physical parameterizations, the dynamical core solver, the coupling between the two (referred to as physics-dynamics coupling) and fluxes from the surface components. The budget is rather complicated partly due to the fact that all parts of an Earth System Model are involved and, even on a continuous level, it is not straightforward how to formulate energetically and thermodynamically consistent equations for a moist atmosphere containing falling hydrometeors.

A detailed analysis of the spurious sources/sinks of TE in the National Center for Atmospheric Research's Community Atmosphere Model (CAM) is given. This includes spurious sources/sinks associated with the parameterization suite, the dynamical core, TE definition discrepancies, and physics-dynamics coupling. It will also be discussed how to move towards a more comprehensive and thermodynamically consistent formulation of TE in CAM.

[2] Available online at https://ams.confex.com/ams/102ANNUAL/meetingapp.cgi/Program/1570

1.3 - Sea Ice Retreat and Navigation: Implications from Climate Scenarios for Arctic Geopolitics

Amanda H. Lynch, Brown Univ., Providence, RI, USA
Charles H. Norchi, Univ. of Maine School of Law, Portland, ME, USA
Xueke Li, Brown Univ., Providence, RI, USA

In the context of retreating sea ice, the Northern Sea Route is thought to present an attractive alternative to the longer Suez Canal route for global trade, despite ongoing issues of satellite navigation coverage, emergency response, expenses associated with Polar Code compliance, and more. Furthermore, ice retreat remains highly variable year on year, and the Arctic environment remains extremely challenging. Nevertheless, there has been a steady growth in within-Arctic shipping – in support of industrial development and tourism – as well as an enhanced military presence by several Arctic nations. CMIP6 scenarios are characterized by uncertainties associated with emissions pathway and model performance, but provide a source of rich and detailed information on the timing and distribution of navigable seas. Here we elucidate their potential to provide insights into sea ice retreat on decadal timescales, which has implications for economic, regulatory and geopolitical friction in this system.

1.4 - Understanding the Global Warming Slowdown (or "Hiatus") of the Early 2000s (Invited Presentation)

Gerald Allen Meehl, NCAR, Boulder, CO, USA

Periods of a decade or more with little or no global warming trend, such as that seen in the early 2000s, occur naturally in nature and in models and are common manifestations of internally generated climate variability (Easterling and Wehner, 2009, GRL). But in the early 2000s when the rate of global warming slowed, CO2 was increasing and heat was still being trapped in the system, so where was the heat going? In a model study, it was demonstrated that the extra heat being trapped in the system during slowdown decades goes into the deeper ocean associated with more downward mixing of heat by the subtropical cells in the Pacific Ocean, less Antarctic Bottom Water formation, and weaker AMOC associated with the negative phase of the IPO (Meehl et al 2011, Nature Climate Change) and was subsequently shown in an ocean reanalysis product (Balmaseda et al., 2013, GRL). An initialized climate model confirmed the Meehl et al 2011 and Balmaseda et al result and simulated the early-2000s hiatus in terms of heat mixing into the deeper ocean (Guemas et al., 2013, Nature Climate Change). There are also accelerated warming decades which are nearly the exact opposite to slowdown decades, with a positive IPO phase and associated processes (Meehl et al. 2013, J. Climate), such that the internally generated decadal timescale variability is superimposed on the warming trend to form a "rising staircase" (Kosaka and Xie, 2016?; Meehl et al, 2016). Hindcasts of the late-1970s (accelerated warming) and early-2000s (slowdown) show initialization could provide some predictive skill for the slowdown (Mochizuki et al., 2010, PNAS; Meehl and Teng, 2012, 2014, GRL; Ding et al., 2013, J. Climate). By specifying observed tropical Pacific SSTs that depict the IPO in a global coupled climate model, the early-2000s slowdown was simulated (Kosaka and Xie, 2013, Nature Clim. Change). An ocean model simulated the negative phase of the IPO as well as the strengthening of the Pacific Ocean subtropical cells that mix heat into the subsurface when the model was driven by the observed anomalously strong surface wind stress in the tropical Pacific, (England et al., 2014, Nature Climate Change). Analysis of observations showed there was a net energy imbalance at the top of atmosphere that indicated extra heat trapped in the system that must be mixed into the subsurface

ocean in association with the negative phase of the IPO (Trenberth and Fasullo, 2013, Earth's Future; Trenberth et al, 2014, J. Climate). Cumulative aerosols from a series of small volcanoes in the early 21st century contributed perhaps about 15% of the slowdown (Santer et al., 2014, Nature Geoscience); contributions from solar and other sources were small (Trenberth and Fasullo, 2013, Earth's Future). An initialized prediction and subsequent verifying observations showed a transition from negative to positive IPO in the 2014-2016 timeframe with a resumption of larger rates of global warming (Meehl et al., 2016).

1.5 - The Legacy of Trenberth and Shea (2006): What Is "Signal" and What Is "Noise" in Atlantic Multidecadal Climate Variability? (Invited Presentation)

Amy C. Clement, Univ. of Miami, Miami, FL, USA
Mark Cane, Lamont-Doherty Earth Observatory, Palisades, NY, USA
Jeremy Klavans, Univ. of Colorado, Boulder, Boulder, CO, USA
Lisa Murphy Goes, Univ. of Miami, Miami, FL, USA

As we observe historic Atlantic hurricane seasons unfold year after year, we, as a community, are faced with the immensely important question of what the role of humans is in driving long-term changes in hurricane activity. Trenberth and Shea (2006) was one of the early papers to ask this question. At the time, the common understanding was that there was a natural mode of sea surface temperature (SST) variability in the Atlantic with a 60-80 year timescale- then referred to as the Atlantic Multidecadal Oscillation (AMO) - which was correlated with Atlantic hurricane activity. Trenberth and Shea noted that an overall (anthropogenic) warming of the basin could confound the link between the AMO and hurricanes, and so they proposed to separate the internal mode from the forced signal by removing the global mean SST. This method is still in wide used in the literature. Trenberth and Shea's interpretation, which was focused on explaining the unusual 2005 season, was that there was only a modest contribution of the AMO compared with overall warming. Since that time, an enormous collection of climate model experiments have afforded a different approach to quantifying the forced signal: by isolating signals that are common across a large number of climate models, or across a large number of ensemble members of one single model in simulations of the past century and a half. Taking this approach, a number of studies have shown that what remains after the forced signal is removed is an important contribution on multi-decadal timescales from internal, natural variability. Taken at face value, it follows that going forward a natural downturn, or cooling, of the AMO could meaningfully offset the anthropogenic warming of the basin, along with its impacts on hurricanes.

Meanwhile, the large, multi-model approach has also been used by a somewhat different community of researchers who have been exploring the prospect of skillful decadal predictions, often with a focus on the North Atlantic. That community has revealed an important shortcoming that is present in almost all models: large ensembles are better at predicting the real world than they are at predicting themselves. This has come to be known as the 'signal to noise paradox' – or stated somewhat differently, the signal to noise ratio is too small in climate models. In this paper, we will link these two lines of exploration in the literature to show that this erroneous signal to noise ratio in models has significant implications for the separation of the forced and internal components of variability in the Atlantic and its impacts. We will offer some hypotheses about the origin of this model error. Circling back to Trenberth and Shea, we will follow their example and conclude that no matter what the exact contribution was of forced signal and internal climate noise,

the global warming influence provides a new background level that increases the risk of future enhanced hurricane activity.

1.6 - Legacy Contributions of Kevin Trenberth to the World Climate Research Program (Invited Presentation)

Ghassem R. Asrar, Universities Space Research Association, Columbia, MD, USA

The World Climate Research Program (WCRP) has served the climate science community for more than five decades, based on voluntary contributions of many community leaders like Kevin Trenberth. As the executive director of WCRP, I had the pleasure and privilege of working with the community leaders from nations around the world for about six years and observed first-hand Kevin's passion and dedication to climate science and international collaboration. During this period, Kevin served WCRP in a variety of positions including the co-chair of WCRP Data and Modeling Panel and later on as the chair of Scientific Advisory Committee of Global Energy and Water Exchange (GEWEX) program. In his capacity as a co-chair of Data and Modeling panel he ensured that WCRP observations, modeling and data assimilation activities are coordinated within WCRP and with the sister programs such as Global Climate Observing System (GCOS), World Meteorological Organization (WMO), Global Earth Observing System of Systems (GEOSS), and other international research coordination programs such as International Geosphere-Biosphere program (IGBP). Under Kevin's leadership, this Panel also ensured these activities are aligned with community modeling efforts such as the Coordinated Modeling Intercomparison Project (CMIP) and the science-based assessment activities by the Intergovernmental Panel on Climate Change (IPCC). Kevin's intimate knowledge of these programs, that he gained through his direct engagement and network of collaborators, combined with his scientific vision and passion for details and perfection were essential ingredients for success in recruiting the best minds from around the world to get involved and contribute to these voluntary efforts.

Later-on, Kevin took on the leadership role of serving as chair of the GEWEX Scientific Advisory Committee during the time that WCRP was developing its vision and research priorities for the subsequent decade. This also coincided with significant debate and discussion about the role of international research coordination programs such as WCRP and IGBP in the coming decades, and how best to add the socioeconomic research and climate services dimensions to these ongoing and successful programs. The ensuing national and international discussions resulted in formation of new programs such as Future Earth and Climate Services and offered some unique opportunities and challenges to programs such as GEWEX about how to coordinate and engage socioeconomics experts to support the required research on socioeconomics in tandem with fundamental understanding and modeling of water and energy cycle that had been the primary focus of GEWEX during previous decades. Kevin did a masterful job of developing a vision and research priorities for GEWEX through a series of community engagement activities including a major conference in the Hague, Netherlands. This conference was truly a major milestone as GEWEX community, under Kevin's leadership, reached out to both natural and social sciences communities to define GEWEX research priorities for the ensuing decade and attracted/sponsored record number of early career scientists to participate in this process. The emerging research strategy has been the blueprint for GEWEX coordination activities since then, and Kevin's influence will continue to have a lasting and legacy impact on GEWEX and WCRP research plan and priorities.

2.1 - Perspectives on Oceans and Their Role in the Global Energy Budget and Water Cycle (Invited Presentation)

Lijing Cheng, IAP/CAS, Beijing, China
John Abraham, Univ. of St. Thomas, Minnesota, MN, USA

Because of the emission of heat-trapping greenhouse gases by human activities, the natural energy flows have been interfered with and currently there is an energy imbalance in the Earth's climate system. More than 90% of the excess heat is accumulated within the global oceans thus leading to an increase of ocean heat content (OHC). Warming of the oceans causes an amplification of the global hydrological cycle, which has a strong fingerprint in the ocean salinity field. The ocean salinity shows a "fresh gets fresher, and salty gets saltier" pattern of change that is linked to the amplification of the global water cycle. The stronger ocean warming within upper layers versus deep water has caused an increase of ocean stratification in the past half century. These changes provide a useful means to quantify climate change. This presentation will introduce our perspectives on oceans and their role in the global energy budget and the water cycle. Many of the studies related to this topic are collaborated with Kevin Trenberth within the past 7 years.

2.2 - The Earth Energy Imbalance: New Advances and Remaining Challenges (Invited Presentation)

Karina von Schuckmann, Mercator Ocean International, Toulouse France

Human-induced atmospheric composition changes cause a radiative imbalance at the top of the atmosphere which is driving global warming. This simple number, the Earth energy imbalance (EEI) – one of the pioneer research topics tackled by Dr. Kevin E. Trenberth - is the most fundamental metric that the scientific community and public must be aware of as the measure of how well the world is doing in the task of bringing climate change under control. Combining multiple measurements and approaches in an optimal way holds considerable promise for estimating EEI and continued quantification and reduced uncertainties can be best achieved through the maintenance of the current global climate observing system, its extension into areas of gaps in the sampling, advance on instrumental limitations, and the establishment of an international framework for concerted multidisciplinary research effort. This talk will provide an overview on the different approaches and their challenges for estimating the EEI. A particular emphasis will be drawn on the heat gain of the Earth system over the past half of a century – and particularly how much and where the heat is distributed – which is fundamental to understanding how this affects warming ocean, atmosphere and land; rising surface temperature; sea level; and loss of grounded and floating ice, which are critical concerns for society. Insights into joint international collaborations on this topic accomplished by Dr. Kevin E. Trenberth will be highlighted throughout this presentation.

2.3 - Evaluating 20-yr Trends in Earth's Energy Flows from Observations

Norman G. Loeb, NASA Langley Research Center, Hampton, VA, USA
Michael Mayer, European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom
Seiji Kato, NASA, Hampton, VA, USA; John T. Fasullo, NCAR, Boulder, CO, USA
Magdalena Balmaseda and Hao Zuo, European Centre for Medium-Range Weather Forecasts, Reading United Kingdom

Recent satellite and ocean in-situ observations indicate a doubling of Earth's Energy Imbalance (EEI) since 2005 that is a consequence of anthropogenic forcing, internal variability, and climate feedbacks. In this study, we follow-up with an assessment of how other components of Earth's energy budget have changed since 2000 and how well these can be tracked. Specifically, we use top-of-atmosphere and surface observations from the Clouds and the Earth's Radiant Energy System (CERES) and calculations of atmospheric divergence of energy transport from ERA-5 to determine the change in total surface flux along with its radiative and turbulent heat flux components. We also assess trends in ocean heat uptake for different ocean layers using various ocean reanalysis datasets. We compare trends derived using various observational and modeling approaches to assess how robust the derived trends are. Our analysis is restricted to global, hemispheric and regional spatial scales and annual mean and seasonal timescales.

2.4 - The Role of Clouds in Modulating Meridional Heat Transport (Invited Presentation)

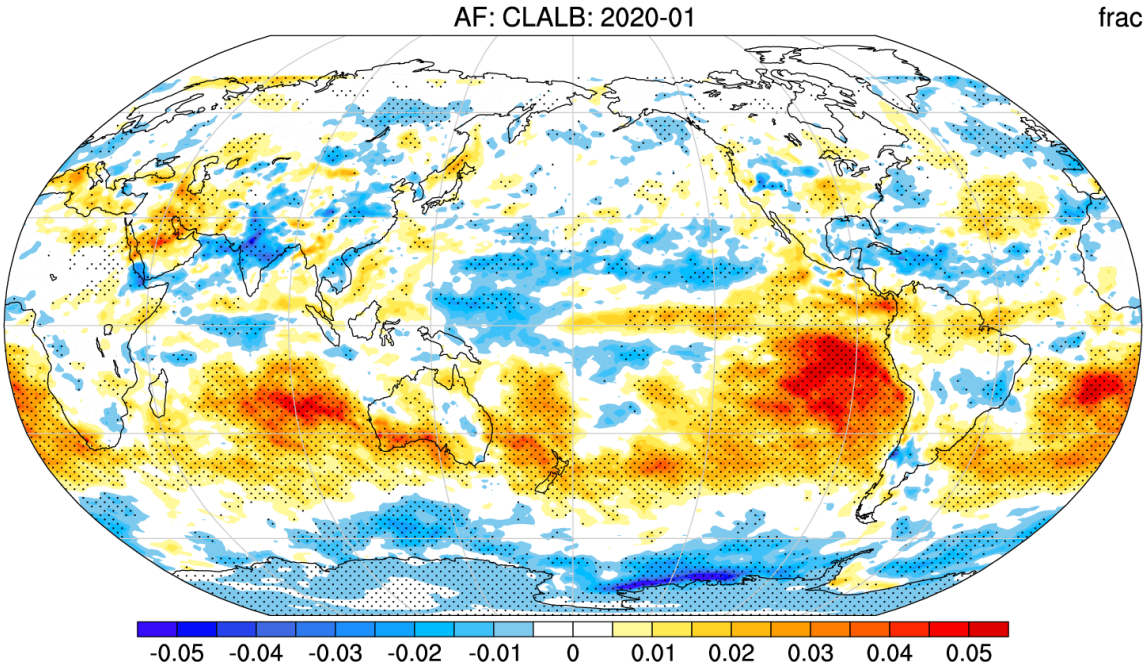
Tristan S L'Ecuyer, Univ. of Wisconsin-Madison, Madison, WI, USA
Ethan Nelson, Univ. of Wisconsin Madison, Madison, WI, USA
Elin McIlhattan, Univ. of Wisconsin Madison, Madison, WI, USA

The transport of surplus heat from the tropics to the poles is a critical driver of the large-scale atmospheric and oceanic circulations on Earth. Kevin Trenberth and his colleagues made significant advances in using top of atmosphere (TOA) and surface fluxes to estimate these poleward heat transports, laying the foundation for utilizing modern satellite sensors to quantify the factors that modulate them. We apply these techniques to quantify the role clouds play in modulating meridional heat transports (MHT) in satellite observations, observation-integrating reanalyses, and climate models. Consistent with previous studies, observed zonal mean TOA fluxes imply a net northward heat transport across the equator. Climate models generally reproduce this result but both of the reanalyses examined imply a net southward transport. Using surface fluxes to separate the atmospheric and oceanic contributions to MHT, reveals much better agreement in estimates of atmospheric heat transport than oceanic heat transport. This may be linked to large differences in the zonal distributions of cloud radiative effects between sources, though variations in turbulent heat fluxes likely also contribute. Climate models exhibit a particularly large spread in predicted cloud influences on TOA and surface fluxes with significant implications for how meridional heat transport is partitioned between the atmosphere and oceans. For example, while nearly all climate models predict net northward heat transport across the equator, they are equally divided as to whether net atmospheric heat transport is northward or southward. This is evidenced by the fact that estimates of the atmospheric equilibrium flux equator in climate models span about 8 degrees of latitude about the geographic equator while both observations and reanalyses favor a Northern Hemisphere location.

2.5 - Wildfire's Emerging Influence on Earth's Energy Imbalance and ENSO (Invited Presentation)

John T. Fasullo, NCAR, Boulder, CO, USA

Among Kevin Trenberth's seminal contributions to climate science are his unique insights into the El Niño / Southern Oscillation and the drivers and effects of Earth's energy imbalance. In this work, these topics are found to be intertwined in the case of recent major wildfires and specifically the Australian bushfire season of 2019/20. Using a 50-member ensemble of CESM2 simulations, the bushfires are shown to have had an impact on the top of atmosphere radiative budget akin to a major volcanic eruption, driving a radiative imbalance across the southern hemisphere subtropics (0-30oS) of almost 3 W m-2. Unlike eruptions, clouds are found to play a central role in the associated energy response, with smoke particulates providing condensation nuclei in the otherwise pristine maritime environments of the southern ocean, increasing cloud drop number and cloud albedo. The inter hemispheric energy imbalance driven by these effects is found to displace the ITCZ northward and increase the odds of an ensuing La Niña event in 2020/21, one that is evident in both our simulations and in nature. Aspects of the simulated responses agree well with CERES and ERA5 observationally-based datasets, though it is noted that further scrutiny of simulated cloud responses is warranted. This scrutiny pertains particularly to biomass emissions, their associated Twomey effect, and their inter-model contrasts.



3.1 - A Brief Tour of Kevin Trenberth's Prolific Contributions to Climate Analysis (Invited Presentation)

Clara Deser, NCAR, Boulder, CO, USA

It is impossible to cover the legacy of Kevin Trenberth's vast contributions to climate analysis in a single presentation. Here, I shall briefly highlight some of Kevin's key papers in climate analysis, and attempt to convey why they have made such a lasting contribution to our understanding of observed climate variability and change. Kevin was (and is!) a prolific scholar and energetic communicator of key concepts in climate, from the fundamentals of the energy and water cycles, to the physical basis for expected changes in the character of precipitation under global warming. Kevin was (and is!) also a champion of observational and reanalysis datasets, which have provided the foundation for our evolving understanding of climate variability and change.

3.2 - The Sutcliffe–Trenberth Omega Equation

Lance F. Bosart, Univ. at Albany, Albany, NY, USA

Kevin Trenberth was motivated both by theoretical and practical considerations when he published his now-famous 1978 paper entitled "On the Interpretation of the Diagnostic Quasi-Geostrophic (QG) Omega Equation" and by the famous Sutcliffe (1947) development theory paper. The primary theoretical consideration was the possible cancellation between the differential absolute vorticity and the Laplacian of thermal advection terms on the right-hand side (RHS) of the traditional form of the diagnostic QG omega equation. In certain synoptic situations (e.g., strong low-level cold-air advection beneath midlevel differential absolute cyclonic vorticity advection), both terms could contribute equally and oppositely to vertical motion. In practice, some forecasters would forget that: (1) cyclonic vorticity advection at a particular level (e.g., 500-hPa) was not the same thing as differential cyclonic vorticity advection through a pressure layer, (2) the magnitude and sign of the Laplacian of thermal advection term was sensitive to the pressure level used in the calculation, and (3) arbitrarily emphasizing one term over the other on the RHS of the QG omega equation was inappropriate.

The primary practical issue was that the Southern Hemisphere (SH) was comprised of mostly ocean and devoid of observations. Radiosonde observations in the 1970s were few and far between. Satellite data coverage did not yet exist. Aircraft upper-level wind observations were limited. Ship observations were few and far between. Given these data limitations, forecasters needed an easy way to determine a dynamics-based practical method that could inform them qualitatively where the primary mid-tropospheric regions of QG ascent and descent were likely to reside. The Sutcliffe-Trenberth omega equation enabled forecasters to estimate where areas of mid-tropospheric ascent (descent) could be found based upon where there was cyclonic (anticyclonic) advection of vorticity by the thermal wind. All that was needed to make qualitative vertical motion estimates was a chart containing sea-level pressure (which could immediately be converted to a 1000-hPa height field), a 500-hPa geopotential height analysis and a 1000–500-hPa thickness analysis obtained by graphical subtraction of the 1000-hPa and 500-hPa geopotential height analyses. The 1000-hPa and 500-hPa geopotential height analyses were used to compute the geostrophic relative vorticity at these levels. We will employ modern gridded datasets to demonstrate the continuing value of the Sutcliffe-Trenberth omega equation to modern weather forecasting.

3.3 - The Origin and Development of Atmospheric Reanalysis (Invited Presentation)

Adrian John Simmons, ECMWF, Reading, United Kingdom

Kevin Trenberth was one of the first to realise both the potential and the pitfalls for climate analysis of using the global atmospheric datasets that began to be produced routinely in the 1970s and 1980s. Intended primarily to provide starting conditions for operational weather forecasts, these datasets were also accumulated to provide comprehensive short-term climate records. Supplementary datasets were provided by syntheses of the enhanced observations made during the 1979 Global Weather Experiment of the Global Atmospheric Research Programme. Although a significant advance on what had been available hitherto, the data records suffered from the deficiencies of the early global assimilation systems. Moreover, interpretation of the interannual variability the data portrayed proved difficult due to the frequent operational changes that had been made to address these deficiencies.

In response, Kevin was at the forefront in the late 1980s in calling for a process of reanalysis of past observations using a current state-of-the-art data assimilation system, a call responded to initially by Europe and the USA, and then by Japan. He has since been deeply involved in the diagnosis of the resulting products and in the international guidance of future efforts.

The talk will review the origins and subsequent development of reanalysis, with emphasis on the ERA family undertaken by ECMWF, latterly under the auspices of the European Union's Copernicus Climate Change Service. It will cover some of the speaker's rewarding interactions with Kevin over the years, particularly on the ERA-40 project and in subsequent activities in support of the World Climate Research Programme and the Global Climate Observing System. Some of the achievements and challenges of the latest ERA5 reanalysis will be illustrated and an indicative timeline for ERA6 will be presented.

3.4 - Atlantic Tropical Cyclone Activity Downscaled from Climate Reanalyses Shows Increasing Risk through the Late Nineteenth and Twenty-First Centuries

Kerry A. Emanuel, MIT, Cambridge, MA, USA

Historical records of Atlantic hurricane activity, extending back to 1851, show increasing activity over time, but much or all of this trend has been attributed to lack of observations in the early portion of the record. Here we use a tropical cyclone downscaling model driven by three global climate analyses that are based mostly on sea surface temperature and surface pressure data. Measures of downscaled tropical cyclone activity agree well with each other and with historical data during the reliable modern portion of the record, and support earlier statistically-based inferences that storms were undercounted in the 19th century. But, in contrast to earlier work, the present analysis shows increasing tropical cyclone activity through the period, interrupted by a prominent hurricane drought in the 1970s and 80s that we attribute to anthropogenic aerosols. All three downscalings show enhanced activity during the Dust Bowl period of the mid to late 1930s. In agreement with earlier work, we show that most of the variability of North Atlantic tropical cyclone activity over the last century was directly related to regional rather than global climate change. Most metrics of tropical cyclones downscaled over all the tropics show weak and/or insignificant trends over the last century, illustrating the special nature of North Atlantic tropical cyclone climatology.

3.5 - Monitoring Tropospheric Temperature Changes from Satellite MSU/AMSU Observations: A Personal Perspective on Kevin Trenberth's Impact

Qiang Fu, Univ. of Washington, Seattle, WA, USA

Tropospheric temperatures measured from satellite microwave sounders (MSU/AMSU) since 1979 have been extensively used in climate change monitoring, verifying climate model simulations, and detecting human fingerprints in the climate change. While enabling significant scientific advances and discoveries, MSU/AMSU temperature data have also been at the center of scientific and political imbroglios. In this presentation I will talk about the debates in the early 2000s related to differences between surface warming inferred from thermometers and tropospheric warming estimated from satellites, and Kevin's impact on my own work.

3.6 - Kevin Trenberth, Community Engagement, and Lessons for All Who Follow (Invited Presentation)

Jonathan T. Overpeck, Univ. of Michigan, Ann Arbor, MI, USA

Kevin Trenberth is a first-generation modern climate scientist, and a pioneering expert on many climate science issues that have come to define the field to the present day, including the water cycle, drought, heat and energy budgets, the attribution of climate events, and climate variability writ large; it's probably impossible to name a climate science topic that Kevin wouldn't have knowledge of, or an opinion on. In other words, he embodies a climate *system* scientist, as well as an extremely productive generator of climate knowledge. His career has coincided with climate variability and change becoming not only one of the most important fields of scientific inquiry, but also one of the most critical for policy- and decision-making in society. It would be easy to celebrate Kevin's career focused solely on his extensive science and publication record alone, but that wouldn't be sufficient. In many ways, Kevin's most important contributions to the field of climate science are those that go far beyond his outstanding research and knowledge creation productivity.

Many will build on the foundation of Kevin Trenberth's research, but hopefully many more will strive to emulate his model of service to the scientific community, and even more to society. Kevin understands how the climate system works, and has been tireless in working to build a national and international climate scientific enterprise that moves the science ahead faster, and at the same time moves it ahead in ways that serve society better. These two goals go hand in hand because society funds the science, and they have to see the benefits of their funding. It's easy for many in the scientific community to do their work oblivious to where their support comes from, but we all rely on colleagues like Kevin who make it the priority to help promote and guide the science by serving on federal advisory and working groups, National Research Council boards and committees, and stepping up to be a leader in national and international science programs. Few in the climate science community have served the community as much Kevin. He's been a tireless advocate for observing systems, reanalysis, ENSO research, climate variability science (e.g., CLIVAR, GEWEX), and much more. Kevin was an even early supporter of paleoclimatology – his wisdom knows no bounds.

Kevin Trenberth was among the first to realize it is no longer enough to be a solid scientist, or even to be a dedicated advocate for stronger science programs and funding. After the summer of

1988, climate change became a national and international issue, a growing crisis for nations around the globe, and at the behest of policymakers around the planet, the IPCC was created to help the leaders of the world figure out what to do about the growing crisis. Almost from the start, Kevin was a major force in the IPCC, serving in critical ways over multiple assessments, and putting himself in the crosshairs of the climate skeptic community (now a denial machine devoid of scientific credibility, but still potent in terms of political influence). Anyone who has served in a leadership role in an IPCC assessment knows that a single assessment demands a lot of effort and time – all volunteer – over multiple years. Kevin served in multiple assessments, and was also tireless in his willingness to work with the U.S. Congress, the media, and the public to ensure that the highly credible IPCC and other climate science was communicated and heard. The climate change crisis needs climate science warriors, and Kevin was one of the first and most dedicated for over two decades. Many a more junior colleague learned a great deal from Kevin, and hopefully even more will strive to serve the community and society as faithfully and unselfishly as Kevin Trenberth.

4.1 - Kevin Trenberth's Role in Improving the Water Cycle in Climate Models (Invited Presentation)

Roy M. Rasmussen, Boulder, CO, USA

The NCAR Water Cycle program started in 2001 as a new NCAR initiative and is still quite active today. Kevin was one of the founding members of this initiative, and one of his notable contributions was to focus our attention on the need to improve the water cycle in climate models. At the time, many climate models did not get the timing, intensity, duration, amount or phase of precipitation correctly, so the Water Cycle program focused on improving this situation. This presentation will discuss the history of this effort, as well as the current status and Kevin's important role.

4.2 - Assessment of Land Surface and Atmospheric Model Mass Flux Using Water Balance Techniques and GRACE/GRACE-FO Data

Benjamin Krichman, Srinivas Bettadpur, Zong-Liang Yang, Tatyana Pekker
The Univ. of Texas at Austin, Austin, TX, USA

GRACE mission data is used to derive variations in terrestrial water storage in order to evaluate approaches to the water balance. The data in the span of the GRACE and GRACE Follow-On missions is analyzed, and long-term behavior of a variety of basins is characterized. Terrestrial water storage variations are calculated via a combination of flux quantities from land surface models and atmospheric reanalyses using two common water balance approaches as well as a third approach using a novel algorithm for basin boundary discretization. Results are used to evaluate the new approach and form an understanding of its limitations, in relation to both the model data ingested as well as the characteristics of the regions in question. From the results, we observe significant variations in model performance over diverse geography and climatic conditions, such as diminished accuracy in atmospheric reanalyses under the effect of long term drought. These observations suggest utility as a diagnostic to assess and inform improvement in the studied

models. Commentary is included regarding aspects of this work that suit it to integration in open science models, such as NASA's Earth System Observatory.

4.3 - Precipitation Observations: Variability and Consistency (Invited Presentation)

Maria Gehne, NOAA, Boulder,, CO, USA

How much uncertainty is in a precipitation estimate? How and where and when do global precipitation estimates differ? What are aspects that the precipitation estimates agree on? I will talk about work with Kevin that tries to address these questions. We consider several different data sets of quasi-global precipitation estimates. The precipitation estimates differ in the goals they are trying to achieve. High-resolution precipitation products intend to produce the best estimate of local instantaneous precipitation. Climate data records prioritize homogeneity over instantaneous accuracy. Global reanalyses produce precipitation estimates that are consistent with their large scale circulation, but are still model forecasts as precipitation is not assimilated. Regional differences in the means and variances can be as large as the means and variances. Similar monthly totals do not guarantee similar rain rate estimates. Annual cycle estimates are able to capture the uni- or bimodal nature of the regional precipitation consistently, but there is large variability in amplitude among the products. Interannual variability is captured consistently among many estimates in some regions (e.g. Australia, Maritime Continent and Europe), but not in others (e.g. South America and Africa). Monthly correlations tend to have a high signal-to-noise ratio overall. In terms of distributions, there is a wide range in the most common rain rates and the rate of occurrence of the highest rain rates. This translates to large differences in which rain rates contribute to the majority of the rain totals. Differences on annual time scales and continental regions are around 0.8mm/day, which corresponds to 23W/m^2.

4.4 - Global Precipitation Means and Variations: The New Version of GPCP

Robert F. Adler, Guojun Gu, Univ. of Maryland, College Park, MD, USA
George J. Huffman, NASA GSFC, Greenbelt, MD, USA
Ali Behrangi, Univ. of Arizona, Tucson, AZ, USA
David T. Bolvin, SSAI, Lanham, MD, USA
Jian-Jian Wang, Univ. of Maryland, College Park, MD, USA
Eric J. Nelkin, SSAI, Lanham, MD, USA

Knowledge of global precipitation means, patterns and variations is essential for understanding the global water cycle. The observation-based global analysis of the Global Precipitation Climatology Project (GPCP) has been a key input to many studies, including those related to means and variations of the global (and regional) water and energy cycles. A new version (Version 3.2) of the GPCP monthly analysis is now available (1983-2019), with finer spatial resolution (0.5º latitude/longitude), updated satellite algorithms, latest gauge analysis over land from the Global Precipitation Climatology Center (GPCC), and with ocean climatologies adjusted using information from the Tropical Rainfall Measuring Mission (TRMM), the Global Precipitation Measurement (GPM) mission and CloudSat. The presentation will give key findings from the new analysis, compare with the previous version, link to studies of the water cycle by Trenberth and others and briefly evaluate the latest climate model results.

The GPCP Monthly V3.2 analysis uses a Tropical Composite Climatology (TCC) using 22 years (1998-2019) of TRMM and GPM-based surface precipitation estimates from passive microwave, radar and combined passive microwave and radar observations to adjust the long-term mean values in the tropics over ocean. At higher latitudes over ocean CloudSat surface precipitation estimates are used in a similar fashion. The result of the new algorithms and procedures is generally increased ocean mean values over both the tropics and higher latitudes. Zonal mean peaks in the tropics increase and the overall tropical ocean mean (25º N to 25º S) increases (from V2.3) about 5% to 3.3 mm/d. At higher latitudes over ocean the mid-latitude peaks also increase, with the spurious double peak in the Southern Hemisphere in V2.3 disappearing and a resulting 60º N to 60º S mean of 3.2 mm/d, an increase of 7%. This increased mean ocean precipitation estimate gives closer agreement with global water budget closures (e.g., Trenberth et al., 2011, J. Clim.; Rodell et al., 2015, J. Clim.) where the GPCP mean ocean estimate was increased to make closure. Over land the gauge analysis (from GPCC in Germany), combined with satellite estimates results in a small decrease (~ 0.5%) from the previous version, giving a total global precipitation number of 2.81 mm/d for V3.1, an increase of 4.5%.

Variations from inter-annual to trend scales over most of the ocean are driven by satellite passive microwave-based precipitation estimates. In this V3.2 the amplitude of inter-annual variations over the ocean was corrected by the use of a combination of two different satellite products. The new GPCP version retains a near zero trend of global precipitation, with significant positive trends in the deep tropics along the Pacific ITCZ and elsewhere, countered by middle latitude decreases, very similar to the previous version of the GPCP Monthly. The pattern of trends is similar to that of AMIP climate model results, driven by observed SSTs for the period in question, but very different from results for "free-running" CMIP historical ensembles, likely due in part to the relatively short comparison period and effects of inter-decadal variations in the GPCP and AMIP results that are not in the "history" models.

4.5 - A Recount of the Global Water Cycle Research Done by Trenberth and Dai (Invited Presentation)

Aiguo Dai, Univ. at Albany, Albany, NY, USA

In this talk I will try to reflect how Kevin Trenberth and I did a number of highly-cited studies from the late 1990s to around 2014 related to the global water cycle, including changes in precipitation characteristics, drought, streamflow and continental discharge. When I came to work with Kevin as a NOAA-funded postdoc in 1997, I did not know any of these topics; but Kevin had already started thinking about how the hydrological cycle, and precipitation in particular, may respond to the ongoing global warming. We first examined the diurnal cycle in precipitation amount, frequency and intensity over the contiguous United States using hourly raingauge data and regional model simulations (provided by F. Giorgi) in a 1999 *JGR* paper. This work was later extended to simulations by NCAR's global climate models and became a major theme of NCAR's *Global Water Cycle Initiative* established in the early 2000s and led by Roy Rasmussen ever since. Summarizing some of our work on precipitation frequency and intensity and motivated by the newly established NCAR's water cycle initiative, Kevin took the initiative to lead a highly-cited 2003 *BAMS* paper on how precipitation frequency and intensity may respond to global warming differently and the challenges for models to realistically simulate these properties and their diurnal

cycles. In the early 2000s, Kevin was also looking at the major water fluxes in the global water cycle, and could not find any updated estimates of continental freshwater discharge, so he asked me whether we could do something about it. Luckily, I found a newly compiled global streamflow dataset in NCAR's data archive and other streamflow data sources and I quickly learned to run a river routing model with specified runoff fields; after some tedious work, we were able to produce much improved estimates of freshwater discharge from all continents and examined their long-term changes in two highly-cited papers published in 2002 and 2009. In the meantime, Kevin and I were also looking at how drought may respond to global warming using the Palmer Drought Severity Index (PDSI), precipitation and streamflow data, and together we published one of the first papers on this topic in 2004 and several related papers later. Kevin, together with me, won the Prince Sultan Bin Abdulaziz Surface Water Prize in 2012 because of our work on streamflow and drought. Up to this date, Kevin and I are still interested in precipitation characteristics (frequency, intensity, and duration) and how they are simulated in models and may change under global warming. It was a wonderful and prolific journey for me working with Kevin on the global water cycle over many years.

4.6 - Reflections on My Role in the Development of Climate Science

Kevin E. Trenberth, NCAR–UCAR, Auckland New Zealand

I have been fortunate to be at the forefront of many major developments in climate science including El Niño, reanalysis, climate change, and attribution. It led to my recent research foci on water and energy, and Earth's Energy Imbalance. The importance of interactions with the international community of scientists is emphasized, especially through the World Climate Research Programme, and the Intergovernmental Panel on Climate Change, as well as U.S. national programs, along with the growing need to publicize the results of research to the general public, but perhaps not through social media. Somewhat in spite of my introverted nature, I became a main go-to guy for media comments on new publications prior to social media, and this sometimes got me into controversies, especially with climate change deniers. I plan to touch on my career from details of my evolution from a meteorologist in New Zealand to that of a true climate scientist and describe a number of major scientific issues and several controversies, such as Climategate, that arose for one reason or another, and how these were overcome.

Poster #1 - Effects of Cloud Feedbacks on Marine Heat Waves

Amanda Culp, RSMAS, Miami, FL, USA
Amy C. Clement, Univ. of Miami, Miami, FL, USA

The past several decades have seen an increase in the number of marine heatwave (MHW) events, which are defined as discrete prolonged periods of anomalously high sea surface temperatures (SSTs). These events occur around the globe, one of the most notable regions being the Northeastern Pacific Ocean. In this study, the Community Earth System Model (CESM) is used with two different simulations to analyze the differences between SST anomalies for cloud-locking and control scenarios. In the cloud-locking scenario, cloud radiative feedbacks are fixed, while in the control scenario, there are no restrictions and clouds are permitted to interact with radiation. SST anomalies are computed based on a 300-year climatological average, and then the warmest thirty anomalies are compared for each scenario. Including cloud feedbacks enhances SST extremes, particularly warm extremes. Cloud feedbacks also shift the area of more extreme temperatures toward the western coast of North America. Hence, the presence of cloud radiative feedbacks in the control simulations strengthen SST anomalies, indicating warmer-than-average temperatures. The anomalies themselves are greatest in the summer months, when the climatological cloud fraction is the highest. During this time, the difference between the anomalies in the simulations is also greatest, which suggests that the presence of cloud radiative feedbacks has the greatest effect in summer; this supports the idea that warmer SST anomalies correspond to areas of greater total cloud fraction. This pattern was also tested in terms of rainfall. In a preliminary analysis of the relationship between cloud feedbacks and coastal precipitation patterns, it was found that the presence of cloud feedbacks actually suppresses rainfall along the southern coast of North America while slightly increasing rainfall in the northern region, if at all. Also compared are CESM simulations with CMIP6 simulations to evaluate the role of cloud feedbacks in intermodal differences in the simulation of marine heatwaves. Improperly forecasted MHWs can have profound effects on climate and weather as well as marine ecosystems and biodiversity, so determining the key processes and their simulation across models is critical.

Poster #2 - Assessing the Influence of the Background State and Climate Variability on Weather Extremes Using Initialized Ensembles in E3SM

Xue Liu, **R. Saravanan,** Ping Chang, Dan, Fu
Texas A&M Univ., College Station, TX, USA
Christina M. Patricola, Iowa State Univ., Ames, IA, USA
Travis A. O'Brien, Indiana Univ., Bloomington, CA, USA

The current generation of general circulation models (GCMs) continues to suffer from significant deficiencies in simulating the observed statistical properties of weather extremes, such as extreme precipitation, tropical cyclones (TCs) and atmospheric rivers (ARs). Factors responsible for these deficiencies include lack of sufficient model resolution and/or errors in model parameterizations, as well as biases in the simulated mean climate. To distinguish among these factors, we carry out a large ensemble of 4-week forecasts initialized from observations using the Energy Exascale Earth System Model (E3SM) atmospheric component (EAM). At the initial time, the ensemble-average forecast does not have a bias as compared to observations (by construction),

even though parameterization and resolution errors are present in the model. The ensemble-average bias grows as the forecast progresses, asymptotically approaching the model bias – as estimated from long control runs – over a few weeks. Different components of climate bias – flow bias and moisture bias – grow at different rates, with the moisture bias growing more slowly than the flow bias.

We analyze the time-varying properties of weather extremes in the large ensemble of forecasts, compared to their properties in observations and in a control run of the model. The responses of extreme events to the biases in the ensemble-mean climate are diverse. Heatwaves are not very sensitive to mean bias. TCs display non-monotonic error evolution, attributable to the differing growth rates for flow and moisture bias. TC strength appears to be controlled by the flow bias, whereas TC numbers are responding to the moisture bias. ARs exhibit a slower evolution of error due to the slower growth of moisture bias. We also carry out sensitivity forecast experiments where we artificially speed-up the development of moisture bias to isolate its impact on simulated weather extreme.

These results help improve our understanding of the impact of the large-scale environment on different types of weather extremes, and potentially bring new insights into the mechanism of such events and/or the impact of model bias, while providing a basis for improving the model simulation and prediction of these events.

Poster #3 - The Observed State and the Climate Change Fate of the Global Precipitation Heat Engine

George Duffy, JPL,Pasadena, CA, USA
Andrew J. Heymsfield, NCAR, Boulder, CO, USA

The most powerful transfer of energy from the Earth surface to the atmosphere comes from precipitation: the latent heat released as water vapor liquifies or crystallizes before falling to the Earth. Snowfall represents a more efficient transfer of energy than rain, adding an extra 334 kJ of warming energy to the atmosphere for every kg of precipitation that doesn't melt on its way to the Earth's surface. It also adds an additional source of cooling into the ocean that is not present during rain. Recent advances in satellite-observed global precipitation measurements allows us to quantify this global heat pump and its phase-related efficiency for the first time. Climate change will have several implications for this heat pump, as any increases or decreases in precipitation will have corresponding changes in atmospheric heat transfers, and an overall transition of snow to rain in warmer winters may ultimately lead to a less-efficient transfer of heat from precipitation. In this study, we evaluate the representation of the global precipitation heat pump, investigate the changes to the heat pump that have occurred in the reanalysis record, and we project changes to the efficiency of the precipitation heat pump in climate change scenarios.

Poster #4 - Evaluation of NASA/GEWEX Surface Radiation Budget Fluxes through the Prism of Weather States

Stephen J. Cox, SSAI, Hampton, VA, USA
Paul W. Stackhouse, NASA Langley Research Center, Hampton, VA, USA
Jennifer Mikovitz, SSAI, Hampton, VA, USA
Taiping Zhang, SSAI, Hampton, VA, USA

The NASA/GEWEX Surface Radiation Budget Version 4 (SRB Rel4) product is now publicly available, covering the period from July 1983 through June 2017. This supersedes the SRB Rel3 (Stackhouse et al., 2011) product which has been used in the community for a wide variety of applications, including climate model validation, agriculture, solar energy, and architecture.

SRB Rel4 uses the newly recalibrated and processed ISCCP HXS product as its primary input for cloud and radiance data, replacing ISCCP DX with a ninefold increase in pixel count (10km instead of 30km). This version retains a 1°x1° resolution but benefits from a much larger number of samples per grid box than the SRB Rel3. ISCCP also provides an atmospheric temperature and moisture dataset known as nnHIRS which we use here, along with Seaflux and Landflux surface and near-surface meteorological parameters.

Rel4 incorporates several important algorithm improvements. These include recalculated shortwave (SW) atmospheric transmissivities and reflectivities yielding a somewhat less transmissive atmosphere. Both shortwave and longwave (LW) now also include variable aerosol composition and radiative properties, allowing for the use of a detailed aerosol history from the Max Planck Institute Aerosol Climatology (MACv1). LW and SW algorithms now produce pristine sky fluxes, allowing the aerosol flux effects to be quantified. For SW, ocean albedo and snow/ice albedo are improved from Release 3. Total solar irradiance is now variable, and reduced to an average of 1361 Wm^{-2}. The radiative treatment of ice cloud is improved. For the LW, a climatological monthly varying spectral surface emissivity is added.

Here we evaluate the SRB Rel4 top of atmosphere (TOA) and surface fluxes in the context of weather states. Weather states (Tselioudis et al., 2013, Tselioudis et al., 2021) are defined by K-means clustering of 2-D histograms of satellite-retrieved cloud optical depths and cloud top pressures. The most recent (Tselioudis et al., 2021) weather states derived from the International Satellite Cloud Climatology Project (ISCCP) H-series data results in eight cloud weather states and one clear sky weather state, for a total of nine. We examine the statistics of SRB Rel4 fluxes for each weather state and a variety of relevant land and ocean regions. We compare to similar analyses performed on CERES EBAF and SYN1Deg flux products, and validate against Baseline Surface Radiometer Network (BSRN) land stations and Pacific Marine Environmental Laboratory (PMEL) ocean buoy data. It is demonstrated that the weather state concept is valuable when examining the comparative strengths and weaknesses of satellite radiative flux algorithms.

Poster #5 - Assessing the Vertical Velocity of the East Pacific ITCZ

Lidia Huaman, Texas A&M Univ., College Station, TX, USA
Courtney J. Schumacher, Texas A&M Univ., College Station, TX, USA
Adam Sobel, Columbia Univ., Palisades, NY, USA

Trenberth et al. (2000) was at the forefront of utilizing reanalyses to diagnose the large-scale overturning of the tropical atmosphere. They found the main mode to be deep, with a maximum in vertical motion around 400 hPa resulting from both meridional and transverse large-scale circulations (namely, the Hadley and Walker cells). They also identified a shallow meridional overturning centered near 800 Pa that contributes on the order of 20% of the variance of the global monsoon, with higher contributions over regions such as Africa and the Atlantic and Pacific intertropical convergence zones (ITCZs). A number of studies have since analyzed the prevalence and importance of these shallow overturning circulations, but significant disagreement still exists between datasets. For example, while reanalyses generally indicate a stronger shallow mode, satellite-based studies suggest a predominance of the deep mode. It has been a challenge to determine which dataset is closer to the truth because of the lack of in situ observations over these regions. Additionally, the vertical structure of the circulation is important to the moist static energy budget, and thus to the theoretical questions about the relationship of convection to large-scale dynamics.

In this study, we assess the vertical velocity structure in the East Pacific ITCZ using dropsonde observations from the Organization of Tropical East Pacific Convection (OTREC) 2019 field campaign, latent heating retrievals from the Global Precipitation Measurement (GPM) satellite, and omega fields from multiple reanalyses (ERA5, MERRA, NCEP-NCAR, and JRA55). Using a suite of methods (case study, climatological comparisons, and Monte Carlo analysis), we find that all of the reanalyses show a predominant shallow mode from 3-10°N across the East Pacific ITCZ, unless they assimilate the dropsondes. Then a deeper mode is found at 8°N. The latter is more consistent with OTREC observations, which indicate a shallow mode from 3-7°N, over a strong meridional gradient in sea surface temperature (SST), but a deep mode from 7-10°N, where SST is warmest. The reanalyses represent a range of resolutions, convective parameterizations, and assimilation schemes so it is unclear why they all have difficulty deepening convection over the East Pacific ITCZ warm pool. Vertical motion derived from the GPM latent heating algorithms has the opposite problem in that the deep mode is predominant from 3-10°N. It is only when shallow convective clouds from CloudSat are included that a shallow mode is found from 3-7°N. Thus, including measurements of the full convective spectrum (i.e., from shallow, non-precipitating to deep, precipitating) is essential in representing the large-scale overturning of the East Pacific ITCZ.

Poster #6 - Satellite Precipitation Evaluation over the U.S. Coastal Land–Water Using the Gauge-Corrected Multi-Radar/Multi-Sensor System Product

Yike Xu, Jorge A. Arevalo, Amir Ouyed, Xubin Zeng
Univ. of Arizona, TUCSON, AZ, USA

Weather and climate over coastal regions have received more and more attention, partly because of substantial population growth and sea level rise. Coastal land/ocean rainfall measurement is available from satellite remote sensing. While numerous papers have been published on the evaluation of satellite precipitation datasets over land (including coastal land), we are not aware of such systematic studies over coastal ocean. Recognizing precipitation radars over coastal land also cover coastal ocean (or lake water), here we use the hourly Multi-Radar/Multi-Sensor System (MRMS) gauge-corrected precipitation product for three years (2018 to 2020) to evaluate the relative performance over the U.S. coastal land versus ocean (and water over the Great Lakes) of three widely used satellite-based precipitation products (IMERG, PERSIANN, and CMORPH). Seasonal precipitation patterns, extreme precipitation, and case studies such as hurricane landfall are analyzed and compared between products. The impact of gauge correction in these satellite-based products is also assessed. The advantages and weaknesses of each satellite precipitation product over the coastal region are presented, and suggestions are made for their future improvement.

Poster #7 - Objective Evaluation of Reanalysis-Derived Convective Profiles

Carlos Mario Cuervo López, and John T. Allen
Central Michigan Univ., Mount Pleasant, MI, USA

The reliability of atmospheric vertical profiles through time can have a significant impact on many applications, including the characterization of convective profiles. Furthermore, instrument precision has changed with emerging technologies; which can lead to variation in the reliability of observed data. This leads to uncertainties when working with historical datasets and evaluating model products. Here, to provide a dataset for evaluation of the global relative performance or reanalysis or model data, we propose a set of statistical techniques to correct the available soundings datasets using local climatology.

Profiles are first quality controlled to exclude unrealistic changes in the profile, poor-quality data, and outliers in the distribution of each variable. To ensure reliable intercomparison, raw profiles are interpolated to regular fixed heights. However, in doing so this approach must be flexible to accommodate that in each sounding levels may have missing or have poor-quality data. The focus of this presentation will be three potential filling methods; through a linear interpolation between the available levels; leveraging non-parameter statistical method of matching the profile to variable distributions in order to reconstruct where data are unavailable or compromised; and a weighted variation of a similar statistical methodology to nudge the profile toward the relevant climatological distribution, similar to the adjustments used in convective parameterization schemes.

Following application of the quality control and filling methodology, preliminary results of comparing the quality-controlled record to the MERRA2, ERA-Interim, and ERA-5 reanalysis will be discussed.

Poster #R9 - Significant Reduction of the Southern Ocean Radiation Bias in a Climate Model

Hideaki Kawai, Seiji Yukimoto, Tsuyoshi Koshiro, MRI, Tsukuba Japan
Naga Oshima, Japan Meteorological Agency, Tsukuba Japan
Taichu Tanaka, JMA, Tokyo Japan
Hiromasa Yoshimura, Ryoji Nagasawa, MRI, Tsukuba Japan

Trenberth and Fasullo (2010) revealed that CMIP models have a serious shortwave radiation bias over the Southern Ocean due to the lack of cloud radiative effect. They also showed that JRA-reanalysis, which was produced by JMA, has a similar bias. The JMA operational global model that was used for JRA-reanalysis and the MRI climate model had a terrible shortwave radiation bias over the Southern Ocean. We were acutely motivated by the paper and the reduction of the bias became our urgent task.

And now, the Southern Ocean radiation bias was significantly reduced in our climate model MRI-ESM2 (Yukimoto et al. 2019, JMSJ), which is used in CMIP6 simulations, by improving various processes related to clouds (Kawai et al. 2019, GMD). The score of the spatial pattern of radiative fluxes at the top of the atmosphere for MRI-ESM2 is ranked in the top seven models among 47 CMIP6 models. We will introduce how we could reduce the serious Southern Ocean radiation bias in MRI-ESM2. We thank Dr. Trenberth for motivating us by the paper to resolve the serious Southern Ocean radiation bias, which is crucially important for climate models.

Poster #R10 - The Indian Summer Monsoon Active-Break Cycle from a New Perspective: Using Modern Reanalyses to Connect Large-Scale Circulation Regimes, Diabatic Heating, and Monsoon Intraseasonal Variability

David M. Straus, George Mason Univ., Fairfax, VA, USA

Using the ERA-Interim reanalysis circulation fields and diabatic heating estimated using ERA-5 reanalysis, both the Indian Monsoon active-break cycle and the tropics-wide boreal summer intra-seasonal oscillation can be diagnosed with minimal time-filtering. This approach connects these oscillations directly to preferred large-scale circulation patterns, and provides a powerful approach for evaluating forecasts and simulations of the monsoonal cycles. An observed daily Indian rainfall product is used only to verify consistency with the oscillations derived from the circulation fields.

Intra-Seasonal circulation regimes are identified from a cluster analysis of 5-day mean (pentad) anomaly fields of 850 hPa horizontal winds from the ERA-Interim reanalysis for the boreal summer season (120 days starting 01June for the years 1979 - 2018) over the broad Indian region (5 E-100 E; 5 S – 35 N). The anomalies are formed with respect to a parabolic (in time) seasonal cycle computed separately for each year, thus filtering out periods of greater than 240 days. The

k-means clustering method was applied in the phase space of the leading principal component modes, yielding k circulation regimes. The degree of clustering is significant when compared to synthetic data sets for any value of k > 3.

The transition matrices (giving the number of transitions between regimes) establish that the system is most likely to stay in the same cluster from one pentad to the next, but that the significant transitions (with 95% confidence level using a modified bootstrap method) form a cycle. The similarity between the cycle as depicted from 4 or 5 clusters is established by composites of 850 hPa winds, 200 hPa divergence, 500 hPa vorticity and vertical pressure velocity: Strong convection (inferred from rainfall, vertical pressure velocity, divergence and vorticity) over the subtropical Indian Ocean, moves to the central Bay of Bengal and over central India, then subsequently to the northern Bay of Bengal and west Bengal, and then further north into the Himalayas. (The Indian rainfall, composited over the periods of the regimes, show a similar cycle.) The phases in which strong convection is seen over central and northern India are seen for about 60% of the time for both k=4 and k=5 analyses.

The number of complete cycles (including a return to the starting cluster) found in the 40 years of data is 7 in the 4-cluster analysis, while the number of times the system undergoes four (three) consecutive legs of the cycle is 16 (31). Fewer instances of complete cycles are found for 5 clusters (only 3), but sequences of five, four and three consecutive legs occur 10, 11 and 28 times respectively.

Composites of the tropics-wide vertically integrated diabatic heating (estimated as a residual in the thermodynamic equation using ERA5 reanalyses) reproduce the characteristics of the boreal summer intra-seasonal oscillation, with northwest-to-southeast oriented bands of heating moving northward from the tropical Indian Ocean into the subtropics. Shown in the Figure is the preferred transition cycle of vertically integrated diabatic heating (in W/m**2) using 5 clusters, with the cycle starting at the top panel (a) and proceeding downwards.

This depiction of the active-break cycle is particularly useful for diagnosing the cycle in short-range forecasts: as long as pentad anomalies can be formed, they can be assigned to one of the observed clusters described in this paper without the need for further time-filtering.

Poster #R11 - Variation Characteristics of Nonrainfall Water and Its Contribution to the Water Balance in China's Summer Monsoon Transition Zone

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Comprising mainly fog water, dew water, and water-vapor adsorption (WVA), non-rainfall water (NRW) makes an important contribution to the local ecology in the arid and semi-arid regions. Although NRW components have been studied individually in previous work, little attention has been paid to the integrated characteristics of NRW and the corresponding relationships among the components. In fact, few other studies have considered how NRW components form and change, let alone how they contribute to land surface water (LSW) balance and influence crop water requirements in China. In this paper, a method will be established for identifying components of NRW, based on a combination of lysimeter measurements and micro-meteorological data from Dingxi Station in the summer monsoon transition zone (SMTZ) of

China. Diurnal time series of NRW components will be given. The relationship between NRW and climatic and environmental factors is then analyzed. Finally, the diurnal and annual variations of NRW and how they contribute to LSW balance are discussed. The results show that the influence of climatic and environmental conditions to occur dew and WVA is different even opposite affects such as relative humidity to that. There is negative feedback between soil moisture and WVA; this does not hold, however, for dew. The variation characteristics of dew and WVA are different. Their diurnal variation shows the complementary characteristics of each other. Not only that, the annual distribution of NRW also complemented with that of precipitation. Although NRW contributes to no more than 15% of the water balance in a full year, NRW plays a leading role during the non-monsoon period, wherein the amount of NRW is 1-3.5 times that of precipitation. It explained that NRW has great significance for reducing agricultural losses and understanding the LSW balance in the SMTZ.

Poster #R12 - Atmospheric Moisture Transports from Ocean to Land as a Function of Wind and Humidity Changes

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We compute ocean to continent water vapour transport in satellite era reanalyses including NCEP CFSR, JRA 55, MERRA 2 and ERA 5. The moisture transport is equal to net precipitation according to the atmospheric budget equation. However, the so-called "physics output" method yields scattered mean estimates. A general positive trend is discernible but superimposed on decadal patterns independent from one reanalysis to the next. The agreement is much better when fluxes are computed directly from wind and humidity (aerological method). What's more, radiosondes can then be used to verify the consistency of the data assimilation. The increasing trend is now univocal with matching variability even on a year to year basis.

We present a method to distinguish between the role of thermodynamics and circulation in producing these changes using Europe as a case study. Moisture transport integrated in time and space depends on average wind and humidity as well as their covariance. To break down the covariance term, we build composites of wind and humidity on pressure levels based on deciles of the vertically integrated flux. The coherence on the vertical ensures that the product of humidity and wind composites is approximately equal to the composite of the product i.e. moisture flux. During the satellite era, the wind composites did not substantially change but the humidity composites did increase and the higher quantiles even more so. Warming temperatures indeed raised the saturation pressure and in turn the vapour transport but relative humidity variations are not to be neglected.

Poster #R13 - From Einstein to Trenberth and Beyond: Earth's Global Mean Energy Budget as the Solution of Four Radiative Transfer Constraint Equations

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Einstein read a paper in Berlin, at the meeting of the Prussian Academy of Sciences in 1914 (chaired by Max Planck) in the absence of the author, Karl Schwarzschild, who served as a soldier in World War I. The paper introduced the integral equation of radiation transfer, our best tool to compute atmospheric radiations. In an earlier paper Schwarzschild (1906, Eq. 11) presented the two-stream approximation to the same problem. For atmospheres in local thermodynamic equilibrium, the upward beam A, the downward beam B and the emission of the layer E is presented as the function of the emerging flux at the upper boundary (A_0) and the optical depth. It was realized soon (Emden, 1913) that in radiative equilibrium there is a discontinuity in the Planck-function at the ground, implying a discontinuity in temperature, balanced by non-radiative energy flows (evaporation and convection) in radiative-convective equilibrium. It is an immanent implication of this solution that the net radiation at the lower boundary, that is, the sum of the convective fluxes (sensible heat plus latent heat) is unequivocally constrained to half of the emerging flux at the upper boundary, independent of the optical depth. This feature is reproduced by standard textbooks as Milne (1930) Eqs. 93-95; Goody (1964) Eq. 2.115; Chamberlain (1987) Eq. 1.2.30; Goody and Yung (1989) Eq. 2.146 and Eq. 9.5; Houghton (1977, 2002) Eq. 2.13; Andrews (2010) Eq. 3.50-3.51, etc.. This relationship in recent notations looks like this: shortwave (SW) + longwave (LW) net radiation at the surface = Outgoing longwave radiation (OLR)/2. We controlled the validity of this equation in the annual global mean, and found it satisfied with a difference of -2.31 Wm^{-2} on the CERES EBAF Ed4.1 dataset for 21 full running years of observation (March 2000 — February 2021). An evident all-sky version can be constructed, by separating atmospheric radiation transfer from the longwave cloud radiative effect (LWCRE): surface SW+LW net radiation (all-sky) = [OLR(all-sky) – LWCRE]/2. This equation is satisfied with a difference of 2.76 Wm^{-2} on the same data product. The second relationship in Schwarzschild (1906, Eq.11) is reproduced by Houghton (1977, 2002) in Eq. 2.15 as the greenhouse equation, describing the total radiative energy absorbed by the surface. This relationship depends on the optical depth. With a specific optical depth of 2 it reads: Surface (SW net + LW down)(clear-sky) = 2OLR(clear-sky). Its all-sky case is: Surface (SW net + LW down)(all-sky) = 2OLR(all-sky) + LWCRE. They are justified within -2.88 Wm^{-2} and 2.42 Wm^{-2}, respectively. These four equations together are satisfied with a mean bias of -0.0025 Wm^{-2} (see presentations by Zagoni at AMS AM101 - 2021, EGU2021, CERES STM 2021). — The all-sky net equation is valid on the Kiehl and Trenberth (1997, Fig.7) global energy budget estimate with a difference of 0.5 Wm^{-2} (surface SW+LW net = 102 Wm^{-2}, (OLR-LWCRE)/2 = 102.5 Wm^{-2}). The greenhouse version has a bias of 8 Wm^{-2} there. The updated distribution (Trenberth et al. 2009; Trenberth and Fasullo 2012) has 97 Wm^{-2} net radiation at the surface; the right-hand side of the equation is (239-30)/2 = 104.5 Wm^{-2}; the difference is 7.5 Wm^{-2}. The greenhouse (total) fluxes at the surface are: 161+333 = 494 Wm^{-2} SW+LW absorption, while 2OLR+LWCRE give 508 Wm^{-2}; the equality is out by 14 Wm^{-2}, mainly because of the low longwave downward radiation. Looking back, it seems that the original non-radiative fluxes (78 + 24 Wm^{-2}) were the more accurate: the NASA Energy and Water-cycle

Study (NEWS, L'Ecuyer et al. 2015, Stephens and L'Ecuyer 2015) give 81 + 26 Wm^{-2} for convective fluxes. On the other hand, the updated surface solar absorption (161 Wm^{-2}) is better: with CERES data, surface solar net radiation = 163 Wm^{-2}, DLR = 345 Wm^{-2} and LWCRE = 26.7 Wm^{-2} seem the best estimates. Altogether, the IPCC-AR5 (2013) global energy budget (Fig. 2.11) and the NEWS study satisfy both the net and the gross all-sky equations within ±2 Wm^{-2}. — Applying known definitions, the set of these four equations has a solution in form of integer ratios, related to LWCRE = **1**. All-sky global mean fluxes: Surface SW net = **6**; Surface LW net = **–2**; DLR = **13**; OLR = **9**. Clear-sky fluxes: Surface SW net = **8**; Surface LW net = **–3**; DLR = **12**; OLR = **10**; Surface upward LW (ULW) = **15** both for all-sky and clear-sky; LWCRE at the surface and at TOA = **1**. The solution prescribes a definite value for the greenhouse effect as well: g(theory, all-sky) = G/ULW = (ULW – OLR)/ULW = (**15** – **9**)/**15** = 0.4. Kiehl and Trenberth (1997) have an excellent approximation: g(KT97, IPCC-AR4) = (390 – 235)/390 = 0.3974, the same as in the most recent CERES EBAF Ed4.1 data for 252 months of observations (ULW = 398.70 Wm^{-2}, OLR = 240.24 Wm^{-2}). TFK2009 and TF12 have an even better g = (396 – 238.5)/396 = 0.3977. The IPCC-AR5 (2013) has g = (398 – 239) / 398 = 0.3995, which is the closest to the theoretical time-independent and greenhouse-gas independent stationary value. — An unexpected, but extremely accurate extension is possible by observing that the TOA reflected solar radiation (RSR), both for all-sky and clear-sky, fit into the integer system. This way total solar irradiance (TSI) becomes a component of the system with TSI = **51** units. Using the best SORCE value of 1360.68 ± 0.5 Wm^{-2}, the unit flux becomes LWCRE = **1** = 26.68 Wm^{-2}, with RSR (all-sky) = **15**/4 = 100.05 Wm^{-2} and RSR (clear-sky) = **8**/4 = **2** units = 53.36 Wm^{-2}, allowing solar absorption in the clear-sky **43**/4 = 286.81 Wm^{-2}, with TOA Net clear-sky imbalance = -TOA Net CRE = **3**/4 unit = 20.01 Wm^{-2} (the corresponding CERES values: 99.00, 53.74, 286.28, -19.48 and 20.25 Wm^{-2}, resp.) Notice that each global mean flux component is an integer on the intercepting cross-section disk to incoming solar radiation; quarters appear only after spherical weighting to the Earth's surface. This is a far-reaching consequence of the equations.

Poster #R14 - Toward Closing the Regional Energy Budget over Ocean in Integrating Satellite-Derived Energy Data Products

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When energy data products are integrated to understand the energy budget and energy flow within the climate system, issues that are not considered in individual energy data products arise,

such as conserving water mass and consideration of the enthalpy of vaporization dependence on temperature in converting precipitation rate to diabatic heating. The water mass in an atmospheric column needs to be balanced among precipitation, evaporation, and horizontal transport. However, when precipitation, latent heat flux, and latent heat divergence data products are combined, regional water mass is not necessarily conserved. In addition, because the enthalpy of vaporization depends on temperature, diabatic heating depends on the temperature at which the water phase change occurred. The enthalpy exchange also occurs between precipitating hydrometeors and the atmosphere. In this presentation, the effects of these two issues on closing the regional energy and water budget of the atmosphere over ocean when integrating satellite derived energy flux data products will be discussed.

Poster #R15 - How ENSO Canonical Patterns Change under Global Warming: Contrasting between 1985–2019 and 1950–84 Indicating No Changes Except for the Mean Climate

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In this work, changes in mean climate, Oceanic Niño Index (ONI) and ENSO canonical teleconnection patterns between 1950-1984 (the past decades) and 1985-2019 (the current decades) are examined using National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis and European Center for Medium-range Weather Forecasts version 5 reanalysis. Warming prevails over most parts of the globe while precipitation shows heterogeneous spatial changes. ONI reveals slight increase trends in frequency and intensity of both El Niño and La Niña events during 1985-2019 when compared to 1950-1984. Remarkable similarities in the anomaly differences (1985-2019 vs. 1950-1984) between El Niño and La Niña to each other and to the differences in mean climate strongly suggest little changes in the ENSO canonical patterns since any changes associated with the ENSO canonical patterns merely reflect the changes in mean climate. It appears unlikely that there will be a more El Niño-like or La Niña-like climate under global warming based on this analysis.