Lecture 3: General Circulation of the Atmosphere

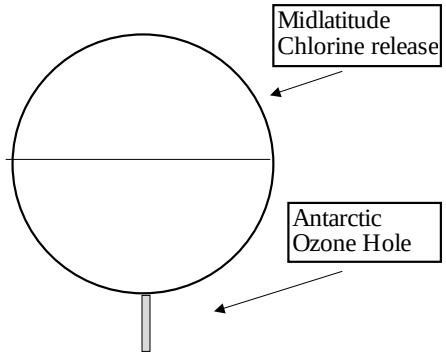
Suggested Reading: Brasseur 1999, Ch. 2

Atmospheric Chemistry
CHEM-5151 / ATOC-5151
Spring 2005
Prof. Brian Toon (PAOS)

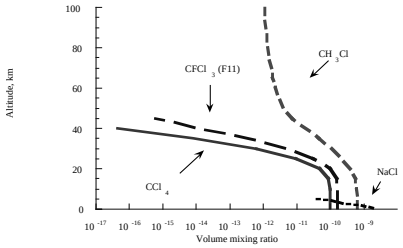
TRANSPORT AND TRANSFORMATION

GENERAL GOAL: TO UNDERSTAND THE INTERPLAY BETWEEN ATMOSPHERIC MOTIONS AND ATMOSPHERIC CHEMISTRY

EXAMPLE: FOR A RELATIVELY INERT MATERIAL THE DISTRIBUTION OF THE GAS IS CONTROLLED BY TRANSPORT. GIVEN ENOUGH TIME THE MATERIAL WILL BE UNIFORMLY MIXED THROUGH THE ATMOSPHERE



EXAMPLE: FOR A SHORT LIVED MATERIAL THE DISTRIBUTION IS CONTROLLED BY CHEMISTRY



SPECIFIC GOALS:

1. DETERMINE THE TRANSPORT TIMES IN VARIOUS PORTIONS OF THE ATMOSPHERE FOR COMPARISON WITH CHEMICAL LIFETIMES
   - A. OBSERVED WINDS
   - B. BOX MODELS

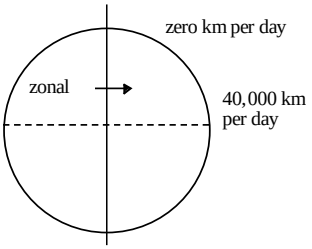
2. UNDERSTAND HOW TO LINK CHEMISTRY AND DYNAMICS
   - A. CONTINUITY EQUATIONS
   - B. METEOROLOGICAL "TRACERS"

3. FIND WAYS TO SIMPLIFY THE DYNAMICS SO WE CAN CONCENTRATE ON THE CHEMISTRY

TRANSPORT TIME SCALES-SOME COMMON TRANSPORT TERMS

1. <u>ZONAL MEAN CIRCULATION</u>- TIME AVERAGED WIND PARALLEL TO LATITUDE CIRCLES

A. FASTEST TRANSPORT SINCE ANGULAR MOMENTUM "ACCELERATES WINDS"



WHAT DRIVES THE ZONAL WINDS? -ANGULAR MOMENTUM CONSERVATION

WE CAN EASILY WORK OUT THE VELOCITY OF THE AIR PARCEL

IF THE PARCEL IS INITIALLY AT REST AT A PARTICULAR PLACE WHERE THE DISTANCE TO THE EARTH'S AXIS IS R THEN, IT HAS ANGULAR MOMENTUM PER UNIT MASS

$J=\Omega R^2$
Ω=ANGULAR ROTATION RATE OF EARTH $7.3X10^{-5}$ RADIANS/SEC

IF WE MOVE TO ANOTHER PLACE WHERE THE DISTANCE TO THE CENTER OF THE EARTH IS R+dR, THE ANGULAR MOMENTUM IS

$(\Omega+dU/(R+dR))\ (R+dR)^2 = \Omega R^2$
HERE dU IS THE VELOCITY THE AIR PARCEL HAS OBTAINED.

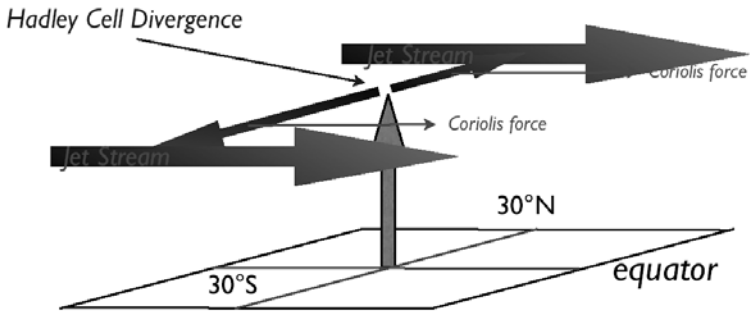
EXPAND OUT AND DROP THE SMALL TERMS dRdU AND dRdR LEAVES

$dU=-2\Omega dR$

EXAMPLE: MOVE AN AIR PARCEL FROM THE EQUATOR TO 30N. dR=-Rearth (1-cos(30))

$dU=2*7.3x10^{-5}*.134*6.4*x10^6$m/s=125 m/s

Jet Streams



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B. TYPICAL ZONAL WINDS

TRADE WINDS- LIGHT WINDS THAT BLOW FROM THE EAST (EASTERLIES) IN THE TROPICS

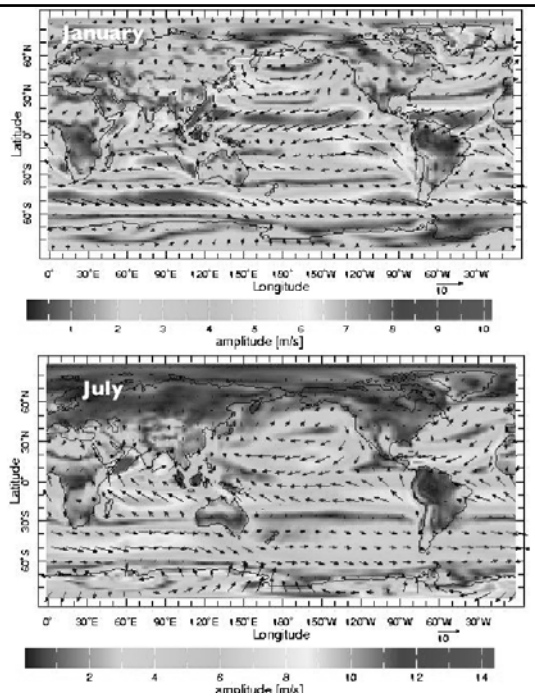
WESTERLIES-NEAR SURFACE WINDS THAT BLOW FROM THE WEST (WESTERLIES) IN MIDLATITUDES

SUBTROPICAL JET-A HIGH SPEED NARROW REGION OF WESTERLY WIND WELL ABOVE THE SURFACE THAT MARKS THE POLEWARD EXTENSION OF THE HADLEY CIRCULATION

POLAR NIGHT JET-A HIGH SPEED NARROW REGION OF WESTERLY WIND WELL ABOVE THE SURFACE THAT MARKS THE BEGINNING OF THE POLAR REGIONS

The Surface Winds

The January and July averaged surface winds. Arrows depict the monthly averaged wind vector (in m/s) see arrow scale below picture). The colors depict the vector magnitude (in m/s) according to the colorscale below. Note the seasonal differences due both to the shift in the location of the maximum in tropical heating and the heating and cooling of the continents.



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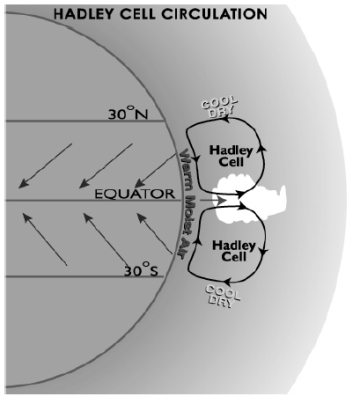
Trade winds



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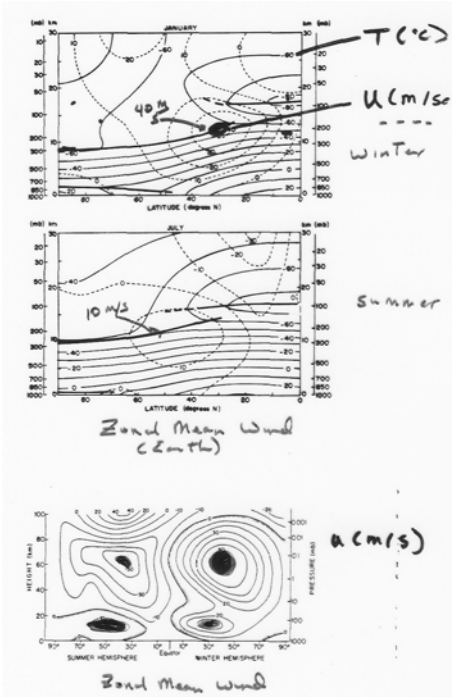
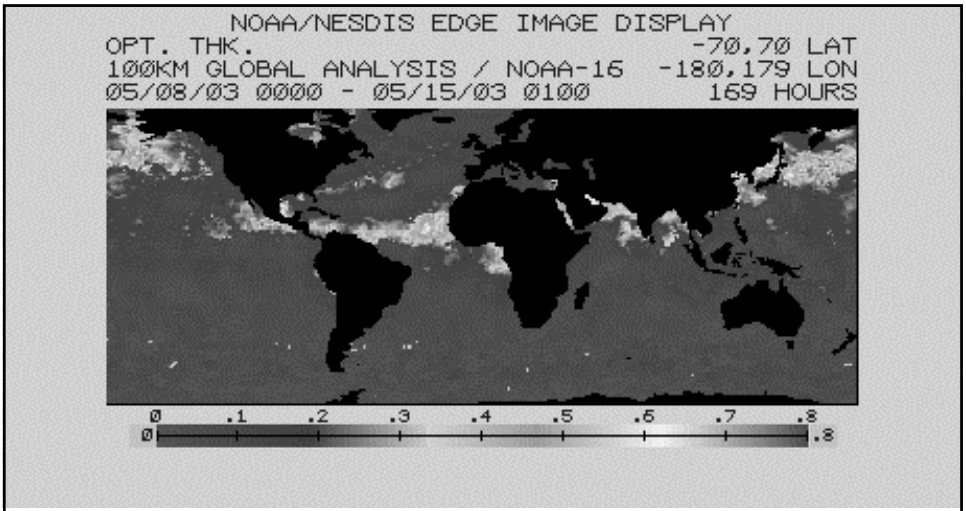


TIME SCALES TO CIRCLE THE EARTH IN THE MEAN ZONAL WIND

NAME OF WIND	TYPICAL WIND SPEED	TYPICAL TIME TO CIRCLE EARTH
TRADE WINDS NEAR SURFACE	<<10 m/s	>one month
WESTERLIES NEAR SURFACE	<10 m/s	>one month
SUBTROPICAL JET-SUMMER	10 m/s	33 days (45^{o}lat)
SUBTROPICAL JET-WINTER	40 m/s	8 days (45^{o}lat)



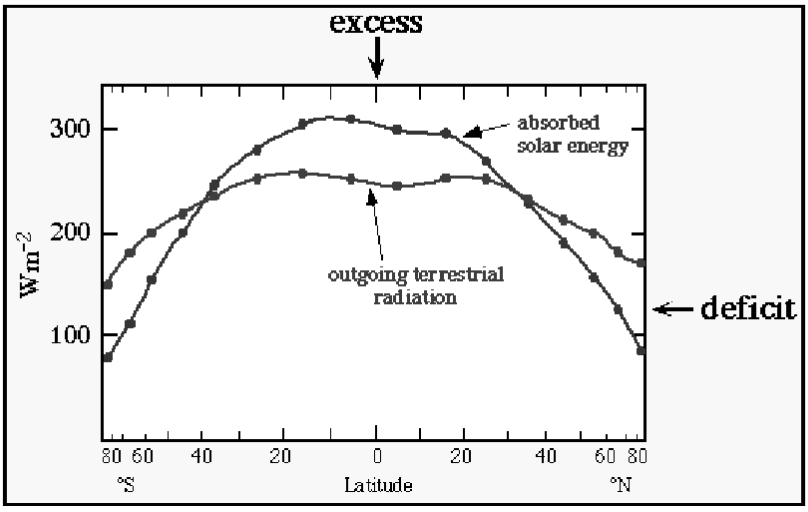
A view of aerosol transport,
There were large fires in Russia prior to this time period,
and dust storms in Africa. Can you tell the source and sink regions just by glancing at the distributions and knowing the winds?

General circulation-CONT

2. MERIDIONAL MEAN CIRCULATION- TIME/LONGITUDE AVERAGED WIND PARALLEL TO LONGITUDE CIRCLES

A. WHAT DRIVES THE MEAN NORTH-SOUTH MOTION?
-THE EQUATOR-TO-POLE HEATING IMBALANCE.
HOWEVER, SUCH MOTIONS ARE DIFFICULT TO ACHIEVE DUE TO ANGULAR MOMENTUM CONSERVATION. SO THE MEAN MOTION IS VERY SLUGGISH.

Latitudinal Radiation Imbalance



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B. TYPICAL MERIDIONAL WINDS

HADLEY CELL- A CIRCULATION WITH RISING MOTIONS IN THE TROPICS AND DESCENT IN THE SUBTROPICS

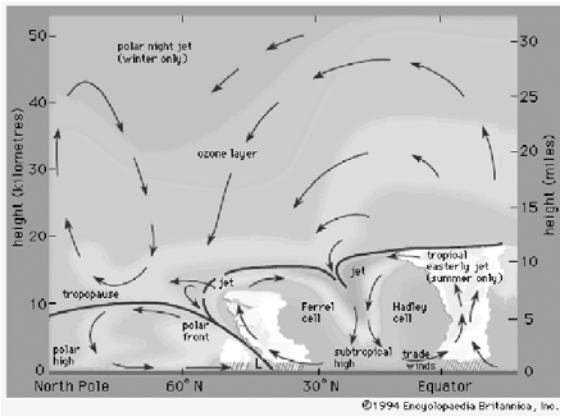
INTERTROPICAL CONVERGENCE ZONE-THE REGION OF RISING AIR, USUALLY FULL OF CONVECTIVE CLOUDS, NEAR THE EQUATOR

FERRELL CELL /POLAR CELLS-OVERTURNING CIRCULATIONS WHICH ARE SO WEAK THAT THEY PLAY LITTLE ROLE IN TRANSPORT.

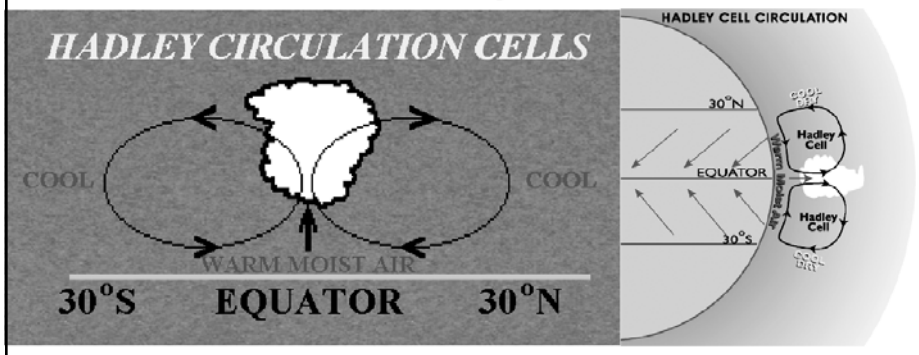
LITTLE TRANSPORT ON EARTH OCCURS BY THE MERIDIONAL CIRCULATION

The Ferrel Cell and the Meridional Mass Circulation

The Hadley Cell ends at about 30° north and south of the equator because it becomes dynamically unstable, creating eddies that are the reason for the weather disturbances of the midlatitude belts (see Lecture IV). These eddies force a downward motion just south of the jet axis and an upward motion between 40 and 60° north and south of the equator, forming the Ferrel Cell. The eddies are also responsible for spreading the westerlies down to the surface.



The Hadley Cells



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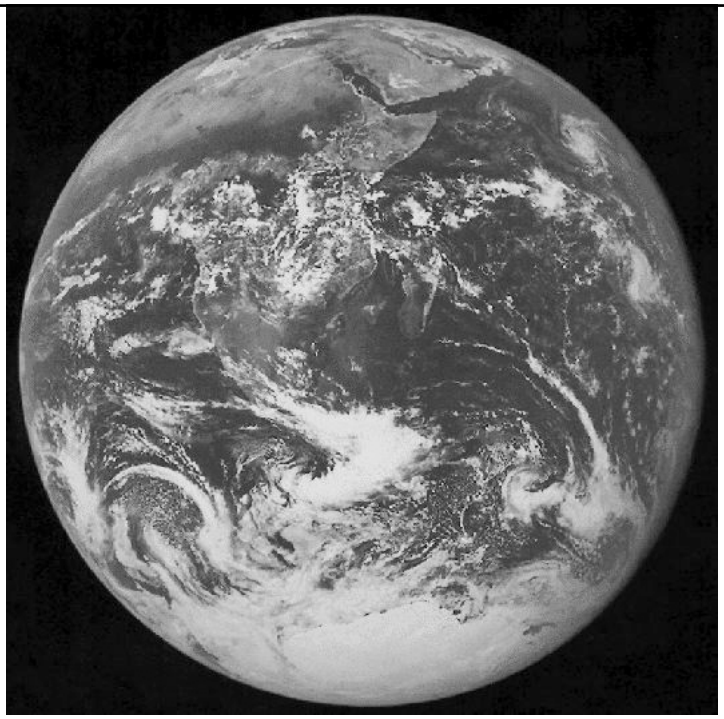
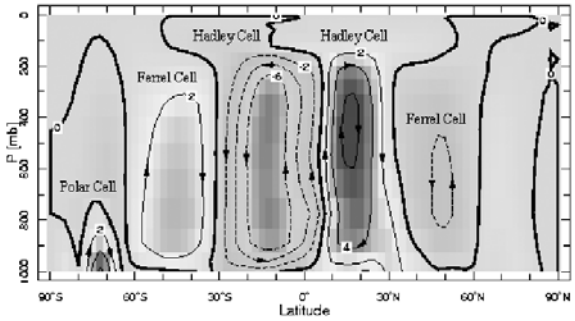


ITCZ,
Apollo

The Zonally Averaged Mass Circulation



The annually-averaged atmospheric mass circulation in the latitude pressure plane (the meridional plan). The arrows depict the direction of air movement in the meridional plane. The contour interval is 2x10 10 Kg/sec - this is the amount of mass that is circulating between every two contours. The total amount of mass circulating around each "cell" is given by the largest value in that cell. Data based on the NCEP-NCAR reanalysis project 1958-1998.

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General circulation-CONT.

3. WAVE TRANSPORT- TIME DEPENDENT WINDS HAVE BOTH NORTH-SOUTH AND EAST-WEST COMPONENTS

NORTH-SOUTH TRANSPORT ON EARTH IS DOMINATED BY WAVES. TIME SCALES ARE SIMILAR TO THOSE FOR ZONAL FLOW.

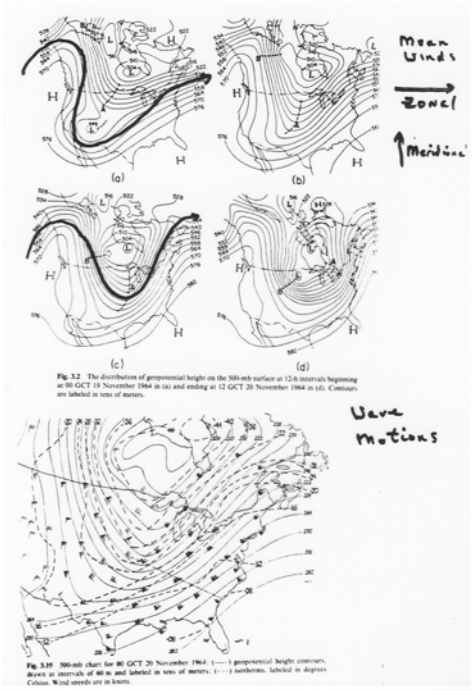
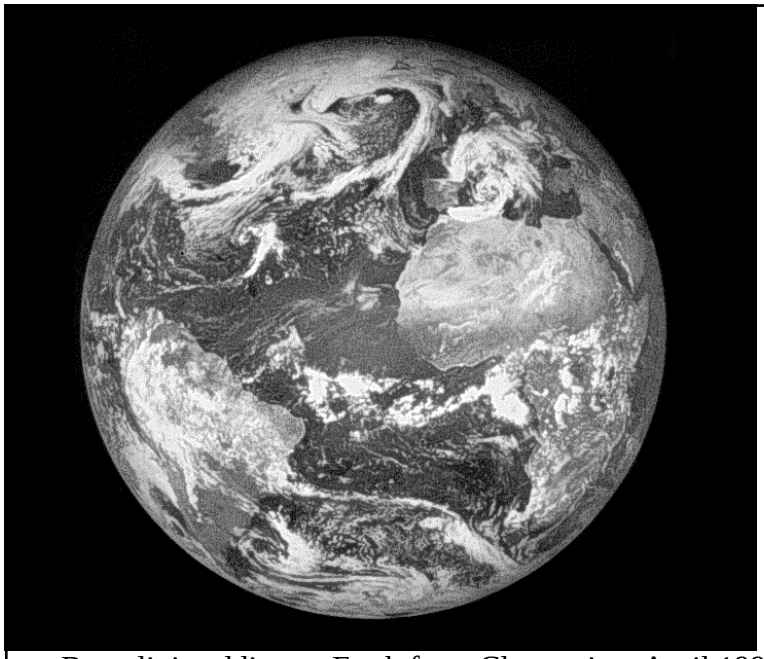


Fig. 3.2 The distribution of geopotential height on the 500-mb surface at 12-h intervals beginning at 00 GCT 19 November 1964 in (a) and ending at 12 GCT 20 November 1964 in (d). Contours are labeled in tens of meters.

Fig. 3.35 500-mb chart for 00 GCT 20 November 1964. (——) geopotential height contours, drawn at intervals of 60 m and labeled in tens of meters, (- - -) isotherms, labeled in degrees Celsius. Wind speeds are in knots.



Baroclinic eddies on Earth from Clementine. April 1994.

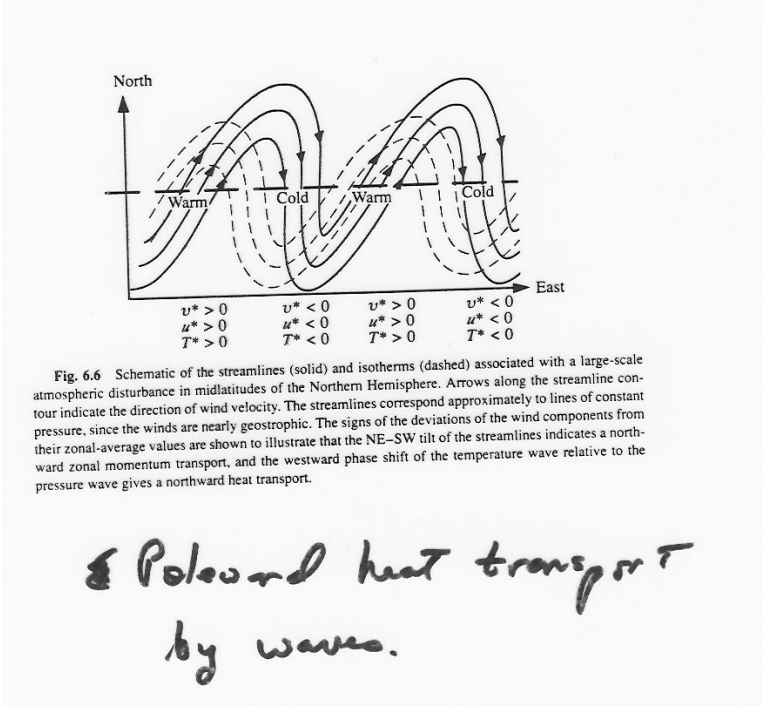


Fig. 6.6 Schematic of the streamlines (solid) and isotherms (dashed) associated with a large-scale atmospheric disturbance in midlatitudes of the Northern Hemisphere. Arrows along the streamline contour indicate the direction of wind velocity. The streamlines correspond approximately to lines of constant pressure, since the winds are nearly geostrophic. The signs of the deviations of the wind components from their zonal-average values are shown to illustrate that the NE–SW tilt of the streamlines indicates a northward zonal momentum transport, and the westward phase shift of the temperature wave relative to the pressure wave gives a northward heat transport.

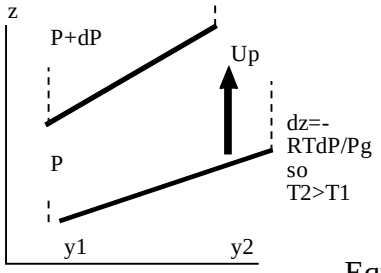
& Poleward heat transport by waves.

SOME COMMON TRANSPORT TERMS-CONT.

4. STRATOSPHERIC TRANSPORT

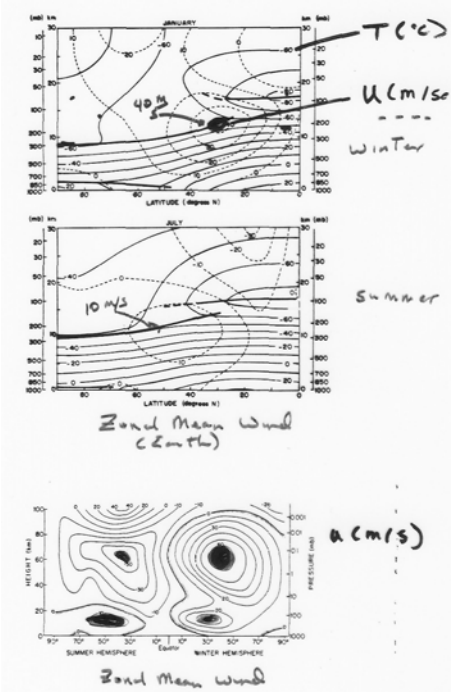
A. THE BASIC STRATOSPHERIC TRANSPORT IS SIMILAR TO THAT IN THE TROPOSPHERE, WITH HIGH ALTITUDE JETS. THE EQUATOR TO POLE TEMPERATURE GRADIENT IS SOMETIMES REVERSED IN THE STRATOSPHERE CLOSING THE JETS.

[THERMAL WIND EQUATION:
U(TOP OF LAYER)-Up(BOTTOM OF LAYER) IS PROPORTIONAL TO (MINUS)HORIZONTAL GRADIENT OF MEAN TEMPERATURE OF LAYER]



pole Equator

Schematic derivation of the thermal wind



B. TYPICAL STRATOSPHERIC WINDS-
ZONAL FLOW DOMINATES

TIME SCALES TO CIRCLE THE EARTH IN THE STRATOSPHERIC ZONAL WIND

NAME OF VOLCANO	TYPICAL TIME TO CIRCLE EARTH
Mt. St. Helens, US. May 18, 1980, 12-15 km, 46 N	15 days (moving eastward)
El Chichon, Mexico - April 4, 1983, 25-30 km, 17 N	three weeks (moving westward)
Pinatubo, Philippines-June 15, 1991, 20-25 km, 15 N	three weeks (moving westward)

QUASI-BIENNIAL OSCILLATION-A ROUGHLY TWO YEAR VARIATION IN THE WIND DIRECTION IN THE TROPICAL STRATOSPHERE.

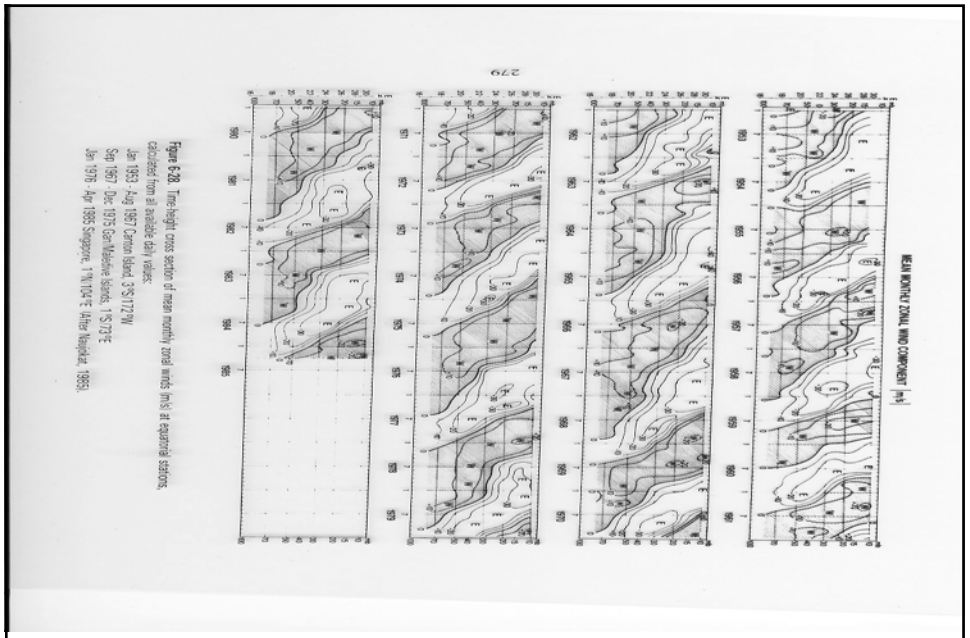


Figure 6.28. Time-height cross section of mean monthly zonal winds (m/s) at equatorial stations, calculated from all available daily values.
Jan 1953-Aug 1967 Canton Island, 3°S 172°W
Sep 1967-Dec 1975 Gan Maldive Islands, 1°S 73°E
Jan 1976-Apr 1995 Singapore, 1°N 104°E (After Naujokat, 1995).

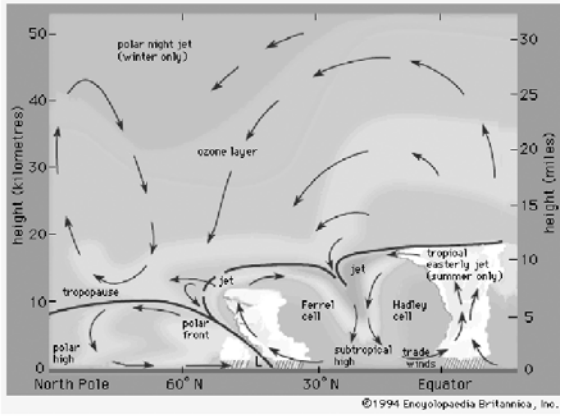
MERIDIONAL FLOW IS STILL IN THE HADLEY SENSE IN THE LOWER STRATOSPHERE DURING WINTER. HOWEVER, IT IS LARGELY DRIVEN BY DYNAMICS RATHER THAN SOLAR HEATING.

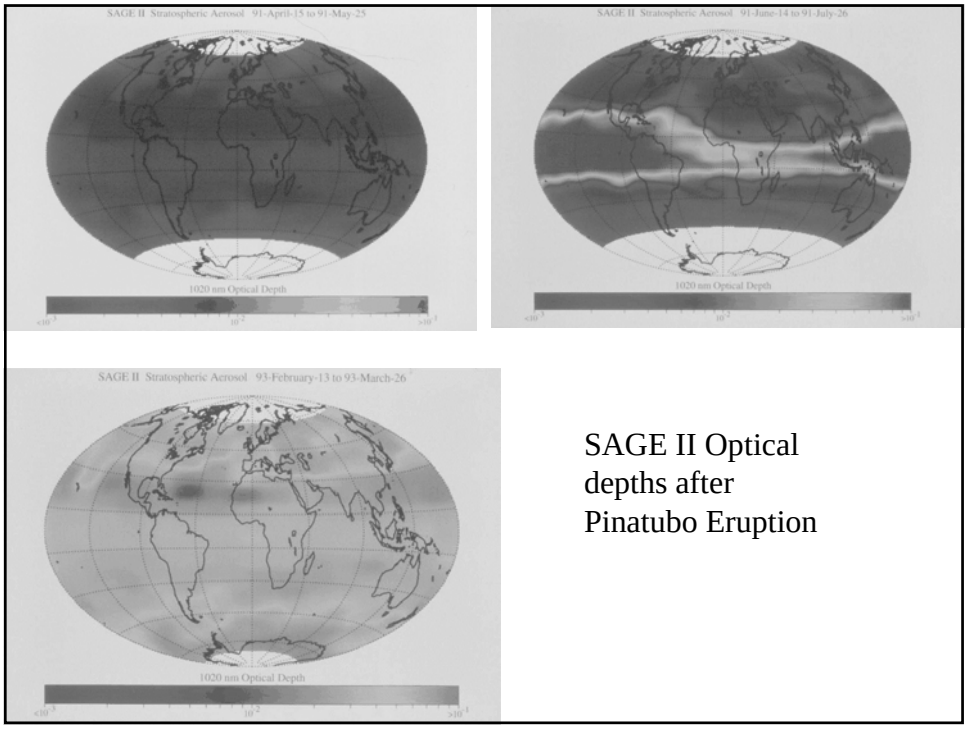
WINTER POLAR VORTEX-A REGION ROUGHLY CONCENTRIC WITH THE POLAR CAPS IN WHICH DESCENT OCCURS FROM ALOFT AND LITTLE EXCHANGE OCCURS WITH THE REST OF THE STRATOSPHERE

TROPICAL PIPE-A REGION OF THE TROPICAL LOWER STRATOSPHERE IN WHICH LITTLE EXCHANGE OCCURS WITH THE REST OF THE LOWER STRATOSPHERE

The Ferrel Cell and the Meridional Mass Circulation

The Hadley Cell ends at about 30° north and south of the equator because it becomes dynamically unstable, creating eddies that are the reason for the weather disturbances of the midlatitude belts (see Lecture IV). These eddies force a downward motion just south of the jet axis and an upward motion between 40 and 60° north and south of the equator, forming the Ferrel Cell. The eddies are also responsible for spreading the westerlies down to the surface.





SAGE II Optical depths after Pinatubo Eruption

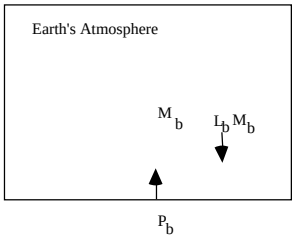
SUMMARY FROM EXAMINING WINDS

1. THERE ARE SYSTEMATIC WIND SYSTEMS THAT CONTROL WHERE MATERIALS ARE DISTRIBUTED ON AN AVERAGE BASIS (ZONAL WINDS, TRADE WINDS, HADLEY CELL, SUBTROPICAL JET ETC.).
2. THE WINDS ARE FUNDAMENTALLY DRIVEN BY THE TEMPERATURE (PRESSURE) GRADIENT, AND ANGULAR MOMENTUM CONSERVATION.
3. WINDS BECOME SO LARGE DUE TO ANGULAR MOMENTUM CONSERVATION THAT THEY FORM JETS, WHICH ARE UNSTABLE AND MAKE WAVES.
4. WAVES ACTUALLY DO MOST OF THE TRANSPORT.
5. WE CAN GET USEFUL TIMES TO CIRCLE THE EARTH FROM THE MEAN ZONAL WINDS (ON THE ORDER OF A FEW WEEKS TO MONTHS DEPENDING ON ALTITUDE AND LATITUDE AND SEASON)
6. WE CAN'T GET USEFUL VERTICAL TRANSPORT TIMES FROM THE WINDS-CONVECTION IS VERY RAPID BUT ISOLATED. MEAN VERTICAL VELOCITY IS VERY SLOW.
7. WE CAN'T GET USEFUL MERIDIONAL TRANSPORT TIMES FROM THE MEAN MERIDIONAL CIRCULATION-TRANSPORT IS BY WAVES.

SOLUTION -LOOK AT DISTRIBUTIONS OF TRACERS TO UNDERSTAND TRANSPORT TIMES.

BOX MODELS

A BOX MODEL IS AN IDEALIZED VOLUME IN WHICH THE CONCENTRATION IS ASSUMED TO BE UNIFORM WITHIN THE BOX, AND IN WHICH THE TRANSPORT ACROSS THE WALLS OF THE BOX IS REPRESENTED AS SIMPLY AS POSSIBLE



A BOX MODEL FOR THE RESIDENCE TIME OF A MATERIAL OF MASS M IN THE ATMOSPHERE

M_b IS THE TOTAL MASS OF THE MATERIAL OF INTEREST WITHIN THE BOX.

P_b IS THE FLUX OF THE MATERIAL INTO THE BOX, SOMETIMES CALLED THE PRODUCTION RATE, OR SOURCE STRENGTH.

GIVEN THE HUGE MASS OF MOST MATERIALS IN THE ATMOSPHERE M_b USUALLY HAS UNITS OF TERRAGRAMS (Tg), AND P_b HAS UNITS OF Tg YR^{-1}. A TERRAGRAM (Tg) IS 10^{12} g, OR EQUIVALENTLY 10^6 METRIC TONS. THE WEIGHT OF ALL THE PEOPLE ON EARTH IS ABOUT 250 Tg.

L_B (WHICH HAS UNITS OF INVERSE TIME), IS THE LOSS RATE.

THEREFORE, WE CAN WRITE THE FOLLOWING EQUATION FOR THE RATE OF CHANGE OF M_b

(1) $$\frac{dM_b}{dt} = P_b - L_b M_b$$

IF M_b IS IN <u>STEADY STATE</u>, OR IN OTHER WORDS IF M_b IS NOT CHANGING IN TIME, THE SIMPLE STEADY STATE SOLUTION IS

$$L_b = P_b / M_b$$

EQUATION 1 HAS THE TIME DEPENDENT SOLUTION (ASSUMING P_b AND L_b ARE NOT VARYING IN TIME)

$$(2) \qquad M_b = \frac{P_b}{L_b} + (M_{b\,(t=0)} - \frac{P_b}{L_b})\exp(-L_b t) \ .$$

IMAGINE THAT PRODUCTION OF THE MATERIAL SUDDENLY STOPPED SO THAT P=0 IN EQ. 2. THEN THE TIME

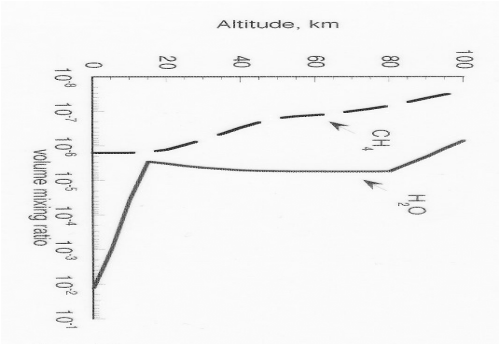
$$\tau_c = 1/L_b$$

IS THE TIME THAT WOULD BE REQUIRED FOR M_b TO DECLINE BY A FACTOR OF e^{-1}.

FOR THIS REASON τ IS CALLED THE LIFETIME OF MATERIAL M_b.

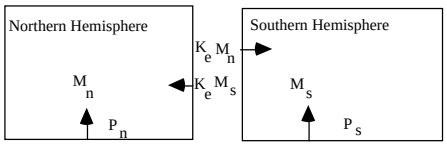
LIFETIMES OF SOME INTERESTING MATERIALS

Material	M_b, Abundance (Tg)	P_b, Source (Tg/yr)	τ_c, Lifetime (yr)
H_2O	1.3×10^7	5×10^8	0.025
CH_4	5×10^3	515	10
COS	5.2	1.2	4.3
SO_2	0.6-0.9	200	.003 -.005
N_2O	2.5×10^3	12 -21	120
CFC-11	6.2	0.25	50
CFC-12	10 .3	0.37	100
CH_3Cl	5	3.5	1.5
NaCl	3.6	1300	0.003



An example of how fluxes can be misleading when comparing species with differing lifetimes.

BOX MODELS CAN BE EXTENDED TO PROVIDE INFORMATION ABOUT THE RATES AT WHICH MATERIALS MOVE BETWEEN VARIOUS REGIONS OF THE ATMOSPHERE.



The exchange rate of air between the two hemispheres is K_e.

We can write the following two equations for the budgets of the tropospheres in the two hemispheres.

$$\frac{dM_n}{dt} = P_n - K_e(M_n - M_s)$$

$$\frac{dM_s}{dt} = P_s - K_e(M_s - M_n)$$

Subtracting the Southern Hemisphere equation from the Northern Hemisphere equation yields

$$\frac{d(M_n - M_s)}{dt} = (P_n - P_s) - 2K_e(M_n - M_s).$$

The solution of this equation, when the production rate and loss rate are not changing in time, is

$$M_n - M_s = \frac{P_n - P_s}{2K_e} + (\{M_n - M_s\}_{(t=0)} - \frac{\{P_n - P_s\}}{2K_e})\exp(-2K_e t)$$

If we allow a time to pass which is much longer than $1/2K_e$ then we can find the exchange rate using

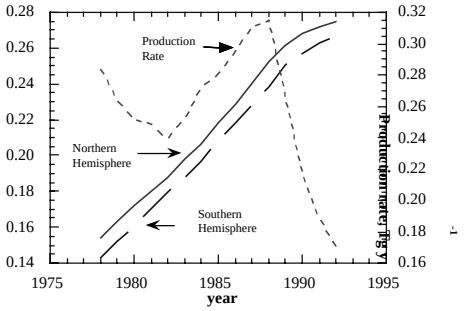
$$2K_e = \frac{(P_n - P_s)}{(M_n - M_s)}$$

If we assume that the production of the material of interest were to suddenly cease the difference in the masses of the material in the two hemispheres will decay by a factor of e^{-1} in a time

$$\tau_e = \frac{1}{2K_e}$$

However, it is usual to consider the transport time just in terms of a single hemisphere. Then the time for the mass of material in a given hemisphere to be reduced by a factor of e^{-1} due to transport to the other hemisphere is

$$\tau_e = \frac{1}{K_e}$$



The mixing ratio of CFC-11 in the Northern and Southern Hemisphere and the rate of production of CFC-11.

Mn-Ms=0.13 Tg, P=.26 Tg yr. So

$\tau_e = \frac{1}{K_e}$ **is about 1yr.**