ANOMALOUS EAST ASIAN WINTER MONSOON IN RELATION TO SYMBOLIC EURASIAN BLOCKING PATTERNS

CHEUNG HO NAM

MASTER OF PHILOSOPHY

CITY UNIVERSITY OF HONG KONG

AUGUST 2011

CITY UNIVERSITY OF HONG KONG
香港城市大學

Anomalous East Asian Winter Monsoon in Relation to Symbolic Eurasian Blocking Patterns
歐亞阻塞形勢與東亞冬季風之異常

Submitted to
School of Energy and Environment
能源及環境學院
in Partial Fulfillment of the Requirements
for the Degree of Master of Philosophy
哲學碩士學位

by

Cheung Ho Nam
張皓嵐

August 2011
二零一一年八月

Abstract

This study attempts to examine the anomalous state of the East Asian Winter Monsoon (EAWM) in relation to spatial and temporal features of atmospheric blocking over Eurasia at the upstream of the climatological Siberian high region. Atmospheric blocking is identified by geopotential height gradients (zonal indices) over the extratropics. Surface air temperature is used to assess the impact of blocking on the EAWM region. Generally, there are two spatially independent blocking patterns of an omega shape with the ridge centered over the Ural-Siberia region and the European continent respectively. The impact is significant if the downstream cyclonic vortex of the blocking system forms a dynamic contact with the Siberian high, which is more confined to the former case. On the whole, the impact can be viewed from the perspective of a single event and a whole season.

Establishment of a blocking high over Ural-Siberia involves interaction between the Siberian high and an upstream cyclone. Three temporal features of the blocking high are investigated: duration, intensity and extension. Firstly, the tropospheric warm-core structure is maintained by which the kinetic energy of the thermal ridge is converted to the potential energy of the blocking ridge. The warm ridge extending poleward induces cold advection to promote sustained development of the Siberian high. Secondly, the amplification of the blocking ridge is dependent on the amount of incoming anticyclonic vorticity advection. The advection can be determined by the zonal pressure gradient between the upstream cyclone and the Siberian high, which tightens when the cyclone is located right to the west of the Siberian high. However, this dynamic factor is not deterministic for the thermodynamic evo-

lution of the Siberian high. Thirdly, the extension may be related to the size of pre-existing cold anomalies over western Siberia. Intense cold air masses tend to tighten the pressure gradient and to amplify the upper-tropospheric trough aloft the upstream cyclone. The thermodynamic feedback from Siberia perhaps supports the blocking high to stay for longer time. Therefore, a long-lasting cold period may take place as a consequence of a long-lasting blocking event.

The blocking-EAWM relationship is close (weak) when outstanding blocking frequency is over Ural-Siberia (Europe). These upstream blocking activities may be regarded as a response to a combined signal of the Arctic Oscillation (AO) and El Niño/Southern Oscillation (ENSO). Weakened (strengthened) meridional flow in the positive (negative) phase of the AO is unfavorable (favorable) for blocking high formations. As the AO shows a close relationship with the North Atlantic Oscillation (NAO), the teleconnection between the AO and the Eurasian blocking activity may exist in the form of an eastward propagating wave-train signal generated over the North Atlantic Ocean. Be that as it may, the transmission of a signal across East Asia may be disturbed by the external effect of the ENSO, which probably suppresses (enhances) the sinking motion near Siberia in its positive (negative) phase. In short, the blocking-EAWM linkage is stronger (weaker) when the AO and ENSO are in phase (out of phase). If both the AO and ENSO attain their positive (negative) phase, the blocking frequency is distinctly low (high) over Ural-Siberia and uniform warming (cooling) would be observed in East Asia. Rather, if they are out of phase, the blocking signal would not be clear over Ural-Siberia and the monsoonal flow in northern (southern) East Asia would be stronger in negative AO (negative ENSO).

Table of Contents

List of Acronyms ix

List of Symbols x

List of Tables xi

List of Figures xii

Chapter 1. Introduction 1

1.1 Background 1

1.2 Objectives 4

1.3 Overview of chapters 5

Chapter 2. Literature Review 6

2.1 East Asian Winter Monsoon (EAWM) 7

2.1.1 Siberian high and winter monsoon surges 8

2.1.2 Implications from Pacific 10

2.1.3 Implications from Atlantic and Arctic 11

2.1.4 Temperature modes 12

2.1.5 Forecasting aspect 14

2.2 Atmospheric blocking 8

2.2.1 Formation and maintenance mechanisms 17

2.2.2 Declining trend of Atlantic blocking frequency 19

2.3 Downstream impact of blocking on East Asian winter climate 20

2.4 Research problems 22

Chapter 3. Data and standardization 23

3.1 Study period 23

3.2 Global datasets 23

3.3 Station data 24

3.4 Climate indices 25

3.4.1 El Niño/Southern Oscillation (ENSO) *25*
3.4.2 Arctic Oscillation (AO) *26*
3.4.3 North Atlantic Oscillation (NAO) *26*
3.5 Standardization of data 27

Chapter 4. Methodology 28
4.1 Collecting atmospheric blocking profile 29
4.1.1 Identifying blocking longitude *29*
4.1.2 Synthesizing blocking region *30*
4.1.3 Recording blocking event *31*
4.1.4 Validating the algorithm via climatology *36*
4.2 Delimiting blocking events over the Eurasian Continent 43
4.2.1 Choice for the domain of Eurasian Continent *43*
4.2.2 Selection for characteristics blocking event *44*
4.3 Extracting major atmospheric circulation patterns 46
4.4 Quantifying the strength of EAWM 47
4.5 Interpreting physical and dynamic mechanisms 51
4.5.1 Rate of change of local temperature *51*
4.5.2 Geopotential height tendency *51*
4.5.3 Omega velocity *52*
4.5.4 Wave activity flux (WAF) *52*

Chapter 5. Characteristics of blocking event 54
5.1 Major Eurasian blocking patterns 55
5.2 Characteristic blocking events 61
5.2.1 Basic framework *65*
5.2.2 Long-lived vs. short-lived *70*
5.2.3 Intense vs. weak *78*
5.2.4 Large vs. small *85*
5.3 Summary and discussion 93
5.3.1 Blocking high structure *93*
5.3.2 Downstream impact on cold surges in East Asia *95*
5.3.3 Discussion *96*

Chapter 6. Bonding with AO and ENSO 98
6.1 Wintertime Eurasian blocking signature 100

6.1.1 EOF1 mode *108*
6.1.2 EOF2 mode *109*
6.1.3 Blocking—EAWM relationship *111*
6.2 Combined effect of AO and ENSO 114
6.2.1 AO+ and ENSO+ *119*
6.2.2 AO+ and ENSO- *119*
6.2.3 AO- and ENSO+ *120*
6.2.4 AO- and ENSO- *121*
6.3 Summary and discussion 124

Chapter 7. Case study: Winter 1983/84 129
7.1 Early season versus late season 130
7.2 January 1984 134
7.2.1 Eurasian blocking event: 14–21 Jan *138*
7.2.2 Eurasian blocking event: 26–30 Jan *145*
7.3 Summary and discussion 151
7.3.1 Cold January and February *151*
7.3.2 Discussion *152*

Chapter 8. Conclusions 157
8.1 Summary 157
8.1.1 Symbolic Eurasian blocking patterns *158*
8.1.2 Characteristic blocking events and cold surges in East Asia *160*
8.1.3 Eurasian blocking and EAWM under combined effect of AO and ENSO *162*
8.2 Future works 164
8.3 Concluding Remarks 168

Bibliography 169

Appendix A. Central region for characteristic blocking events 184
A.1 Long-lived 185
A.2 Short-lived 185
A.3 Intense 186
A.4 Weak 186
A.5 Large 187
A.6 Small 187

Appendix B. Profile for characteristic blocking events 188
B.1 Long-lived 188
B.2 Short-lived 189
B.3 Intense 190
B.4 Weak 190
B.5 Large 191
B.6 Small 191

Appendix C. Blocking event calendar in January-March 1984 192

List of Acronyms

AO	Arctic Oscillation
AOI	Arctic Oscillation index
BI	Blocking intensity of a blocking region
BI_{max}	Maximum blocking intensity of a blocking event
BI_{mean}	Mean blocking intensity of a blocking event
CPC	Climate Prediction Center
DJF	December through February
EAWM	East Asian winter monsoon
EAWMI	East Asian winter monsoon index
ENSO	El Niño/Southern Oscillation
EOF (n)	(The n-th leading) Empirical orthogonal function
Ext	Extension of a blocking region
Ext_{max}	Maximum extension of a blocking event
Ext_{mean}	Mean extension of a blocking event
GHGN	Geopotential height gradient in the north
GHGS	Geopotential height gradient in the south
IPCC	Intergovernmental Panel on Climate Change
IPCC AR4	The fourth assessment report of IPCC
PC	Principal component
PCA	Principal component analysis
PC (n)	The (n-th) leading principal component
PDO	Pacific Decadal Oscillation
NAO	North Atlantic Oscillation
NCAR	National Center for Atmospheric Research
NCC	National Climate Center
NCEP	National Centers for Environmental Prediction
NDJFM	November through March
NOAA	National Oceanic and Atmospheric Administration
QG	Quasi-geostrophic
SLP	Sea level pressure
SST	Sea surface temperature
WAF	Wave activity density flux
B06	Barriopedro et al. (2006)
S96	Shi et al. (1996)

TM90	Tibaldi and Molteni (1990)
LC99	Lu and Chan (1999)
JL04	Jhun and Lee (2004)
Z07	Zhou et al. (2007)

List of Symbols

∇	Gradient operator
∇^2	Laplacian
$-\nabla_h.T$	Horizontal temperature advection
$-\nabla_p.T$	Vertical temperature advection due to adiabatic heating
ϕ	Latitude
ϕ_N	Northernmost latitude of a blocking region
ϕ_S	Southernmost longitude of a blocking region
η_g	Absolute geostrophic vorticity
λ	Longitude
λ_E	Easternmost longitude of a blocking region
λ_W	Westernmost longitude of a blocking region
λ_k	Explained variance of the k-th EOF
θ	Potential temperature
ρ	Density
ψ'	Perturbation stream-function
ζ	Relative vorticity
f_0	Planetary vorticity at 45^oN
c_p	Specific heat capacity under constant pressure
$q_{0.25}$	Lower quartile (25^{tb} percentile)
$q_{0.75}$	Upper quartile (75th percentile)
N^2	Static stability
R	Gas constant
T (p)	Temperature (at p-hPa isobaric level)
U (p)	Zonal wind (at p-hPa isobaric level)
U_g	Zonal component of geostrophic wind
V (p)	Meridional wind (at p-hPa isobaric level)
V_g	Meridional component of geostrophic wind
W (p)	Vertical velocity (omega) (at p-hPa isobaric level)
Z (p)	Geopotential height (at p-hPa isobaric level)

List of Tables

Table 3.1: Information about nine selected stations in China. 24

Table 4.1: Profile for the blocking regions over Asia−Pacific in 27–29 Mar 2008 34

Table 4.2: Annually and seasonally climatological mean and standard deviation of various characteristics of blocking events, where BI and Ext represent blocking index and extension respectively. The subscript mean and max in BI or Ext represents the mean and maximum value of that quantity. 39

Table 4.3: Statistics of lifespan, BI_{max} and Ext_{mean} for blocking events centered between 60° and 87.5^{o}E when they established. The terms $q_{0.25}$ and $q_{0.75}$ represent 25th and 75th percentile respectively. 45

Table 4.4: List of four East Asian Winter Monsoon Indices (EAWMIs). 47

Table 6.1: Correlation between the area-averaged blocking frequency over 30°−100°E in NDJFMs and four EAWMIs, where the bold values exceed 95% confidence level.102

Table 6.2: List of years with dominant mode of the positive and negative phase of EOF1 and EOF2.....105

Table 6.3. Correlation table among PC time series and climate indices, where the value(s) that exceeds 99% (95%) confidence level are bold (italic). 114

Table 6.4. Classification of the 60 winters from 1950 to 2009 into four groups based on the polarities of AO and ENSO.....115

List of Figures

Fig. 1.1: Topographic map of Eurasia and some important geographic names. 2

Fig. 2.1: The climatological mean of (a) SLP (unit: hPa), (b) Z500 (unit: m) and (c) U300 (unit: ms^{-1}) for the winters from 1950/51 to 2009/10 based on NCEP—NCAR Reanalysis datasets. 8

Fig. 2.2: Daily composite of Z500 showing two typical blocking patterns as illustrated in Fig. 1 of Barriopedro et al. (2006): (a) dipole block (22 Dec 1948) and (b) omega block (6 Mar 1948).....16

Fig. 3.1: Geographic location of 550 stations in China. The blue dots indicate the nine selected station (1−9) representing different areas in China and the information of these stations are listed in Table 3.1. 25

Fig. 4.1: Number of blocking events lasting at least a given number of days, but the numbers of events are now plotted on a log scale (to base *e*). The dashed lines show linear regressions for the short blocking event data (duration 1–3 days) and the midrange sector blocking episode data (duration 6–16 days). Only the midrange episode data is used to avoid the slightly more noisy tail end of the distribution. The corresponding timescale t_0 is indicated for each of these regressions. (adapted from Fig.10 in Pelly and Hoskin 2003) 33

Fig. 4.2: An example illustrates the blocking event detection algorithm. (i). Composite maps and (ii) GHGN and GHGS on (a) 27 Mar and (b) 29 Mar 2008. In (i), contour represents Z500 and shading represents standardized anomaly of T1000; the dotted area represents the blocking region which center is indicated by the white cross. 35

Fig. 4.3: Longitudinal distribution of annually and seasonally averaged relative blocking frequency over the Northern Hemisphere: the black solid line, black dash line, grey solid line, grey dotted line and blue solid line represent the value in whole-year, spring (MAM), summer (JJA), autumn (SON) and winter (DJF) respectively. 37

Fig. 4.4: Longitudinal frequency distribution of the center longitude of blocking events on annual and seasonal average. 38

Fig. 4.5: Longitudinal frequency distribution of the intensity of blocking events (BI) on annual and seasonal average. 41

Fig. 4.6: Longitudinal frequency distribution of the extension of blocking events (Ext) on annual and seasonal average. 41

Fig. 4.7: Longitudinal frequency distribution of genesis longitude (solid) and decaying longitude (dashed) of blocking events in four seasons: a) MAM, b) JJA, c) SON and d) DJF. 42

Fig. 4.8: Longitudinal frequency distribution of genesis longitude (solid) and decaying longitude (dashed) of blocking events born in NDJFM. 43

Fig. 4.9: Blocking index for the Northern Hemisphere mid-latitudes for January 2008. Values are computed on a daily basis and are given as relative frequencies versus longitude: percentage of block days per month (y axis) and longitude (x axis). Values for January 2008 (black line), NCEP mean value for January 1950−2007 (grey line) and 95th percentile for 1950−2007 (dashed line) (from Fig.4 in Zhou et al., 2009).....43

Fig. 4.10: Correlation map between the four EAWMIs and surface air temperature: (a) S96, (b) LC99, (c) JL04 and (d) Z07, where the dotted area represents the values exceed 95% confidence level. 49

Fig. 4.11: Standardized time-series of four EAWMIs: (a) S96, (b) LC99, (c) JL04 and (d) Z07, where the blue solid line represents the linear trend of each EAWMI.....50

Fig. 4.12: Low-pass-filtered Z250 anomalies (contoured every 100m; dashed line for negative), horizontal component of WAF (vector with unit m^2s^{-2}). Heavy and light stippling signifies the flux convergence and divergence, respectively, whose magnitudes are greater than $1.5x10^{-5}$ ms^{-2} (adapted from Fig.1 in Takaya and Nakamura, 2005b).....53

Fig. 5.1: The first four daily leading spatial Z500 patterns obtained from the EOF analysis: (a) EOF1, (b) EOF2, (c) EOF3 and (d) EOF4. 56

Fig. 5.2: Number of blocking days (black) and non-blocking days (grey) demonstrating dominance for a particular spatial pattern in EOF1, EOF2, EOF3, EOF4 or others (EOF5−10). 56

Fig. 5.3: Composite maps for the common circulation patterns over the Eurasian Continent: (a) EOF1+, (b) EOF 1-, (c) EOF2+ and (d) EOF2-, where contour and shading represent Z500 (unit: m) and standardized anomaly of T1000 respectively... 57

Fig. 5.4: Composite maps for the common blocking patterns over the Eurasian Continent: a) EOF1+, b) EOF2+ and c) EOF2-, where contour and shading represent Z500 (unit: m) and standardized anomaly of T1000 respectively. 57

Fig. 5.5: Cumulative frequency distributions of Eurasian blocking patterns against the center of blocking events over the Eurasian Continent. 58

Fig. 5.6: Lag composites of Z500 (contour) and standardized anomaly of T1000 (shading) for the blocking events born in 30°−57.5^{o}E (left panel) and 60°−87.5^{o}E (right panel). 62

Fig. 5.7: Composite maps for the onset day of characteristic blocking events centered between 60° and 87.5^{o}E when they established: (a) long-lived, (b) short-lived, (c) intense, (d) weak, (e) large and (f) small, where the number of cases is indicated at the top right hand corner of each sub-plot. 63

Fig. 5.8: Composite maps of (i) Z200/T200, (ii) Z500/T500 and (iii) SLP/T1000 on (a) day -2, (b) day 0, (c) day 2 and (d) day 4 with respect to the establishment day of all blocking highs born in 60°−87.5^{o}E. The contour level for the red contour (T) is indicated at the bottom left and that for the black contour (Z or SLP) is indicated at the bottom right. 68

Fig. 5.9: Lag composites of Z500 (contour), standardized anomaly of T1000 (shading) and WAF300 (vector) on day -4, 2, 0, 3, 6 and 9 with respect to the establishment of the long-lived (left panel) and short-lived (right panel) blocking events born in 60°−87.5^{o}E. 70

Fig. 5.10: Vertical profile of (upper panel) dZ/dt (contour) and standardized anomaly of Z (shading) for (a) the long-lived group and (b) short-lived group; (lower panel) $f_0\nabla h \cdot V_{g\eta g}$ for (c) the long-lived group and (d) short-lived group. Units: m day^{-1} for

dZ/dt and $f_0\nabla h \cdot V_{g\eta g}$ and dimensionless for standardized anomaly of Z. 75

Fig. 5.11: Vertical profile of (upper panel) $\partial T/dt$ (contour) and standardized anomaly of T (shading) for (a) the long-lived group and (b) short-lived group; (middle panel) $-\nabla h \cdot T$ for (c) the long-lived group and (d) short-lived group; (lower panel) $-\nabla p \cdot T$ for (e) the long-lived group and (f) short-lived group. Units: dimensionless for standardized anomaly of T and K day^{-1} for other terms.....76

Fig. 5.12: Composite maps of (a)-(b) Z200/T200, (c)-(d) Z500/T500 and (e)-(f) SLP/T1000 on day 2 with respect to the onset day for which long-lived (left) and short-lived (right) blocking highs born in 60°–87.5^oE. The number of events extracted for long-lived and short-lived cases are listed at the top left hand corner in (a) and (b) respectively.....77

Fig. 5.13: Lag composites of Z500 (contour), standardized anomaly of T1000 (shading) and WAF300 (vector) on day -4, -2, 0, 3, 6 and 9 with respect to the establishment of the intense (left panel) and weak (right panel) blocking events born in 60°–87.5^oE. 78

Fig. 5.14: Vertical profile of (upper panel) dZ/dt (contour) and standardized anomaly of Z (shading) for (a) the intense group and (b) weak group; (lower panel) $f_0\nabla h \cdot V_{g\eta g}$ for (c) the intense group and (d) weak group. 82

Fig. 5.15: Vertical profile of (upper panel) $\partial T/dt$ (contour) and standardized anomaly of T (shading) for (a) the intense group and (b) weak group; (middle panel) $-\nabla h \cdot T$ for (c) the intense group and (d) weak group; (lower panel) $-\nabla p \cdot T$ for (e) the intense group and (f) weak group. Units: dimensionless for standardized anomaly of T and K day^{-1} for other terms. 83

Fig. 5.16: Composite maps of (a)-(b) Z200/T200, (c)-(d) Z500/T500, (e)-(f) SLP/T1000 on day -2 with respect to the onset day for which intense (left) and weak (right) blocking highs born in 60°–87.5^oE. The number of events extracted for intense and weak cases are listed at the top left hand corner in (a) and (b) respectively. 84

Fig. 5.17: Lag composites of Z500 (contour), standardized anomaly of T1000 (shading) and WAF300 (vector) on day -4, -2, 0, 3, 6 and 9 with respect to the establishment of the large (left panel) and small (right panel) blocking events born in 60°–87.5^oE. 85

Fig. 5.18: Vertical profile of (upper panel) dZ/dt (contour) and geopotential height anomaly (shading) for (a) the large group and (b) small group; (lower panel) $f0\nabla h \cdot V_{g\eta g}$ for (c) the large group and (d) small group. 89

Fig. 5.19: Vertical profile of (upper panel) $\partial T/dt$ (contour) and standardized anomaly of T (shading) for (a) the large group and (b) small group; (middle panel) $-\nabla h \cdot T$ for (c) the large group and (d) small group; (lower panel) $-\nabla p \cdot T$ for (e) the large group and (f) small group. Units: dimensionless for standardized anomaly of T and K day^{-1} for other terms. 90

Fig. 5.20: Composite maps of (a)-(b) Z200/T200, (c)-(d) Z500/T500 and (e)-(f) SLP/T1000 on day -2 with respect to the onset day for which large (left) and small (right) blocking highs born in $60^{o}-87.5^{o}$E. The number of events extracted for large and small cases are listed at the top left hand corner in (a) and (b) respectively. 91

Fig. 5.21: Composite maps of (a)-(b) Z200/T200, (c)-(d) Z500/T500 and (e)-(f) SLP/T1000 on day 0 (the onset day) for which large (left) and small (right) blocking highs born in $60^{o}-87.5^{o}$E. The number of events extracted for large and small cases are listed at the top left hand corner in (a) and (b) respectively. 92

Fig. 5.22: Lag composites of Z500 (contour) and standardized anomaly of T1000 (shading) for the long-lived blocking events born in $30^{o}-57.5$E 97

Fig. 6.1: Interannual time-series of area-averaged blocking frequency in $30^{o}—100^{o}$E during NDJFM. 100

Fig. 6.2: Correlation map between area-averaged blocking frequency over $30^{o}-100^{o}$E and (a) surface air temperature, (b) SLP, (c) U300 and (d) V1000 from 1950 to 2009, where the dotted area represents the linear correlation coefficients exceeding the 95% confidence level. 101

Fig. 6.3: Correlation map between area-averaged blocking frequency over $30^{o}-100^{o}$E and (a) T1000, (b) SLP, (c) U300, and (d) V1000 for the period from 1950 to 1979, where the dotted area represents the linear correlation coefficients exceeding the 95% confidence level. 103

Fig. 6.4: Same as Fig. 6.3, but the period for the period from 1980 to 2009 only. 103

Fig. 6.5 The first four seasonal leading spatial patterns of Z500 from Empirical Orthogonal Function (EOF) analysis: (a) EOF1, (b) EOF2, (c) EOF3 and (d) EOF4. The explained variance of each EOF is shown at the top right hand side of each plot.104

Fig. 6.6: Composite maps for the standardized anomaly of T1000 (shading) and Z500 (contour) in NDJFM that is made up of the years demonstrating dominance in (a) positive EOF1 mode, (b) negative EOF1 mode, (c) positive EOF2 mode and (d) negative EOF2 mode. Contour interval: 0.4 (dimensionless).....106

Fig. 6.7: Longitudinal distribution of the departure of number of blocking days from 1950−2009 climatological mean for the winters demonstrating dominance in the first two leading EOFs. 107

Fig. 6.8: Distribution of the four EAWMIs. (a) EOF1+, (b) EOF1-, (c) EOF2+ and (d) EOF2-. 107

Fig. 6.9: Interannual variation of the standardized time series of (a) PC1 or (b) PC2 (black), AO index (blue) and NAO index (green) from Year 1950−2009, where the linear correlation coefficient between AO/NAO and PC1 or PC2 is shown at the top left hand side. 112

Fig. 6.10: 31-year moving correlation between AO and PC1 time-series (black solid)/PC2 time-series (grey solid), where the black dotted line represents the 95% confidence level. 113

Fig. 6.11: Composite maps for the standardized anomaly of T1000 (shading) and Z500 (contour) in NDJFM for the years in (a) AO+ and ENSO+, (b) AO+ and ENSO-, (c) AO- and ENSO+ and (d) AO- and ENSO-. Contour levels: 0.3 dimensionless) .116

Fig. 6.12: Anomalous blocking days in NDJFM for AO+ and ENSO+ (red), AO+ and ENSO- (orange), AO- and ENSO+ (green) and AO- and ENSO- (purple). Unit: days.117

Fig. 6.13: Distribution of the four EAWMIs. (a) AO+ and ENSO+, (b) AO+ and ENSO-, (c) AO- and ENSO+ and (d) AO- and ENSO-. 117

Fig. 6.14: Ratio of the two polarities of the first two leading EOF modes under different phases of AO and ENSO: (a) AO+ and ENSO+, (b) AO+ and ENSO-, (c) AO- and ENSO+ and (d) AO- and ENSO-. 118

Fig. 6.15. Composite maps for the standardized anomaly of U300 (shading) and 500-hPa wind field (vector) in NDJFM for the years in (a) AO+ and ENSO+, (b) AO+ and ENSO-, (c) AO- and ENSO+ and (d) AO- and ENSO-.....123

Fig. 6.16. Composite maps for the standardized anomaly of 300-hPa vertical velocity (shading) and 1000-hPa wind field (vector) in NDJFM for the years in (a) AO+ and ENSO+, (b) AO+ and ENSO-, (c) AO- and ENSO+ and (d) AO- and ENSO-. 123

Fig. 6.17: Schematic diagram for the strength of EAWM under different phases of AO and ENSO. 124

Fig. 7.1: Time-longitude plot showing the blocking region over the Northern Hemisphere (top) and day-to-day variation of the two leading principal components (PC1 and 2) of Z500 (down) in winter 1983/84.....130

Fig. 7.2: Longitudinal distribution of anomalous blocking frequency in winter 1983/84: whole season (black), early season (red) and late season (blue).....131

Fig. 7.3: Standardized anomalies of Z500 (contour) and T1000 over the Northern Hemisphere in winter 1983/84. Contour interval: 0.4 (dimensionless). 131

Fig. 7.4: Temperature anomaly of 549 stations in China in early and late winter of 1983/84 with respect to 1971−2000 climatology, (a) early season: 15 Nov−14 Jan and (b) late season: 15 Jan−14 Mar (unit: ^{o}C). 133

Fig. 7.5: Hovmöller diagram along 50°−70°N at 250-hPa, where contour represents: (a) standardized geopotential height anomaly and (b) vorticity advection. Unit for dZ/dt: m day^{-1}; unit for advection terms: day^{-3}. 135

Fig. 7.6: Hovmöller diagram along 50°−70N at 500 hPa: (a) standardized temperature anomaly, (b) $-\nabla h \cdot T$ and (c) $-\nabla p \cdot T$. Unit for advection terms: K day^{-1}. 136

Fig. 7.7: Daily mean temperature in nine selected cities located at different parts of China during January and February in winter 1983/84 (thick solid line), where the black thin line represents the 1971−2000 climatological mean and 1.5 standard deviation (S.D.) above and below the mean is represented by the red and blue thin lines respectively. 137

Fig. 7.8: Composites for different stages of the Eurasian blocking event on 14−21 Jan 1984: (a) 8 Jan, (b) 10 Jan, (c) 12 Jan, (d) 14 Jan (the day it formed), (e) 21 Jan (the day it decayed) and (f) life-time averaged, where shading indicates standardized anomaly of T1000, contour represents Z500 with a contour interval of 80m and vector represents WAF300. 138

Fig. 7.9: Vertical profile of (a) dZ/dt (contour) and standardized anomaly of Z (shading) and (b) $f0\nabla h \cdot V g\eta g$ of the event in 14−21 Jan 1984.....141

Fig. 7.10: Vertical cross section of the thermal structure and diagnostics of terms along the blocking high center of the event in 14−21 Jan 1984. Contour in (a): $\partial T/dt$; shading: (a): standardized anomaly of T, (b): $-\nabla h \cdot T$, (c): $-\nabla p \cdot T$. Units: K day^{-1}...142

Fig. 7.11: Composite maps of (a)-(b) Z200/T200, (c)-(d) Z500/T500, (e)-(f) SLP/T1000 on 14 Jan and 16 Jan 1984. The contour level for the red contour (T) is indicated at the bottom left and that for the black contour (Z or SLP) is indicated at the bottom right. 143

Fig. 7.12: Composite maps of (a)-(b) Z200/T200, (c)-(d) Z500/T500, (e)-(f) SLP/T1000 on 18 Jan and 20 Jan 1984. The contour level for the red contour (T) is indicated at the bottom left and that for the black contour (Z or SLP) is indicated at the bottom right. 144

Fig. 7.13: Composites for different stages of the Eurasian blocking event on 26−30 Jan 1984: (a) 20 Jan, (b) 22 Jan, (c) 24 Jan, (d) 26 Jan (the day it formed), (e) 30 Jan (the day it decayed) and (f) life-time averaged, where shading indicates standardized anomaly of T1000, contour represents Z500 with a contour interval of 80 m and vector represents WAF300. 145

Fig. 7.14: Vertical profile of (a) dZ/dt (contour) and standardized anomaly of Z (shading) and (b) $f0\nabla h \cdot V g\eta g$ of the event in 26−30 Jan 1984.....148

Fig. 7.15: Vertical cross section of the thermal structure and diagnostics of terms along the center of the blocking event in 26−30 Jan 1984. Contour in (a): $\partial T/dt$; shading: (a): standardized anomaly of T, (b): $-\nabla h \cdot T$, (c): $-\nabla p \cdot T$. Units: K day^{-1}...149

Fig. 7.16: Composite maps of (a)-(b) Z200/T200, (c)-(d) Z500/T500, (e)-(f) SLP/T1000 on 24 Jan and 26 Jan 1984. 150

Fig. 7.17: (a)-(c) Local wavelet power spectrum of standardized anomaly of Z500 (unit^2) in (a) R1: 50°−70°N, 30°−50°E, (b) R2: 50°−70°N, 50°−70°E and (c) R3: 50°−70°N, 70°−90°E; (d) cross wave power spectrum between the standardized anomaly of Z500 of R1 (50°−70°N, 30°−50°E) and R3 (50°−70°N 70 ^{o}−90°E). Analysis period: 1 Oct 1983 to 30 Apr 1984. The dotted area in (a)-(d) represents the amplitude of power exceeds 95% confidence level, whereas the vector in (d) indicates the phase relationship between the two time series only if they show significant power. 155

Fig. 7.18: (a). Hovmöller plot averaged over 50°−70°N; height−time plot averaged over (b) 50°−70°N, 30°−50°E and (c) 50°−70°N 70 ^{o}−90°E of standardized anomaly of Z500 (shading) and 15−25 days band-pass filtered Z500 (contour) in winter 1983/84. 156

Fig. 8.1: (a) Daily composite of T1000 (shading) and Z500 (contour) on 21 Dec 2004 and (b) local wavelet power spectrum of standardized anomaly of Z500 (unit^2) over 60°−80 ^{o}N, 80 ^{o}−100°E from 1 Nov 2004 to 31 Mar 2005, where the dotted area represents the variance exceeds the 95% confidence level. Contour level for (a): 80 m. 166