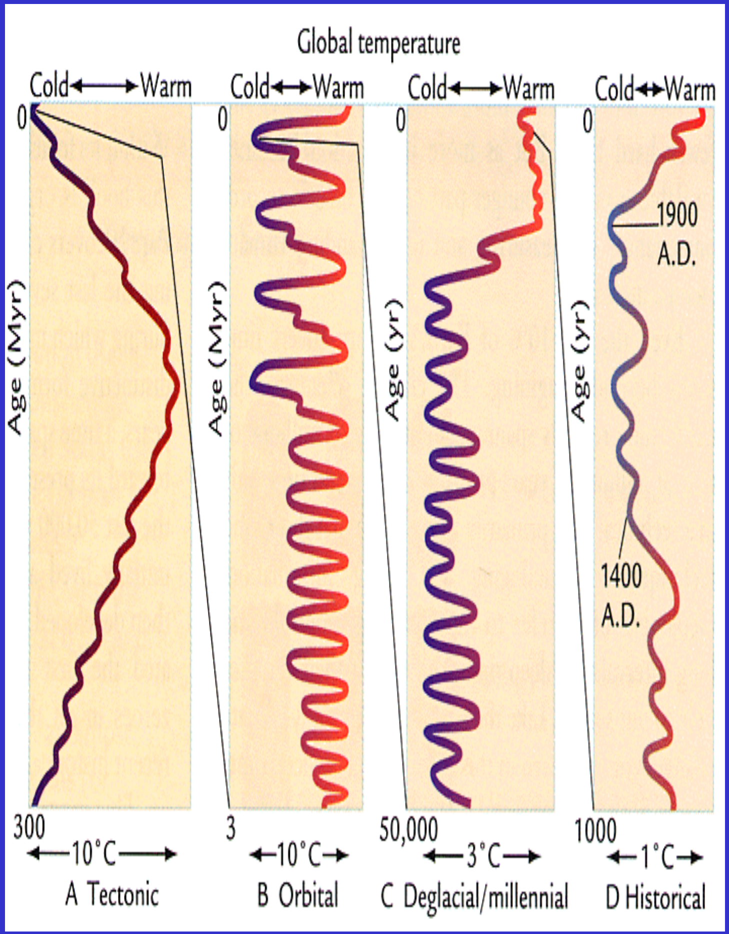
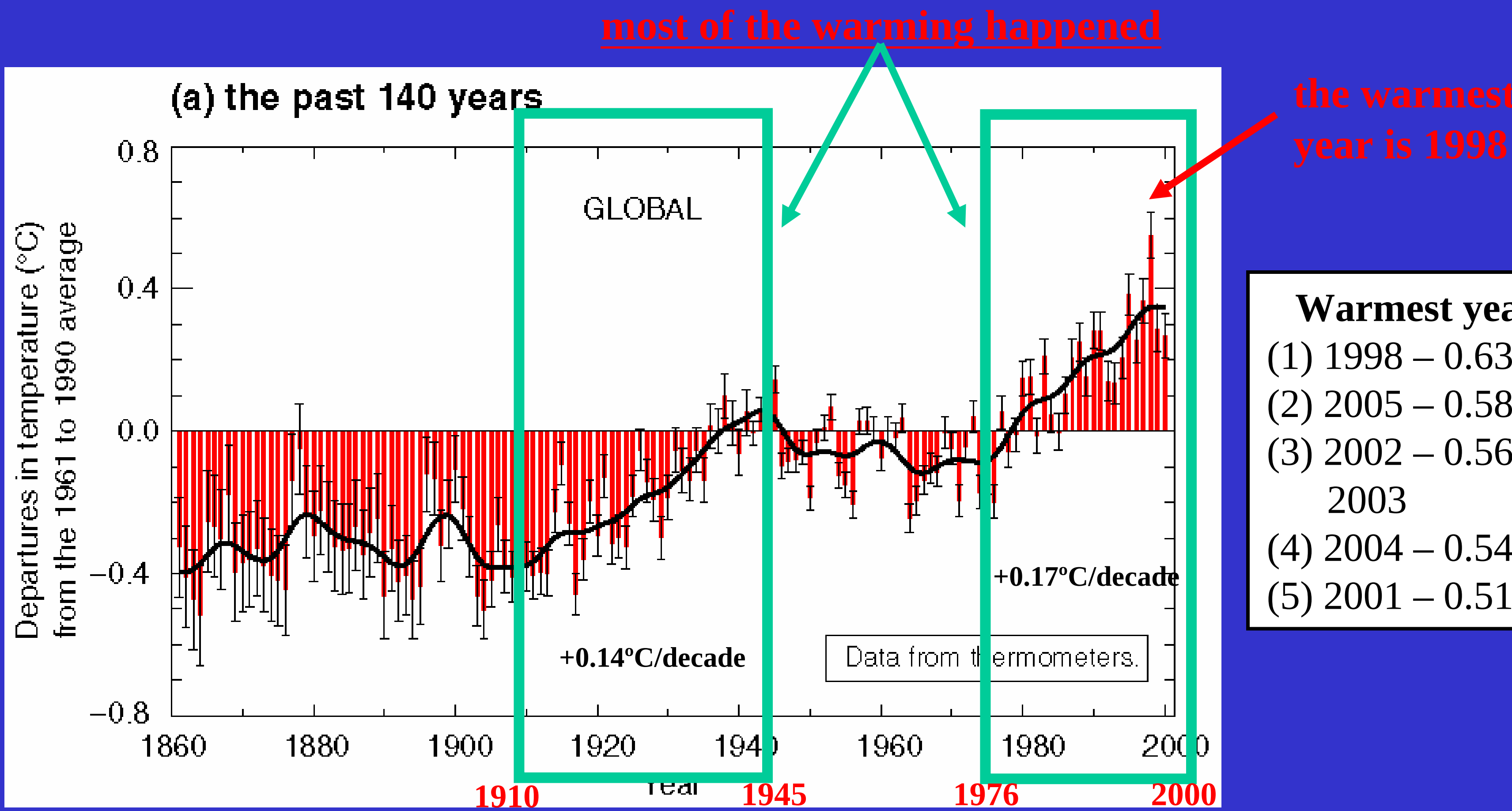
Lecture 6: Climate Changes



(from *Earth's Climate: Past and Future*)

- ❑ Tectonic-Scale Climate Changes
- ❑ Orbital-Scale Climate Changes
- ❑ Deglacial and Millennial Climate Changes
- ❑ Historical Climate Changes
- ❑ Global Warming

Global Surface Temperature

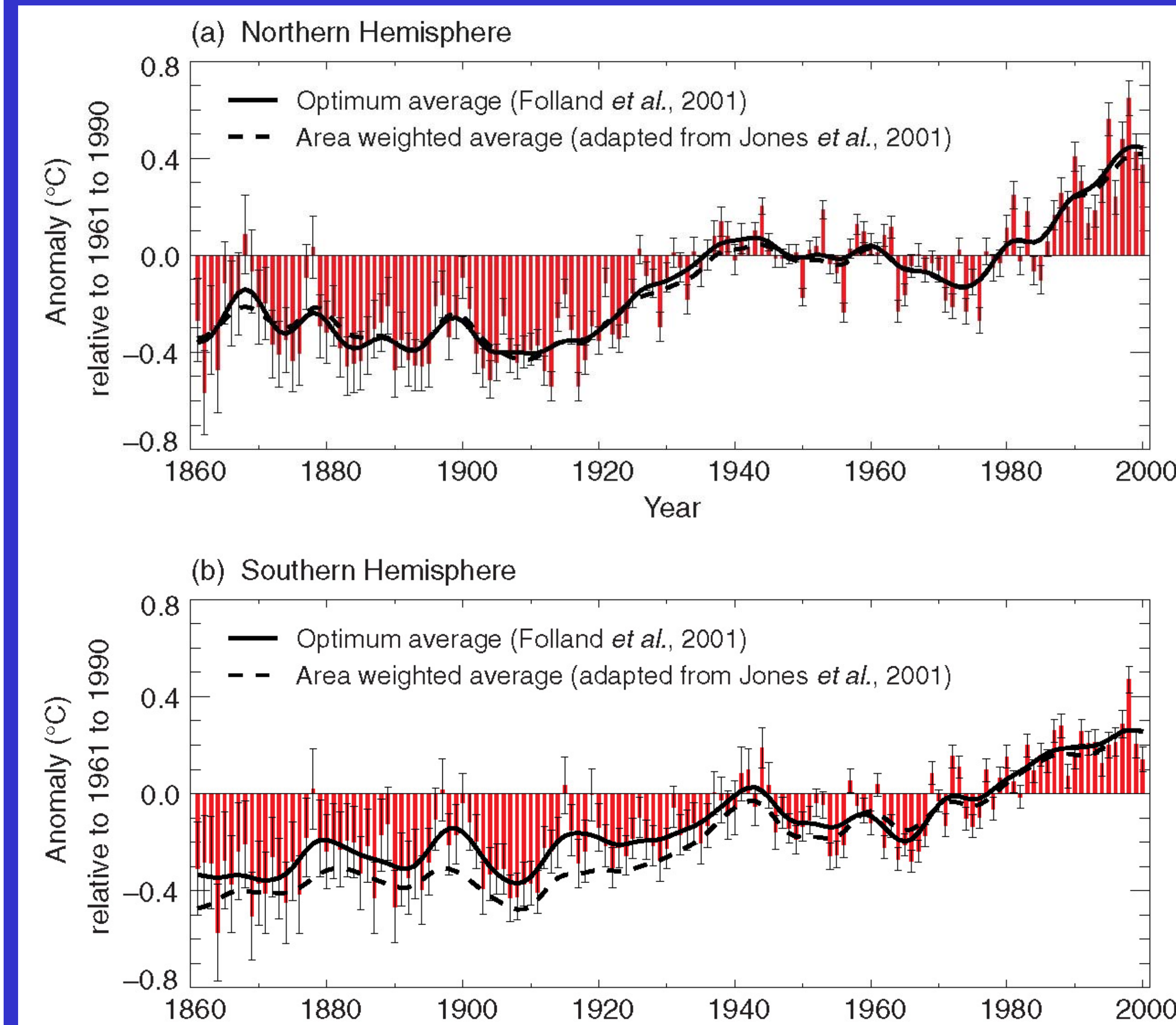


Warmest years

(1) 1998 – 0.63ºC
(2) 2005 – 0.58ºC
(3) 2002 – 0.56ºC
2003
(4) 2004 – 0.54ºC
(5) 2001 – 0.51ºC

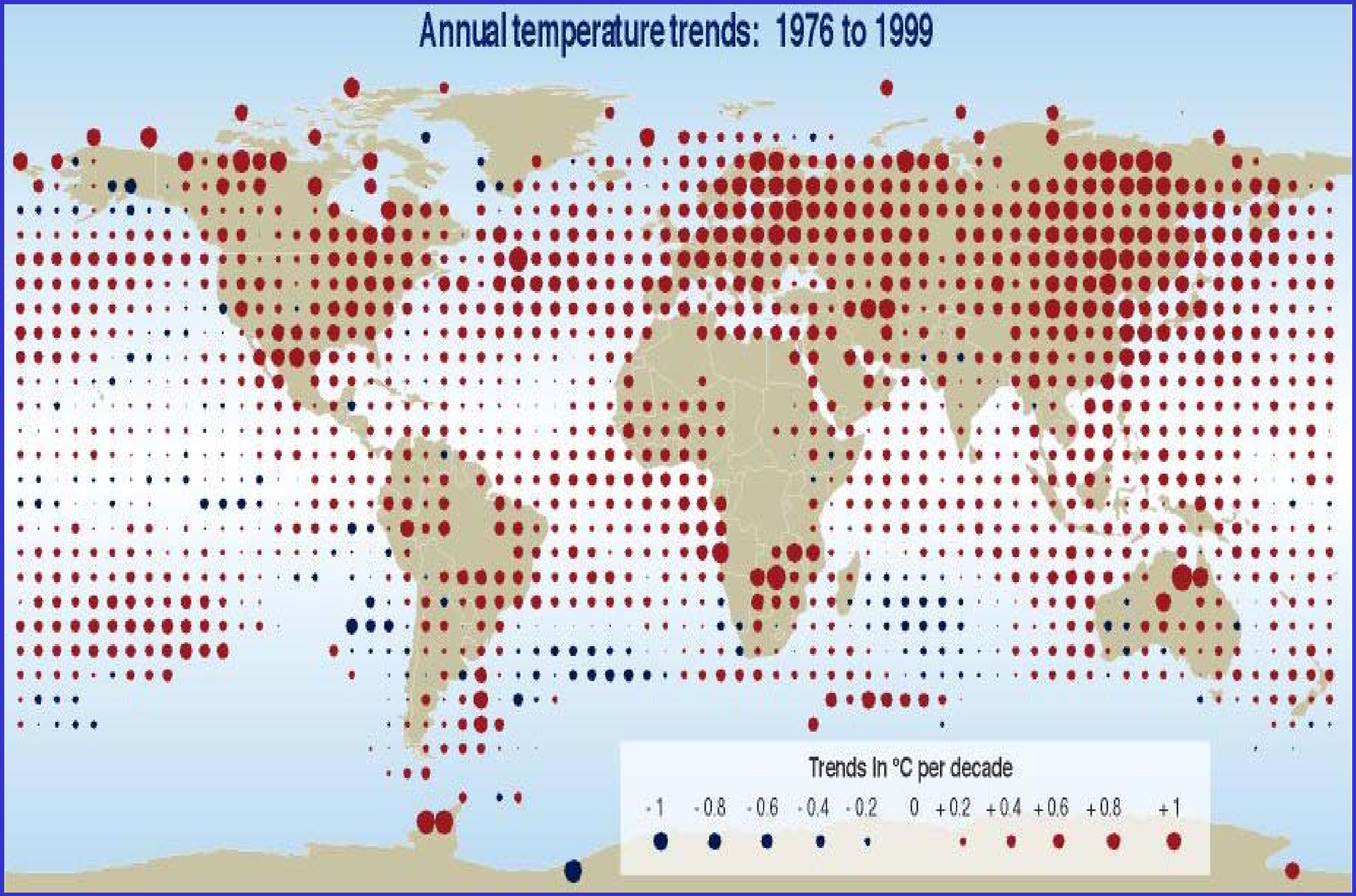
The global average surface temperature has increased over the 20th century by about 0.6°C.

More Warming in the N.H.



Both the earlier period of warming (1910 to 1945) and the more recent one (1976 to 1999) saw rates of warming about twice as great in the Northern Hemisphere than in the Southern Hemisphere.

Faster Warming Trend Over Lands



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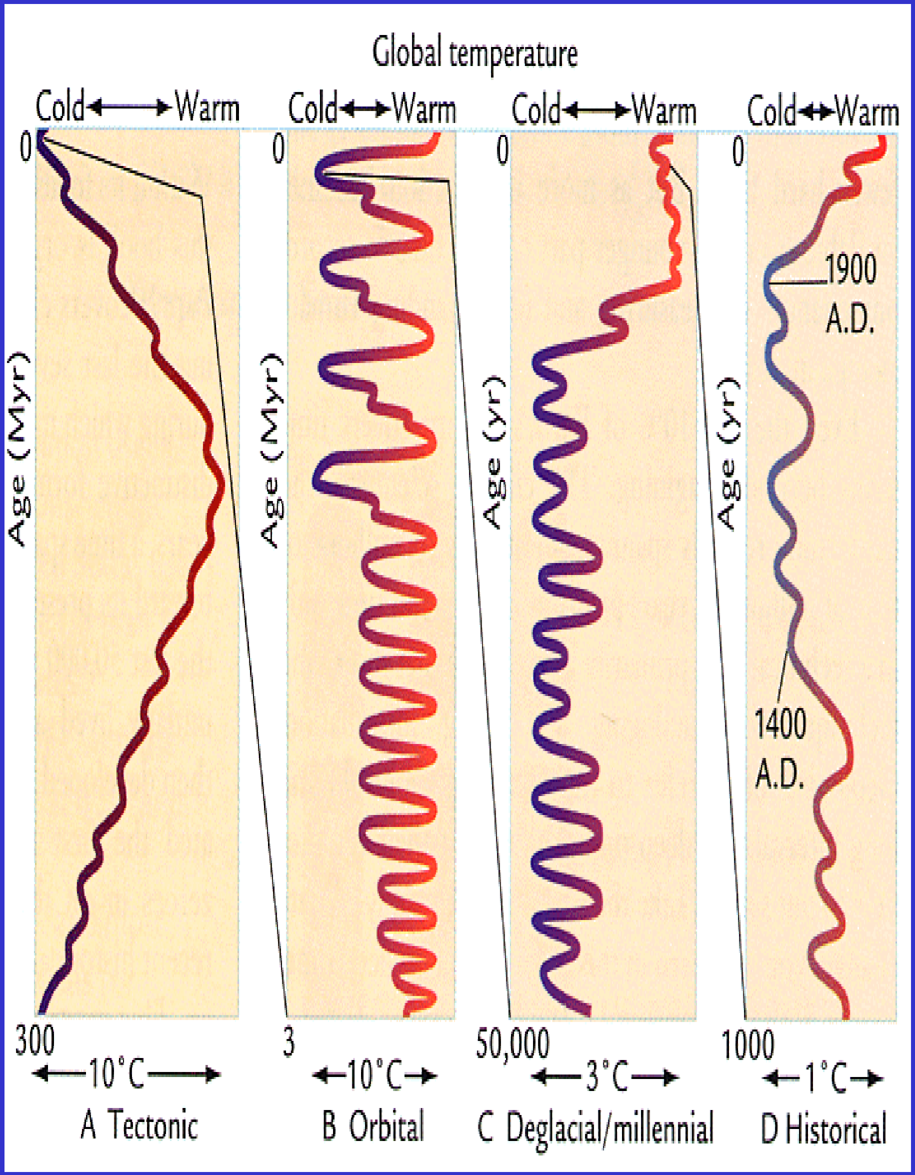
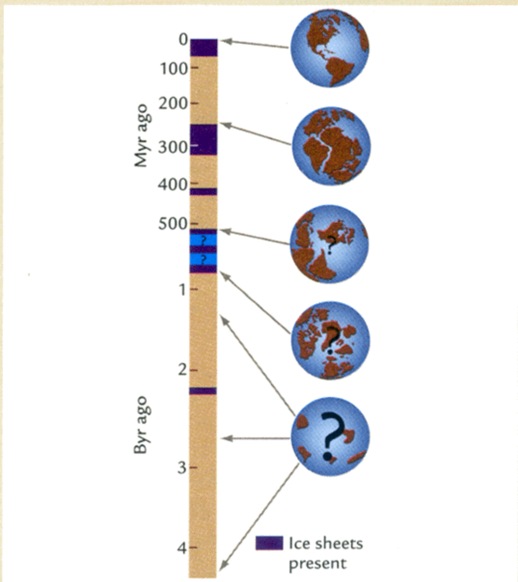
Climate Change on Various Time Scales



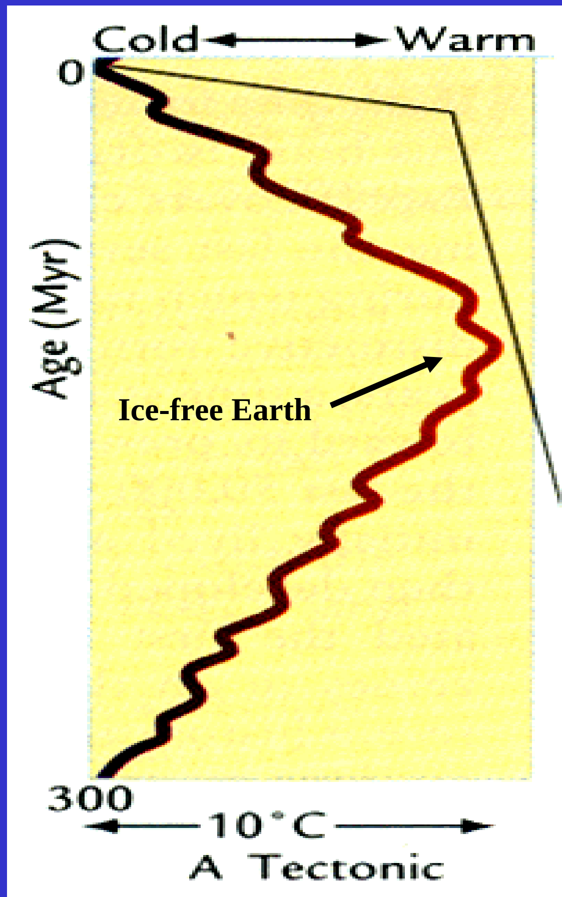
(from *Earth's Climate: Past and Future*)

- Tectonic-Scale Climate Changes
- Orbital-Scale Climate Changes
- Millennial Climate Changes
- Historical Climate Change
- Anthropogenic Climate Changes

Tectonic-Scale Climate Change



Past glaciations and continental positions. During Earth's 4.55-billion-year history, intervals when large continental ice sheets were present alternated with times when they were not (left). The earliest history of these changes is poorly defined because few ancient records are preserved. The movements of continents in relation to ocean basins are well known only for the last several hundred million years (right). (Globes adapted from D. Merritts et al., *Environmental Geology*, © 1997 by W. H. Freeman and Company.)

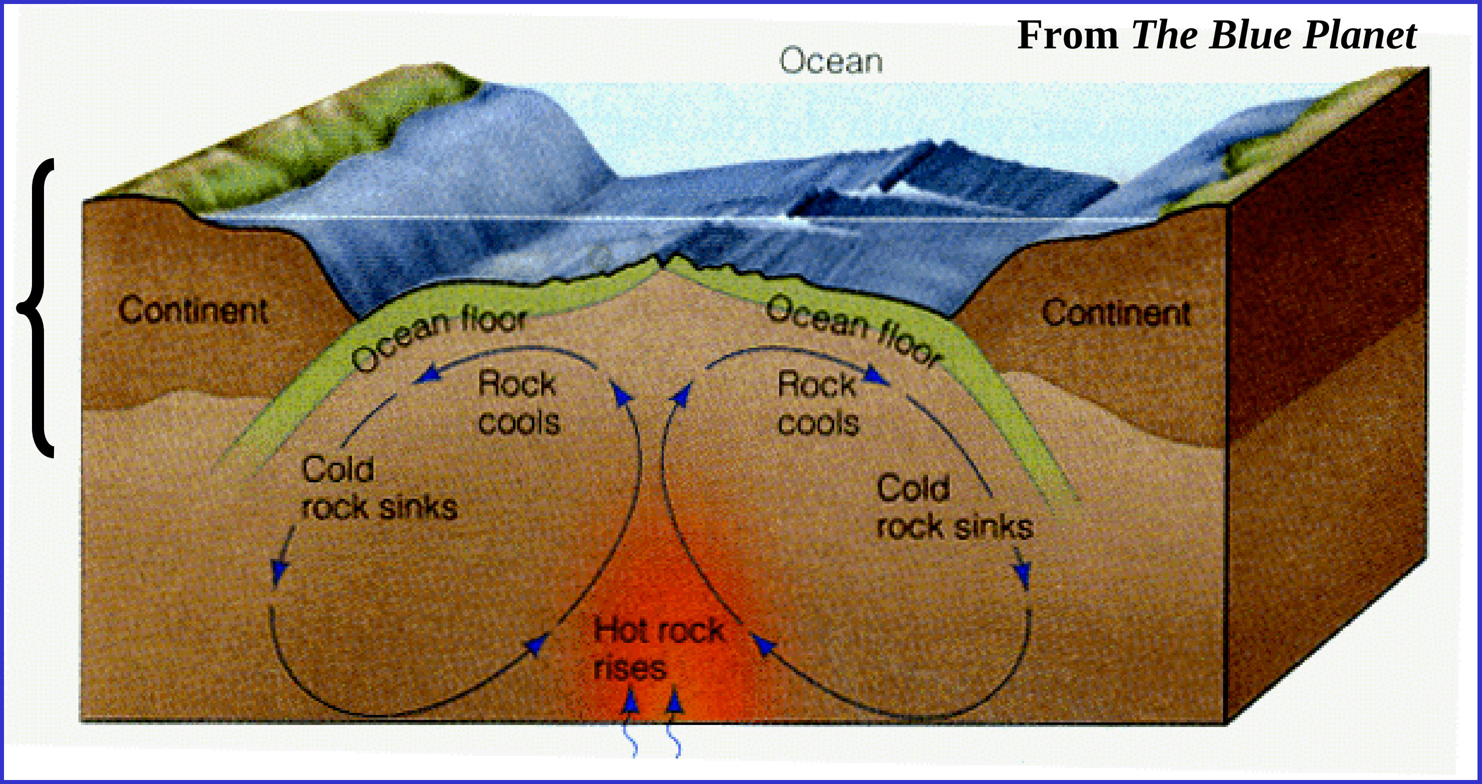


(from *Earth's Climate: Past and Future*)

- The faint young Sun paradox and its possible explanation.
- Why was Earth ice-free even at the poles 100 Myr ago (the Mesozoic Era)?
- What are the causes and climate effects of changes in sea level through time?
- What caused Earth's climate to cool over the last 55 Myr (the Cenozoic Era)?

Circulation of the Solid Earth

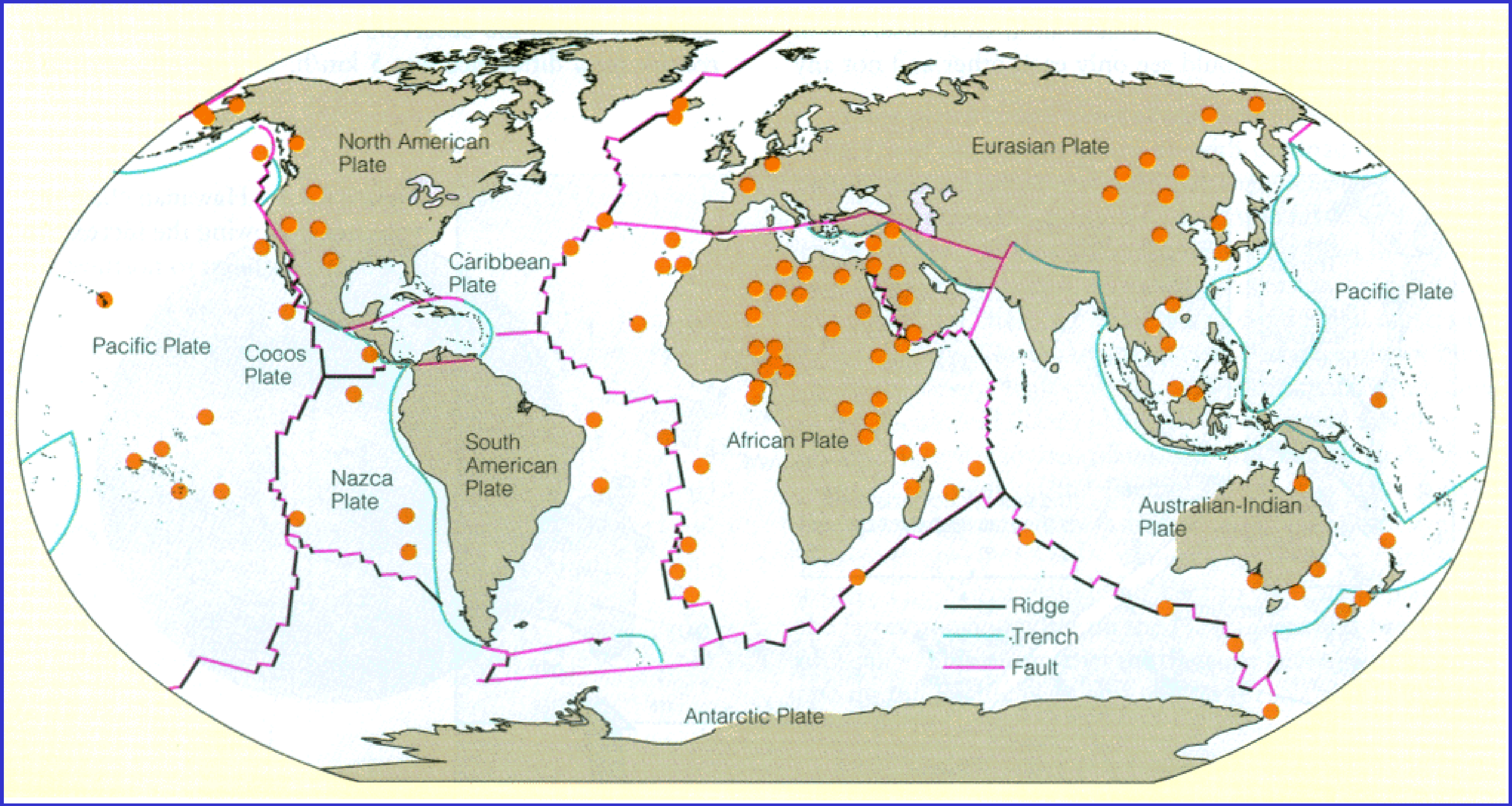
Cold Lithosphere



❑ The rising hot rocks and slid-away flows are thought to be the factor that cont5rol the positions of ocean basins and continents.

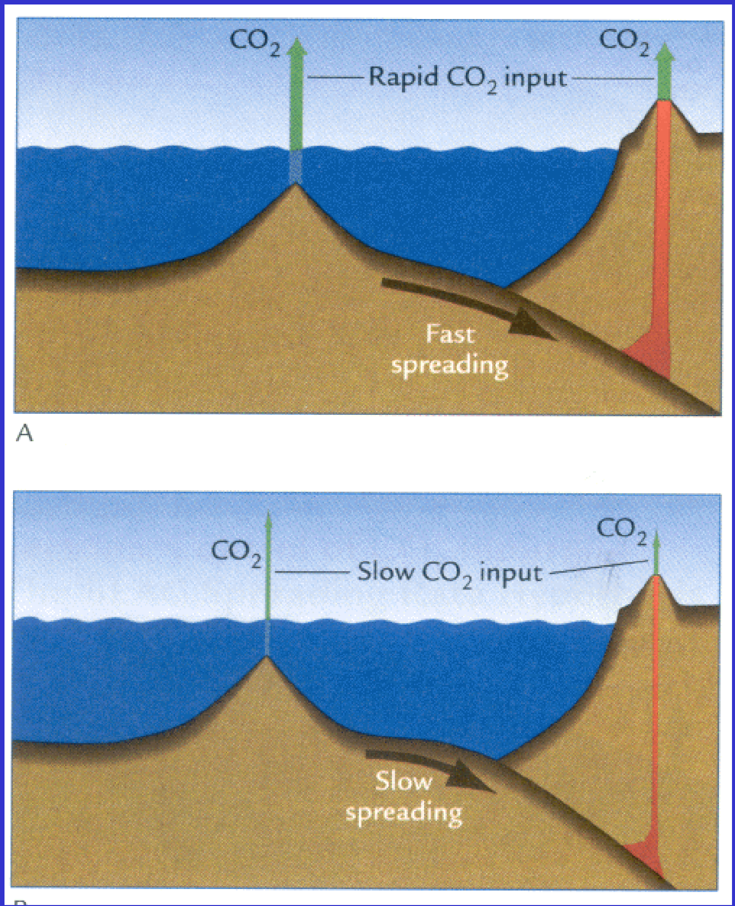
➔ The convection determines the shape of the Earth.

Twenty Rigid Plates



From *The Blue Planet*

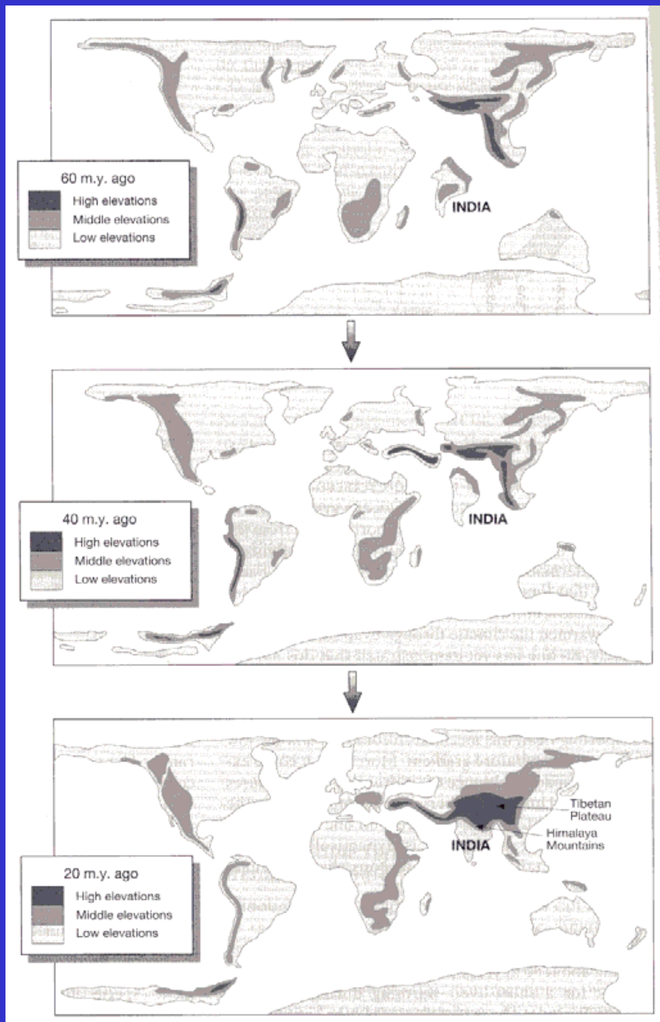
Tectonic Control of CO_2 *Input* – The Seafloor Spreading Rate Hypothesis



(from *Earth's Climate: Past and Future*)

- During active plate tectonic processes, carbon cycles constantly between Earth's interior and its surface.
- The carbon moves from deep rock reservoirs to the surface mainly as CO_2 gas associated with volcanic activity along the margins of Earth's tectonic plates.
- The centerpiece of the seafloor spreading hypothesis is the concept that changes in the rate of seafloor spreading over millions of years control the rate of delivery of CO_2 to the atmosphere from the large rock reservoir of carbon, with the resulting changes in atmospheric CO_2 concentrations controlling Earth's climate.

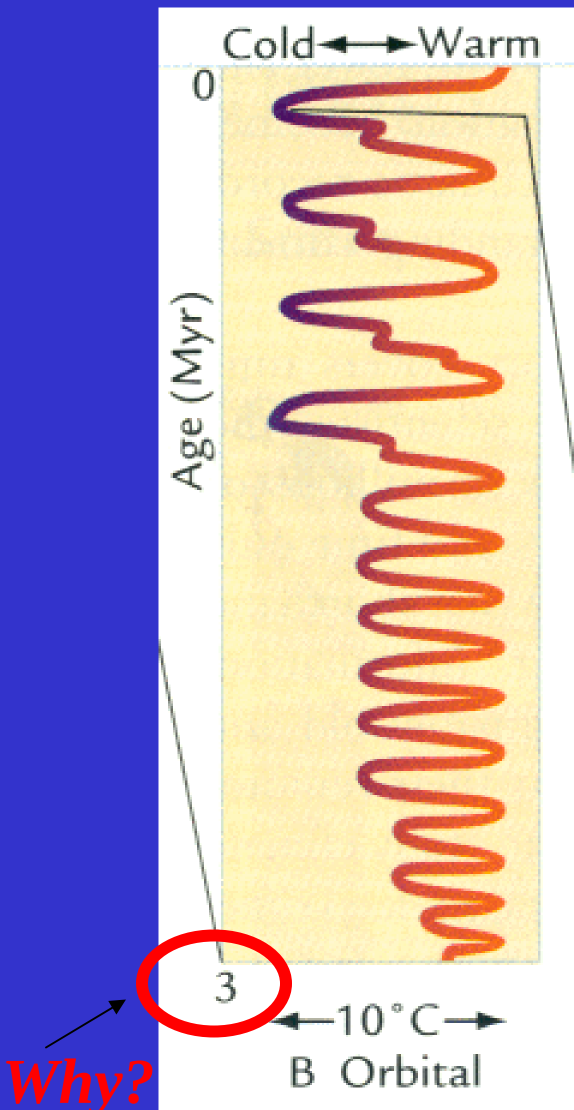
Why the Cooling over the Last 50 Myr?



(from *The Earth System*)

- The collision of Indian and Asia happened around 40 Myr ago.
- The collision produced the Himalayas and a huge area of uplifted terrain called the Tibetan Plateau.
- The Himalayas Mountains provided fresh, readily erodable surfaces on which chemical weathering could proceed rapidly.
- At the same time, the uplifting of the Tibetan Plateau create seasonal monsoon rainfalls, which provided the water needed for chemical weathering.
- Therefore, the collision of India and Asia enhanced the chemical weathering process and brought down the atmospheric CO2 level to the relatively low values that prevail today.
- This reduced the greenhouse effect and cooled down the climate over the last 50 Myr.

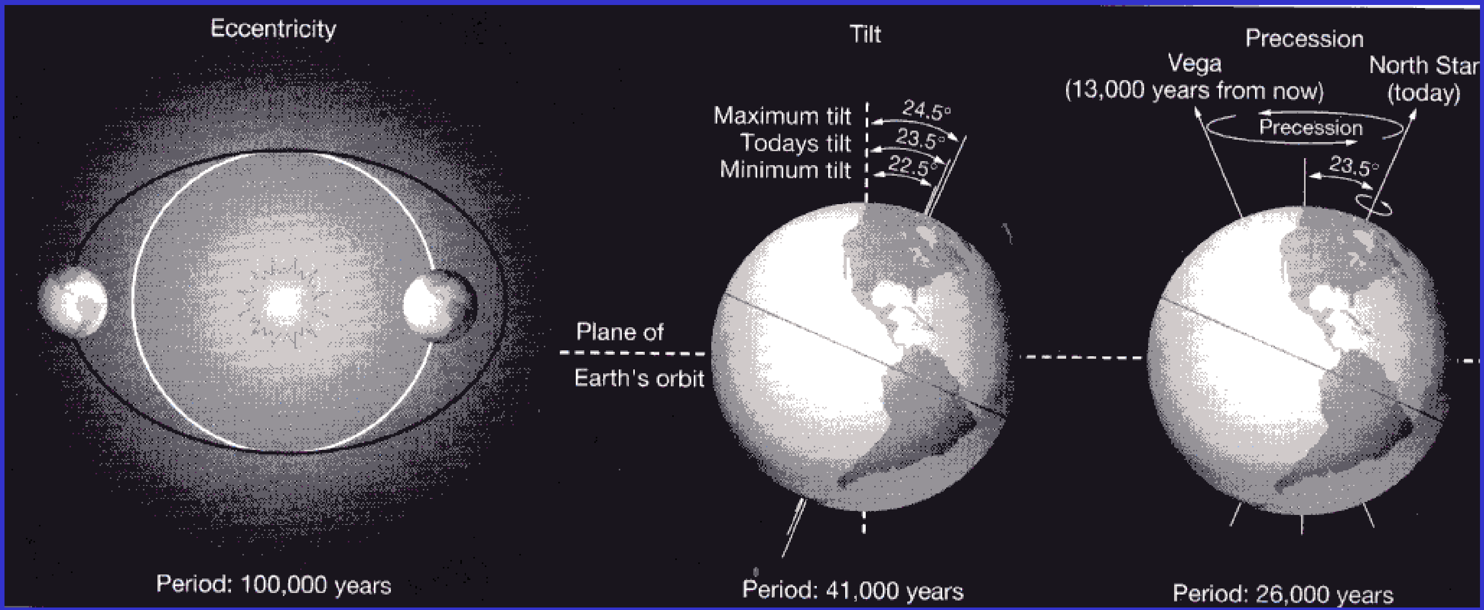
Orbital-Scale Climate Change



- **Changes in solar heating driven by changes in Earth's orbit are the major cause of cyclic climate changes over time scales of tens to hundreds of thousands of years (23k years, 41k years, and 100k years) .**
- Earth's orbit and its cyclic variations: tilt variations, eccentricity variations, and precession of the orbit.
- How do orbital variations drive the strength of tropical monsoons?
- How do orbital variations control the size of northern hemisphere ice sheets?
- What controls orbital-scale fluctuations of atmospheric greenhouse gases?
- What is the origin of the 100,000-year climate cycle of the last 0.9 Myr (ice sheets melt rapidly every 100,000 years)?

(from *Earth's Climate: Past and Future*)

Earth's Orbit and Its Variations



(from *The Earth System*)

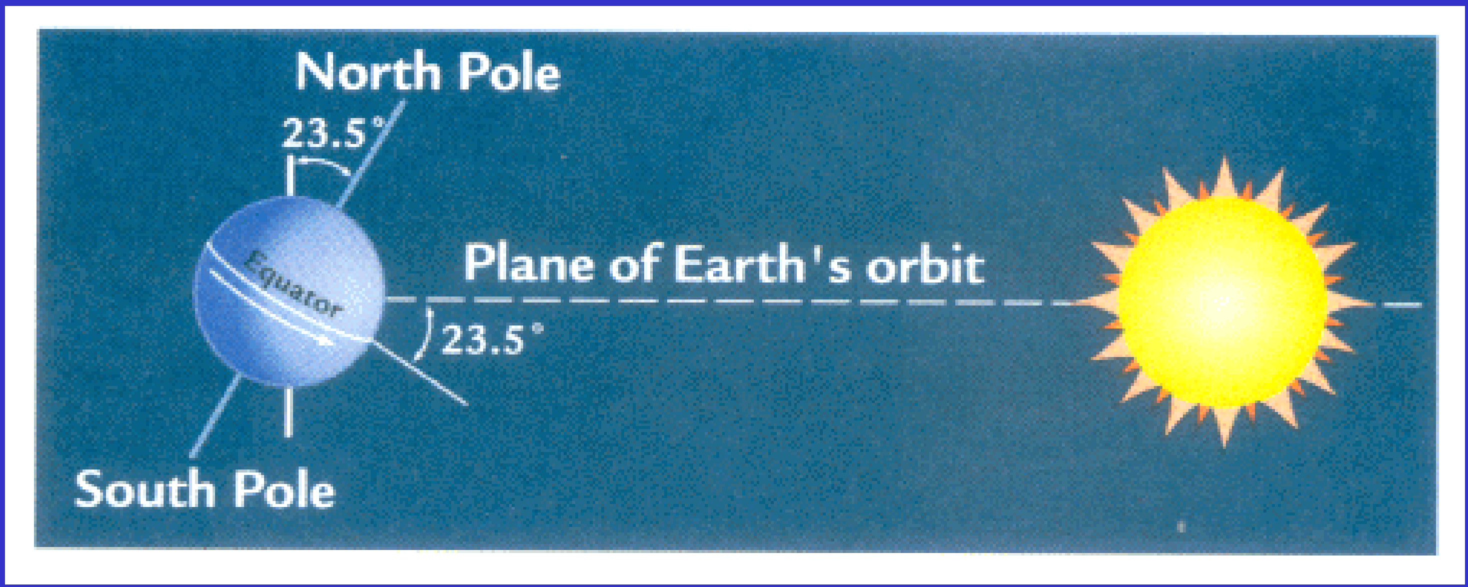
- First, Earth spins around on its axis once every day ➔ The ***Tilt.***
- Second, Earth revolves around the Sun once a year ➔ The shape of the ***Orbit***.
- Both the tilt and the shape of the orbit have changed over time and produce three types of orbital variations:

  (1) obliquity variations

  (2) eccentricity variations

  (3) precession of the spin axis.

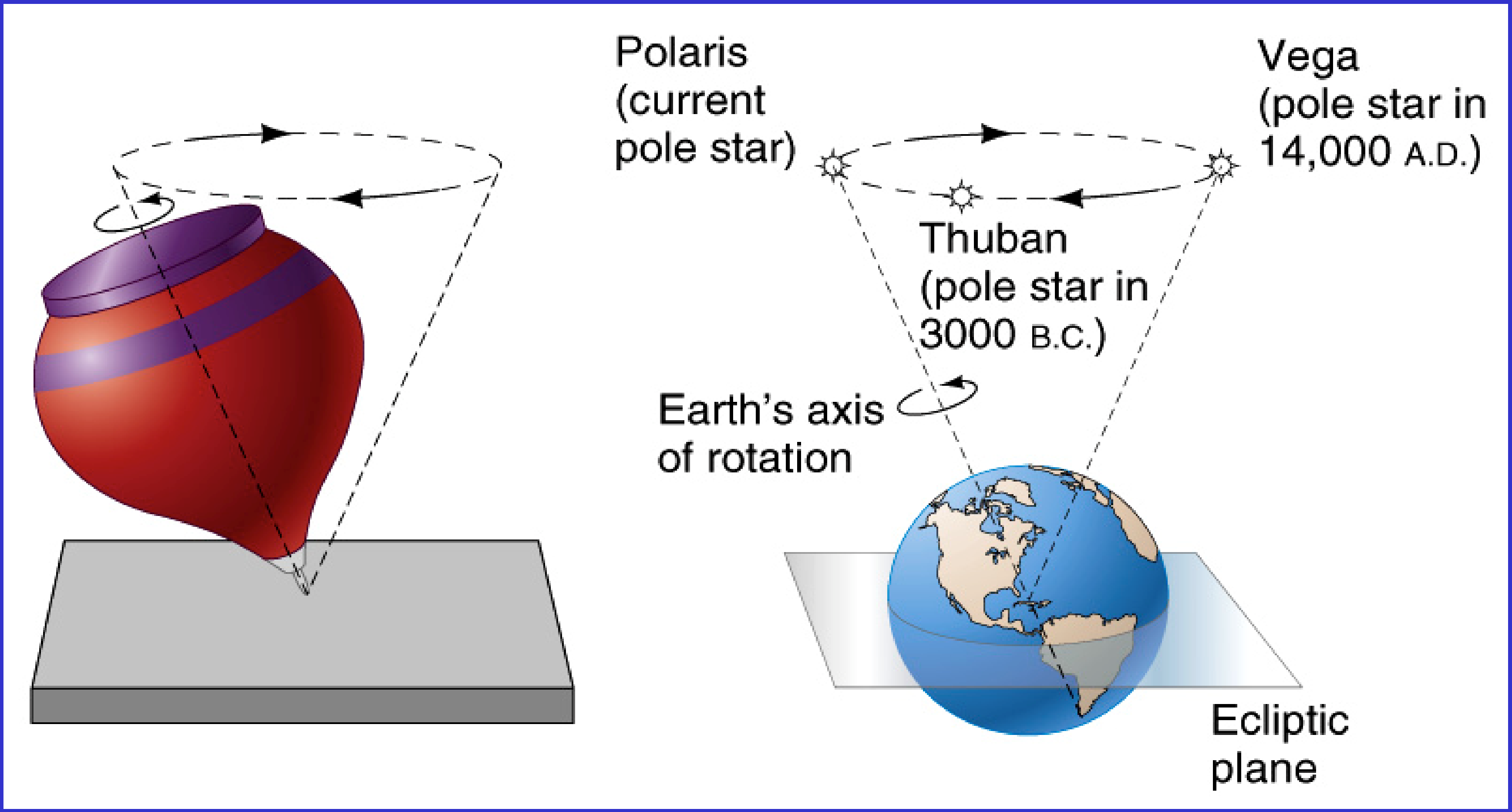
How Does the Tilt Affect Climate?



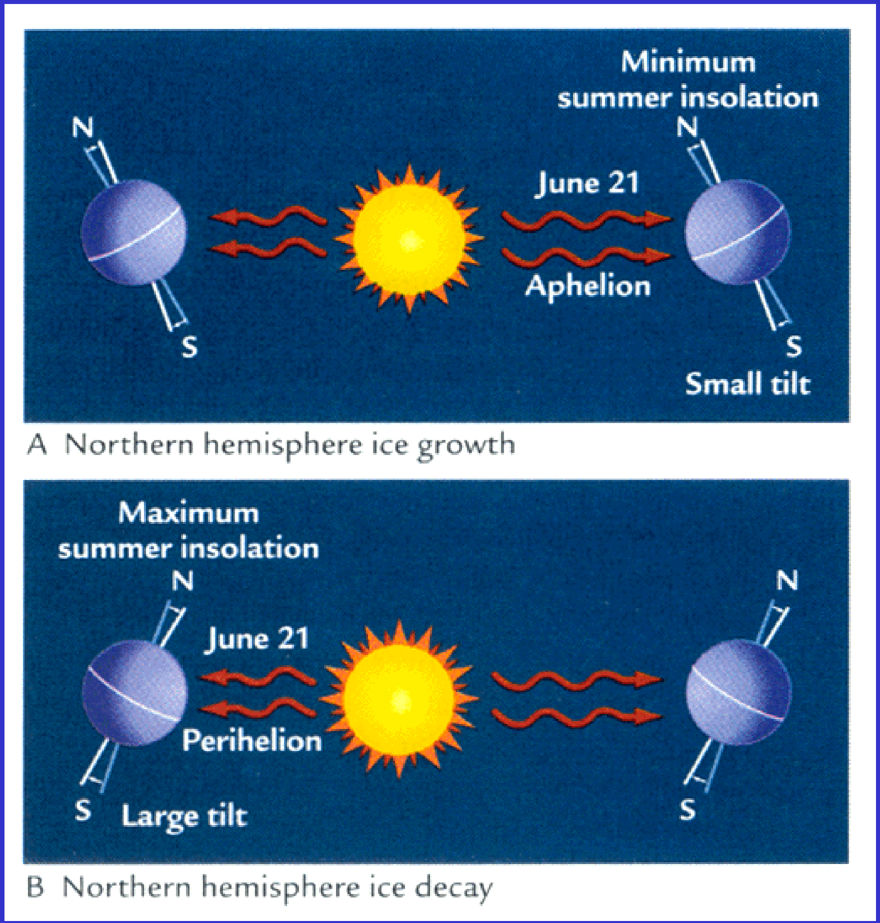
(from *Earth's Climate: Past and Future*)

- At present-day, the axis is tilted at an angle of 23.5°, referred to as Earth's "obliquity", or "tilt".
- The Sun moves back and forth through the year between 23.5°N and 23.5°S.
- Earth's 23.5° tilt also defines the 66.5° latitude of the Artic and Antarctic circles. No sunlight reaches latitudes higher than this in winter day.
- The tilt produces ***seasons***!!

Precession


Polaris
(current
pole star)
Vega
(pole star in
14,000 A.D.)
Thuban
(pole star in
3000 B.C.)
Earth's axis
of rotation
Ecliptic
plane

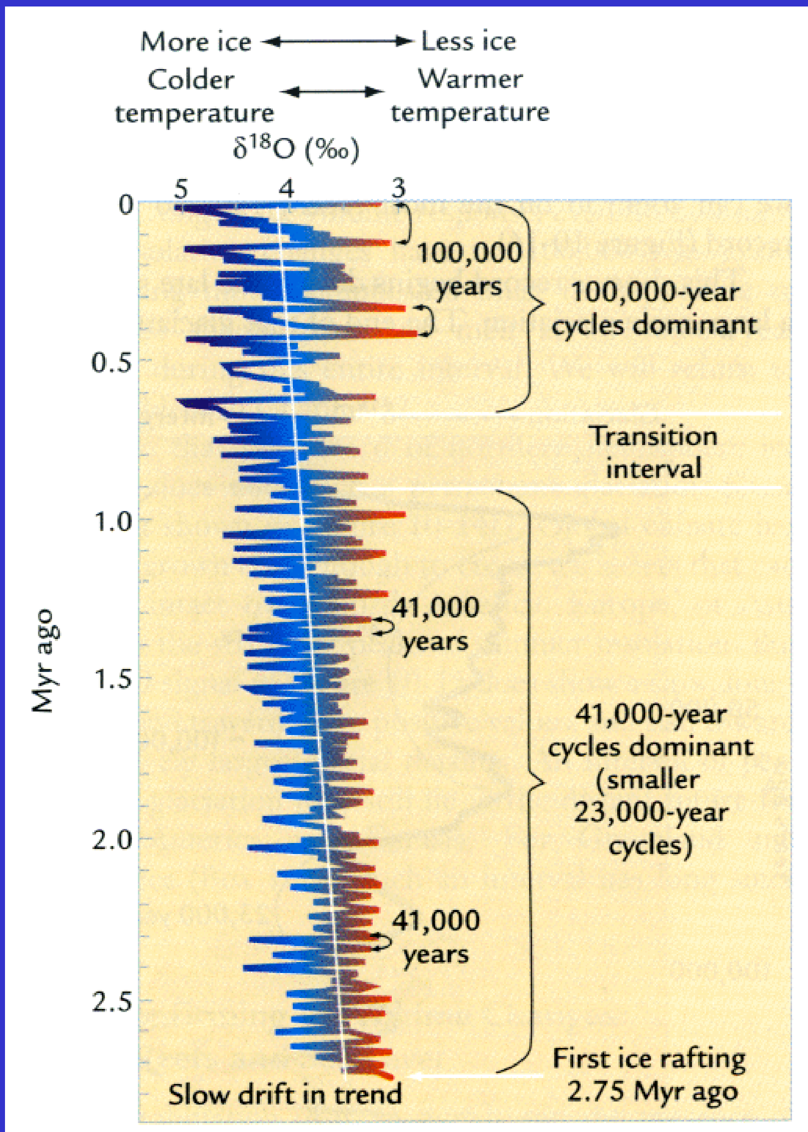
Milankovitch Theory



(from Earth's Climate: Past and Future)

- Milankovitch suggested that the critical factor for Northern Hemisphere continental glaciation was the amount of summertime insolation at high northern latitudes.
- Low summer insolation occurs during times when Earth's orbital tilt is small.
- Low summer insolation also results from the fact that the northern hemisphere's summer solstice occurs when Earth is farthest from the Sun and when the orbit is highly eccentric.

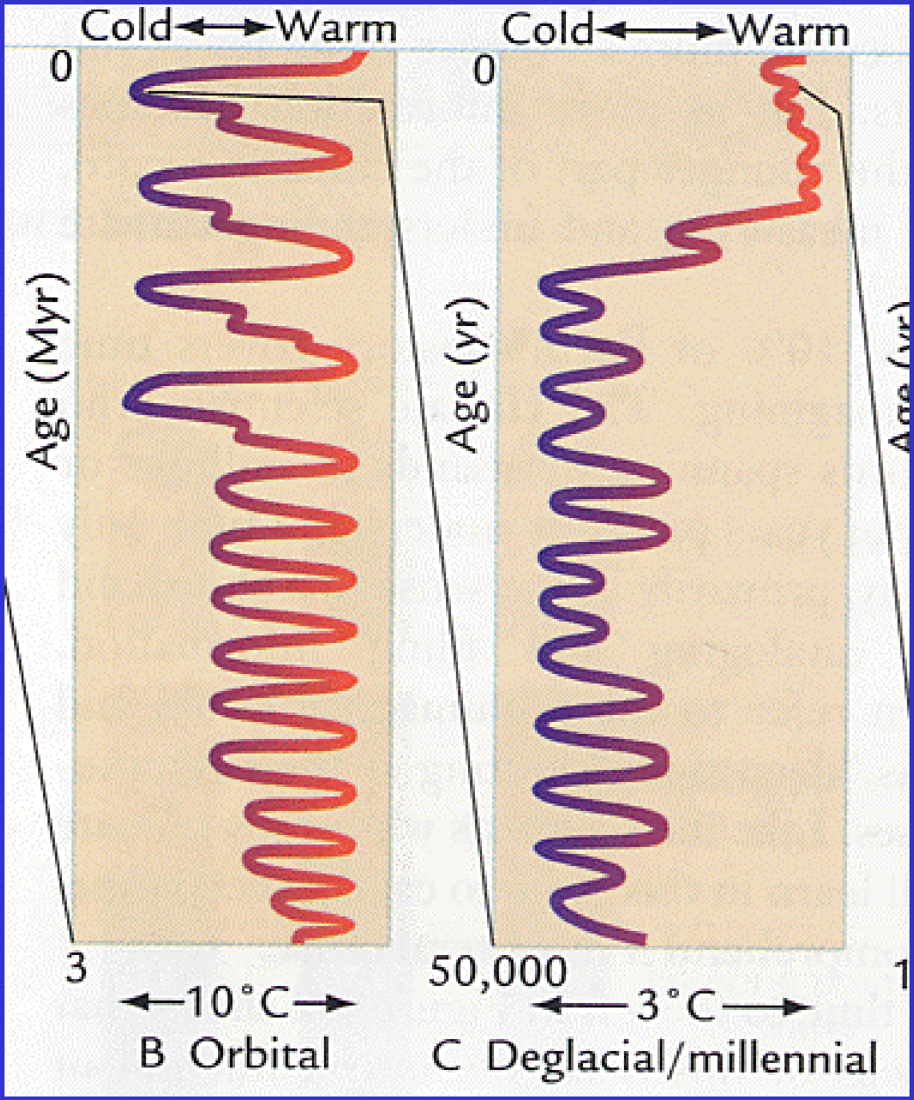
Evidence of Ice Sheet Evolution



(from Earth's Climate: Past and Future)

- This figures shows a North Atlantic Ocean sediment core holds a 3 Myr $\delta^{18}O$ record of ice volume and deep-water temperature changes.
- There were no major ice sheets before 2.75 Myr ago.
- After that, small ice sheets grew and melted at cycles of 41,000 and 23,000 years until 0.9 Myr ago.
- After 0.9 Myr ago, large ice sheet grew and melted at a cycle of 100,000 years.

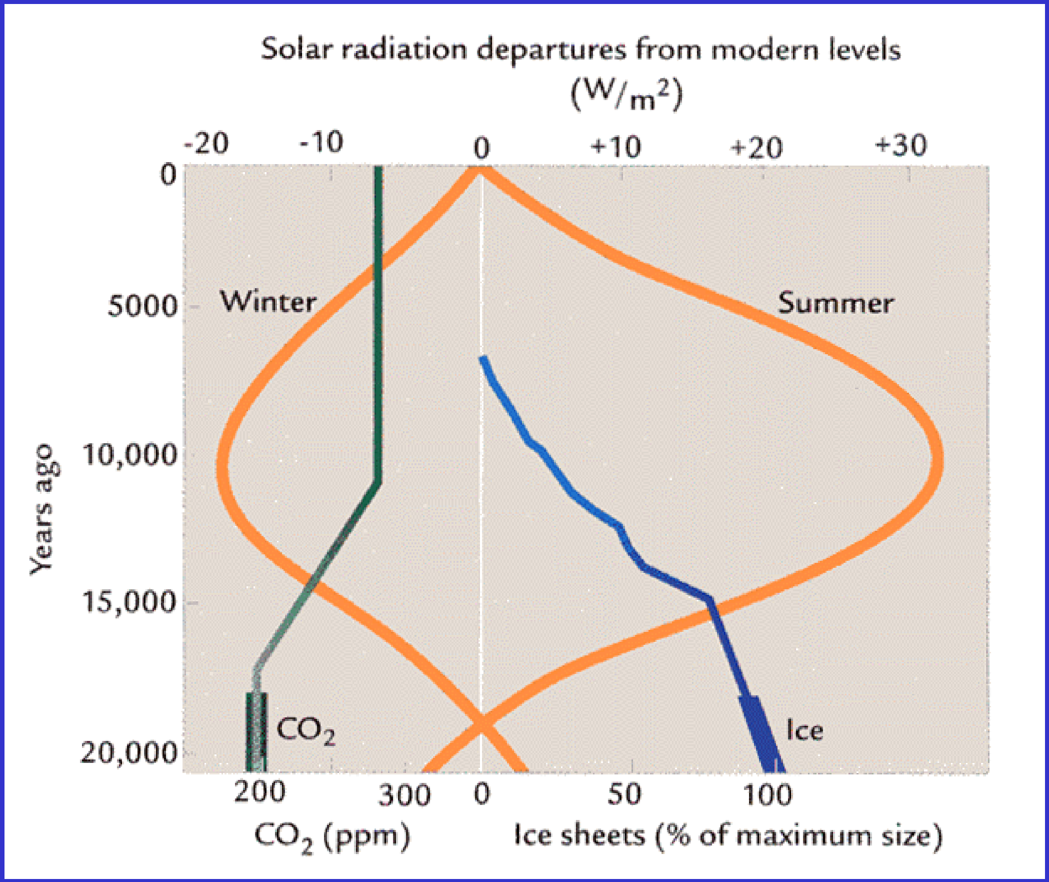
Deglacial and Millennial Scales



(from *Earth's Climate: Past and Future*)

- Climate changes of these scales in the past several tens of thousands of years occurred within the time span of recorded human civilization.

The Last Glacial Maximum (21,000 Years Ago)



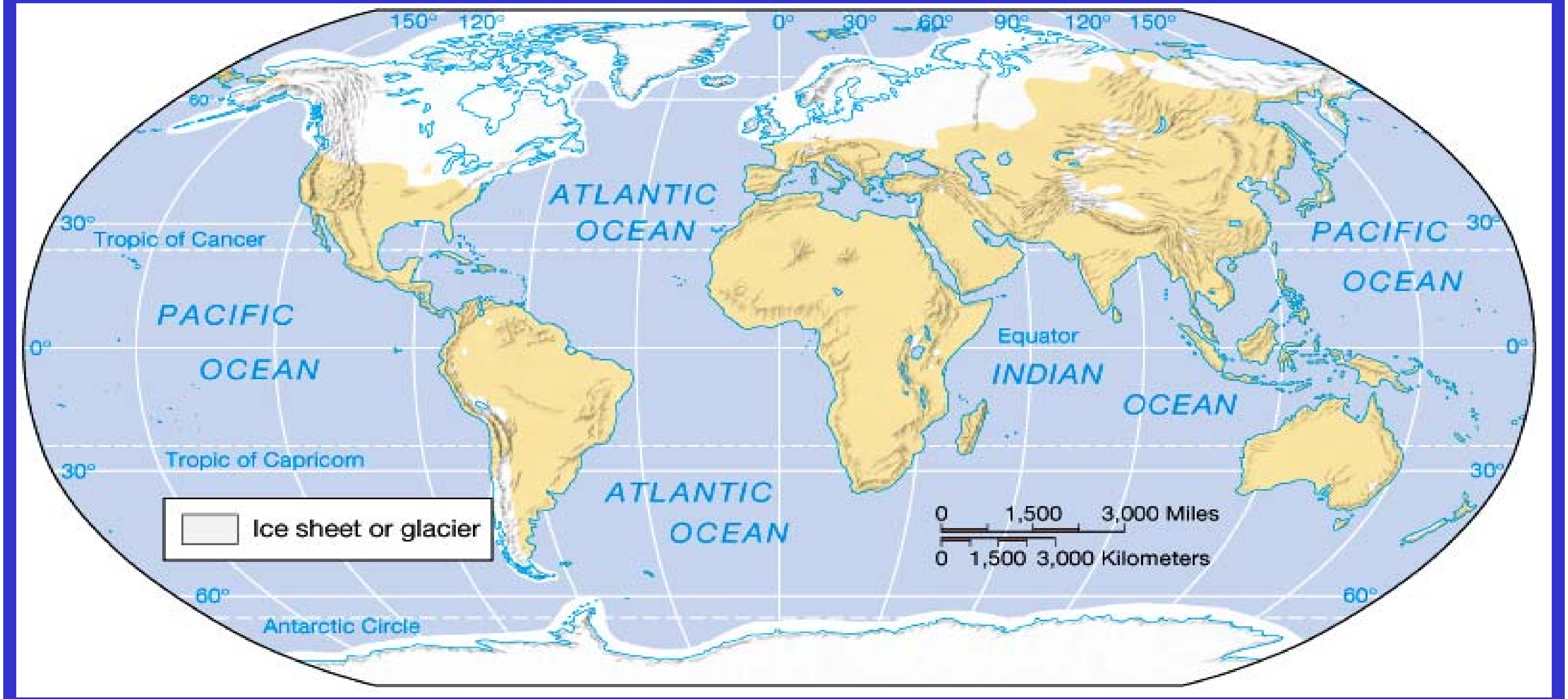
(from *Earth's Climate: Past and Future*)

- Seasonal insolation levels 21,000 years ago were nearly identical to those today.
- The only factors that can explain the colder and drier glacial maximum climate 21,000 years ago are:

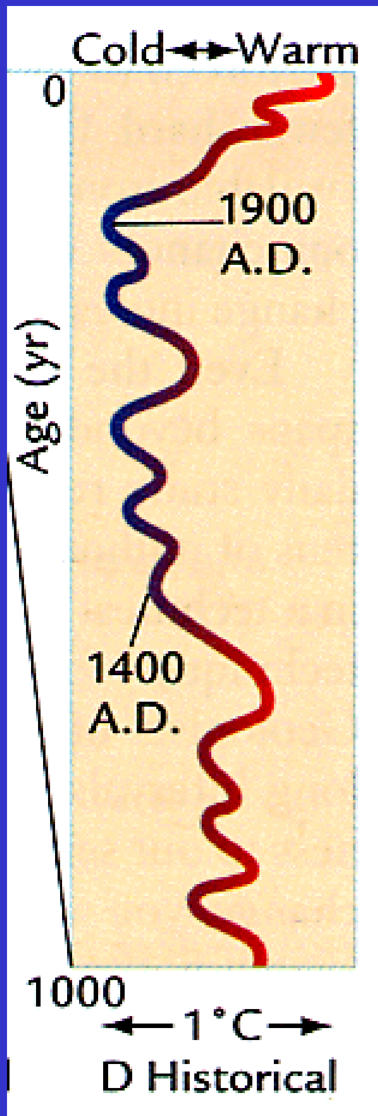
  (1) the large ice sheets

  (2) the lower values of greenhouse gases.

Ice extent during the last glacial



Historical Climate Changes

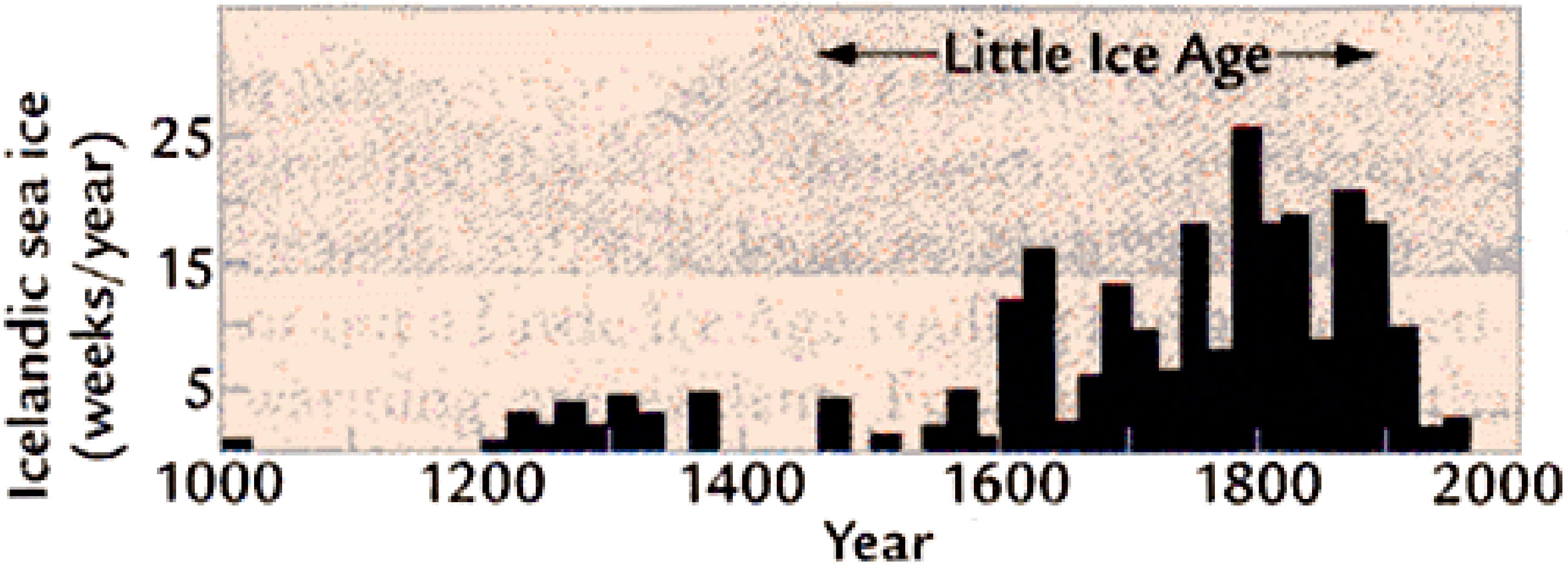


(from *Earth's Climate: Past and Future*)

- Climate changes over the last 1000 years have been smaller than those over tectonic, orbital, and glacial-age millennial time scales, never exceeding 1°C on a global basis.
- Climate changes over the last several thousand years have been highly variable in pattern from region to region.

The Little Ice Age

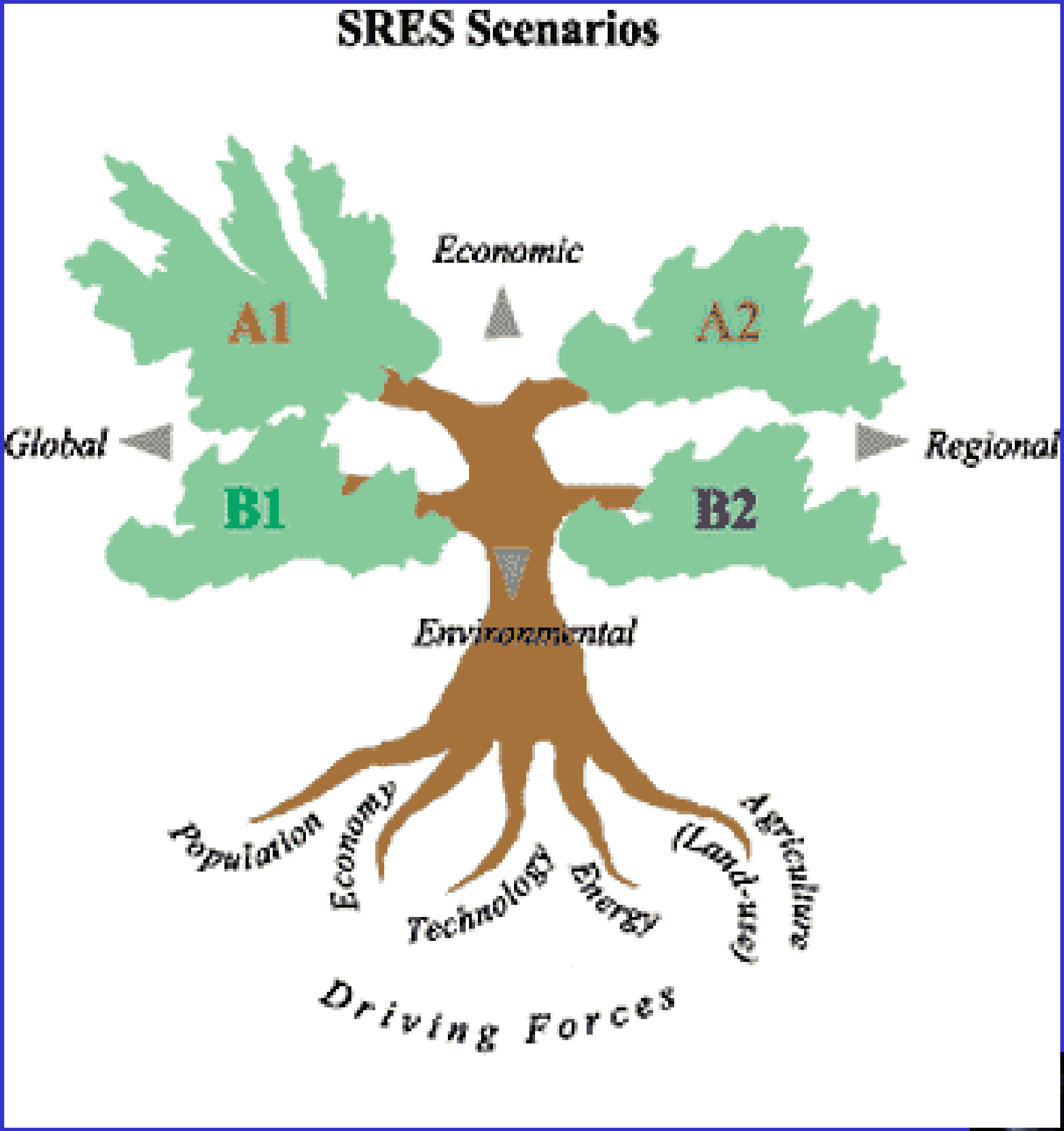
(from *Earth's Climate: Past and Future*)



- **Medieval Warming**: A relatively warm climate near 1000 to 1300.
- **Little Ice Age**: The cooling during 1400-1900 that seriously affect Europe.
- **Twentieth-Century Warming**

IPCC AR4
Ch. 10: Global Climate Projections

IPCC Special Report on Emission Scenarios (SRES)



A1 Scenario

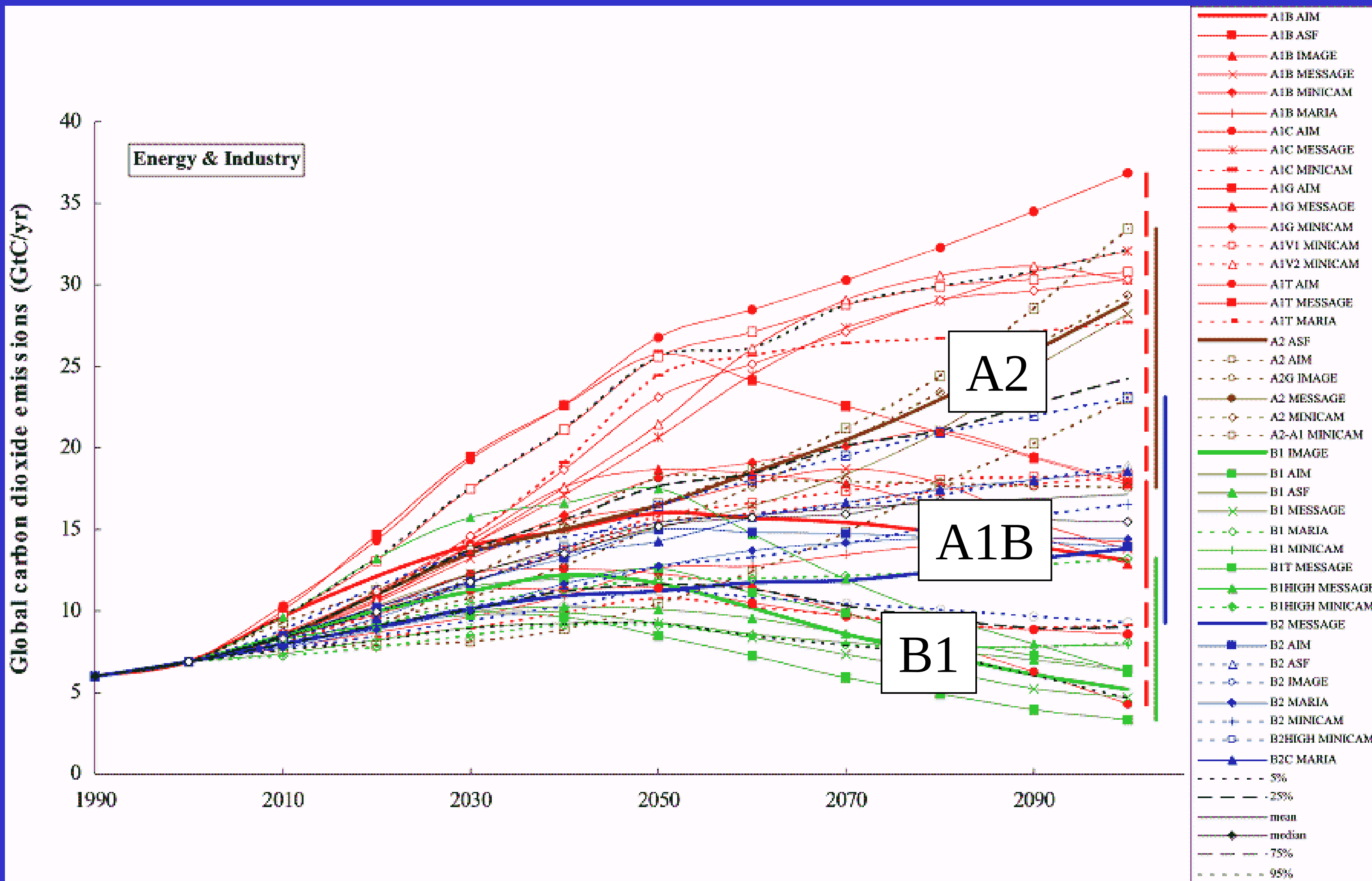
- The A1 story line is split into 4 scenarios which each are modeled in different ways.

- There is an energy intensive A1 group called ***A1T***, an oil and gas resource focused A1 called ***A1G***, a coal based A1 resource ***A1C***, or a mix of resources which was called ***A1B***.

AR4 Simulations

- The AR4 scenarios were bases on three scenarios: ***A2*** (high emission), ***A1B*** (medium emission), and ***B1*** (low emission).

CO2 Emission for All Scenarios



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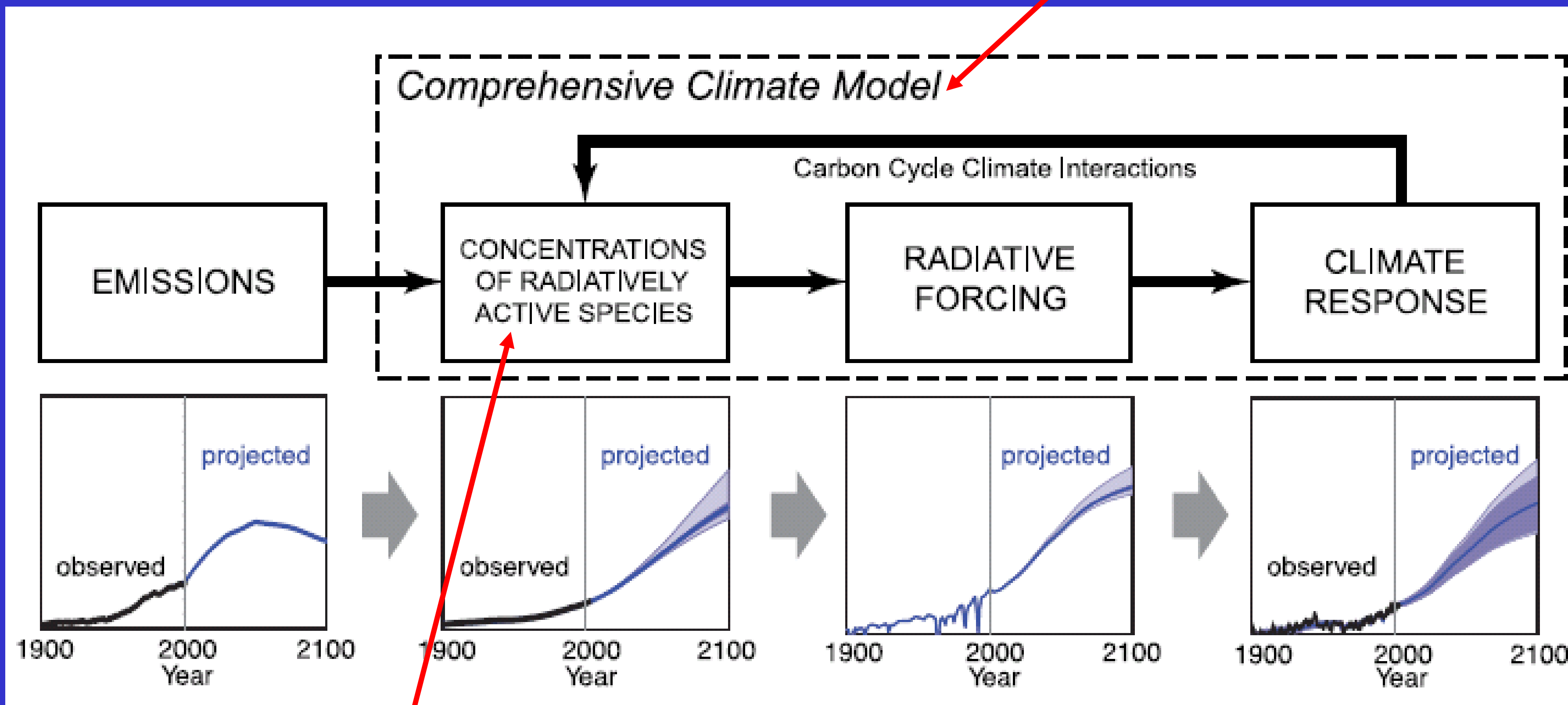
Multi-model (23 AOGCMs) ensembles

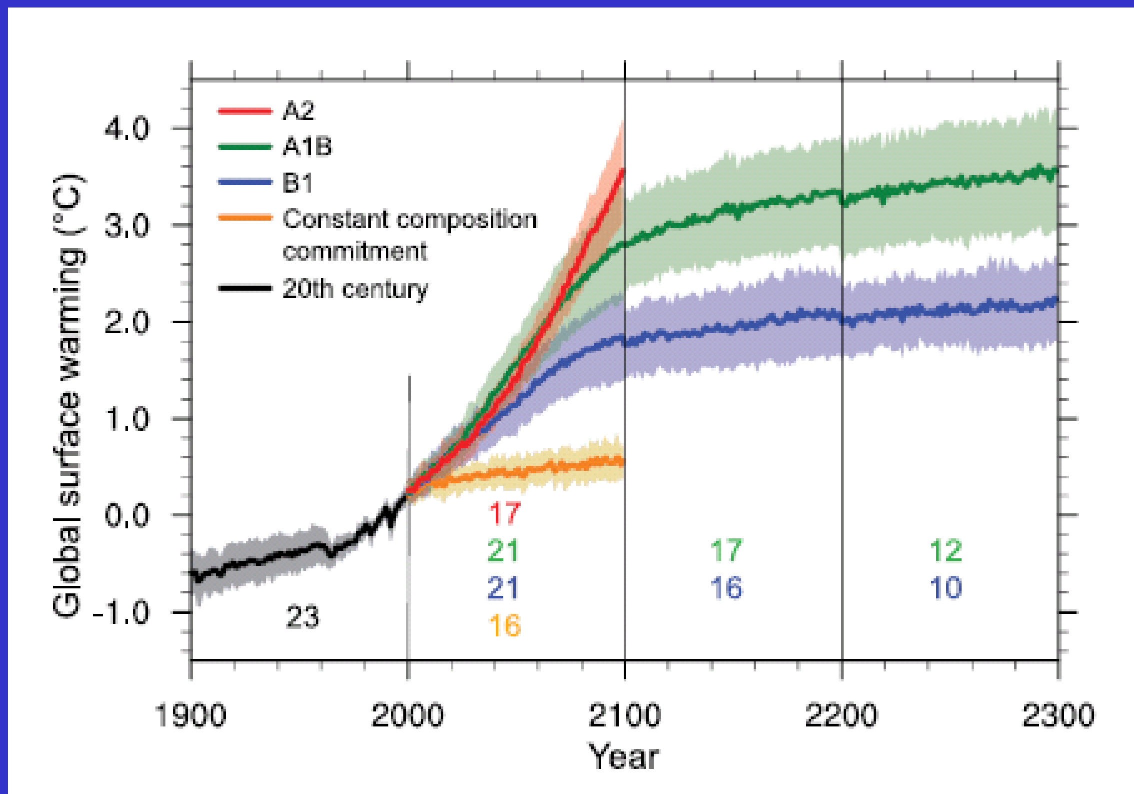


Section 10.2

CO_2, CH_4, N_2O, CFC, SO_4

Projected Surface Warming

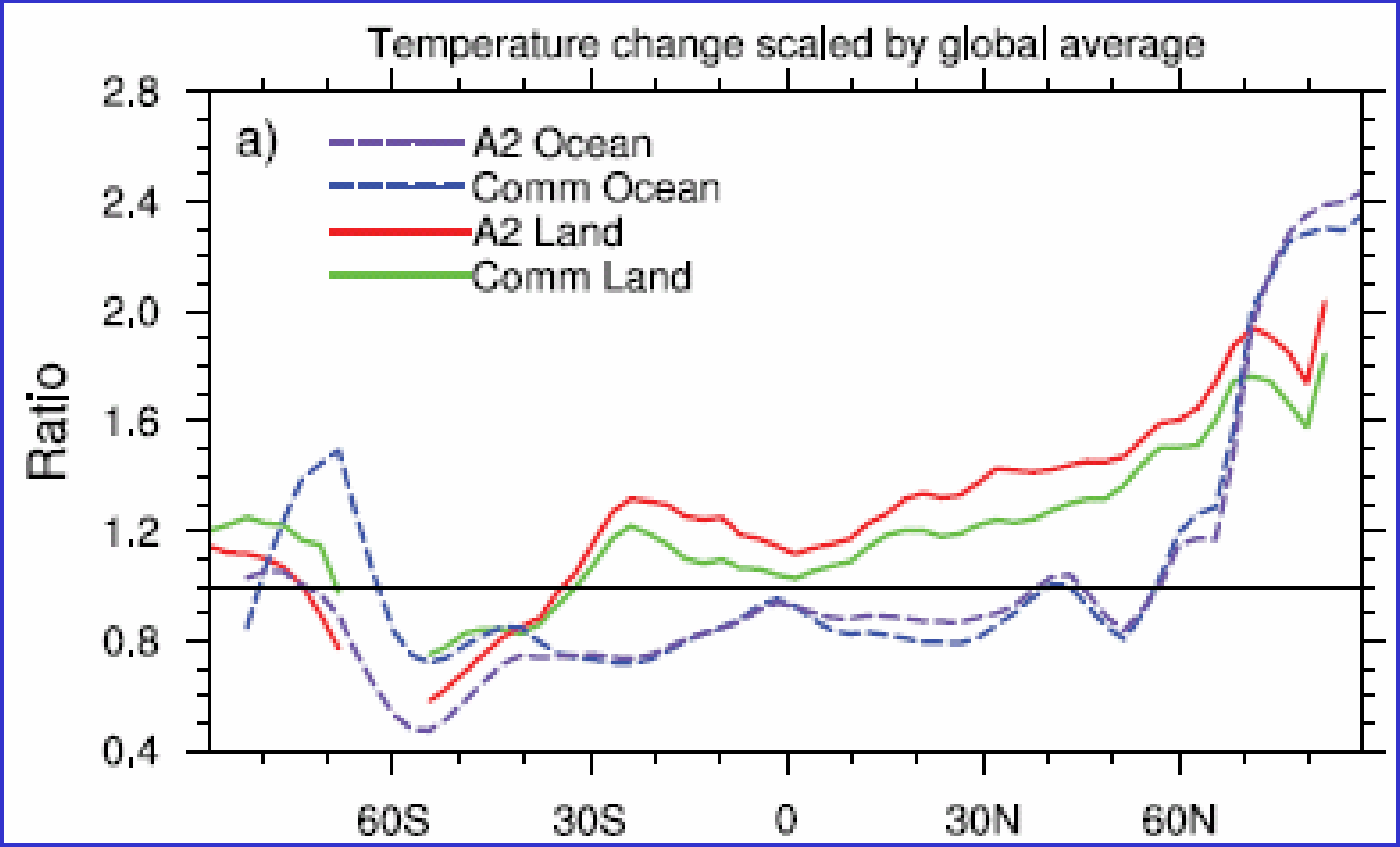
(relative to 1980-1999)



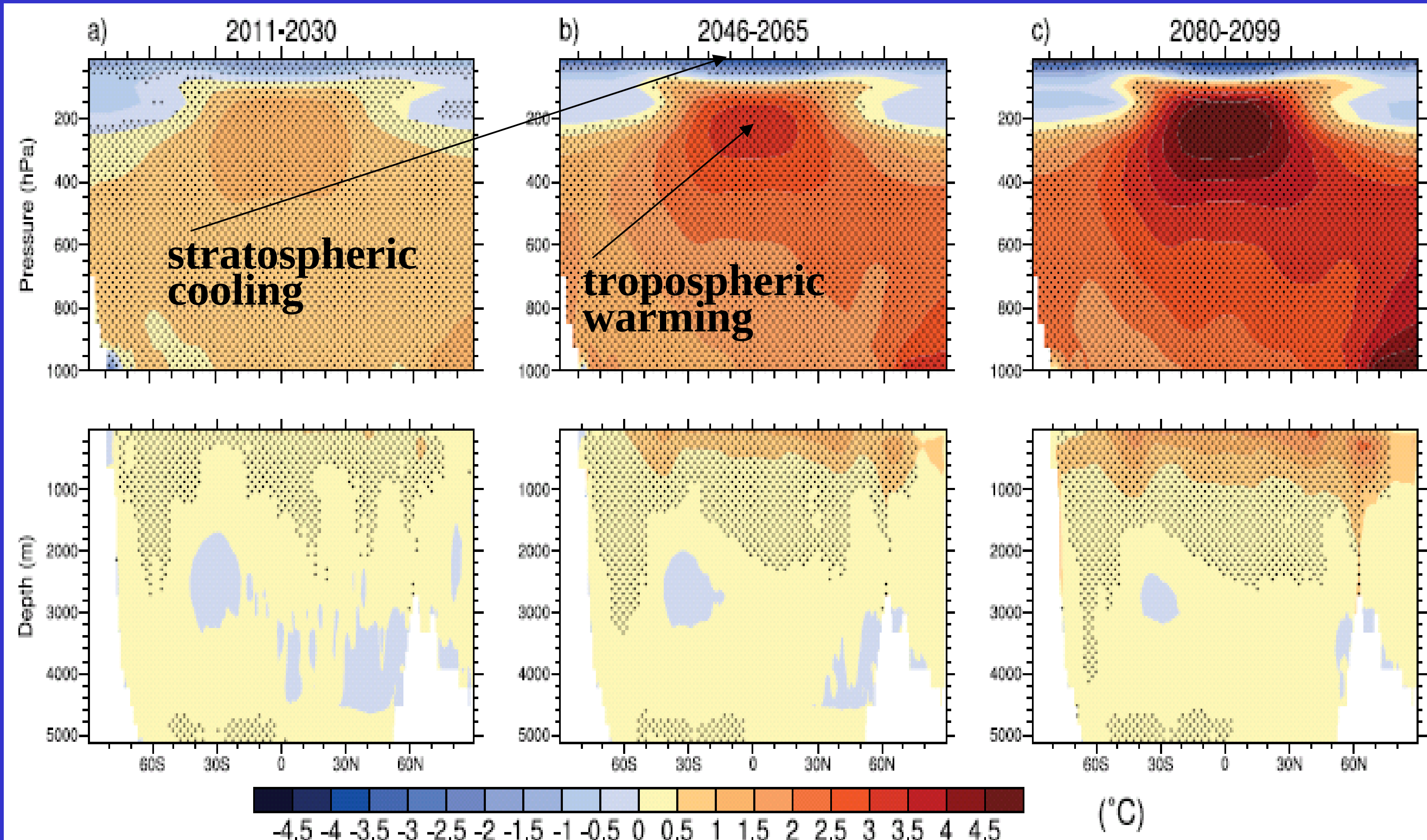
	Global mean warming (°C)			
	2011–2030	2046–2065	2080–2099	2180–2199
A2	0.64	1.65	3.13	
A1B	0.69	1.75	2.65	3.36
B1	0.66	1.29	1.79	2.10
Commit[a]	0.37	0.47	0.56	

Warming Pattern / Ocean vs. Land

(during 2080-2099)



Vertical Distribution of Warming



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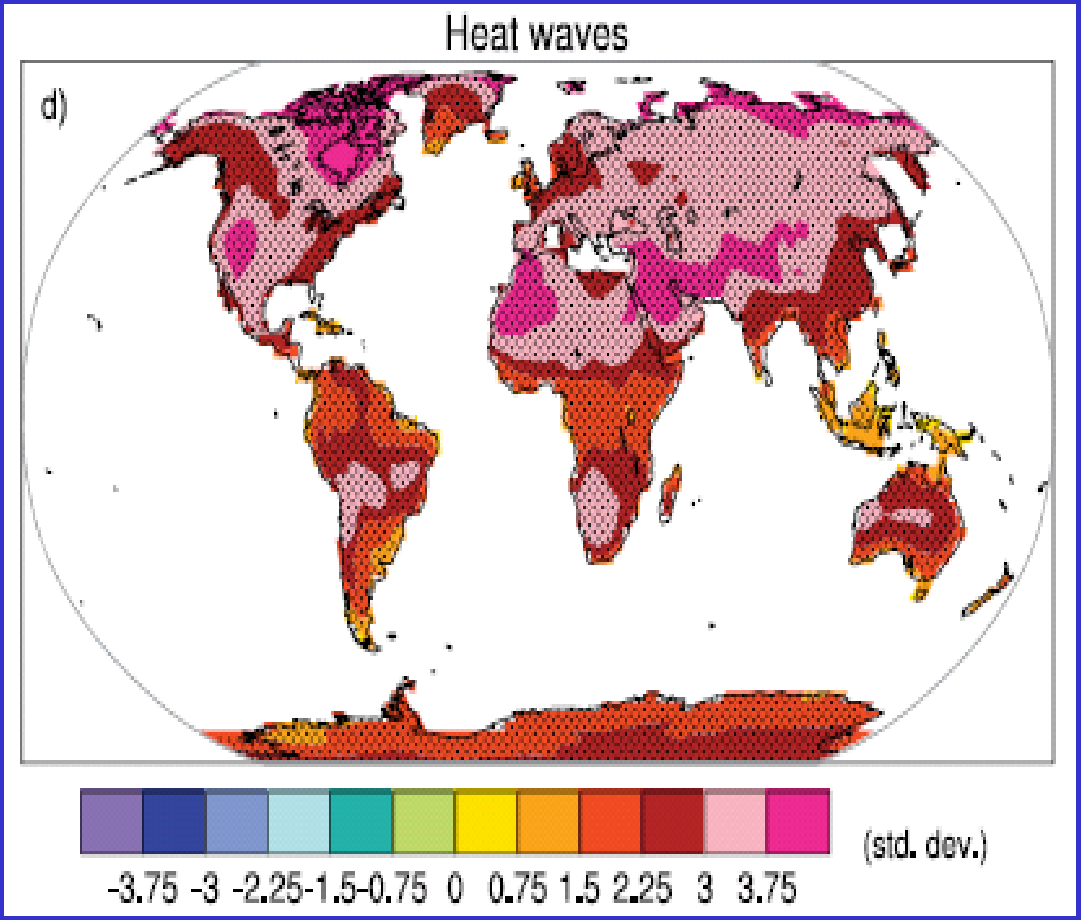
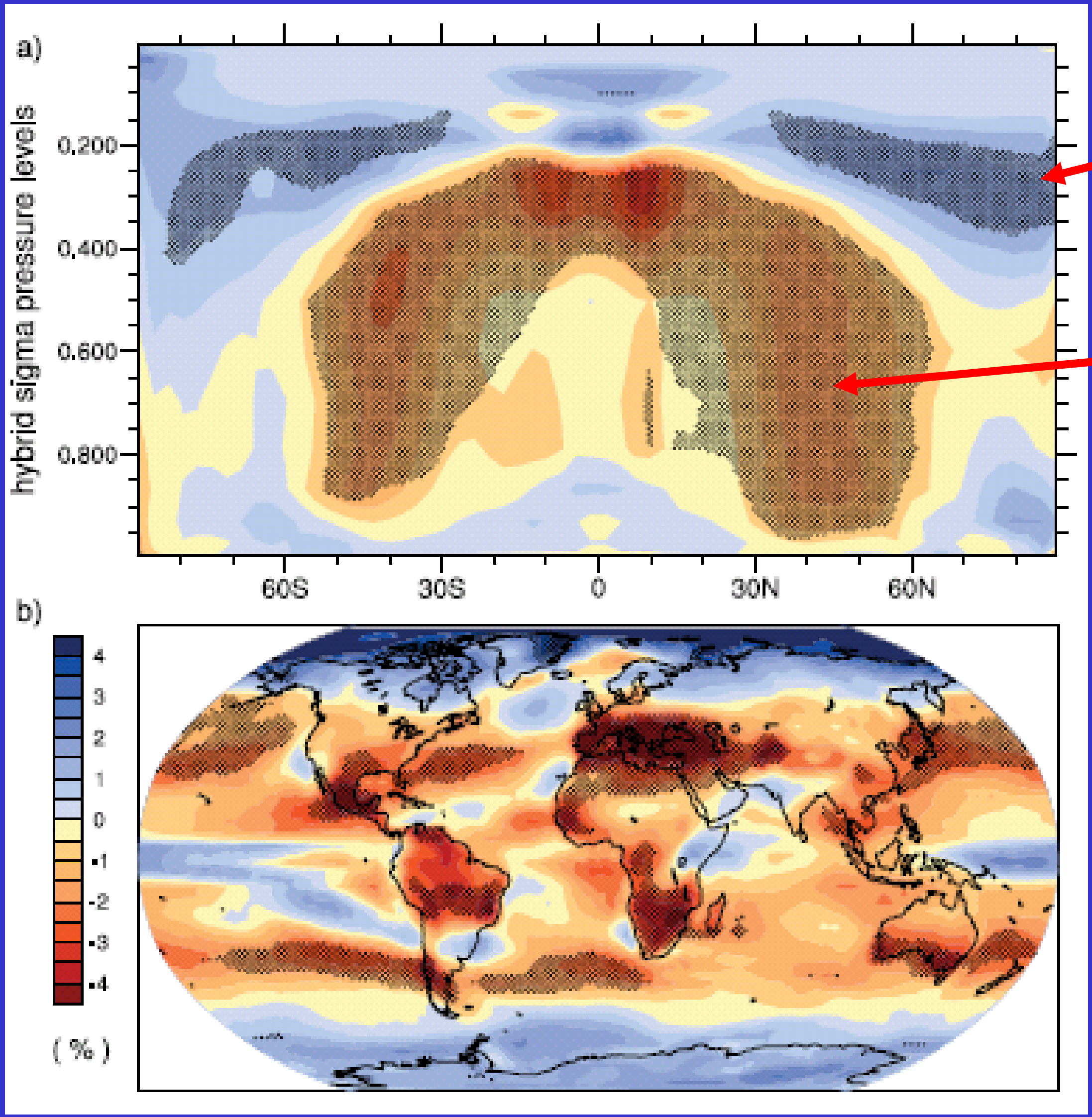
Projected Temperature Extreme



- It is *very likely* that heat waves will be more intense, more frequent and longer lasting in a future warmer climate. Cold episodes are projected to decrease significantly.
- Almost everywhere, daily minimum temperatures are projected to increase faster than daily maximum temperatures, leading to a decrease in diurnal temperature range.

Projected Changes in Cloud Cover

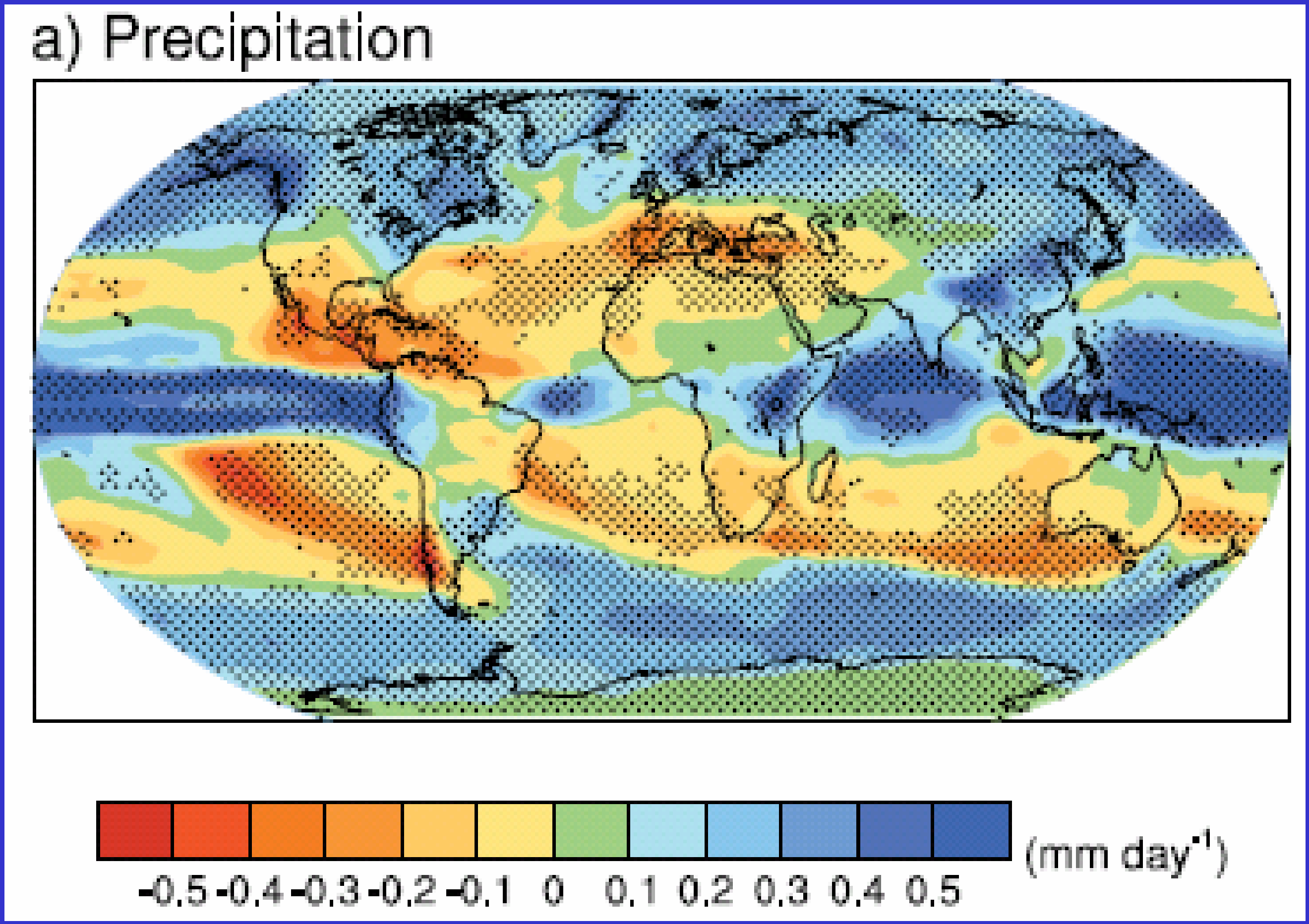


more high clouds

less middle clouds

decease cloud cover

Projected Precipitation Changes

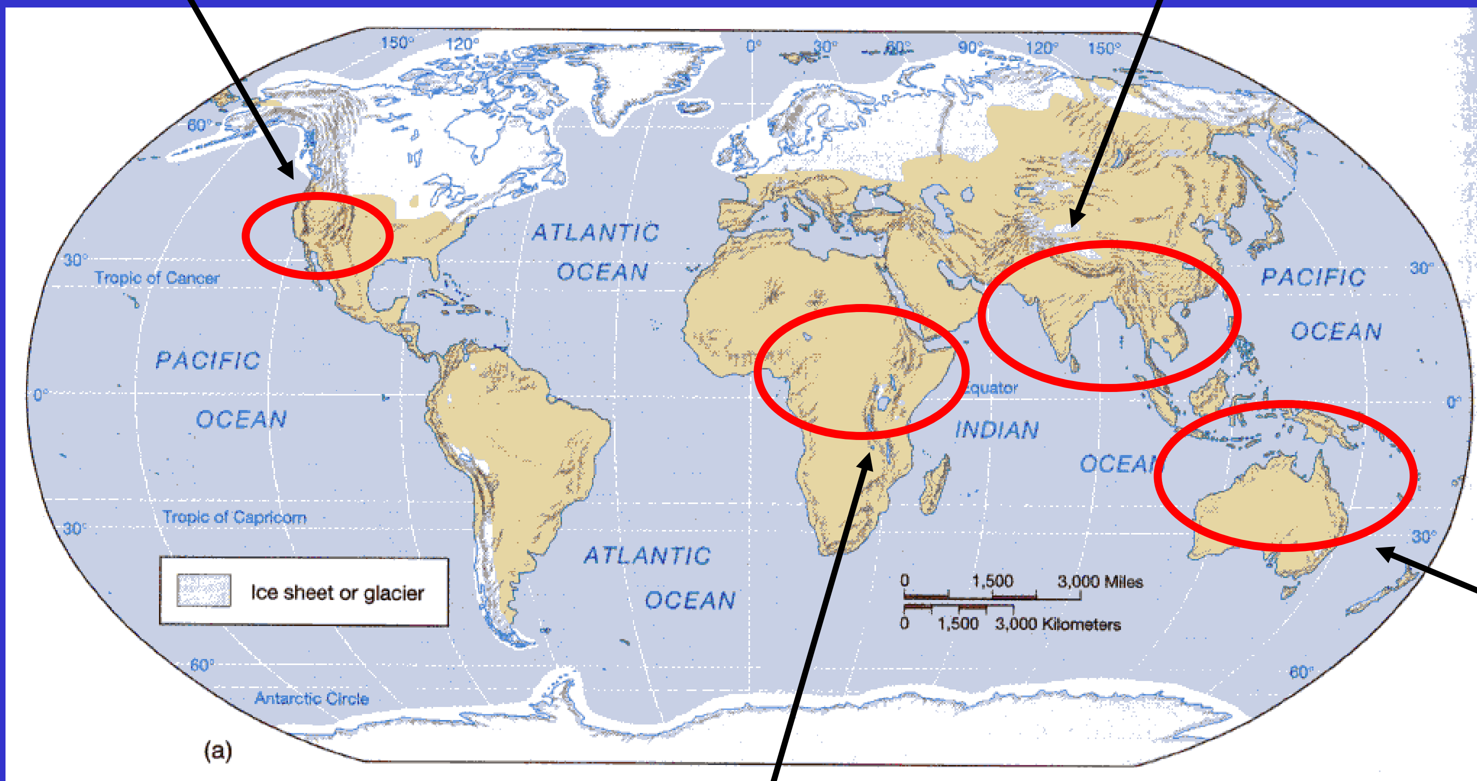


- Precipitation generally increases in the areas of regional tropical precipitation maxima (such as the monsoon regimes) and over the tropical Pacific.
- Precipitation generally decreases in the subtropics and increases at high latitudes → due to the poleward shift of the storm track → due to the expansion of the Hadley circulation.

Projected Monsoon Precipitation Changes

North America Monsoon **(decrease)**

Asian Monsoon **(increase)**

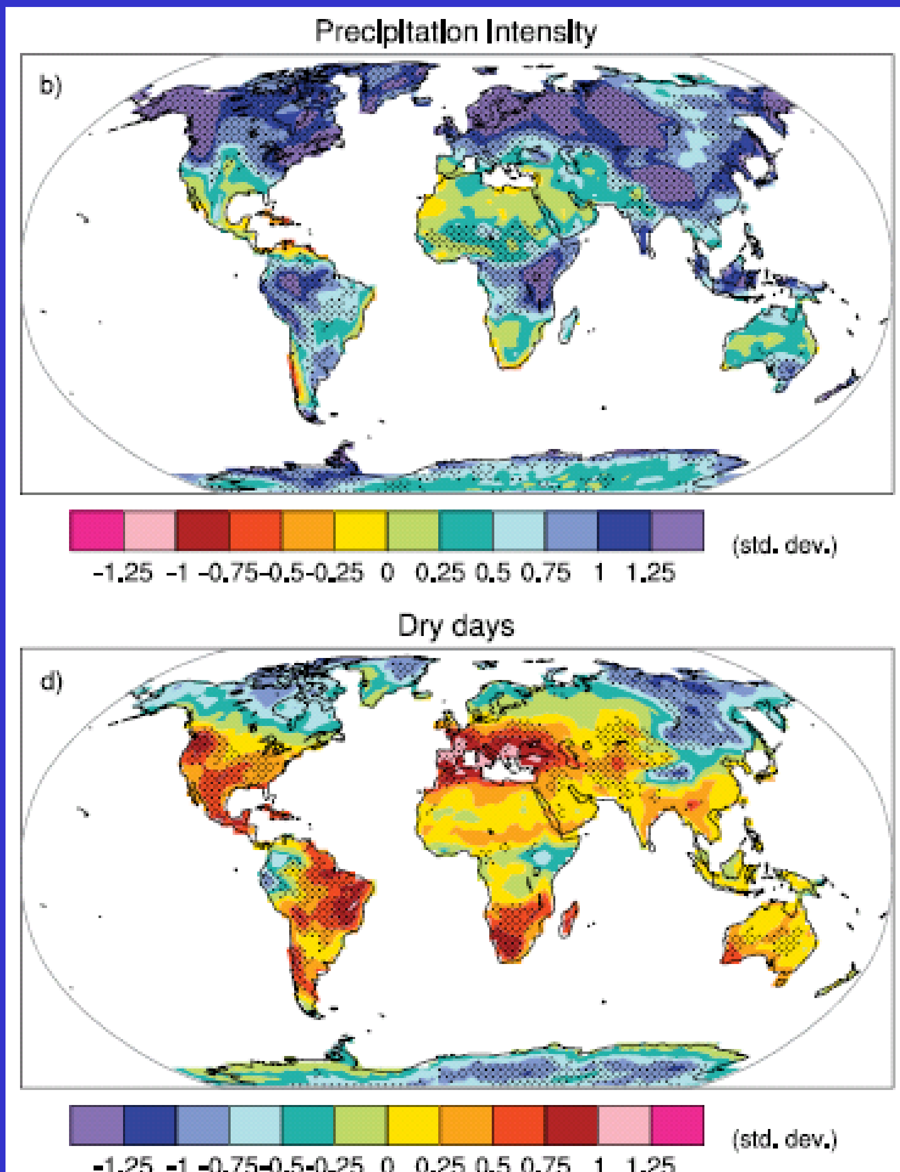


Australian Monsoon **(increase)**

Weaker monsoon circulation
+ more water vapor available
= increase monsoon rainfalls

West Africa Monsoon **(increase)**

Projected Precipitation Extreme



- Intensity of precipitation events is projected to increase, particularly in tropical and high latitude areas that experience increases in mean precipitation.

- The number of dry days increases between precipitation events in the subtropics and lower mid-latitudes

- There is a tendency for drying of the mid-continental areas during summer, indicating a greater risk of droughts in those regions.

Projected Hurricane Activities

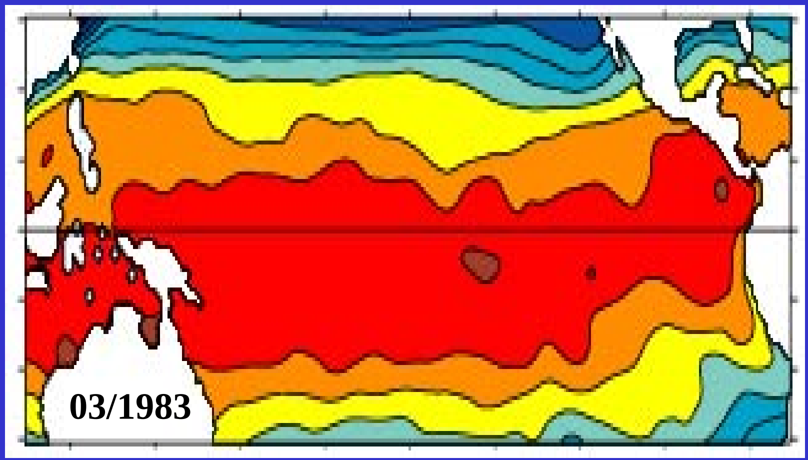
- Most recent published modelling studies projected a decrease in the overall number of storms.
- Although less confidence, studies projected decrease of relatively weak storms in most basins, with an increase in the numbers of the most intense tropical cyclones.

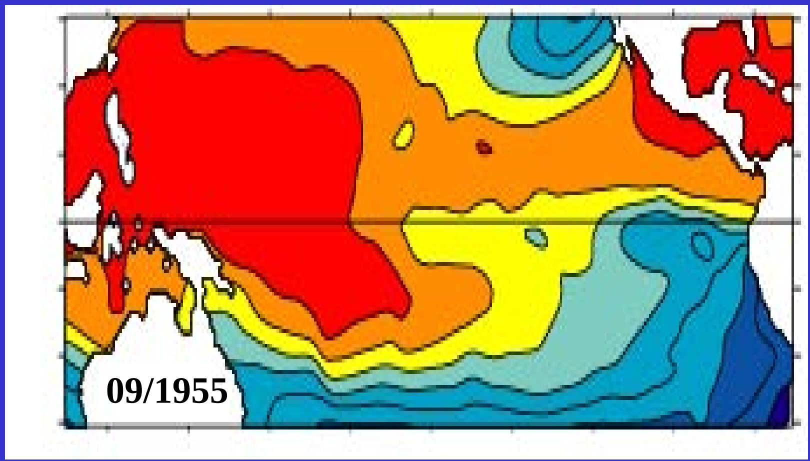
Projected Extratropical Storms

- For a future warmer climate, a poleward shift of storm tracks in both hemispheres that is particularly evident in the SH, with greater storm activity at higher latitudes.
- A future tendency for more intense extratropical storms, although the number of storms could be less.

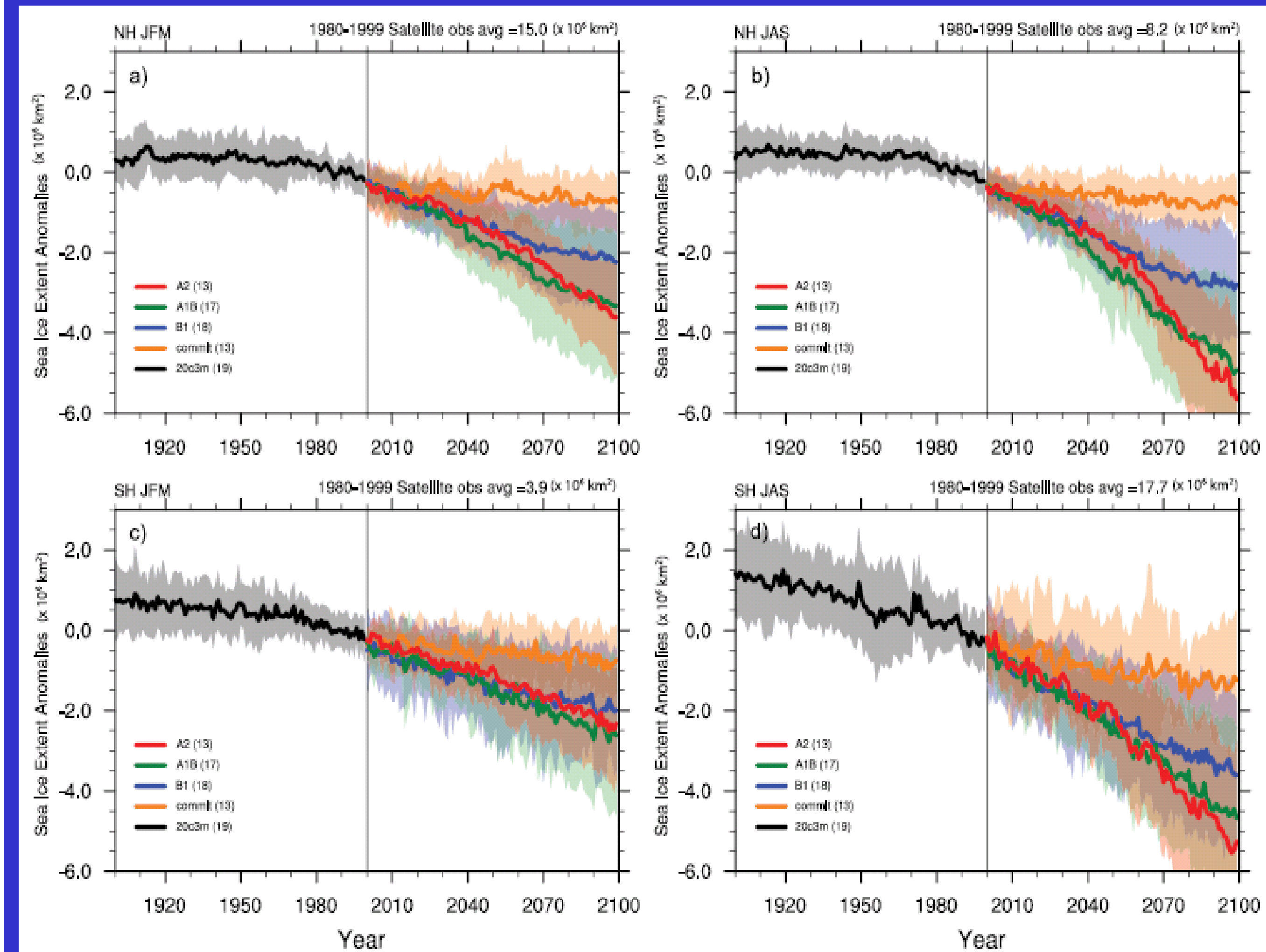
Projected ENSO Activity

- No conclusion: different AOGCMs project different results.
- Mean state in the Pacific will become more El Nino-like.





Projected Sea Ice Cover



- Sea Ice cover will reduce in both the Arctic and Antarctic.
- .The decline will be faster in summer than in winter.
- The decline will be larger in the Arctic than the Antarctic.
- Sec ice volume decreases more quickly than sea ice cover.

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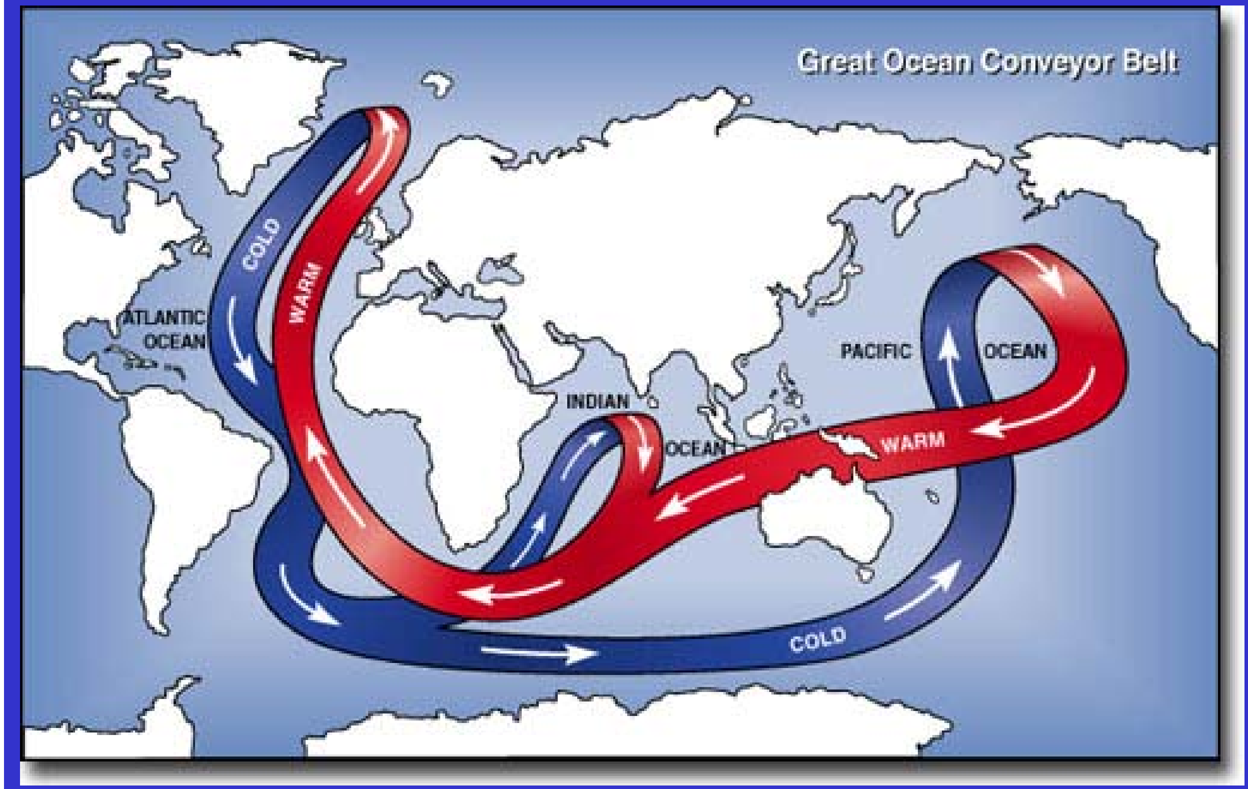
Projected Change in Atlantic Meridional Overturning Circulation (MOC)



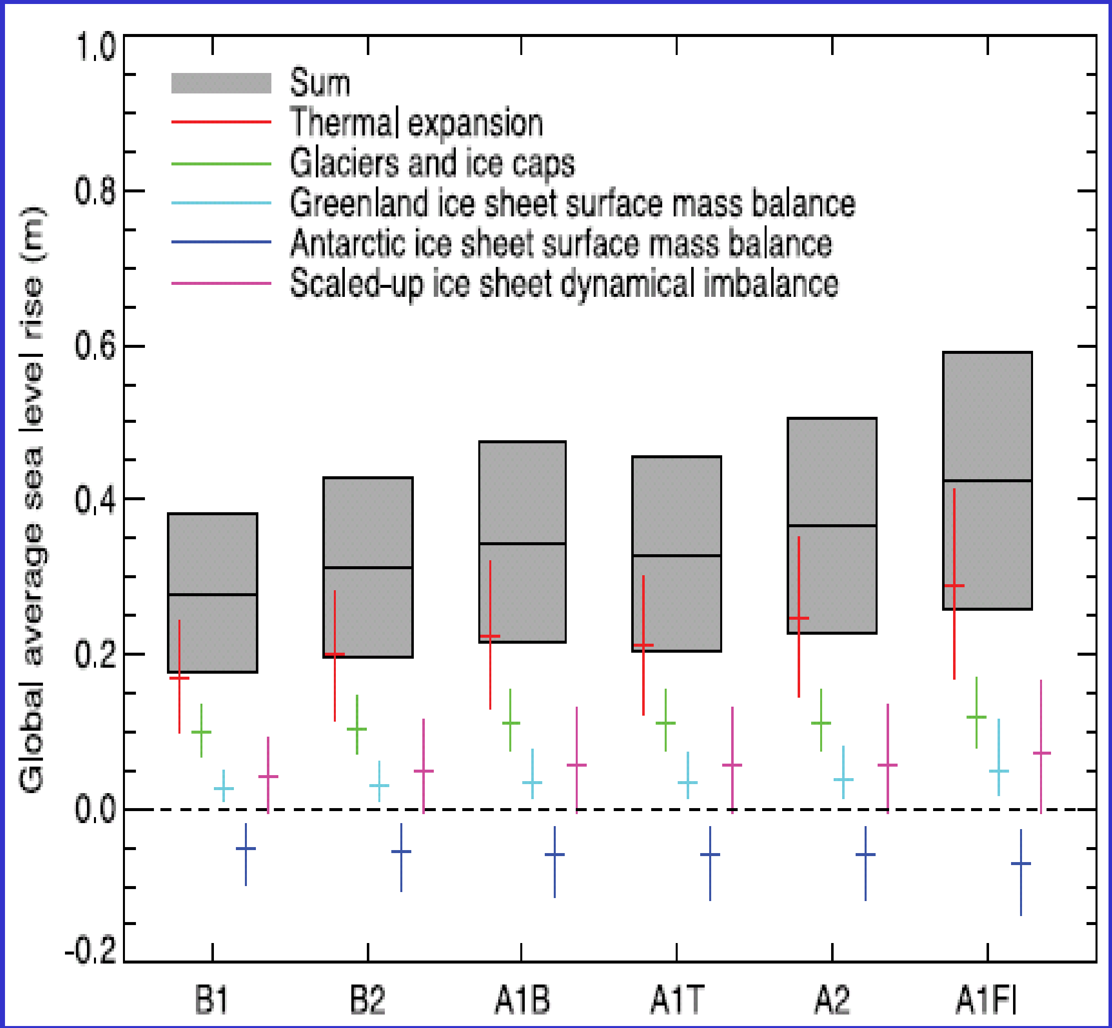
- The MOC is an indicator of ocean circulation changes in response to global warming.
- The MOC is projected to slow down in the future.
- It is due to the warming and increased precipitation at higher latitudes.
- The weakened MOC will help to reduce global warming at higher latitude, because less heat will be transported there.

Positive Climate-Carbon Cycle Feedback

- Future climate change would reduce the efficiency of the Earth system (land and ocean) to absorb anthropogenic CO2.
- As a result, an increasingly large fraction of anthropogenic CO2 would stay airborne in the atmosphere under a warmer climate.

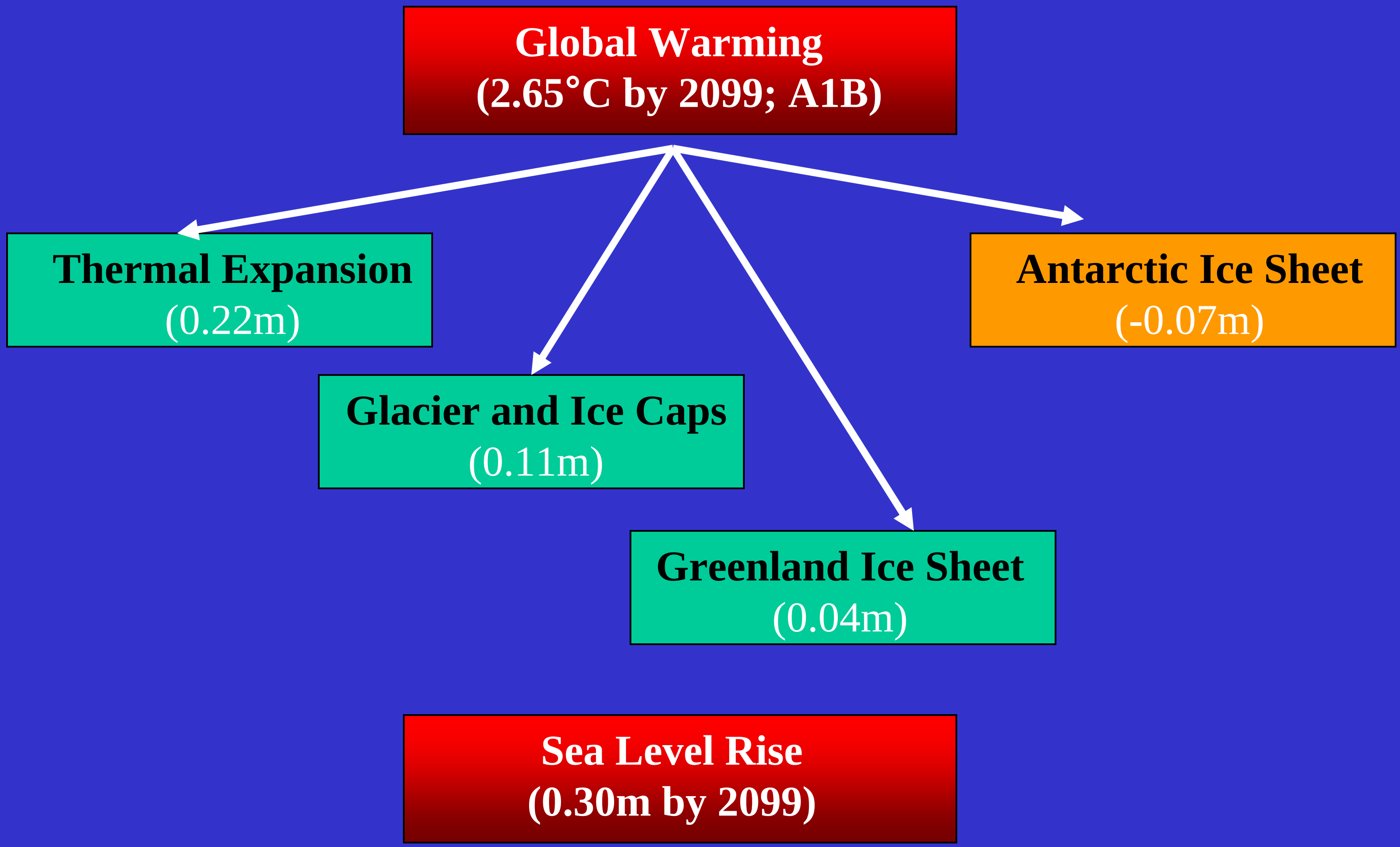
Projected Sea Level Rise

(2090-2099) minus (1980-9999)



- During 2090 to 2099 under A1B, the central estimate of the rate of rise is 3.8 mm yr–1.
- In all scenarios, the average rate of rise during the 21st century *very likely* exceeds the 1961 to 2003 average rate (1.8 ± 0.5 mm yr–1).

Global Warming and Sea-Level Change



IPCC AR4
Ch. 11: Regional Climate Projections

How to Make Regional Projections?

Regional climate change projections presented here are assessed drawing on information from four potential sources:

(1) AOGCM simulations;

(2) Downscaling of AOGCM-simulated data using techniques to enhance regional detail;

(3) Physical understanding of the processes governing regional responses;

(4) Recent historical climate change.

Table 11.1

The time takes for the projected climate response (to the CO2 increase) to be 95% significant, compared to the internal variability.

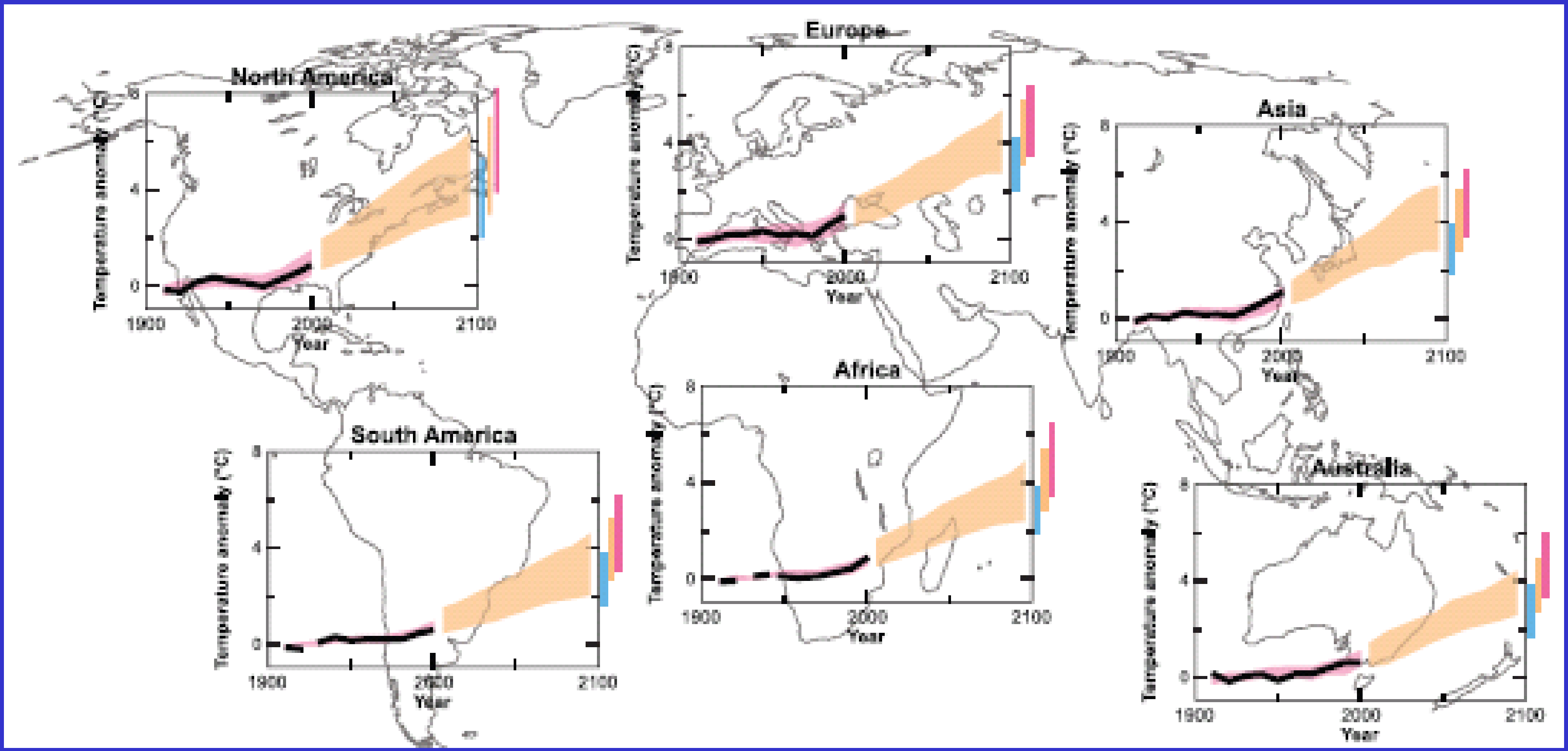
Region[a]	Season	Temperature Response (°C) Min	25	50	75	Max	T yrs	Precipitation Response (%) Min	25	50	75	Max	T yrs	Extreme Seasons (%) Warm	Wet	Dry
POLAR REGIONS																
ARC[b]	DJF	4.3	6.0	6.9	8.4	11.4	15	11	19	26	29	39	25	100	90	0
	MAM	2.4	3.7	4.4	4.9	7.3	15	9	14	16	21	32	25	100	79	0
60N,180E	JJA	1.2	1.6	2.1	3.0	5.3	15	4	10	14	17	20	25	100	85	0
to	SON	2.9	4.8	6.0	7.2	8.9	15	9	17	21	26	35	20	100	96	0
90N,180W	Annual	2.8	4.0	4.9	5.6	7.8	15	10	15	18	22	28	20	100	100	0
ANT[c]	DJF	0.8	2.2	2.6	2.8	4.6	20	-11	5	9	14	31	50	85	34	3
	MAM	1.3	2.2	2.6	3.3	5.3	20	1	8	12	19	40	40	88	54	0
90S,180E	JJA	1.4	2.3	2.8	3.3	5.2	25	5	14	19	24	41	30	83	59	0
to	SON	1.3	2.1	2.3	3.2	4.8	25	-2	9	12	18	36	45	79	42	1
60S,180W	Annual	1.4	2.3	2.6	3.0	5.0	15	-2	9	14	17	35	25	99	81	1

Table 11.1

Region[a]	Season	Temperature Response (°C) Min	25	50	75	Max	T yrs	Precipitation Response (%) Min	25	50	75	Max	T yrs	Extreme Seasons (%) Warm	Wet	Dry
POLAR REGIONS																
ARC[b]	DJF	4.3	6.0	6.9	8.4	11.4	15	11	19	26	29	39	25	100	90	0
	MAM	2.4	3.7	4.4	4.9	7.3	15	9	14	16	21	32	25	100	79	0
60N,180E	JJA	1.2	1.6	2.1	3.0	5.3	15	4	10	14	17	20	25	100	85	0
to	SON	2.9	4.8	6.0	7.2	8.9	15	9	17	21	26	35	20	100	96	0
90N,180W	Annual	2.8	4.0	4.9	5.6	7.8	15	10	15	18	22	28	20	100	100	0
ANT[c]	DJF	0.8	2.2	2.6	2.8	4.6	20	-11	5	9	14	31	50	85	34	3
	MAM	1.3	2.2	2.6	3.3	5.3	20	1	8	12	19	40	40	88	54	0
90S,180E	JJA	1.4	2.3	2.8	3.3	5.2	25	5	14	19	24	41	30	83	59	0
to	SON	1.3	2.1	2.3	3.2	4.8	25	-2	9	12	18	36	45	79	42	1
60S,180W	Annual	1.4	2.3	2.6	3.0	5.0	15	-2	9	14	17	35	25	99	81	1

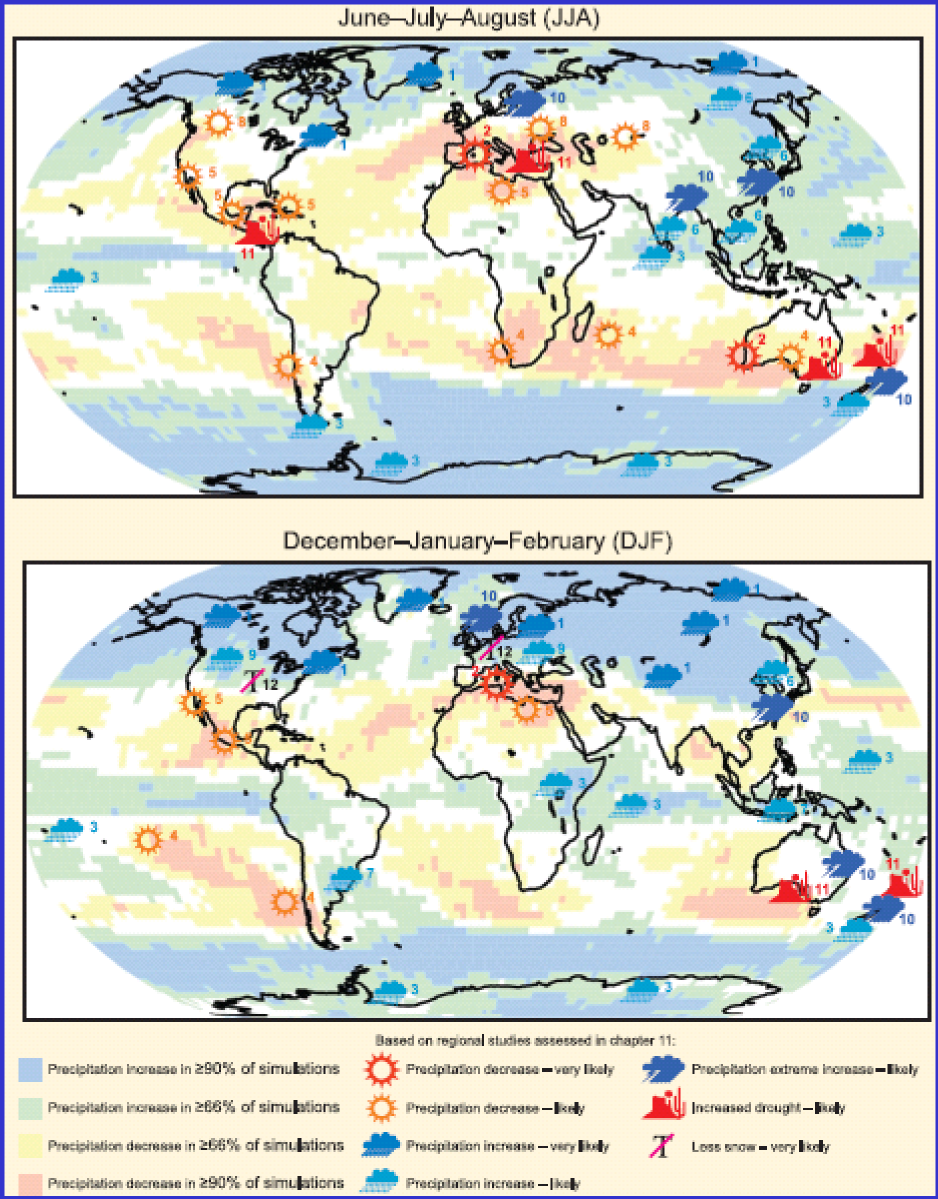
The percentage of the number of seasons/years that the simulated Temp./Precip. in the projected simulations during 2080-2099 are greater than the extreme T/P value during the control simulation of 1980-1999.

Summary of Regional Responses - Temperature

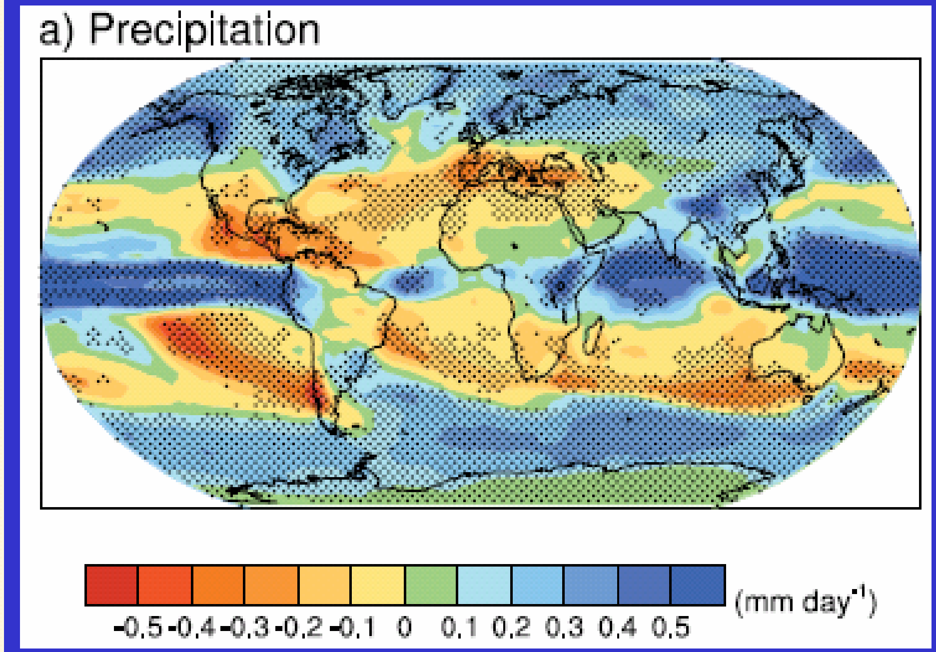


N.H. regions warm more than the S.H. regions

Summary of Regional Responses - Precipitation



(from global projections)



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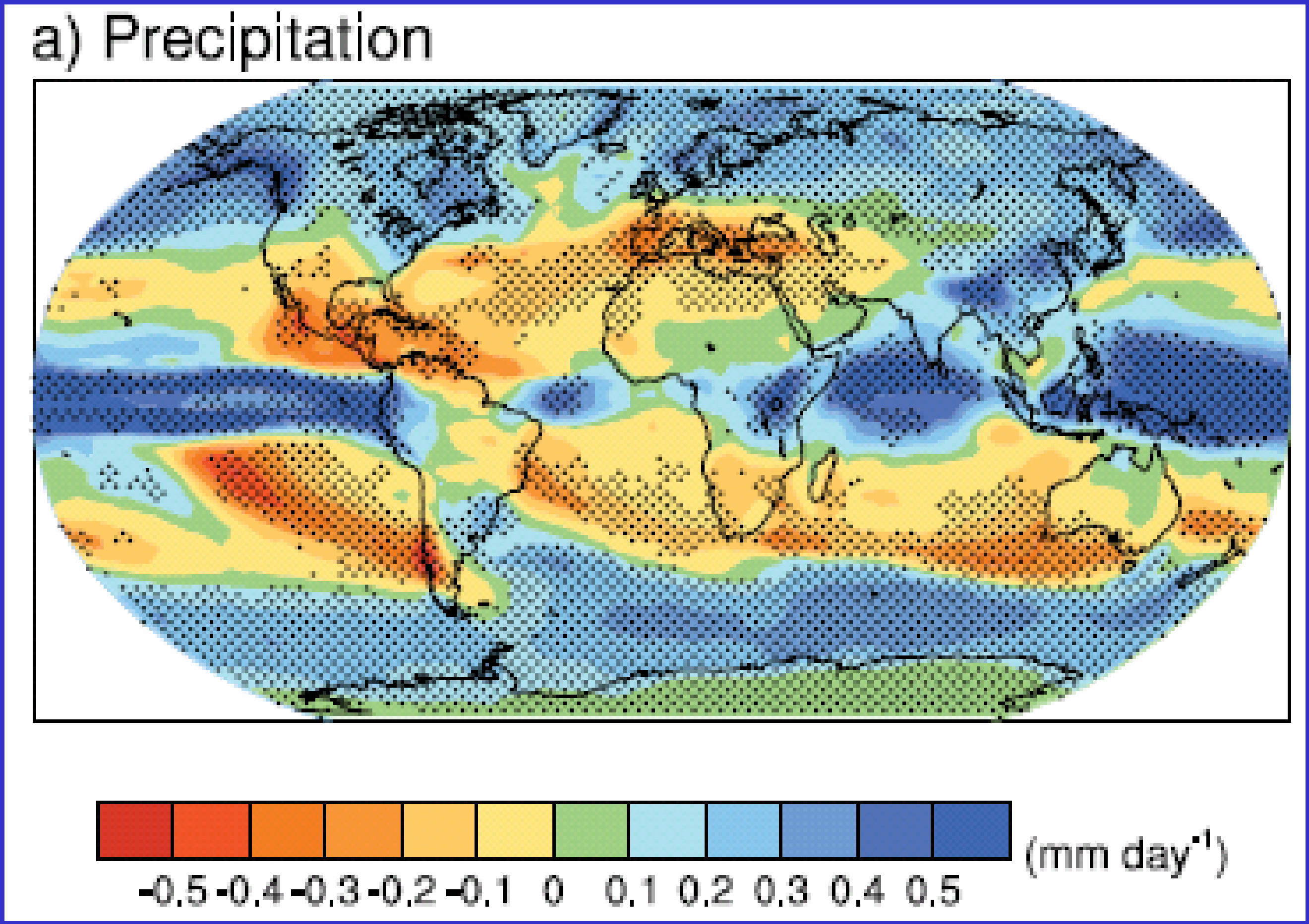
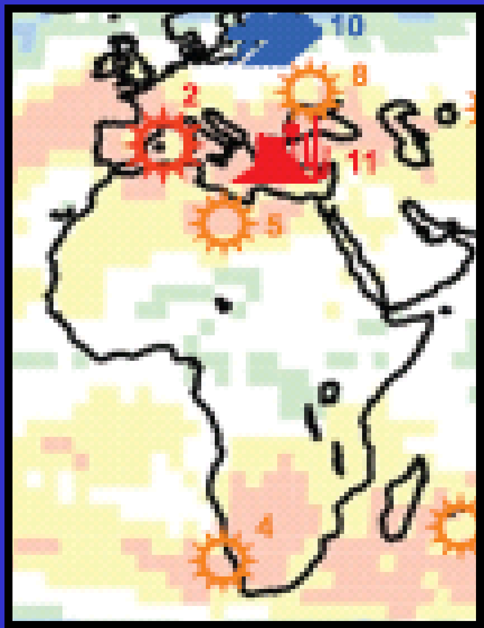
Projected Precipitation Changes



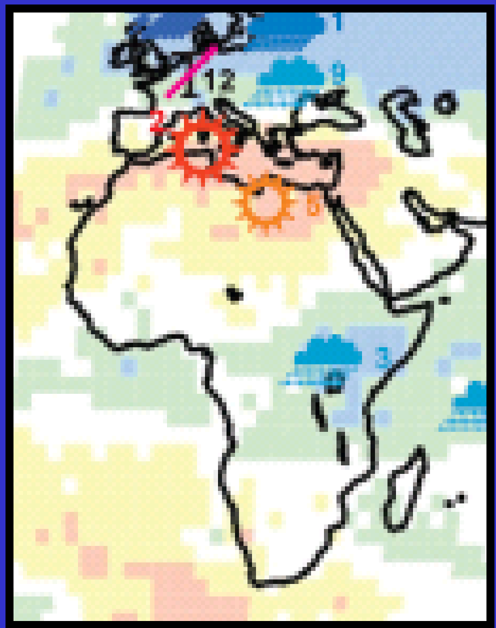
- Precipitation generally increases in the areas of regional tropical precipitation maxima (such as the monsoon regimes) and over the tropical Pacific.
- Precipitation generally decreases in the subtropics and increases at high latitudes → due to the poleward shift of the storm track → due to the expansion of the Hadley circulation.

Africa

JJA

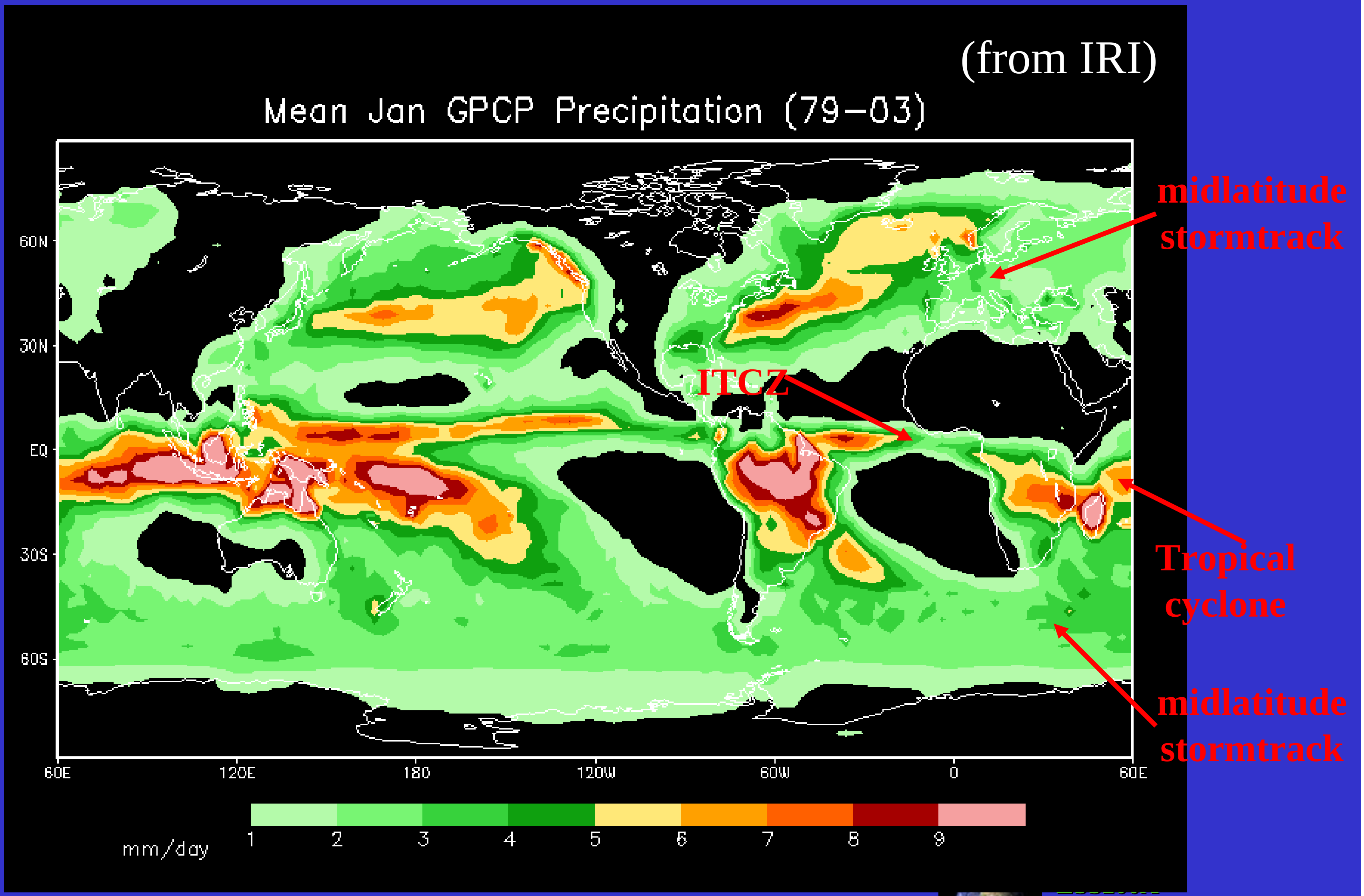


DJF

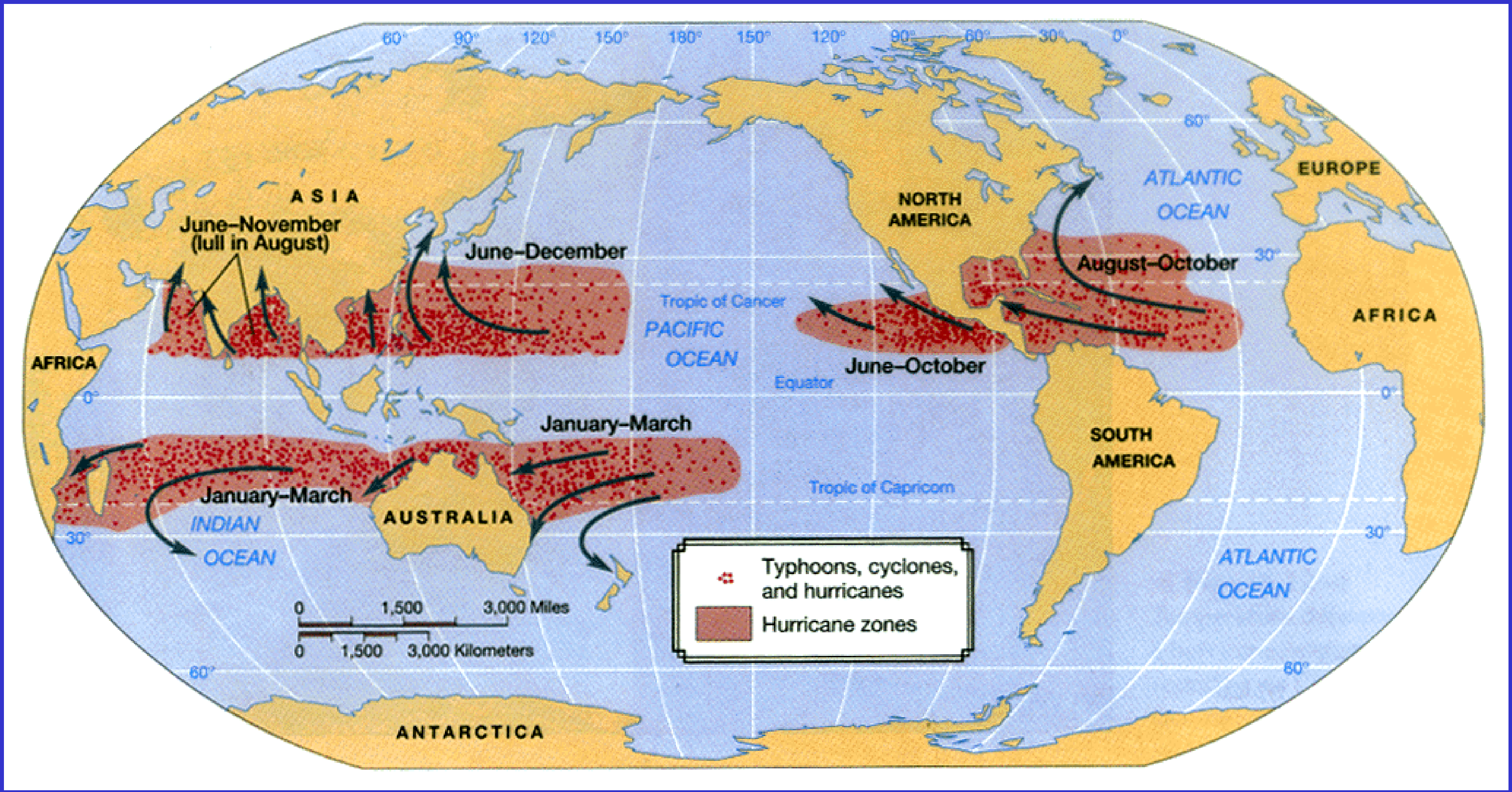


- Drying in most of the subtropical African.
- Increased (or no change) rainfalls in the tropical African.

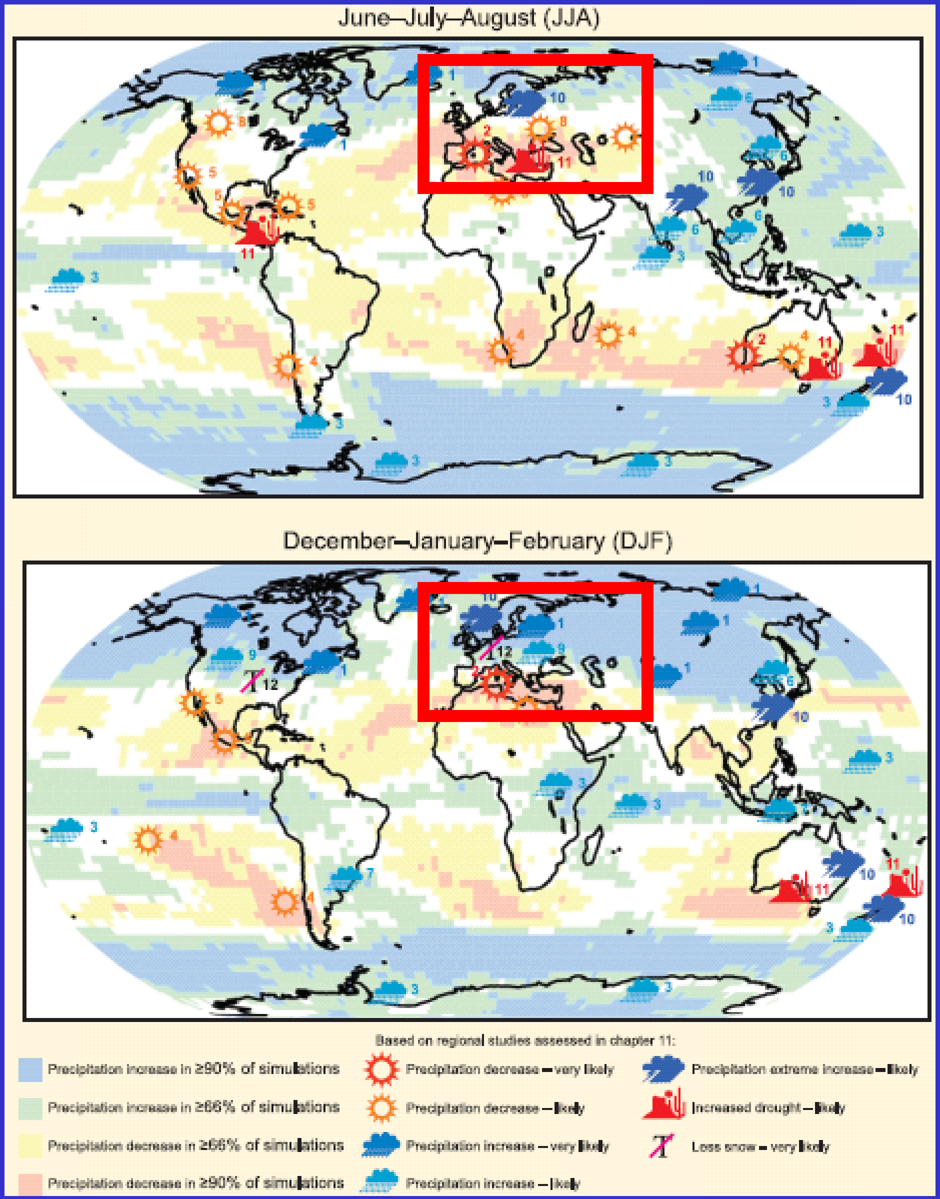
Key Processes to African Rainfalls



Hurricane Distribution



Europe and Mediterranean



- Annual precipitation is very likely to increase in most of northern Europe and decrease in most of the Mediterranean area.

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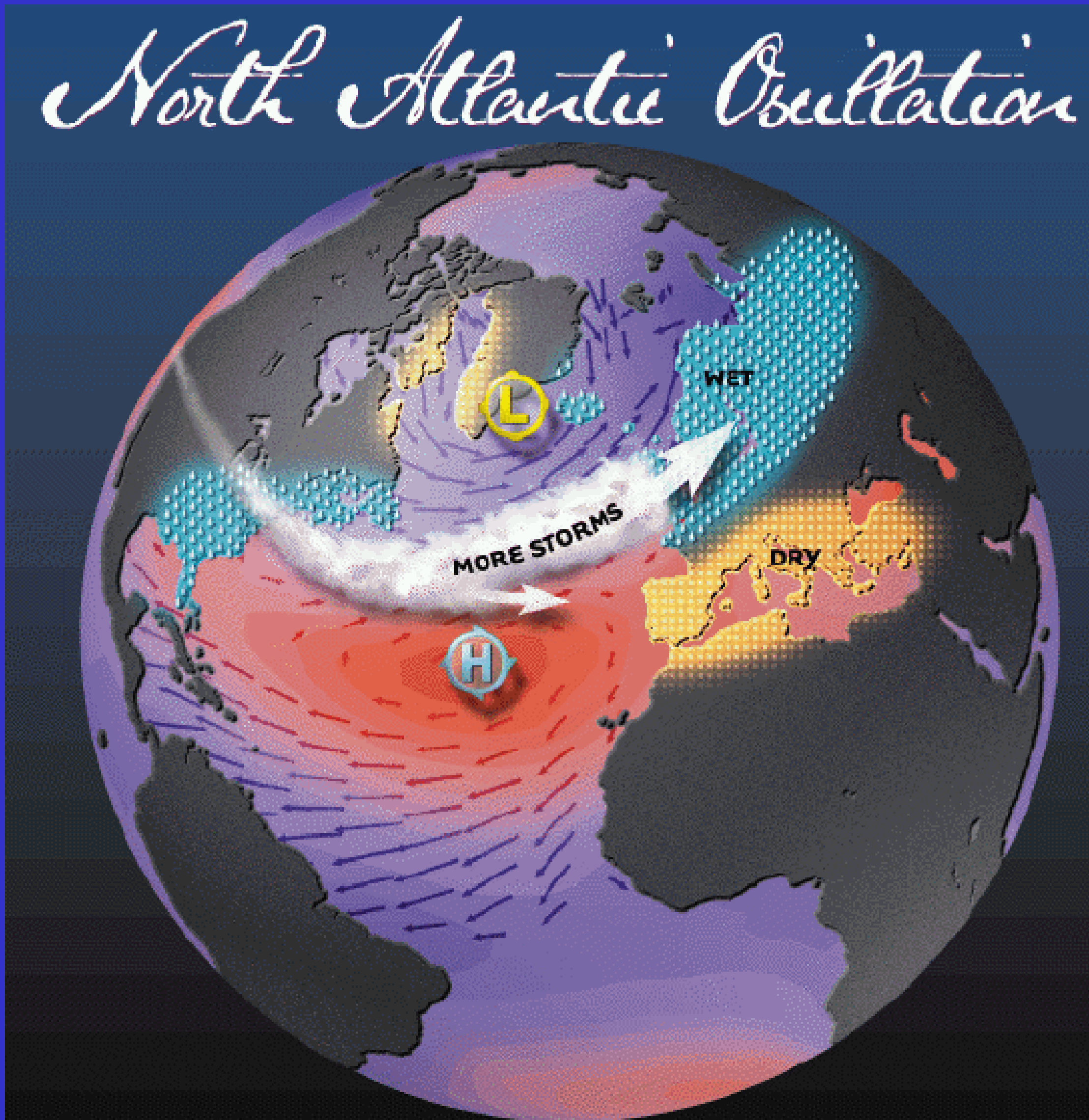
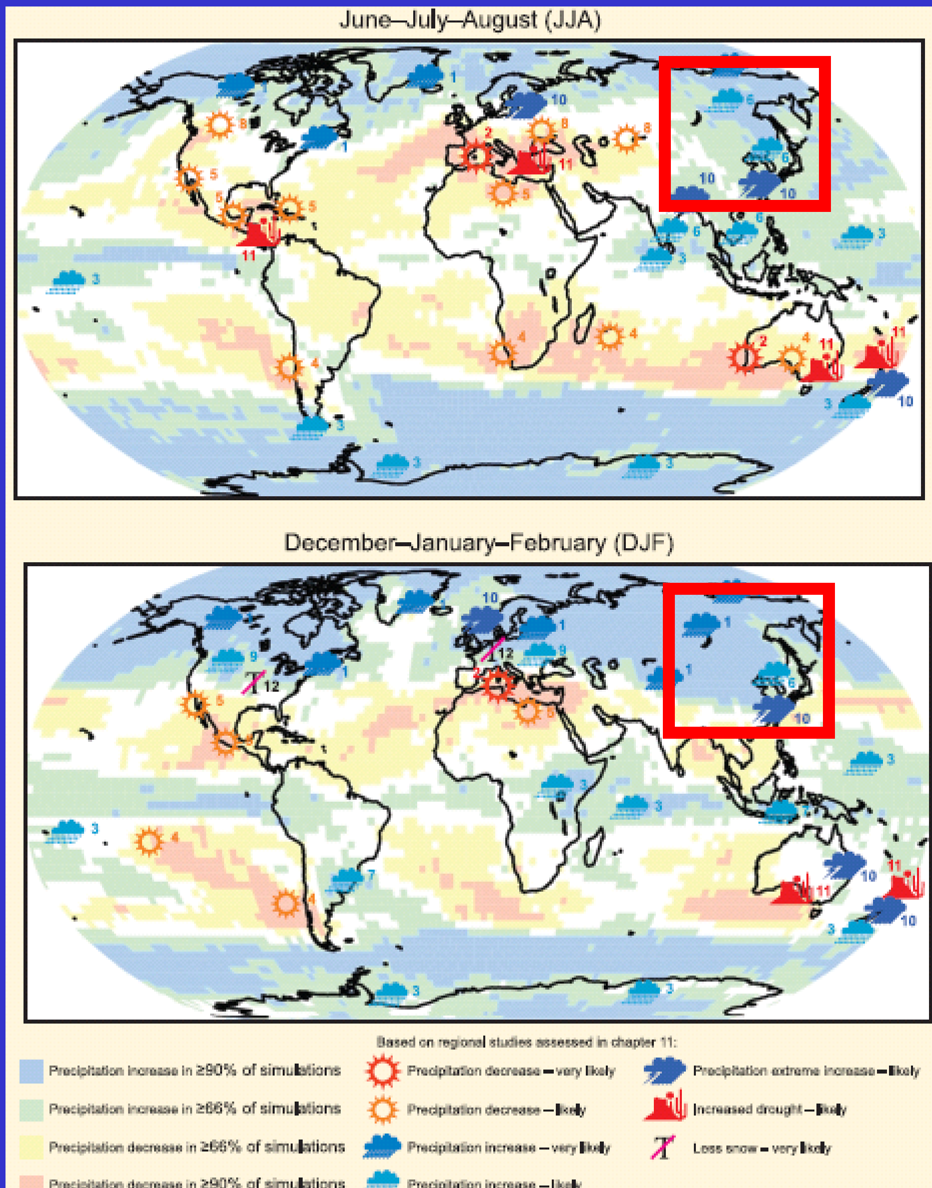
North Atlantic Oscillation



(from http://www.ldeo.columbia.edu/res/pi/NAO/)

- The NAO is the dominant mode of winter climate variability in the North Atlantic region ranging from central North America to Europe and much into Northern Asia.
- The NAO is a large scale seesaw in atmospheric mass between the subtropical high and the polar low.
- The corresponding index varies from year to year, but also exhibits a tendency to remain in one phase for intervals lasting several years.

Asia



- Most of the Asia will receive increased rainfall, except Central Asia in summer.

- Key climate factors for rainfalls: (1) monsoon, (2) ENSO, (3) tropical cyclone, and (4) Tibetan Plateau.

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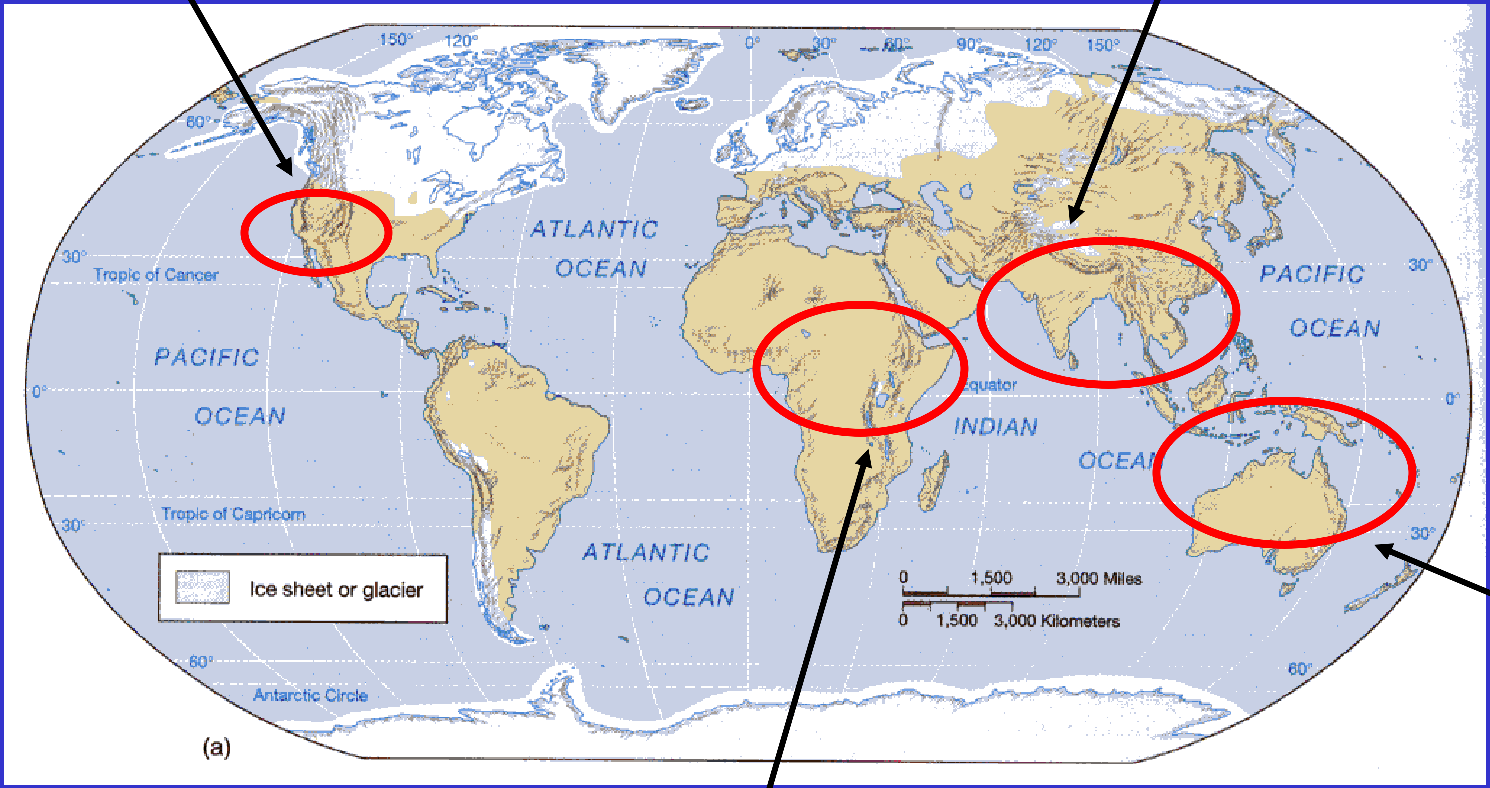
Projected Monsoon Precipitation Changes

North America Monsoon **(decrease)**

Asian Monsoon **(increase)**



Australian Monsoon **(increase)**

West Africa Monsoon **(increase)**

Weaker monsoon circulation
+ more water vapor available
= increase monsoon rainfalls

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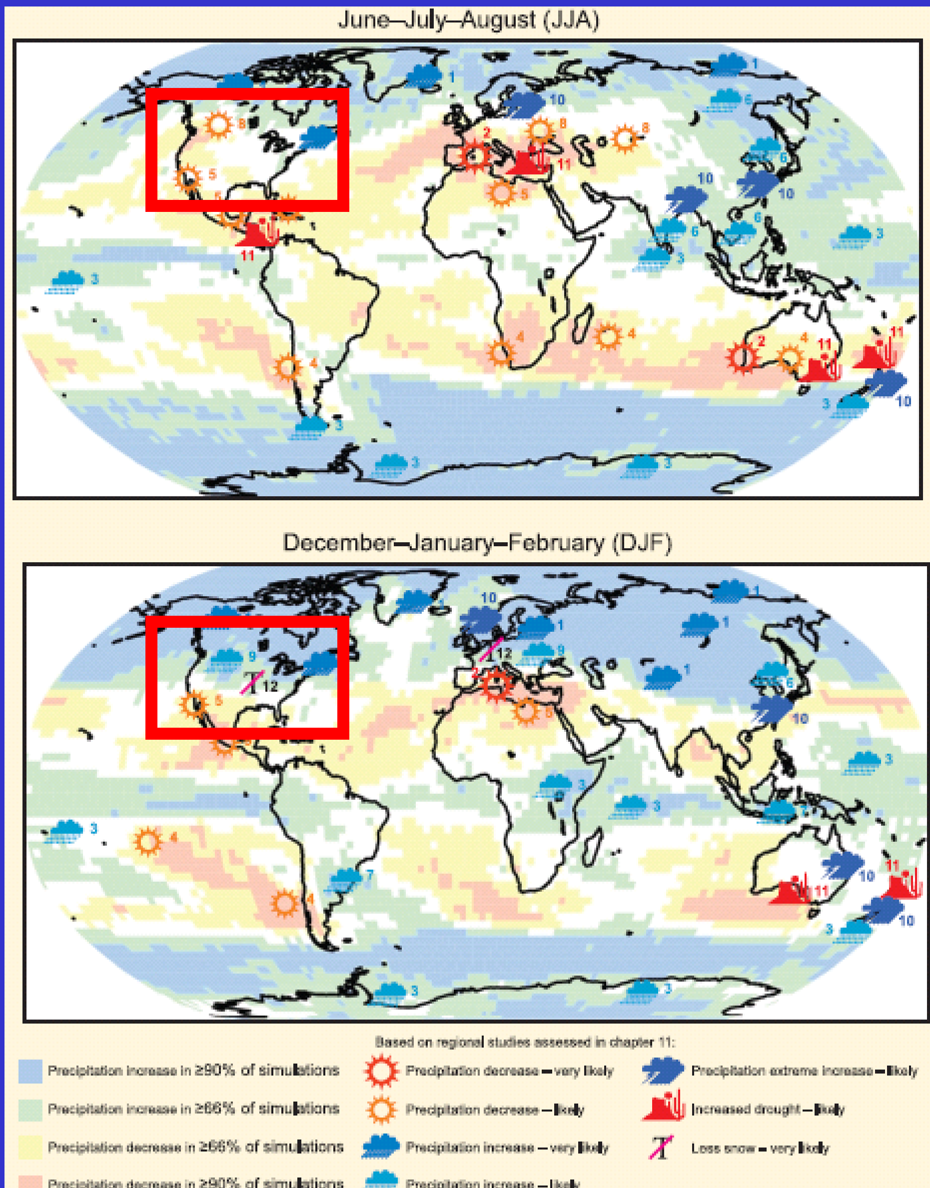
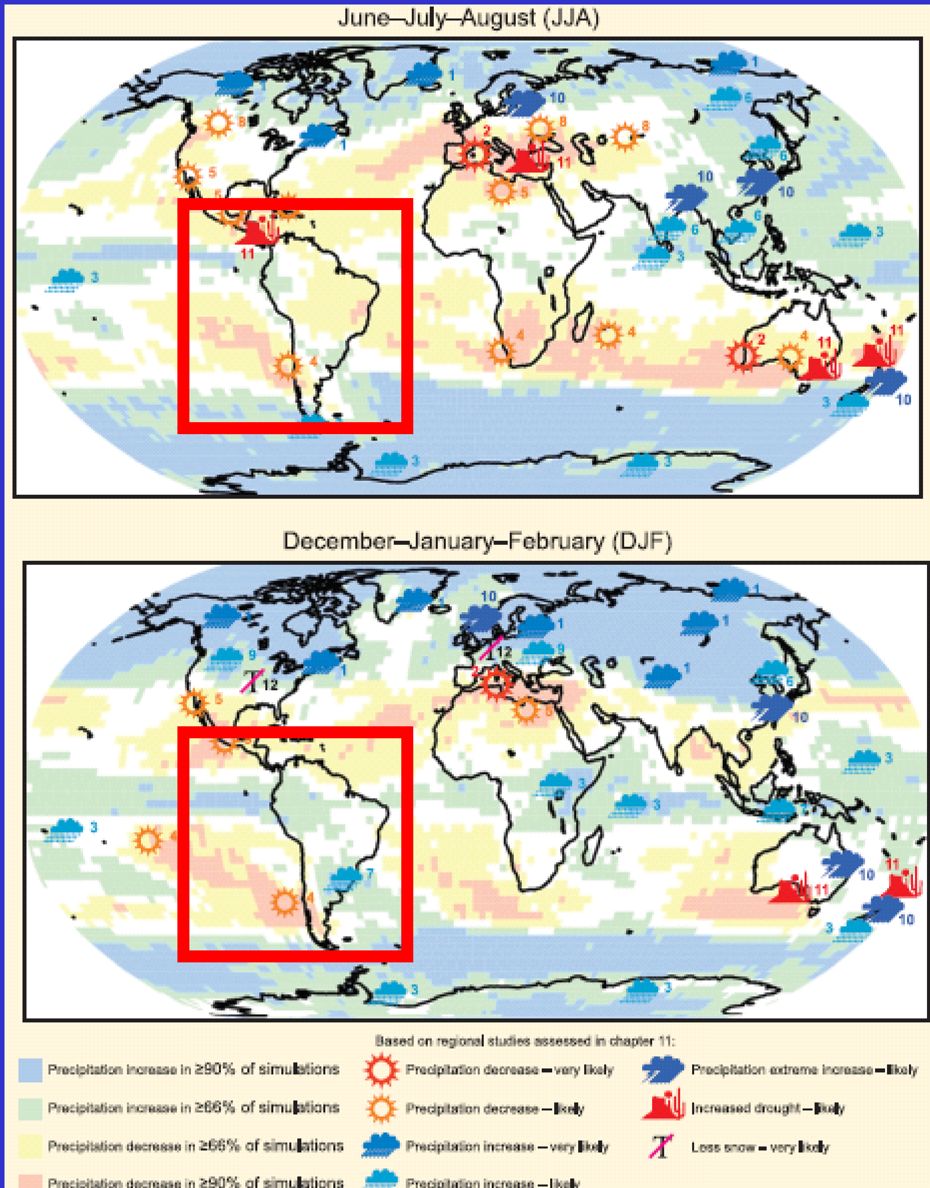
North America



- Rainfalls increased in Canada and northeast USA but decrease in southwest USA and Mexico.
- Major climate features that affect the rainfalls: (1) mid-latitude storms, (2) tropical cyclone, (3) North American monsoon.
- Projections: (1) more positive AO (i.e., northward shift of storm track), (2) weaker N.-A. monsoon, (3) intensified subtropical high in the eastern Pacific.
- In California: (1) increase in extreme hot events, (2) larger diurnal temperature range, (3) increase precipitation extreme in cold seasons.

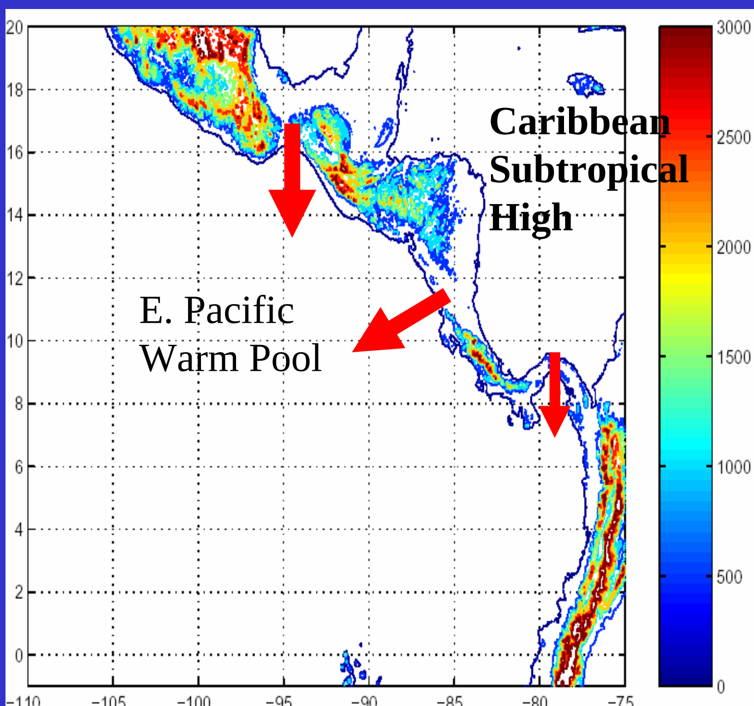
Central and South America

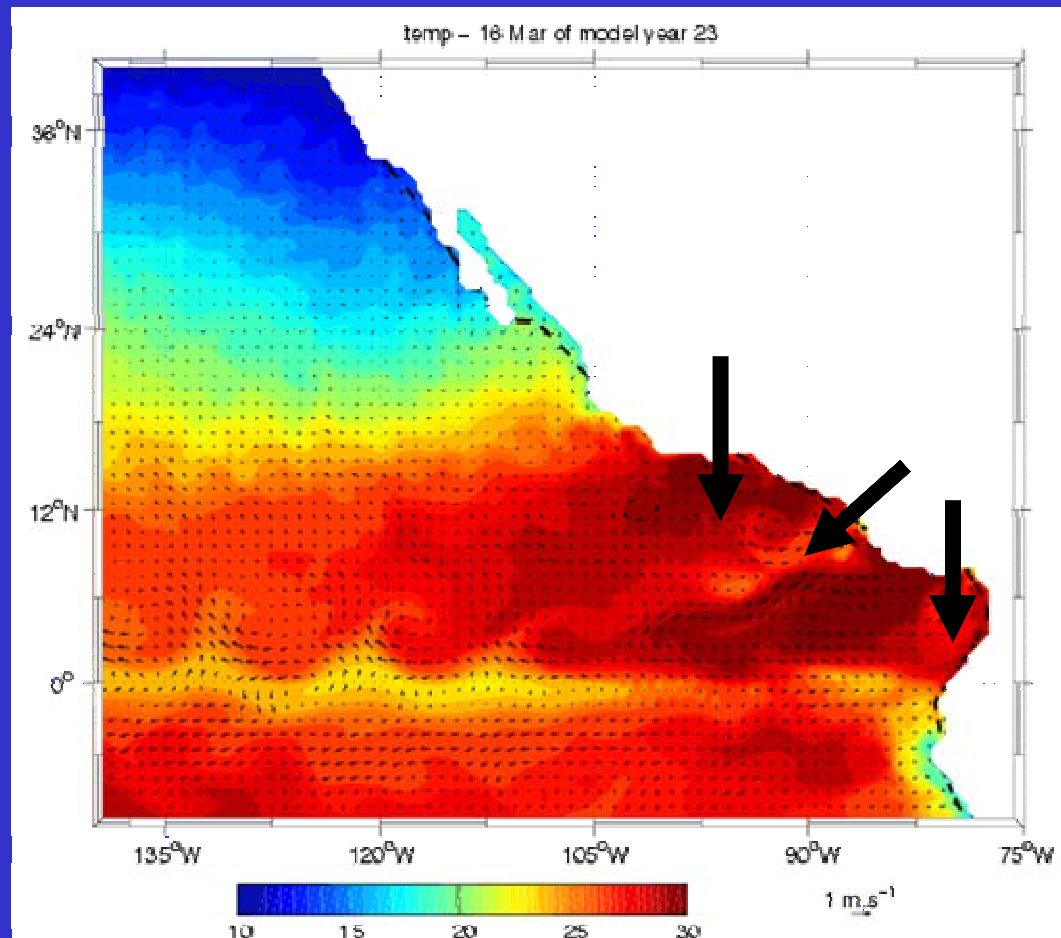


- Rainfalls decrease in Central America and southern Andes,
- Rainfalls increase in Tierra and Fuego during winter and in south-eastern South America during summer.
- In northern South America, rainfalls increase in Ecuador and northern Peru but decrease in southern northeast Brazil and northern tip of the continent.
- Rainfall changes are uncertain in the Amazon forest.

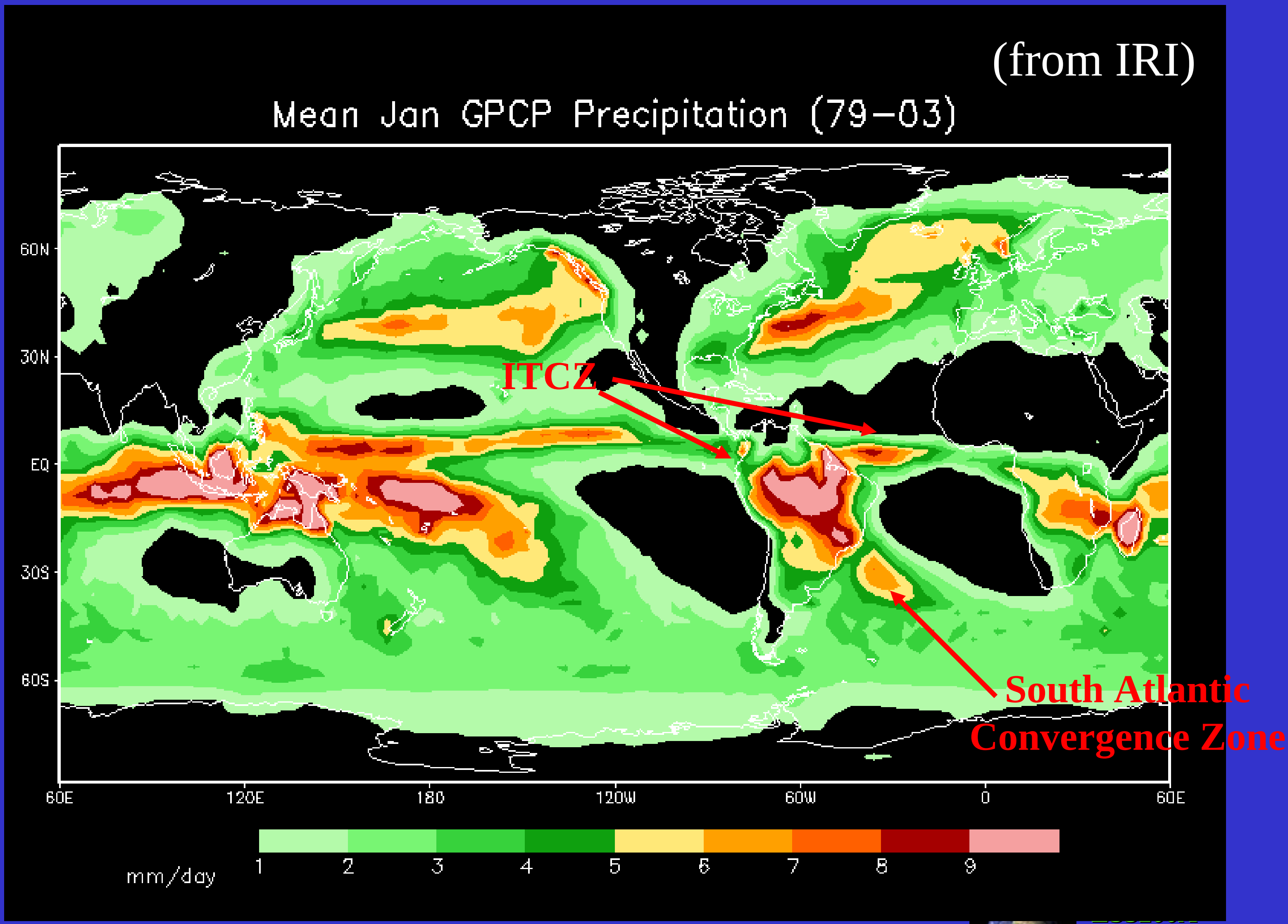
Central America Climate

Topography (meter)





Key Processes to South America Rainfalls



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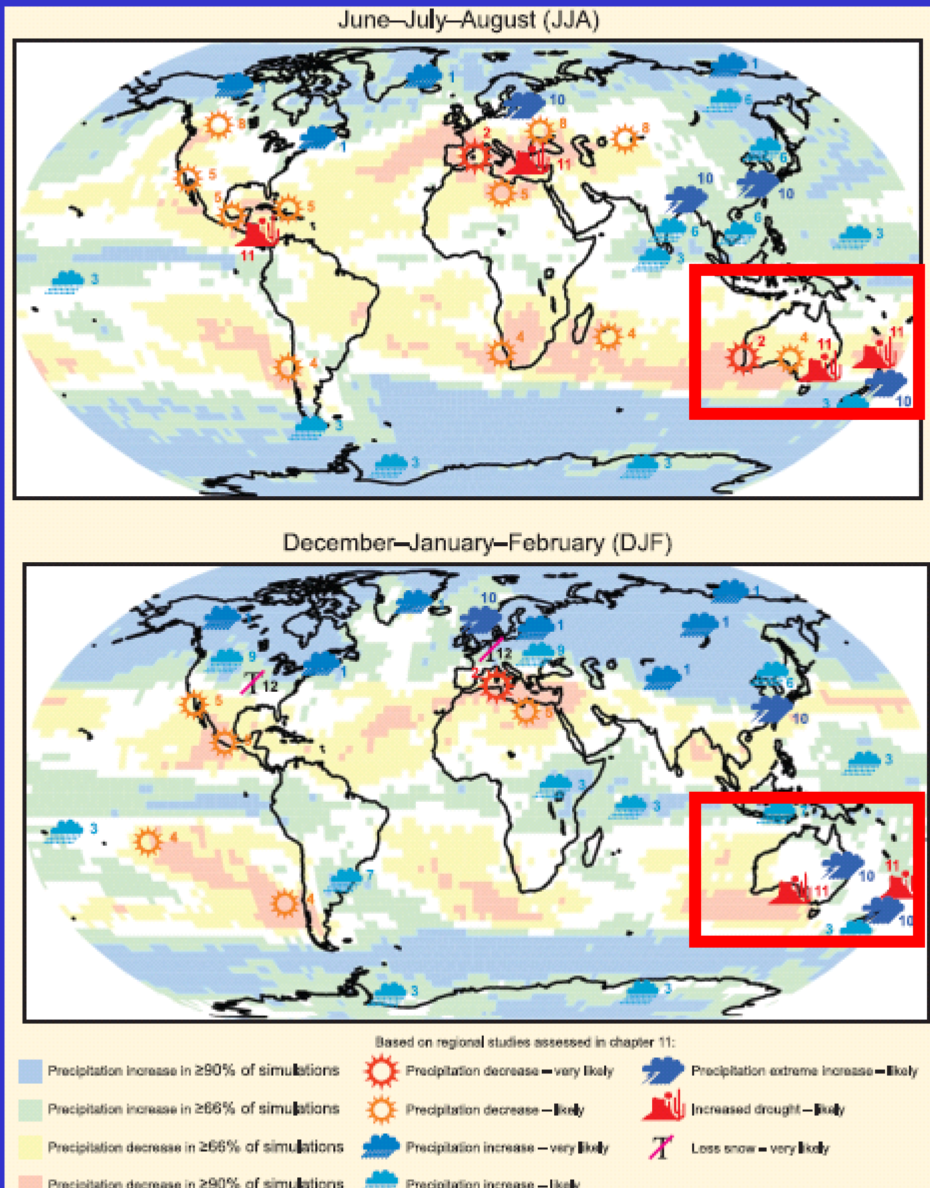
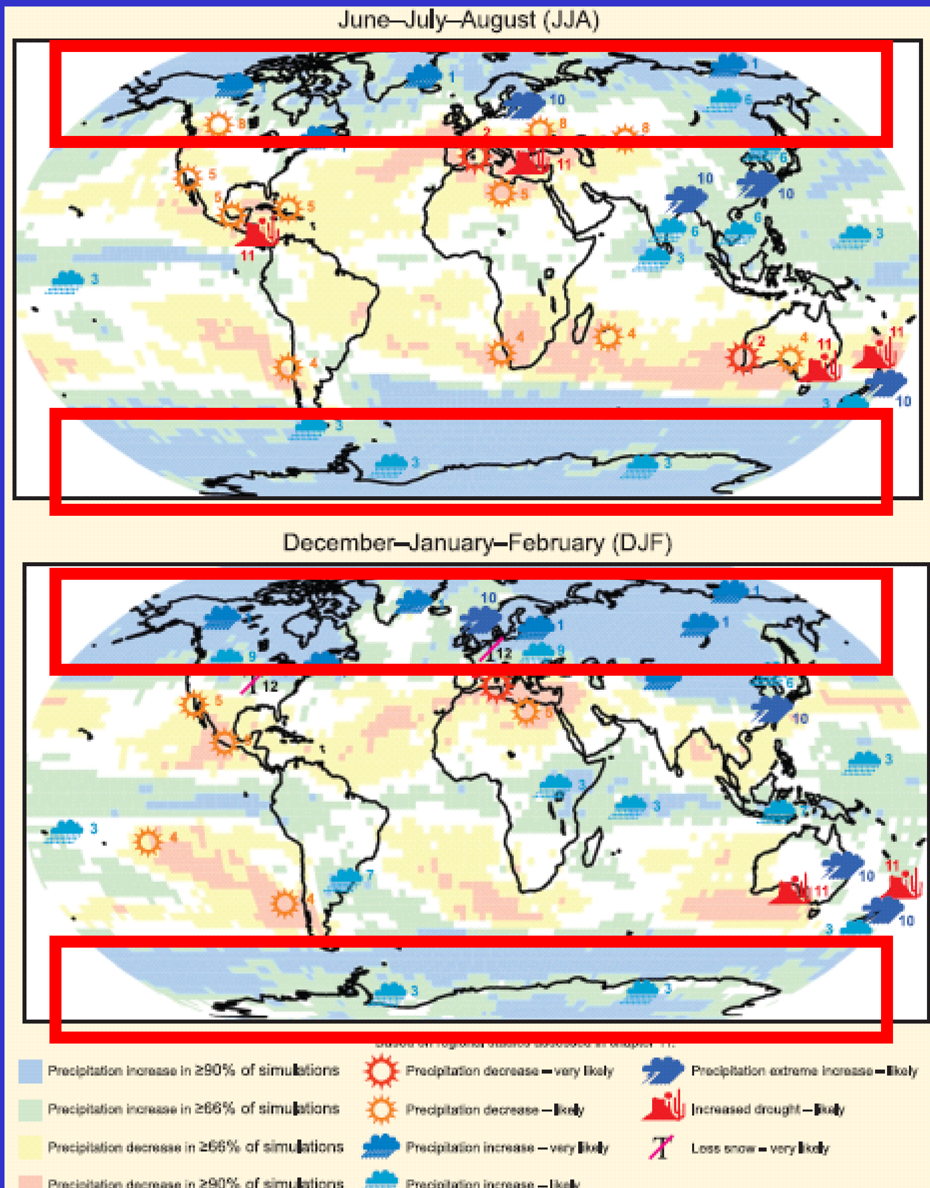
Australia and New Zealand



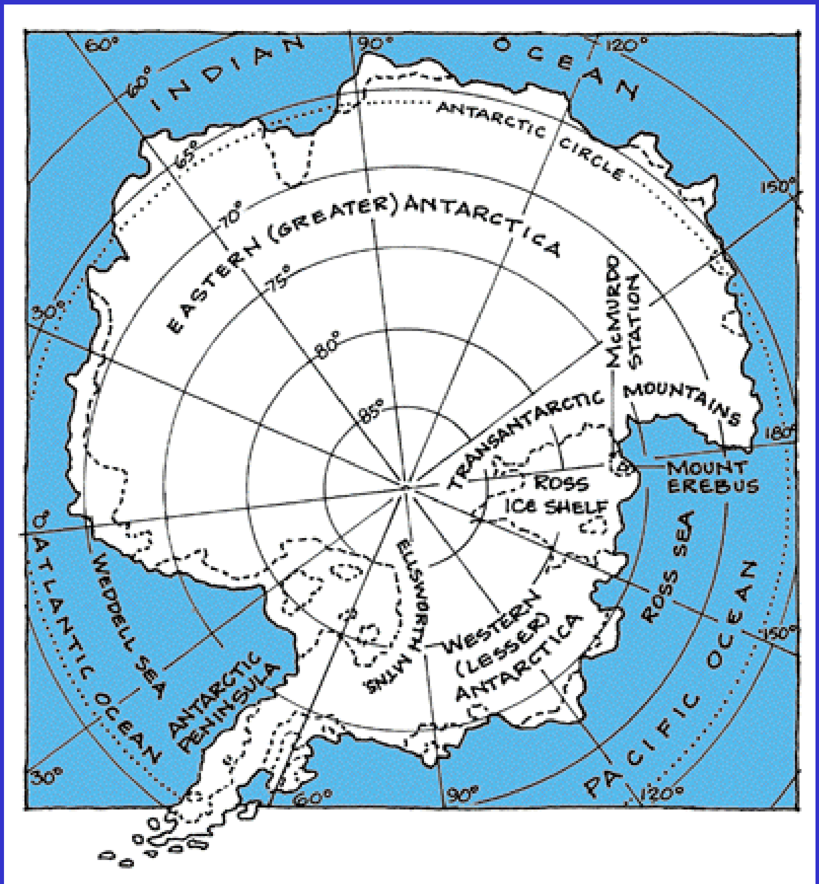
- Rainfalls decrease in southern Australia (due to poleward shift of the storm track) but increase in the west of the South Island of New Zealand.
- Rainfall changes uncertain in other parts of the region.
- It is uncertain how ENSO and Australian monsoon will respond in the future climate change.

Arctic and Antarctic



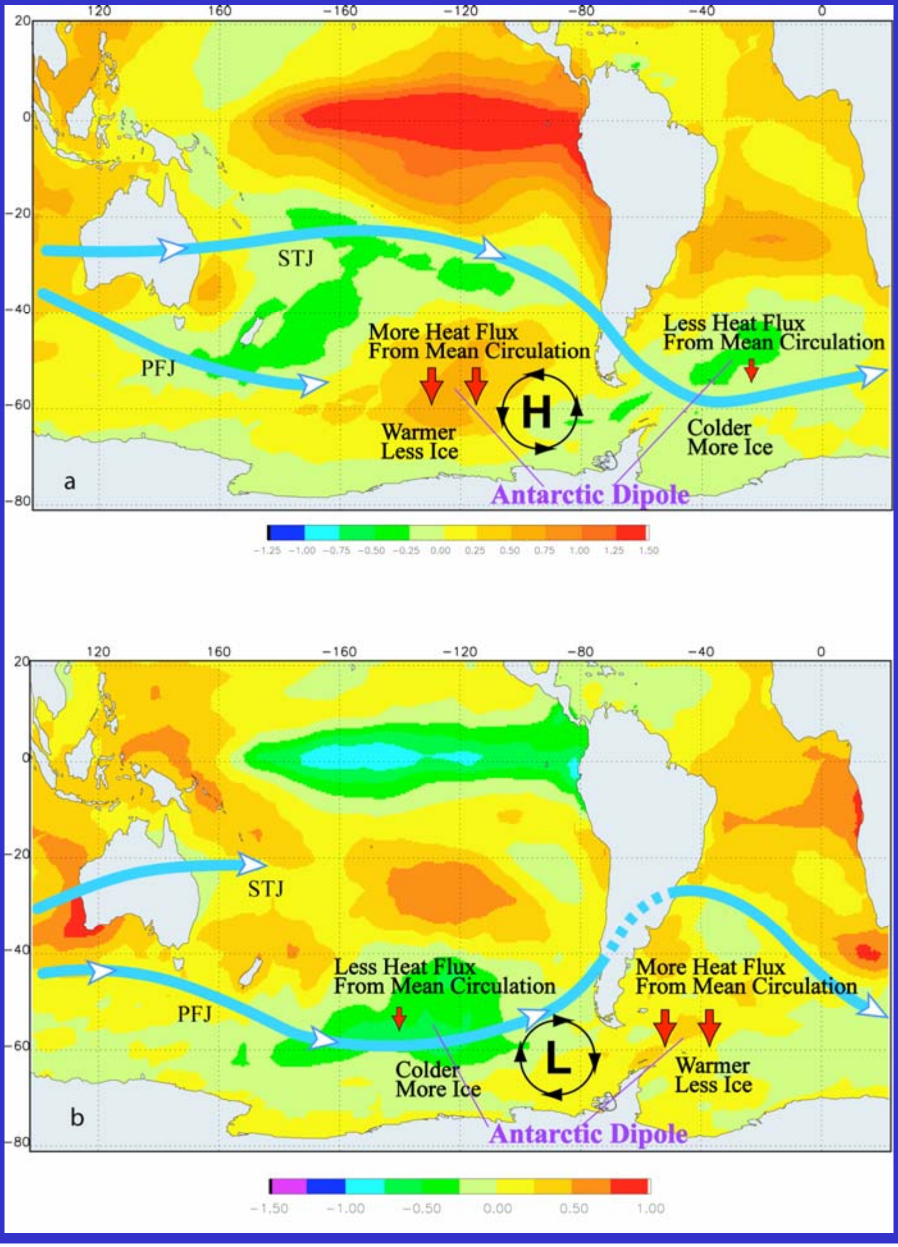
- Precipitations increase in both Arctic and Antarctic.
- Polar climate in complex, involving atmosphere-land-cryosphere-ocean-ecosystem interactions.
- Not enough observations to valid and improve climate models.

Antarctic Temperature Changes



- Antarctic climate is affected by Southern Annual Mode, ENSO, and ozone hole.
- In recent decades, Arctic climate has been affected by a trend toward the positive phase of Southern Annual Mode, which is characterized by warm anomalies in the Antarctic Peninsula but cold anomalies in the rest of the continent.
- This temperature change pattern is not projected to continue in the 21st century, although the SAM is predicted to be in a more positive phase. ➔ indicating the need to consider the role of ozone hole in the present-day peninsula warming.

ENSO and Antarctic Climate



El Nino

La Nina

(from Yuan 2003)

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