Lecture 29: Observed Climate Variability and Change

1. Introduction

This chapter focuses on 6 questions -

- Has the climate warmed?
- Has the climate become wetter?
- Are the atmosphere/ocean circulations changing?
- Has the climate become more variable or extreme?
- Is the 20th century warming unusual?
- Are the observed trends internally consistent?

The answers to these questions critically depend on the availability of accurate, complete and consistent series of observations. If conclusions regarding trends cannot always be drawn, it does not necessarily mean that the trends are absent!

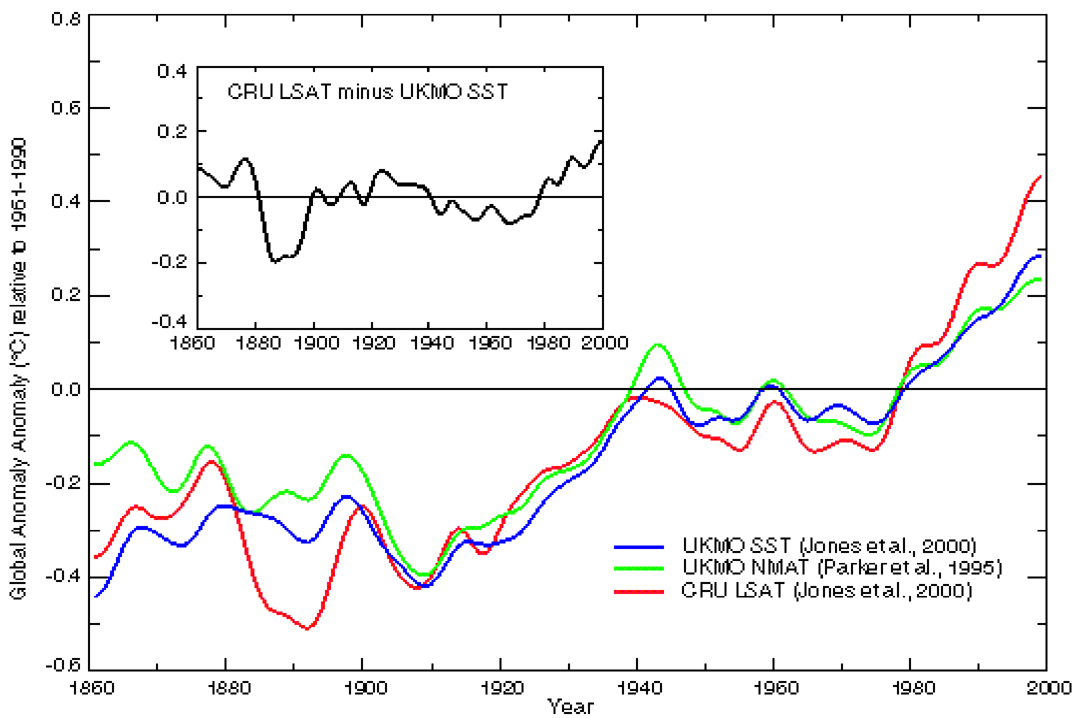
2. Has the Climate Warmed?

2.A. Land And Sea Surface Temperatures Combined

The figure summarises the relative changes of U.K. Met Office (UKMO) Sea Surface Temperature (SST), UKMO Night Marine Air Temperature (NMAT) and Climate Research Unit (CRU at University of East Anglia in the U.K.) land surface air temperature. The greater warming of the land in recent years is clear, but otherwise all three curves have a generally similar shape except that modest cooling of NMAT in the late nineteenth century is not seen in the SST data.

- The global trend from 1861 to 1999 can be cautiously interpreted as an equivalent linear warming of 0.6C over the 139-year period, with a 95% confidence level uncertainty of +/-0.15C.

- From 1901 an equivalent warming of 0.57C has occurred, with an uncertainty of +/-0.18C.



2.B. Spatial Distribution of Surface Temperature Trends

Most of the warming of the 20th century occurred in two distinct periods separated by several decades of little overall globally averaged change. The figure highlights the worldwide behavior of temperature change in the three periods. These linear trends have been calculated from a gridded combination of UKMO SST and CRU temperatures. The periods chosen are 1910-1945 (first warming period), 1946-1975 (period of little global temperature change), 1976-1999 (second warming period, where all four seasons are shown in Figure 3) and the 20th century, 1901-1999.

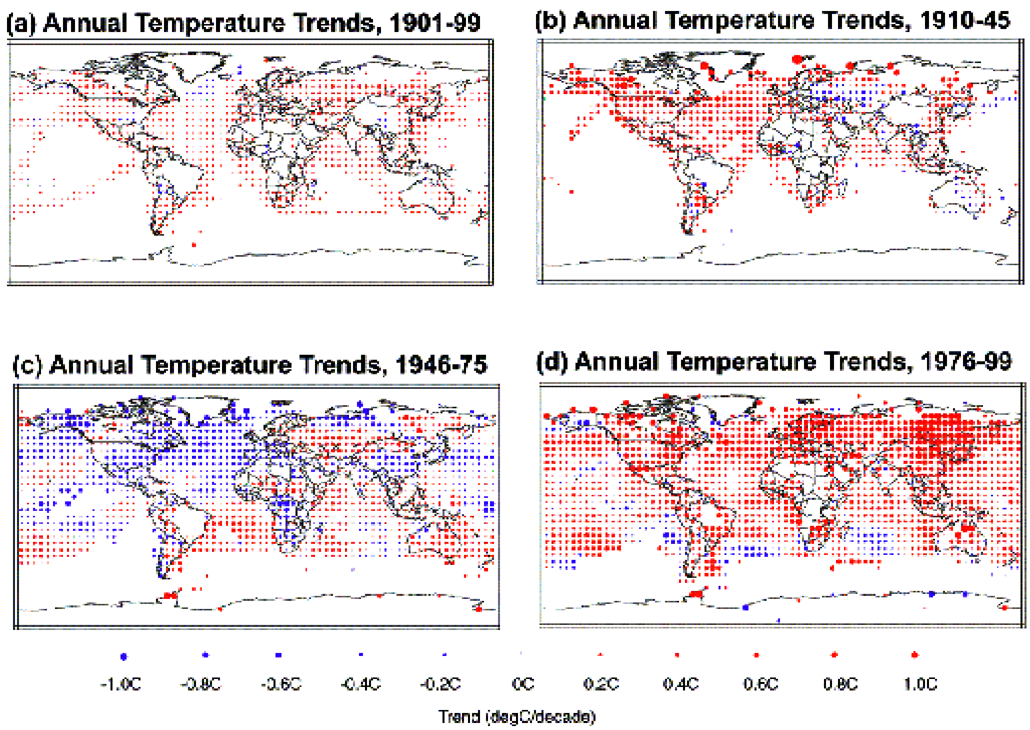
- It can be seen that there is a high degree of local consistency between the SST and land air temperature across the land-ocean boundary, noting that the corrections to SST are independent of the land data.

- The 1910-1945 warming was greatest in, but not limited to, the North Atlantic, Arctic and northern North America.

- By contrast, the period 1946-1975 shows widespread cooling in the Northern Hemisphere relative to much of the Southern. Much of the cooling was seen in the Northern Hemisphere regions that showed most warming in 1910-1945.

• In accord with the results in Inter-governmental Panel on Climate Change (IPCC)-1995, recent warming has been greatest over the mid latitude Northern Hemisphere continents in winter.

• Over 1901-99 as a whole, warming is seen everywhere except south of Greenland and in a few scattered continental regions in the tropics or subtropics. Faster warming of the land surface temperature than the ocean surface temperature in the last two decades could in part be a signal of anthropogenic warming.

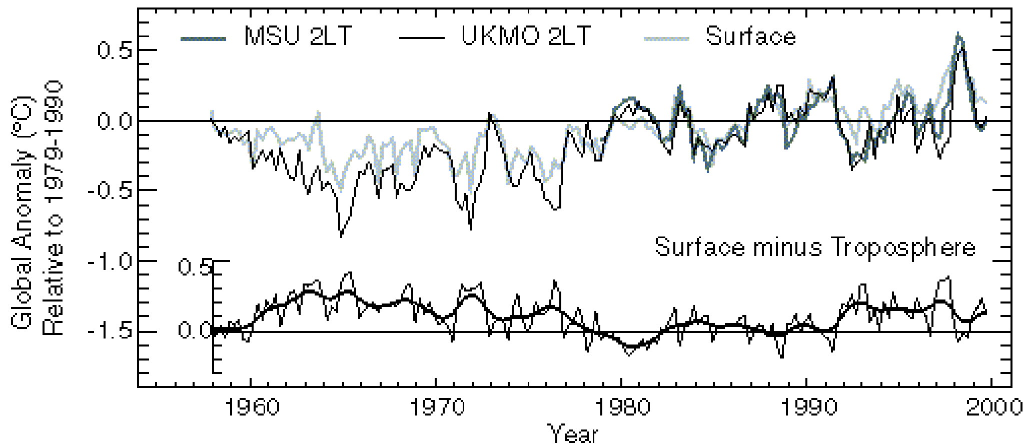


We conclude that in the twentieth century we have seen a consistent large-scale warming of the land and ocean surface. Some regional details can be explained from accompanying atmospheric circulation changes.

2.C. Trends in Tropospheric Temperature

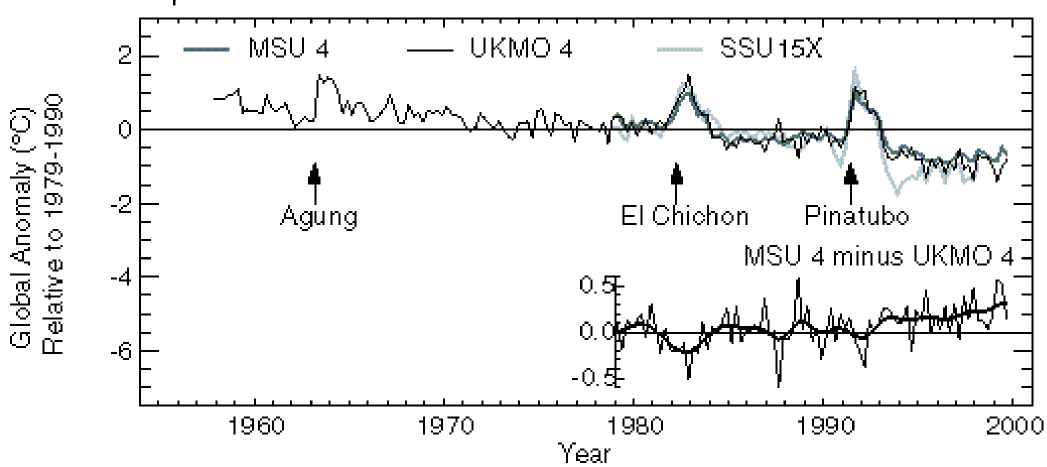
The surface, tropospheric and stratospheric temperature variations since 1958 using representative data sets are shown in the figure below. Especially consistent is the relative shift to warmer temperatures in the troposphere compared to the surface around 1977, followed by large variations due to ENSO (particularly in 1998) and volcanic events (El Chichon in 1982 and Mt. Pinatubo in 1991).

a) Troposphere and Surface



Global variations and trends in the lower stratosphere are temporally more coherent than in the troposphere (see the figure below). The warming effects due to the volcanic eruptions are clearly evident. All stratospheric data sets indicate significant negative trends. Blended information for 5 km thick levels in the stratosphere at 45N show a negative trend temperature increasing with height: -0.5C/decade at 15 km, -0.8C/decade at 20-35 km, and -2.5C/decade at 50 km. These large, negative trends are consistent with models of the combined effects of ozone depletion and increased concentrations of infrared radiating gases, mainly water vapor and carbon dioxide.

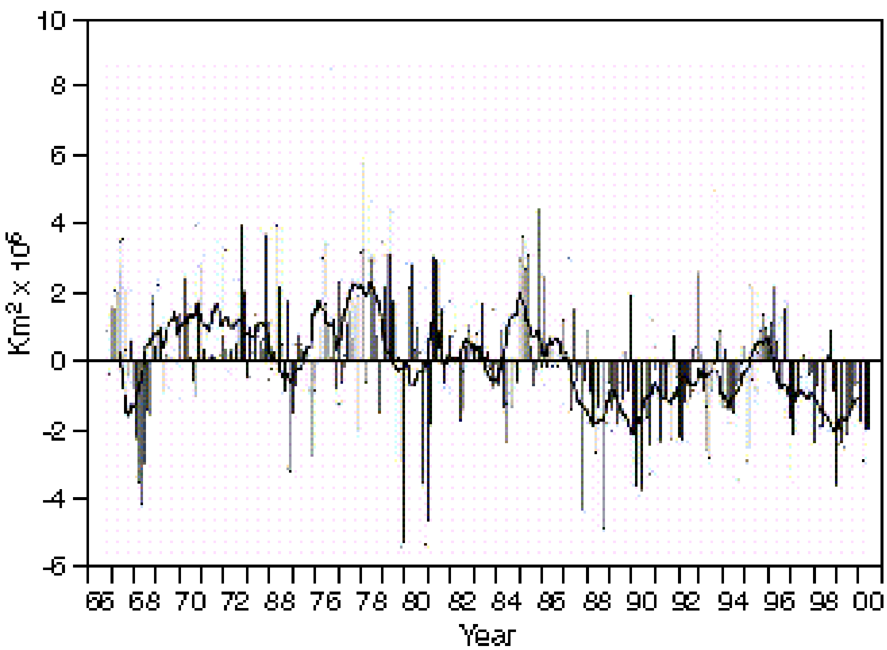
b) Lower Stratosphere



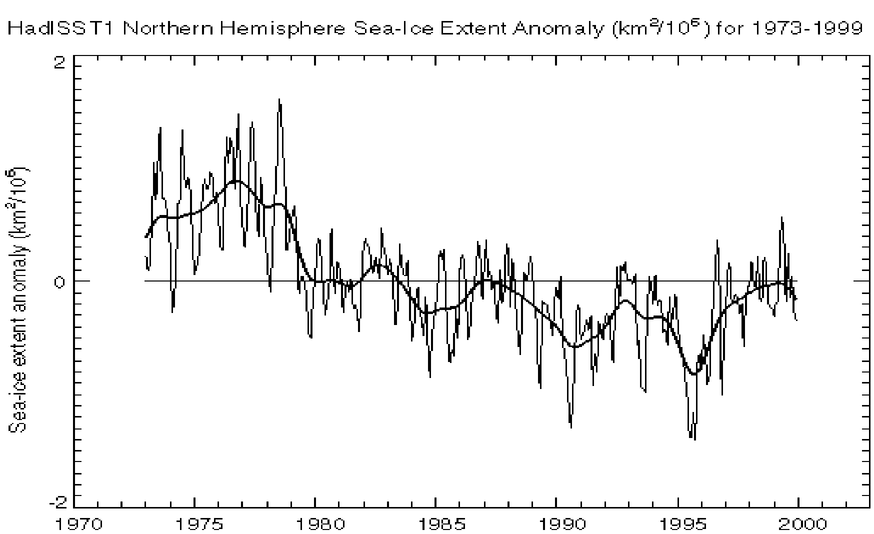
It is very likely that the surface has warmed relative to the troposphere, and the troposphere has warmed relative to the stratosphere since 1979. There is evidence that the troposphere warmed relative to the surface in the pre-satellite era (1958-1979), though confidence in this finding is lower.

2.D. Changes in the Cryosphere

- *Snow cover*: Satellite records indicate that Northern Hemisphere annual snow cover extent (SCE) has decreased by about 10% since 1966 largely due to decreases in spring and summer since the mid-1980s over both the Eurasian and American continents (figure below)



- *Sea-ice extent*: During November 1978 through December 2000, the sea ice extent over the Northern Hemisphere showed a decrease of -2.8% +/- 0.3% per decade (figure below). Related to the decline in sea ice extent is a decrease in the length of the sea ice season and an increase in the length of the Arctic summer melting season.



• *Lakes and river ice*: A recent analysis has been made of trends in very long Northern Hemisphere lake and river ice records over the 150-year period 1846-1995. Ice break-up dates now occur on average about nine days earlier in the spring than at the beginning of the record, and autumn freeze-up occurs on average about ten days later.

• *Glaciers*: The general picture is one of widespread retreat. In a few regions a considerable number of glaciers are currently advancing very likely due to increases in precipitation due to the positive phase of the North Atlantic Oscillation.

2.E. Summary

• Global surface temperatures have increased between 0.4 and 0.8C since the late 19th century, but most of this increase has occurred in two distinct periods, 1910-45 and since 1976.

• The rate of temperature increase since 1976 has been almost 0.2C per decade.

• New analyses of mean daily maximum and minimum temperatures continue to support a reduction in the diurnal temperature range with minimum temperatures increasing at about twice the rate of maximum temperatures.

• Seasonally, the greatest warming has occurred during the Northern Hemisphere winter and spring, but the disparity of warming between summer and winter has decreased.

• Largest rates of warming continue to be found in the middle and high latitude continental regions of the Northern Hemisphere.

• Analyses of overall temperature trends in the low to mid troposphere and near the surface since 1958 are in good agreement, with a warming of about 0.1C per decade.

• Since the beginning of the satellite record (1979), however, low to mid troposphere temperatures have warmed in both satellites and weather balloons at a global rate of only about 0.05 C/decade. This is about 0.15 C/decade less than the rate of temperature increase near the surface since 1979. About half of this difference in warming rate is very likely to be due to the combination of differences in spatial coverage and the real physical affects of volcanoes, ENSO. The remaining difference remains unexplained, but is likely to be real.

3. Has the Climate Become Wetter?

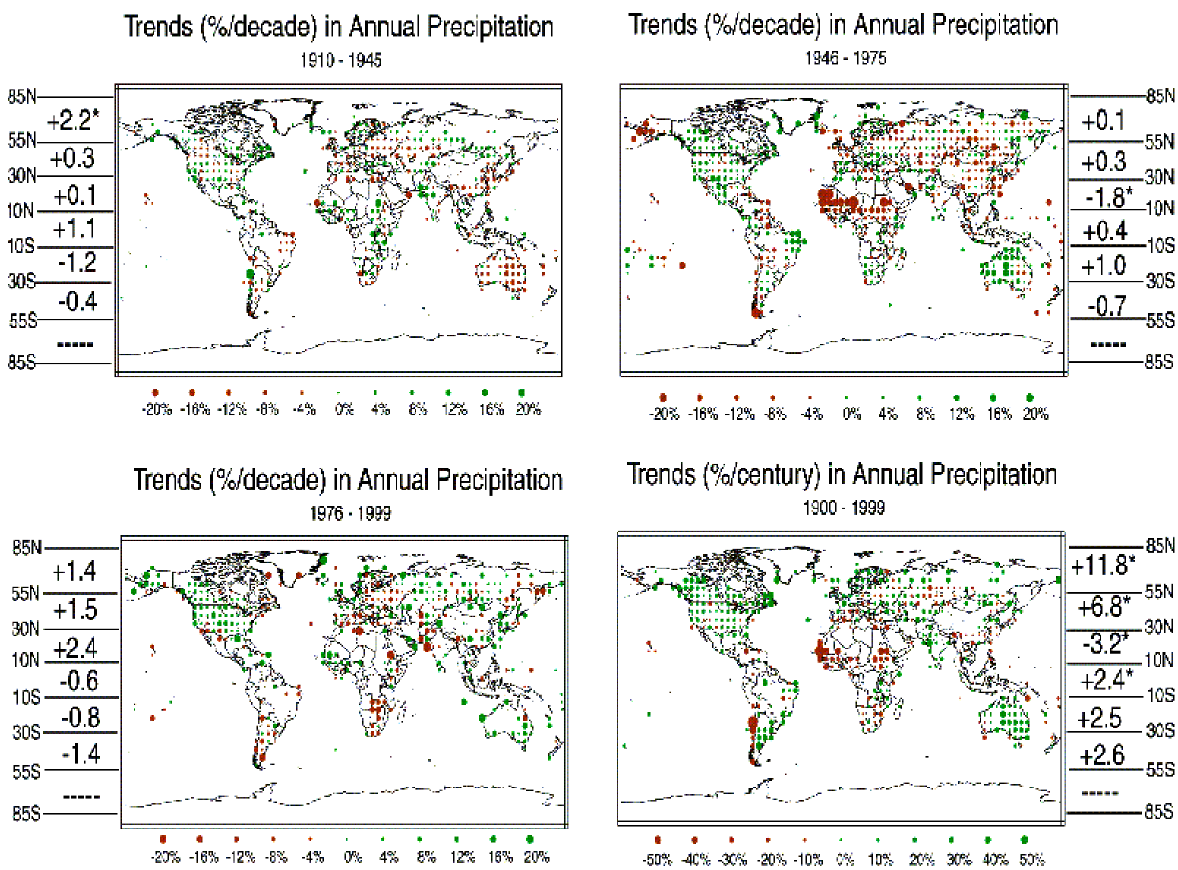
Increasing global surface temperatures are very likely to lead to changes in precipitation and atmospheric moisture because of changes in atmospheric circulation, a more active hydrologic cycle, and increases in the water holding capacity throughout the atmosphere.

Atmospheric water vapor is also a climatically critical greenhouse gas, and an important chemical constituent in the troposphere and stratosphere.

3.A. Land Precipitation

Overall, global land precipitation has increased by about 2% since the beginning of the 20th Century. The increase is statistically significant but has neither been spatially nor temporally uniform.

Mid and High Latitudes: During the 20th Century, annual-zonally averaged precipitation increased between 9% and 16% for the zones 30N to 85N and by about 2 to 5% between 0S to 55S during this time. The figure below shows mostly increasing precipitation in the Northern Hemisphere mid and high latitudes, especially during the autumn and winter, but these increases vary both spatially and temporally.



• Precipitation over the United States has increased between 5-10% since 1900 but this increase has been interrupted by multi-year anomalies like the drought years of the 1930s and early 1950s.

- Precipitation in Canada has increased by an average of more than 10% over the 20th Century.

- Over the last 50 years there has been a slight decrease in annual precipitation over China.

- There have been marked increases in precipitation in the latter part of the 20th Century over northern Europe.

- Precipitation has increased since 1891 by about 5% west of 90E, accompanied by increases in streamflow and a rise in the level of the Caspian Sea. Soil moisture data for large regions of Eurasia show large upward trends.

- Annual total rainfall has increased over much of Australia with significant increases of 15-20% in large areas.

Tropics and Sub-Tropics: The increase of precipitation in the middle and high latitudes contrasts with decreases in the northern subtropics.

- There is little evidence for a long-term trend in Indian monsoonal rainfall but there are multi-decadal variations.

- There has been a pattern of continued aridity since the late 1960s throughout North Africa south of the Sahara. The driest period was in the 1980s with some recovery occurring during the 1990s.

3.B. Ocean Precipitation

The strong spatial variability inherent in precipitation requires the use of estimates based on satellite observations for many regions. Thus satellite data are essential to infer global changes of precipitation, as the oceans account for 70% of the global surface area. The first satellite instrument specifically designed to make estimates of precipitation did not begin operation until 1987, but this record it is too short to draw conclusions.

3.C. Summary

- Since IPCC-1995, land surface precipitation has continued to increase in the Northern Hemisphere mid and high latitudes; over the subtropics, the drying trend has been ameliorated somewhat.

- Where data are available, changes in annual streamflow relate well to changes in total precipitation.

- Little can be said about changes in ocean precipitation as satellite data sets have not yet been adequately tested for time-dependent biases.

- Changes in water vapor have been analyzed most for selected Northern Hemisphere regions, and show an emerging pattern of surface and tropospheric water vapor increases over the past few decades.
- Over land, an increase in cloud cover of a few percent since the turn of the century is observed, which is shown to closely relate to changes in the diurnal temperature range.

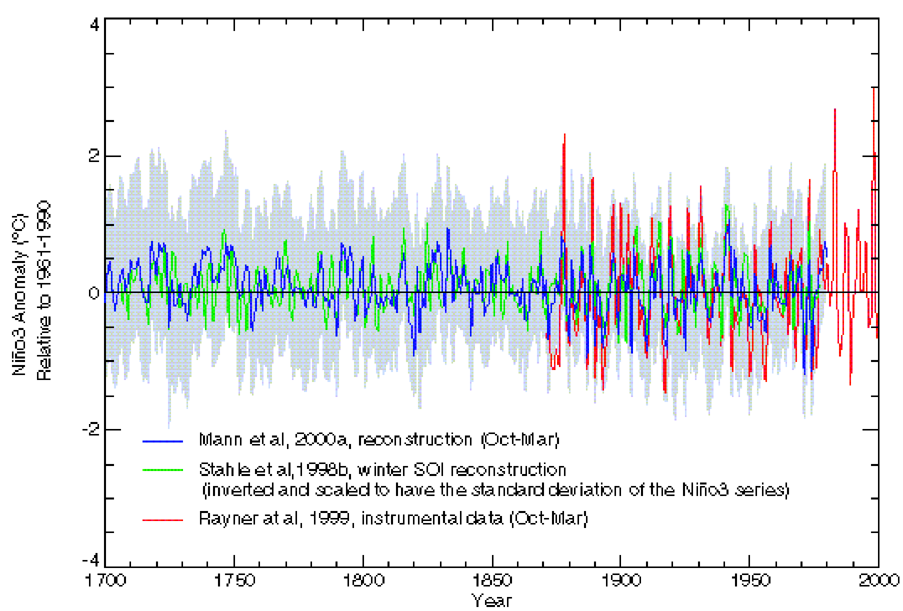
4. Are the Atmosphere/Ocean Circulations Changing?

Changes or fluctuations in atmospheric and oceanic circulation are important elements of climate. Such circulation changes are the main cause of variations in climate elements on a regional scale. El Nino Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) are such examples.

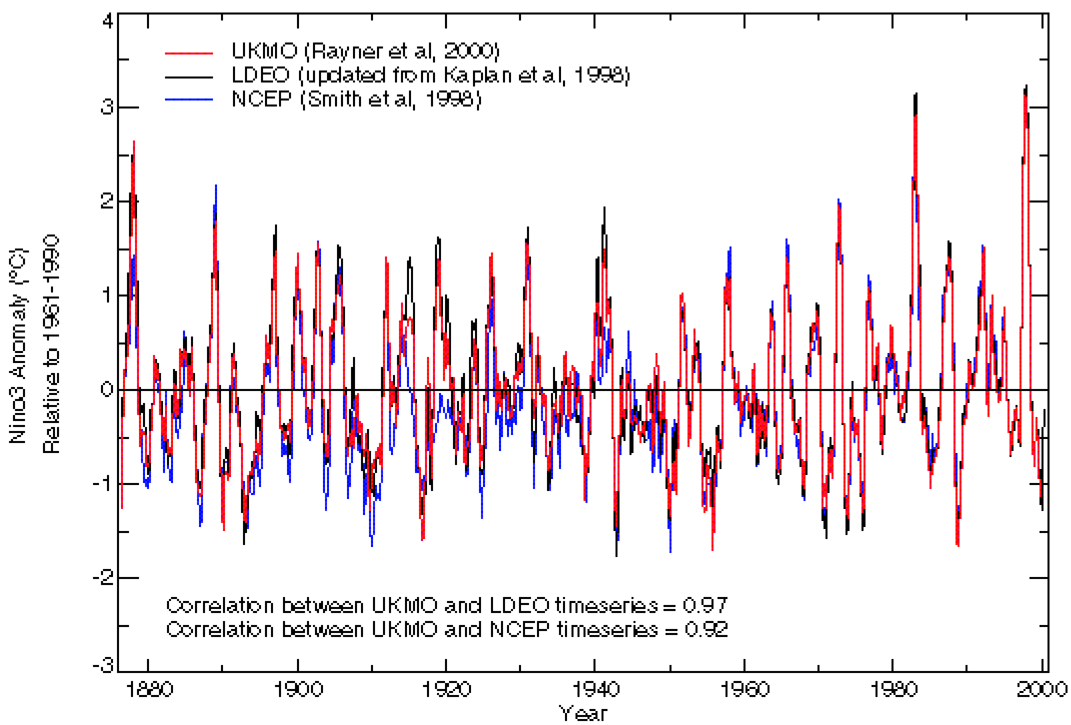
4.A. ENSO

ENSO is the primary global mode of climate variability in the 2-7 year time band. El Nino is defined by SST anomalies in the eastern tropical Pacific while the Southern Oscillation (SO) is a measure of the atmospheric circulation response in the Pacific-Indian Ocean region.

Multiproxy-based reconstructions of the behavior of ENSO have recently been attempted for the past few centuries. The figure below compares the behavior of two such reconstruction series with recent ENSO behavior. The two reconstructions, based on independent methods and partially independent data, have a linear correlation r=0.64 during the pre-calibration interval. While the estimated uncertainties in these reconstructed series are substantial, they suggest that the very large 1982-83 and 1997-98 warm events might be outside the range of variability of the past few centuries.



Instrumental records have been examined to search for possible changes in ENSO over the past 120 years. Three new reconstructions of SST in the eastern Equatorial Pacific (figure below) exhibit strong similarities. The dominant 2-6 year timescale in ENSO is apparent. Both the activity and periodicity of ENSO have varied considerably since 1871 with considerable irregularity in time. There was an apparent shift in the temperature of the tropical Pacific around 1976 to warmer conditions, discussed in IPCC-1995, which appeared to continue until at least 1998. During this period ENSO events were more frequent, intense or persistent. Whether global warming is influencing El Nino, especially given the remarkable El Nino of 1997-1998, is a key question, especially as El Nino affects global temperature itself.



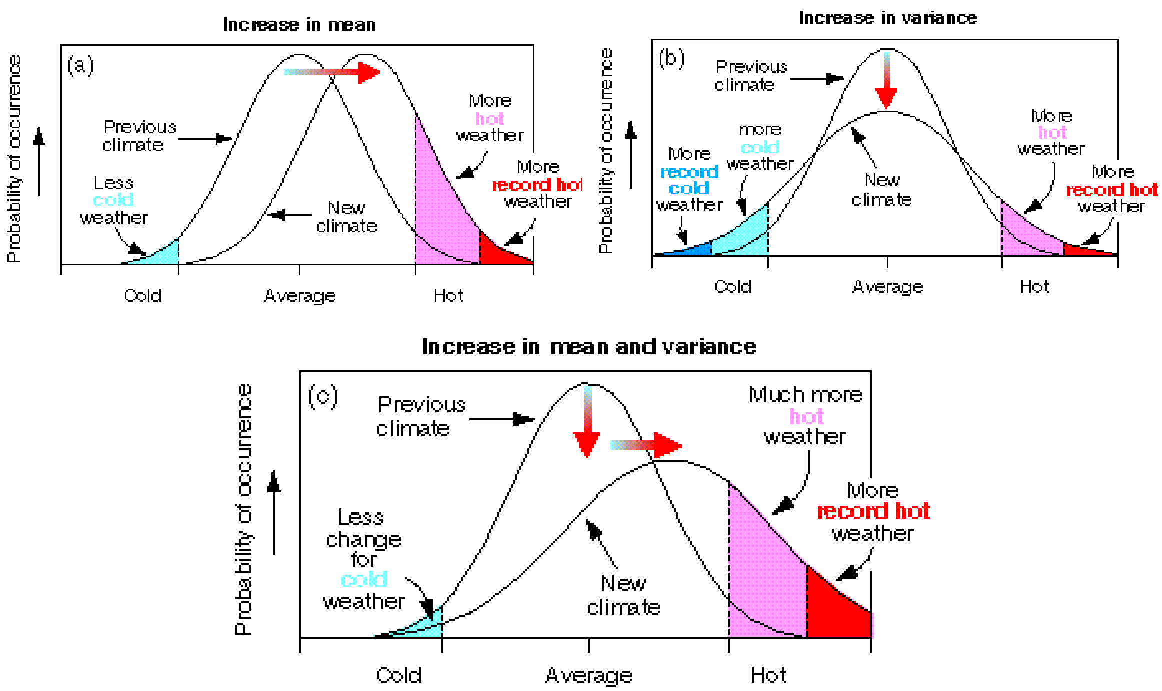
4.B. Summary

- The interannual variability of ENSO has varied substantially over the last century, with notably reduced variability during the period 1920-60, compared to adjacent periods.

- It remains unclear whether global warming has influenced the shift towards less frequent La Nina episodes since 1976, including the abnormally protracted ENSO 1990-95 event and the exceptionally strong 1982-83 and1997-98 events.

5. Has the Climate Become More Extreme or Variable?

Changes in climate variability and extremes of weather and climate events have received increased attention in the last few years. Understanding changes in climate variability and climate extremes is made difficult by interactions between the changes in the mean and variability. The distribution of temperatures often resembles a normal distribution. An increase in the mean leads to new record high temperatures (Panel A), but a change in the mean does not imply any change in variability. For example, in Panel A, the range between the hottest and coldest temperatures does not change. An increase in variability without a change in the mean implies an increase in the probability of both hot and cold extremes as well as the absolute value of the extremes (Panel B). Increases in both the mean and the variability are also possible (Panel C), which affects (in this example) the probability of hot and cold extremes, with more frequent hot events with more extreme high temperatures and fewer cold events.



• It is likely that there has been a widespread increase in heavy and extreme precipitation events in regions where total precipitation has increased, e.g., the mid and high latitudes of the Northern Hemisphere.

• Increases in the mean have often been found to be amplified in the highest precipitation rates total.

- In some regions, increases in heavy rainfall have been identified where the total precipitation has decreased or remained constant, such as eastern Asia. This is attributed to a decrease in the frequency of precipitation.

- New record high night-time minimum temperatures are lengthening the freeze-free season in many mid and high latitude regions.

- The increase of global temperatures has resulted mainly from a significant reduction in the frequency of much below-normal seasonal mean temperatures across much of the globe, with a corresponding but smaller increase in the frequency of much above normal temperatures.

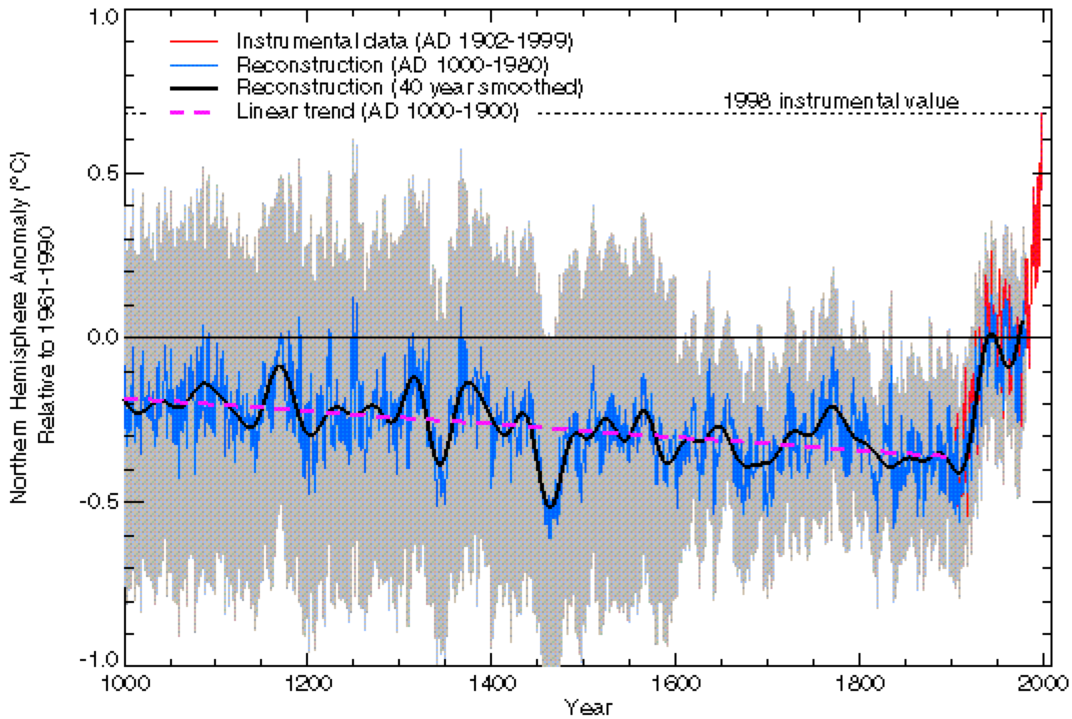
- There is little sign of long-term changes in tropical storm intensity and frequency.

6. Is the 20th Century Warming Unusual?

To determine whether 20th century warming is unusual, it is essential to place it in the context of longer-term climate variability. Owing to the sparseness of instrumental climate records prior to the 20th century (especially prior to the mid 19th century), estimates of global climate variability during past centuries must often rely upon indirect *proxy* indicators - natural or human documentary archives that record past climate variations, but must be calibrated against instrumental data for a meaningful climate interpretation.

Coarsely resolved climate trends over several centuries are evident in many regions e.g., from the recession of glaciers or the geothermal information provided by borehole measurements. Large-scale estimates of decadal, annual or seasonal climate variations in past centuries, however, must rely upon sources that resolve annual or seasonal climatic variations. Such proxy information includes width and density measurements from tree rings, layer thicknesses from laminated sediment cores, isotopes from ice cores and corals, etc.

There have been several attempts to combine various types of high-resolution proxy climate indicators to create large-scale paleoclimate reconstructions. Mann et al reconstructed global patterns of annual surface temperature several centuries back in time. They calibrated a combined terrestrial (tree ring, ice core, and historical documentary indicator) and marine (coral) multiproxy climate network against dominant patterns of 20th century global surface temperature. Averaging the reconstructed temperature patterns over the far more data-rich Northern Hemisphere half of the global domain, they estimated Northern Hemisphere mean temperature back to AD 1000 (figure below). The uncertainties (the shaded region in this figure) expand considerably in earlier centuries because of the sparse network of proxy data. Taking this into account, Mann et al concluded that the 1990s were likely to have been the warmest decade, and 1998 the warmest year, of the past millennium for at least the Northern Hemisphere.



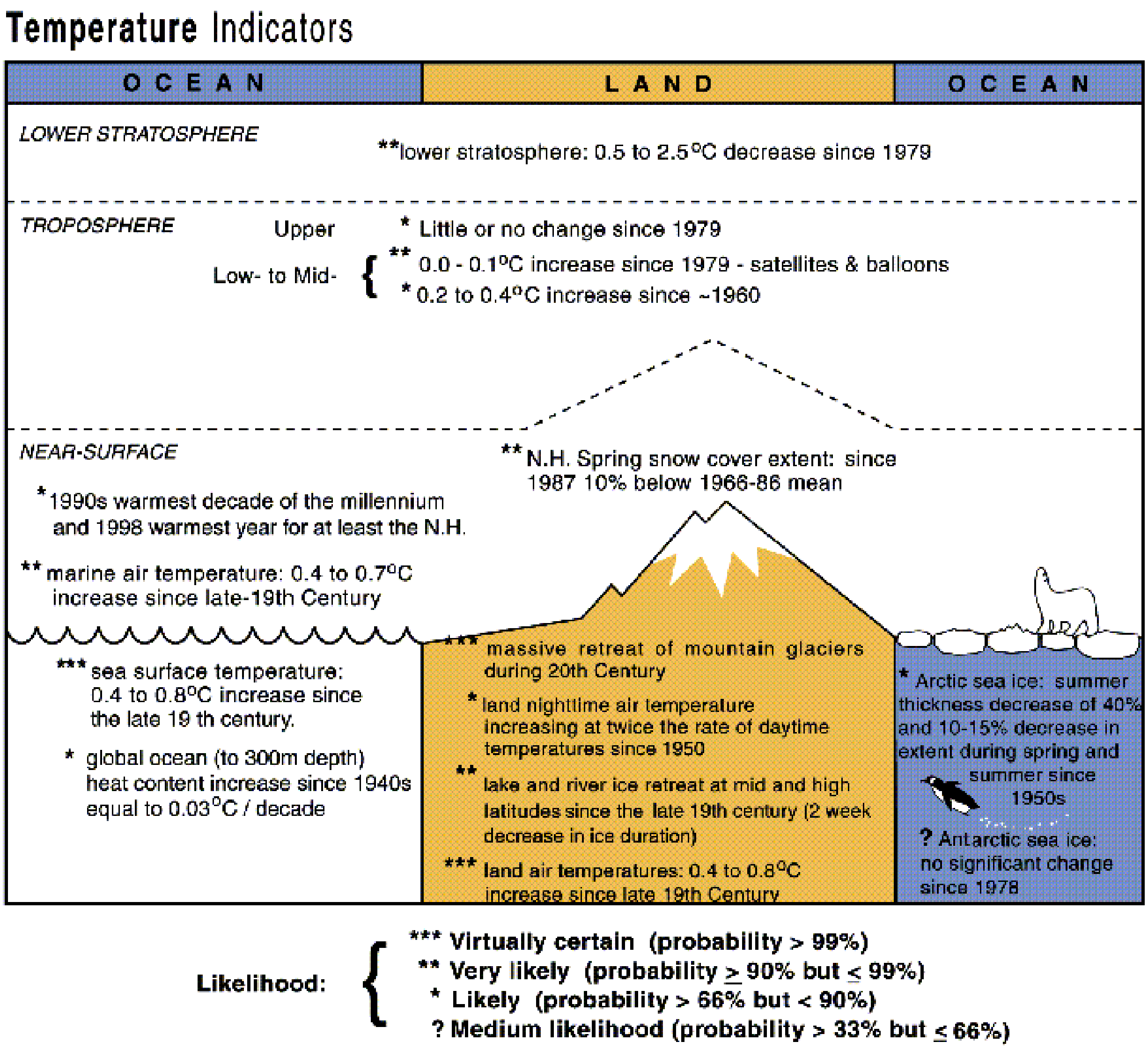
Summary: The warming of the 20th century has a convincing global signature and is consistent with the paleoclimate evidence that the rate and magnitude of global or hemispheric surface 20th Century warming is very likely to have been the largest of the millennium, with the 1990s and 1998 likely to have been the warmest decade and year, respectively, in the Northern Hemisphere.

- **7. Are the Observed Trends Internally Consistent?**

It is very important to compare trends in the various indicators to see if a physically consistent picture emerges as this will critically affect the final assessment of our confidence in any such changes. A number of qualitative consistencies among the various indicators of climate change have increased our confidence in our analyses of the historical climate record: The two figures below summarize the changes in various temperature and hydrological indicators respectively, and provide a measure of confidence about each change. Of particular relevance are the changes identified below:

- Temperature over the land and oceans, with two estimates for the latter, are measured and adjusted independently, yet all three show quite consistent increasing trends (0.51 to 0.61 C/Century) over the 20th Century.

- The nearly worldwide decrease in mountain glacier extent and mass is consistent with 20th century global temperature increases. A few recent exceptions in maritime areas have been affected by atmospheric circulation variations and related precipitation increases.



• Though less certain, substantial proxy evidence points to the exceptional warmth of the late 20th Century relative to the last 1000 years. The 1990s are likely to have been the warmest decade of the past 1000 years over the Northern Hemisphere as a whole.

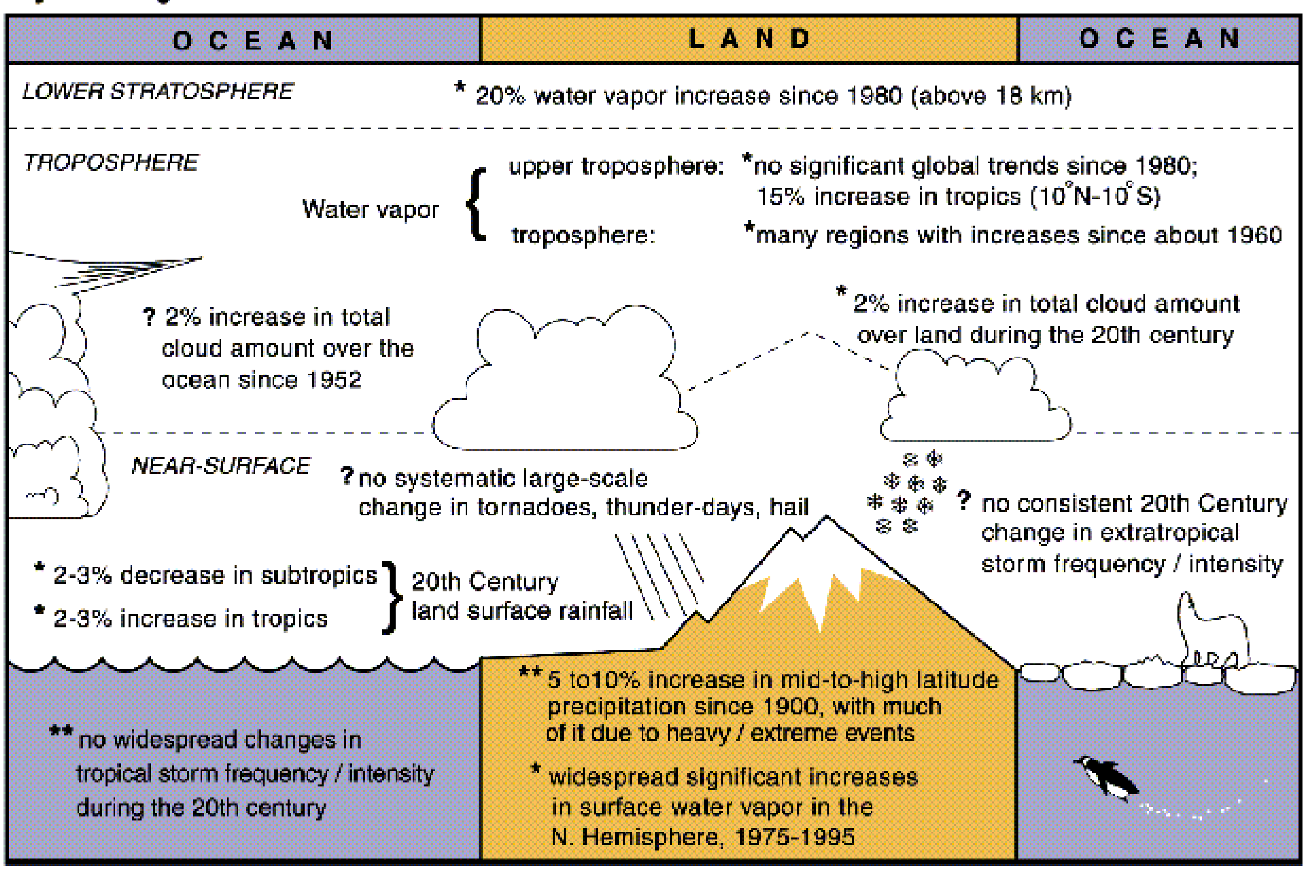
• Satellite and balloon measurements agree that lower tropospheric temperatures have increased only slightly since 1979, though there has been a faster rate of surface temperature increase.. Balloon measurements indicate a larger lower tropospheric temperature increase since 1958, similar to that shown by global surface temperature measurements. Balloon and satellite measurements agree that lower stratospheric temperatures have declined significantly since 1979.

• Trends of world-wide land surface temperatures (as opposed to combined land and ocean temperatures) derived from weather stations are in close agreement with satellite derived temperatures of the low-to-mid troposphere. This suggests that urban heat island biases are not significantly affecting surface temperatures.

• Decreases in spring snow cover extent since the 1960s and in the duration of lake and river ice over at least the last century, relate well to increases in Northern Hemispheric surface air temperatures.

• The systematic decrease of spring and summer Arctic sea-ice extent in recent decades is broadly consistent with increases of temperature over most of the adjacent land and ocean. The large reduction in the thickness of summer and early autumn Arctic sea ice over the last 30-40 years is consistent with this decrease in spatial extent, but we are unsure to what extent poor temporal sampling and multidecadal variability are affecting the conclusions.

Hydrological and Storm-Related Indicators



Likelihood:
- *** Virtually certain (probability > 99%)
- ** Very likely (probability ≥ 90% but ≤ 99%)
- * Likely (probability > 66% but < 90%)
- ? Medium likelihood (probability > 33% but ≤ 66%)

- The increases in lower tropospheric water vapor and temperature since the mid 1970s are qualitatively consistent with an enhanced hydrologic cycle. This is in turn consistent with a greater fraction of precipitation being delivered from extreme and heavy precipitation events, primarily in areas with increasing precipitation, e.g., middle and high latitudes of the Northern Hemisphere.

- Where data are available, changes in precipitation generally correspond with consistent changes in streamflow and soil moisture.

Summar*y:* We conclude that the variations and trends of the examined indicators consistently and very strongly support an increasing global surface temperature over at least the last century, though substantial shorter term global and regional deviations from this warming trend are very likely to have occurred.