THE UNIVERSITY OF AUCKLAND
NEW ZEALAND
Te Whare Wānanga o Tāmaki Makaurau

School of Environment

GEOG 101 - Geography of the Natural Environment – 2011 S1

Climate Section - Lecture and Study Notes

The material presented in this booklet is arranged by lecture. It consists of black and white thumbnail copies of selected slides used in lectures, lecture outlines, key words and recommended reading. Focussing questions are given to help direct your study and understanding of the various themes. Please bring this booklet to each lecture in this section of the course.

Coloured versions of thumbnails of visual material used in lectures are also available on Cecil. Keep in mind it is better to use resources on Cecil, as colour keys can be recognised and you can zoom in on detail in small scale diagrams and figures. Most figures and diagrams shown in the thumbnails can be found in the readings, mainly in the Strahler and Strahler text described below.

The information contained here and the thumbnail lecture notes on Cecil are not intended to be primary source material. It is intended only as a memory aid to help you recall the structure of lectures. You are expected to find the relevant material in the readings to build on what is presented here and in the lectures and laboratory exercises.

The basic reading texts are: a) Strahler, A. and Strahler, A, 2005. *Physical Geography - Science and Systems of the Human Environment, 3rd* edition, John Wiley and Sons, New York; and b) Smithson, P, Addison, K. and Atkinson, K., 2002 *Fundamentals of the Physical Environment*, 3rd edition, Routledge, London. The books are complementary. Some of the detail in Smithson et al (2002) is indicative of how themes will be developed in more advanced courses, in particular, GEOG 201. Note that chapter and page numbers given here refer to the 3rd editions. There are three editions of each book. If you are using the 1st edition of Strahler and Strahler (1997), notice that chapter numbers are two less than in the 2nd edition (2002) or 3rd edition (e.g. Chap 3 in 1997 edition is equivalent to Chapter 5 in the 2005 edition). The earlier editions of the other text (the equivalent of Smithson et al, 2002) are quite different, so readings refer only to the 3rd edition. Carefully look through both of these books and read those parts that coincide with themes or topics covered in lectures. There are some additional basic reading sources listed after lecture summaries. Details of the readings, including where to find them, are given in the general course handout.

Lecture schedule – Climate Section S1 2011

2	March	Basics of climate I: Earth's atmosphere and role of the Sun
3	March	Basics of climate II: radiation and temperature
7	March	Air masses and cyclogenesis
9	March	Nature and causes of winds
10	March	Atmosphere and ocean circulation
14	March	Decadal-scale circulation systems (ENSO)
16	March	Weather forming systems
17	March	Climate variability and change
21	March	Test – Climate section

Chris de Freitas
Feb 2011

Lecture 1 The basics of climate I: Earth's atmosphere and role of the Sun

Content

Climate, key climate variables and controlling factors are defined and explained, with emphasis on the importance of location. Radiation from the sun drives the processes that determine climate. An understanding of radiation is therefore fundamental to climatology. In this lecture we follow solar radiation through the atmosphere to the surface of the planet as well as examine long wave radiation exchanges.

Themes

What is climate and what the main climate controls?
Composition of the atmosphere
Factors affecting climate
Earth's rotation and orbit
Radiation and electromagnetic spectrum
Insolation and world latitudinal zones
Controls on radiation

Lecture objectives

1. List the gases that make up the atmosphere.
2. Climate significance of Earth's rotation on its axis and its revolution around the Sun.
3. Relate the tilt of the Earth's axis with seasonal variation.
4. Distinguish between a solstice and an equinox.
5. Demonstrate the effect latitude has upon the amount of insolation received by the surface of the Earth (thus the creation of world latitudinal climate zones).

Key words

troposphere	stratosphere	shortwave radiation	longwave radiation
Watt and Joule	solar spectrum	solar constant	insolation
solstice solar angle	Earth-Sun distance	equinox	direct radiation
global radiation	diffuse radiation	greenhouse effect	atmospheric window
net radiation	scattering	albedo	

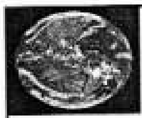
Focussing questions

What are gases make up the Earth's atmosphere?
Why is solar angle so important and what factors determine solar angle?
What is insolation?
What is the significance of the seasonal imbalance of net radiation between hemispheres?
Give four reasons why the intensity of solar radiation at the Earth's surface is always less than the solar constant.
Why do most objects reflect little or no longwave radiation?
Describe atmospheric transmissivity and optical air mass.
What is the significance of the tilt of the Earth's axis (in terms of climate)?

Reading

Strahler, A. and Strahler, A. 2002, *Physical Geography - Science and Systems of the Human Environment* 2nd or 3rd ed., John Wiley and Sons, New York. Relevant parts of Chapters 3 and 4.

Smithson, P, Addison, K. and Atkinson, K., 2002 *Fundamentals of the Physical Environment*, 3rd edition, Routledge, London. Pages: 18-24, 26-29, 39-51.



GEOG 101 - Climate Section

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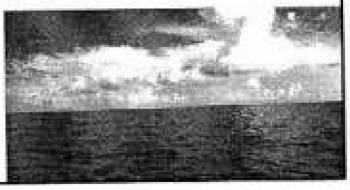
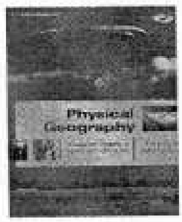


Main texts



Strahler, Alan and Strahler, Arthur, _Physical Geography_. John Wiley and Sons, New York.

Smithson, P., Addison, K. and Atkinson, K., 2002. _Fundamentals of the Physical Environment_. 3rd edition, Routledge, London.

↳ Climatology better book more critical

Strahler, Alan and Arthur Strahler: _Physical Geography: Science and Systems of the human Environment_, Wiley.

Watch out for variations!

Chapters

1st edition		2nd edition		3rd edition
1	►	3	►	3
2	►	4	►	4
3	►	5	►	5
4	►	6	►	6
5	►	7	►	7
6	►	8	►	8
7	►	9	►	9
8	►	10	►	10
9	►	11	►	11

GEOG 101 - Climate Section

LECTURES

1. The basics of climate I: Earth's atmosphere and role of the Sun
2. The basics of climate II: radiation and temperature
3. Air masses & their relevance to weather and climate
4. Winds
5. Atmosphere and ocean circulation
6. Decadal-scale systems
7. Weather forming systems
8. Climate variability and change

GEOG 101 – Lecture

Earth's atmosphere and role of the Sun

Lecturer: Chris de Freitas

Sun drives climate system critical to earth

Lecture Outline

- Composition and structure of the atmosphere
- Earth's rotation and orbit
- Sun-Earth geometry
- Controls on radiation
- Radiation and electromagnetic spectrum
- Solar and terrestrial radiation
- Radiation and energy balance, including counter radiation, albedo and greenhouse effect
- Net radiation and poleward heat transfer
- Latent and sensible heat (also at start of following lecture)

Controls on radiation

The Earth's Atmosphere

near ground

- Atmosphere = gaseous envelope surrounding the Earth. fluid medium like water → always becomes thin.
- Conceived of as a series of concentric layers.
- Atmosphere is held down by gravity. holds us down
- Most of the atmosphere's mass is near the surface. greatest at surface

action layer bottom.

as we move up pressure has dropped. not many molecules

Composition of the atmosphere in the troposphere

Constant gases

Nitrogen 78% (converted by bacteria into a useful form in soils)

Oxygen 21% (produced by green plants in photosynthesis and used in respiration)

Argon ~1% (inert)

≈ *100%. So what about the 'other' gases?*

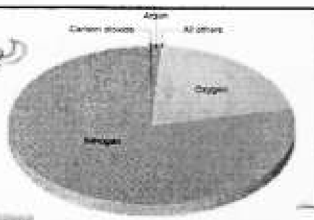
So small don't figure.

Water vapour? and is exception not the rule!.

Other gases trace gases

dry.

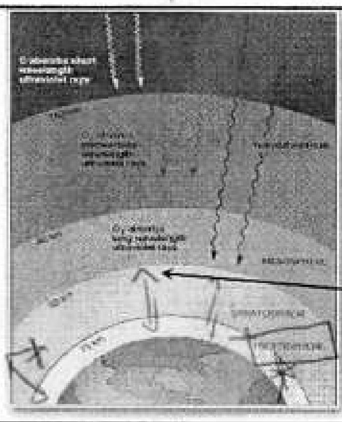
Table 1-1 Principal gases of dry air		
Constituent	Percent by Volume	Concentration in Parts Per Million (PPM)
Nitrogen (N_2)	78.084	780,840.0
Oxygen (O_2)	20.946	209,460.0
Argon (Ar)	0.934	9,340.0
Carbon dioxide (CO_2)	0.036	360.0
Neon (Ne)	0.00182	18.2
Helium (He)	0.000524	5.24
Methane (CH_4)	0.00015	1.5
Krypton (Kr)	0.000114	1.14
Hydrogen (H_2)	0.00005	0.5



What's missing?

Note: Gives gases in dry air

however plants use CO_2 for food so most important so amount not important.



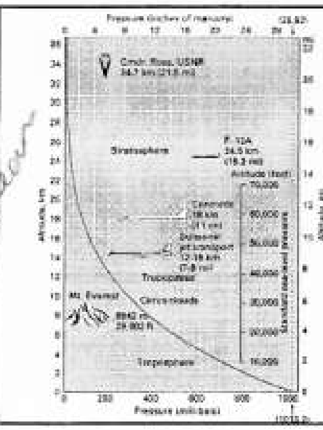
Ozone (0_3) layer

water always in atmosphere.

troposphere main focus

30° to each side of equator

Solar energy



Jetstream

Atmospheric pressure decreases rapidly with altitude near the surface

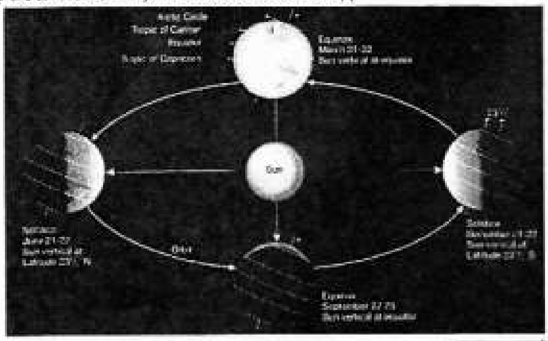
Therefore a small change in elevation will often produce a significant change in air pressure

Earth's climate is driven by energy from the Sun

e.g. flying Perth to NZ quicker than NZ → perth because of jetstream

Controls on radiation

Earth's distance from the Sun: perihelion (nearest), aphelion (farthest). (Leads to approximately 3.4% more solar radiation at the Earth's surface in January and 3.4% less radiation in July.)

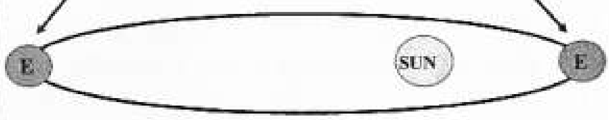


Jan our summer
3.4% more
radiation
diff in climate
SH clearer than NH

The Sun is not in the middle of the plane of the ecliptic

Aphelion - the Earth furthest away from Sun (July 4)

Perihelion - the Earth closest to Sun (January 3)



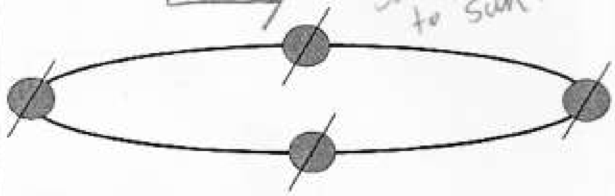
Variation in distance of 3%

Diagram exaggerates distance variation

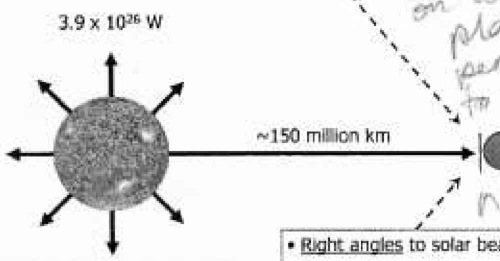
not constant to earth
average varies
(as we read more accurately)

The Earth rotates from west to east once every 23 hours 56 mins. every 4 years leap year

As the Earth's axis points same way it remains parallel (parallelism) → tilt always same to sun



Solar Constant = 1370 W/m^{-2}



- Right angles to solar beam
- Outside atmosphere

on a plain perpendicular to the sun assuming we have no atmosphere

no sun everything dies
0° absolute nothing exist
3 laws
one hot object sun
hotter the object shorter

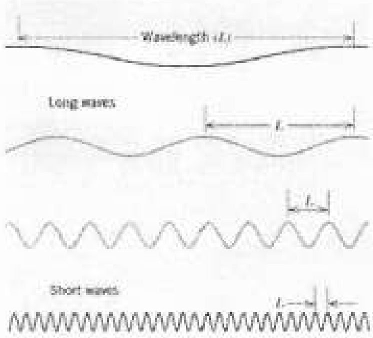
that's when climate begins

Once solar radiation enters the earth-atmosphere system the movement and distribution of the resulting radiant energy to a very large extent determine the climate experienced at a any given location.

Sun sets winds due affect

generally

Wavelength of radiation



Energy Units

1 W (Watt) = 1 J per second

1 W/m² ☛ energy flux density i.e. flow per unit area)

W m⁻² (W/m2) = terminology most likely to encounter

Radiation

Everything above -273°C (= absolute zero, 0 Kelvin) emits radiation.

Sun emits shortwave

Earth emits longwave

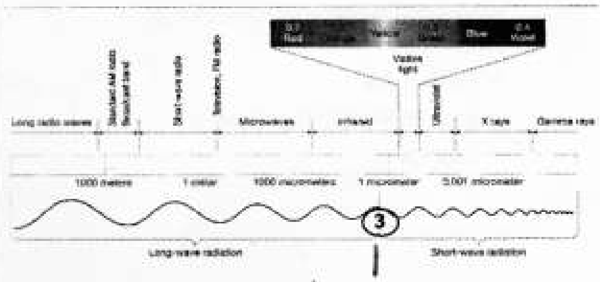
Basic Radiation Concepts

The hotter the object the shorter the wavelength

Very hot object (only one: Sun) ↘
shortwave radiation
[Solar]

Cooler objects (everything else) ↘
longwave radiation
infrared [thermal] not tech.

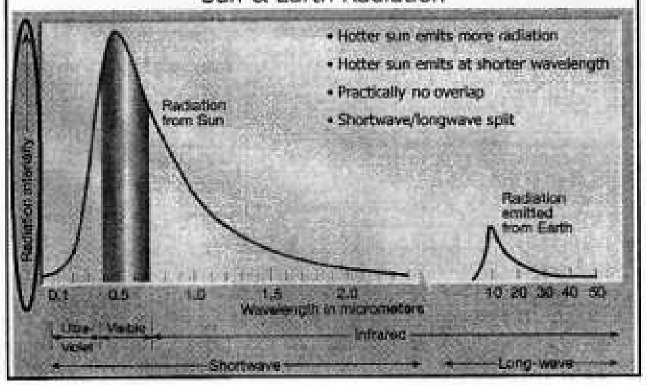
Electro-Magnetic Spectrum



1 millionth of a metre.
= 1 micron.

LW doesnt overlap w/ shortwave.

Sun & Earth Radiation



Solar Radiation

= 9 hot object outside starts to cool

- Uneven global receipt of solar radiation → explains regional climate diffs
- Triggers vast transfers of energy
  - Winds
  - Ocean currents
- Largely responsible for the variety in climates over the Earth's surface
- Climatology requires understanding of the basic processes

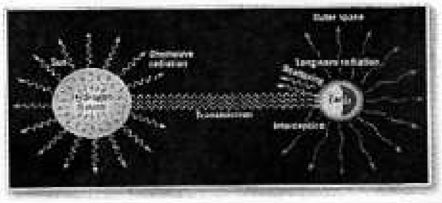
Controls on radiation

Solar energy

Insolation (incoming solar radiation)

Measured in units of watts per square meter (W/m^2)

Varies mainly because variable 'solar angle'



Solar relation varies because of angle e.g time of day seasons latitude.

Controls on intensity of solar radiation at the surface

1) Angle of incidence (solar angle)
2) Daylight hours length of time
3) Effective depth of atmosphere

time of

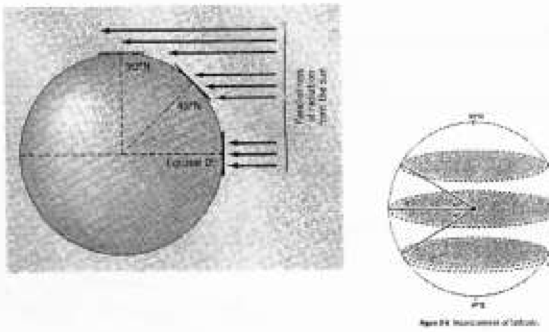
Solar angle (angle of incidence) is a function of:

- ✓ Time of day
- ✓ Solar declination (i.e. season)
- ✓ Latitude

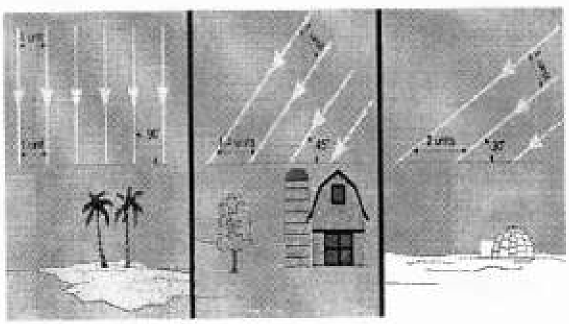
spread over larger area.

never change

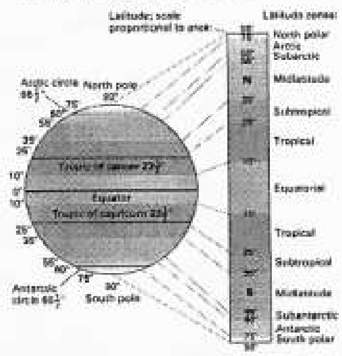
Effect of latitude on intensity of solar radiation



Latitude and Intensity of Solar Beam



World Latitude Zones



Globe divided into broad latitude zones that we use to describe climatic and other geographic zones

tilt of earth
gives us season

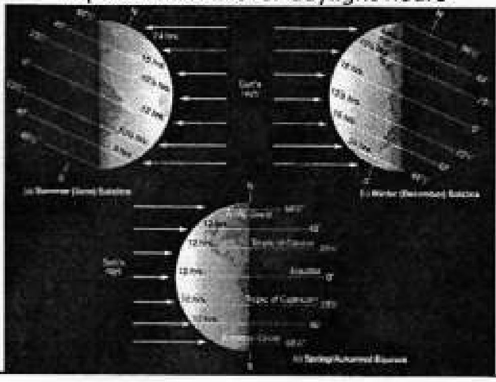
Controls on intensity of solar radiation at the surface

1) Angle of incidence (solar angle)

→ 2) Daylight hours

3) Effective depth of atmosphere

Implication of tilt for daylight hours



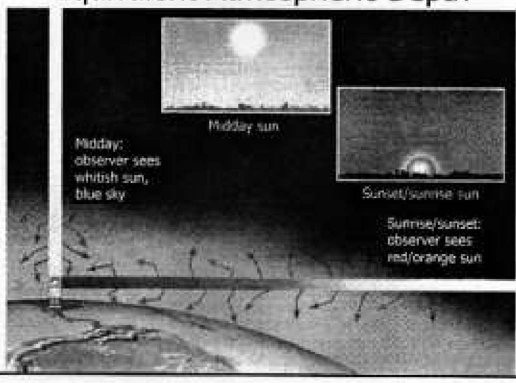
Controls on intensity of solar radiation at the surface

1) Angle of incidence (solar angle)

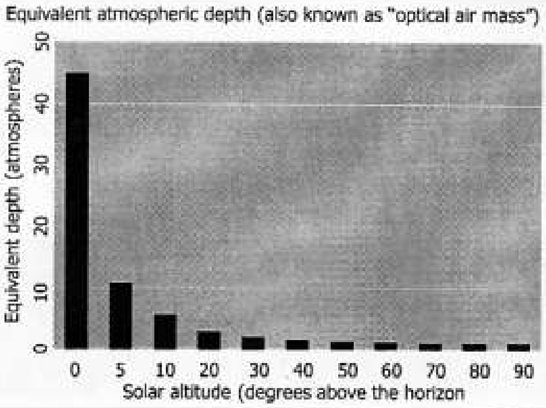
2) Daylight hours

→ 3) Effective depth of atmosphere

Equivalent Atmospheric Depth



Equivalent atmospheric depth (also known as "optical air mass")



Depth (quantity) of atmosphere

PLUS ↘

Content (quality) of atmosphere
(which includes clouds)

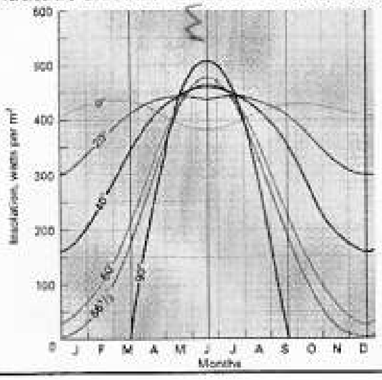
EQUALS ↘

Atmospheric transmissivity

ability to transmit
solar radiation

more energy
north pole
24hr light

Effect of latitude on solar radiation received at the surface



equator
always
energy

intercept
radiation

Controls on Solar Radiation at the Surface

Clouds

Albedo

bright sand reflects heat desert

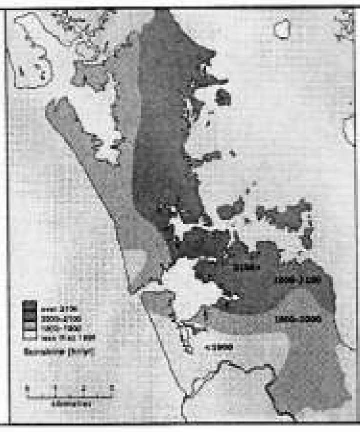
$K^* = (K\downarrow - K\uparrow)$

K = Shortwave [solar] radiation

K* = Net shortwave [solar] radiation

NOTE: $K\downarrow$ = <u>direct</u> plus <u>diffuse</u> solar radiation

Sunshine (hrs/yr): Shows influence of cloudiness



Albedo

- $\boxed{\text{Shortwave}}$ radiation reflectivity
- Determines incident $\boxed{\text{shortwave}}$ radiation <u>available</u> at the surface
- Typical values:

bright mgs

• Clouds	0.3-0.9	Fresh snow	0.9
• Sand	0.2-0.5	Grass	0.3
• Forest	0.03-0.2	Water	0.03-0.9

NOTE: "<u>Reflectivity</u>" is expressed as percentage (%)
"<u>Albedo</u>" is proportion of 1 (0 ⇔1)

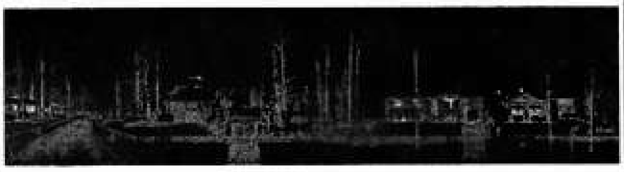
30% of
suns energy
never gets to us cos
we planet

Planetary Albedo (Reflectivity)

Total = 0.3 (30%)
- ✓Clouds: 0.2 (20%)
- ✓Atmosphere: 0.06 (6%)
- ✓Surface: 0.04 (4%)

What happens to absorbed radiation?

- All objects emit radiation
- <u>Longwave</u> radiation for objects at typical earth surface temperatures (~300 K)
- But very different interaction with the atmosphere compared to shortwave...



Lecture 2 The basics of climate II: radiation and temperature

Content/Themes

Net radiation at the surface is energy available to heat the air and evaporate water (including transpiration from leaves of plants) and to drive winds. It is the single most important climatic variable. Net radiation is seldom zero.

Radiation and energy balance including counter radiation, albedo and greenhouse effect
Latent (evaporative) and sensible heat
Net radiation and poleward heat transfer
Temperature measurement
Factors affecting temperature
Temporal and spatial characteristics of air temperature
Thermal characteristics of water and land

Lecture objectives

1) Describe the factors affecting climate.
2) Distinguish between sensible heat and latent heat.
3) Identify five important controls on air temperature.
4) Describe the global energy system and the various pathways for both absorbing and scattering the radiation passing through the atmosphere.
5) Define net radiation and explain its relationship to latitude
6) Discuss methods for measuring outside air temperature and the instruments used for this process.
7) Correlate the daily cycle of air temperature with daily insolation and net radiation.
8) Contrast the rural environment with the urban environment in relationship to air temperature.
9) Explain the concept of the urban heat island.
10) Visualize the temperature structure of the various levels of the atmosphere.
11) Explain the reasons for the annual cycle of air temperature, especially in relationship to net radiation.
12) Describe the factors controlling air temperature patterns worldwide.
13) Why are latitude and location (maritime or continental) important factors in determining the annual temperature cycle of a climate station?

Key words

sensible heat flux
convection
measurement of air temperature
urban vs. rural temperatures
temperature structure of the atmosphere
stratosphere
land and water contrasts
environmental lapse rate
latent heat flux
radiation balance
daily and annual cycle of air temperature
urban heat island
troposphere
temperature inversion
continentality

Reading

Strahler, A. and Strahler, A. 2002, *Physical Geography - Science and Systems of the Human Environment* 2nd / 3rd ed., John Wiley and Sons, New York. Relevant parts of Chapters 5.

Smithson, P, Addison, K. and Atkinson, K., 2002 *Fundamentals of the Physical Environment*, 3rd edition, Routledge, London. Pages: 51-55.

Focussing questions

Define net allwave radiation and explain how it links the surface radiation and energy budgets.

What is the atmospheric window?

How does solar radiation received at the top of the atmosphere differ from solar radiation received at the Earth's surface?

What role do clouds play in the longwave radiation budget of the Earth's surface?

How does the atmosphere affect longwave radiation flow from the Earth's surface to space?

How are net radiation and temperature related?

What is a thermometer shelter? Why is it built in the way it is?

What five factors affect temperature?

Why is the minimum temperature for the day reached about one-half hour after sunrise?

Describe the concept of the urban heat island.

Why is it that a heat island effect is less likely to be seen in cities set in a desert environment?

How is mean daily air temperature calculated?

Compare land and water as energy systems, describe the thermal differences between them and the significance of these in terms of climate.

GEOG 101 – Lecture
Radiation and Temperature

Chris de Freitas

Outline

- Radiation and global energy balance
- Temperature measurement
- Factors affecting temperature
- Temporal and spatial characteristics

(so called) global warming not temp energy

If we look at how much radiation we receive from the Sun and compare it to our current temperature, the Earth is warmer than it should be.

This is because it is harder for longwave radiation to leave, so the Earth is warmed.

~~one~~ takes awhile for shortwave to get out.

$\boxed{\text{The longwave radiation is absorbed by gases in the atmosphere.}}$

LW = slowed down
main ~~factor~~ factor is water vapour

"Greenhouse Effect"

Greenhouse gases include water vapour, carbon dioxide, ozone, methane, CFCs.

They absorb longwave radiation. They also radiate it to the surface and to space

The Earth is warmer (by ~33 °C) than it would be without these gases.

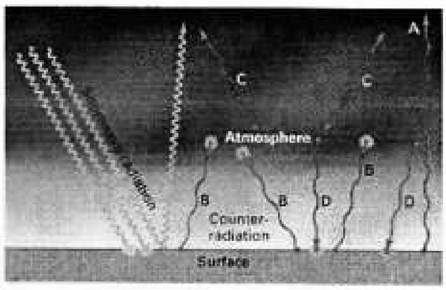
= *"greenhouse effect"* – (not a good term)

even double CO_2 doesnt have effect → water vapour to cooling

energy from sun slowed down because LW has to get through gases

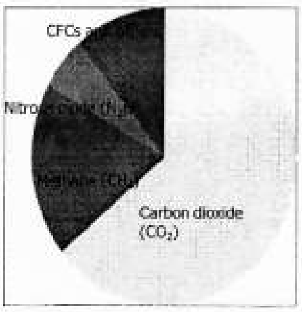
'Greenhouse Effect'

The atmosphere absorbs longwave radiation. It therefore emits radiation to space and also toward the surface



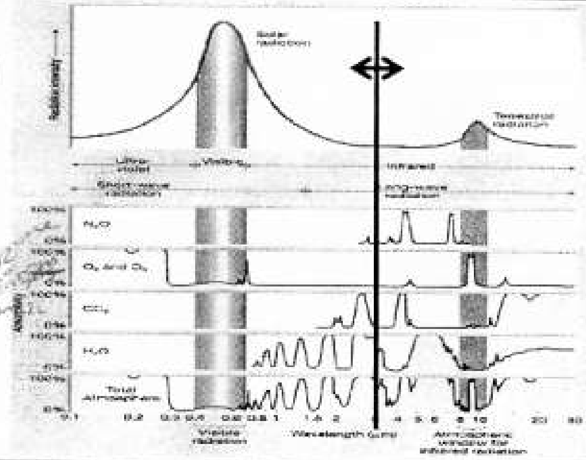
LW radiation re radiated not reflected. LW 24hr Solar only day

Relative importance of greenhouse gases in the atmosphere, excluding water vapour

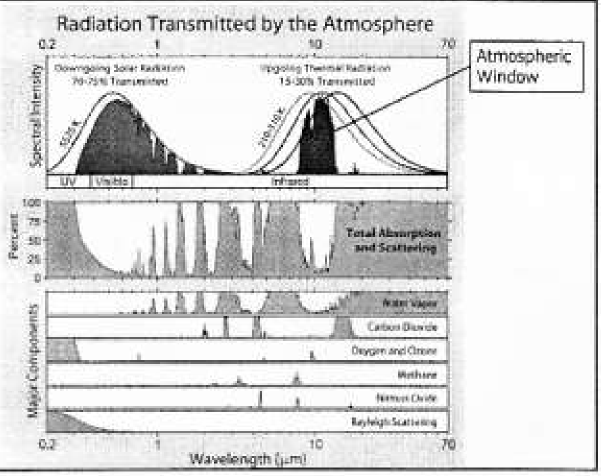


- Emissions
- Radiative properties
- Lifetime in atmosphere
- Water vapour (50 times more than CO_2; accounts for most of greenhouse effect)

absorption of radiant energy



methane is missing



Radiation & Energy Budgets

- Incoming and outgoing radiation rarely equal at
  - Any point in time
  - Any point in space
- What accounts for the surplus or deficit?
- The energy budget is the key...

always working to achieve an equal liberium

Radiation Balance

- Shortwave [solar] (K)
- Longwave (L)
- Net allwave radiation (Q*)

what is left over is available.

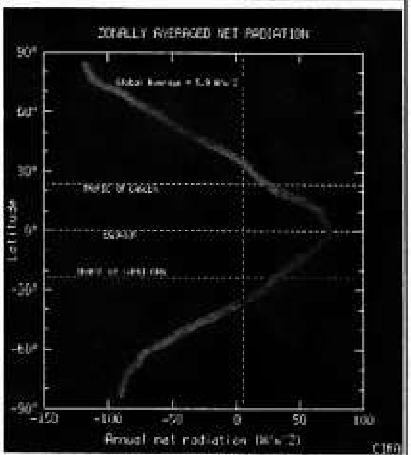
➢ Day: $Q^* = (K\downarrow - K\uparrow) + (L\downarrow - L\uparrow)$

➢ Night: $Q^* = L\downarrow - L\uparrow$

some incoming SW reflected & LW radiation

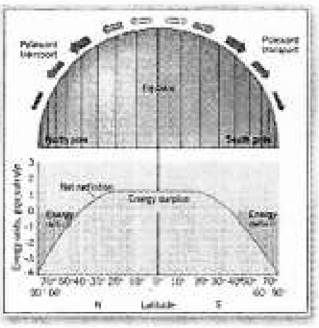
am interested in energy left over driving planet system

Mean Annual Q^* (W m^{-2})



always in surplus

Ocean but doesn't boil because of [illegible]



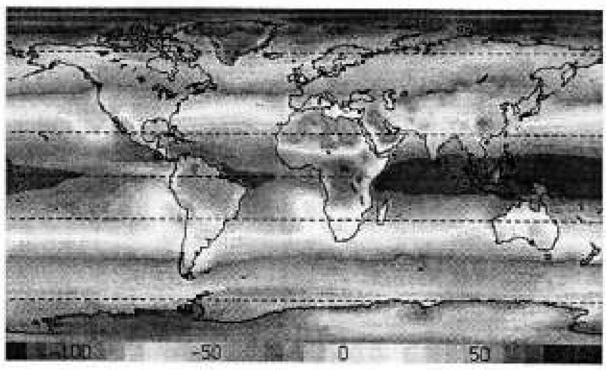
Net radiation -

The difference between incoming and outgoing radiation

At high latitudes there is an energy deficit

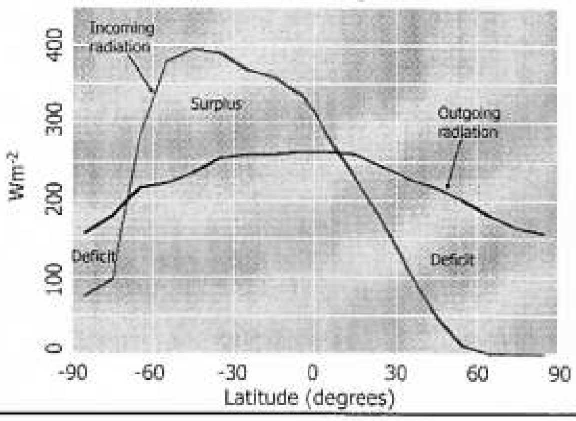
Poleward heat transfer moves surplus energy from low to high latitudes

Mean Annual Net Radiation (W m^{-2})



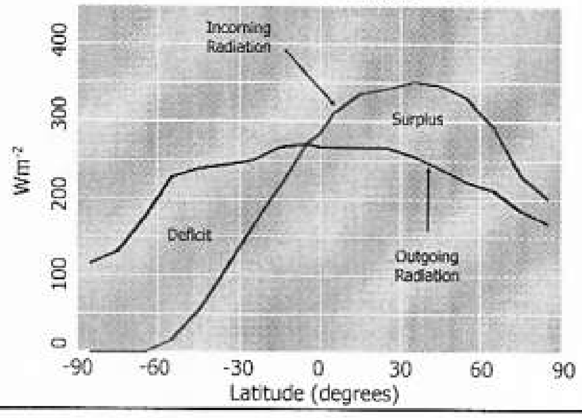
Winds moving → circulation of surplus energy

Latitudinal net radiation budget - December



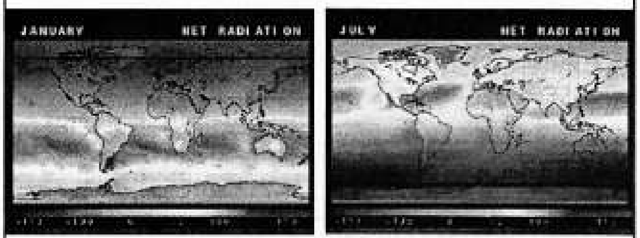
our summer.

Latitudinal net radiation budget - June



our winter

imbalance seasonal



It is this net allwave radiation (also known as "available energy") that:

a) heats the air by convection, and

b) evaporates water by convection

air moving moisture & dry heat

Convection is a process by which eddies of air move water vapour (evaporation and transpiration) and heat between the surface and the air.

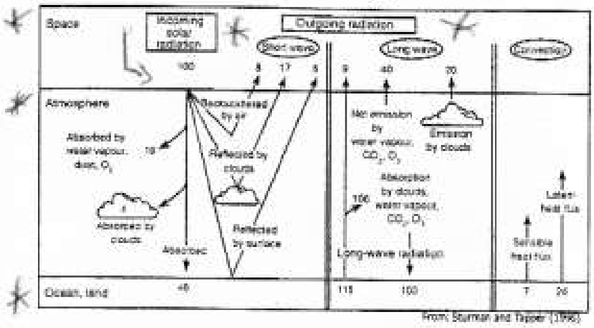
e.g. sweating lose energy → evaporation

Main energy transfer processes

- Radiation
  - Sun (shortwave)
  - Other objects (longwave)
- Convection (mixing)
  - Transfer of heat (& vapour) in air
  - Transfer of heat in water

greenhouse gases 'cooling' atmosphere.

Global Radiation and Energy Balance



Surface budget: 46 - 115 + 100 = +31 = (24+7) → evap

Atmosphere budget: 23 - 100 + 115 - 69 = -31 = (24+7)

100 units from sun
↓
46 actually gets in (like taxes)

115 = slowing down

Factors Affecting Climate

- Insolation - daily and seasonal variations
- Latitude - angular term related to the above
- Surface type – surface albedo and moisture state
- Coastal vs. interior location - temperature range is lower at coasts
- Elevation - thinner atmosphere means lower air pressure and reduced greenhouse effect

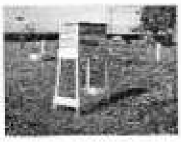
Air temperature is a key indicator of the influence of the above factors

Temperature

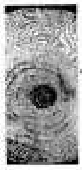
The atoms and molecules which make up a gas are in constant motion. Temperature is a measure of the speed with which they move. (More exactly it is a measure of their kinetic energy.) The higher the temperature, the faster they move.

→ of itself

Sources of temperature data:

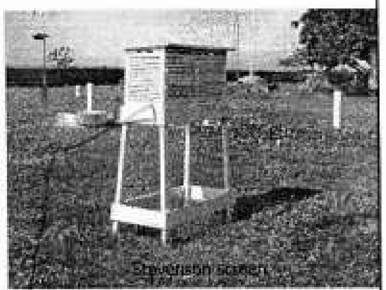



- 'Surface' data
- Balloon data
- Satellite (MSU) data
- Proxy data



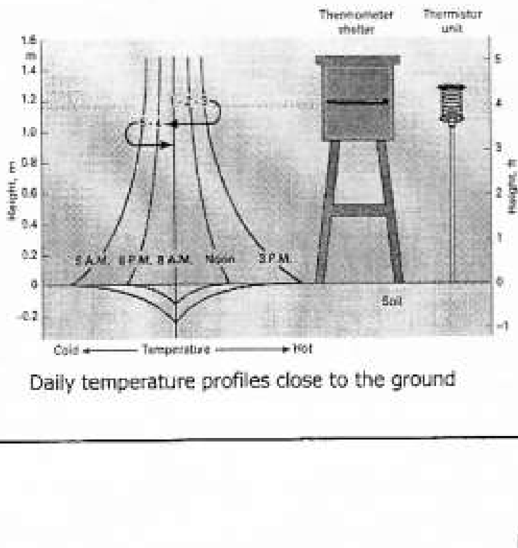

Temperature

- Thermometers – a common sensor to measure temperature.
- Temperature declines with height in the troposphere.
- Warm air is less dense than cold air.
- Warm air rises, cold air sinks.



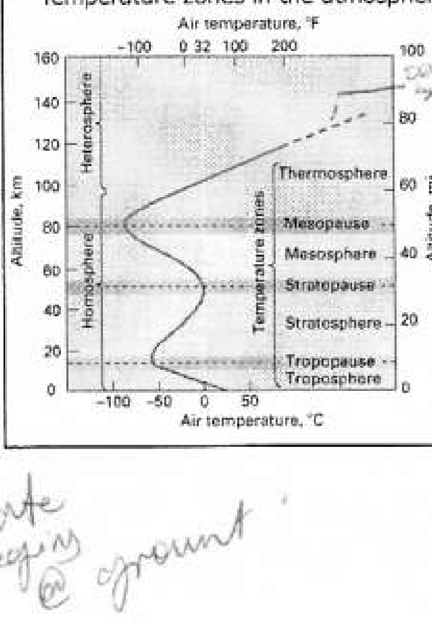
Stevesen screen

3-4 m above ground



Daily temperature profiles close to the ground

Temperature zones in the atmosphere



Troposphere bounded by the tropopause (~12km).

Above this is the stratosphere in the stratosphere temperature increases with altitude.

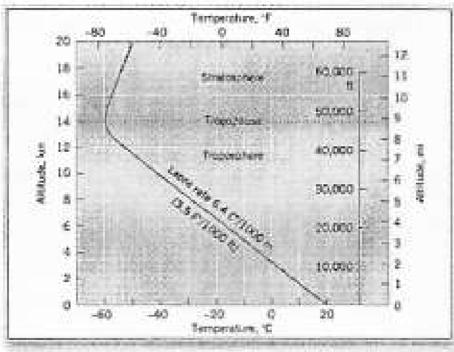
Thermosphere: Temp increases due to absorption of solar radiation by atoms of oxygen and nitrogen – not much heat as atmosphere is very thin.

climate logging @ ground

Thermal structure of the atmosphere

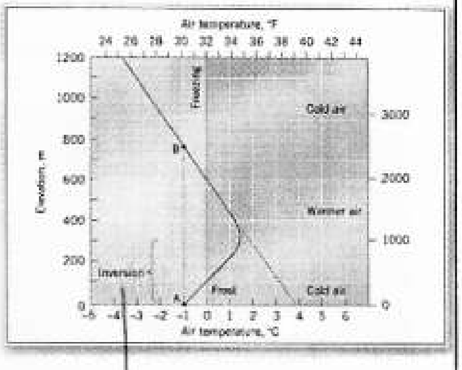
The troposphere is the layer nearest the ground.

Temperature decreases on average by 6.4°C per 1000 metres in the troposphere = environmental lapse rate (vs. adiabatic lapse).



Normally temperature decreases with height

- But sometimes upper air is warmer than lower air = temperature inversion.
- Occurs if the ground cools overnight.
- Or cold air may flow into an area.



→ ground cooler than air

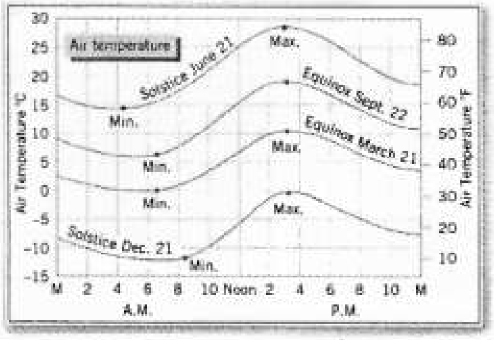
Factors affecting air temperature

- Insolation - daily and seasonal cycles.
- Latitude – insolation cycles vary systematically with latitude (affects energy deficit or surplus).
- Surface type - albedo of surface as well as surface moisture (esp. city vs. rural)
- Coastal vs. interior location - temperature range is lower at coasts.
- Elevation - thinner atmosphere and lower pressure.

explaining climate of a place link these factors

Daily insolation and air temperature - mid-latitude, Northern Hemisphere

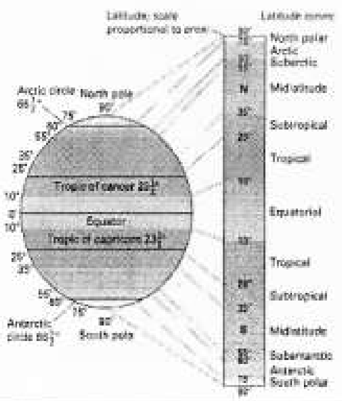
- Daily maxima and minima
- Positive net radiation leads to an increase in air temperature, but there is a time lag.



L convection process (people confuse this, even stronger)

Temperature is a used as an indicator

World Latitude Zones



Globe divided into broad latitude zones that we use to describe climatic and other geographic zones

SURFACE TYPE

Temperatures - rural areas

- Transpiration from leaves cools the surface
- Evaporation from moist soils plus transpiration = evapotranspiration

Temperatures - urban areas

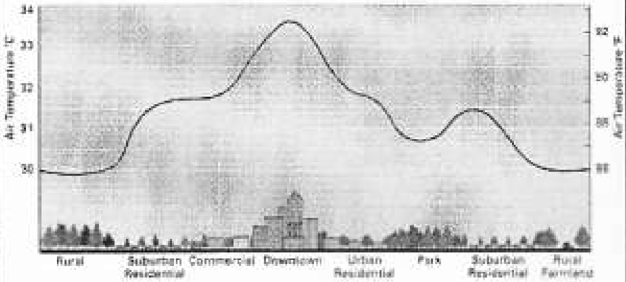
- Water is channeled so surfaces dry; thus available energy heats the air rather used in evaporation
- Surfaces are often dark (asphalt)
- Building materials store heat, and heat is released from buildings at night.

Urban area heat air

Urban

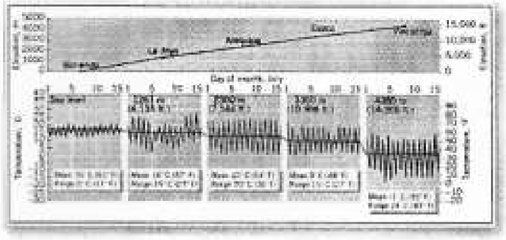
The Urban Heat Island

- Heat island tends to persist over night
- Parks can reduce the heating
- Urban areas in deserts usually do not exhibit heat islands, where irrigated vegetation may make the city cooler.



Elevation and Temperature

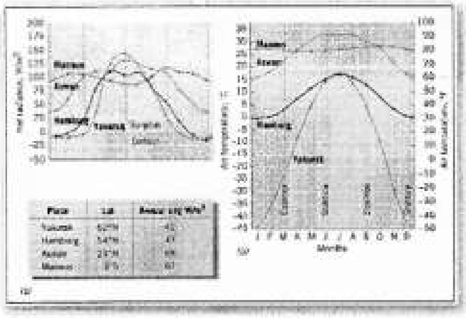
- Generally temperatures drop with altitude (except Cuzco that has a heat island)
- Daily temperature range also increases due to decreased pressure



Cities in Peru: temperature change with altitude

Net Radiation and Temperature

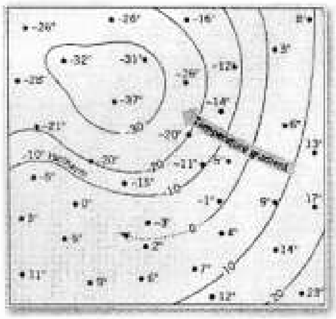
- Low latitudes have greater amounts and longer periods of surplus energy
- Where does highest net radiation occur?



High latitudes have large and long periods of deficit

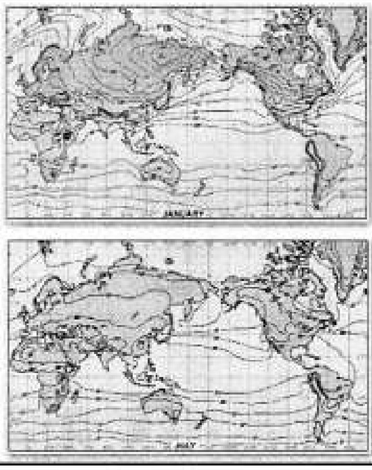
World patterns of air temperature

- Distribution of air temperatures shown on a map uses isotherms (lines of equal temperature).
- Reveal centers of low or high temperatures, and temperature gradients.

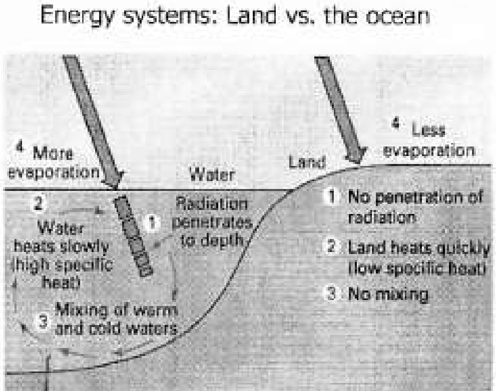


Why water different surface to land

- Temperatures in equatorial regions change little from January to July.
- Isotherms make a large north-south shift from January to July over continents in midlatitude and subarctic zones.



Energy systems: Land vs. the ocean



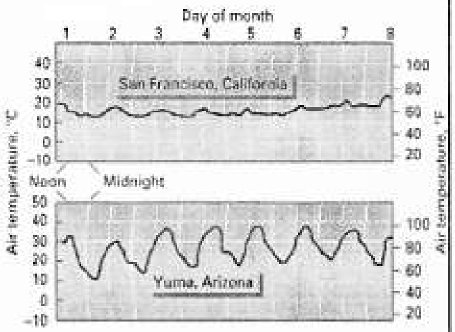
natural convection mixing

different energy regions to land

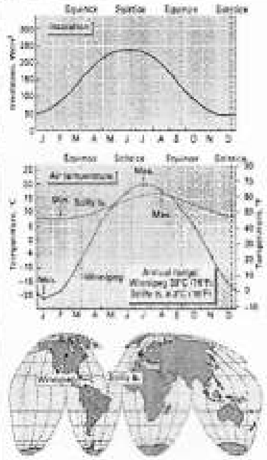
Maritime and continental climates

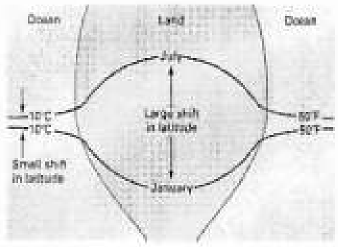
Land heats and cools quickly while water heats and cools slowly, thus:

- Ocean surface has a smaller annual range of temperature (maritime climates)
- Land surface has a larger annual range (continental climates)

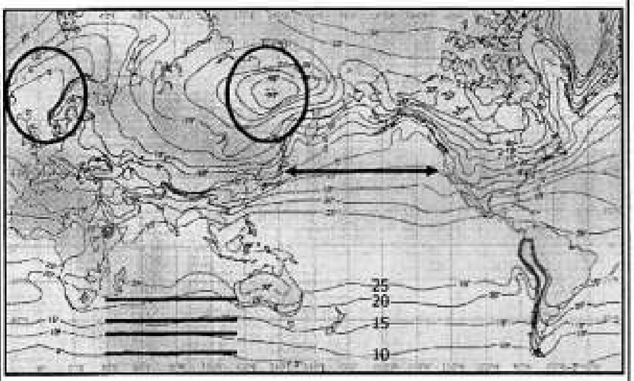


Maritime and continental climates

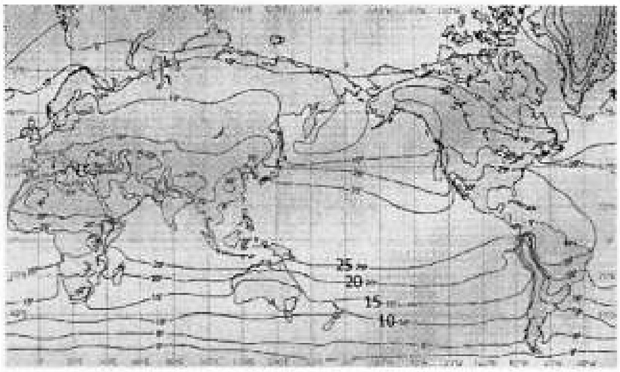




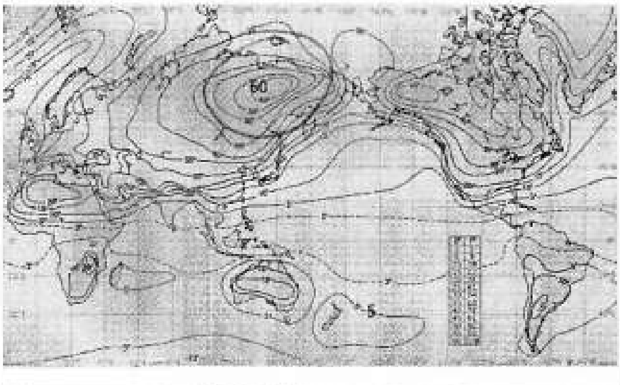
Surface air temperatures (Jan)



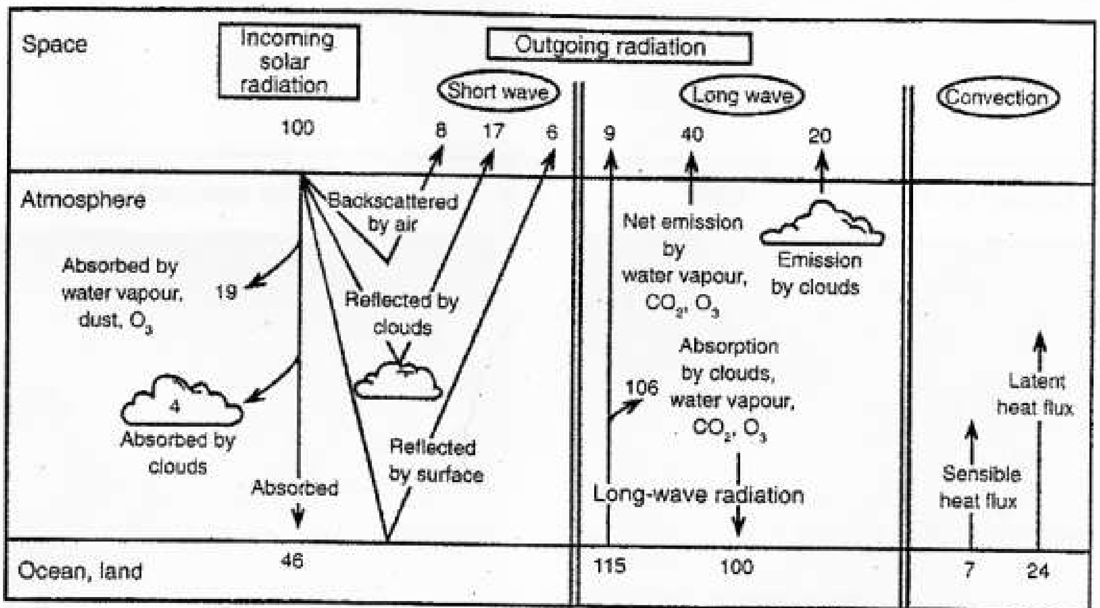
Surface air temperatures (July)



Air temperature range (Jan-Jul)



Global Radiation and Energy Balance



From: Sturman and Tapper (1996)

Surface budget: 46 - 115 + 100 = +31 = (24+7)

Atmosphere budget: 23 - 100 + 115 - 69 = -31 = (24+7)

Lecture 3 Air masses and cyclogenesis

Content

Air masses are large bodies of air with fairly uniform temperature and moisture characteristics. They are classified on the basis of their latitudinal position and the nature of the underlying surface of their source regions. The coming together of contrasting air masses is important for the formation of certain types of precipitation. This lecture is an overview of air mass climatology and deals with the precipitation process covering: humidity, condensation mechanisms, lapse rates and cyclogenesis.

Themes

Air-masses: types and role
Water holding capacity of air
Cyclogenesis

Lecture objectives

1. Describe the different types air masses and the criteria used for their classification.
2. Identify the sources of various air masses.
3. Understand the changes that take place in a parcel of air as it rises or falls.
4. Explain the processes leading to formation of weather fronts, including wave cyclones.

Key words

cold front	mid-latitude cyclones	warm front
cold front	occlusion	cyclogenesis
air mass mixing	source region	dewpoint
stability	dewpoint temperature	

Reading

Strahler, A. and Strahler, A. 2002, *Physical Geography - Science and Systems of the Human Environment* 2nd / 3rd ed., John Wiley and Sons, New York. Relevant parts of Chapter 8.

Smithson, P, Addison, K. and Atkinson, K., 2002 *Fundamentals of the Physical Environment*, 3rd edition, Routledge, London. Pages: 121-130.

Focussing questions

Describe the characteristics of an air mass that originates over a hot dry desert area. How does it differ from an air mass that originates over the Pacific ocean around Rarotonga?
Define air mass? What features are used to classify air masses?
In the context of air masses, what is a source region?
Describe the characteristics of five typical source regions.
Compare the characteristics and source regions of mP and cT air mass types.
Identify the air masses that are important in determining New Zealand's climate.
Describe the formation of a cold and warm front. What weather accompanies them?
How does an occluded front form?
Why does the precipitation die off soon after occluded front formation?
What determines the water holding capacity of air?
Identify three types of fronts and draw a cross section through each.
Draw a cross section through an occluded front and describe the process in cyclogenesis leading up to it.

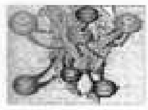
GEOG 101 – Lecture
Airmasses and their relevance
to weather and climate

Chris de Freitas

THE UNIVERSITY OF AUCKLAND
NEW ZEALAND

Lecture Outline:

➢Airmasses: types and role



➢Cyclogenesis

↳ fits w/ precipitation patterns. (weather)

Air masses

change condition in air

Experience (in Auckland) tells us...

➢N winds bring warm moisture-laden air
- ✓Often unpleasantly sticky in summer, thunderstorms...
- ✓Pleasantly warm in winter although often with rain

➢S winds bring cool conditions
- ✓Unpleasantly cold in winter (often showery)
- ✓Pleasantly cool and dry in summer

The characteristics are from the parent air-mass or source

comes from cooler place

Airmasses

➢ Immense bodies of air
- 100s to 1000s of km across
- Several km deep
- Up to millions of km^2

➢ Characterised by homogenous characteristics
- Temperature
- Moisture content

➢ Characteristics determined by source region

Source Regions

Recall that the atmosphere is:
- Heated from below (i.e. from the surface)
- Gains its moisture by evaporation from the surface

moisture

➢ Criteria for source regions:
- Extensive
- Physically uniform
- Stagnation of atmospheric circulation - usually in stationary or slow-moving anticyclones

temp & moisture

Source Regions

A air from these areas

• Arctic/Antarctic	A	Arctic ocean and fringe lands
	AA	Antarctica
• Polar (close to A: AA)	P	Poleward of 50 degrees north and south latitudes (50-65° lat.)
• Tropical	T	Within about 25° lat. of equator
• Equatorial	E	Oceans close to equator

Either:

• Continental	c	Over large landmasses - dry
• Maritime	m	Over the oceans - moist

thermal zones

no land & cold.

driest air in world Antarctica & Arctic.

Typical Airmasses

cA	continental Arctic	very cold, very dry (also cAA)
cP	continental polar	cold, dry, stable — moist rising
cT	continental tropical	warm, dry (stable air aloft - unstable surface air)
mP	maritime polar	cold, moist (unstable)
mT	maritime tropical	warm, moist (usually unstable)
mE	maritime equatorial	warm, very moist (very unstable)

always moist - water.

anything else is regional, these are the major 6

Stability

Stable air resists uplifting and mixing. Often air temperature increases with altitude. *Precipitation is unlikely to occur.*

In unstable air, convectional mixing and uplifting of air readily occur. Air temperature decreases with altitude. *Uplift will cause cooling and this can result in precipitation.*

useful descriptor

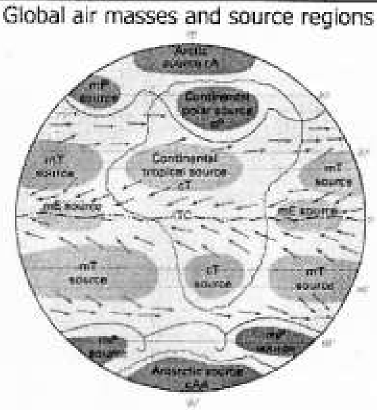
mT

Unstable

cT

Stable

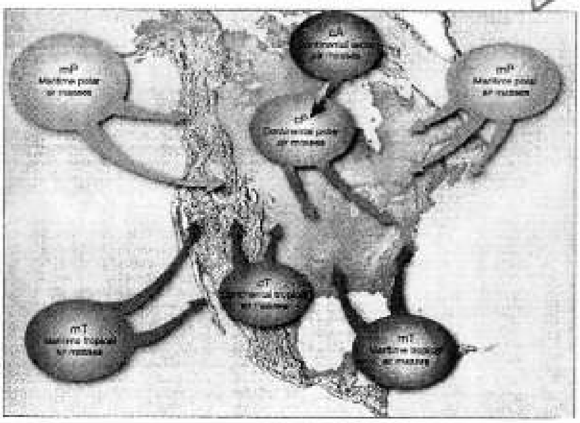
Global air masses and source regions



Source: Strahler and Strahler (2002) Fig 8.1

41°S

important for day to day weather forecasting esp. North America



mixing of air masses gives us weather

COOLING AND PRECIPITATION ?

[is linked with air mass interaction]

Precipitation is caused when air is cooled to its saturation point – condensation occurs.

For example, when a warm air mass mixes with a cooler air mass

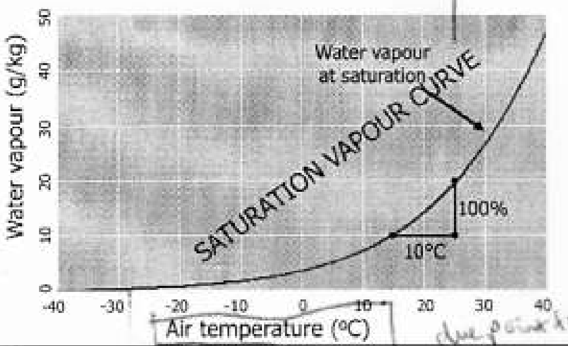
climate of place

warmer it more it can hold.

always in this position

if you know temp if you know saturation of air e.g. as Sponge saturation capacity

Water Holding Capacity



dew point temp.

amount of water in air. air conditioning dry to heat up (Korea cold dry skin) no moisture.

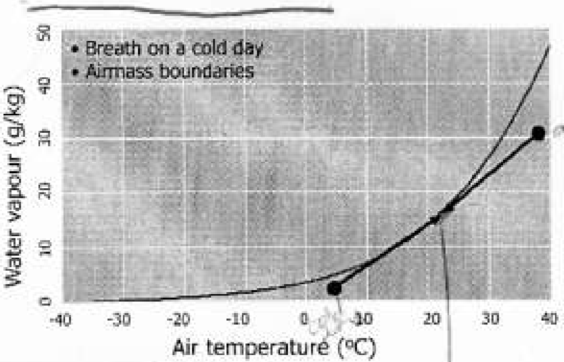
Condensation is a key stage in the precipitation process, caused by:

1) Air mass mixing
   - Vertical
   - Horizontal

2) Increased water content

3) Dynamic (adiabatic) cooling when air parcel is moved around
   - Adiabatic process
   - Cooling/warming due to expansion/compression
   - No heat added or subtracted

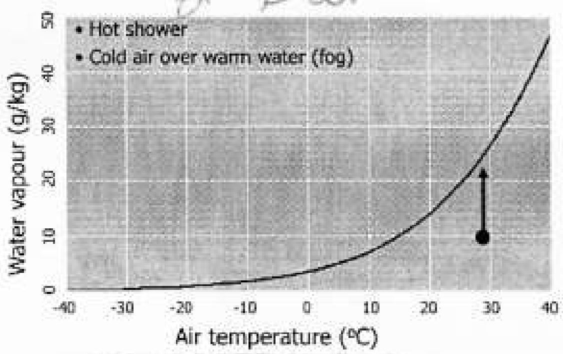
1. Mixing of airmasses



hitting saturation curve.

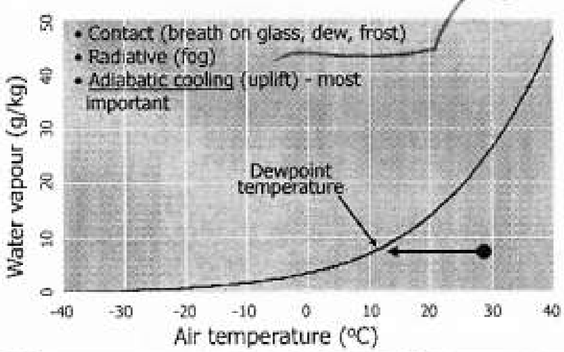
2. Increased water content

Steam + condensation.



ground has cooled

3. Cooling



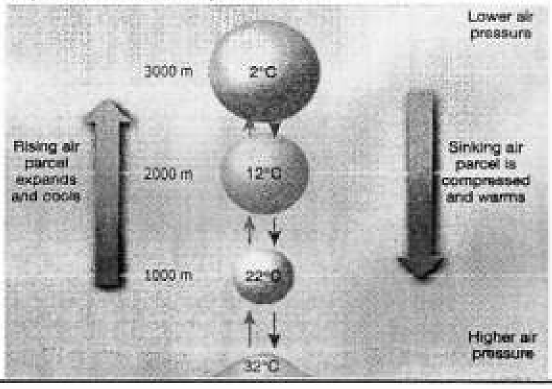
Adiabatic temperature change

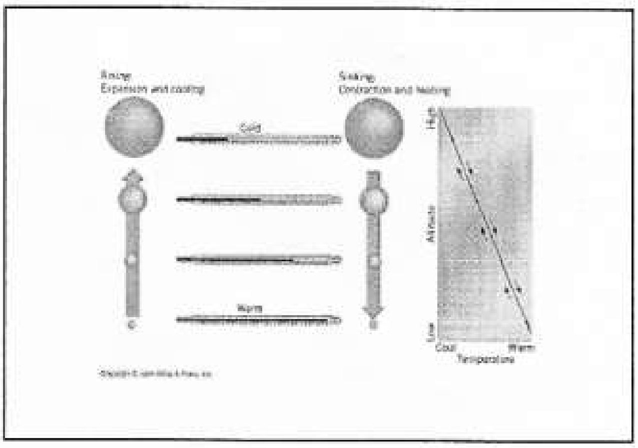
Vertical Displacement
↓
Lower Pressure
↓
Expansion
↓
Cooling

changes temp.

→ Condensation if dew point reached

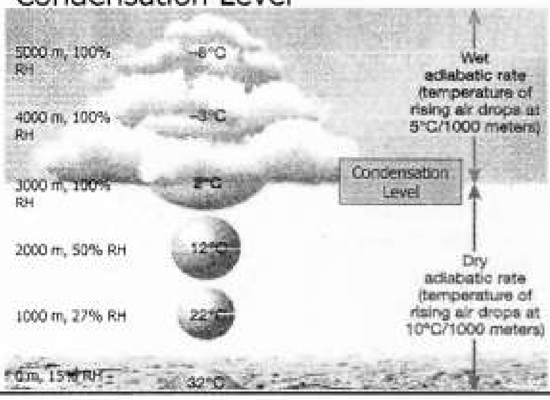
Dry Adiabatic Lapse Rate





when air mass meet.

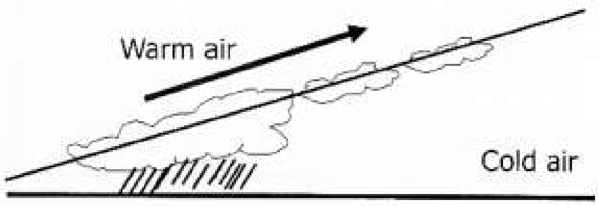
Condensation Level

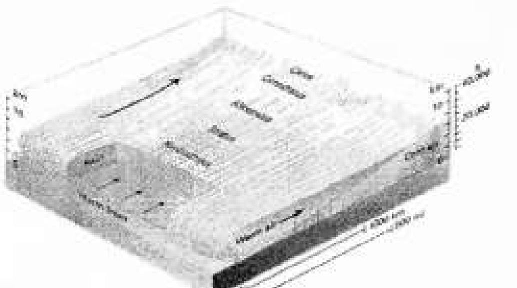


Fronts

Two types: warm and cold fronts

1. Warm fronts — brings precipitation.

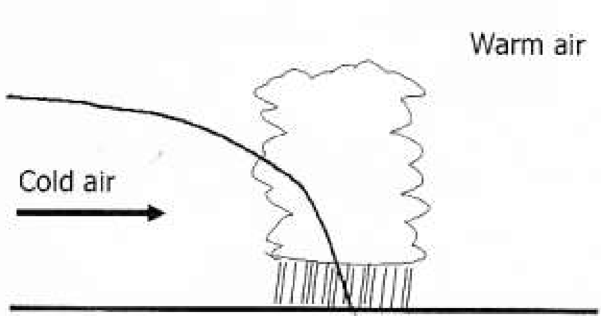




In a warm front, warm air advances toward cold air and rises up and over the cold air. Rain falls from the dense stratus cloud layer.

fog

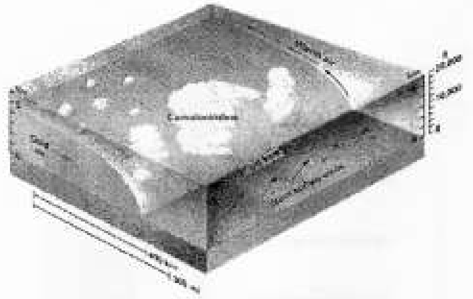
2. Cold fronts



Steeper collision

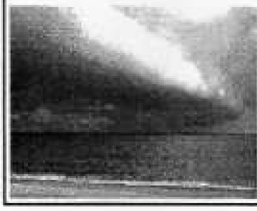
Cold advancing on warm.

undercutting warm air.



At a cold front, a cold air mass lifts a warm air mass aloft. The upward motion can set off a line of thunderstorms.

Cold front



Comparing Fronts

Front type ⇒	Warm	Cold
Speed	Slow moving	Fast
Rain duration	Long	Short
Rain amount	Light	Heavy

long light rain

short & heavy.

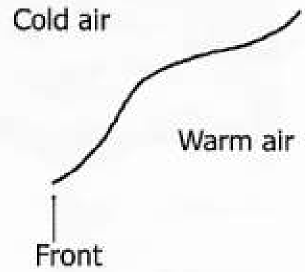
Birth & death of frontal systems

CYCLOGENESIS

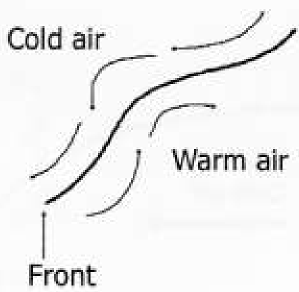
Mid latitude cyclones (depressions)

- Develop through the process of cyclogenesis.

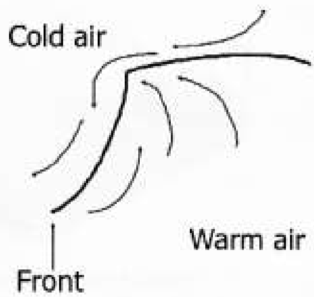
1. A front forms and convergence takes place.



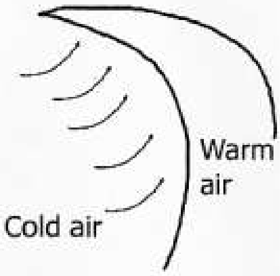
2. A bend or wave forms on the front, producing lower pressures



3. Air on either side of the front flows inwards



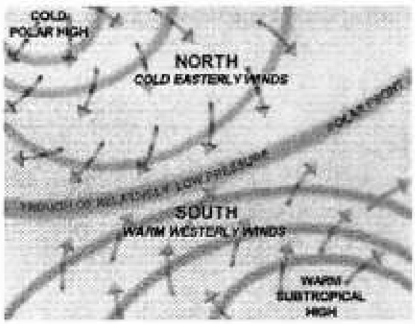
4. Cold fronts move faster than warm fronts, so the cold front catches up to produce an <u>occluded front</u>.



In an occluded front, a warm front is overtaken by a cold front.

The warm air is pushed aloft and it is not longer in contact with the ground.

Cyclogenesis



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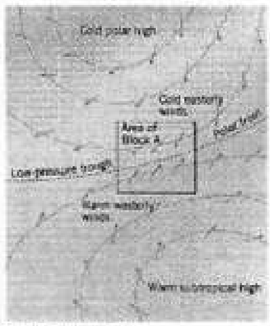
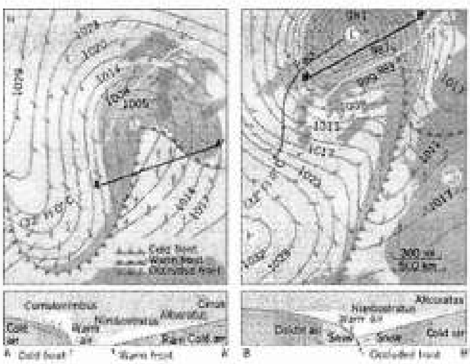
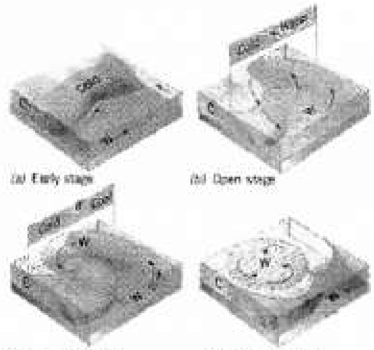
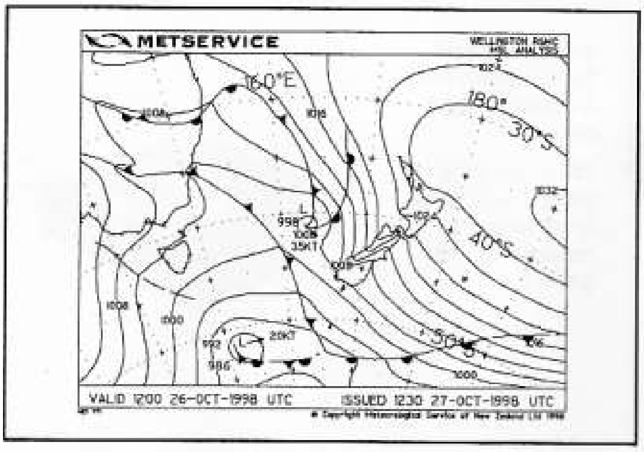


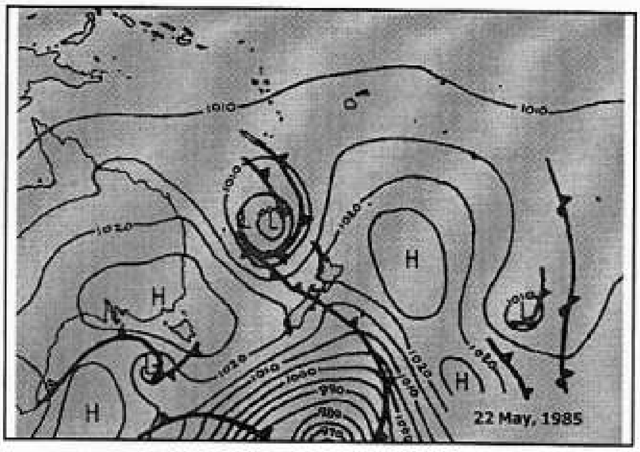
Cyclogenesis

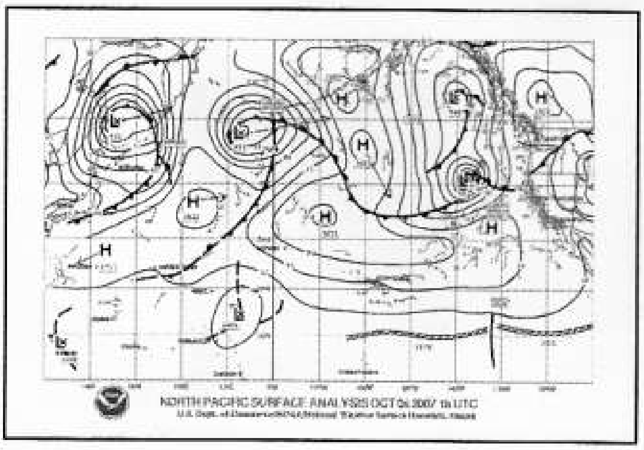


Cyclogenesis




METSERVICE
VALID 1200 26-OCT-1998 UTC
ISSUED 1230 27-OCT-1998 UTC
160°E
180°
30°S
40°S
50°S


22 May, 1985


NORTH PACIFIC SURFACE ANALYSIS

End

Lecture 4 Nature and causes of winds

Content/Themes

Wind symbols
Presenting wind information
Anemometers
Nature and causes of winds
Coriolis force
Pressure gradient force
Intertropical Convergence;

Lecture objectives

1. Describe the relationship between pressure gradients and wind.
2. Describe the role of the Coriolis effect
3. Show relationship between global winds and pressure patterns.
4. Discuss the relationship between local winds and terrain.
5. Show the relationship between winds aloft, pressure gradients and surface friction.

Key words

Wind rose	Pressure gradient force	Anemometer
Coriolis effect	Gradient wind	Geostophic wind
Barometer	Pressure fields	Friction force
Cyclonic flow	Anticyclonic flow	

Reading

Strahler, A. and Strahler, A. 2002, *Physical Geography - Science and Systems of the Human Environment* 2nd / 3rd ed., John Wiley and Sons, New York. Relevant parts of Chapter 7.

Smithson, P, Addison, K. and Atkinson, K., 2002 *Fundamentals of the Physical Environment*, 3rd edition, Routledge, London. Pages: 100-109, 158-159.

Focussing Questions

What is an anemometer?
What is a wind rose?
What determines wind speed and direction?
What causes the global winds?
Describe the basic pattern of global surface winds.
How are winds, the Coriolis effect, and pressure gradients related?
How is information about wind presented?

GEOG 101 – Lecture

Nature and causes of winds

Chris de Freitas

GEOG 101 – Lecture
Nature and Causes of Wind

Outline

- How wind is measured
- How wind information is portrayed
- How winds are produced
- How winds are directed
- What controls the strength of winds
- Nature of global air circulation (to next lecture)

energy left from sun
↳ wind distributes imbalance
nature trying to establish equalibrium.

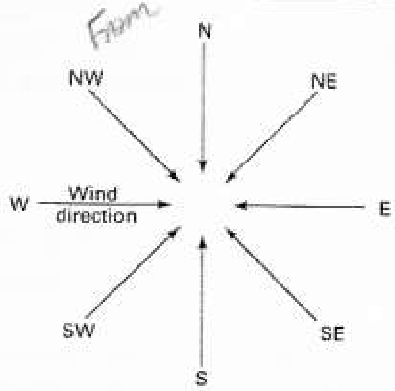
Wind

general climatology.

✓Movement of air (mainly horizontal)
- two main properties: speed and direction

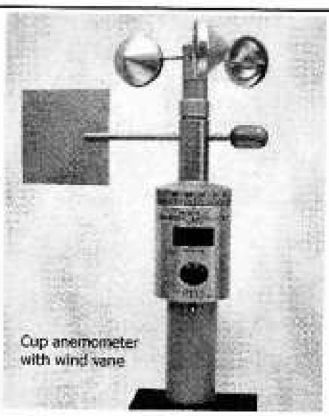
✓Winds are named for the direction from which they flow

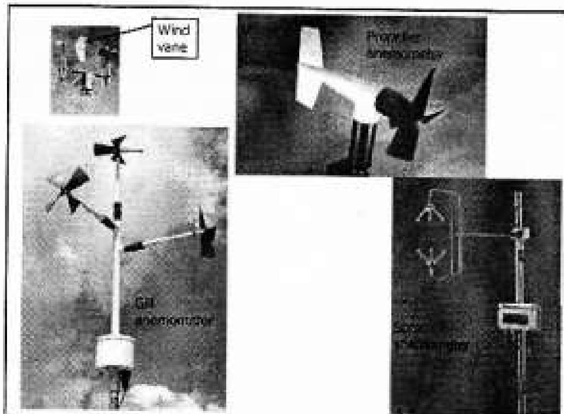
Eg: Westerlies flow toward the east.



northley from the north
Westerlies from the west

Anemometer - measures wind speed





↳ common
standard

Mast: 30 feet (~10 m)

everywhere standardised height.

higher you go faster

Hotwire anemometer

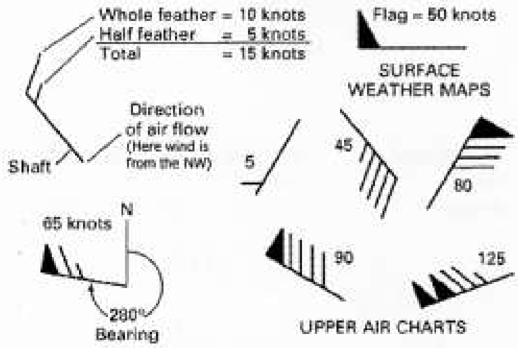
hot wire

rate of cooling measures wind speed.

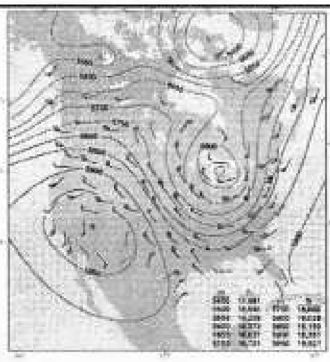
cars etc

Wind arrows,

feather end points to direction wind is coming



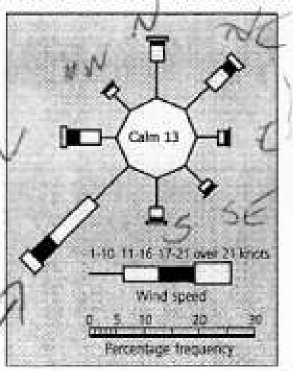
Wind arrows used on weather maps and upper air charts.



Variations in height are analogous to variations in pressure. High height fields correspond to high pressure fields.

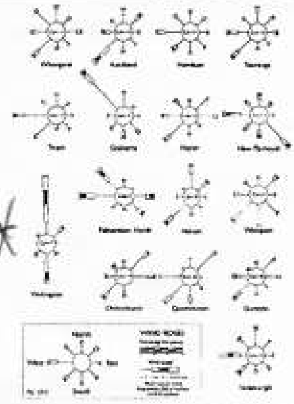
Used on weather maps and upper air charts (500 mb)

Wind Rose for Auckland

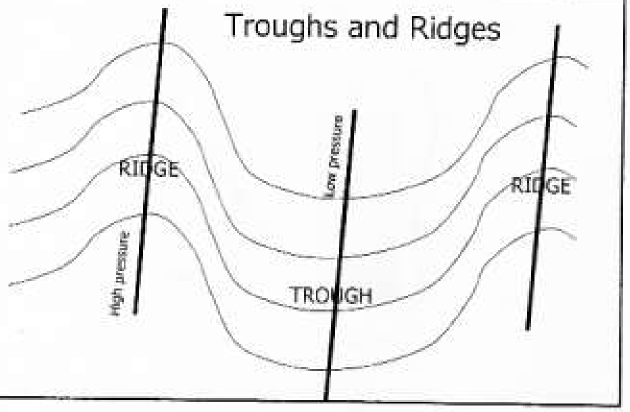


frequency & speed.

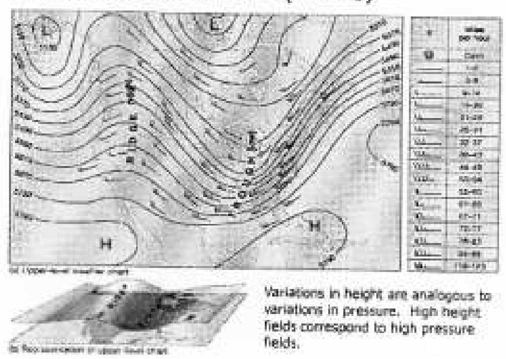
At a glance most winds from SW in AK.



Troughs and Ridges



Upper Level Weather Chart (500 mb)

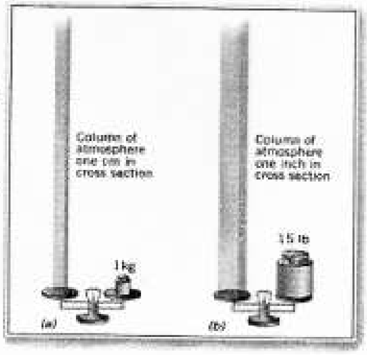


Variations in height are analogous to variations in pressure. High height fields correspond to high pressure fields.

Atmospheric Pressure

As the atmosphere is held down by gravity, it exerts a force upon every surface (pressure = force per unit area)

At sea level the force is the weight of 1 kg of air that lies above each square centimeter of the surface, on average (or 15 lbs per inch).



Pressure Units

Weather Related	Sea Level	5,000 feet	10,000 feet
Pascals	101,325		
Millibars	1013.25	500	250

1mb = 0.1 kP
1 kP = 10 mb

TO MEASURE PRESSURE

* can't go by plane
explode
* cheap

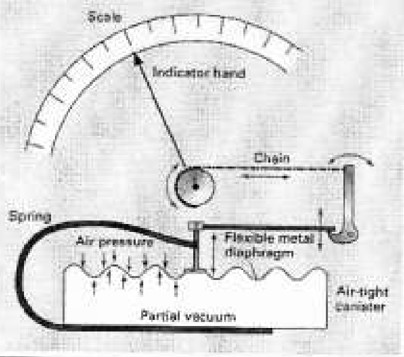
partially evacuated cylinder

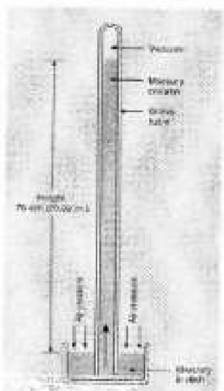
Measure the movement.

Aneroid Barometer

Atmospheric Pressure

As the atmosphere is held down by gravity, it exerts a force upon every surface (pressure = force per unit area)





Mercury barometer

Average sea level pressure is 29.92 in Hg, or 1013.25 mb.

Nature of Winds

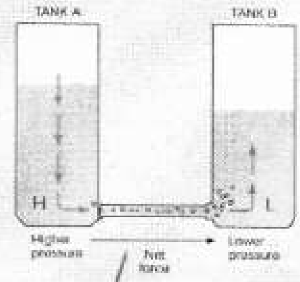
Pressure

Atmospheric pressure proportional to ***temperature*** and density.

Forces and Motion

Pressure forces are only one influence on the movement of atmospheric air.

Air responds similarly as water to this force, moving from higher pressure to lower pressure.



Winds response to disequalibrium. tendancy to move to equal librium.

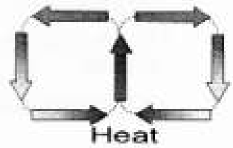
Circulation

- Air cannot just vanish, hence...
- We talk about circulations rather than winds

Temperature Controls

& moving pressure systems.

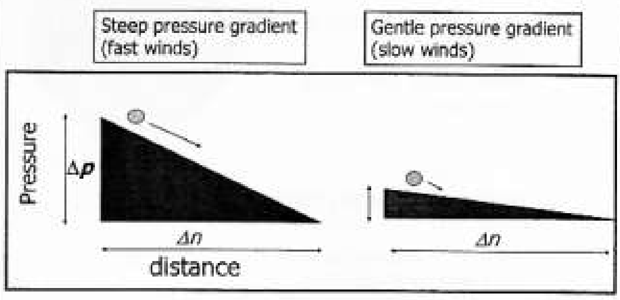
- Solar radiation heats land, water, air
  - Land warms, heats air
  - Air circulates
    - Convection cells
      - warms -> expands -> rises
      - cools -> contracts -> sinks
  - Water circulates
    - Currents driven by wind & Earth rotation
    - Water temperature increases SLOWLY
      - Large energy change needed for small temp. change



Three factors determine the speed and direction of wind:

- Pressure gradient force
- Coriolis effect (Coriolis "force")
- Friction

Pressure Gradient Force



Differences in air pressure = a pressure gradient

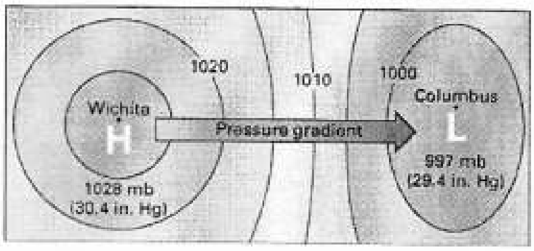
The pressure gradient forces acts at right angles to the isobars (90 degrees)

weak pressure gradient

strong pressure gradient

Wind — Pressure Gradient Force

- Caused by difference in air pressure over a specific distance.
- Winds move from high to low pressure, across isobars.

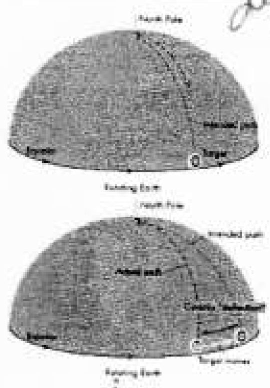


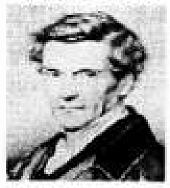
The planet Earth also rotates

- In the northern hemisphere air appears to be deflected to the right
- In the southern hemisphere, deflected to the left
- This deflective force = Coriolis 'force'

deflected to right.

Coriolis Effect



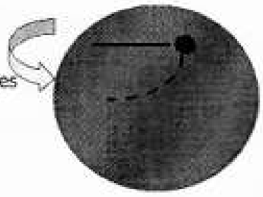


Gaspard Gustave de Coriolis 1792 – 1843 (French mathematician)

like ships navigation earth spins. Southern hemis to left

Imagine a turntable

- When not turning, a ball traces straight line
- When moving, ball traces a curved line

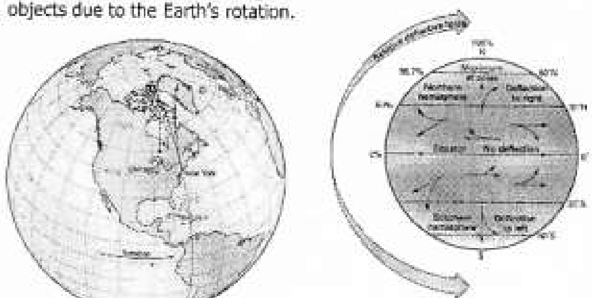


Imagine a ball tied to a length of string swinging from your hand above your head:

- The ball is moving fast relative to the speed of the string near your hand.

Wind — Coriolis Effect

Deflection of horizontal moving objects due to the Earth's rotation.



force varies depending on how far from equator

Nature of Winds

Differences in air pressure = a pressure gradient

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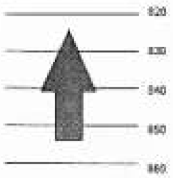
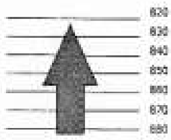


weak pressure gradient



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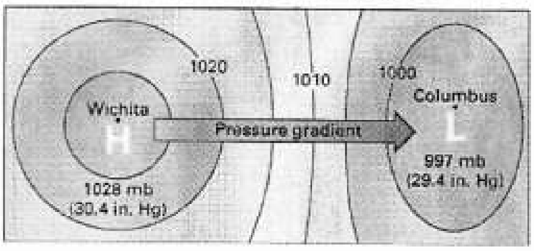

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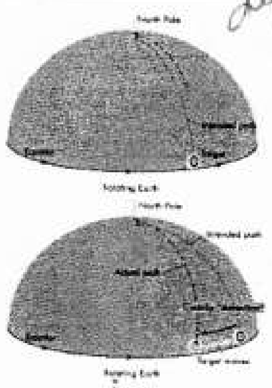

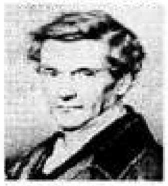

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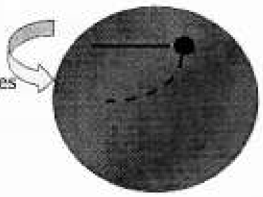

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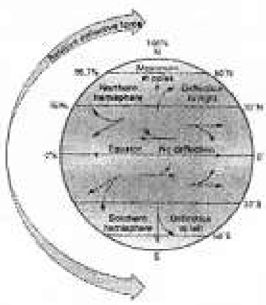
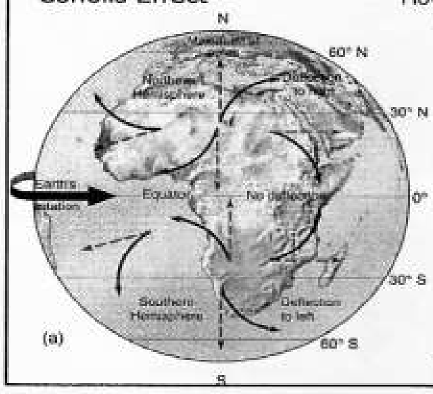


force varies depending on how far from equator

Nature of Winds

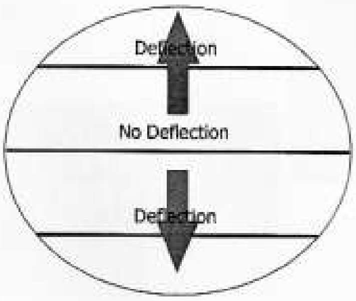
Coriolis Effect



Moving objects are deflected

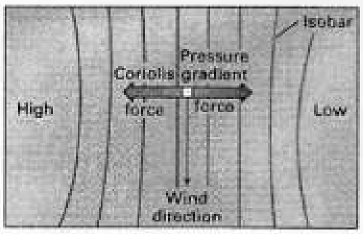
- to their right in northern hemisphere
- to their left in southern hemisphere

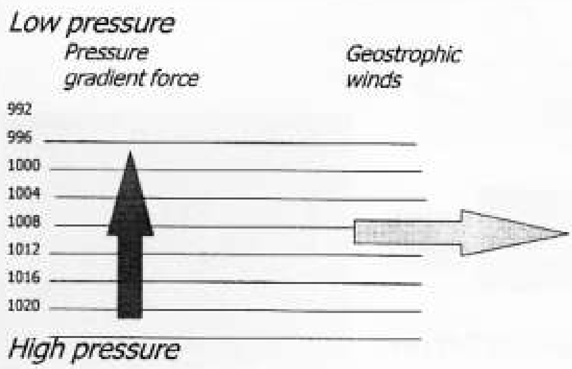
General Circulation of the Earth's Atmosphere



Deflection is least at the equator and greatest at the poles

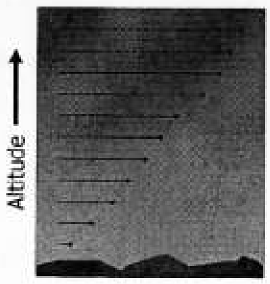
- The deflective force - Coriolis force – offsets the pressure gradient force
- Because the wind is deflected it now flows parallel to the isobars = geostrophic wind





Friction

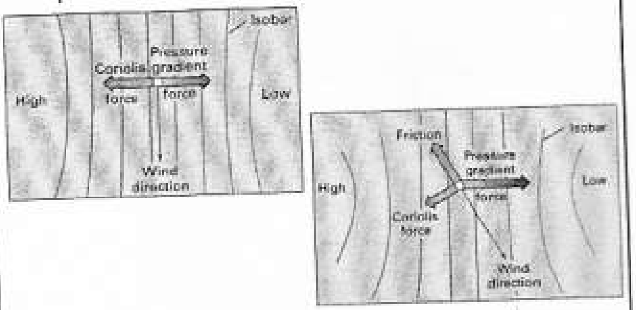
- Friction acts at the surface.
- The effect of friction decreases with altitude.
- Also, winds at the surface aren't as strong as those at higher altitudes

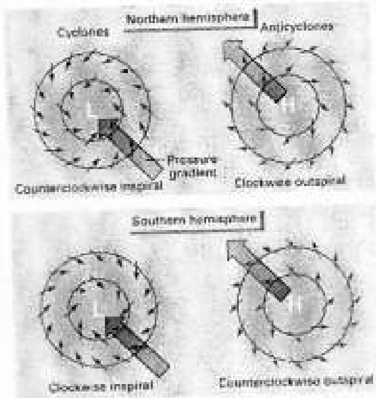


<u>Friction forces</u>

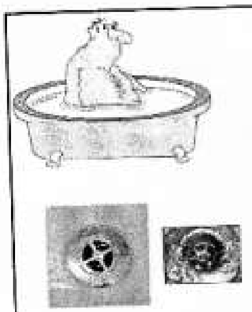
- As wind flows over the surface friction reduces the speed
- Friction also changes the direction of the geostrophic wind
- The pressure gradient force over powers the Coriolis effect
- As a result wind flow across the isobars

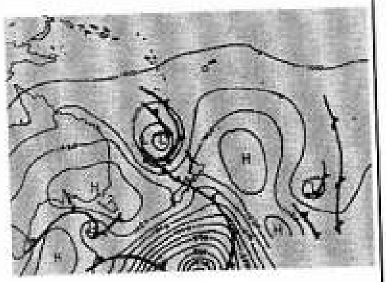
Pressure gradient and Coriolis forces
plus friction = Resultant wind





net affect

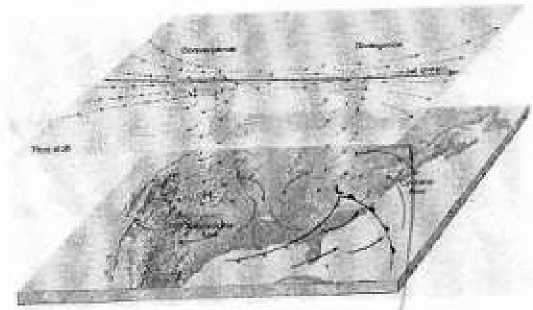




Coriolis Effect?

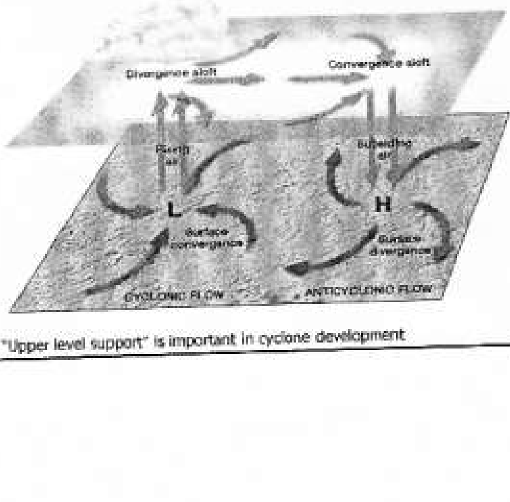
has to be large system.

Cyclone and Anticyclone Circulations



mixing ← vortex

Airflow Associated with Cyclones and Anticyclones

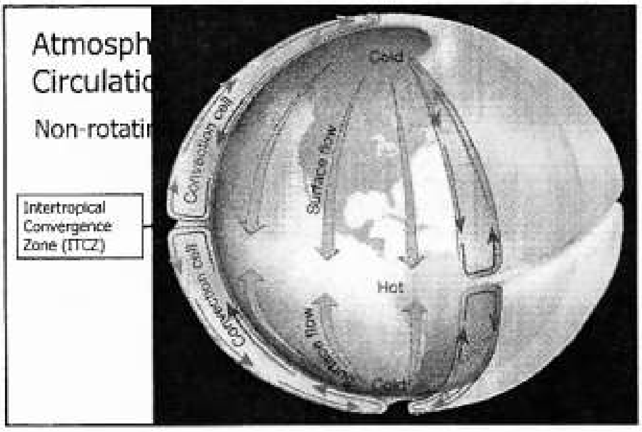


"Upper level support" is important in cyclone development

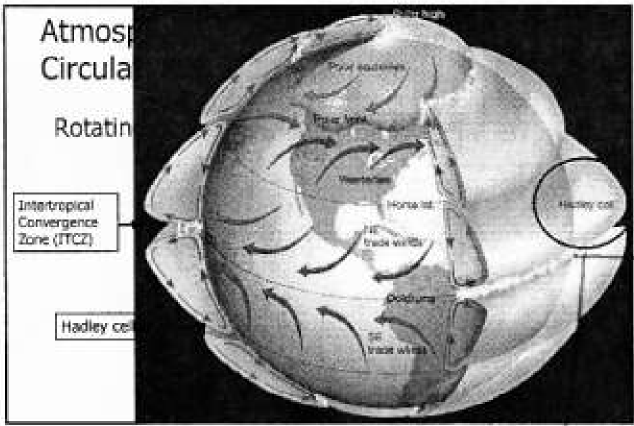
General Circulation of the Atmosphere

(Assumes uniformity of the Earth's surface)

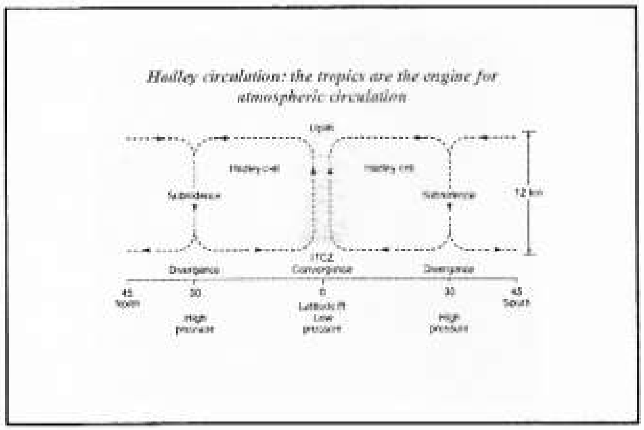
Nature of Winds

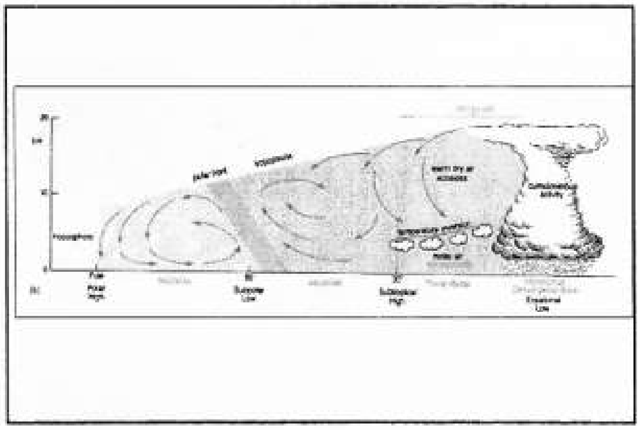


Climate = response to imbalance

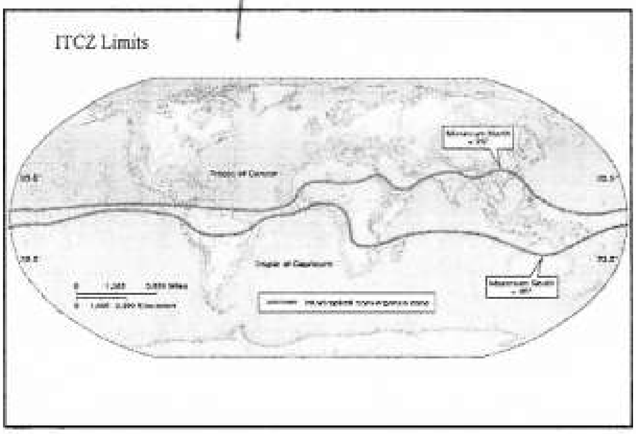


engine room of the climate

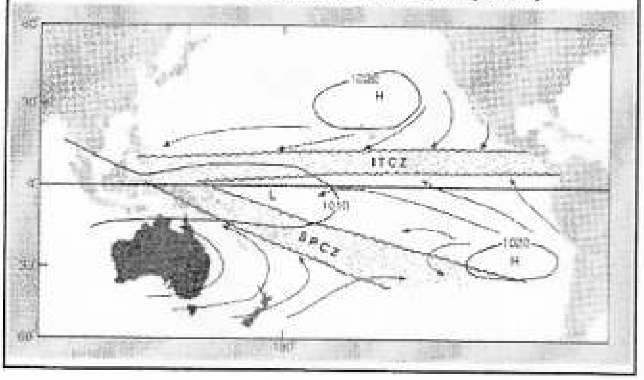




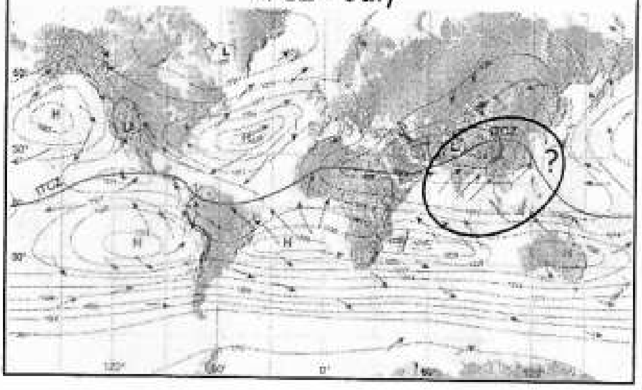
determines airflow on a global scale



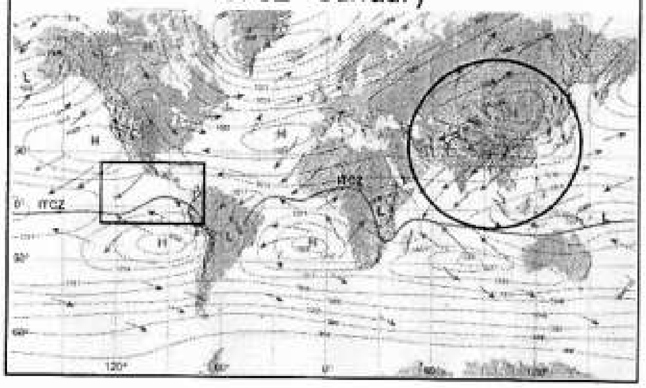
South Pacific Convergence Zone (SPCZ)

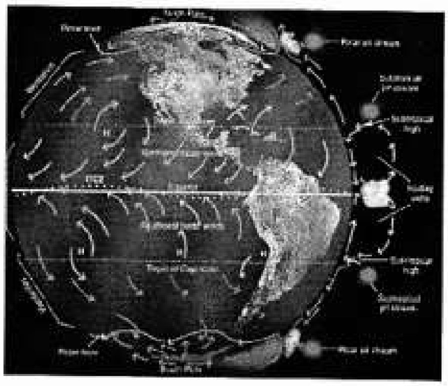


ITCZ - July



ITCZ - January





Summary

- We have seen
  - How wind information is portrayed
  - How wind is measured
  - How winds are produced
  - How winds are directed
  - What controls the strength of winds
  - Intertropical Convergence Zone (ITCZ)

Next: Primary, secondary and tertiary winds

Lecture 5 Atmosphere and ocean circulation

Content and Themes

Hadley circulation;
Poleward transport of heat
Primary winds (general worldwide)
Jet streams
Rossby waves
Secondary winds (migratory high and low pressure systems)
Tertiary: local winds (valley and mountain winds, sea and land breezes)
Ocean Heat Transport: Surface currents; Thermohaline circulation

Lecture objectives

1. Detail the mechanisms of poleward transport of heat and moisture.
2. Distinguish the major features of travelling cyclones and anticyclones.
3. Describe the nature, causes and movement of the Intertropical Convergence Zone
4. Describe Rossby waves
5. Demonstrate the relationship between ocean currents and wind patterns.
6 Explain the significance of thermohaline circulation

Key Words

Ocean heat transport	Upwelling	Ocean heat transport	Thermohaline circulation
Trade winds	Westerlies	Hadley cell	ITCZ
Polar easterlies	Valley wind	Sea breeze cell	Subtropical high pressure belt
Slope winds	Jet streams	Rossby waves	Convergenece
Katabatic wind	Anabatic wind		

Reading

Strahler, A. and Strahler, A. 2002, *Physical Geography - Science and Systems of the Human Environment* 2nd / 3rd ed., John Wiley and Sons, New York. Relevant parts of Chapter 7.
Smithson, P, Addison, K. and Atkinson, K., 2002 *Fundamentals of the Physical Environment*, 3rd edition, Routledge, London. Pages: 118-119.

Focussing Questions

What is the ITCZ?
Describe the Intertropical Convergence Zone and give the causes of its movement.
How does the movement of the ITCZ linked with the Asian monsoon?
What are the various temperature layers of the ocean? What does the thermocline represent?
Discuss the climatological significance of oceans.
How does thermohaline circulation induce deep ocean currents?
Describe the patterns of valley and mountain winds and their causes.
Describe the basic pattern of global surface winds.
What are jet streams?
What is a katabatic wind?

GEOG 101 – Lecture

Atmosphere and Ocean Circulation

Chris de Freitas

GEOG 101 – Lecture
Atmosphere and Ocean Circulation

Atmosphere
- Intertropical convergence
- Rossby waves
- Hadley circulation
- Poleward transport of heat
- Valley and mountain winds
- Sea and land breeze

Ocean
- Ocean Heat Transport
  - Surface currents
  - Thermohaline circulation

fluid + convectional flow of air, global scale

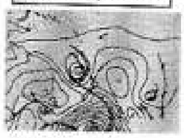
fronts mid latitude cyclone

Atmospheric Circulation

- Three levels (categories) of winds:
  - ✓Primary (general worldwide)
  - ✓Secondary (migratory high and low pressure systems)
  - ✓Tertiary (local winds and temporal weather patterns)

Primary winds

Secondary winds



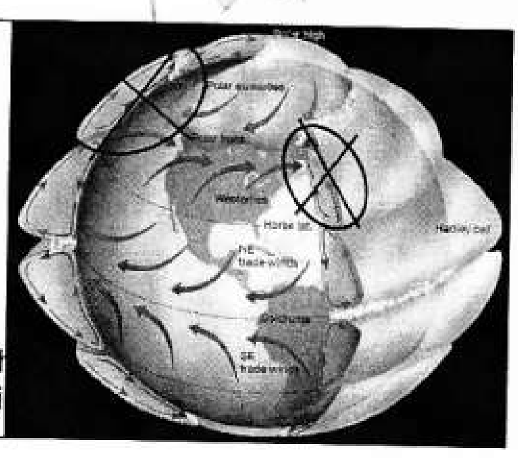
We have already dealt with this

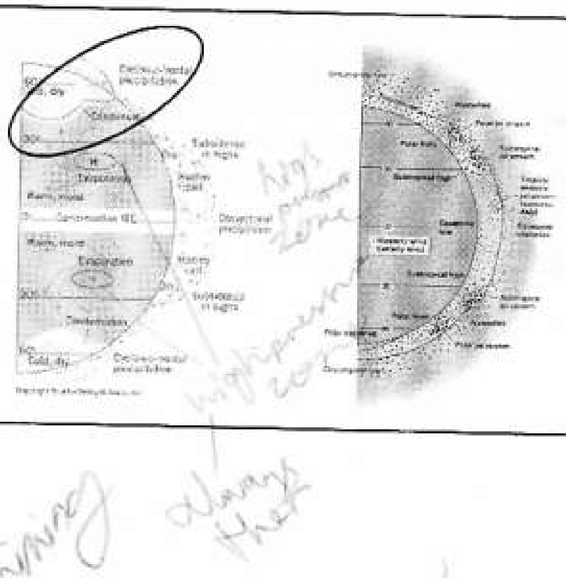
Tertiary winds

not cellular
not a cell
Ferrel cell
(air mass mixing)

sea breezes

Atmosph
Circulati





highs pressure zone

high pressure zone

hadley
→ el nino causes global warming

always that mistaken as human!

Nature of Winds

Lecture 5 Atmosphere and ocean circulation

Content and Themes

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GEOG 101 – Lecture

Atmosphere and Ocean Circulation

Chris de Freitas

GEOG 101 – Lecture
Atmosphere and Ocean Circulation

Atmosphere
- Intertropical convergence
- Rossby waves
- Hadley circulation
- Poleward transport of heat
- Valley and mountain winds
- Sea and land breeze

Ocean
- Ocean Heat Transport
  - Surface currents
  - Thermohaline circulation

fluid - convectional flow of air

global scale

fronts mid latitude cyclone

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  - ✓Primary (general worldwide)
  - ✓Secondary (migratory high and low pressure systems)
  - ✓Tertiary (local winds and temporal weather patterns)

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Secondary winds

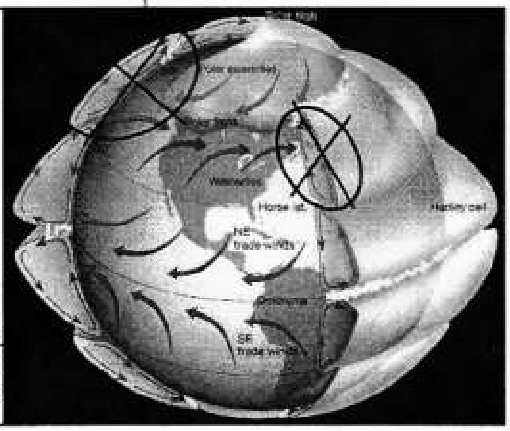
We have already dealt with this

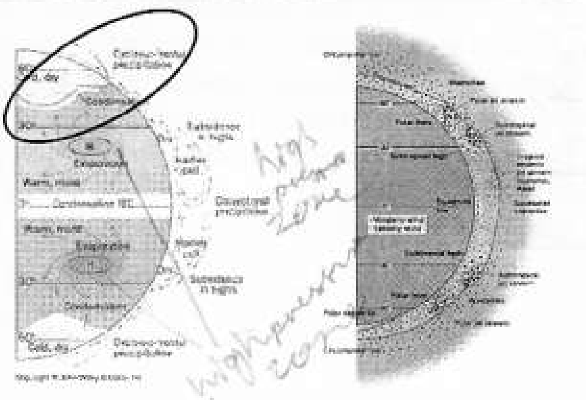
Tertiary winds

not cellular, not a cell, level cell, air moving, mixing.

sea breeze

Atmosph
Circulati





high pressure zone

high pressure zone

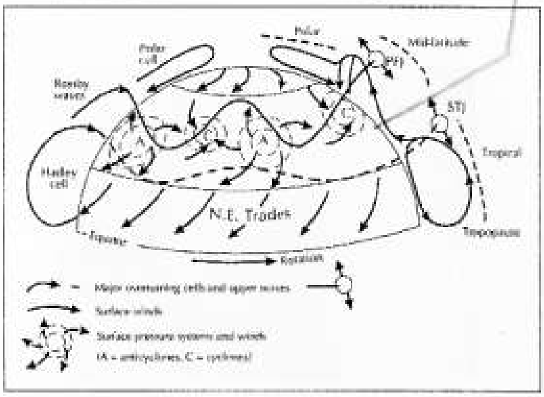
hadley
el nino causes global warming

always that mistaken as human!

Nature of Winds

moving energy mixing air masses -

look and know where these are.

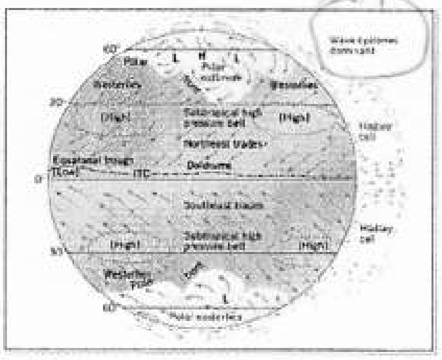


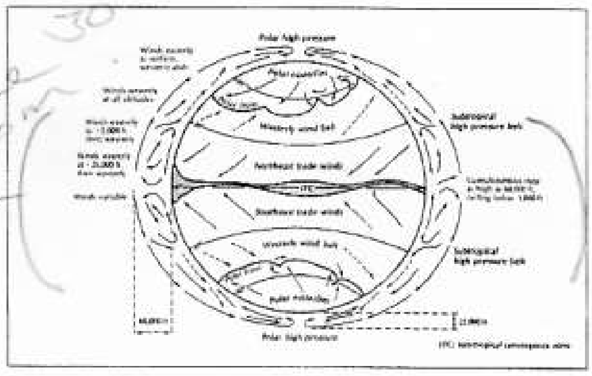
General Circulation of the Atmosphere
(Key features)

- Intertropical Convergence Zone (ITCZ): Equatorial zone of convergence, ascent of warm humid air. Ascending edge of Hadley cell.
- Trade Winds (Easterlies): NE Trade Winds, SE Trade Winds
- Subtropical Highs: Descending high pressure systems. In midlatitudes (30°) (Horse Latitudes)
- Westerlies
- Polar Easterlies
- Polar Highs: Diverging high pressure above the poles
- Polar Front: Boundary between Polar Easterlies and Westerlies

Frontal systems dominant in mid lat.

30° of equator





Upper Atmospheric Circulation

- Jet streams
- Rossby waves

Jet Streams

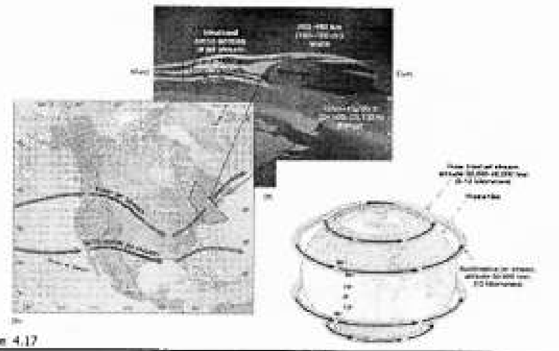
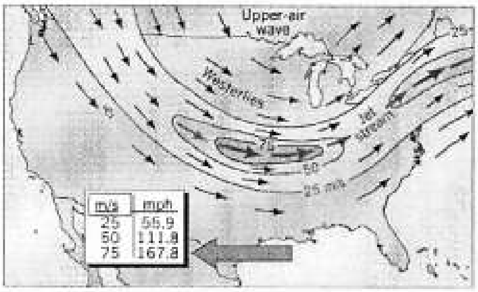


Figure 4.17

Nature of Winds



General Atmospheric Circulation

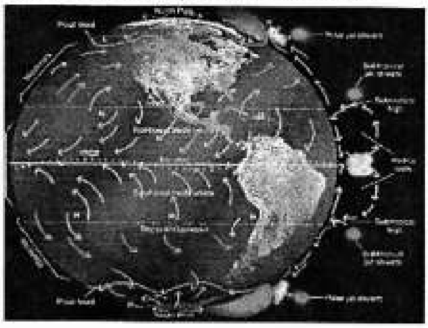


Figure 4.13

General Atmospheric Circulation

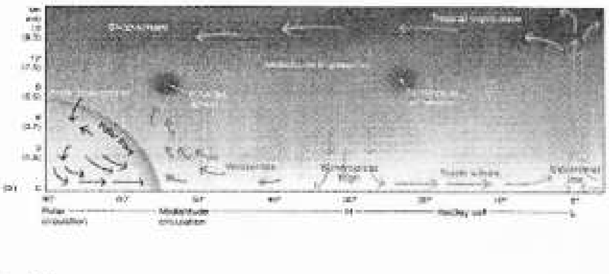
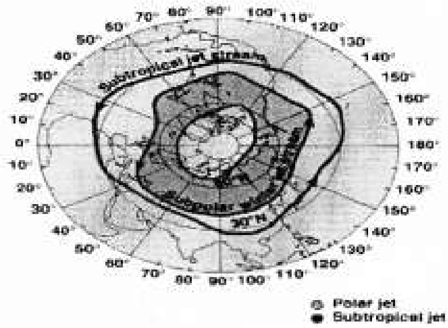


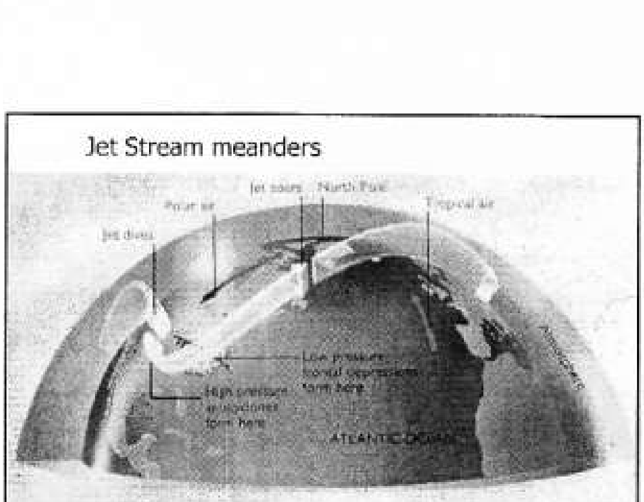
Figure 4.13

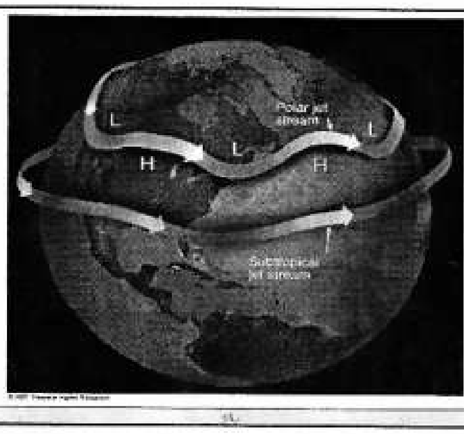
Upper Air Winds

Jet Stream meanders



Jet Stream meanders



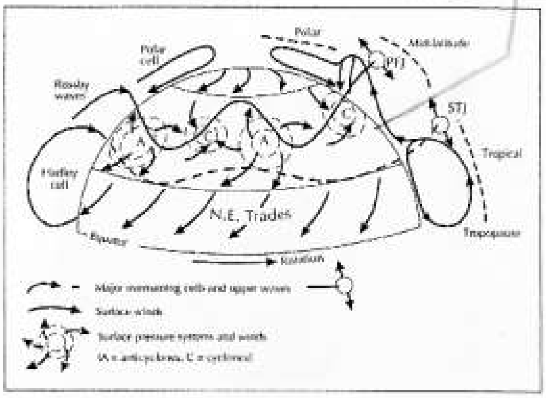


Rossby Waves

* look on ceil for rest of notes or Strahler

moving energy
mixing air masses.

look and know where these are.



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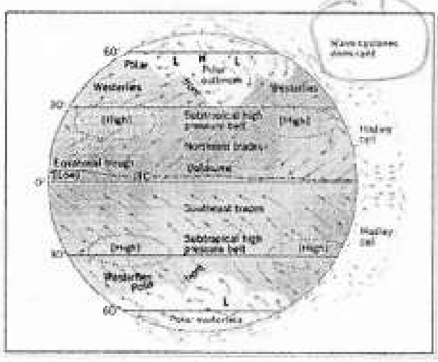
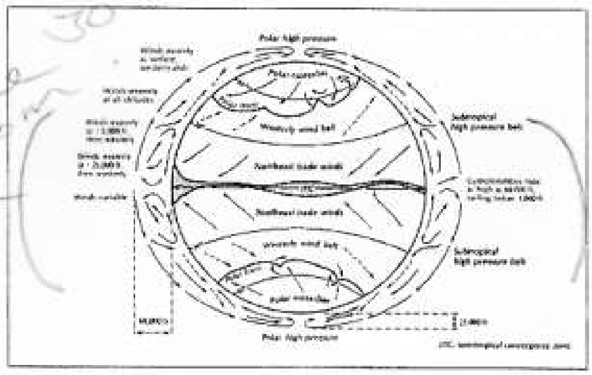
30° of equator.

engine room





Upper Atmospheric Circulation

- Jet streams
- Rossby waves

Jet Streams

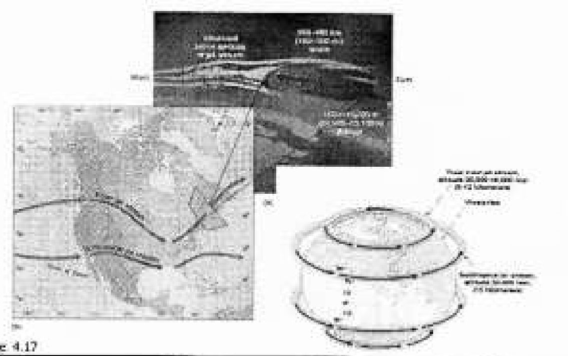


Figure 4.17

Nature of Winds

Lecture 6 Decadal-scale circulation systems (ENSO)

Content

Climate is dominated by diurnal and seasonal cycles imposed by the Earth's rotation and orbit, particularly at high latitudes where the influences are amplified. However, because these two cycles are so predictable and reliable, society is normally well attuned and copes. More problematic are the often smaller but less predictable variations that occur at decadal and longer scales. This lecture explores the El Niño – Southern Oscillation (ENSO) phenomenon as an example of decadal-scale variability and its causes. The physical basis of ENSO, its global scope, and its implications for Auckland's climate will be reviewed. The importance of atmosphere-ocean interactions is emphasised.

Themes

El Niño-Southern Oscillation (ENSO): Physical basis; Influence on climate – global, regional, Auckland

Lecture objectives

1. Detail the workings of the Southern Oscillation.
2. Describe the Walker Circulation
3. Define El Nino
4. Describe La Nina
5. Demonstrate the realtionshiop between line between sea surface temperature and the Southern Oscillation (ocean-atmosphere coupling).
6. Explain the significance of thermohaline circulation
7. Define El Nino and its effects upon weather.

Key Words

El Niño	Ocean-atmopshere coupling	La Niña
SST anomaly	SOI	ENSO
Teleconnections	Walker circulation	Thermocline

Reading

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Focussing Questions

What is El Niño and how does it compare with the normal pattern?
How would describe a La Niña situation?
What are teleconnections?
Describe the Walker circulation.

GEOG 101 – Lecture

Decadal-scale climate variability

thing that happen occasion.

Chris de Freitas

Lecture Outline

- Decadal scale climate variability
- El Niño-Southern Oscillation (ENSO)
  - Physical basis
  - Influence on climate
    - Global
    - Regional
    - Auckland

Oceans (things happen more slowly) time scales longer than a year (not 100s of years).

Decadal-Scale Climate Variability

- Diurnal and annual cycles dominate
- But nature and society are well attuned
  - ✓Predictable
  - ✓Reliable
- Sensitivity is to deviation from the normal
- Often associated with decadal-scale variation
- Atmosphere-ocean interactions are particularly important in this context

massive heat capacity

→ often considered out of the ordinary → climate NOT constant. e.g. not every winter is as cold

Climate relevance of ocean heat transport

- Currents redistribute vast amounts of energy
- Influence on regional climate
  - E-W Pacific and E-W Atlantic contrast
  - Maritime influence on NZ's climate as NZ is islands due to ocean
- Variation in ocean heat transport occurs
  - Often decadal-scale oscillations (and longer)
  - Resulting in decadal-scale climate variability
    - North Atlantic Oscillation (NAO)
    - Pacific Decadal Oscillation (PDO)
    - Antarctic Circumpolar Oscillation
    - El Niño–Southern Oscillation (ENSO)

Understanding, reconstructing and predicting these is focus of much of modern climatology

South Pacific & global significants. * not CO2

Contrary to popular perception, these decadal-scale oscillations are not well-understood phenomena. In fact, we do not know what causes them.

This is an example of "name-dropping" in climate science. Invent a new word for an unexplained phenomenon and then explain other phenomena as caused by the invented name.

ENSO, QBO, NAO, PDO are just some examples of names that are mentioned as the cause of some other variable. None of them is understood as a consequence of defined causal physical processes.

even some scientist forget this

cycle we see in the data & give it a name

El Niño

- Best known sea surface temperature (SST) anomaly
- Abnormally warm water occasionally appearing in Peru's coastal waters
  - Often develops in late December
    hence name: "The Christ Child"
  - 'Anti El Niño' = 'La Niña'
  - Displacement of nutrient rich upwelling cool water
  - Devastating impacts on fisheries
  - Evident since at least beginning of historical records
  - Referred to as 'ENSO'
    → * something else linked but differ

deviation from normal

Oceans and ENSO

Lecture 6 Decadal-scale circulation systems (ENSO)

Content

Climate is dominated by diurnal and seasonal cycles imposed by the Earth's rotation and orbit, particularly at high latitudes where the influences are amplified. However, because these two cycles are so predictable and reliable, society is normally well attuned and copes. More problematic are the often smaller but less predictable variations that occur at decadal and longer scales. This lecture explores the El Niño – Southern Oscillation (ENSO) phenomenon as an example of decadal-scale variability and its causes. The physical basis of ENSO, its global scope, and its implications for Auckland's climate will be reviewed. The importance of atmosphere-ocean interactions is emphasised.

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How would describe a La Niña situation?

What are teleconnections?

Describe the Walker circulation.

impact mainly on peru fisheries

El Niño–Southern Oscillation (ENSO)

sea surface temperature

El Niño is an SST anomaly (abnormally warm appearing off Peru's coast)

in same area

Southern Oscillation is zonal air circulation over the tropical Pacific

Stonorton meridian. zonal East → west

Remember "name-dropping" in climate science.

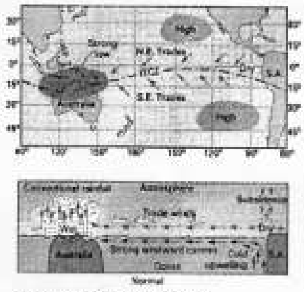
Invent a new word for an unexplained phenomenon and then explain other phenomena as caused by the invented name. ENSO, QBO, NAO, PDO are just some examples of names that are mentioned as the cause of some other variable. None of them are understood as a consequence of defined causal physical processes.

El Niño

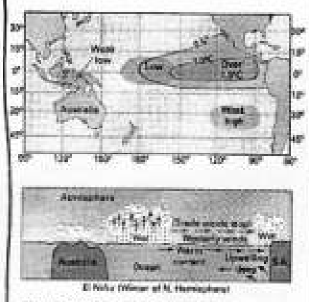
- Initially thought to be of only local importance

  de fisheries trying to link to hadley circ?

- Now recognised to be part of a large-scale atmosphere-ocean phenomenon
- Major advance in comprehending global climate
- Has been referred to as 'Earth's heart beat' (!)
  - A measure of its significance



In normal year, low pressure dominates in Malaysia and northern Australia.



In an El Niño year, low pressure moves east to the central part of the western Pacific.

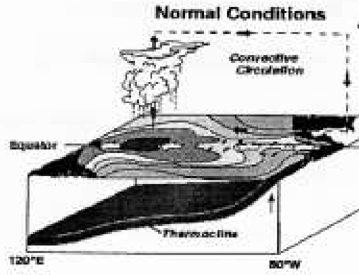
southern oscillation

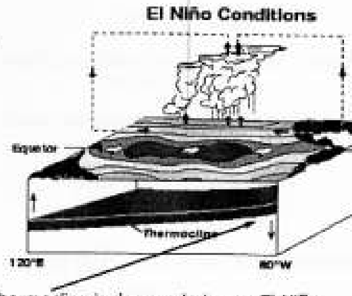
El niño

zonal circulation

broken down

Walker Circulation



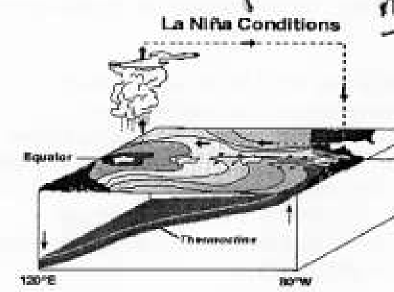


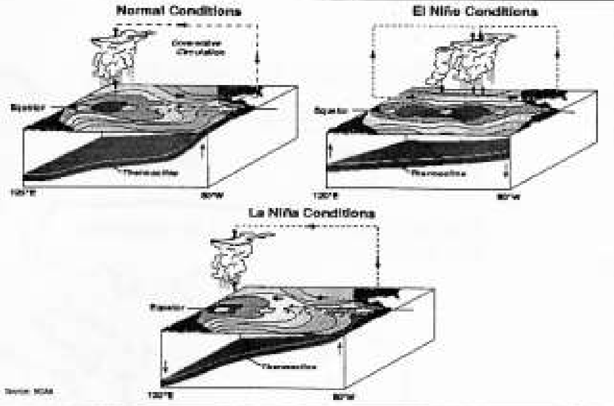
Thermocline is deeper during an El Niño

La Nina extreamly normal situation

Well developed
↑ walker circulation

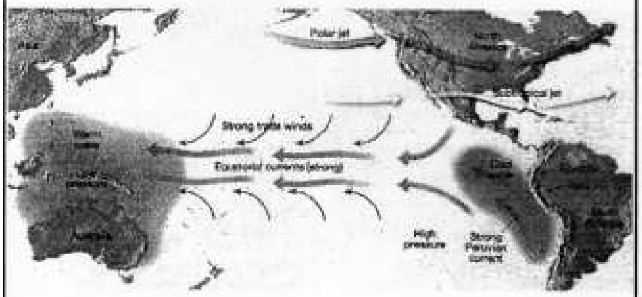
extreme
normal



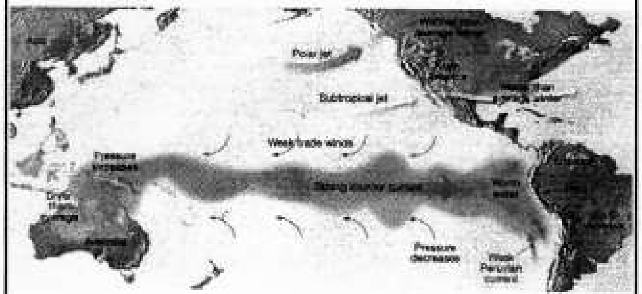


Southern osculation
Break down
of walker.

Normal



El Niño



Normal

Strong easterly trade winds
↓
Drag on oceans
↓
Thicker & warmer surface layer in W (higher sea level: 40 cm)
↓
Warm moist air rises over Indonesian region (SST ca. 30°C)
↓
Cloud & rain, low pressure
↓
W → E upper air flow
↓
Descending air in the E Pacific, high pressure
↓
Oceanic dry zone off S. America

El Niño

Weaker easterly trade winds
↓
Reduced drag on oceans
↓
Warm water back to E (Sea level similar, upwelling stopped)
↓
Warmer SST moves east
↓
Walker cell split
↓
Air Pressure changes

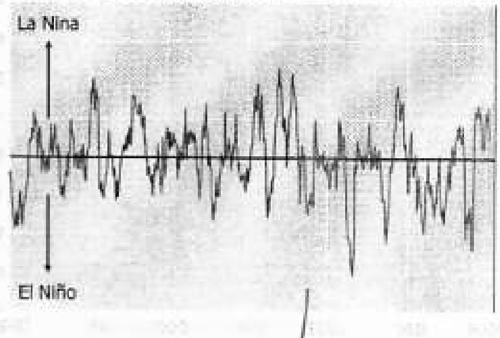
global cooling.

Southern Oscillation Index (SOI)

Air pressure difference between Tahiti and Darwin (weather stations)

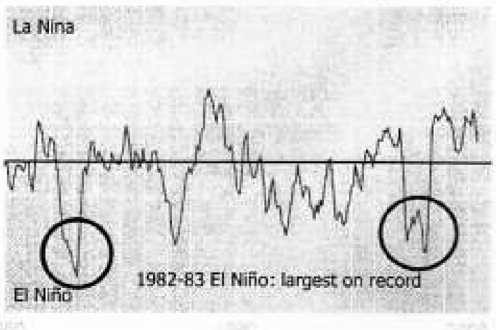
linked to El Niño.
W long record of weather in Tahiti & Darwin.

Southern Oscillation Index (SOI)



high freq of El Niño bring global warming

Southern Oscillation Index (SOI)



cycles.
not normal
mother nature doesn't have normal.

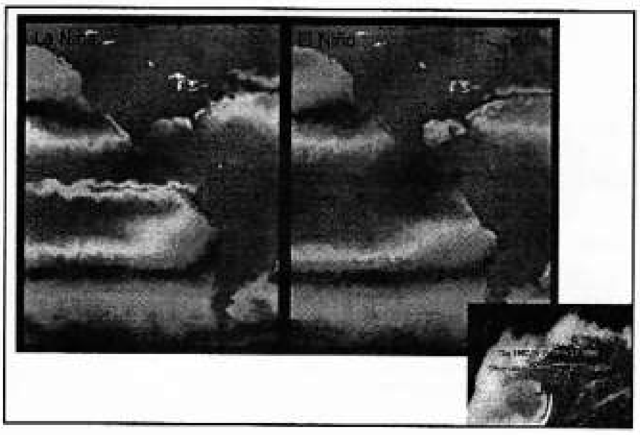
1982/83 El Niño

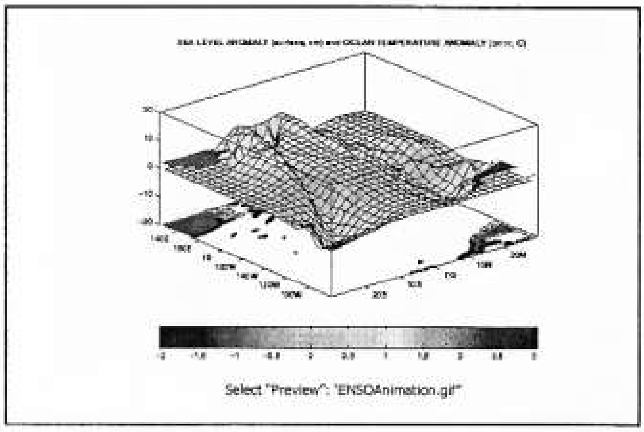
- Trade winds slackened mid-1982
- Late Sept: 4 °C SST increase off Peru (24 hrs)
- Record SST anomaly in E. tropical Pacific (>5 °C)
- 10-20 million m^3/s (36-72 km^3/h)

1998 El Niño

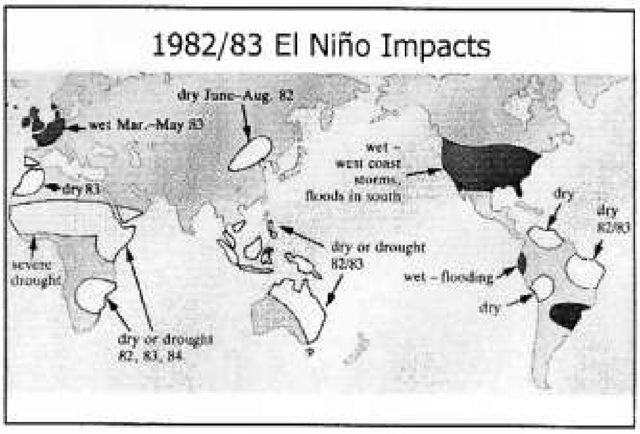
- Not as stong as 1982 event
- But lasted longer
- Lasted over two years (1997- 1999)
- Showed up as global warming – i.e. effects widespread

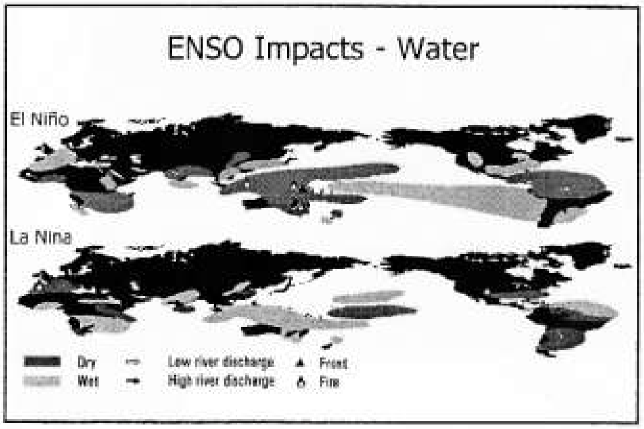
hottest years ever.

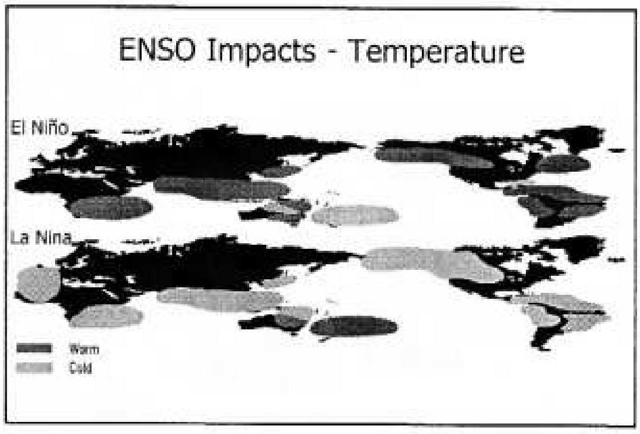


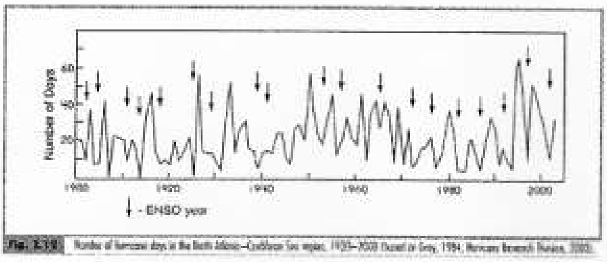


40cm sea level rise



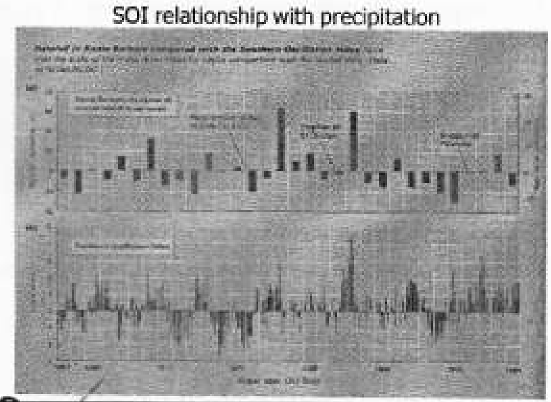




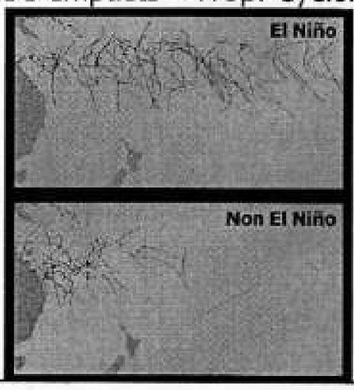


Some links but not as much as people make out

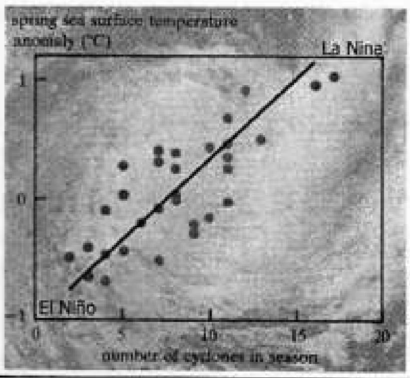
SOI relationship with precipitation



ENSO Impacts - Trop. Cyclones



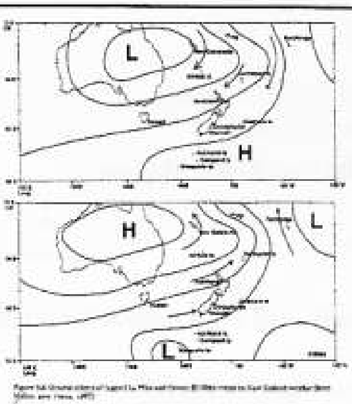
Trop cyclones north of Australia



Note this is area north of Australia – during La Nina warm water surges east taking trop cylcones with it.

La Niña

El Niño



generalisation

ENSO Impacts - Auckland

El Niño	La Nina
Higher than normal pressure over Australia	Lower than normal pressure over Australia
⇓	⇓
Increased SW flow	Decreased SW flow
⇓	⇓
Cooler & drier	Warmer & wetter
Drought?	**Floods?**

more apparent than real

Lecture 7 Weather forming systems

Content

This topic extends our investigation of precipitation through examination of extreme precipitation and storms.

Themes

- Types of precipitation
- Causes of uplift
- Spatial patterns
- Hurricanes, Tropical Cyclones, Typhoons
- Storm tracks
- Intense rainfall
- Monsoons

Lecture objectives

1. Distinguish the major features of hurricanes and tropical cyclones.
2. Identify the tracks of tropical cyclones and hurricanes.
3. Explain the processes leading to formation of weather fronts (revise).
4. Determine the factors necessary for the formation of tropical cyclones.
5. Describe the conditions that can give rise extreme precipitation.
6. Describe the nature and causes of monsoons

Key words

adiabatic cooling	condensation	convergence
orographic lifting	precipitation regime	convectional precipitation
tropical cyclone	hurricane	Winter monsoon
typhoon	storm surge	Summer monsoon
tropical cyclone tracks	Simson-Saffir scale	

Reading

Strahler, A. and Strahler, A. 2002, *Physical Geography - Science and Systems of the Human Environment* 2nd / 3rd ed., John Wiley and Sons, New York. Relevant parts of Chapter 7. Also, generally Chapters 10 and 11 (unrelated to this topic but useful to round out section).

Smithson, P, Addison, K. and Atkinson, K., 2002 *Fundamentals of the Physical Environment*, 3rd edition, Routledge, London. Pages: 126-140.

Focussing questions

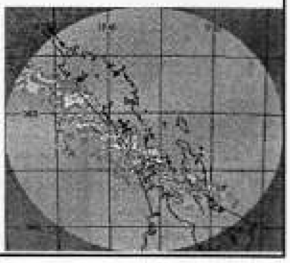
Describe the processes that lead to three different types of precipitation.
What processes are responsible for the global precipitation regimes?
Explain the various circumstances producing rainfall in the Auckland region.
Why are tropical cyclones so dangerous?
Where and when do tropical cyclones occur?
Describe the structure of tropical cyclones.
What is the nature of the energy that fuels a tropical cyclone and how is this relevant to a life cycle of a tropical cyclone?
What weather conditions have led to extreme rainfall events in Auckland?
Explain the temporal and spatial pattern of Auckland's precipitation.
What is the Asian Monsoon? Compare its features in summer and winter.

Test use focusing questioning, Short answers cover key points.

GEOG 101 - Lecture
Weather Forming Systems

Chris de Freitas

- Precipitation:
  - causes
  - spatial patterns
  - temporal patterns
- Monsoons
- Hurricanes



Bring together themes

all forms of water FROM SKY

Types of precipitation

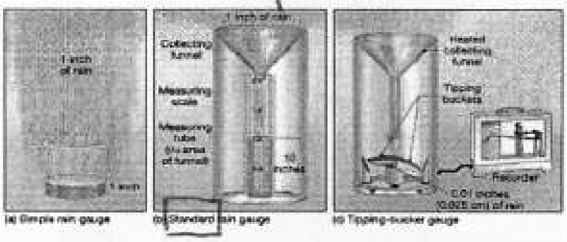
- Rain (liquid drops)
- Drizzle (light rain - small uniform droplets)
- Freezing rain (ice crystals freeze onto a frozen surface)
- Snow (ice crystals that have not melted)
- Sleet (rain freezes - or ice crystals melt - on way down)
- Hail (melting and refreezing crystals that form in thunder storm clouds)

Dew is condentation.

Measuring precipitation (rain)

sealed.

Raingauges



Lab Exercise

to minimise errors.

Precipitation is caused by uplift and subsequent cooling of air:

Types of precipitation according to causal process (i.e. uplift):

- Convective
- Orographic
- Cyclonic frontal cold ⇔ hot air mixing
- Convergence

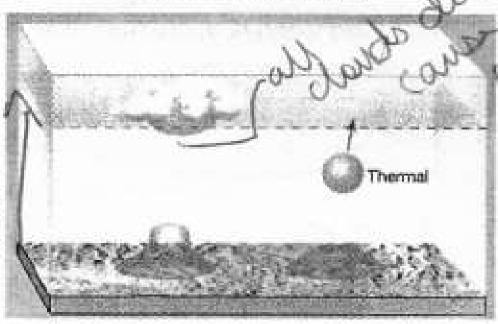
due point temp

Convective Lifting

cool

heat

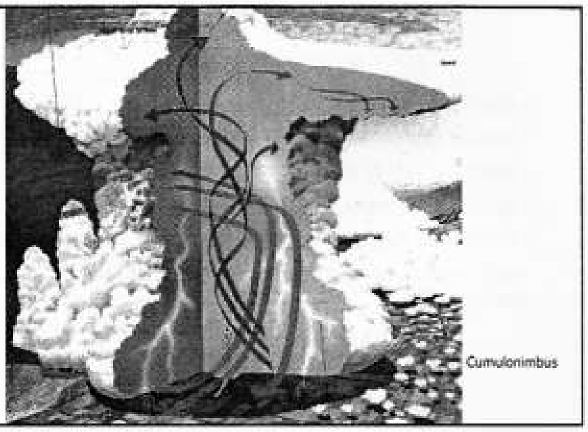
all clouds don't cause rain



1. Convection
   (Convectional Precipitation)

- warm air rises
- cools to dew point and clouds form
- latent heat release
- adds energy and increases updraft
- can produce thunderstorms ⟹

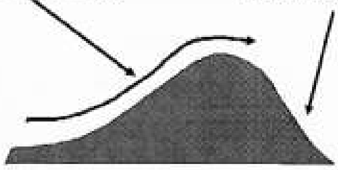
Stratosphere



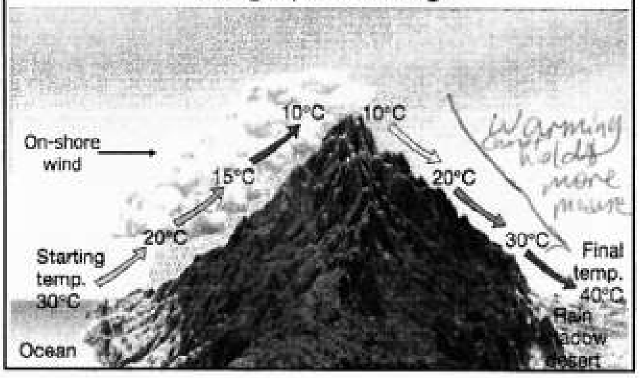
relating to mountains or hills

2. Orographic lifting
- Air rising over mountain
- Change in temperature (cooling) alters the relative humidity
- Saturation occurs
- Cloud forms and possibly precipitation
- Intercepting slope = windward slope (wetter)

leeward slope - drier (rainshadow)



Orographic Lifting



↳ quickly.
why West Cost of S Island more rain & Hawaii

mid lat cyclone

3. Cyclonic (frontal) precipitation
- Where air masses with different temperatures come together
- Warm air lifted by cold dense air, or rises over cold, along a weather front (frontal wedging)
- leads to frontal precipitation

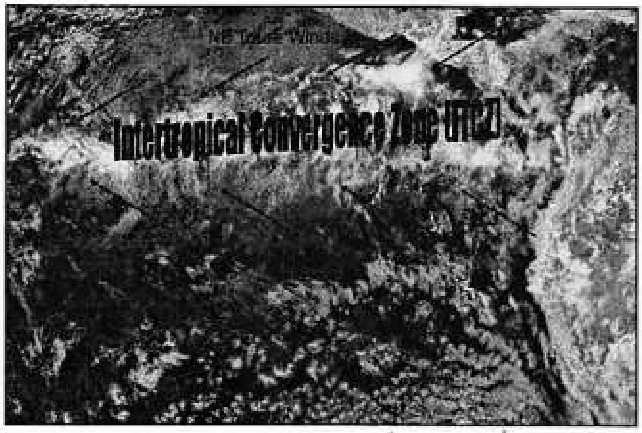
i.e. cyclical cyclones

This was dealt with earlier in lecture 'Airmasses and Weather'

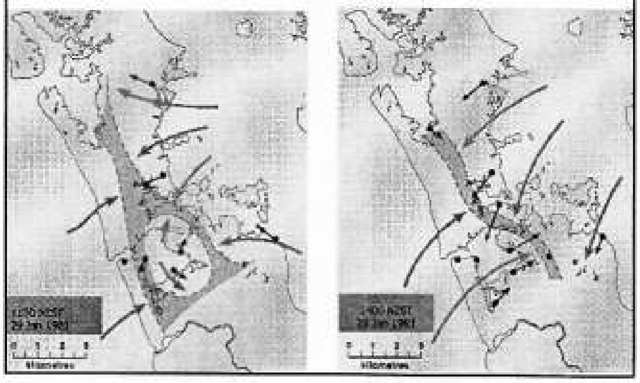
4. Convergence

(as we have already seen)

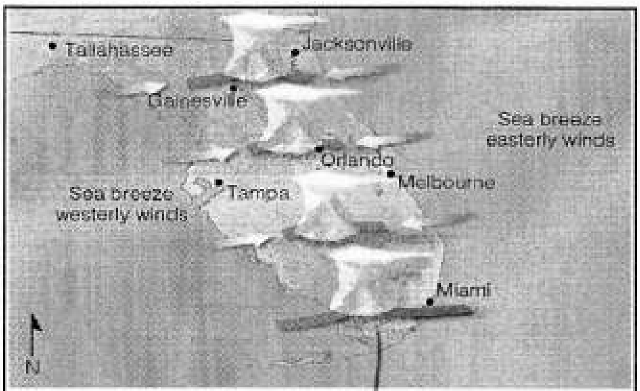
ICZ



4) Convergence (of sea breezes)



lotsa cloud, water
& precipitation
large scale convergence.



convergence
precipitation

Temporal and spatial patterns of precipitation

if you live in
mid latt
under influence
of cold &
warm fronts

Asian & African
monsoonal effect.

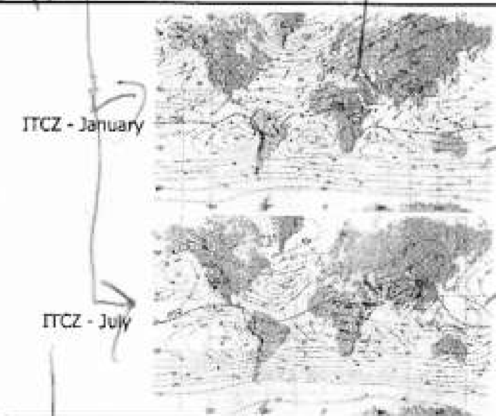
high pressure

seasonal phenomen
time!

Monsoon (winter and summer)
(derived from Arabic meaning "season")

- ✓They are regular, permanent features of the atmosphere.
- ✓They have beginning and ending times each year.
- ✓They have geographic limits. *

reg
&
permanent
features
of climate.



way south

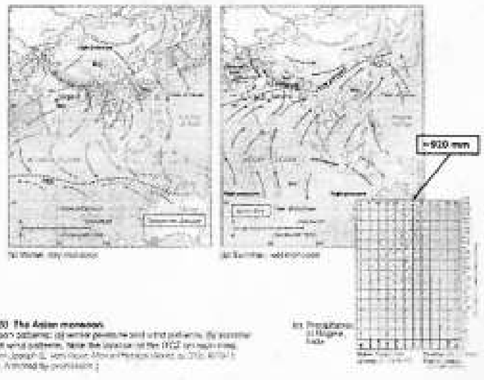
way north

position gets distorted
because
of heating

south winter
further north

Winter
cold
air
DRY

Summer
Warm
& Moist

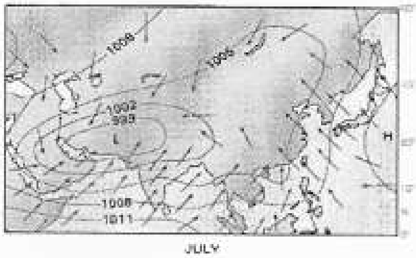


extreme monsoon can bring flooding

Summer Monsoon

In July the position of the ITCZ moves North

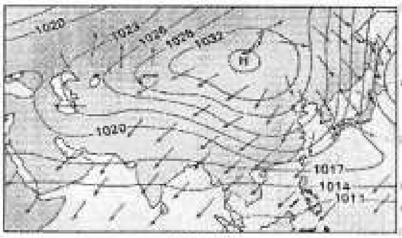
- Low pressure over the land causes winds to flow off the ocean
- This brings heavy rainfall



JULY

Winter Monsoon

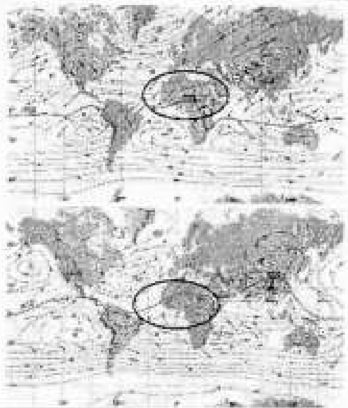
In January high pressure over the land produces dry winds. Air is flowing towards the ITCZ



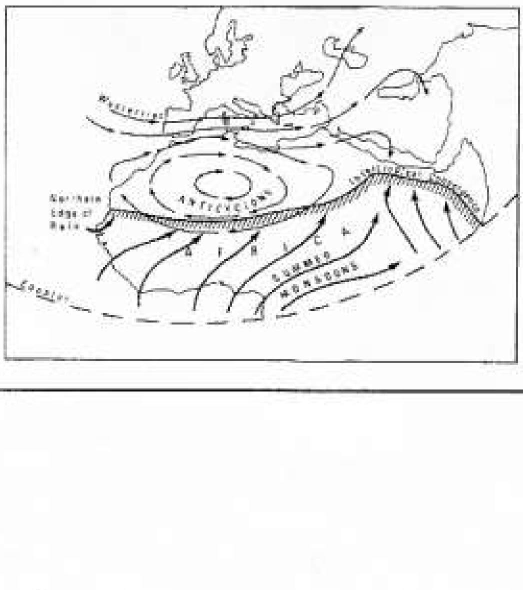
JANUARY

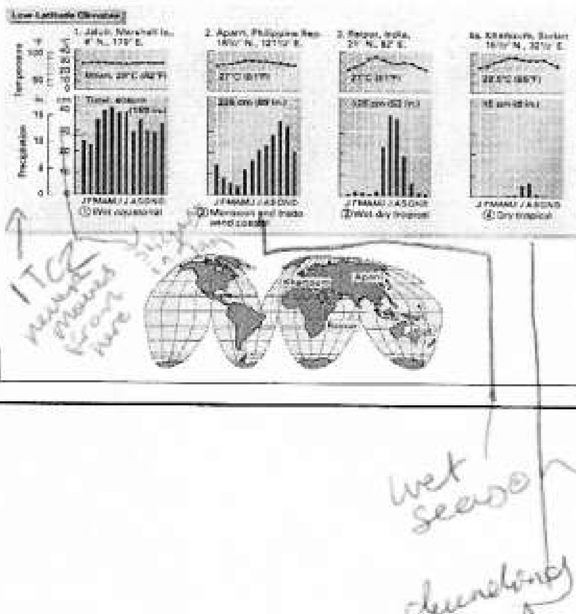
ITCZ - January

ITCZ - July



can be affected by humans beings but NOT related to global warming



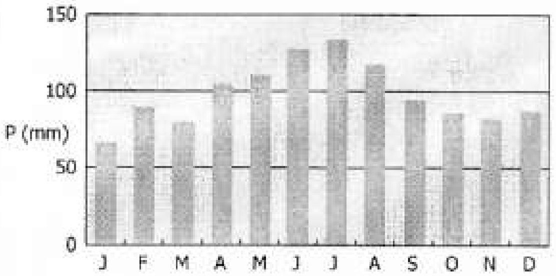


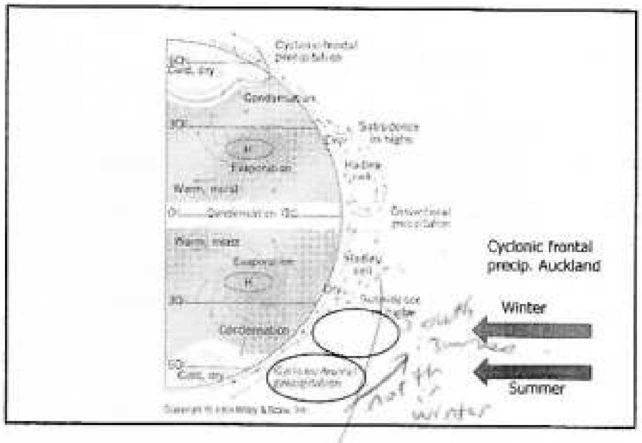
ITCZ never moves from here

wet season

changing edge of Hadley cell

Mean monthly precipitation, Auckland Airport

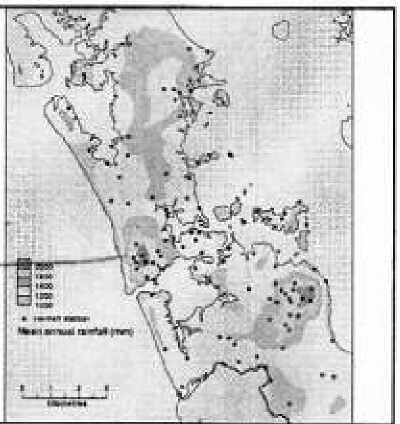




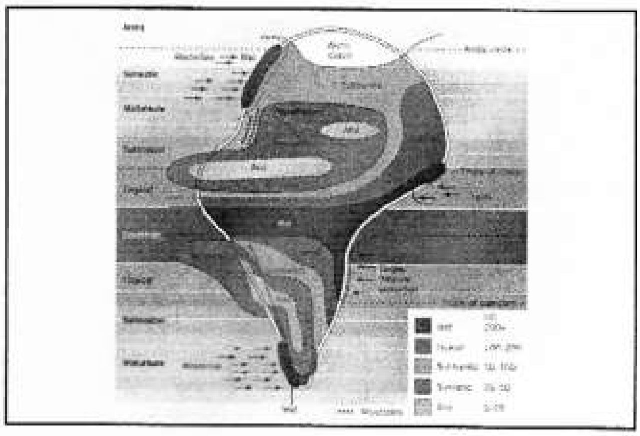
Average annual precipitation (mm) in the greater Auckland region

Where is highest and lowest? Why?

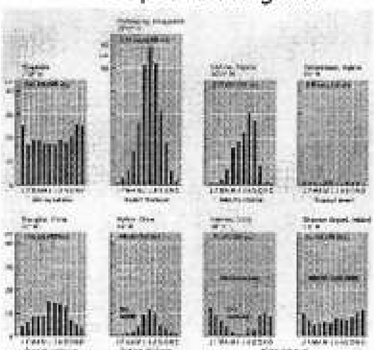
around Ranges waitakerers

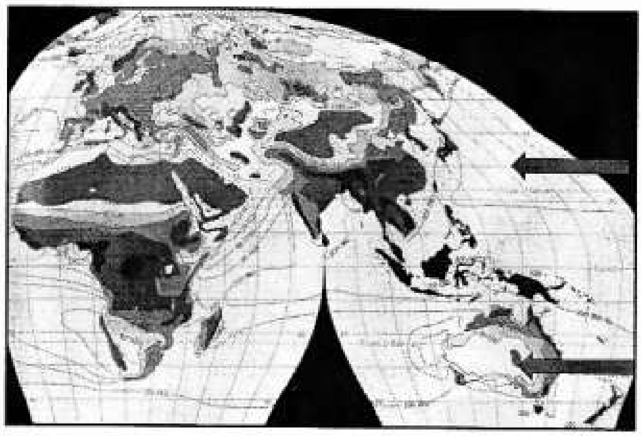


anyuplift will cause precipitation is highly variable in space & time



Precipitation Regimes





Weather systems

important for precipitation.

Tropical Cyclones

all same thing

- ✓ Hurricane (western hemisphere), Typhoon (western Pacific and Asia); Tropical cyclone (Pacific and Indian Ocean)
- ✓ Develop over warm ocean surfaces (≥ 28°C) between 8° and 15° latitude, migrate westward and curve toward the poles.
- ✓ Tropical cyclones often create tremendous damage.

need warm water

need coriolis effect so not close to equator 10-15° latt

Impacts of Tropical Cyclones

- Storm surge - low pressure, high winds and the shape of bays can produce sudden rise in water level
- Wind damage
- Heavy rain – flooding inland, landslips
- Wave damage
- Activity varies from year to year (number and strength)
- Season usually from May to November in Atlantic; November to May in Pacific.

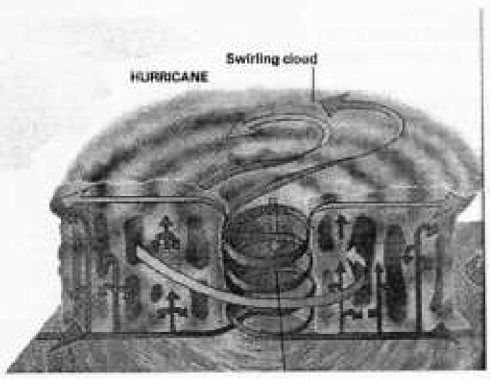
ocean too cold

Tropical cyclones

St making sinking air

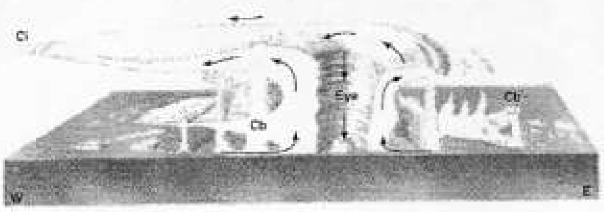
- Characteristic central "eye" (clear skies and calm winds)
- Air descends from high altitudes, warming
- Wind speeds are highest at the "eye wall"
- Winds spiral outward creating high wind speeds

very specific order



Speed highest at eye edge

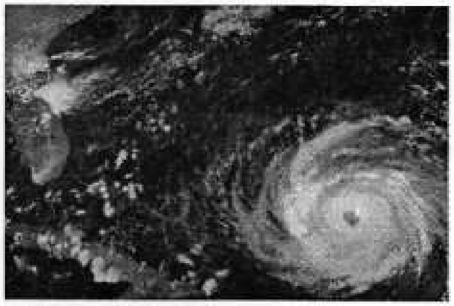
Schematic diagram of a hurricane: cumulonimbus (Cb) clouds in concentric rings though dense stratiform clouds; cirrus (Ci) clouds out ahead of storm; width of diagram about 1000 km.



Source: Strahler and Strahler (2002)

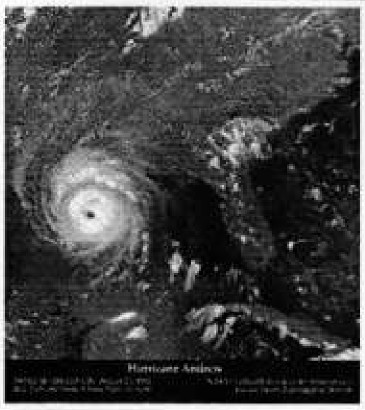
Tropical cyclones: formation and structure

Hurricane Floyd



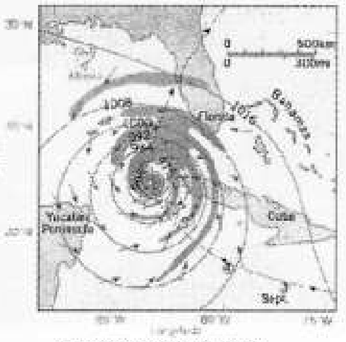
Caribbean, September 1999

Hurricane Andrew,
Aug 25, 1992



Hurricane Gladys

Simplified weather map of hurricane in the Caribbean. Daily locations beginning Sept 3 are shown as circled numbers. Path is over Florida.



Source: Strahler and Strahler (2002)

Typical tracks of tropical cyclones

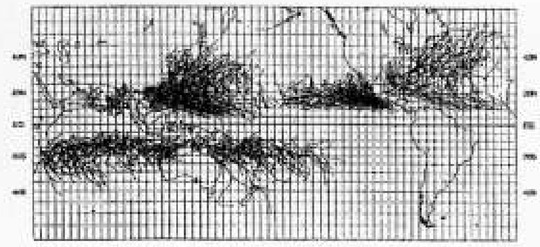
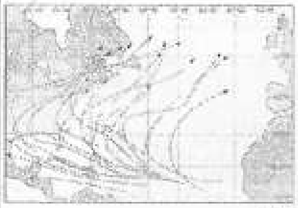


Figure 11.13 Tracks of tropical cyclones with winds above 17.4 m/s during the period 1979-88

hard to predict path.

Weather systems



Tracks of some typical tropical cyclones in the Caribbean and western Pacific. On entering region of prevailing westerlies, the storms change direction, toward the northeast in the N. Hemisphere and southeast in the S. Hemisphere.

Rotorua hurricane

if any condition is removed hurricane dies

Summary: Tropical cyclone (hurricane or typhoon)

- Intense storm
- Circular rotating system
- Forms 10° to 20° N and S latitudes (not closer to equator)
- Forms over the sea, in vicinity of ITCZ
- To form, sea surface temperatures ≥ 28°C required
- Storm gains energy from release of latent heat
- Dies when removed from water and latitude belt (tracks)
- Move west in the trade wind belt, 10-20 km/hr
- Mean wind speeds > 120 km/hr (75 mph)
- Structure: eye; wind patterns etc

Simpson-Saffir Scale of Tropical Cyclone Intensity

- Categories 1 to 5 (5 is most devastating)
- Measured by central pressure, storm surge and mean wind speed

strength important. adaptation.

cost high energy zone.

Lecture 8   Natural climate variability and change

Content

Human perception of climate tends to be focused on the regular diurnal and annual cycles and on the unpredictable variability at decadal-scale time scales that have obvious relevance in the context of a typical human lifetime. However, it is important to appreciate that this variability is superimposed on changes in climate (sometimes vast in scale) operating at much longer time scales. This lecture examines the character of long-term climate change and the mechanisms for change. We will also look briefly at methods used to reconstruct past climates. The reading below by Whyte (1995) is strongly recommended.

Themes

Past climates
Proxy climate data
Causes of climate change

Lecture objectives

1. Describe changes in past climate at various time scales.
2. Identify various climate periods over geological timescales and the more recent past.
3. Look in detail at climate variability and identify possible trends over the past 100 years.
4. Compare the surface instrumental record of global temperature with recent satellite global temperature data.
5. Give examples of the various types of climate proxy climate data and describe how they are derived.
6. Describe the possible causes of natural climate change and variability.

Key words

Holocene
Inter-glacials
Sunspots
Pleistocene
climate proxies
orbital variations
Ice Ages
Little Ice Age
dendroclimatology

Reading

Whyte, I.D. 1995, *Climatic Change and Human Society*, Arnold, London. Chapters 1 and 2.

Strahler, A. and Strahler, A. 2002, *Physical Geography - Science and Systems of the Human Environment* 2nd / 3rd ed., John Wiley and Sons, New York. Chapters 10 and 11 (unrelated to this topic but useful to round out section). Also pages 570-572.

Smithson, P, Addison, K. and Atkinson, K., 2002 *Fundamentals of the Physical Environment*, 3rd edition, Routledge, London. Pages: 161-174.

Focussing questions

What is a climate proxy?
How are climate proxies used?
What are the potential causes of climate change?
Is climate change predictable?
Describe the various methods used to gather evidence on the nature of past climates, that is, proxy sources of climate data.

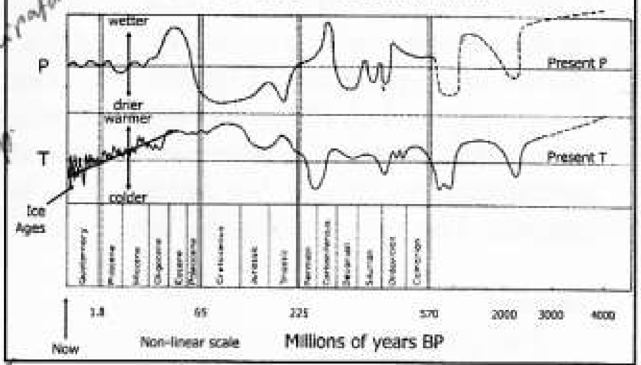
Past climate

GEOG 101 - Lecture
Climate Variability and Change

Chris de Freitas

- Past climate
  - Character of past climate
  - Sources of information
- Causes of climate change
  - Variable sun
  - Orbital variation
  - Volcanism
  - Ocean heat transport variation
  - Greenhouse gases

Global Climate - 4.5 billion years



precipitation

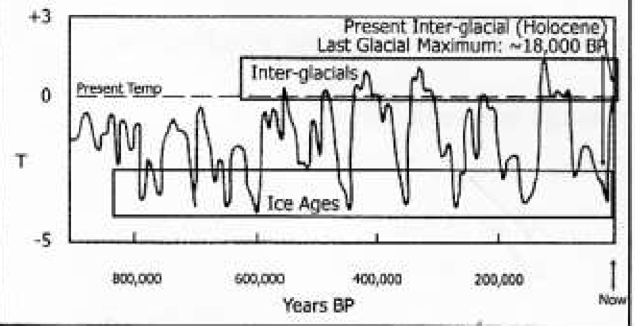
temp

negative feedback stops change going to far

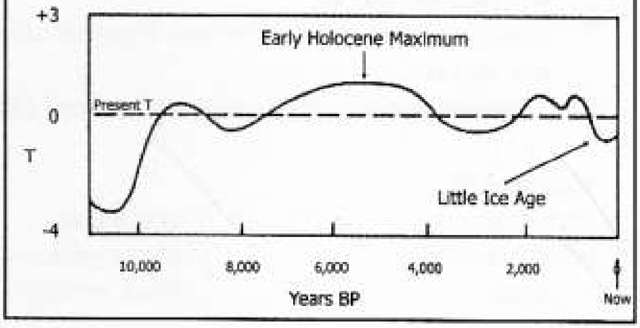
mean

Climate never constant always varying.

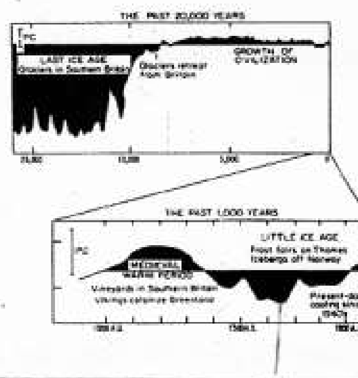
Global temperature: 900,000 years



Global temperature: Holocene



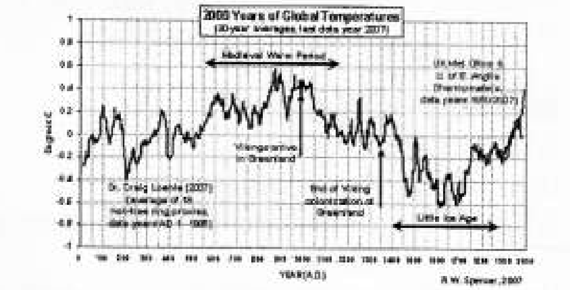
CO_2 not well correlated with temperature at all.



recovery from little ice age

Plague etc.

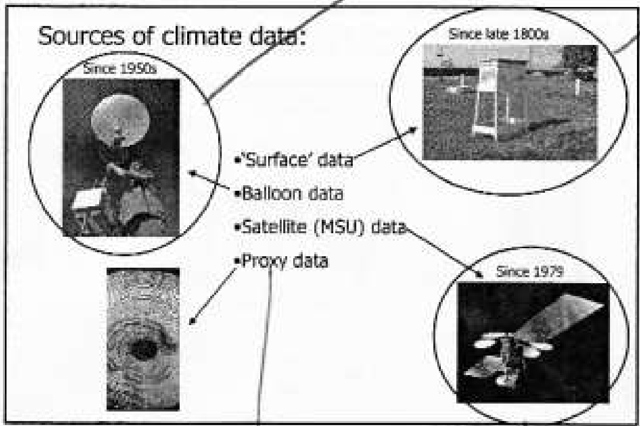
Global average temperature reconstruction based upon 18 temperature proxies for the period 1 A.D. to 1995, combined with the thermometer-based dataset from the UK Met Office and University of East Anglia, covering the period 1850 to 2007. Note that for both datasets each data point represents a 30-year average.



Source: Spencer 2008

good quality data point. spot

poor quality.



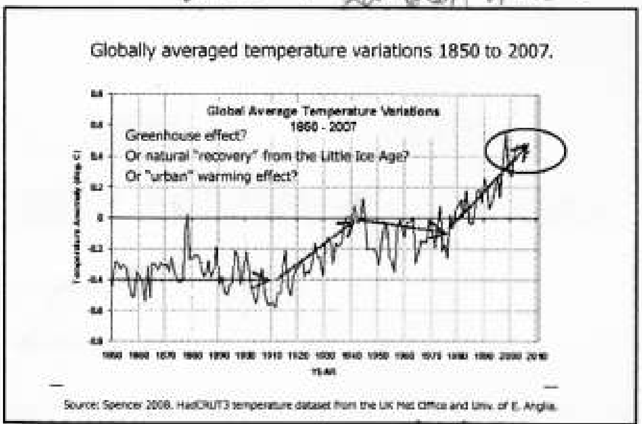
The surface instrumental record

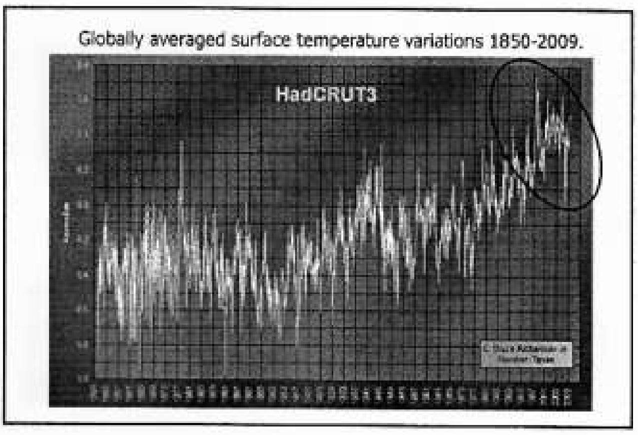
- Barometer
  - ✓Invented 17th C.
  - ✓Mid 18th C. before a useful network (Europe)
  - ✓Little coverage outside N. Atlantic until mid-19th C.
- Air Temperature
  - ✓A few records back to 18th C.
  - ✓200 years rare
- Precipitation
  - ✓Daily records in Florence (1654)
  - ✓200 years rare — and not global.

spotty until 20th C.

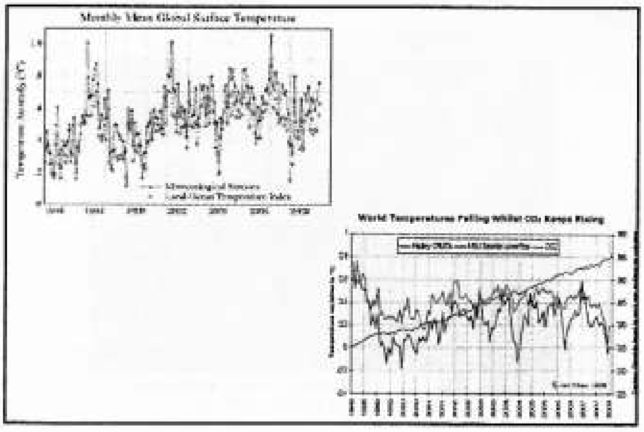
Using a surrogate to indicate what climate might have been like.

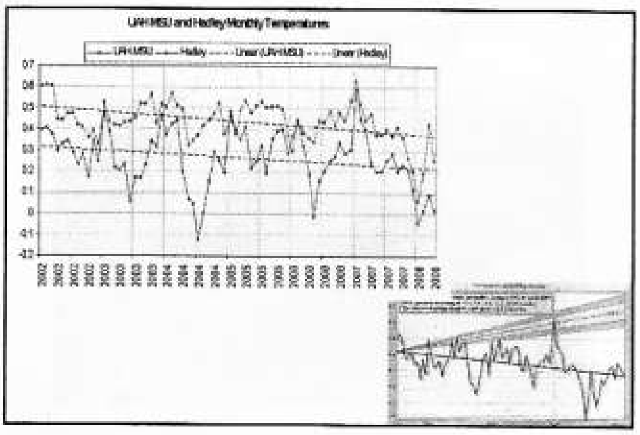
Very good quality

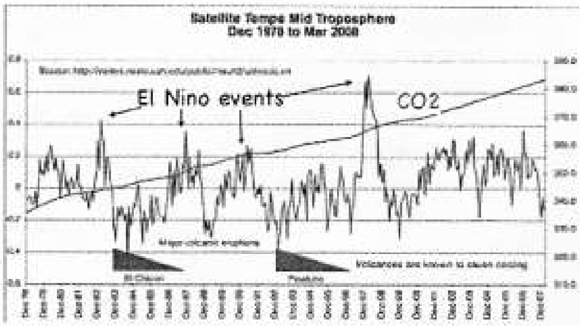




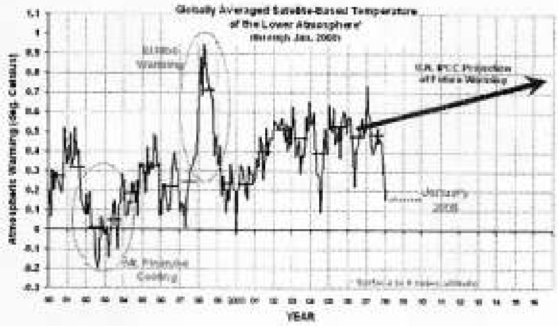
anomaly data deviation from the mean.







Global air temperature from satellites, 1990-2007. Note the conspicuous effect of the 1997/98 El Niño & Mt. Pinatubo eruption. Without these there is no 'global warming'.



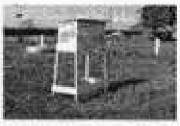
Source: Spencer 2008

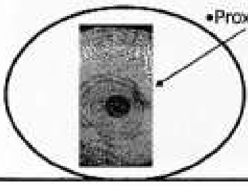
CO_2 has a lot of beneficial effects

dont believe propaganda

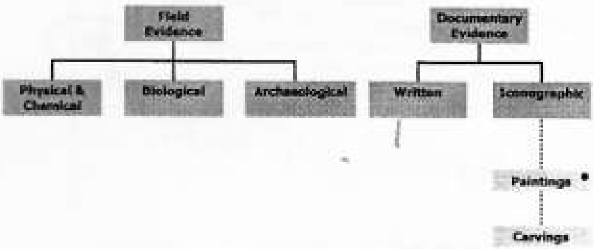
Sources of climate data:

- 'Surface' data
- Balloon data
- Satellite (MSU) data
- Proxy data





Indirect (Proxy) Sources



Iconographic Evidence

natural vegetation

types of crops

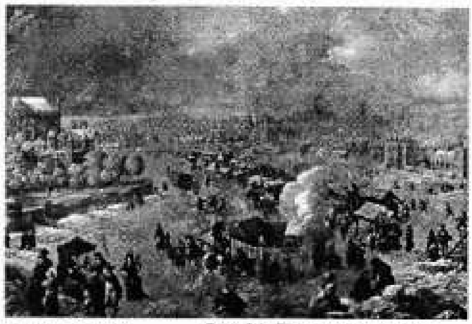
weather events

architecture

glacial positions

frost fairs

Iconographic Evidence



'Little Ice Age' Frost Fair, Thames River, London, Jan Griffier, c.1680

Iconographic Evidence

Argentière Glacier, French Alps

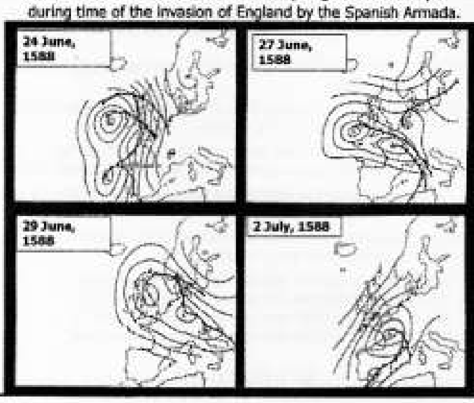
c. 1855

Today

Indirect (Proxy) Sources

- Field Evidence
  - Physical & Chemical
  - Biological
  - Archeological
- Documentary Evidence
  - Written
    - Vintages — grapes wine
    - Flowering — Plants buds etc
    - Logbooks — Ships
  - Iconographic

Written Evidence – assembled from ship' logs around Europe during time of the invasion of England by the Spanish Armada.

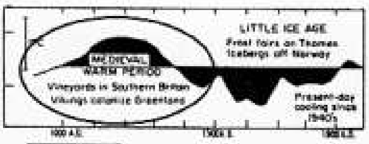


Indirect (Proxy) Sources

- Field Evidence
  - Physical & Chemical
  - Biological
  - Archeological
    - Old Sites
- Documentary Evidence
  - Written
  - Iconographic

Archaeological Evidence

people were there once.



Viking settlements, Greenland

http://www.archaeology.org/online/features/greenland/

Viking church, Greenland

Archaeological Evidence

Viking Great Hall, Greenland

http://www.archaeology.org/online/features/greenland/

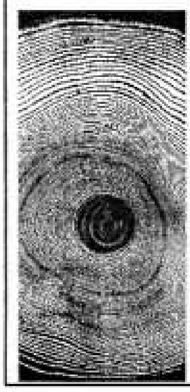
Sizable communities

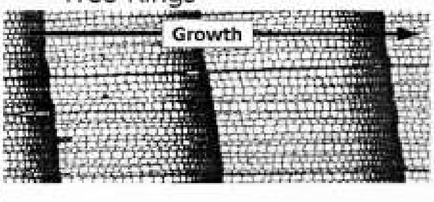
Indirect (Proxy) Sources

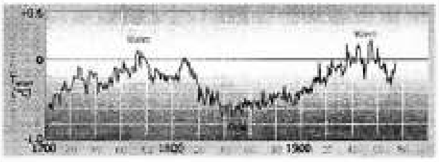
- Field Evidence
  - Physical & Chemical
  - Biological
    - Pollen
    - Tree-rings •
    - Coral •
  - Archeological
- Documentary Evidence
  - Written
  - Iconographic

assumes faster in warmer

Tree-Rings







PROBLEMS WITH TREE RINGS

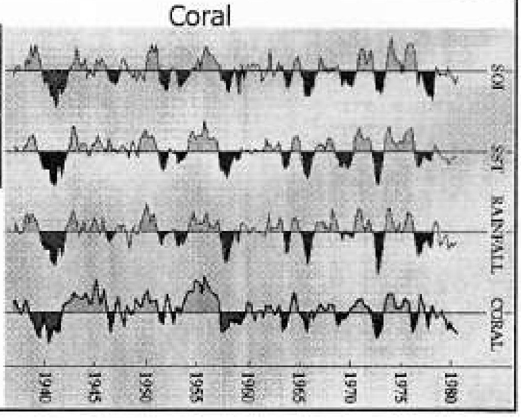
- Research shows that the long lived Kauri trees grow faster (thicker rings) in cooler years:
- Research shows that the long lived Kauri trees grow faster (thicker rings) in sunnier years (i.e. not wetter).
- Little growth happens in the colder months, so the tree ring analysis is generally only a proxy for 1/2 years - the growing season.
- A heavy snowpack could shorten the following growing season, just as an early winter could shorten the current growing season.
- A given tree could experience any mixture of the following, in any given year, or any given set of years.

1. Above average warmth and above average precipitation
2. Below average warmth and below average precipitation
3. Above average warmth and below average precipitation
4. Below average warmth and above average precipitation

So which is it?

gives different climatology

Coral



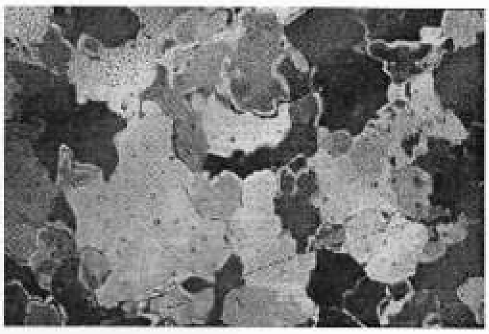
Indirect (Proxy) Sources

- Field Evidence
  - Physical & Chemical
    - Isotopes •
    - Varves •
  - Biological
  - Archeological
- Documentary Evidence
  - Written
  - Iconographic

Ice Core Sampling

Also Oxygen isotope data – ratio of ^{18}O and ^{16}O atoms related to temperature – ocean sediments, ice and snow.

Air Bubbles in Ice



So much going on in climate. blaming it on CO_2 stupid & naive.

more subtle.

Varves

Thin layers in still water - annual.

Different thickness and grain size.

Winter – slow glacial melt fine grain deposition of suspended material.

Summer – coarse grain from rapid melt.

Possible Causes of Climate Change

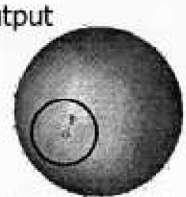
- Change in solar output: Change in solar radiation received
- Orbital characteristics: Change in the spatial receipt of radiation
- Change in planetary albedo: Change in radiation absorbed
- Change in ocean currents: Change in energy redistribution
- Change in atmosphere-surface radiation exchanges: Greenhouse effect – i.e. changes is greenhouse gas concentrations
- Others:
  Mountain building
  Continental drift

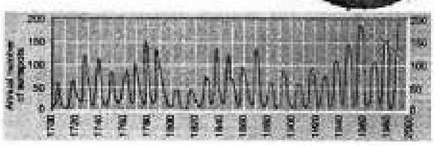
Dealt with earlier

Variation in Solar Output

E.G.

- Sun spots
  - 11 year cycle
  - Century-scale variation
  - ~1.5 W/m² variation





But also variability in: UV output, solar wind, solar magnetic field ...

Variation in Solar Output

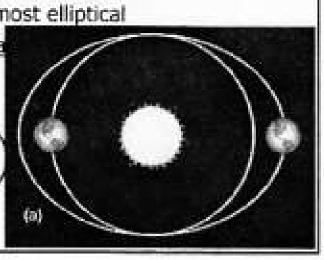
- Total Solar Irradiance (TSI) – sunspots (visible light)
  - Schwabe cycle: 0.1% variation over 11 years
  - Larger change over longer periods (>0.3%)
- UV intensity
  - 1-3% variation
  - Affects stratosphere
- Hale cycle (22 years) Sun's magnetic field reverses during each Schwabe cycle - magnetic poles return to same state after 2 reversals.
- Solar cycle length (weak magnetic cycles)
  - Shorter cycles = warming (Current Cycle 23 is longest since 1700s
- Geomagnetic intensity - Solar wind: electrons & protons from Sun shield Solar System from cosmic rays (energetic particles & radiation from outer space). Reduced solar wind linked to cloud formation via increased cosmic ray flux.

Sun/earth geometry

Effects of Orbital Cycles (1)

- Orbital eccentricity
  - Presently near circular
  - 3.5% radiation diff. between perihelion & aphelion
  - Up to 30% when orbit most elliptical
  - Implications for seasona

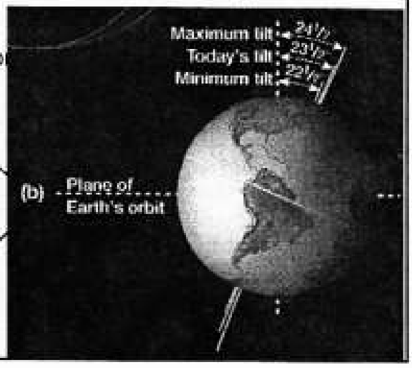
≈ 96,000 yr cycle



Effects of Orbital Cycles (2)

- Axial tilt
  - Implications fo

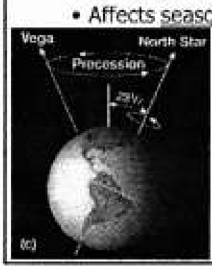
≈ 41,000 yr cycle



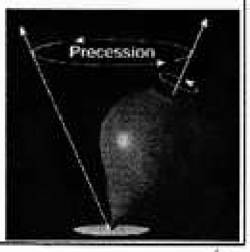
all changes occurring together

Effects of Orbital Cycles (3)

- Precession of the equinoxes
  - Due to axis "wobble"
  - Changes the timing of perihelion & aphelion
  - Affects seasonal contrast



≈ 21,000 yr cycle

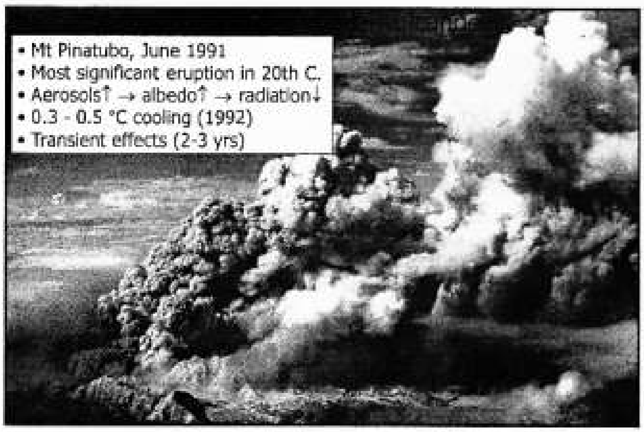


Effects of Orbital Cycles (4)

- Cycles act simultaneously
  But they are not synchronous
- Long and complex time series of climate forcing

big effect on climate for short period

(People attribute cause without a mechanism)



TEST upcoming
- True/False questions
- Multi-choice questions
- Short-answer questions

EG:

Trade winds are:

a) Surface level winds associated with the Hadley cell.

b) Surface level winds associated with the Ferrel cell.

c) Upper level winds associated with the Hadley cell.

d) Upper level winds descending to the "Horse Latitudes".

Past climate