大气环流

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课程简介

* 课程要求

- * 熟悉大气环流的基本分布和形态
- ◆ 掌握各主要环流系统的维持和变化机制
- * 建立各环流系统形成的物理模型
- * 了解现阶段的大气环流模式
- * 知道大气环流方向有待解决的科学问题



大气环流概述一观测资料



- 地面资料 (陆地, 航船)
- 探空资料
- 卫星资料
- Aircraft report (AIREP)
- 海洋资料



大气环流概述一资料处理与分析



data assimilation "froze" analysis technique technique always in development, e.g. using models with higher resolution, better parameterization reanalysis data

ERA-40

授课教师:张洋 4

NCEP/NCAR



大气环流概述一资料处理



NCEP/NCAR 再分析资料

• 物理量及分类

- A (strongly influenced by observed data, hence, in the most reliable class): geopotential height, T, u, v...
- B (although there are observational data directly affecting the value of the variable, the model also has a strong influence): relative humidity, w(vertical velocity), lowest level u and v...
- C (no observations directly affecting the variable, so that it is derived solely from the model forced by the data assimilation): radiation fluxes, surface heat fluxes, cloud forcing, precipitation rate...
- D (*fixed* from climatological values and does NOT depend on models): surface roughness, surface geopotential height...



Question 1



- 西风带,东风带
 - 对流层,平流层
 - 随纬度的变化
- 水平, 垂直结构
- 季节变化:位置,强度,副热带与温带
 急流
- 与温度场的匹配



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6



Question 2







Question 2





SP







大气环流概述一分析方法



Decompose a field in both time and space: (the results depend on whether we average in time or zonally first.

$$\begin{split} \overline{[vT]} &= \overline{[([v] + v^*)([T] + T^*)]} = \overline{[v][T]} + \overline{[v^*T^*]} \\ &= \overline{([v] + [v]')([T] + [T]')} + \overline{[v^*T^*]} \\ &= \overline{[v]}[\overline{T}] + \overline{[v]'[T]'} + \overline{[v^*T^*]} \\ \end{split}$$

$$\begin{aligned} \text{transport by the steady mean meridional circulation} & \text{transport by the steady mean meridional circulation} \\ \text{transport by the steady mean meridional circulation} & \text{transport by the steady mean meridional circulation} \\ \text{Alternatively,} \\ \hline [vT] &= \overline{[(\overline{v} + v')(\overline{T} + T')]} = [\overline{v}\overline{T}] + [\overline{v'T'}] \\ &= [([\overline{v}] + \overline{v}^*)([\overline{T}] + \overline{T}^*)] + [\overline{v'T'}] \\ &= [v][\overline{T}] + [\overline{v}^*\overline{T}^*] + [\overline{v'T'}] \\ &= [v][\overline{T}] + [\overline{v}^*\overline{T}^*] + [v'T'] \\ &= \overline{v} \text{transport by transport by transport by stationary eddies} \\ \end{split}$$



大气环流概述一内容简介



- 外部强迫:
 - 辐射强迫
 - 下界面强迫
- 经向环流系统(纬向平均环流, zonally averaged circulations):
 - Hadley 环流
 - Ferrel 环流、急流、波流相互作用
- 纬向环流系统(non-zonal circulations):
 - Storm tracks
 - Monsoon
 - ENSO and Walker circulation
- 不同复杂度的大气环流模式
- 全球暖化背景下的大气环流











From the solar radiation...



At TOA





Figures: the zonally averaged incident solar radiation, observed in the Earth Radiation Budget Experiment (ERBE).



energy budget











Wunsch (2005), J. Climate



Wunsch (2005), J. Climate



Simple energy balance climate models



- Simplest models in which the interactions between stradiation and dynamic heat transport can be considered.
 - Assumptions are made below:
 - One-dimensional, only latitude dependences are considered;
 - Global energy budgets are assumed to be expressed in *T_{sur}*;
 - Only annual mean conditions are considered;

 $\mathcal{C}\frac{\partial T(x,t)}{\partial t} = \text{solar radiation} - \text{infrared cooling} \\ -\text{divergence of heat flux}$

 $x = \sin \phi$, where ϕ is latitude.

$$C\frac{\partial T(x,t)}{\partial t} = F_{rad}^{top} - \frac{1}{2\pi a^2}\frac{\partial}{\partial x}f(x)$$



Simple energy balance climate models



solar radiation – infrared cooling
 –divergence of heat flux

 $x = \sin \phi$, where ϕ is latitude.

solar radiation = $Qs(x)\mathcal{A}(T)$

s(x) – latitudinal distribution of SW, whose integral from the equator to pole is unity

$$C\frac{\partial T(x,t)}{\partial t} = Qs(x)\mathcal{A}(T) - I(T) + F(T)$$

In equilibrium,

 $\mathcal{C}\frac{\partial T(x,t)}{\partial t}$

$$Qs(x)\mathcal{A}(T) - I(T) + F(T) = 0$$



Simple energy balance climate models

In equilibrium,

$$Qs(x)\mathcal{A}(T) - I(T) + F(T) = 0$$

In real atmosphere:

$$Qs(\phi)\mathcal{A}(\phi) - I(\phi) = \frac{1}{2\pi a^2 \cos\phi} \frac{\partial}{\partial\phi} f(\phi)$$

Integrate over latitude belt:

$$2\pi a^2 \int_{\phi_1}^{\phi_2} F(T) \cos \phi \, \mathrm{d}\phi = 2\pi a^2 \int_{x_1}^{x_2} F(T) \, \mathrm{d}x$$







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- Observations



- Summary (小结)

- Temperature field: the equator-pole temperature gradient is much smaller than the RE temperature gradient.
- Wind fields: meridional winds strongest at tropopause and surface; vertical velocity strongest at mid-level of the troposphere.
- Jets (zonal winds): strong subtropical jet at upper level with its maximum in the latitudes at the edge or just poleward of the descending branch of the Hadley cell; surface winds-easterlies near the equator and westerlies in the extratropics.
- Strong seasonal variations: in summer or winter, Hadley cell always appears as a strong single cell across the equator with the ascending branch in the tropics of the summer hemisphere.







Held-Hou model (1980)





Held-Hou model

-Angular momentum

The absolute angular momentum per unit mass is

$$M = (\Omega a \cos \phi + u) a \cos \phi$$

Due to earth's Deviation from
solid rotation the solid rotation

$$\frac{D}{Dt}M = -\frac{1}{\rho}\frac{\partial p}{\partial \lambda} + a \cos \phi F_{\lambda}$$

In an **axisymmetric flow** ([M]=M)

$$\frac{D}{Dt}[M] = a \cos \phi[F_{\lambda}]$$

In an inviscid (frictionless), **axisymmetric**
flow, the angular momentum is conserved.



Held-Hou model

-Angular momentum

$$[M] = (\Omega a \cos \phi + [u]) a \cos \phi$$

At the equator, as the parcels rise from the surface, where the flow is weak, we assume that the zonal flow is zero there.

$$[u] = \Omega a \frac{\sin^2 \phi}{\cos \phi} \equiv U_M$$

Then, what is the UM at 10, 20, 30 degree?

Answers: 14, 57, 134 m/s, respectively

Combined with the weak surface flow, this indicates strong vertical shear of the zonal wind.

 \boldsymbol{a}

 $a\cos\phi$









第四章:

中纬度的经向环流系统

- Ferrel cell, baroclinic eddies and the westerly jet



Observations



Summary:

- Zonal-mean flow:
 - Ferrel Cell: an indirect cell centered at 40-60 degree, with strong seasonal variation in N.H.
 - Westerly jet: surface westerlies centered at 40-60 degree
- Eddies: transient eddies are dominant with stationary eddies only obvious in N.H.
 - Kinetic energy
 - Momentum flux
 - (Sensible) Heat flux



The Ferrel Cell



The balance equations:





Conclusions:

Necessary condition for baroclinic instability: PV gradient changes sign in the interior or boundaries (Charney-stern theory), according to which the midlatitude atmosphere is baroclinic unstable. Different models. i.e. Eady and Charney models have more rigorous conditions.

Growth rate:
$$\sigma=kc_ipprox 0.3\,\Lambdarac{f_o}{N}$$
 in both Eady and Charney models!

Eady number/Eady growth rate

Most unstable mode:
$$k_{\max}^{-1} \propto L_d^{-1} = \left(\frac{NH}{f_o}\right)^{-1}$$
 $k_{\max}^{-1} \propto \Lambda \frac{f_o}{\beta N}$ EadyCharney



Baroclinic eddies



From linear to nonlinear





In a QG, steady, adiabatic and frictionless flow:

Momentum equation:

Baroclinic eddies

- Continuity equation:
- Thermodynamic equation:

$$[v] = \frac{1}{f} \frac{\partial}{\partial y} ([u^* v^*])$$
$$[\omega] = -\frac{\partial}{\partial y} \left(\frac{[\theta^* v^*]}{\partial \theta_s / \partial p}\right)$$

 $\begin{aligned} f[v] - \frac{\partial ([u^* v^*])}{\partial y} &= 0 \\ \frac{\partial [v]}{\partial y} + \frac{\partial [\omega]}{\partial p} &= 0 \implies \nabla \cdot \mathcal{F} = 0 \\ [\omega] \frac{\partial \theta_s}{\partial p} + \frac{\partial ([\theta^* v^*])}{\partial y} &= 0 \end{aligned}$

- E-P flux

Define Eliassen-Palm flux:

$$\mathcal{F} \equiv -[u^*v^*]\,\mathbf{j} + f\frac{[v^*\theta^*]}{\partial\theta_s/\partial p}\,\mathbf{k}$$



TEM equations: $\frac{\partial[u]}{\partial t} = f[\tilde{v}] + \nabla \cdot \mathcal{F} + [F_x], \quad \frac{\partial[\theta]}{\partial t} = -[\tilde{\omega}]\frac{\partial \theta_s}{\partial p} + \left(\frac{p_o}{p}\right)^{R/c_p}\frac{[Q]}{c_p}$



Baroclinic eddies





In isentropic coordinate

Case 2: Observed circulation





- The westerly jet

$$\mathcal{F} \equiv -[u^*v^*] \mathbf{j} + f \frac{[v^*\theta^*]}{\partial \theta_s / \partial p} \mathbf{k}$$

 $ec{\mathcal{F}}=ec{\mathbf{c_g}}\mathcal{A}$







 $\frac{\partial}{\partial t} < [u] > = -\frac{\partial}{\partial y} < [u^*v^*] > -r[u_{\text{surf}}]$

< > means vertical average

westerlies at midlatitudes.



$$\mathcal{F} \equiv -[u^*v^*] \,\mathbf{j} + f \frac{[v^*\theta^*]}{\partial \theta_s / \partial p} \,\mathbf{k}$$

- $ec{\mathcal{F}}=ec{\mathbf{c_g}}\mathcal{A}$
 - Numerical results and observations: eddies generate in the lower level, propagate **upwards** and **away** from the eddy source region.

$$\frac{\partial[u]}{\partial t} = f[\tilde{v}] + \nabla \cdot \mathcal{F} + [F_x]$$

- Accelerating the lower jet, decelerating the upper jet, reduce the vertical shear of U
- Momentum budget indicates that there MUST be surface westerlies in the eddy source latitude.





Zonal mean and eddy components:

• Kinetic energy (动能): $K_{\rm M} = \frac{1}{2} \left([u]^2 + [v]^2 \right)$ $K_{\rm E} = \frac{1}{2} \left([u^{*2}] + [v^{*2}] \right)$

Available potential energy (有效位能):

$$P_{\rm M} = \frac{c_p}{2} \Gamma\left([T] - T_s\right)^2 \qquad P_{\rm E} = \frac{c_p}{2} \Gamma[T^{*2}]$$

Tendency equations under the QG assumption:

$$\frac{\partial}{\partial t} \int K dm = -R \int \frac{\omega T}{p} dm + \int (uF_x + vF_y) dm$$
$$\frac{\partial}{\partial t} \int P dm = R \int \frac{\omega T}{p} dm + \int \Gamma(T - T_s)(Q - Q_s) dm$$

Q - diabatic heating



Equations under the **Quasi-geostrophic** assumption:

$$\begin{split} &\frac{\partial}{\partial t} \int K \mathrm{d}m = -R \int \frac{\omega T}{p} \mathrm{d}m + \int (uF_x + vF_y) \mathrm{d}m \\ &\frac{\partial}{\partial t} \int K_{\mathrm{M}} \mathrm{d}m = -R \int \frac{[\omega][T]}{p} \mathrm{d}m + \int [u^*v^*] \frac{\partial [u]}{\partial y} \mathrm{d}m + \int ([u][F_x] + [v][F_y]) \mathrm{d}m \\ &\frac{\partial}{\partial t} \int K_{\mathrm{E}} \mathrm{d}m = -R \int \frac{[\omega^*T^*]}{p} \mathrm{d}m - \int [u^*v^*] \frac{\partial [u]}{\partial y} \mathrm{d}m + \int ([u^*F_x^* + v^*F_y^*]) \mathrm{d}m \\ &\frac{\partial}{\partial t} \int P \mathrm{d}m = R \int \frac{\omega T}{p} \mathrm{d}m + \int \Gamma(T - T_s)(Q - Q_s) \mathrm{d}m \\ &\frac{\partial}{\partial t} \int P_{\mathrm{M}} \mathrm{d}m = R \int \frac{[\omega][T]}{p} \mathrm{d}m + c_p \int \Gamma[v^*T^*] \frac{\partial [T]}{\partial y} \mathrm{d}m + \int \Gamma([T] - T_s)([Q] - Q_s) \mathrm{d}m \\ &\frac{\partial}{\partial t} \int P_{\mathrm{E}} \mathrm{d}m = R \int \frac{[\omega^*T^*]}{p} \mathrm{d}m - c_p \int \Gamma[v^*T^*] \frac{\partial [T]}{\partial y} \mathrm{d}m + \int \Gamma[T^*Q^*] \mathrm{d}m \end{split}$$









第六章:

能量与水汽的分布、平衡与输送



Distribution of each component









Distribution of each component



Total energy:

 $E = I + \Phi + LH + K$

Vertical distribution:

Total energy: decreases with height.

The available energy: PE: peaks near tropopause and surface; KE: strongest at tropopause.







$$\left(\frac{dq}{dt}\right)_p = s(q) + D$$
 $s(q) = e - c$

Integrate above equation vertically and over a latitudinal belt:





Surface

 $Q_{\rm RAD} + Q_{\rm B} \approx -g \frac{\partial}{\partial n} (F_{\rm rad} + F_{\rm sh})$

From the momentum, thermodynamic equation and the water vapor budget:











第五章:

大气环流中的纬向环流系统 5.1 Storm Tracks



Fig. 7.9. The tracks of low pressure centres over the North Atlantic for the period December 1985 to February 1986. The shading indicates the region where the high frequency $\overline{Z'^2}^{1/2}$ exceeded 90 m in the ECMWF analyses for the same period.





Summary:

- Structure: zonally located in the north Pacific and Atlantic, with the mean flow baroclinicity, jet, eddy activity, eddy heat and momentum flux in different zonal distribution.
- Seasonal variation: different variations between the Pacific and Atlantic storm tracks; for the Pacific storm zone, mid-winter minimum observed.
- Inter-annual variation: Pacific storm track shifts equatorward and downstream during El Nino years.
- Decadal variation: variations in intensity occur in both storm zones, with the storm tracks in the 1990s stronger than in the 1960s.



Baroclinic eddy life cycle in time:



Storm track structure can heuristically equate with an eddy life cycle in **space**:





Storm track dynamics

- Transient eddy energy budget

For storm tracks, define a **total transient eddy energy**:

$$E = K_{\rm TE} + P_{\rm TE} = \frac{1}{2}\overline{(u'^2 + v'^2)} + \frac{c_p}{2}\Gamma\overline{(T'^2)} = \frac{1}{2}\overline{(u'^2 + v'^2)} - \frac{\alpha_m}{2\theta_m}\frac{\overline{\theta'^2}}{\partial\theta_s/\partial p}$$

Transient eddy energy budget:

$$\frac{\partial E}{\partial t} = \nabla \cdot \overline{(\mathbf{v}E + \mathbf{v}'_{\mathbf{a}}\phi')} + \frac{\alpha_m}{\theta_m} \frac{\overline{\mathbf{v}'\theta'}}{\partial \theta_s/\partial p} \cdot \nabla \theta - \overline{\mathbf{v}' \cdot (\mathbf{v}' \cdot \nabla)V_m} - \text{diss} + \text{diab}$$

advective energy flux baroclinic generation barotropic $D(K_E) = G(P_E)$



Storm track dynamics

- Transient eddy energy budget



Strongly compensate the baroclinic conversion term in the entrance region.

from Chang et al, JC, 2002



Geographical Extent of the Global Surface Monsoons



The red, green, and blue areas indicate the tropical, subtropical, and temperate-frigid monsoons, respectively. The red and blue thick lines represent the ITCZ in summer and winter, respectively. (Li, J., and Q. Zeng, 2005)



- 65% of world's population lives within monsoon;
- Monsoon precipitation is crucial to the life, food production, economy et al in these regions;
- Proper forecasting of location and quantity of precipitation is crucial to theses regions.





- Summary:
 - A monsoon climate is characterized by the obvious seasonal reverse of wind, precipitation and atmospheric circulation.
 - From a global view: south asian monsoon is associated with the seasonal migration of ITCZ and Hadley circulation, which also plays an important role in the global meridional moisture and latent energy transport.
 - South asian monsoon exhibits obvious sudden onset, with the low-level winds and the whole monsoonal circulation built in two weeks.
 - Intra-seasonal variation: show periods in 4-5 days, 10-20 days and 40-50 days.
 - Inter-annual variation: Relatively weaker precipitation occurs during El Nino years.



Monsoon dynamics



- Land-sea contrast
 - thermal contrast: strongest heating over subtropical land
 - moisture advection: provide precipitation water
- Orography
 - Thermal forcing as an upper level heat source
 - Mechanical forcing:
 - a local precipitation enhancement
 - a widespread barrier of cold, dry air
- GCM results
 - strong seasonal heating due to the small heat capacity of the underlying surface seems to be crucial to the formation of monsoonal circulation; monsoonal circulation is associated with the eddy activity transition;
 - the special topography of south asian reinforces the monsoon, especially by protecting warm and moist tropical air from the cold and dry extratropics
 - thermal heating from the south slope of TP suggested strengthen the monsoon
 - Monsoon variation in timescales as intra-seasonal, inter-annual scales needs

further studies







(B)

60° E

Africa

Walker Circulation



180°

Longitude

0.005 m s⁻¹ 120° W

0.01

60° W

South

America

0.015

120° F

-0.005

Maritime

continent

-0.007

El Nino years:

Raising motion prevailed at almost all longitudes with a peak in central pacific.

La Nina years:

An enhanced Walker Circulation.

Adapted from Lau et al, 2002





• A summary from the AMIP I results:

- Ensemble mean shows that the average large-scale seasonal distributions of pressure, temperature, and circulation are reasonably close to what are believed to be the best observational estimates available;
- The average large-scale distributions of pressure, temperature and circulation shows relatively large intermodel differences in high/polar latitudes compared to low/mid latitudes.
- The large-scale structure of the ensemble mean precipitation also resembles the observed estimates but show particularly large intermodel differences in low latitudes.
- The total cloudiness, on the other hand, is rather poorly simulated.



■•利用不同复杂意的动动前。 我各种复杂气候现象后的物理机制。



64

期末考试

- * 考前答疑时间: 12月10日, 12月17日下午4: 00-5: 30, 大气楼B410
- * 考试时间: 12月18日(周三),下午2:00-4:30
- * 地点: 仙II-104
- * 要求:
 - * 闭卷,但是可以携带30条公式
 - * 携带计算器
 - * 试卷以6-7道大题的形式,认真回答每一个小问题