Lecture 28: Observed Climate Variability and Change

1. Introduction

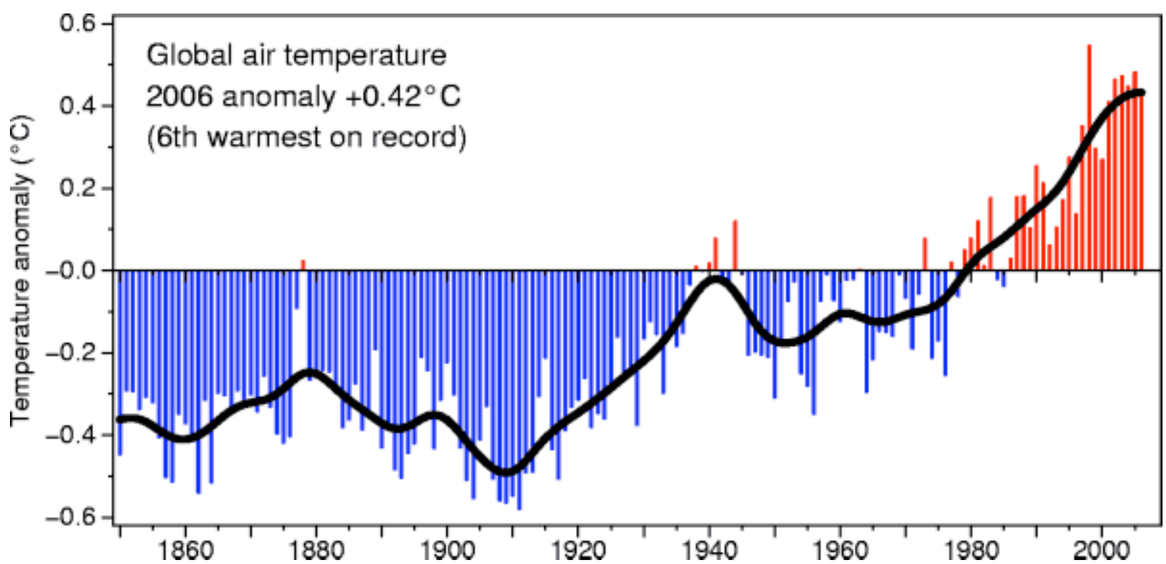
This chapter focuses on 6 questions -

- 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. Surface Temperatures



The time series shows the combined global land and marine surface temperature record from 1850 to 2006. This time series is being compiled jointly by the Climatic Research Unit & the UK Met. Office Hadley Centre.

- 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.

- The year 2006 was sixth warmest on record, exceeded by 1998, 2005, 2003, 2002 and 2004.

- The 1990s were the warmest decade in the series.

- The warmest year of the entire series has been 1998, with a temperature of 0.546°C above the 1961-90 mean.

- Eleven of the twelve warmest years in the series have now occurred in the past twelve years (1995-2006).

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.

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.

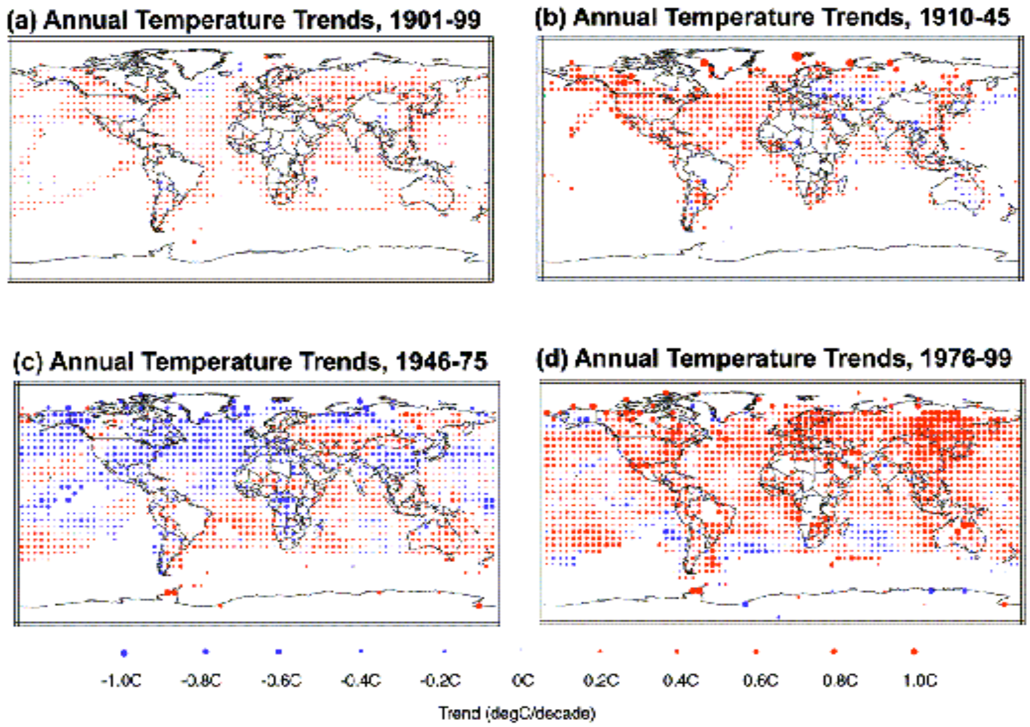
- It can be seen that there is a high degree of local consistency between the SST and land air temperature across the land-ocean boundary, noting that the corrections to SST are independent of the land data.

- 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.

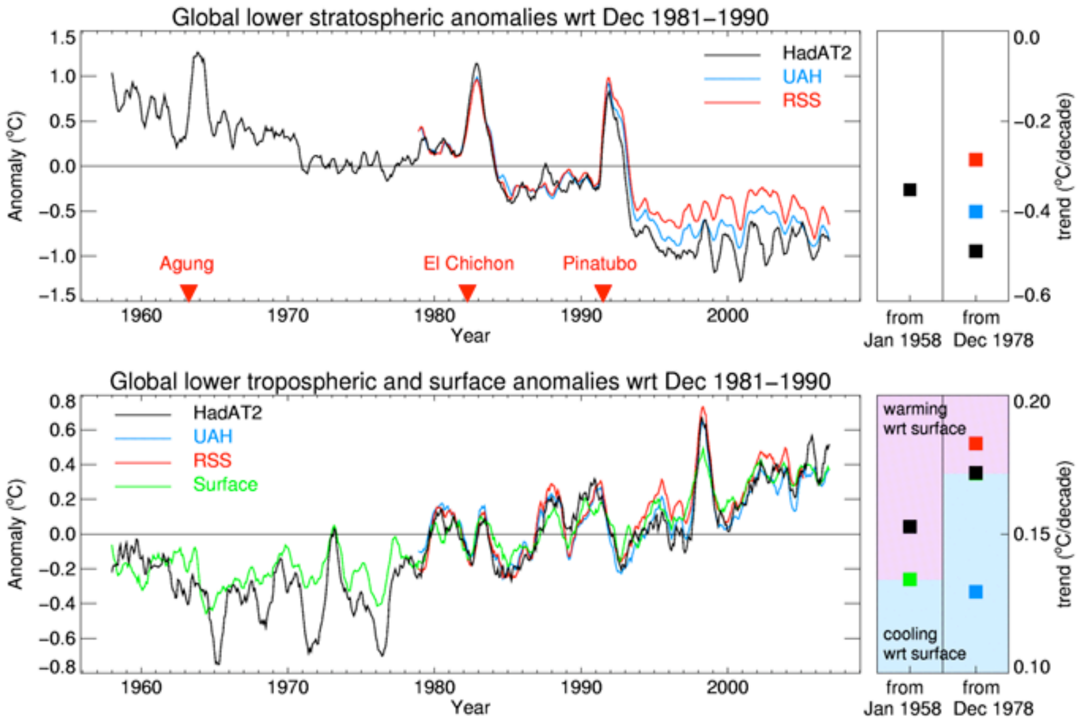
- Over 1901-99 as a whole, warming is seen everywhere except south of Greenland and in a few scattered continental regions in the tropics or subtropics. Faster warming of the land surface temperature than the ocean surface temperature in the last two decades could in part be a signal of anthropogenic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

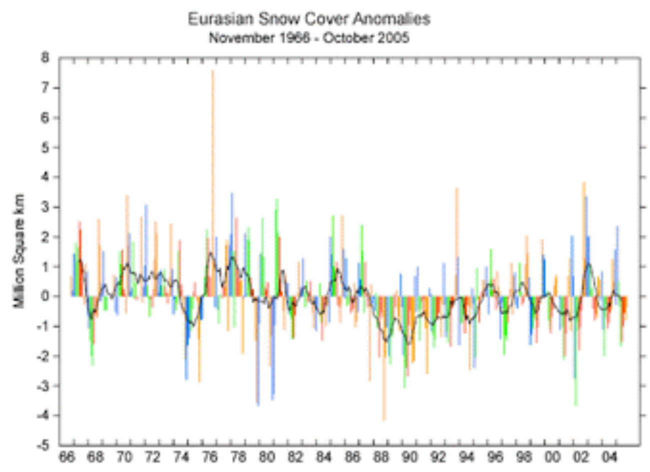
The surface, tropospheric and stratospheric temperature variations since 1958 using representative data sets are shown in the figure below. As predicted by greenhouse theory, cooling of the lower stratosphere and warming of the lower troposphere are observed in both satellite and radiosonde data. The lower troposphere warming is also consistent with observations of surface warming, but some discrepancy prior to 1980s should be noted.

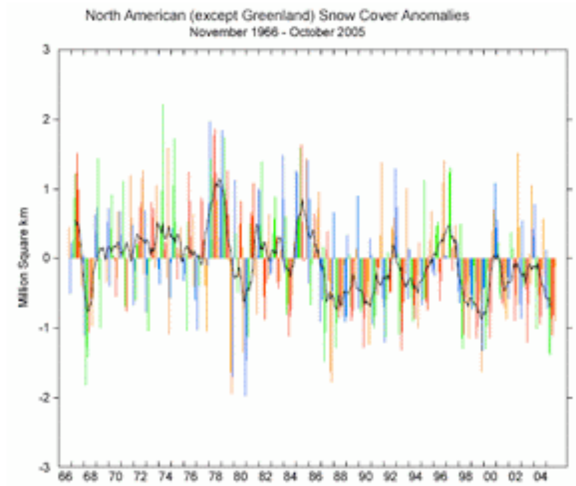


HadAT2 radiosonde data and HadCRUT3 surface data are produced by the Hadley Centre and are available at www.hadobs.org
UAH MSU satellite data are produced by the University of Alabama in Huntsville and are available at www.nsstc.uah.edu/public/msu courtesy of John Christy and Roy Spencer
RSS MSU satellite data are produced by Remote Sensing Systems and are available at www.remss.com courtesy of Carl Mears

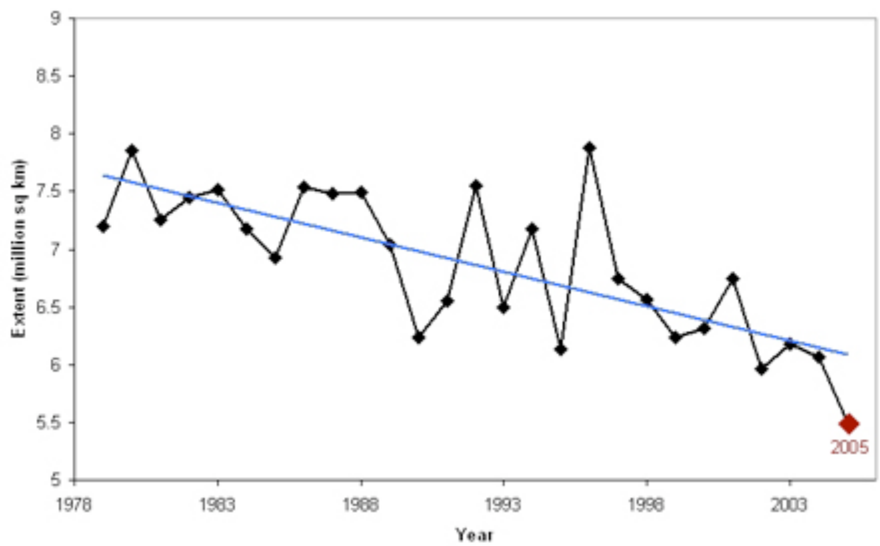
2.D. Changes in the Cryosphere

• *Snow cover*: The Arctic is generally snow covered in winter, so variations in snow cover extent actually occurs in the sub-Arctic more than in the Arctic. Snow cover area in Eurasia decreased in the early 1990s and during a cold event in 2003, but generally the observational record (based on satellite data) shows large year-to-year variability. Snow cover area in North America decreased from the late 1980s onward, again with much year-to-year variability. The twenty-four year trend in mean annual hemispheric snow extent indicates a decrease of approximately 4% per decade.

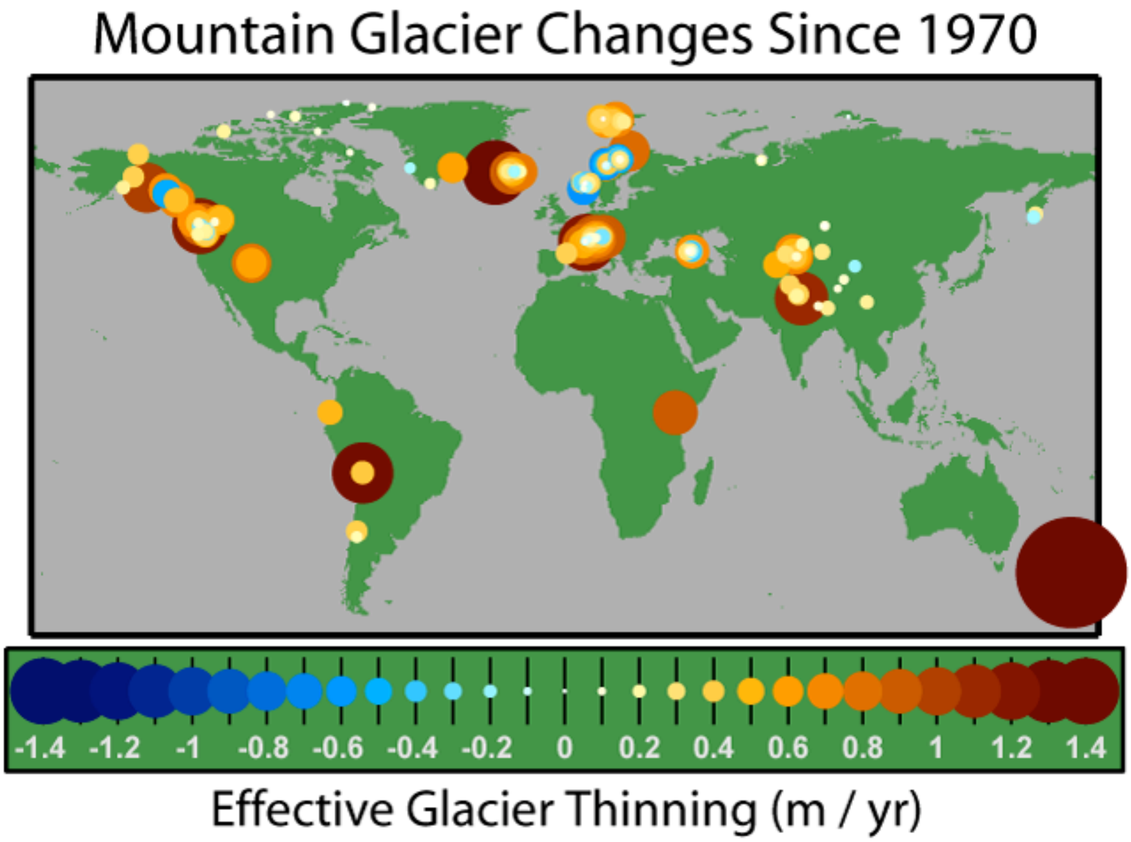




• *Sea-ice extent*: This graph depicts the decline in arctic summer sea ice extent from 1978-2005. The September trend from 1979 to 2005, now showing a decline of more than 8 percent per decade, is shown with a straight blue line.



• *Glaciers*: The effective rate of change in glacier thickness, also known as the glaciological mass balance, is a measure of the average change in a glacier's thickness after correcting for density variations associated with the compaction of snow and conversion to ice. The map shows the average annual rate of thinning since 1970 for the 173 glaciers that have been measured at least 5 times between 1970 and 2004. Larger changes are plotted as larger circles and towards the back. All survey regions except Scandinavia show a net thinning. This widespread glacier retreat is generally regarded as a sign of global warming. During this period, 83% of surveyed glaciers showed thinning with an average loss across all glaciers of 0.31 m/yr. The most rapidly growing glacier in the sample is Engabreen glacier in Norway with a thickening of 0.64 m/yr. The most rapidly shrinking was Ivory glacier in New Zealand which was thinning at 2.4 m/yr. Ivory glacier had totally disintegrated by circa 1988.



• *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.

<u>2.E. Summary</u>

• 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.

- Changes in Northern Hemisphere snow cover extent, sea ice extent, glacier retreat and other cryospheric changes are consistent with temperature increases over the past 100 odd years.

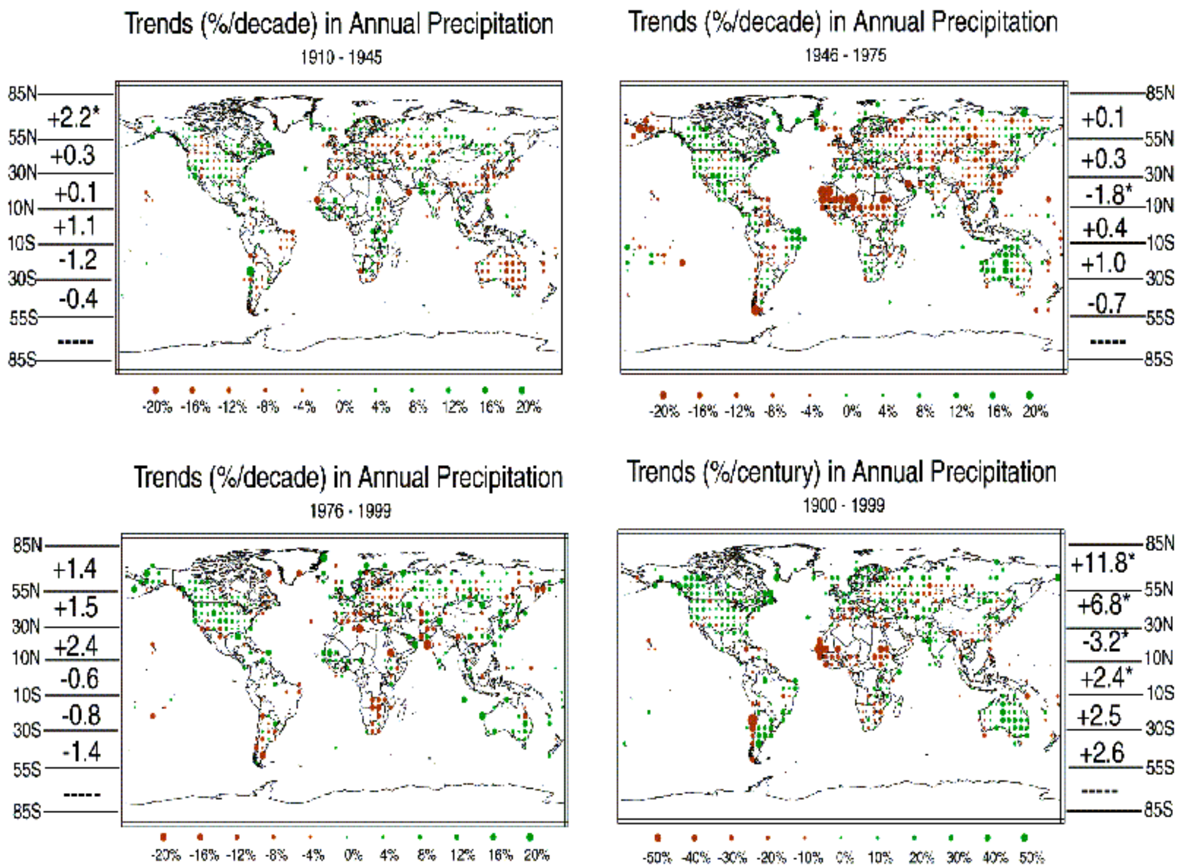
3. Has the Climate Become Wetter?

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.

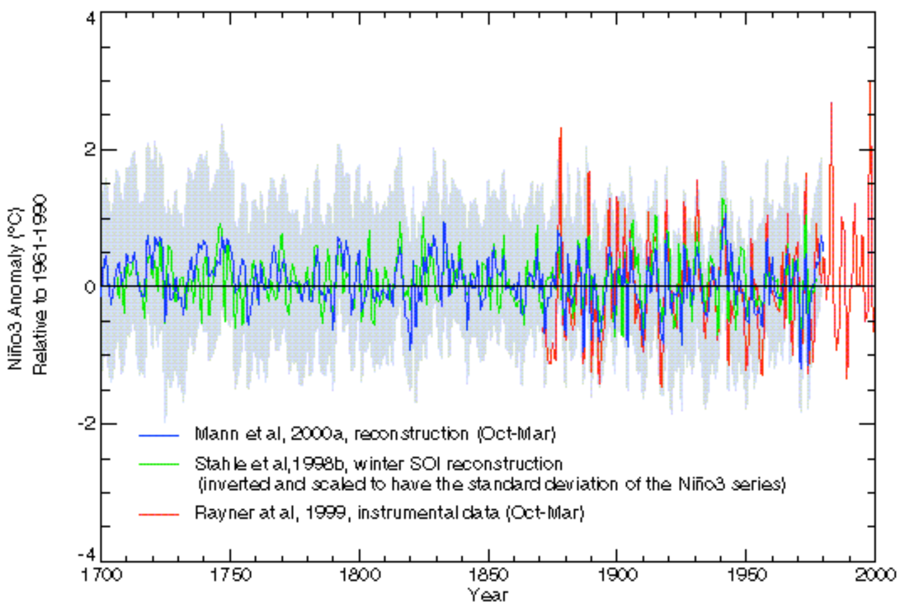
4. Are the Atmosphere/Ocean Circulations Changing?

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.

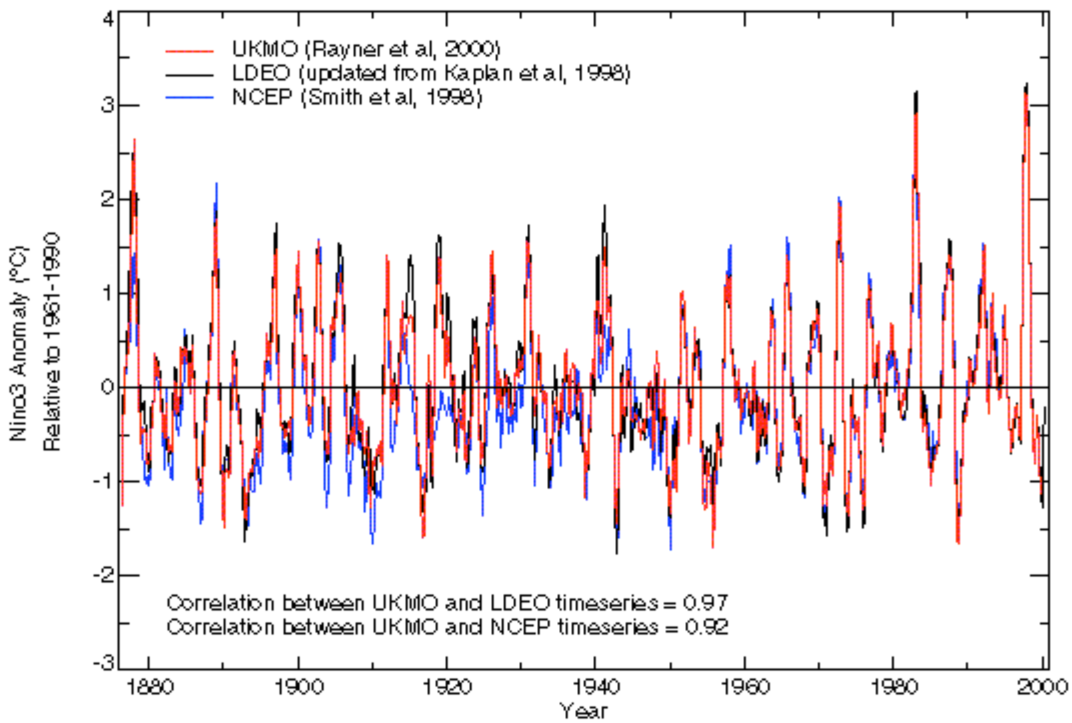
4.A. ENSO

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.



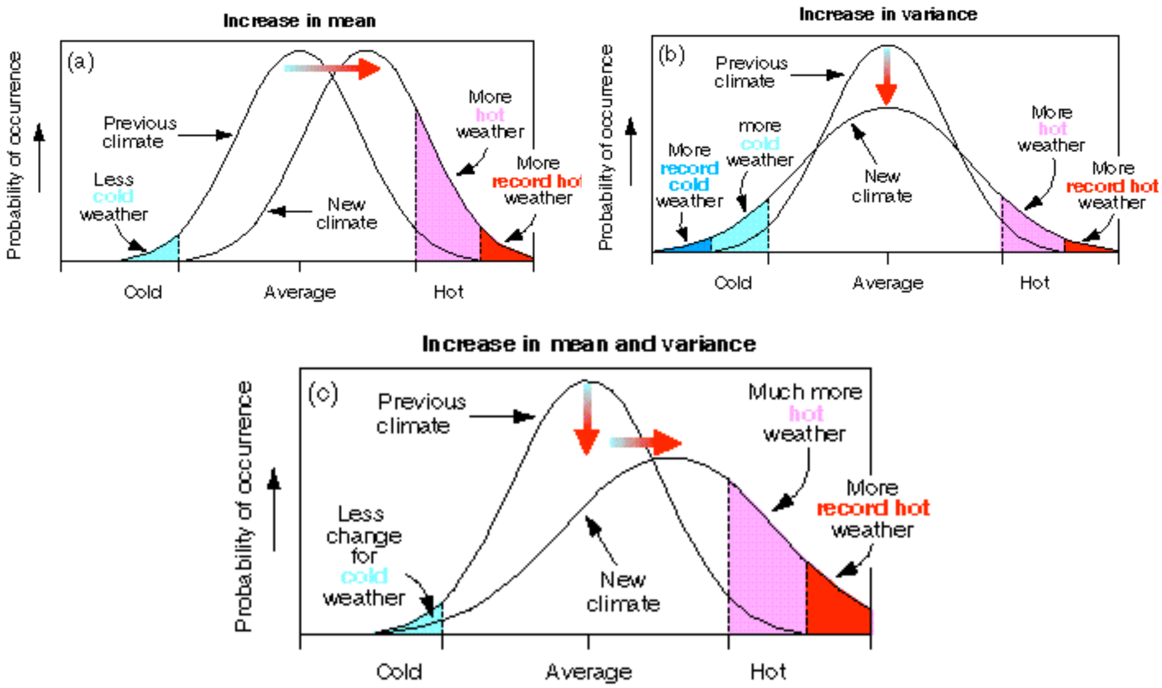
4.B. Summary

- 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.



IPCC 2007 report provides the following table on recent trends, assessment of human influence on the trend and projections for extreme weather events for which there was an observed late 20th centure trend.

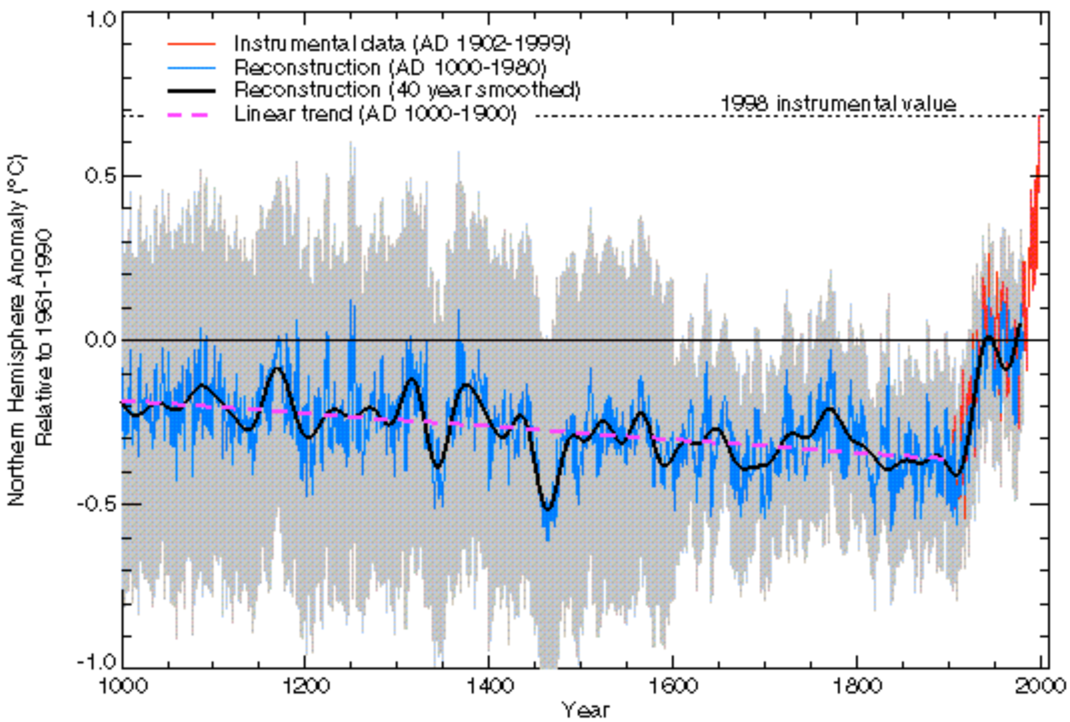
Phenomenon[a] and direction of trend	Likelihood that trend occurred in late 20th century (typically post 1960)	Likelihood of a human contribution to observed trend [b]	Likelihood of future trends based on projections for 21st century using SRES scenarios
Warmer and fewer cold days and nights over most land areas	*Very likely*[c]	*Likely*[d]	*Virtually certain*[d]
Warmer and more frequent hot days and nights over most land areas	*Very likely*[e]	*Likely (nights)*[d]	*Virtually certain*[d]
Warm spells / heat waves. Frequency increases over most land areas	*Likely*	*More likely than not*[f]	*Very likely*
Heavy precipitation events. Frequency (or proportion of total rainfall from heavy falls) increases over most areas	*Likely*	*More likely than not*[f]	*Very likely*
Area affected by droughts increases	*Likely* in many regions since 1970s	*More likely than not*	*Likely*
Intense tropical cyclone activity increases	*Likely* in some regions since 1970	*More likely than not*[f]	*Likely*
Increased incidence of extreme high sea level (excludes tsunamis) [g]	*Likely*	*More likely than not*[f, h]	*Likely*[i]

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.



A more recent study reported reconstructions of (Northern Hemisphere average or global average) surface temperature variations from six research teams (in different color shades) along with the instrumental record of global average surface temperature (in black in the figure below). Each curve illustrates a somewhat different history of temperature changes, with a range of uncertainties that tend to increase backward in time (as indicated by the shading in the figure below). These results suggest

- There is a high level of confidence that the global average temperature during the last few decades was warmer than any comparable period during the last 400 years.
- Present evidence suggests that temperatures at many, but not all, individual locations were higher during the past 25 years than any period of comparable length since A.D. 900. However, uncertainties associated with this statement increase substantially backward in time.
- Very little confidence can be assigned to estimates of hemisphere average or global average temperature prior to A.D. 900 due to limited data coverage and challenges in analyzing older data.

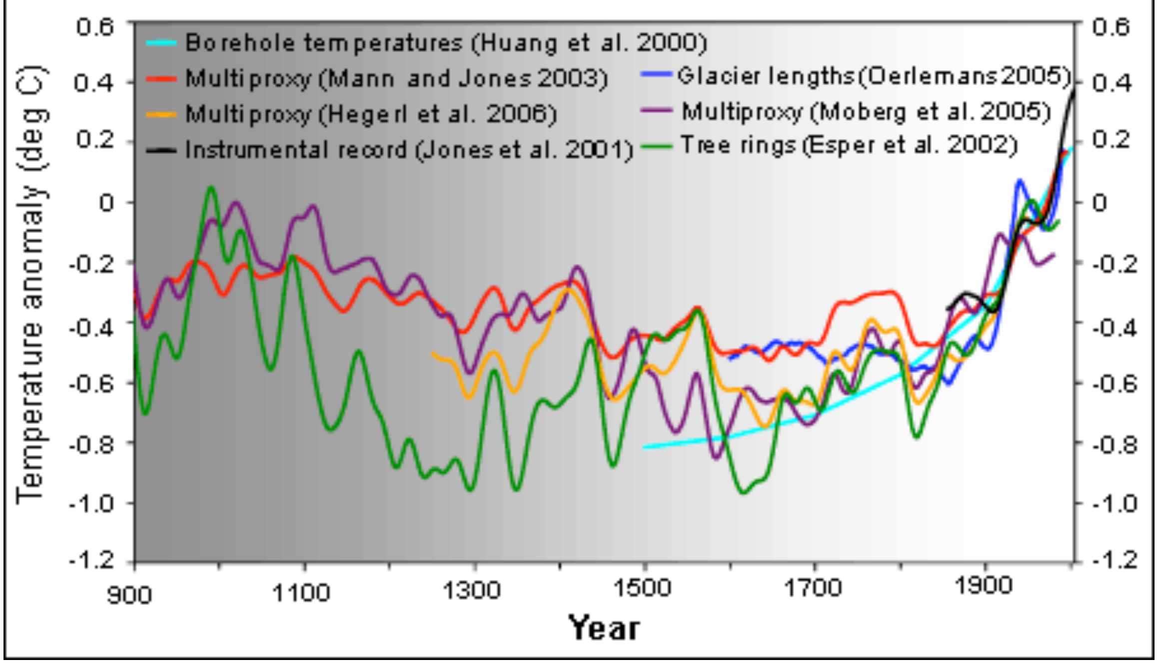


Figure 2: Surface Temperatures over the last 1,100 Years

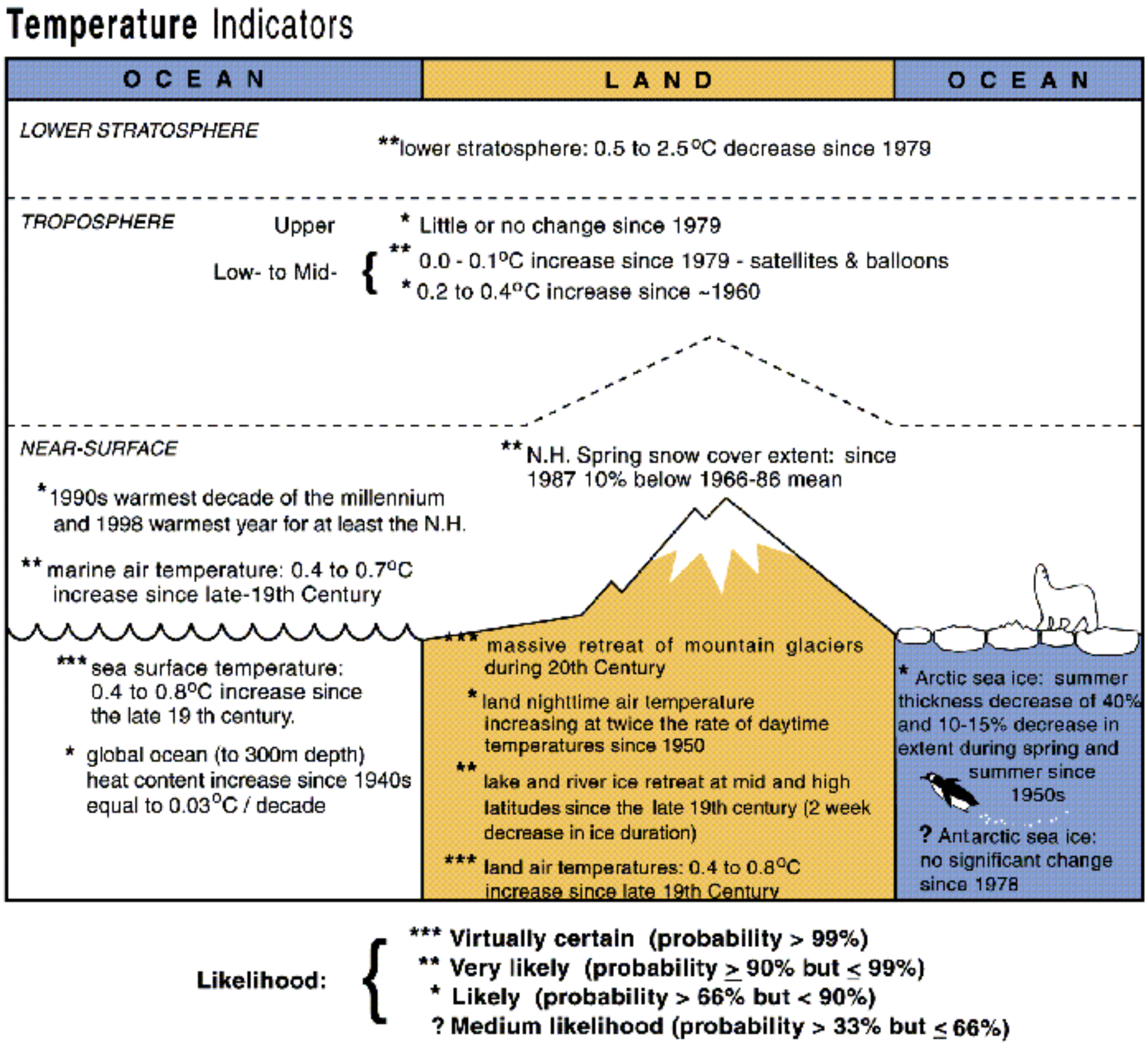
Summary: IPCC 2007 reports "Average Northern Hemisphere temperatures during the second half of the 20th century were very likely higher than during any other 50-year period in the last 500 years and likely the highest in at least the past 1300 years. "

- **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.



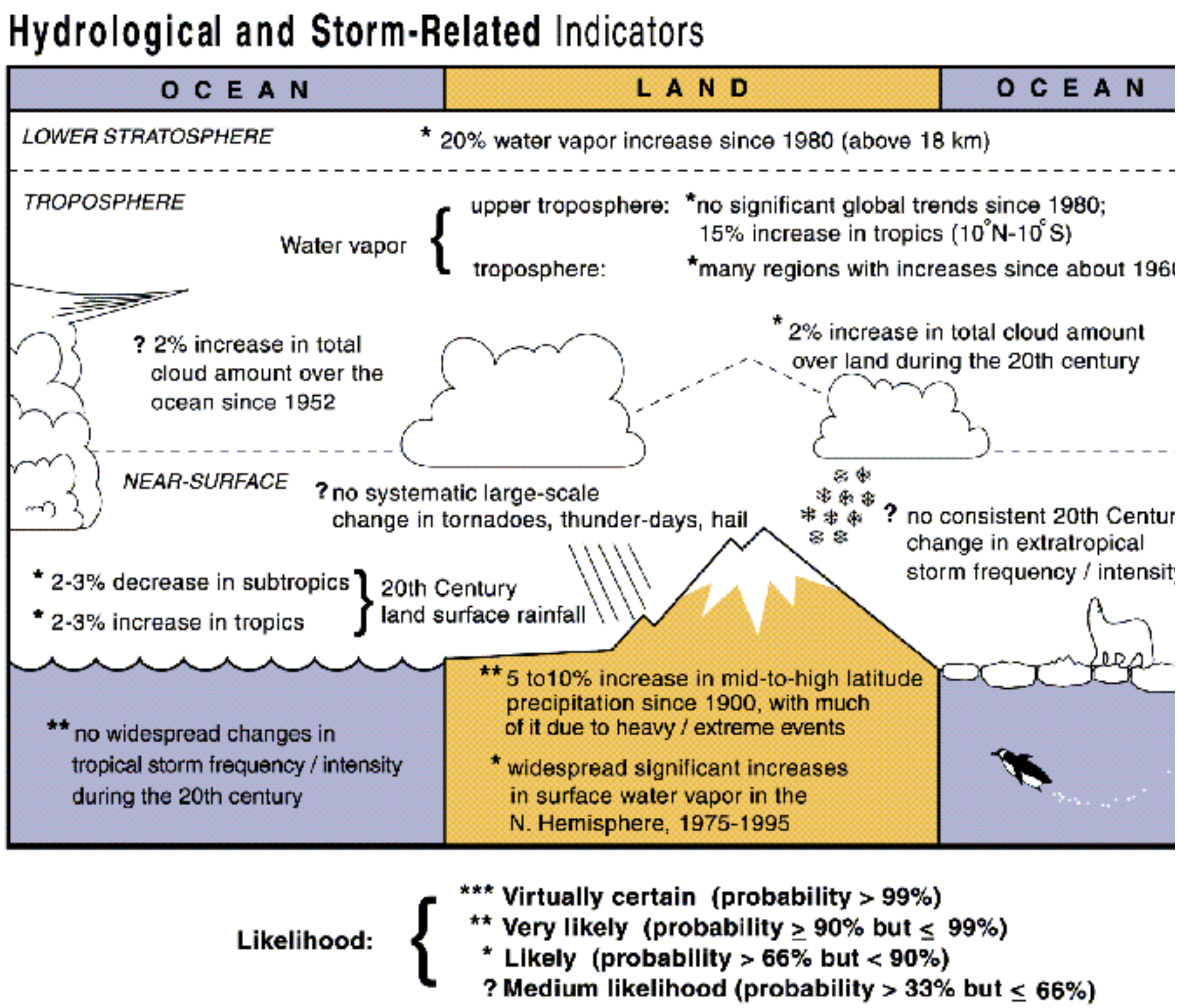
• Though less certain, substantial proxy evidence points to the exceptional warmth of the late 20th Century relative to the last 1000 years. The 1990s are likely to have been the warmest decade of the past 1000 years over the Northern Hemisphere as a whole.

• 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.



- 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.