Triskels and Symmetries of Mean Global Sea-Level Pressure

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ABSTRACT

The evolution of mean sea-level atmospheric pressure since 1850 is analyzed using singular spectrum analysis. Maps of the main components (the trends) reveal striking symmetries of order 3 and 4. The northern hemisphere (NH) displays a set of three positive features, forming an almost perfect equilateral triangle. The southern hemisphere (SH) displays a set of three positive features arranged as an isosceles triangle, with a possible fourth (weaker) feature. This geometry can be modeled as Taylor-Couette flow of mode 3 (NH) or 4 (SH). The remarkable regularity and order three symmetry of the NH triskel occurs despite the lack of cylindrical symmetry of the northern continents. The stronger intensity and larger size of features in the SH is linked to the presence of the annular AAO. In addition to the dominant trends, quasi-periodic components of ~130, 90, 50, 22, 15, 4, 1.8, 1, 0.5, 0.33, and 0.25 years, i.e. the Jose, Gleissberg, Hale and Schwabe cycles, the annual cycle and its first three harmonics are identified.

Key words. Global Sea Level Pressure, Taylow-Couette flow, Triskel pattern

1. Introduction

Understanding the mean circulation of air masses is one of the most ancient problems in meteorology (cf. Lorentz (1967); Lindzen et Hou (1988)). Solar insolation drives the first order structure and motions of atmospheric masses. Early views thought them to be organized in planetary scale circulation cells, arranged roughly symmetrically with respect to the equator. In the troposphere, warm winds blow from the equator, forming the top of the Hadley cells (cf. Hadley (1735)); air cools, becomes denser and sinks near 30° (N and S), generating two belts of high pressures. The circuit is closed by return winds blowing towards the (low pressure) equator. Cold winds in the lower atmosphere blow from the poles to warmer regions, their density decreases as they approach 60° (N and S) latitude, where they rise. The circuit is closed by return winds in the troposphere, back to the polar high pressures, forming the polar cells. The Ferrel cells (cf. Ferrel (1856)) located between the polar and Hadley cells, extend between 30° and 60° (N and S).

Lindzen et Hou (1988) summarize the situation at the end of the first half of the 20th century: “By the early part of this century (Jeffreys 1926), the idea was being put forth that the zonally averaged circulation might, in large measure, be forced by eddies” … “Starr (1948) was going so far as to suggest that the symmetric circulation was inconsequential”. Schneider and Lindzen (1977) and Schneider (1977) were probably the first to propose an explicit calculation of the symmetric circulation; they showed that purely symmetric circulations could maintain strong subtropical jets and contribute to the maintenance of surface winds. The symmetry of the mean heat received by Earth was sufficient to force the symmetry of the cell structure, the symmetry of the subtropical currents and the general wind pattern.

Based on a decade of observations (1963-1973), Lindzen et Hou (1988) found that as soon as the peak heating is a few degrees in latitude off the equator, profound asymmetries in the Hadley circulation result, with the summer cell becoming negligible. The annually averaged Hadley circulation is much larger than that forced by the annually averaged heating.

We know that the heat coming from the Sun’s activity varies with time (e.g. Usoskin et al. (2003); Solanki et al. (2004); Lockwood et al. (2011); Vieira et al. (2011); Abreu et al. (2012); Kutiev et al. (2013); Thuillier et al. (2014); Le Mouël et al. (2020a,b); Courtillot et al. (2021)) and so does the inclination of our planet’s rotation axis (e.g. Barnes et al. (1983); Rochester (1977); Lambeck (2005); Schindelegger et al. (2013); Lopes et al. (2017); Barkin et al. (2019); Le Mouël et al. (2019a); Krylov et al. (2020); Le Mouël et al. (2021a); Lopes et al. (2021)). Consequences of these two variabilities are expected to affect the atmosphere, and in particular the climate (e.g. Mörh et Schlamming (1979); Barnes et al. (1983); Lindzen (1994); Solanki et al. (2004); Gray et al. (2010, 2013); Roy et Haigh (2010); Abreu et al. (2012); Kutiev et al. (2013); Schindelegger et al. (2013); Johnstone and Mantua (2014); Le Mouël et al. (2019b); Gruzdev and Bevorkhni (2020); Cionco et al. (2021); Connolly et al. (2021); Drews et al. (2021); Sonechkin et Vakulenko (2021)). To these already complex interactions,
one must add those due to the ocean, the largest heat exchanger that warms and cools on its own (longer) time scales. Lindzen (1978) was the first to show how (to first order) atmospheric circulation was forced by the physics of the ocean surface.

Interest in recent climate warming has led to question how the convection cells, and in particular the Hadley cells, being the main ones, react to a temperature increase (e.g. Chang et al. 1995; Dima et Wallace 2003; Frierson et al. 2007; Hu et Fu 2007; Kharin et al. 2007; Lu et al. 2007; Tandon et al. 2013; Shepherd 2014; Tao et al. 2016; Grise and Davis 2020). Also, how do these variations affect extreme meteorological events (e.g. Schaeffer et al. 2005; Stott et al. 2010; Rahmstorf and Coumou 2011; Rummukainen 2012; Trenberth et al. 2015)?

Most authors who have studied the space-time evolution of convection cells call upon the analysis in terms of components of sea-level pressure (SLP). SLP is directly related to climate indices (e.g. Vaideanu et al. 2020; Le Mouel et al. 2019b). Decomposition methods often use “Empirical Orthogonal Functions” (EOF). In this paper, we select an alternate method: the time decomposition of SLP using “Singular Spectrum Analysis” (SSA, e.g. Golyandina and Zhigljavsky 2013), a method that we have used extensively with success in some recent works (e.g. Lopes et al. 2017; Le Mouël et al. 2019a, 2020a, b; Courtillot et al. 2021; Le Mouël et al. 2021a; Lopes et al. 2021)

The SLP data we use are described in section 2, their analysis using SSA in section 3 and the results are discussed in section 4.

2. The SLP Data

The SLP data are maintained by the Met Office Hadley Centre. They are available in map form for global pressure every month since 1850 to the present, with a spatial sampling of 5°x5°. As indicated by the Met Office, the series is not homogeneous in time (two intervals from 1850 to 2004 and 2005 to 2020 in which the means are homogeneous but the variances differ). Allan and Ansell (2006) discuss the locations and number of ground observations they use to build the series. We show the map of 1850 to 2020 mean pressures in Figure 1.

The map of Figure 1 is very similar to that obtained from simply averaging monthly SLP maps, demonstrating the very stable geometry of the global atmospheric structure. Well-known patterns are clearly rendered by the map: in the Southern hemisphere, the structure is dominated by three large positive features in the southern parts of the main oceans (Pacific, Atlantic and Indian) separated by the southern ends of the three southern continents (South America, South Africa and Australia). This approximate three-fold symmetry actually seems to “leak” into a four-fold symmetry: the positive feature extending from Australia to Western South America can be described as exhibiting two weaker features, the one over

![Fig. 1: 1850 to 2020 mean pressure at sea level (SLP) (Hammer-Aitoff projection).](https://www.metoffice.gov.uk/hadobs/hadslp2/data/download.html)

Australia and East of it being the weakest.

The pattern in the Northern hemisphere is similar to that in the Southern hemisphere, with two features extending over the northern Pacific and Atlantic oceans, similar to the southern structure, but with the third positive anomaly lying over the Asian continents (central Asia and Tibet). This overall structure of global positive pressure features could be roughly described as the intersection of a series of three strong and one weaker cylinder, parallel to the Earth’s axis of rotation, with the earth’s surface. South of 40°S latitude, the features turn negative and form the quasi-circular Antarctic oscillation (AAO), also known as the Southern annular mode (SAM), a belt of low pressures surrounding the frozen continent (e.g. Marshall 2003; Gillett et al. 2006). A zonal average of Figure 1 is not really consistent with the classical latitudinal description of the Hadley, Ferrel and polar cells, with relatively moderate low pressures over the equatorial belt, high pressures around 30°N and lower values at higher latitudes, particularly over Antarctica (see also Figure 4). The overall averaged zonal structure is not symmetrical with respect to the equator (Lindzen and Hou 1988).

Winds are proportional to the space derivative of pressure (Figure 2, which is the map most people are familiar with), and thus in space phase quadrature with pressure features. The space derivative is a high-pass operator which exacerbates discontinuities and promotes oscillations one order higher than the causative features. Figure 2 shows how winds (the gradients of pressure) are slowed or suppressed by continental masses; also, the red and blue ” anomalies ” are often paired, which reminds one of Laplace’s statement that the vector sum of winds must be close to zero at any instant.

3. The SSA of SLP Data

Rather than building a map of spatial likelihood of pressure structures at a given time, we build the time series of pressure for each couple of (longitude, latitude) coordinates. These are analyzed using the method of Singular spectrum analysis (ISSA e.g. Golyandina and Zhigljavsky 2013): each time

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1 https://www.metoffice.gov.uk/hadobs/hadslp2/data/download.html
Fig. 2: 1850 to 2020 time average of the spatial pressure gradients (i.e. winds up to a constant) at sea level (Hammer-Aitoff projection).

series is decomposed into a sum of a trend and periodic or quasi-periodic components.

Note: the trend is the first component “extracted” by SSA, it is a sort of mean with respect to time, a non-oscillating function of time; it should not be confused with the spatial mean of maps in time (see for example Figure 2).

The trend (∼1008 hP), that is the first and largest SSA component, represents more than 70% of the total variance (sv) of the original series. The sequence of the next quasi-periodic components is, in decreasing order of periods, ∼130 years (∼0.7 hP, ∼0.06% of the sv; Jose (1965)), ∼90 yr (∼21 hP, ∼1.9% of the sv; Gleissberg (1939); Le Mouël et al. (2017)), ∼50 yr (∼0.2 hP, ∼0.02% of the sv), ∼22 yr (∼0.50 hP, ∼0.04% of the sv; Hale cycle, Usoskin (2017)), ∼15 yr (∼0.2 hP, ∼0.02% of the sv, upper bound of the Schwabe cycle; Schwabe (1844), ∼4 yr (∼0.3 hP, ∼0.03% of the sv), ∼1.8 yr (∼0.3 hP, ∼0.03% of the sv), then 1 yr (∼93 hP, ∼8.3% of the sv), 0.5 yr (∼65 hP, ∼5.8% of the sv), 0.33 yr (∼44 hP, ∼3.9% of the sv) and 0.25 yr (∼21 hP, ∼1.9% of the sv).

These are readily recognized as the Jose, Gleissberg, Hale and Schwabe cycles, the quasi biennial oscillation and the annual cycle followed by its first three harmonics. Figure 3 represents the mean (from 1850 to 2020) of the SSA trends of SLP in Hammer-Aitoff and North and South stereographic polar projections. This mean is representative, since the observed (decreasing) overall variation of pressure is only 0.1% in the 170 years of the study. We illustrate the stability of the SLP trend both in space and time with Figure 4, which shows the variation in the trend of SLP since 1850 as a function of latitude. Indeed, the latitudinal structure of mean pressure (SSA trend) is remarkably stable over 170 years (a rather rare feature in geophysics and geodynamics, both internal and external to the solid Earth), with its typical asymmetry between the two hemispheres.

Fig. 3: 1850 to 2020 mean of trends of pressure at sea level (SLP) from, determined using Singular spectrum analysis (SSA) (top: Hammer-Aitoff projection; lower left: stereographic projection of the NH; lower right: stereographic projection of the SH).

The stereographic projections of Figure 3 give a clear image of the large scale atmospheric circulation. They are close to the original mean of Figure 1, and the same large scale features appear, with sharper contours. The polar projections are particularly revealing. There is a strong negative feature south of Greenland. In the northern hemisphere, three sharp positive features lie on a circle at 40°N latitude and are located at the three apices of an equilateral triangle. The center of this 3-fold symmetry (that we will call a “triskel”, a Celtic symbol) is located near 77°N, 90°W (13° away from the North pole). In the southern hemisphere, the pattern is closer to 4-fold symmetry, with one of the four features much weaker than the other three.

4. Discussion

The physics that is appropriate to analyze the motions of fluid masses in the atmosphere, ocean (and mantle) is that of stationary turbulent flow (e.g. Chandrasekhar (1961); Frisch et Kolmogorov, (1995)). The large Hadley, Ferrel and polar cells are generally interpreted in terms of Taylor-Couette flow. Analytical solutions are available in the case of a cylindrical geometry (e.g. Taylor (1923)), but raise problems in the spherical case (e.g. Schrauf (1986); Mamun et Tuckerman...
Fig. 4: Evolution of the SSA trend of SLP as a function of time (170 yr since 1850) and latitude, illustrating the stability of the zonal pressure structure in time.

Forbes and Bassom (2018) show that a simple solution for Taylor-Couette flow of a viscous fluid between two concentric cylinders with radii $a$ and $b$ rotating in opposite directions and submitted to an azimuthal perturbation with angle $\theta$, can be written as:

$$r(\xi) = r_n + \epsilon a \cos(q\xi)$$  \hspace{1cm} (1a)$$

$$\theta(\xi, t) = \xi - \left(\frac{b^2}{(b^2 + a^2) - \omega * t} \star \left[1 - \frac{r_n^2}{r^2(\xi)}\right]\right)/(b^2 - a^2)$$  \hspace{1cm} (1b)$$

in which $r_n$ is the neutral radius and $q$ is an integer corresponding to the flow mode. One has:

$$r_n = \sqrt{\frac{2a^2 + b^2}{a^2 + b^2}}$$

The solutions of system (1a,1b) are displayed in Figure 5 for stationary flows with integers $q = 1$ to 4, with $a = 0.5$, $b = 1$, $\omega * t = 1$ and $\epsilon = 0.1$. Modes corresponding to parameter $q$ evolve and $q$ is fixed by the nature and symmetry of the flow.

Figure 6a shows the superimposition of a pattern of Taylor-Couette flow with mode $q = 3$ and the SLP trend map of Figure 3 (lower left) for the northern hemisphere. We invert equations (1a,1b) by simulated annealing (Kirkpatrick et al. 1983) for $\omega * t = 1$ (flow stationary and constant in time). The amplitude of the flow perturbation $\epsilon$ is on the order of 0.100 ± 0.002, and the triskel pattern is centered on 91.3 ± 0.1°W - 77.1 ± 0.2°N. The fit is excellent and compatible with the shearing due to the direction of winds (East to West) at mid latitudes, opposite to the direction of Earth’s rotation from West to East.

Figure 6b shows the superimposition of a pattern of Taylor-Couette flow with mode $q = 4$ and the SLP trend map of Figure 3 (lower right) for the southern hemisphere. The amplitude of the flow perturbation $\epsilon$ is reduced to 0.05 ± 0.01, and the symmetry 4 is centered on 88.1 ± 0.2°W - 7.5 ± 0.1°N.

The Hadley, Ferrell or polar type cells change with season. This is why the zonal structure of the atmosphere is shown in seasonal (monthly, bi-monthly) maps that can be averaged over several years. These oscillations cannot be analyzed through spatial decomposition methods such as EOF or spherical harmonics. On the other hand, SSA is a scalar time analysis and can extract from the data temporal features. We have shown that atmospheric surface pressures display simple geometric/geographic features that are stable both in space and time. The oscillatory components belong to the harmonic families of the Schwabe (33, 22, 11, 5.5, 3.3 and 1.6 yr) and annual (1, 1/2, 1/3, 1/4 and 1/5 yr) cycles, plus the dominant 90 yr Gleissberg cycle.

Finally, one can only be struck by the kinship between the axial cylinders that form the main components of the sea-level pressure structure (with the quasi-symmetry of the outline of these cylinders, yet the failure of perfect symmetry, with 3 cylinders in the northern hemisphere and more like 4 in the southern hemisphere). These are geometrically reminiscent of the axial cylinders found by Gubbins and Bloxham (1987) and Gubbins and Kelly (1993) in their analyses of flow in the Earth’s molten outer core that generates the geomagnetic field. The physics in both cases appears quite distinct but the analogy may indicate a path to finding the mechanism that generates these features.

5. Conclusion

In this note, we have analyzed the time evolution of mean sea-level pressure SLP since 1850, using the iSSA method of spectral analysis. The method decomposes the original time series into a set of time dependent components and a trend. The quasi-periodic components are in decreasing order...
Figure 6: Superimposition of the Taylor-Couette patterns both North and South hemispheres.

As far as the general trends of sea-level pressure extracted with SSA are concerned, they have fluctuated by less than 0.1% in 170 years (or $6.10^{-3} \text{hPa/yr}$). The mid latitudes of each hemisphere of the Earth’s surface harbor a set of positive features (on the order of 20 hPa), all but one (over central Asia and Tibet) lying over the main ocean basins (Figure 3, top). This is in full agreement with Schneider and Lindzen (1977), who see the oceans as the main engine driving the 194 general circulation of the atmosphere. In stereographic polar projection, the northern hemisphere displays a set of three positive features, forming an almost perfect equilateral triangle or triskel (Figure 03, lower left). The southern hemisphere also features a set of three main positive features but arranged as an isosceles triangle, with a possible fourth (but much fainter) feature (Figure 3, lower right). A preliminary analysis suggests that the atmosphere in the two hemispheres could be the site of Taylor-Couette (sheared) differential flow of mode 3 (N hemisphere) or mode 4 (S hemisphere). The mode is imposed by the geometry of the oceanic vs continental nature of the Earth’s surface. The remarkable regularity and order three symmetry of the northern hemisphere triskel occurs despite the lack of cylindrical symmetry of the northern continents. The stronger intensity and larger size of features in the southern hemisphere is due to the presence of the annular flow of cold air over the southern ocean and the obstacles due to the southern parts or tips of South America, Southern Africa and Australia.

Singular spectrum analysis is a scalar analysis as a function of time, which is useful in detecting time varying patterns and features. Spatial components that SSA extracts are not artefacts, contrary to what could happen when using spherical harmonics or EOF. A component is present only if there is spatial coherency in the observational data. In the case of sea-level pressure, we find stable (non oscillatory) components/features (as we have called them), The stability of pressure trends over the 170 years of the analysis implies that the idea of eddies maintaining the cells and forcing their oscillations is no more warranted. Taylor-Couette flow between rotating cylinders provides a good fit to the observations. The geometrical analogy with the cylinders generating the geodynamo may be a promising path to solving the dynamics of the large scale circulation in the Earth’s atmosphere.

Of periods, cycles of approximately 130, 90, 50, 22, 15, 4, 1.8, 1, 0.5, 0.33, and 0.25 years. These are recognized as the Jose, Gleissberg, Hale and Schwabe “long” (decadal and multi-decadal) cycles (with some harmonics of the well-known Schwabe “solar” cycle$^2$) and the “short” annual cycle and its first three harmonics. These periods are encountered in many solar and terrestrial phenomena and are now attributed to commensurable periods of the Jovian planets (Mörth et Schlammlinger 1979; Lopes et al. 2021).

$^2$ The Schwabe quasi-cycle is traditionally given as being 11 yr long but actually spans the 9 to 14 yr period range.
References

Abreu, J. A., Beer, J., Ferriz-Mas, A., McCracken, K. G., and Steinhilber, F., “Is there a planetary influence on solar activity?”, Astronomy & Astrophysics, 548, A88.

Allan, R., and Ansell, T., “A new globally complete monthly historical gridded mean sea level pressure dataset (HadSLP2): 1850–2004”, Journal of Climate, 19(22), 5816-5842.

Barnes, R. T. H., Hide, R., White, A. A., and Wilson, C. A., “Atmospheric angular momentum fluctuations, length-of-day changes and polar motion”, Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences, 387(1792), 31-73.

Barkin, M. Y., Krylov, S. S. and Perepelkin, V. V., “Modeling and analysis of the Earth pole motion with nonstationary perturbations”, In Journal of Physics: Conference Series, (Vol. 1301, No. 1, p. 012005), IOP Publishing.

Chandrasekhar, S., “Hydrodynamic and hydromagnetic stability”, Oxford University Press.

Chang, E. K., “The influence of Hadley circulation intensity changes on extratropical climate in an idealized model”, Journal of Atmospheric Sciences, 52(11), 2006-2024.

Cionco, R. G., Kudryavtsev, S. M. and Soon, W. H., “Possible Origin of Some Periodicities Detected in Solar-Terrestrial Studies: Earth’s Orbital Movements”, Earth and Space Science, 8(8), e2021EA001805.

Connolly, R., Soon, W., Connolly, M., Baliunas, S., Berglund, J., Butler, C. J., ... and Zhang, W., “How much has the Sun influenced Northern Hemisphere temperature trends? An ongoing debate”, Research in Astronomy and Astrophysics, 21(6), 131, 2021.

Courtillot, V., Lopes, F., and Le Mouël, J. L., “On the prediction of solar cycles”, Solar Physics, 296(1), 1-23.

Dima, I. M. and Wallace, J. M., “On the seasonality of the Hadley cell”, Journal of the atmospheric sciences, 60(12), 1522-1527.

Drews, A., Huo, W., Matthies, K., Kodera, K. and Kruschke, T., “The Sun’s Role for Decadal Climate Predictability in the North Atlantic”, Atmospheric Chemistry and Physics Discussions, 1-17.

Ferrel, W., “Essay on the winds and ocean currents”, Nashville J. of Medicine and Surgery, 11, 287-301.

Frisch, U. and Kolmogorov, A. N., “Turbulence: the legacy of AN Kolmogorov”, Cambridge university press.

Frierson, D. M., Lu, J. and Chen, G., “Width of the Hadley cell in simple and comprehensive general circulation models”, Geophysical Research Letters, 34(18).

Forbes, L. K. and Bassom, A. P., “Interfacial behaviour in two-fluid Taylor–Couette flow”, The Quarterly Journal of Mechanics and Applied Mathematics, 71(1), 79-97.

Garcia F, Seilmayer M, Giesecke A, Stefani F., “Modulated rotating waves in the magnetised spherical Couette system”, Journal of Nonlinear Science. 29(6), 2735-59.

Gillett, N. P., Kell, T. D., and Jones, P. D., “Regional climate impacts of the Southern Annular Mode”, Geophysical Research Letters, 33(23).

Gleissberg, W., “A long-periodic fluctuation of the sunspot numbers”, Observatory 62, 158.

Golyandina, N. and Zhigljavsky, A., “Singular Spectrum Analysis for time series”, (Vol. 120). Berlin: Springer, 2013

Gray, L., J., Beer, J., Geller, M., Haigh, J. D., Lockwood, M., Matthes, K., ... and White, W., “Solar influences on climate”, Reviews of Geophysics, 48(4), 2010.

Gray, L. J., Scaife, A. A., Mitchell, D. M., Osprey, S., Ineson, S., Hardiman, S., ... and Kodera, K., “A lagged response to the 11 year solar cycle in observed winter Atlantic/European weather patterns”, Journal of Geophysical Research: Atmospheres, 118(24), 13-405.

Grise, K. M. and Davis, S. M., “Hadley cell expansion in CMIP6 models”, Atmospheric Chemistry and Physics, 20(9), 5249-5268.

Gruzdev, A. N. and Bezverkhni, V. A., “Manifestation of the 11-year solar cycle in the North Atlantic climate”, In IOP Conference Series: Earth and Environmental Science, (Vol. 606, No. 1, p. 012018), IOP Publishing.

Gubbin., D., and Bloxham, J., “Morphology of the geomagnetic field and implications for the geodynamo”, Nature, 325(6104), 509-511.

Gubbin., D., and Kelly, P., “Persistent patterns in the geomagnetic field over the past 2.5 Myr”, Gubbins, 365(6449), 829-832.

Hadley, G., “VI. Concerning the cause of the general trade-winds”, Philosophical Transactions of the Royal Society of London, 39(437), 58-62, 1735.

Hollerbach, R., Junk, M. and Egbers, C., “Non-axisymmetric instabilities in basic state spherical Couette flow”, Fluid dynamics research, 38(4), 257.

Hu, Y. and Fu, Q., “Observed poleward expansion of the Hadley circulation since 1979”, Atmospheric Chemistry and Physics, 7(19), 5229-5236.

Jeffreys, H., “On the dynamics of geostrophic winds”, Quart. J. Roy. Meteor. Soc., 52(217), 85-104, 1926.

Johnstone, J. A., and Mantua, N. J., “Atmospheric controls on northeast Pacific temperature variability and change, 1900–2012”, Proceedings of the National Academy of Sciences, 111(40), 14360-14365.

Jose, P. D., “Sun’s motion and sunspots”, The Astronomical Journal, 70(3), 193-200.

Kharin, V. V., Zwiers, F. W., Zhang, X. and Hegerl, G. C., “Changes in temperature and precipitation extremes in the IPCC ensemble of global coupled model simulations”, Journal of Climate, 20(8), 1419-1444.

Kirkpatrick, S., Gelatt, C. D., and Vecchi, M. P., “Optimization by simulated annealing”, Science, 220(4598), 671-680.

Krylov, S. S., Perepelkin, V. V. and Filippova, A. S., “Long-Period Lunar Perturbations in Earth Pole Oscillatory Process: Theory”, In Advances in Theory and Practice of Computational Mechanics: Proceedings of the 21st International Conference on Computational Mechanics and Modern Applied Software Systems, (Vol. 173, p. 315). Springer Nature.

Kutiev, I., Tsagouri, I., Perrone, L., Pancheva, D., Mukhtarov, P., Mikhailov, A., ... and Torta, J. M., “Solar activity impact on the Earth’s upper atmosphere”, Journal of Space Weather...
and Space Climate, 3, A06.

Lambeck, K., “The Earth's variable rotation: geophysical causes and consequences”, Cambridge University Press.

Le Mouël, J. L., Lopes, F. and Courtillot, V., “Identification of Gleissberg cycles and a rising trend in a 315-year-long series of sunspot numbers”, Solar Physics, 292(3), 43.

Le Mouël, J. L., Lopes, F., Courtillot, V. and Gibert, D., “On forcings of length of day changes: From 9-day to 18.6-year oscillations”, Physics of the Earth and Planetary Interiors, 292, 1-11, 2019a.

Le Mouël, J. L., Lopes, F. and Courtillot, V., “A solar signature in many climate indices”, Journal of Geophysical Research: Atmospheres, 124(5), 2600-2619.

Le Mouël, J. L., Lopes, F., and Courtillot, V., “Characteristic time scales of decadal to centennial changes in global surface temperatures over the past 150 years”, Earth and Space Science, 7(4), e2019EA000671.

Le Mouël, J. L., Lopes, F., and Courtillot, V., “Solar turbulence from sunspot records”, Monthly Notices of the Royal Astronomical Society, 492(1), 1416-1420.

Le Mouël, J. L., Lopes, F. and Courtillot, V., “Sea-Level Change at the Brest (France) Tide Gauge and the Markowitz Component of Earth’s Rotation”, Journal of Coastal Research.

Lindzen, R. S., “On a calculation of the symmetric circulation and its implications for the role of eddies”, The General Circulation-Theory, Modeling, and Observations, 257-281.

Lindzen, R. S. and Hou, A. V., “Hadley circulations for zonally averaged heating centered off the equator”, Journal of Atmospheric Sciences, 45(17), 2416-2427.

Lindzen, R. S., “Climate dynamics and global change”, Annual Review of Fluid Mechanics, 26(1), 353-378.

Lorentz, E. N., ”The nature and theory of the general circulation of the atmosphere”, WMO 218, TP-115, 161 pp., World Meteorol., Organ., Geneva, Switzerland.

Lockwood, M., Owens, M. J., Barnard, L., Davis, C. J., and Steinhilber, F., “The persistence of solar activity indicators and the descent of the Sun into Maunder Minimum conditions”, Geophysical Research Letters, 38(22).

Lopes, F., Le Mouël, J. L. and Gibert, D., “The mantle rotation pole position. A solar component”, Comptes Rendus Geoscience, 349(4), 159-164.

Lopes, F., Le Mouël, J. L., Courtillot, V., and Gibert, D., “On the shoulders of Laplace”, Physics of the Earth and Planetary Interiors, 316, 106693.

Lu, J., Vecchi, G. A. and Reichler, T., “Expansion of the Hadley cell under global warming”, Geophysical Research Letters, 34(6), 2007.

Mahloul, M., A. Mahamadia, and Kristiawan, M., “The spherical Taylor–Couette flow”, European Journal of Mechanics B/Fluids, 59 (2016): 1-6.

Mamun, C. K., and Tuckerman, L. S., “Asymmetry and Hopf bifurcation in spherical Couette flow”, Physics of Fluids, 7.1 (1995): 80-91.

Mannix, P. M., and A. J.,Mestel, “Bistability and hysteresis of axisymmetric thermal convection between differentially rotating spheres”, Journal of Fluid Mechanics, 911.
2010.
Tandon, N. F., Gerber, E. P., Sobel, A. H., and Polvani, L. M., “Understanding Hadley cell expansion versus contraction: Insights from simplified models and implications for recent observations”, *Journal of climate*, 26(12), 4304-4321.
Tao, L., Hu, Y., and Liu, J., “Anthropogenic forcing on the Hadley circulation in CMIP5 simulations”, *Climate dynamics*, 46(9-10), 3337-3350.
Taylor, G. I., VIII. “Stability of a viscous liquid contained between two rotating cylinders”, *Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character*, 223(605-615), 289-343.
Trenberth, K. E., Fasullo, J. T., and Shepherd, T. G., “Attribution of climate extreme events”, *Nature Climate Change*, 5(8), 725-730.
Thuillier, G., Bolsée, D., Schmidke, G., Foujols, T., Nikutowski, B., Shapiro, A. I., ... and Schmutz, W., “The solar irradiance spectrum at solar activity minimum between solar cycles 23 and 24”, *Solar Physics*, 289(6), 1931-1958.
Usoskin, I. G., Solanki, S. K., Schüssler, M., Mursula, K. and Alanko, K. “Millennium-scale sunspot number reconstruction: Evidence for an unusually active Sun since the 1940s”, *Physical Review Letters*, 91(21), 211101.
Usoskin, I. G., “A history of solar activity over millennia”, *Living Reviews in Solar Physics*, 14(1), 1-97.
Vaideanu, P., Dima, M., Pirloaga, R. and Ionita, M., “Disentangling and quantifying contributions of distinct forcing factors to the observed global sea level pressure field”, *Climate Dynamics*, 54(3), 1453-1467.
Vieira, L. E. A., Solanki, S. K., Krivova, N. A., and Usoskin, I. “Evolution of the solar irradiance during the Holocene”, *Astronomy & Astrophysics*, 531, A6, 2011.