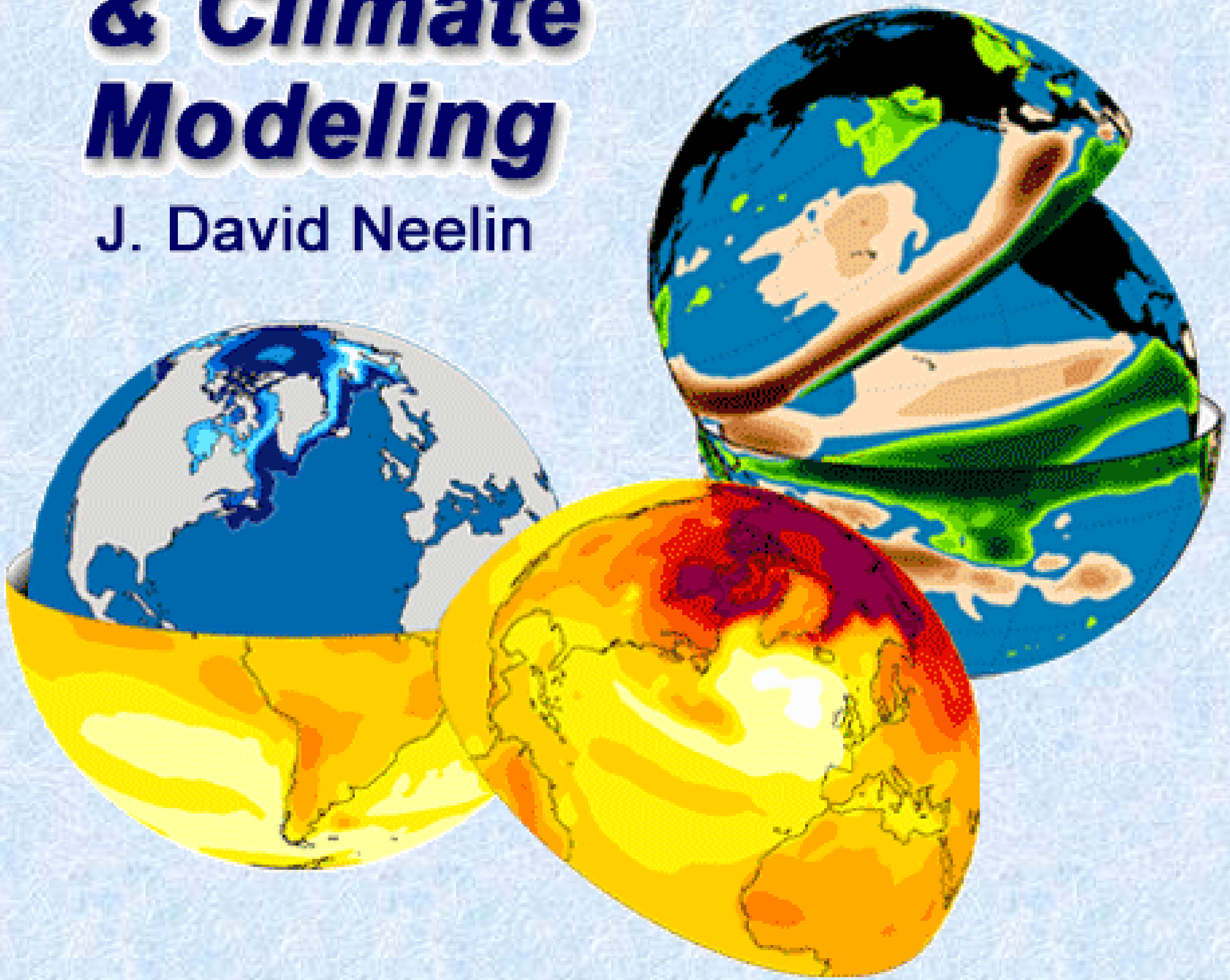
Climate Change & Climate Modeling

J. David Neelin



Neelin, 2011. *Climate Change and Climate Modeling*, Cambridge University Press

Chapter 1
Overview of Climate Variability and Climate Science

1.1 Climate dynamics, climate change and climate prediction

1.2 The chemical and physical climate system

1.3 Climate models – a brief overview

1.4 Global change in recent history

1.5 El Nino: An example of natural climate variability

1.6 Paleoclimate variability

1.1 Climate dynamics, climate change and climate prediction

- ***Climate***: **average condition of the atmosphere, ocean, land surfaces and the ecosystems in them.**
  - **e.g., "Baja California has a desert climate"**
- ***Weather***: **state of atmosphere and ocean at given moment.**
- **Climate includes average measures of weather-related variability.**
  - **e.g., typical range of temperature variations during January in Chicago, probability of a rainfall event with greater than 10mm–or 100mm—accumulation in September in Boulder Colorado, …**
  - **particular event is weather;**
    probability of it occurring is climate

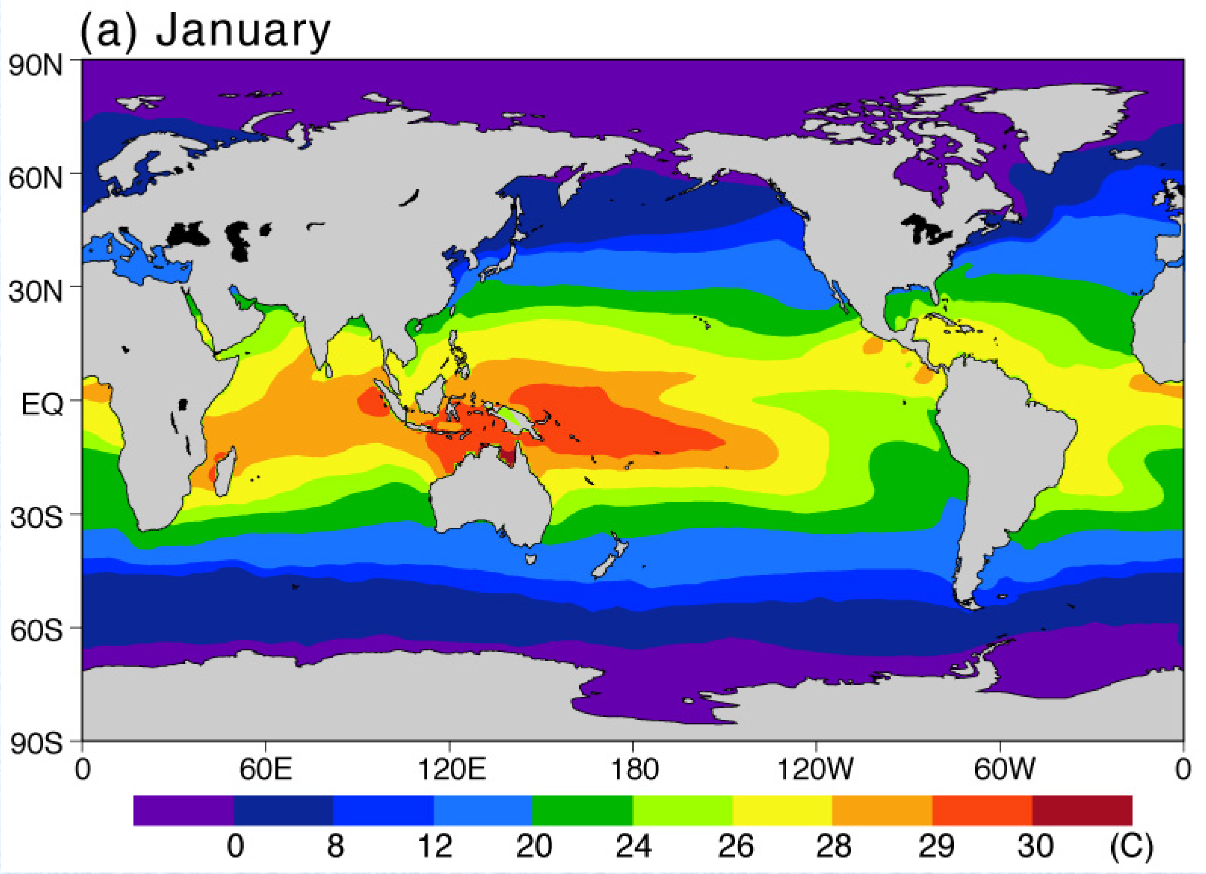
Photo by Bob Henson, UCAR

Neelin, 2011. *Climate Change and Climate Modeling*, Cambridge UP

- **Climate quantities defined by averages or other statistics over the weather for some sufficiently long interval.**
  - **e.g. 1, average taken over January of many different years to obtain a climatological value for January, many Februaries to obtain February climatology, etc.**

Chapter 2 Preview (Figure 2.16)

Climatology of sea surface temperature for January (15 year average)



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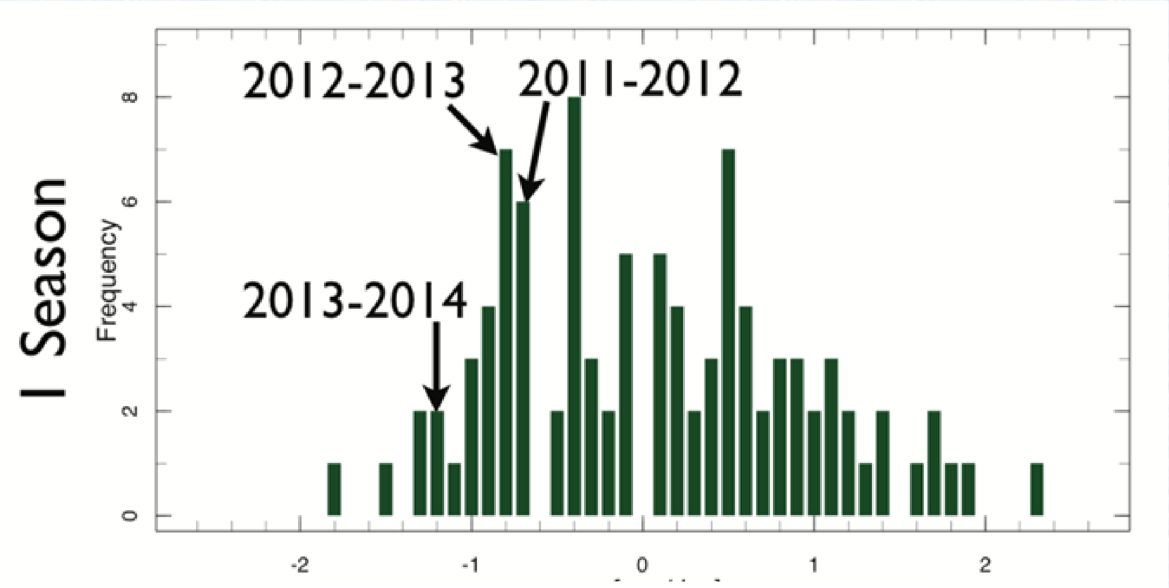
- Climate quantities defined by **averages or other statistics over the weather** for some sufficiently long interval.
  - **e.g. 2**, histogram of precipitation a given amount above or below a long-term average taken over November-April of many different years to obtain climatological probabilities.

Chapter 4 Preview

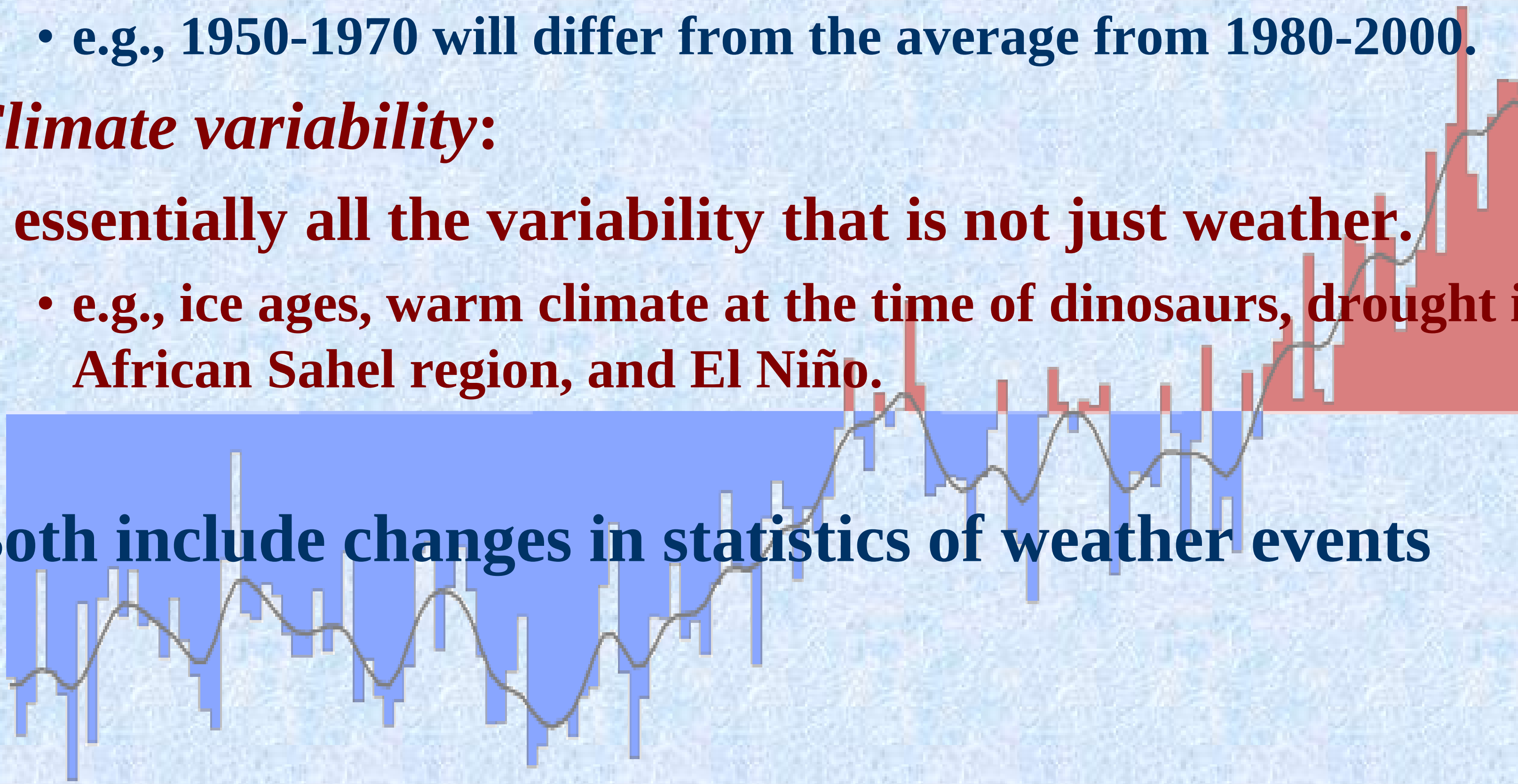
Histogram of California winter (November-April) average precipitation for individual years from 1895-2014)



Precip (mm/day) relative to normal

Seager et al., 2014. *NOAA Assessment Report*, Causes and Predictability of the 2011-14 California Drought

- ***Climate change*:**
  - **occurring on many time scales, including those that affect human activities.**
  - **time period used in the average will affect the climate that one defines.**
    - **e.g., 1950-1970 will differ from the average from 1980-2000.**
- ***Climate variability*:**
  - **essentially all the variability that is not just weather.**
    - **e.g., ice ages, warm climate at the time of dinosaurs, drought in African Sahel region, and El Niño.**
- **Both include changes in statistics of weather events**



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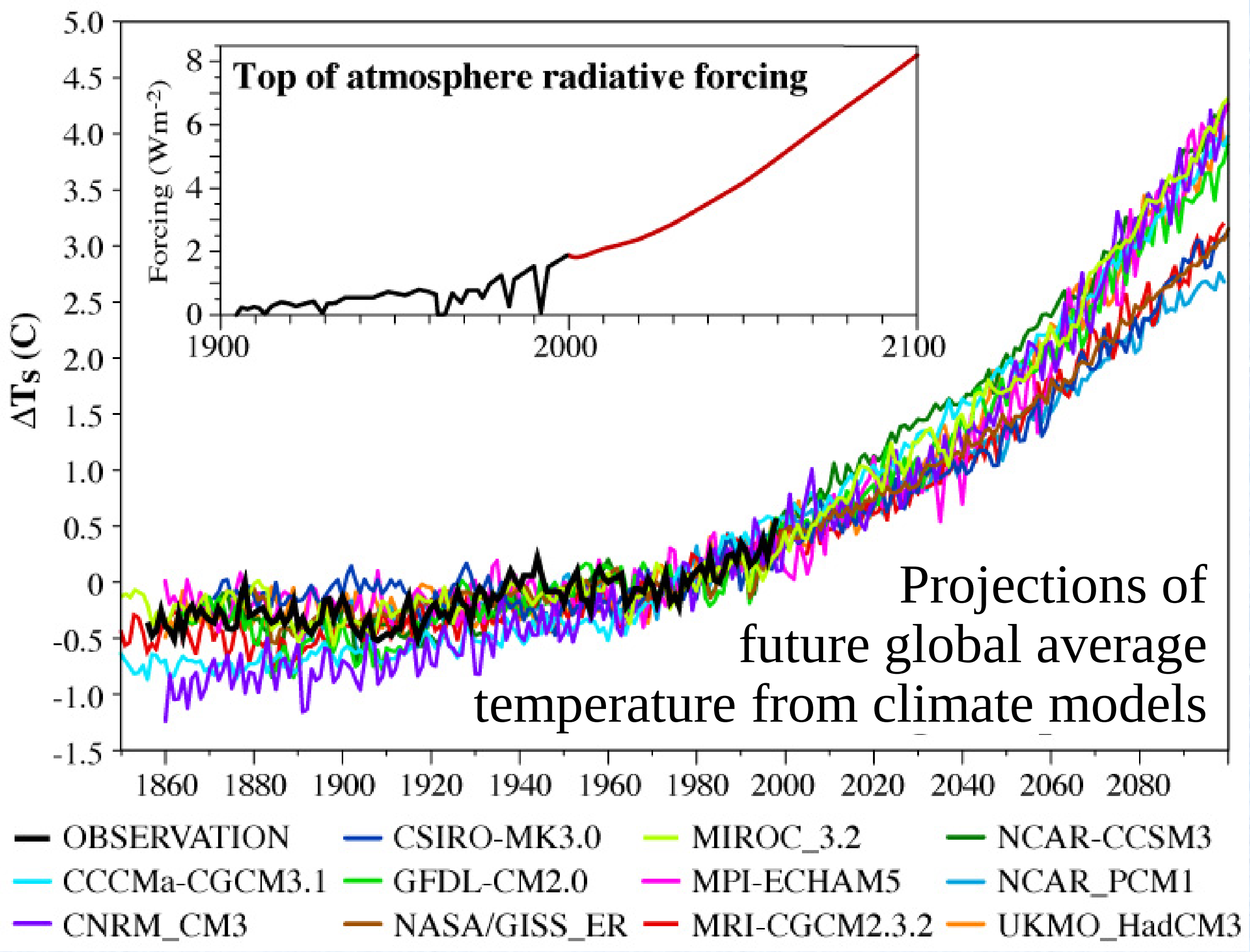
- ***Anthropogenic climate change*: due to human activities.**
  - **e.g., ozone hole, acid rain, and global warming.**

Chapter 7 Preview (Figure 7.4)



Data from the Program for Model Diagnosis and Intercomparison (PCMDI) archive.

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- ***Global warming***: **predicted warming, & associated changes in the climate system in response to increases in "greenhouse gases" emitted into atmosphere by human activities.**
- ***Greenhouse gases***: **e.g., carbon dioxide, methane and chlorofluorocarbons: trace gases that absorb infrared radiation, affect the Earth's energy budget.**
  - **$\Rightarrow$ warming tendency, known as the greenhouse effect**
- ***Environmental change***: **even more general (including air, water pollution, deforestation, ecosystems change, …)**
- ***Climate prediction:*** **endeavor to predict not only human-induced changes but the natural variations. e.g., El Niño**

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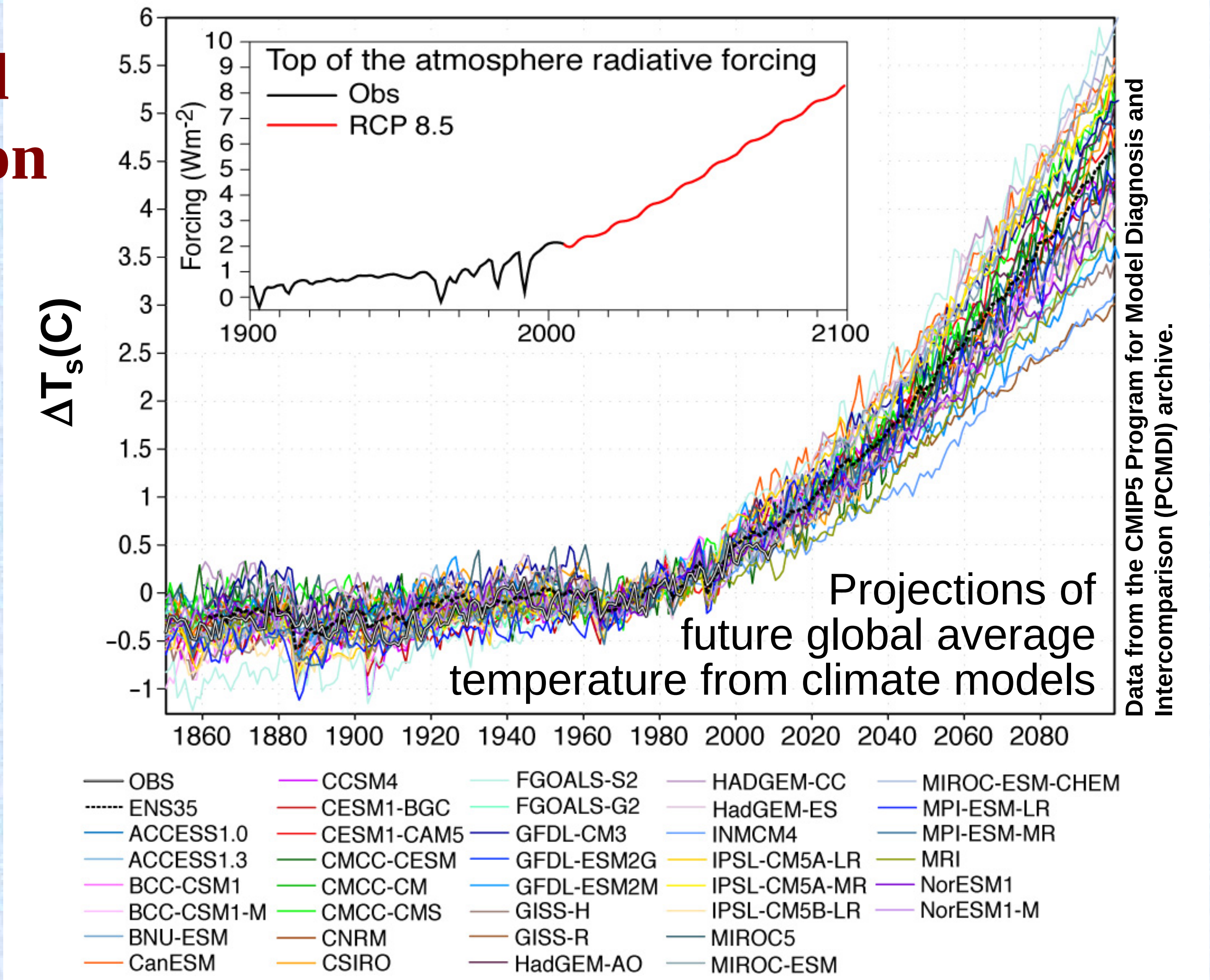
- **Assessments of potential anthropogenic changes are repeated with each generation of climate models**

Chapter 7 Preview (Figure 7.4 – CMIP5 update)

Coupled Model Intercomparison Project 5 (CMIP5), 2014



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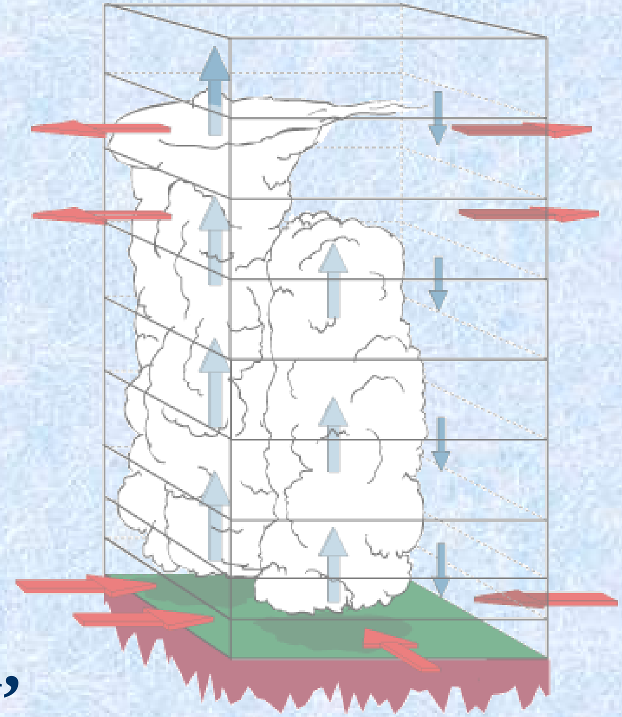
- *Climate Dynamics or Climate Science*: studies climate and climate change processes (older term, “climatology”).
- *Climatology* now used for average variables, e.g., “the January precipitation climatology”.
- *Climate models*:
  - Mathematical representations of the climate system
    - typically equations for temperature, winds, ocean currents and other climate variables solved numerically on computers.



- *Climate System or Earth System*: global, interlocking system; atmosphere, ocean, land surfaces, sea and land ice, and biosphere (plant and animal component).

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1.2 The chemical and physical climate system

- ***Physical Climate System*: parts of the system studied with fixed chemistry and biology.**
  - **e.g., composition of the atmosphere fixed and held constant except for specified changes in carbon dioxide.**
- ***Earth system model*: models that include physical, chemical and biological aspects.**
- **This course: emphasis on physical climate system (other courses have environmental chemistry, oceanography, biogeochemistry, …)**
- ***Complex Systems*: simplify and/or separate subsystems where possible, understand, then assemble**
  - **e.g., global warming response for specified CO_2**
  - **e.g., El Niño tropical models**

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- ***Examples of phenomena associated with climate subsystems***
  - **Physical Climate System: weather, El Niño, North Atlantic Oscillation, Asian Monsoon variations, North American Monsoon variations, droughts, floods, circulation of the atmosphere and oceans, deep ocean circulation, ice ages, ...**
  - **Environmental Chemistry: the ozone hole, urban air pollution, aerosol formation, haze, ...**
  - **Biosphere: evolution of the atmosphere, oxygen production, carbon cycle between biomass and carbon dioxide and other atmospheric and oceanic constituents, land surface processes, biodiversity,...**
  - **Linkages: the carbon cycle affects carbon dioxide concentration and thus the greenhouse effect, effects of dynamical processes on ozone hole formation (the stratospheric polar vortex, stratospheric ice clouds), vegetation affects absorption of sunlight and evaporation from land surfaces, ...**

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- **El Niño:**
  - **largest interannual (year-to-year) climate variation interaction between the tropical Pacific ocean and the atmosphere above it.**
  - **a prime example of natural climate variability.**
  - **first phenomenon for which the essential role of dynamical interaction between atmosphere and ocean was demonstrated.**

  - **Many of the same tools — e.g. climate models, observing systems — are used to study and/or predict weather and natural climate variability as are used to study anthropogenic climate change**

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1.3 Climate models - a brief overview

- **Motions, temperature, etc. governed by basic laws of physics (chap. 3) solved numerically (chap. 5):**
  - **e.g., divide the atmosphere and ocean into discrete grid boxes**
  - **equation for balance of forces, energy inputs etc. for each box.**
  - **obtain the acceleration of the fluid in the box, its rate of change of temperature, etc.**
  - **from this compute the new velocity, temperature, etc. one time step later (e.g., twenty minutes for the atmosphere, hour for ocean).**
  - **equations for each box depend on the values in neighboring boxes.**
  - **computation is done for a million or so grid boxes over the globe.**
  - **repeated for the next time step, and so on until the desired length of simulation is obtained.**
  - **common to simulate decades or centuries in climate runs**

  $\Rightarrow$ ***computational cost* a factor**

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- **Basic method of solving equations has much in common with, e.g., flow over an aircraft wing.**
- **Close relationship to weather forecasting models**
- **Major differences:**
  - **complexity of the climate system.**
  - **range of phenomena at different time scales, (chap. 2).**
  - **“messier”: clouds, aerosols, vegetation, ...**
- **More attention to processes that affect the long term**

- **The most complex climate models, known as *General Circulation Models* or GCMs.**
  - **Once a phenomena has been simulated in a GCM, it is not necessarily easy to understand.**
- **Intermediate complexity climate models are also used.**
  - **construct a model based on same physical principles as a GCM but only aspects important to the target phenomenon are retained.**
    - **e.g., first used to simulate, understand and predict El Niño (chap 4).**
- **Simple climate models:**
  - **e.g., globally averaged energy-balance model, to understand essential aspects of the greenhouse effect (chap. 6).**
- **Global warming simulations with GCMs (chap. 7) ⇒ detailed processes, 3-D response.**

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1.4 Global change in recent history

Table 1.1

Air main constituants	Formula	Concentration
Nitrogen	N_2	78.08%
Oxygen	O_2	20.95%
Argon	Ar	0.93%
Water	H_2O	0.1 to 2 %
Trace gas name		**Concentration (in 2004)**
Carbon dioxide	CO_2	377 (parts per million) ppm, ~0.038%
Methane	CH_4	1.75 ppm
Nitrous oxide	N_2O	0.32 ppm
Ozone	O_3	0.000251 ppm (atm. average) (~10 ppm max in stratosphere)

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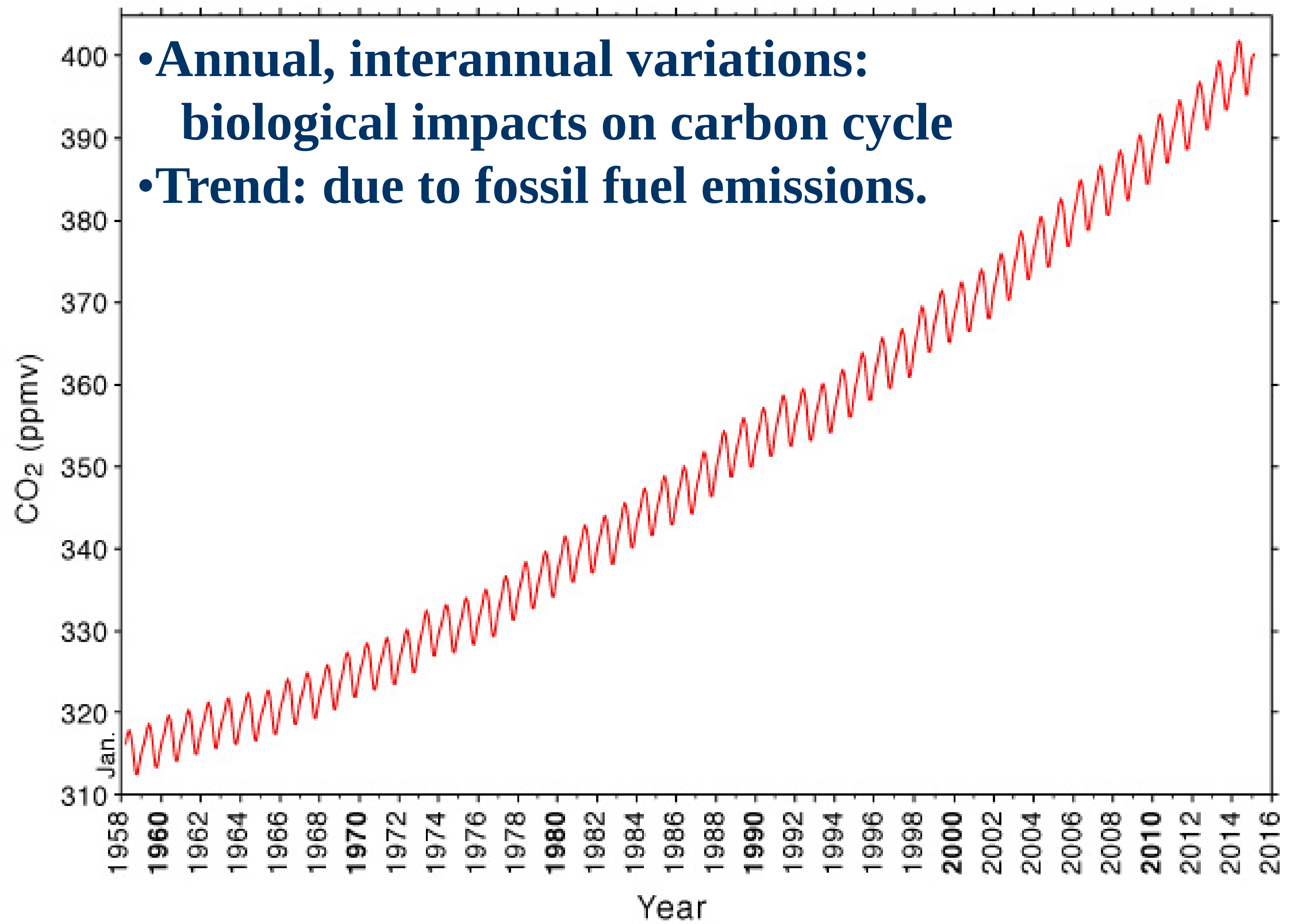
Figure 1.1

Carbon dioxide concentrations since 1958, measured at Mauna Loa, Hawaii.



From the NOAA Climate Monitoring and Diagnostics Lab. Data prior to 1974 are from C. D. Keeling, 1976, *Tellus*.

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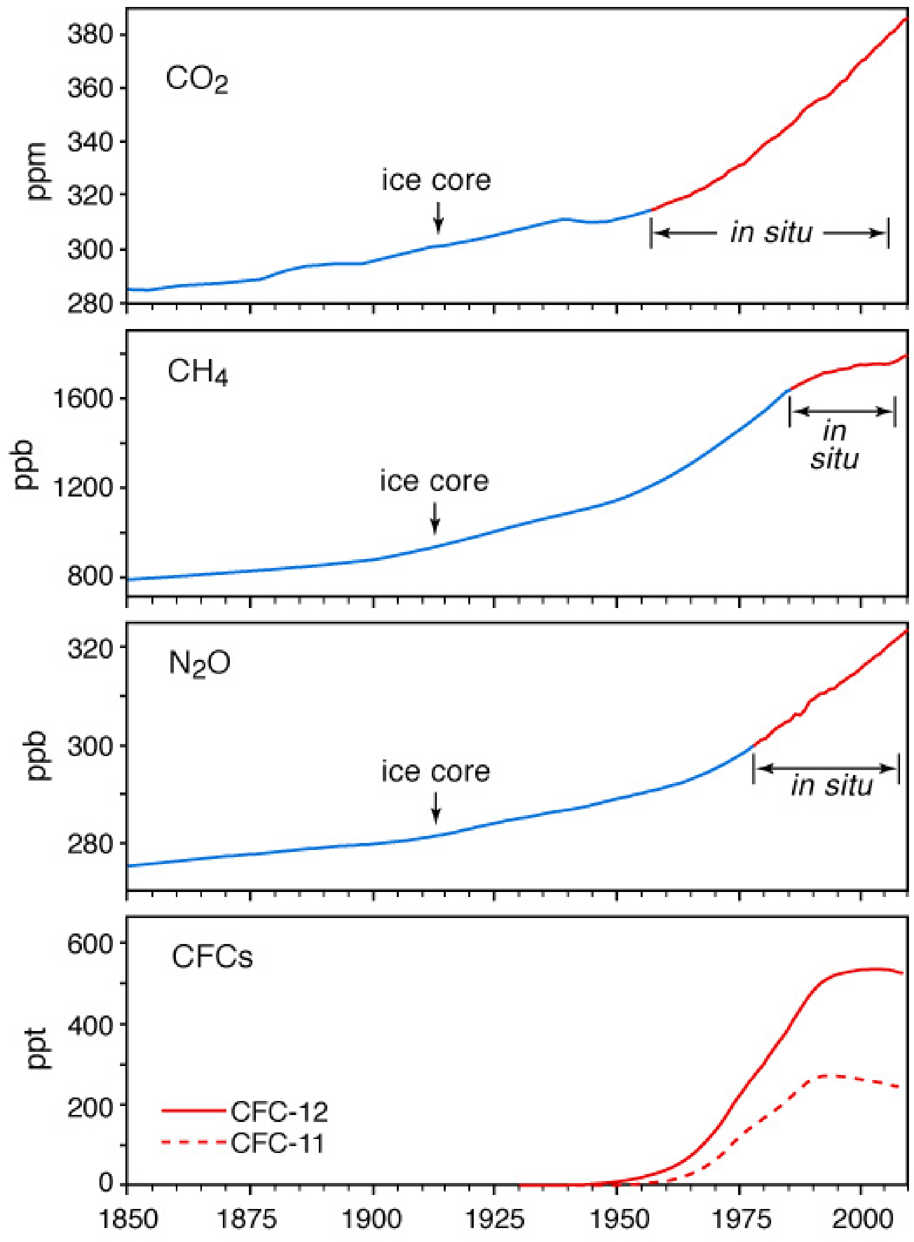
Figure 1.2

Concentration of various trace gases estimated since 1850

- Methane: Cattle, sheep, rice paddies, fossil fuel by-product; wetlands, termites (parts per billion).
- Nitrous Oxide: biomass burning, fertilizers?
- Chlorofluorocarbons: man-made, zero before 1950 (parts per trillion).



Data from Goddard Institute for Space Studies following Hansen et al., *1998, J. Geophys. Res.*

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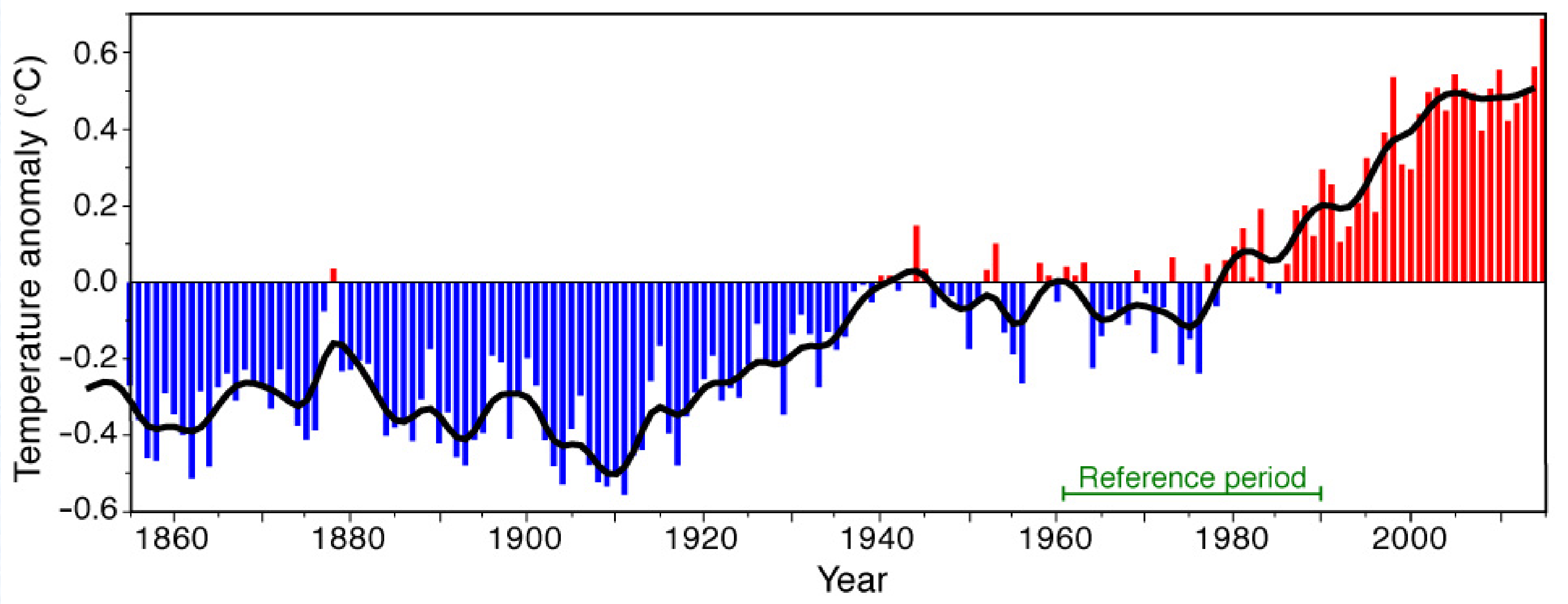
- **Ozone hole**
  - **CFC ozone destruction predicted by Sherwood Rowland and Mario Molina in 1974.**
  - **1985, J. C. Farman and coworkers: observations of Antarctic ozone depletion in southern spring**
  - **Montreal Protocol in 1987 timetable for phase-out of CFC emissions.**
  - **Reservoir effect of existing CFCs ⇒ 50 years before recovery underway (relative success; aided by "spray-can ban" late 1970s).**
  - **Prediction of ozone destruction involving CFCs was correct overall but degree of ozone destruction enhanced by polar stratospheric clouds**
  - **Ozone hole is essentially a chemical effect.**

  (for details see atm. chem. course)

Figure 1.3

Global mean surface temperatures estimated since preindustrial times



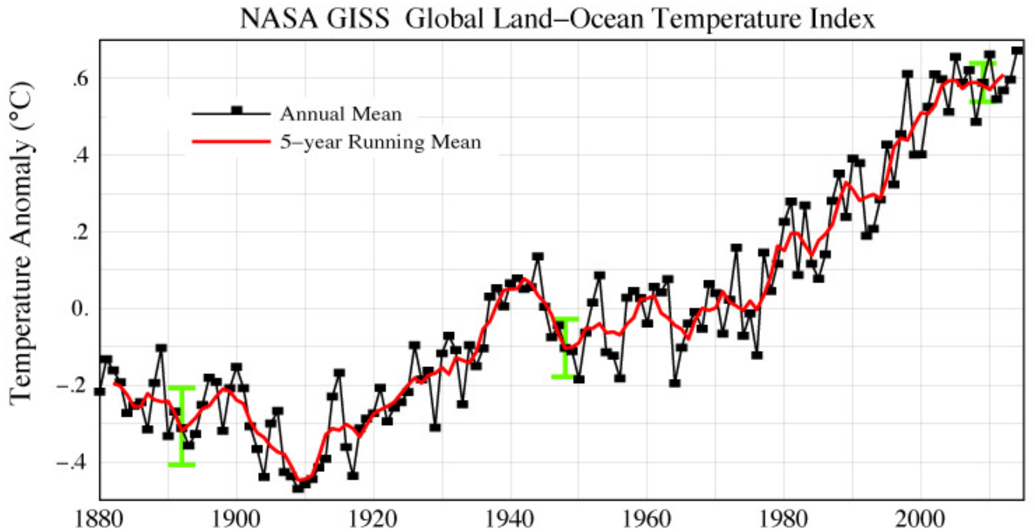
From the University of East Anglia CRU (data following Brohan et al. 2006; Rayner et al. 2006)

- **Anomalies relative to 1961-1990 mean**
- **Annual average values of combined near-surface air temperature over continents and sea surface temperature over ocean.**
- **Curve: smoothing similar to a decadal running average.**

Supplementary Fig.: Global Mean Temperature Anomalies from other data centers (NASA GISS* & NOAA NCDC**)

***National Aeronautics and Space Administration Goddard Institute for Space Studies. Anomalies relative to 1951-1980 average.**

****National Oceanic and Atmospheric Administration National Climatic Data Center. Anomalies relative to 20th Century average (with linear trend estimates over 30 year and longer intervals).**



Updated Fig. 1A from Hansen et al., Proc. Natl. Acad. Sci., 2006.

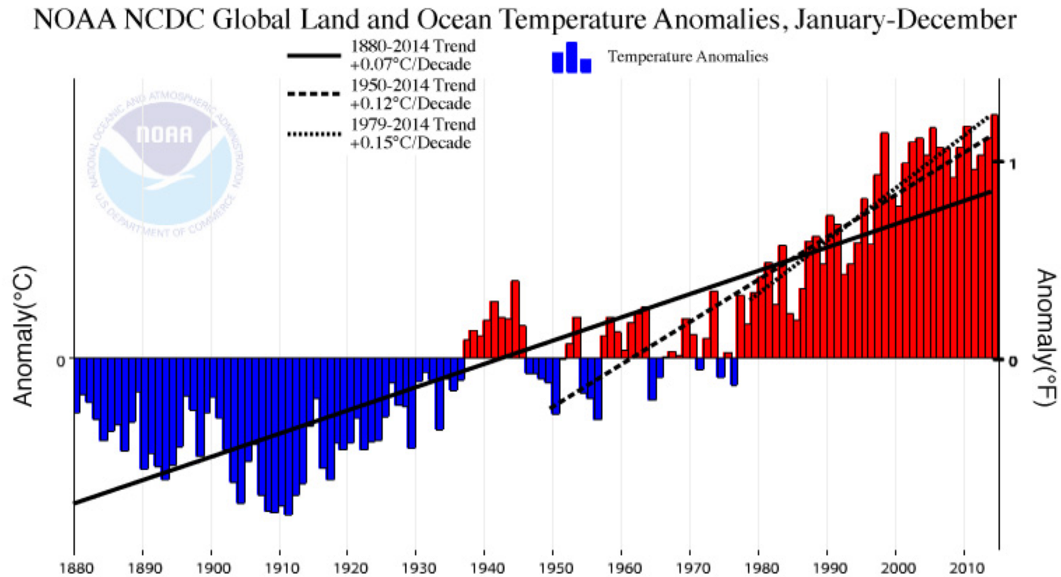


Figure courtesy of National Climatic Data Center following Smith et al., *J. Clim.*, 2Temp08.

Table 1.2

Some events in the history of global warming studies

1850s	Beginning of the industrial revolution.
1861	John Tyndall notes H_2O and CO_2 are important for infrared absorption and thus potentially for climate. The warming effect of the atmosphere and analogy to a greenhouse had been noted by J. B. Fourier in 1827.
1868	Stefan's law for blackbody radiation.
1896-1908	Svante Arrhenius postulates a relation between climate change and CO_2 and that global warming may occur as a result of coal burning.
1917	W. M. Dines estimates a heat balance of the atmosphere that is approximately correct.
1938	G. S. Callendar attempts to quantify warming by CO_2 release by burning of fossil fuels.
late 1950s	Popularization of global warming as a problem, notably by Roger Revelle.
1958	Start of C. D. Keeling's monitoring of CO_2 at Mauna Loa.
1975	1st 3-D global climate model of CO_2 induced climate change (Suki Manabe)
1979	Charney report
late 1980s	7 of 8 warmest years of the century to that point.
1990 & 92	Intergovernmental Panel on Climate Change (IPCC) Report & Supplement

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1992	**Rio de Janeiro United Nations Conference on the Environment & Development; Framework Convention on Climate Change. "*ultimate objective...stabilization of greenhouse gas concentrations*… at a level that would prevent dangerous… *interference with the climate system*".**
1995-96	**Second Assessment Report of the IPCC: "*The balance of evidence suggests a discernible human influence on global* climate. [....] There are still many uncertainties. [...]".**
1995	**Start of ongoing series of Conferences of the Parties to the Climate Convention: Discussion of short term objectives in terms of *rates* of greenhouse gas emissions by developed countries.**
1997	**Kyoto Protocol sets targets on greenhouse gas emissions at ~5% below 1990 levels by 2008 - 2012.**
2001	**Third Assessment Report of the IPCC.**
2004	**Nine of the ten warmest years since 1856 occurred in past ten years (1995-2004) (1996 was less warm than 1990).**
2005	**Kyoto protocol enters into force**
2007	**Fourth Assessment Report of the IPCC. Nobel Peace Prize awarded to the few thousand scientists of the IPCC process and one politician.**
2013	**Fifth Assessment Report of the IPCC.**

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Intergovernmental Panel on Climate Change (IPCC)

- Established 1988 by United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO).
- Reviews and assesses scientific and socio-economic information (does not conduct research, monitor data,…)
- Thousands of scientists on a voluntary basis.
- Working Group I: Physical Science Basis of Climate Change;
- Working Group II: Climate Change Impacts, Adaptation and Vulnerability (socio-economic and natural systems, negative and positive consequences, options for adaptation);
- Working Group III: Mitigation of Climate Change (limiting or preventing greenhouse gas emissions; activities that remove them; costs /benefits of approaches; available policy measures);
- 3 separate reports + Synthesis Report.

There are also independent reports by national or other organizations, e.g., 2010 report by US National Academies

1.5 El Niño: An example of natural climate variability

- ***ENSO*: El Niño/Southern Oscillation.**
  - **El Niño is associated with warm phase of a phenomenon that is largely cyclic.**
  - **originally El Niño was thought of as the oceanic part, Southern Oscillation referred to the atmospheric part.**
  - **Since ENSO is the prime example of a phenomenon that depends fundamentally on ocean-atmosphere interaction, ENSO includes both.**
- **El Niño now used for both atmospheric and oceanic aspects during the warm phase of the cycle.**
- ***La Niña* for the cold phase.**

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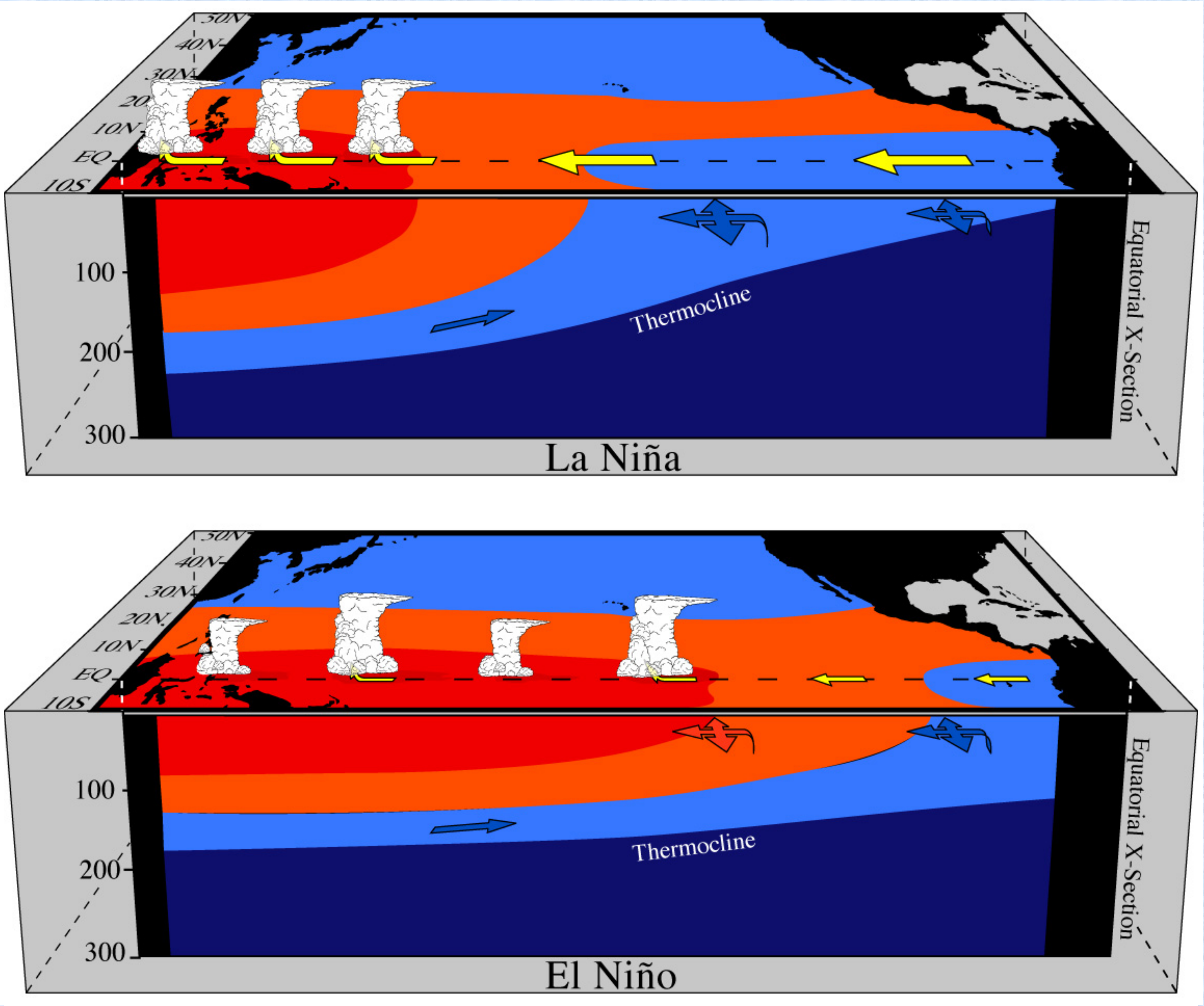
- **El Niño is sometimes applied to the entire phenomenon, e.g., the "El Niño cycle".**
- **El Niño arises in tropical Pacific along the equator.**
  - **Changes in sea surface temperature, ocean subsurface temperatures down to a few hundred meters depth, rainfall, and winds.**
  - **Variations in the Pacific basin within about 10-15 degrees latitude of the equator are the primary variables.**

Figure 4.2 (Chapter 4 preview)



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- ***Teleconnections*: remote effects of El Niño (or other regional climate variations).**
- ***Anomaly*: departure from normal climatological conditions.**
  - **calculated by difference between value of a variable at a given time, e.g., pressure or temperature for a particular month, and subtracting the climatology of that variable.**
- ***Climatology* includes the normal seasonal cycle.**
  - **e.g., anomaly of summer rainfall for June, July and August 1997, = average of rainfall over that period minus averages of all June, July and August values over a much longer period, such as 1950-1998.**
  - **To be precise, the averaging time period for the anomaly and the averaging time period for the climatology should be specified.**
    - **e.g., monthly averaged SST anomalies relative to 1950-2000 mean.**

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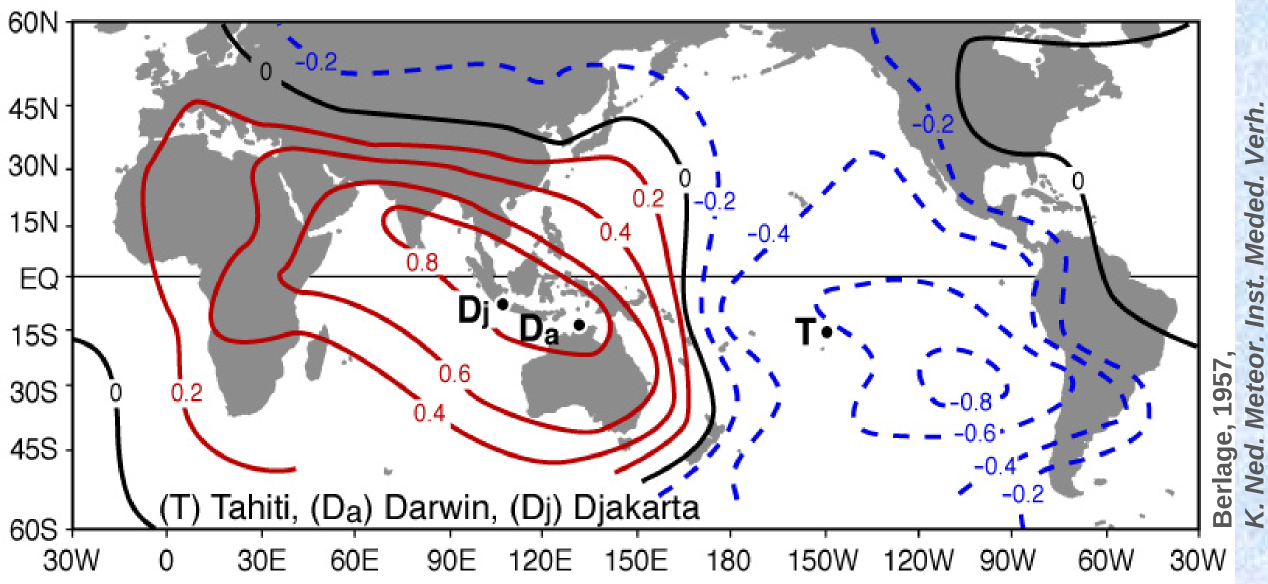
Figure 1.4

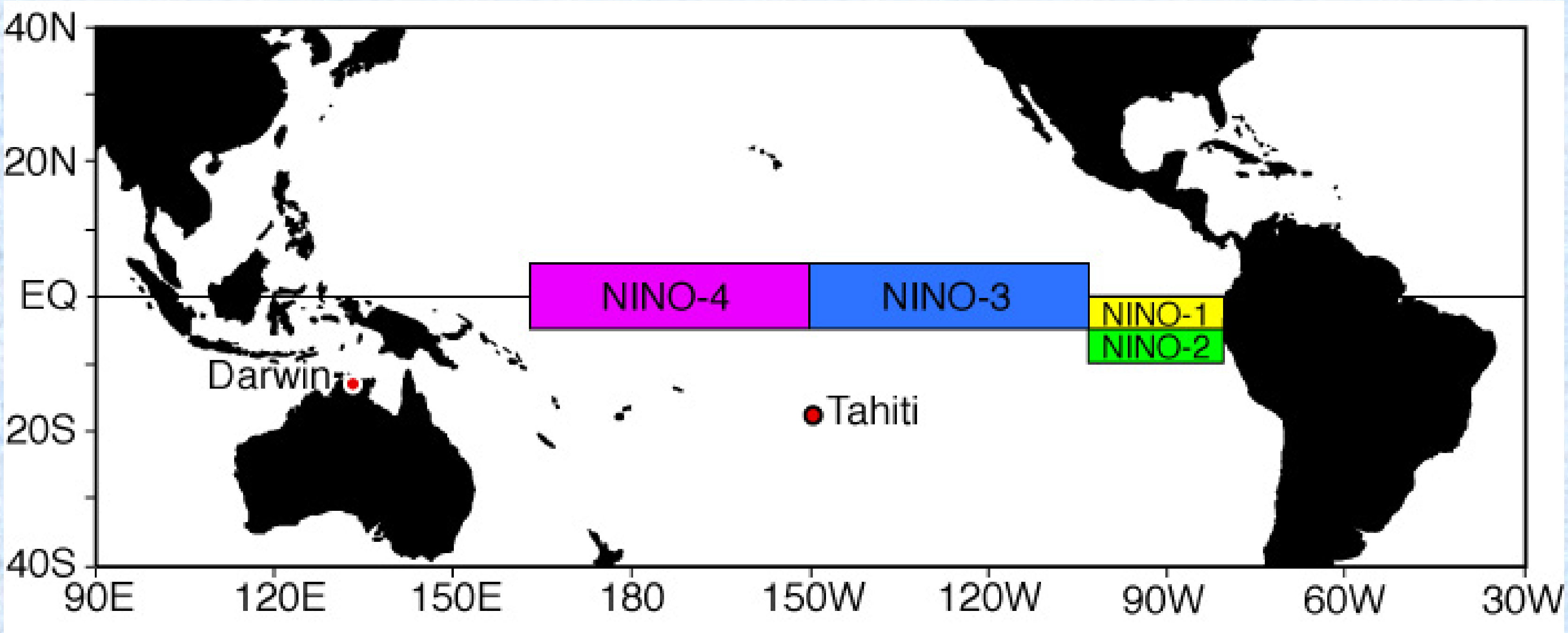
The Southern Oscillation large scale atmospheric pattern associated with El Niño as originally seen in surface pressure



- History: Peruvian fisherman ⇒ name El Nino originally warming of the coastal waters that begins around Christmas.
- Atmospheric side early 1900s, Sir Gilbert Walker negative correlation between atmospheric surface pressure in the western and eastern Pacific.
- Similar to G. Walker (1923), this figure from Berlage (1957).
- Correlates pressure data at points everywhere on the map with pressure at one point (Djakarta, Indonesia, marked Dj).
- Pressure data used to construct the Southern Oscillation Index (SOI).
- Normalized surface pressure anomalies at Tahiti minus those at Darwin.

Figure 1.5

Commonly used index regions for ENSO SST anomalies



- **When SST in the Niño-3 region is warm during El Niño, the SOI tends to be negative, i.e., pressure is low in the eastern Pacific relative to the west.**
- **Pressure gradient tends to produce anomalous winds blowing from west to east along the equator.**
- **Reverse during periods of cold equatorial Pacific SST (La Niña).**

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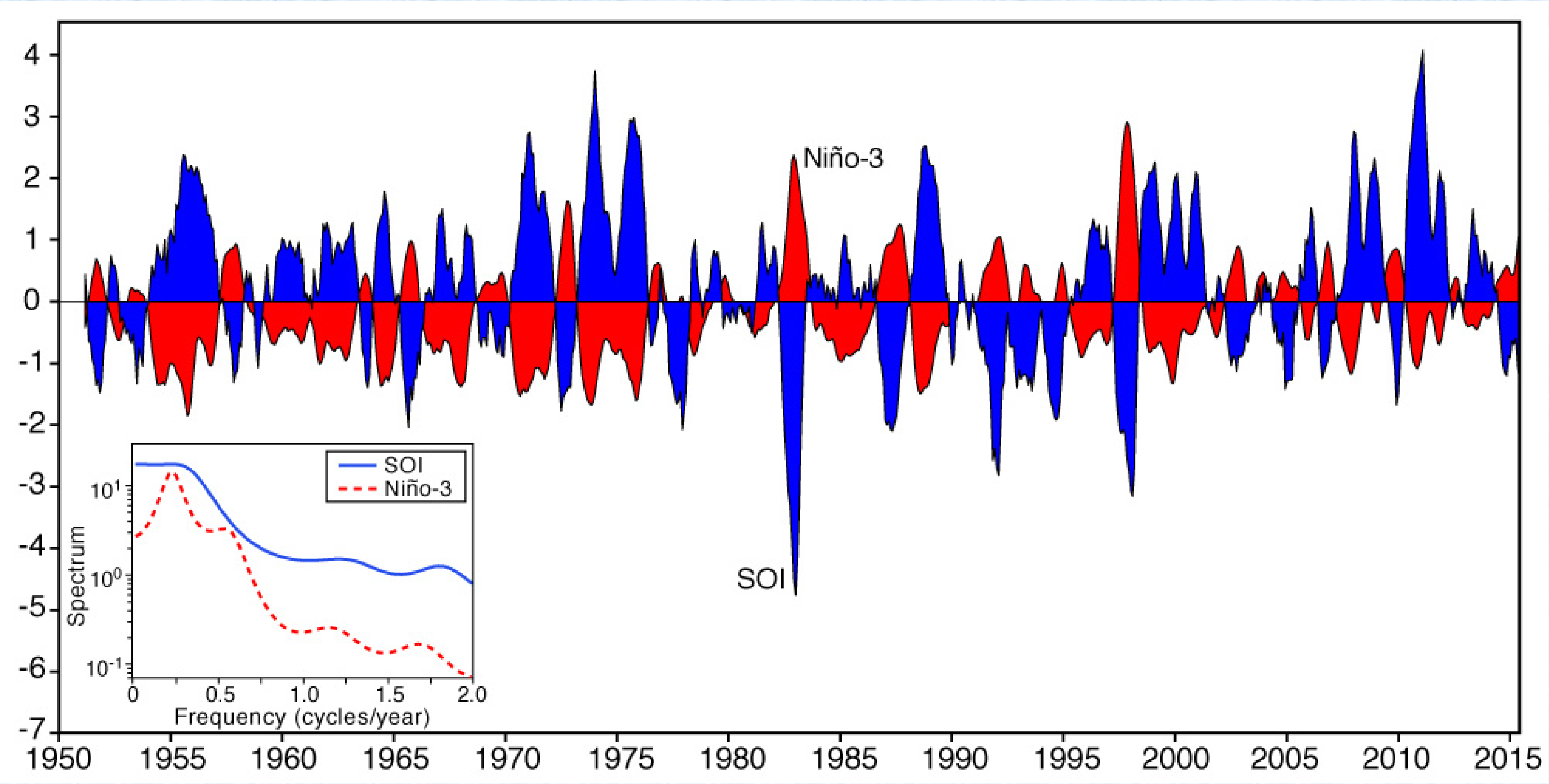
Figure 1.6

Nino-3 index of equatorial Pacific sea surface temperature anomalies and the Southern Oscillation Index of atmospheric pressure anomalies



Nino-3 data from the Reynolds data set following Reynolds (1988). SOI data are from the NOAA Climate Diagnostics Center.

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Table 1.3

Some events in the development of El Nino studies

late 1800s	Peruvian sailors refer to a coastal current that appears after Christmas in certain years as the current of “El Niño”, the Child Jesus.
1923	Sir Gilbert Walker, working in India on Monsoon predictors, publishes negative correlation of pressure in western and eastern Pacific ocean. He later shows that this irregular oscillation is associated with changes in rainfall and winds. He names it the *Southern Oscillation*.
1957	H. P. Berlage follows up on Walker’s work but receives scant notice.
1969	Jacob Bjerknes (UCLA) looks at both atmospheric variables and ocean surface variables and hypothesizes that ocean-atmosphere coupling is essential to the development of El Niño (see the *Bjerknes hypothesis*).
1975	One step forward: Klaus Wyrtki (U. of Hawaii) notices that an increase in sea level height in the western Pacific tends to precede El Niño warm phases and notes the potential role of oceanic dynamics in communicating this to the eastern basin. But one step back: he blames the ocean entirely.

Table 1.3 (cont.)

late 70s-early 80s	Developments in tropical oceanography and modeling.
1982-83	The biggest El Niño of the century catches experts unawares.
1985	The Tropical Ocean–Global Atmosphere program is launched.
1985-87	Mark Cane and Stephen Zebiak (Columbia U) develop first coupled ocean-atmosphere model with realistic El Niño (CZ model).
1986	First El Niño forecast with a physically based coupled model forecast (CZ). At the time, there was controversy over whether to trust it since the phenomenon was still not understood.
late 80s-early 90s	Developments in ENSO theory, including reconciling the role of subsurface ocean memory with the Bjerknes Hypothesis. Development of more complex ocean-atmosphere models including the first successful coupled general circulation model simulation of El Niño by George Philander and co-workers.
1997-98	El Niño becomes a household word. Forecasts by national weather services and the newly established International Research Institute for Seasonal to Interannual Climate Prediction.

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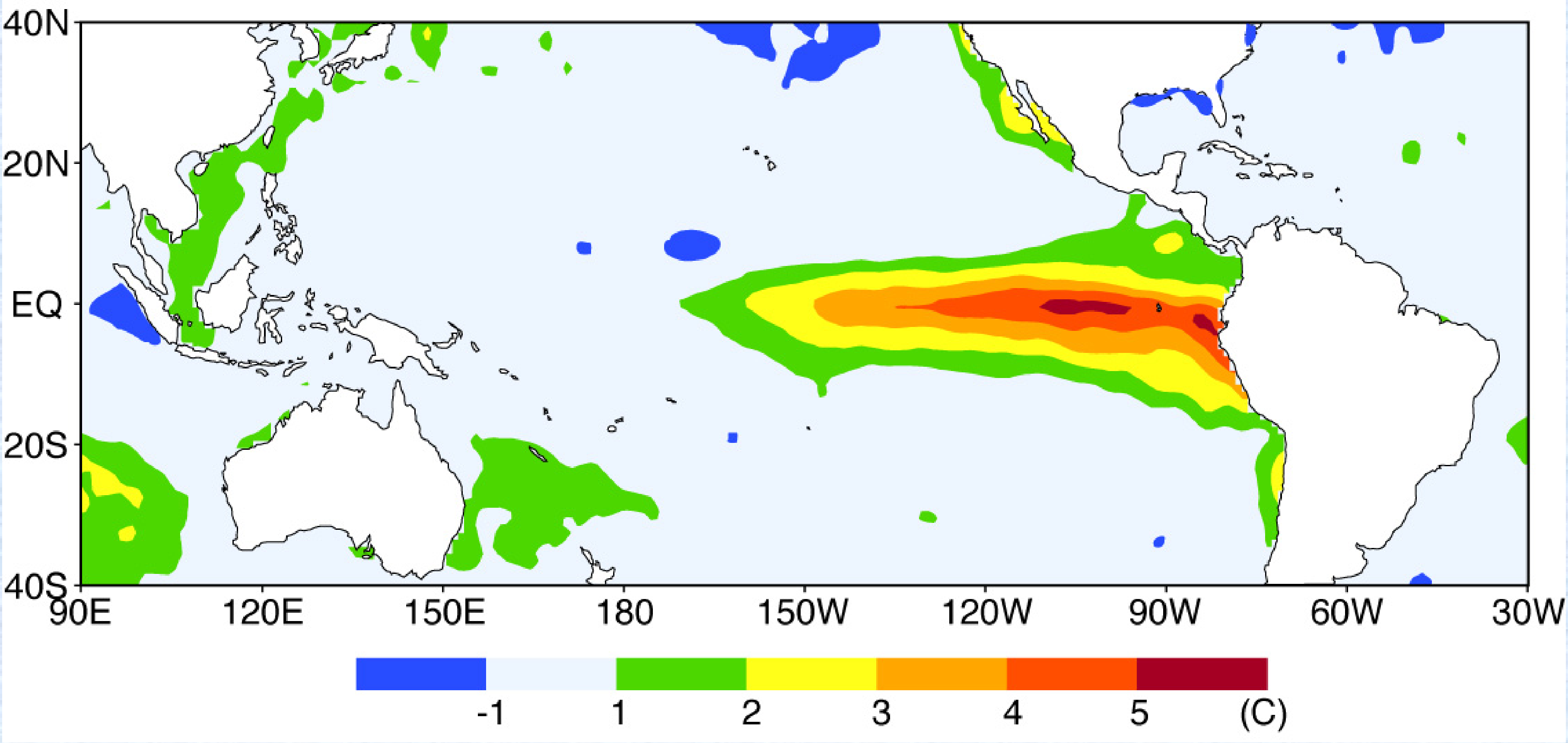
Figure 1.7

December 1997 Anomalies of sea surface temperature during the fully developed warm phase of ENSO



Reynolds data set following Reynolds (1988)and Reynolds and Smith (1999).

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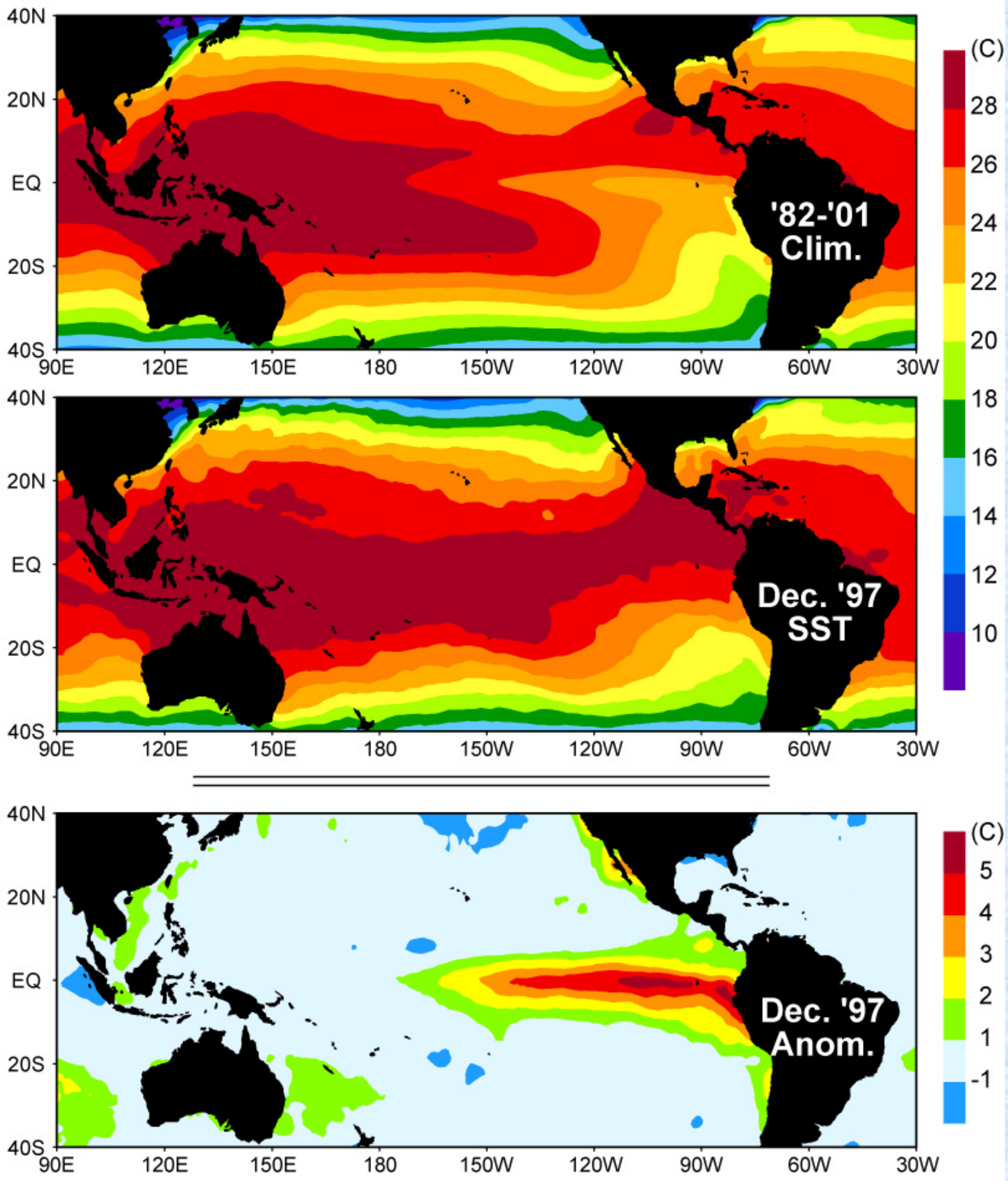
Supplementary Fig.: Sea surface temp., clim. & anom. Dec. 1997

Reynolds SST data set

Climatology
1982-2001 (C)

Sea Surface Temp.
Dec. 1997

Anomaly
(Dec.97 SST-Clim.)



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Supplementary Figure: Composite SST anomalies

El Nino:
Average of El Nino winters Dec.-Feb 1982-83, 86/87, 91/92, 94/95, 97/98 Minus Clim. (1982-2001)

La Nina:
Average of La Nina winters Dec.-Feb 1984-85, 88/89, 95/96, 98/99, 99/00 Minus Cim. (1982-2001)

A means of examining "typical" event

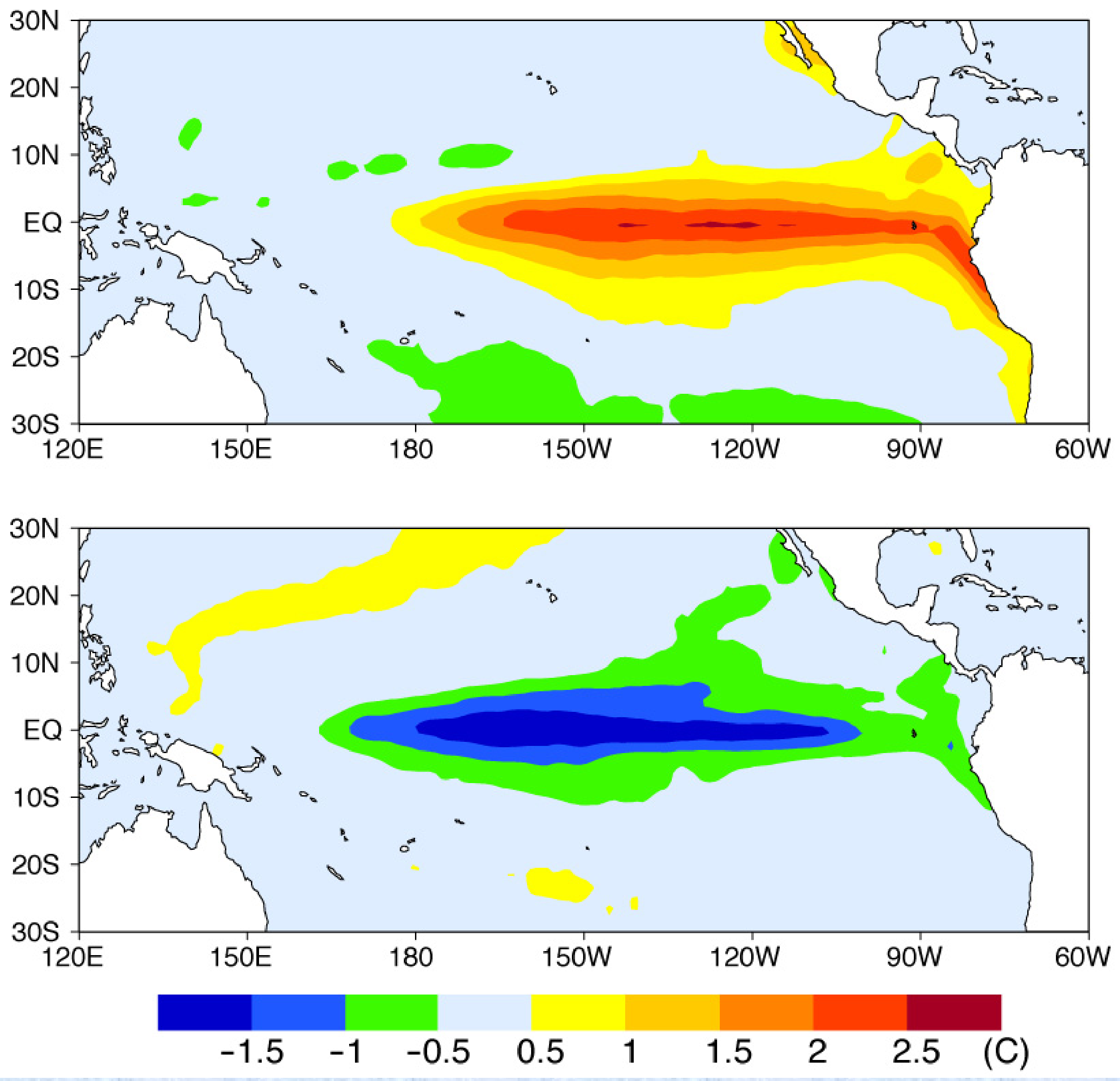

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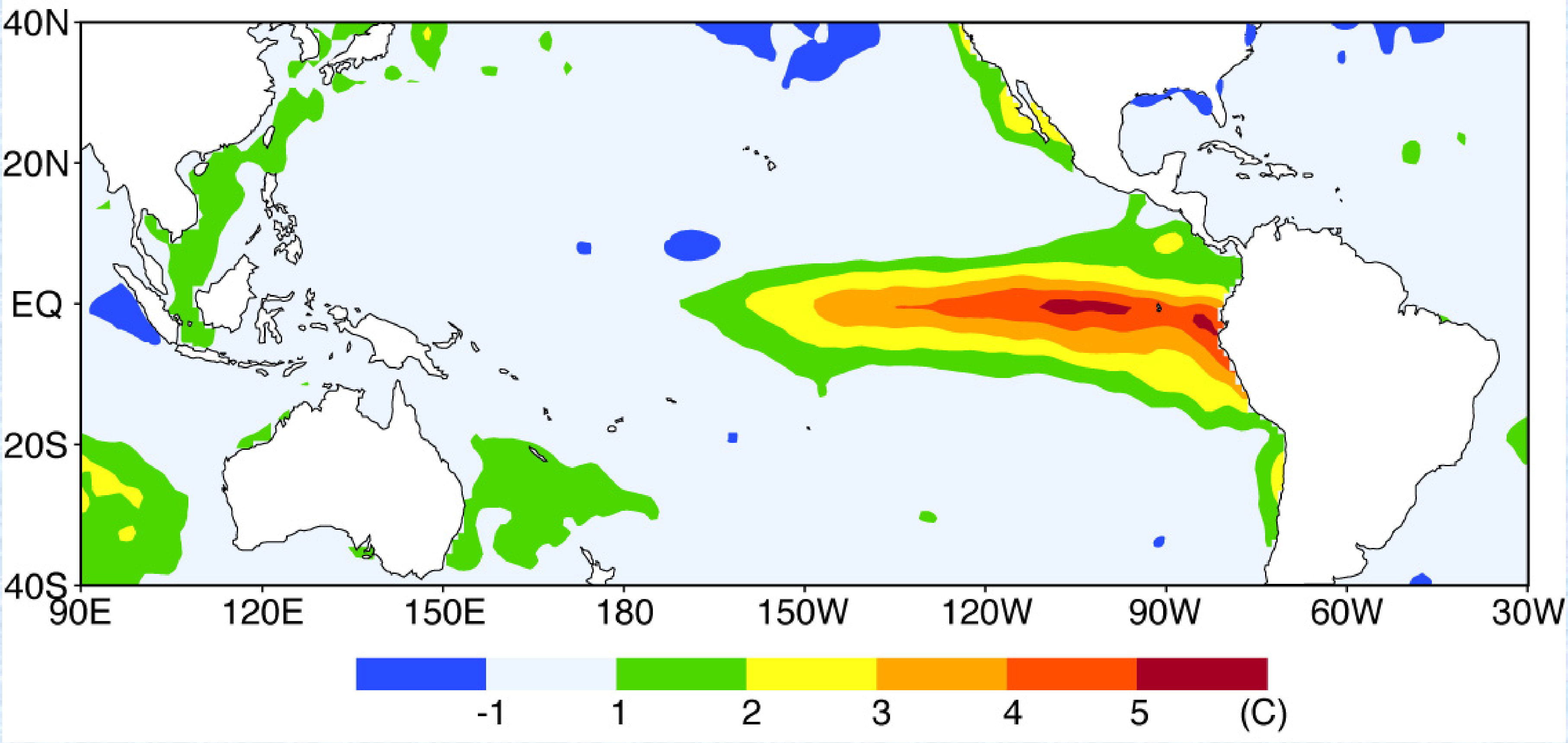
Figure 1.7 (repeated)

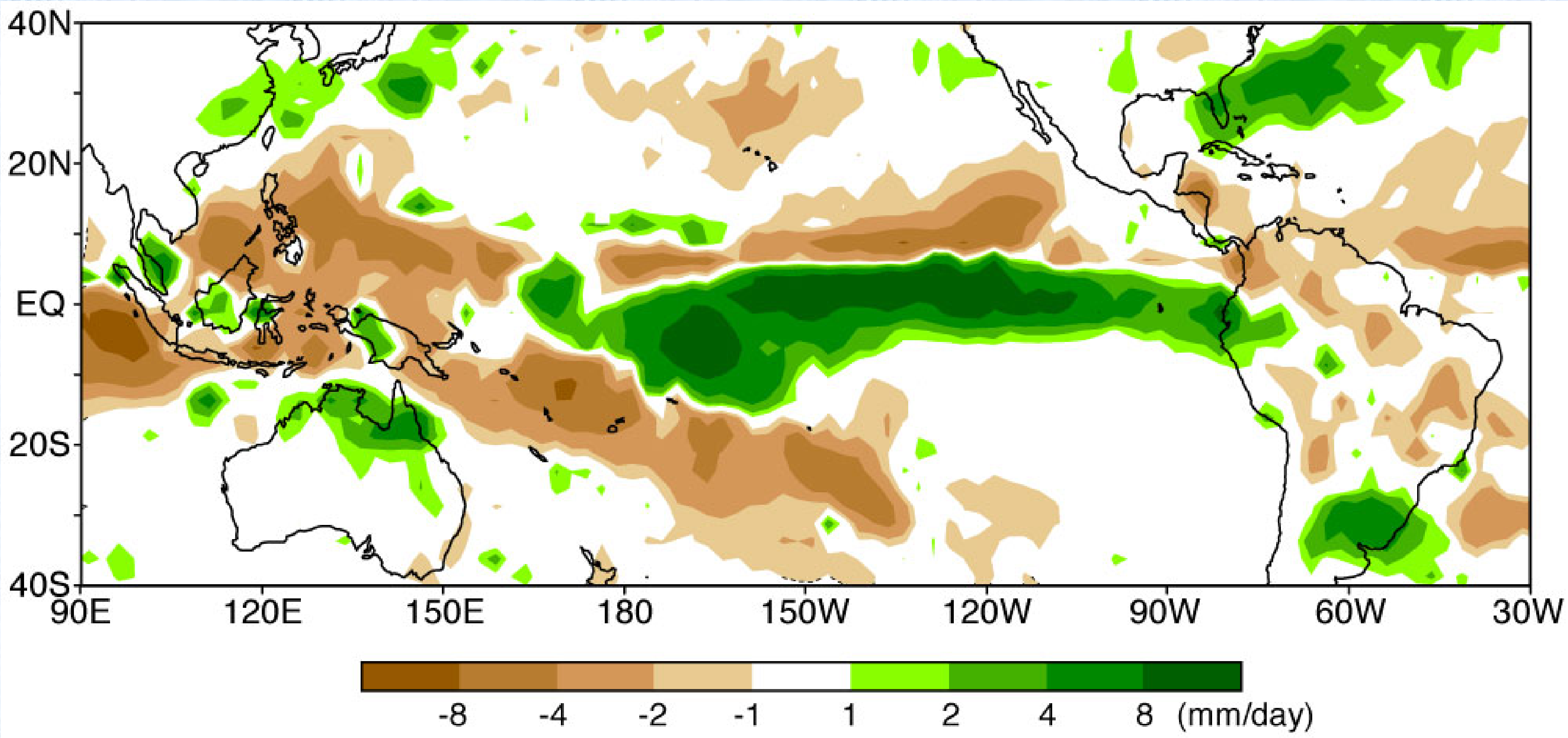
December 1997 Anomalies of sea surface temperature during the fully developed warm phase of ENSO



Reynolds data set following Reynolds (1988) and Reynolds and Smith (1999).

Figure 1.8

December 1997 Anomalies of precipitation during the fully developed warm phase of ENSO



Data from the NOAA Climate Prediction Center, following Xie and Arkin (1996).

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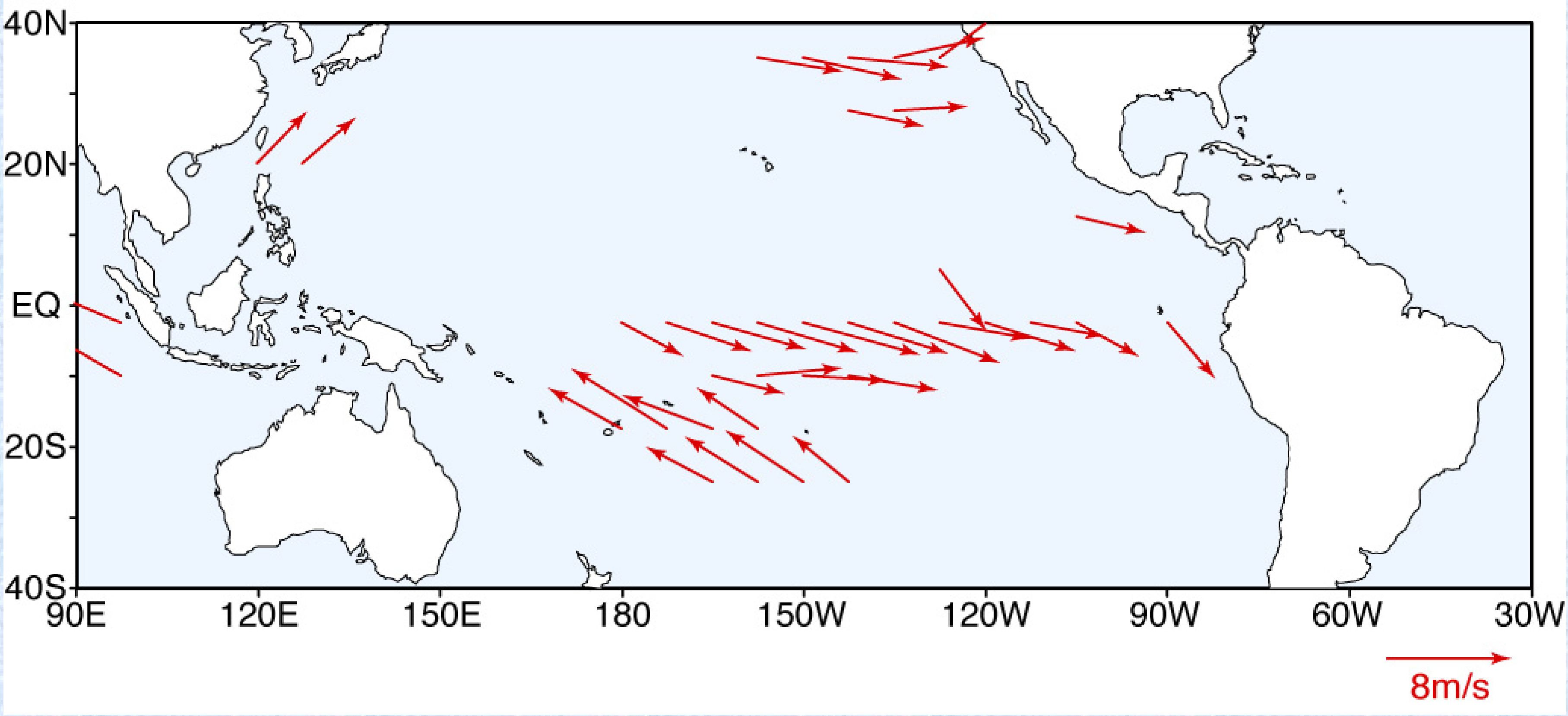
Figure 1.9

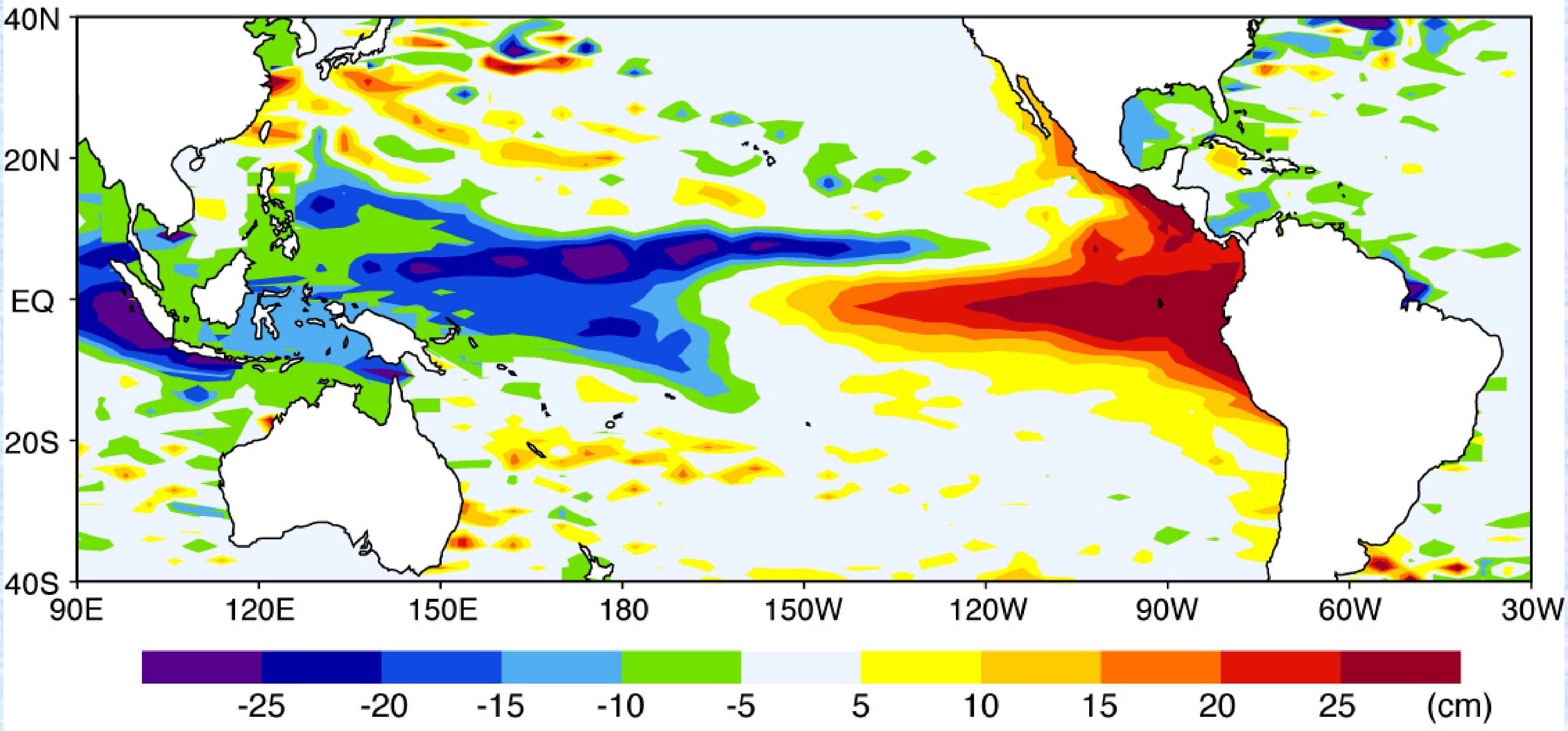
DJF Low-level wind anomalies during the 1997-98 El Niño relative to the 1958-98 climatology



National Centers for Environmental Prediction (NCEP) analysis data set. Kalney et al. 1996, *Bull. Amer. Meteor. Soc.*

Figure 1.10

December 1997 Anomalies of sea level height during the fully developed warm phase of ENSO

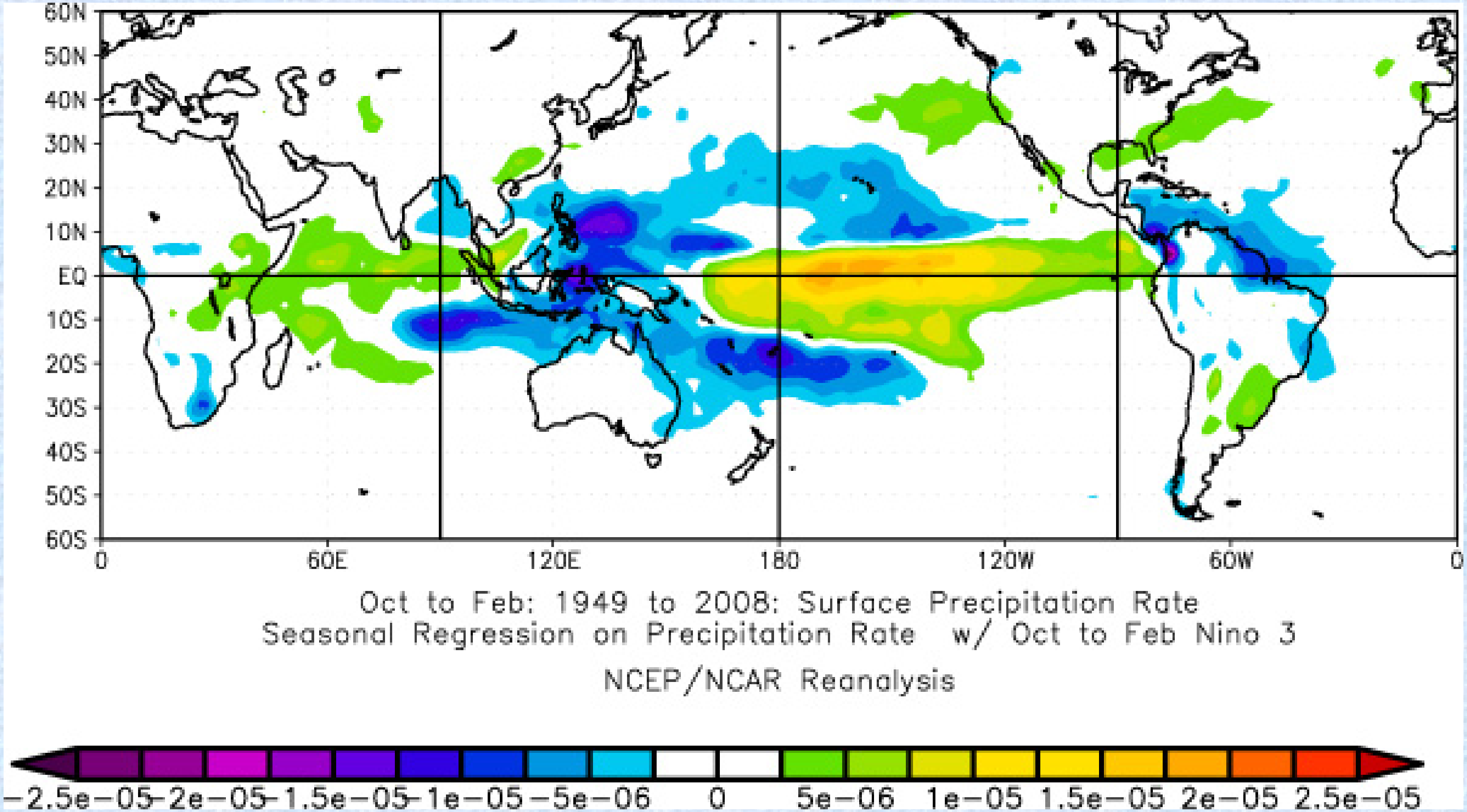


Data from NOAA Laboratory for Satellite Altimetry following Cheney et al., 1994, *J. Geophys. Res.*

Neelin, 2011. *Climate Change and Climate Modeling*, Cambridge UP

In discussion section: Pb Set 1A
Data exploration with correlation and regression program

e.g., Oct-Feb Anomalies of precipitation associated with ENSO by regression on Nino3 SST index



Data from NOAA Earth System Research Lab).

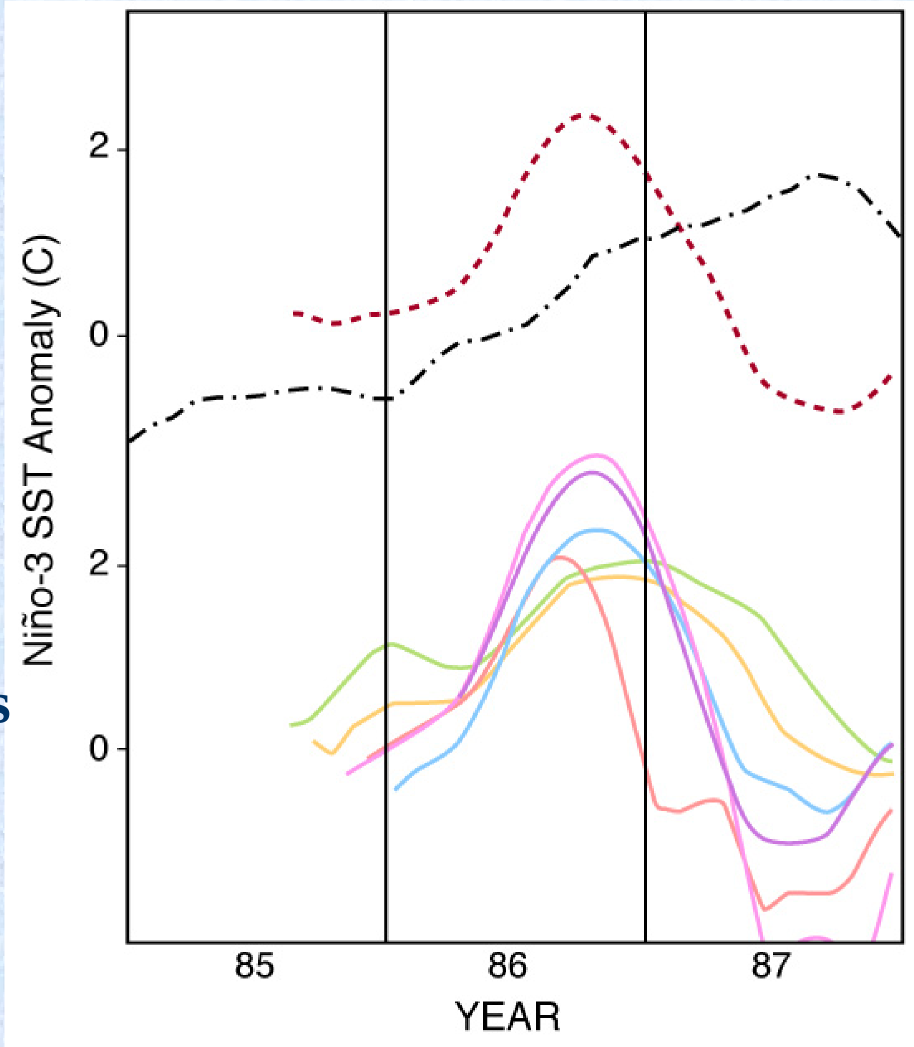
Regression: how much precipitation changes at each point per change in SST index; Correlation: how strong is the relationship?

Figure 1.11

First published real-time forecast of El Niño, by Cane and Zebiak, published June 1986

Forecast (red; Avg. individual forecasts shown below) Observations (Black) added from later data

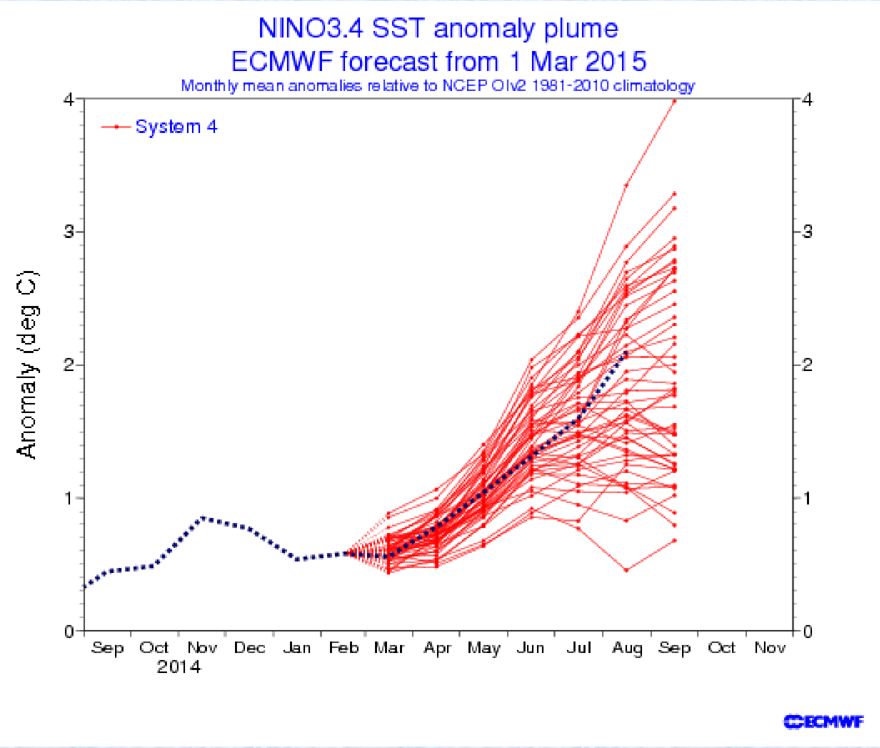
Ensemble of forecasts from different initial conditions (see Ch. 4)

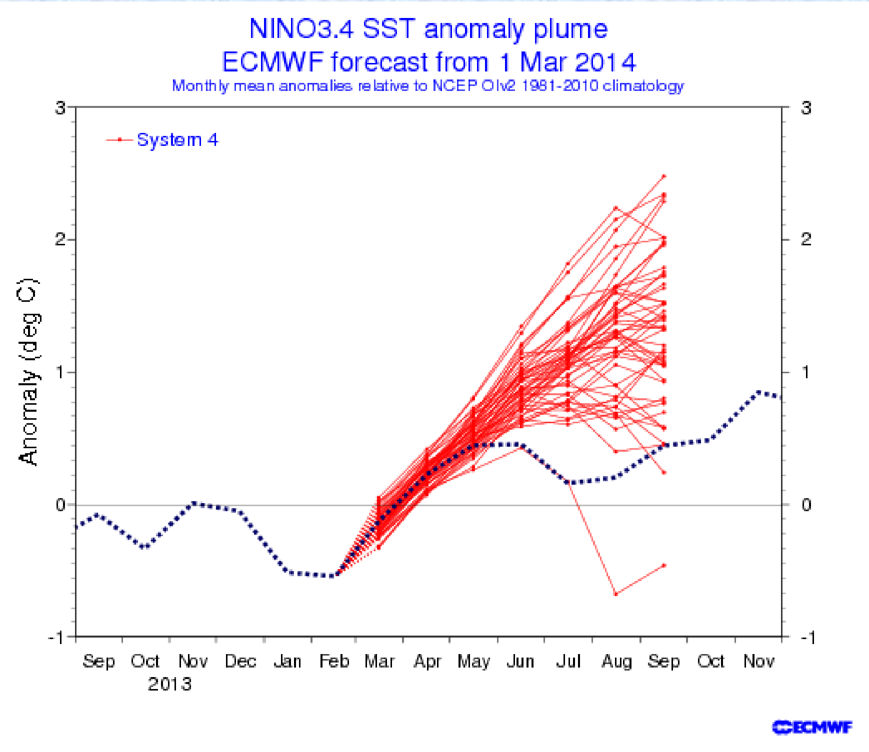


Cane et al., 1986, *Nature*

Not a success by current standards, but initiated climate forecasts on these time scales

ECMWF forecast from Mar 1 2015 vs. 2014

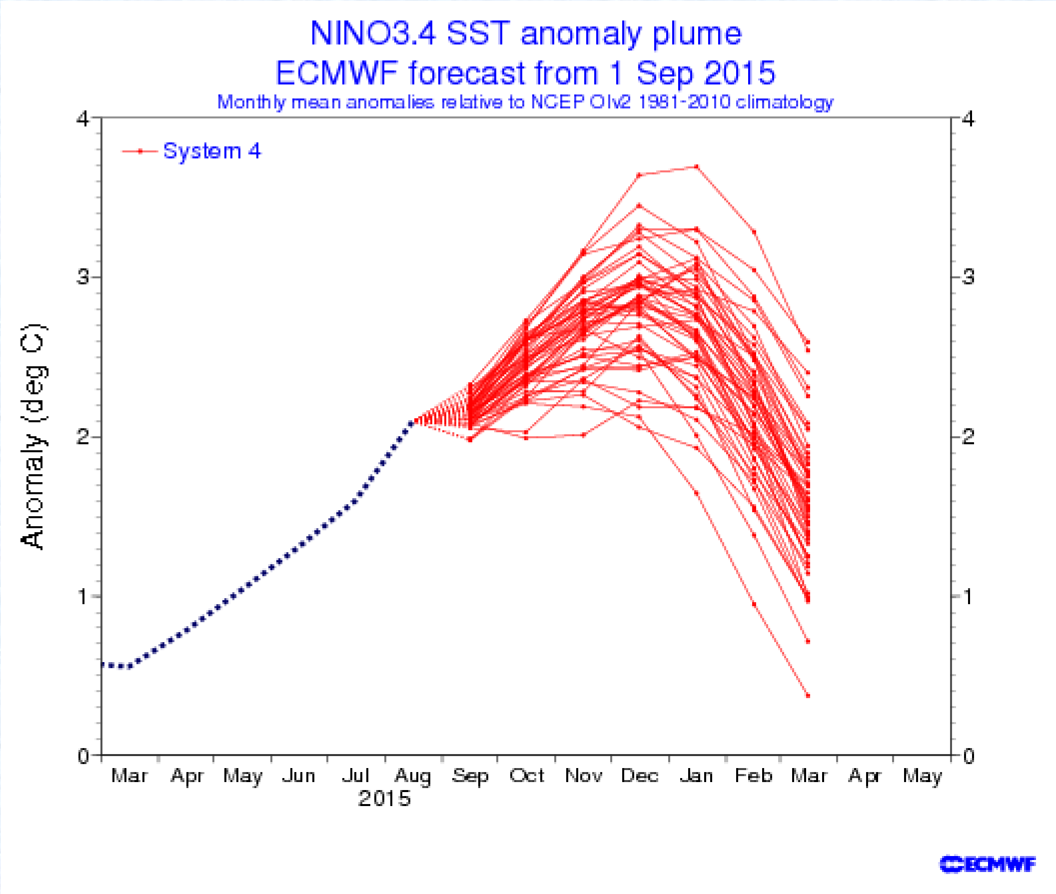




Courtesy of the European Centre for Medium-range Weather Forecasting.

Courtesy of the European Centre for Medium-range Weather Forecasting.

ECMWF forecast from Sep 1 2015



Courtesy of the European Centre for Medium-range Weather Forecasting.

Courtesy of the European Centre for Medium-range Weather Forecasting.

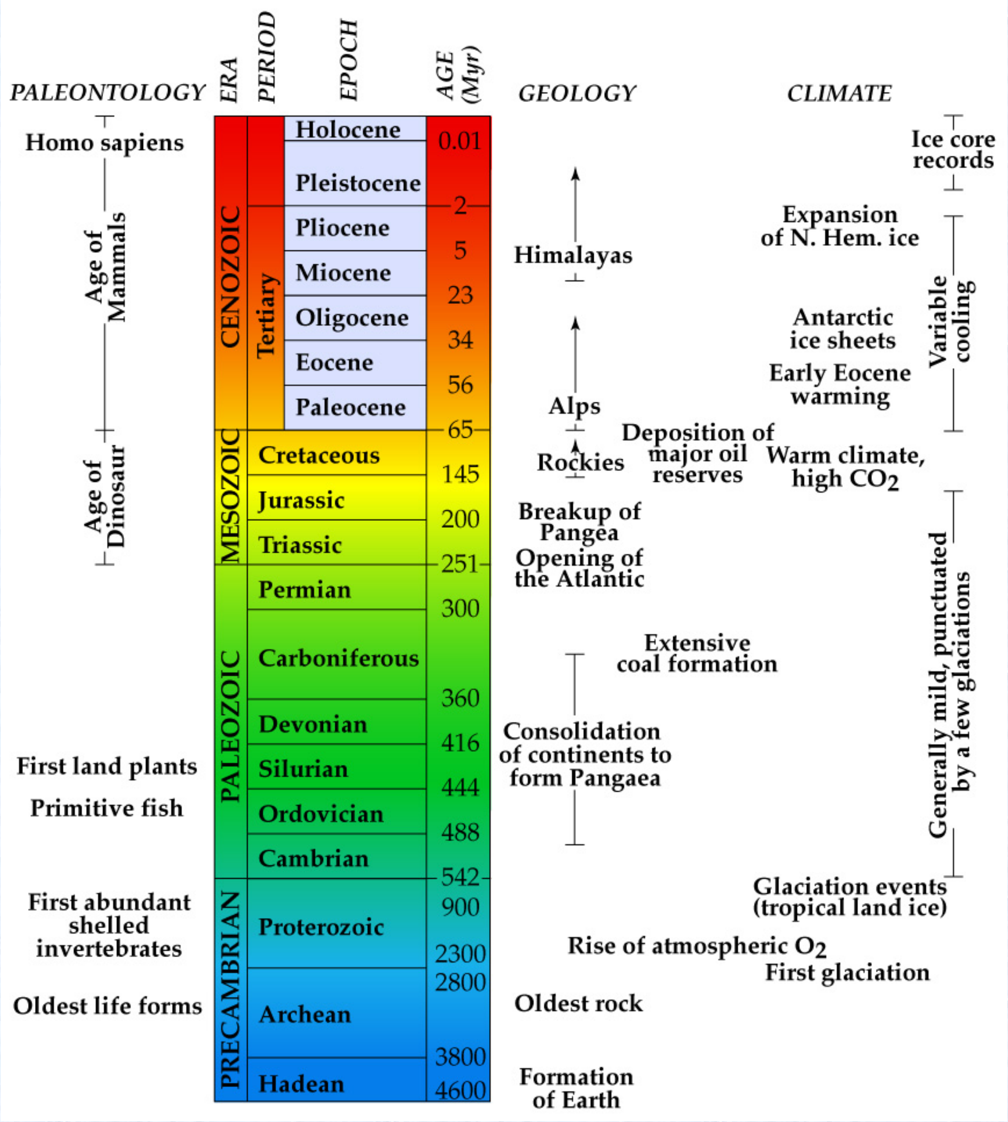
Figure 1.12

Paleoclimate: A few climate notes with Geological time scale

- **Very distant past ---**
  Myr = millions of years

Key points:

- **Climate can vary substantially, on all timescales**
- **Long periods in deep past with warmer climate than present (& higher est. CO_2)**
- **Deposition over millions of years sequesters carbon dioxide as fossil fuels (oil, coal, natural gas)**
- **Return of this CO_2 to atmosphere occurring over very short period.**



Adapted* from Crowley 1983, *Rev. of Geophysics and Space Physics*
*Paleoclimate information & updates follow Crowley and North, 1991, Zachos et al., 2001 & Royer, 2007

Neelin, 2011. *Climate Change and Climate Modeling*, Cambridge UP

Supplementary Fig.: Antarctic Ice Core Drilling Sites (& other stations)

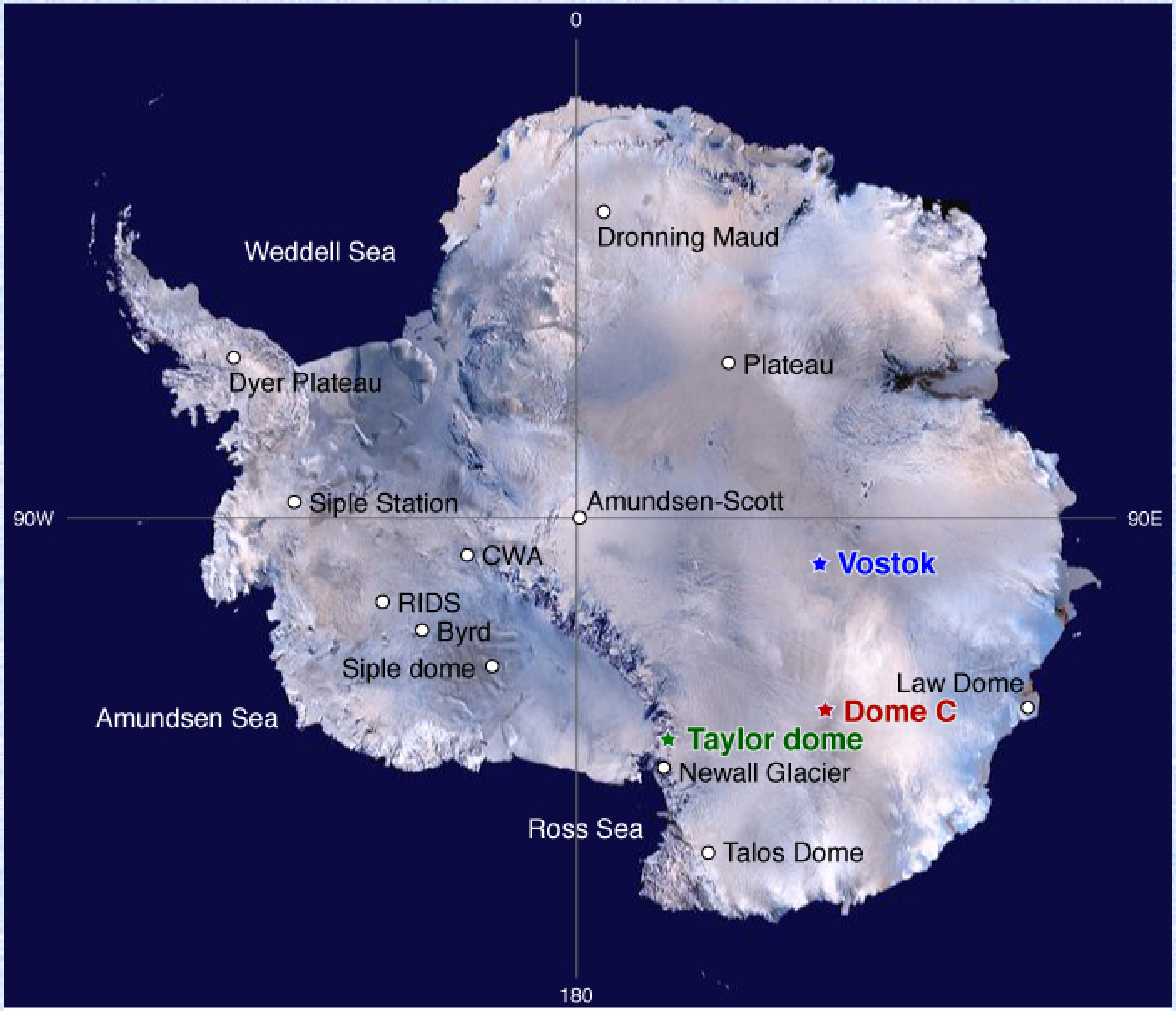


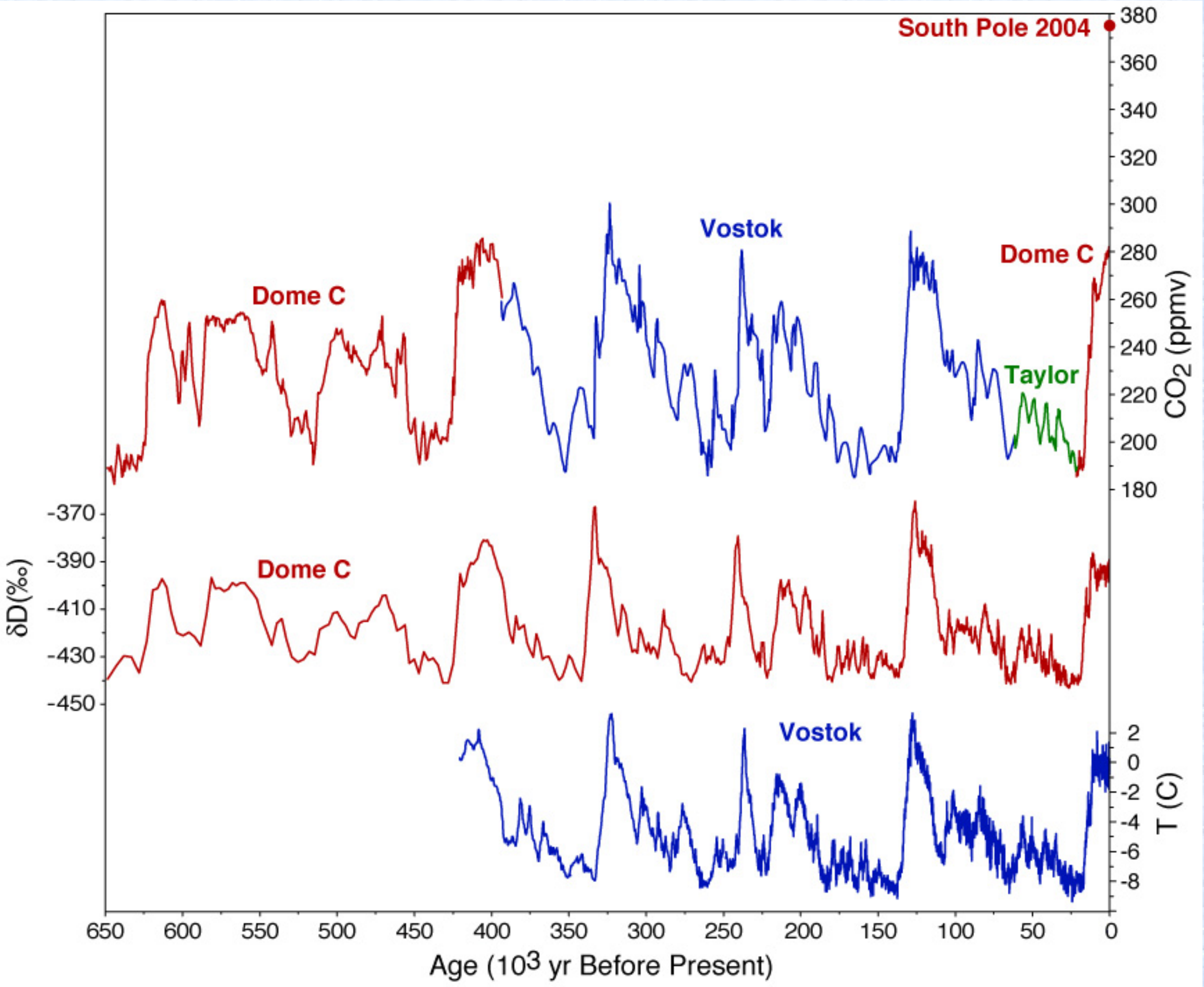
Image courtesy of NASA.

Figure 1.13

Antarctic ice core records of CO_2, deuterium isotope ratio variations (δD), and Antarctic air temperature inferred from δD

•**Deuterium D: isotope of hydrogen with one extra neutron; δD (units per mil): isotope ratio as departures from standard ratio, divided by standard ratio.**

•**Water molecules containing heavier isotopes, D instead of H or ^{18}O instead of ^{16}O evaporate less easily/condense more easily (*fractionation*); depends on temperature T so empirical relationships give *rough* Antarctic T estimate**



Data from the National Climate Data Center archive following Siegenthaler et al., 2005; bottom curve Petit et al. (1999).

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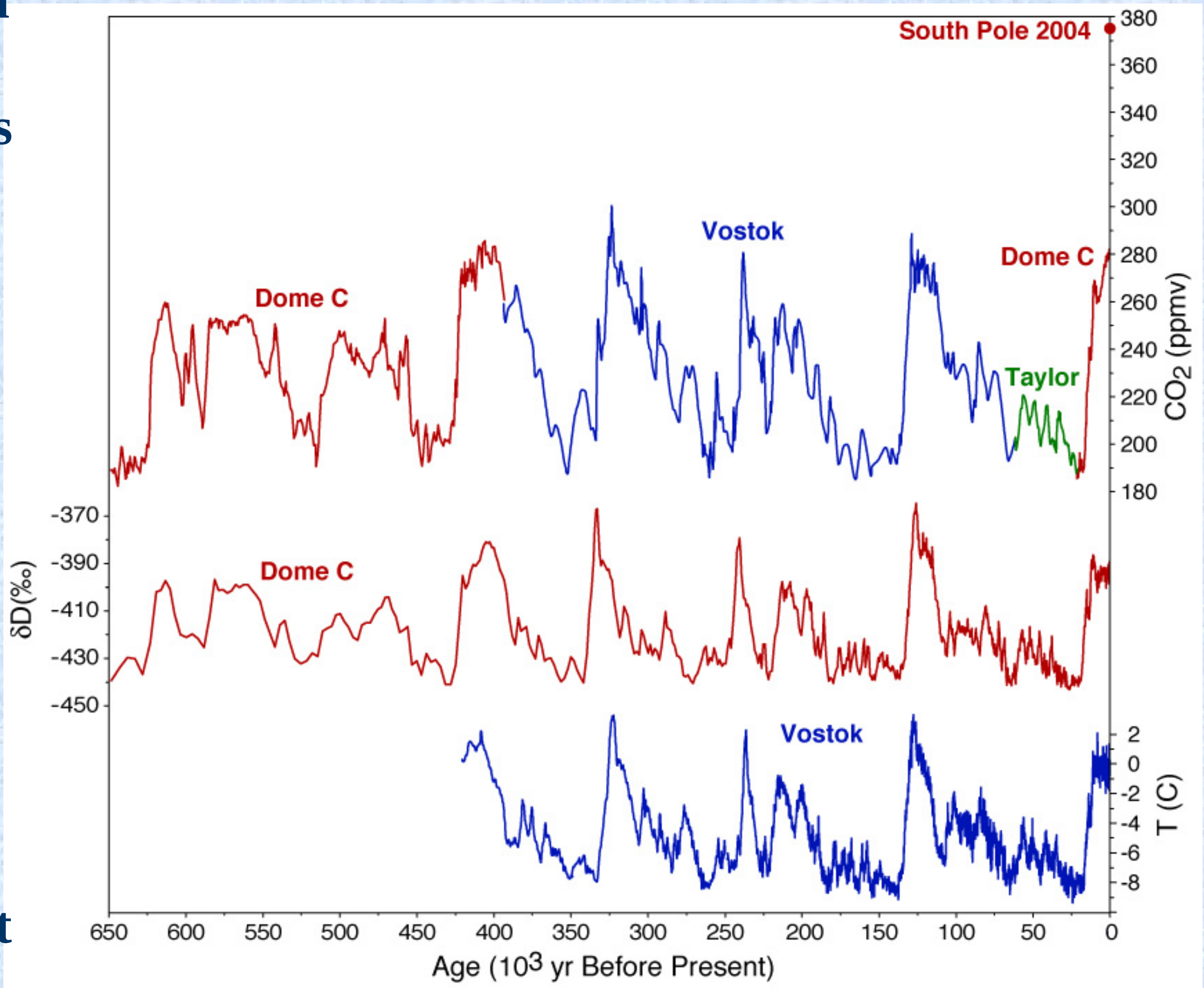
Figure 1.13

Antarctic ice core records of CO_2, deuterium isotope ratio variations (δD), and Antarctic air temperature inferred from δD

- •irregular vbty, but preferred time scales e.g. last 5 glacial cycles ~100,000 year intervals
- •Orbital parameter drivers, Milankovitch theory: tilt of axis &eccentricity of orbit (see ch.2) periods 19, 23, 41, 100, 400ky affecting seasonal distribution of insolation.
- •recent CO2 conc > natural in past 650,000y
- •Association high T & CO2
- •Glacial values ~180 ppm; interglacial ~280 ppm
- •sea level 120m below present last glacial maximum; 4-6 m above present last interglacial



Data from the National Climate Data Center archive following Siegenthaler et al., 2005; bottom curve Petit et al. (1999).

Neelin, 2011. *Climate Change and Climate Modeling*, Cambridge UP