ATMOS 1020 Climate Change

9. Past Temperature Observations

Thomas Reichler, Dept. of Atmospheric Sciences, March 1, 2022

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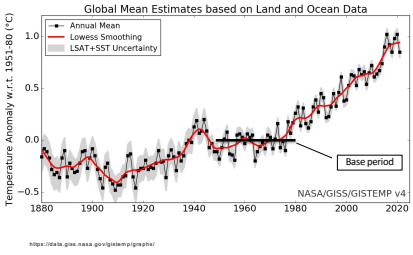
Outline

- Measuring the global warm up
- Techniques, pitfalls, controversies
- Why we shouldn't focus on particular years
  - 2016 was warmest year ever…
  - this is not that important though
  - we can't say what the global temperature is with perfect accuracy
- Why we can still make strong statements about **trends**
  - e.g., the 2010s was the **warmest decade ever**
- Trends in other variables
- Distinguishing human influences and natural variability

2

The NASA Record

- Global temperature since 1880: warming is about **1.0°C**



- Global mean land-ocean temperature anomalies by year
- With respect to 1951-1980 base period
- Black is the annual mean
- Solid red is the five-year mean
- Grey envelope shows uncertainty (95%)

- 2016 was the warmest
- 2020 comes second

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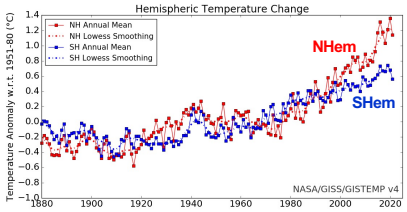
Separation Into Hemispheres



https://data.giss.nasa.gov/gistemp/graphs/

- Northern Hemisphere has warmed more
- Southern Hemisphere has warmed more steadily though
- Slight cooling from 1940-1975 essentially only in the N. Hem. record; likely due to aerosols

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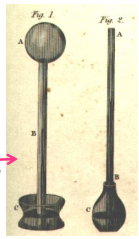
Thermometers

- Temperature is relatively easy to measure
- Some history:
  - ancient **Greeks** knew that things expand when heated
  - **Galileo** played around with thermometer-type devices (1592): "thermoscope"
    - thermoscopes: glass tubes open at one end, partially filled with water; were subject to changes in air pressure
  - **Ferdinand II de Medici**, Grand Duke of Tuscany, invented **sealed** glass thermometer (much more **accurate**) around 1650
    - established the first international network of weather stations: 7 stations in Italy, also Warsaw, Paris, Innsbruck, Osnabrück



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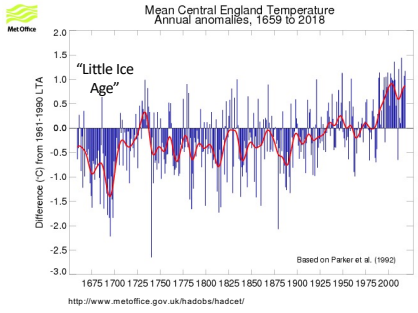
Central England Record (CET)

- Longest temperature record at one station. Since 1659!



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Weather Observations

- Meteorological Society of Mannheim (Germany) (1780)
  - 37 stations in Europe, 2 in North America
  - rigorous procedures for making measurements, calibrating instruments, etc.
- Invention of **telegraph** allowed for quick construction of weather maps by 1850
- First International Meteorological Conference (August 1853)
- US Navy Lieutenant Matthew Fontaine Maury developed **standard procedure** for meteorological **observations on ships**

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Surface Temperature Protocol

- Thermometer between **1.25-2 m** (4-6.5 ft) above ground
- In instrumentation **shelter** to reflect away direct sunlight
- Passive aspiration by "Stevenson shield"
  - white colored
  - slats for air circulation

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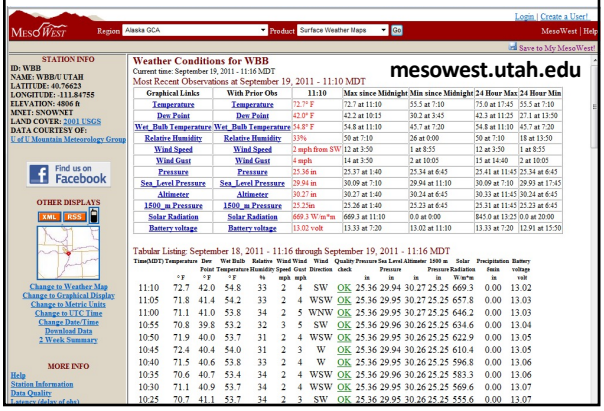
Raw Weather Station Data



mesowest.utah.edu

Weather Conditions for WBB

Current time: September 19, 2011 - 11:16 MDT

Most Recent Observations at September 19, 2011 - 11:10 MDT

Graphical Links	With Prior Obs	11:10	Max since Midnight	Min since Midnight	24 Hour Max	24 Hour Min
Temperature	Temperature	72.7° F	72.7 at 11:10	55.5 at 7:10	75.0 at 17:45	55.5 at 7:10
Dew Point	Dew Point	42.0° F	42.2 at 10:15	30.2 at 3:45	42.3 at 11:25	27.1 at 13:50
Wet_Bulb Temperature	Wet_Bulb Temperature	54.8° F	54.8 at 11:10	45.7 at 7:20	54.8 at 11:10	45.7 at 7:20
Relative Humidity	Relative Humidity	33%	50 at 7:10	26 at 0:00	50 at 7:10	18 at 13:50
Wind Speed	Wind Speed	2 mph from SW	12 at 3:50	1 at 8:55	12 at 3:50	1 at 8:55
Wind Gust	Wind Gust	4 mph	14 at 3:50	2 at 10:05	15 at 14:40	2 at 10:05
Pressure	Pressure	25.36 in	25.37 at 1:40	25.34 at 6:45	25.41 at 11:45	25.34 at 6:45
Sea_Level Pressure	Sea_Level Pressure	29.94 in	30.09 at 7:10	29.94 at 11:10	30.09 at 7:10	29.93 at 17:45
Altimeter	Altimeter	30.27 in	30.27 at 1:40	30.24 at 6:45	30.33 at 11:45	30.24 at 6:45
1500_m Pressure	1500_m Pressure	25.25in	25.26 at 1:40	25.23 at 6:45	25.31 at 11:45	25.23 at 6:45
Solar Radiation	Solar Radiation	669.3 W/m*m	669.3 at 11:10	0.0 at 0:00	845.0 at 13:25	0.0 at 20:00
Battery voltage	Battery voltage	13.02 volt	13.33 at 7:20	13.02 at 11:10	13.33 at 7:20	12.91 at 15:50

Tabular Listing: September 18, 2011 - 11:16 through September 19, 2011 - 11:16 MDT

Time(MDT)	Temperature °F	Dew Point °F	Wet Bulb Temperature °F	Relative Humidity %	Wind Speed mph	Wind Gust mph	Wind Direction	Quality check	Pressure check	Pressure in	Sea Level Pressure in	Altimeter in	1500 m Pressure in	Solar Radiation W/m*m	Precipitation 6min in	Battery voltage volt
11:10	72.7	42.0	54.8	33	2	4	SW	OK	25.36	29.94	30.27	25.25	669.3	0.00	13.02
11:05	71.8	41.4	54.2	33	2	4	WSW	OK	25.36	29.95	30.27	25.25	657.8	0.00	13.03
11:00	71.1	41.0	53.8	34	2	5	WNW	OK	25.36	29.95	30.27	25.25	646.2	0.00	13.03
10:55	70.8	39.8	53.2	32	3	5	SW	OK	25.36	29.96	30.26	25.25	634.6	0.00	13.04
10:50	71.9	40.0	53.7	31	2	4	WSW	OK	25.36	29.95	30.26	25.25	622.9	0.00	13.05
10:45	72.4	40.4	54.0	31	2	3	W	OK	25.36	29.94	30.26	25.25	610.4	0.00	13.05
10:40	71.5	40.6	53.8	33	2	4	W	OK	25.36	29.95	30.26	25.25	596.8	0.00	13.06
10:35	70.6	40.7	53.4	34	2	4	WSW	OK	25.36	29.96	30.26	25.25	583.3	0.00	13.06
10:30	71.1	40.9	53.7	34	2	4	WSW	OK	25.36	29.95	30.26	25.25	569.6	0.00	13.07
10:25	70.7	41.1	53.7	34	2	3	SW	OK	25.36	29.95	30.26	25.25	555.6	0.00	13.07

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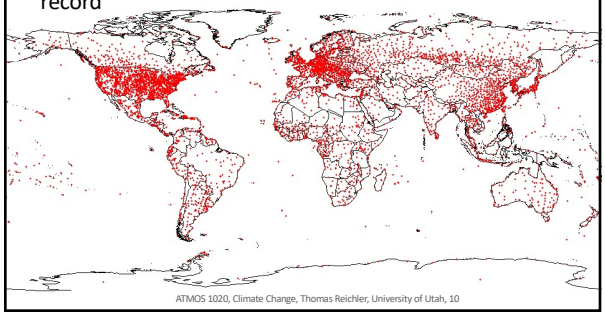
Global Climate Network Stations

- Station location and density today
- Only a small subset of selected stations is used for climate record



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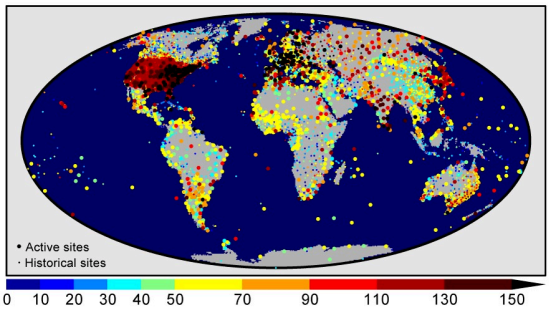
Global Climate Network Stations

- Color: length of station record (years)



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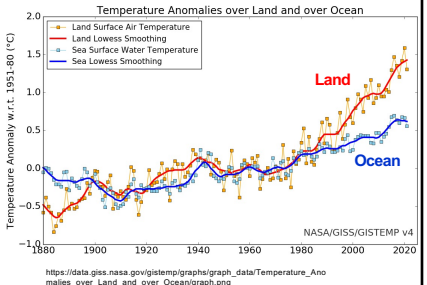
Land Surface Temperatures

- NASA separates their analysis into **land station data only** and **ocean data only**
- Warming in the land station record is larger than in the full record (**~1.5ºC** as opposed to 1.0ºC)



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Sea Surface Water Temperatures

Standard bucket (~1891) | Canvas bucket (pre WWII) | Insulated bucket (now)

- "Bucket" temperature: older style subject to **evaporative cooling**

Starting around WWII: many temperature measurements taken from ship engine's condenser **intake pipe** instead of from buckets. **Typically warmer** than old style buckets.

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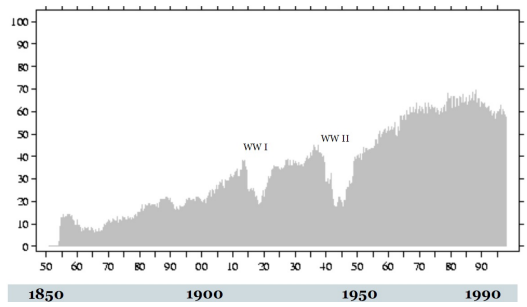
Ocean Measurements

- Percent coverage of ocean by year:



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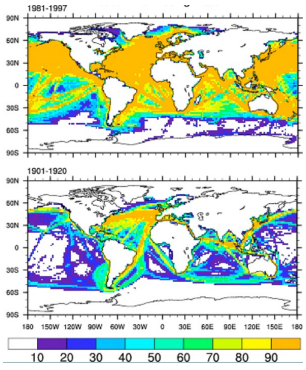
Percent Coverage of Ocean

- 1981-1997
- 1901-1920
- 10% = 1 in 10 months had a ship measurement



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Constructing a Global Record

- Reasonable global coverage started around 1880-1890
- Various groups construct global temperature based on data that follows these procedures
- Who are these groups?
- And what do these groups do to the raw data?

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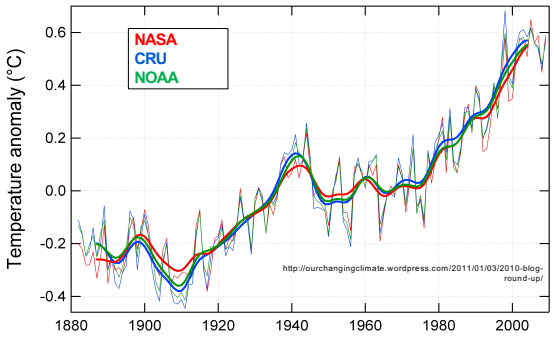
Estimates From Various Groups



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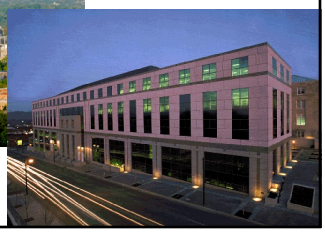
NOAA-NCDC

- NOAA: National Oceanic and Atmospheric Administration
- NCDC: National Climatic Data Center, Asheville, NC



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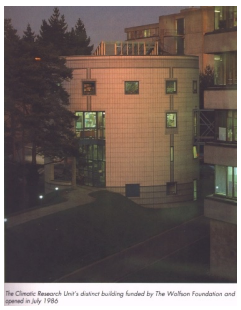
HAD-CRU

- HAD: Hadley Centre, Exeter, England
- CRU: Climate Research Unit, University of East Anglia: Norwich, England



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NASA

- NASA: Goddard Institute for Space Studies, New York, NY

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Complications

- Incomplete spatial and temporal sampling
  - some regions are unobserved
  - short and "gappy" records
- Instrument changes
- Changes in station site, sometimes undocumented
- Changes in exposure of station site
  - e.g., forest growth, "Urban heat island" effect
- Changes in observing protocol
  - e.g., time of observation
- Transcription errors
- Invalid data (faulty instruments, unreliable observers)

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Virtue of Temperature Measurements

- Many stations
  - redundancy
- Three different data sets (land, ocean, upper-air)
- Multiple analysis methods by different groups
  - random errors tend to average out
  - systematic errors can be removed by calibration
  - estimated **uncertainty** with global temperature measurements: **currently 0.1°C** (more in the past)

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Constructing Global Temperature

- Groups like NASA, NOAA, and CRU have **two steps**:
  - **homogenization:** remove irregularities in individual stations due to changes in observing practices, station environment, or other non-meteorological factors
    - e.g., urban stations are removed
  - **filling data gaps** and **combining fragmented record**
  - these steps are well documented
- You can download raw weather station data from the "World Monthly Surface Station Climatology"
  - http://rda.ucar.edu/datasets/ds570.0/

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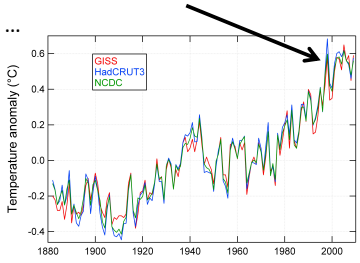
Constructing Global Temperature

- Centers have **different procedures** for **homogenization** and for **filling in gaps** where there's no data
- Notice how there are some differences among centers?
- Let's discuss why …



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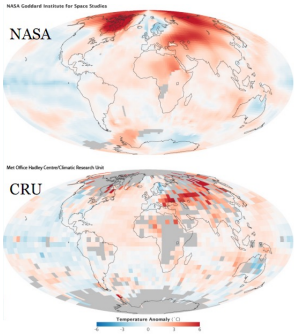
Constructing Global Temperature

- CRU and NOAA **don't include** the Arctic Ocean and other regions where there's no data
- NASA **fills** these points with the nearest station
- So, CRU and NOAA are not including locations that clearly warm the fastest!
- But that's their procedure & they're sticking to it …



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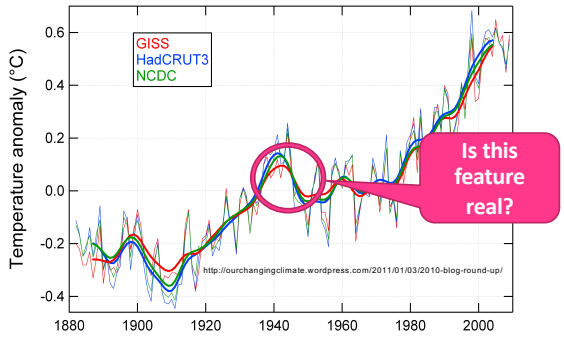
Surface Air Temperatures



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nature
Vol 453|29 May 2008|doi:10.1038/nature06982

LETTERS

A large discontinuity in the mid-twentieth century in observed global-mean surface temperature

David W. J. Thompson[1], John J. Kennedy[2], John M. Wallace[3] & Phil D. Jones[4]

Data sets used to monitor the Earth's climate indicate that the surface of the Earth warmed from ~1910 to 1940, cooled slightly from ~1940 to 1970, and then warmed markedly from ~1970 onward[1]. The weak cooling apparent in the middle part of the century has been interpreted in the context of a variety of physical factors, such as atmosphere–ocean interactions and anthropogenic emissions of sulphate aerosols[2]. Here we call attention to a previously overlooked discontinuity in the record at 1945, which is a prominent feature of the cooling trend in the mid-twentieth century. The discontinuity is evident in published versions of the global-mean temperature time series[1], but stands out more clearly after the data are filtered for the effects of internal climate variability. We argue that the abrupt temperature drop of ~0.3 °C in 1945 is the apparent result of uncorrected instrumental biases in the sea surface temperature record. Corrections for the discontinuity are expected to alter the character of mid-twentieth century temperature variability but not estimates of the century-long trend in global-mean temperatures.

The time series of global-mean surface temperatures (T_G) reflects the cooling of the ocean, and the global-mean temperature for that month is anomalously high. Months with abnormally weak surface westerlies are marked by global-mean temperature anomalies in the opposite sense. The calculation of the COWL pattern and its associated index time series is described in Methods. The COWL index time series (T_{COWL}) accounts for a substantial amount of the month-to-month weather-related 'noise' in T_G but also has weak secular variability due in part to trends in the atmospheric circulation (Fig. 1).

The influences of ENSO and the COWL pattern on surface temperatures were removed by subtracting the linearly fitted T_{ENSO} and T_{COWL} index time series from T_G (Methods). The resulting residual global-mean temperature time series ($T_G^{residual}$) is shown at the bottom of Figs 1 and 2. Filtering out ENSO and the COWL pattern reduces substantially the amount of interannual and month-to-month variance in T_G without reducing its temporal resolution. Consequently, the residual time series provides a cleaner rendition of the interdecadal variability in the time series of twentieth-century global-mean temperatures while retaining and increasing the prominence of numerous discrete drops in it. Most of the more prominent drops that are apparent in $T_G^{residual}$ coincide with large tropical

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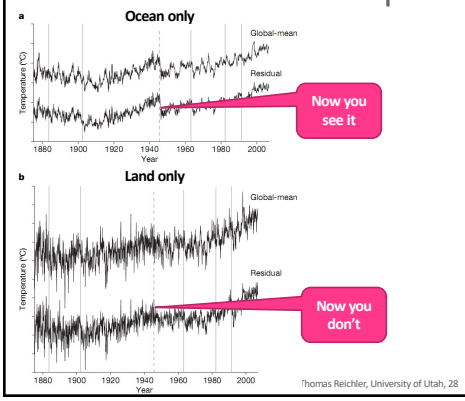
Land vs. Ocean Temperatures



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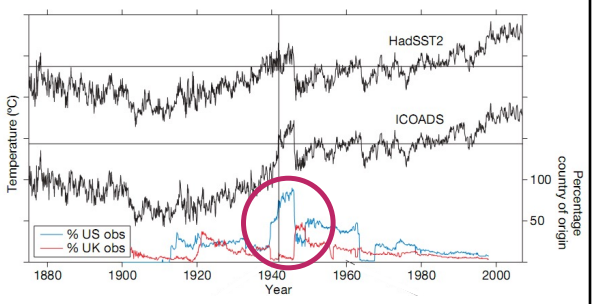
Ocean Observations by Country



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Reason for Discontinuity

- US ships mostly used engine room intake measurements
  - these are biased slightly warm
- UK ships mostly used un-insulated bucket measurements
  - these are biased slightly cold
- **Switch from mostly US ships** during the war **to a lot more UK ships** after the war led to the false increase and drop in temperature
- Groups are working on correcting this now

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Upper-Air Temperatures - Radiosondes

- Radiosondes / weather balloons
  - from fixed locations, fly up to 30 km altitude
  - since 1946
  - e.g., Sippican Mark IIA
    - measures: temperature, humidity, and pressure
    - equipped with GPS receiver to determine location of the radiosonde
      - this information is used to calculate the wind (speed and direction) during the ascent

- temperature sensor is on wire, humidity sensor is inside
- radio transmitter sends the data to the office

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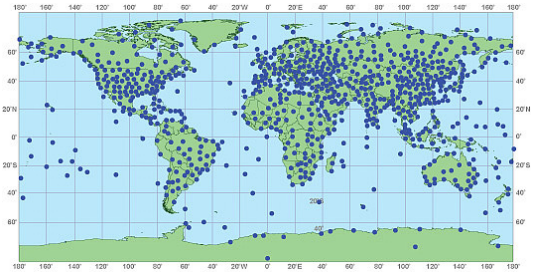
Global Radiosonde Network

- Many regions of the Earth are unobserved, in particular the oceans (which cover 70% of Earth):



https://www.weather.gov/jetstream/radiosondes

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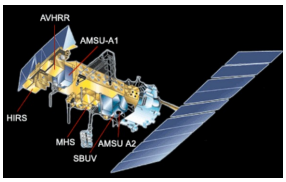
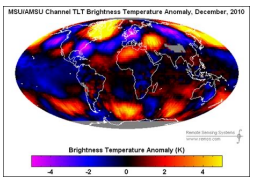
Upper-Air Temperatures - Satellites

- Satellites
  - microwave sounding unit (MSU): since 1979
  - works like an infrared thermometer
  - multiple wavelength channels give temperatures at different heights (lower stratosphere, upper and lower troposphere)
  - global coverage twice daily





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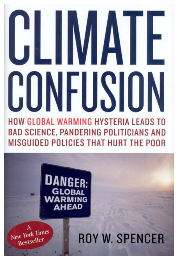
Upper-Air Warming: UAH

- UAH: University Alabama in Huntsville
- Prior to 2001, global warming skeptics Roy Spencer (NASA) and John Christy (UAH) were the sole producers of the MSU satellite estimates

Roy Spencer, formerly NASA



John Christy, University of Alabama-Huntsville

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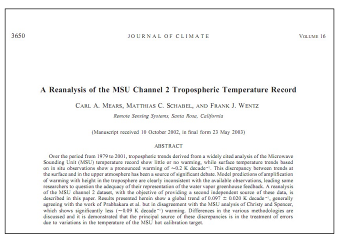
Upper-Air Warming Controversy

- But in 2003, another group (RSS) made an independent analysis of the MSU data
- The study **found errors** in Christy and Spencer's work and corrected it



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A Reanalysis of the MSU Channel 2 Tropospheric Temperature Record

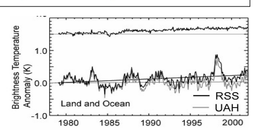
CARL A. MEARS, MATTHIAS C. SCHABEL, AND FRANK J. WENTZ

Remote Sensing Systems, Santa Rosa, California

(Manuscript received 10 October 2002, in final form 23 May 2003)

ABSTRACT

Over the period from 1979 to 2001, tropospheric trends derived from a widely cited analysis of the Microwave Sounding Unit (MSU) temperature record show little or no warming, while surface temperature trends based on in situ observations show a pronounced warming of ~0.2 K decade^{-1}. This discrepancy between trends at the surface and in the upper atmosphere has been a source of significant debate. Model predictions of amplification of warming with height in the troposphere are clearly inconsistent with the available observations, leading some researchers to question the adequacy of their representation of the water vapor greenhouse feedback. A reanalysis of the MSU channel 2 dataset, with the objective of providing a second independent source of these data, is described in this paper. Results presented herein show a global trend of 0.097 ± 0.020 K decade^{-1}, generally agreeing with the work of Prabhakara et al. but in disagreement with the MSU analysis of Christy and Spencer, which shows significantly less (~0.09 K decade^{-1}) warming. Differences in the various methodologies are discussed and it is demonstrated that the principal source of these discrepancies is in the treatment of errors due to variations in the temperature of the MSU hot calibration target.



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RSS Upper-Air Warming

- The RSS team now offers an independent estimate of trends and shows significant upper-air warming
- 1979-2009 upper-air trend: warming almost everywhere

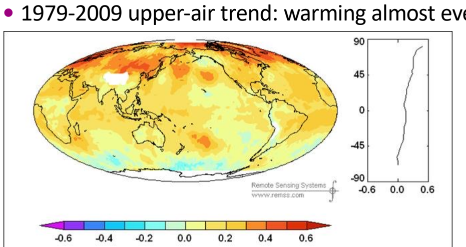

Figure 3. Color coded map of decadal trends in MSU channel TLT (1979 - 2009). Data poleward of 82.5° North and 70° South, as well as areas with land or ice elevations above 3000 meters, are not available and are shown in white.

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Homework

- HW8 (feedbacks) due today
- HW9 (past temperatures) posted today, due 3/15

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Global Temperature Rise

- Analysis of the five global temperature time series
  - surface data and upper-air data show very similar global-average warming
  - this is consistent with what is expected from human-induced global warming
- Evidence of 20th-century global warming is unequivocal

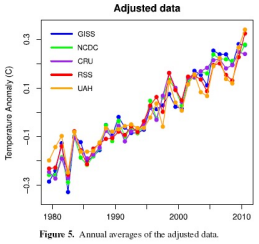

Figure 5. Annual averages of the adjusted data.

Foster and Rahmstorf (2011)

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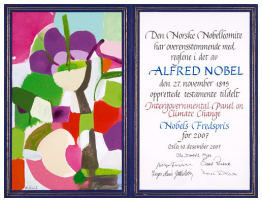
What is the IPCC?

- Intergovernmental Panel on Climate Change
- Scientific body of the UN
- Produces reports to understand the scientific basis of climate change
- No own original research; assessment are solely based on published literature
- Nobel Peace Prize 2007 was awarded jointly to the IPCC and former Vice President Al Gore



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The 6th Climate Assessment Report

- AR6 was just recently released (Fall 2021)

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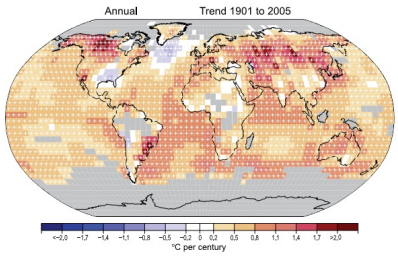
Is the Warming Global?

- Yes, although enhanced over land at high latitudes (as expected)

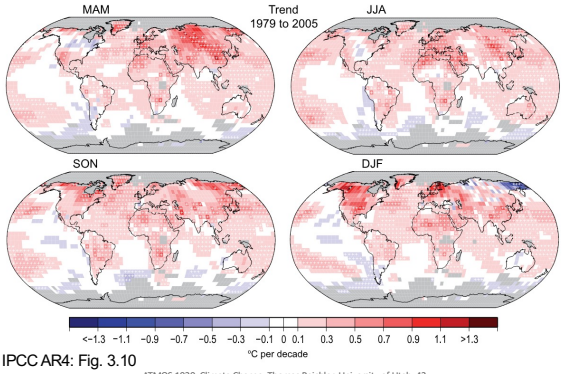
IPCC AR4: Fig. 3.9



Trends significant at the 5% level are indicated by white + marks, grey indicates areas with incomplete data

41

Consistency With Season



IPCC AR4: Fig. 3.10

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Warming Extends Above Surface

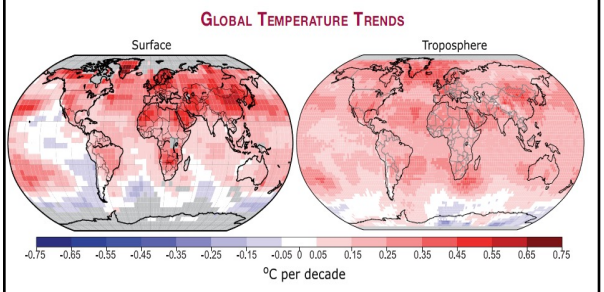

Figure TS.6. *(Top) Patterns of linear global temperature trends over the period 1979 to 2005 estimated at the surface (left), and for the troposphere from satellite records (right). Grey indicates areas with incomplete data.*

IPCC AR4: Fig. TS.6

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Other Signs of Global Warming

- Consistency across observations
  - melting mountain **glaciers**
  - decrease in winter **snow cover**
  - increasing atmospheric **water vapor**
  - warming at the **surface**
  - warming in the **troposphere**
  - warming of global **oceans**
  - warming below **ground** (bore holes)
  - rising **sea level** (due to warming and land-ice melt)
  - timing of **seasonal events**: e.g. earlier thaws, later frosts
  - thinning and disappearing Arctic **sea ice**
  - species **range shifts** (poleward and upward)
- Each of these data sets can be questioned to some extent
- However, the **totality of evidence** of global warming **is convincing**

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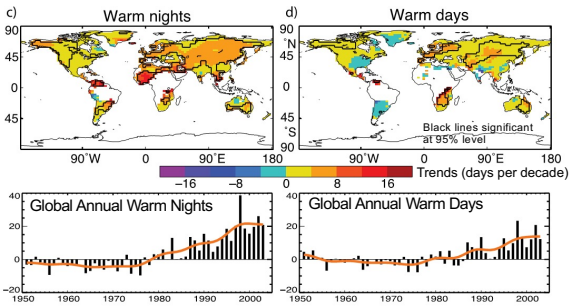
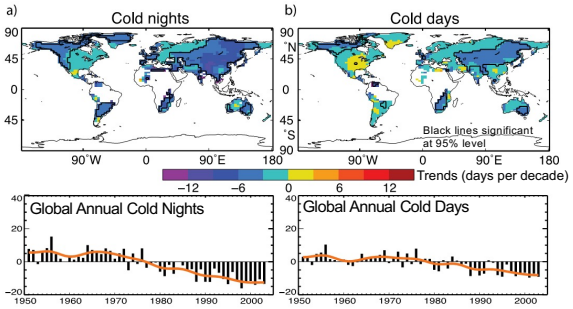
Increasing Warmth …



IPCC AR4: FAQ. 3.3, Figure 1: Observed trends (days per decade) (1951-2003) in frequency of extreme temperatures, based on 1961 to 1990 values, as maps for the **90th percentile**: (c) warm nights and (d) warm days

45

… & Decreasing Cold



IPCC AR4: FAQ. 3.3, Figure 1: Observed trends (days per decade) (1951-2003) in frequency of extreme temperatures, based on 1961 to 1990 values, as maps for the **10th percentile**: (a) cold nights and (b) cold days

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Diurnal Temperature Range

- **Nights warm faster** than days
  - this decreases the diurnal temperature range
- Very likely a consequence of climate change
- Possible mechanism?
  1. cloudiness increase
     - warming during night b/c greenhouse effect
     - cooling during day b/c solar reflection
  2. aerosol increase
     - cooling only during day because it requires sun light

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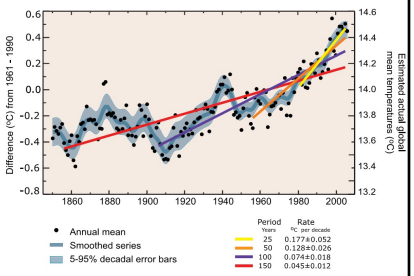
Accelerated Warming

- Trend analysis reveals accelerated warming
- Linear trends
  - last 25 (yellow)
  - 50 (orange)
  - 100 (magenta)
  - 150 years (red)



IPCC AR4: Fig. TS.6

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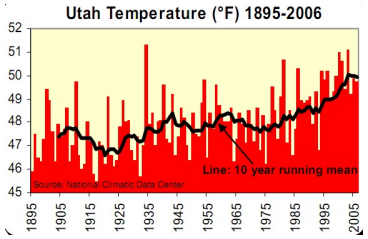
Past Warming in Utah

- Temperature increase in Utah amounts to about **2°F** over the past 100 years



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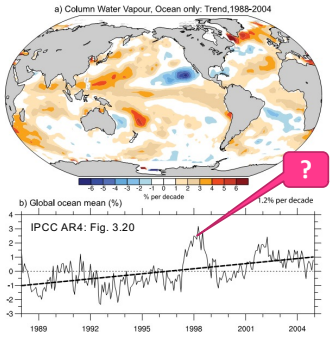
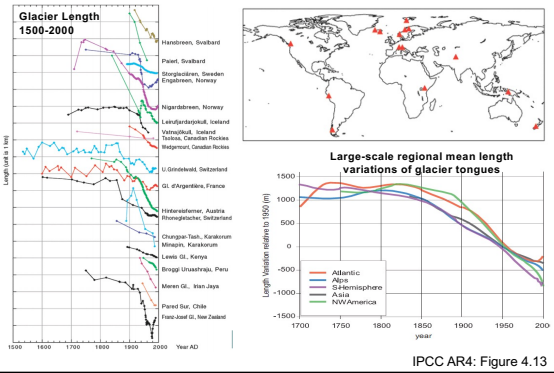
Increasing Water Vapor

- Top: linear **trends** in water vapor (total column) in % per decade
- Bottom: monthly **time series** of water vapor anomalies relative to 1988-2004 in % over the global ocean plus linear trend



50

Global Shrinkage of Glaciers



IPCC AR4: Figure 4.13

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Northern Hemisphere Snow Cover

- Snow cover has **decreased** by 7.5% since 1922
- Yellow shading shows uncertainty

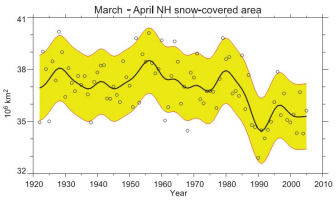

Figure 4.2. *Update of NH March–April average snow-covered area (SCA) from Brown (2000). Values of SCA before 1972 are based on the station-derived snow cover index of Brown (2000); values beginning in 1972 are from the NOAA satellite data set. The smooth curve shows decadal variations (see Appendix 3.A), and the shaded area shows the 5 to 95% range of the data estimated after first subtracting the smooth curve.*

IPCC AR4: Figure 4.2

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Detection and Attribution

- **Detection**: Determine whether a change is **unusual** or whether it is within the normal ups and downs.
- **Attribution**: Determine the **cause** of a change. Are humans to blame or something else?
  - climate modelling can be used to attribute global warming to human activity

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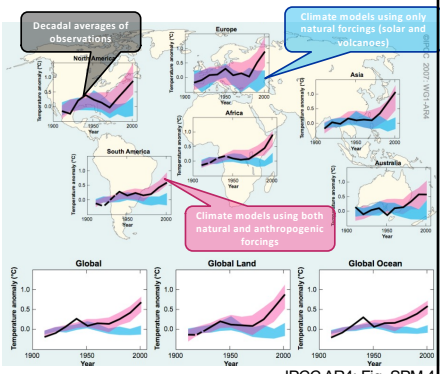
Who is to Blame?

- Shown are temperature simulations from climate models for the past 100 yrs
- Climate models reproduce past warming only when forced with both natural and anthropogenic forcings



IPCC AR4: Fig. SPM 4

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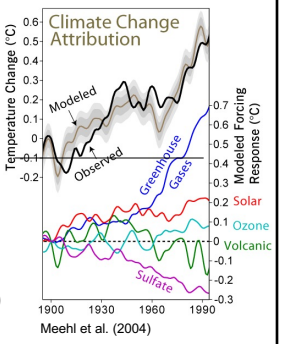
More Attribution

- This is from one model only
- The model has been run several times, with one forcing factor at a time
- Temperature change can be decomposed into various factors
- The pause in warming from ~1950-1980 is consistent with natural (volcanoes & solar) and human (sulfate aerosol & ozone) forcings
- The warming trend can only be explained (and is consistent with) human induced increases in greenhouse gases



Meehl et al. (2004)

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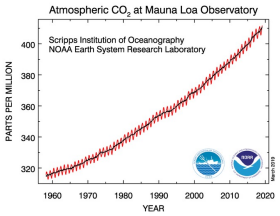
Another Important Record: CO_2

- CO_2 monitored accurately at Mauna Loa since 1958
- That **CO_2 is rising rapidly due to human activity** is equally important as the temperature rise in the whole big picture of global warming



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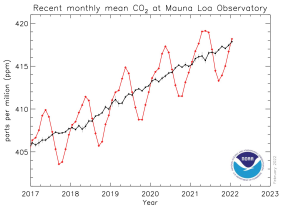
Mauna Loa Record

- First reading in 1958: **316** ppm
- Most recent reading (January 2021): **418** ppm
- Why Mauna Loa?
  - high mountain is away from near-surface variations
  - Hawaii gets clean ocean air most of the time



http://www.esrl.noaa.gov/gmd/ccgg/trends/

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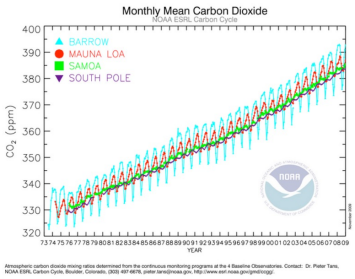
Carbon Dioxide at Other Sites

- Other sites agree with Mauna Loa, but with different seasonality
- Seasonality is due to the growth of **vegetation** during summer, decay during winter
- **May** has the highest CO_2 concentration in the NH



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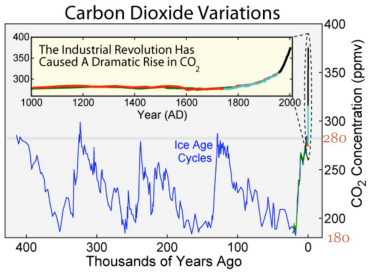
Connection to Paleoclimate

- We also know CO_2 levels are higher than they've been in several hundred thousand years
- **Natural variation** over Ice Age Cycles: **180-280 ppm**



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Evidence of Anthropogenic Rise

- Comparisons with industrial fossil fuel usage and deforestation rates show emissions are larger than atmospheric increase
  - **55%** of emissions go into the ocean or terrestrial biosphere
  - only 45% stay in the atmosphere
- But how do we know that the CO_2 emissions are due to human activity?
  - for example, it could be that outgassing from the ocean is to blame
- As with the temperature record, there is complementary evidence for anthropogenic causes of CO_2 rise as well
  - two independent pieces of evidence …

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Evidence I

- Concentrations of **oxygen** have been **decreasing**
- Oxygen is used up when fossil fuels/forests are burned
- If exchange with the ocean was the culprit for CO_2 increase, O_2 levels would have stayed the same

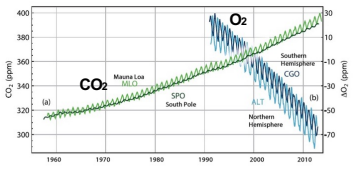

Figure 1: The diagram above shows concentrations of carbon dioxide and oxygen in the atmosphere. Atmospheric concentration of a) carbon dioxide in parts per million by volume from Mauna Loa (MLO, light green) in the northern Hemisphere and the South Pole (SPO, dark green) and of b) changes in the atmospheric concentration of O_2 from the northern hemisphere (ALT, light blue) and the southern hemisphere (CGO, dark blue).

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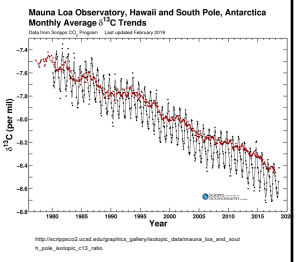
Evidence II

- Anthropogenic emissions also have different isotope concentrations
- **Isotope**: have different number of neutrons in the atom, so different weight
- Carbon isotopes: C^{12}, C^{13}, C^{14}
- **Plants** use **more C^{12}** than C^{13} as compared to the atmosphere
  - burning fossil fuels releases extra **C^{12}** and decreases the relative amount of **C^{13}** (= C^{13} fraction)
  - **C^{13} fraction** has been actually observed to **decrease,** indicating burning of former plant material is the reason



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Summary

- Definitely not perfect temperature data
  - not fully global coverage (even now, except for satellites)
  - changes in station sites in the past
  - instrument changes (e.g., bucket vs. intake on ships)
- On the other hand…
  - lots of overlapping nearby stations
  - data over land, ocean, upper air give different perspectives

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Other Records

- Consistency of other records gives added confidence that significant global warming is occurring
  - glaciers melting
  - sea ice disappearing
  - rising sea levels
  - water vapor increasing
  - oceans warming

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In the News

- Leonardo Di Caprio: Oscar for Best Actor at the 2016 Academy Awards

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Extra Slides

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Recent Hiatus in Global Warming

- During the 2000s global temperatures have risen more slowly than before
- New ice age?
- A combination of reasons!

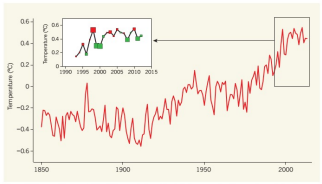

Figure 1 | Temperature evolution. The graph shows the global mean surface temperature relative to the 1961–90 mean, based on the HadCRUT4.2.0.0 data set[18]. The inset shows the 1993–2012 time span, with green denoting La Niña years and red, El Niño years; the size of the symbol indicates the strength of La Niña/El Niño according to the Ocean Niño Index[19]. (The Niño index for year N is computed by averaging from October of year N−1 to September of year N to account for the lag between the El Niño–Southern Oscillation and global mean temperature.) Kosaka and Xie[5] argue that a cooling trend in a region covering only about 8% of Earth's surface in the eastern equatorial Pacific, a trend associated with a preponderance of La Niña events, explains the absence of global mean warming over the most recent decade.

http://www.nature.com/nature/journal/v501/n7467/pdf/501318a.pdf

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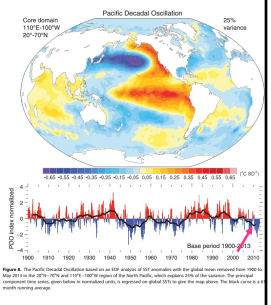
Some Cool Forcing Factors

- External forcings
  - increased aerosols by volcanoes and Chinese power plants
  - decrease of CFCs
  - deep and long solar minimum (2010)
- Natural variability
  - predominance of cold La Niña conditions
  - natural decadal variability, related to the negative phase of the Pacific Decadal Oscillation (PDO); can last 20 years
    - during La Nina and cold PDO, more heat is stored in deeper parts of ocean, leading to less surface warming
- Arctic data gap
  - lack of Arctic data, where warming is strongest



http://onlinelibrary.wiley.com/doi/10.1002/2013EF000165/full

http://www.realclimate.org/index.php/archives/2013/12/the-global-temperature-jigsaw/

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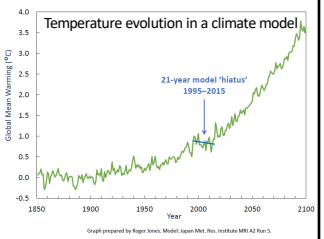
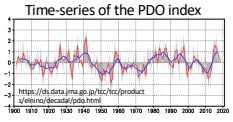
Likely Reasons for Slowed Warming

- Hiatus was short; not a trend
- Due to natural variability and some "cool forcing factors"
- Global warming has not stopped; it is merely manifested in different ways, not just surface warming
  - satellites show difference between amount of sunlight absorbed and longwave energy emitted is greater now (2000-2012) than before (1985-1999) (Allen et al. 2014 GRL)
- There is no reason to expect less warming in the future
  - warming will accelerate when PDO becomes positive and/or next El Nino will happen
- Indeed, last four years were warmest on record





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Rain From Very Wet Days

- A larger % of the rainfall is falling on the wettest days:
  - Top: observed trends in the contribution to total annual precipitation from very wet days
  - Bottom: % change of contribution from very wet days