Vertical structure of predictability and information transport over the Northern Hemisphere*

Feng Ai-Xia(冯爱霞)[a)†], Wang Qi-Gang(王启光)[b)], Gong Zhi-Qiang(龚志强)[c)], and Feng Guo-Lin(封国林)[c)]

[a)] *Data Service Office, National Meteorological Information Center, China Meteorological Administration, Beijing* 100081, *China*
[b)] *China Meteorological Administration Training Center, China Meteorological Administration, Beijing* 100081, *China*
[c)] *Laboratory for Climate Studies, National Climate Center, China Meteorological Administration, Beijing* 100081, *China*

(Received 16 April 2013; revised manuscript received 23 July 2013; published online 20 December 2013)

Based on nonlinear prediction and information theory, vertical heterogeneity of predictability and information loss rate in geopotential height field are obtained over the Northern Hemisphere. On a seasonal-to-interannual time scale, the predictability is low in the lower troposphere and high in the mid-upper troposphere. However, within mid-upper troposphere over the subtropics ocean area, there is a relatively poor predictability. These conclusions also fit the seasonal time scale. Moving to the interannual time scale, the predictability becomes high in the lower troposphere and low in the mid-upper troposphere, contrary to the former case. On the whole the interannual trend is more predictable than the seasonal trend. The average information loss rate is low over the mid-east Pacific, west of North America, Atlantic and Eurasia, and the atmosphere over other places has a relatively high information loss rate on all-time scales. Two channels are found steadily over the Pacific Ocean and Atlantic Ocean in subtropics. There are also unstable channels. The four-season influence on predictability and information communication are studied. The predictability is low, no matter which season data are removed and each season plays an important role in the existence of the channels, except for the winter. The predictability and teleconnections are paramount issues in atmospheric science, and the teleconnections may be established by communication channels. So, this work is interesting since it reveals the vertical structure of predictability distribution, channel locations, and the contributions of different time scales to them and their variations under different seasons.

Keywords: geopotential height field, information theory, information loss rate, predictability

PACS: 92.60.Wc **DOI:** 10.1088/1674-1056/23/2/029202

1. Introduction

Forecasting is one of the central problems in atmospheric research, considering how the future can be predicted.[1,2] Three general approaches have been exploited to solve the problem, which are: the dynamical method, the empirical method, and the dynamical–empirical method. Empirical approach is based on the natural occurrence of analogues; that is, similar weather situation in meteorology. Farmer and Sidorowich[3] presented a nonlinear model on observed data to predict the chaotic time series. Sugihara and May[4] simplified and improved the method for making short-term predictions of chaotic dynamical system. Tsonis and Elsner[5] used the model to distinguish between the chaos sequence and the random fractal sequence. Elsner and Tsonis[6] studied the climate predictability in 500 hPa by using the approach. All of the above studies have proved that the model is effective to make predictions of time series from artificial and experimental systems to the natural world.

Teleconnections have attracted a lot of interest from scholars and researchers in atmospheric sciences, including observational studies,[7–10] and further theoretical/modeling studies.[11–13] These studies have revealed the interactions between the tropics and high latitudes, and the mechanisms through which the teleconnections might be established. Factors leading to teleconnections are also studied, such as El Nino. Using a new tool called complex networks to study the atmospheric phenomenon — El Nino has revealed that the communication between the tropical region and extratropical region is less and is unstable during the El Nino years.[14,15] By using the complex networks, the different dynamical mechanisms in the tropics and high latitudes were found.[16] So, there exists an interaction between tropics and high latitudes. The remaining work is how to depict aspects of the communication during the interaction and provide the exact locations where physical entities are exchanged between them. Tsonis and Elsner[5] have made a great step on the problems by studying the communication transmission at 500 hPa. Information communication of intra-seasonal and inter-annual oscillation signals and information transfer of Walker circulation were also studied.[17,18] But more work should be done to understand the vertical condition and influences of different time scales and four seasons.

We will focus on describing the heterogeneity of predictability between different pressure levels by using the non-

*Project supported by the National Key Basic Research and Development Program, China (Grant Nos. 2012CB955902 and 2013CB430204) and the National Natural Science Foundation of China (Grant Nos. 41305059, 41305100, 41275096 and 41105070).

†Corresponding author. E-mail: fax20032008@163.com

© 2014 Chinese Physical Society and IOP Publishing Ltd

linear method introduced above, and depicting the communication condition by the rate of information loss based on information theory, in order to identify channels at different pressure levels during the interaction between the tropics and the extratropical. The influence of different time scales and four seasons on the predictability and channels are also studied. The rest of the present paper is organized as follows. The data and method are introduced in Section 2. In Section 3, vertical distribution of predictability and information communication, the influences of different time scales and four seasons on predictability and information communication are shown. The conclusion is given in the last section.

2. Data and method

The data used are from the NCEP/NCAR reanalysis of monthly-averaged geopotential height. The pressure levels of 100 hPa, 150 hPa, 200 hPa, 250 hPa, 300 hPa, 400 hPa, 500 hPa, 600 hPa, 700 hPa, 850 hPa, 925 hPa, and 1000 hPa are chosen to be studied. At each level the data cover 1080 grid points over the Northern Hemisphere between 20° N and the North Pole with a latitude–longitude resolution of 5×5 degrees. The data period is from January 1966 to December 2012. The seasonal and interannual signal are obtained by 1 to 2 month second order Butterworth Band-Pass filter and low pass filter, choosing a year as the boundary.[19] For the study of four-season influences, the data of spring (MAM), summer (JJA), autumn (SON), and winter (DJF) are removed to obtain the corresponding season effect for enough data size, which is similar to the method used by Zhi and Gong did.[20]

The nonlinear prediction model is applied to the above processed data. At each level for a grid point i, the first 480 (360 for four-season influence tested) values are chosen as the training set, the remaining values as the target set. For the training set, an appropriate embedding dimension (n) and time delay (τ) are chosen, and the corresponding points in phase space are produced. The vector of the time series is

$$\begin{aligned} X_i(t) &= \{x_i(t), x_i(t+\tau), \ldots, x_i(t+(n-1)\tau)\} \\ & t = 1, 2, \ldots, 564-(n-1)\tau, i = 1, 2, \ldots, 1080. \end{aligned} \quad (1)$$

Here, embedding dimension is $n = 5$ and time delay is $\tau = 2$ the same as the values in Tsonis and Elsner's paper.[5] The target set is used for prediction. In each prediction, the maximum leading time is 12 steps (i.e. a year). For the same leading time, the correlation coefficients are calculated between predicted and observed values with Pearson correlation coefficient, and the average of all the coefficients is taken in order to be viewed as the grid point predictability. Thus, the 1080 grid point predictability at different pressure levels is obtained.

Wales[21] demonstrated that the Kolmogorov entropy (K) was related to the initial decay of Pearson correlation coefficient (r) and the relationship first presented by Tsonis and Elsner;[5] that is,

$$r(t) = 1 - C\mathrm{e}^{2Kt}. \quad (2)$$

Based on the information theory, the first derivative of information content (i.e. the mean loss of information per unit time) is equal to the negative of Kolmogorov entropy, namely

$$\begin{aligned} K &\equiv \lim_{T\to 0}\lim_{l\to 0}\lim_{m\to\infty} \frac{1}{mT}\sum_{j=0}^{m-1}(k_{j+1}-k_j) \\ &= -\lim_{T\to 0}\lim_{l\to 0}\lim_{m\to\infty} \frac{1}{mT}\sum_{t_0\ldots t_m}^{p_{t_0\ldots t_m}\ln} p_{t_0\ldots t_m}, \end{aligned}$$

where $p_{t_0\ldots t_m}$ is the joint probability, when phase space is divided into D-dimensional hypercubes of content l^D and a trajectory in hypercube is denoted as i_0 at $t = 0$, i_1 at $t = T$, i_2 at $t = 2T$, etc. So

$$r(t) = 1 - C\mathrm{e}^{2Kt} = 1 - C\mathrm{e}^{-2\dot{I}t}, \quad (3)$$

where C is a positive constant. For a period time t, the mean value of Pearson's correlation coefficient is

$$\langle r\rangle = \frac{1}{t}\int_t (1 - C\mathrm{e}^{-2\dot{I}t})\mathrm{d}t. \quad (4)$$

The angular brackets represent taking average of r. So, the mean coefficient is related to the information loss rate via a function of f (i.e. $\langle r\rangle = f(\dot{I})$). For a given longitude, the derivative of Eq. (4) with respect to latitude is

$$\frac{\mathrm{d}\langle r\rangle}{\mathrm{d}\lambda} = \frac{\mathrm{d}f(\dot{I})}{\mathrm{d}\lambda} = \frac{\mathrm{d}f(\dot{I})}{\mathrm{d}\dot{I}}\frac{\mathrm{d}\dot{I}}{\mathrm{d}\lambda}. \quad (5)$$

It is shown that the north–south gradient of $\langle r\rangle$ is proportional to the north–south gradient of information loss rate. Here, the information about these atmospheric phenomena can be exchanged between the tropics and mid-high latitudes, such as El Nino, the 40–50 day oscillation, and so on. If the north–south gradient of $\langle r\rangle$ is small, it means that the rate of information loss along the latitude is slow and the information can flow easily along the longitude. Otherwise, the rate of information loss is fast and the information cannot transport easily between the tropics and mid-high latitudes.

3. Results

Using the above data and method, we study the predictability and communication of the atmosphere, as well as their variations induced by different time scales and four seasons over the Northern Hemisphere.

3.1. Vertical characteristics of predictability and information communication

The vertical profile of seasonal to interannual predictability is shown in Fig. 1. Setting 30° N to be the boundary between the tropics and mid-high latitudes, a profile is also drawn (Fig. 2). All results have been smoothed using a nine-point uniform filter. The Pearson correlation coefficient is of the linear correlation between observed and predicted values, ranging from 0 to 1. If the correlation is close to 1, it means these areas are more predictable, otherwise the place is less predictable. So, from Fig. 1, we can find that on the whole the predictability grows as altitude increases, that is to say, the lower pressure levels (1000 hPa to 700 hPa) have poor predictabilities with Pearson correlation coefficients ranging from 0.4 to 0.7, and the high pressure levels (600 hPa–100 hPa) have better predictabilities in a range from 0.7 to 0.8. This fact is easy to be explained: it happens because the lower levels are affected by rather complex surface and strong convection, making the cycle signal not obvious. Therefore they are harder to predict and the outcomes are not desirable. While the high levels are relatively stable and predicted easily. Figure 2 is similar to Fig. 1 except for four regions marked by rectangles with black lines. In rectangles 1 and 2 there are poor predictability compared with in other regions along the same altitude. The two regions spans just from about 120° W to 150° E and 20° W to 80° W, respectively. This can contribute to the strength of the annual cycle, as suggested by Tsonis and Elsner,[5] and Elsner and Tsonis. The atmosphere over large ocean regions is not sensitive to the seasonal cycle because sensible heat from water can modulate tropospheric temperature and cause it to be rather steady. The hot Gulf Stream can also make the tropospheric temperature in the region 2 steady, so the region is not sensitive to the seasonal cycle. So the poor predicatability is obviously observed in the regions over the oceans compared with those over continent. As for the area of rectangle 3, it has a high predictability than in other regions along the same altitude. The outcomes may be not credible because a lot of geopotential heights in 1000 hPa are minus because of high terrain of Tibet Plateau (74° E to 104° E, 25° N to 40° N) located in the region. The area of rectangle 4 is just above Tibet Plateau, and has a poor prediction, which may contribute to the complex surface of the plateau. The vertical predictability of other latitudes is similar to the average value. The vertical predictability of boundary (linking the tropics with mid-high latitudes) is different from the average value, as shown in Fig. 2, which indicates the particularity of the boundary.

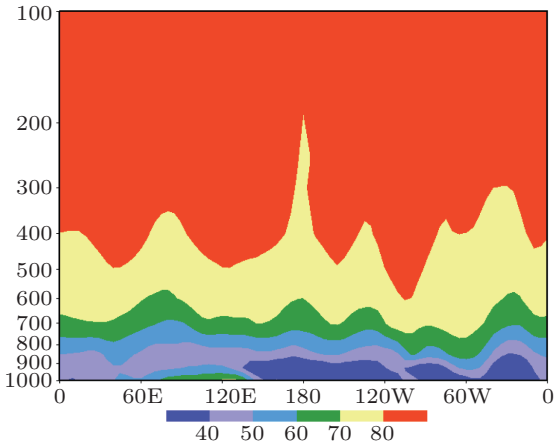


Fig. 1. (color online) Pearson correlation coefficient (×100) distribution from 1000 hPa to 100 hPa, which is averaged between 20° N and the North Pole for each pressure level. In the figure, 60E is the abbreviation for 60° E.

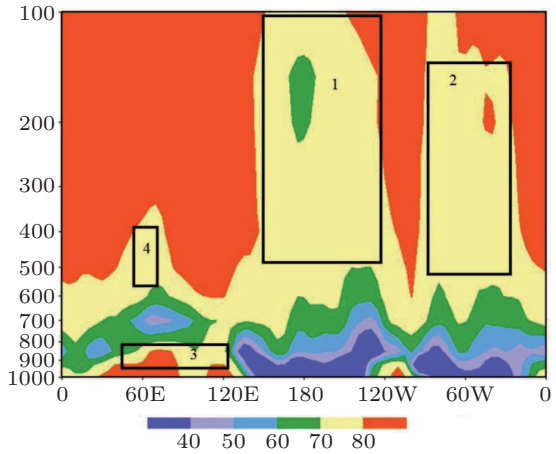


Fig. 2. (color online) Pearson correlation coefficient (×100) distribution along 30° N from 1000 hPa to 100 hPa.

In Fig. 3 we display the average rate of the information loss per distance along longitudes according to Eq. (5), in which $\mathrm{d}\dot{I}/\mathrm{d}\lambda$ is proportional to $\mathrm{d}\langle r\rangle/\mathrm{d}\lambda$ (for $\mathrm{d}f(\dot{I})/\mathrm{d}\dot{I} > 0$). If $\mathrm{d}\langle r\rangle/\mathrm{d}\lambda$ is close to zero, then the information is not easy to lose. Therefore, the information can easily flow along longitudes from tropics to mid-high latitude or in the opposite direction. If the absolute value of $\mathrm{d}\langle r\rangle/\mathrm{d}\lambda$ is much greater than zero, then the information loses quickly. So, the information does not flow easily along longitudes. The areas covered by the values ranging from -2 to 2 (with low information loss rate) are the regions where the information can be easily transported between the tropics and the extratropical. A narrow one is located in the mid-upper troposphere (from about 600 hPa to 100 hPa) over the mid-east Pacific and west part of North America (about $-160°$ to $-100°$; that is, 100° W to 160° W). Another wide region is over the Atlantic and Eurasia, with different altitude ranges in different longitude ranges. (The longitude range is from about 60° W to 60° E and the altitude range is from about 500 hPa to 100 hPa, while the longitude range is from about 60° E to 120° E and the altitude range is

from about 300 hPa to 100 hPa.) The remaining areas covered by the values greater than 2 or less than −2 are those regions where information cannot be easily transported. Tsonis and Elsner[5] pointed out two communication corridors laid over the Pacific Ocean and Atlantic Ocean at 500 hPa in the subtropics. So, the profile of information loss rate in subtropics is also drawn to identify channels, and the result is illustrated in Fig. 4. The narrow channel over the Pacific exists from about 500 hPa to 100 hPa but the center moves from about 160° W to 130° W. The center of the wider area over Atlantic moves from about 20° W to 15° W. A new narrow channel is found from about 500 hPa to 100 hPa centered at 60° E. The channels and their locations are of importance because they provide the exact locations at different levels where information exchanges between the low and the mid-high latitudes and through which they interact with each other to affect the global weather and climate.

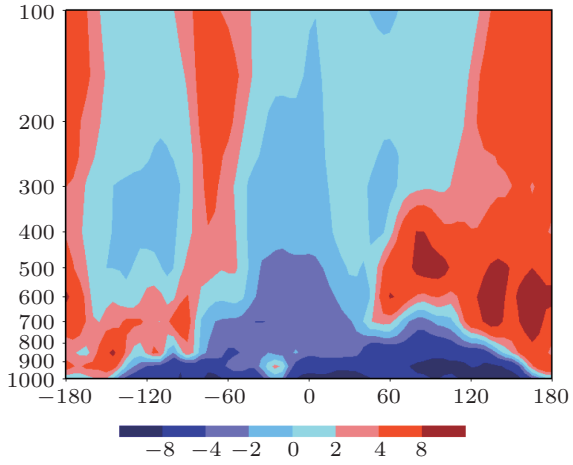


Fig. 3. (color online) North–south gradient of Pearson correlation coefficient (×100) in each level and the same latitude average as in Fig. 1. The regions covered by the values ranging from −2 to 2 are the locations where information flows easily, and the other regions are the locations where information does not flow easily. In order to put the regions of low information loss rate together, the abscissa is not the same as those in Figs. 1 and 2, negatives represent west longitudes and positives refer to east longitudes.

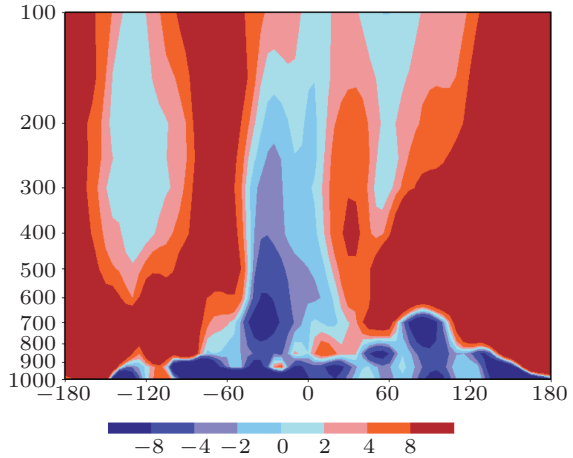


Fig. 4. (color online) The same as Fig. 3 but averaged between 20° N and 30° N. The regions covered by the values ranging from −2 to 2 are the channels where most information exchanges between tropics and extratropical region at different levels.

3.2. Predictability and channels on seasonal and interannual time scales

In order to know the predictabilities on different time scales as well as their roles in exchanging between tropics and extratropical region, the original data are filtered into seasonal and interannual components with the multi-stage filter.[19] The predictabilities of the two components are shown in Figs. 5(a) and 5(b), respectively. Each of the predictabilities has a strong relationship with altitude, but the seasonal predictability grows with the increasing of altitude but the interannual predictability is just opposite. Meanwhile, the interannual predictability is better (in a range from 0.89 to 0.92) than the seasonal one (from 0.4 to 0.8). This means that the interannual trend is more

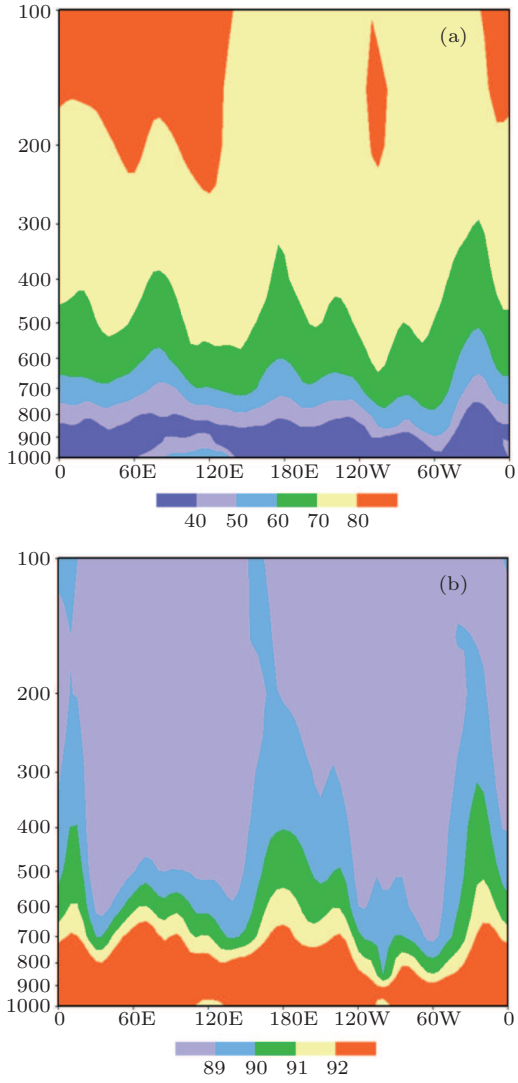


Fig. 5. (color online) The same as Fig.1 but on seasonal (a) and interannual (b) time scale: the predictability of interannual signal is better than that of seasonal signal, and predictability of the former decreases with altitude increasing but the latter is opposite.

predictable than the seasonal trend. The pattern of seasonal predictability is similar to that of the seasonal-to-interannual time scale, indicating that the seasonal cycle plays a great role in climate system.

Figure 6 displays the numbers and the locations of channels at different levels of the subtropics on the two time scales. Both of the two time scales contribute a lot to the tropics and high latidude exchange because the two channels over Pacific Ocean and Atlantic Ocean steadily exist on the two time scales except for the changes in altitude range and width (comparison can be seen from Table 1). So, the exchange between tropical time scale and extratropical time scale happens from seasonal to interannual time scale. From our study, through the two channels over oceans the teleconnections influencing the global weather and climate are established. There also exist unstable channels, such as the one over Tibet Plateau from 400 hPa to 100 hPa with longitudes from about 80° E to 120° E, existing only on an interannual time scale, and the narrow channel is centered at 60° E, which may come into being through interaction between seasonal time scale and interanual time scale since its exists only on a seasonal — interanuual time scale. Meanwhile, on a seasonal time scale the information mainly transports from tropics to high latitudes (with a positive information loss rate) but the interannual time scale is opposite mainly from high latitudes to tropics (i.e., with a negative information loss rate), which can be obviously seen from Fig. 6. This is very interesting.

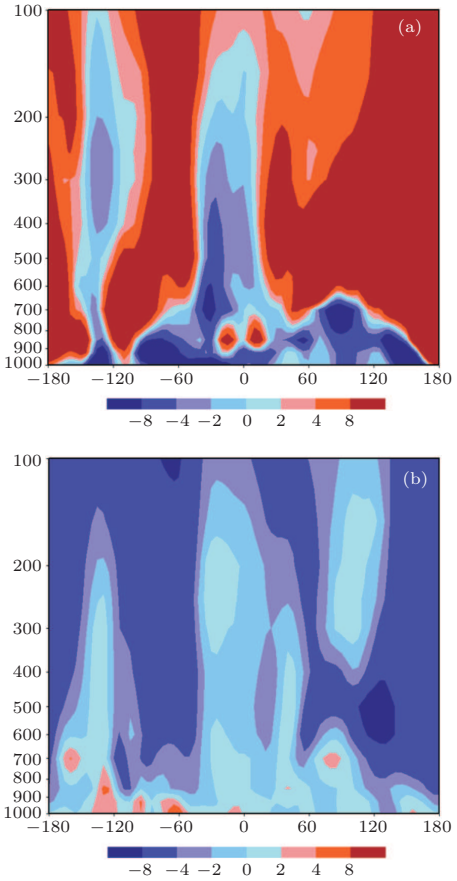


Fig. 6. (color online) The same as Fig. 4, showing the channels on a seasonal time scale (a) and on an interannual time scale (b) along longitudes in subtropical time scale: the two time scales both contribute a lot to the two channels over Pacific Ocean and Atlantic Ocean, while the interannual time scale has one more channel which ranges from 400 hPa to 100 hPa with longitudes from 80° E to 120° E.

Table 1. The communication channels on different time scales, affected by different seasons and their locations.

Data	Number	Channels (over)	Altitudes/hPa	Longitudes (center)
Seasonal to interannual time scale	3	Pacific Ocean	500–100	110° W–150° W (130° W)
		Atlantic Ocean	500–100	45° W–15° E (15° W)
		narrow one	500–100	55° E–65° E (60° E)
Spring data removed	0			
Summer data removed	1	Pacific Ocean	500–150	115° W–150° W (130° W)
Autumn data removed	1	narrow one	400–100	55° E–75° E (65° E)
Winter data removed	3	Pacific Ocean	400–150	110° W–140° W (125° W)
		Atlantic Ocean	300–100	40° W–0(20° W)
		narrow one	300–100	55° E–65° E (60° E)
Seasonal time scale	2	Pacific Ocean	700–100	115° W–150° W (130° W)
		Atlantic Ocean	400–150	45° W–10° E (15° W)
Interannual time scale	3	Pacific Ocean	700–200	120° W–150° W (135° W)
		Atlantic Ocean	1000–150	45° W–10° E (15° W)
		Tibet Plateau	400–100	80° E–120° E (100° W)

3.3. Influence of four seasons on predictability and communication channel

The predictability and information communication over the Northern Hemisphere are closely related to the seasonal cycle. In order to know what roles the different seasons play in predictability and information communication, spring, summer, autumn, and winter data are artificially removed. For example, to study the contribution of spring, geopotential heights of March, April, and May are removed from the time series from 1966 to 2012. Then, the above theory and procedure are applied to the remaining data.

Figure 7 shows the predictabilities when spring, summer, autumn, winter data are removed. Figure 8 shows the difference in prediction between the whole and the remaining data. The predictability would be low when any season data are removed, especially for the mid-upper troposphere, which indicates that the annual circle is a standard circle of a major external forcing. Among the seasons, spring has the strongest influence on predictability, followed by the autumn and summer, and the winter influence is smallest. For spring and autumn, the reduction of predictability is somewhat related to the altitude. The influences of summer and winter seem to be different in different longitude ranges.

The seasons have a great influence on the channels in the subtropics, except for winter (Fig. 9). Spring has the greatest effect on the channels, almost all three channels disappear when its data are removed. The influence of summer mainly concentrates on the disappearance of the channel over the Atlantic Ocean and the one centered at 60° E less affects the channel over Pacific Ocean. The narrow channel centering 60° E is not sensitive to autumn, but the other two almost disappear when the autumn data are removed. All the three channels are less affected by winter than other seasons: they each have just a change in altitude range and width compared with the original ones. In other words, spring contributes more to the north–south information exchange through controlling the corridor openings in subtropics, summer controlling the Atlantic Ocean channel and the one centered at 60° E as well, and autumn controlling the Pacific Ocean one and the Atlantic Ocean one. The winter has a little influence on the channels, which is why all the teleconnection patterns can steadily exist in winter. So, it is of great importance to understand the roles of seasons in meridional information communication and teleconnection communication. The channels affected by different time scales and seasons can be obtained in Table 1.

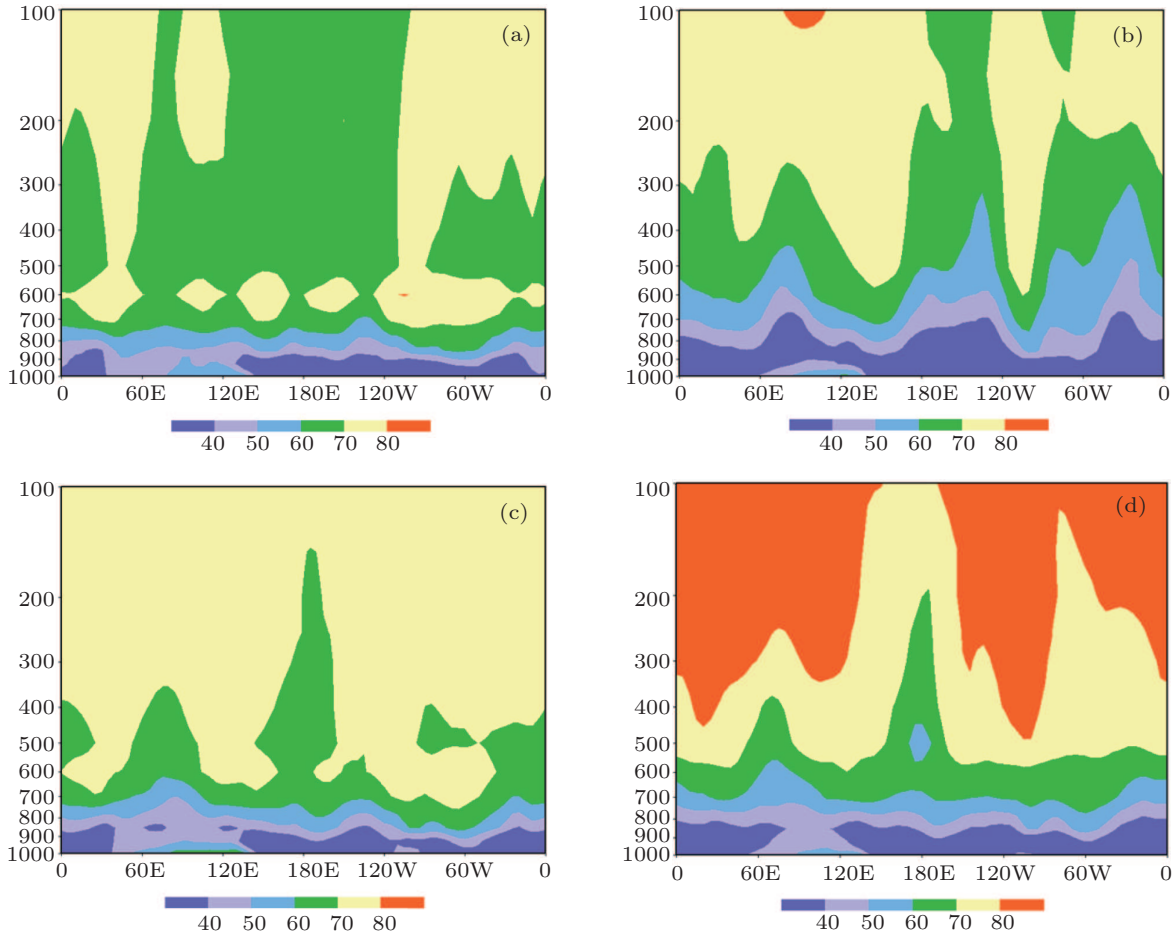


Fig. 7. (color online) The same as Fig. 1 but showing the situations with removing the data of (a) spring, (b) summer, (c) autumn, and (d) winter.

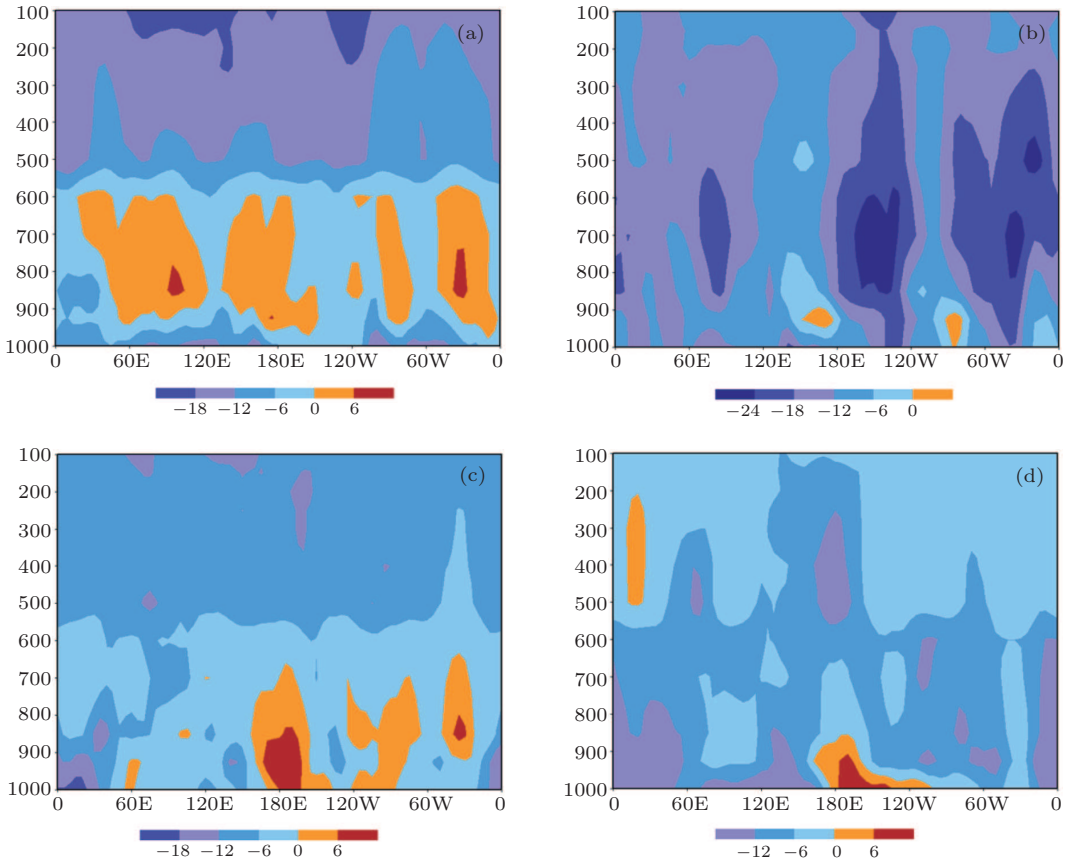


Fig. 8. (color online) Differences between Fig. 1 and Fig. 7: (a) Fig. 7(a) subtracting Fig. 1; (b) Fig. 7(b) subtracting Fig. 1; (c) Fig. 7(c) subtracting Fig. 1; and 1(d) Fig. 7(d) subtracting Fig. 1.

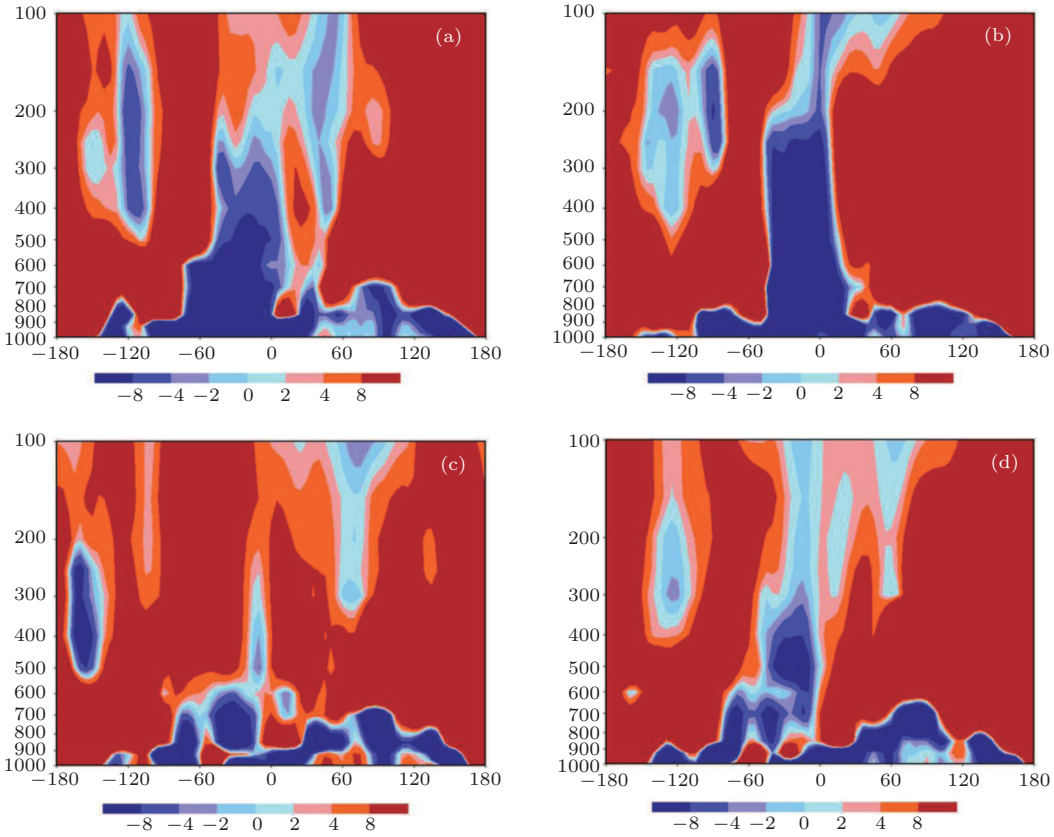


Fig. 9. (color online) Effects of seasons on channels in subtropics, showing that (a) the three channels are sensitive to the spring: when its data are removed almost all the channels disappear, (b) only the channel over Pacific Ocean is not very sensitive to summer, (c) the narrow channel centered at 60° E is not very sensitive to autumn but the other two are sensitive to autumn, and (d) none of the three channels is very sensitive to the winter.

4. Conclusions

The predictability and the information communication between 20° N and the North Pole in troposphere are investigated on the basis of nonlinear prediction and information theory. The predictability is low in the lower troposphere and high in the mid-upper troposphere on seasonal and seasonal to interannual time scales. In contrast, the interannual predictability is high in the lower troposphere and low prediction in the mid-upper troposphere. The predictability of interannual time scale is better than that of seasonal time scale, indicating that the interannual trend is more predictable than the seasonal trend. This is consistent with our common sense. Meanwhile the predictability is low no matter what season data are removed, which verifies that the annual cycle plays a great role in large scale dynamics. Among the four seasons, winter has the smallest influence and spring has the biggest effect on the predictability of the atmosphere.

This study of the vertical information communication indicates that the average information loss rate is low in the mid-upper troposphere over mid-east Pacific, west part of North America, Atlantic, and Eurasia, and high in atmosphere over mid-west Pacific, east part of America, and low troposphere over Asia. Two channels are found to be steady over the Pacific Ocean and Atlantic Ocean in subtropics, which contribute to both the seasonal time scale signal and the interannual time scale signal. The seasonal-to-interannual unstable channel centered at 60° E in upper troposphere may come into being through interaction between seasonal and interanual signals. The interannual unstable channel is located in a region from 400 hPa to 100 hPa with longitude being from about 80° E to 120° E. The seasons except winter play an important role in influencing the existence of the channels, which controls the information exchange between the tropics and the mid-latitudes, especially in spring. The lower influence on the channels in winter may explain why patterns of teleconnections steadily exist in winter.

One important thing is that this study demonstrates the Tibet Plateau plays a great role in predictability and information communication over the Northern Hemisphere. And the most interesting thing is that, on a seasonal time scale the information mainly transports from tropics to high latitudes but it is just opposite on an interannual time scale. The delineation of these channels of communication provides us with a new insight to large scale dynamics in the atmosphere. The existence of the corridors may explain teleconnections since their locations determine the place where the information exchanges between the low and the mid-high latitudes, through which the tropical region and extratropical region interact with each other to affect the global weather and climate.

References

[1] Lorenz E N 1969 *Bull. Am. Meteor. Soc.* **50** 345
[2] Feng G L, Dai X G, Wang A H and Chou J F 2001 *Acta Phys. Sin.* **50** 606 (in Chinese)
[3] Farmer J D and Sidorowich J J 1987 *Phys. Rev. Lett.* **59** 845
[4] Sugihara G and May R M 1990 *Nature* **344** 734
[5] Tsonis A A and Elsner J B 1996 *Physica D* **92** 237
[6] Elsner J B and Tsonis A A 1994 *Nonlinear Process. Geophys.* **1** 41
[7] Wallace J M and Gutzler D S 1981 *Mon. Wea. Rev.* **109** 784
[8] Horel J D and Wallace J M 1981 *Mon. Wea. Rev.* **109** 813
[9] Gong Z Q, Zhi R, Hou W, Wang X J and Feng G L 2012 *Acta Phys. Sin.* **61** 029202 (in Chinese)
[10] Yang J H, Song J Q and Cao X Q 2013 *Acta Phys. Sin.* **61** 029203 (in Chinese)
[11] Hoskins B J and Karoly D J 1981 *J. Atmos. Sci.* **38** 1179
[12] Webster P J 1981 *J. Atmos. Sci.* **38** 554
[13] Webster P J and Chang H R 1988 *J. Atmos. Sci.* **45** 803
[14] Tsonis A A and Swanson K L 2008 *Phys. Rev. Lett.* **100** 228502
[15] Yamasaki K, Gozolchiani A and Havlin S 2008 *Phys. Rev. Lett.* **100** 228501
[16] Gong Z Q, Zhou L, Zhi R and Feng G L 2008 *Acta Phys. Sin.* **57** 5351 (in Chinese)
[17] Feng A X, Gong Z Q, Wang Q G, Sun S P and Feng G L 2011 *Acta Phys. Sin.* **60** 059205 (in Chinese)
[18] Zhang Z S, Gong Z Q and Zhi R 2013 *Acta Phys. Sin.* **62** 129203 (in Chinese)
[19] Zheng D W and Dong D N 1986 *Acta Astron. Sin.* **27** 368 (in Chinese)
[20] Zhi R and Gong Z Q 2008 *Acta Phys. Sin.* **57** 4629 (in Chinese)
[21] Wales D J 1991 *Nature* **350** 485