Mountain Meteorology and Climatology

by

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Meteorology is the study of the earth's atmosphere and the atmospheric processes that produce weather and climate.

Weather is the state of the atmosphere during a short period of time (e.g., days or weeks), as measured by variables such as temperature, humidity, wind speed and direction, cloudiness, precipitation, and pressure.

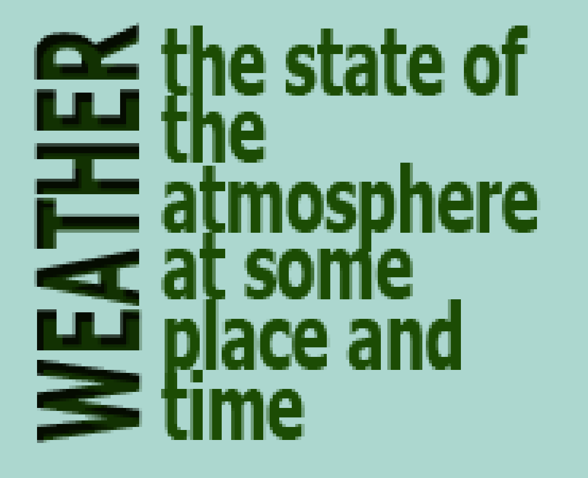
Climate is the average or generally prevailing weather of a given region over a long period of time (e.g., months, years, or centuries).

Mountain meteorology focuses on the weather and climate of mountainous regions.

ARE WEATHER AND CLIMATE THE SAME?

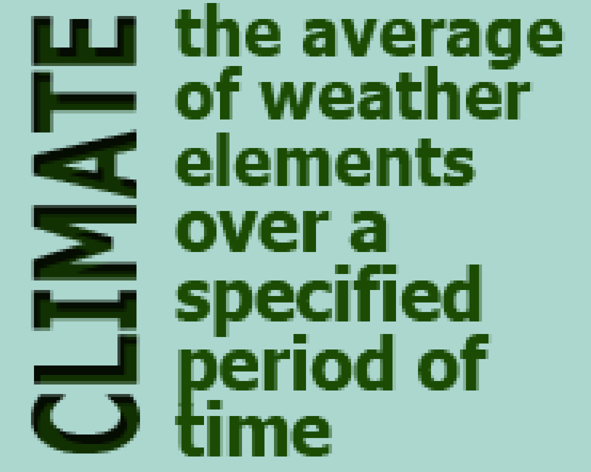
Weather is defined as the state of the atmosphere at some place and time, usually expressed in terms of temperature, air pressure, humidity, wind speed and direction, precipitation, and cloudiness. Meteorologists study weather.

Climate is defined in terms of the average (mean) of weather elements (such as temperature and precipitation) over a specified period of time (30 years according to the World Meteorological Organization).



WEATHER

the state of the atmosphere at some place and time



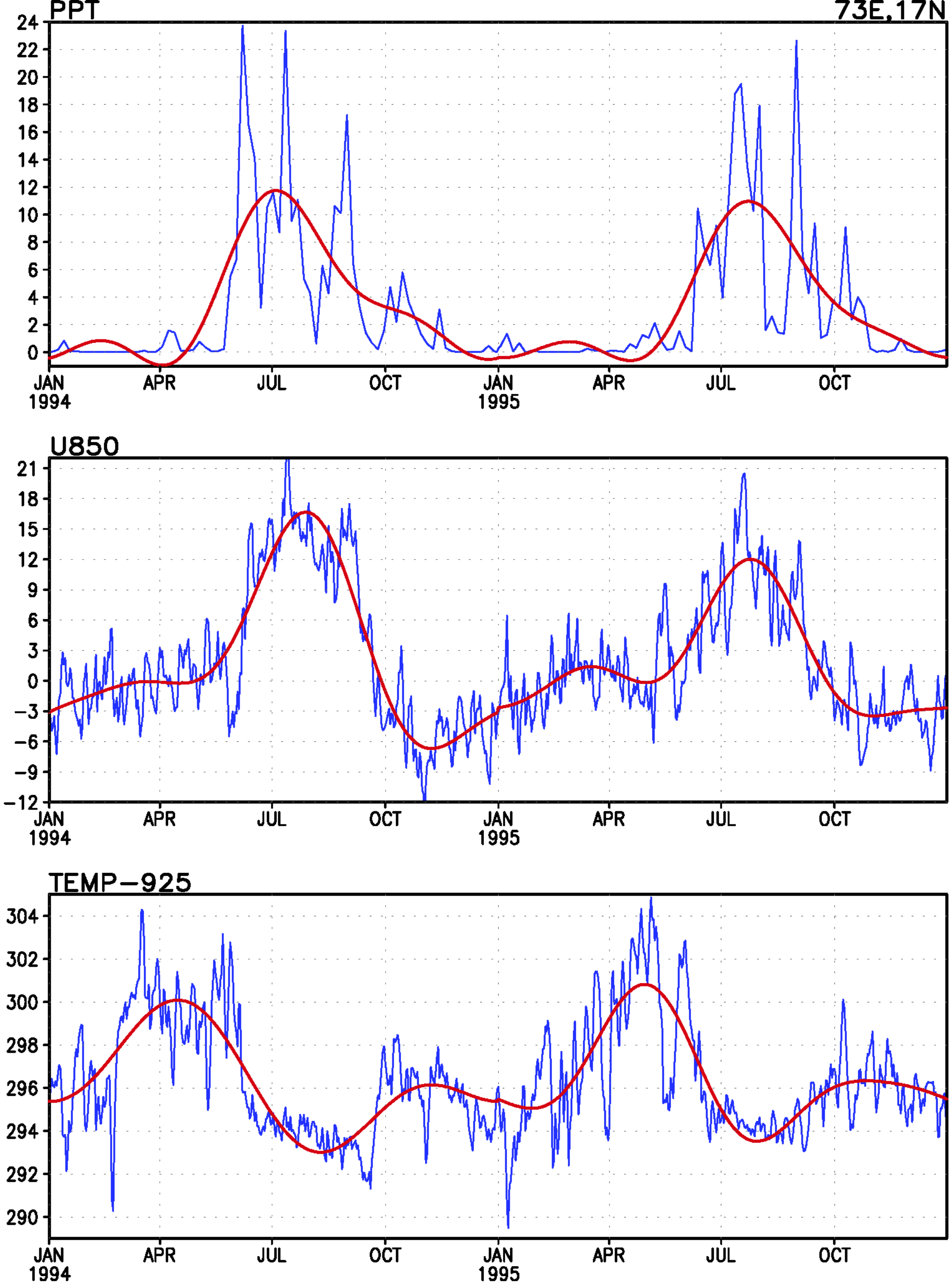
CLIMATE

the average of weather elements over a specified period of time

Weather and Climate

Weather (fluctuating component, what we *see*)

Climate (the mean condition, what we *expect*)



Daily time series of precipitation (PPT), eastward component of wind at 850 hPa level (U850) and temperature near the surface at 925 hPa at a tropical station around Bombay. The red line is the annual cycle or expected values.

CLIMATE

- The two most important aspects of climate are **temperature** and **precipitation**.
  - These two factors determine what type of species (biome) will be found in a given location.
- The climate in an area is determined by
  1. Latitude
  2. Direction from which winds arrive
  3. Proximity to large bodies of water and mountains

Introduction

- Significant orographic features occupy close to 25% of continental surfaces.
- About 26% of the world's population resides within mountains or in the foothills of the mountains.
- Mountain-based resources indirectly provide sustenance for over half of the world's population.
- 40% of global population lives in the watersheds of rivers originating in various mountains of the world.
- Although mountain differ considerably from one region to another, one common characteristic is the complexity of their topography.
- Orographic features include some of the sharpest gradients found in continental areas which include rapid and systematic changes in climatic parameters, such as temperature and precipitation, over very short distances.

Mountain climates are governed by five major factors, namely

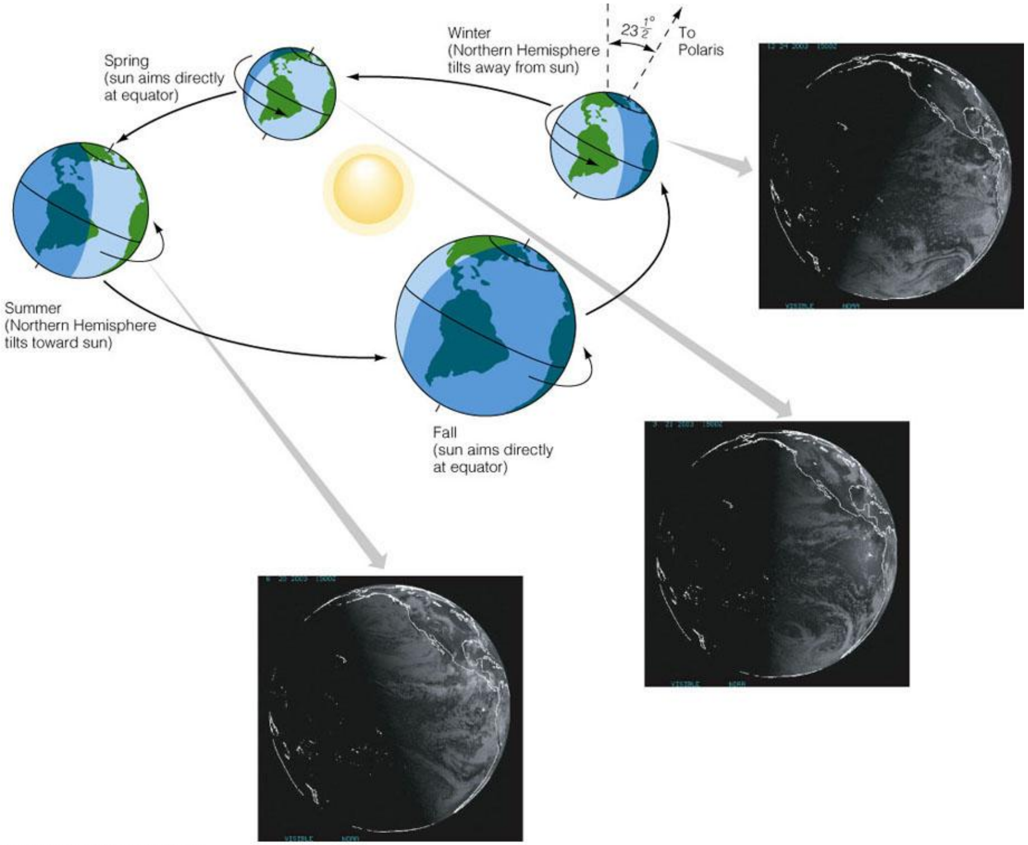
1. **Continentality** (the distance from the sea)
2. **Latitude** (the angular distance north or south from the equator)
3. **Altitude** (the height above sea level)
4. **Topography** (terrain projections)
5. **Exposure to regional circulations** (winds and ocean currents)

Circulation of the Atmosphere

Solar Radiation - initial source of energy to the Earth. It can be absorbed, reflected and reradiated. The redistribution of this energy controls the structure and dynamics of the Atmosphere and Oceans.

The Seasons: solar heating varies with seasons

- Earth revolves around the Sun (365 days)
- Earth rotates about its own axis (1 day)
- angle (‘tilt’) that axis of rotation makes with plane that contains trajectory around the Sun is 23½° and it remains that way (same orientation) as the Earth revolves around Sun



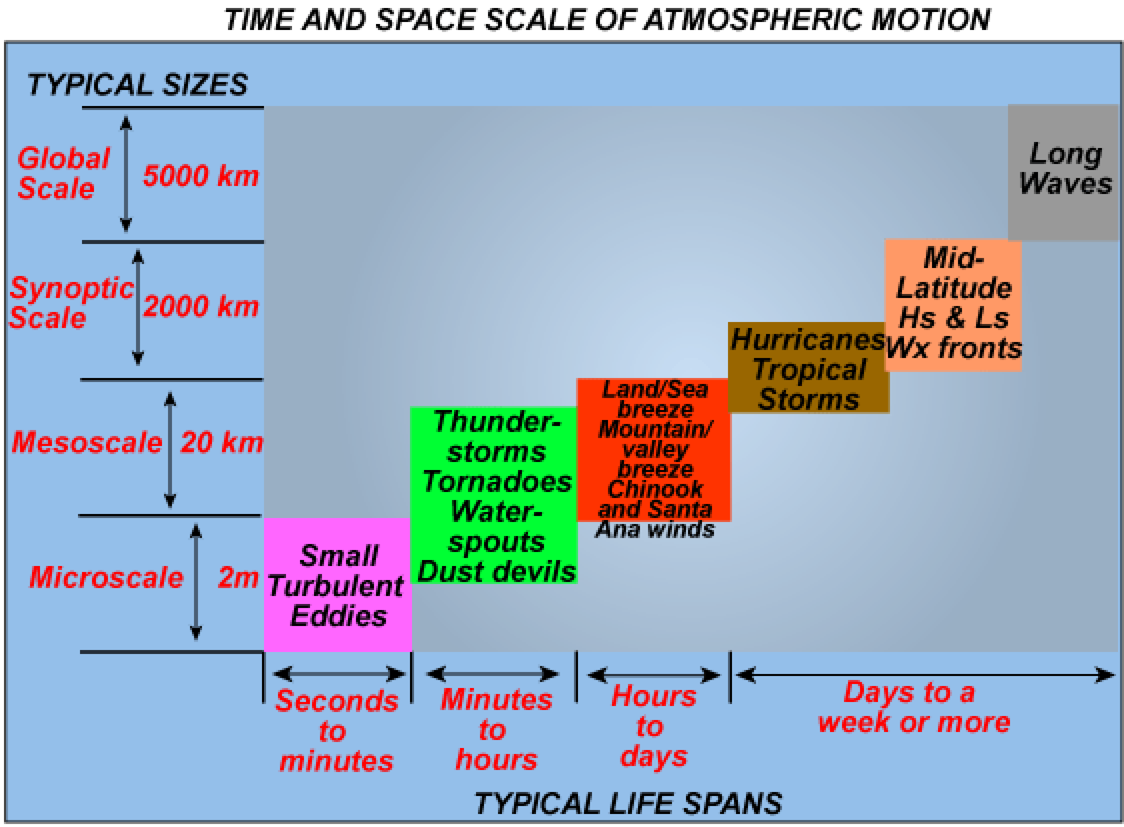
During the Northern Hemisphere winter, the Southern Hemisphere is tilted toward the sun and the Northern Hemisphere receives less light and heat. During the Northern Hemisphere summer, the situation is reversed.

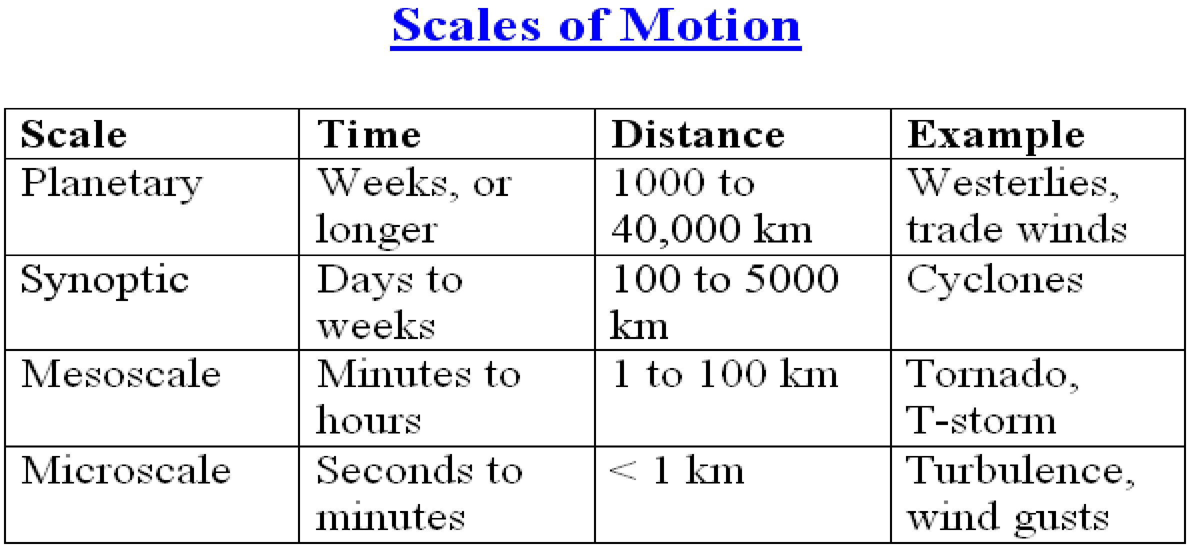
Scales of Atmospheric Motion

Atmospheric motions/phenomena occur on many diverse spatial and temporal scales

yet microscale motions affect our lives daily - most microscale phenomena form in the *boundary layer* which is where we live!

can't forecast microscale motions - spatial scale is to small for current models - motions are chaotic, unpredictable

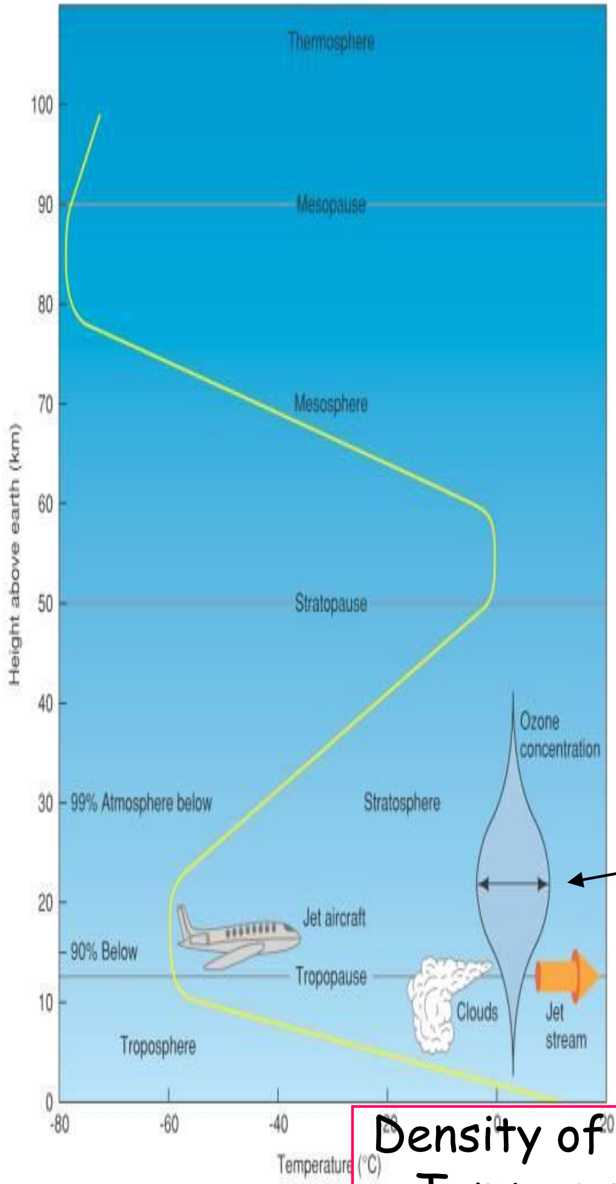




Scales of Motion

Scale	Time	Distance	Example
Planetary	Weeks, or longer	1000 to 40,000 km	Westerlies, trade winds
Synoptic	Days to weeks	100 to 5000 km	Cyclones
Mesoscale	Minutes to hours	1 to 100 km	Tornado, T-storm
Microscale	Seconds to minutes	< 1 km	Turbulence, wind gusts

The Atmosphere



O_3 absorbs UV Solar Radiation, heats Atm.

Vertical (thermal) structure of the atmosphere

- Troposphere: lowest layer 0-12 km, temperature decreases with altitude
- Tropopause: minimum temperature zone between the troposphere and stratosphere
- Stratosphere: layer above tropopause 12-50 km, temperature increases with altitude
- Mesosphere: layer above stratosphere 50-90 km, temperature decreases with height
- Thermosphere: layer above mesosphere >90 km, extends out to space

Density of air depends on temperature, water vapor and altitude

- Temperature decrease = density increase
- Water vapor increase = density decrease
- Altitude increase = density decrease

Gases: permanent and variable

- Permanent = present in constant relative % of total volume

- Variable = concentration changes with time and location

- Suspended microscopic particles

- Water droplets

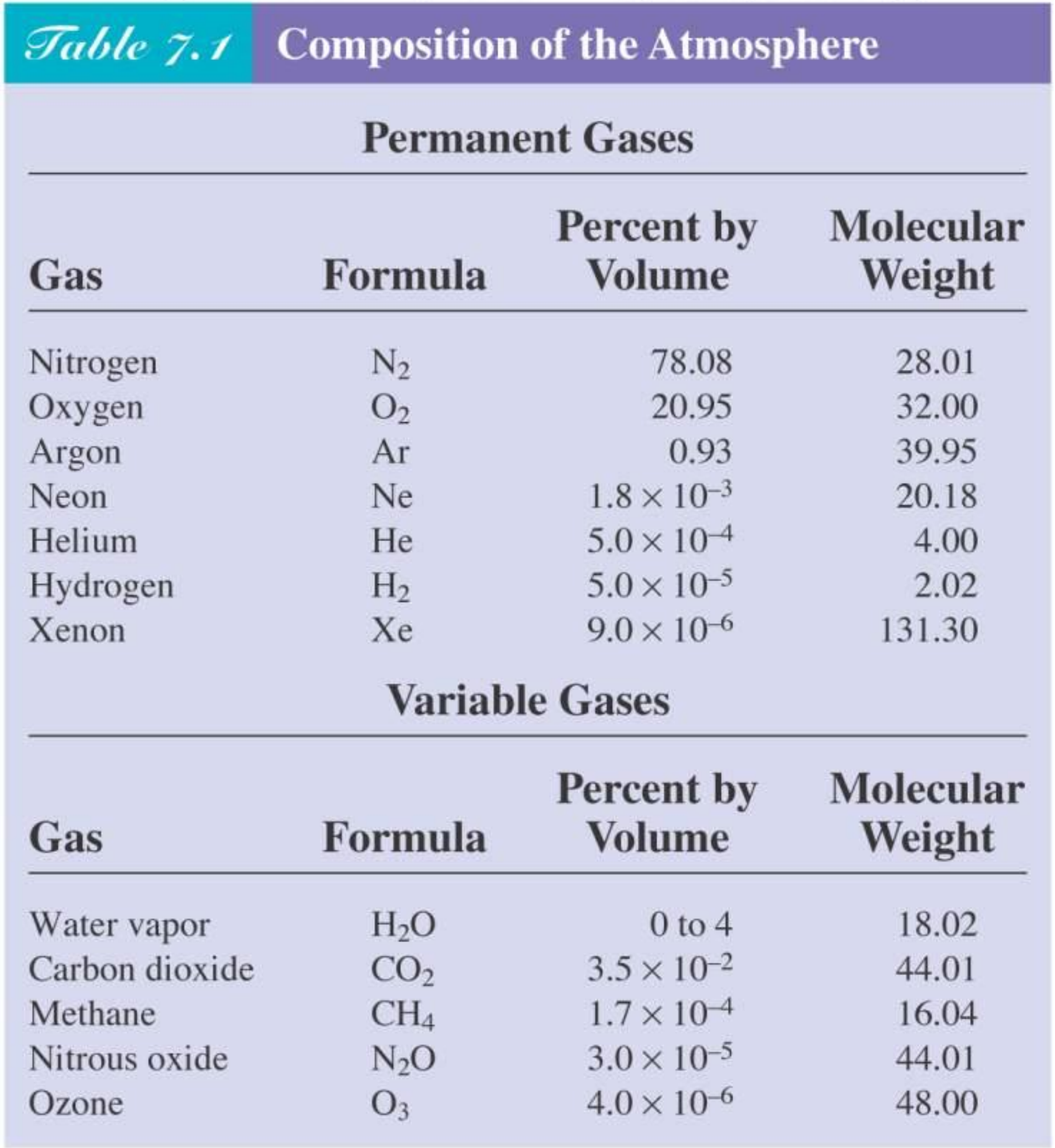


Table 7.1 **Composition of the Atmosphere**

Permanent Gases

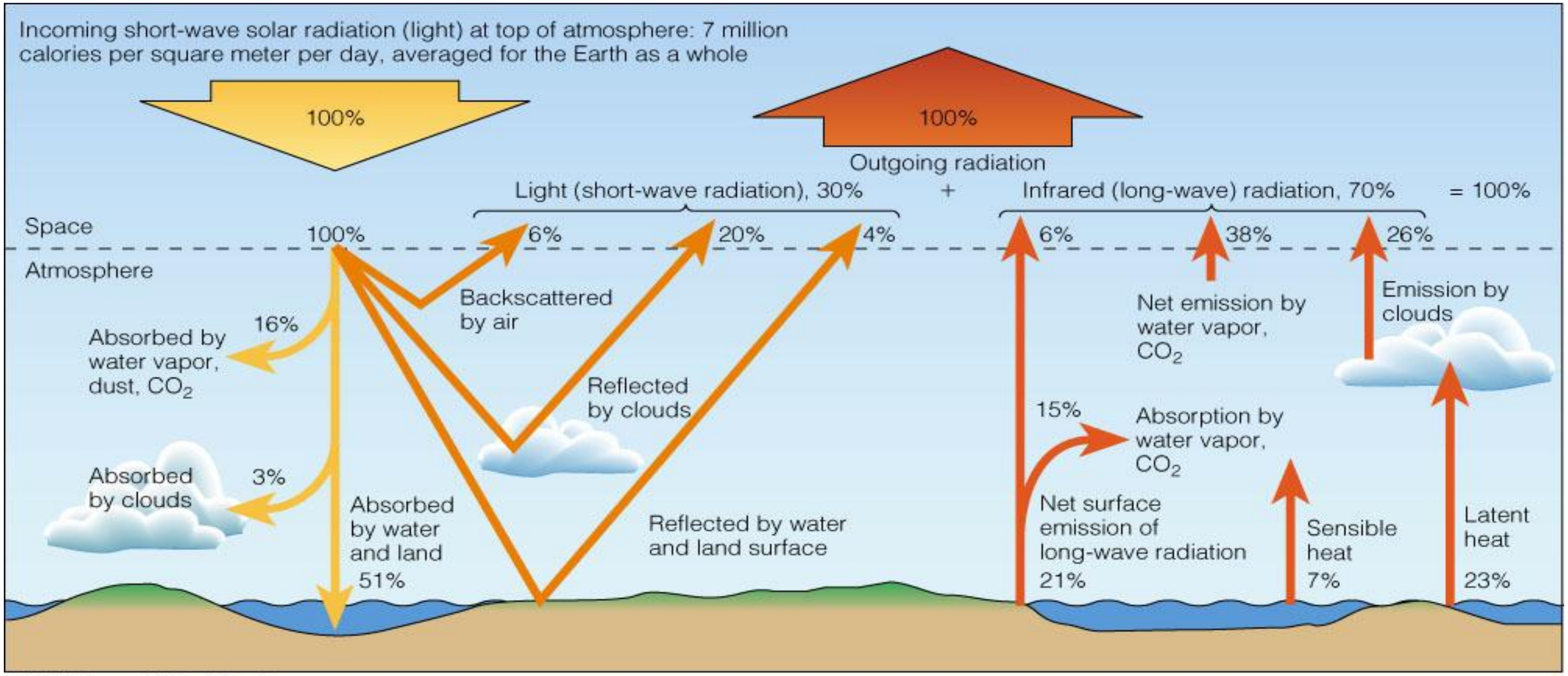
Gas	Formula	Percent by Volume	Molecular Weight
Nitrogen	N_2	78.08	28.01
Oxygen	O_2	20.95	32.00
Argon	Ar	0.93	39.95
Neon	Ne	1.8×10^{-3}	20.18
Helium	He	5.0×10^{-4}	4.00
Hydrogen	H_2	5.0×10^{-5}	2.02
Xenon	Xe	9.0×10^{-6}	131.30

Variable Gases

Gas	Formula	Percent by Volume	Molecular Weight
Water vapor	H_2O	0 to 4	18.02
Carbon dioxide	CO_2	3.5×10^{-2}	44.01
Methane	CH_4	1.7×10^{-4}	16.04
Nitrous oxide	N_2O	3.0×10^{-5}	44.01
Ozone	O_3	4.0×10^{-6}	48.00

Greenhouse Gases

The Atmosphere Moves in Response to Uneven Solar Heating and Earth's Rotation



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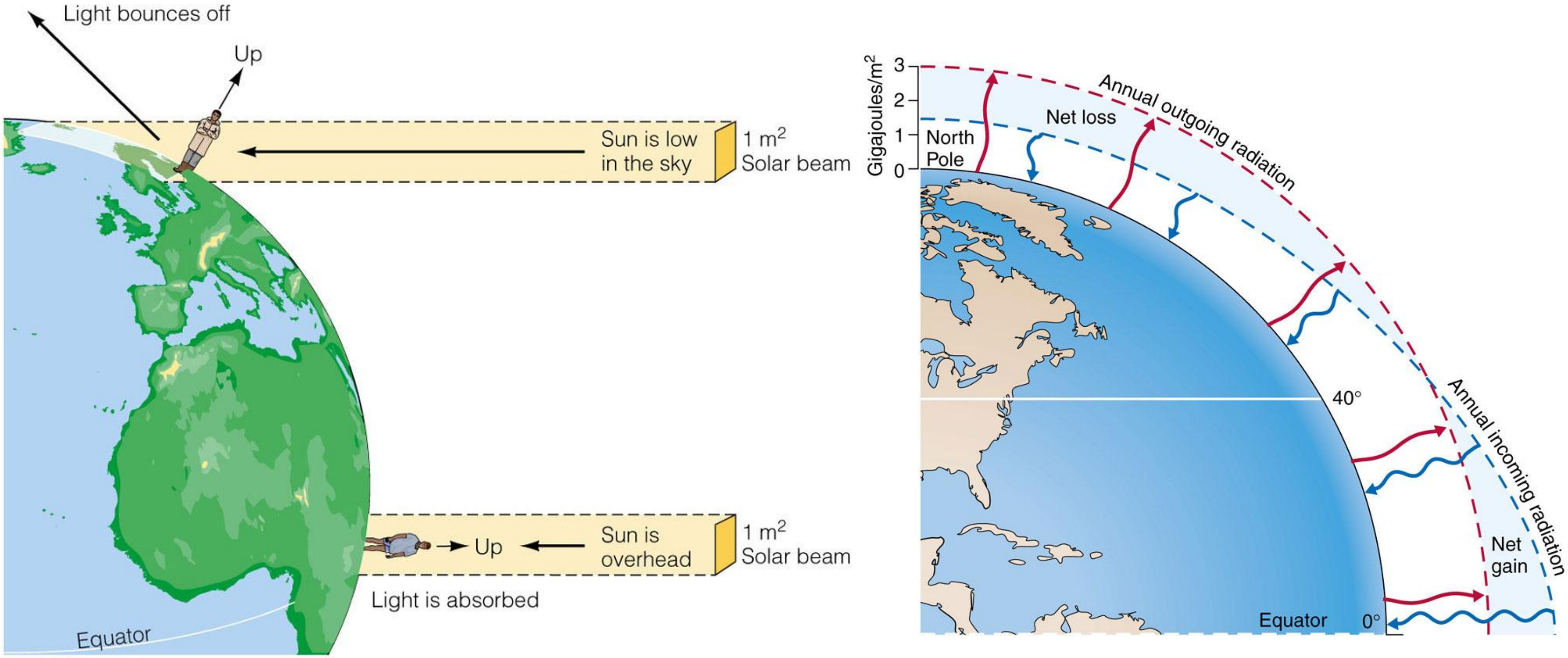
An estimate of the heat budget for Earth. On an average day, about half of the solar energy arriving at the upper atmosphere is absorbed at Earth's surface. Light (short-wave) energy absorbed at the surface is converted into heat. Heat leaves Earth as infrared (long-wave) radiation. Since input equals output over long periods of time, the heat budget is balanced.

The Solar Heating of Earth Varies with Latitude

The atmosphere reflects, scatters and absorbs solar radiation. At high latitudes solar radiation travels a longer path through atmosphere.



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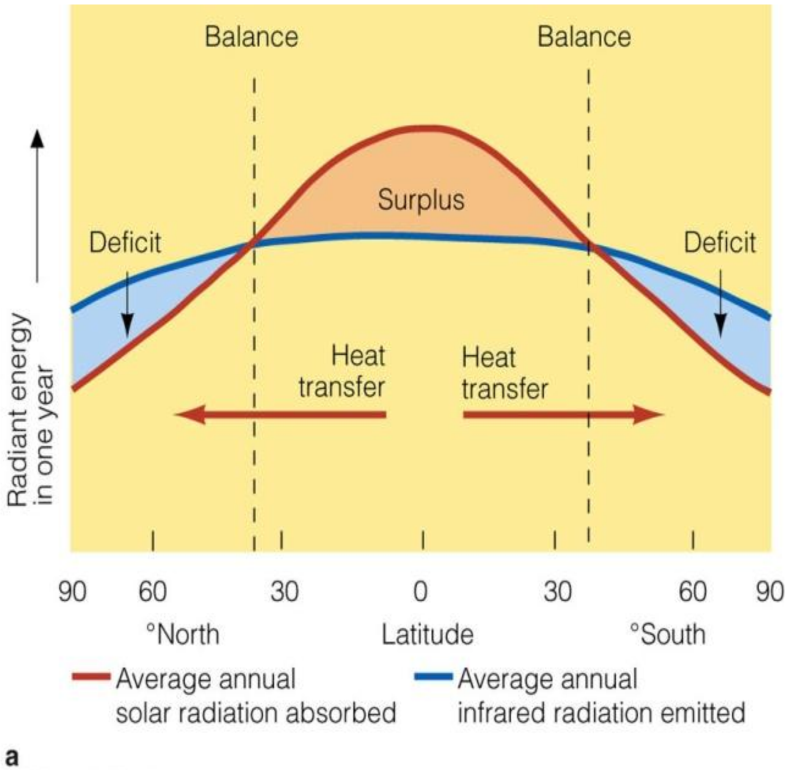
How solar energy input varies with latitude.

Equal amounts of sunlight are spread over a greater surface area near the poles than in the tropics.

Ice near the poles reflects much of the energy that reaches the surface there.

The Solar Heating of Earth Varies with Latitude



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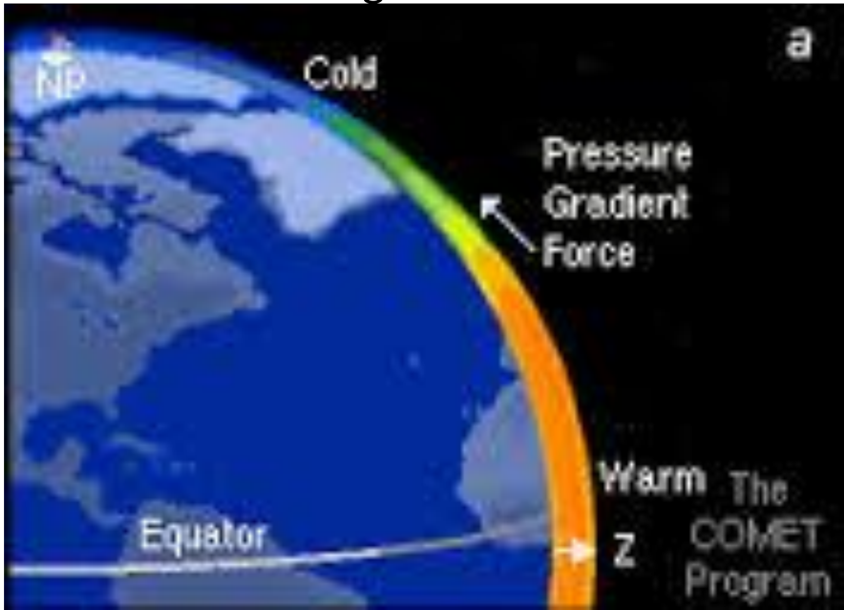
Earth as a whole is in thermal equilibrium, but different latitudes are not.

The average annual incoming solar radiation (red line) absorbed by Earth and the average annual infrared radiation (blue line) emitted by Earth. Polar latitudes lose more heat to space than they gain, and tropical latitudes gain more heat than they lose. The amount of radiation received equal the amount lost at about 38°N and S. The area of heat gained (orange area) equals the area of heat lost (blue areas) so Earth’s total heat budget is balanced.

What factors govern the global circulation of air?

- Uneven solar heating
- The Coriolis effect



The COMET Program

Role of the Atmosphere

- Decreases Long Wave (LW) radiation loss to space
- Depends on clouds, Water vapor, and CO_2 distributions

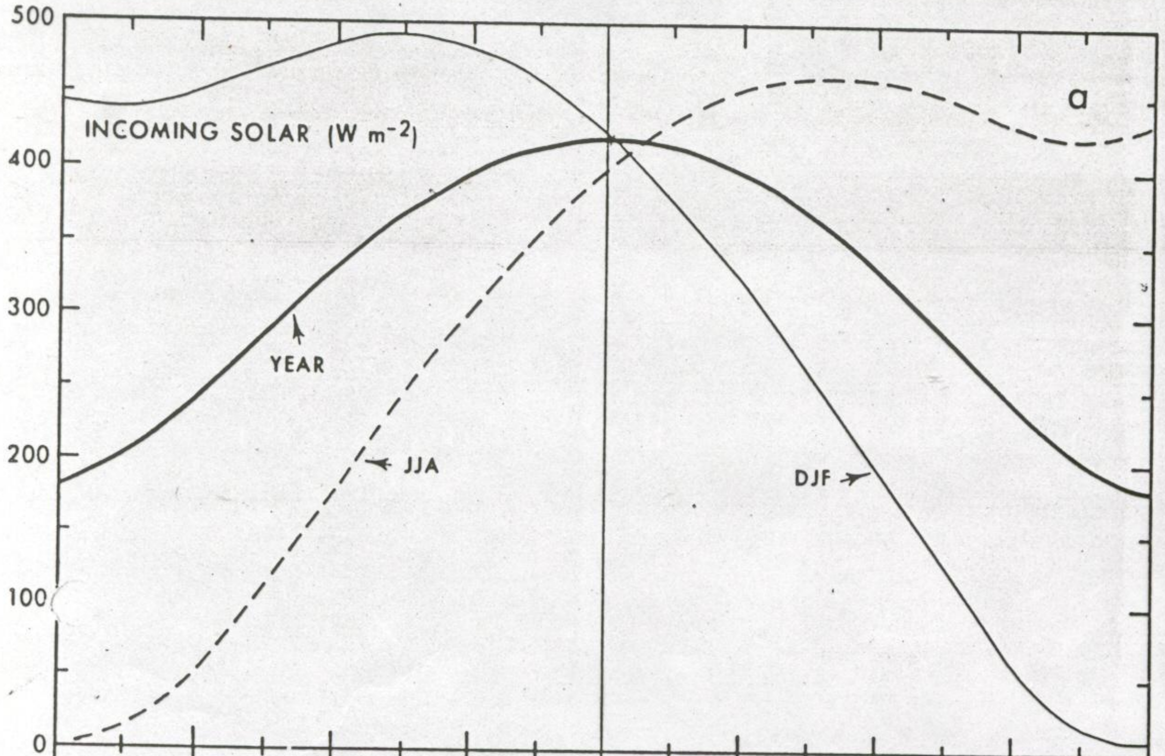
However, if the earth had one uniform temperature, there would be no pressure gradient and no motion (winds)!

So, the energy balance model, just described is only a zero-order model of the earth's climate!

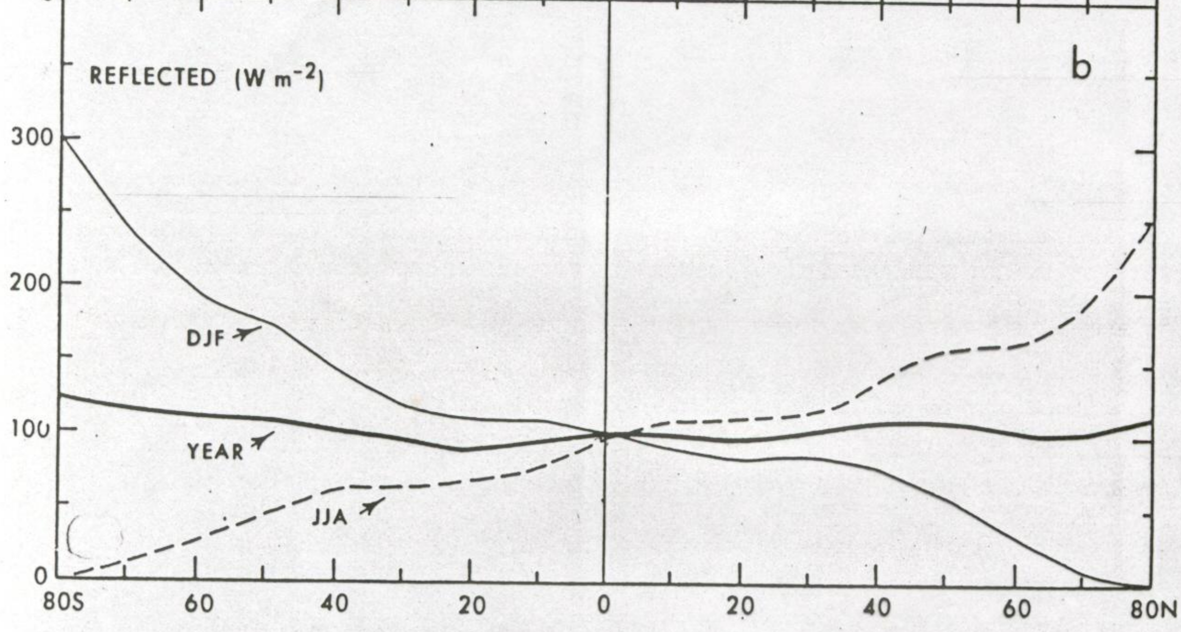
In reality, due to the sphericity of the earth and its inclination of its axis in the ecliptic plane, radiation received varies with latitude.

Next, the latitudinal variation of radiation balance is described.

Zonal mean incoming solar radiation ($W\ m^{-2}$) at the top of the atmosphere, annual mean (thick solid), JJA (dashed line) and DJF (thin solid) as a function of latitude.



Zonal mean reflected solar radiation ($W\ m^{-2}$) at the top of the atmosphere, annual mean (thick solid), JJA (dashed line) and DJF (thin solid) as a function of latitude.

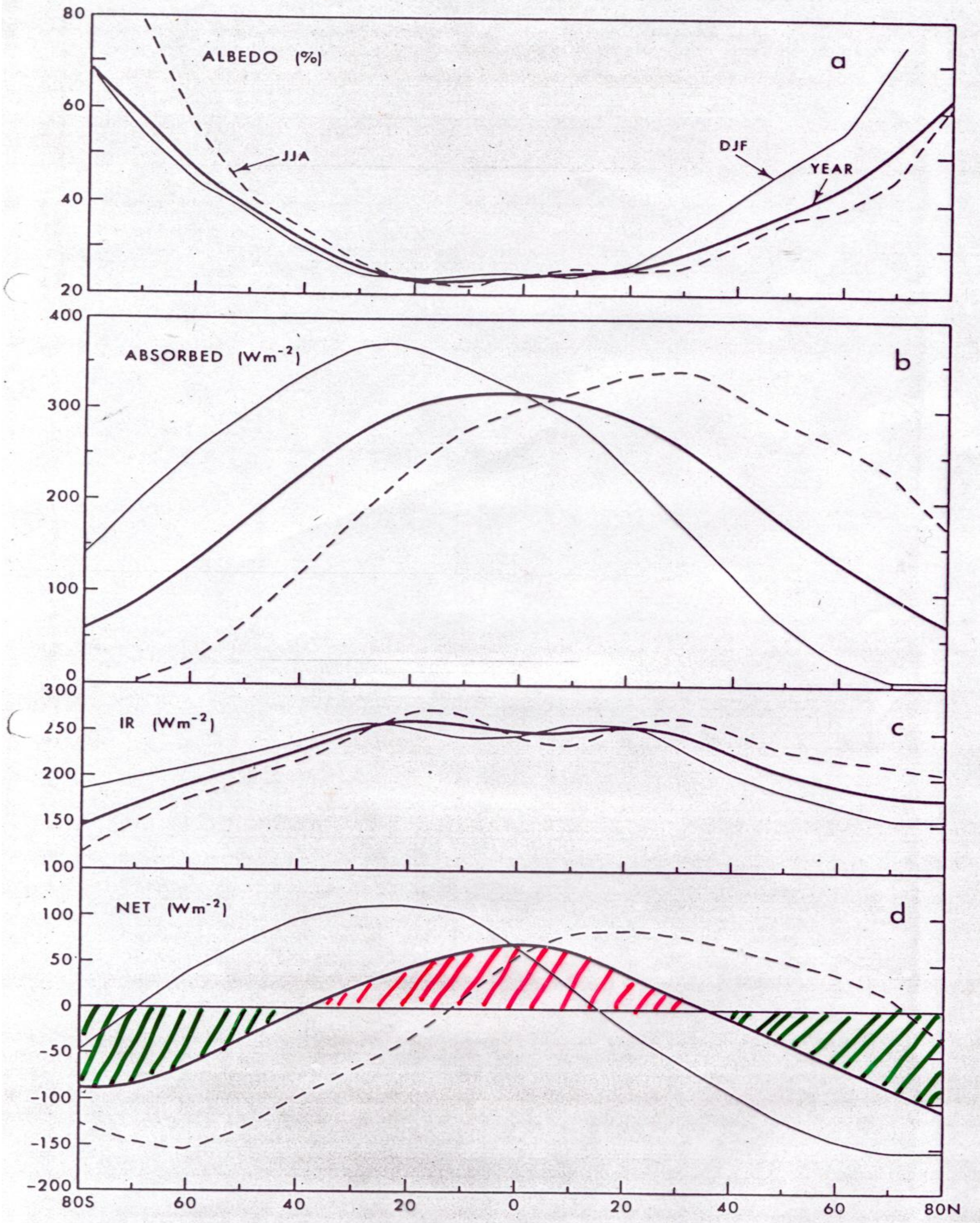


Zonal mean **Albedo** (%) at the top of the atmosphere, annual mean (thick solid), JJA (dashed line) and DJF (thin solid) as a function of latitude.

Zonal mean **absorbed radiation** (W m^{-2}), annual mean (thick solid), JJA (dashed line) and DJF (thin solid) as a function of latitude.

Zonal mean **emitted radiation** (W m^{-2}), annual mean (thick solid), JJA (dashed line) and DJF (thin solid) as a function of latitude.

Zonal mean **net radiation** (W m^{-2}) at the top of the atmosphere, annual mean (thick solid), JJA (dashed line) and DJF (thin solid) as a function of latitude.



Breakdown of Energy Transports

Sensible-heat (T) transport is representative of the total energy transport.

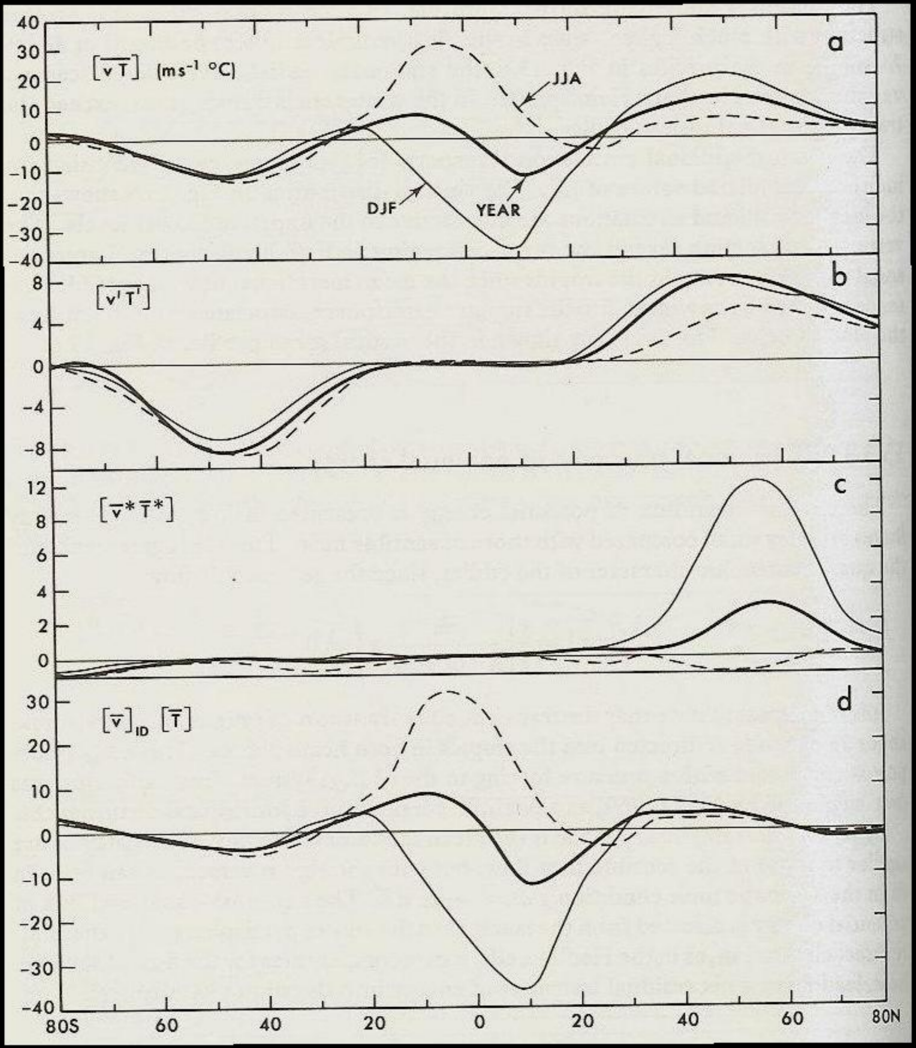
Zonally symmetric motions do most of the transport in the tropics.

Waves do most of the transport in midlatitudes.

Stationary waves are important in NH winter;

At other times, and in the SH, transient waves dominate.

Meridional Flux of Sensible Heat



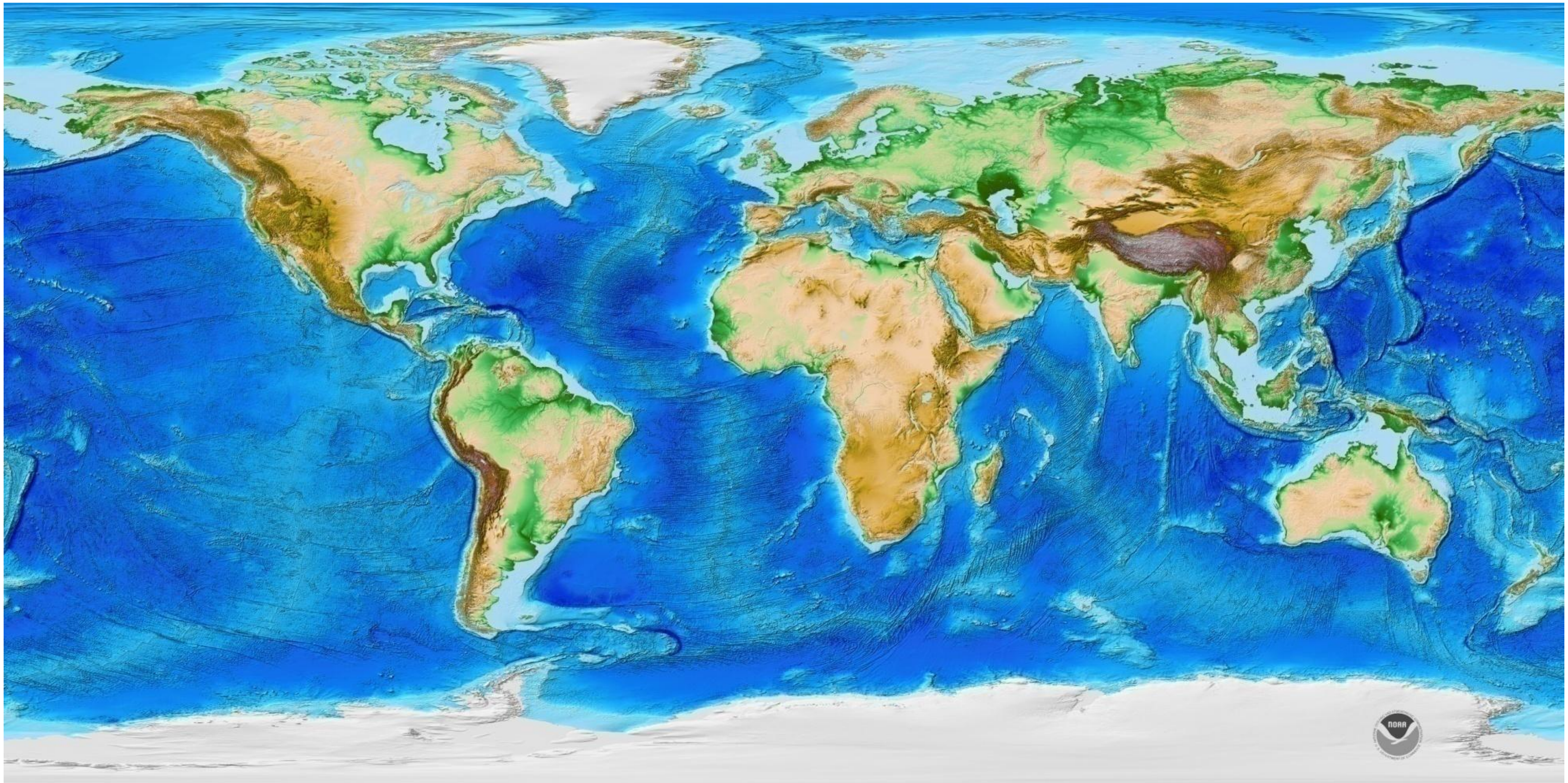
Transient eddy transport

Stationary eddy transport

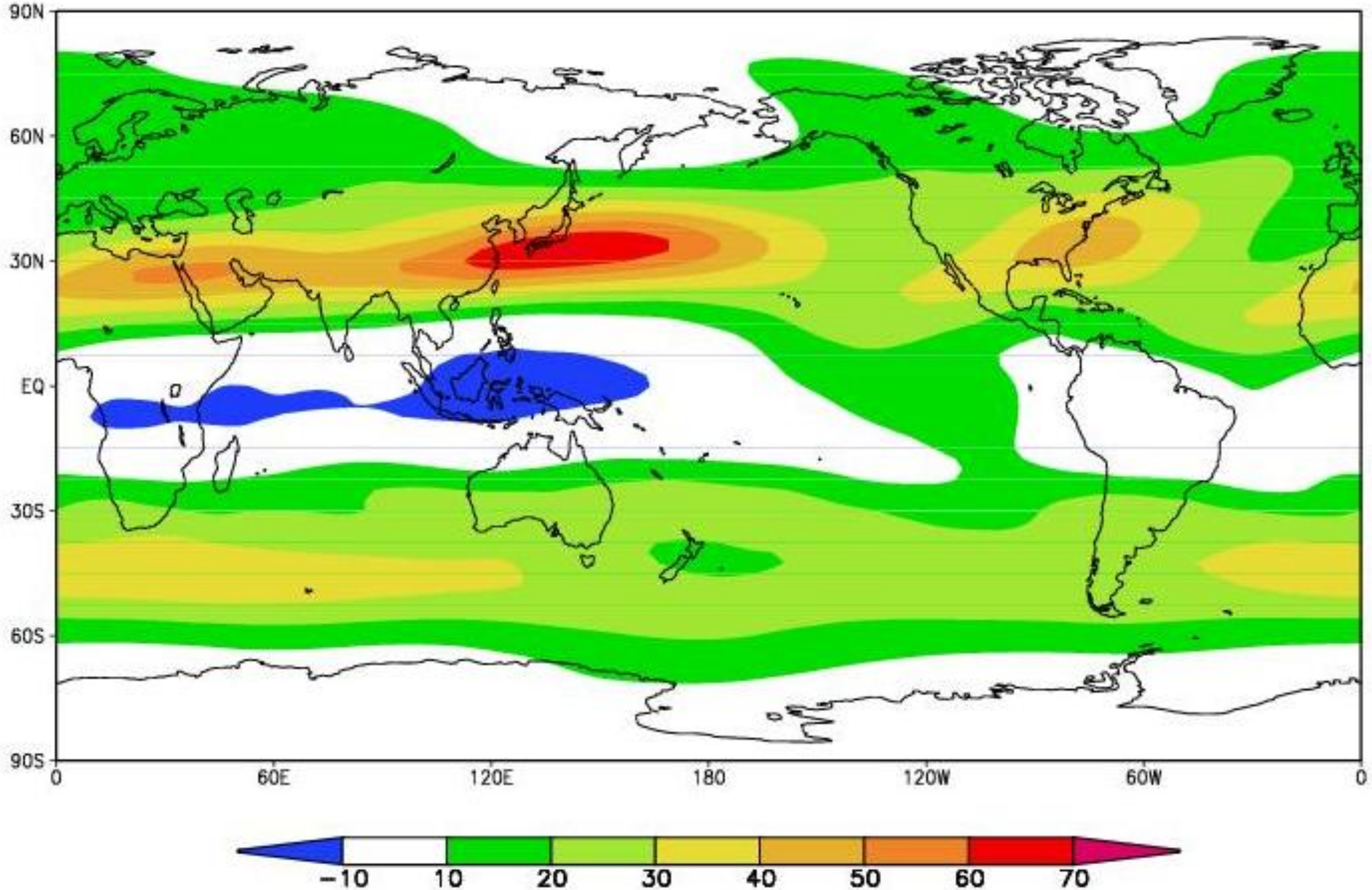
MMC transport

Peixoto and Oort 1992

Orography



200 hPa Zonal Wind



How are the Atmospheric motions generated?

Positive net heating in Tropics & negative net heating in polar regions

→Warmer tropics & Colder polar regions

→Lower Pressure in the tropics and higher pressure in the polar regions

→Air moves under the action of the pressure gradient force and motion is generated.

→As the earth is rotating, Coriolis force modifies this motion and observed circulation is generated.

- Thus, estimation of the mean meridional circulation (e.g.zonal mean vertical velocity) indicates the existence of three meridional cells in each hemisphere.

- Three meridional cells in each hemisphere are also required to explain the surface easterlies in the equatorial region and surface westerlies in middle latitude.

- The middle cell where ascending motion takes place around 60 deg where the surface is relatively cooler and descending motion takes place around 30 deg where the surface is relatively warmer is a thermally ‘indirect’ cell, also called Ferrel cell.

- What is responsible for the ‘indirect’ Ferrel cell? What makes air to rise over a surface which is colder than over its descending region?

So, What is responsible for the ‘indirect meridional cell?

I mentioned that large amplitude Rossby waves are important part of middle latitude circulation. Could these waves play a role is causing the ‘indirect’ meridional cell?

What are the amplitudes of these waves? Plot standard deviation.

Can they transport heat and momentum? We shall calculate transport of heat ([v’t’]) and [v’u’].

Our atmosphere exhibits dynamic variability associated with midlatitude baroclinic waves, or eddies.

Eddies may be either TRANSIENT (not fixed to a specific geographic location) or STATIONARY (fixed geographically; caused by mountain ranges, continent-ocean contrasts, etc.)

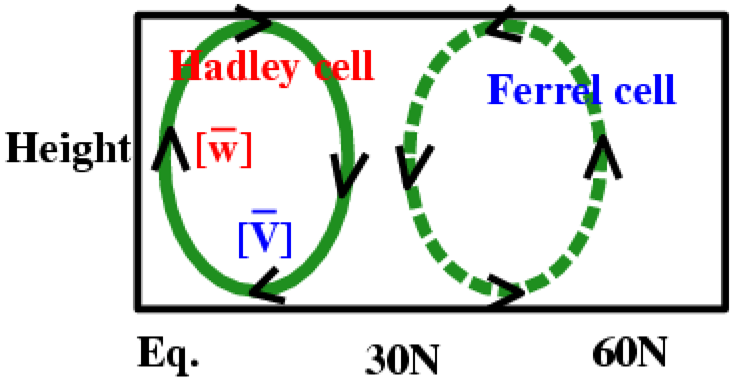
Eddies play a very important role in governing the strength of the general circulation.

Atmospheric eddies are the primary mechanism by which low latitude HEAT is transported poleward ($v'T'>0$). This occurs in the growth phase of baroclinic waves.

They are also the primary mechanism by which the zonal mean (and, by angular momentum conservation, the meridional mean)
flow is forced ($u'v'>0$). This occurs in the Rossby wave decay phase of the baroclinic wave, in which easterly momentum is transported equatorward.

More Eddy Activity→Stronger Circulation

Mean Meridional Circulation



$[\overline{v}]$ **: Driven by divergence of eddy momentum flux (stationary eddies and transient eddies), surface drag, and absolute vorticity of the mean zonal flow**

$[\overline{w}]$ **: Driven by divergence of eddy heat flux and diabatic heating rates**

Ferrel cell: driven by midlatitude eddies

Hadley cell: driven by eddies and diabatic heating in the tropics. Direct and indirect eddy forcing acounts for 75% of the cell's strength (Kim and Lee, 2001)

Equatorial easterlies are primarily the result of near surface pressure gradients, which in turn are influenced by the strength of subtropical subsidence

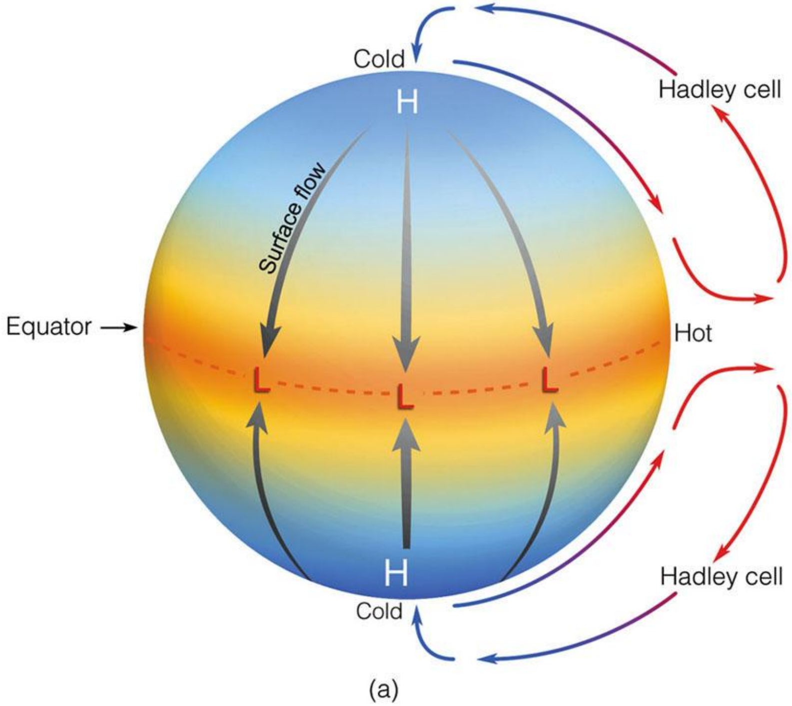
Increased midlatitude eddies drive stronger subtropical subsidence, a stronger Hadley cell and, through angular momentum conservation, stronger equatorial easterlies.

Eddy activity depends on the meridional temperature gradients of the climatological background state.

Stronger temperature gradients increase the rate of eddy formation (can be shown from linear theory).

Single-Cell Model

- Assumptions:
  - Earth's surface uniformly covered with water
  - Sun is always directly over equator
  - The earth does not rotate
- A huge thermally direct cell develops in each hemisphere
  - Warm air rises and cold air sinks



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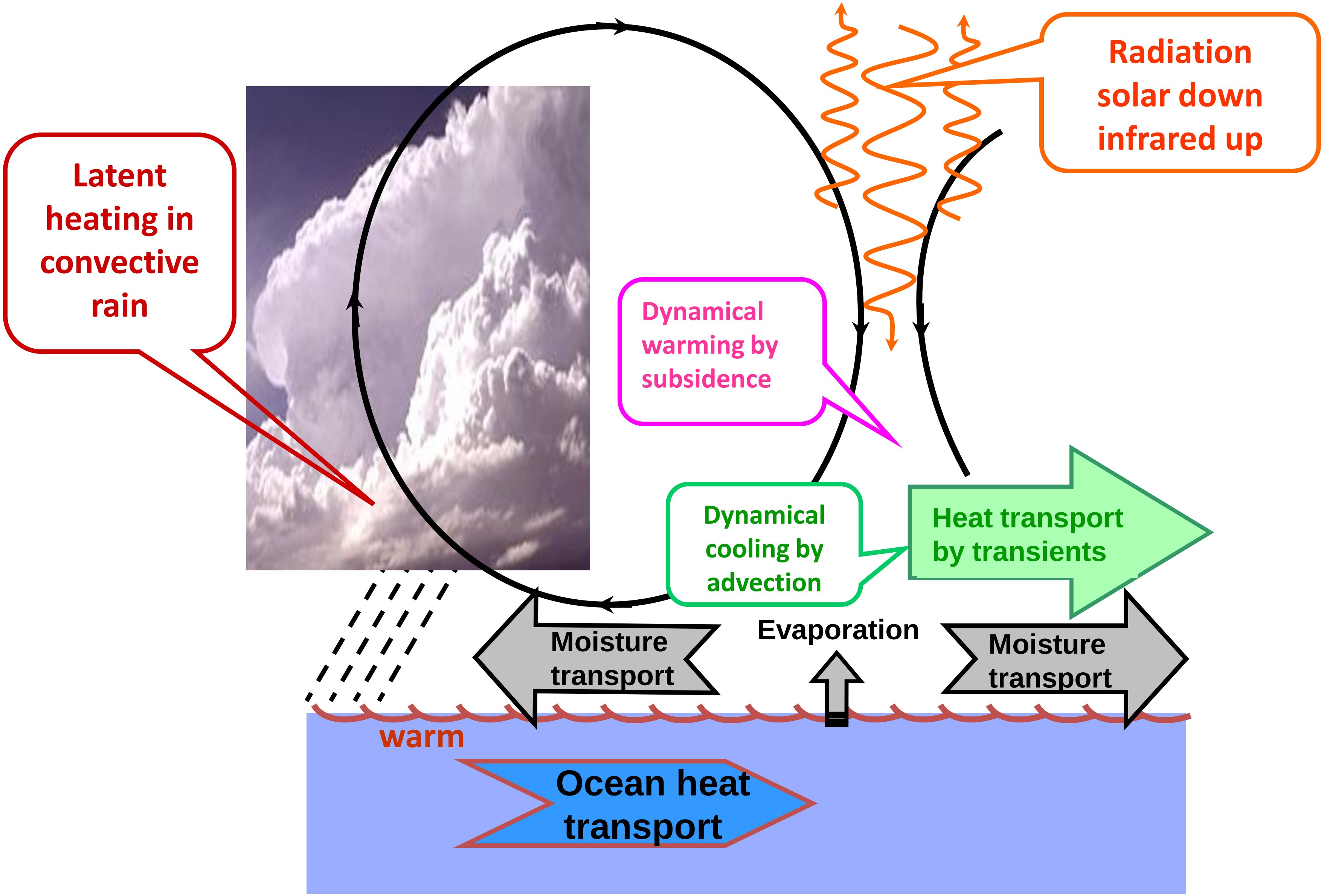
Hadley circulation and heat budget in subtropics



Trenberth and Stepaniak 2003

Why is there a Hadley circulation?

Fundamentally it is the most efficient way to transport heat (energy) polewards in the Tropics.

It is primarily driven by latent heating in upward branch. But the moisture is evaporated in subtropics and is transported by the circulation into upward branch, so this is not fundamental but is rather a secondary result.

Often also thought to be driven by radiative cooling to space in subtropics. This is partly a MYTH!

Instead there has to be a link with extratropical poleward energy transport by baroclinic eddies and quasi-stationary waves.

- **Theories successfully account for several features of Hadley circulation:**
  Width of circulation, position of subtropical jet which are controlled by geostrophy and conservation of heat and momentum

The Hadley circulation is driven mostly from the subtropics through cooling by transient baroclinic waves in storm tracks at mid-lats.

This is reason Hadley circulation reverses with annual cycle.

The cooling drives the downward branch of the Hadley circulation, clears the skies to allow OLR to contribute, and allows solar radiation through to surface where it provides moisture through evaporation.

Tropical SSTs determine where the upward motion is favored, and the upward motion is driven by latent heating. But the moisture comes mostly from the subtropics, transported by the Hadley circulation itself.

The subtropical OLR and the tropical latent heating are secondary consequences of the more fundamental drivers.

Three-Cell Model

Add in rotation…

Three cells in each hemisphere

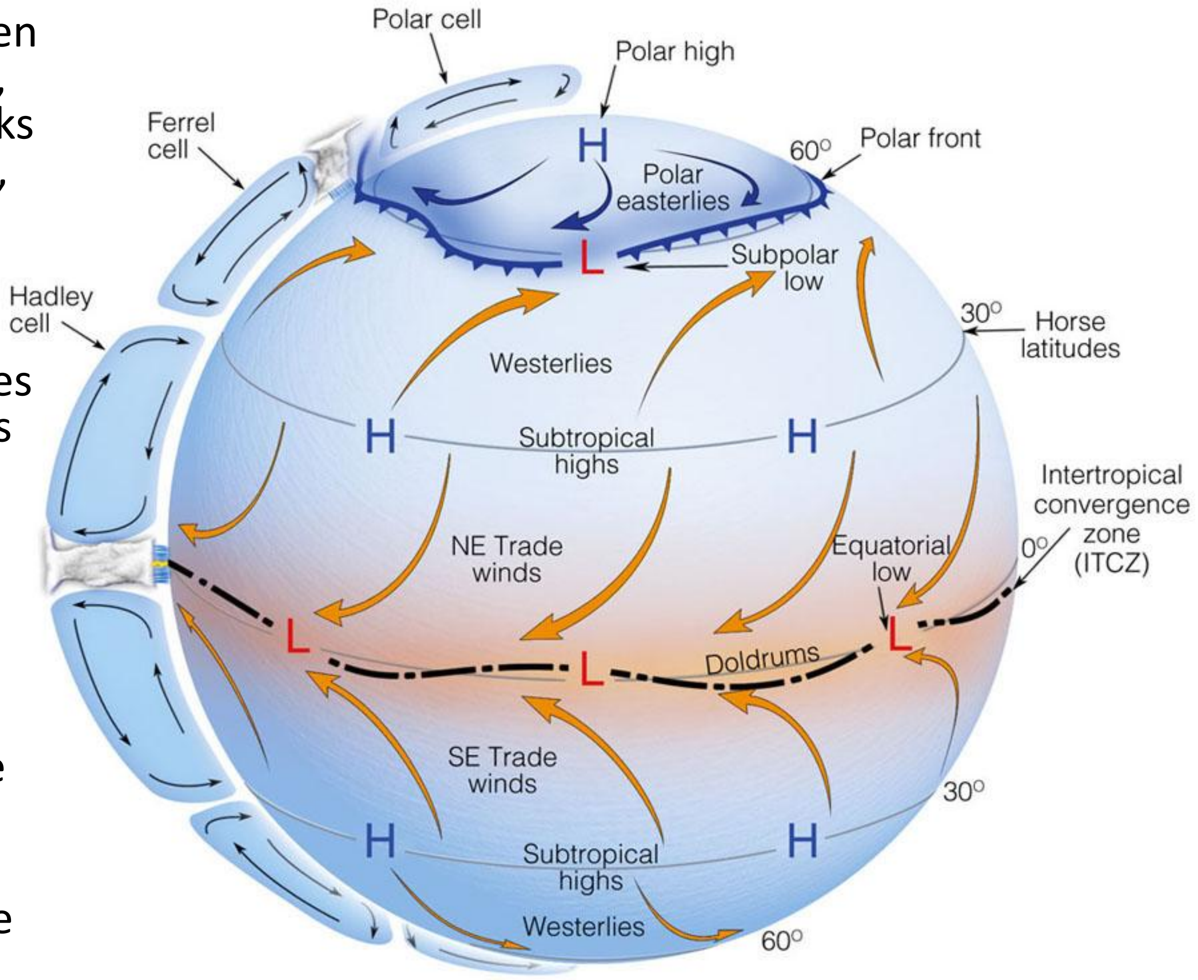
<u>Hadley cell</u> Thermally direct, Driven by meridional gradient in heating, Air rises near the equator and sinks near 30 degrees, Explains deserts, trade winds, ITCZ

<u>Ferrel cell</u> Thermally indirect, Driven by heat transports of eddies (storms), Air rises near 60 degrees and sinks near 30 degrees

<u>Polar cell</u> Thermally direct

Weak winds at the Equator (doldrums) and 30 degrees (horse latitudes)

Boundary between cold polar air and mid-latitude warmer air is the *polar front*.



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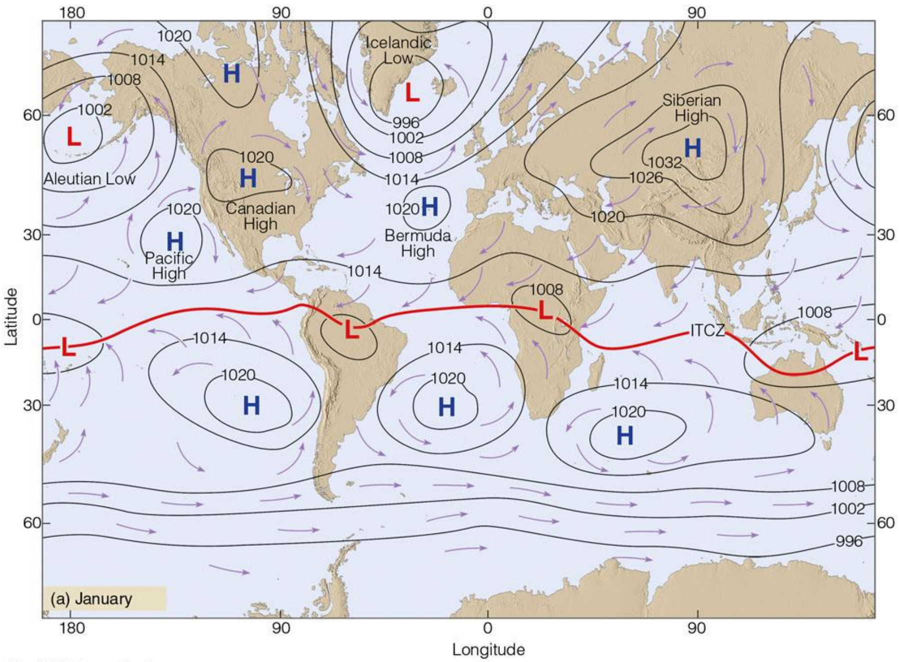
Inside the Ferrel Cell

- Westerly momentum is transferred from the earth to the atmosphere in the trade wind belt
- Westerly momentum is transferred from the atmosphere to the earth in the midlatitudes
- Why don’t the midlatitude westerlies slow down over time?
  - Eddies (storms) transfer momentum poleward in the upper troposphere
  - This momentum transfer weakens the Hadley circulation, but drives the Ferrel Cell

Global Pressure Patterns



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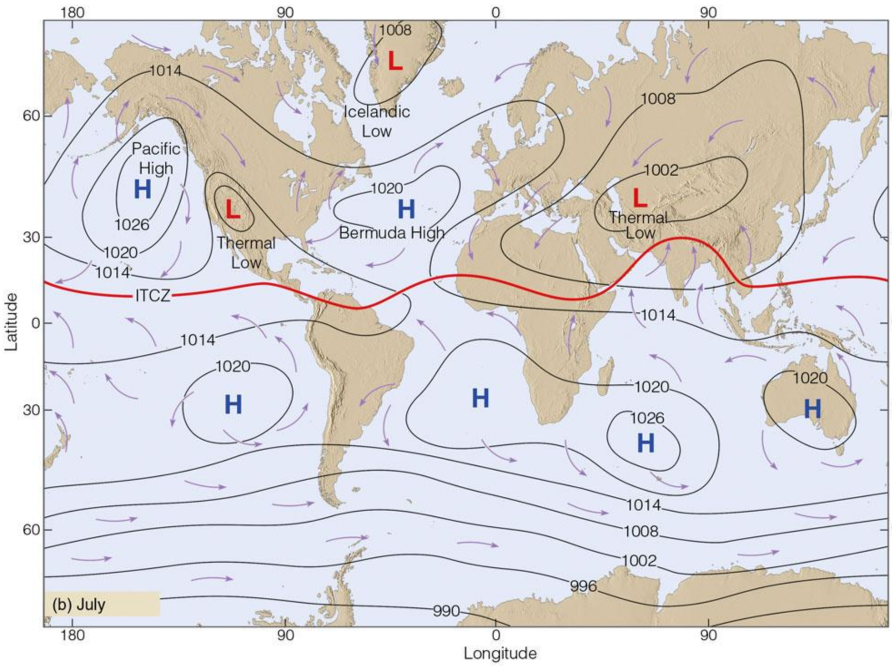
Winter



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Summer

- *Semi-Permanent Pressure Cells* are large areas of higher or lower atmospheric pressure than the surface average
  - They may be thermally induced (rising warm air or subsiding cold air) or they may be caused dynamically by converging or diverging wind patterns)
  - They fluctuate seasonally
- Northern hemisphere semi-permanent cells
  - The Aleutian, Icelandic, and Tibetan lows
  - Siberian, Hawaiian, and Bermuda-Azores highs
  - ITCZ (low)

Take Home Concepts

Driven by differential solar heating between the equator and the poles. Acts to move heat poleward.

In Hadley cell, warmer air rises and moves poleward.

Ferrel cell is driven by heat and momentum fluxes by eddies.

In the NH, air is deflected to the right as it moves. Opposite in SH.

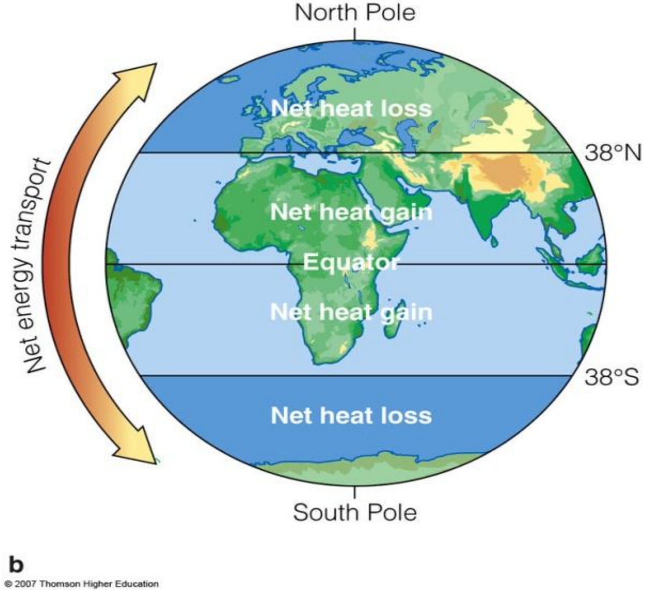
Pole-to-pole Hadley Cell is unstable in the presence of rotation, hence the single cell model breaks down.

Rotation makes the trade winds, surface westerlies, and jet streams

Re-distribution of heat

- Heat gained at Equatorial latitudes
- Heat lost at higher latitudes
- Winds and ocean currents redistribute heat around the Earth

Oceans do not boil away near the equator or freeze solid near the poles because heat is transferred by winds and ocean currents from equatorial to polar regions.



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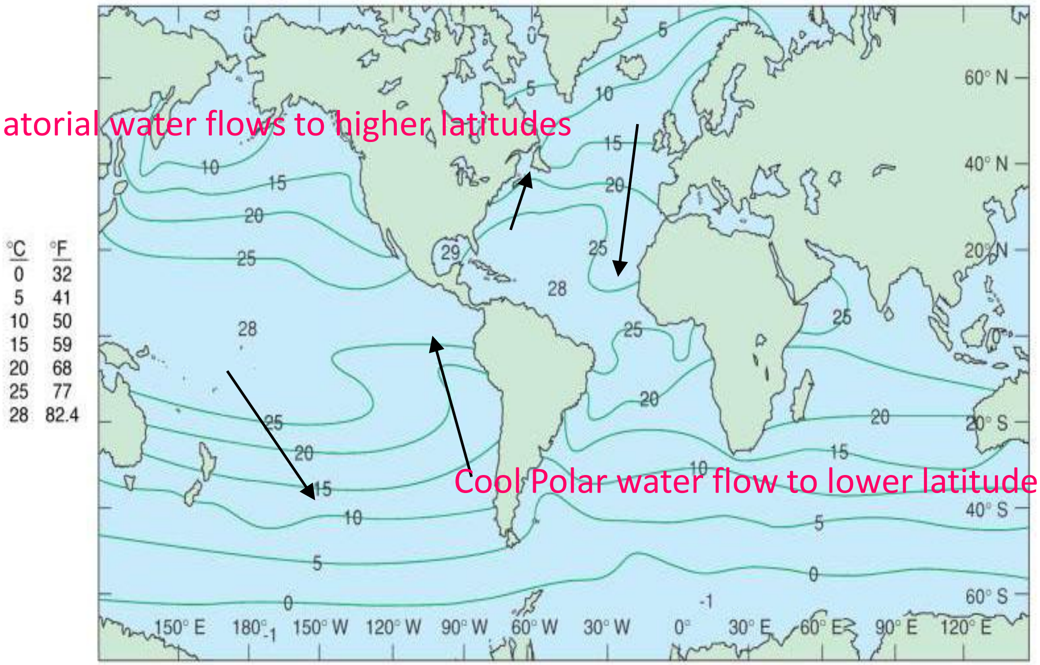
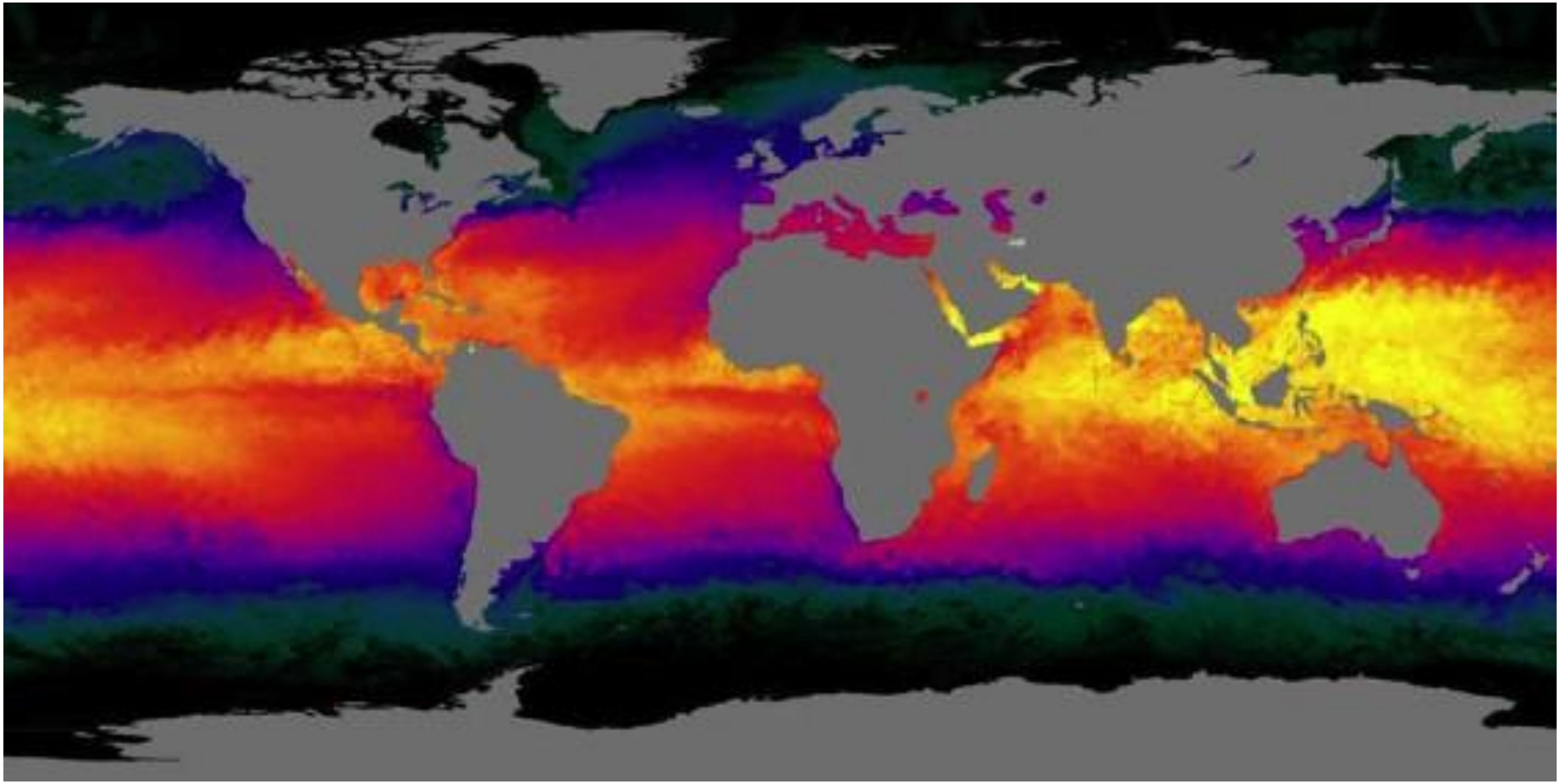


Warm equatorial water flows to higher latitudes

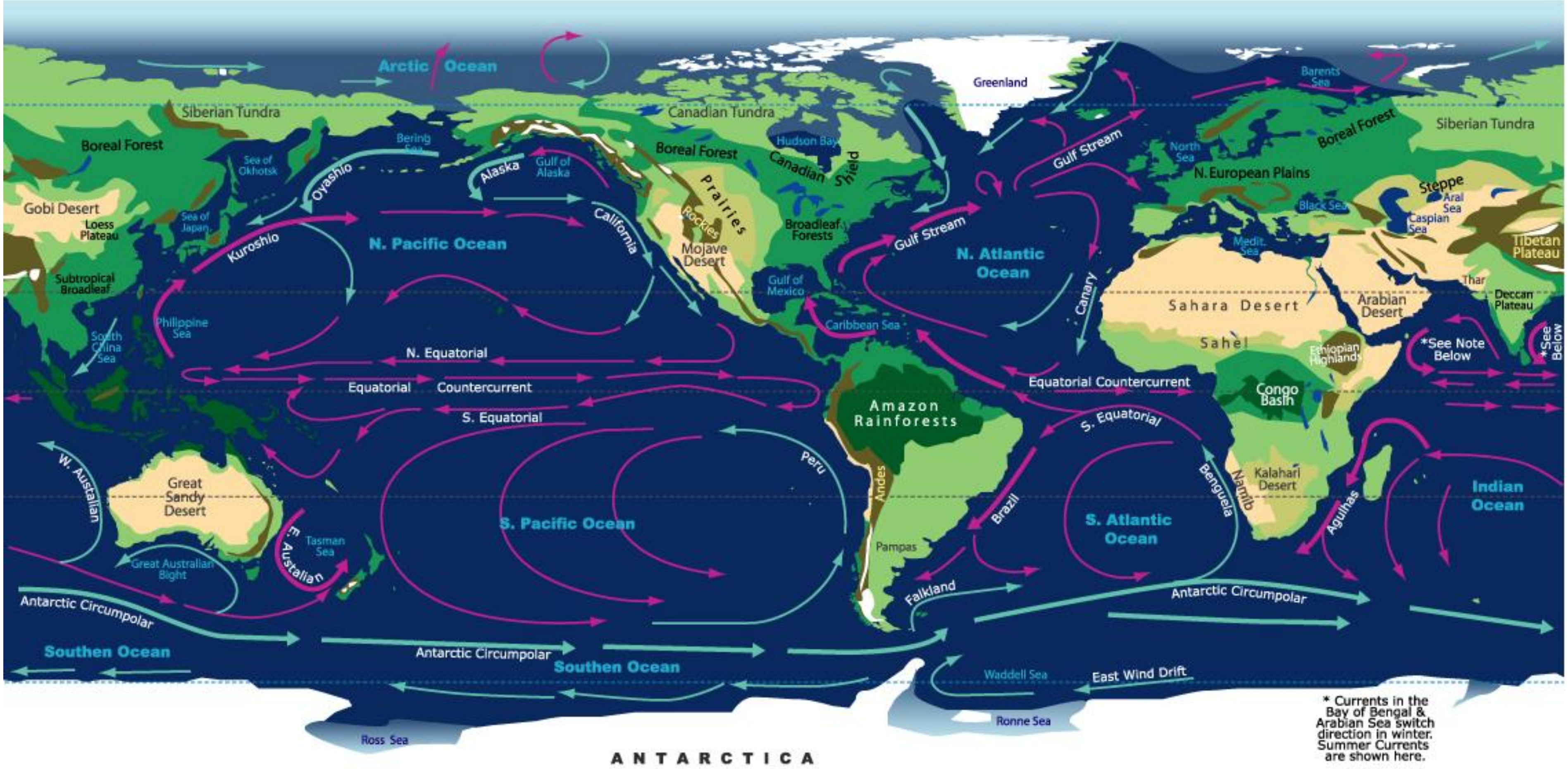
Cool Polar water flow to lower latitudes

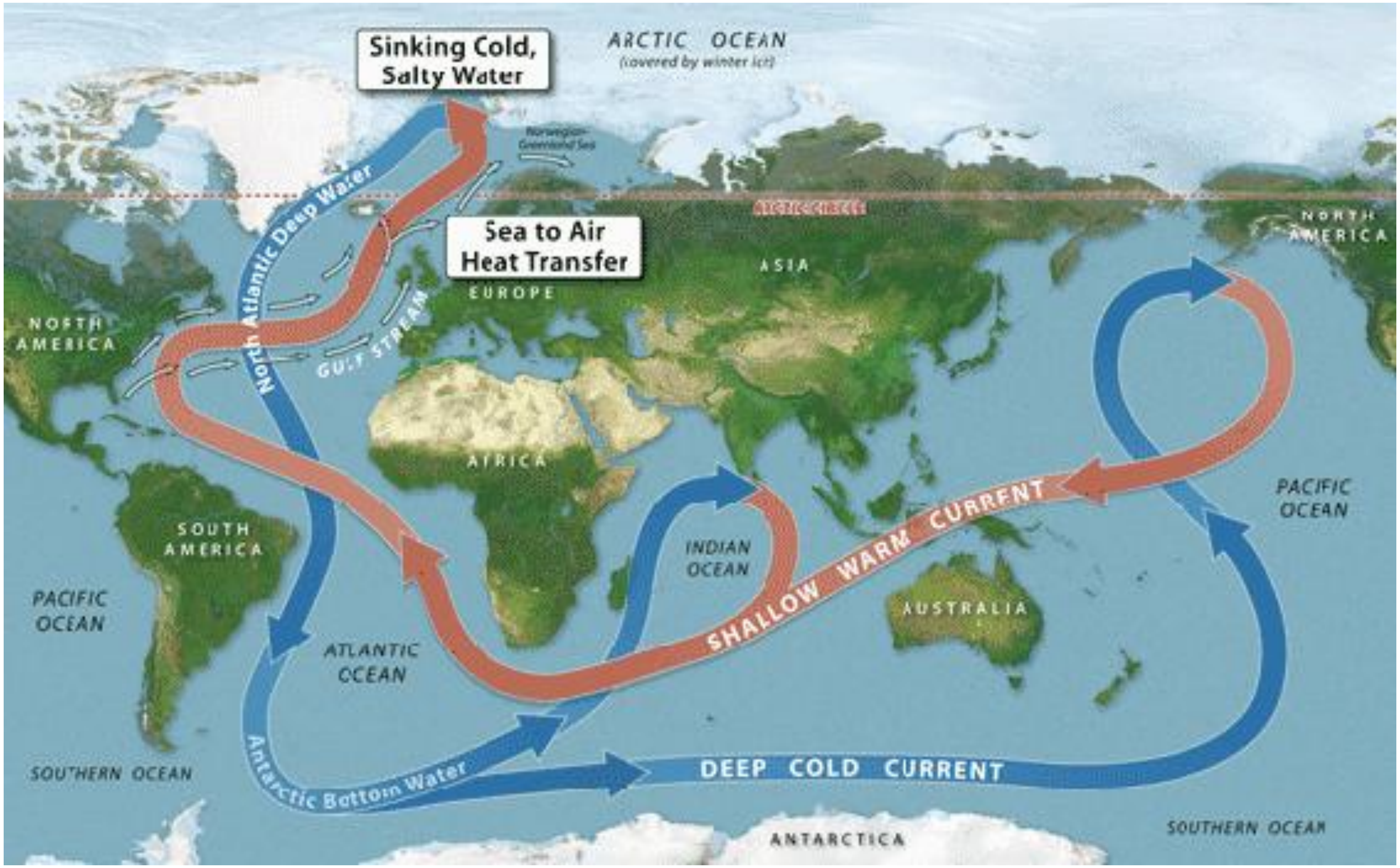
But What about the Oceans?



Sea Surface Temperatures

Ocean Currents




Sinking Cold, Salty Water
ARCTIC OCEAN
(covered by winter ice)
Norwegian-Greenland Sea
ARCTIC CIRCLE
North Atlantic Deep Water
Sea to Air Heat Transfer
NORTH AMERICA
ASIA
EUROPE
NORTH AMERICA
GULF STREAM
AFRICA
PACIFIC OCEAN
SHALLOW WARM CURRENT
SOUTH AMERICA
INDIAN OCEAN
PACIFIC OCEAN
AUSTRALIA
ATLANTIC OCEAN
SOUTHERN OCEAN
Antarctic Bottom Water
DEEP COLD CURRENT
SOUTHERN OCEAN
ANTARCTICA

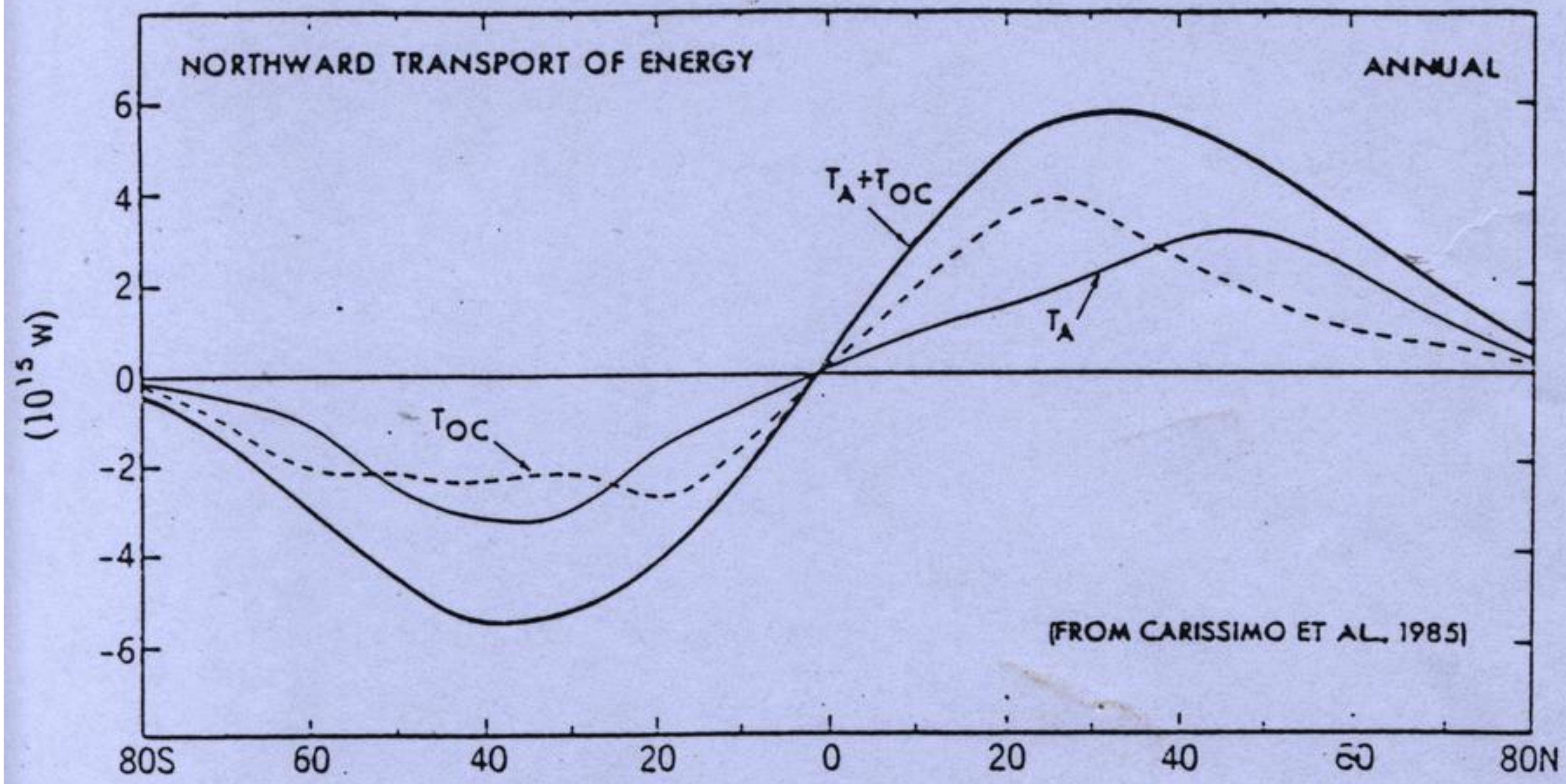
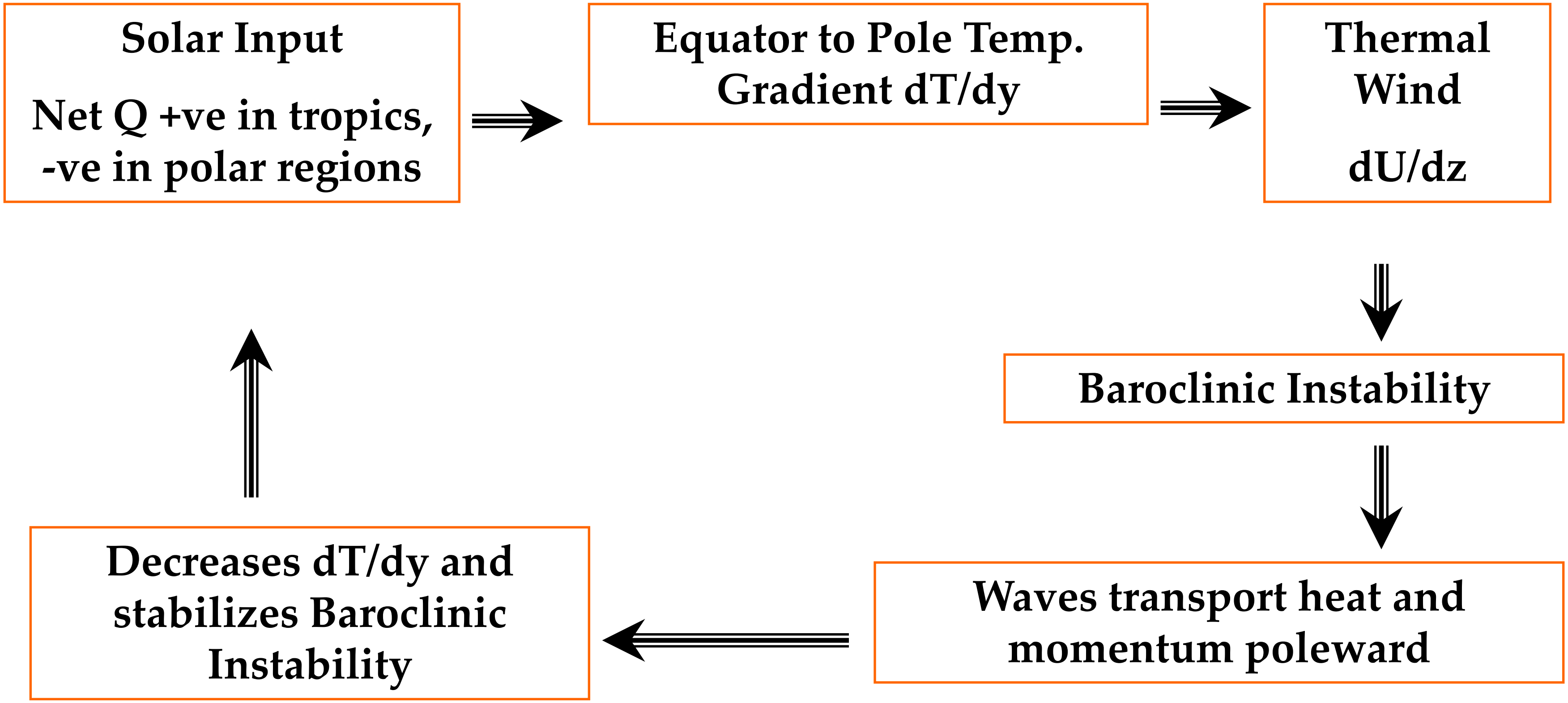


FIGURE 13.17. Meridional profiles of the northward transport of energy by the total system ($T_A + T_{OC}$), the atmosphere (T_A), and the oceans (T_{OC}) for annual-mean conditions in units of 10^{15} W (based on data from Carissimo *et al.*, 1985).

Maintenance of General Circulation of the Atmosphere



Solar Input

Net Q +ve in tropics, -ve in polar regions

Equator to Pole Temp. Gradient dT/dy

Thermal Wind

dU/dz

Baroclinic Instability

Waves transport heat and momentum poleward

Decreases dT/dy and stabilizes Baroclinic Instability

The General Circulation

In its broadest sense the general circulation of the atmosphere is usually considered to include the totality of motions that characterizes the global scale atmospheric flow.

Specifically, the study of the general circulation is considered with the dynamics of climate-that is, with the temporally averaged structures of the fields of wind, temperature, humidity, precipitation, and other meteorological variables.

The general circulation may thus be considered to consist of the flow averaged in time over a period sufficiently long to remove the random variations associated with individual weather systems, but short enough to retain monthly and seasonal (summer and winter) variations.

Observed mean structure of the Atmosphere

- Observed vertical and horizontal (3-dimensional) structure of the atmosphere.

- Temperature, winds and humidity fields.

- What maintains this distribution?

- Solar radiation and earth’s radiation and radiation balance.

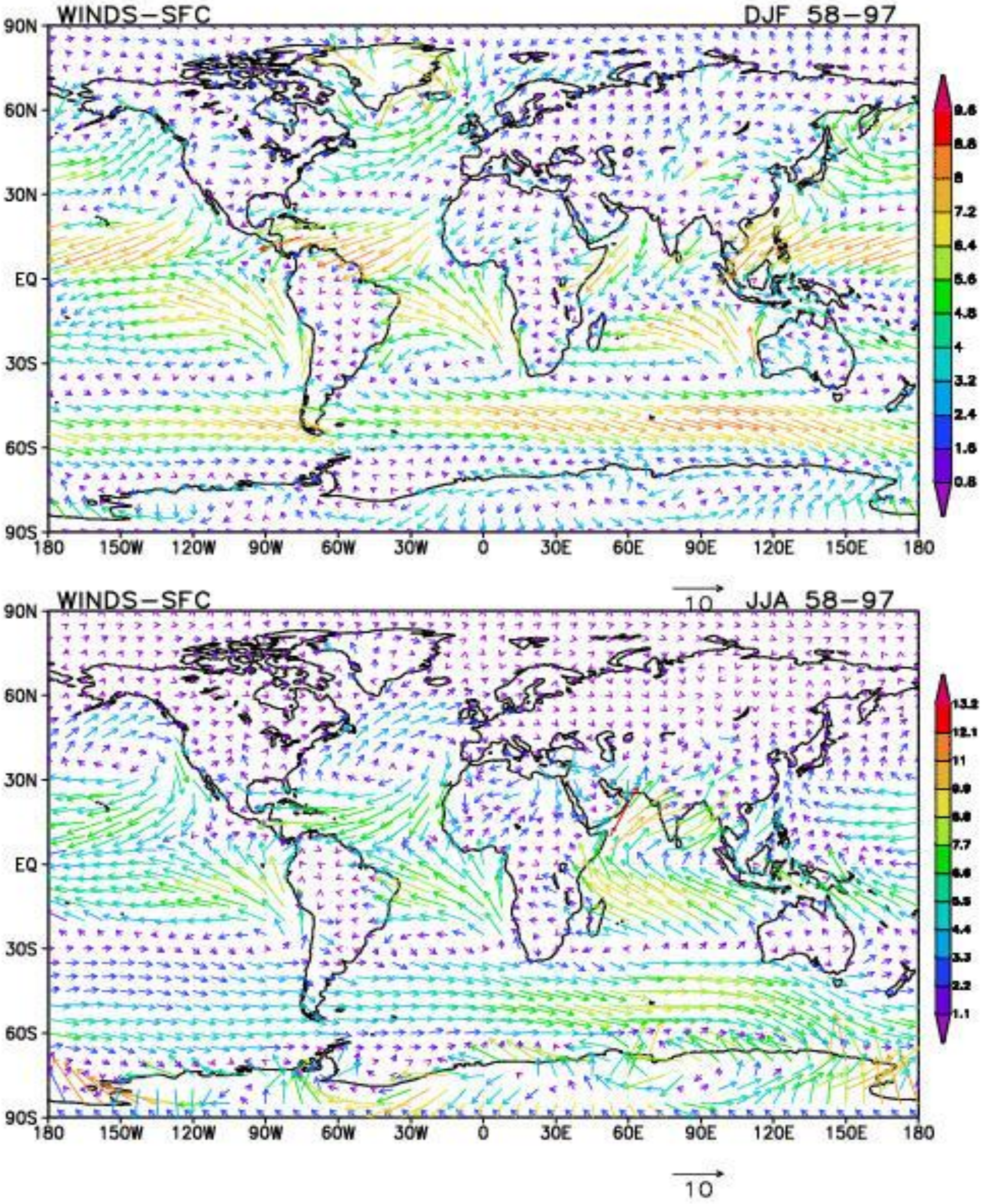
- Simple estimate of global mean surface temperature.

- Greenhouse effect and examples of surface temperature of some other planets and their radiative equilibrium.

Long term mean seasonal average vector winds during NH winter (DJF) and summer (JJA) at the surface. This is based on 40 years of NCEP/NCAR reanalysis. Colors indicate wind magnitude.

Easterlies in the tropics and westerlies in the middle latitudes may be noted.

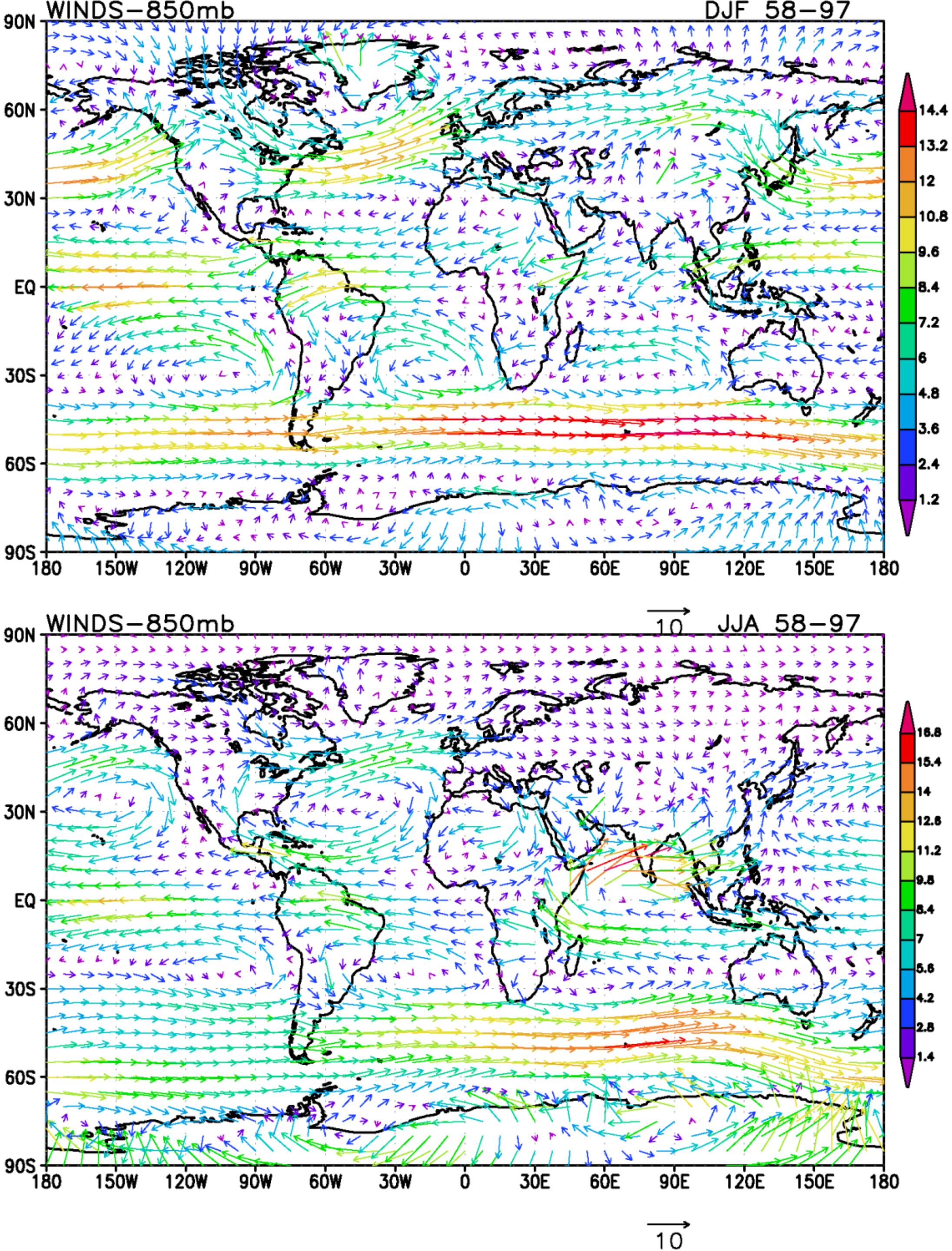
Reversal of winds between the two seasons over the monsoon regions is seen.



Long term mean seasonal average vector winds during NH winter (DJF) and summer (JJA) at 850 hPa. This is based on 40 years of NCEP/NCAR reanalysis. Colors indicate wind magnitude.

Easterlies in the tropics and westerlies in the middle latitudes may be noted.

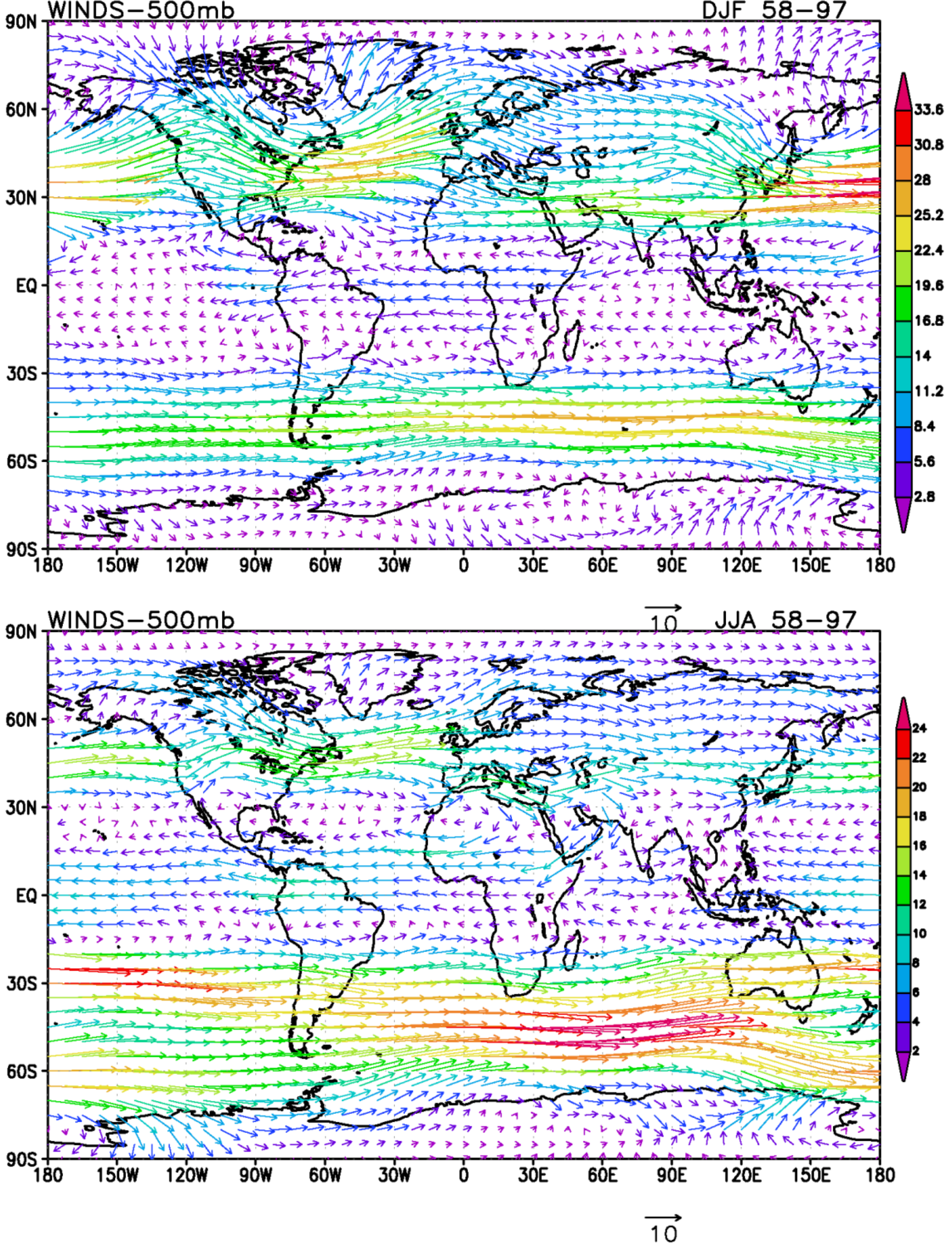
Reversal of winds between the two seasons over the monsoon regions is seen.



Long term mean seasonal average vector winds during NH winter (DJF) and summer (JJA) at 500 hPa. This is based on 40 years of NCEP/NCAR reanalysis. Colors indicate wind magnitude.

Easterlies in the tropics and westerlies in the middle latitudes may be noted.

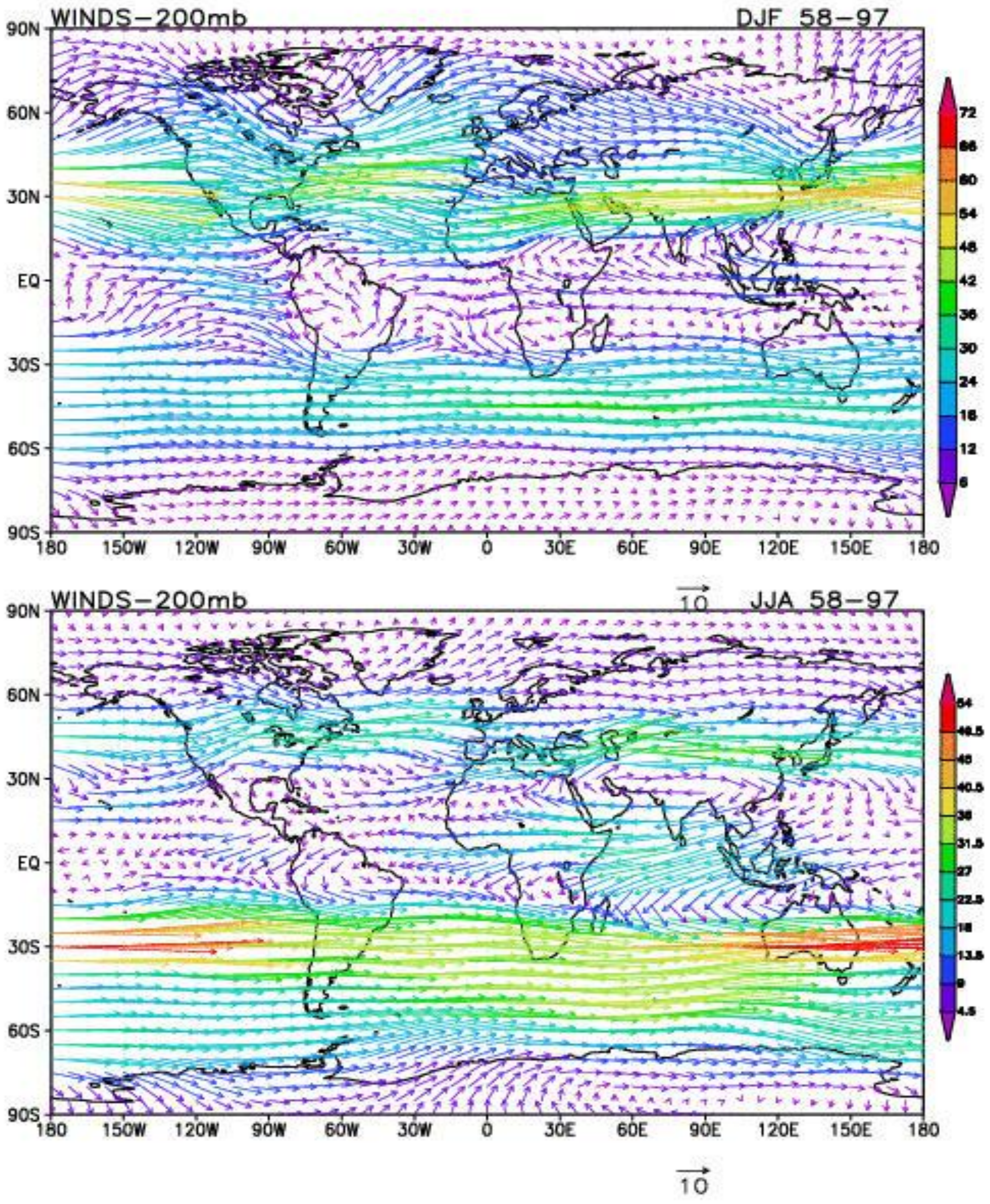
Winds at this level over the monsoon regions are weak during both seasons.



Long term mean seasonal average vector winds during NH winter (DJF) and summer (JJA) at 200 hPa. Colors indicate wind magnitude.

Easterlies in the tropics and jet-like strong westerlies are seen in the sub-tropics.

Westerly jet in the winter hemisphere is stronger than that in the summer hemisphere.

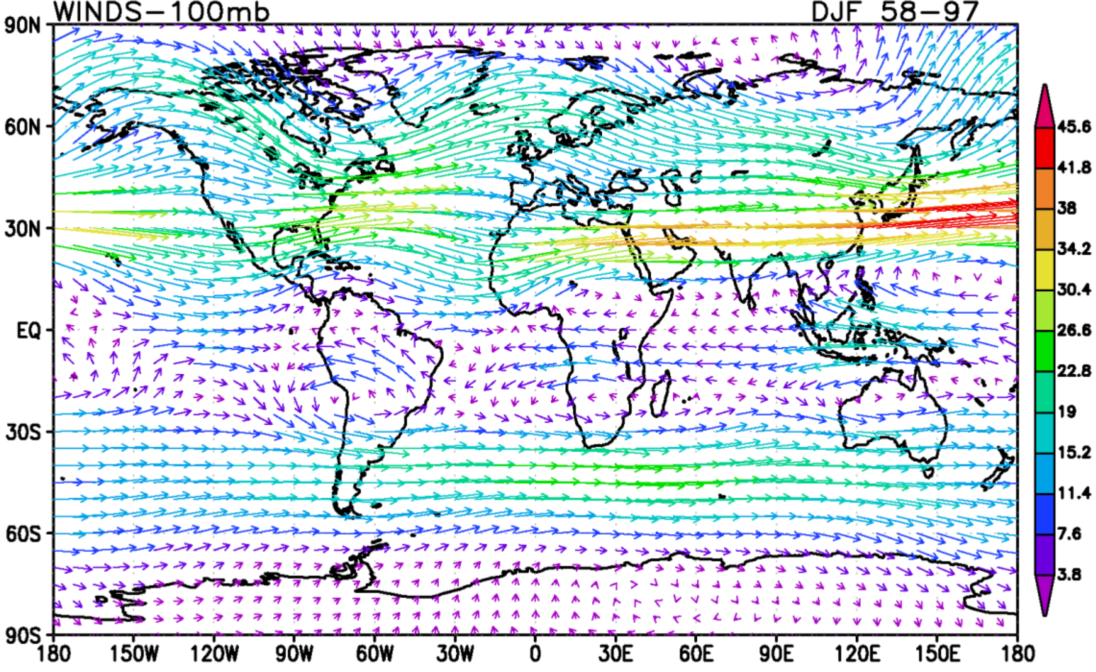


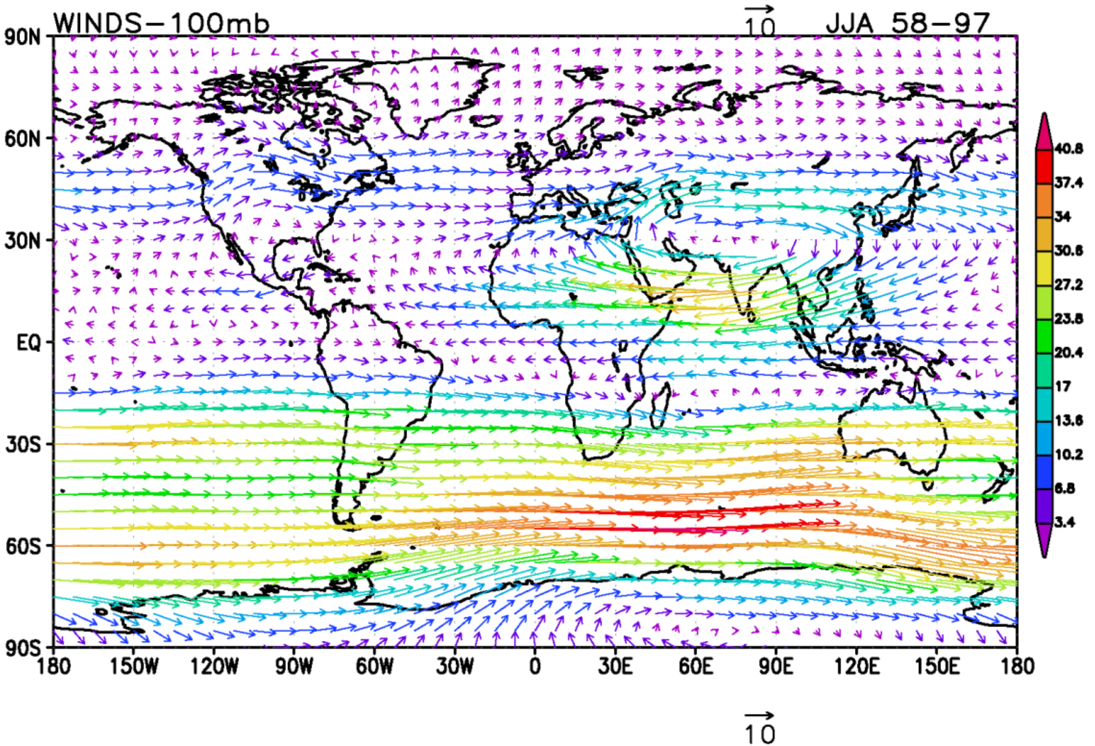
Long term mean seasonal average vector winds during NH winter (DJF) and summer (JJA) at 100 hPa. Colors indicate wind magnitude.

Easterlies in the tropics and jet-like strong westerlies are seen in the sub-tropics.

An easterly jet over the equatorial monsoon region during summer.

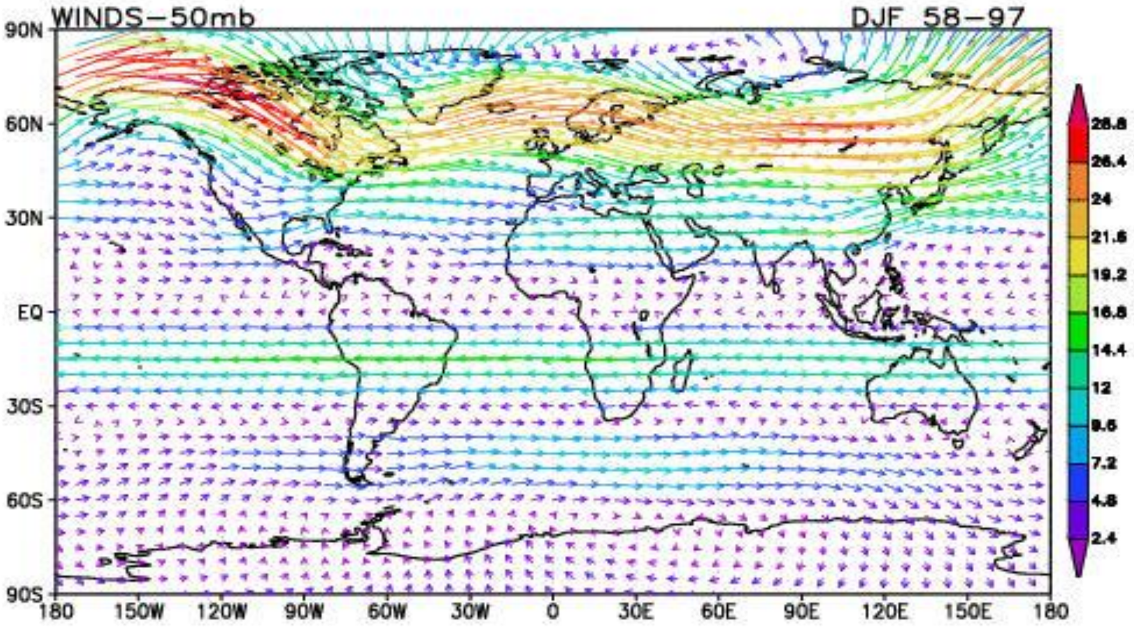
Also a massive anticyclonic circulation sits over the Tibet during summer.

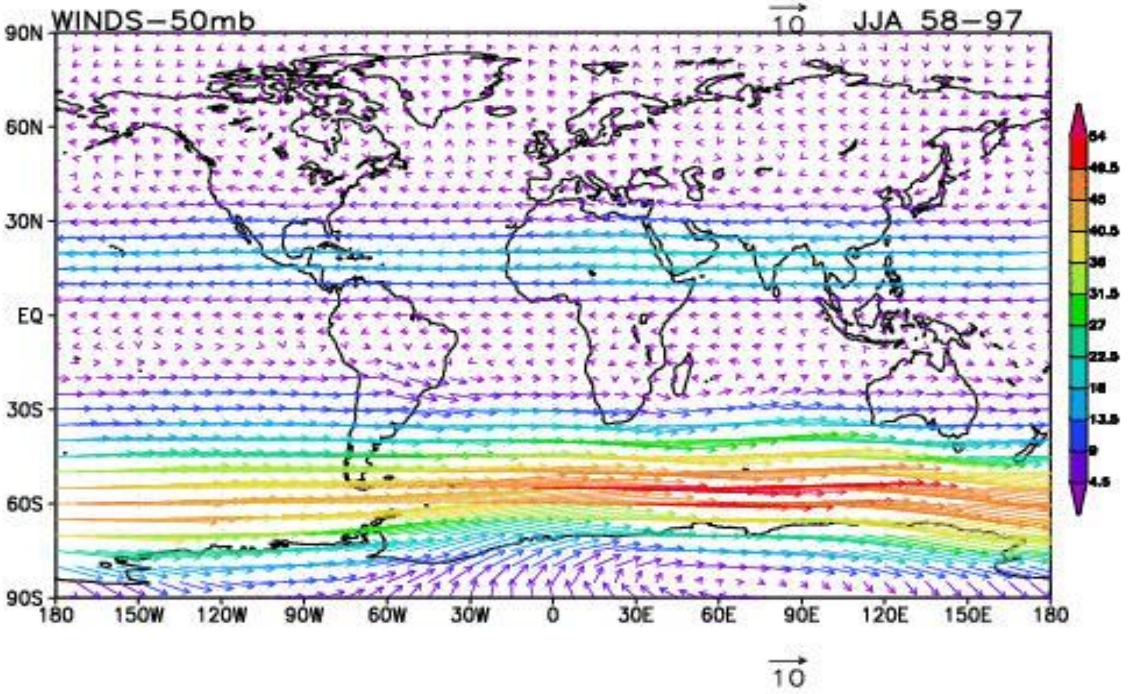




Long term mean seasonal average vector winds during NH winter (DJF) and summer (JJA) at 50 hPa (lower stratosphere). Colors indicate wind magnitude.

The striking feature is that westerly jet is asymmetric about the equator at this level. Summer hemisphere does not have westerly jet and the jet is located closer to the winter hemispheric polar region.

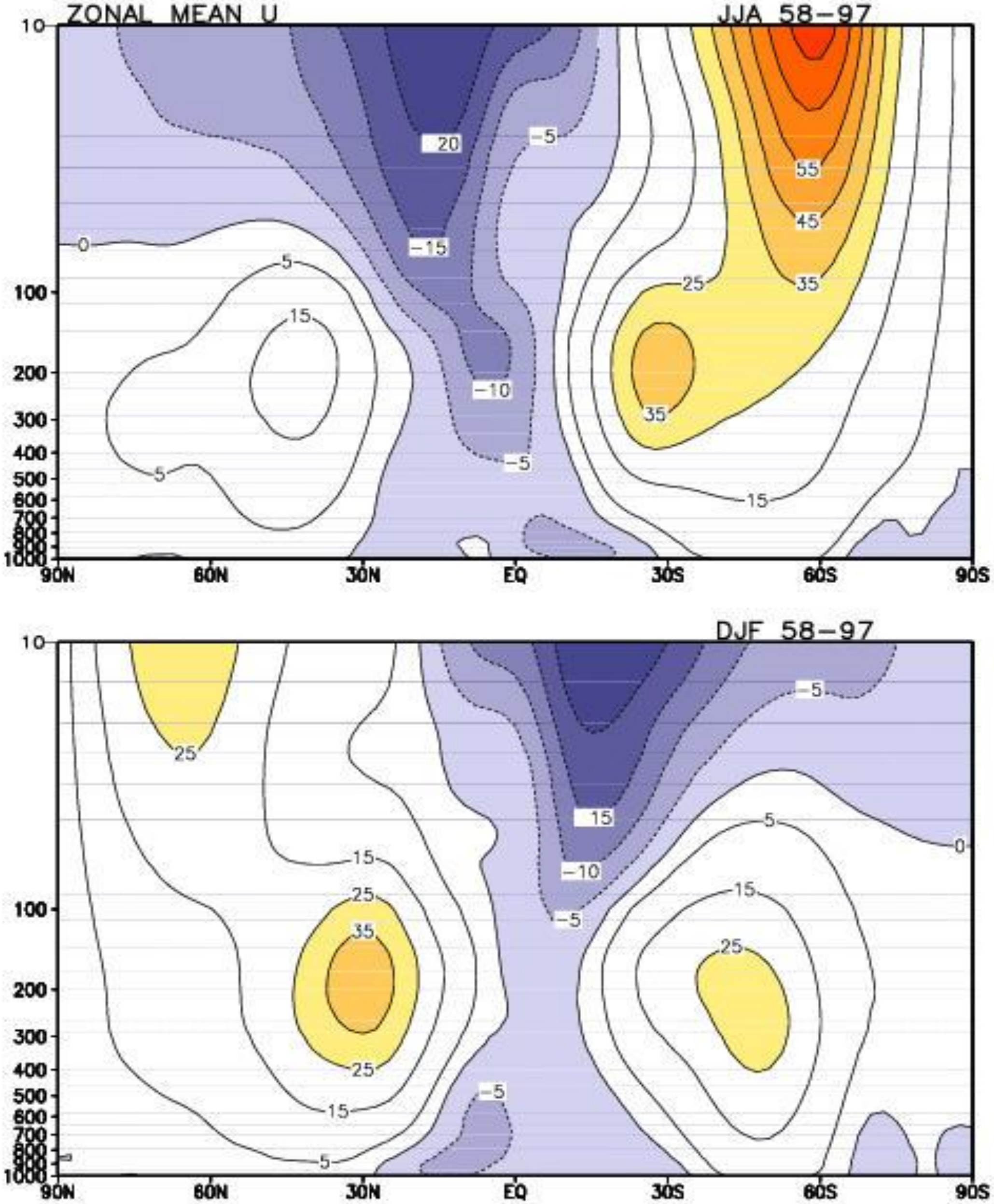




Eastward component of the winds (zonal winds, u) averaged along a latitude circle (zonal average) as a function of latitude and height (represented in pressure from 1000 hPa to 10 hPa.

In the troposphere (below 100 hPa), subtropical westerly jets in both hemispheres may be seen.

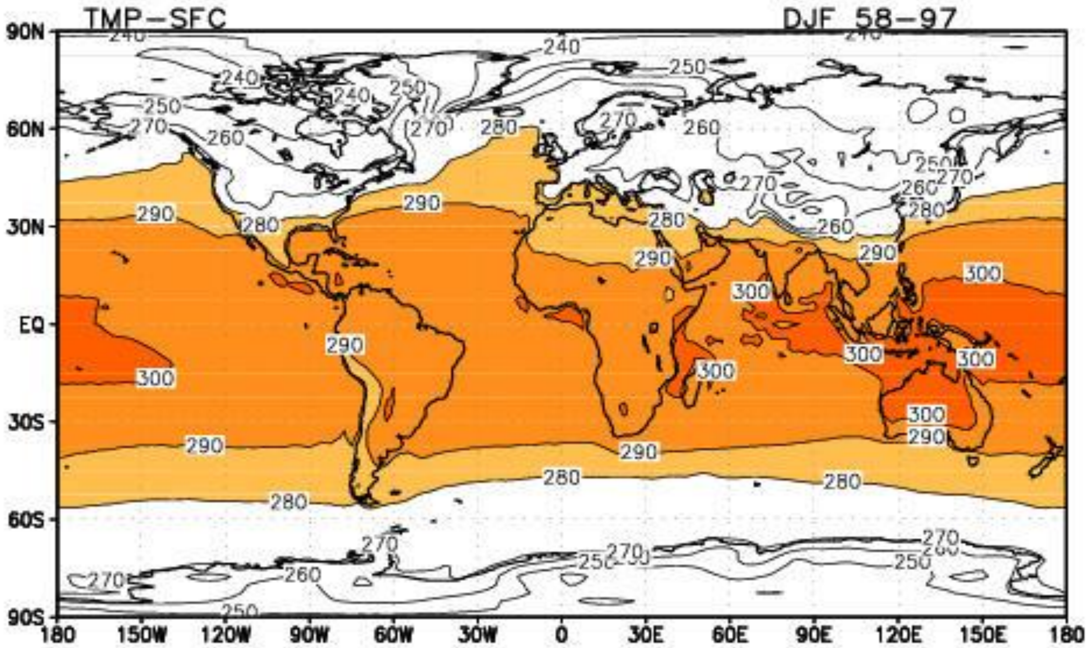
Westerly jet in the winter hemisphere and easterly jet in the summer hemisphere are seen the stratosphere.



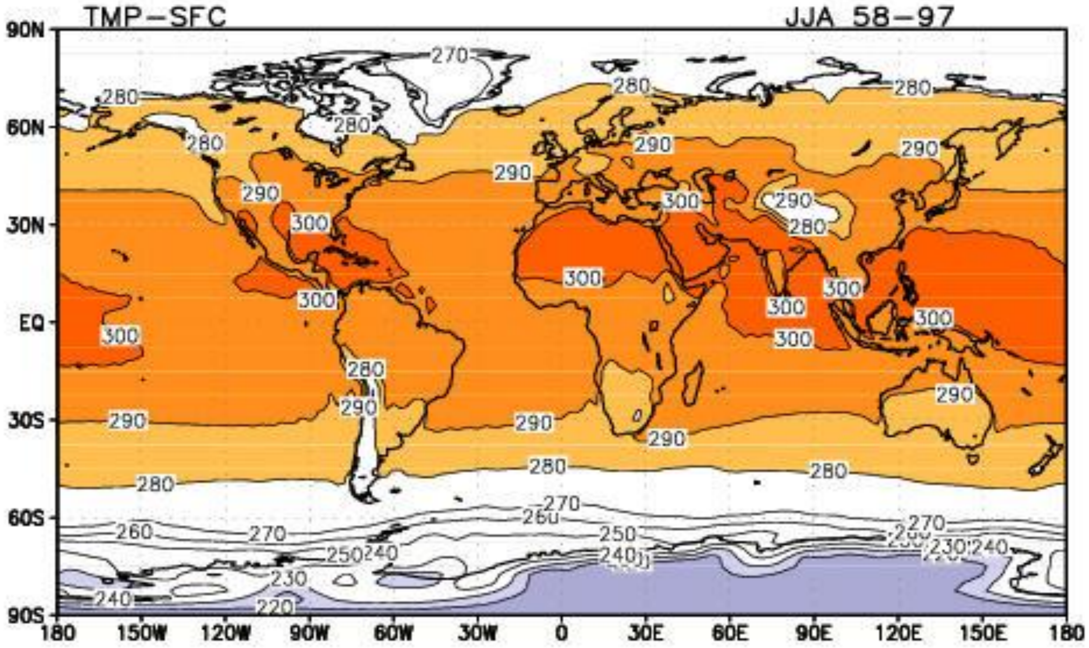
Long term mean seasonal average temperature (K) during NH winter (DJF) and summer (JJA) at the surface. This is based on 40 years of NCEP/NCAR reanalysis.

In the tropics (between 30S and 30N), latitudinal variations of temp. is very weak. It is rapid in the middle latitude.

The equator-to-pole temp. difference is around 60K (40K)in winter (summer) hemisphere.

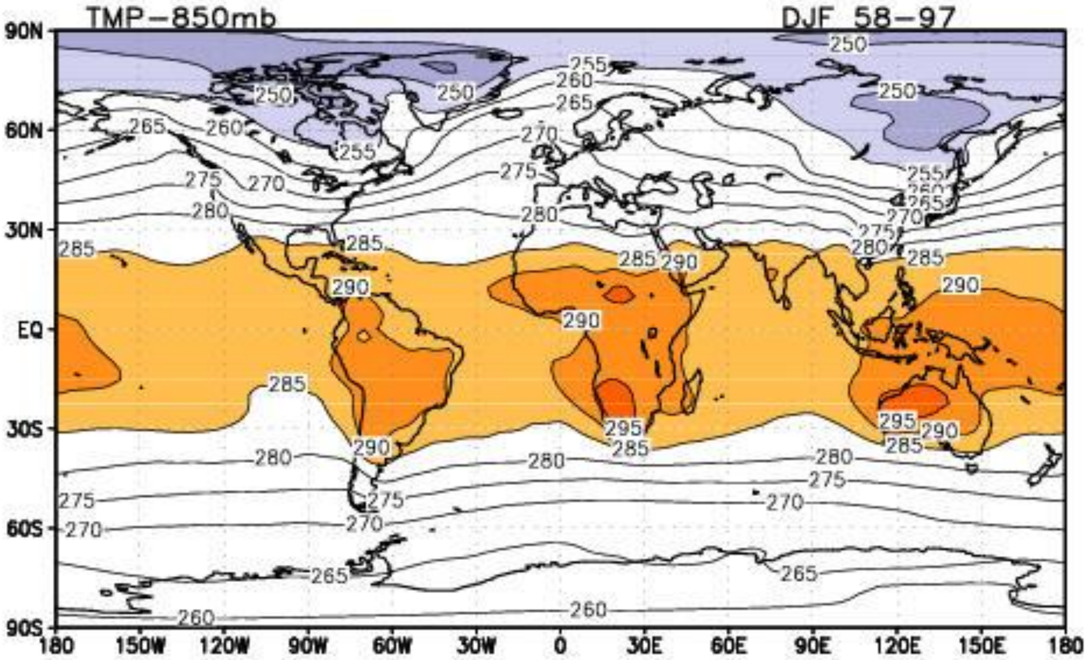


TMP−SFC DJF 58−97

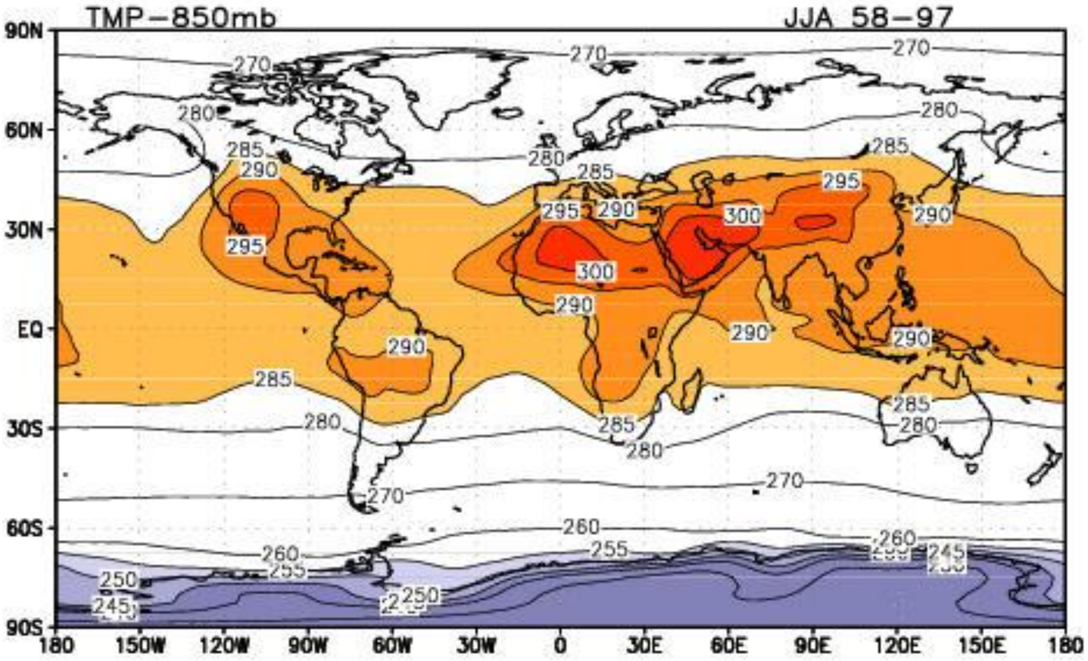


TMP−SFC JJA 58−97

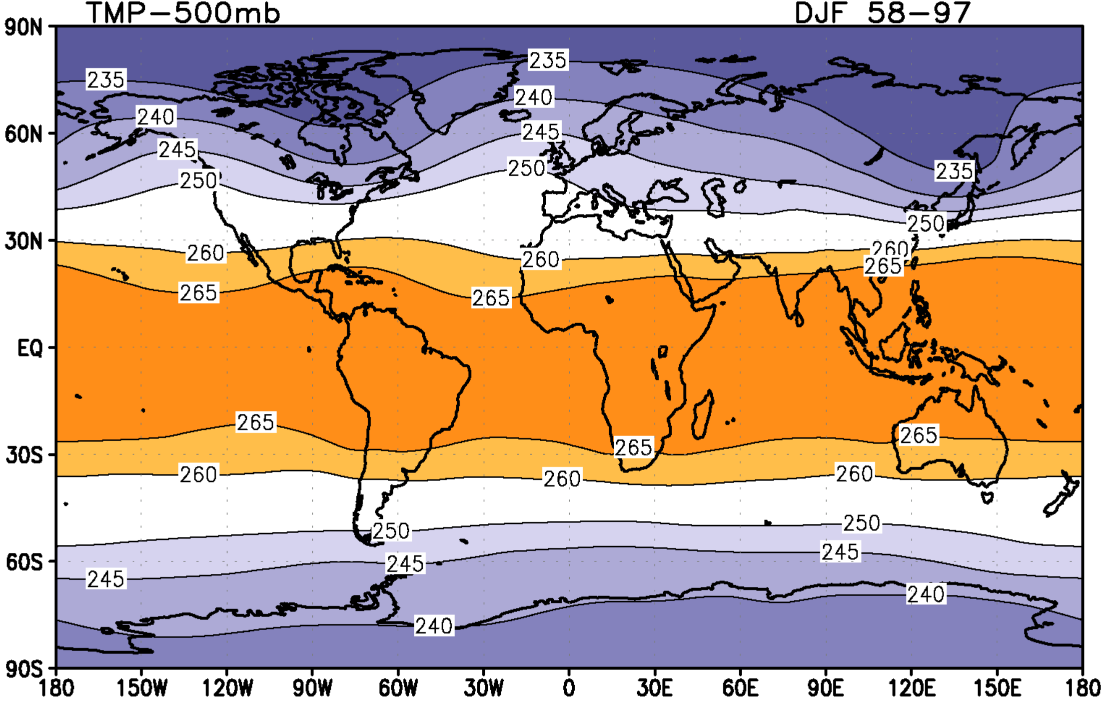
Long term mean seasonal average temperature (K) during NH winter (DJF) and summer (JJA) at 850 hPa.



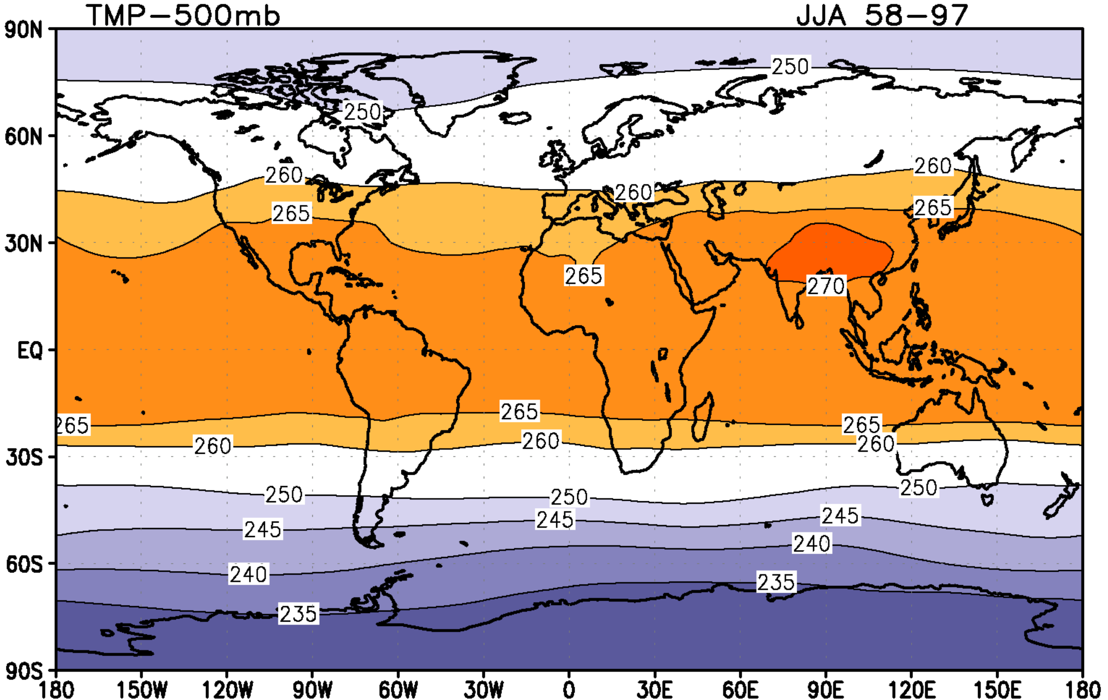
Similar to that at surface but the magnitude has decreased. The wave like structure of Temp. contours in NH winter (DJF) is due to land-ocean contrasts.



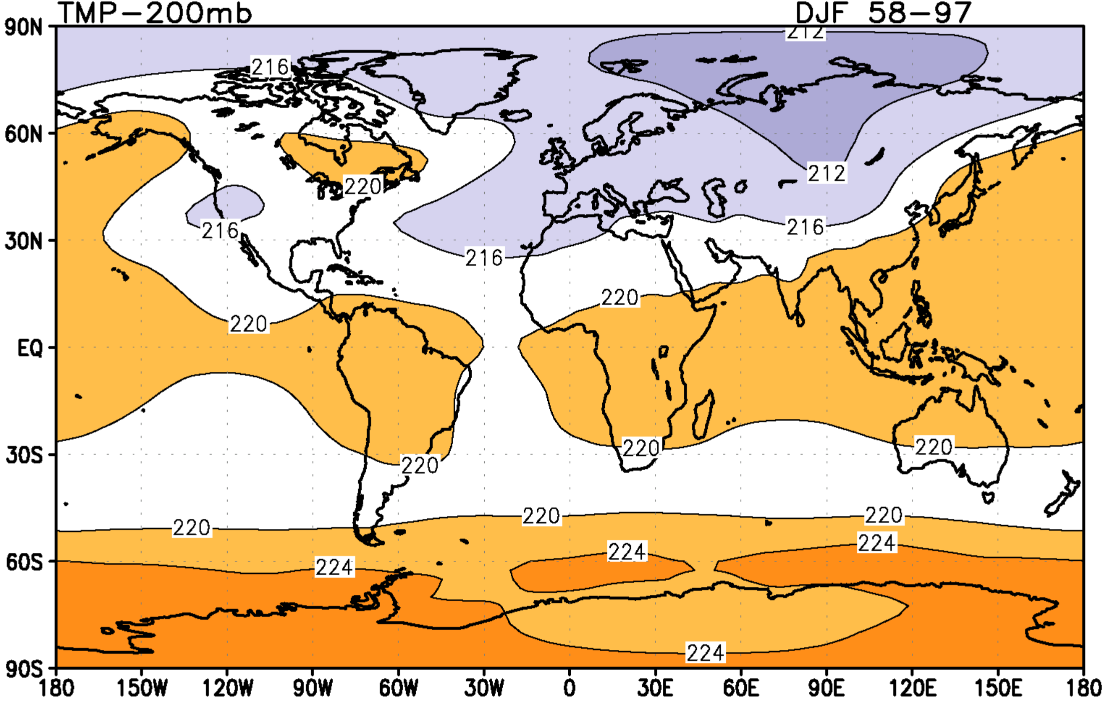
Long term mean seasonal average temperature (K) during NH winter (DJF) and summer (JJA) at 500 hPa.



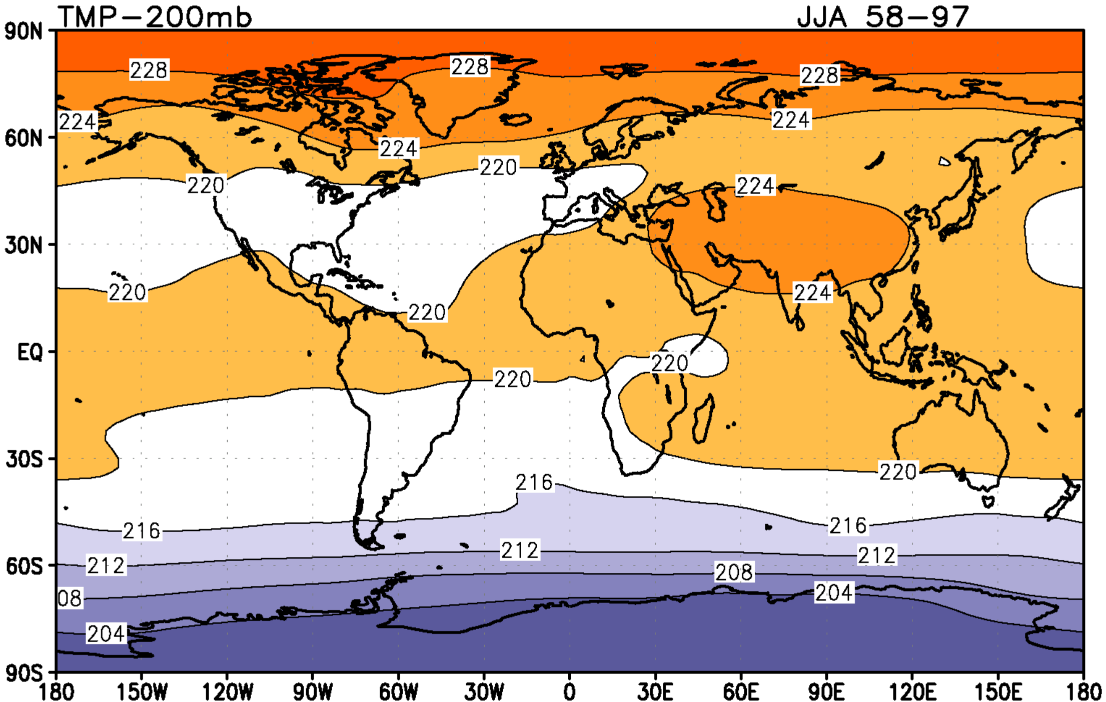
Similar to that at 850 hPa but the magnitude has further decreased. The wave like structure of Temp. contours in NH winter (DJF) is due to land-ocean contrasts.



Long term mean seasonal average temperature (K) during NH winter (DJF) and summer (JJA) at 200 hPa.

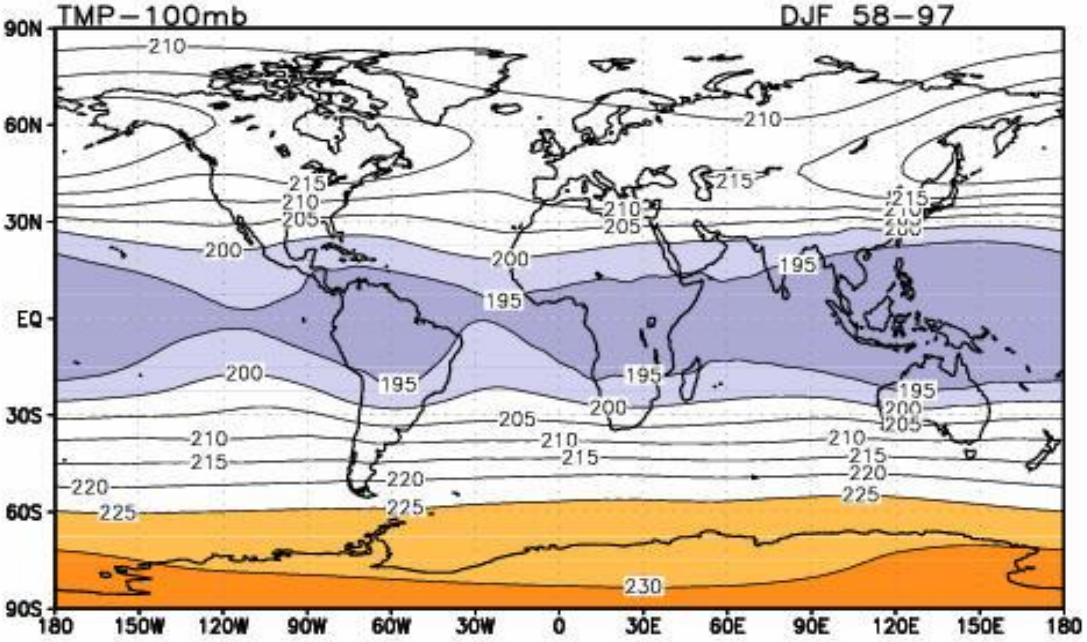


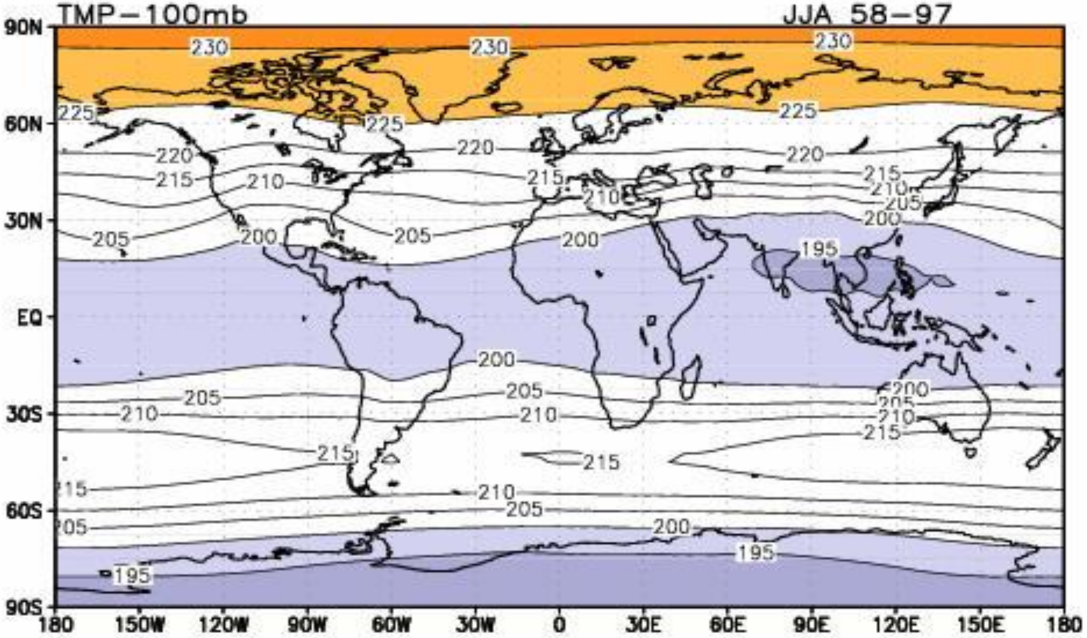
Similar to that at 500 hPa but the magnitude has further decreased.



Long term mean seasonal average temperature (K) during NH winter (DJF) and summer (JJA) at 100 hPa.

It may be noted that at this level, the equator is colder than the polar region reversing the equator to pole temperature gradient at this level compared to that at the surface.



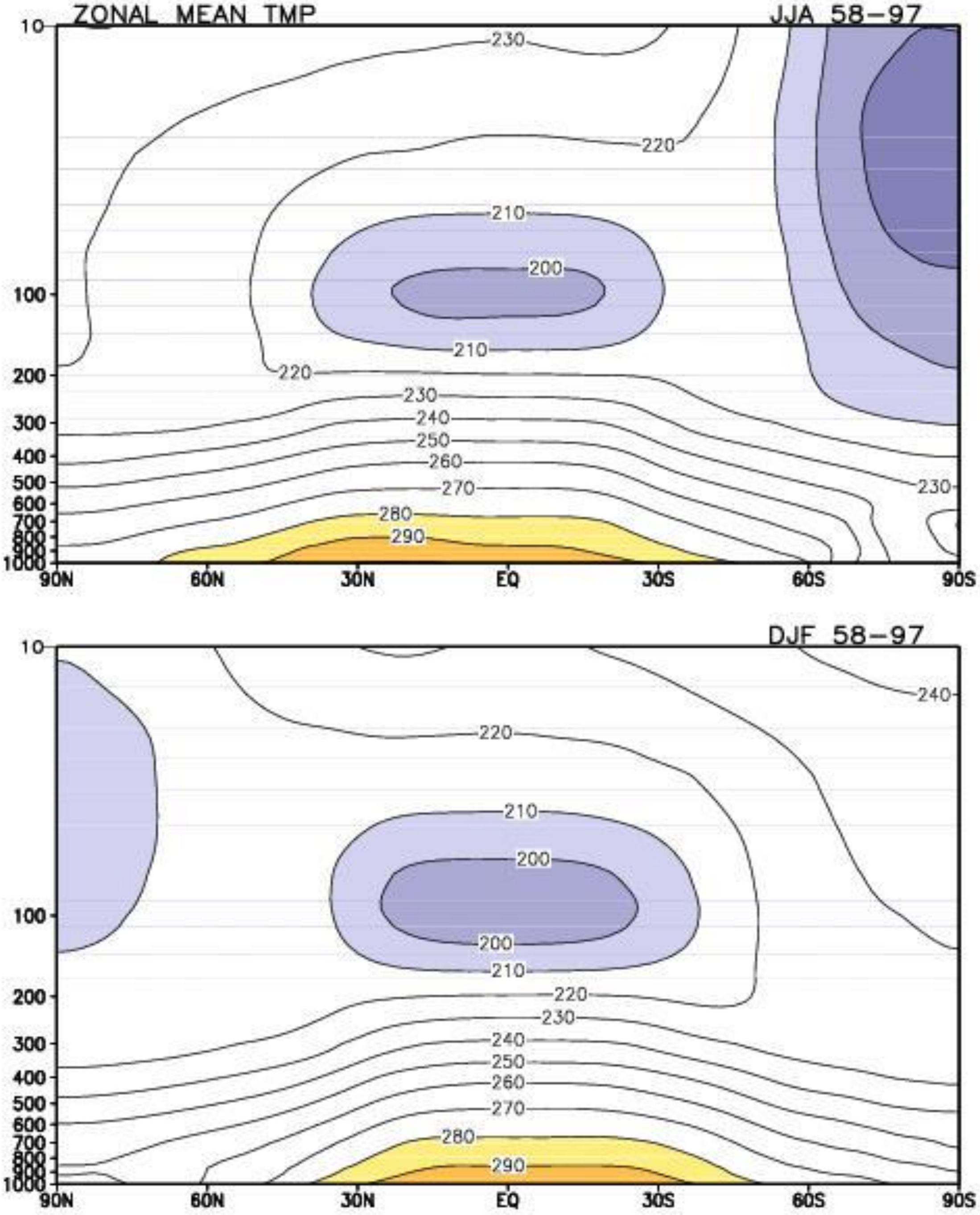


Temperature (K) averaged along a latitude circle (zonal average) as a function of latitude and height (represented in pressure from 1000 hPa to 10 hPa.

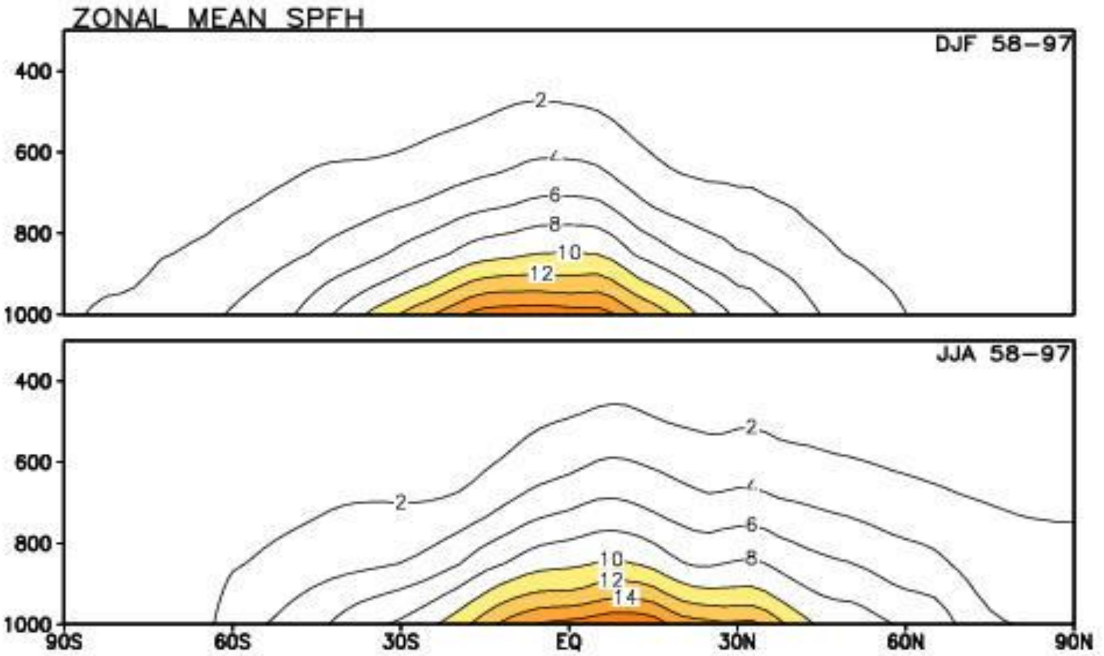
The temperature decreases to a height (tropopause) and increases thereafter.

Height of the tropopause in the tropics is about 100 hPa while it is 300 hPa in polar regions.

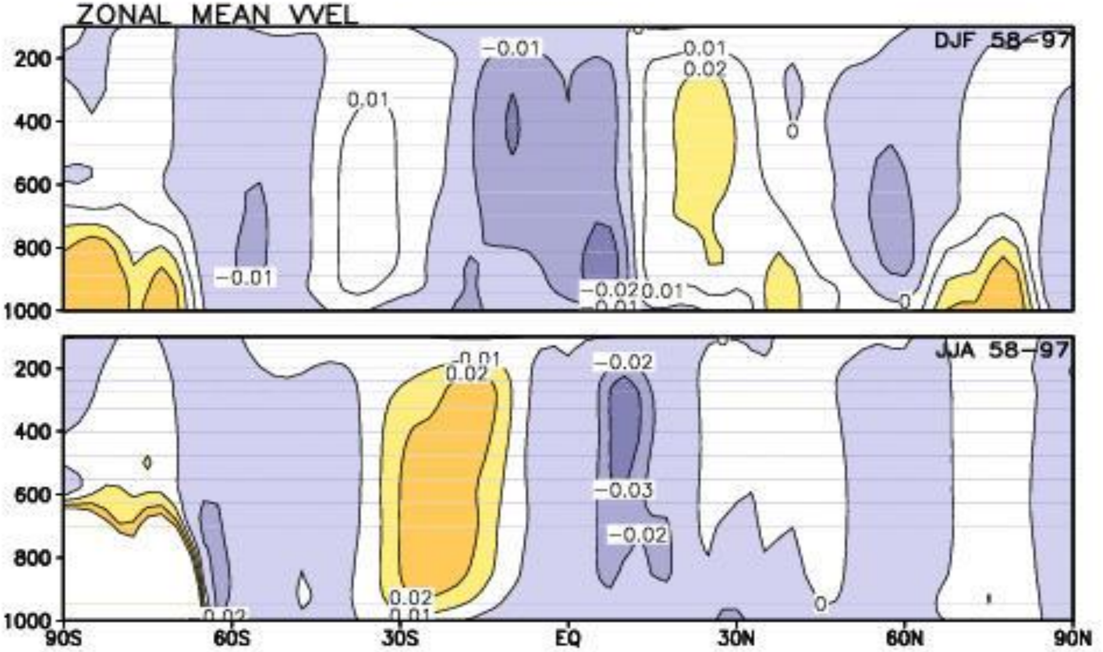
The symmetry of the temperature profile around the equator in the troposphere and its asymmetry in the stratosphere may be noted.



Specific humidity (g/kg) averaged along a latitude circle (zonal average) as a function of latitude and height (represented in pressure from 1000 hPa to 300 hPa.



Pressure vertical velocity (hPa/s) averaged along a latitude circle (zonal average) as a function of latitude and height (represented in pressure from 1000 hPa to 100 hPa. Negative values represent upward motion.



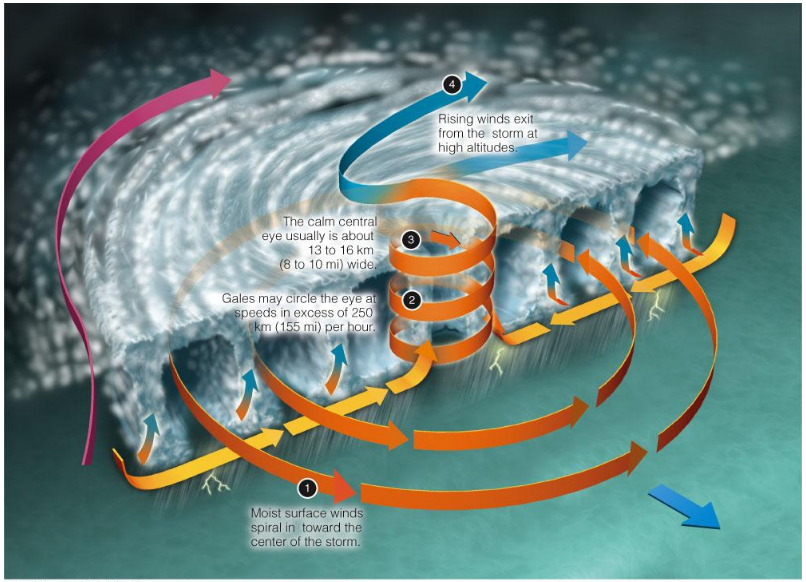
Storms Are Variations in Large-Scale Atmospheric Circulation

Storms are regional atmospheric disturbances. Storms have high winds and most have precipitation.

Tropical cyclones occur in tropical regions. These storms can cause millions of dollars worth of damage and endanger life.

Extratropical cyclones occur in Ferrel cells, and are winter weather disturbances. These storms can also cause extensive damage.

Both types of storms are **cyclones,** or rotating masses of low-pressure air.



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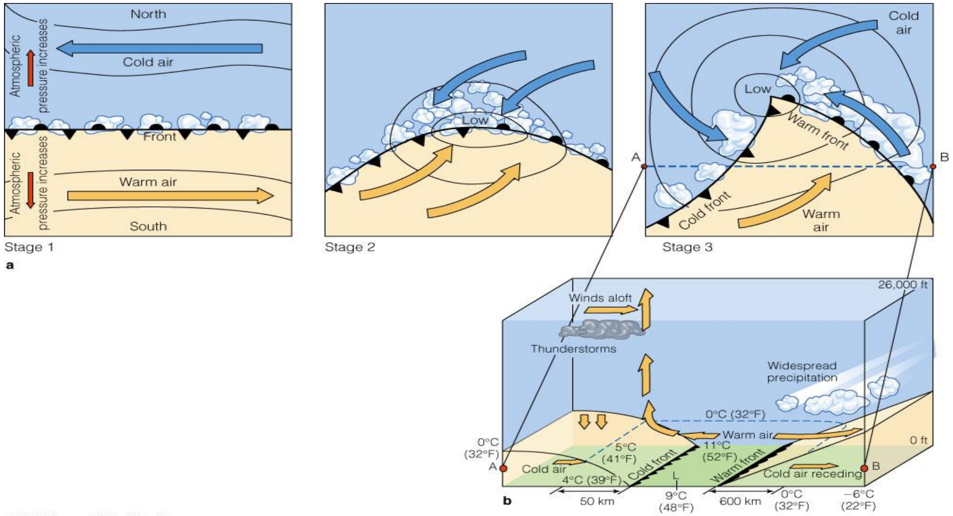

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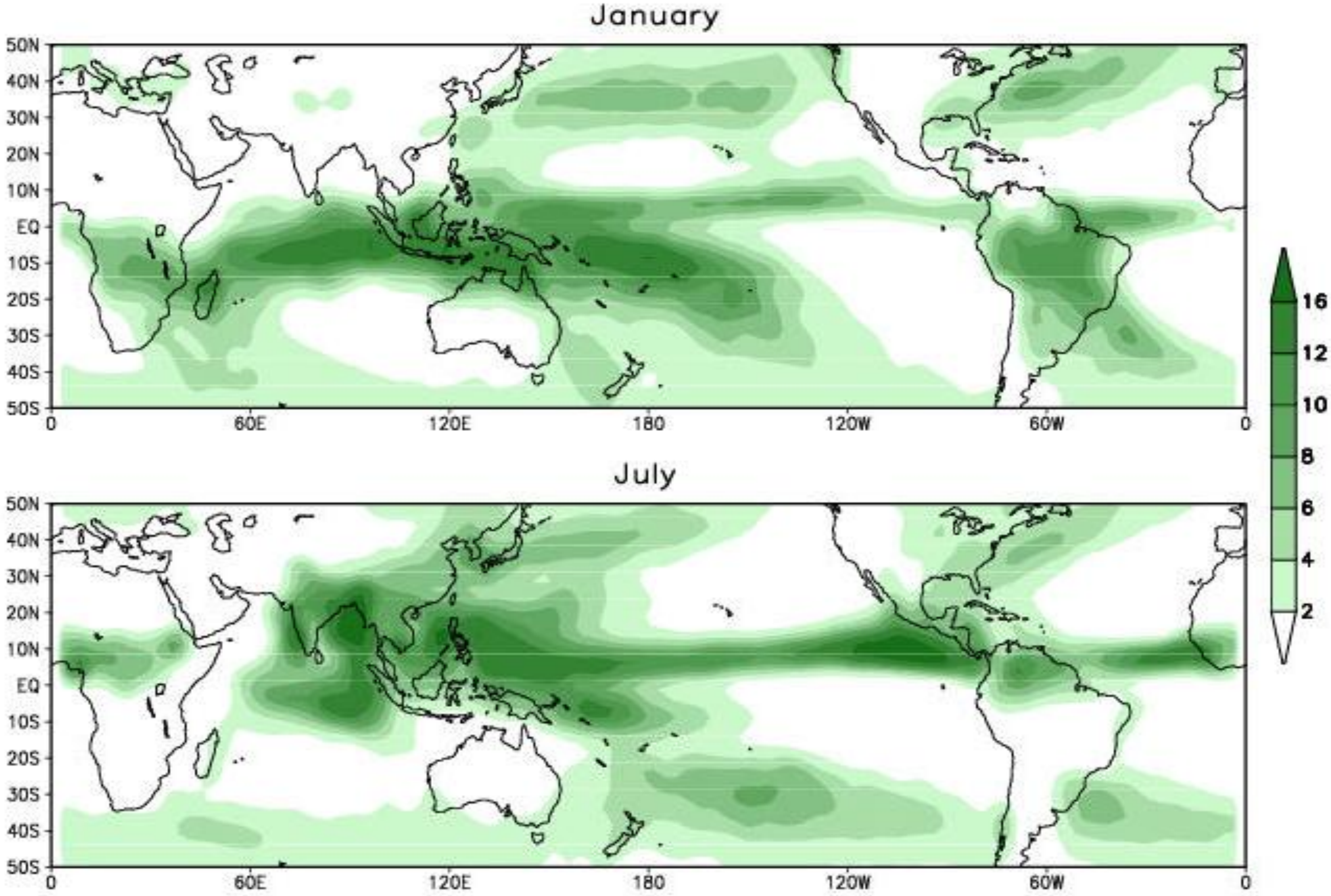
Precipitation (mm day^{-1})



Climatological mean precipitation (mm day^{-1}) for January and July.

Very Wet in the tropics (ITCZ) & Monsoon Regions.

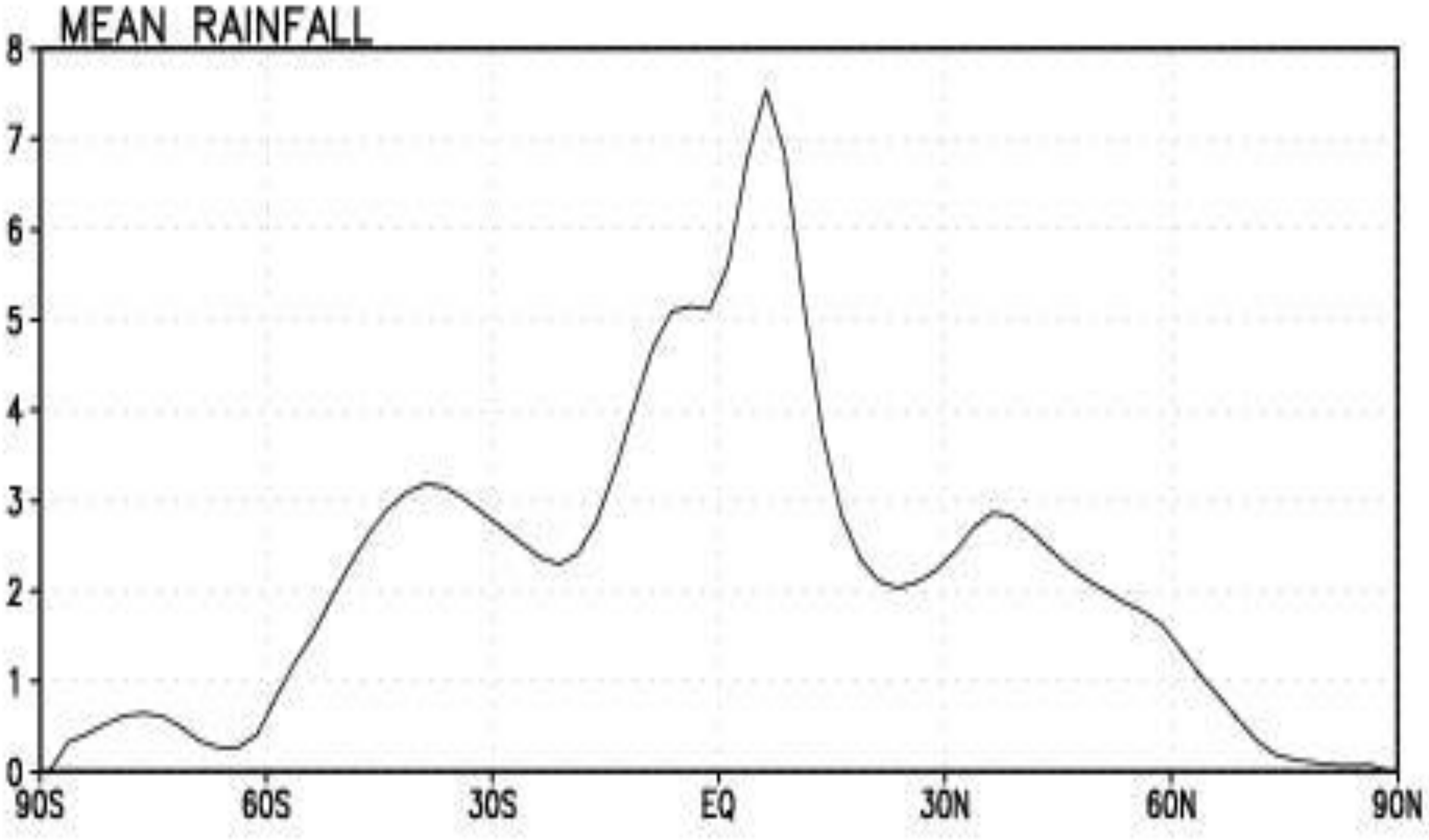
Seasonal Shift of the ITCZ.

Mid latitudes get more rain in the summer.

Storm tracks

More variability in the NH

Zonal Mean Annual Precipitation (mm day^{-1})



Some important features of the observed Mean condition of the atmosphere

- Surface **easterlies** in the tropics & surface **westerlies** in the middle latitudes

- **Westerly jet stream** in the upper atmosphere subtropics. Winter hemisphere jet tends to be stronger than the summer hemisphere one.

- **Easterly jet** in the upper atmosphere over the equatorial region during summer monsoon region

- Three cell meridional structure

Some important features of the observed Mean condition of the atmosphere (contd.)

- **Equator to pole temperature difference is about 60^0K in the winter hemisphere and about 35^0K in the summer hemisphere**

- **The temperature gradient in the meridional direction is weak in the tropics and strong in the middle latitude.**

- **Height of the tropopause is much lower in the polar region as compared to the equatorial region**

What drives this temperature and wind distribution in the Atmosphere?

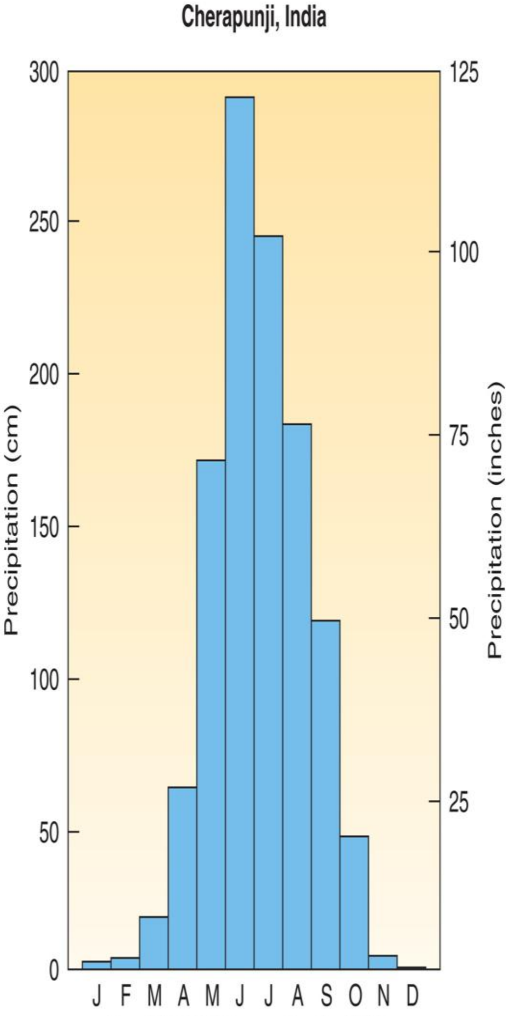
- Major Wind Systems of the Earth
  - *Monsoons*
    - Thermal induced seasonal wind patterns associated with shifts of the ITCZ
    - Monsoons are characterized by dry offshore winter flow and wet onshore summer flow
    - The monsoon in East Asia experiences orographic enhancement

Winter monsoon

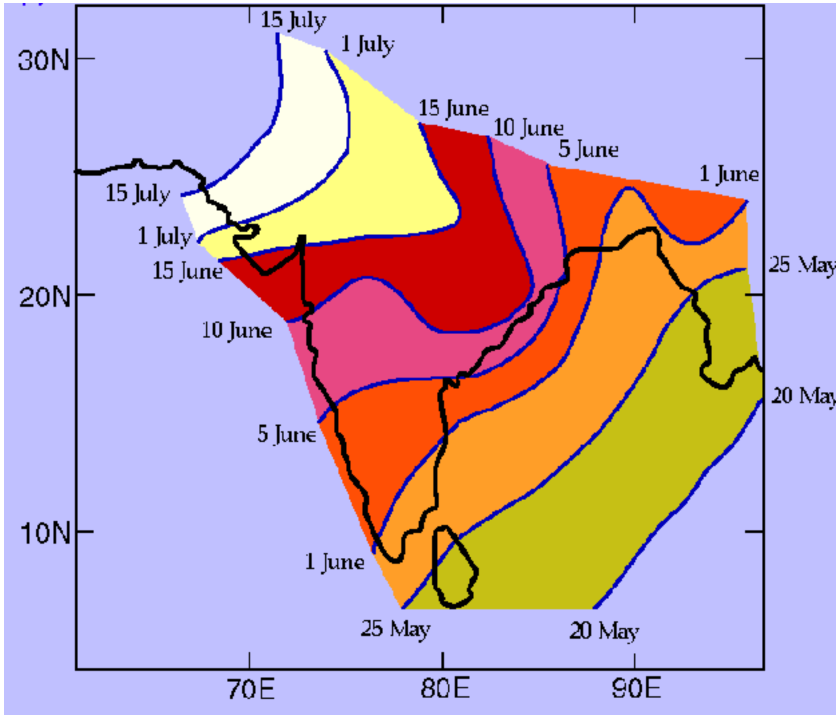
Summer
monsoon

Topography enhances monsoonal effects

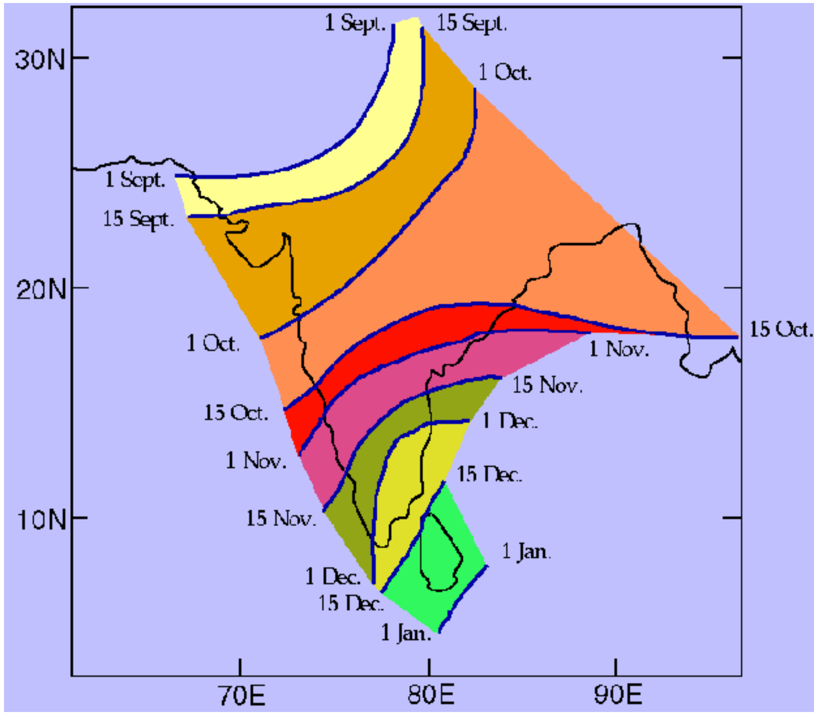
(b)



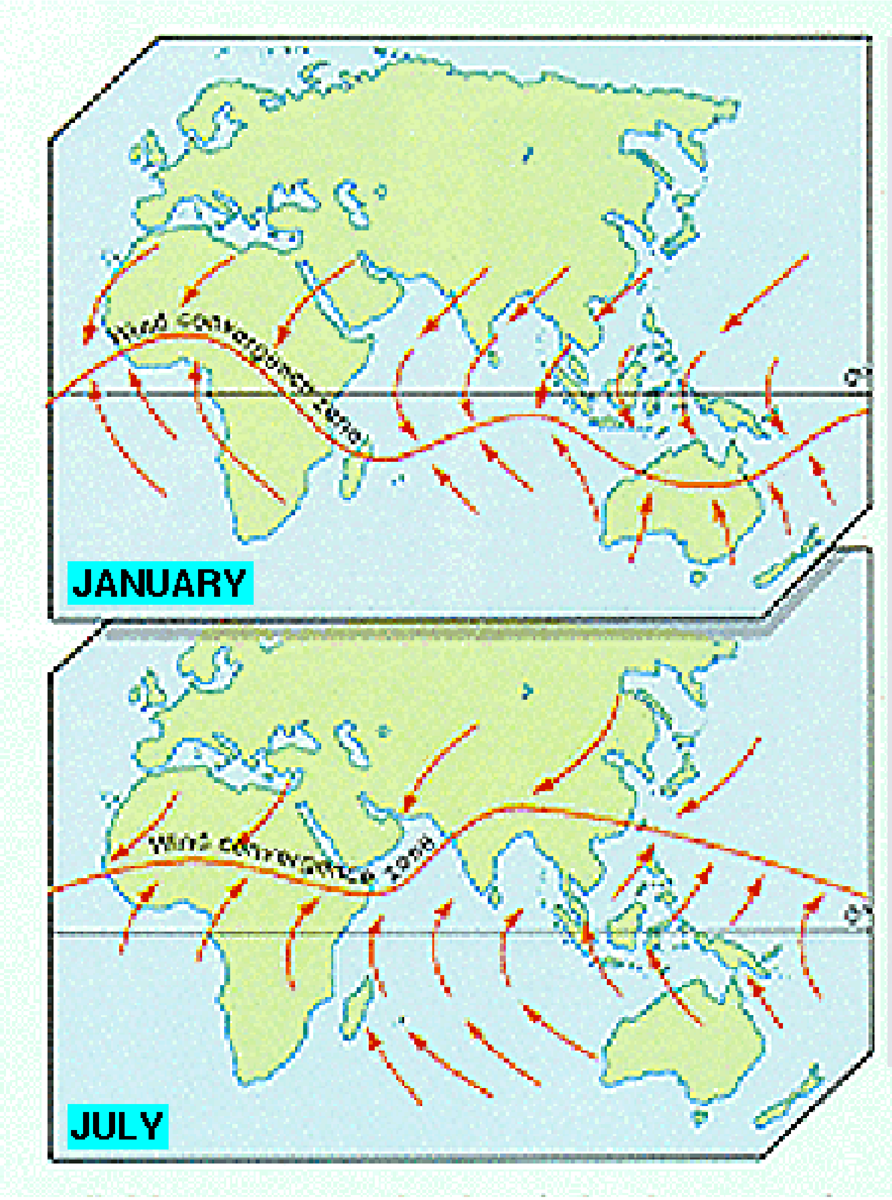
Onset of South-West Monsoon



Retreat of Monsoon



ITCZ



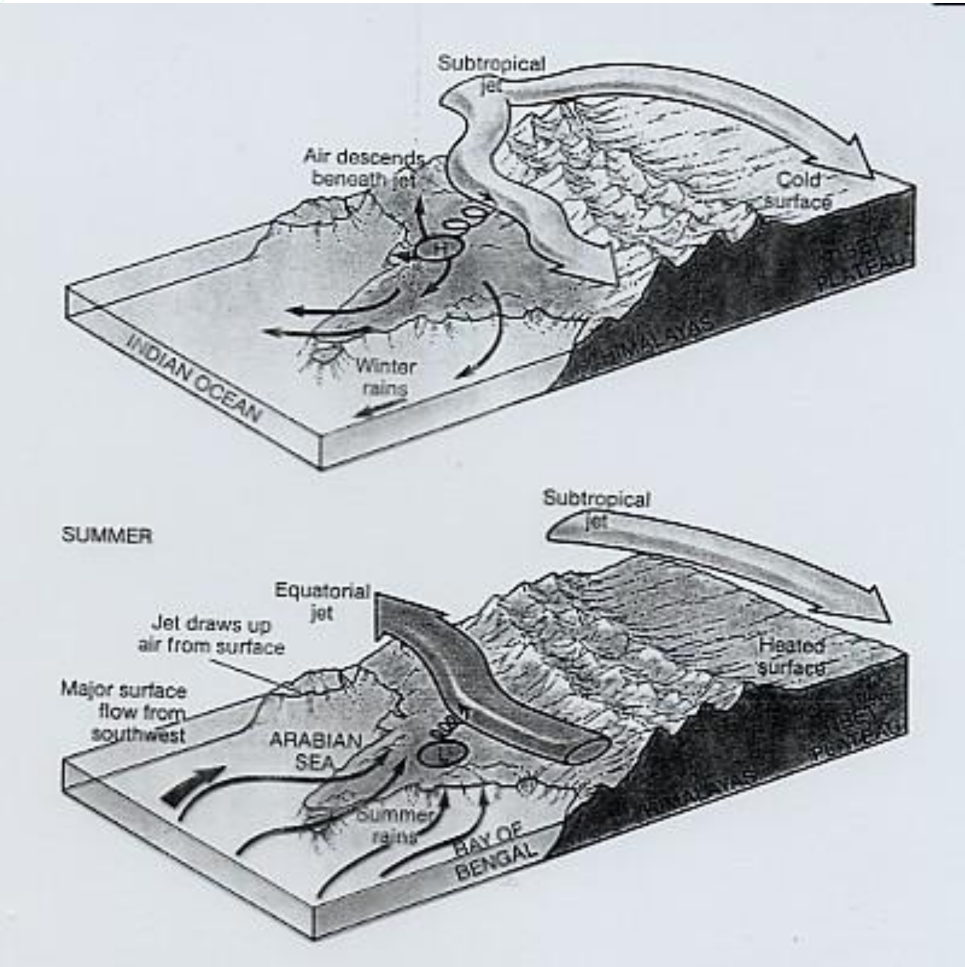
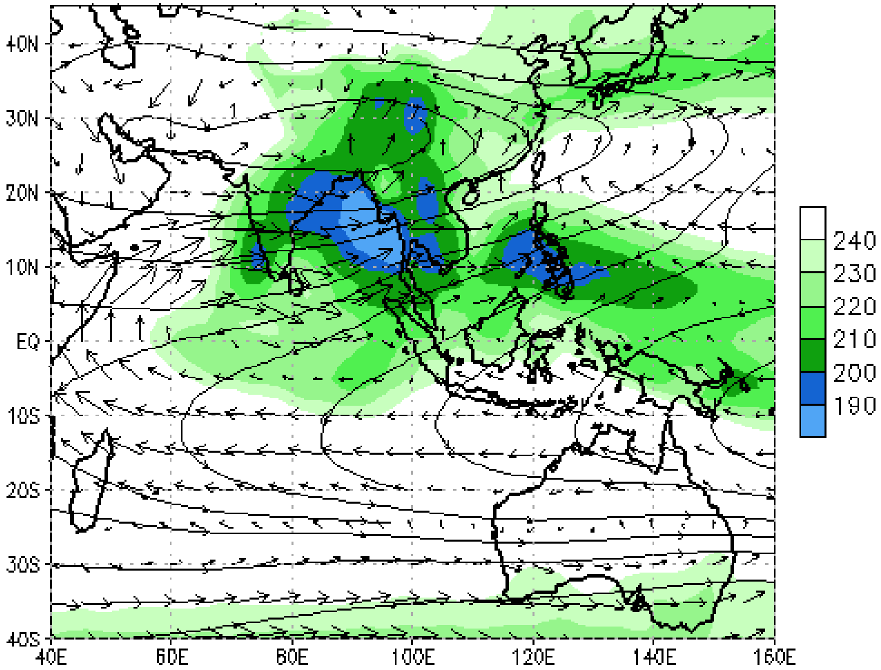


Figure 8-22 The seasonal monsoon of the Indian subcontinent in relation to the surface and upper troposphere winds.

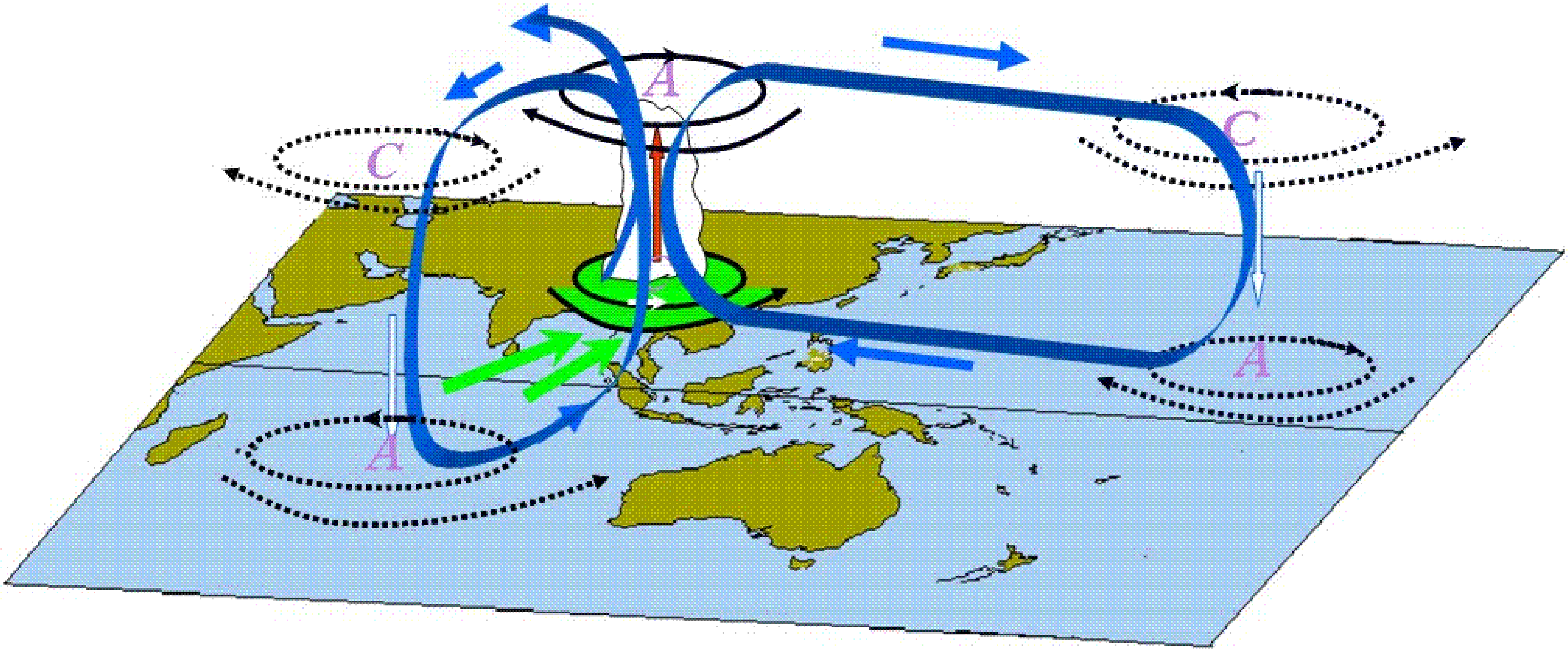


OLR, 200-hPa Streamlines and 850-hPa Wind Clim (1979-1995)

02JUL

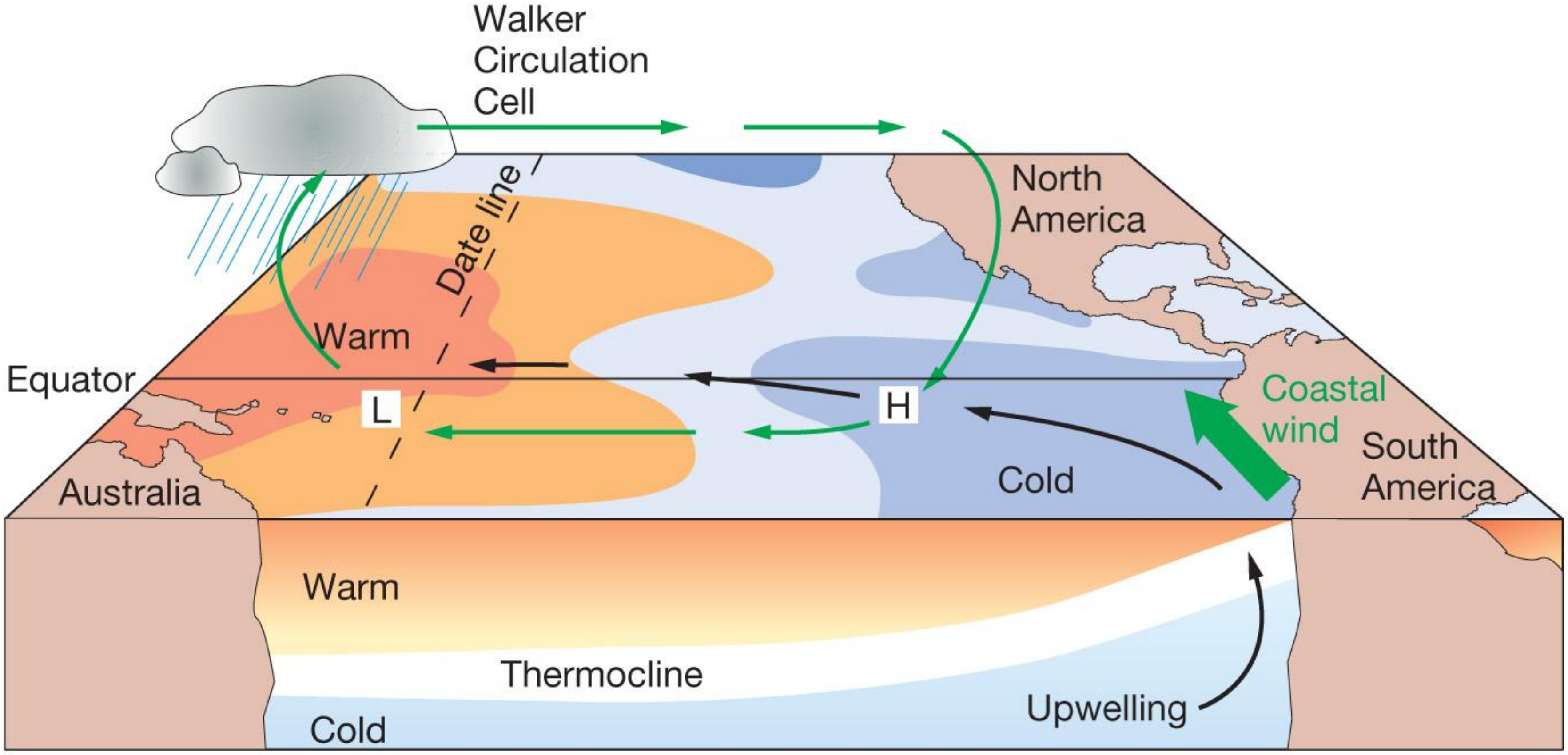
Data Sources: OLR – NESDIS/ORA, Winds – NCEP CDAS/ Reanalysis

Summer Broad-Scale Circulations



- Air-Sea Interactions in the Equatorial Pacific
  - El Niño, La Niña, and the Walker circulation
    - *El Niño* events
      - Unusually warm water in the eastern equatorial Pacific Ocean
      - Linked to global weather anomalies
      - 2 to 5 year recurrence
    - *La Niña* events -- wind and temperature patterns reversed of El Niño patterns
    - *Walker circulation*
      - Vertical and horizontal tropospheric flow in the equatorial Pacific that controls areas of heavy rainfall

Normal Conditions, Walker Circulation



(a) Normal conditions

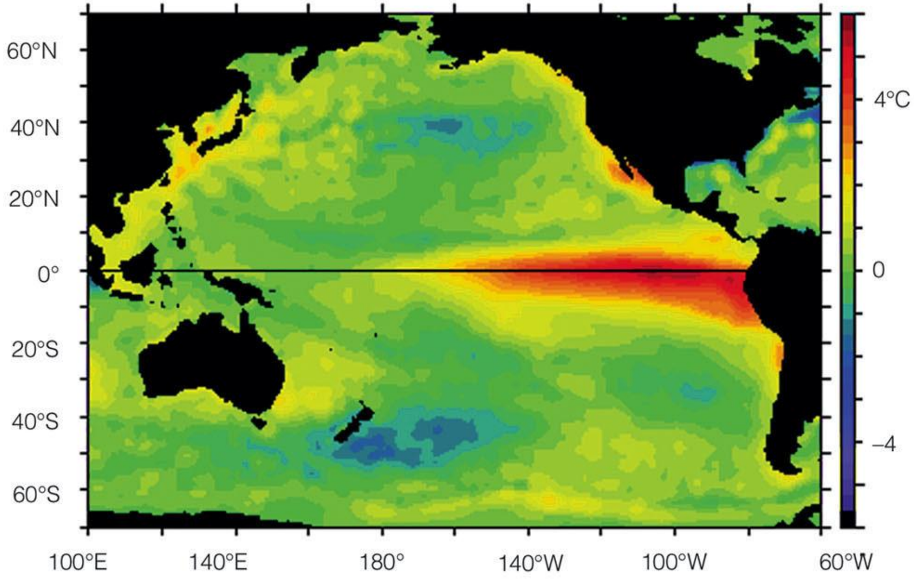
El Nino Animation

- http://esminfo.prenhall.com/science/geoanimations/animations/26_NinoNina.html

GEOSCIENCE
Animations

ENSO (El Niño/Southern Oscillation) events -- oscillations between El Niño and La Niña conditions

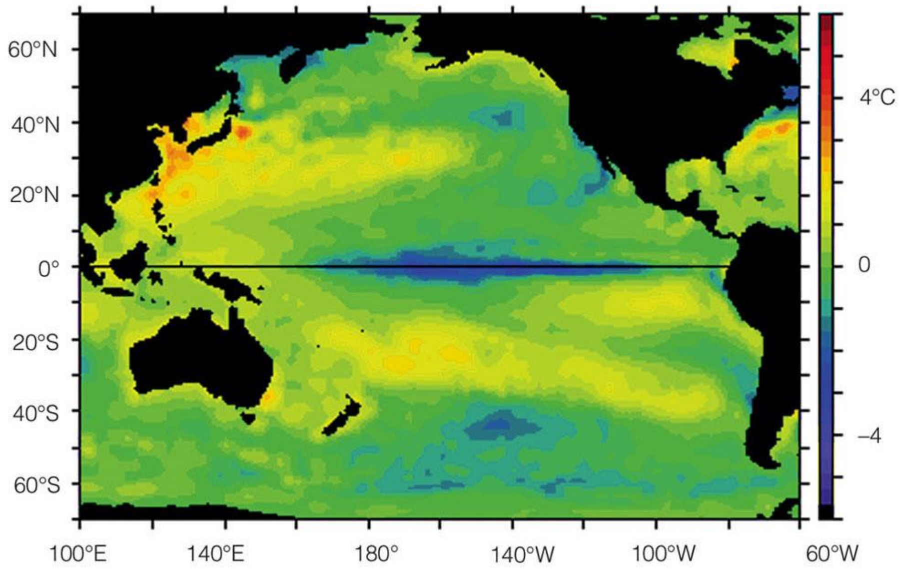
ENSO results in global *teleconnection* patterns (weather effects far from the equatorial Pacific)



(a) El Niño Conditions, December, 1997

El Nino

© Brooks/Cole, Cengage Learning

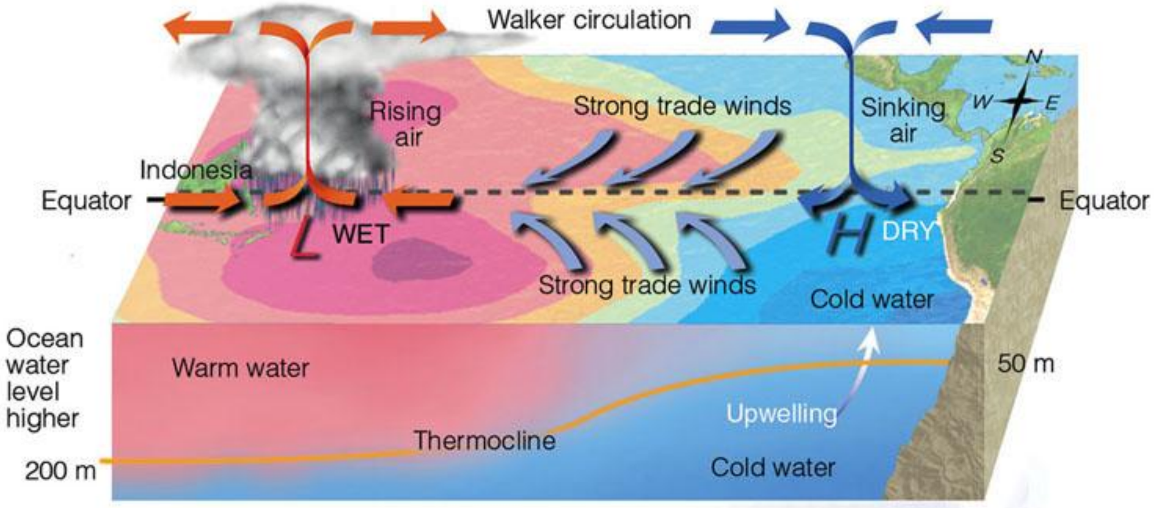


(b) La Niña Conditions, December, 1998

La Nina

© Brooks/Cole, Cengage Learning

El Nino & La Nina

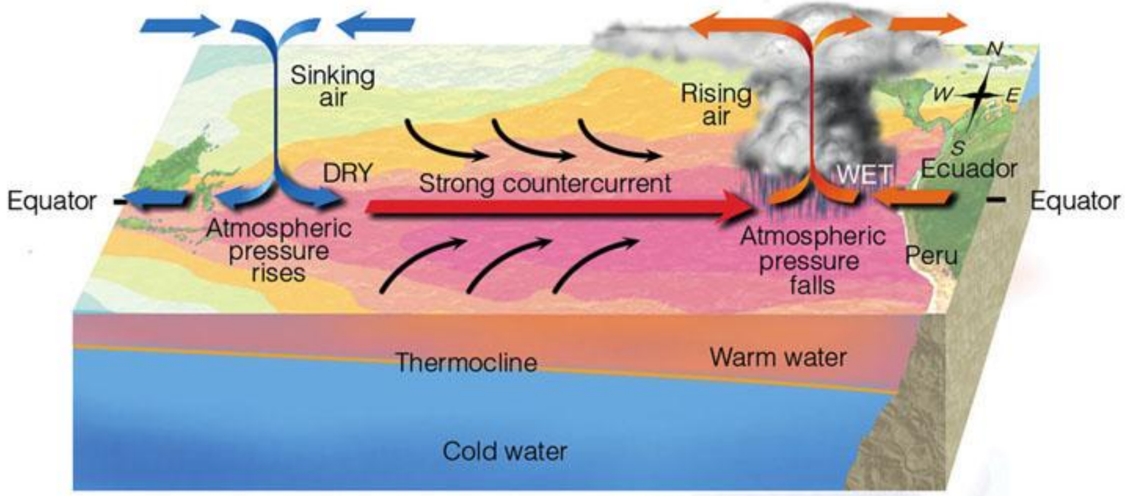


(a) Non-El Niño conditions

Non-El Nino:

Upwelling and cooler water in eastern Pacific

Warmer water in western Pacific



(b) El Niño Conditions

© Brooks/Cole, Cengage Learning

El Nino:

Change in pressure causes trades to reverse

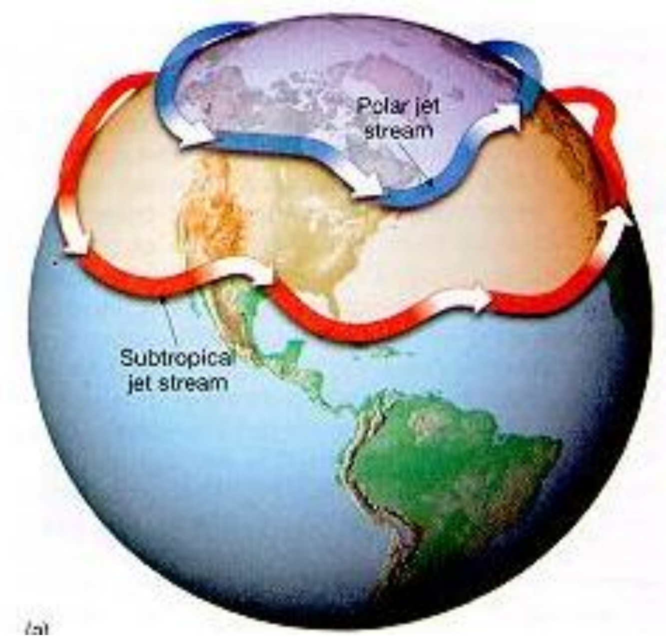
Reverses figure above - warmer in eastern Pacific

Causes of Weather

- *Energy flow along gradient*
  - *Temperature differences*
  - *Pressure differences*
  - *Moisture differences*
  - *The bigger the difference, the stronger the wind and other weather effects.*

Large Scale Influences

- *Prevailing Wind: SW.*
- *Jet Stream.*
- *Mountain Ranges.*
- *Ocean and Lakes.*
- *Season.*

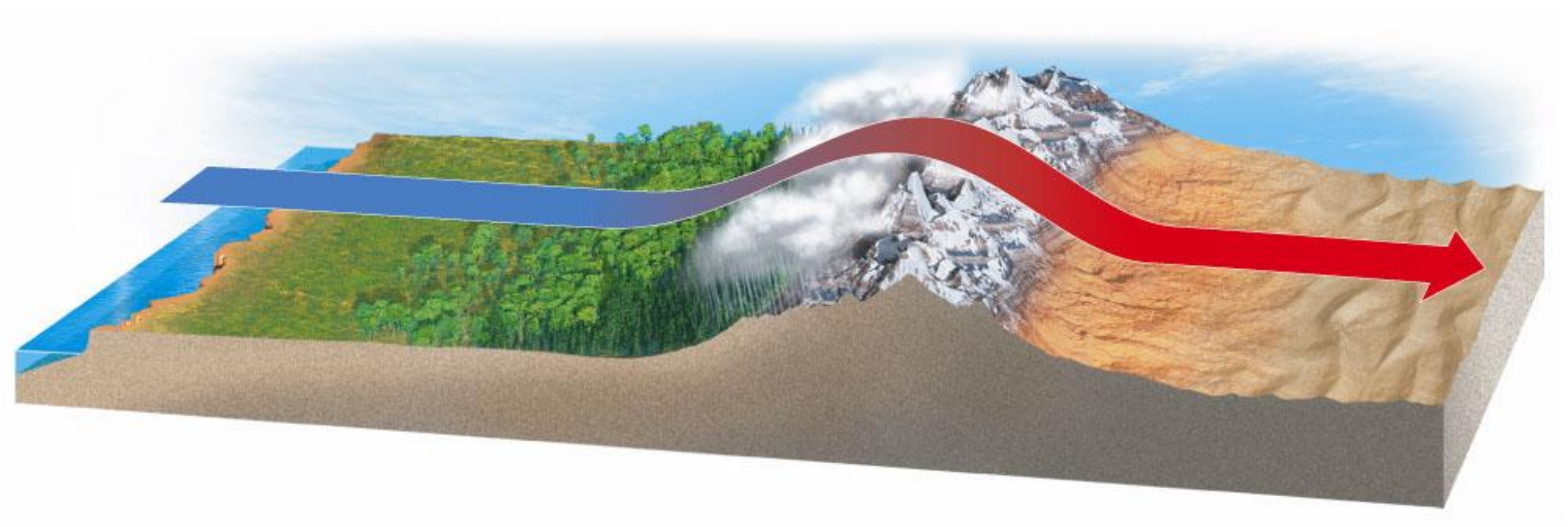


http://www.crystalinks.com/jetstream.html

Prevailing winds pick up moisture from an ocean.

On the windward side of a mountain range, air rises, cools, and releases moisture.

On the leeward side of the mountain range, air descends, warms, and releases little moisture.

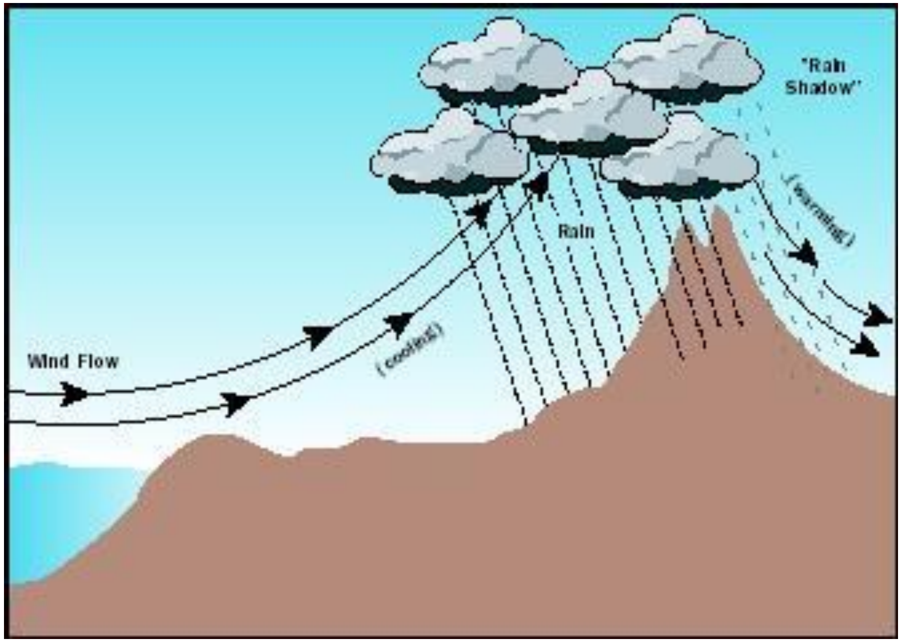


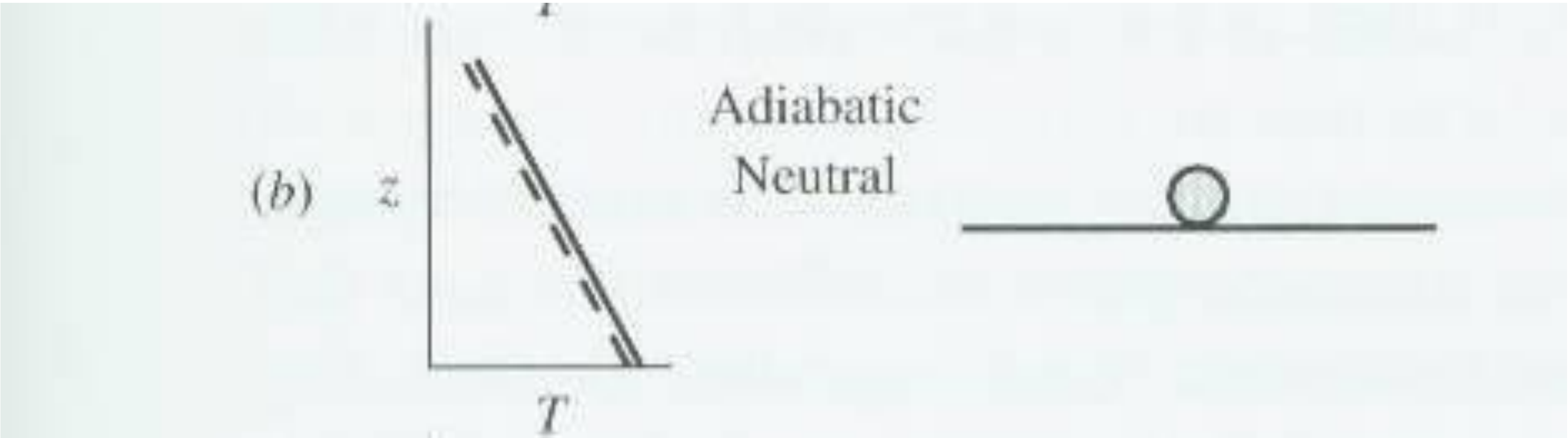
Rain Shadow Effect

Fig. 7-7, p. 145

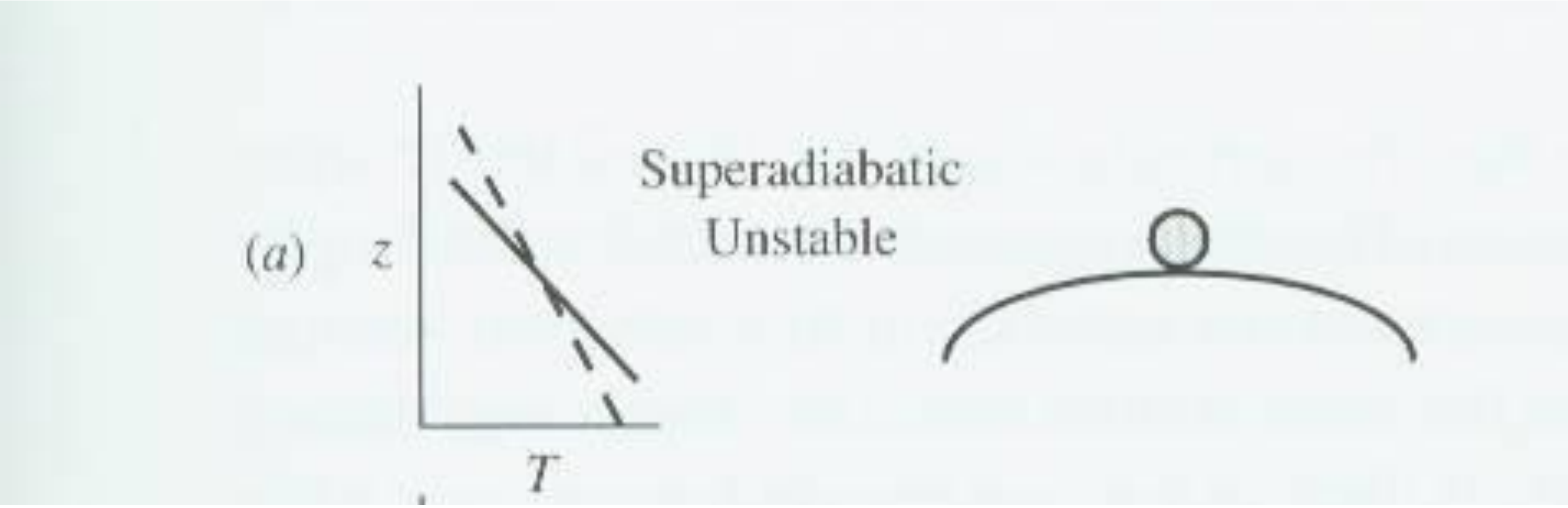
Small Scale Influences

- *Local topography*
  - *Orographic Lifting*
  - *Elevation*
  - *“Rain Shadow”*
  - *“Chinook”*
- *Time of day*
  - *Up slope winds in morning.*
  - *Afternoon thunderstorms build above ridges.*
  - *Down slope winds at night.*
  - *Quiet times at sunrise and sunset*
- *Season*

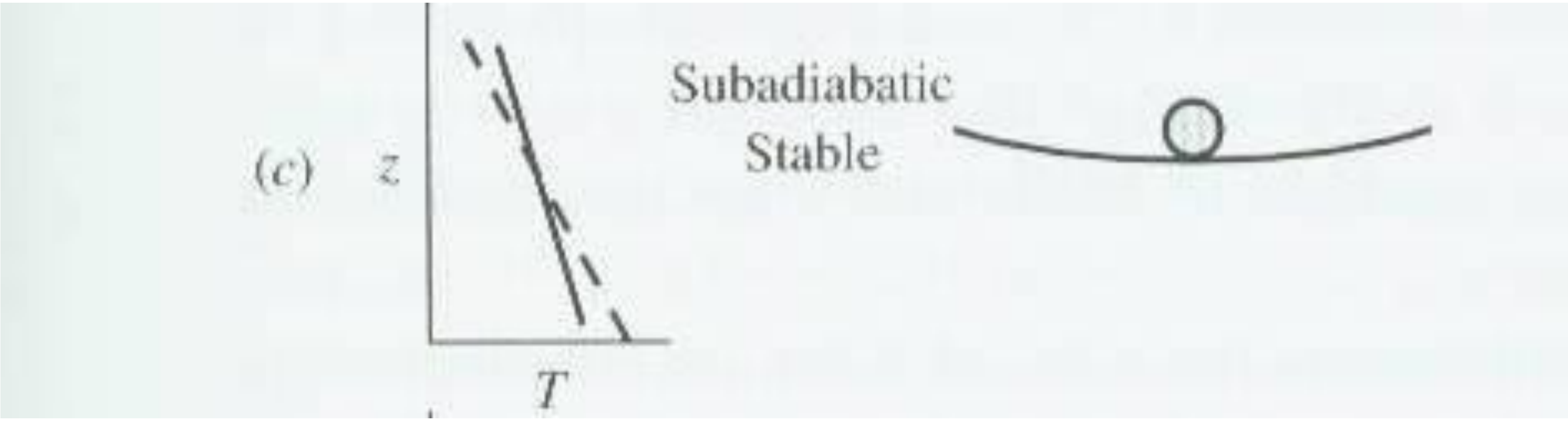




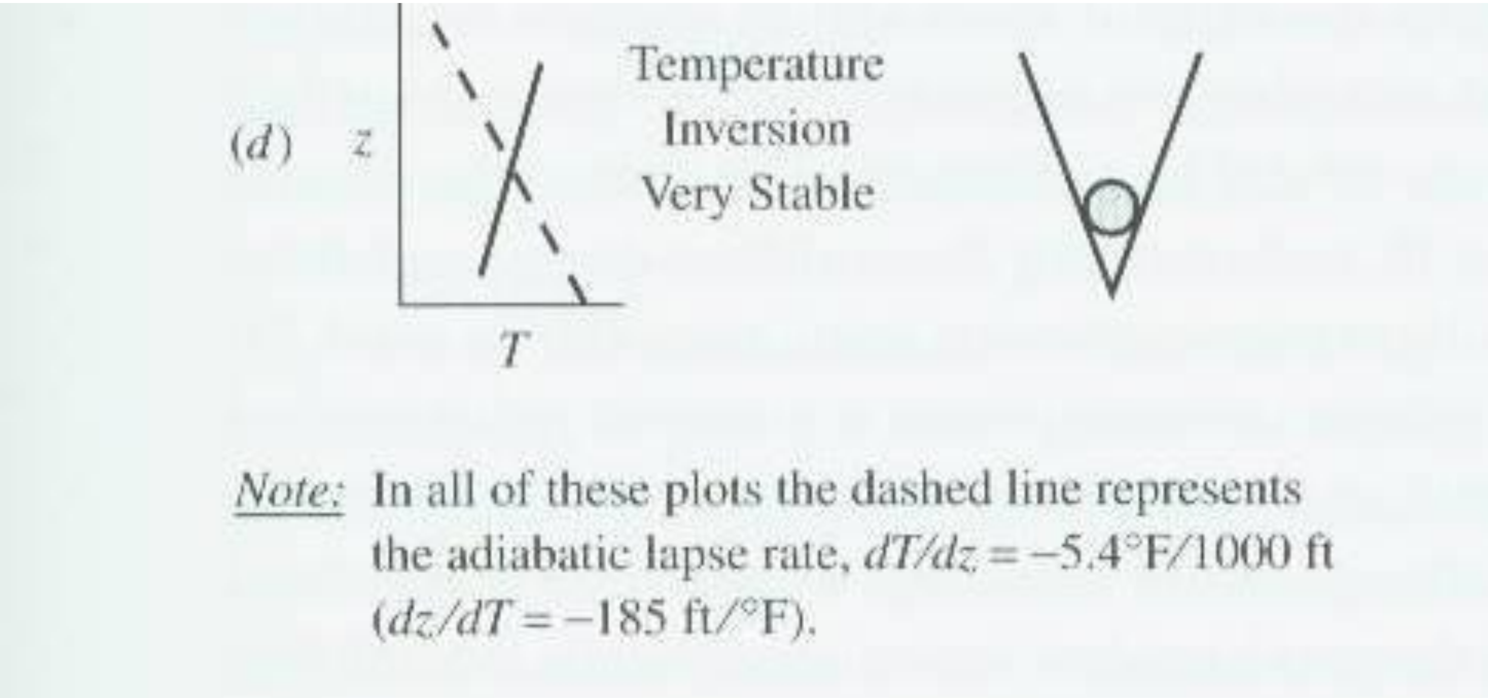
- **Neutral**
  - Environmental lapse rate is same as the dry adiabatic lapse rate
  - A parcel of air carried up or down will have same temp as environment at the new height
  - No tendency for further movement



- **Superadiabatic --- Unstable**
  - Environmental lapse rate > Γ
  - i.e. Actual temp. gradient is more negative
  - Small parcel of air displaced approximates adiabatic expansion
  - Heat transfer is slow compared to vertical movement
  - At a given point, $T_{parcel} > T_{surrounding\ air}$
    - less dense than surrounding air
  - Parcel continues upward

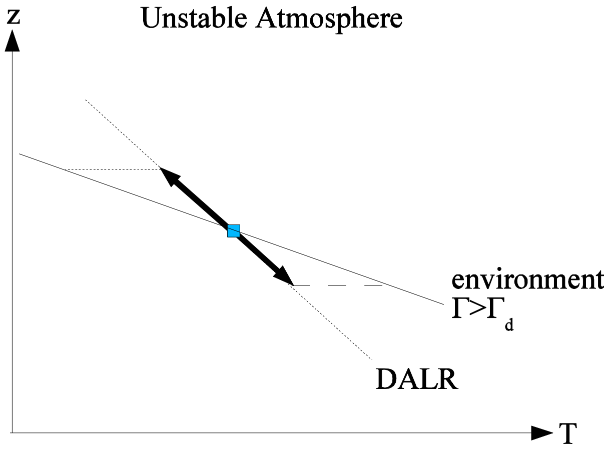


- **Subadiabatic --- Stable**
  - Environmental lapse rate < Γ
  - greater temp. gradient
  - No tendency for further vertical movement due to temp. differences
  - Any parcel of air will return to its original position
  - Parcel is colder than air above – moves back



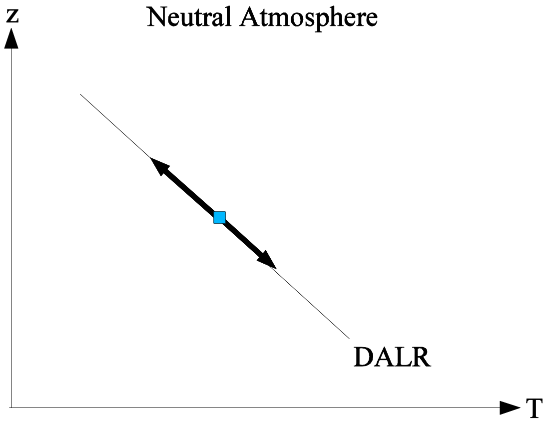
Note: In all of these plots the dashed line represents the adiabatic lapse rate, $dT/dz = -5.4°\text{F}/1000$ ft ($dz/dT = -185$ ft/°F).

- **Inversion --- Strongly Stable**
  - Environmental lapse rate is negative
  - Temp. increases with height
  - No tendency for further vertical movement due to temp. differences
  - Any parcel of air will return to its original position
  - Parcel is colder than air above – moves back
  - Concentrates pollutants

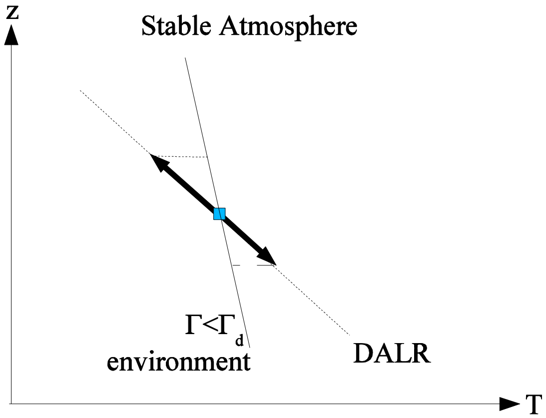


Actual/Environmental lapse rate = 6.5 K/km
Dry adabatic lapse rate= 9.8 K/km
Wet/Moist adabatic lapse rate= 5 K/km

If $\partial\theta/\partial z < 0$, i.e. θ decreases with height, the atmosphere is said to be **unstable, statically unstable, or unstably stratified**.



If $\partial\theta/\partial z = 0$, the atmosphere is said to be **neutral**,or **neutrally stratified,** and the lapse rate is equal to the dry adiabatic lapse rate (DALR) Γ_d ~= 10 K km^{-1} i.e. the temperature decreases by 10 K every km.



If $\partial\theta/\partial z > 0$, i.e. θ increases with height, the atmosphere is said to be **stable, statically stable, or stably stratified**.

Cloud Development

- Clouds form as air rises, expands and cools
  - Once T cools to T_D then condensation can take place
  - Water *vapour* condenses onto particles (called cloud condensation nuclei) in the atmosphere to form cloud droplets
- What causes the air to rise?

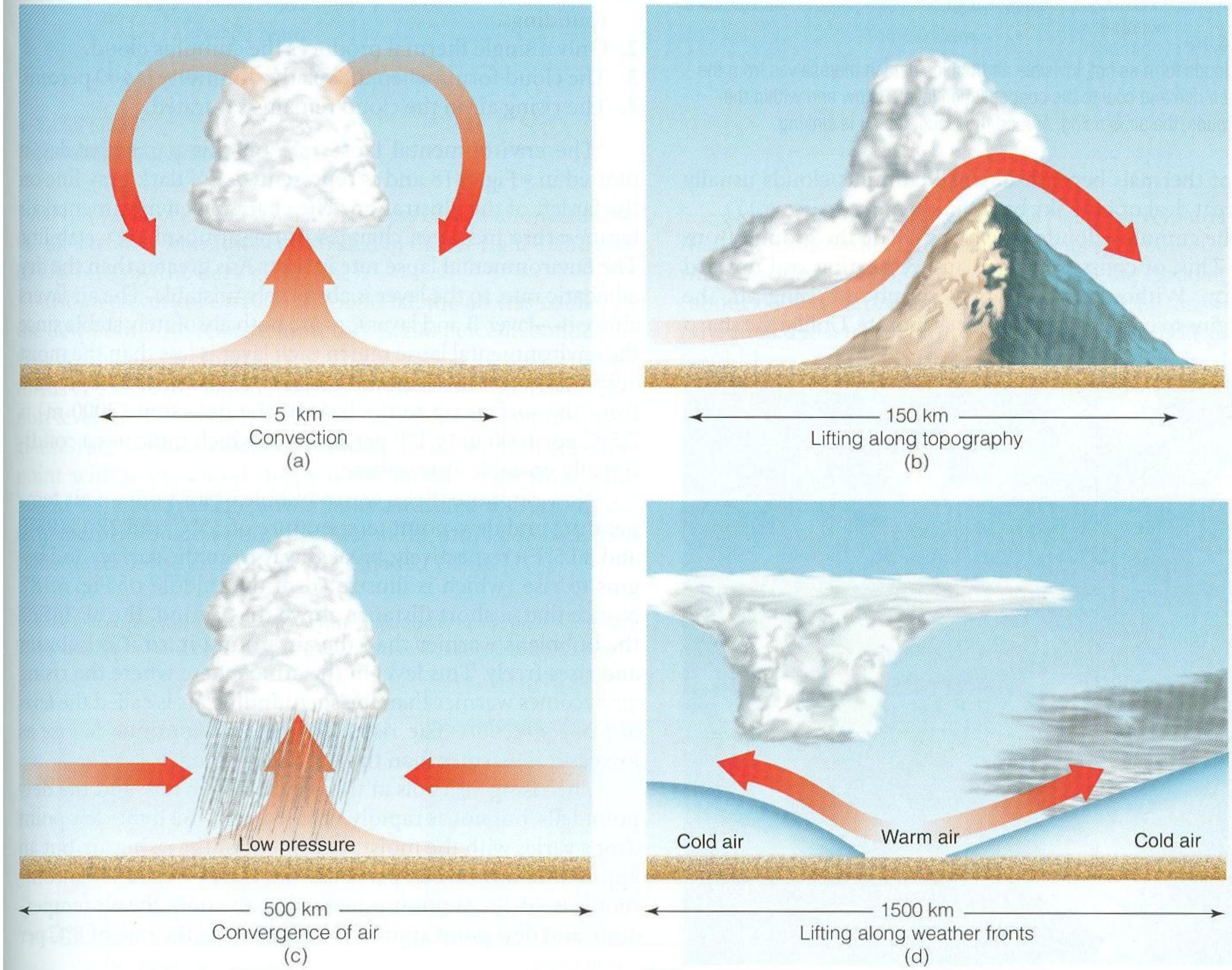
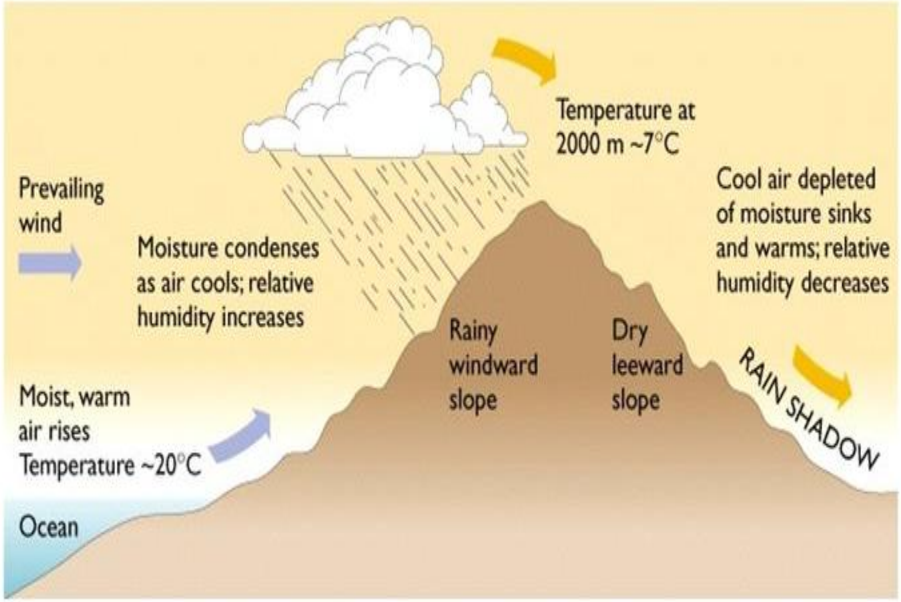


FIGURE 6.15

The primary ways clouds form: (a) surface heating and convection; (b) forced lifting along topographic barriers; (c) convergence of surface air; (d) forced lifting along weather fronts.

Mountain Precipitation

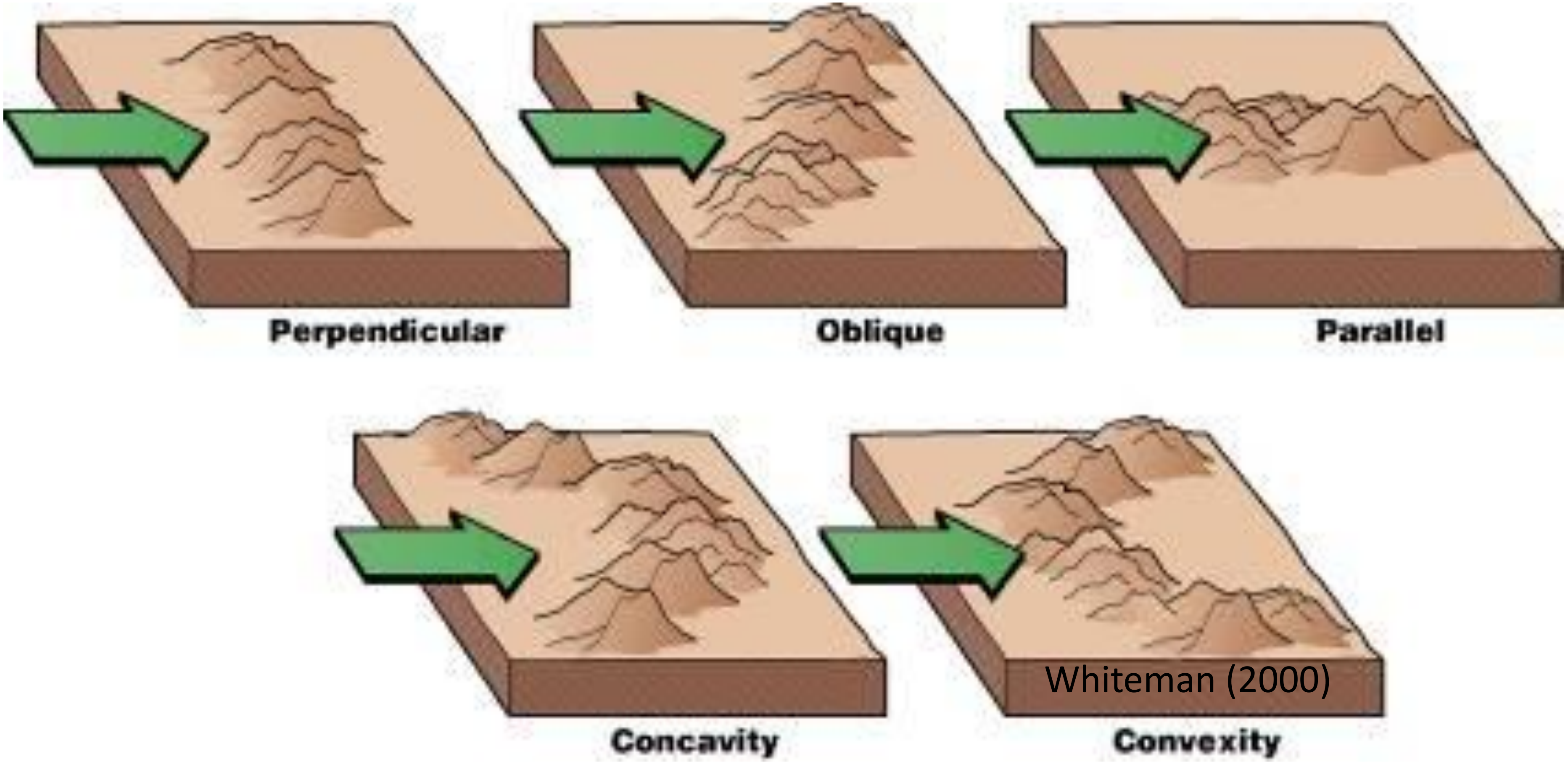
- As air is lifted by the mountain, water vapor can condense into a cloud. There are a couple of processes that change these clouds droplets into much bigger rain droplets. Precipitation can happen if the rain droplets get too heavy. These raindrops then fall to the ground as rain!
- Once the air makes it over the mountain, it sinks and warms.
- Since the air on the other side has less moisture and the air is sinking, clouds are not likely to form. This leaves the back side of the mountains often dry and desert-like.



Sometimes Mountains Create Warm Winds

- http://www.usatoday.com/weather/wdnslope.htm

Winds and Mountain Range Shape



Perpendicular

Oblique

Parallel

Concavity

Convexity

Whiteman (2000)

- The direction of the winds relative to the shape of the mountain range will affect the way that winds move over the mountains. The best way to lift the air is to have the winds move perpendicular to the mountain range.

- *Foehn* winds are strong, downslope winds that adiabiatically compress, raising the air temperature. Foehn winds are associated with hot, dry, clear weather
- *Chinook* winds are foehn winds along the east slope of the Rockies (“snow eaters”)
- *Santa Ana* winds are foehn winds that blow from the deserts and over the mountains into the valleys of southern and central California
- *Katabatic* winds are cold, dense winds that flow down mountain slope. They warm as they descend, but they are still colder than the surrounding air.
  - *Boras* and *mistral* winds are forms of katabatic winds in Europe

- *Sea* and *land breezes* form due to temperature differences over land and sea. Sea breezes form during the day, and land breezes form at night.

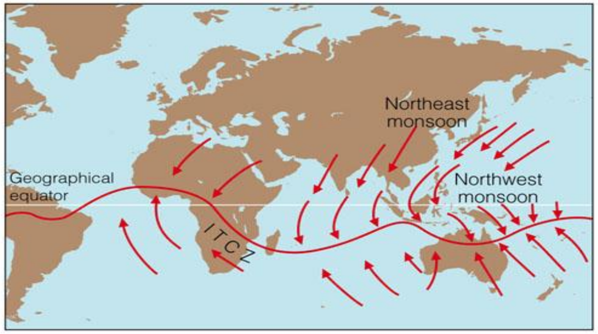
- *Valley* and *mountain breezes* form due to heating and cooling on mountain sides. Valley breezes form during the day, and mountain breezes form at night (similar to katabatic winds)

Monsoons Are Wind Patterns That Change with the Seasons

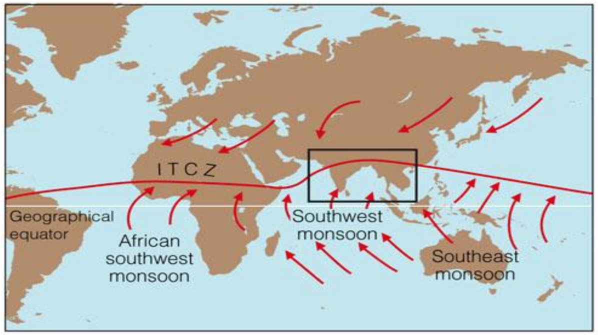
Monsoons are patterns of wind circulation that change with the season. Areas with monsoons generally have dry winters and wet summers.

Sea breeze is cool air from over the water moving toward land. Sea breezes occur after sunrise.

Land breezes occur after sunset when air warmed by the land blows toward the water.



a January



b July
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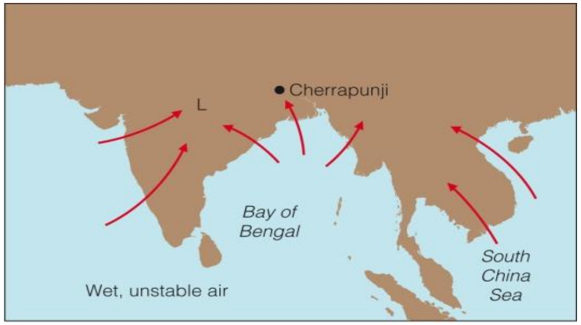

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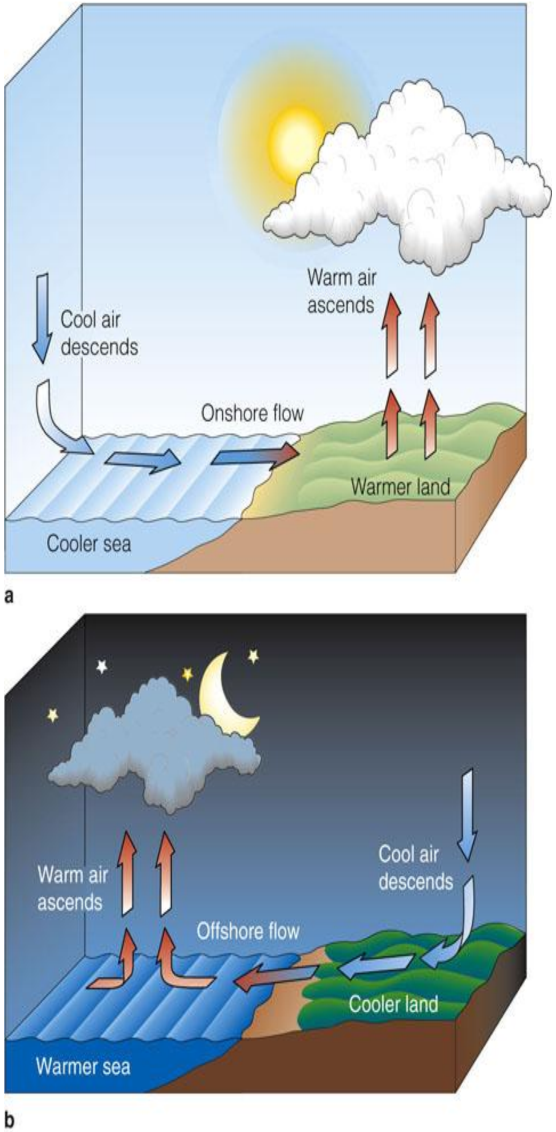

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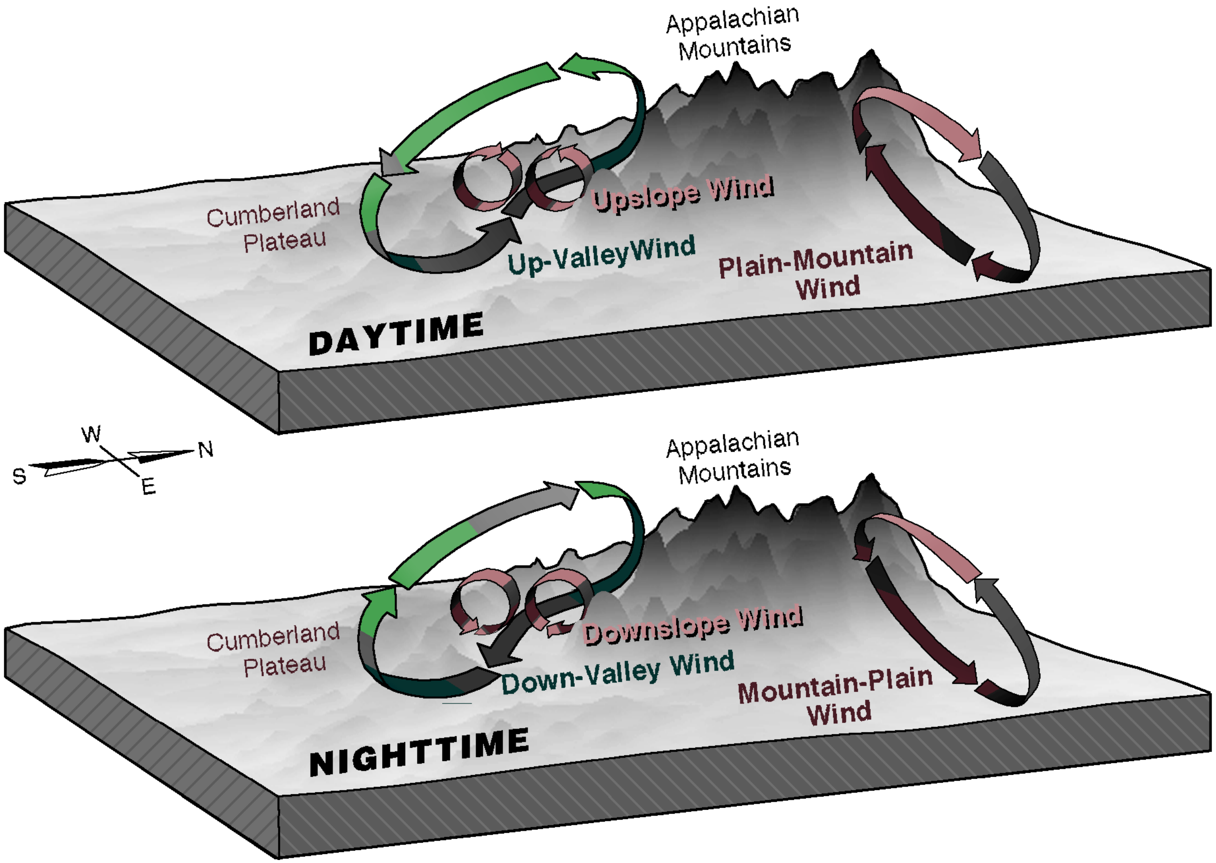
Diurnal mountain wind systems/Valley and mountain breeze development

During the day, the sun heats the ground and the ground heats the air. This warm thin layer of air on the mountain slopes rises up the mountain side creating an “Upslope Flow.”

At night, the sun no longer shines on the mountainside and the air on the mountain slopes begins to cool down. This cool air slides down the mountain slope and is called the “down slope flow or drainage flow.”



Whiteman (2000)

Lee Troughing and PV

- Conservation of potential vorticity

$$P \equiv (\zeta_\theta + f)\left(-g\frac{\partial\theta}{\partial p}\right)$$ Ertel Potential Vorticity

  - conserved for adiabatic frictionless motion
    - Ratio of absolute vorticity and depth of vortex

$$P = (\zeta_z + f)/h = \mathrm{Const}$$ Potential Vorticity

  - for a homogeneous incompressible fluid
    - ζ evaluated at constant height

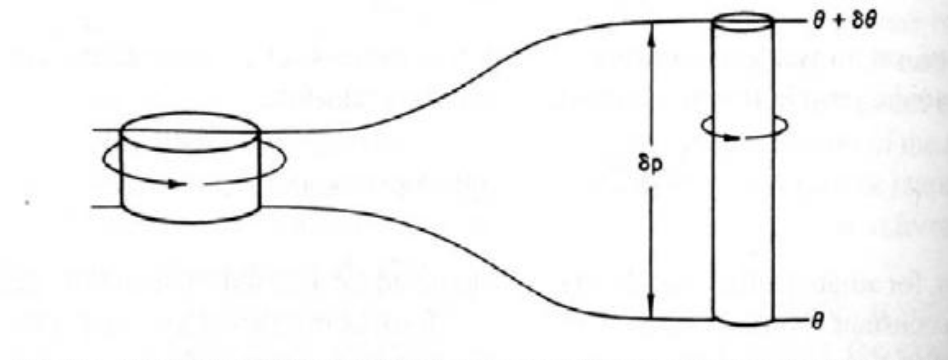


Fig. 4.7 A cylindrical column of air moving adiabatically, conserving potential vorticity.

(Holton 2004, p. 96)

- Conservation of potential vorticity
  - When the depth of the vortex changes following motion, its absolute vorticity must change to maintain conservation of potential vorticity

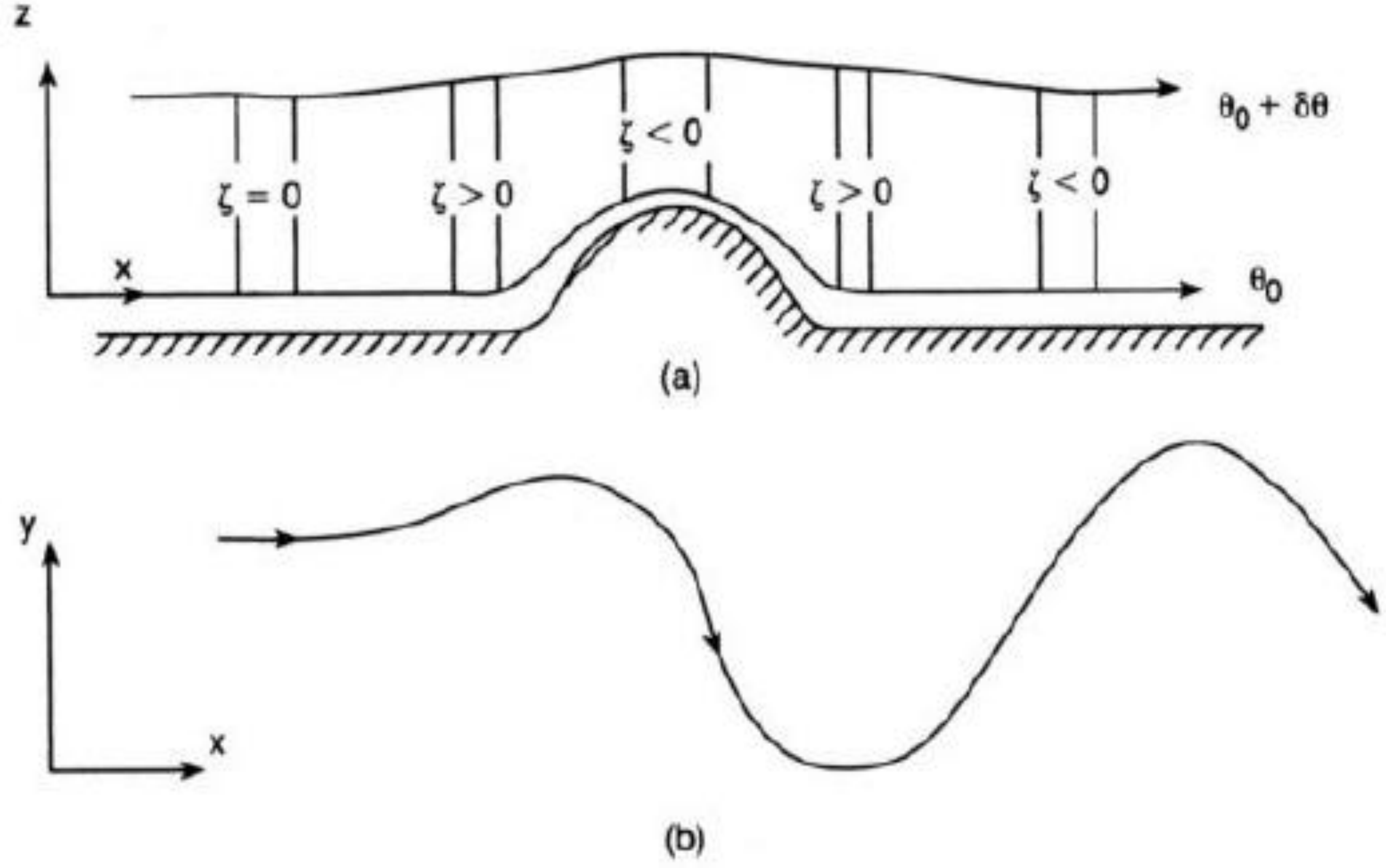


Fig. 4.9 Schematic view of westerly flow over a topographic barrier: (a) the depth of a fluid column as a function of x and (b) the trajectory of a parcel in the (x, y) plane.

(Holton 2004, p. 98)

- Conservation of potential vorticity
  - For westerly flow impinging on an *infinitely long* mountain range…
- (a) upstream, zonal flow is uniform ($\delta u/\delta y = 0$, $v=0$), $\zeta = 0$
- (b) deflection of upper θ surface upstream of barrier → increases *h* → absolute vorticity must increase → air column turns cyclonically

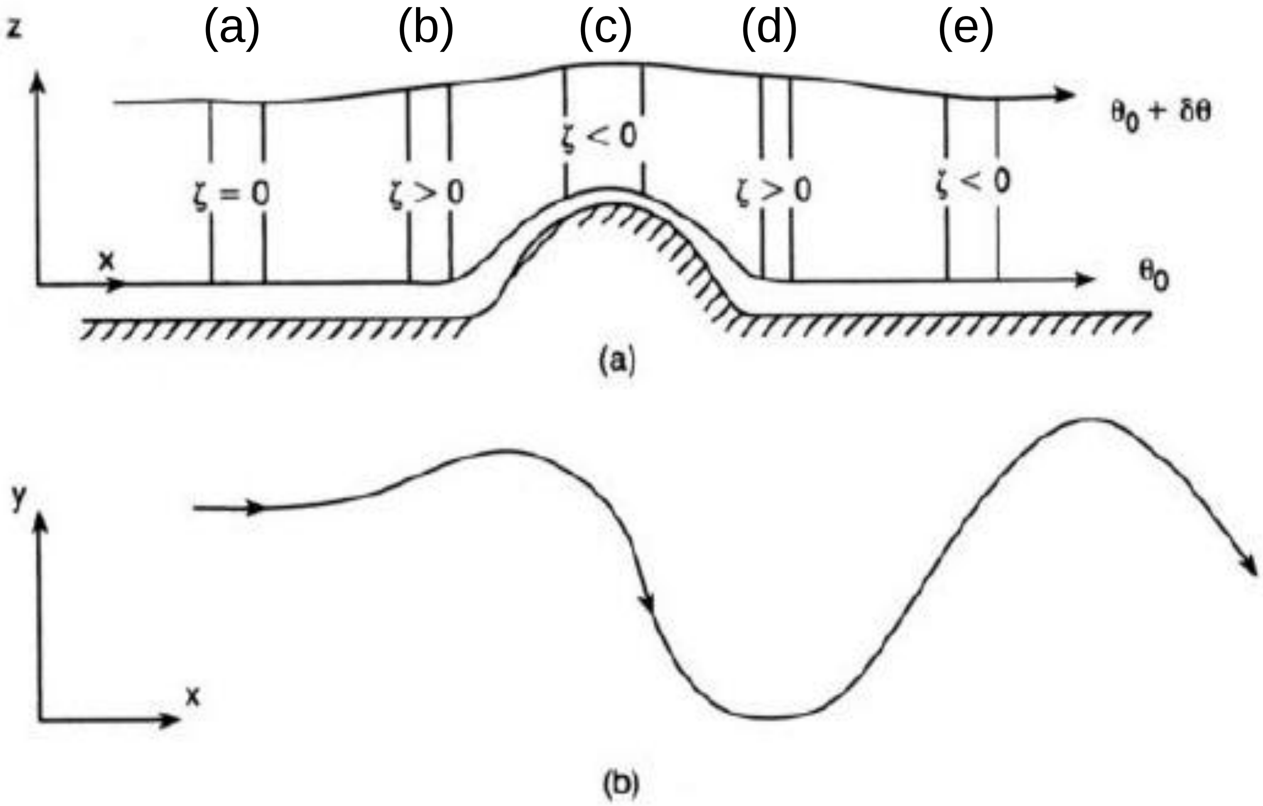


Fig. 4.9 Schematic view of westerly flow over a topographic barrier: (a) the depth of a fluid column as a function of x and (b) the trajectory of a parcel in the (x, y) plane.

(Holton 2004, p. 98)

  - poleward drift in (b) also causes increase in *f*
- (c) as column crosses mountain, *h* decreases → absolute vorticity must decrease → ζ becomes negative → air column drifts equatorward
- (e) alternating series of ridges and troughs downstream of mountain range
- cyclonic flow pattern immediately to the east of the mountains (*lee side trough*)

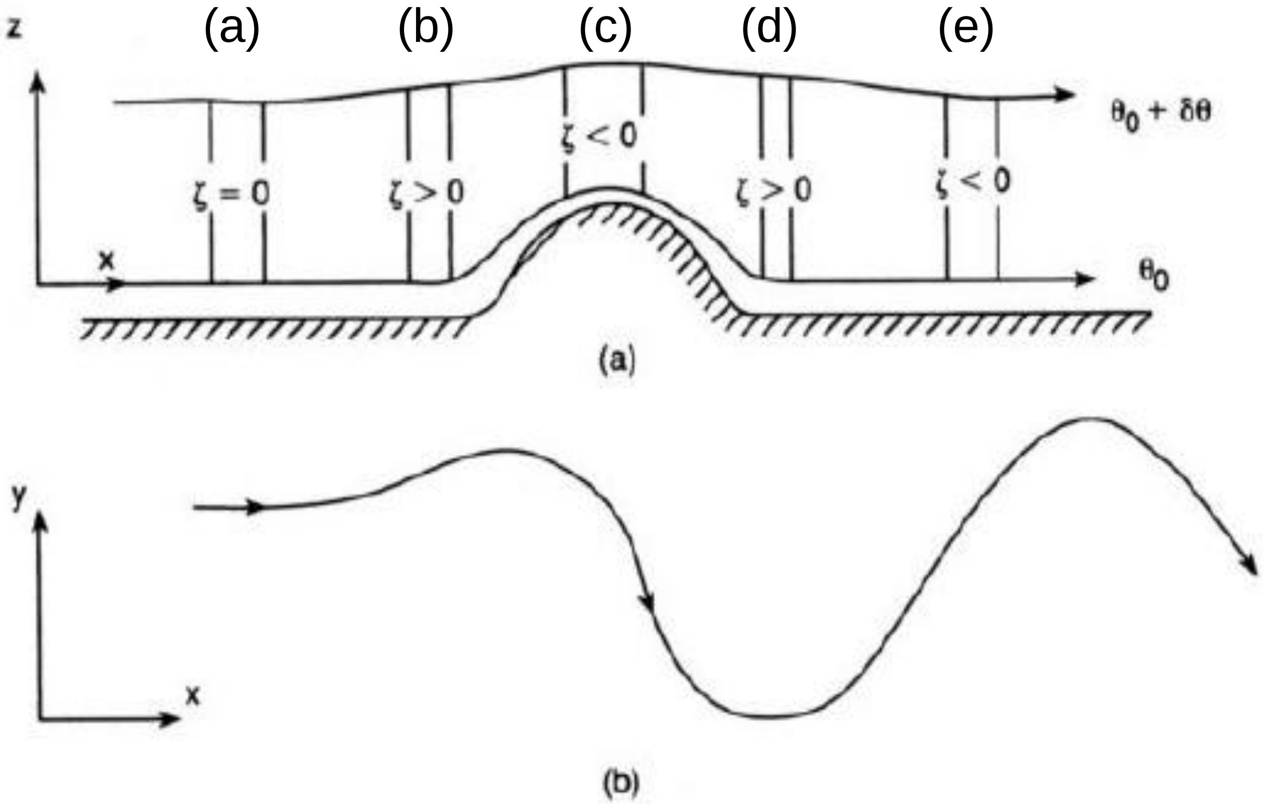
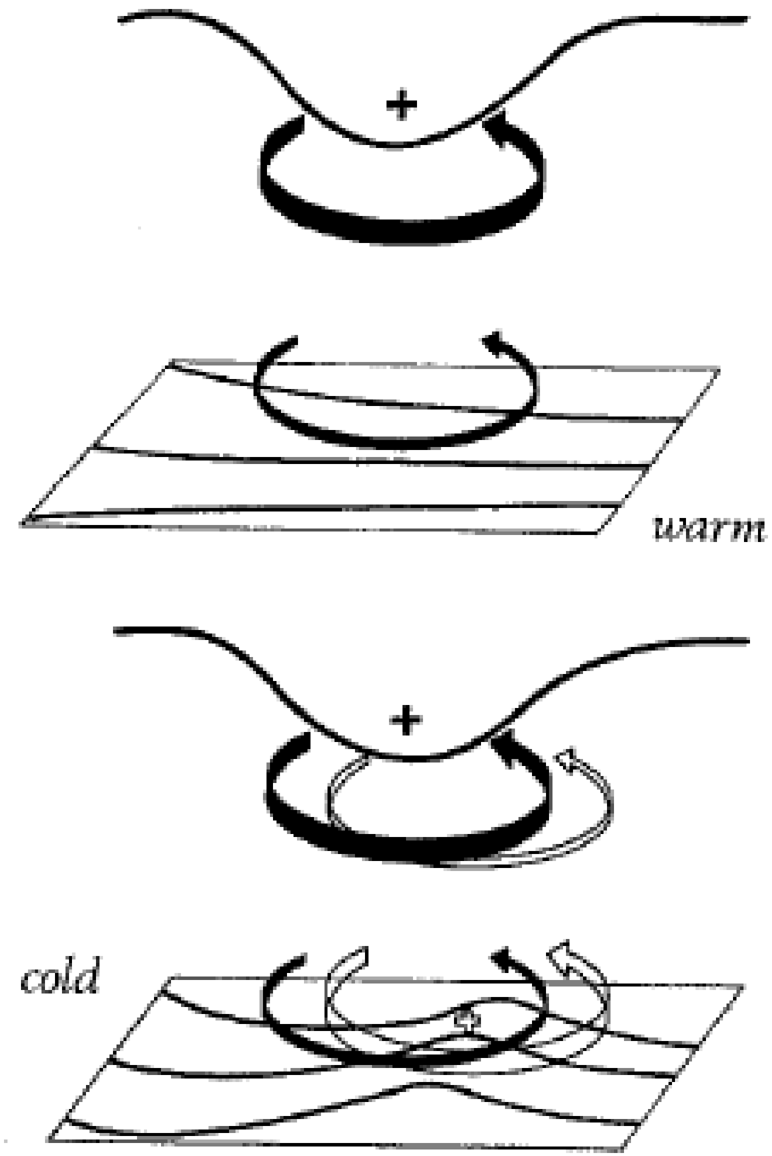


Fig. 4.9 Schematic view of westerly flow over a topographic barrier: (a) the depth of a fluid column as a function of x and (b) the trajectory of a parcel in the $(x,\ y)$ plane.

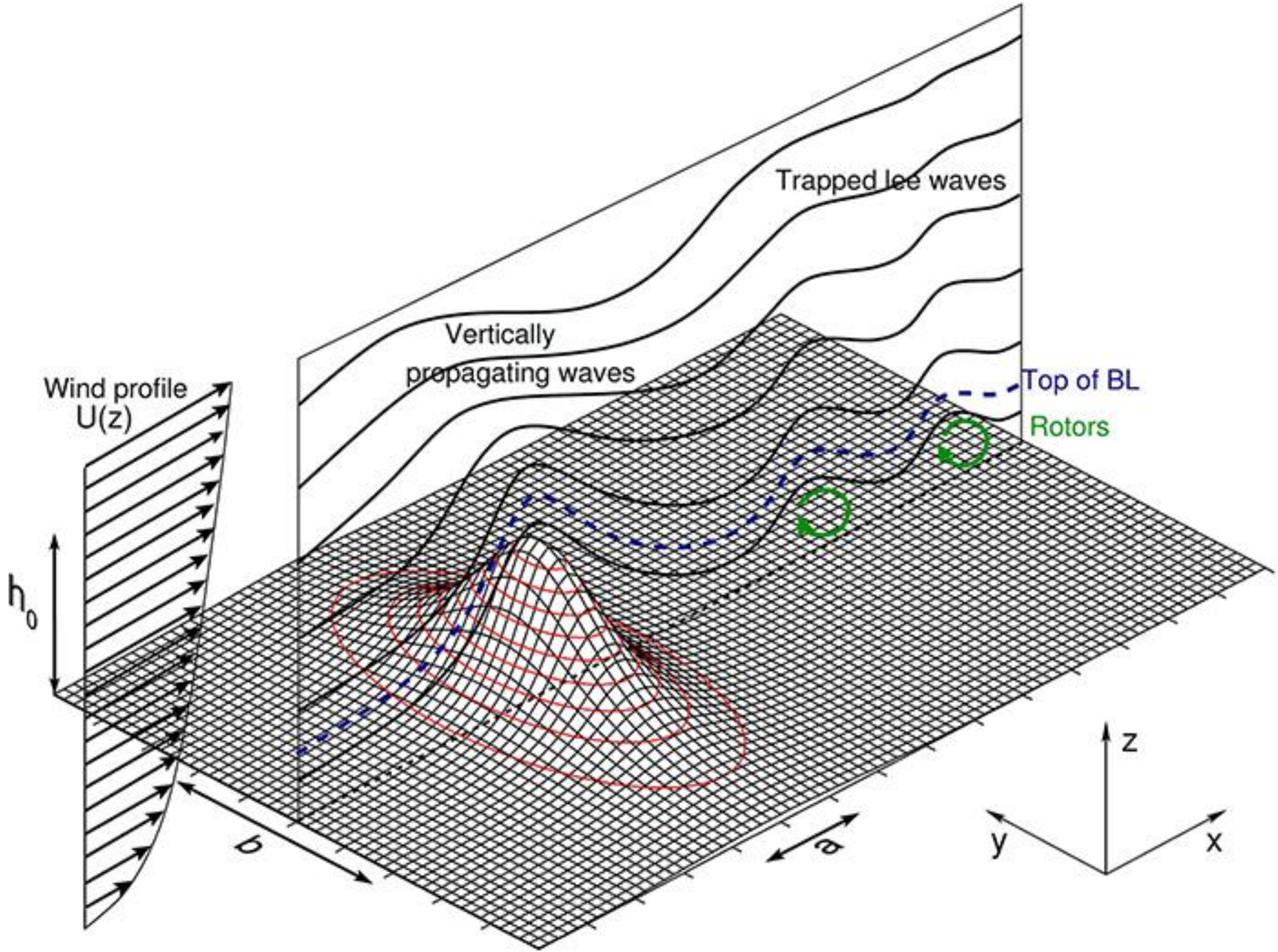
(Holton 2004, p. 98)

Cyclogenesis from a PV-thinking perspective



- Upper-level PV anomaly and surface thermal anomaly become "phase locked" and mutually amplify
- Upper-level PV anomaly overtakes low-level frontal zone
- Cyclonic circulation associated with upper-level PV anomaly produces a warm tongue/anomaly
- Two anomalies become phase locked, mutually amplify, and cyclogenesis occurs
  - Cyclonic circulation induced by surface warm anomaly advects high PV air aloft equatorward enhancing upper level PV anomaly
  - Cyclonic circulation induced by upper-level PV anomaly amplifies surface thermal anomaly
- Overall cyclonic circulation amplifies

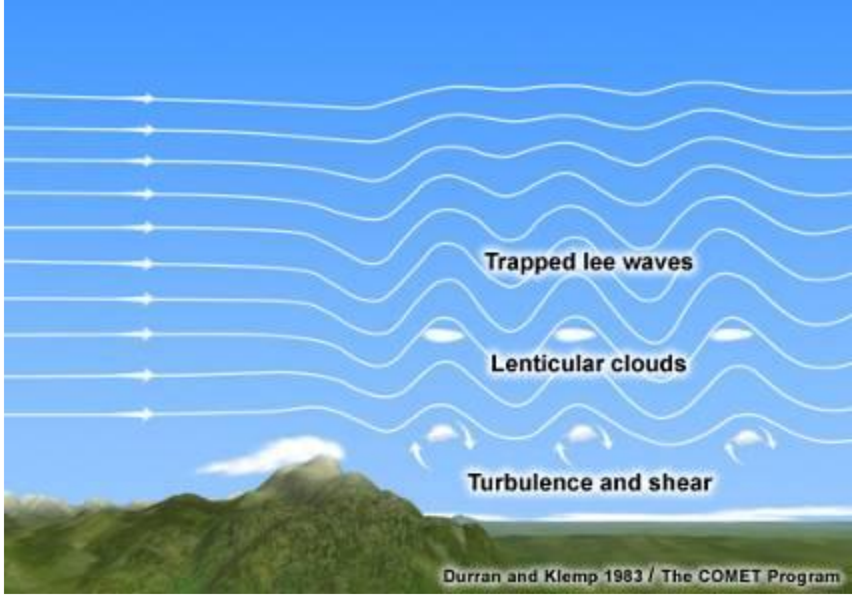
Mountain Wave



Mountain waves

Mountain (or Lee) Waves are formed by wind flowing over the ridge of a mountain:

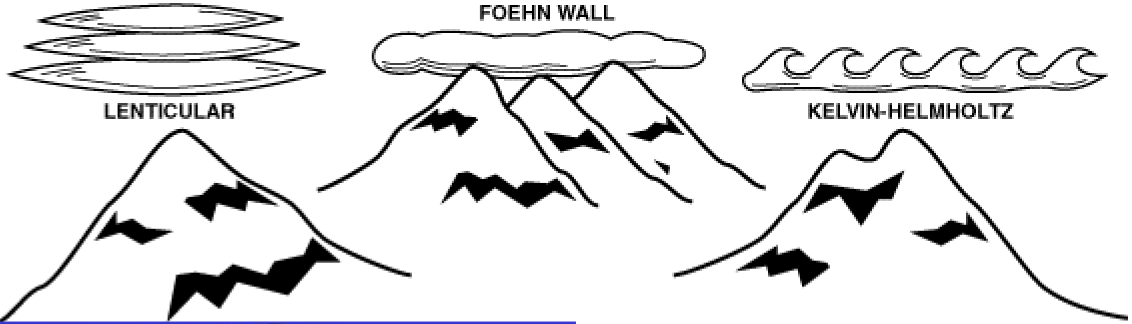
- **May extend for many km downwind**
- **May extend high into the atmosphere (60,000ft)**
- **Vertically transverse waves: wavelength 4-20km.**

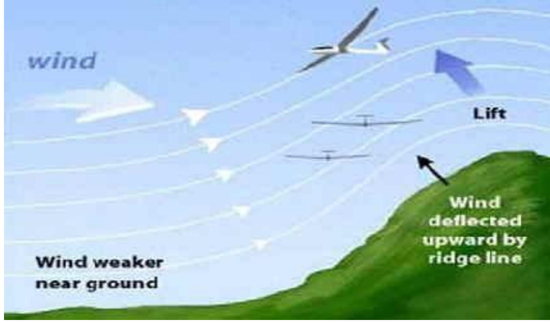


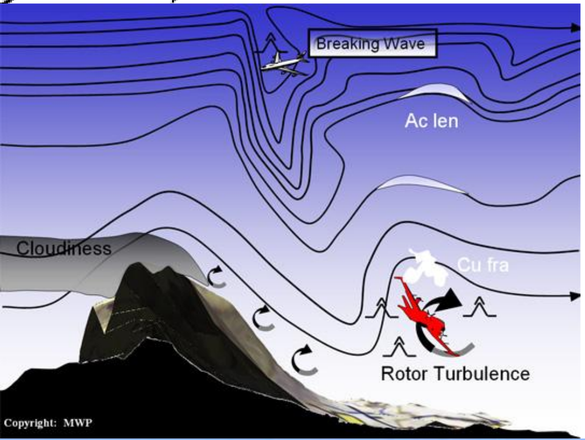
Durran and Klemp 1983 / The COMET Program

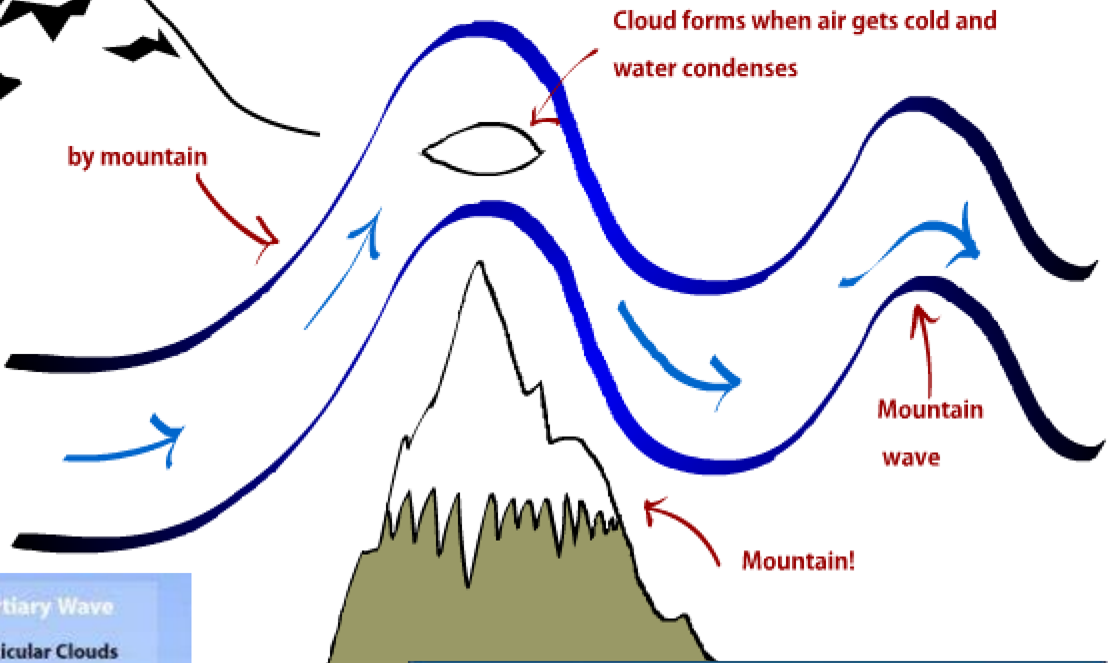
- What causes a mountain wave?
- **A wind is pushed up the face of the mountain**
- Must be within 30 degrees of perpendicular to the mountain ridge
- The wind must be strong: at least 20-25 knots (11-14ms^{-1})
- How can the mountains change the way air flows over mountains?
  - Air can form waves in the atmosphere and small spinning circles of air, called eddies.

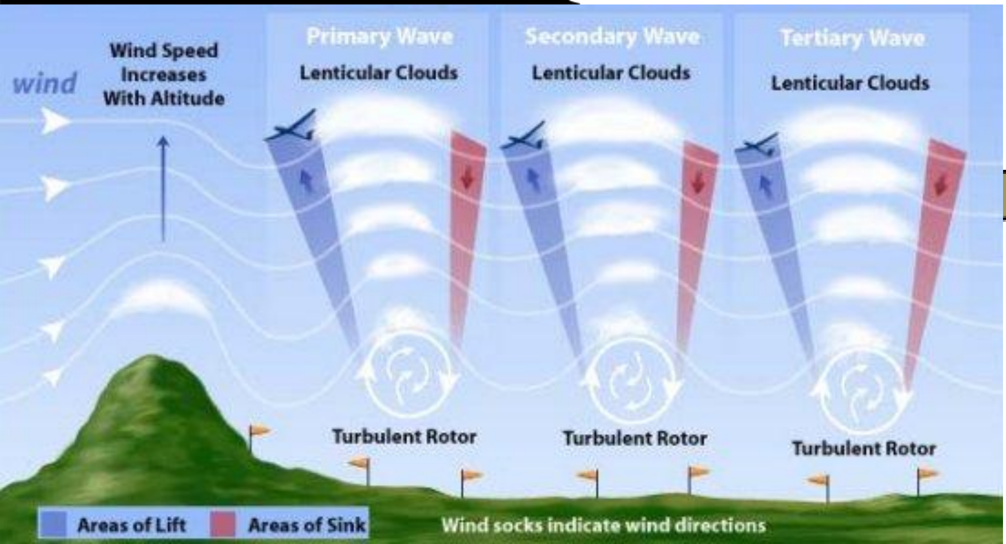
Mountain Waves

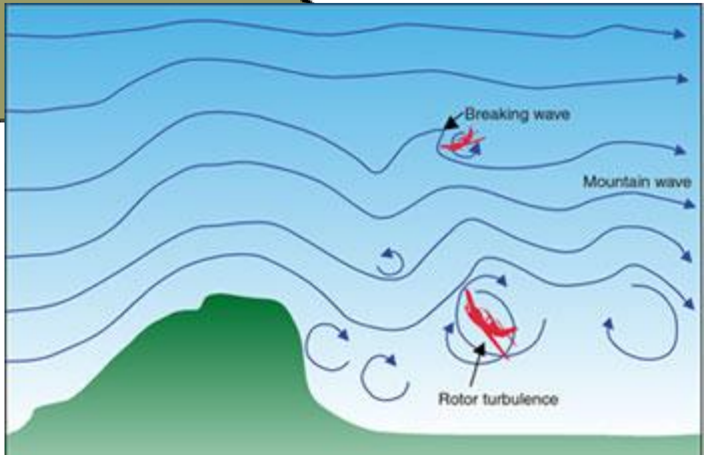




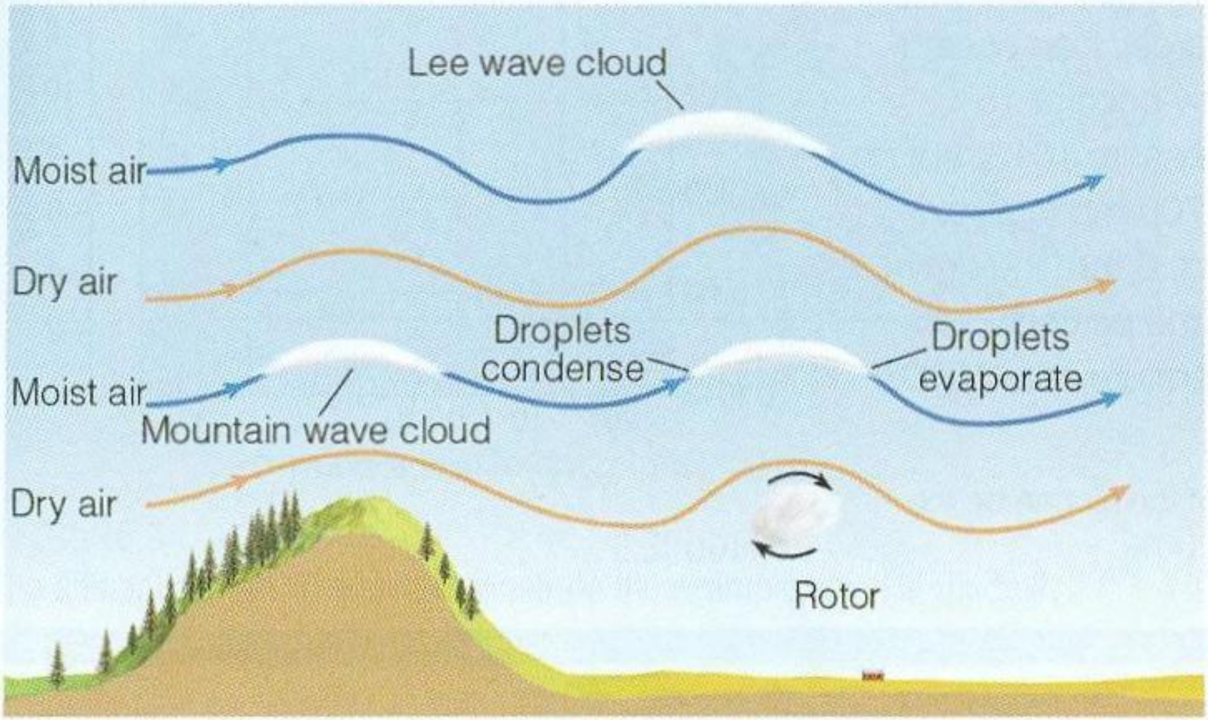






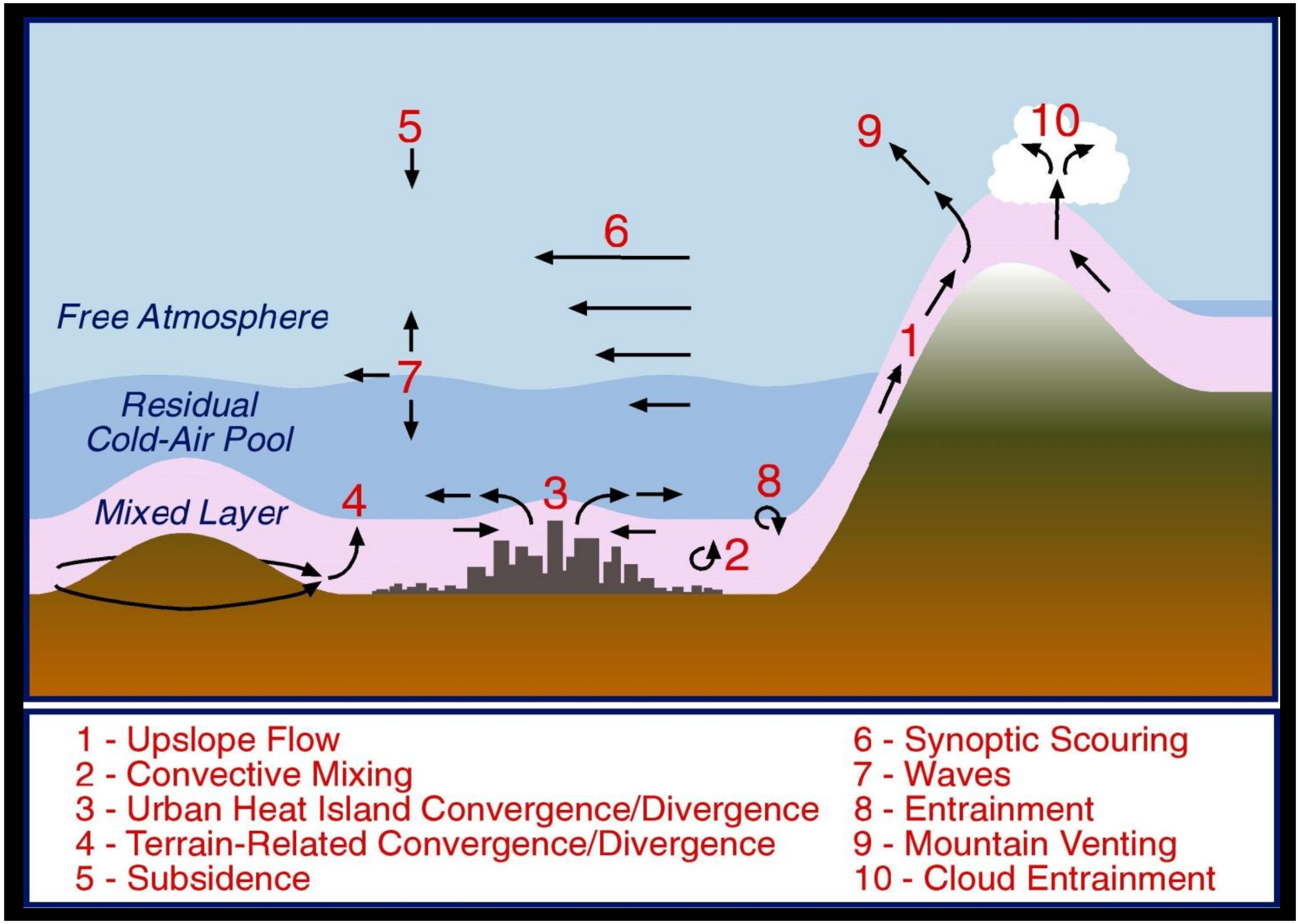


Development of lenticular clouds



● FIGURE 6.24
Clouds that form in the wave directly over the mountains are called *mountain wave clouds*, whereas those that form downwind of the mountain are called *lee wave clouds*.

Daytime vertical mixing processes



1 - Upslope Flow
2 - Convective Mixing
3 - Urban Heat Island Convergence/Divergence
4 - Terrain-Related Convergence/Divergence
5 - Subsidence
6 - Synoptic Scouring
7 - Waves
8 - Entrainment
9 - Mountain Venting
10 - Cloud Entrainment

Jerome Fast

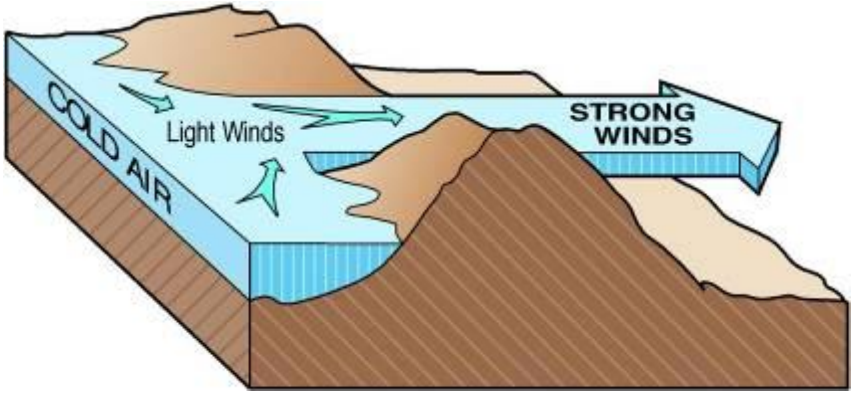
Mountain Wave Indicators

- Lenticular clouds can develop when air moves quickly over the top of mountains. Standing waves, like water flowing over a rock in rapids, can develop which can be dangerous for airplanes.

NCAR/UCAR/NSF

Mountains Channeling Winds

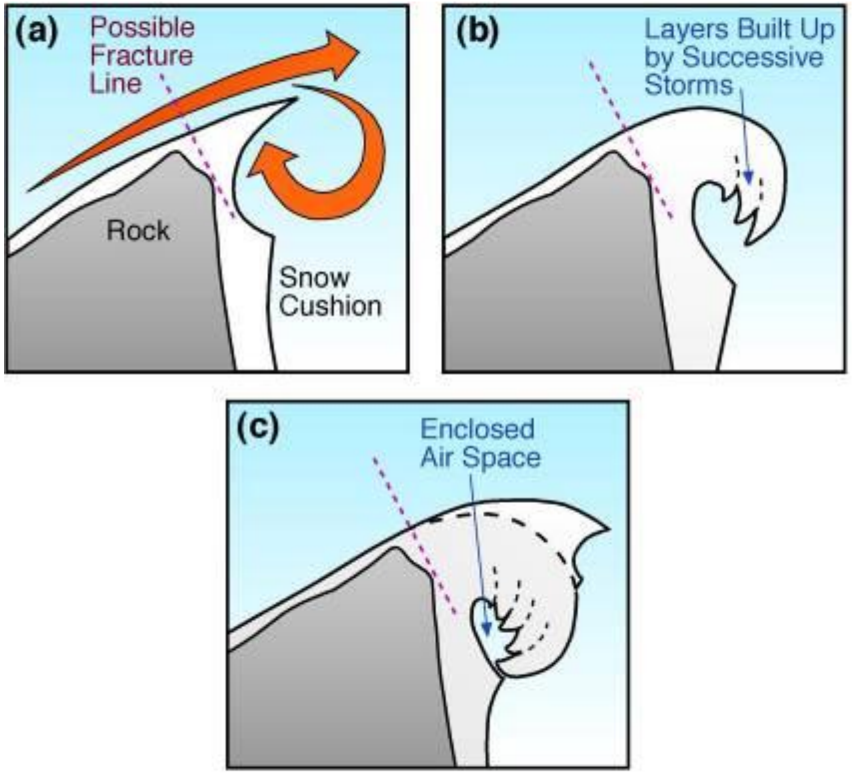
- Sometimes mountains channel the winds so they move very quickly through a small space. This movement is similar to how water moves quickly out the spout of a hose if you put your finger over part of the spout.



Whiteman (2000)

Winds Shaping Snow

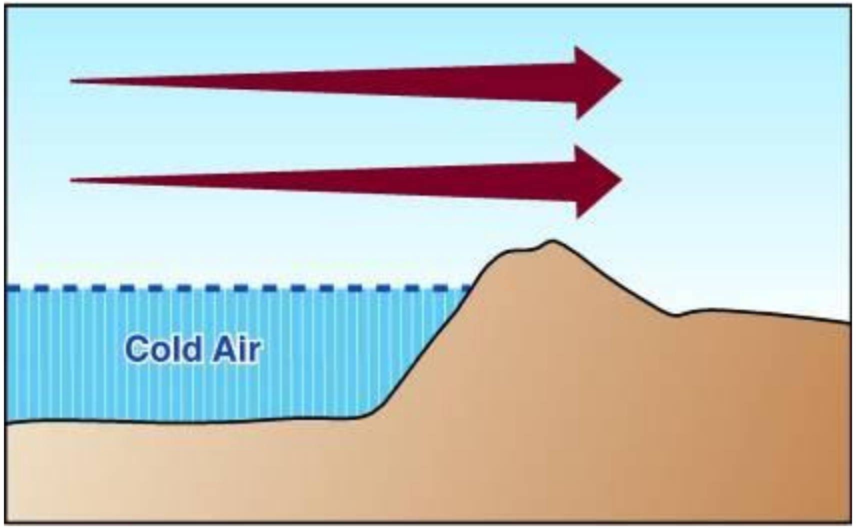
- Winds can move snow from one side of the slope to another and can build giant cornices as shown in the figure. These cornices can be very dangerous to walk on. Figure a shows where this cornice might break. If these cornices break, you can trigger an avalanche.



Whiteman (2000)

Can air be warmer at the top of a mountain?

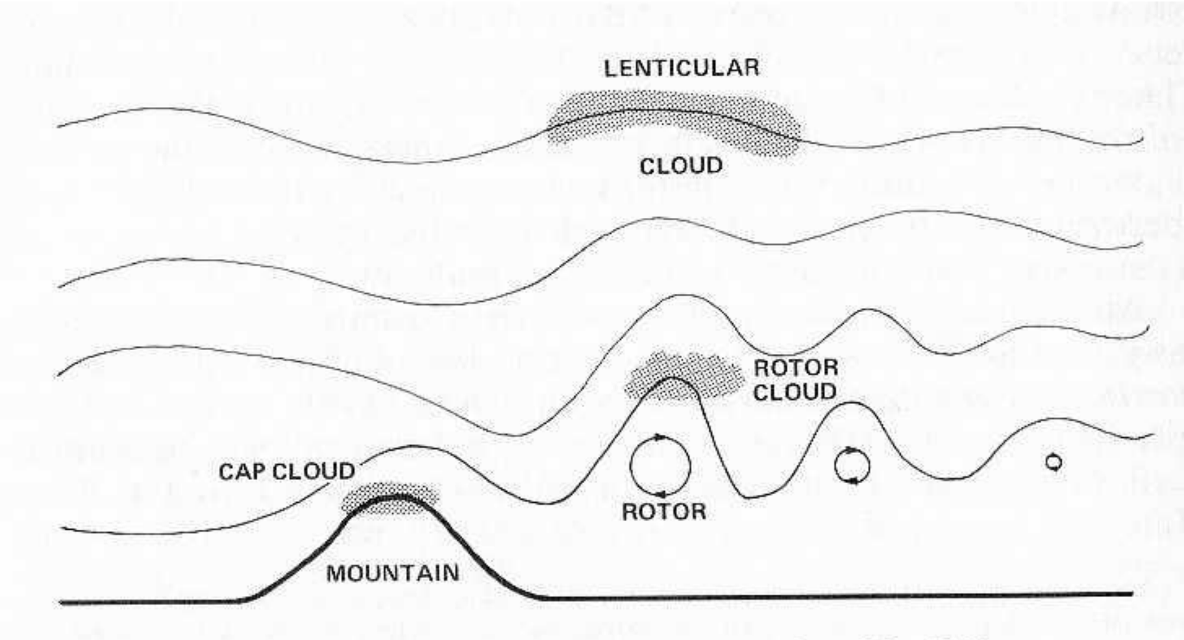
- Sometimes storms with cold air move up to a mountain and the cold air does not make it all the way across. The cold air, since it is more dense, can easily remain in what is called a cold pool (click here to link to Jenny's stuff).



Whiteman (2000)

Observation of Mountain Waves

1. **Fly an aircraft into one!**
   -in 1966 a mountain wave ripped apart a Boeing 707 near Mt. Fuji in Japan.
2. **Look at the cloud formations:**



1.3 The idealized airflow over mountains (after Alaka, 1960)

- Lenticular clouds
- Rotor clouds
- Pilatus 'cap' clouds

Cap Clouds

Willowy pilatus clouds are often seen coming up the windward face of a mountain.

Air is cooled as it is lifted up the mountain face, usually at about 6° Celsius per km.

When the air cools to its dew point, the cap cloud forms.

?

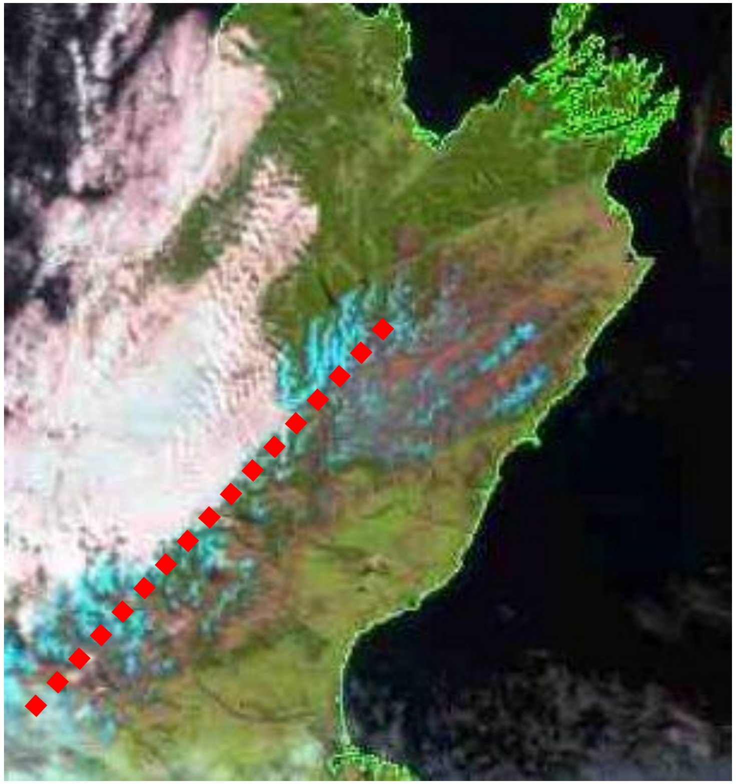
Why don’t we see continuous pilatus clouds downwind of the mountain?

The Foehn Effect

The foehn effect often causes clouds to abruptly cease upon reaching the summit.

- frequently exhibited by the Southern Alps: the Nor-West Arch.

Air on the lee side of a mountain is:



Warm

The latent heat from the condensation of air moisture makes the air warmer downwind (for the same altitude).

Dry

Condensation has already removed some of the air's water.

Buoyancy Waves

Once the air is displaced upwards, it will oscillate around its initial altitude.

A vertical atmospheric wave is called a **gravity wave.**

The temperature-altitude gradient:

The temperature of the air in the troposphere **decreases** with altitude.

Air temperature decreases when air is displaced upwards **adiabatically** (no heat added).

The local air **must be stable** for standing waves to occur.

Stability

The troposphere is stable if:

Adiabatic Lapse Rate > Troposphere Temperature Gradient

In a stable atmosphere:

- When air is lifted adiabatically, it is cooler than the surroundings and sinks
- When air is lowered adiabatically, it is warmer than the surroundings and rises

Each crest of a standing wave may be accompanied by a **Lenticular Cloud**.

Amplitude & Wavelength

Observed wavelengths (from satellite data) range from 4 to 20km - consistently around **15km** over the Tararua ranges

Main Wavelength factors: **wind speed** and **atmospheric stability**

- *A wavelength of 15km implies a wind speed of roughly 30m/s (Beer's "Atmospheric Waves")*

Main Amplitude factors: **topography**

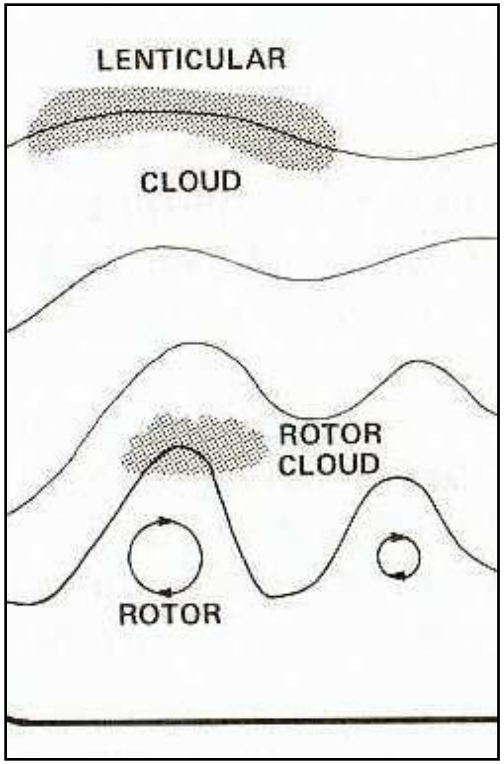
- *Wave amplitude depends mainly on the width of the ridge, and also on height, altitude and wind speed (Scorer).*
- *Mountain waves can have resonance with mountains placed an integer number of wavelengths downwind from the source. (California)*

Rotors

If the amplitude of the mountain wave is great enough, rotors may form.

A rotor is a **discrete vortex.**

Rotor clouds are not visible from satellite photographs, as they occur beneath the lenticular clouds over the gravity wave crests.



Rotor Clouds may form at the rotor if the air is moist enough.

Requirements

The observations of mountain wave clouds over New Zealand are consistent with the theoretical behavior of airflow over a mountain.

Expect mountain waves when:

- Wind is a strong breeze: 11-14 ms^{-1} or greater
- The wind is blowing into the face of a suitable mountain ridge
- The atmosphere has a stable temperature gradient

Or a low flying aircraft breaks into small pieces

Mountain wave clouds will occur when the air is sufficiently moist.

- *Rossby waves* are the wave-like pattern of ridges and troughs in the upper troposphere winds. Ridges and troughs (Rossby waves) will migrate either east or west with time

Cases to be examined

- Sinusoidal terrain
  - l^2 constant with height – flow with constant stability and mean wind
  - l^2 variable with height
- Isolated mountain
- Conditions for wave trapping leading to lenticular clouds

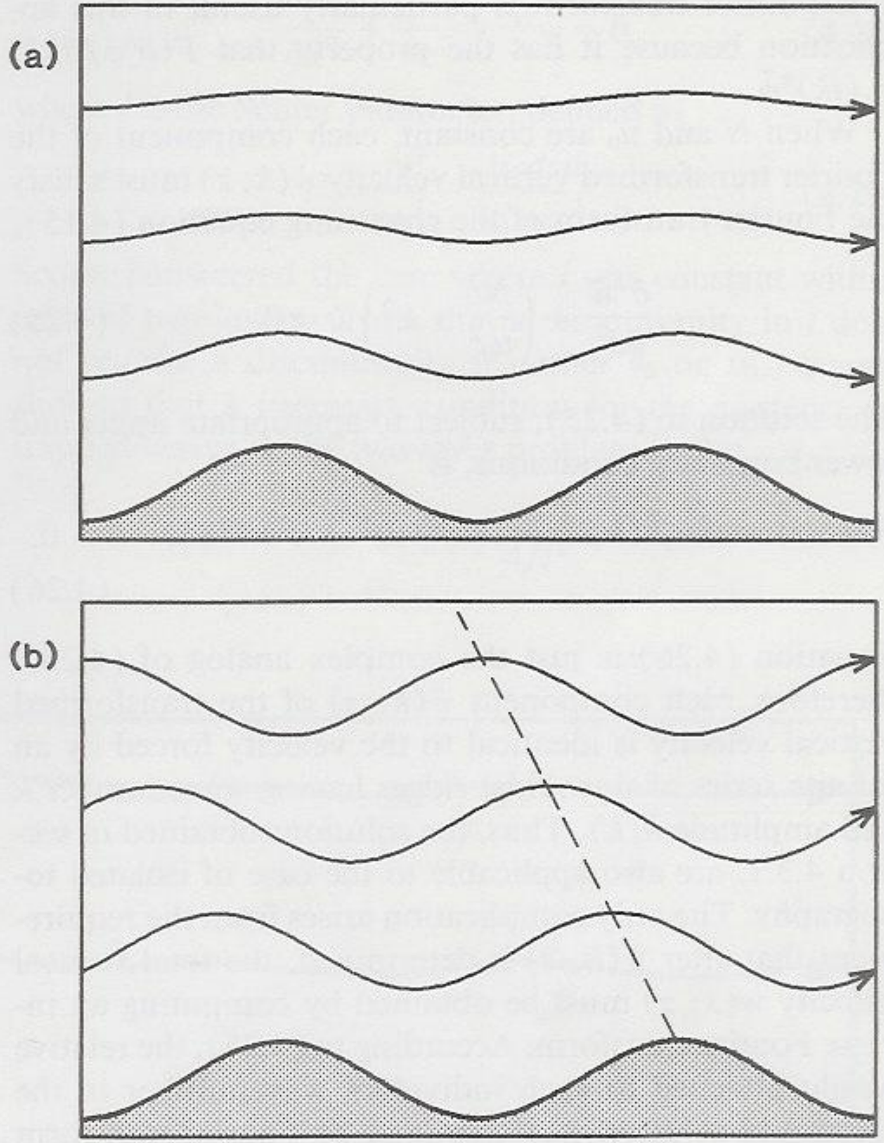


FIG. 4.2. Streamlines in steady airflow over an infinite series of sinusoidal ridges when (a) $u_0 k > N$, or (b) $u_0 k < N$. The dashed line (b) shows the upstream tilt of the lines of constant phase. Unless otherwise stated, the airflow in this and all subsequent figures is from left to right.

Sinusoidal mountain

$l^2 < k^2$

Narrow mountain

Waves decay w/ z

$l^2 > k^2$

Wide mountain

Waves preserved w/ z, mimic mountain shape

Isolated ridge

Narrow mountain

wide mountain

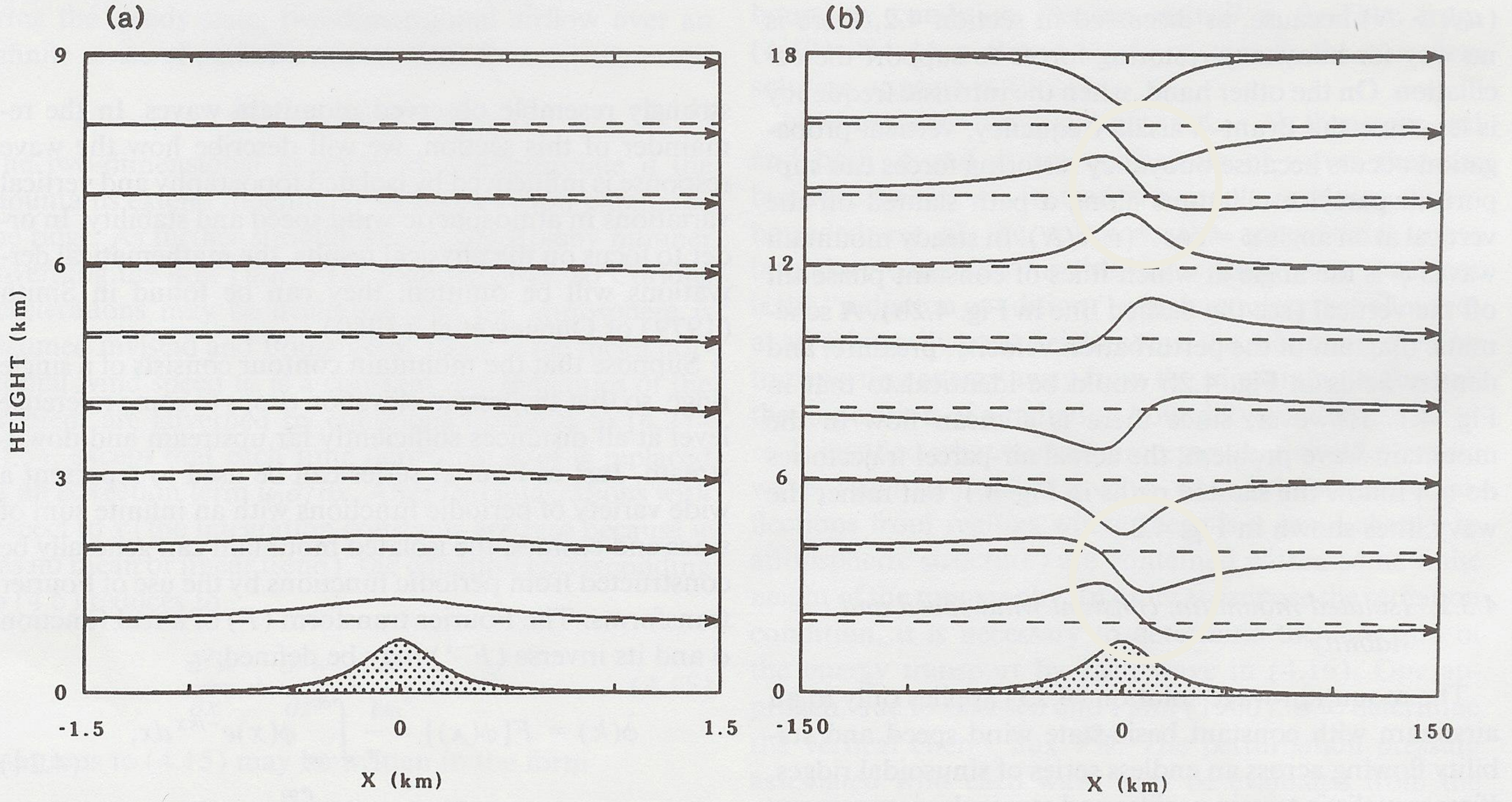
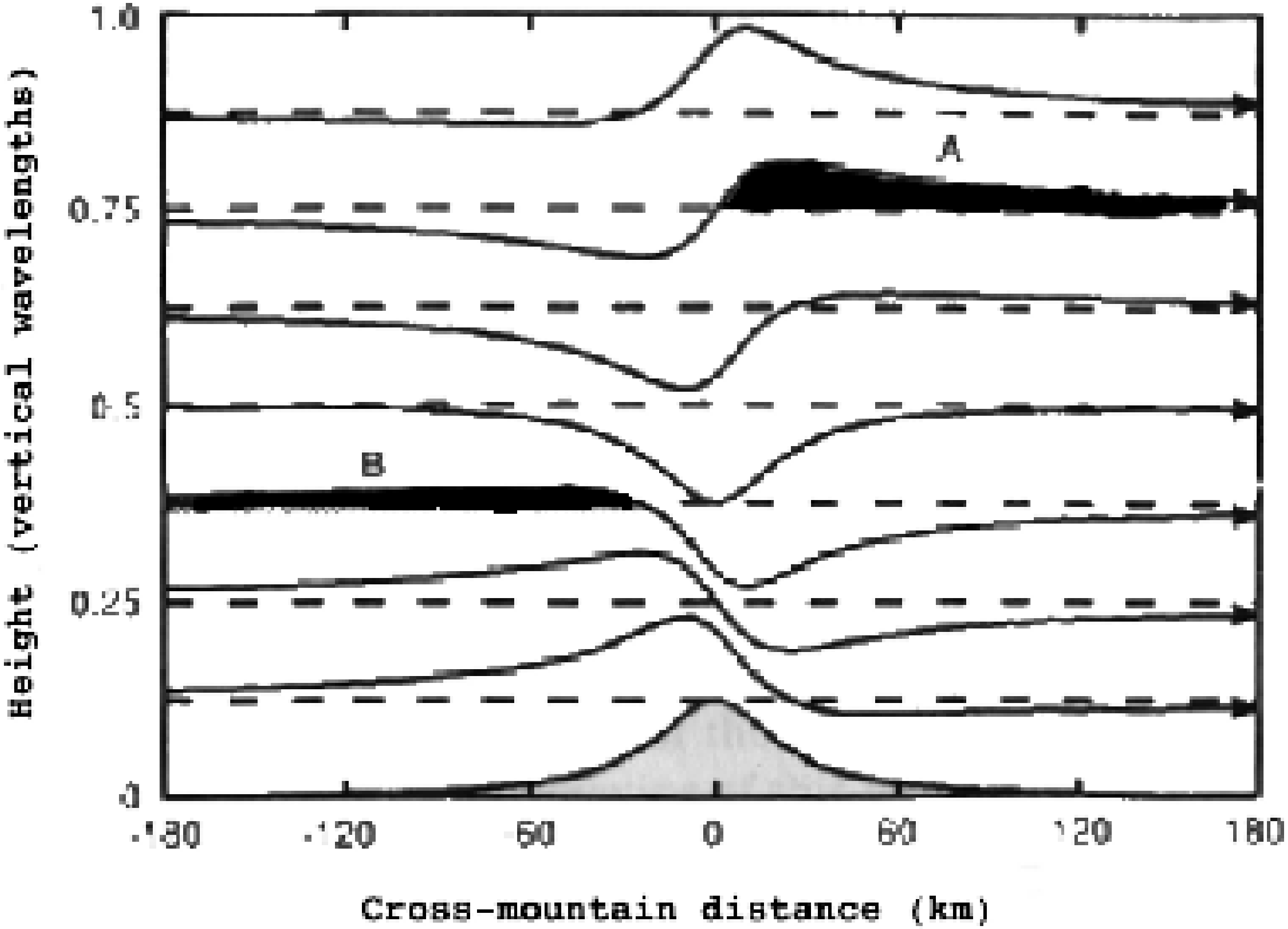


FIG. 4.3. Streamlines in steady airflow over an isolated bell-shaped ridge when (a) $u_0 a^{-1} \gg N$, or (b) $u_0 a^{-1} \ll N$.

$l^2 < k^2$

$l^2 > k^2$


Height (vertical wavelengths)
1.0
0.75
0.5
0.25
0
A
B
-180
-120
-60
0
60
120
180
Cross-mountain distance (km)

More stable layer below - trapped lee waves
& lenticular/lee wave clouds

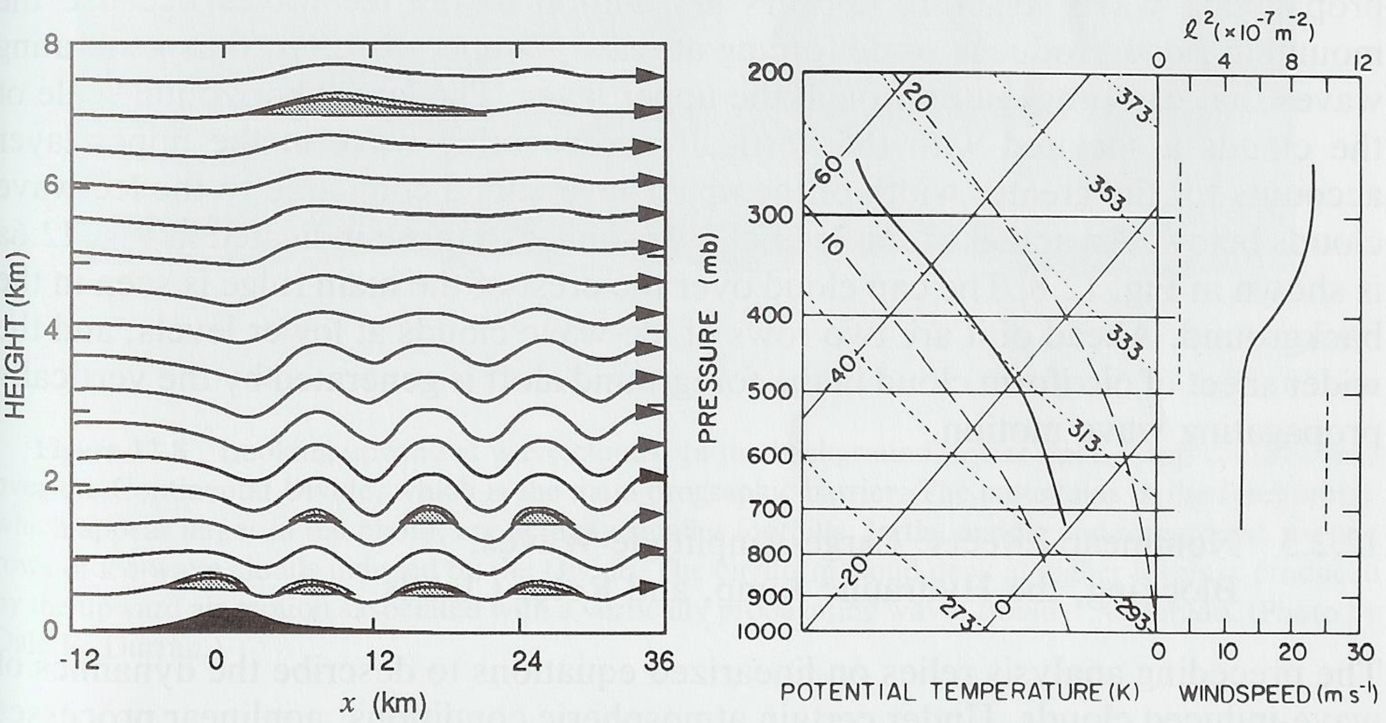
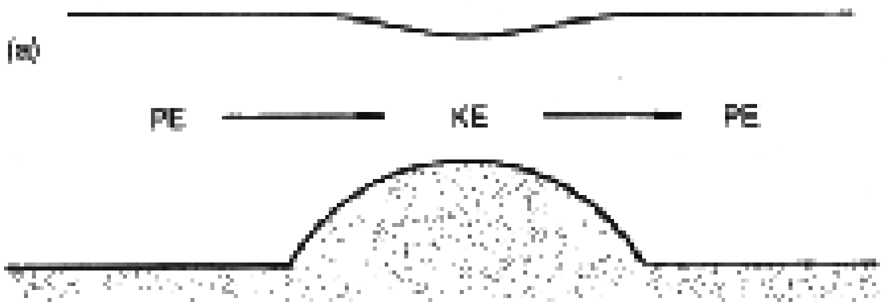


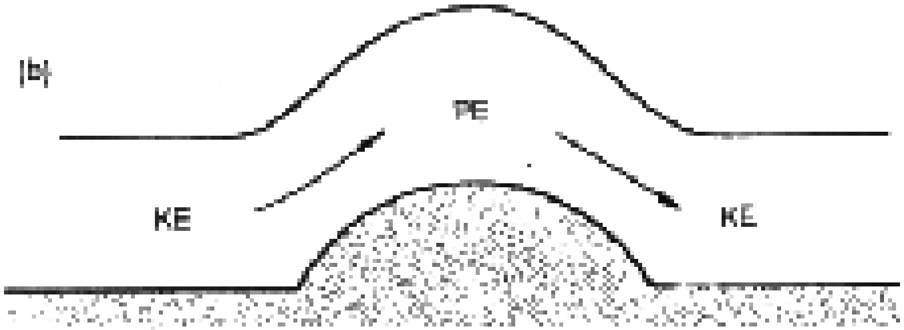
Figure 12.6 (a) Streamlines of steady flow over an isolated two-dimensional bell-shaped ridge for a case in which the stratification of the undisturbed flow supports trapped waves. Lighter shading indicates possible locations of clouds. Darker shading indicates bottom topography. (b) The vertical distribution of temperature and wind speed (solid lines) in the undisturbed flow. This temperature and wind layering implies a discontinuous two-layer structure for the Scorer parameter (dashed line on right panel). (From Durran, 1986b. Reprinted with permission from the American Meteorological Society.)

Downslope Windstorms

Flow over an obstacle for a barotropic fluid with free surface



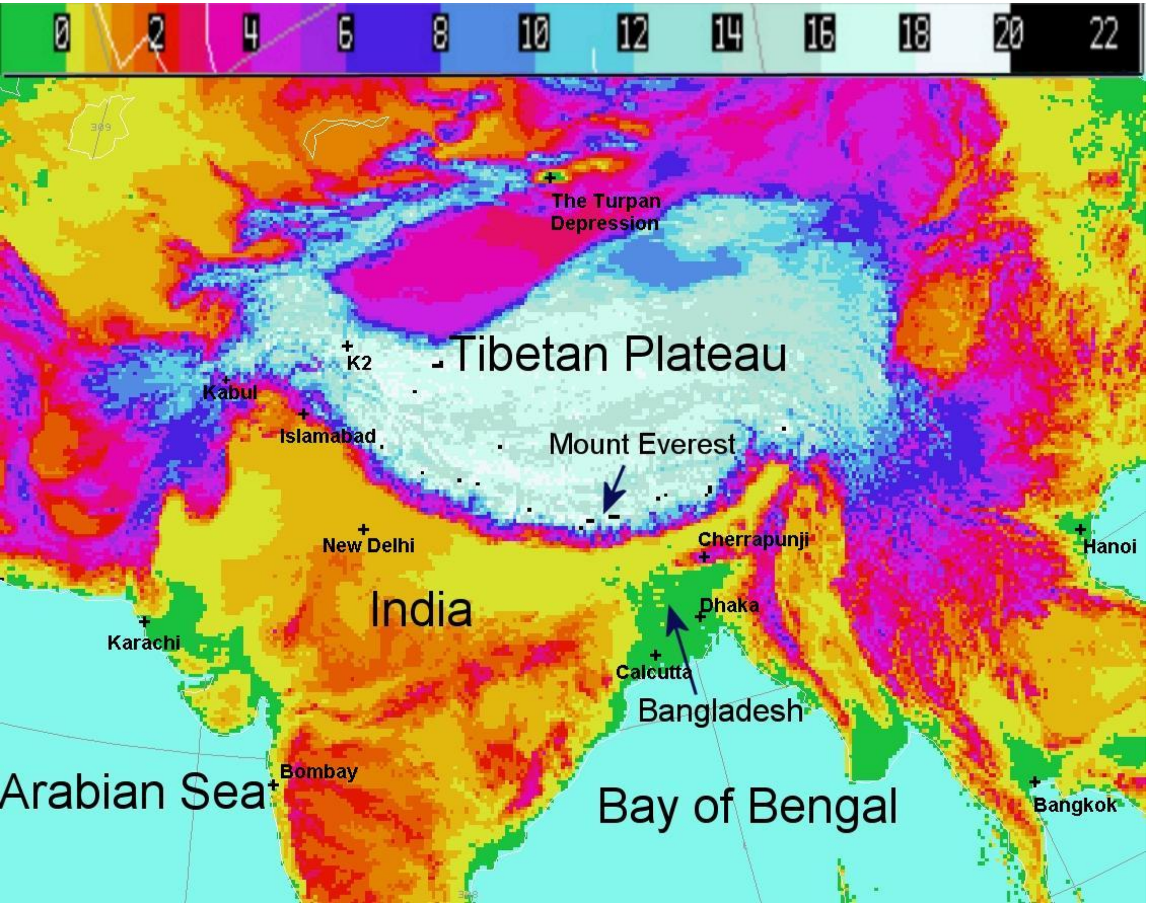
(a) Subcritical flow

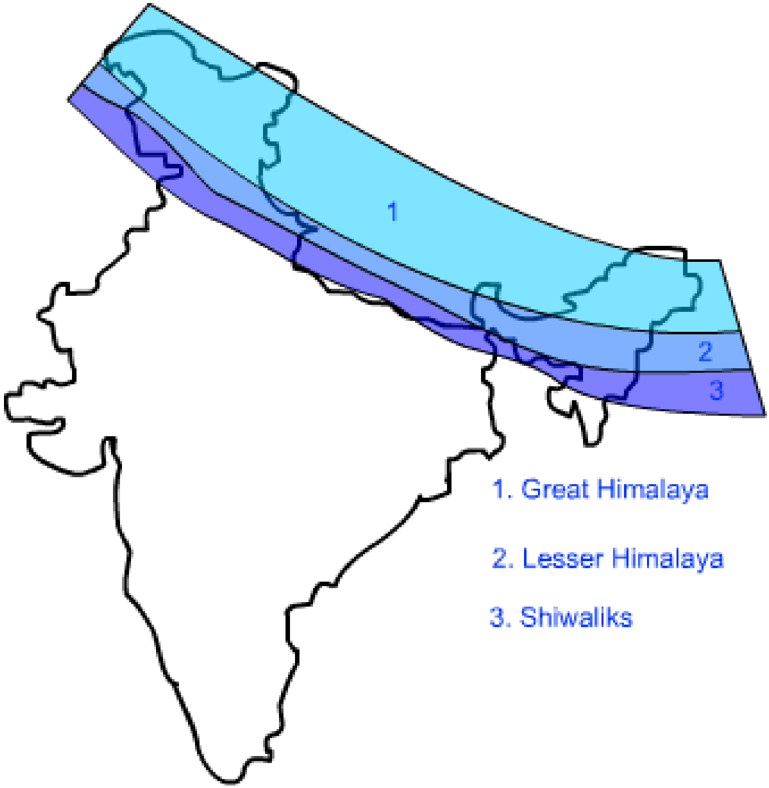


(b) Supercritical flow

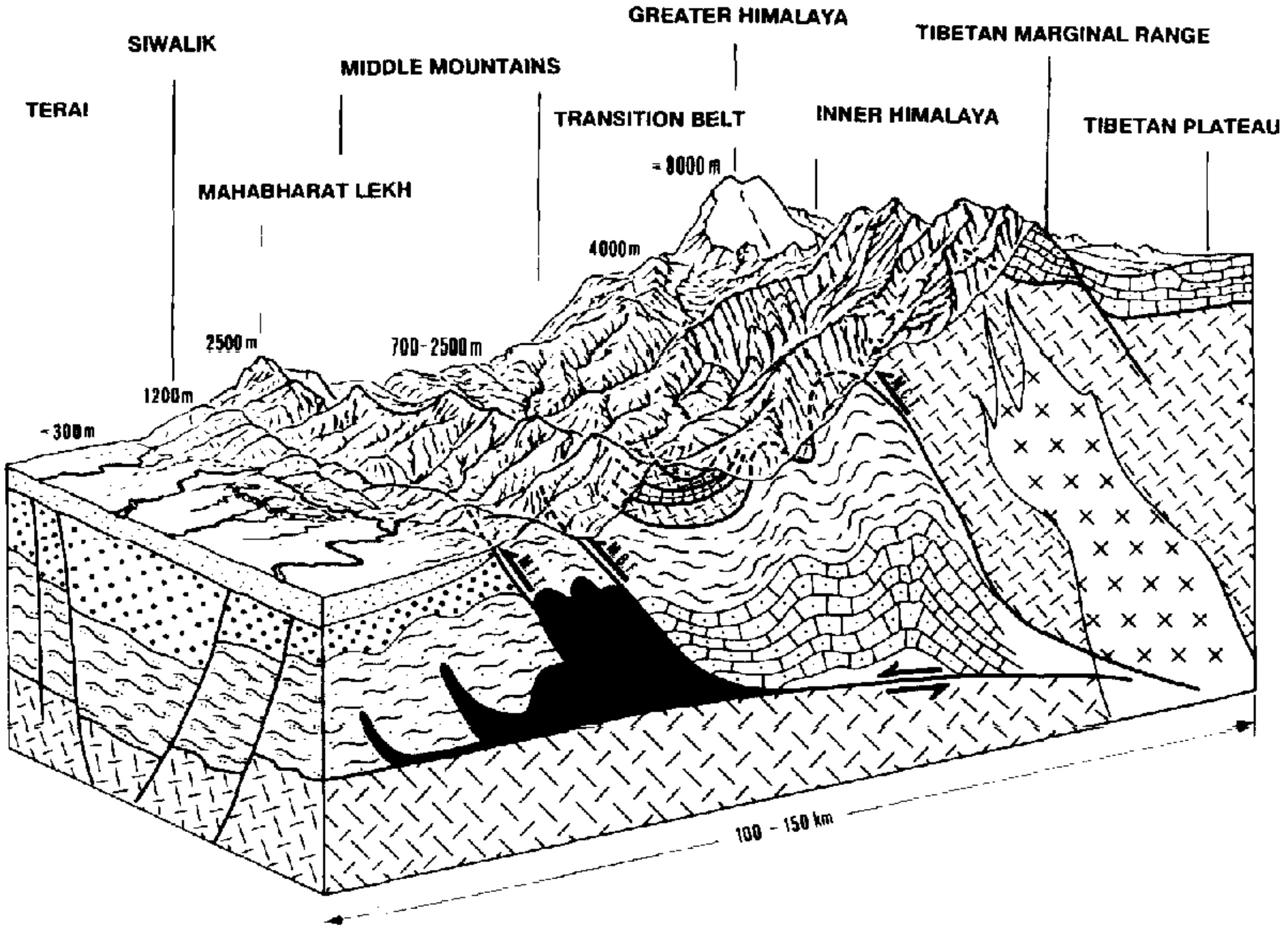
(c) Supercritical flow on lee slope with Adjustment to subcricital flow at Hydraulic jump near base of obstacle

Topography


0
2
4
6
8
10
12
14
16
18
20
22
The Turpan Depression
Tibetan Plateau
K2
Kabul
Islamabad
Mount Everest
New Delhi
Cherrapunji
Hanoi
India
Karachi
Dhaka
Calcutta
Bangladesh
Arabian Sea
Bombay
Bay of Bengal
Bangkok

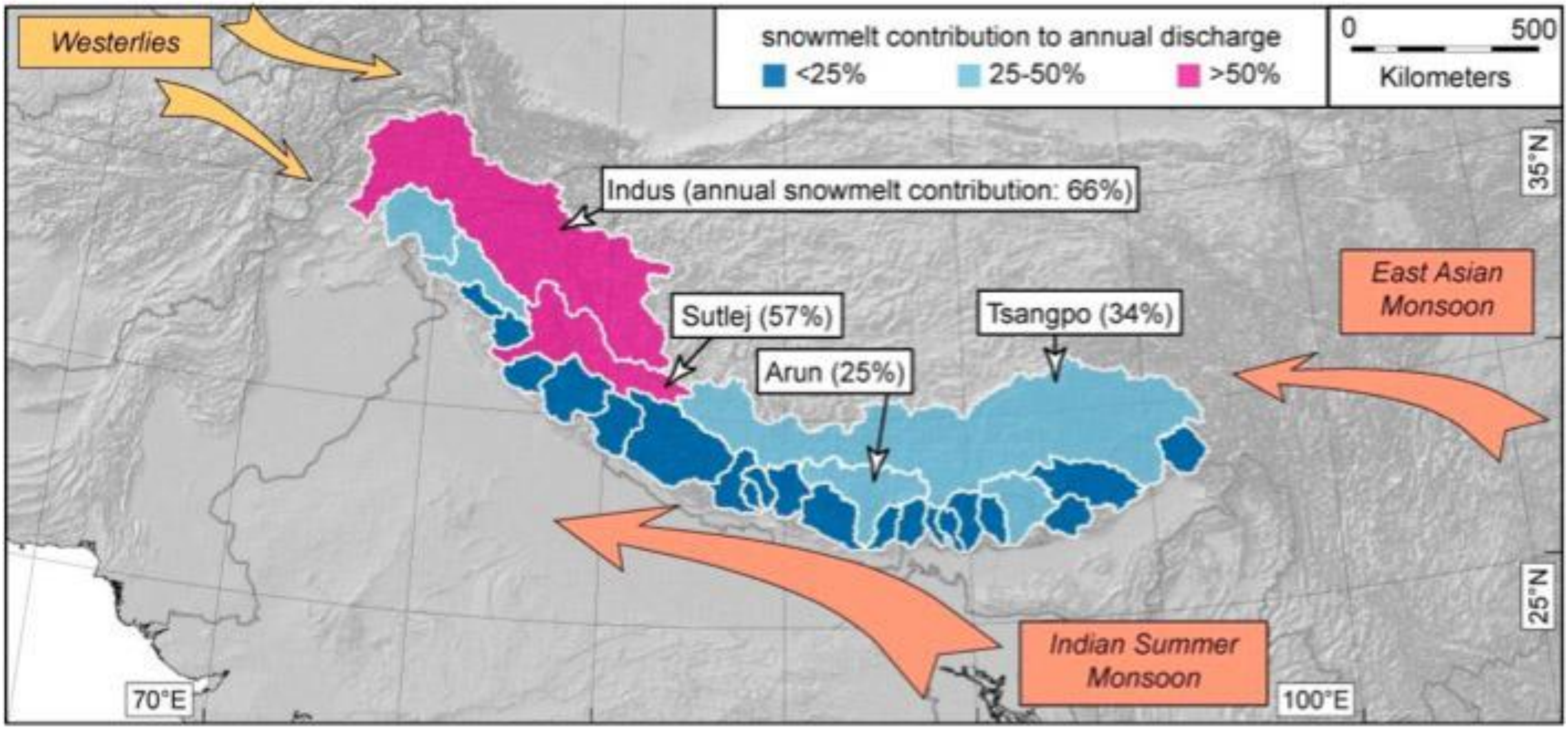

1
2
3
1. Great Himalaya
2. Lesser Himalaya
3. Shiwaliks

Himalaya

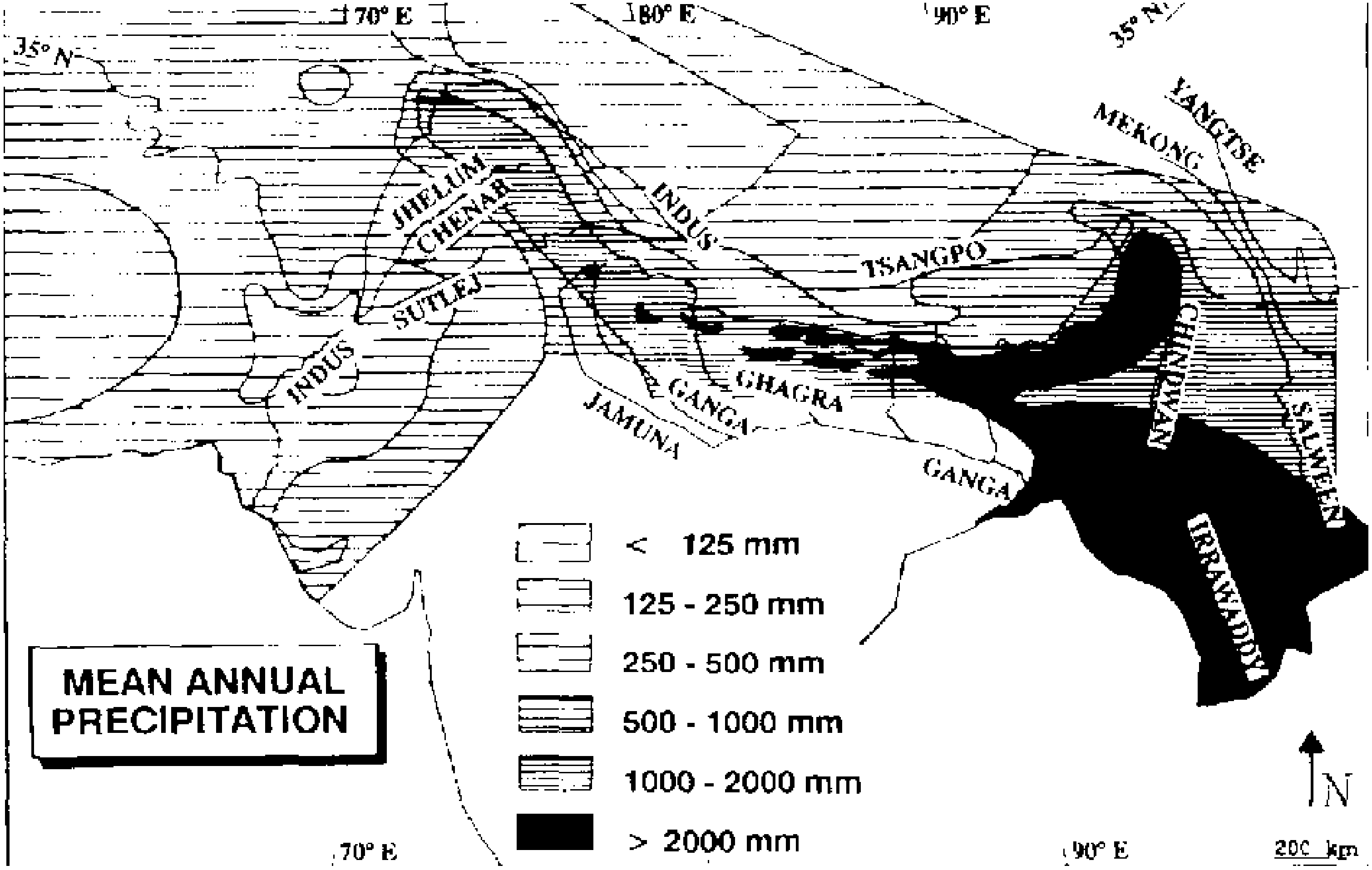


	Litho-tectonic units	Rock type
░	Quaternary	Alluvial sediments
⁘	Upper Siwalik	'Molasse' sandstone & shale
≋	Middle Siwalik	
■	Lower Siwalik	
≈	Paleozoic and younger sediments of the lesser Himalaya	Schist & Limestone
▦	Paleozoic and younger sediments of the Higher Himalaya	Limestone & Marl
▦	Upper Precambrian and Lower Paleozoic sediments	Phyllite & Quartzite
▨	Lower Precambrian crystalline basement	Gneiss & Migmatite
⊠	Tertiary Leucogranite	Tourmaline Granite
M.F.T.	Main Frontal Thrust	
M.B.F.	Main Boundary Fault	
M.C.T.	Main Central Thrust	

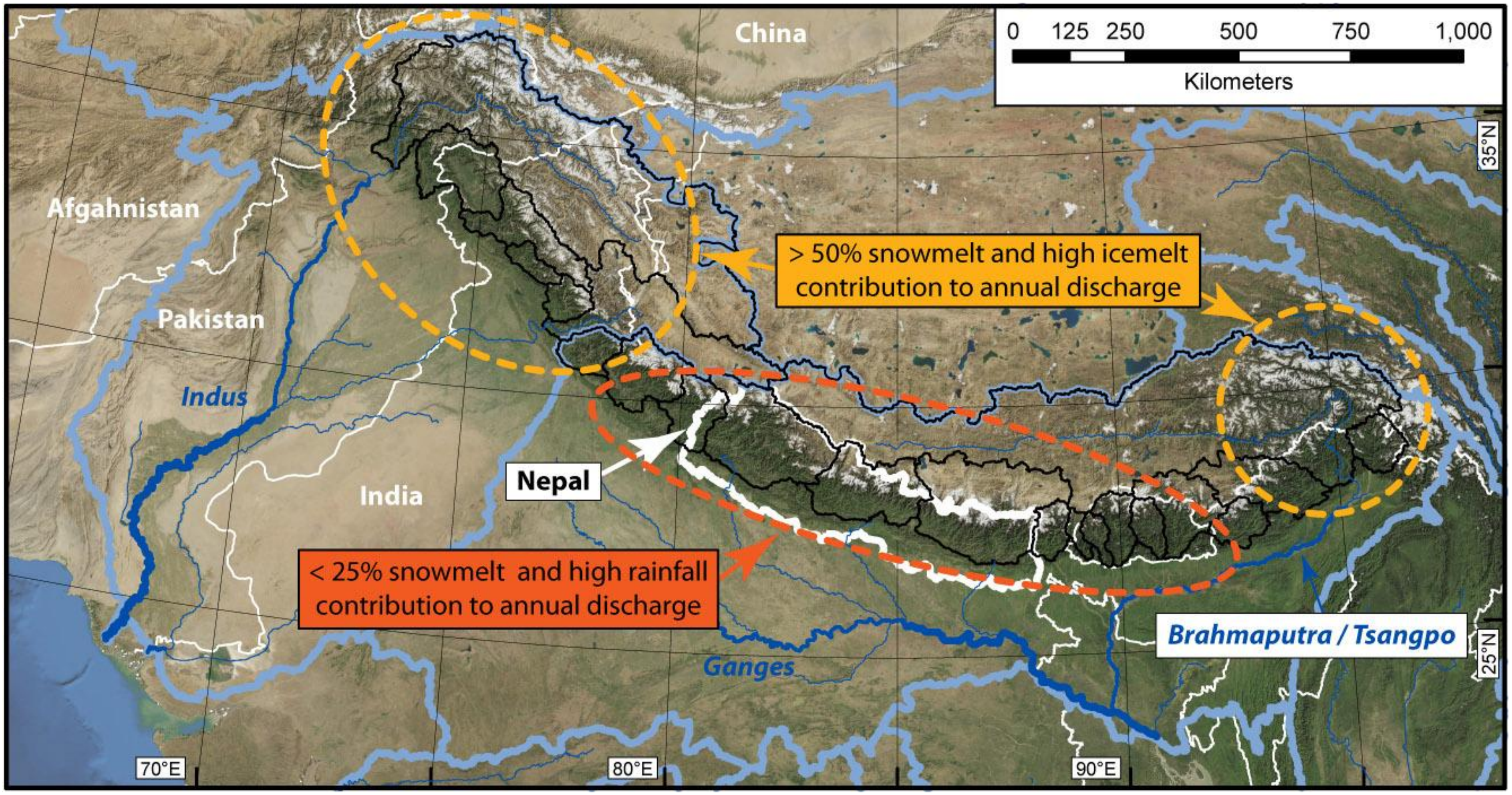
Types of synoptic systems



Mean Annual Precipitation



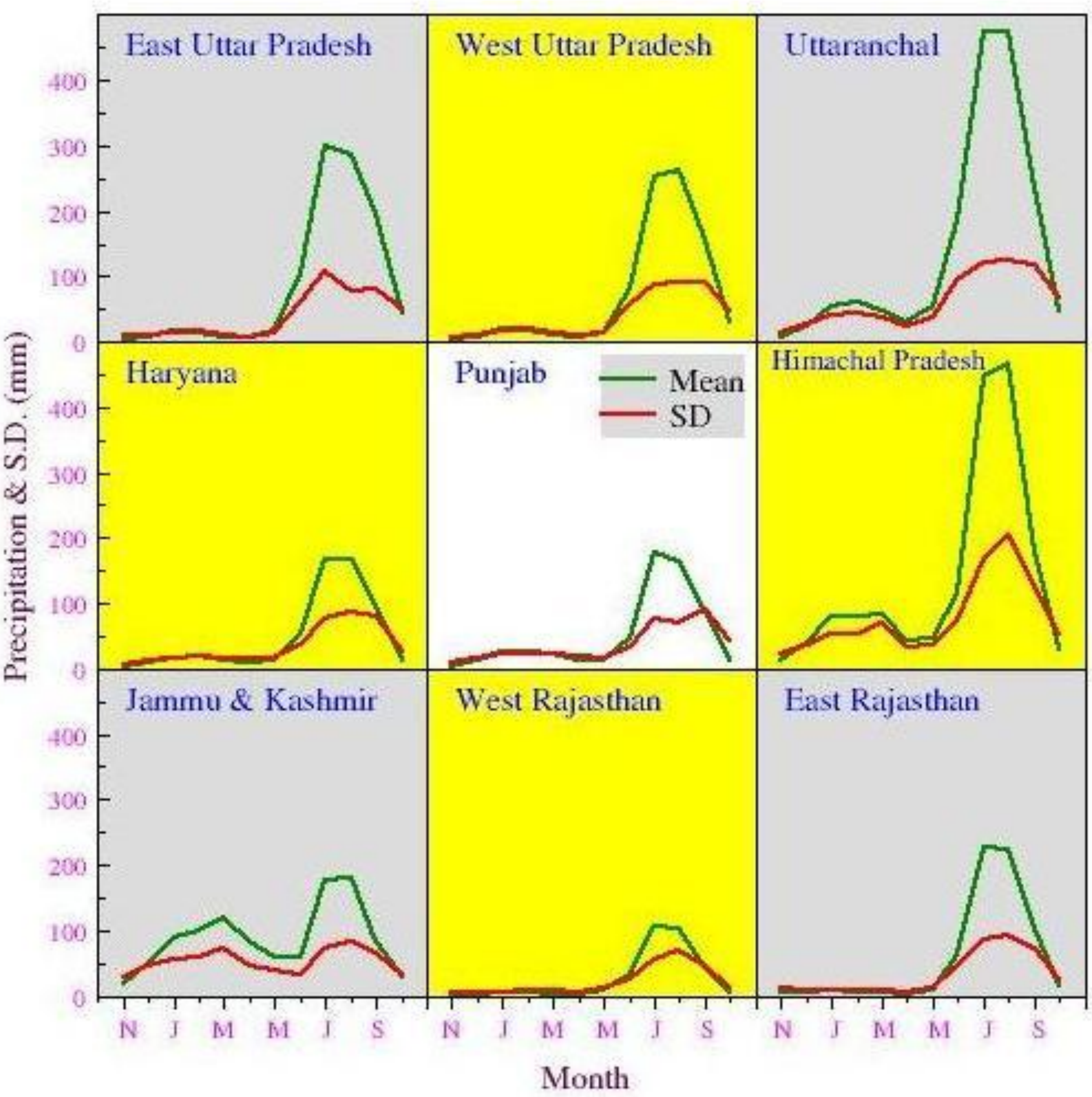
Snowmelt



> 50% snowmelt and high icemelt contribution to annual discharge

< 25% snowmelt and high rainfall contribution to annual discharge

Annual Precipitation and SD cycle



Role of equatorial central Pacific and northwest of North Atlantic SSTs in modulating ISM variability

ERA 40 Data : 1958-2001

R.K. Yadav; 2009; Role of equatorial central Pacific and northwest of North Atlantic 2-metre surface temperatures in modulating Indian summer monsoon variability; **Climate Dynamics**; 32; pp 549-563; DOI: 10.1007/s00382-008-0410-x (**IF=4.602**)

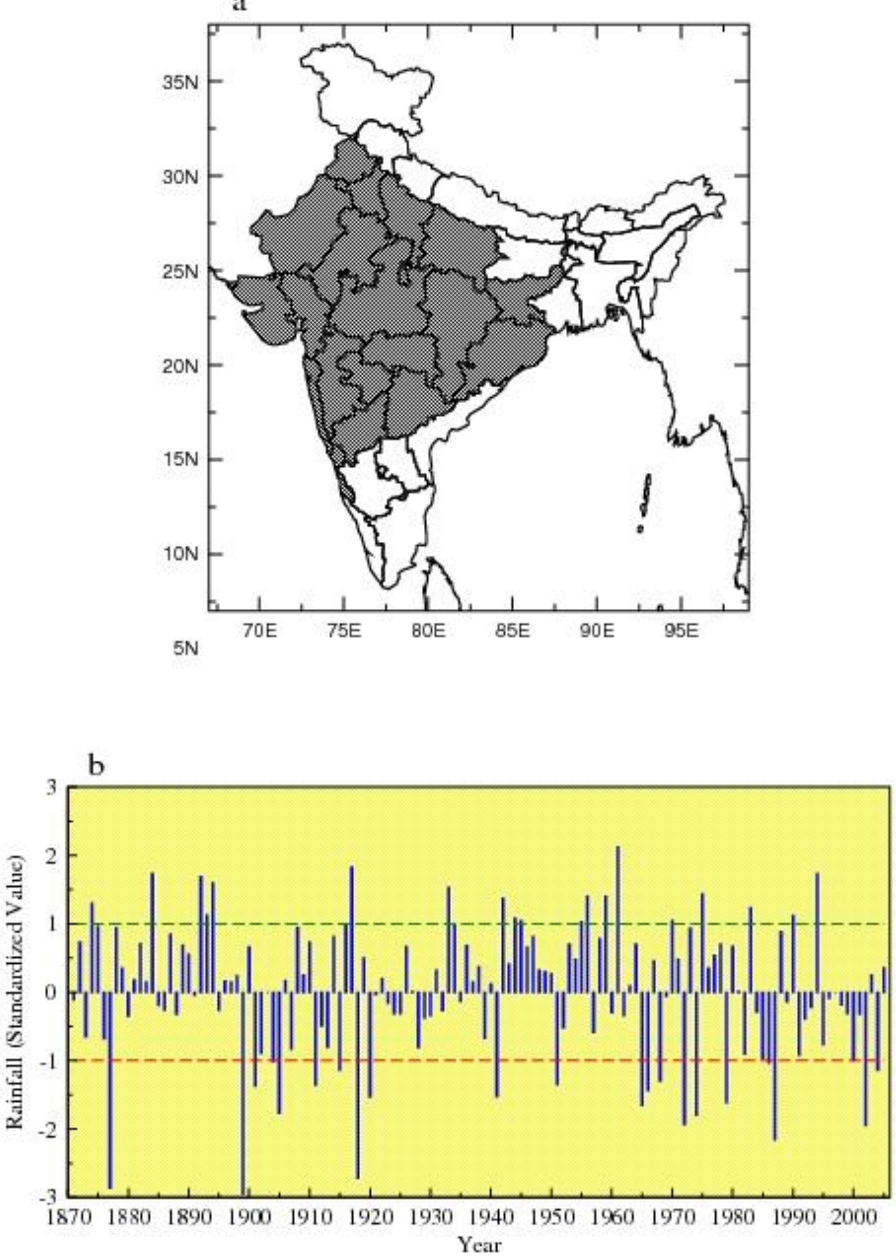
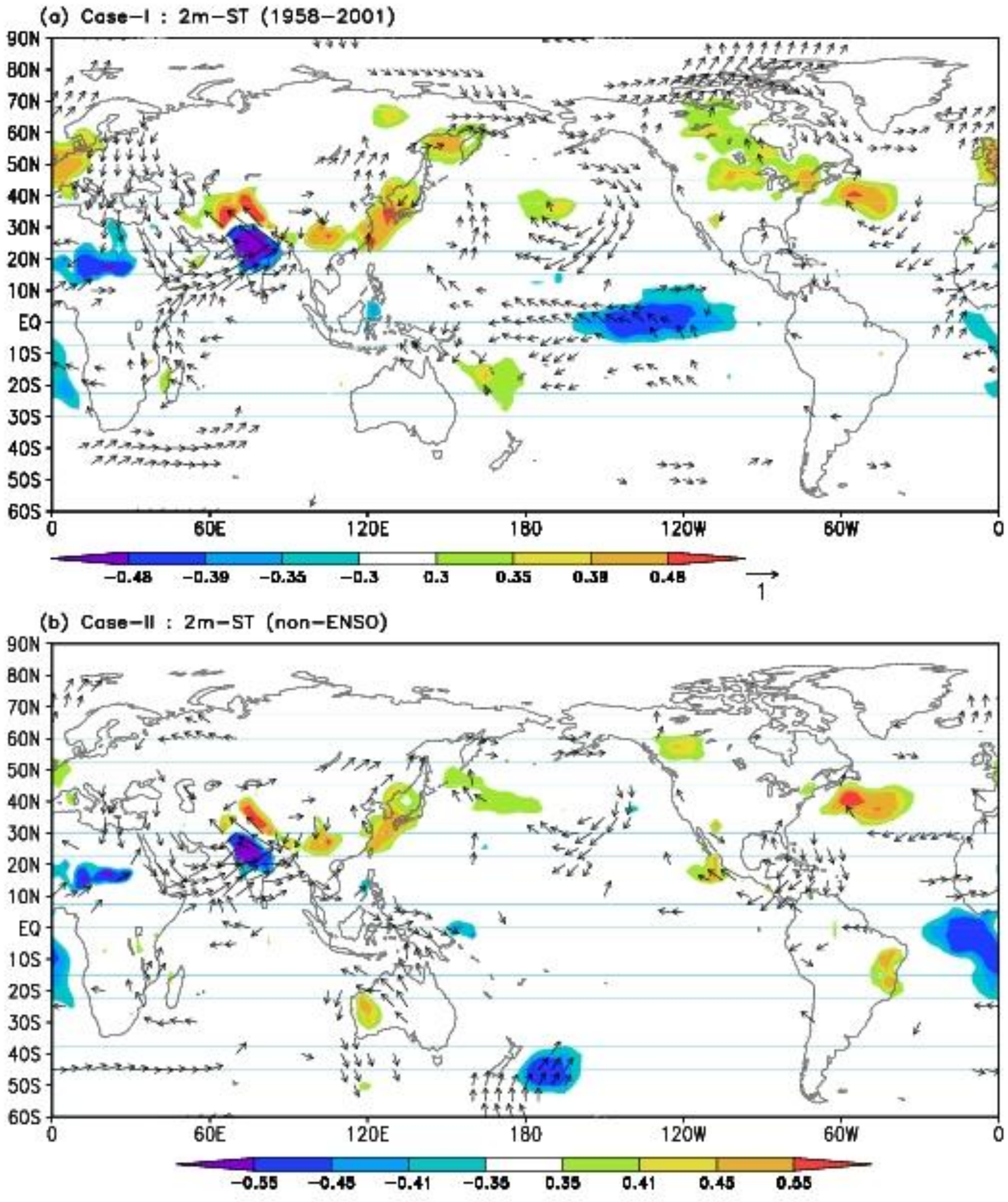


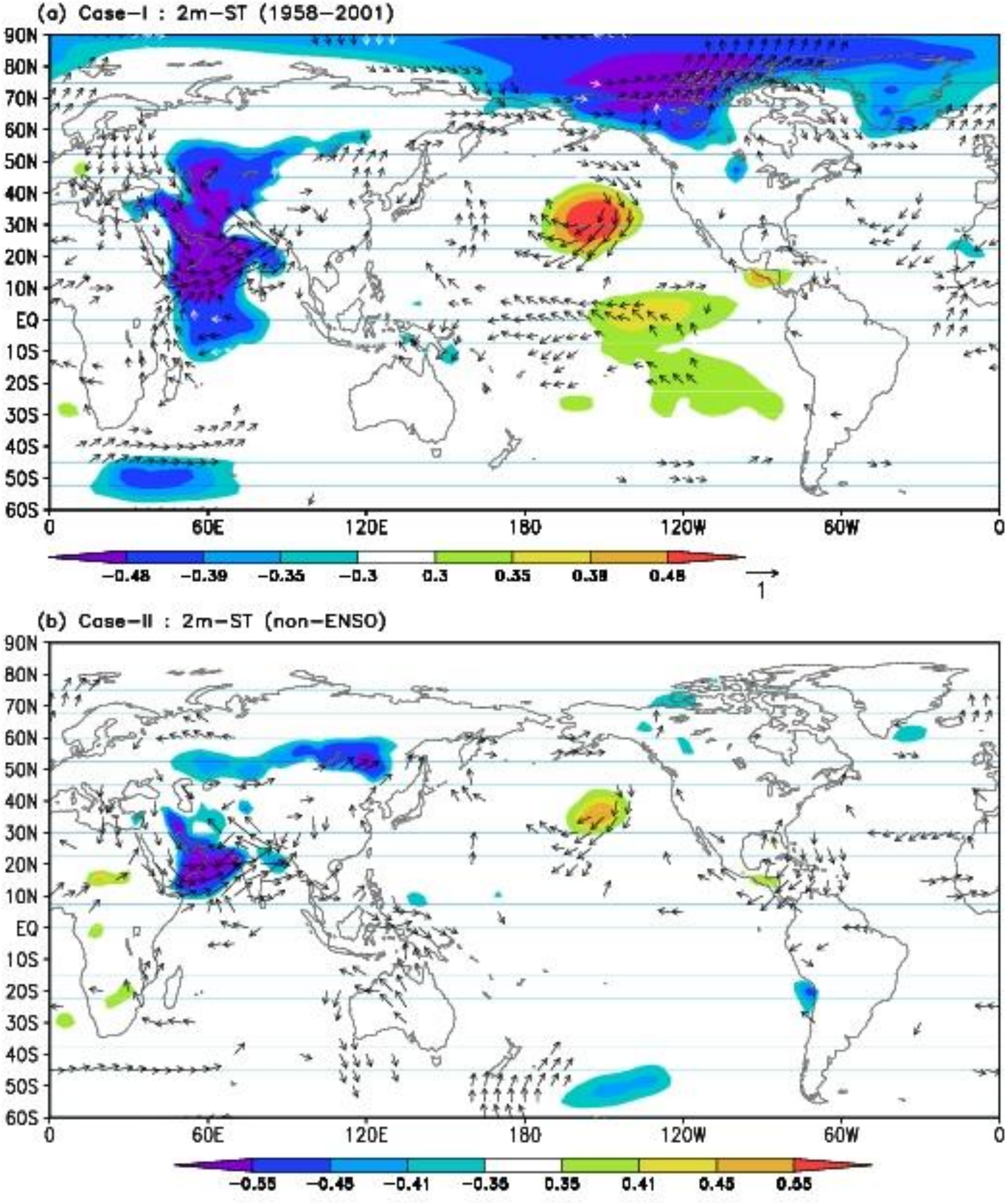
Figure 1 : (a) Geographical pattern for different meteorological subdivisions of India. Shaded regions are 20 meteorological subdivisions of India considered for Indian Summer Monsoon Rainfall (ISMR). (b) The time-series of ISMR for the period 1871-2005 expressed as the standardized values of area weighted seasonal rainfall from the long period normal.

Shaded regions are 20 meteorological sub-divisions of India considered for ISMR.

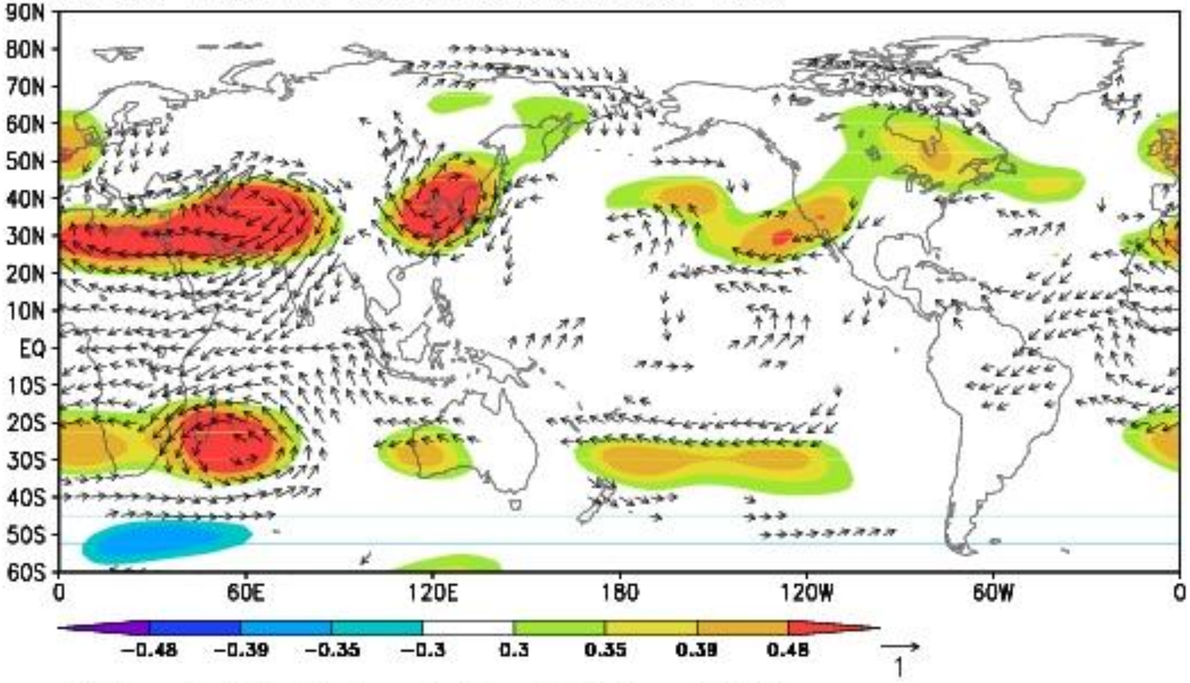
The time series of ISMR for the period 1871-2005 expressed as the percent departure of area weighted seasonal summer rainfall from the long period normal.

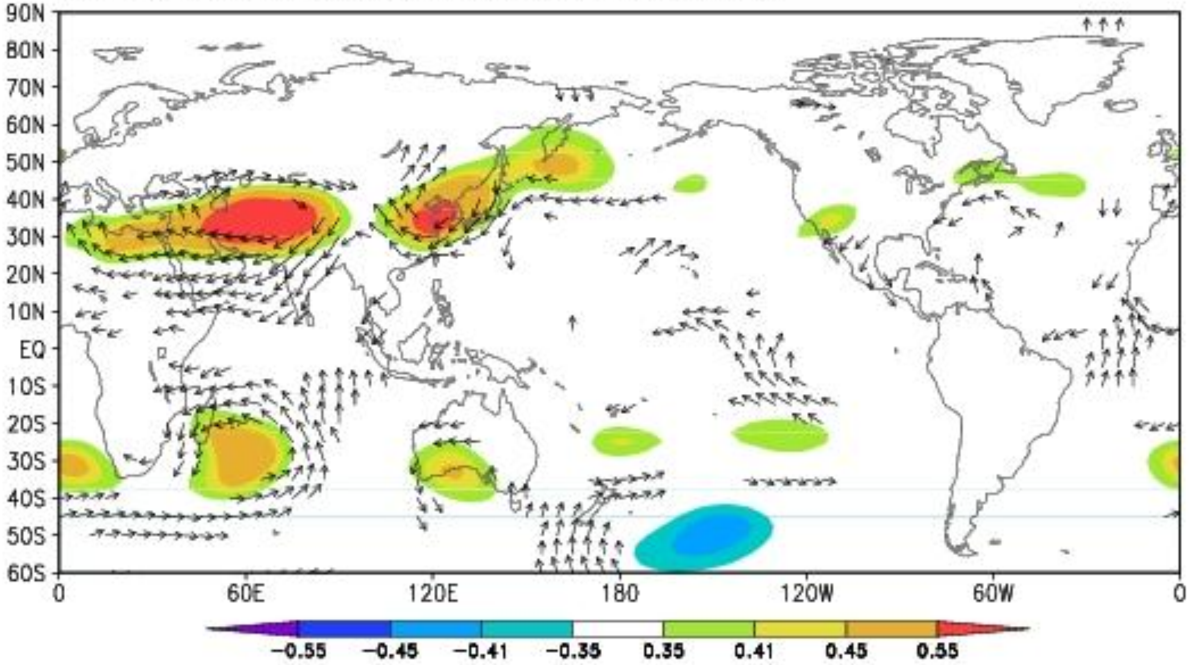


CC of ISMR with 2mST and 850-hPa wind vectors during for the period 1958-2001 and for non-ENSO years.

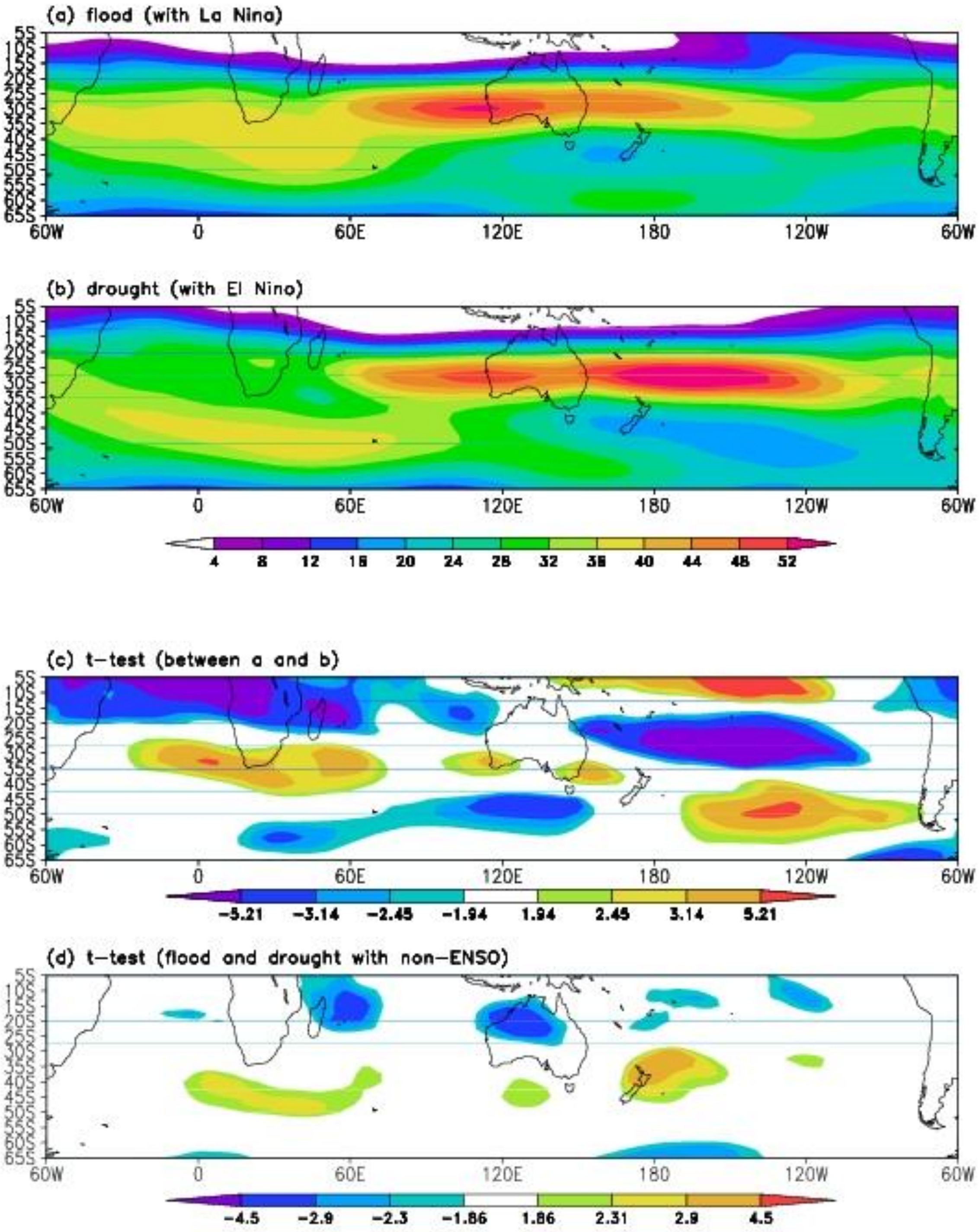


Same as previous fig but for MSLP

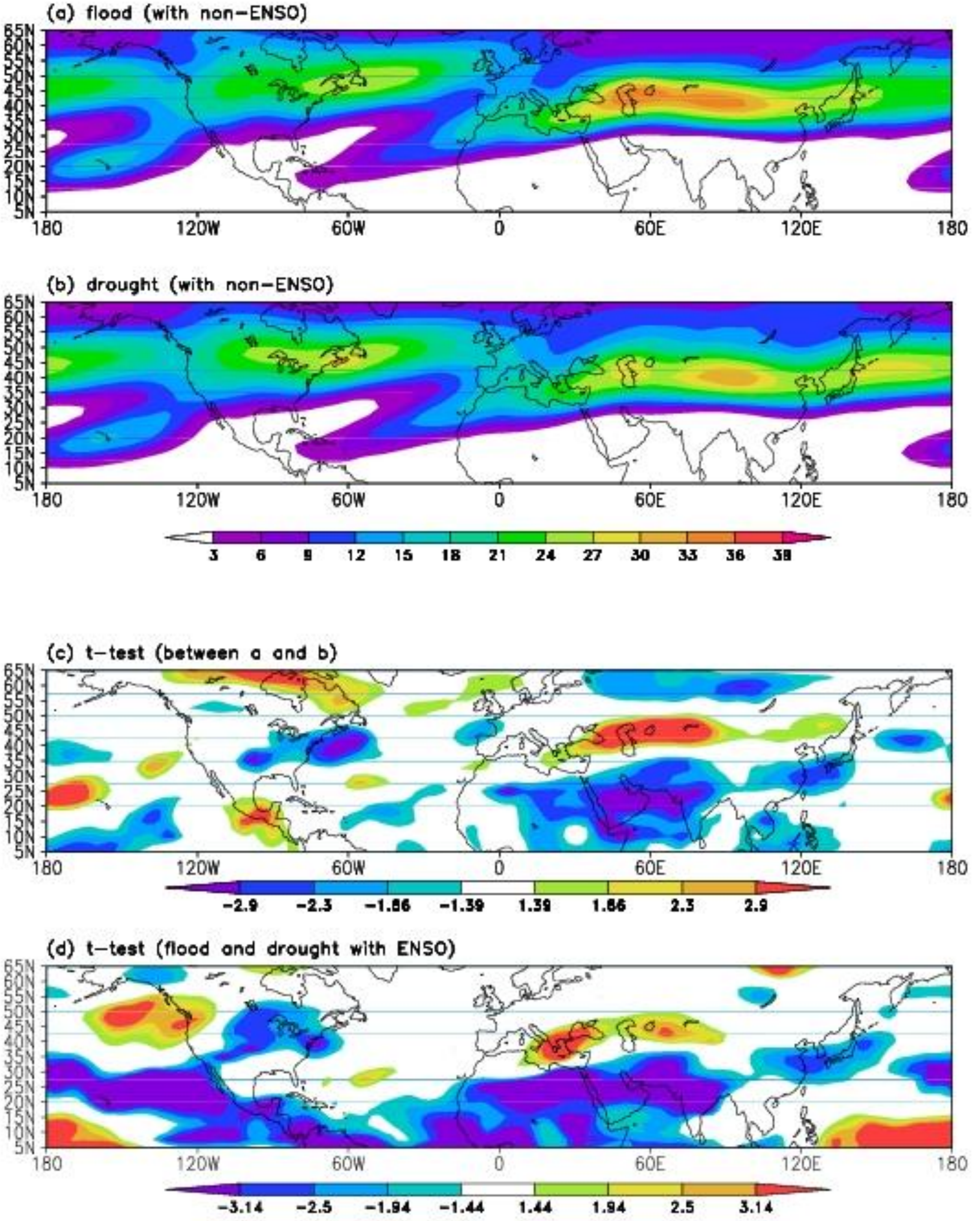

(a) Case-I : 200-hPa Geopotential and Wind (1958-2001)


(b) Case-II : 200-hPa Geopotential and Wind (non-ENSO)

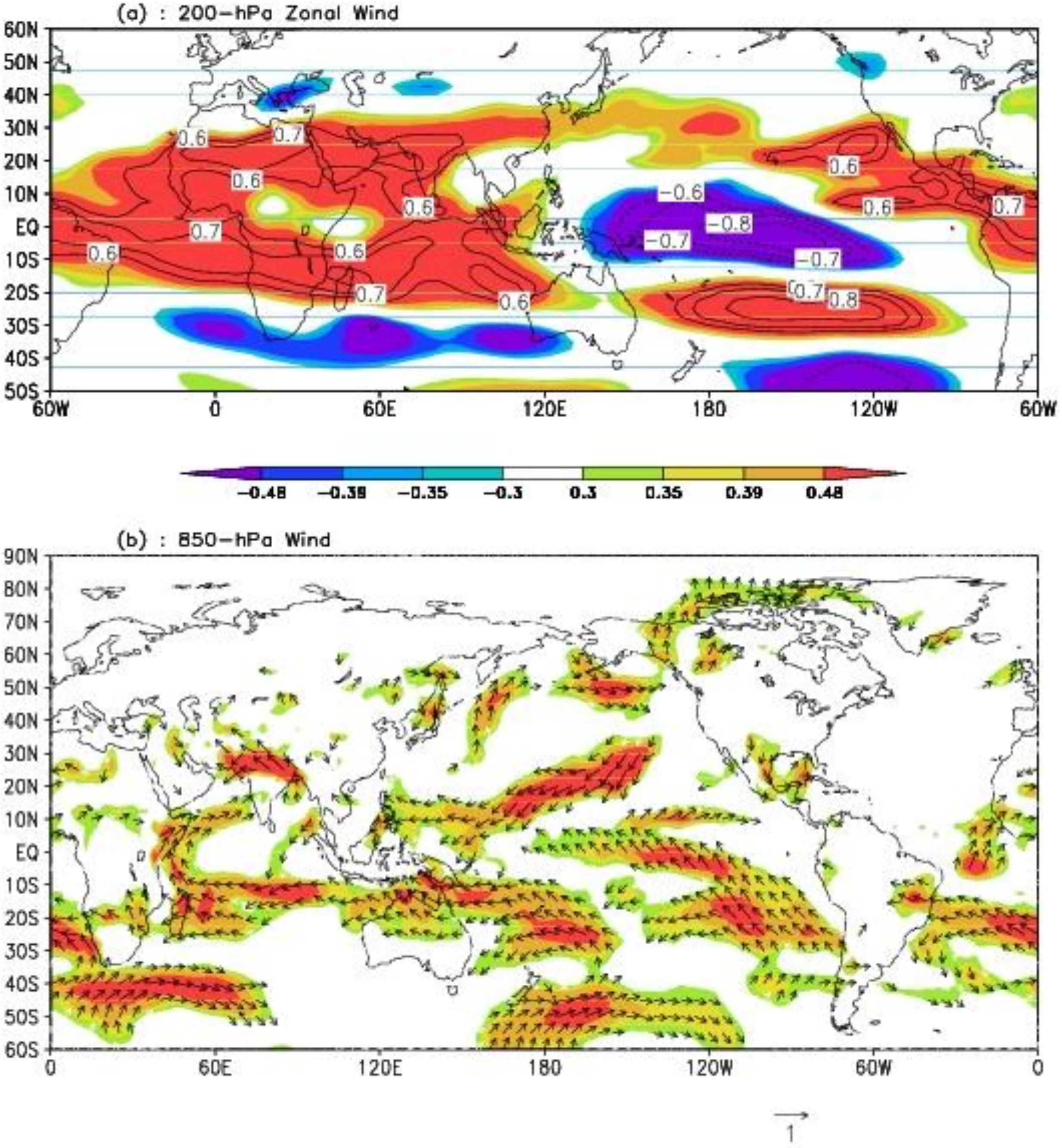
Same as previous fig but for 200-hPa geopotential and wind vectors.



Composite of 200-hPa zonal wind during (a) flood and (b) drought years of ISMR having simultaneous La Niña and El Niño conditions, respectively. (c)Statistical t-test of (a) and (b), and (d) statistical significance of composite of flood and drought during non-ENSO years .

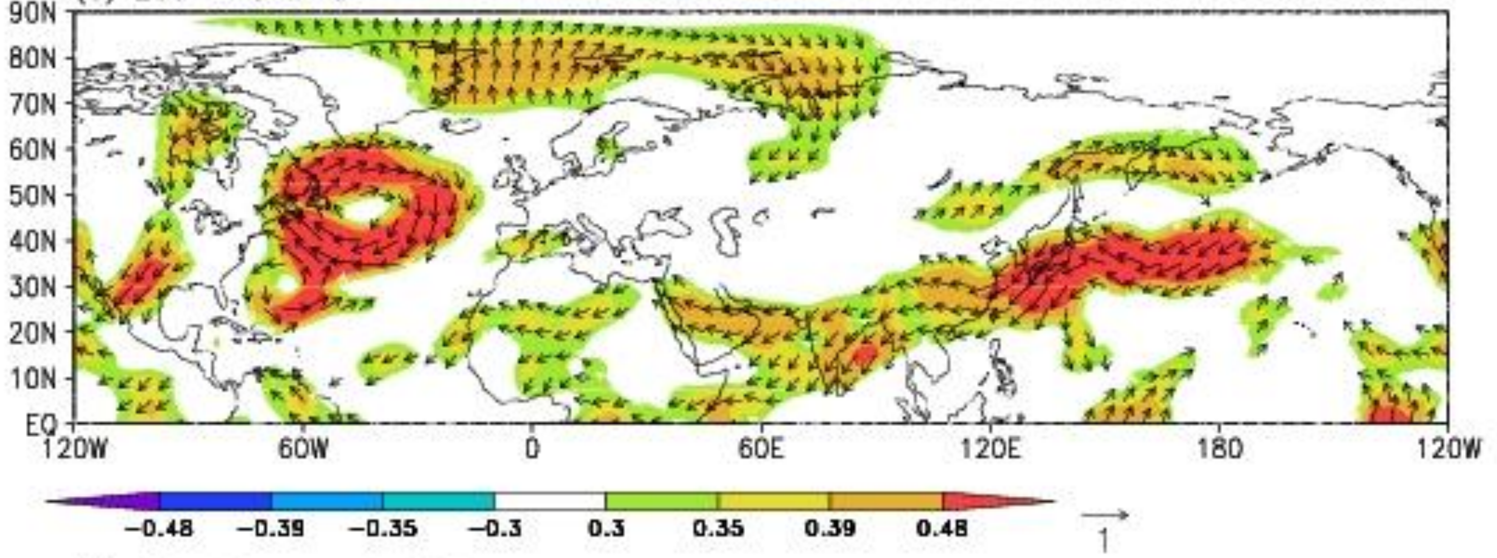


Composite of 200-hPa zonal wind during (a) flood and (b) drought years of ISMR during non-ENSO condition. (c)Statistical t-test of (a) and (b), and (d) statistical significance of composite of flood and drought having simultaneous La Niña and El Niño conditions, respectively.

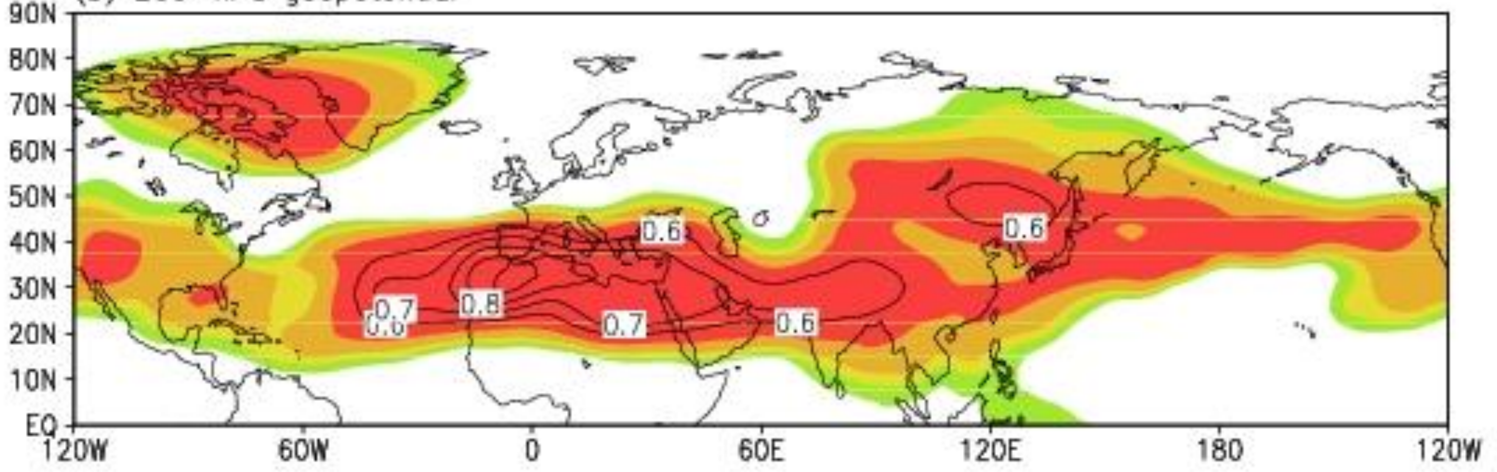


CC of ECP SST with 200-hPa zonal wind and CC of 200-hPa geopotential SE of Madagascar with 850-hPa wind vectors.

(a) 200-hPa Wind



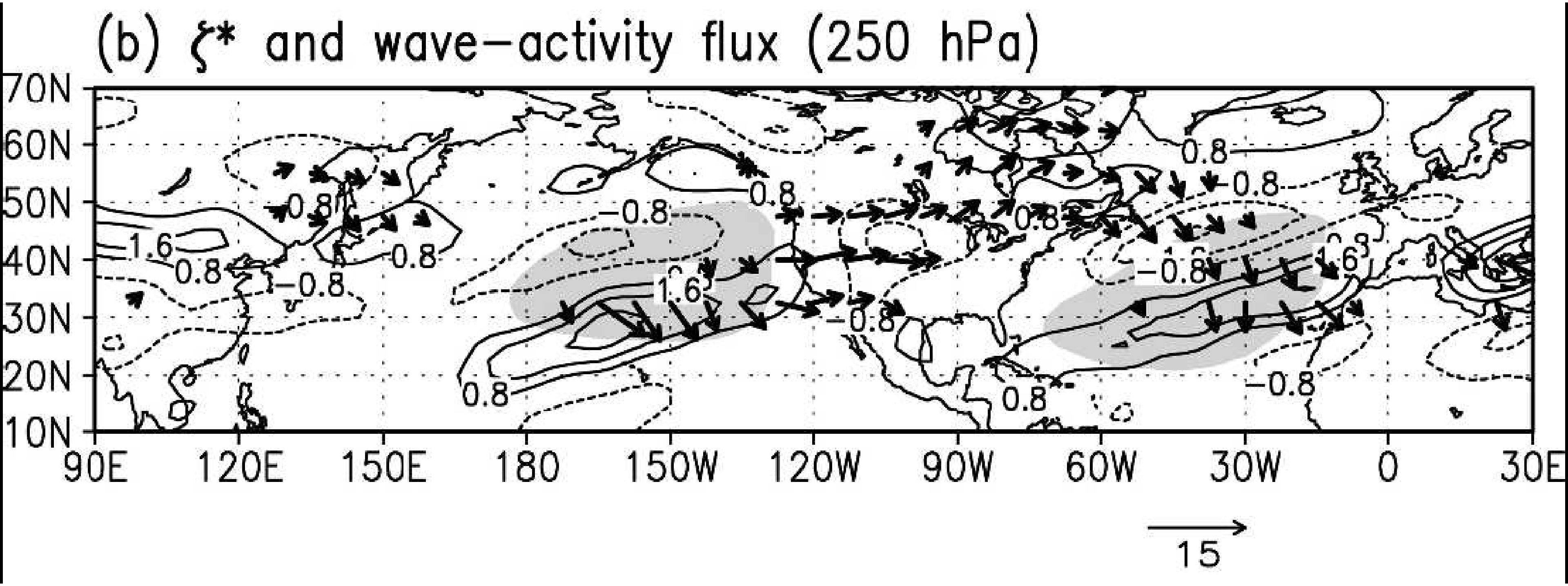
(b) 200-hPa geopotential



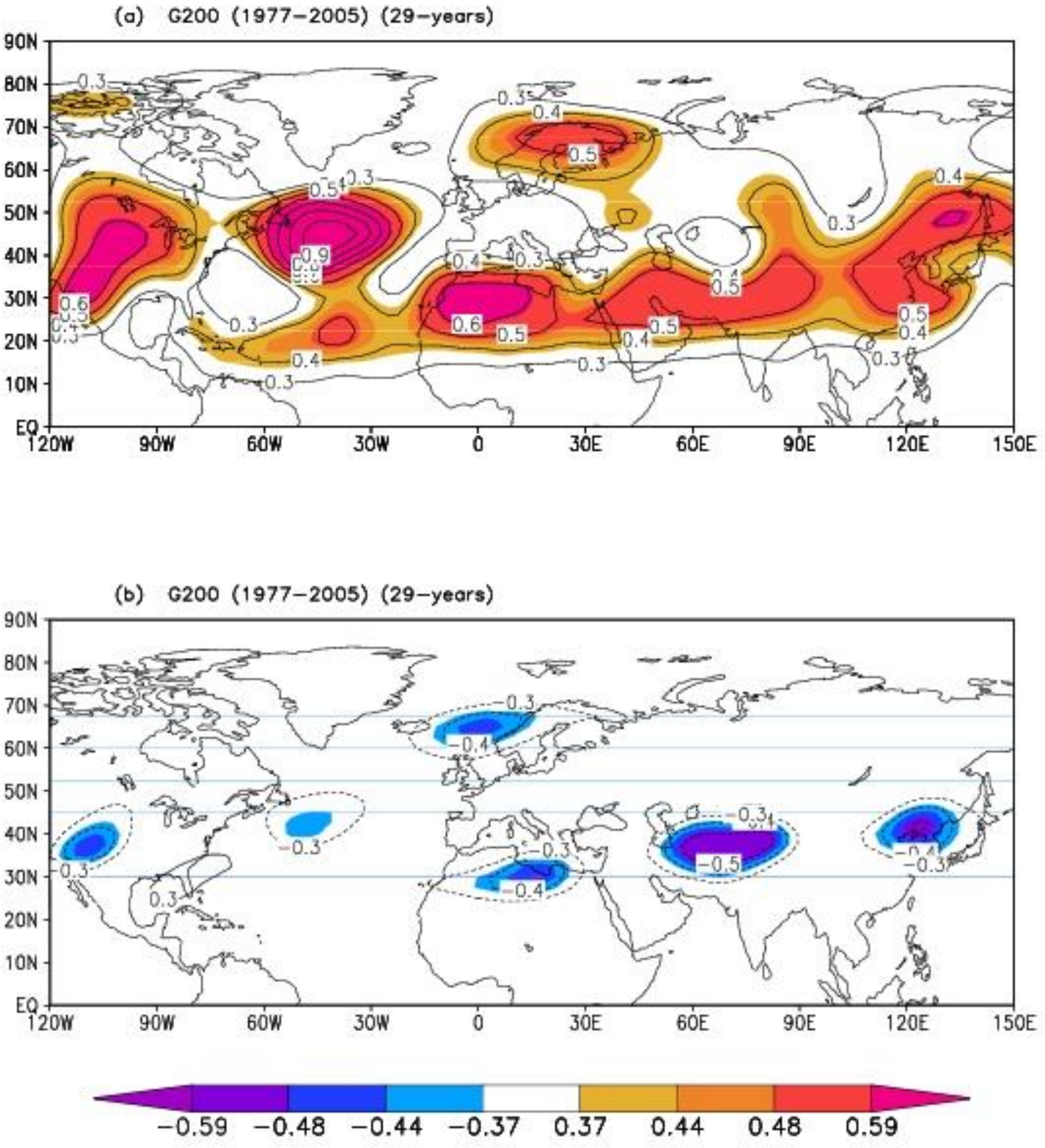
CC of (a) NWA SST with wind vectors at 200-hPa level and (b) one-point correlation between the base-point (32.5N, 10W) and 200-hPa geopotential.

250-hPa relative vorticity and plantary waves

Miyasaka & Nakamura (2005) J. Climate


(b) ζ^* and wave-activity flux (250 hPa)

A wave activity flux for stationary Rossby waves diverges out of the vorticity dipole toward downstream in the upper troposphere above the Azores high with its significant upward component in the mid-troposphere, suggesting that the source of the planetary waves must be in the lower troposphere associated with the surface high. Also the upper-tropospheric wave activity injection from upstream is stronger into the Azores high, which reinforce the upper-tropospheric vorticity dipole.



CC between North Atlantic 200 hPa geopotential and MSLP during 1977-2005.

Conclusion

- ✓ The simultaneous CC for the season JJAS between ISMR and ERA-40 dataset reveals mostly the negative phase of ENSO (La Niña) type circulation when considering the whole dataset from 1958-2001.
- ✓ However, while removing the ENSO years from the datasets, the CC shows simultaneous relationship with North Atlantic circulation.
- ✓ During La Niña years, the SST over tropical west Pacific rises and the SH subtropical westerly jet stream over south Indian Ocean, SW Australia and SE Atlantic intensifies due to the consequence of thermal wind balance.

Conclusion continue

- ✓ The intensification of jet stream forms anticyclonic circulation anomaly which intensifies the Mascarene High at the lower level as the atmospheric response over the region is equivalent barotropic in nature.
- ✓ The Mascarene High intensifies the cross-equatorial flow and hence Indian monsoon monsoon (ISM) circulation.
- ✓ This intensifies the Tibetan High which excite downstream Rossby wave train extending to the North Pacific.
- ✓ The interaction between the ISM and La Niña influence northern China via the ISM and the strong CGT is formed in the NH.

Conclusion continue

- ✓ The intense Tibetan High also intensifies the anticyclone SE of Madagascar through strong Hadley Cell.
- ✓ The intensified SH jet, acts as Rossby waveguide and enhances the CGT in the SH .
- ✓ Further, La Niña years are also linked to positive phase of Arctic Oscillation (AO) which produces trough over Greenland.
- ✓ The north-westerly winds parallel to the west coast of the Greenland associated with the trough, coming from cold Arctic, cools the SST over NW of North Atlantic and hence reduces the effect of North Atlantic circulation.

Conclusion continue

- ✓ While, during non-ENSO years, the SST over NW of North Atlantic increases.
- ✓ The increase in SST intensifies and shift the North Atlantic jet stream to higher latitudes.
- ✓ The jet stream intensifies the meridional vorticity dipole formed due to Azores High.
- ✓ The cyclonic circulation anomaly of the dipole intensifies the Asian jet stream over Eurasia.

Conclusion continue

- ✓ Also, a wave activity flux for stationary Rossby waves diverges out of the vorticity dipole toward downstream over the Eurasian region.
- ✓ The successive troughs and ridges of the Rossby waves travel along the jet stream and influence upper-tropospheric Tibetan High and hence ISM circulation.
- ✓ Also, the waveguide effect of North Atlantic jet stream induce anticyclonic circulation anomaly over north Europe.
- ✓ The anticyclonic circulation anomaly may be responsible for the formation of troughs over eastern Europe and a ridge over Caspian Sea which will intensify the Tibetan high and hence ISM circulation

Schematic diagram

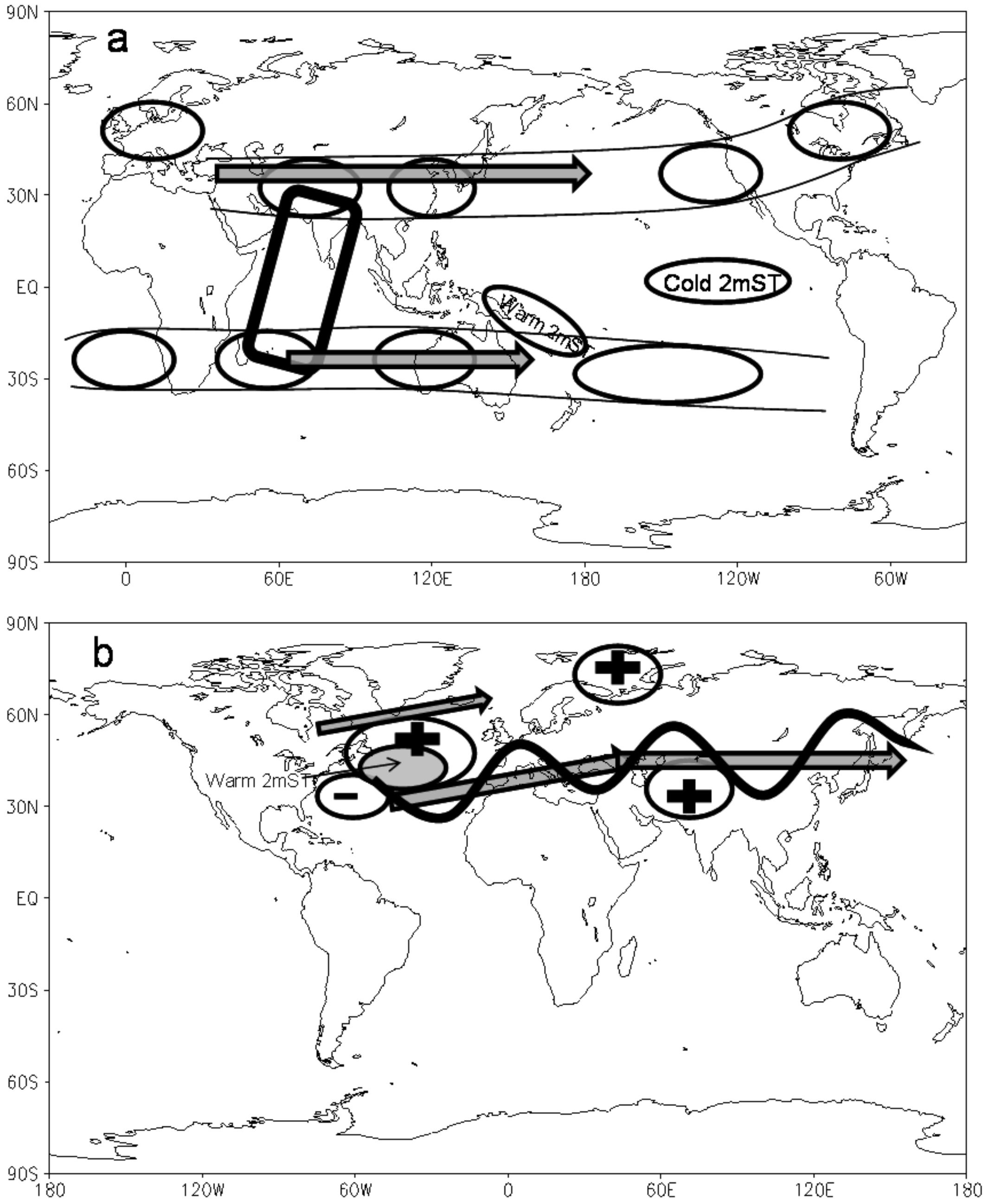
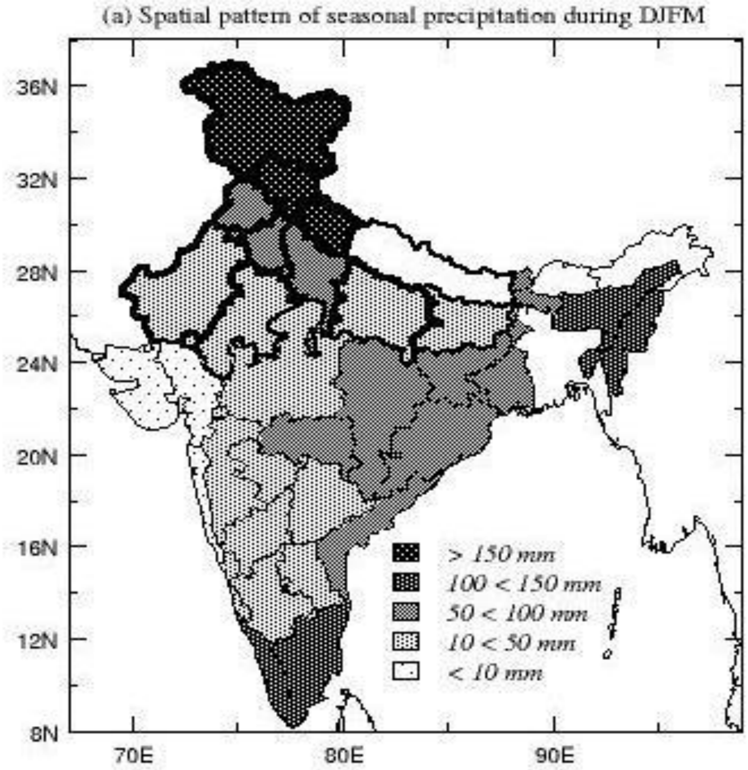


Fig. 10 : Schematic diagram

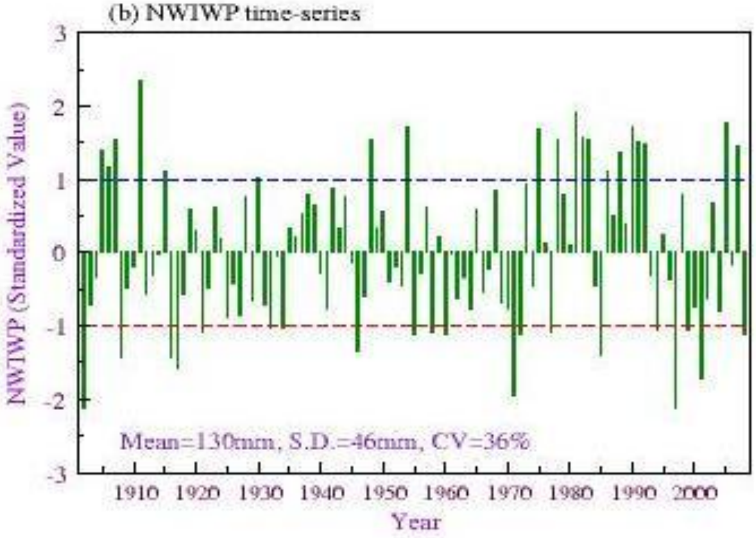
North-West India Winter Precipitation

1. **Yadav RK**, Rupa Kumar K and Rajeevan M. 2009 Increasing influence of ENSO and decreasing influence of AO/NAO in the recent decades over northwest India winter precipitation; **Journal of Geophysical Research-Atmospheres**, 114, D12112.
2. **Yadav RK**, Rupa Kumar K and Rajeevan M. 2009 Out-of-phase relationships between convection over north-west India and warm-pool region during winter season; **International Journal of Climatology**, 29, 1330-1338.
3. **Yadav RK**, Yoo JH, Kucharski F and Abid MA. 2010 Why is ENSO influencing northwest India winter precipitation in recent decades? ; **Journal of Climate**. 23, 1979-1993

Increasing influence of ENSO and decreasing influence of AO/NAO in the recent decades over northwest India winter precipitation: 1950-2008



(a) Spatial pattern of seasonal mean climatology of precipitation (mm) for different meteorological sub-divisions of India for the season DJFM. The northwest India meteorological subdivisions are shown in thicker lines.



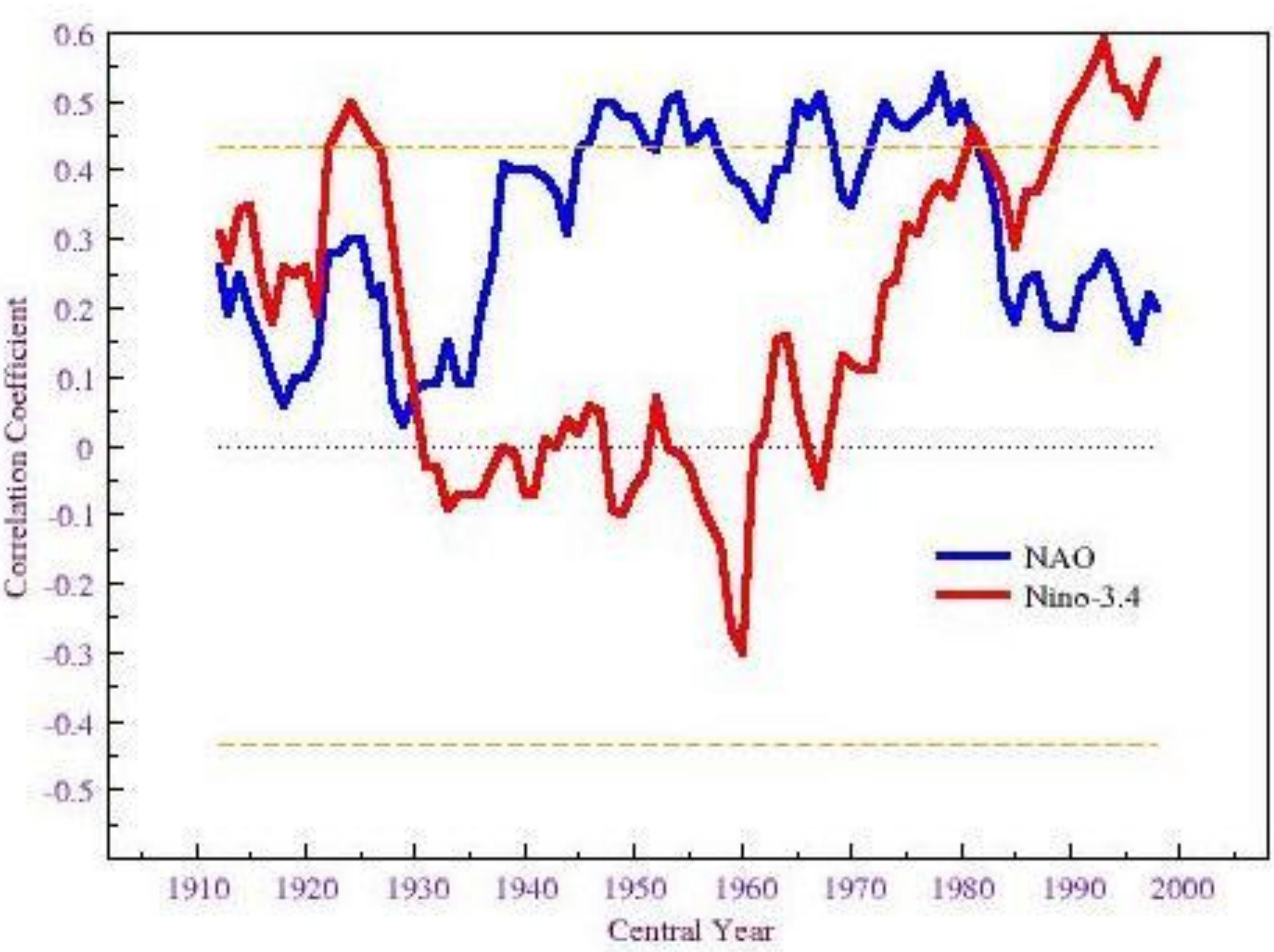
(b) The time series of northwest India winter precipitation (NWIWP) for the period 1902-2008 expressed as the standardized values (SVs) of area weighted seasonal NWIWP from the long period normal. The horizontal dash lines are +1 and -1 SV.

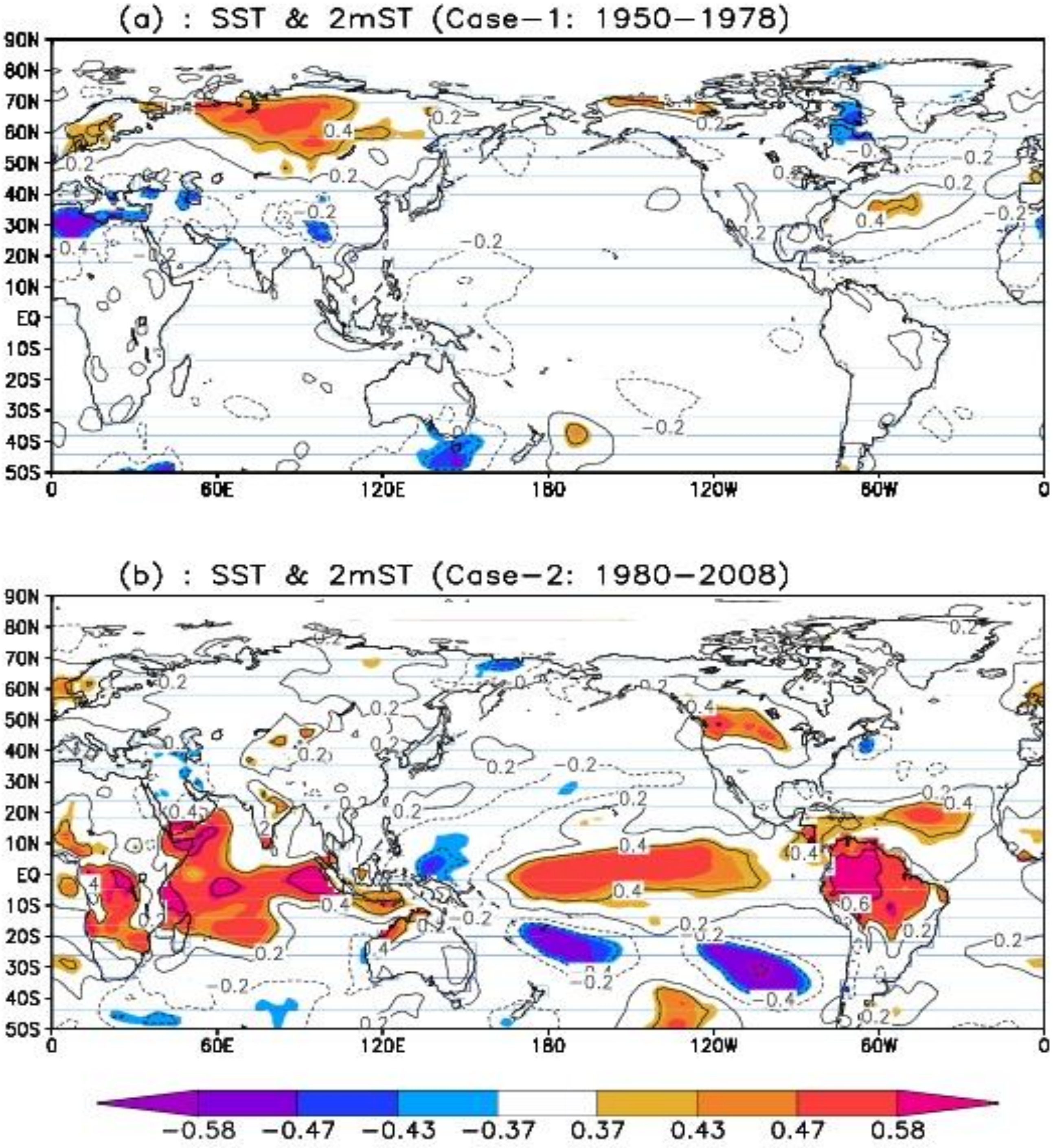
The CC of Niño-3.4 and NAO with NWIWP for the period 1968-2008 and 1940-1980, respectively which are statistically significant at 99% level.

The CC between ENSO and NAO indices for the period 1902-2008 is very poor and insignificant

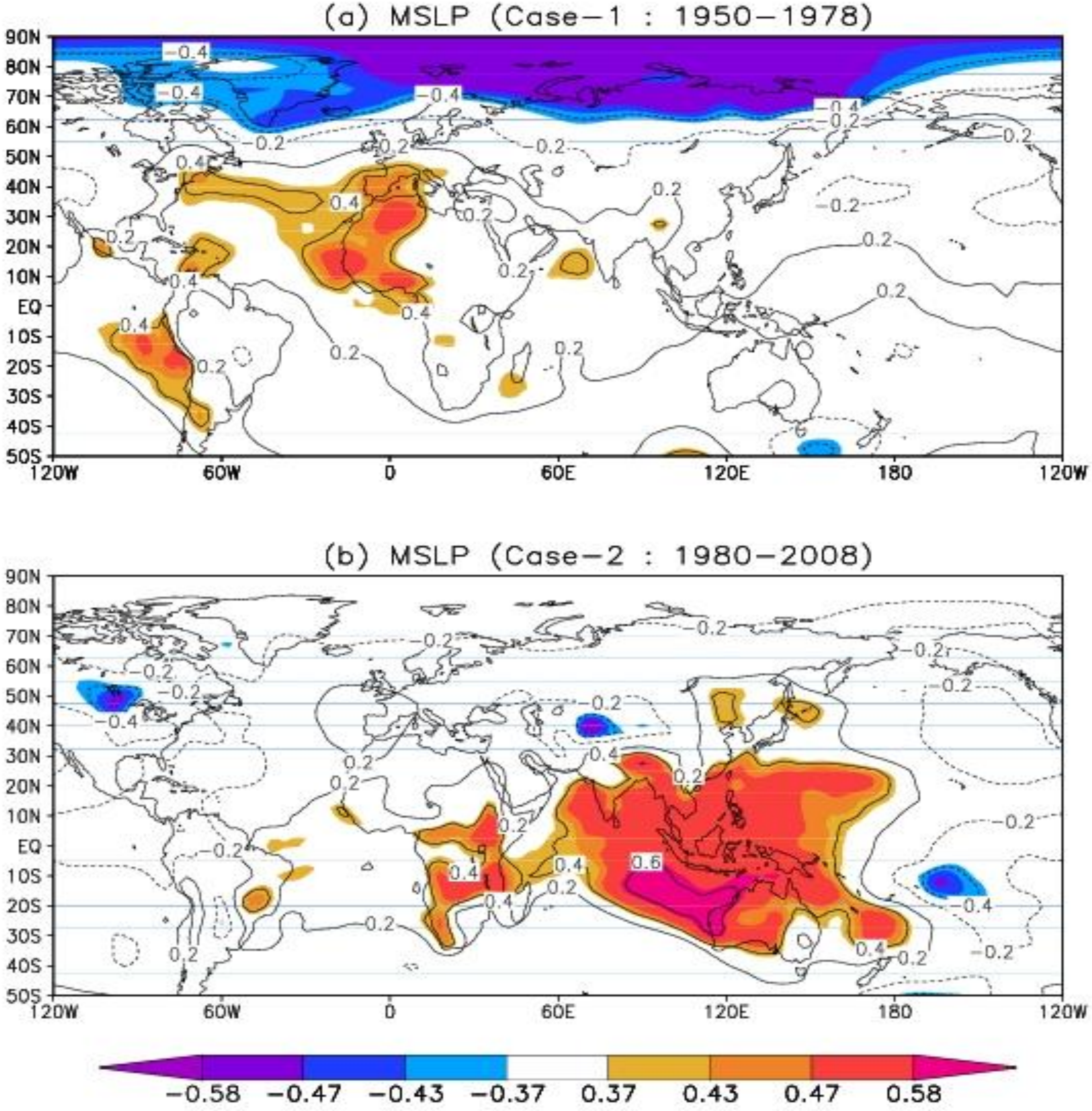
	NAO	Nino-3.4	NWIWP
NAO	1	0.04	0.42
Nino-3.4		1	0.46
NWIWP			1

Sliding correlations on a 21-year moving window among NWIWP and NAO and Nino-3.4 region SST indices for the period 1902-2008 for the season of DJFM. Values are plotted at the centre of 21-year period. The dash line indicates 95% significance level.



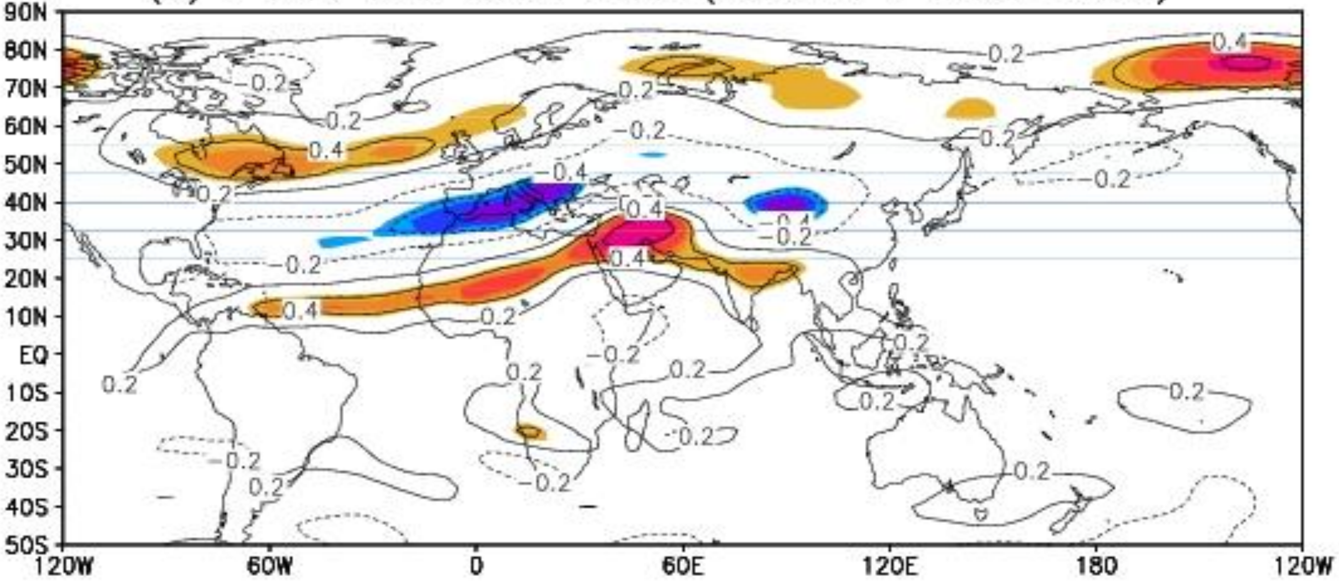


Spatial pattern of correlation between NWIWP and surface temperature (SST over ocean basins and 2-meter Surface Temperature over land region) during (a) (Case-1 : period 1950-1978) and (b) (Case-2 : period 1980-2008).

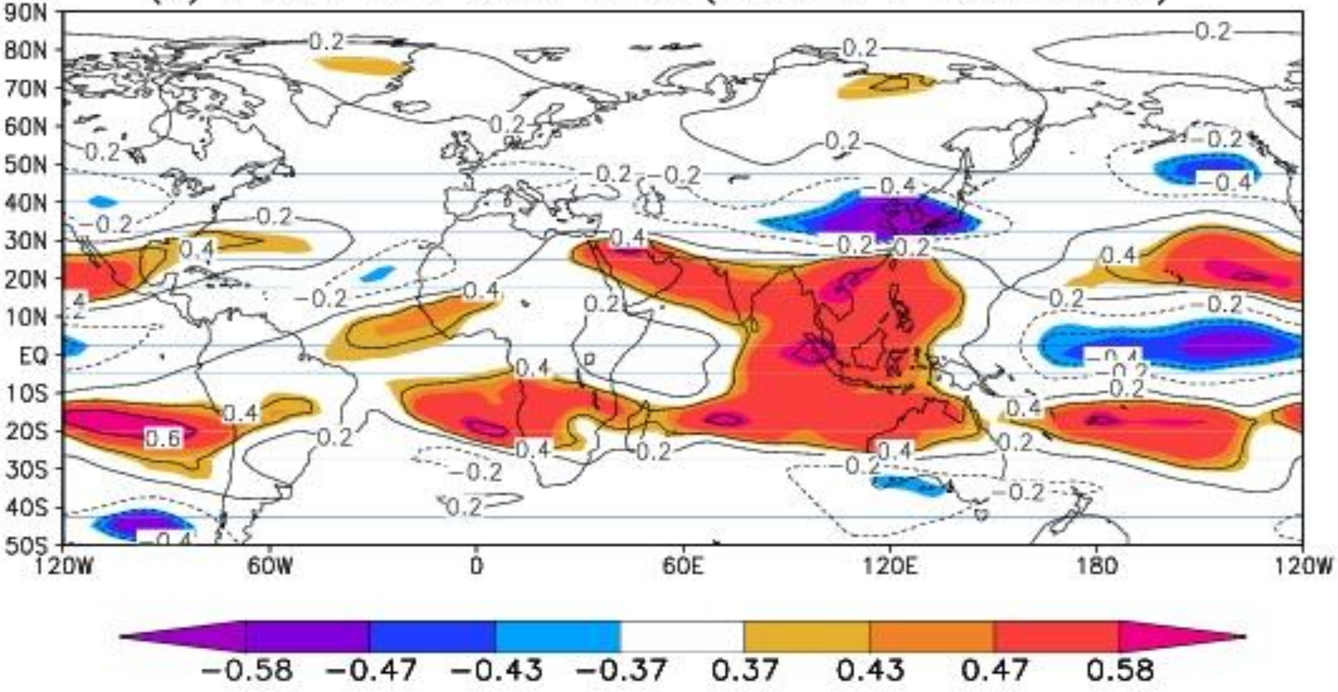


Same as previous Figure but for MSLP

(a) : 200-hPa Zonal Wind (Case-1 : 1950-1978)



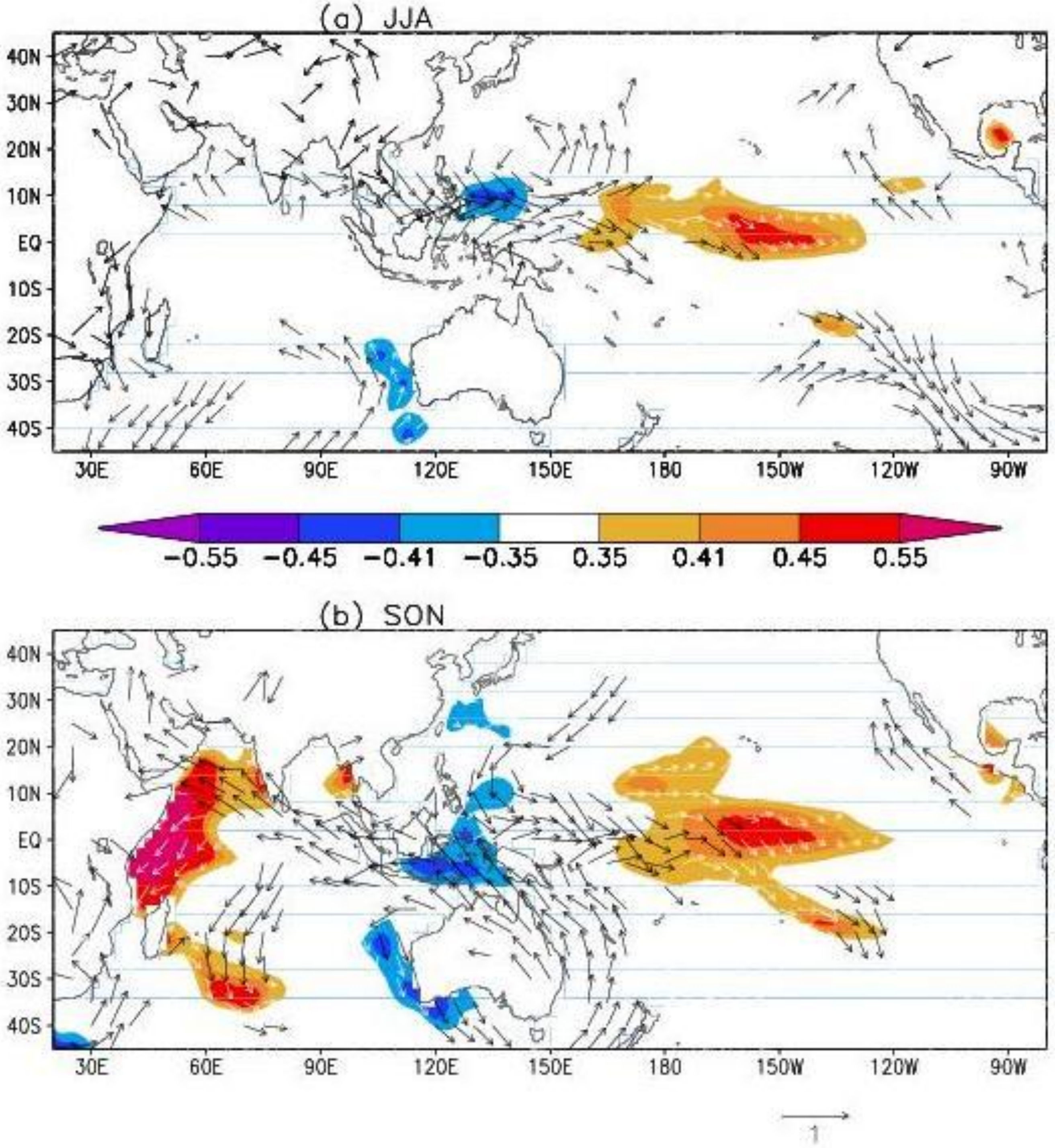
(b) : 200-hPa Zonal Wind (Case-2 : 1980-2008)



Same as previous Figures but for zonal wind at 200-hPa level

Predictive Relationship

Out-of-phase relationships between convection over north-west India and warm-pool region during winter season

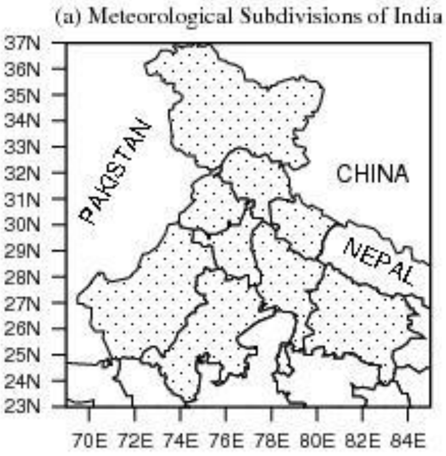


Predictive Relationship

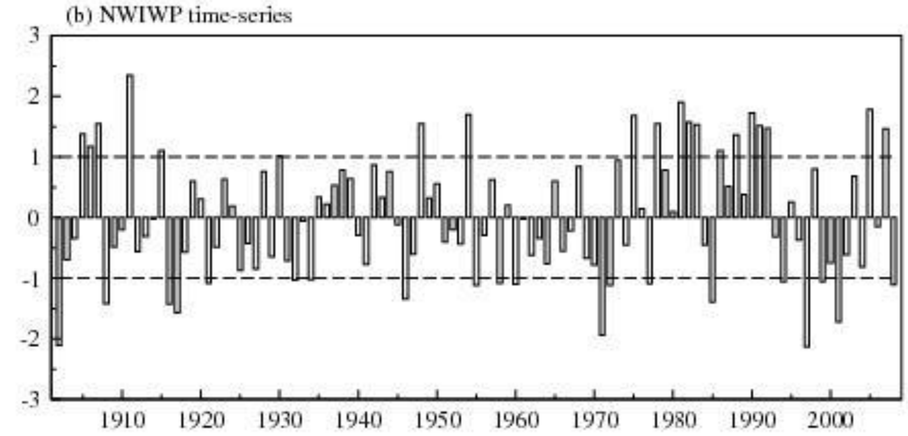
Why is ENSO influencing northwest India winter precipitation in recent decades?

- ✓ Yadav RK, Yoo JH, Kucharski F, Abid MA. 2010, Why is ENSO influencing northwest India winter precipitation in recent decades?, **Journal of Climate**, 23, 1979-1993.

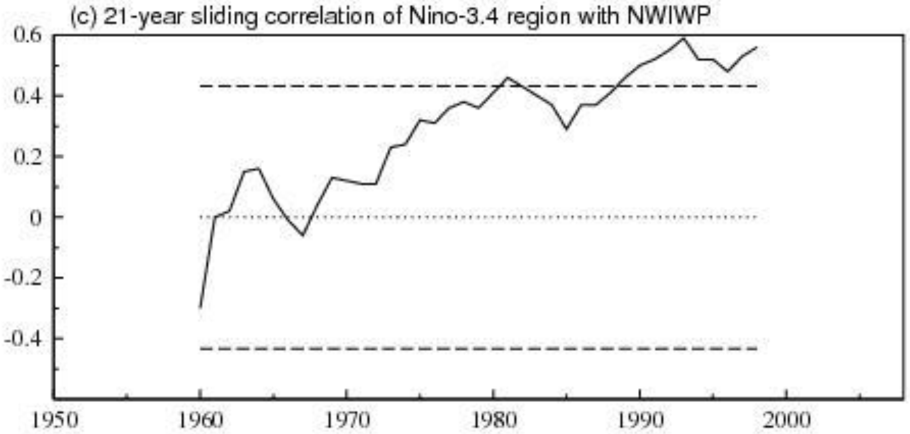
- Period 1950-2008



(a) Geographical location of NW India

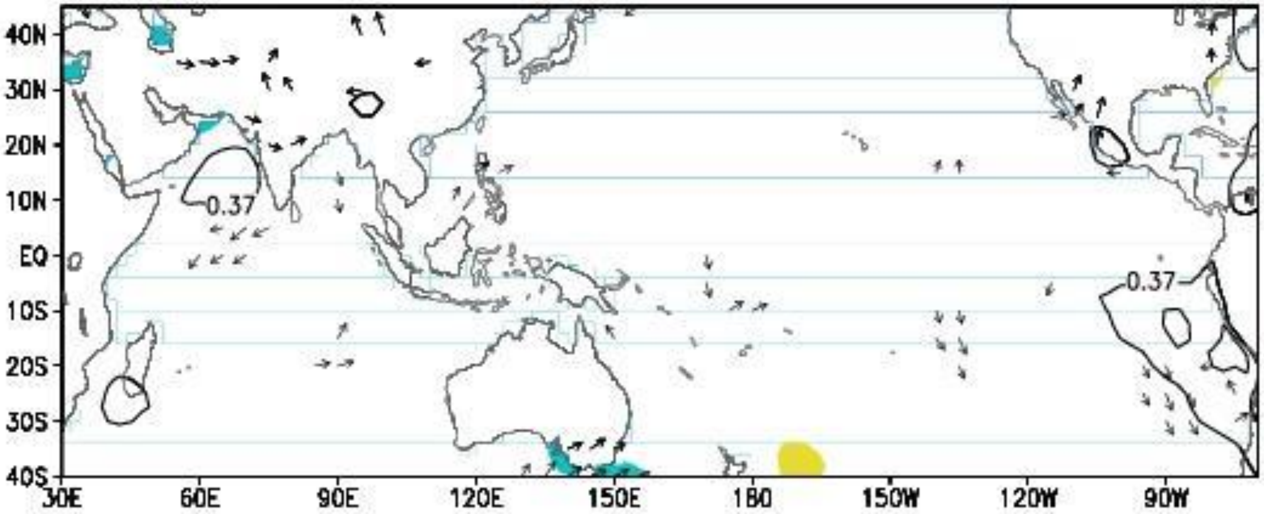


(b) The time series of NWIWP for the period 1902-2008

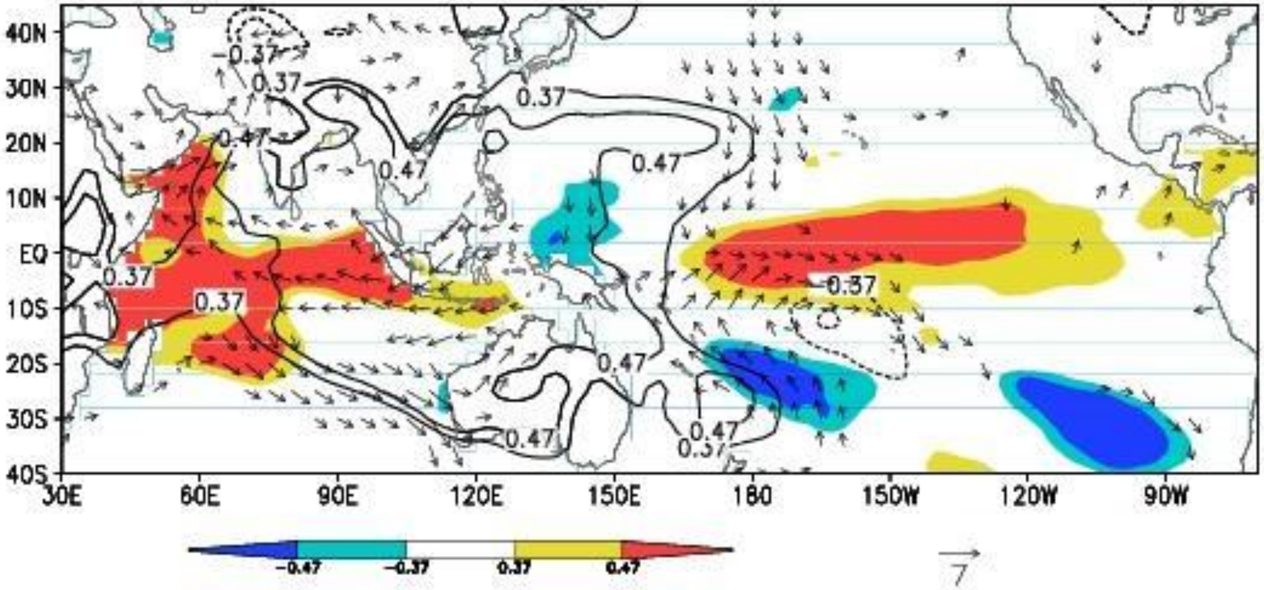


(c) 21-year sliding correlation between Nino-3.4 region SST and NWIWP index

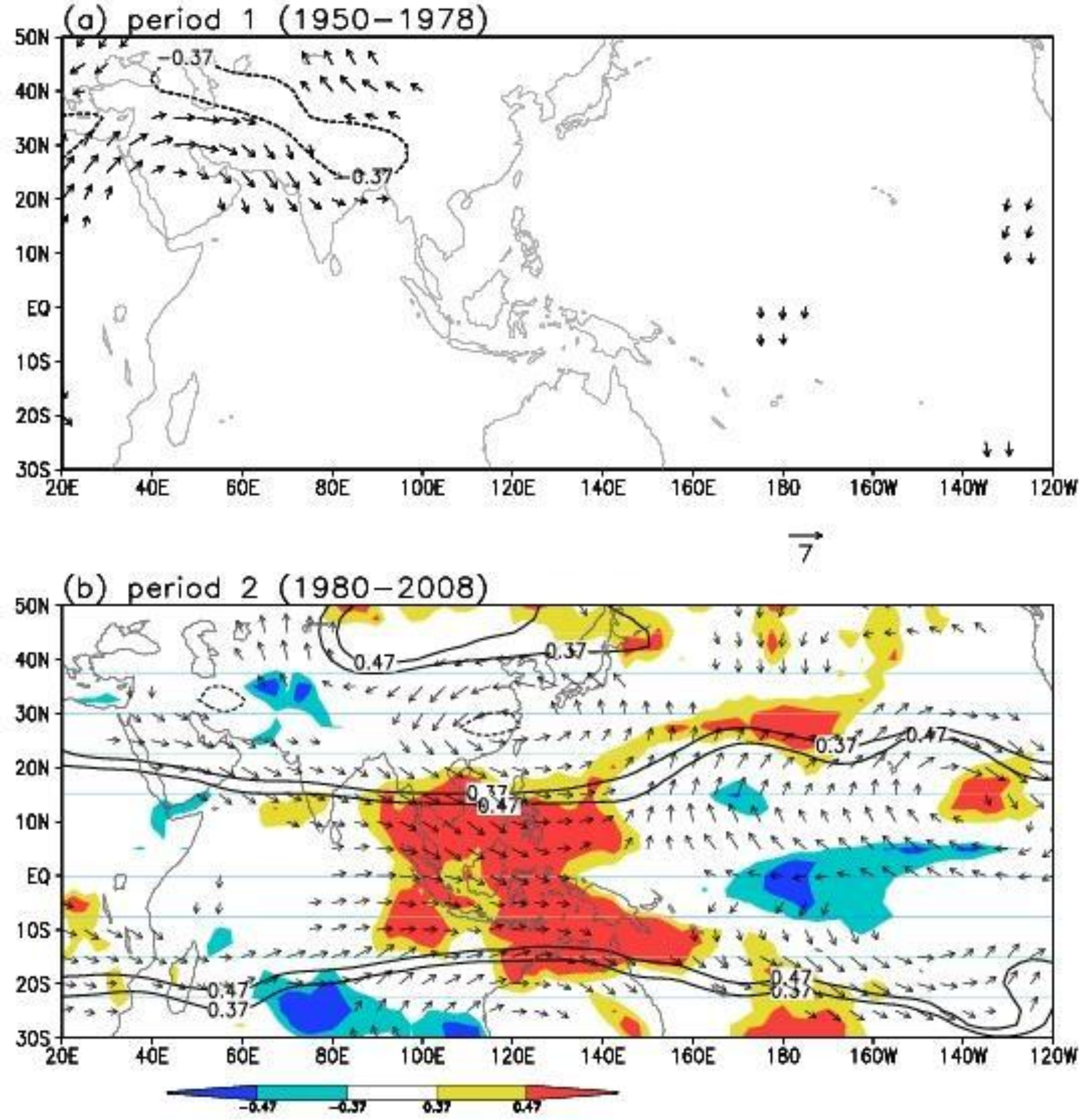
(a) period 1 (1950−1978)



(b) period 2 (1980−2008)

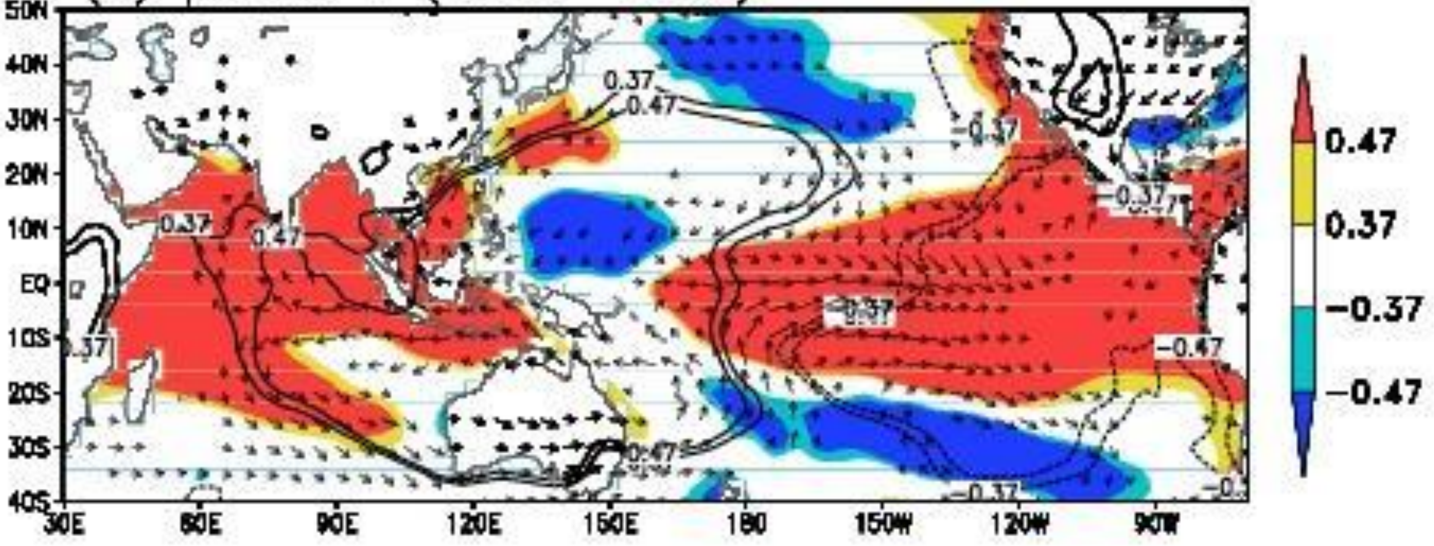


correlation of SST and MSLP and regression of 850-hPa winds with NWIWP during (a) period 1 (1950-1978) and (b) period 2 (1980-2008).

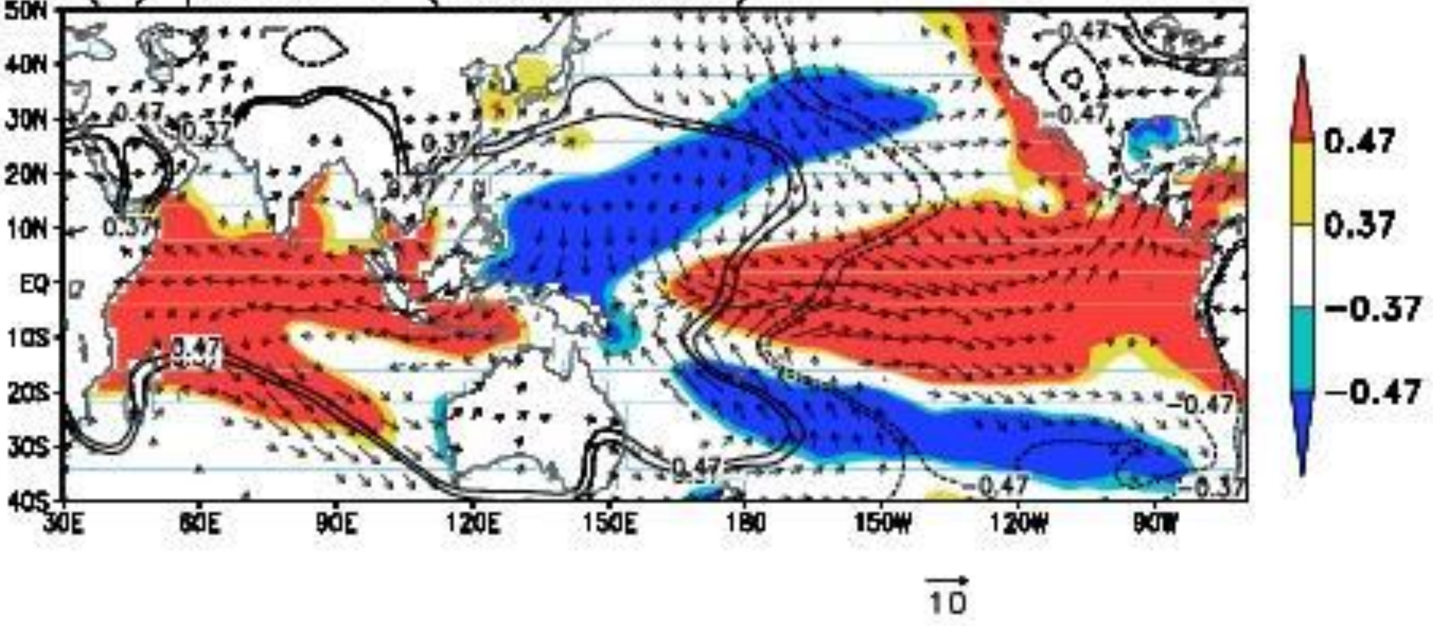


correlation of 200-hPa geopotential and regression of 200-hPa winds with NWIWP during (a) period 1 and additional correlation of OLR during (b) period 2.

(a) period 1 (1950−1978)

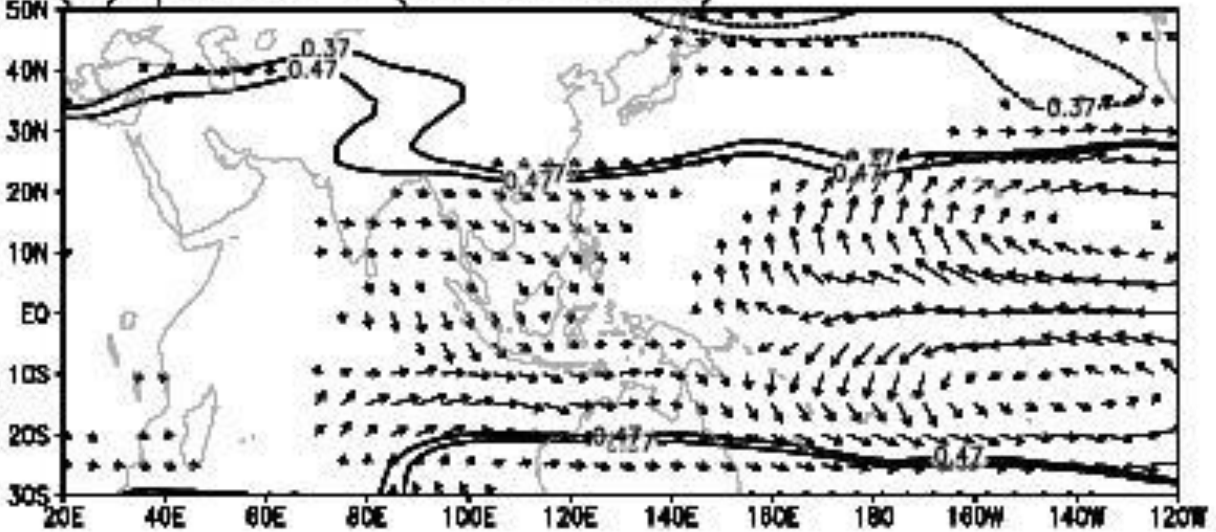


(b) period 2 (1980−2008)

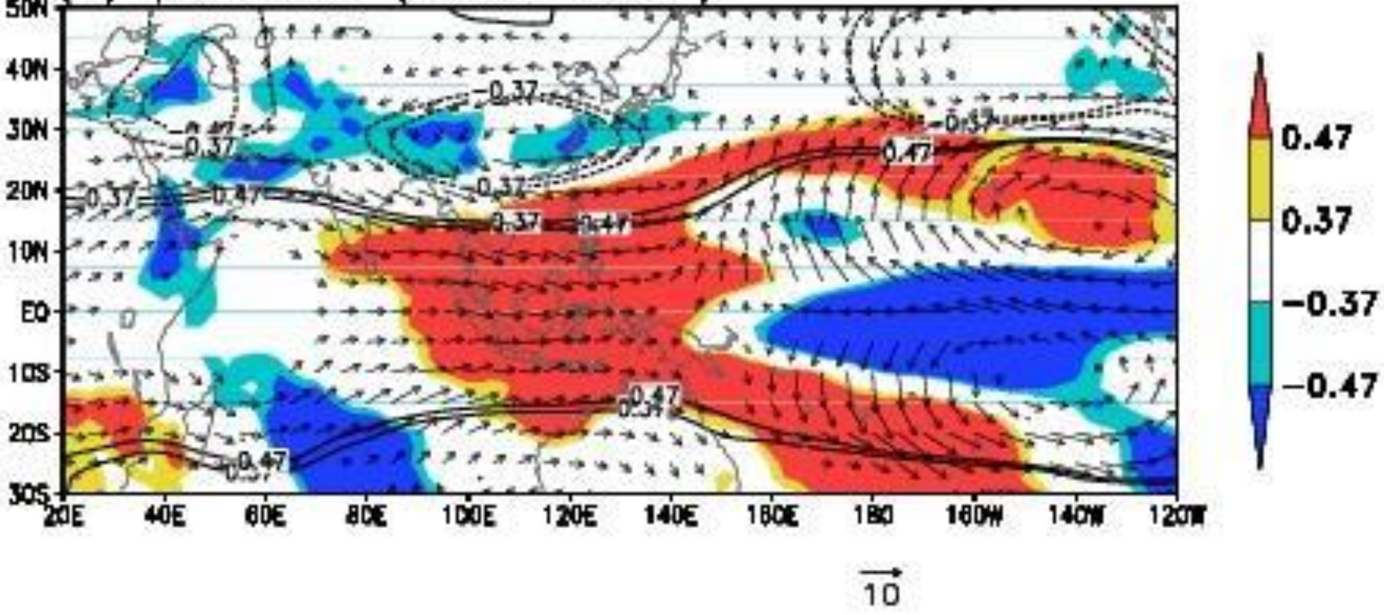


Same for Nino-3.4 indices

(a) period 1 (1950–1978)



(b) period 2 (1980–2008)



Same for Nino-3.4 indices

To support the results from the observational data, we use ensembles of Atmospheric General Circulation Model (AGCM) simulations performed for the CLIVAR International “Climate of the 20th Century” (C20C) Project. These integrations cover the period from 1950-2002.

Regression of observed SSTs onto the Nino3.4 index.

a) 1950-1978,

b) 1980-2002.

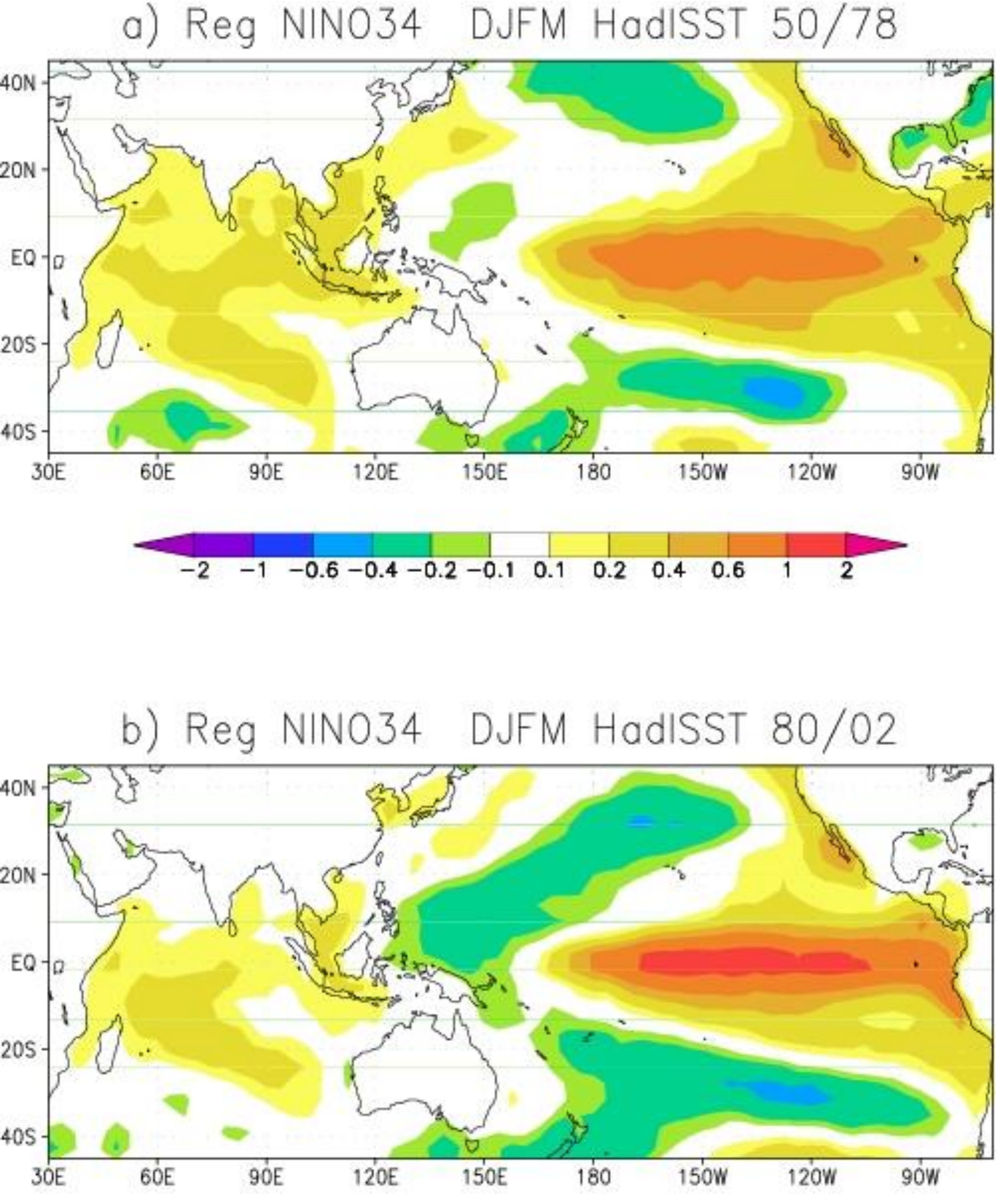
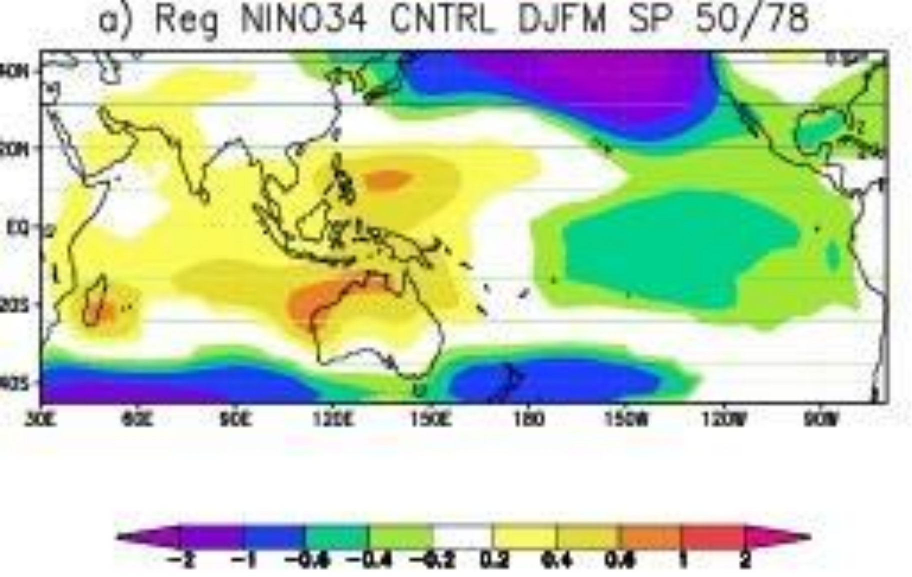
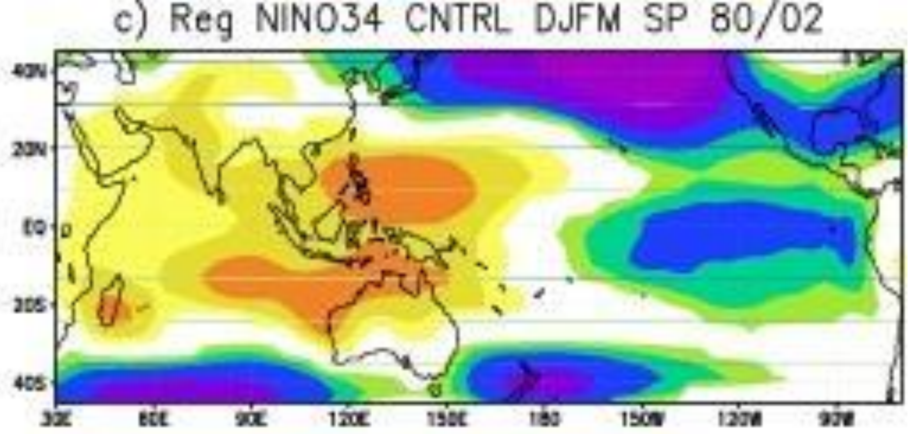
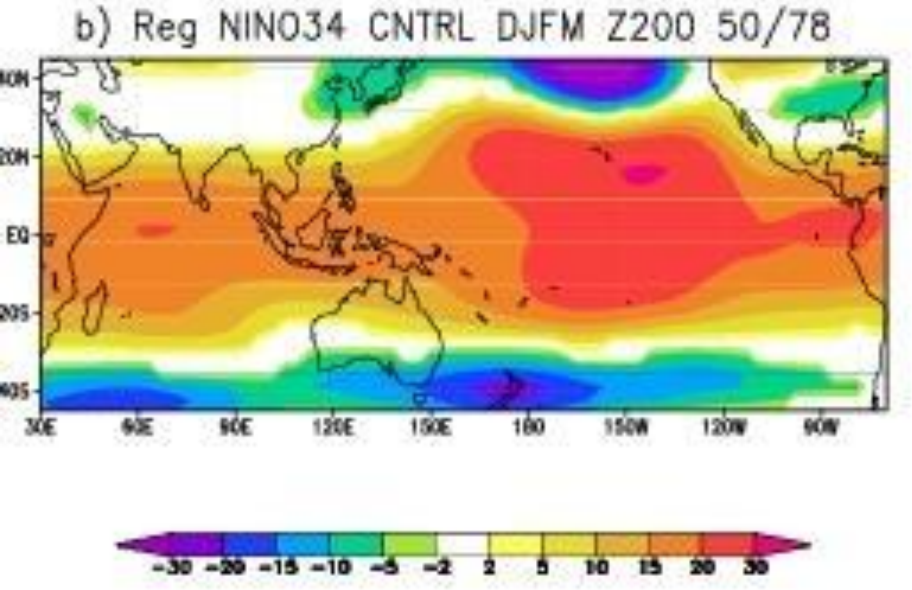


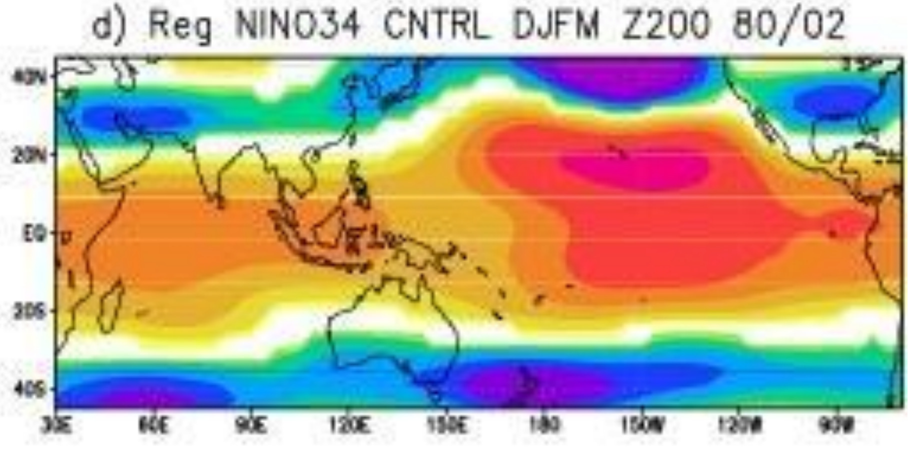
Figure 6: Regression of observed SSTs onto the Nino3.4 index. a) 1950−1978, b) 1980−2002. Units are K.

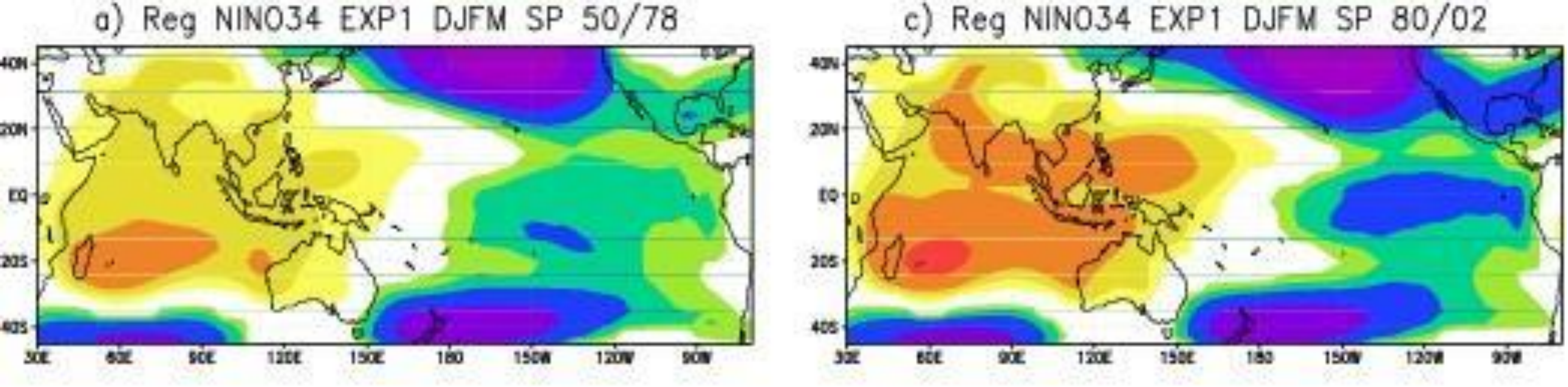




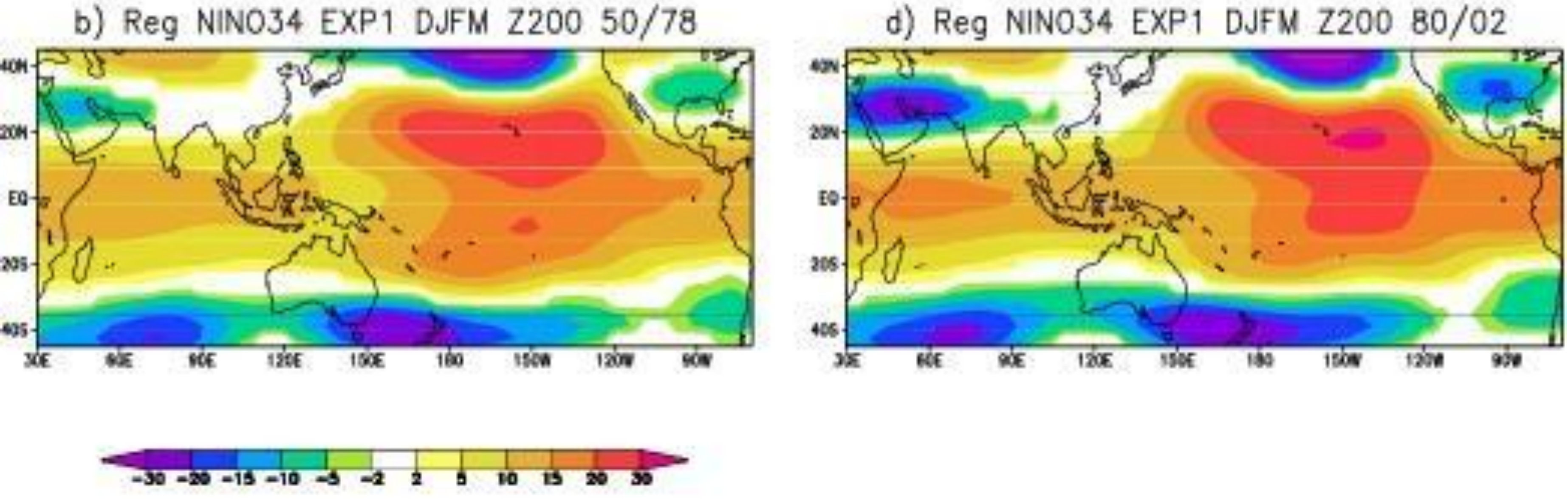
Regression onto the Nino3.4 index of modeled (CNTRL) a) surface pressure 1950-1978,
b) 200-hPa geopotential height 1950-1978,
c) surface pressure 1980-2002,
d) 200-hPa height 1980-2002.

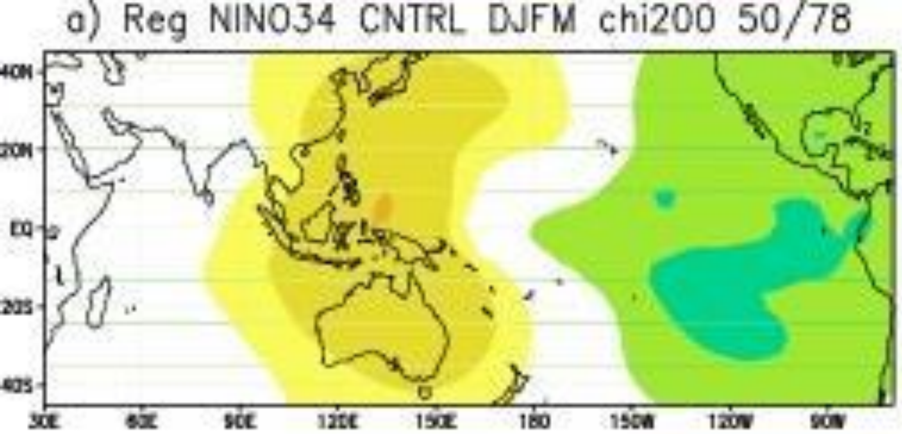


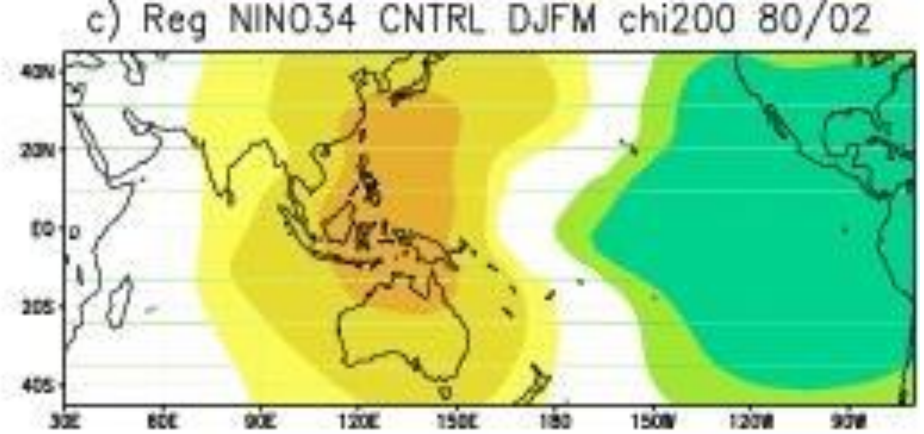




Regression onto the Nino3.4 index of modeled (EXP1) a) surface pressure 1950-1978,
b) 200-hPa geopotential height 1950-1978,
c) surface pressure 1980-2002,
d) 200-hPa height 1980-2002.





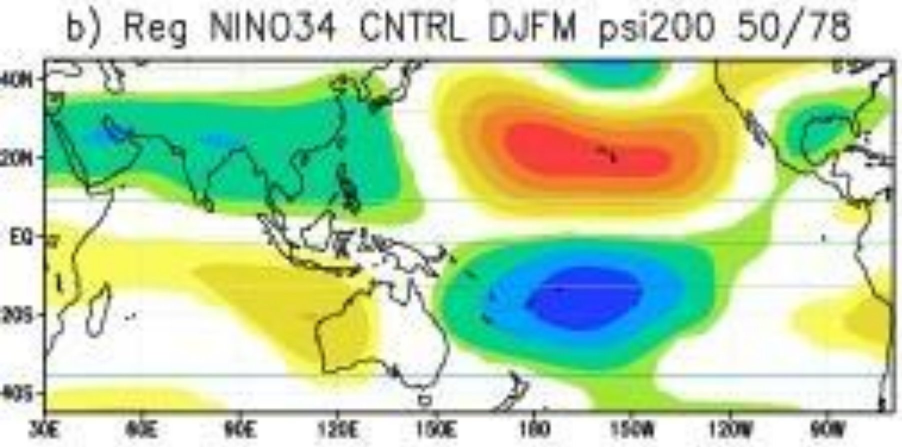


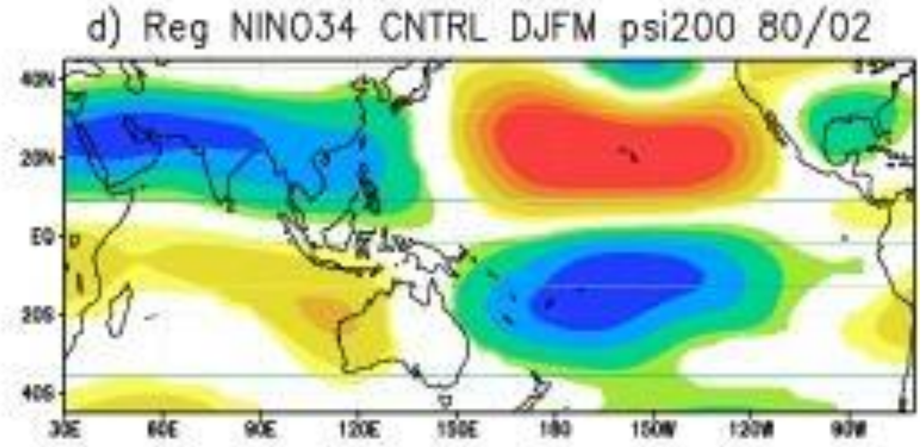
Regression onto the Nino3.4 index of modeled (CNTRL) a) 200-hPa velocity potential 1950-197

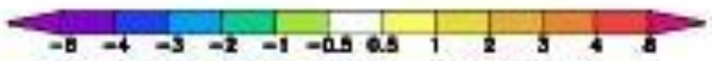
b) 200-hPa eddy streamfunction 1950-1978,

c) 200 hPa velocity potential 1980-2002,

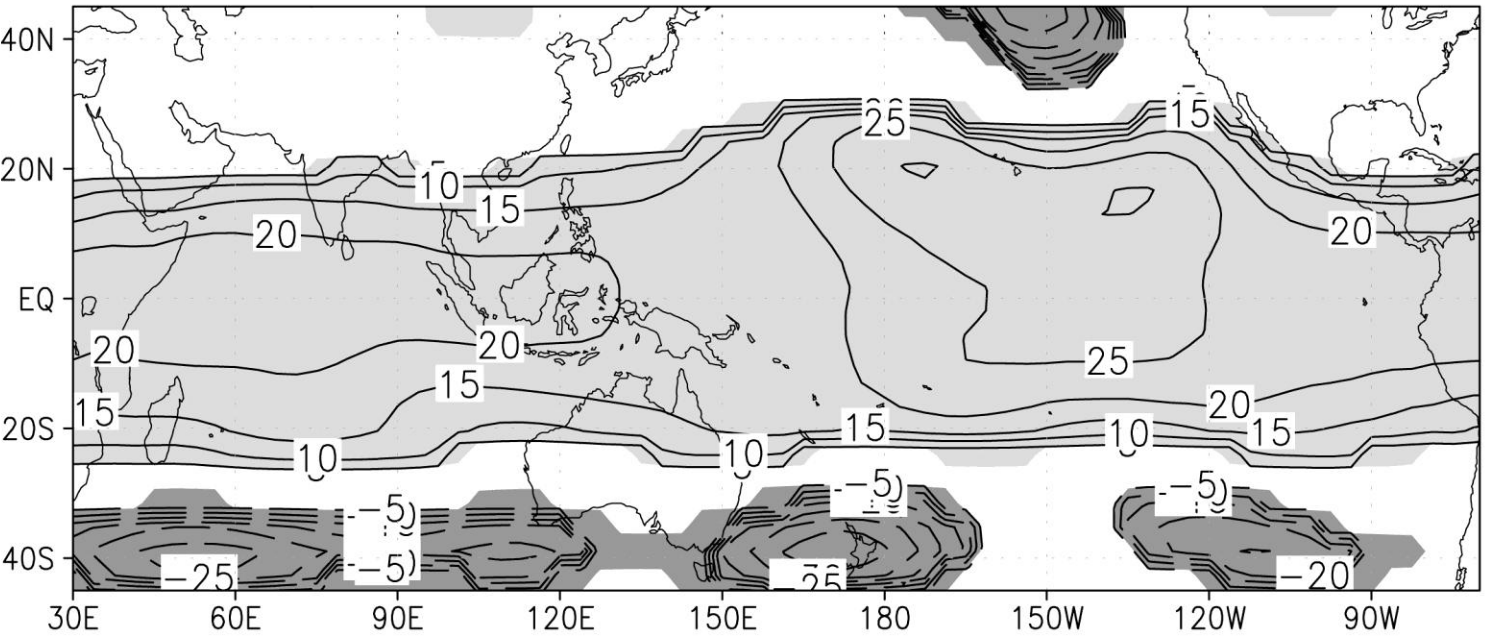
d) 200-hPa streamfunction 1980-2002.



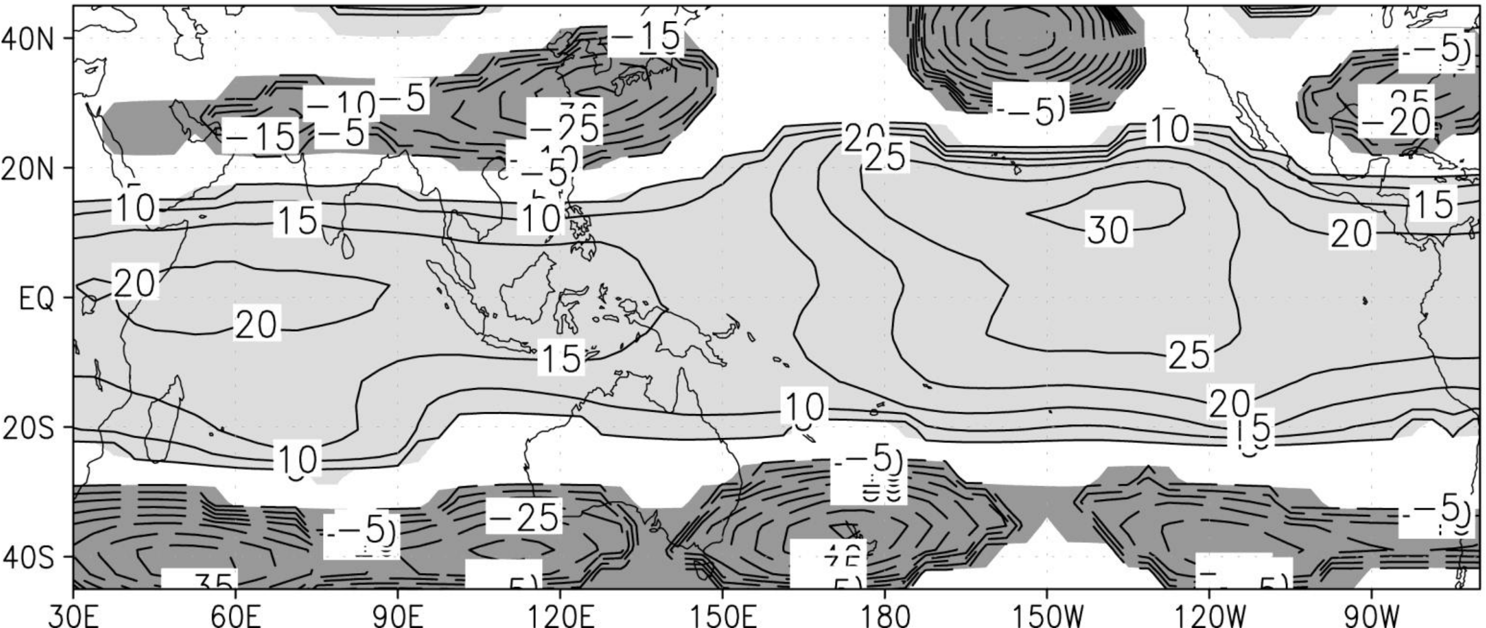




a) Resp NINO34 ANOM1–CLIM DJFM Z200 50/78



b) Resp NINO34 ANOM2–CLIM DJFM Z200 80/02



Response of 200-hPa height (m) to idealized SST forcing (a) ANOM1-CLIM (period 1) and (b) ANOM2-CLIM (period 2)

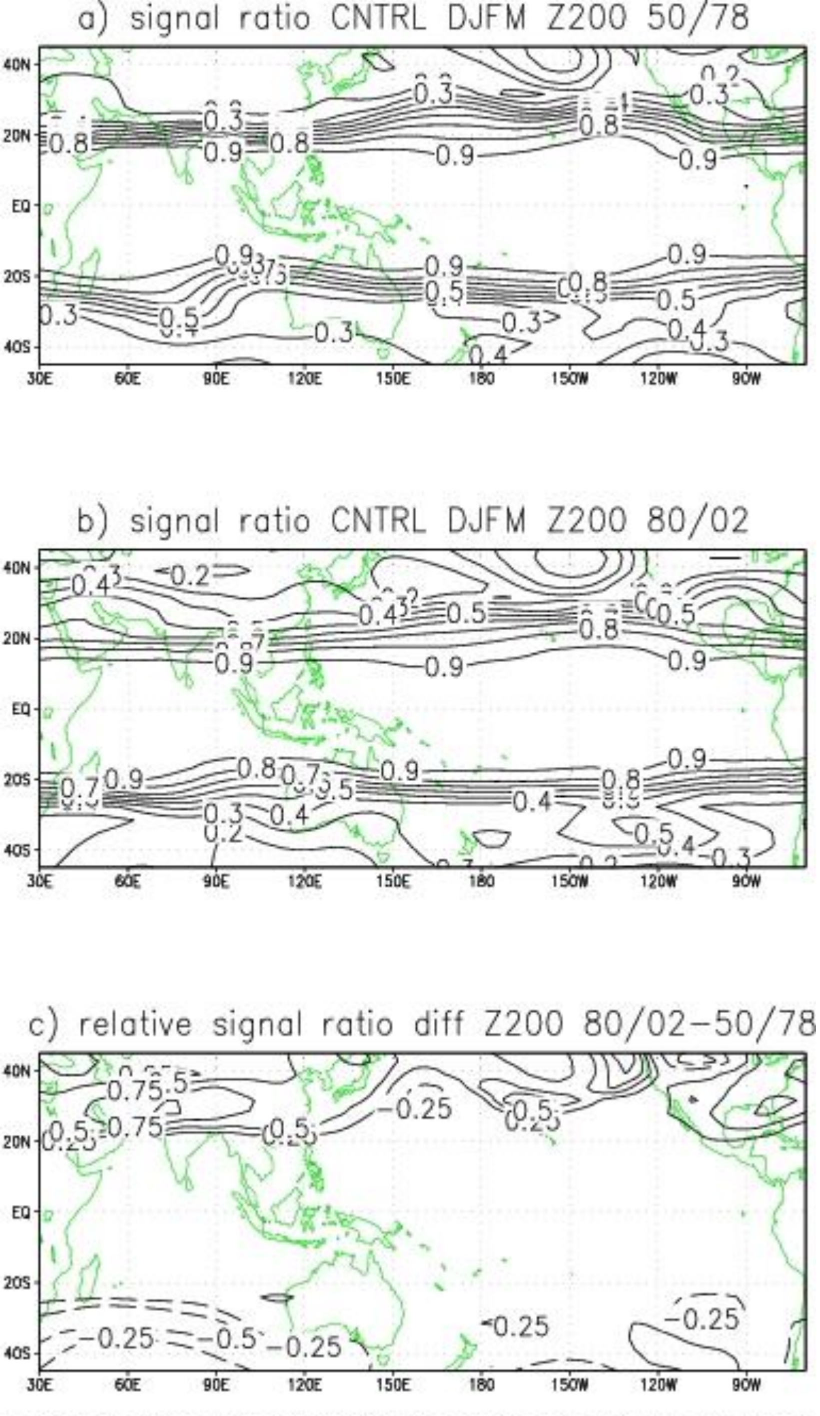


Figure 9: Ratio of forced variance (derived from the ensemble mean of CNTRL) to total variance

Ratio of forced variance (derived from the ensemble mean of CNTRL) to total variance (mean variance of individual ensemble members) a) 1950-1978, b) 1980-2002, c) difference of b) and a) divided by the mean of a) and b).

Climate Change Scenarios for Northwest India Winter Season

Introduction

- An increasing body of observations gives a collective picture of global warming and other changes in the climate system. It is believed that there are mainly two forcings associated with these changes,
- i) natural and
- ii) anthropogenic.

These changes have already affected many physical and biological systems. Also, there are significant differences in these changes at regional levels.

- Climate variations and change, caused by external forcings, may be partly predictable, particularly on the larger spatial scales such as continental or global.

While global atmosphere-ocean coupled models have provided good representations of the planetary scale features, their application to regional studies is limited by their coarse resolution (~300 km).

- Developing high-resolution models on a global scale is not only computationally prohibitively expensive for climate change simulations, but also suffers from the errors due to inadequate representation of high-resolution climate processes worldwide.

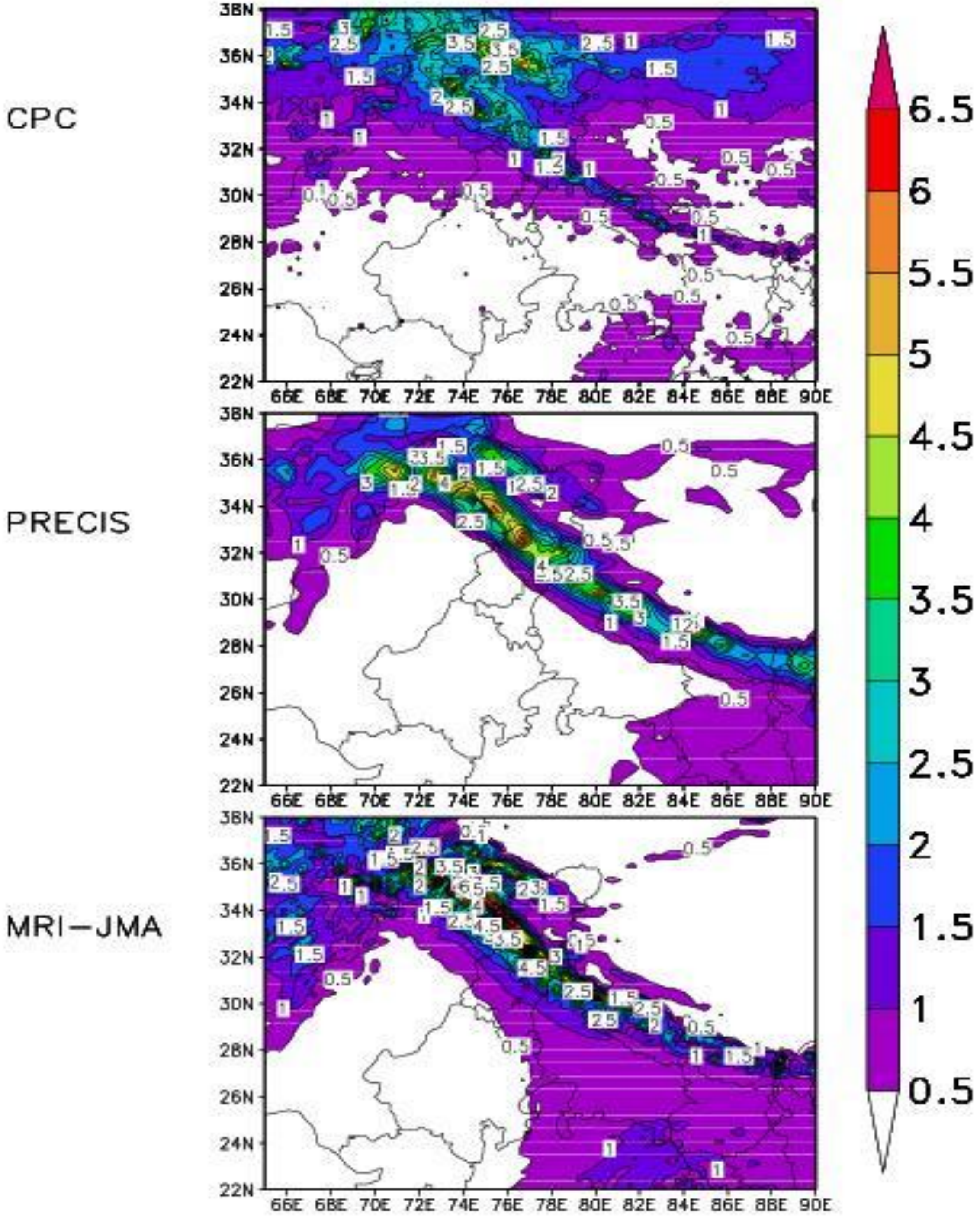
The regional climate models (RCMs) provide an opportunity to dynamically downscale global model simulations to superimpose the regional detail of specified regions

1. PRECIS (Providing REgional Climates for Impacts Studies) the second generation Hadley Centre regional climate model
2. MRI-JMA (Meteorological Research Institute-Japan Meteorological Agency) AGCM (Atmospheric General Circulation Model)

Simulations using PRECIS have been performed to generate the climate for present (1961-1990) and a future period (2071-2100) for two different socio-economic scenarios both characterized by regionally focused development but with priority to economic issues in one (A2 scenario) and to environmental issues in the other (B2 scenario).

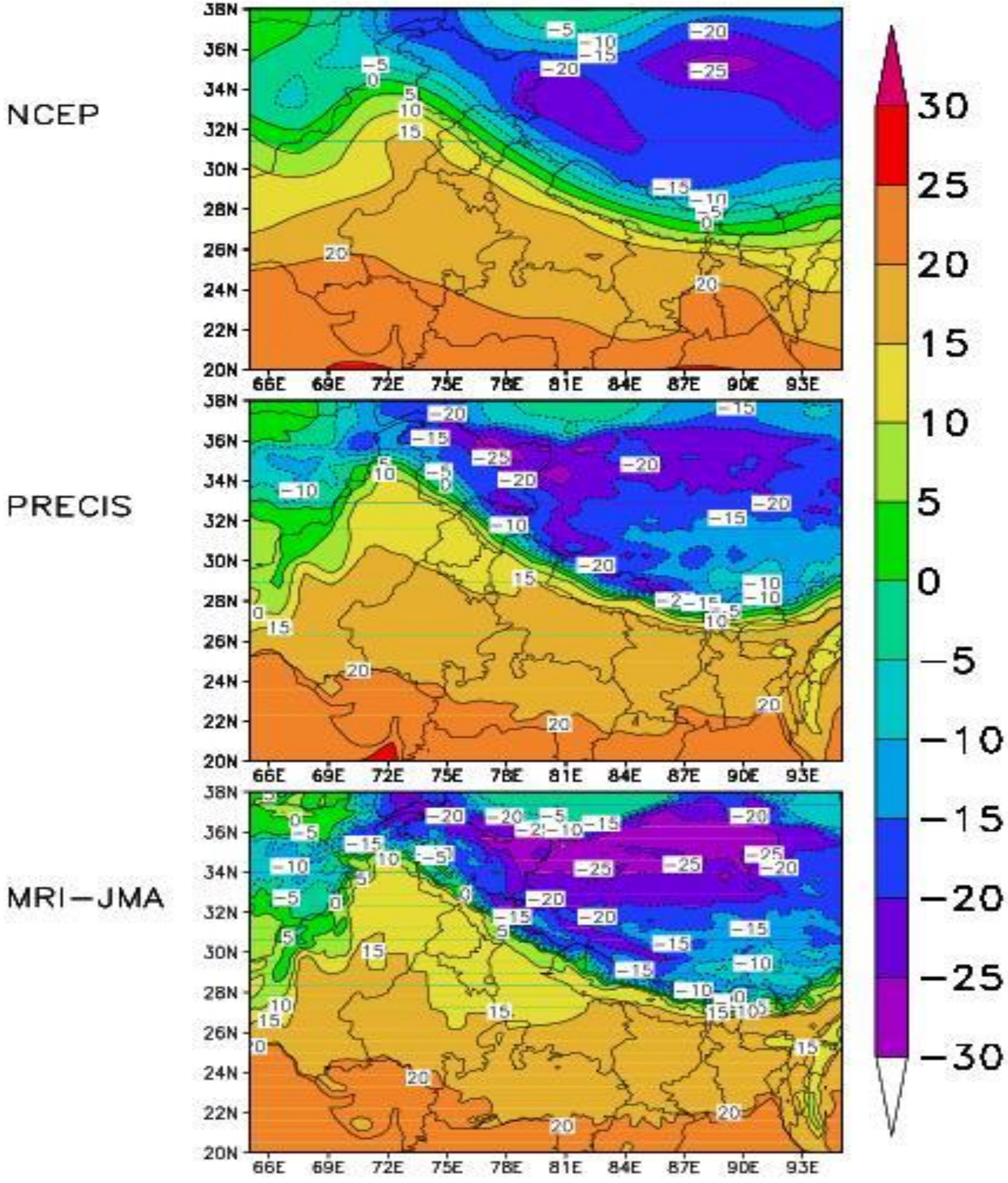
- MRI-JMA have been used from the two 10-year runs, namely a present climate simulation (representing the 1990s) and for the end of the 21st century (2090s). The future simulation is followed by IPCC SRES (Special Report on Emission Scenario) A1B.

Observed and Simulated (baseline)



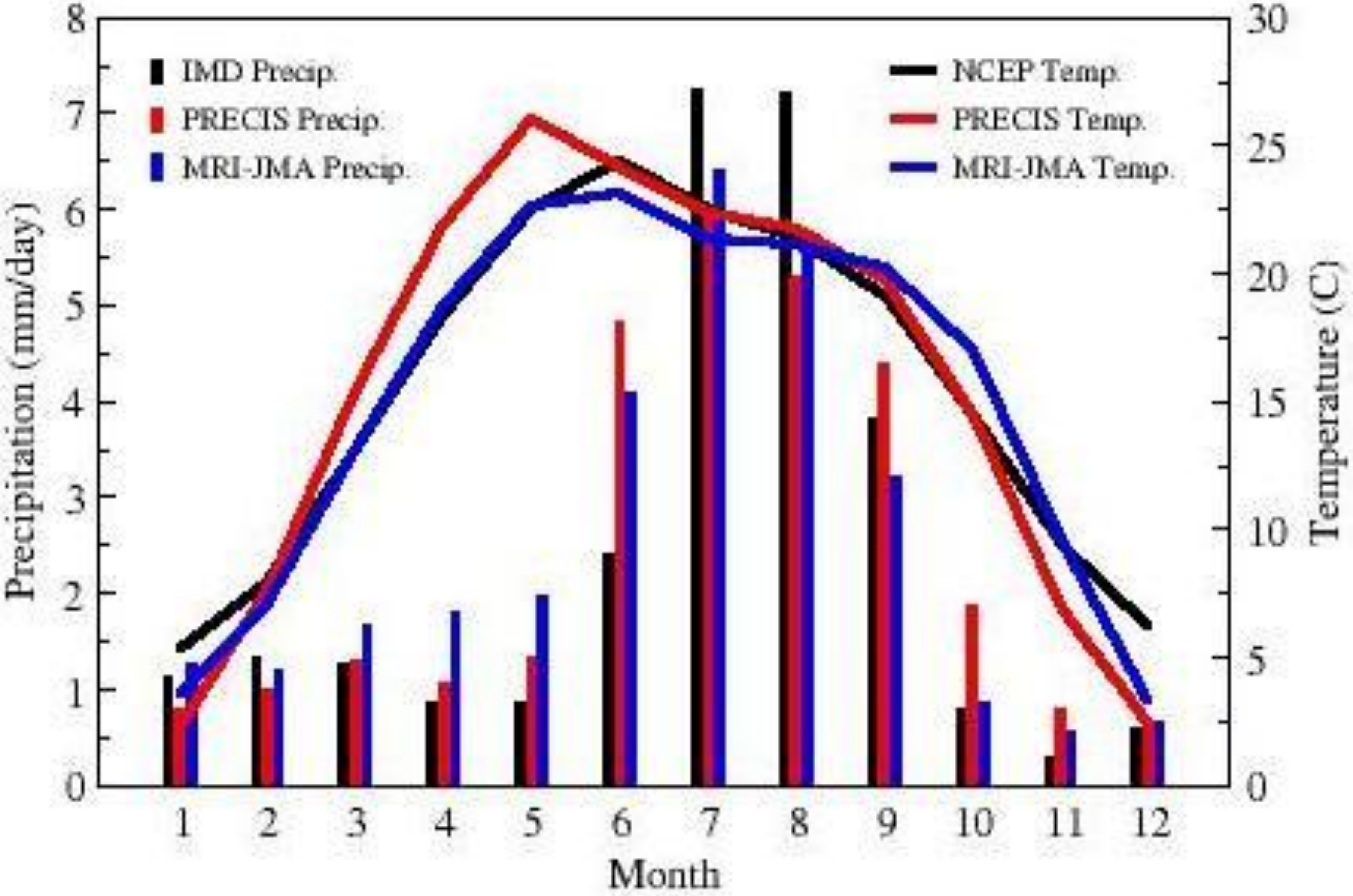
Evaluation of PRECIS and MRI-JMA AGCM simulations

- The NWIWP based on IMD monthly precipitation data, averaged over the period of 1902-2004, has mean value 129.2 mm, with a standard deviation (SD) of 45.7 mm and coefficient of variation (CV) 35.3%.
- The mean NWIWP for the baseline (1962-1990), simulated by PRECIS is 235.7 mm with SD 56.7 mm and C.V. 24.1%.
- The mean NWIWP for present (9 years), simulated by MRI-JMA AGCM is 143.7 mm with SD 27 mm and CV 18.8%.
- While the models seem to have overestimated the NWIWP, they have underestimated the variability.

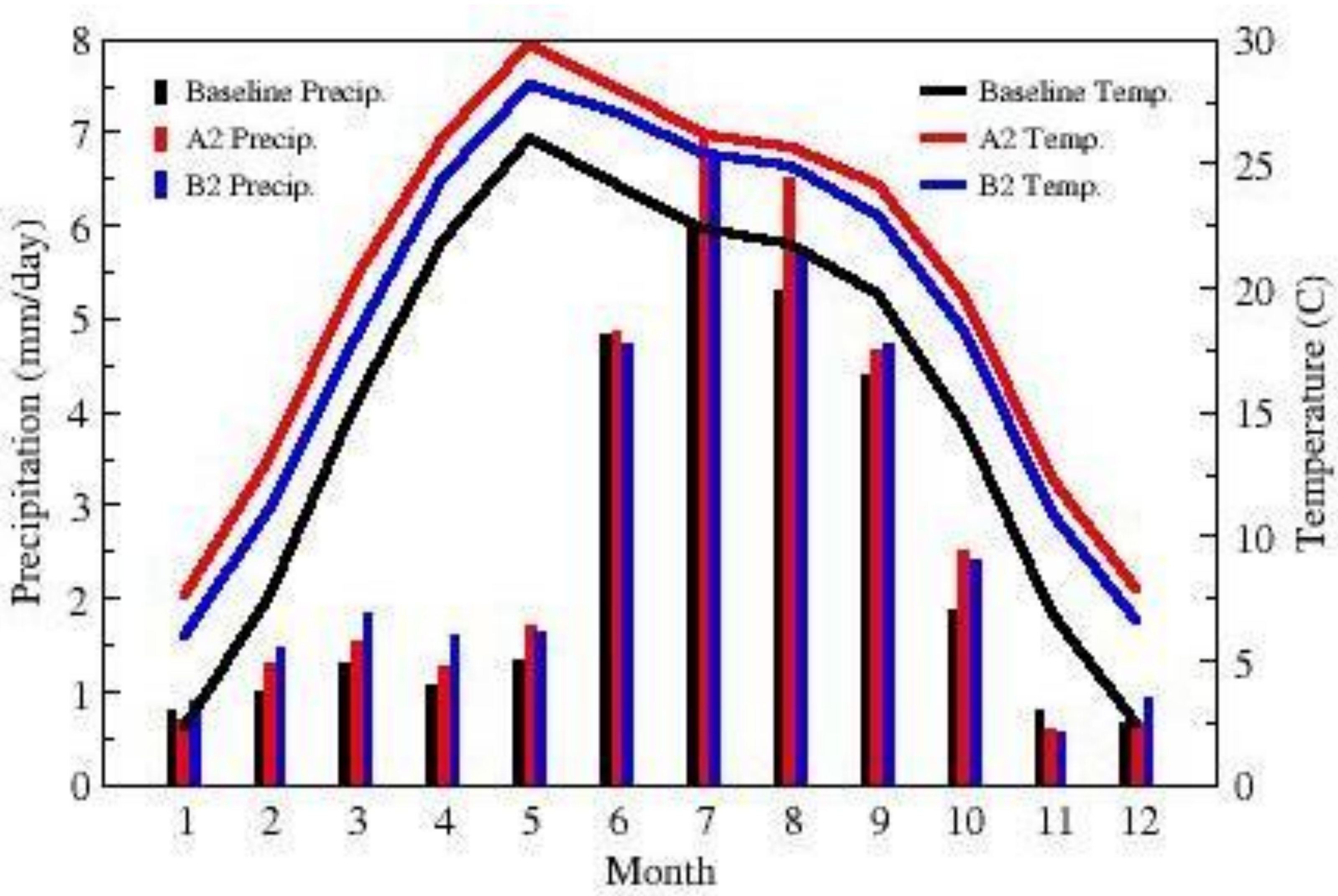


Observed (NCEP) and Simulated (baseline)

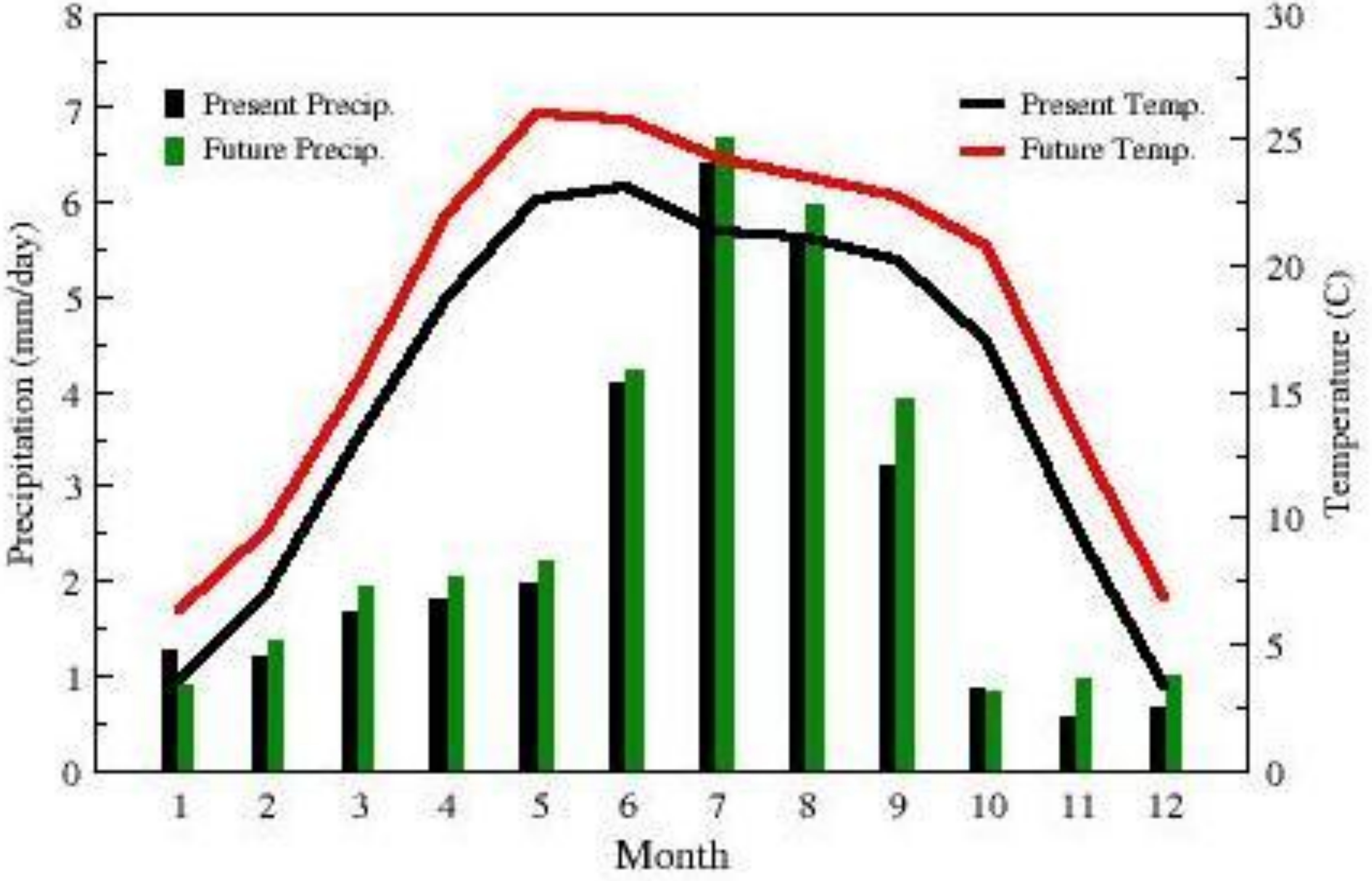
Observed and Simulated over NW India

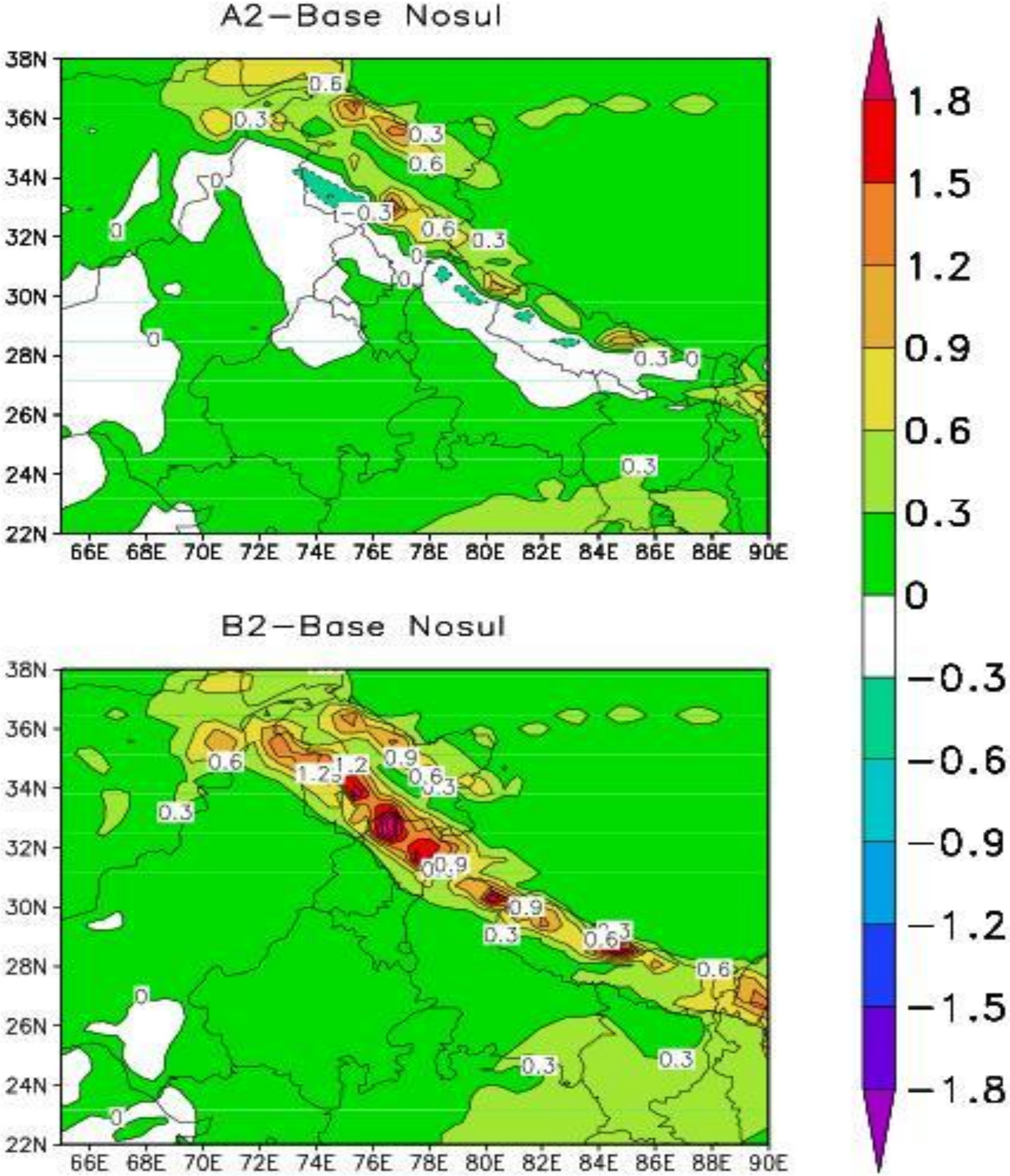


Baseline and Future Scenarios of PRECIS

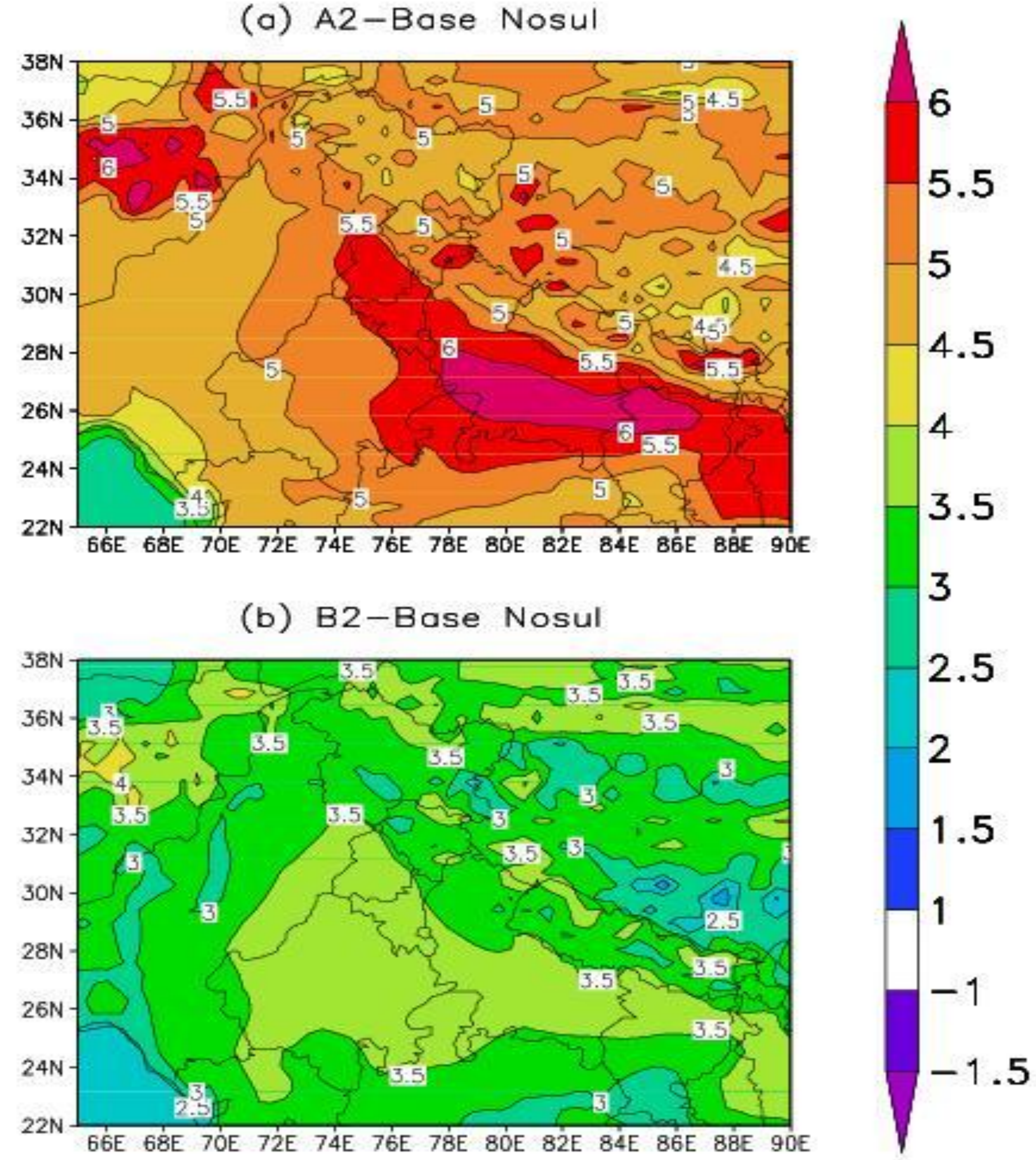


Baseline and Future Scenarios of MRI-JMA



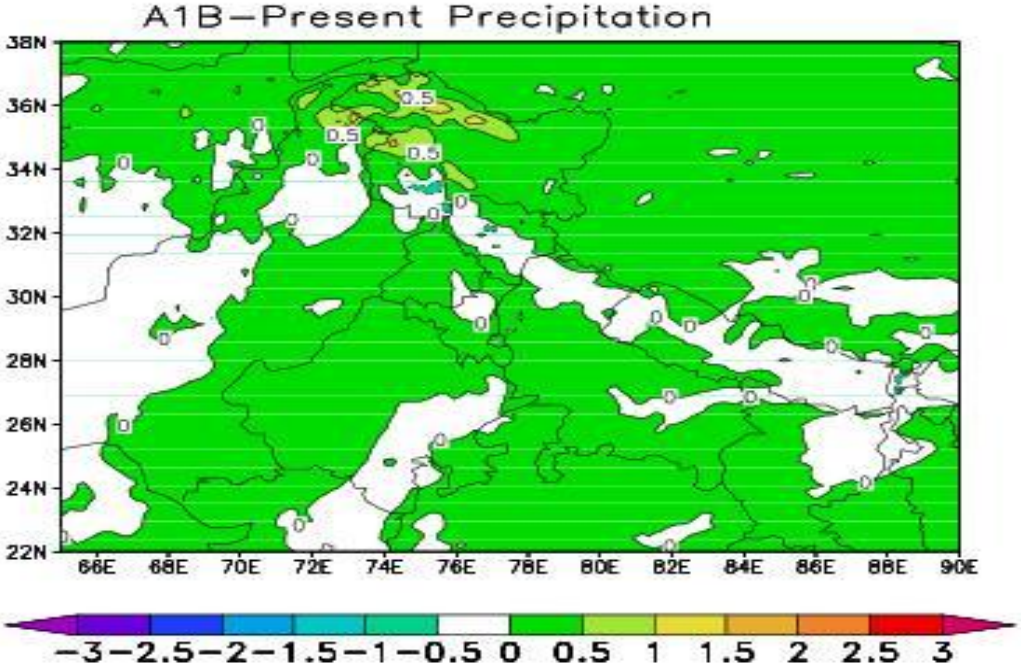


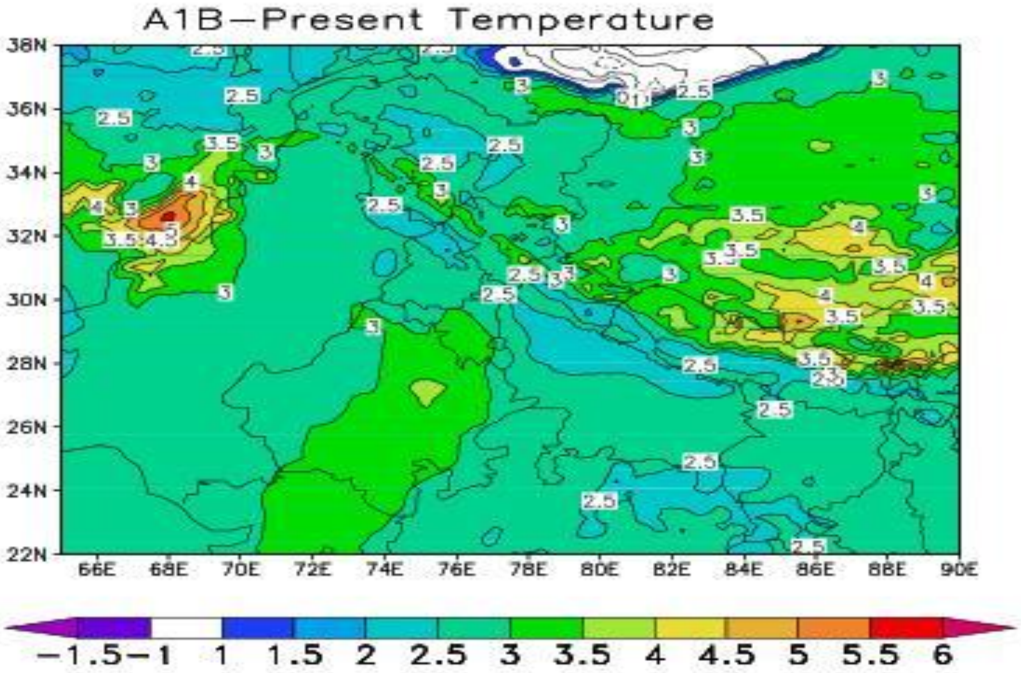
Projected Change in NWIWP towards the end of 21st Century by PRECIS



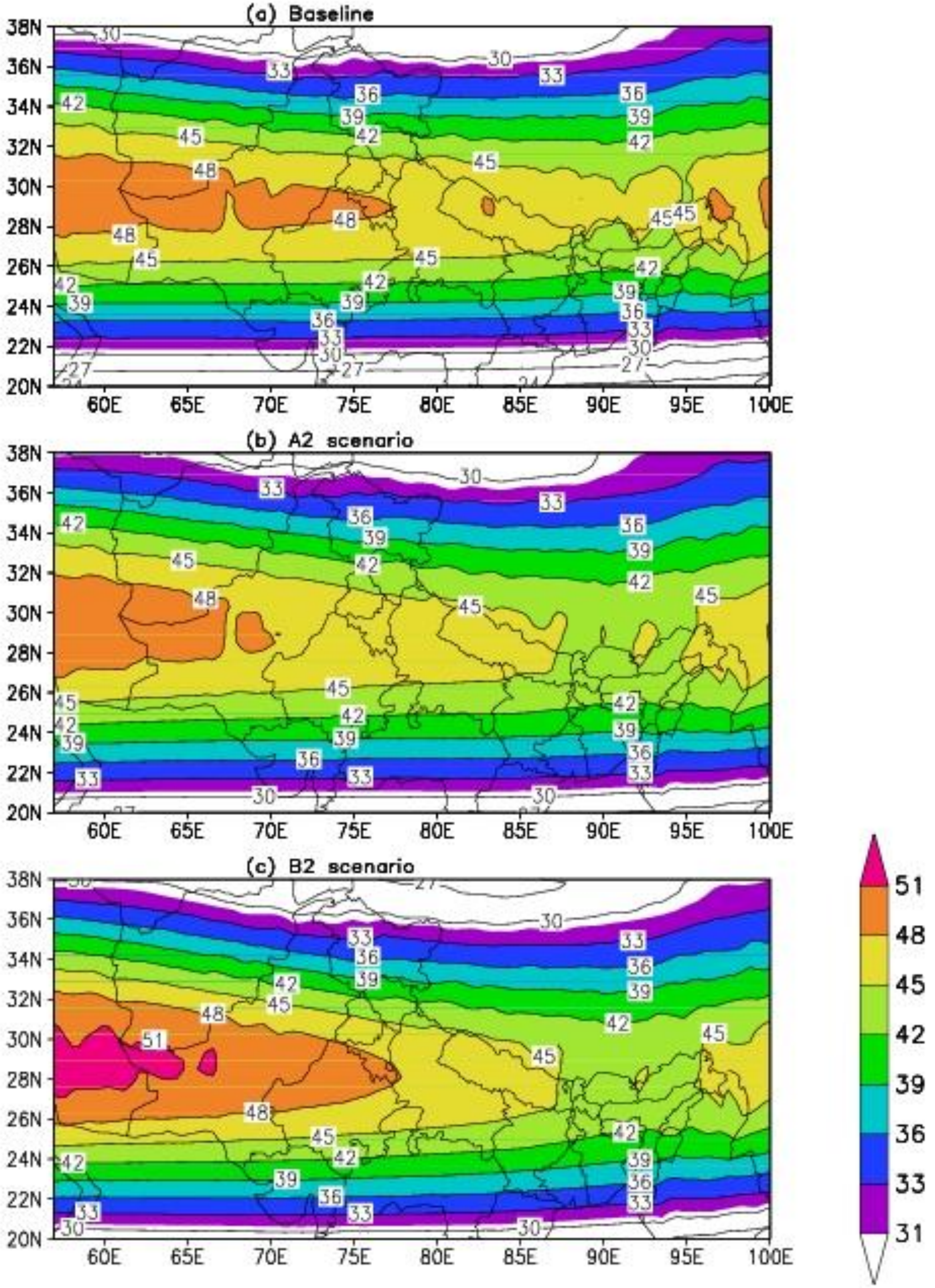
Projected Change in Surface Temperature towards the end of 21st Century by PRECIS

Projected Change in Precipitation and Surface Temperature for A1B Scenarios by MRI-JMA

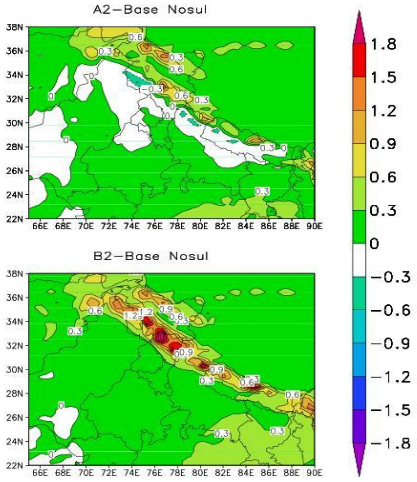




200u

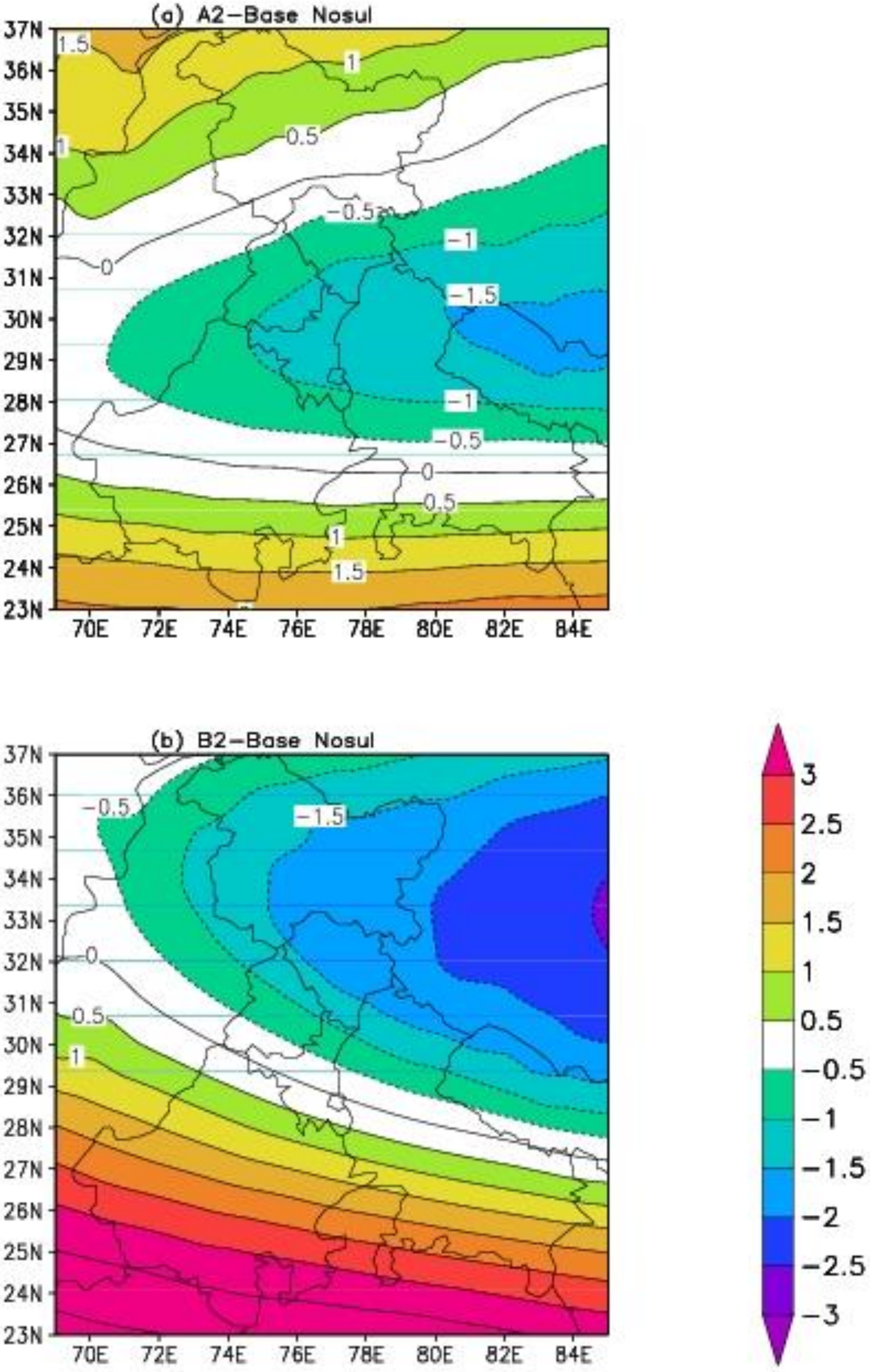


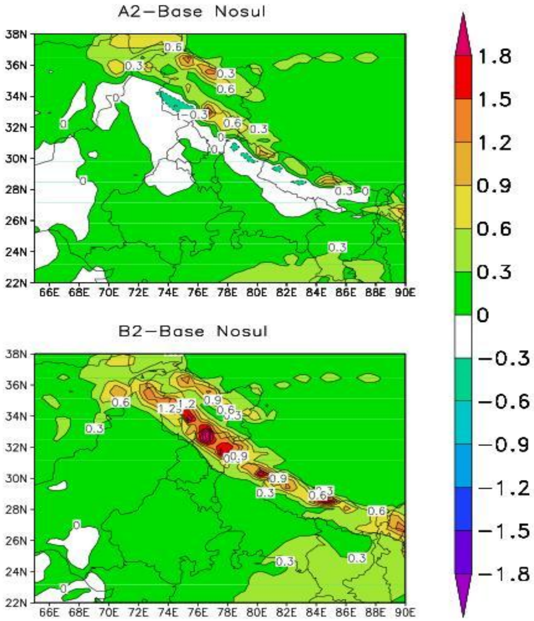
- 200-hPa Zonal Wind for Baseline, A2 and B2 Scenarios



Difference 200u

- 200-hPa zonal wind difference from baseline for A2 and B2 scenarios





Conclusion

- ✓ Regional climate change scenarios for NWIWP simulated by the PRECIS and MRI-JMA AGCM indicate increase in winter precipitation over western Himalaya and surface air temperature by more than 3°C all over NW India in their future scenarios.
- ✓ Though there is a general indication of increase in winter precipitation over NW India, the associated increase in temperature suggests that the proportion of liquid precipitation is likely to increase. This, coupled with a direct impact of the overall warming on enhanced snow melting, has serious implications for the glacier extent over Western Himalaya.

Thank You