The Impact of SSW On The Extreme Variability of Snowfall Climatology In Boston And Along The Northeast Urban Corridor of the U.S.

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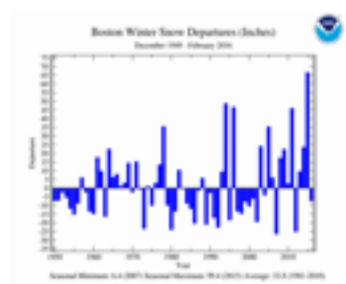
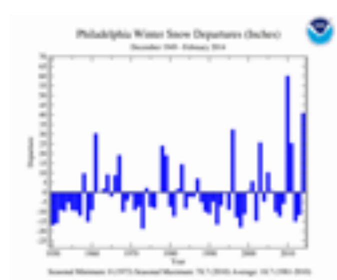
The average winter snowfall for Boston's Logan Airport (BOS) has increased from 42 inches. (106 cm) / yr to 55 inches (140 cm) in the period beginning in 1997. In addition the return frequency of synoptic scale cyclones that produce >20 in (51 cm) has increased from 1:56 yr to 1:6 during this same period. Such increase may be attributed to SSW / WAFz (Wave activity flux) and the distribution of mass / circulation of the polar vortex coupled with changes in the SST of the North Pacific and Atlantic basins including the PDO (Pacific Decadal Oscillation and Atlantic Multi-decadal oscillation) and ENSO (El Nino Southern Oscillation) For example the winter of 2014-201(especially during the late January - early March period) featured a significant SST warm anomaly in the NE Pacific basin along the coast of NW North America. This feature forced a persistent Rossby wave train that favored an upper atmospheric ridge across NW North America and trough over E. North America. As a consequence synoptic scale cyclones propagated downstream within this flow undergoing re-intensification in the vicinity of the Mid-Atlantic coast resulting in a record winter snowfalls across many locations of the within the Industrial corridor including a record 110 inches (280 cm) at Boston's Logan Airport.

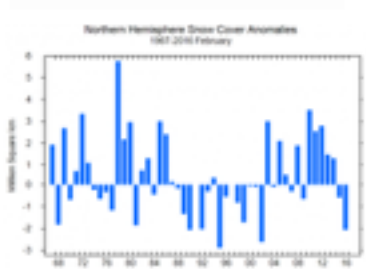
The following winter of 2015-2016 featured a positive ENSO signal i.e. and El Nino in which SST in zone 3.4 ranged between + 2.5c - 3.0c. Moreover, the AO (Arctic Oscillation) was persistently positive resulting in a strong polar vortex and strong zonal flow in the Mid Latitudes

Overview

It may be speculated that the increase in seasonal snowfall in several locations along the urban corridor commenced during the early 1990s. The Boston snowfall climatology in particular indicates a marked increase in the frequency positive seasonal anomalies beginning in 1992 and especially during the period from 2002 - ending in 2017 with a positive anomaly ratio of 9/15 or 73%. A few noteworthy features in the selected data samples. 1) Boston: Negative anomalies between 1997 - 2001 2) Philadelphia: A positive anomaly ration of 6/15 or 40% between 2002-2017 and just one positive anomaly (1995-1996) during the period beginning in 1992. 3) Northern Hemisphere: Consistent negative anomalies from the period beginning in 1988 - 2003 followed by a significant shift toward positive anomalies with a ratio of 9/15 or 73% during the period between 2002-2017. Such anomalies were the likely the outcome of changes in terrestrial boundary conditions (polar amplification in particular) coupled with solar variability. Although the following sections will elaborate upon these boundary conditions it remains subjects of ongoing research. (See **fig 1** below)

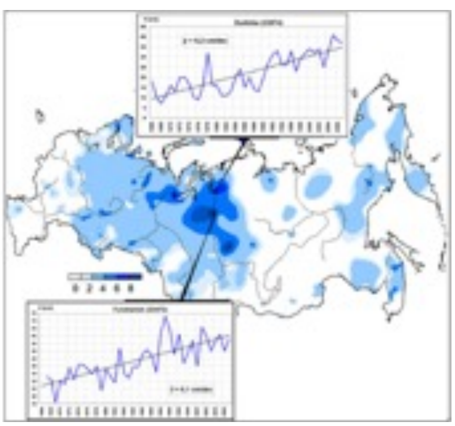






Polar Amplification and SSW.

The mean global surface temperature has increased 0.8C during the 20th through the first part of the 21st century. Although this increase is the result of stochastic processes e.g internal / external variability there can be little doubt that anthropogenic greenhouse gas forcing is among the principal positive feedbacks for a warming terrestrial climate. In correlation with this warming the boreal polar ice cap has been diminishing at the rate of 10% / 10yrs (***) resulting in significant changes in polar hydrostatic boundary conditions
For example, investigations by Cohen et al. have demonstrated that more exposure of the Arctic ocean has amplified the hydrologic cycle resulting in an increase positive snowfall anomalies especially during October (**Figure 2 below)**.



This anomalous snow mass, in turn produces an increase hydrostatic pressure within the column of the lower troposphere resulting in a significant polar anticyclone. This perturbation is then propagated upward into the stratosphere through the process of WAFz (wave activity flux) resulting in adiabatic warming, i.e. a "sudden stratospheric warming" event (SSW) This perturbation is then redirected back downward into the troposphere reinforcing the anticyclonic environment thus reducing the indices for the Arctic Oscillation. The impacts are the following A) a weaker polar vortex B) polar jet stream amplification C) an increase meridional exchanges of airmass e.g. cold air outbreaks (CAO) especially in the continental mid-latitudes D) amplification in extratropical resulting from local increases in positive vorticity advection (PVA).

The aforementioned process can become amplified within downstream coastal plains e.g. the urban corridor (UC) of the Northeastern U.S. through cold air damming further decreasing baroclinic / hydrostatic that contribute to both type A and B Miller cyclogenesis (Kocin and Ucellini 1994, 2001).
In fact it may be speculated that the rise in SST along the NE coast may contribute to cyclonic amplification through increased sensible and latent heat fluxes, decreased hydrostatic instability, and increased baroclinic instability.

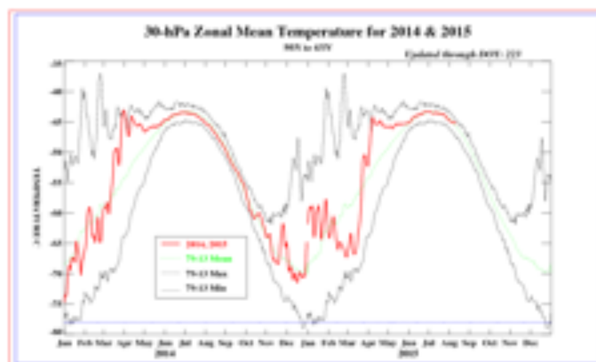
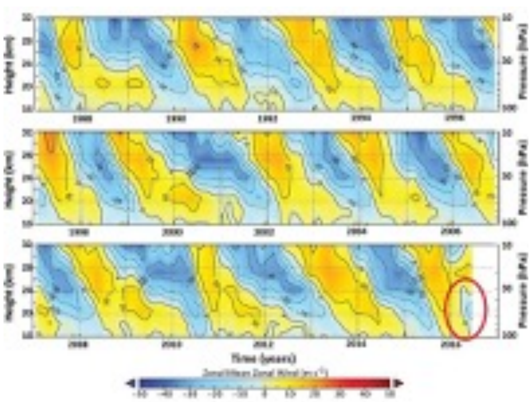


Figure 3: **Two SSW events that occurred during the winter of 2014-2015. The second more significant event was antecedent to record snowfall in Boston and other locations along the urban corridor**

The Norther Annual Mode

As aforementioned SSW is closely coupled with the negative phase of both the arctic oscillation (A0-) and the North Atlantic oscillation. Recent climatology indicates that these respective signals results in 500 hPa - 200 hPa height anomalies (ridge) across western North America which in turn is teleconnected to a negative height anomalies downstream (trough) across eastern North America. The associated meridional air mass exchange tends to favor positive temperature anomalies especially along and west of the cordillera with negative anomalies occurring especially over the northeastern U.S. Recent studies indicate a higher return frequency of the negative phase of the AO hence a decrease in the mean indices value especially within the past two decades, commensurate with the increase in positive annual snowfall anomalies in the U.S. urban corridor **(Figure 5 below)**

The Quasi-biennial Oscillation.



The QBO tends to correlate with phases of the AO. In this case QBO+ west (yellow - orange contours in figure 5) is associated with an AO+, while QBO- east (blue contours) is associated with an AO- signal. The phase return frequency is generally between 26 - 28 months.

The PDO / ONI Index

This investigation revealed that when ONI index ranged between > -1.0 - < 1.0 that the probability for annual positive snowfall anomalies (SF+) at Boston increased to 63% (or 12 out of 19 winters). Conversely values outside of this range were correlated with negative snowfall anomalies due to the more poleward shift of the polar jet stream resulting in the zonal advection of milder marine air masses originating in the North Pacific Basin. Noteworthy cases when ONI indices > 2.0 occurred during the winters of 1982-83,

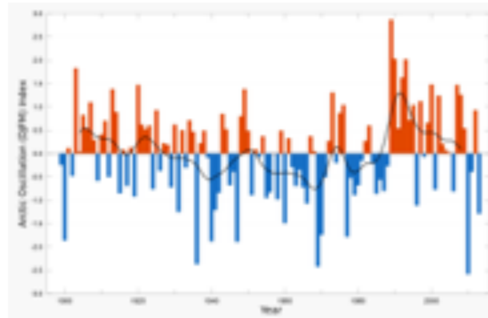


Figure 4: AO DJM indices for the period 1900-2015. Note the mean decrease after 2000.

1997-1998, and 2015-16. However the urban corridor was not exempt from single SF+ events and periods (as in these cases the strong ONI+ signal may have been temporarily overridden by a negative northern annular mode) Example are the SF+ event of 2/12/83 - 2/13/83 that produced between 20 - 30 cm of snowfall along the urban corridor, and 1/22/16- 24/16 that deposited record snowfall of up to 55 cm along the mid-Atlantic portion of the urban corridor.

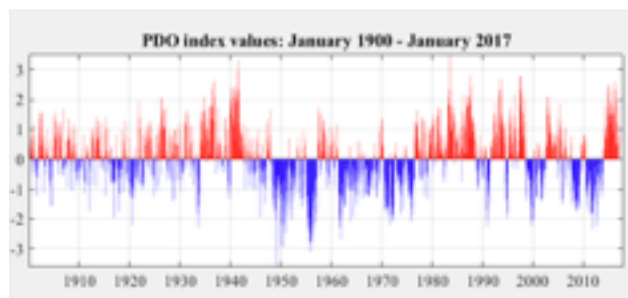


Figure 6: The Pacific Decadal Oscillation: Note the shift toward a higher return frequency beginning in the late 1970s. Also note oscillations between ONI >2.0 e.g. 1982-83; and < -2.0 e.g. 1999-2000.

During phases when ONI values were < -2/0 e.g. 1990-1991, 1999 - 2000 and 2006 - 2007 a SF- signal was observed at many locations along the urban corridor. However these winters were also punctuated by periods of CAO and SF+ events e.g. a SF+ event along the mid-Atlantic urban corridor 1/24/00 - 1/25/00 where snowfall totals approached 25 cm.

Solar Cycles

Solar cycle irradiance values i.e. he solar constant at the top of the atmosphere only vary in the order of 2-3 watts / m^2 . However more importantly studies conducted by Svensmark et al. suggest a correlation between solar activity and the solar magnetic field i.e. the latter is reduced commensurate with diminished solar activity (as indicated by sunspot number). This signal, in turn triggers a chain of causality within the terrestrial atmosphere resulting in an increased rate of cosmic ray impact and ionization for condensation nuclei thereby increasing cloud cover hence the terrestrial albedo decreasing the mean surface temperature.

Although this study is subject to further research there appears to be some correlation between solar cycles and SF both in the urban corridor and the northern hemisphere

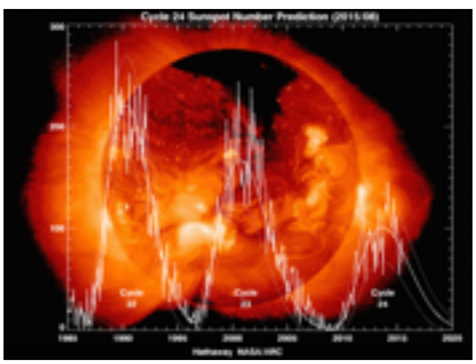


Figure (7) Solar cycles 22-24. Both maxima and minima are coincident with SF- and SF+ winters in the urban corridor respectively. However NH SF indicated less consistency especially during 1995-96. Also note the increase in return frequency from 11 to 14 yrs between cycle 23 and 24 that can be correlated with a decrease in global mean temperature.

It is interesting to note that SF+ winters in the urban corridor e.g. 1995-96, 2008-09 are coincident with solar minima, and SF- winters with solar cycle maxima i.e. cycle 22 and 23. with 1990-91, 2001-02. These respective anomalies are also coincident with NH SF anomalies with the exception of winter 1995-96 where the NH indicates a SF- anomaly reflecting internal variability. Also studies indicate a correlation between increase in length between cycles can be correlated with a decrease in global mean surface temperature (Strum,)

The Anomalous Winter of 2014-2015 in the Upper Urban Corridor.

A deep extratropical cyclone (920 hPa) located in the Aleutian Gulf during early November forced significant trough amplification downstream across most of North America especially east of the cordillera. The outcome was a series CAOs (Cold Air Outbreaks)and widespread negative temperature anomalies commensurate with SF+ anomalies in the urban corridor. It is also suspected that the WAFz associated with this perturbation contributed to an AO- signal (as indices reached -2 std) that dominated much of the month of November. The resulting positive snow mass anomaly across Canada and the northern U.S. provided the positive feedback loop for the subsequent winter weather pattern of 2014 - 2015.

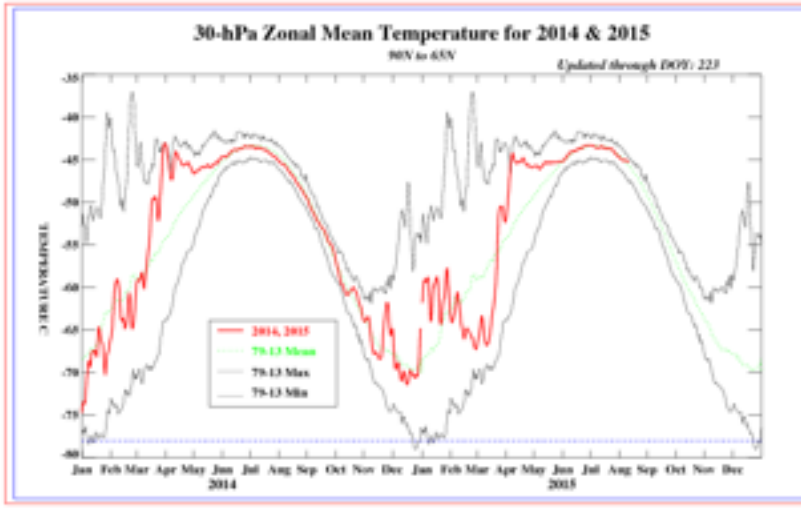
A transition to an AO+ occurred in December as indices ranged up to +3 std.while this signal lingered through mid January resulting in above average temperatures and below average snowfall especially in the urban corridor. In fact the AO oscillated between and A0 - (-1) / AO + (+2) signal before a SSW event during mid-January forced an AO- during late January continuing into early February then turning progressively positive for the remainder of February. approaching +5 std in mid March before turning sharply negative again (Figure 8A and 8B).

However the SSW event was incongruent to the relatively weak response of the AO- as record snowfall coupled with CAO occurred especially from the NYC - Boston portion i.e. upper urban corridor during February. (In fact Boston's Logan Airport had only observed 14 cm of snowfall by late January, well below the climatological mean of 50 cm by this point in the winter!) It is also suspected that a positive PDO that featured significant positive SST anomalies off the NW coast of North America resulted in positive height anomalies across western North America i.e. a thermally forced ridge amplifying a downstream trough and negative height anomalies across eastern North America (a pattern consistent with a PNA+). Associate cold air advection, vorticity pooling and polar subtropical jet stream fusion resulted in four type C coastal cyclogenetic / SF+ events i.e. “nor’easters” along the urban corridor during a three week period from late January - mid February that commenced with an historic cyclone on 1/26-27/15 with SF+ accumulations ranging up to 70 cm in eastern most New England. In fact the four successive coastal extratropical cyclones deposited total 228 cm of snowfall in Boston during this three week period significantly impacting commerce, transportation and school closings coupled with record cold i.e. averaging -12 f in February!

It is also suspected that the AMO + (Atlantic Multi-decadal oscillation) featured above average SST across the western Atlantic basin contributing to the highly cyclogenetic environment along the urban corridor coast through decreased hydrostatic stability commensurate with an increase in sensible / latent heat fluxes and baroclinic instability (consistent with criteria associated with urban corridor SF+ events as described by Kocin and Uccellini, 1993, 2004).

The AMO (Atlantic Multi-decadal Oscillation)

The AMO underwent a high amplitude oscillation between 1930 and 1970 (mostly positive), before transitioning to a mostly negative phase of equal magnitude through approximately 1998 before reversing to the current positive phase (figure 9). Studies have indicated a relationship between AMO signals and U.S. precipitation as an AMO+ is correlated to lower precipitation and and an AMO - with higher precipitation (Mestas and Nunez 2001). Additionally (as aforementioned in a



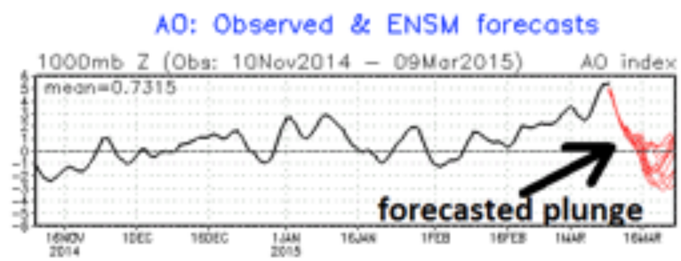
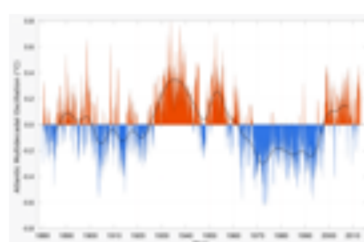


Figure 8A: Top- SSW events Dec. 2014 and Jan. 2015. Bottom diagram: 8B Bottom -The AO- response was relatively weak until mid March

previous) an increase in SST across the western Atlantic basin may also contribute to the cyclogenetic environment through increased hydrologic forcing including the thermal gradient i.e. “baroclinic ribbon” necessary for type C cyclogenesis.

However the AMO+ tends to decouple with Northeast precipitation near the turn of the millennium as the latter continues to signal positive anomalies that had commenced during the AMO- phase during late 1960s (figure) . (Whether this decoupling may be attributed anthropogenic forcing is a matter of speculation and beyond the scope of this investigation.) **Figure 9 belo**w



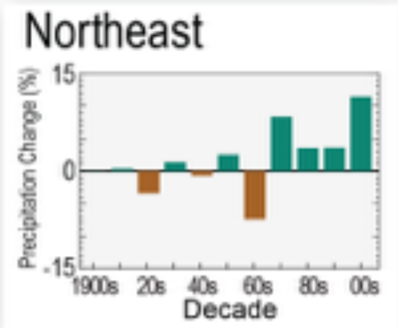


Figure 10 (Above)

A Global Perspective

Two periods dominated by global positive precipitation anomalies appear between 1950 and 1980 and again from 1995 to the present (figure 11) In fact global precipitation has increased 10% during the past three decades including a two fold increase in extreme precipitation events (National Climate Center). Such oscillations are the result of stochastic variability and likely include anthropogenic forcing especially during the latest period of positive anomalies. Therefore the increase in snowfall climatology particularly within the upper urban corridor may be, at least in part, congruent to the overall increase in global precipitation. This trend is also reflected by the increase in NH the frequency of positive snowfall anomalies from 2003 - present.

Figure 11 (Below)

The Impact of Eruption of Mt. Pinatubo of Global Temperature

The eruption of Mt Pinatubo took place on 6/15/91 on the island of Luzon in the Philippines. Rated 6 on the VEI scale, and 7.8 on the Richter scale the eruption ejected 5 x10^3 m^3 of material that reached an altitude of 3.5 x 10^4 m i.e. the upper layer of the stratosphere. The increased albedo resulting from volcanic aerosols diminished global surface temperatures by 0.5C - 0.7C (Self, et al. 1999). Although the impact of eruption on lower spatial / temporal scales remains subject to further research there are a few noteworthy climatological events that occurred between 1992 - 1994 1) The decoupling between NH negative snowfall anomaly signal (that had commenced in 1988 fig *) and the significant positive anomaly signal in the upper urban corridor (Boston 1992-93, 1993-94; New York City 1993-1994,(Fig 4) 2) The UC anomalies occurred during a period when indices for both the AO and NAO were mainly positive! Additionally, a type C extratropical cyclone of unusual magnitude propagated NE along the UC affecting the eastern 1/3 of the U.S. resulting in multiple extreme impacts including SF+ (approaching 100 cm in parts of the Appalachians), wind > 120 km / hr coupled with significant storm surge along parts of the coast, and severe weather / tornadoes over the SE U.S.

To reiterate, the chain of causality resulting from volcanic aerosol forcing downscaled from a global the global to the synoptic scale is speculative at best. However it may also be hypothesized that the reduction in solar UV radiation due to sulphate aerosol loading hence increased albedo in the stratosphere may have diminished the production of ozone. This in turn may have resulted in reduced greenhouse gas forcing from ozone cooling the polar stratosphere hence strengthening of the polar vortex. This may at least in part explain the higher AO / NAO index values during this period.

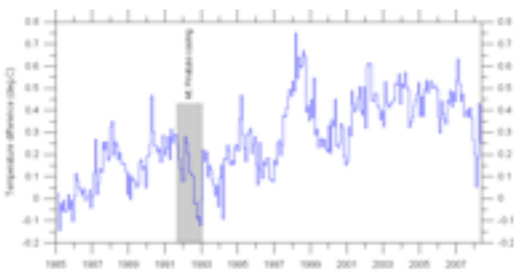


Figure 12

Cyclogenetic SF+ Events.

Another interesting component of the change in UC snowfall climatology is the increase in frequency of SF+ events. For example, the increase return frequency events >50 cm is evident in all three locations featured in this study beginning in 1997 as compared to the climatological period beginning in 1872: Boston has increased from 1/56 yrs to 1997 to 1/4. NYC (including the winter of 1996) has increased from 1/56 yr to approximately 1/5 yrs. Philadelphia from 1/56 to 1/ 6.6 yrs

The increase in return frequency may be correlated to the following change in boundary conditions both locally and globally that may amplify cold season type C cyclogenesis in the western Atlantic basin. 1) Increase in the frequency of A0- / NAO- phases. 2) Increase in SST (+1f, NOAA) that contribute to an accelerated hydrologic cycle, sensible / latent heat fluxes hence increasing hydrostatic / baroclinic instability. 3) Two fold global Increase in the frequency of extreme precipitation (National Climate Center). 4) Solar cycle # 24 minima and lowest maxima since the Dalton minimum 1800 A.D.

However this speculation is subject to further investigation especially where anthropogenic forcing is concerned e.g. the complex causal link between diminished polar ice, SSW events and the AO / NAO / Polar vortex, and increased SST especially in the western Atlantic basin

Hybrid Superstorms

Amplification of cold season cyclogenesis especially in the western Atlantic may merit a third classification for synoptic scale cyclones that undergo rapid, or "explosive" intensification i.e. > - 3hPa / hr. coupled with sustained surface winds of 63 km / hr within a radius >100 km, and liquid precipitation output > 5 cm (described in the popular media as "winter hurricanes" or "snow-canes"). Although cyclones in this category are isentropically "cold core", their morphological and dynamic features mimic tropical cyclones e.g. concentric rotation, symmetric instability induced mesoscale and synoptic scale "banding" signatures, and a diabatically induced "eye like" structure centered approximate to the triple point of the occluding front. (Byrne, 1994, 1997, 1999). Examples of cyclones that fall within the criteria of classification include two type C cyclones that impacted the UC (especially eastern New England) include the SF+ events on 2/9-10/13, and 1/26-27/15.

Although anthropogenic forcing may contribute to the amplification of type C cyclones in the western Altantic basin this remains a subject for further research.

Summary: Anthropogenic Forcing?

The increase season positive snowfall anomalies in especially upper portion of the urban corridor i.e. NYC to Boston commenced in 2002 continuing through the present. This increase is also consistent with Eurasian and NH positive snowfall anomalies during this period. In fact it may be speculated that at Boston (and parts of eastern New England) this period commenced during the winter of 1992 - 1994. 1995-96 during which seasonal snowfall nearly doubled the climatological mean breaking a seasonal record in the case of the latter until the winter of 2014-15. This period was then temporarily repressed by an ONI signal that emerged during the 1990s culminating with an oscillation ranging between > +2C in 1997 -98, and < -1.5 C in

1998-99, 1999-2000. (It is also interesting to note that this SF- period is also coupled with solar cycle #23 maxima). The SF+ signal re-emerged in 2002 with greater frequency with an 11/15 ratio through 2016-17 as Boston's seasonal.

Finally, media outlets tend to focus on anthropogenic forcing as a primary cause of climate anomalies especially during the last few decades. It is the viewpoint of this author that climate anomalies are the outcome of the stochastic processes of internal and external variability among which anthropogenic forcing is becoming increasing evident as a significant climate change signal. However, this merits continuing research all the more imperative including its impact on polar amplification and its associated teleconnections and impacts throughout the biosphere.

Future Considerations

As aforementioned the complexity of climate and most especially its present accelerated state of change cannot be underscored enough. Therefore ongoing investigation e.g. continuing to improve model and statistical research in addition to direct studies that include monitoring internal variability and its respective teleconnections is crucial. This, in turn, will impact environmental policy and behavior thus mitigating the effects of anthropogenic forcing on the biosphere.

This particular study is but a first step in an investigation that will require considerably more data especially data points within the urban corridor (as the study was limited to three). It would also be illuminating to compare the coastal data points to more interior locations to better determine the impact of the marine environment on snowfall climatology e.g. accelerated hydrologic cycle, sensible/ latent heat fluxes due to increased SST and their impact on type C cyclogenesis and propagation. Finally the role of CAO associated with and AO- / NAO- signal within the urban corridor.

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Data Resources

N.E. U.S. Climate Assessment
NOAA
Northeast Regional Climate Center
Swiss National Science Foundation.