IMAU-workshop on the Northern Annular Mode (April, 2018)

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On April 19, 2018, a workshop on the "Northern Annular Mode" (NAM) was held at IMAU. The NAM represents an irregular oscillation in the strength of the westerly winds in the middle latitudes, both at the earth's surface and near the tropopause. A complete understanding of the physical origin or cause of this oscillation is still lacking. The NAM is an important factor in determining the temperature- and precipitation-anomalies both in Eurasia and in North America, especially in winter. For example, in the negative phase of the NAM, surface temperatures in Northern Eurasia and Eastern United States are well below normal.

FIGURE 1. Workshop participants. From left to right: Bob Ammerlaan, Chiel van Heerwaarden, Hans de Leeuw, Aarnout van Delden, Maarten Ambaum, Lars van Galen, Robert Mureau, John van Boxtel, Wim Verkley, Twan van Noije, Annalisa Cherchi, Frank Selten, Michiel Baatsen, Barend Odijk, Wim van Caspel and Ioannis Christofidis. Missing on this group photograph are Michiel van den Broeke, Hylke de Vries and Leo van Kampenhout.

About 20 researchers attended the meeting (**figure 1**). After an introductory talk by the organizer of the workshop and author of this report, Maarten Ambaum, professor of meteorology at Reading University (UK), gave a personal overview of initial developments around the NAM and related oscillations, such as the "North Atlantic Oscillation" (NAO) and the "Arctic Oscillation" (AO). The "mother-version" of the NAM/NAO/AO is the so-called "zonal index cycle", which was identified first by Carl Gustav Rossby and Jerome Namais (Namais, 1950). The zonal index cycle represents an oscillation in time of the strength *and* position of the westerlies. The westerlies reach their greatest strength at the earth's surface at about 50°N at the time of "high zonal index". At the time of "low zonal index", the westerlies reach their greatest strength higher up in the troposphere at a more equatorward latitude. Almost at the same time, Edward Lorenz (1951) concluded that the Northern Hemisphere "tends to contain two homogeneous zones, centered near 70°N and 35°N, separated by a transition zone near 50°N. Pressures within either homogeneous zone tend to be correlated positively with other pressures in the same zone and negatively with pressures in the other zone, while pressures within the transition zone tend to be uncorrelated with other pressures" . In line with this finding, Li and Wang (2003) proposed a "zonal index" or "Northern Annular Mode index" (NAM-index), defined as the *difference* of the monthly mean zonal mean sea level pressure *anomalies* at, respectively, 35°N and 65°N, "normalised" with the standard deviation of this difference.

Figure 2 shows the NAM-index for all 38 months of January between 1979 and 2016. An extreme negative NAM-phase occurred in January 2010. The term, "Northern Annular Mode", was introduced by Thomson and Wallace (2000). At the same time, research on the North Atlantic Oscillation, which is the regional (in the Atlantic Ocean) manifestation of the NAM, flourished under influence of interest in the relation between atmospheric composition changes and atmospheric circulation changes. In fact, some interpreted the increase of the NAM-index throughout the 1980's and into the 1990's (**figure 2**) as a manifestation of the effect of anthropogenic CO_2-emissions.

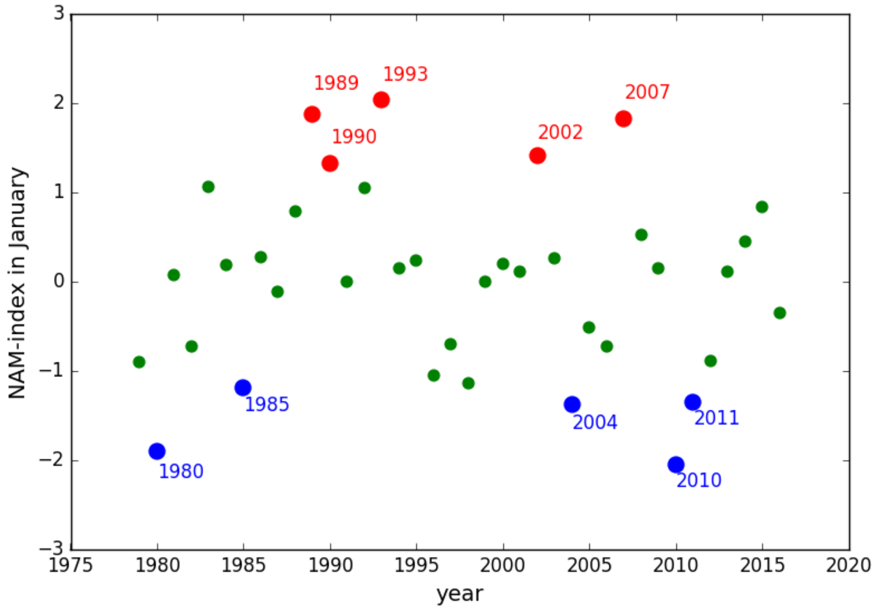

FIGURE 2. The NAM-index in January of the years 1979 to 2016. The five most extreme years (in a **negative** and **positive** sense) are indicated explicitly. A NAM-index greater than 2 (e.g. in January 1993) implies that the anomaly is larger than two times its standard deviation. The standard deviation is calculated from anomalies for 38 months of January. Based on ERA-Interim reanalysis (http://apps.ecmwf.int/datasets/).

The great interest in the NAO and the NAM also spawned a debate on the question which perspective should be taken: the "regional perspective", which emphasizes regional teleconnection patterns, such as the NAO, or the "annular perspective", which favours the view that the hemispheric scale circulation plays an important role in organizing local eddy activity, presumably through positive feedbacks between zonal mean zonal flow (the primary circulation) and wave disturbances or eddies. This feedback is mediated through a "secondary" zonal mean meridional circulation, which is frequently referred to as "Ferrel cell" (**figure 3**).

Maarten Ambaum (Ambaum et al., 2001) was, and still is, a proponent of the regional perspective. However, when we take the other (annular) perspective, we can make use of the "quasi-geostrophic" equations, which explicitly describe and quantify the above-mentioned wave-mean flow interaction. The third speaker, Wim van Caspel (IMAU), gave an overview of the most recent and, at present, best theoretical insights on the NAM, based on annular perspective and the quasi-geostrophic equations. The take-home message of this theory (Limpasuvan and Hartmann, 2000) is that the positive NAM-phase occurs when Rossby waves, which are excited in the lower troposphere by inhomogeneous boundary conditions, or by baroclinic instability, propagate upward and equatorward, depositing their *westward* momentum in the subtropics, thus decelerating the sub-tropical jet while accelerating the westerlies at higher latitudes. The opposite occurs in the negative NAM-phase.

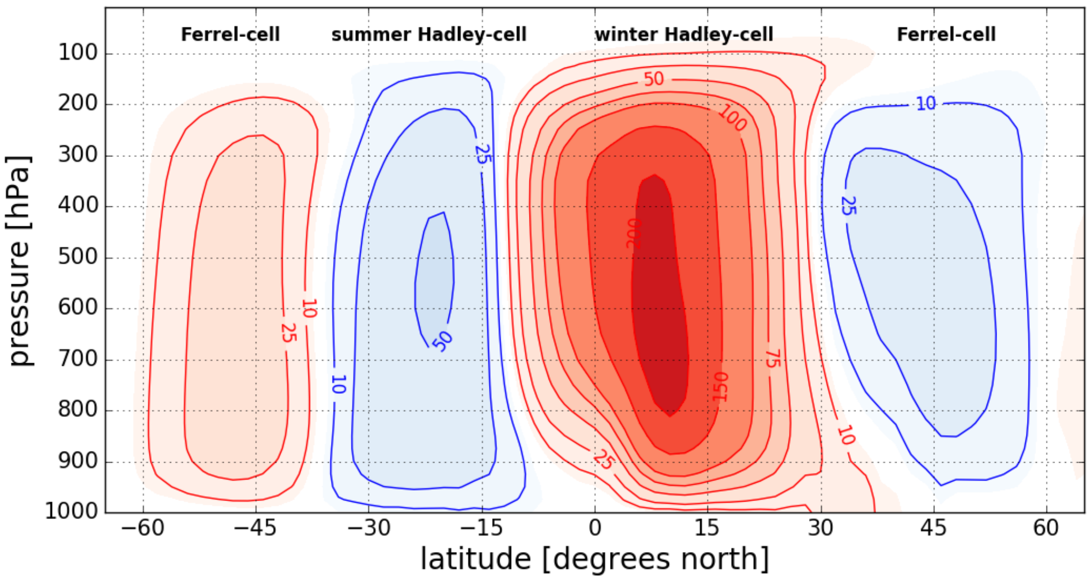

FIGURE 3. Ensemble monthly mean, zonal mean, mass streamfunction as a function of pressure (the vertical coordinate) and latitude, in **January** in the period 1979-2017. Contours are labeled in units of 10^{-9} kg s^{-1}. **Positive values of the streamfunction are red**; **negative values are blue**. At low levels air converges at about 10° south of the equator, at the so-called **Intertropical Convergence Zone** (ITCZ). The strongest topical circulation cell is the **winter Hadley cell**. Upward zonal mean motion is observed around the latitudes of -60°, -10° and +60°. Air moves downward in the subtropics and again upward at higher latitudes in the so-called **Ferrel cell**. The streamfunction is derived from the ERA-Interim re-analysis of the zonal mean meridional velocity, [*v*], using the contimuity equation in pressure coordinates.

The fourth speaker was Wim Verkley (KNMI), who talked about the interaction between waves and eddies and the large scale (zonal mean) motion in relation to “Blocking” of the westerly flow. Nearly stationary anticyclones, which are associated with high sea level pressure, occur especially over Scandinavia and Alaska. These anticyclones block the westerly flow. But why do the waves remain stationary for an appreciable time?

Annalisa Cherchi (Bologna), the last speaker before lunch, gave an overview of the plethora of possible tropical triggers of NAM-oscillations. The influence of the tropics on the NAM is manifest principally through intensity variations of the tropical Hadley circulation, which feeds the subtropical high-pressure systems. Local sources of intense latent heat release in the tropical belt can also force planetary waves, which propagate poleward. The recent review of Stan et al. (2017) is a valuable source of information on this topic.

After lunch Frank Selten (KNMI) gave a presentation on the skewness of geopotential height fluctuations. Skewness is a measure of the asymmetry of the probability density function. Large skewness at a particular location is indicative of the existence of two flow regimes: one, which prevails most of the time and another, which occurs relatively infrequently and is, therefore, characterized by large anomalies. The latter regime is associated with blocking anticyclones.

Next, Aarnout van Delden gave a short overview of recent research at IMAU, which reveals that the negative NAM-phase is highly correlated with large net poleward isentropic mass fluxes in the upper troposphere (**figure 4**), which explains the high sea level pressure at high latitudes in the negative NAM-phase. Poleward mass fluxes occur principally over the Eastern Atlantic and the Eastern Pacific Oceans in the Northern Hemisphere. This might also explain the preferred positions of blocking high pressure systems over Alaska and Scandinavia.

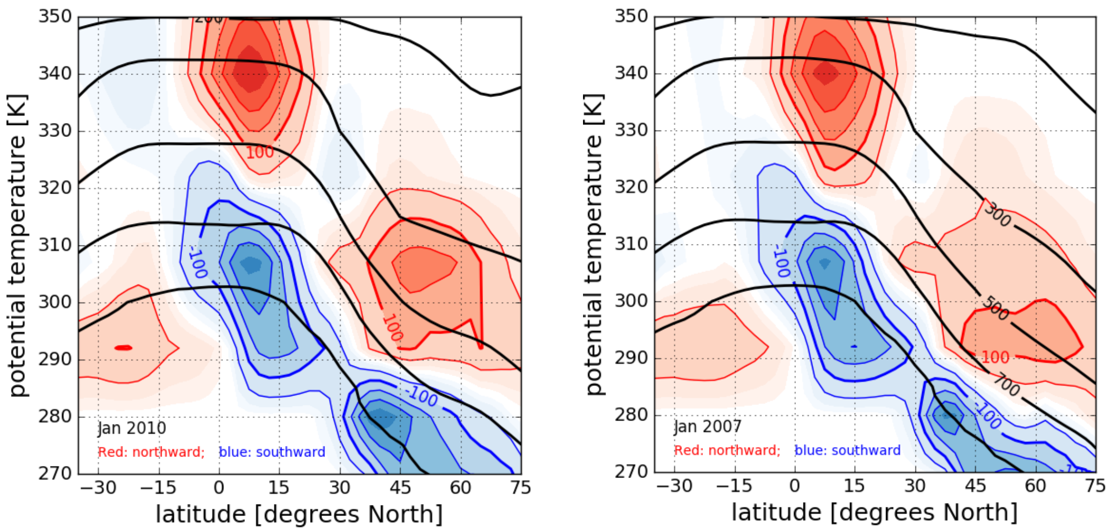

FIGURE 4. Monthly mean, zonal mean isentropic mass flux and monthly mean, zonal mean pressure, as a function of potential temperature and latitude, for **January 2010** (left) (negative-NAM-phase) and **January 2007** (right) (positive NAM-phase). **Red contours and shading corresponds to northward mass flux**. **Blue contours and shading corresponds to southward mass flux**. Contours are are drawn at 50 [kg s^{-1} K^{-1} per m in longitude] intervals. Shading starts at ±10 kg s^{-1} K^{-1} per m. Black contours represent on which p=900 hPa, 700 hPa, 500 hPa, 300 hPa and 200 hPa. Based on the ERA-Interim reanalysis.

A large zonal mean net poleward isentropic mass flux is correlated with a very weak or negative poleward isentropic eddy vorticity flux, in which case the eddies do *not* accelerate the zonal mean westerly wind, hence perpetuating the weak background flow and the stationary character of the waves and blocking anticyclones. Acceleration of the zonal mean zonal flow by large scale eddies in a rotating baroclinic atmosphere occurs in association with an intense positive (poleward) meridional vorticity gradient, which is typical of the subtropical jet. The isentropic vorticity flux is directed up the isentropic meridional vorticity gradient. This manifestation of "negative viscosity" induces a feedback, which indeed perpetuates the existing NAM-phase.

The final official workshop-presentation, due to Bob Ammerlaan (IMAU), was concerned with identifying the physical factors that determine the intensity of the poleward isentropic branch of the meridional circulation of mass due to unstable baroclinic waves, using a simplified primitive equation model. The model is able to reproduce the structure and intensity of the observed eddy driven mass circulation in middle latitudes. The intensity of the poleward mass flux appears to be most sensitive to changes in the width of the baroclinic zone and to changes in the intensity of cross-isentropic downwelling at high latitudes. The matter is complicated by the sensitivity of the solution to the initial conditions.

Maarten Ambaum, in a thought provoking final "colloquium", which was open to all interested, on the interaction between baroclinic wave life cycles and jetstream variability, stated that weather forecast busts are frequently associated with the initial stage of "blocking" and thus also with the initial stage of a negative NAM-phase. An increased understanding of the physics of the NAM and associated blocking of the westerly flow is, therefore, necessary to improve weather forecasts.

A one-day workshop is unfortunately insufficient to agree on many issues on the question of the physics of the Northern Annular Mode and Blocking. In fact, the theoretical perspective, the *regional* or the *annular*, is still under discussion.

In times when the meteorological research community is focused very much on the rather practical problem of evaluating the consequences of global warming, it is good to go back and discuss existing more fundamental problems, which are now receiving too little attention. In this sense, the workshop on the NAM was a big success.

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