第五章:

大气环流中的纬向环流系统

5.1 Storm Tracks
Non-zonal circulations
Outline

- Observed features
  - from two basic approaches
  - seasonal variation
  - inter-annual, decadal variations
- Storm track dynamics
  - Baroclinic eddy life cycle
  - Transient eddy energy budget
- Summary and discussion
Observed features

Two basic approaches to diagnosing storm tracks:

- The traditional one: track the position of individual weather systems, produce statistics for their distributions, e.g. track densities, storm life span...

- The bandpass filtering approach (in synoptic time scales): estimate the statistics at a set grid points in analyzed fields, which can provide a 3-d picture of storm tracks.
Observed features

Fig. 1. A figure from an 1888 geography text showing storm frequency distribution as viewed in the mid-nineteenth century. The stipling denotes high storm frequency, while the arrows indicate individual storms. Reproduced from Hinman (1888).
Observed features

Shaded: standard deviation of 24-h filtered 500-hPa geopotential height (contour interval 20 m) computed from the Januaries of 1982-1994 (NCEP/NCAR reanalysis)

Two storm track zones in N.H.

Two-dimensional

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 $Z^{1/2}$ exceeded 90 m in the ECMWF analyses for the same period.
Observed features

The storm zones occur in association with the jet streams;

The storm zones are most intense near the longitude of the jet exits.
Observed features

b) NCEP/NCAR storm tracks

Temperature distribution from NCEP/NCAR data

DJF mean at 500 hpa from 1980 to 2000

Temperature distribution from NCEP/NCAR data

DJF mean at 850 hpa from 1980 to 2000

Temperature distribution from NCEP/NCAR data

DJF mean at 500 hpa from 1980 to 2000
Observed features

Using ECMWF, MSLP, from Hoskins and Hodges, 2002
Observed features

\[ \sigma = kc_i \approx 0.3 \Lambda \frac{f_o}{N} \]

Eddy kinetic energy

Fig. 2. Left: the Eady growth rate, \( \sigma_{E} \), at 500 hPa in units of 1/day. Right: The average eddy kinetic energy at 250 hPa in units of \((m/s)^2\). Both are for the Northern Hemisphere winter (DJF), computed from the NCEP/NCAR re-analysis. The maxima in EKE are downstream of the maxima in growth rate, and the Pacific storm track does not fully decay before the beginning of the Atlantic storm track. The prime meridian (Greenwich) is at 6 O’clock.
Observed features

eddy momentum flux

eddy heat flux

Fig. 3. Left: the eddy momentum fluxes at 250 hPa (m/s)². Right: the eddy heat fluxes at 500 hPa (mK/s), for the Northern Hemisphere winter (DJF). Both sets of data are band-pass filtered, allowing variability from 2 to 10 days, from the NCEP/NCAR re-analysis. Red values are large, blue values weak or negative.

from Vallis and Gerber, 2008
Observed features

From Dai Ying, 2011
Observed features

From Dai Ying, 2011
Beyond the zonal average: Zonal variation

- Transient eddy transport of $vq$:

Strongest over the western coast of oceans in the midlatitudes of the Northern Hemisphere
Observed features
- Seasonal variation

Most intense in the transition seasons, MAM and SON, weaker in DJF (mid-winter minimum), whose variation is not consistent with the mean flow baroclinicity.

Strongest in DJF and least pronounced in JJA, with the actual position varies little.

Fig. 1. Midwinter suppression of the Pacific storm track, shown as the variance in geopotential height at 300 hPa: (a) Pacific domain (20°–70°N, 140°E–180°) and (b) Atlantic domain (20°–70°N, 30°–70°W). The contour interval is 1500 m² starting at 2000 m². This is an update of Fig. 2 in Nakamura (1992) for the ERA-40 dataset between 1958 and 2001. The data are 2–6 day bandpass filtered using a fourth-order Butterworth filter to obtain daily climatologies. Results are smoothed with a 31-day running mean filter and plotted every five days. Large tick marks on the abscissa correspond to the first day of each month.
Observed features
- Seasonal variation

Most intense in the transition seasons, MAM and SON, weaker in DJF (mid-winter minimum), whose variation is not consistent with the mean flow baroclinicity.

Mean flow baroclinic zone moves equatorward and becomes strongest in winter.
Ioannou and Lindzen (1986) found that the meridional extent of the jet stream is a reasonable first-order approximation to the meridional wavelength of storms. Based on these results, previous work concerning the midwinter suppression assumed that the meridional wavelength of storms in the Pacific storm track will be less in winter than it is in the shoulder seasons (Harnik and Chang 2004), an assumption that does not appear to be true in this region.

APPENDIX B

Comparing Eulerian Variance with Feature-Tracking Statistics

Our intention has been to understand how the midwinter suppression manifests in the individual disturbances that make up the Pacific storm track. However, it is also worth considering how the results from feature tracking compare with Eulerian variance at the same location.

To make a rough comparison we use the simple analogy of a traveling wave. Consider a single sine-shaped pulse with period $t = \frac{C}{2}$ traveling by a point (take $x = 50$ for simplicity) in the time interval $[0, T]$, where $t = C/2$:

$$Z = Z_0 \sin \left( \frac{2\pi}{C} x \right), \quad \text{for } t = \frac{C}{2}.$$  \(B1\)

The variance at this location owing to a single traveling pulse is

$$\left( \frac{Z}{2} \right)^2 = Z_0^2 \sin \left( \frac{2\pi}{C} x \right), \quad \text{for } t = \frac{C}{2}.$$  \(B2\)

where $c$ and $l$ are the velocity and wavelength of the traveling wave, respectively, $Z_0$ is its amplitude, and \(\int dt\) is the integral over the time of interest, $T$. In this framework, if the number of traveling sine-shaped pulses ($N$) doubles, then there is twice as much variance. Therefore, the total variance must scale linearly with the number of disturbances passing overhead. Noting that

$$\int dt \sin \left( \frac{2\pi}{C} x \right) = \frac{1}{2a},$$

we see that Eulerian variance is proportional to feature tracking in the following way:

$F \propto I.$

As in Fig. 3 but for relative vorticity at 300 hPa. Units in (a) and (c) are $10^{-5} \text{ s}^{-1}$.

Different seasonalities between the Pacific and Atlantic storm tracks.

from Penny et al, JC, 2010
Observed features
- Inter-annual variation

The Pacific storm track shifts equatorward and downstream during El Nino years, which is considered in response to the local enhancement of the Hadley Cell.

from Chang et al, JC, 2002
Observed features

- Decadal variation

Stronger storm tracks during 1990s in both storm tracks, which shows significant interdecadal variabilities.

from Chang et al, JC, 2002
Observed features

Summary:

- **Structure:** zonally located in the north Pacific and north 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.
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Storm track dynamics
- from the baroclinic eddy life cycle

- Eddies’ development with idealized GCM:

  - Small amplitude perturbations
  - Finite amplitude perturbations

  (Thorncroft et al, 1993, Q.J.R.)
Storm track dynamics
- from the baroclinic eddy life cycle

Baroclinic eddy life cycle in time:

Relatively small amplitude pert. → Baroclinic growth → Finite amplitude perturbation → Barotropic decay

Numerical results from Simmons and Hoskins, 1978, JAS

From Vallis (2006)
Storm track dynamics
Storm track dynamics

Numerical simulation from Orlanski
Storm track dynamics
- from the baroclinic eddy life cycle

Baroclinic eddy life cycle in time:

Relatively small amplitude pert. → Baroclinic growth → Finite amplitude perturbation → Barotropic decay

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

Upstream end: perturbations are introduced and begin develop. (entrance region)

develop in space and time

Downstream end: decay stage of the eddy life cycle. (exit region)
For storm tracks, define a **total transient eddy energy**:

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

\[
A' = A - \bar{A}, \text{ "}m\text{"} \text{ denotes mean quantities, } \alpha = 1/\rho
\]
Storm track dynamics
- Transient eddy energy budget

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

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

**Transient eddy energy budget**:

\[
\frac{\partial E}{\partial t} = \nabla \cdot (\mathbf{v} E + \mathbf{v}_a \phi') + \frac{\alpha_m}{\theta_m} \frac{\bar{v}'\theta'}{\partial \theta_s / \partial p} \cdot \nabla \theta - \mathbf{v}' \cdot (\mathbf{v}' \cdot \nabla) \mathbf{V}_m - \text{diss} + \text{diab}
\]

- **Advective energy flux**
- **Baroclinic generation**
- **Barotropic conversion**
- \( D(K_E) \)
- \( G(P_E) \)
Storm track dynamics
- Transient eddy energy budget

(a) Total eddy energy
(b) Eddy kinetic energy

from Chang et al, JC, 2002
Storm track dynamics
- Transient eddy energy budget

c) baroclinic conversion
d) barotropic conversion

Located upstream
Positive over the entrance region
negative over the exit region

from Chang et al, JC, 2002
Storm track dynamics
- Transient eddy energy budget

![Diagram](image)

- **e)** energy flux
- **f)** mechanical dissipation

energy sink

from Chang et al, JC, 2002
Storm track dynamics
- Transient eddy energy budget

e) energy flux

The role of energy flux: **redistribute** energy from the region where it is generated to downstream regions, **extending** storm track in the zonal direction.

Strongly compensate the baroclinic conversion term in the entrance region.

from Chang et al, JC, 2002
Storm track dynamics
- Transient eddy energy budget

Moist heating: strong along the storm tracks, with the maximum generation rate over the storm track entrance region. (large-scale condensation dominant)

Sensible heating: a strongly negative contribution along the continental east coasts.

Total effect: difference between Pacific and Atlantic region. In the mid and exit regions of Pacific storm track, latent heating dominant and enhancing the eddy energy; in the Atlantic region, sensible heating dominant.

from Chang et al, JC, 2002
Discussions

Though the structure of the storm tracks can be partially understood from the view of baroclinic energy cycle occurring in space, many questions are left:

- **Structure:** a (causal) relationship between the variability eddies and that of the background flow; the feedbacks between storm track anomalies and the slowly varying planetary-scale flow? e.g. what determines how far downstream of the region of the max baroclinicity the storm tracks extend? Whether the storm track properties can be solely determined by the mean flow? The group propagation of storms...

- **Seasonal variation:** the reason of mid-winter minimum?

- **Inter-annual variation:** the detailed mechanism of Pacific storm track shift between El nino and La nina years?

- **Decadal variation:** the reason for decadal variation and its relation to the global warming?

- **Simulations:** AGCM and storm track model

