https://doi.org/10.5194/egusphere-2026-4087
Preprint. Discussion started: 31 August 2026

CLIMATE MODUS OPERANDI

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Abstract

This overview paper is a culmination of decades of research into climate, chaos, and nonlinear dynamics. It is a voyage of work done since the early 1980's in nonlinear dynamics in climate. As an expected extension, in 2004 networks introduced into atmospheric sciences (Tsonis and Roebber, 2004). Ever since it is realized that at longer time and space scales climate operates with its major modes interacting with each other, and that rules and randomness co-exist. Here we present an overview of what we have learned so far.

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1. Introduction

Imagine that you would like to have a general idea of your health. What do you think your doctor does? They would not test how every little cell is doing. They will take samples of your blood and urine (and maybe others) and performs tests that would give indications of what is the state of your major body parts (heart, liver, kidneys, etc.). When we talk about climate, we basically do the same thing. We test the major signals.

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This is the main idea behind the theory of networks. A network is defined by a set of nodes and their links, where any pair of nodes is connected according to some rule. Usually, a node is a time series of some variable and its connection to the other nodes is defined by some deterministic/statistical measure (for example, cross-correlation). The architecture of a network (set of connections between the nodes), can reveal important and novel features of the system it represents (Albert and Barabasi 2002; Strogatz 2001; da F. Costa et al. 2007). One such feature is communities (Newman and Girvan 2004). Communities represent subsets in the network of densely connected nodes, with a few connections between the subsets which help the communities influence each other (Arenas et al. 2006). Identification of these communities can offer useful insights about the dynamics of the system under investigation.

Climate networks were introduced in the atmospheric sciences in 2004 (Tsonis and Roebber, 2004). In the climate system, network communities have been identified to correspond to major climate modes, such as the Pacific North America (PNA) pattern, the North Atlantic Oscillation (NAO), and other major climate modes, all connected to climate teleconnections (Tsonis et al. 2008, Tsonis et al. 2011). Since then, network theory was applied to climate with impressive results, for example, the discovery of a new dynamical mechanism for major climate shifts (Tsonis et al. 2006; Tsonis et al. 2007; Tsonis et al. 2008; Tsonis and Swanson 2008; Yamasaki et al. 2008; Gozolchiani et al. 2008; Swanson and Tsonis 2009). As we list below, many studies followed, using major climate modes, where interaction between climate modes from several fields (pressure, temperature etc.) was investigated using various mathematical methods such as nonlinear prediction, causality, convergence cross mapping, slow-feature analysis, and others. The following are major examples of causality and interaction between major climate modes. The list of the major climate modes referred in this work is shown in Appendix 1. For detail references of these indexes see Wyatt et al. (2011), Lin et al. (2005), Zhang et al. (2026) and references therein.

2. Results

1) According to Tsonis et al. (2007) study, NAO, PDO (and NPI), PNA, and ENSO interact with each other and the stratosphere in a way that determines climate shifts. As Figure 1 shows, NAO

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influences PDO and NPI, ENSO affects NPI and PNA, and through the stratosphere the cycle closes back to NAO. If during this interaction the modes synchronize, and the coupling between the modes increases, climate shifts from a positive (negative) to a negative (positive) global temperature regime. This study explained for the first time all global temperature trend changes in the global temperature record.

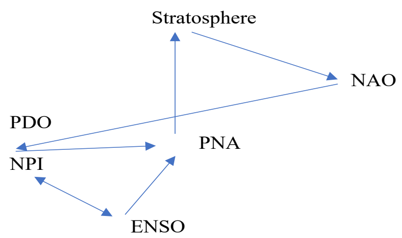

Figure 1: Tsonis et al. (2007), Wang et al. 2009. Method: Network Synchronization and coupling strength between modes.

This study provided the grounds for investigating the interaction of several major climate modes. Many studies followed this development, where interaction between climate modes was investigated using the mathematical methods mentioned above. The following are several major examples of causality and interaction between major climate modes.

2) An extension of the above study including NAM and using a different method is shown next.

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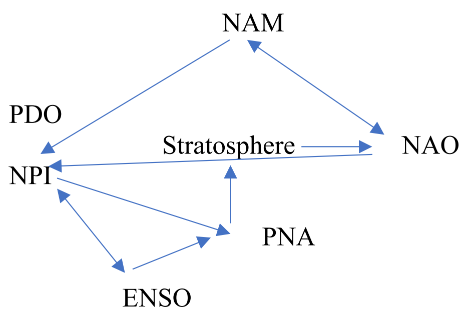
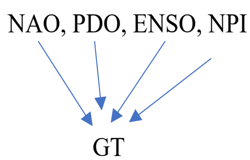


<u>Figure 2</u>: Pan et al. (2020). Method: Slow Feature Analysis (Blaschke et al. 2006). <u>Main results:</u> Results suggest that the base periods and their harmonic oscillations related to stratosphere and ENSO, act as key connections among other climatic modes with synchronous behaviors, highlighting the important roles of these oscillations in the variability of the Earth's climate.

3) Directional influences



<u>Figure 3:</u> Wang et al. (2012): <u>Method:</u> Nonlinear Prediction on actual (not filtered) data. <u>Main results:</u> Prediction of Global Temperature improves as we add more and more dominant modes.

4) Stadium wave

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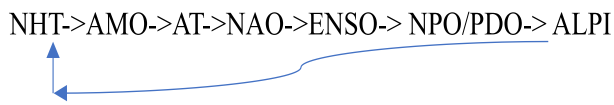
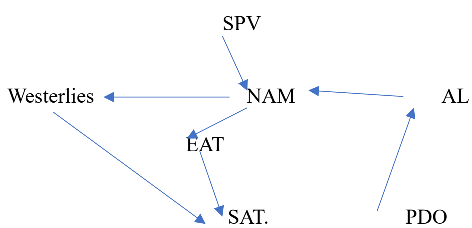


<u>Figure 4</u>: Wyatt et al. (2011). Method: Synchronization, Multichannel Singular Spectrum Analysis. <u>Main results:</u> Initial changes in the North Atlantic temperature anomaly associated with AMO culminate in an oppositely signed hemispheric signal about 30 years later. Results presented there support the hypothesis that AMO plays a significant role in hemispheric and, by inference, global climate variability.

5) Including Asian modes



<u>Figure 5</u>: Lin et al. (2025). <u>Method:</u> Convergence Cross Mapping (Sugihara et al. 2012). <u>Main results</u>: The relationship between NAM and SAT during winter is strongly modulated by PDO phase shifts, which affect the intensity of the Aleutian Low, thereby impacting the Pacific center of NAM and altering its influence on Northeast Asia.

6) Including another set of Asian modes

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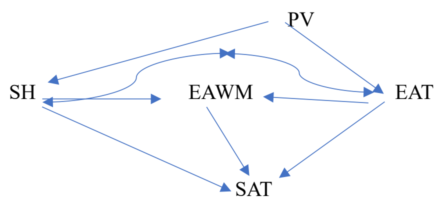

Figure 6: Zhang et al. (2026). Method: Convergence Cross-Mapping (Sugihara et al. 2012). *Main results: The above network applies to both positive and negative NAM phases. Findings reveal that interactions between the modes vary on interannual and interdecadal scales. On interannual scales, NAM (in both positive and negative phase) and EAWM show similar influence patterns on winter surface air temperature (SAT). NAM plays a pivotal role in the EAWM's decadal influence on SAT through quasi-stationary planetary wave activity. Moreover, EAT exerts a consistently positive influence on SH.*

Other studies have added to these connections, including (among others): 1) CR → GT, Tsonis et al. (2015), Method: Convergence Cross-Mapping (Sugihara et al. 2012), 2) NAM -> SAT, Zhang et al. (2018), Method: Convergence Cross-Mapping (Sugihara et al. 2012), 3) the effect of 8-yr information flow from larger to smaller scales in long term SAT records from European stations (Jajcay et al 2016), 4) the effect of phase low frequency interannual processes on quasi-annual variability of amplitude and phase of extreme ENSO events (Jajkay et al. 2018), 5) the strong relation of climate networks to climate teleconnections and how teleconnections stabilize climate (Tsonis and Roebber, 2004, Tsonis et al. 2008). Figure 7 combines the above presented results.

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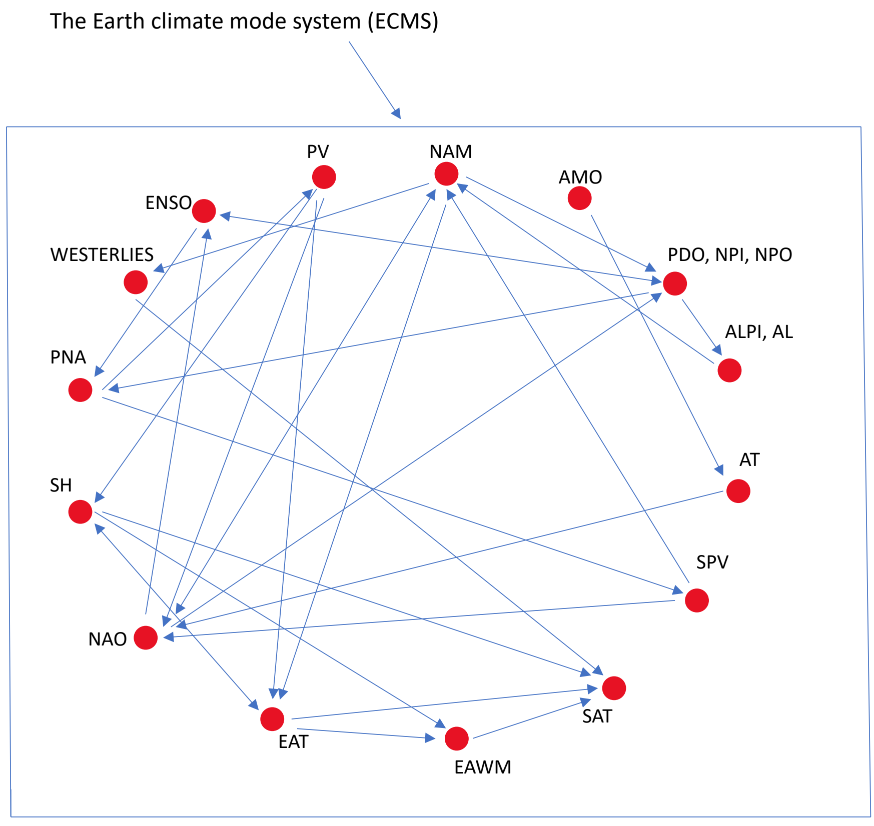

Figure 7: *This figure represents a picture of causality in climate dynamics of the "Earth system" based on the studies mentioned above. It is by no means the complete picture of climate modes interactions, but is serves as an idea of what is the background of climate mode interactions. Note that in some cases, causality is bidirectional. The location of the nodes is arbitrary.*

The above figure of causality in climate dynamics is by no means the final picture, as many other connections may be identified in future studies, or that some modes may be exhibit "commonalities" to other modes, but the general picture remains very coherent. We are dealing with a complex network, which is also a "small-world" network, in the sense that communication between modes in the network is very efficient (we can go from one mode to any other mode in just a few steps). This provides a new perspective of how climate may be operating and how climate teleconnections manifest themsleves. However, the picture is not complete unless the

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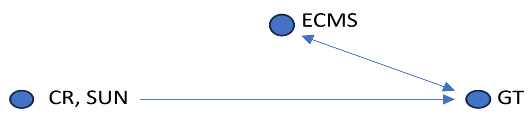
extraterrestrial influence (solar output, and cosmic rays), which affect global temperature, are included, as it is shown in Figure 8. This Figure points to the fact that we are dealing with a "3-body problem" with nonlinear components (CR, SUN, Earth Climate Mode System), which by definition is complex and chaotic, and thus quite unpredictable.



<u>Figure 8</u>: As an addition to Figure 7, here we show that possible connections to extraterrestrial forces and climate.

When we are dealing with data where "noise" is present, the validity of the results is based on statistical significance. Therefore, (as we all know), while a result from a solid mathematical method may be statistically significant, it does not guarantee that "noise" sometimes will not take over and "ruin" the predictions based on the mathematical projections. Rules and randomness co-exist and when rules prevail, prediction are reliable, but when randomness (noise) becomes more dominant, predictions fail, as we all know from personal experience with climate predictions (not to mention weather predictions).

3) Instead of Conclusions

Major signals or modes emerge in the complex climate system and their interactions provide unique clues and insights into the dynamics of climate, long-range correlation/teleconnections, and climate shifts, over time scales closely related to our experiences of weather, climate changes, and extremes.

Digging deeper in this idea of causality in climate, noise (randomness), and unpredictability, one has to wonder what is the bigger picture. Climate may be thought as being just an isolated part in

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our universe, but could there be a bigger picture? In the general sense of the Universe, there is the physical system (the laws of nature) and the formal mathematical system (the language of the physical system). How does complexity and randomness connect to it? Is there randomness in the physical system? As it has been known for years, randomness in the physical system, through the second law of thermodynamics (irreversibility), through the sensitivity in initial conditions (chaos), through quantum-mechanics, and through stochasticity (the interaction of infinite agents), is an inherited property of nature. At the same time, due to theories by Gödel, Cantor, Chaitin, Kolmogorov and others (Hofstadter, 1979, Tsonis, 2007, Tsonis, 2024), it is clear that in the pure mathematical system (not statistics) there is plenty of randomness. This may not be surprising if we assume that the formal mathematical system is the language of nature.

Rules alone or randomness alone do not produce networks that are both stable and efficient. What makes them both stable and efficient is the co-existence of rules and randomness. As an example, let's consider cumulus cloud formations. Even though, this example refers to a small-scale phenomenon, it demonstrates the co-existence of rules and randomness at all scales. Given a rather uniform surface, the air at the surface gets warm during the day, then it rises, and as it rises, it expands and cools. This increases the relative humidity. At some point the relative humidity reaches 100% and then the cloud bases form, basically at the same level everywhere in the area. Up to this point everything is determined by physics. But once the bases are formed the cloud development is rather random. Given the fact that cubic or spherical clouds have never been observed, the formation of a rather well-defined cloud bases is followed by irregular vertical structures. But why? One could imagine that once the cloud bases are formed, rules could dictate that each molecule in the original rising air moves and interacts with the other molecules in such a way as to always form a cube or a sphere. But can you imagine the effort and energy that the atmosphere will have to make in order for this to happen? Clearly this will basically require infinite power and energy. But, does nature want to use infinity and infinite power for every little process? Nature reserves infinity for bigger purposes. Instead, after the rules are set, randomness comes into picture, and molecules are left to move randomly, thus generating irregular cloud shapes, while minimizing effort. This is in accordance with the principle of the least possible energy consumption (least effort, energy efficiency) as has been suggested by George Zipf (Zipf, 1949), and mathematically and physically demonstrated by the

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work of Ilya Prigogine (Prigogine 1980), which won him the Nobel prize in Chemistry in 1997. Thus, randomness emerges as a property of nature. Even though the above example refers to a small-scale phenomenon, it demonstrates the co-existence of rules and randomness. This "inherited" randomness (which involves the free interaction of many agents- otherwise referred to as stochasticity) becomes a property of nature.

This co-existence is the main recipe for basically all processes in the Universe and life, including most natural processes, Darwinian evolution (random variations and natural selection), life, DNA structure, languages, music, and as we show here, climate(Tsonis, 2008, Tsonis 2024). And, as the random deviations of the Cosmic Microwave Radiation (the relic of Big Bang, Fixsen, 2009) would suggest, this co-existence is present since the beginning of time. Therefore, while the notion of infinity appears abstract, infinity, irreversibility, sensitivity to the initial conditions, too many interacting agents (stochasticity, or inherited randomness), and energy efficiency may be the key players in the dynamics of the Universe. These ideas are summarized in Figure 9, which indicates the possible connections between the physical and mathematical system and the five main ingredients of rules and randomness in both systems. Again, we need to mention that this is not by any means a final answer, but just a perspective based on what we understand right now.

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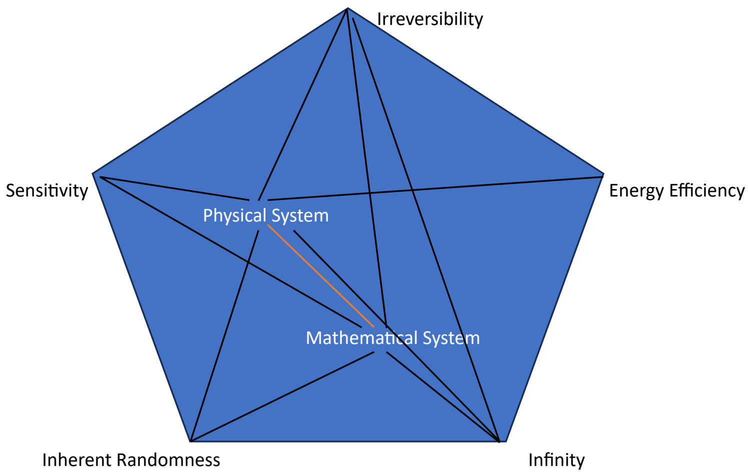

Figure 9: This figure shows the possible connections between the physical and mathematical system and the five main ingredients of rules and randomness in both systems. The position of the nodes in this figure is strictly arbitrary. The actual physical position of the "actors" involved in this picture remains open to debate. This is not by any means the complete picture of how the universe works, but just a suggestion of where we are at right now.

Authors contributions: AAT designed the paper, with all the figures, and wrote the first version. GW was part of most of networks included in this paper, and contributed to interpreting results and improving this paper.

Competing interests: The authors declare that they have no conflict of interest.

Code and data availability: All codes and data availability have been cited in the references and are available by the authors

References

https://doi.org/10.5194/egusphere-2026-4087
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Albert, R., and Barabasi, A.-L.: Statistical mechanics of complex networks, Rev. Mod. Phys., 74, 47–101., 2002.

Arenas, A., Diaz-Guilera, A., and Perez-Vicente, C. J.: Synchronization reveals topological scales in complex networks, Phys. Rev. Lett., 96, 114102, doi:10.1103/PhysRevLett.96.114102. 2006.

Blaschke, T., Berkes, P., and Wiskott, L.: What is the relation between slow feature analysis and independent component analysis? Neural Comput., 18, 2495-2508, https://doi.org/10.1162/neco.2006.18.10.2495, 2006.

Costa, L. D. F., Rodrigues, F.A., Travieso, G., and Villas Boas P. R.: Characterization of complex networks: A survey of measurements, Adv. Phys., 56, 167–242, 2007.

Gozolchiani, A., Yamasaki, K., Gazit, O., and Havlin, S.: Pattern of climate network blinking links follow El Niño events, Europhys. Lett., 83, 28005, doi:10.1209/0295-5075/83/28005, 2008.

Hofstadter, D. R.: Gödel, Escher, Bach: an eternal golden braid. Basic Books, 1979.

Lin, Y., Wang G., and Tsonis, A. A.: Northern annual mode and Northern Asian temperature anomalies: exploring causality and the cause of non-stationarity. Clim. Dyn. 63:387. https://doi.org/10.1007/s00382-025-07893-4, 2025.

Newman, M. E. J., and Girvan, M.: Finding and evaluating community structure in networks, Phys. Rev. E, 69, 026113, doi:10.1103/PhysRevE.69.026113, 2004.

Pan, X., Wang, G., Yang, P., Wang, J., and Tsonis, A. A.: On the interconnections among major climate modes and their common driving factors. Earth Syst. Dynam. 11, 525-535, https://doi.org/10.5194/esd-11-525-2020, 2020.

Prigogine, I.: From being to becoming. Freeman, 1980.

Strogatz, S. H.: Exploring complex networks, Nature, 410, 268–276, 2001.

Sugihara, G., May, R., Ye, H., Hsieh, C-h., Deyle, E., Fogarty, M., and Munch, S.: Detecting causality in complex ecosystems. Science 338 (61060;496-500, https://doi.org/10.1126/science.1227079, 2012.

Swanson, K. L., and Tsonis, A. A.: Has the climate recently shifted? Geophys. Res. Lett., 36, L06711, doi:10.1029/2008GL037022, 2009.

Tsonis, A. A., and Roebber, P. J.: The architecture of the climate network. *Physica,* **333A,** 497–504, 2004.

Tsonis, A. A., and Swanson, K. L.: Topology and predictability of El Niño and La Niña networks, Phys. Rev. Lett., 100, 2008, 228502, doi:10.1103/PhysRevLett.100.228502.

Tsonis, A. A.2008: Randomnicity: Rules and randomness in the realm of the infinite. Imperial College Press, 196 pp., 2008.

Tsonis, A. A., and Swanson, K. L.: Climate mode co-variability and climate shifts, Int. J. Bifurcat. Chaos, 21, 3549–3556, doi:10.1142/S0218127411030714, 2011.

Tsonis, A. A., Swanson, K. L., and Roebber, P. J.: What do networks have to do with climate? Bull. Am. Meteorol. Soc., 87, 585–595, doi:10.1175/BAMS-87-5-585, 2006.

Tsonis, A. A., Swanson, K. L. and Kravtsov, S.: A new dynamical mechanism for major climate shifts, Geophys. Res. Lett., 34, L13705, doi:10.1029/2007GL030288, 2007.

Tsonis, A. A., Swanson, K. L., and G. Wang G.: On the role of atmospheric teleconnection in climate, J. Clim., 21, 2990–3001., 2008.

Tsonis, A. A., Wang, G., Swanson, K. L., Rodrigues, F.A., and Costa L. D. F.: Community structure and dynamics in climate networks, Clim. Dyn., 37, 933–940, doi:10.1007/s00382-010-0874-3, 2011.

Tsonis, A. A., and Swanson K. L.: Climate mode co-variability and climate shifts, Int. J. Bifurcat. Chaos, 21, 3549–3556, doi:10.1142/S0218127411030714, 2011.

https://doi.org/10.5194/egusphere-2026-4087
Preprint. Discussion started: 31 August 2026

Tsonis, A. A.: On the origins of randomness. *Perspectives of Earth and Space Scientists*, *5*, e2023CN000228. https://doi.org/10.1029/2023CN000228, 2024.

Tsonis, A.A., Deyle, E.R., May, R. M., Sugihara, G., Swanson, K., Verbeten, J. D., and Wang, G.: Dynamical evidence for causality between galactic cosmic rays and interannual variation in global temperature. www.pnas.org/cgi/doi/10.1073/pnas.1420291112, 2015.

Wang, G., Swanson, K. L., and A. A. Tsonis, A. A.: The pacemaker of major climate shifts, Geophys. Res. Lett., 36, L07708, doi:10. 1029/2008GL036874, 2009.

Watts, D. J., and S. H. Strogatz S. H.: Collective dynamics of 'small-world' networks, Nature, 393, 440–442., 1998.

Wyatt, M.G, Kravtsov, S, and Tsonis, A. A.: Atlantic multidecadal oscillation and northern hemisphere's climate variability. Clim. Dyn. Doi 10.1007/s00382-011-1071-8, 2011.

Yamasaki, K., A. Gozolchiani, A., and Havlin, S.: Climate net- works around the globe are significantly affected by El Niño, Phys. Rev. Lett., 100, 228501, doi:10.1103/PhysRevLett.100. 228501, 2008.

Zhang, N. N., Wang, G., and Tsonis, A. A.: Dynamical evidence for causality between Northern Hemisphere annular mode and winter surface air temperature over Northeast Asia. Clim. Dyn. 52:3175–3182.https://doi.org/10.1007/s00382-018-4317-x, 2019.

Zhang, L., Lin Y., Wang, G., Tsonis, A. A., and Sugihara, G.: Interaction dynamics in a network of winter climate drivers in Northeast Asia. Stoch. Env. Res. Risk Asses. (In Press).

Zipf, G.: Human behavior and the principle of least effort. Addison-Wesley, 1949.

https://doi.org/10.5194/egusphere-2026-4087
Preprint. Discussion started: 31 August 2026

APPENDIX

The list of the major climate modes referred in this work. For detail references of these indexes see Wyatt et al. (2011), Lin et al. (2005), Zhang et al. (2026) and references therein.

1. NAM (Northern Hemisphere Annual Mode). Note that NAM is also referred to as AO (Arctic Oscillation)
2. SAT (Wintertime Surface Air Temperature Over NE Asia)
3. NAO (North Atlantic Oscillation)
4. PDO, NPI, NPO (Pacific Decadal Oscillation, North Pacific Index, North Pacific Oscillation)
5. ENSO (El Nino Southern Oscillation)
6. PNA (Pacific North American pattern index)
7. SPV (Strength of Stratospheric Polar Vortex)
8. AMO (Atlantic Multi Decadal Oscillation)
9. AT (Atmospheric-Mass Transfer Anomalies)
10. ALPI, AL (Aleutian Low-Pressure Index)

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11. PV (Index relating to total air mass in NH between 500-hPa isobaric surface and the boundary of polar vortex)
12. SH (Siberian High)
13. EAWM (East Asian Winter Monsoon)
14. EAT (East Asian Trough)
15. Westerlies (mid-to high-latitude westerly jet intensity)
16. Extraterrestrial forces (Solar activity and Cosmic Rays)
17. GT/NHT (Global Temperature, North Hemisphere Temperature)

Note that, some modes may have "commonalities" to other modes but they all have distinct "ingredients" associated with them. For example, PV refers to the intensity of the tropospheric polar vortex calculated as the total air mass in NH between 500-hPa isobaric surface and the boundary of polar vortex, while SPV represents the strength of arctic stratospheric polar vertex calculated as the mean zonal wind averaged over 600-900 N and 50-10 hPa. SPV is also related to Quasi-Biennial-Oscillation (QBO).