A census of atmospheric variability from seconds to decades

Article

Published Version

Williams, P. D., Alexander, M. J., Barnes, E. A., Butler, A. H., Davies, H. C., Garfinkel, C. I., Kushnir, Y., Lane, T. P., Lundquist, J. K., Martius, O., Maue, R. N., Peltier, W. R., Sato, K., Scaife, A. A. and Zhang, C. (2017) A census of atmospheric variability from seconds to decades. Geophysical Research Letters, 44 (21). pp. 11201-11211. ISSN 0094-8276 doi: https://doi.org/10.1002/2017GL075483 Available at https://centaur.reading.ac.uk/73811/

Published version at: http://dx.doi.org/10.1002/2017GL075483
To link to this article DOI: http://dx.doi.org/10.1002/2017GL075483

Publisher: American Geophysical Union

AGU PUBLICATIONS

Geophysical Research Letters

COMMENTARY

10.1002/2017GL075483

Key Points:

- The state of the atmosphere is observed to vary naturally on all time scales from seconds to decades and longer
- This paper synthesizes and summarizes that variability through a phenomenological census
- The paper provides an authoritative, concise, and accessible point of reference for the most important modes of atmospheric variability

Correspondence to:
P. D. Williams,
p.d.williams@reading.ac.uk

Citation:
Williams, P. D., Alexander, M. J., Barnes, E. A., Butler, A. H., Davies, H. C., Garfinkel, C. I., … Zhang, C. (2017). A census of atmospheric variability from seconds to decades. *Geophysical Research Letters*, *44*, 11,201–11,211. https://doi.org/10.1002/2017GL075483

Received 29 AUG 2017
Accepted 12 OCT 2017
Published online 15 NOV 2017

A Census of Atmospheric Variability From Seconds to Decades

Paul D. Williams[1], M. Joan Alexander[2], Elizabeth A. Barnes[3], Amy H. Butler[4,5], Huw C. Davies[6], Chaim I. Garfinkel[7], Yochanan Kushnir[8], Todd P. Lane[9], Julie K. Lundquist[10], Olivia Martius[11], Ryan N. Maue[12], W. Richard Peltier[13], Kaoru Sato[14], Adam A. Scaife[15,16], and Chidong Zhang[17]

[1]Department of Meteorology, University of Reading, Reading, UK, [2]NorthWest Research Associates, Boulder, CO, USA, [3]Department of Atmospheric Science, Colorado State University, Fort Collins, CO, USA, [4]Cooperative Institute for Research in Environmental Sciences, Boulder, CO, USA, [5]Chemical Sciences Division, NOAA Earth System Research Laboratory, Boulder, CO, USA, [6]Institute for Atmospheric and Climate Science, ETH Zürich, Zürich, Switzerland, [7]The Fredy and Nadine Herrmann Institute of Earth Sciences, Hebrew University, Jerusalem, Israel, [8]Lamont Doherty Earth Observatory, Palisades, NY, USA, [9]School of Earth Sciences, University of Melbourne, Melbourne, Victoria, Australia, [10]Department of Atmospheric and Oceanic Sciences, University of Colorado Boulder, Boulder, CO, USA, [11]Oeschger Centre for Climate Change Research, Institute of Geography, University of Bern, Bern, Switzerland, [12]Weather.us, Atlanta, GA, USA, [13]Department of Physics, University of Toronto, Toronto, Ontario, Canada, [14]Department of Earth and Planetary Science, The University of Tokyo, Tokyo, Japan, [15]Met Office Hadley Centre, Exeter, UK, [16]College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, UK, [17]NOAA Pacific Marine Environmental Laboratory, Seattle, WA, USA

Abstract This paper synthesizes and summarizes atmospheric variability on time scales from seconds to decades through a phenomenological census. We focus mainly on unforced variability in the troposphere, stratosphere, and mesosphere. In addition to atmosphere-only modes, our scope also includes coupled modes, in which the atmosphere interacts with the other components of the Earth system, such as the ocean, hydrosphere, and cryosphere. The topics covered include turbulence on time scales of seconds and minutes, gravity waves on time scales of hours, weather systems on time scales of days, atmospheric blocking on time scales of weeks, the Madden–Julian Oscillation on time scales of months, the Quasi-Biennial Oscillation and El Niño–Southern Oscillation on time scales of years, and the North Atlantic, Arctic, Antarctic, Pacific Decadal, and Atlantic Multidecadal Oscillations on time scales of decades. The paper serves as an introduction to a special collection of *Geophysical Research Letters* on atmospheric variability. We hope that both this paper and the collection will serve as a useful resource for the atmospheric science community and will act as inspiration for setting future research directions.

1. Introduction

The state of the atmosphere is observed to vary naturally on all length scales from the Kolmogorov dissipation scale of millimeters up to the planetary scale of thousands of kilometers, and on all time scales from seconds to decades and longer. This Commentary synthesizes and summarizes that variability through a phenomenological census. The focus of the Commentary is necessarily restricted, not least because we have to get from seconds to decades within the space of only a few pages! Therefore, we focus mainly on unforced variability in the troposphere, stratosphere, and mesosphere. Our scope includes coupled modes, in which the atmosphere interacts with the other components of the Earth system, such as the ocean, hydrosphere, and cryosphere. Given these interactions, and the importance of the atmosphere for weather and climate, our intended audience is the entire *Geophysical Research Letters* readership. Our aim is to provide an authoritative, concise, and accessible point of reference for the most important modes of atmospheric variability.

This Commentary serves as an introductory foreword to a virtual special collection of *Geophysical Research Letters* on atmospheric variability. To initiate the collection, we have identified some of the most influential and definitive papers to have been published in this journal in recent years. Our hope and expectation is that this will be a living collection, which will grow over time whenever seminal new papers are published.

The contents of the Commentary are ordered in terms of increasing time scale, from seconds and minutes (section 2), to hours (section 3), days (section 4), weeks (section 5), months (section 6), years (section 7), and decades (section 8). We note at the outset, however, that the time scales of many atmospheric phenomena are not unambiguously defined. For example, the Madden–Julian Oscillation (section 6) is monitored and forecasted from week to week but its spectral peak is 30–90 days, and a typical El Niño–Southern Oscillation event (section 7) has a duration of seasons but its spectral peak is 2–7 years. Therefore, while some phenomena are most easily identified in data spanning longer periods, their impacts may be experienced on considerably shorter time scales.

2. Seconds and Minutes: Turbulence

Atmospheric turbulence is an important component of dynamical variability on time scales of less than a few minutes. The atmospheric boundary layer, which is the lowest part of the atmosphere, mediates the vertical transport of heat, moisture, and momentum between Earth's surface and the free atmosphere. The rapid diurnal cycle of the boundary layer generates turbulence, which makes the boundary layer and its clouds challenging to represent in numerical weather prediction models and global climate models (Bony et al., 2015; Holtslag et al., 2013; Pithan et al., 2015). The challenges associated with boundary layer turbulence have implications for weather forecasting, assessment of regional climate variability (Ludwig et al., 2017), and climate change mitigation (Rigden & Li, 2017). Rapid atmospheric turbulence at the air–sea interface may have significant climatic impacts because of nonlinearities in the ocean's response to atmospheric forcing (Williams, 2012). At short spatiotemporal scales, large-eddy simulations may be used to assess the atmospheric boundary layer's impacts on clouds (Chu et al., 2014), pollution transport (Cécé et al., 2016), wildfires (Coen et al., 2012), and renewable energy (Worsnop et al., 2017). Dynamic downscaling of mesoscale simulations to large-eddy simulations incorporates mesoscale variability while introducing challenges when parameterized atmospheric boundary layer turbulence interacts with directly represented turbulence (Shin & Dudhia, 2016). Recent progress in coupling large-eddy simulations and weather models is promising (Muñoz–Esparza et al., 2017).

Above the atmospheric boundary layer, in the upper troposphere and lower stratosphere, turbulence affects aviation and contributes to stratosphere–troposphere exchange of atmospheric constituents. Although the importance of Kelvin–Helmholtz instability for clear-air turbulence is accepted (e.g., Dutton & Panofsky, 1970; Whiteway et al., 2004), interactions between wind shear and gravity waves (see section 3) have emerged as an important clear-air turbulence generation process (e.g., Knox et al., 2008; Pavelin et al., 2002; Sharman et al., 2012). Convective clouds are also an important source of turbulence. The spatial patterns of thunderstorm-generated turbulence have been exposed by high-resolution simulations (Lane & Sharman, 2014), with gravity wave breaking identified as an important mechanism (Lane et al., 2012). Moreover, new observations and mesoscale models have shown that turbulence often extends well beyond a thunderstorm's convective region, caused by Kelvin–Helmholtz instability in upper outflow regions (Trier & Sharman, 2009) and by gravity wave breaking above storms (Trier et al., 2012).

3. Hours: Gravity Waves

With oscillations centered on time scales of hours but ranging from minutes to days and spanning the mesoscale, gravity wave variability lies at the heart of many current research foci. In particular, gravity waves span the range of resolutions in current global models developed for weather forecasting (~10 km) and climate prediction (~100 km). In these models, gravity wave drag controls wind biases that affect synoptic weather and climate patterns of variability (Alexander et al., 2010; Plougonven & Zhang, 2014). However, even at resolutions of around 10 km, global models severely under-resolve the gravity wave spectrum (Holt et al., 2016; Jewtoukoff et al., 2015) and their drag effects are still parameterized. Observing these waves stretches the limits of global observing systems (Alexander, 2015; Geller et al., 2013). In the tropics, gravity waves may influence the Madden–Julian Oscillation (Yang & Ingersoll, 2014; see section 6). At high latitudes, gravity waves affect polar temperatures and ozone loss (Eckermann et al., 2009), and localized wave sources that generate large-amplitude waves are key to simulating realistic climate (de la Cámara & Lott, 2015). Whether jet stream imbalance is an important gravity wave source remains unclear (Williams et al., 2005, 2008). Resolving the gravity wave sources and the breaking process remains a challenge for even the highest-resolution models (Lane & Sharman, 2006; Fritts, Wang, et al., 2016). Poorly resolved short vertical wavelength waves (sometimes with very large horizontal scales) modulate tropopause temperatures, ozone, and tropical cirrus (Pierce & Grant, 1998; Jensen et al., 1996; J.-E. Kim et al., 2016). Thus, atmospheric gravity waves impact atmospheric variability on spatial scales ranging from the global to the microscale.

Above the troposphere and stratosphere, momentum deposition by gravity waves affects the zonal-mean wind, temperature, and meridional circulation in the mesosphere (Fritts & Alexander, 2003; Holton, 1983; Matsuno, 1982). Simulations using recently developed gravity wave-permitting general circulation models indicate that gravity waves emitted from tropospheric sources such as topography, convection, and jet-front systems may propagate large distances horizontally before reaching the mesosphere (Liu et al., 2014; Sato et al., 2009). Quantitative observational studies of momentum fluxes and wave characteristics have been performed using state-of-the-art instruments (Chu et al., 2011) and by combining multiple instruments (Alexander, 2015; Fritts, Smith, et al., 2016). Other important gravity wave phenomena include vertical coupling associated with an elevated stratopause (Chandran et al., 2011; Manney et al., 2009; Tomikawa et al., 2012) and interhemispheric coupling initiated by Sudden Stratospheric Warming events that may modify gravity wave propagation (Karlsson et al., 2009; Körnich & Becker, 2010).

4. Days: Weather Systems

In the extratropics, synoptic-scale weather systems drive atmospheric variability on time scales from days to weeks. Extratropical cyclones feature weather fronts, strong surface pressure variations, and rapidly ascending airstreams (Catto, 2016). They can produce strong surface winds (Ulbrich et al., 2001), heavy precipitation (Pfahl et al., 2014), and intense convection (Schemm et al., 2017). Quasi-stationary anticyclones, which are also known as atmospheric blocks (see section 5), can lead to prolonged dry and cold conditions in winter (Buehler et al., 2011) and dry and hot conditions in summer (Black et al., 2004). The movement of weather systems (and therefore the occurrence of weather extremes) is steered by the large-scale flow (Rothlisberger et al., 2016). However, the large-scale flow is also strongly affected by the weather systems (Yamada & Pauluis, 2017). In particular, weather systems resulting in surface extremes can exert a very strong feedback on the large-scale flow and low-frequency variability (Riviere & Orlanski, 2007) such as the North Atlantic Oscillation and its teleconnections (see sections 7 and 8). They can also move the flow into or out of a state in which weather extremes occur in one particular location (Hanley & Caballero, 2012).

In the tropics, the modulation of global cyclone activity as observed during the past 50 years is exemplified by low-frequency, intraseasonal to interannual oscillatory variability including the Madden–Julian Oscillation (Maloney & Hartmann, 2000), El Niño–Southern Oscillation (Camargo & Sobel, 2005), Pacific Decadal Oscillation (Chan, 2008), and Atlantic Multidecadal Oscillation (Bell & Chelliah, 2006; Gray, 1984). On average, 87 ± 8 named tropical cyclones (>34 knots or 17 m s^{-1}) occur annually, of which 47 ± 7 reach hurricane strength (>64 knots or 33 m s^{-1}), and they are distributed unevenly among the active Pacific, Indian, and Atlantic Ocean basins (Klotzbach & Landsea, 2015). Integrated activity metrics such as the Accumulated Cyclone Energy have fluctuated considerably over the past three decades, closely related to modes of global climate variability (Maue, 2011). Climate modeling studies suggest that global tropical cyclone numbers are predictable on seasonal to decadal timescales (Smith et al., 2010; Vecchi et al., 2014) and may see a slight increase in intensity against a decrease in frequency by 2100 due to global warming (Knutson et al., 2010).

5. Weeks: Atmospheric Blocking

An atmospheric block is a weather regime comprising a quasi-stationary region of high pressure that disrupts the extratropical westerly storm tracks, persists for around a week or longer, and possesses a horizontal half-width of a thousand or more kilometers. The airflow around the block is anticyclonic and Ω-shaped. Many of the weather extremes that impact the midlatitudes are associated with atmospheric blocks, such as heat waves (Dole et al., 2011), cold spells (Cattiaux et al., 2010), poor air quality (Fowler et al., 2008), and even Superstorm Sandy (Barnes et al., 2013). Blocks occur most frequently over the Pacific and Atlantic oceans and result from Rossby-wave breaking and the emergence of a low potential vorticity pool in the upper troposphere (Pelly & Hoskins, 2003; Schwierz et al., 2004). Blocks are precursors of, and linked to, the North Atlantic Oscillation and the Eastern Atlantic and Pacific-North America patterns of interannual climate variability (Croci–Maspoli et al., 2007a; Woollings et al., 2010; see section 8) and the occurrence of Sudden Stratospheric Warming events (Martius et al., 2009). Blocks often contribute substantially to seasonal anomaly patterns, and therefore they need to be captured adequately in weather and climate models (Dole et al., 2011; Matsueda, 2011; Scaife et al., 2011).

Recent and future climatological trends in blocking are of considerable interest (Croci–Maspoli et al., 2007b, Sillmann & Croci–Maspoli, 2009) because anthropogenic climate change is expected to cause significant changes in climate and weather extremes (Seneviratne et al., 2012). While it is well known that variations in blocking frequency are tightly tied to variations in the midlatitude jet streams and storm tracks (Berrisford et al., 2007), the extent to which these relationships explain the response of blocking to climate warming is unclear (Hassanzadeh & Kuang, 2015). Part of the confusion is due to disagreement about whether we have already witnessed changes in blocking over the satellite record. For example, some studies suggest that the recent decline of Arctic sea ice and associated Arctic warming have driven increases in blocking frequency throughout the northern midlatitudes (Francis & Vavrus, 2012; Liu et al., 2012). On the other hand, Barnes et al. (2014) compared regional trends in three unique blocking data sets and four different reanalysis products and concluded that no robust hemispheric trends in blocking have been observed. Furthermore, causal links between future Arctic warming and increasing blocking frequencies have been challenged in the literature (Hassanzadeh et al., 2014; Woollings et al., 2014). The extensive and dichotomous scientific debate about blocking trends in the present and coming decades highlights the difficulty of identifying forced trends in blocking from a background of substantial internally driven interannual and decadal variability.

6. Months: The Madden–Julian Oscillation

The Madden–Julian Oscillation (MJO) is an atmospheric phenomenon in the tropics with dominant timescales of 30–90 days (Madden & Julian, 1971, 1972). It features eastward propagation of large-scale patterns of rainfall, zonal wind, and humidity at an average speed of 5 m s^{-1} along the equator from the Indian Ocean to the Pacific Ocean (Zhang, 2005). Tremendous progress has been made in the study of the MJO during the past four decades (Zhang et al., 2013) and recently in its understanding (Ma & Kuang, 2016; Xu & Rutledge, 2016; Yang & Ingersoll, 2014), simulation (Ajayamohan et al., 2013; Ling et al., 2017; Song & Seo, 2016), and prediction (Chen et al., 2014; Shelly et al., 2014). Because of its timescale and expected eastward propagation, the MJO is considered to be a major source of predictability on subseasonal to seasonal timescales (Vitart, 2017; Waliser et al., 2003).

In the tropics, the MJO influences higher-frequency phenomena such as tropical cyclones (see section 4) and lower-frequency phenomena such as El Niño (see section 7). The tropical diabatic heating associated with the MJO excites subtropical planetary waves via its divergent outflow, and these subtropical Rossby waves then propagate poleward and impact the extratropical Pacific and Indian Ocean sectors (Bao & Hartmann, 2014; Seo & Son, 2012) including populated regions of Asia and North America (Higgins et al., 2000; Zhang, 2013). These wave perturbations can then influence hemispherically symmetric weather patterns in the extratropics of both the Southern (Matthews & Meredith, 2004) and Northern Hemispheres (L'Heureux & Higgins, 2008; Riddle et al., 2013) and modulate the North Atlantic Oscillation (Lin et al., 2009). The MJO has also been linked to changes in individual cyclones and blocking events (Guo et al., 2017; Henderson et al., 2016). These linkages influence the distribution of climate extremes (Hoell et al., 2014; Zhang, 2013), and they also impact the stratosphere (Garfinkel et al., 2012; Garfinkel et al., 2014).

7. Years: The Quasi-Biennial Oscillation and El Niño–Southern Oscillation

Seasonal-to-decadal forecasts of the three-dimensional state of the atmosphere are routinely produced using general circulation models (GCMs) initialized with observations and integrated forward months or years ahead. Coupled modes involving the slowly varying tropical ocean provide predictability, some of which leaks into the extratropics where it drives potentially useful predictions (Scaife, Arribas, et al., 2014). The Quasi-Biennial Oscillation (QBO) is a notable exception to this ocean-dominated picture. The QBO is a purely internal atmospheric phenomenon, which has period of around 28 months. It is driven by momentum fluxes from vertically propagating internal waves (Geller et al., 2013) and is now reproduced in GCMs (Giorgetta et al., 2002; Scaife et al., 2000). Much less well studied is its predictability. Scaife, Athanassiadou, et al. (2014) showed that the QBO can be skillfully predicted out to several years. However, this predictability does not extend to the QBO's modeled surface impacts (Baldwin et al., 2001; Ebdon, 1975). The prediction systems analyzed by Scaife, Athanassiadou, et al. (2014) showed only a weak version of the observed surface signal.

This may be part of a wider issue (Eade et al., 2014) and could provide additional skill in future improved prediction systems.

The El Niño–Southern Oscillation (ENSO) is a coupling between the tropical atmosphere and ocean on timescales of roughly 2–7 years, with societal and economic impacts spanning the globe (Arblaster & Alexander, 2012; Greatbatch et al., 2004; Hoell et al., 2016; Klotzbach, 2011; Lyon, 2004; Zeng & Pyle, 2005). During the El Niño phase of ENSO, a relaxation of the tropical trade winds flattens the oceanic thermocline, reducing upwelling of cold deep water and driving anomalously warm sea surface temperatures (SSTs) in the eastern tropical Pacific. Conversely, anomalously cool SSTs in the eastern Pacific form during the La Niña phase. Shifts in the region of warm SSTs modify convective patterns, driving remote changes to the global atmospheric circulation via both tropospheric and stratospheric pathways (Butler & Polvani, 2011; Iza & Calvo, 2015; Trenberth et al., 1998). Because ENSO explains a nontrivial fraction of midlatitude atmospheric variability (Seager et al., 2003), it is an important predictor in seasonal climate forecasts (Ropelewski & Halpert, 1987), despite the diversity of ENSO events (Capotondi et al., 2015) and the difficulty of isolating the ENSO signal from large internal atmospheric variability (Deser et al., 2017). Predicting the phase and amplitude of ENSO itself also remains challenging for certain seasons and lead times (Barnston et al., 2017; Levine & McPhaden, 2015; Martín-Rey et al., 2015; McPhaden et al., 2006; Wang et al., 2011).

8. Decades: The North Atlantic, Arctic, Antarctic, Pacific Decadal, and Atlantic Multidecadal Oscillations

The North Atlantic Oscillation (NAO) is a perturbation of the atmospheric circulation over the North Atlantic Ocean. It is a north–south seesaw in atmospheric mass, simultaneously affecting the strengths of the surface Icelandic low and Azores high (Hurrell et al., 2003; Wanner et al., 2001). While the nominal persistence of the perturbation is measured in days, the NAO exhibits variability on a broad range of time scales including interannual and decadal. The NAO is expressed through the depth of the troposphere by a pressure dipole, straddling the mean latitude of the jet stream (Kushnir & Wallace, 1989). In that respect, the NAO resembles the Arctic Oscillation, which has an additional footprint in the North Pacific and emphasizes a deep extension into the stratosphere (Deser, 2000; Wallace, 2000). The analogous mode in the Southern Hemisphere is the Antarctic Oscillation or Southern Annular Mode, which is an important driver of rainfall variability in southern Australia (Gong & Wang, 1999; Meneghini et al., 2007). Geostrophy implies that the NAO is also a simultaneous perturbation in the latitudinal position and strength of the North Atlantic jet stream. The north–south swings interact with the parallel movement of the extratropical storm track (Riviere & Orlanski, 2007). The NAO changes the surface wind strength and direction, thereby forcing changes in the ocean (Dickson et al., 2000; Eden & Jung, 2001; Kwok, 2000; Visbeck et al., 1998). Because of its considerable climatic impacts, many attempts have been made to predict the winter NAO using statistical methods (Cohen & Entekhabi, 1999) and general circulation models (Scaife, Arribas, et al., 2014). The societal benefits of skillful predictions could be large (Smith et al., 2016).

The Pacific Decadal Oscillation (PDO) (Mantua et al., 1997) and the Atlantic Multi-decadal Oscillation (AMO) (Kerr, 2000) are defined in terms of sea surface temperature variability in the northern portions of these individual basins. Their existence relies upon dynamical coupling between the atmosphere and the ocean. Empirical orthogonal function analyses of appropriately filtered sea surface temperature data for the Pacific Ocean north of 20°N (d'Orgeville & Peltier, 2007) demonstrate the PDO to consist of two primary components with characteristic periods of around 20 years and 60 years. The lower-frequency component simply modulates the amplitude of the higher-frequency component. The higher-frequency component is interpreted as a basin-scale mode governed by westward propagating Rossby wave dynamics within the ocean (Latif and Barnett, 1996; Cessi & Louazel, 2001). Models are highly successful in capturing the PDO (d'Orgeville & Peltier, 2009a), although the predictability may be low (see Newman et al., 2016, for a recent discussion). The AMO, on the other hand, has a characteristic period of around 60 years and is strongly connected to variability in the strength of the Atlantic Meridional Overturning Circulation. Models have generally been found to have difficulty in capturing the observed 60 year period of this mode (but see d'Orgeville & Peltier, 2009b). d'Orgeville and Peltier (2007) demonstrate that the 60 year modulation of the amplitude of the PDO is simply a phase-lagged version of the AMO, suggesting that these northern hemisphere modes of coupled ocean–atmosphere dynamics may be deeply connected.

9. Summary

This Commentary has attempted to provide an authoritative, concise, and accessible point of reference for the most important modes of atmospheric variability. We make no claims that our coverage of the subject matter has been comprehensive, and the astute reader will certainly find gaps. For example, we have largely neglected interactions between the modes, such as the known dependence of turbulence on the North Atlantic Oscillation (J.-H. Kim et al., 2016). With one or two exceptions, we have also largely neglected the forced component of variability, which originates from anthropogenic interference, volcanic activity, and solar variability. For example, some aspects of the variability may be modified by anthropogenic climate change, such as the hypothesized future increase in turbulence induced by changes to the jet stream (Storer et al., 2017; Williams, 2017; Williams & Joshi, 2013). Finally, we have hardly touched on the problem of how to parameterize the impacts of the subgrid-scale variability on the resolved flow in numerical models, or the question of whether simulations will be improved by increased model resolution. Nevertheless, we hope that the Commentary will serve as a useful resource for the atmospheric science community and that the papers contained within the special collection will act as inspiration for setting future research directions.

Acknowledgments
P.D.W. is funded by the Royal Society under a University Research Fellowship award UF130571. E.A.B. is funded by the National Science Foundation under grant AGS-1545675. C.I.G. is funded by the Israel Science Foundation under grant 1558/14 and by the European Union Horizon 2020 research and innovation program under European Research Council starting grant 677756. T.P.L. is funded by the Australian Research Council's Centre of Excellence for Climate Extremes under grant CE170100023. J.K.L. is funded by the National Science Foundation under CAREER award AGS-1554055. O.M. is supported by the Swiss National Science Foundation under grant 200021-156059. K.S. is funded by the Japan Society for the Promotion of Science Grants-in-Aid for Scientific Research grant 25247075 and by the Japan Science and Technology Agency under CREST grant JPMJCR1663. A.A.S. is funded by the joint DECC/DEFRA Met Office Hadley Centre Climate Programme under grant GA01101. Through the coauthorship of C.Z., this paper is Pacific Marine Environmental Laboratory contribution number 4703. This paper contains no new data or models.

References

Ajayamohan, R. S., Khouider, B., & Majda, A. J. (2013). Realistic initiation and dynamics of the Madden–Julian Oscillation in a coarse resolution aquaplanet GCM. *Geophysical Research Letters*, *40*, 6252–6257. https://doi.org/10.1002/2013GL058187

Alexander, M. J. (2015). Global and seasonal variations in three-dimensional gravity wave momentum flux from satellite limb-sounding temperatures. *Geophysical Research Letters*, *42*, 6860–6867. https://doi.org/10.1002/2015GL065234

Alexander, M. J., Geller, M., McLandress, C., Polavarapu, S., Preusse, P., Sassi, F., … Watanabe, S. (2010). Recent developments in gravity-wave effects in climate models and the global distribution of gravity-wave momentum flux from observations and models. *Quarterly Journal of the Royal Meteorological Society*, *136*, 1103–1124. https://doi.org/10.1002/qj.637

Arblaster, J. M., & Alexander, L. V. (2012). The impact of the El Niño–Southern Oscillation on maximum temperature extremes. *Geophysical Research Letters*, *39*, L20702. https://doi.org/10.1029/2012GL053409

Baldwin, M. P., Gray, L. J., Dunkerton, T. J., Hamilton, K., Haynes, P. H., Randel, W. J., … Takahashi, M. (2001). The quasi-biennial oscillation. *Reviews of Geophysics*, *39*, 179–229. https://doi.org/10.1029/1999RG000073

Bao, M., & Hartmann, D. L. (2014). The response to MJO-like forcing in a nonlinear shallow-water model. *Geophysical Research Letters*, *41*, 1322–1328. https://doi.org/10.1002/2013GL057683

Barnes, E. A., Dunn-Sigouin, E., Masato, G., & Woollings, T. (2014). Exploring recent trends in Northern Hemisphere blocking. *Geophysical Research Letters*, *41*, 638–644. https://doi.org/10.1002/2013GL058745

Barnes, E. A., Polvani, L. M., & Sobel, A. H. (2013). Model projections of atmospheric steering of Sandy-like superstorms. *Proceedings of the National Academy of Sciences*, *110*(38), 15,211–15,215. https://doi.org/10.1073/pnas.1308732110

Barnston, A. G., Tippett, M. K., Ranganathan, M., & L'Heureux, M. L. (2017). Deterministic skill of ENSO predictions from the North American Multimodel Ensemble. *Climate Dynamics*, 1–20. https://doi.org/10.1007/s00382-017-3603-3

Bell, G. D., & Chelliah, M. (2006). Leading tropical modes associated with interannual and multidecadal fluctuations in North Atlantic hurricane activity. *Journal of Climate*, *19*(4), 590–612. https://doi.org/10.1175/JCLI3659.1

Berrisford, P., Hoskins, B. J., & Tyrlis, E. (2007). Blocking and Rossby wave breaking on the dynamical tropopause in the southern hemisphere. *Journal of the Atmospheric Sciences*, *64*(8), 2881–2898. https://doi.org/10.1175/JAS3984.1

Black, E., Blackburn, M., Harrison, G., Hoskins, B., & Methven, J. (2004). Factors contributing to the summer 2003 European heatwave. *Weather*, *59*(8), 217–223. https://doi.org/10.1256/wea.74.04

Bony, S., Stevens, B., Frierson, D. M. W., Jakob, C., Kageyama, M., Pincus, R., … Webb, M. J. (2015). Clouds, circulation and climate sensitivity. *Nature Geoscience*, *8*(4), 261–268. https://doi.org/10.1038/ngeo2398

Buehler, T., Raible, C. C., & Stocker, T. F. (2011). The relationship of winter season North Atlantic blocking frequencies to extreme cold or dry spells in the ERA-40. *Tellus A*, *63*(2), 174–187. https://doi.org/10.1111/j.1600-0870.2010.00492.x

Butler, A. H., & Polvani, L. M. (2011). El Niño, La Niña, and stratospheric sudden warmings: A reevaluation in light of the observational record. *Geophysical Research Letters*, *38*, L13807. https://doi.org/10.1029/2011GL048084

Camargo, S. J., & Sobel, A. H. (2005). Western North Pacific tropical cyclone intensity and ENSO. *Journal of Climate*, *18*(15), 2996–3006. https://doi.org/10.1175/JCLI3457.1

Capotondi, A., Wittenberg, A. T., Newman, M., Di Lorenzo, E., Yu, J., Braconnot, P., … Yeh, S. (2015). Understanding ENSO diversity. *Bulletin of the American Meteorological Society*, *96*(6), 921–938. https://doi.org/10.1175/BAMS-D-13-00117.1

Cattiaux, J., Vautard, R., Cassou, C., Yiou, P., Masson–Delmotte, V., & Codron, F. (2010). Winter 2010 in Europe: A cold extreme in a warming climate. *Geophysical Research Letters*, *37*, L20704. https://doi.org/10.1029/2010GL044613

Catto, J. L. (2016). Extratropical cyclone classification and its use in climate studies. *Reviews of Geophysics*, *54*, 486–520. https://doi.org/10.1002/2016RG000519

Cécé, R., Bernard, D., Brioude, J., & Zahibo, N. (2016). Microscale anthropogenic pollution modelling in a small tropical island during weak trade winds: Lagrangian particle dispersion simulations using real nested LES meteorological fields. *Atmospheric Environment*, *139*, 98–112. https://doi.org/10.1016/j.atmosenv.2016.05.028

Cessi, P., & Louazel, S. (2001). Decadal oceanic response to stochastic wind forcing. *Journal of Physical Oceanography*, *31*(10), 3020–3029. https://doi.org/10.1175/1520-0485(2001)031%3C3020:DORTSW%3E2.0.CO;2

Chan, J. C. L. (2008). Decadal variations of intense typhoon occurrence in the western North Pacific. *Proceedings of the Royal Society A*, *464*(2089), 249–272. https://doi.org/10.1098/rspa.2007.0183

Chandran, A., Collins, R. L., Garcia, R. R., & Marsh, D. R. (2011). A case study of an elevated stratopause generated in the Whole Atmosphere Community Climate Model. *Geophysical Research Letters*, *38*, L08804. https://doi.org/10.1029/2010GL046566

Chen, N., Majda, A. J., & Giannakis, D. (2014). Predicting the cloud patterns of the Madden–Julian Oscillation through a low-order nonlinear stochastic model. *Geophysical Research Letters*, *41*, 5612–5619. https://doi.org/10.1002/2014GL060876

Chu, X., Xue, L., Geerts, B., Rasmussen, R., & Breed, D. (2014). A case study of radar observations and WRF LES simulations of the impact of ground-based glaciogenic seeding on orographic clouds and precipitation. Part I: Observations and model validations. *Journal of Applied Meteorology and Climatology*, *53*(10), 2264–2286. https://doi.org/10.1175/JAMC-D-14-0017.1

Chu, X., Yu, Z., Gardner, C. S., Chen, C., & Fong, W. (2011). Lidar observations of neutral Fe layers and fast gravity waves in the thermosphere (110–155 km) at McMurdo (77.8°S, 166.7°E), Antarctica. *Geophysical Research Letters*, *38*, L23807. https://doi.org/10.1029/2011GL050016

Coen, J. L., Cameron, M., Michalakes, J., Patton, E. G., Riggan, P. J., & Yedinak, K. M. (2012). WRF-fire: Coupled weather–wildland fire modeling with the Weather Research and Forecasting Model. *Journal of Applied Meteorology and Climatology*, *52*(1), 16–38. https://doi.org/10.1175/JAMC-D-12-023.1

Cohen, J., & Entekhabi, D. (1999). Eurasian snow cover variability and Northern Hemisphere climate predictability. *Geophysical Research Letters*, *26*, 345–348. https://doi.org/10.1029/1998GL900321

Croci–Maspoli, M., Schwierz, C., & Davies, H. C. (2007a). Atmospheric blocking: Space-time links to the NAO and PNA. *Climate Dynamics*, *29*(7-8), 713–725. https://doi.org/10.1007/s00382-007-0259-4

Croci–Maspoli, M., Schwierz, C., & Davies, H. C. (2007b). A multi-faceted climatology of atmospheric blocking and its recent linear trend. *Journal of Climate*, *20*, 633–649. https://doi.org/doi.org/10.1175/JCLI4029.1

de la Cámara, A., & Lott, F. (2015). A parameterization of gravity waves emitted by fronts and jets. *Geophysical Research Letters*, *42*, 2071–2078. https://doi.org/10.1002/2015GL063298

Deser, C. (2000). On the teleconnectivity of the "Arctic Oscillation". *Geophysical Research Letters*, *27*, 779–782. https://doi.org/10.1029/1999GL010945

Deser, C., Simpson, I. R., McKinnon, K. A., & Phillips, A. S. (2017). The northern hemisphere extratropical atmospheric circulation response to ENSO: How well do we know it and how do we evaluate models accordingly? *Journal of Climate*, *30*(13), 5059–5082. https://doi.org/10.1175/JCLI-D-16-0844.1

Dickson, R. R., Osborn, T. J., Hurrell, J. W., Meincke, J., Blindheim, J., Adlandsvik, B., … Maslowski, W. (2000). The Arctic Ocean response to the North Atlantic Oscillation. *Journal of Climate*, *13*(15), 2671–2696. https://doi.org/10.1175/1520%E2%80%930442(2000)013%3C2671:Taortt%3E2.0.Co;2

Dole, R., Hoerling, M., Perlwitz, J., Eischied, J., Pegion, P., Zhang, T., … Murray, D. (2011). Was there a basis for anticipating the 2010 Russian heat wave? *Geophysical Research Letters*, *38*, L06702. https://doi.org/10.1029/2010GL046582

d'Orgeville, M., & Peltier, W. R. (2007). On the Pacific Decadal Oscillation and the Atlantic Multidecadal Oscillation: Might they be related? *Geophysical Research Letters*, *34*, L23705. https://doi.org/10.1029/2007GL031584

d'Orgeville, M., & Peltier, W. R. (2009a). Implications of both statistical equilibrium and global warming simulations with CCSM3. Part 1: On the decadal variability in the North Pacific Basin. *J. Climate*, *22*, 179–199. https://doi.org/10.1175/2009JCL12428.1

d'Orgeville, M., & Peltier, W. R. (2009b). Implications of both statistical equilibrium and global warming simulations with CCSM3. Part 2: On the multidecadal variability in the North Atlantic Basin. *Journal of Climate*, *22*, 200–220. https://doi.org/10.1175/2009JCL12775.1

Dutton, J. A., & Panofsky, H. A. (1970). Clear air turbulence: A mystery may be unfolding. *Science*, *167*(3920), 937–944. https://doi.org/10.1126/science.167.3920.937

Eade, R., Smith, D., Scaife, A. A., & Wallace, E. (2014). Do seasonal to decadal climate predictions underestimate the predictability of the real world? *Geophysical Research Letters*, *41*, 5620–5628. https://doi.org/10.1002/2014GL061146

Ebdon, R. A. (1975). The quasi-biennial oscillation and its association with tropospheric circulation patterns. *Meteorological Magazine*, *104*, 282–297.

Eckermann, S. D., Hoffmann, L., Höpfner, M., Wu, D. L., & Alexander, M. J. (2009). Antarctic NAT PSC belt of June 2003: Observational validation of the mountain wave seeding hypothesis. *Geophysical Research Letters*, *36*, L02807. https://doi.org/10.1029/2008GL036629

Eden, C., & Jung, T. (2001). North Atlantic interdecadal variability: Oceanic response to the North Atlantic Oscillation (1865–1997). *Journal of Climate*, *14*(5), 676–691. https://doi.org/10.1175/1520-0442(2001)014%3C0676:NAIVOR%3E2.0.CO;2

Fowler, D., Amann, M., Anderson, R., Ashmore, M., Cox, P., Depledge, M., … Stevenson, D. (2008). Ground-level ozone in the 21st century: Future trends, impacts and policy implications, Royal Society Science Policy Report 15/08, Royal Society, London, UK.

Francis, J. A., & Vavrus, S. J. (2012). Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophysical Research Letters*, *39*, L06801. https://doi.org/10.1029/2012GL051000

Fritts, D. C., & Alexander, M. J. (2003). Gravity wave dynamics and effects in the middle atmosphere, *Reviews of Geophysics*, *41*(1), 1003. https://doi.org/10.1029/2001RG000106

Fritts, D. C., Smith, R. B., Taylor, M. J., Doyle, J. D., Eckermann, S. D., Dörnbrack, A., … Ma, J. (2016). The deep propagating gravity wave experiment (DEEPWAVE): An airborne and ground-based exploration of gravity wave propagation and effects from their sources throughout the lower and middle atmosphere. *Bulletin of the American Meteorological Society*, *97*(3), 425–453. https://doi.org/10.1175/BAMS-D-14-00269.1

Fritts, D. C., Wang, L., Geller, M. A., Lawrence, D. A., Werne, J., & Balsley, B. B. (2016). Numerical modeling of multiscale dynamics at a high Reynolds number: Instabilities, turbulence, and an assessment of Ozmidov and Thorpe scales. *Journal of the Atmospheric Sciences*, *73*(2), 555–578. https://doi.org/10.1175/JAS-D-14-0343.1

Garfinkel, C. I., Benedict, J. J., & Maloney, E. D. (2014). Impact of the MJO on the boreal winter extratropical circulation. *Geophysical Research Letters*, *41*, 6055–6062. https://doi.org/10.1002/2014GL061094

Garfinkel, C. I., Feldstein, S. B., Waugh, D. W., Yoo, C., & Lee, S. (2012). Observed connection between stratospheric sudden warmings and the Madden–Julian Oscillation. *Geophysical Research Letters*, *39*, L18807. https://doi.org/10.1029/2012GL053144

Geller, M. A., Alexander, M. J., Love, P. T., Bacmeister, J., Ern, M., Hertzog, A., … Zhou, T. (2013). A comparison between gravity wave momentum fluxes in observations and climate models. *Journal of Climate*, *26*(17), 6383–6405. https://doi.org/10.1175/JCLI-D-12-00545.1

Giorgetta, M. A., Manzini, E., & Roeckner, E. (2002). Forcing of the quasi-biennial oscillation from a broad spectrum of atmospheric waves, *Geophysical Research Letters*, *29*(8), 1245. https://doi.org/10.1029/2002GL014756

Gong, D., & Wang, S. (1999). Definition of Antarctic Oscillation index. *Geophysical Research Letters*, *26*, 459–462. https://doi.org/10.1029/1999GL900003

Gray, W. M. (1984). Atlantic seasonal hurricane frequency. Part I: El Niño and 30 mb quasi-biennial oscillation influences. *Monthly Weather Review*, *112*(9), 1649–1668. https://doi.org/10.1175/1520-0493(1984)112%3C1649:ASHFPI%3E2.0.CO;2

Greatbatch, R. J., Lu, J., & Peterson, K. A. (2004). Nonstationary impact of ENSO on Euro–Atlantic winter climate. *Geophysical Research Letters*, *31*, L02208. https://doi.org/10.1029/2003GL018542

Guo, Y., Shinoda, T., Lin, J., & Chang, E. K. (2017). Variations of northern hemisphere storm track and extratropical cyclone activity associated with the Madden–Julian Oscillation. *Journal of Climate*, *30*(13), 4799–4818. https://doi.org/10.1175/JCLI-D-16-0513.1

Hanley, J., & Caballero, R. (2012). The role of large-scale atmospheric flow and Rossby wave breaking in the evolution of extreme windstorms over Europe. *Geophysical Research Letters*, *39*, L21708. https://doi.org/10.1029/2012GL053408

Hassanzadeh, P., & Kuang, Z. (2015). Blocking variability: Arctic amplification versus Arctic Oscillation. *Geophysical Research Letters*, *42*, 8586–8595. https://doi.org/10.1002/2015GL065923

Hassanzadeh, P., Kuang, Z., & Farrell, B. F. (2014). Responses of mid-latitude blocks and wave amplitude to changes in the meridional temperature gradient in an idealized dry GCM. *Geophysical Research Letters*, *41*, 5223–5232. https://doi.org/10.1002/2014GL060764

Henderson, S., Maloney, E., & Barnes, E. (2016). The influence of the Madden–Julian Oscillation on Northern Hemisphere winter blocking. *Journal of Climate*, *29*(12), 4597–4616. https://doi.org/10.1175/JCLI-D-15-0502.1

Higgins, R. W., Schemm, J. E., Shi, W., & Leetmaa, A. (2000). Extreme precipitation events in the western United States related to tropical forcing. *Journal of Climate*, *13*(4), 793–820. https://doi.org/10.1175/1520-0442(2000)013%3C0793:EPEITW%3E2.0.CO;2

Hoell, A., Barlow, M., Wheeler, M. C., & Funk, C. (2014). Disruptions of El Niño–Southern Oscillation teleconnections by the Madden–Julian Oscillation. *Geophysical Research Letters*, *41*, 998–1004. https://doi.org/10.1002/2013GL058648

Hoell, A., Hoerling, M., Eischeid, J., Wolter, K., Dole, R., Perlwitz, J., … Cheng, L. (2016). Does El Niño intensity matter for California precipitation? *Geophysical Research Letters*, *43*, 819–825. https://doi.org/10.1002/2015GL067102

Holt, L. A., Alexander, M. J., Coy, L., Molod, A., Putman, W., & Pawson, S. (2016). Tropical waves and the Quasi-Biennial Oscillation in a 7-km global climate simulation. *Journal of the Atmospheric Sciences*, *73*(9), 3771–3783. https://doi.org/10.1175/JAS-D-15-0350.1

Holton, J. R. (1983). The influence of gravity wave breaking on the general circulation of the middle atmosphere. *Journal of the Atmospheric Sciences*, *40*(10), 2497–2507. https://doi.org/10.1175/1520-0469(1983)040%3C2497:TIOGWB%3E2.0.CO;2

Holtslag, A. A. M., Svensson, G., Baas, P., Basu, S., Beare, B., Beljaars, A. C. M., … van de Wiel, B. J. H. (2013). Stable atmospheric boundary layers and diurnal cycles: Challenges for weather and climate models. *Bulletin of the American Meteorological Society*, *94*(11), 1691–1706. https://doi.org/10.1175/BAMS-D-11-00187.1

Hurrell, J. W., Kushnir, Y., Ottersen, G., & Visbeck, M. (2003). An overview of the North Atlantic oscillation. In J. W. Hurrell, et al. (Eds.), *The North Atlantic Oscillation: Climatic significance and environmental impact*, *Geophysical Monographs Series*, (pp. 1–35). Washington, DC: American Geophysical Union.

Iza, M., & Calvo, N. (2015). Role of stratospheric sudden warmings on the response to Central Pacific El Niño. *Geophysical Research Letters*, *42*, 2482–2489. https://doi.org/10.1002/2014GL062935

Jensen, E. J., Toon, O. B., Pfister, L., & Selkirk, H. B. (1996). Dehydration of the upper troposphere and lower stratosphere by subvisible cirrus clouds near the tropical tropopause. *Geophysical Research Letters*, *23*, 825–828. https://doi.org/10.1029/96GL00722

Jewtoukoff, V., Hertzog, A., Plougonven, R., Cámara, A. D., & Lott, F. (2015). Comparison of gravity waves in the southern hemisphere derived from balloon observations and the ECMWF analyses. *Journal of the Atmospheric Sciences*, *72*(9), 3449–3468. https://doi.org/10.1175/JAS-D-14-0324.1

Karlsson, B., Randall, C. E., Benze, S., Mills, M., Harvey, V. L., Bailey, S. M., & Russell, J. M. (2009). Intra-seasonal variability of polar mesospheric clouds due to inter-hemispheric coupling. *Geophysical Research Letters*, *36*, L20802. https://doi.org/10.1029/2009GL040348

Kerr, R. (2000). A North Atlantic climate pacemaker for the centuries. *Science*, *288*(5473), 1984–1985. https://doi.org/10.1126/science.288.5473.1984

Kim, J.-E., Alexander, M. J., Bui, T. P., Dean-Day, J. M., Lawson, R. P., Woods, S., … Jensen, E. J. (2016). Ubiquitous influence of waves on tropical high cirrus clouds. *Geophysical Research Letters*, *43*, 5895–5901. https://doi.org/10.1002/2016GL069293

Kim, J.-H., Chan, W. N., Sridhar, B., Sharman, R. D., Williams, P. D., & Strahan, M. (2016). Impact of the North Atlantic Oscillation on transatlantic flight routes and clear-air turbulence. *Journal of Applied Meteorology and Climatology*, *55*(3), 763–771. https://doi.org/10.1175/JAMC-D-15-0261.1

Klotzbach, P. J. (2011). El Niño–Southern Oscillation's impact on Atlantic basin hurricanes and U.S. landfalls. *Journal of Climate*, *24*(4), 1252–1263. https://doi.org/10.1175/2010JCLI3799.1

Klotzbach, P. J., & Landsea, C. W. (2015). Extremely intense hurricanes: Revisiting Webster et al. (2005) after 10-years. *Journal of Climate*, *28*(19), 7621–7629. https://doi.org/10.1175/JCLI-D-15-0188.1

Knox, J. A., McCann, D. W., & Williams, P. D. (2008). Application of the Lighthill–Ford theory of spontaneous imbalance to clear-air turbulence forecasting. *Journal of the Atmospheric Sciences*, *65*(10), 3292–3304. https://doi.org/10.1175/2008JAS2477.1

Knutson, T. R., McBride, J. L., Chan, J., Emanuel, K., Holland, G., Landsea, C., … Sugi, M. (2010). Tropical cyclones and climate change. *Nature Geoscience*, *3*(3), 157–163. https://doi.org/10.1038/ngeo779

Körnich, H., & Becker, E. (2010). A simple model for the interhemispheric coupling of the middle atmosphere circulation. *Advances in Space Research*, *45*(5), 661–668. https://doi.org/10.1016/j.asr.2009.11.001

Kushnir, Y., & Wallace, J. M. (1989). Low-frequency variability in the northern hemisphere winter—Geographical-distribution, structure and time-scale dependence. *Journal of the Atmospheric Sciences*, *46*(20), 3122–3143. https://doi.org/10.1175/1520-0469(1989)046%3C3122:LFVITN%3E2.0.CO;2

Kwok, R. (2000). Recent changes in Arctic Ocean sea ice motion associated with the North Atlantic Oscillation. *Geophysical Research Letters*, *27*, 775–778. https://doi.org/10.1029/1999GL002382

Lane, T. P., & Sharman, R. D. (2006). Gravity wave breaking, secondary wave generation, and mixing above deep convection in a three-dimensional cloud model. *Geophysical Research Letters*, *33*, L23813. https://doi.org/10.1029/2006GL027988

Lane, T. P., & Sharman, R. D. (2014). Intensity of thunderstorm-generated turbulence revealed by large-eddy simulation. *Geophysical Research Letters*, *41*, 2221–2227. https://doi.org/10.1002/2014GL059299

Lane, T. P., Sharman, R. D., Trier, S. B., Fovell, R. G., & Williams, J. K. (2012). Recent advances in the understanding of near-cloud turbulence. *Bulletin of the American Meteorological Society*, *93*(4), 499–515. https://doi.org/10.1175/BAMS-D-11-00062.1

Latif, M., & Barnett, T. P. (1996). Decadal climate variability over the North Pacific and North America: Dynamics and Predictability. *Journal of Climate*, *9*, 2407–2423. https://doi.org/10.1175/1520-0442(1996)009<2407:DCVOTN>2.0.CO;2

Levine, A. F. Z., & McPhaden, M. J. (2015). The annual cycle in ENSO growth rate as a cause of the spring predictability barrier. *Geophysical Research Letters*, *42*, 5034–5041. https://doi.org/10.1002/2015GL064309

L'Heureux, M. L., & Higgins, R. W. (2008). Boreal winter links between the Madden–Julian Oscillation and the Arctic Oscillation. *Journal of Climate*, *21*(12), 3040–3050. https://doi.org/10.1175/2007JCLI1955.1

Lin, H., Brunet, G., & Derome, J. (2009). An observed connection between the North Atlantic Oscillation and the Madden–Julian Oscillation. *Journal of Climate*, *22*(2), 364–380. https://doi.org/10.1175/2008JCLI2515.1

Ling, J., Zhang, C., Wang, S., & Li, C. (2017). A new interpretation of the ability of global models to simulate the MJO. *Geophysical Research Letters*, *44*, 5798–5806. https://doi.org/10.1002/%202017GL073891

Liu, H., Mcinerney, J. M., Santos, S., Lauritzen, P. H., Taylor, M. A., & Pedatella, N. M. (2014). Gravity waves simulated by high-resolution Whole Atmosphere Community Climate Model. *Geophysical Research Letters*, *41*, 9106–9112. https://doi.org/10.1002/2014GL062468

Liu, J., Curry, J., & Wang, H. (2012). Impact of declining Arctic sea ice on winter snowfall. *Proceedings of the National Academy of Sciences*, *109*(11), 4074–4079. https://doi.org/10.1073/pnas.1114910109

Ludwig, P., Pinto, J. G., Raible, C. C., & Shao, Y. (2017). Impacts of surface boundary conditions on regional climate model simulations of European climate during the Last Glacial Maximum. *Geophysical Research Letters*, *44*, 5086–5095. https://doi.org/10.1002/2017GL073622

Lyon, B. (2004). The strength of El Niño and the spatial extent of tropical drought. *Geophysical Research Letters*, *31*, L21204. https://doi.org/10.1029/2004GL020901

Ma, D., & Kuang, Z. (2016). A mechanism-denial study on the Madden–Julian Oscillation with reduced interference from mean state changes. *Geophysical Research Letters*, *43*, 2989–2997. https://doi.org/10.1002/2016GL067702

Madden, R. A., & Julian, P. R. (1971). Detection of a 40–50-day oscillation in zonal wind in tropical Pacific. *Journal of the Atmospheric Sciences*, *28*(5), 702–708. https://doi.org/10.1175/1520-0469(1971)028,0702:DOADOI.2.0.CO;2

Madden, R. A., & Julian, P. R. (1972). Description of global-scale circulation cells in tropics with a 40–50 day period. *Journal of the Atmospheric Sciences*, *29*(6), 1109–1123. https://doi.org/10.1175/1520-0469(1972)029,1109:DOGSCC.2.0.CO;2

Maloney, E. D., & Hartmann, D. L. (2000). Modulation of Eastern North Pacific Hurricanes by the Madden–Julian Oscillation. *Journal of Climate*, *13*(9), 1451–1460. https://doi.org/10.1175/1520-0442(2000)013%3C1451:MOENPH%3E2.0.CO;2

Manney, G. L., Schwartz, M. J., Krüger, K., Santee, M. L., Pawson, S., Lee, J. N., … Livesey, N. J. (2009). Aura Microwave Limb Sounder observations of dynamics and transport during the record-breaking 2009 Arctic stratospheric major warming. *Geophysical Research Letters*, *36*, L12815. https://doi.org/10.1029/2009GL038586

Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., & Francis, R. C. (1997). A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society*, *78*(6), 1069–1079. https://doi.org/10.1175/1520-0477(1997)078%3C1069:APICOW%3E2.0.CO;2

Martín-Rey, M., Rodríguez-Fonseca, B., & Polo, I. (2015). Atlantic opportunities for ENSO prediction. *Geophysical Research Letters*, *42*, 6802–6810. https://doi.org/10.1002/2015GL065062

Martius, O., Polvani, L. M., & Davies, H. C. (2009). Blocking precursors to stratospheric warming events. *Geophysical Research Letters*, *36*, L14806. https://doi.org/10.1029/2009GL038776

Matsueda, M. (2011). Predictability of Euro-Russian blocking in summer of 2010. *Geophysical Research Letters*, *38*, L06801. https://doi.org/10.1029/2010GL046557

Matsuno, T. (1982). A quasi one-dimensional model of the middle atmosphere circulation interacting with internal gravity waves. *Journal of the Meteorological Society of Japan*, *60*(1), 215–226.

Matthews, A. J., & Meredith, M. P. (2004). Variability of Antarctic circumpolar transport and the Southern Annular Mode associated with the Madden–Julian Oscillation. *Geophysical Research Letters*, *31*, L24312. https://doi.org/10.1029/2004GL021666

Maue, R. N. (2011). Recent historically low global tropical cyclone activity. *Geophysical Research Letters*, *38*, L14803. https://doi.org/10.1029/2011GL047711

McPhaden, M. J., Zhang, X., Hendon, H. H., & Wheeler, M. C. (2006). Large scale dynamics and MJO forcing of ENSO variability. *Geophysical Research Letters*, *33*, L16702. https://doi.org/10.1029/2006GL026786

Meneghini, B., Simmonds, I., & Smith, I. N. (2007). Association between Australian rainfall and the Southern Annular Mode. *International Journal of Climatology*, *27*(1), 109–121. https://doi.org/10.1002/joc.1370

Muñoz–Esparza, D., Lundquist, J. K., Sauer, J. A., Kosović, B., & Linn, R. R. (2017). Coupled mesoscale–LES modeling of a diurnal cycle during the CWEX-13 field campaign: From weather to boundary-layer eddies. *Journal of Advances in Modeling Earth Systems*, *9*(3), 1572–1594. https://doi.org/10.1002/2017MS000960

Newman, M., Alexander, M. A., Ault, T. R., Cobb, K. M., Deser, C., Di Lorenzo, E., … Smith, C. A. (2016). The Pacific decadal oscillation, revisited. *Journal of Climate*, *29*, 4399–4427. https://doi.org/10.1175/LCLI-D-15-0508.1

Pavelin, E., Whiteway, J. A., Busen, R., & Hacker, J. (2002). Airborne observations of turbulence, mixing, and gravity waves in the tropopause region. *Journal of Geophysical Research*, *107*(D10), 4084. https://doi.org/10.1029/2001JD000775

Pelly, J. L., & Hoskins, B. J. (2003). A new perspective on blocking. *Journal of the Atmospheric Sciences*, *60*(5), 743–755. https://doi.org/10.1175/1520-0469(2003)060%3C0743:ANPOB%3E2.0.CO;2

Pfahl, S., Madonna, E., Boettcher, M., Joos, H., & Wernli, H. (2014). Warm Conveyor Belts in the ERA-Interim Dataset (1979-2010). Part II: Moisture origin and relevance for precipitation. *Journal of Climate*, *27*(1), 27–40. https://doi.org/10.1175/Jcli-D-13-00223.1

Pierce, R. B., & Grant, W. B. (1998). Seasonal evolution of Rossby and gravity wave induced laminae in ozonesonde data obtained from Wallops Island, Virginia. *Geophysical Research Letters*, *25*, 1859–1862. https://doi.org/10.1029/98GL01507

Pithan, F., Angevine, W., & Mauritsen, T. (2015). Improving a global model from the boundary layer: Total turbulent energy and the neutral limit Prandtl number. *Journal of Advances in Modeling Earth Systems*, *7*(2), 791–805. https://doi.org/10.1002/2014MS000382

Plougonven, R., & Zhang, F. (2014). Internal gravity waves from atmospheric jets and fronts. *Reviews of Geophysics*, *52*, 33–76. https://doi.org/10.1002/2012RG000419

Riddle, E. E., Stoner, M. B., Johnson, N. C., L'Heureux, M. L., Collins, D. C., & Feldstein, S. B. (2013). The impact of the MJO on clusters of wintertime circulation anomalies over the North American region. *Climate Dynamics*, *40*(7-8), 1749–1766. https://doi.org/10.1007/s00382-012-1493-y

Rigden, A. J., & Li, D. (2017). Attribution of surface temperature anomalies induced by land use and land cover changes. *Geophysical Research Letters*, *44*, 6814–6822. https://doi.org/10.1002/2017GL073811

Riviere, G., & Orlanski, I. (2007). Characteristics of the Atlantic storm-track eddy activity and its relation with the North Atlantic Oscillation. *Journal of the Atmospheric Sciences*, *64*(2), 241–266. https://doi.org/10.1175/jas3850.1

Ropelewski, C., & Halpert, M. (1987). Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation. *Monthly Weather Review*, *115*(8), 1606–1626. https://doi.org/10.1175/1520-0493(1987)115%3C1606:GARSPP%3E2.0.CO;2

Rothlisberger, M., Pfahl, S., & Martius, O. (2016). Regional-scale jet waviness modulates the occurrence of midlatitude weather extremes. *Geophysical Research Letters*, *43*, 10,989–10,997. https://doi.org/10.1002/2016GL070944

Sato, K., Watanabe, S., Kawatani, Y., Tomikawa, Y., Miyazaki, K., & Takahashi, M. (2009). On the origins of mesospheric gravity waves. *Geophysical Research Letters*, *36*, L19801. https://doi.org/10.1029/2009GL039908

Scaife, A. A., Arribas, A., Blockley, E., Brookshaw, A., Clark, R. T., Dunstone, N., … Williams, A. (2014). Skilful long range prediction of European and North American winters. *Geophysical Research Letters*, *41*, 2514–2519. https://doi.org/10.1002/2014GL059637

Scaife, A. A., Athanassiadou, M., Andrews, M. B., Arribas, A., Baldwin, M. P., Dunstone, N., … Williams, A. (2014). Predictability of the Quasi-Biennial Oscillation and its northern winter teleconnection on seasonal to decadal timescales. *Geophysical Research Letters*, *41*, 1752–1758. https://doi.org/10.1002/2013GL059160

Scaife, A. A., Butchart, N., Warner, C. D., Stainforth, D., Norton, W. A., & Austin, J. (2000). Realistic quasi-biennial oscillations in a simulation of the global climate. *Geophysical Research Letters*, *27*, 3481–3484. https://doi.org/10.1029/2000GL011625

Scaife, A. A., Copsey, D., Gordon, C., Harris, C., Hinton, T., Keeley, S., … Williams, K. (2011). Improved Atlantic winter blocking in a climate model. *Geophysical Research Letters*, *38*, L23703. https://doi.org/10.1029/2011GL049573

Schemm, S., Sprenger, M., Martius, O., Wernli, H., & Zimmer, M. (2017). Increase in the number of extremely strong fronts over Europe? A study based on ERA-Interim reanalysis (1979–2014). *Geophysical Research Letters*, *44*, 553–561. https://doi.org/10.1002/2016GL071451

Schwierz, C., Croci–Maspoli, M., & Davies, H. C. (2004). Perspicacious indicators of atmospheric blocking. *Geophysical Research Letters*, *31*, L06125. https://doi.org/10.1029/2003GL019341

Seager, R., Harnik, N., Kushnir, Y., Robinson, W., & Miller, J. (2003). Mechanisms of hemispherically symmetric climate variability. *Journal of Climate*, *16*(18), 2960–2978. https://doi.org/10.1175/1520-0442(2003)016%3C2960:MOHSCV%3E2.0.CO;2

Seneviratne, S. I., Nicholls, N., Easterling, D., Goodess, C. M., Kanae, S., Kossin, J., … Zhang, X. (2012). Changes in climate extremes and their impacts on the natural physical environment. In C. B. Field, et al. (Eds.), *Managing the risks of extreme events and disasters to advance climate change adaptation* (pp. 109–230). Cambridge, UK: Cambridge University Press. https://doi.org/10.1017/CBO9781139177245.006

Seo, K. -H., & Son, S. -W. (2012). The global atmospheric circulation response to tropical diabatic heating associated with the Madden–Julian Oscillation during northern winter. *Journal of the Atmospheric Sciences*, *69*(1), 79–96. https://doi.org/10.1175/2011JAS3686.1

Sharman, R. D., Trier, S. B., Lane, T. P., & Doyle, J. D. (2012). Sources and dynamics of turbulence in the upper troposphere and lower stratosphere: A review. *Geophysical Research Letters*, *39*, L12803. https://doi.org/10.1029/2012GL051996

Shelly, A., Xavier, P., Copsey, D., Johns, T., Rodríguez, J. M., Milton, S., & Klingaman, N. (2014). Coupled versus uncoupled hindcast simulations of the Madden–Julian Oscillation in the year of tropical convection. *Geophysical Research Letters*, *41*, 5670–5677. https://doi.org/10.1002/2013GL059062

Shin, H. H., & Dudhia, J. (2016). Evaluation of PBL parameterizations in WRF at subkilometer grid spacings: Turbulence statistics in the dry convective boundary layer. *Monthly Weather Review*, *144*(3), 1161–1177. https://doi.org/10.1175/MWR-D-15-0208.1

Sillmann, J., & Croci–Maspoli, M. (2009). Present and future atmospheric blocking and its impact on European mean and extreme climate. *Geophysical Research Letters*, *36*, L10702. https://doi.org/10.1029/2009GL038259

Smith, D. M., Eade, R., Dunstone, N. J., Fereday, D., Murphy, J. M., Pohlmann, H., & Scaife, A. A. (2010). Skilful multi-year predictions of Atlantic hurricane frequency. *Nature Geoscience*, *3*(12), 846–849. https://doi.org/10.1038/ngeo1004

Smith, D. M., Scaife, A. A., Eade, R., & Knight, J. R. (2016). Seasonal to decadal prediction of the winter North Atlantic Oscillation: Emerging capability and future prospects. *Quarterly Journal of the Royal Meteorological Society*, *142*(695), 611–617. https://doi.org/10.1002/qj.2479

Song, E. J., & Seo, K. H. (2016). Past- and present-day Madden–Julian Oscillation in CNRM-CM5. *Geophysical Research Letters*, *43*, 4042–4048. https://doi.org/10.1002/2016GL068771

Storer, L. N., Williams, P. D., & Joshi, M. M. (2017). Global response of clear-air turbulence to climate change. *Geophysical Research Letters*, *44*, 9976–9984. https://doi.org/10.1002/2017GL074618

Tomikawa, Y., Sato, K., Watanabe, S., Kawatani, Y., Miyazaki, K., & Takahashi, M. (2012). Growth of planetary waves and the formation of an elevated stratopause after a major stratospheric sudden warming in a T213L256 GCM. *Journal of Geophysical Research*, *117*, D16101. https://doi.org/10.1029/2011JD017243

Trenberth, K. E., Branstator, G. W., Karoly, D., Kumar, A., Lau, N.-C., & Ropelewski, C. (1998). Progress during TOGA in understanding and modeling global teleconnections associated with tropical sea surface temperatures. *Journal of Geophysical Research*, *103*, 14,291–14,324. https://doi.org/10.1029/97JC01444

Trier, S. B., & Sharman, R. D. (2009). Convection-permitting simulations of the environment supporting widespread turbulence within the upper-level outflow of a mesoscale convective system. *Monthly Weather Review*, *137*(6), 1972–1990. https://doi.org/10.1175/2008MWR2770.1

Trier, S. B., Sharman, R. D., & Lane, T. P. (2012). Influences of moist convection on a cold-season outbreak of clear-air turbulence CAT. *Monthly Weather Review*, *140*(8), 2477–2496. https://doi.org/10.1175/MWR-D-11-00353.1

Ulbrich, U., Fink, A. H., Klawa, M., & Pinto, J. G. (2001). Three extreme storms over Europe in December 1999. *Weather*, *56*(3), 70–80. https://doi.org/10.1002/j.1477-8696.2001.tb06540.x

Vecchi, G. A., Delworth, T., Gudgel, R., Kapnick, S., Rosati, A., Wittenberg, A. T., … Zhang, S. (2014). On the seasonal forecasting of regional tropical cyclone activity. *Journal of Climate*, *27*(21), 7994–8016. https://doi.org/10.1175/JCLI-D-14-00158.1

Visbeck, M., Cullen, H., Krahmann, G., & Naik, N. (1998). An ocean model's response to North Atlantic Oscillation-like wind forcing. *Geophysical Research Letters*, *25*, 4521–4524. https://doi.org/10.1029/1998GL900162

Vitart, F. (2017). Madden–Julian Oscillation prediction and teleconnections in the S2S database. *Quarterly Journal of the Royal Meteorological Society*, *143*(706), 2210–2220. https://doi.org/10.1002/qj.3079

Waliser, D. E., Lau, K. M., Stern, W., & Jones, C. (2003). Potential predictability of the Madden–Julian oscillation. *Bull. Amer. Meteor. Soc.*, *84*(1), 33–50. https://doi.org/10.1175/BAMS-84-1-33

Wallace, J. M. (2000). North Atlantic Oscillation/Annular Mode: Two paradigms–one phenomenon. *Quarterly Journal of the Royal Meteorological Society*, *126*(564), 791–805. https://doi.org/10.1256/smsqj.56401

Wang, W., Chen, M., Kumar, A., & Xue, Y. (2011). How important is intraseasonal surface wind variability to real-time ENSO prediction? *Geophysical Research Letters*, *38*, L13705. https://doi.org/10.1029/2011GL047684

Wanner, H., Bronnimann, S., Casty, C., Gyalistras, D., Luterbacher, J., Schmutz, C., … Xoplaki, E. (2001). North Atlantic Oscillation—Concepts and studies. *Surveys in Geophysics*, *22*(4), 321–381. https://doi.org/10.1023/A:1014217317898

Whiteway, J. A., Klaassen, G. P., Bradshaw, N. G., & Hacker, J. (2004). Transition to turbulence in shear above the tropopause. *Geophysical Research Letters*, *31*, L02118. https://doi.org/10.1029/2003GL018509

Williams, P. D. (2012). Climatic impacts of stochastic fluctuations in air–sea fluxes. *Geophysical Research Letters*, *39*, L10705. https://doi.org/10.1029/2012GL051813

Williams, P. D. (2017). Increased light, moderate, and severe clear-air turbulence in response to climate change. *Advances in Atmospheric Sciences*, *34*(5), 576–586. https://doi.org/10.1007/s00376-017-6268-2

Williams, P. D., Haine, T. W. N., & Read, P. L. (2005). On the generation mechanisms of short-scale unbalanced modes in rotating two-layer flows with vertical shear. *Journal of Fluid Mechanics*, *528*, 1–22. https://doi.org/10.1017/S0022112004002873

Williams, P. D., Haine, T. W. N., & Read, P. L. (2008). Inertia–gravity waves emitted from balanced flow: Observations, properties, and consequences. *Journal of the Atmospheric Sciences*, *65*(11), 3543–3556. https://doi.org/10.1175/2008JAS2480.1

Williams, P. D., & Joshi, M. M. (2013). Intensification of winter transatlantic aviation turbulence in response to climate change. *Nature Climate Change*, *3*(7), 644–648. https://doi.org/10.1038/nclimate1866

Woollings, T., Hannachi, A., & Hoskins, B. J. (2010). Variability of the North Atlantic eddy-driven jet stream. *Quarterly Journal of the Royal Meteorological Society*, *136*(649), 856–868. https://doi.org/10.1002/qj.625

Woollings, T., Harvey, B., & Masato, G. (2014). Arctic warming, atmospheric blocking and cold European winters in CMIP5 models. *Environmental Research Letters*, *9*(1), 14002. http://doi.org/10.1088/1748-9326/9/1/014002

Worsnop, R. P., Lundquist, J. K., Bryan, G. H., Damiani, R., & Musial, W. (2017). Gusts and shear within hurricane eyewalls can exceed offshore wind turbine design standards. *Geophysical Research Letters*, *44*, 6413–6420. https://doi.org/10.1002/2017GL073537

Xu, W., & Rutledge, S. A. (2016). Time scales of shallow-to-deep convective transition associated with the onset of Madden–Julian Oscillations. *Geophysical Research Letters*, *43*, 2880–2888. https://doi.org/10.1002/2016GL068269

Yamada, R., & Pauluis, O. (2017). Wave–mean-flow interactions in moist baroclinic life cycles. *Journal of the Atmospheric Sciences*, *74*(7), 2143–2162. https://doi.org/10.1175/JAS-D-16-0329.1

Yang, D., & Ingersoll, A. P. (2014). A theory of the MJO horizontal scale. *Geophysical Research Letters*, *41*, 1059–1064. https://doi.org/10.1002/2013GL058542

Zeng, G., & Pyle, J. A. (2005). Influence of El Niño Southern Oscillation on stratosphere/troposphere exchange and the global tropospheric ozone budget. *Geophysical Research Letters*, *32*, L01814. https://doi.org/10.1029/2004GL021353

Zhang, C. (2005). Madden–Julian Oscillation. *Reviews of Geophysics*, *43*, RG2003. https://doi.org/10.1029/2004RG000158

Zhang, C. (2013). Madden–Julian Oscillation: Bridging weather and climate. *Bulletin of the American Meteorological Society*, *94*(12), 1849–1870. https://doi.org/10.1175/BAMS-D-12-00026.1

Zhang, C., Gottschalck, J., Maloney, E. D., Moncrieff, M. W., Vitart, F., Waliser, D. E., … Wheeler, M. C. (2013). Cracking the MJO nut. *Geophysical Research Letters*, *40*, 1223–1230. https://doi.org/10.1002/grl.50244