第一章:

大气环流概述(II)

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2023. 9. 28

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大气环流概述(II)

Reference reading： PO Chapter 5.1-5.2, 4.1;
James Chapter 2.2, 2.4

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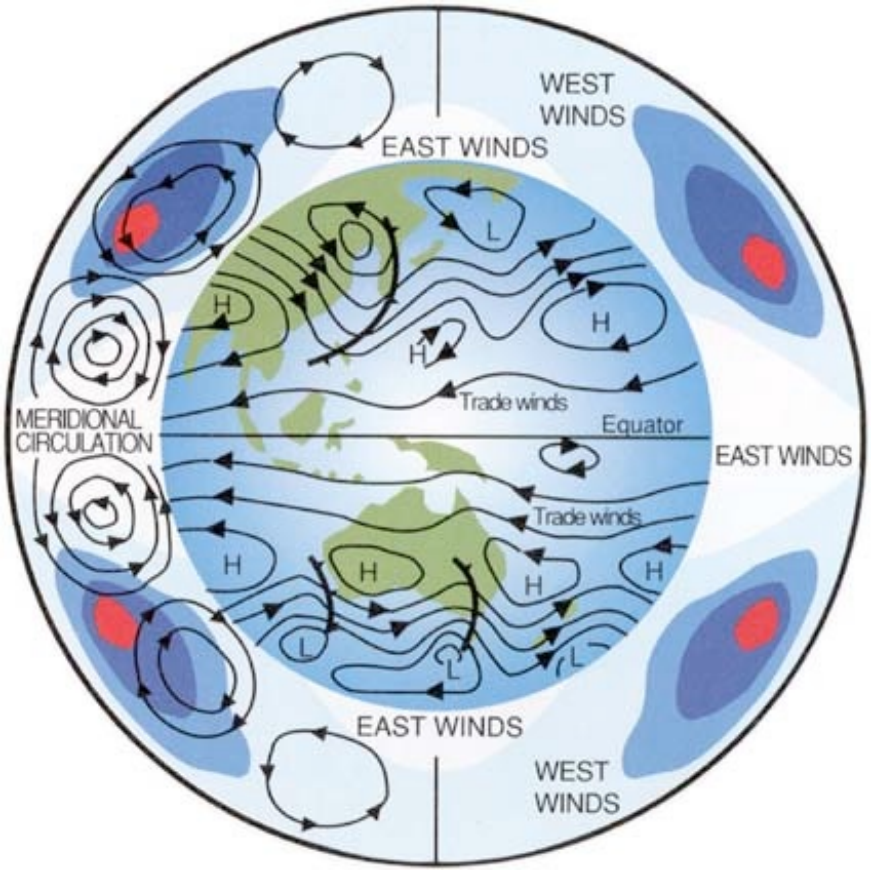
大气环流概述

- 历史回顾
- 内容简介
- 观测资料
- 资料处理与分析
- 再分析资料
- 分析方法

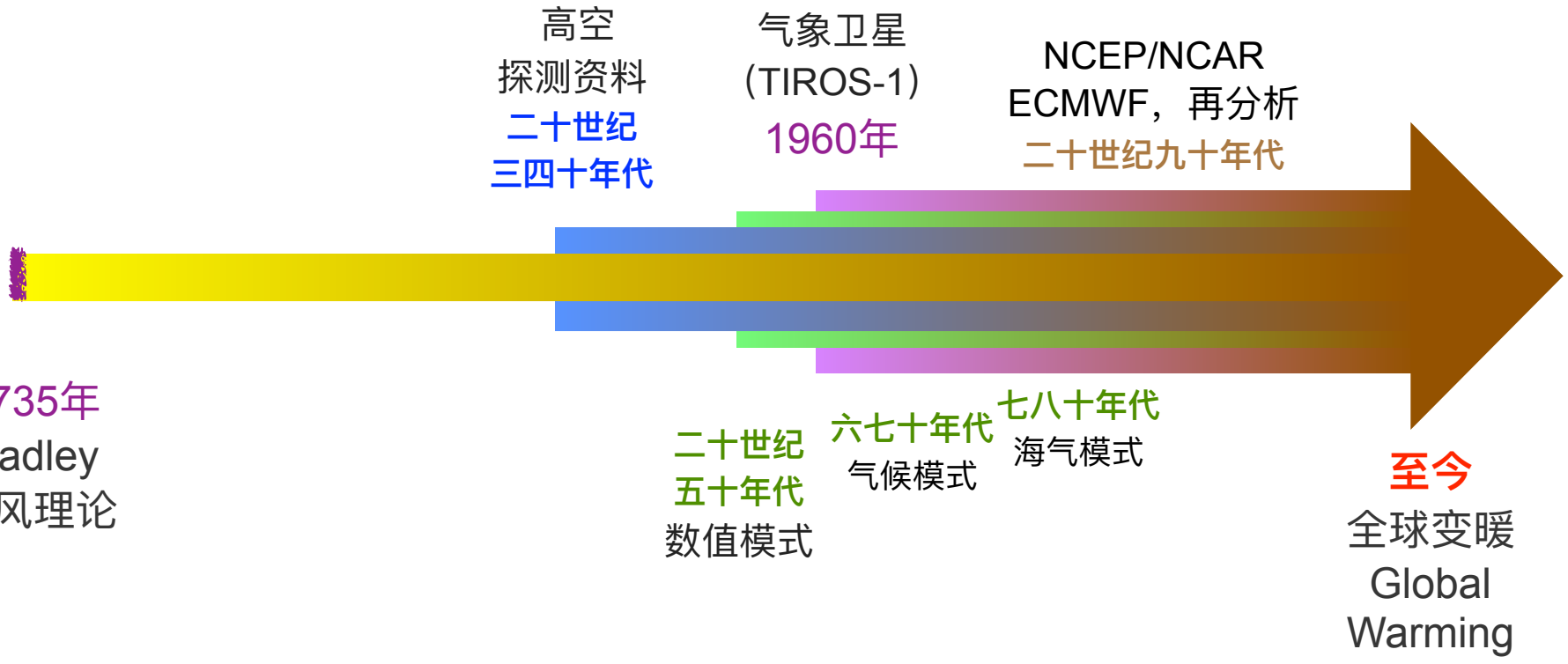
大气环流概述－内容简介

Review

- 外部强迫：
  - 辐射强迫
  - 下界面过程
- 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：
  - 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



大气环流概述－历史简介


高空
探测资料
二十世纪
三四十年代
气象卫星
（TIROS-1）
1960年
NCEP/NCAR
ECMWF，再分析
二十世纪九十年代
1735年
Hadley
信风理论
二十世纪
五十年代
数值模式
六七十年代
气候模式
七八十年代
海气模式
至今
全球变暖
Global
Warming

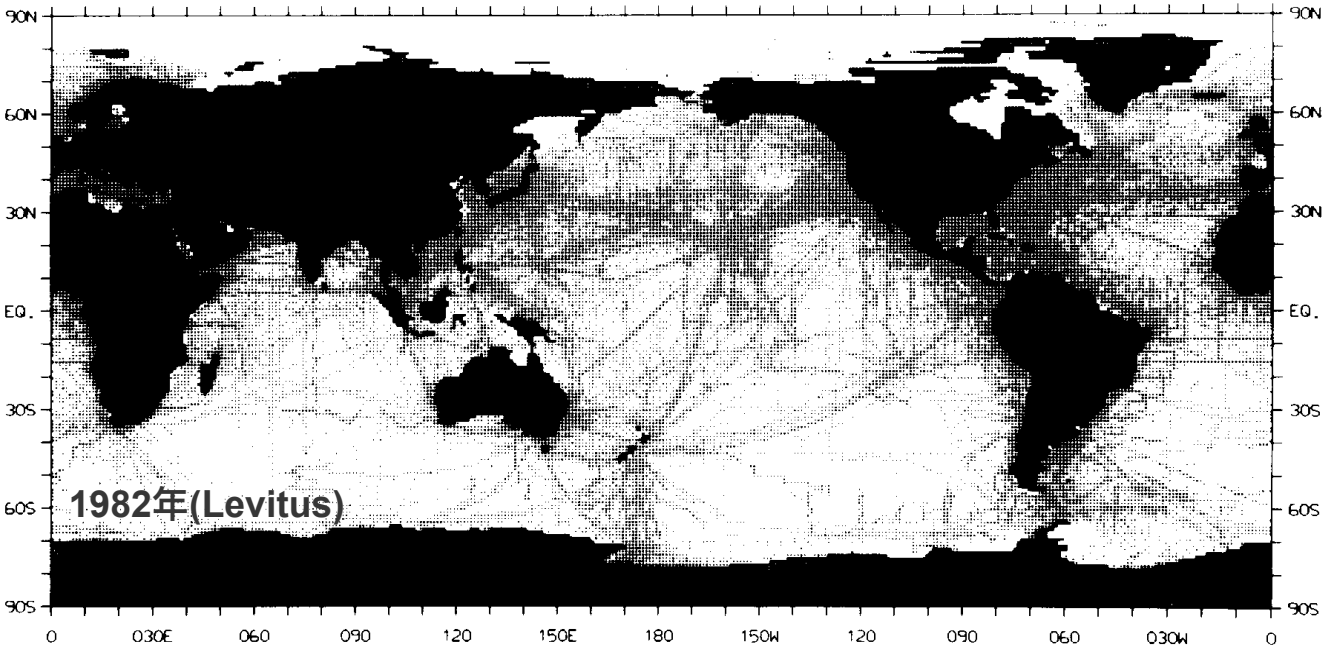
大气环流概述－观测资料

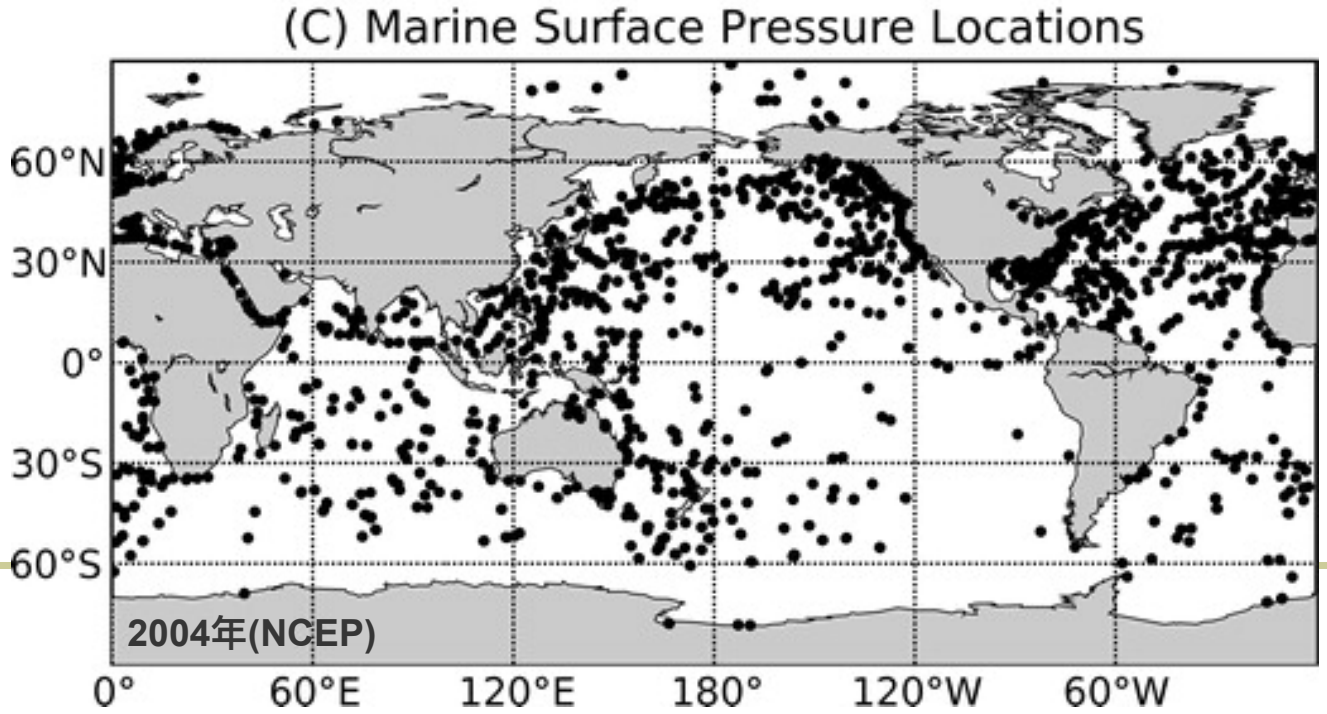
- 地面资料 （陆地，航船）
- 探空资料
- 卫星资料
- Aircraft report (AIREP)
- 海洋资料

大气环

海洋资料

- Research vessels: temperature, salinity, oxygen content,concentrations of various nutrients.
- Shorter time coverage.
- Still limited knowledge on the dynamical structure of the oceans.

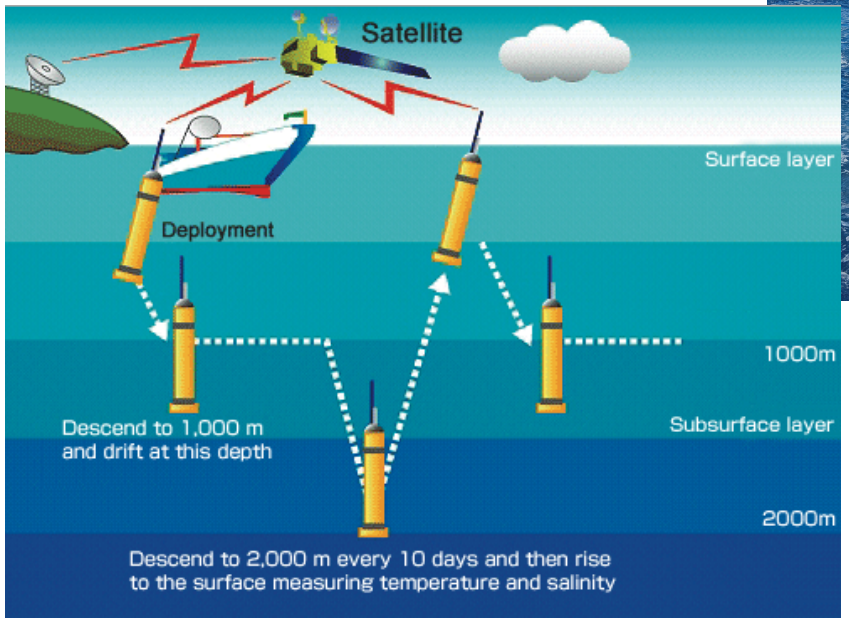




大气环流概述－观测资料

海洋资料: Argo

- 覆盖全球海洋、提供实时海洋上层观测数据。
- Consist of almost 4000 drifting, profiling **float**: temperature, salinity and currents.
- Coverage since 2000s.
- Drift at 1000m, every 10 days, dive to 2000m then move to surface.



大气环流概述－观测资料

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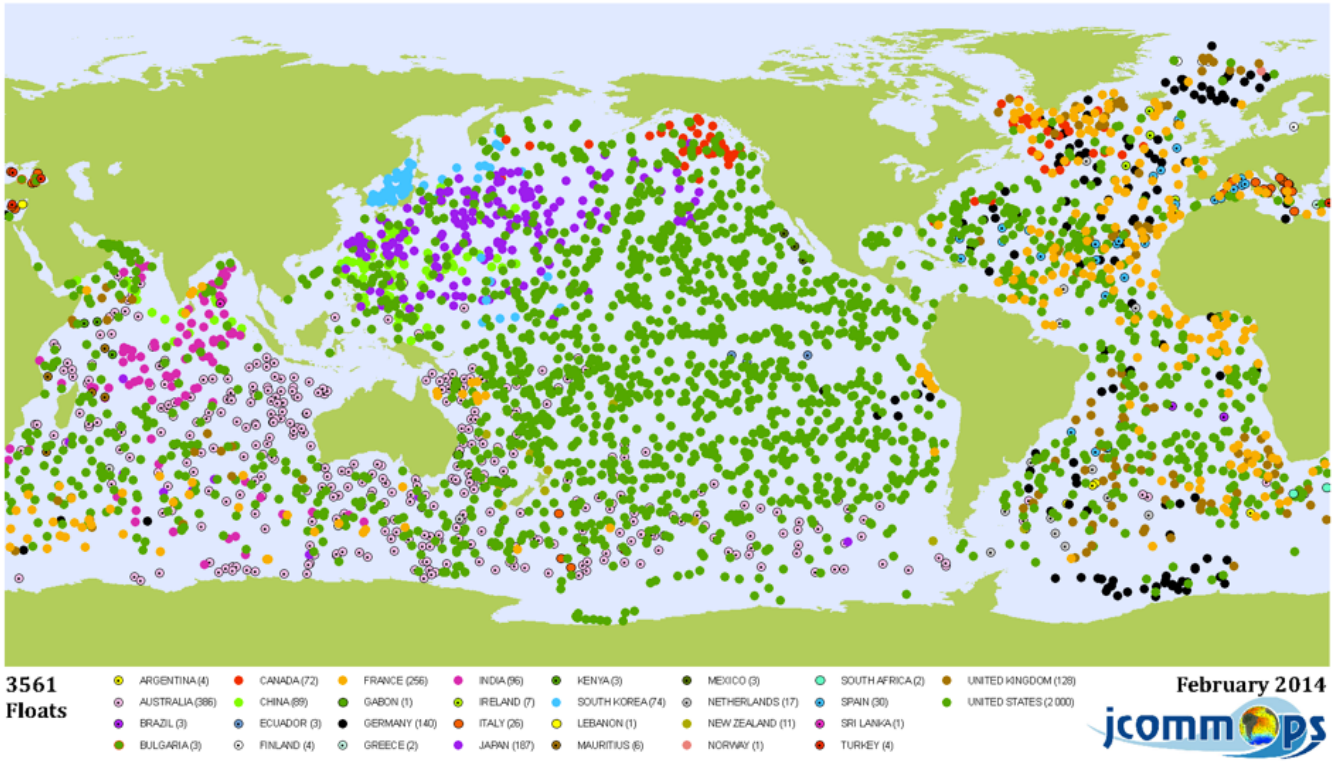

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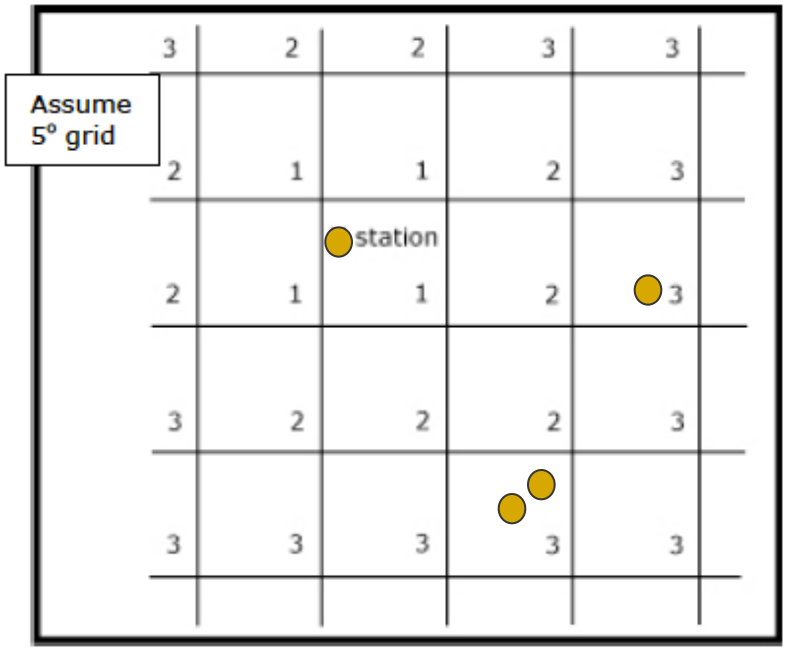
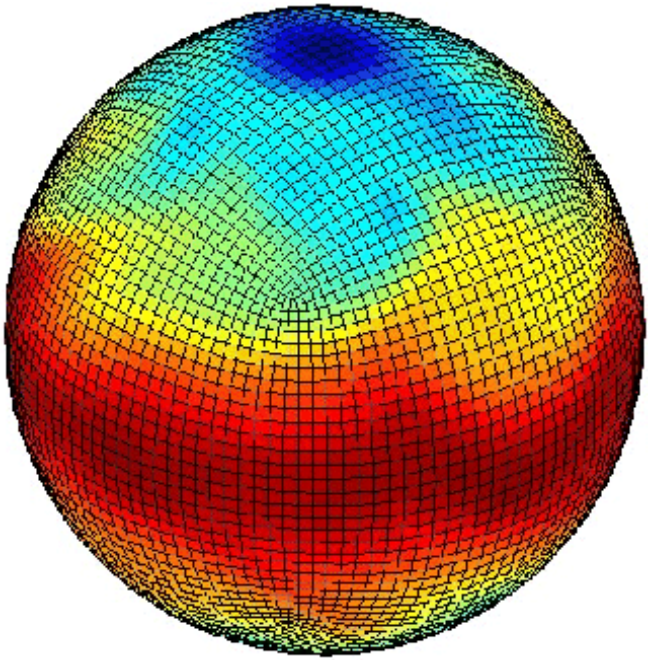
- 再分析资料
- 分析方法

大气环流概述－资料处理与分析

- 举例: 从站点资料到格点资料

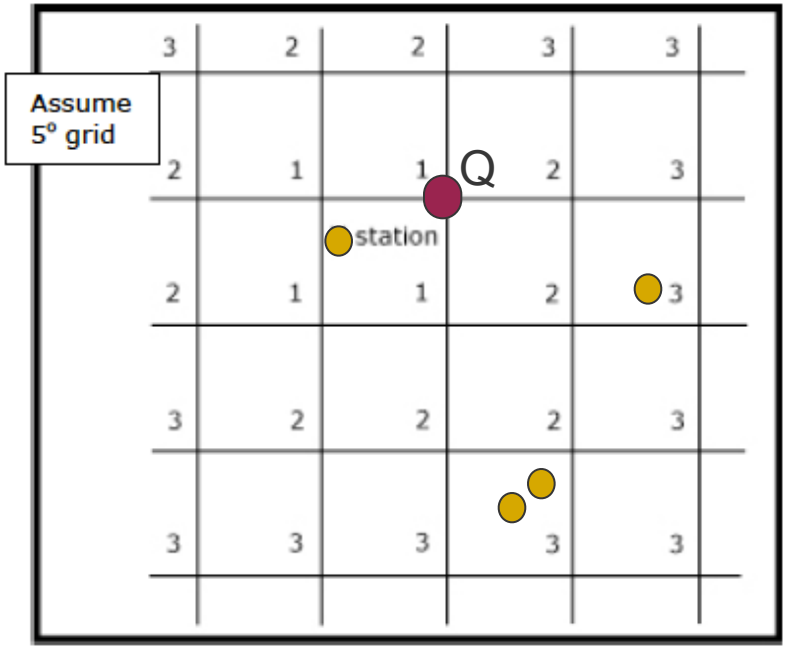




From Stone, 2005

大气环流概述－资料处理与分析

- 举例: 从站点资料到格点资料 (radiosonde based)



From Stone, 2005

- Initial guess Q_g for the actual field Q.
- Refine Q_g from any observations within a certain distance of each grid point:

$$Q_r = (1 - \sum_i W_i) Q_g + \sum_i W_i Q_i$$

The heart of the method is the appropriate choice of the weights W_i. In general, it depends on the distance of the observation from grid points. More sophisticated schemes might also consider the balance condition between variables.

- 举例: 从站点资料到格点资料 (**data assimilation**)

- Data assimilation:
  - process by which **observations** are incorporated into a **computer model** of a real system;
  - In each analysis cycle, **observations** of the current (and possibly past) state of a system are combined with the results from a numerical weather **prediction model** (the forecast) to produce an *analysis*, which is considered as 'the best' estimate of the current state of the system;
  - Data assimilation tries to balance the uncertainty in the **data** and in the **forecast**.

大气环流概述－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　　NCEP/NCAR

大气环流概述－再分析资料

- 再分析资料：ERA-40和NCEP/NCAR
  - NCEP(National Centers for Environmental Prediction)/ NCAR(National Center for Atmospheric Research)
    - Dataset Product:
      - 1948.01.01-present, global grids
      - 4-times daily and monthly
      - Horizontal: 2.5 X 2.5 degree (Basic)
      - Vertical: 17 pressure levels (Basic)
    - Model for data assimilation: T62 with 28 levels
    - Reference: Kalnay et al.,1996: The NCEP/NCAR 40-year reanalysis project, *Bull. Amer. Meteor. Soc.*, 77, 437-470.
    - http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html

大气环流概述－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...

大气环流概述－再分析资料

- 再分析资料：ERA-40和NCEP/NCAR
  - ERA-40 (earlier ECMWF re-analysis, ERA-15, 1979 to 1993)
    - Dataset product:
      - mid-1957 to mid-2002, global grids
      - 4-times daily, monthly
      - Horizontal: 2.5 X 2.5 degree (Basic)
      - Vertical: 23 pressure levels (Basic)
    - Model for data assimilation: TL159 with 60 levels
    - Reference: Uppala, S.M., Kållberg, P.W., Simmons, A.J., Andrae, U., da Costa Bechtold, V., Fiorino, M., Gibson, J.K., Haseler, J., Hernandez, A., Kelly, G.A., Li, X., Onogi, K., Saarinen, S., Sokka, N., Allan, R.P., Andersson, E., Arpe, K., Balmaseda, M.A., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S., Hólm, E., Hoskins, B.J., Isaksen, L., Janssen, P.A.E.M., Jenne, R., McNally, A.P., Mahfouf, J.-F., Morcrette, J.-J., Rayner, N.A., Saunders, R.W., Simon, P., Sterl, A., Trenberth, K.E., Untch, A., Vasiljevic, D., Viterbo, P., and Woollen, J. **2005: The ERA-40 re-analysis. Quart. J. R. Meteorol. Soc.,** 131, 2961-3012.doi:10.1256/qj.04.176
    - http://www.ecmwf.int/products/data/archive/descriptions/e4/index.html,
    - http://dss.ucar.edu/pub/era40/

大气环流概述－再分析资料

- ERA-Interim:
  - Dataset:
    - 1979 to 2019, global grids
    - 3-hourly surface variables, 6-hourly upper air variables in the troposphere and stratosphere, monthly mean
    - Horizontal: 0.75 X 0.75 degree (ERA40: 2.5 degree)
    - Vertical: 37 pressure levels (ERA40: 23 levels)
  - Model: TL255 (ERA40: TL159), 60 levels
  - Reference: Dee DP, Uppala SM, Simmons AJ, Berrisford P, Poli P, Kobayashi S, Andrae U, Balmaseda MA, Balsamo G, Bauer P, Bechtold P, Beljaars ACM, van de Berg L, Bidlot J, Bormann N, Delsol C, Dragani R, Fuentes M, Geer AJ, Haimberger L, Healy SB, Hersbach H, Holm EV, Isaksen L, K ´ allberg P, K ˚ ohler M, ¨ Matricardi M, McNally AP, Monge-Sanz BM, Morcrette J-J, Park B-K, Peubey C, de Rosnay P, Tavolato C, Thepaut J-N, Vitart F. 2011. **The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Q. J. R. Meteorol. Soc.** 137: 553–597. DOI:10.1002/qj.828.
  - http://www.ecmwf.int/research/era/do/get/era-interim

大气环流概述－再分析资料

- ERA-Interim vs. ERA40:
  - Higher horizontal and vertical resolutions
  - Improved model: T255 horizontal resolution, improved model physics, and improved fast radiative transfer model;
  - Better data assimilations to overcome the difficulties related to the use of satellite data, including
    - 4D-Var;
    - Variational bias correction of satellite radiance data, and other improvements in bias handling;
    - More extensive use of radiances.
  - Improvements in:
    - representation of the hydrological cycle
    - the quality of the stratospheric circulation
    - the consistency in time of the reanalysed fields

大气环流概述－再分析资料

- ERA5:
  - Dataset:
    - 1979 to present, (back extension 1950-1978), global grids
    - Horizontal 0.25 X 0.25 degree (~31 km)
    - Vertical: interpolated to 37 pressure levels
  - Model: 31 km，137 levels
  - Reference: Hersbach, H, Bell, B, Berrisford, P, et al.,2020: **The ERA5 global reanalysis.** *Q J R Meteorol Soc.*, 146: 1999– 2049. https://doi.org/10.1002/qj.3803
  - https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5

大气环流概述－再分析资料

- NCEP Climate Forecast System Reanalysis (CFSR):
  - 1979 to present, global grids of atmosphere, ocean and land surface
  - hourly, 6-hourly, monthly mean
  - Horizontal: 0.5 X 0.5 degree
  - Vertical: 37 atmospheric pressure (hPa) levels; 40 levels (m) for ocean; and 16 isentropic levels (K) for atmosphere
  - Model: a global atmosphere–ocean–land surface–sea ice coupled system
    - a global atmosphere resolution ~38 km (T382) with 64 levels extending from the surface to 0.26 hPa;
    - a global interactive ocean (GFDL MOM4) with latitudinal spacing 0.25° at the equator, extending to a global 0.5° beyond the tropics, with 40 levels to a depth of 4737 m;
    - a global interactive land surface model (NCEP Noah Land model) with 4 soil levels;
    - a global interactive sea-ice model with 3 layers.
  - Reference: Saha, Suranjana, and Coauthors, 2010: The NCEP Climate Forecast System Reanalysis. *Bull. Amer. Meteor. Soc.*, **91**, 1015–1057.
  - http://cfs.ncep.noaa.gov/cfsr/

大气环流概述－再分析资料

- 其它再分析资料：
  - JRA25 （Japanese 25-year Reanalysis）
    - 日本气象厅(The Japan Meteorological Agency，JMA)与电力工业中心研究所 (the Central Research Institute of Electric Power Industry，CRIEPI)
    - 第一套亚洲承担的长期再分析数据， 目的之一为提高亚洲数据的质量，考虑了ERA40中大多数的观测数据，并使用了JMA最新的同化系统以及较多的观测数据。另外，JRA-25第一次使用了热带气旋风速廓线 (Wind profile retrievals surrounding tropical cyclones，TCR，源于重建数据)、SSM/I雪盖资料、中国雪深资料等。
    - Dataset:
      - Jan. 1979 to Dec. 2004 (26 years), global grids
      - 4-times daily, monthly
      - Horizontal: 2.5 X 2.5 degree (Basic)
      - Vertical: 23 pressure levels (Basic)
    - Model: T106 with 40 levels
    - Reference: Onogi, K., J. Tsutsui, H. Koide, M. Sakamoto, S. Kobayashi, H. Hatsushika, T. Matsumoto, N. Yamazaki, H. Kamahori, K. Takahashi, S. Kadokura, K. Wada, K. Kato, R. Oyama, T. Ose, N. Mannoji and R. Taira (2007) : **The JRA-25 Reanalysis. J. Meteor. Soc**. Japan, 85, 369-432.
    - http://jra.kishou.go.jp/JRA-25/AboutJRA25_en.html

大气环流概述－再分析资料

- 其它再分析资料：
  - JRA-55
    - Release in November 2013 (now with JRA-55, JRA-55C, JRA-AMIP option)
    - Dataset span from 1958 to present, global grids
    - 4-times daily, monthly
    - Model: TL319 L60 (~60 km)
    - 4Dvar data assimilation
    - Variational bias correction for satellite radiance data to reduce the jumps
    - New radiation scheme to reduce the temperature biases
    - Updated dynamical and physical processes
    - In contrast to JRA-25 where CO2 was held constant, JRA-55 ingests CO2
    - http://jra.kishou.go.jp/JRA-55

大气环流概述－再分析资料

Name	Organization	Period	Model Resolution	Assimilation
NCEP-NCAR(Reanalysis-1)	NCEP-NCAR	1948-present	T62 L28	3DVAR
NCEP-DOE AMIP-II(Reanalysis-2)	NCEP-DOE	1979-present	T62 L28	3DVAR
NCEP CFSR	NCEP	1979-present	T382L64 (coupled model)	3DVAR
ERA-15	ECMWF	1979-1993	T106 L31	OI
ERA-40	ECMWF	1957.9-2002.8	TL159 L60	3DVAR
ERA-Interim	ECMWF	1979-present	TL255 L60	4DVAR
JRA-25	JMA/CRIEPI	1979-2004	T106L40	3DVAR
JRA-55	JMA/CRIEPI	1958-present	TL319 L60	4DVAR

大气环流概述－再分析资料

Summary of Atmospheric Reanalysis products

Name	Source	Domain	Period of Record	available timestep(s)	available resolution	available format(s)	Model Resolution	scheme & model vintage
Arctic System Reanalysis (ASR)	Byrd Polar Research Center, The Ohio State University/ David Bromwich,NCAR,CIRES,U Illinois	Arctic	2000/01 to 2012/12	Sub-daily, Monthly	ASR v1; 30 km; 71 levels; 10hPA top, ASR v2; 15 km; 71 levels; 10hPA top	netCDF	30 km and 15 km	WRF-VAR
CERA-20C: ECMWF's Coupled Ocean-Atmosphere Reanalysis of the 20th Century	ECMWF	Global	1901/01 to 2010/12	Sub-daily, Daily, Monthly	~ 125km; 160 x 320; 91 model levels/ 37 pressure levels / 16 potential temperature levels, and the 2 PVU potential vorticity level	netCDF, GRIB		4DVAR | 2016
Climate Forecast System Reanalysis (CFSR)	NCEP	Global	1979/01 to 2017/11	Sub-daily, Monthly	.5°x.5° & 2.5°x2.5°, 0.266 hPA top	GRIB	T382 x 64 levels	3DVAR | 2009
ERA-15	ECMWF	Global	1979/01 to 1993/12	Sub-daily, Monthly	T106, 2.5 x 2.5	GRIB	T106 (1.125)	
ERA-20C: ECMWF's atmospheric reanalysis of the 20th century (and comparisons with NOAA's 20CR)	ECMWF	Global	1900/01 to 2011/01	Sub-daily, Daily, Monthly	~ 125km; 160 x 320; 91 model levels/ 37 pressure levels / 16 potential temperature levels, and the 2 PVU potential vorticity level	netCDF, GRIB		4DVAR | 2012
ERA-Interim	ECMWF	Global	1979/01 to 2019/09	Sub-daily, Daily, Monthly	0.75°x0.75°x60 lev 0.1 hPA top	netCDF, GRIB	T255, 60 levels	4DVAR | 2006
ERA40	ECMWF	Global	1957/09 to 2002/08	Sub-daily, Monthly	2.5°x2.5° / 1.125°x1.125°; 60 levels 0.1 hPA top	netCDF, GRIB	T159, 60 levels	3DVAR | 2004
ERA5 atmospheric reanalysis		Global	1959/01 to 2022/06	Sub-daily, Daily, Monthly	~31 km, 137 levels to 1 Pa	netCDF, GRIB		4DVAR | 2016; IFS release 41r2

下页继续

https://climatedataguide.ucar.edu/climate-data/atmospheric-reanalysis-overview-comparison-tables

大气环流概述－再分析资料

Summary of Atmospheric Reanalysis products

Name	Source	Domain	Period of Record	available timestep(s)	available resolution	available format(s)	Model Resolution	scheme & model vintage
JRA-25	Japanese Meteorological Agency	Global	1979/01 to 2004/12	Sub-daily, Monthly	1.125x1.125/2.5x2.5; 0.4 hPA top	GRIB	T106, 40 levels	3DVAR | 2004
JRA-55	Japanese Meteorological Agency	Global	1957/12 to 2022/09	Sub-daily, Monthly	T319 x 60 levels, 0.1 hPA top	GRIB	T319 x 60 levels	4DVAR | 2009
NASA MERRA	NASA	Global	1979/01 to 2016/02	Sub-daily, Monthly	0.5° x 0.667° x 72 , 0.01 hPA top	netCDF, HDF	0.5° x 0.667° x 72	GEOS IAU | 2009
NASA's MERRA2 reanalysis	NASA Global Modeling and Assimilation Office	Global	1980/01 to 2017/11	Sub-daily, Daily, Monthly	½° latitude by ⅝° longitude by 72 model levels (also interpolated to 42 pressure levels)	netCDF	Cubed sphere grid, stored at ½° latitude by ⅝° longitude by 72 model levels (also interpolated to 42 pressure levels)	3DVAR | 2014
NCEP NARR	NCEP	North America	1979/01 to 2022/09	Climatology, Sub-daily, Monthly	32km	GRIB	32km x 45 eta	3DVAR | 2003
NCEP Reanalysis (R2)	NCEP,DOE	Global	1979/01 to 2022/09	Sub-daily, Daily, Monthly	2.5°x2.5° 28 levels 3 hPA top	netCDF, GRIB	T62 28 levels	3DVAR | 2001
NCEP-NCAR (R1): An Overview	NCEP,NCAR	Global	1948/01 to 2022/09	Sub-daily, Daily, Monthly	2.5°x2.5°; 3 hPA top	netCDF, GRIB	T62 - 28 levels	3DVAR | 1995
NOAA 20th-Century Reanalysis, Version 2 and 2c	NOAA ESRL,CIRES CDC / Gil Compo	Global	1850/12 to 2014/12	Sub-daily, Daily, Monthly	2°x2°, 28 levels 10 hPA top	netCDF, GRIB	T62 28 levels	Ensemble Kalman Filter | 2009

https://climatedataguide.ucar.edu/climate-data/atmospheric-reanalysis-overview-comparison-tables

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大气环流概述－数据分析方法

- In this course, instead of weather, we are rather interested in the "climate" of the atmosphere, i.e., in the average state over some time:

$$\overline{A} = \frac{1}{\tau}\int_0^{\tau} A dt$$

where τ might be a season, a year, or some multi-year, multi-decadal period.

- The fluctuating part:

$$A' = A - \overline{A}$$

大气环流概述－数据分析方法

$$\overline{A'} = 0$$

However, this does **NOT** mean that the fluctuating part of the field is irrelevant to climate.

- For example, kinetic energy per unit mass

$$\frac{1}{2}\overline{u^2} = \frac{1}{2}\overline{(\bar{u} + u')^2} = \frac{1}{2}(\bar{u}^2 + \overline{u'^2})$$

大气环流概述－数据分析方法

- Climate generally varies more strongly with latitude than with longitude (as we will see) and therefore much attention has been devoted to the zonal mean climate and how it is maintained. The zonal mean state:

$$[A] = \frac{1}{2\pi}\int_0^{2\pi} A d\lambda$$

- The eddy part:

$$A^* = A - [A] \quad \text{and} \quad [A^*] = 0$$

- The covariance in time and space:

$$\overline{AB} = \bar{A}\bar{B} + \overline{A'B'}$$

$$[AB] = [A][B] + [A^*B^*]$$

大气环流概述－数据分析方法

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

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

transport by the steady mean meridional circulation

transport by the transient mean meridional circulation

transport by the spacial eddy circulation

Alternatively,

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

transport by stationary eddies

transport by transient eddies

大气环流概述－数据分析方法

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

	Station A		Station B	
	u	v	u	v
Day 1	0	-2	6	6
Day 2	2	-4	4	8

大气环流概述－数据分析方法

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

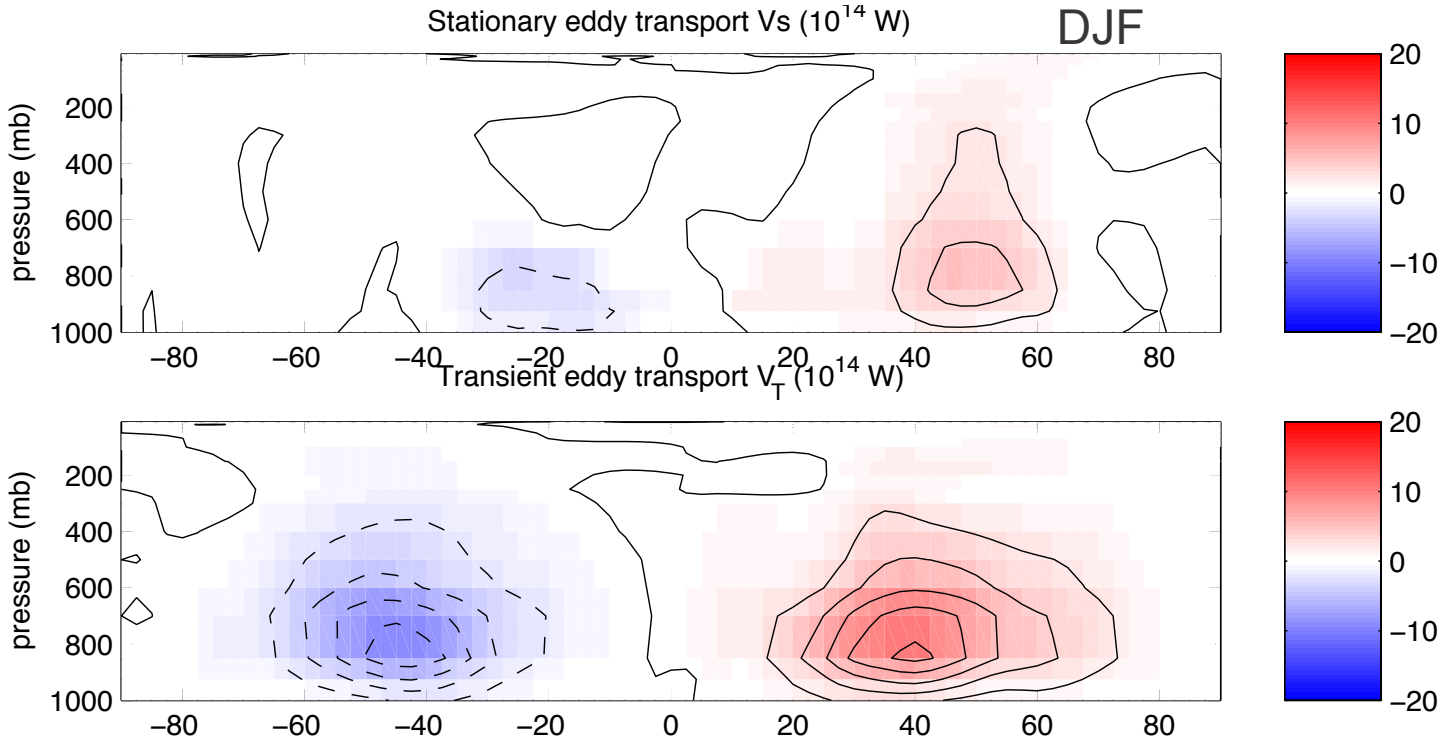
	Station A		Station B			
	u	v	u	v	[u]	[v]
Day 1	0	-2	6	6	3	2
Day 2	2	-4	4	8	3	2
Time mean	**1**	**-3**	**5**	**7**	**3**	**2**

	Station A		Station B	
	u*	v*	u*	v*
Day 1	-3	-4	3	4
Day 2	-1	-6	1	6
Time mean	**-2**	**-5**	**2**	**5**

	Station A		Station B	
	u’	v’	u’	v’
Day 1	-1	1	1	-1
Day 2	1	-1	-1	1
$\overline{u'v'}$	-1		-1	

大气环流概述－数据分析方法

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



大气环流概述－数据分析方法

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