Environment and Climate Change Canada   Environnement et Changement climatique Canada

Canada

Identifying wave processes associated with predictability across subseasonal to seasonal time scales

Gilbert Brunet
Meteorological Research Division
Environment and Climate Change Canada (ECCC)
John Methven
Department of Meteorology
University of Reading, UK

Second International Conference on Subseasonal to Seasonal Prediction (S2S)
Boulder, USA. Monday, 17th September, 13h15.

Acknowledgements: Franco Molteni, Dinh Tran and Ayrton Zadra

Outline

- Introduction
- Partitioning atmospheric behavior using its conservation properties
- S2S variability: Empirical Normal Mode (ENM) analysis in application
  - Northern Hemisphere variability on the 315K isentrope
  - Global upper troposphere: reanalyses and model diagnostics
  - Sudden Stratospheric Warmings (SSW)
- Conclusion

Introduction

- **Identifying wave processes associated with predictability across subseasonal to seasonal time scales**

A chapter in the coming S2S book "The Gap Between Weather And Climate Forecasting: Sub- Seasonal To Seasonal Prediction"

Editors: Andrew W. Robertson and Frederic Vitart

- **Partitioning atmospheric behavior using its conservation properties**

To provide a decomposition of the atmospheric flow into components described by well-known equations and theories:

  - a basic state that is influenced only by slow processes such as radiative cooling; and,
  - slow oscillation phenomena or propagating modes responsible for enhanced predictability in the S2S range.

Partitioning atmospheric behavior using its conservation properties

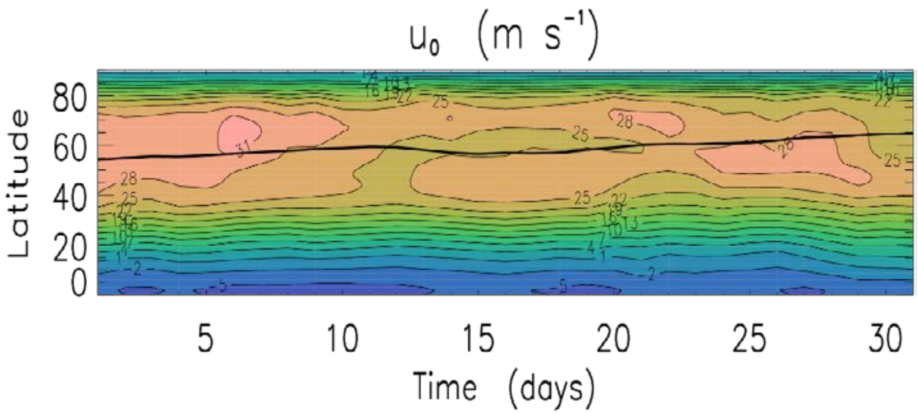
Mean Basic State

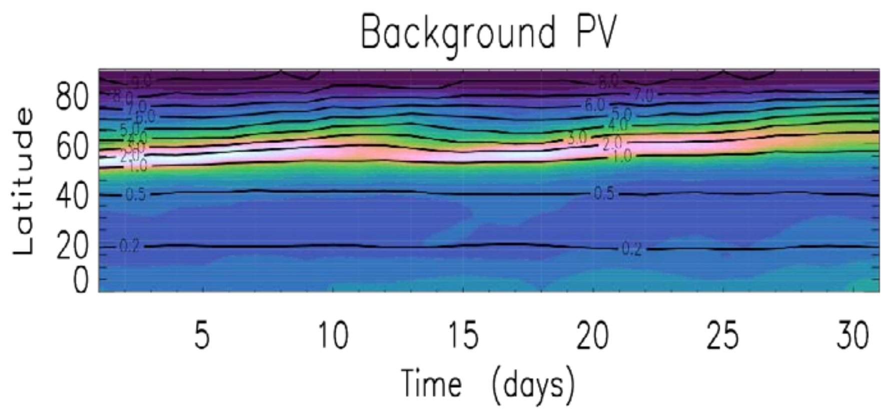
- Eulerian Zonal mean
- Modified Lagrangian Mean (MLM)

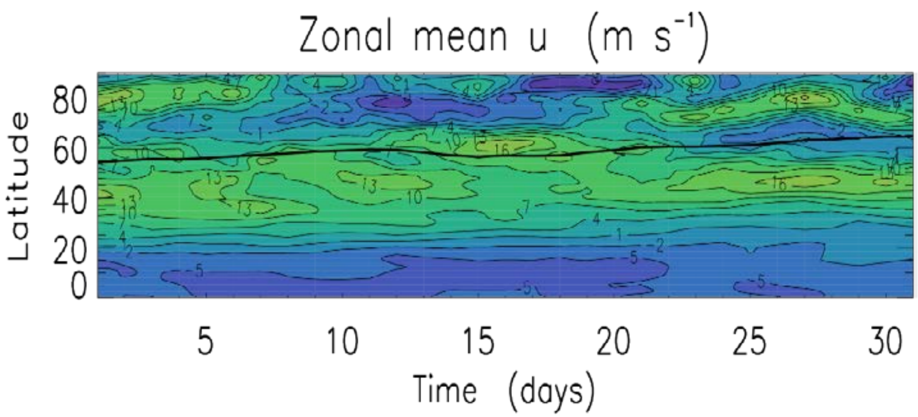
To describe the zonal mean basic state in conserved variable coordinates using potential temperature and Potential Vorticity (PV) where motion (of atmospheric mass) is only possible through the action of diabatic or frictional processes.

Evolution of the atmosphere on the 320K isentropic surface calculated from daily ERA-Interim data for June 2007

Modified Lagrangian Mean (MLM) Framework







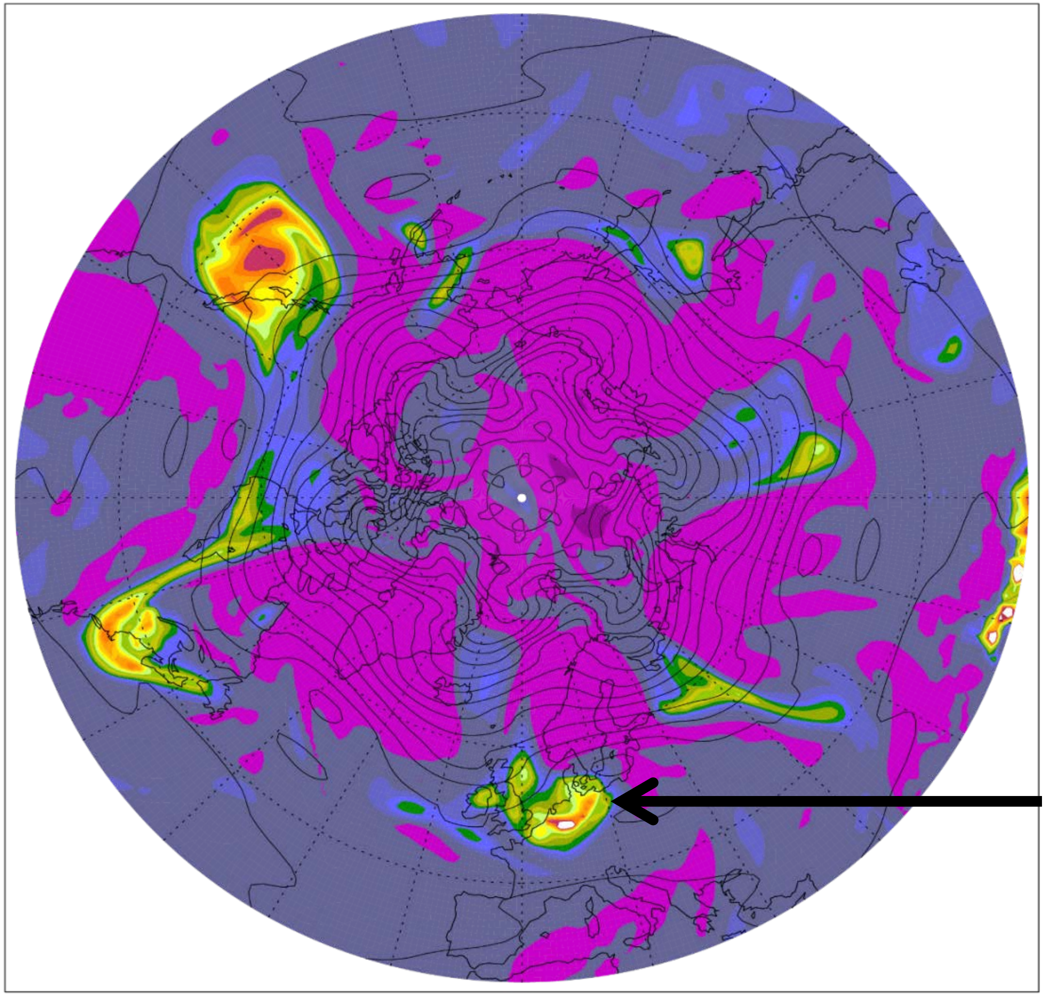
- Potential Vorticity (PV) contours and meridional PV gradient (largest values in pink).

- MLM basic state zonal mean u_0.
- Eulerian zonal mean wind.
- Solid line: tropopause (2PVU)

The seasonal march of the tropopause

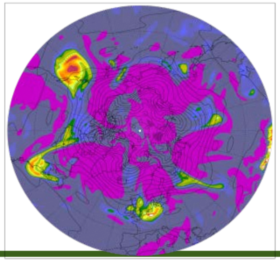
The ‘vortex erosion’ (Legras and Dritschel, 1993), where continuous filamentation of PV by Rossby wave breaking on the polar vortex edge transports mass within PV filaments away from the edge region into the ‘surf zone’ where the PV is mixed (McIntyre and Palmer, 1984).

PV anomaly (23 June 2007) on the 320K isentropic surface



- The contour lines show PV, Fourier filtered to zonal wavenumber 6 (interval 0.5 PVU);
- The shading shows the PV anomaly;
- This pattern recurred throughout June and July 2007 (positive PV anomaly in red) ;
- The trough over western Europe gave rise to extreme monthly rainfall (Blackburn et al., 2008).

Partitioning atmospheric behavior using its conservation properties



- <u>Conservation Laws</u>

Once we have the basic state, we need to characterize the evolution of perturbations from it.

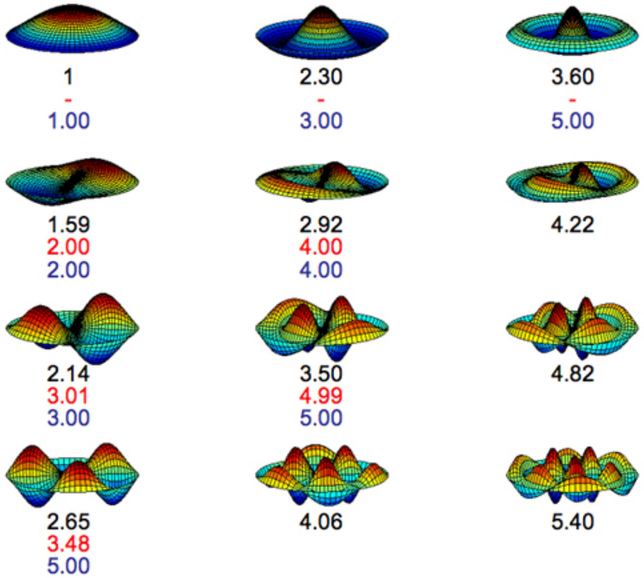
We propose to use

$$\frac{\partial A}{\partial t} + \nabla . \underline{F} = D$$

A is a wave activity density, $\underline{F}$ is the wave activity flux and D stands for the effects of non-conservative processes only.

- WHY?
  – To develop a phase space and statistical framework based on <u>normal mode theory</u> for studying the S2S variability as a <u>low-order dynamical system</u>;
  – To think about the S2S predictability and dynamical processes in terms of well established theories.

Empirical Normal Modes (ENMs) Theory or How to extract empirically the resonant modes of a physical system?



Basic State

Normal Modes

Empirical Normal Mode (ENM) analysis in application: Quasi-Geostrophic theory

Diagnostic on the 315K isentropic surface for 24 winters

the PV perturbation is

$$q' = \frac{\partial^2 \psi'}{\partial x^2} + \frac{\partial^2 \psi'}{\partial y^2} + \frac{1}{\rho}\frac{\partial}{\partial z}\left(\epsilon\rho\frac{\partial \psi'}{\partial z}\right) \qquad (5)$$

with $\epsilon = f^2/N^2$ and f the local value of the Coriolis parameter. The ambient meridional PV gradient is

$$q_{0_y} = \beta - \frac{\partial^2 u_0}{\partial y^2} - \frac{1}{\rho}\frac{\partial}{\partial z}\left(\epsilon\rho\frac{\partial u_0}{\partial z}\right), \qquad (6)$$

Brunet, G. 1994 Empirical normal mode analysis of atmospheric data. J. Atmos. Sci., **51**, 932-952.

Empirical Normal Mode (ENM) analysis

$$\frac{\partial A}{\partial t} + \nabla \cdot \mathbf{F} = 0,$$

Conservation Laws

where $\mathbf{F}$ is the corresponding flux vector. The integrated value of A over all the domain, denoted as $\langle A \rangle$, is conserved if the flux terms vanish on the domain boundary. Then two wave activities, the pseudomomentum and pseudoenergy, can be derived from Eq.

Pseudo-momentum Pseudo-energy

$$J = -\rho \frac{1}{2}\frac{q'^2}{q_{0_y}} \quad \text{and} \quad A = \rho\left\{\frac{1}{2}\left[u'^2 + v'^2 + \epsilon\left(\frac{\partial \psi'}{\partial z}\right)^2\right] - \frac{u_0}{2q_{0_y}} q'^2\right\}$$

Empirical Normal Mode (ENM) analysis

- For a linear atmospheric model that is stochastically forced and damped, the EOFs constructed with the pseudomomentum norm

$$J = -\rho \frac{1}{2} \frac{q'^2}{q_{0_y}}$$

are the normal modes of the evolution equation.

- The ENM theory bridges 3 important diagnostic tools of geophysical fluid dynamics: Empirical Orthogonal Function (EOF), Wave Activity and Normal Mode analyses.

Empirical Normal Mode (ENM) analysis

• The ENM phase speed **c** provides the **resonant frequency** ω_n of the mode where *k* is the zonal wave number (Held, 1985; Zadra, 2000)

Total pseudo-energy

$$\omega_n = kc \text{ and } c = \frac{\langle A_{k,c} \rangle}{\langle J_{k,c} \rangle}$$

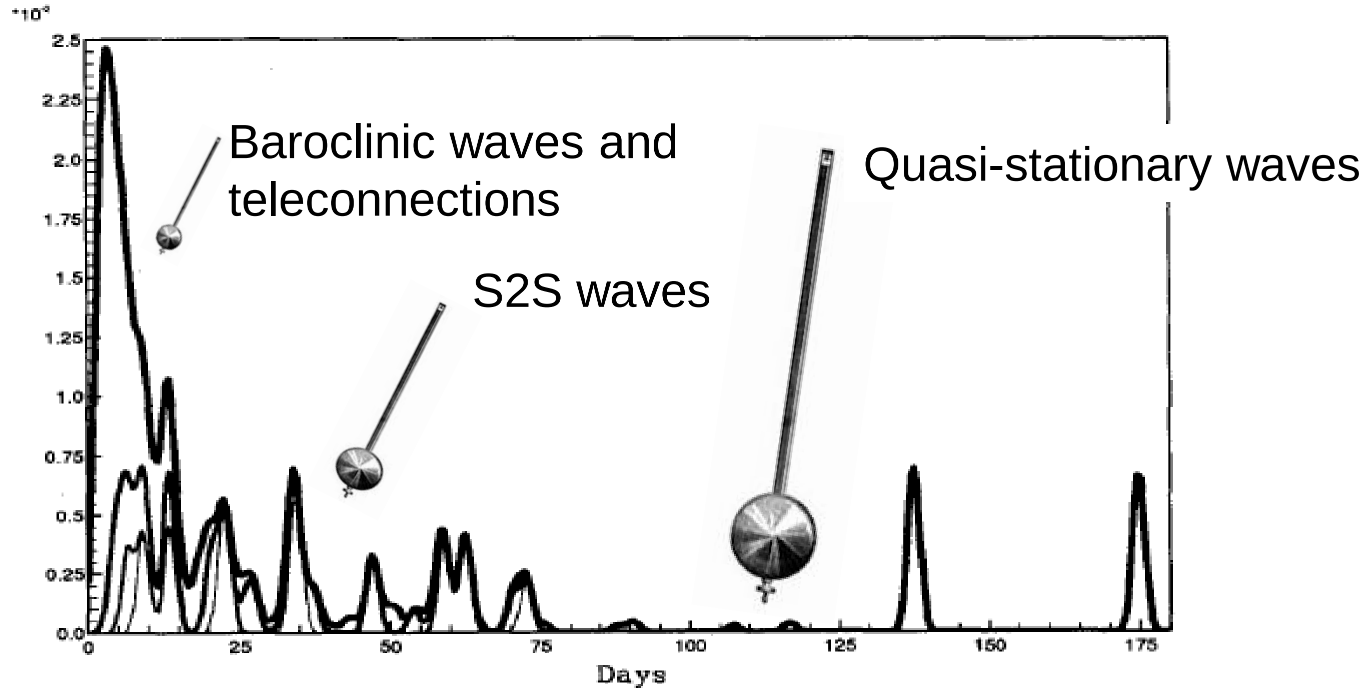
Total pseudo-momentum

$$T \approx 2\pi\sqrt{\frac{L}{g}}$$

• Hence the ENM phase speed provide important information on **its resonant behavior and its critical line associated to wave breaking region (i.e. phase speed is equal to the zonal wind basic state).**

Wave Activity on the NH 315K isentropic surface for 24 winters

- Cumulative wave activity in function of calculated ENM resonant time period

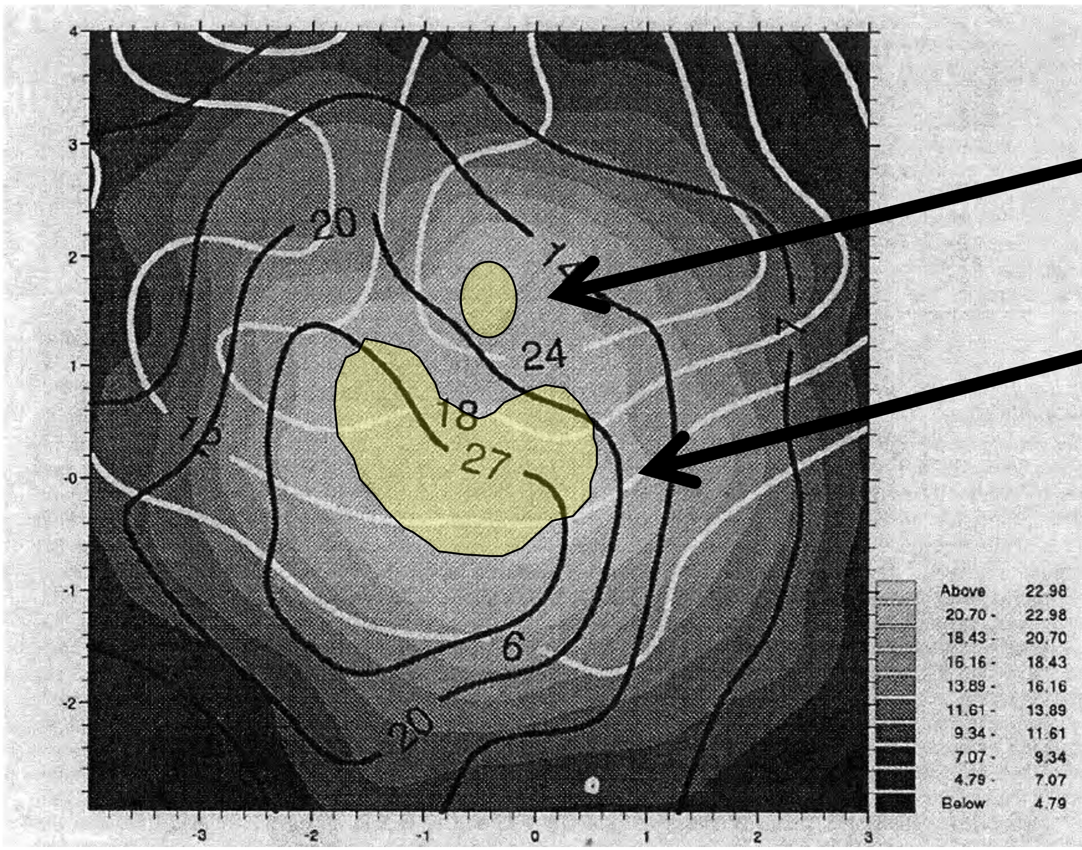


10 days 50 days 100 days 150 days

Continuous spectrum (80%) Discrete spectrum (dim. ~ 12, 20%)

- The low frequency variability (NAO, PNA, Atlantic blockings, MJO …) controls significantly the distribution of high-impact weather (like the Atlantic storm track and wave guides).

Blockings and resonances: phase space diagram of wave number 2, first ENM (Brunet, JAS,1994)



- Vautard (MWR, 1990)
  - Altlantic blockings (white contours)
  - Zonal regimes (black contours)

$$\frac{\partial}{\partial t}\hat{A}(x,t) = -\frac{\partial}{\partial x}\left[\left(C(x)-\alpha\hat{A}\right)\hat{A}\right] + \hat{S} - \frac{\hat{A}}{\tau} + D\frac{\partial^2\hat{A}}{\partial x^2}$$

Charney & Devore (JAS, 1979) proposed orographic induced linear and nonlinear resonance mechanisms to explain phase locking of weather regimes.

OR

“Atmospheric blocking as a traffic jam in the jet stream.”
Nakamura and Huang (Science, 2018)

ENM in Application: shallow water upper troposphere simulation with stochastic forcing

G. Brunet and R. Vautard 1996: Empirical normal modes versus empirical orthogonal functions for statistical prediction. *J.Atmos.Sci.*, 53, 3468-3489.

- The observed and theoretical resonant period compare very well (linear and nonlinear 4000-day simulations);
- Well tuned S2S phase speeds need proper numerical accuracy (~T42-64);
- The resonant response can be significantly damped if there is a bias in the mean state or forcing;

$$\tilde{a}_n = \frac{\tilde{\epsilon}_n}{i(\omega - \omega_n) + \gamma}$$

- An explanation for the signal-to-noise paradox (Scaife and Smith, 2018) in weather regime forecasts? (Strommen, B5-03, Wednesday)

Observed period ENM resonant period

TABLE 1. The pseudomomentum variance, $|\bar{J}_{s,n}|$; the observed period calculated from the mass spectra center formula (32), $T'_{s,n}$; and the theoretical period calculated from (20) for the more important ENMs. Only the cases s = 1, 2, and 3 are shown for (a) $h = 0.01$ and (b) $h = 0.16$. The time unit are in days and the pseudomomentum unit are in $\Omega^2 a\ 10^2$.

a)

Zonal wave number	n	$\lvert\bar{J}_{s,n}\rvert$	$T'_{s,n}$	$T_{s,n}$
1	1	0.48	−45.1	−44.7
1	2	0.39	−8.6	−7.2
2	1	1.29	−61.7	−56.1
2	2	0.24	−7.0	−5.2
2	3	0.09	103.6	299.2
3	1	0.36	−7.5	−6.08
3	2	0.16	−531.2	−163.0
3	3	0.09	26.4	22.8

S2S: linear simulation

s	n	$\lvert\bar{J}_{s,n}\rvert$	$T'_{s,n}$	$T_{s,n}$
1	1	9.93	−41.4	−42.0
1	2	4.97	−8.14	−6.72
2	1	7.75	−35.2	−33.2
2	2	3.60	−1147.4	−350.6
2	3	2.01	−7.05	−4.7
3	1	4.11	−6.97	−5.42

S2S: nonlinear simulation

ENM in Application: upper troposphere 3D ENM decomposition of NCEP reanalyses

Zadra et al., 2002: An empirical normal mode diagnostics algorithm applied to NCEP reanalyses *J. Atmos. Sci*., 59, 2811-2829.

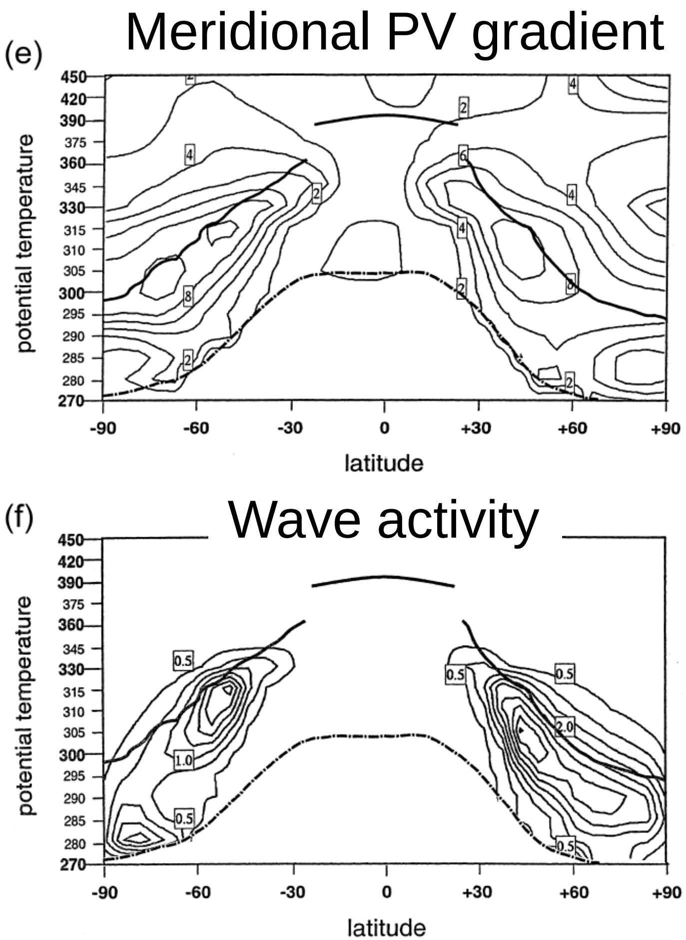


FIG. 1. (*Continued*)

Observed period

ENM resonant period

S2S

TABLE 2. Observed (T_{obs}, c_{obs}) and theoretical (T_{th}, c_{th}) values of the mean period in days, and phase speed (m s^{-1}), of some leading modes with wavenumbers s = 1, 5, and 9.

Zonal wave number		T_{obs}	T_{th}	C_{obs}	C_{th}
1	1	100	55	4.6	8.4
1	3	63	44	7.4	10.6
1	5	39	48	11.9	9.7
1	7	94	106	4.9	4.4
1	10	60	58	7.7	8.0
1	15	94	88	4.9	5.3
5	1	6.6	8.0	14.1	11.6
5	3	9.1	12.0	10.2	7.7
5	4	10.4	11.0	8.9	8.4
5	5	15.0	11.0	6.2	8.4
5	7	8.4	13.0	11.1	7.1
5	12	14.0	11.0	6.6	8.4
5	15	9.7	14.0	9.6	6.6
5	17	12.0	12.0	7.7	7.7
9	2	3.4	5.2	15.2	9.9
9	3	6.6	7.0	7.8	7.4
9	7	4.4	5.4	11.7	9.6
9	8	6.4	7.3	8.1	7.1
9	9	7.1	7.6	7.3	6.8
9	15	12.0	9.9	4.3	5.2
9	16	11.0	12.0	4.7	4.3

Quasi-modes contribute significantly to the wave activity at the tropopause
An example: the Southern Hemisphere 10 day wave

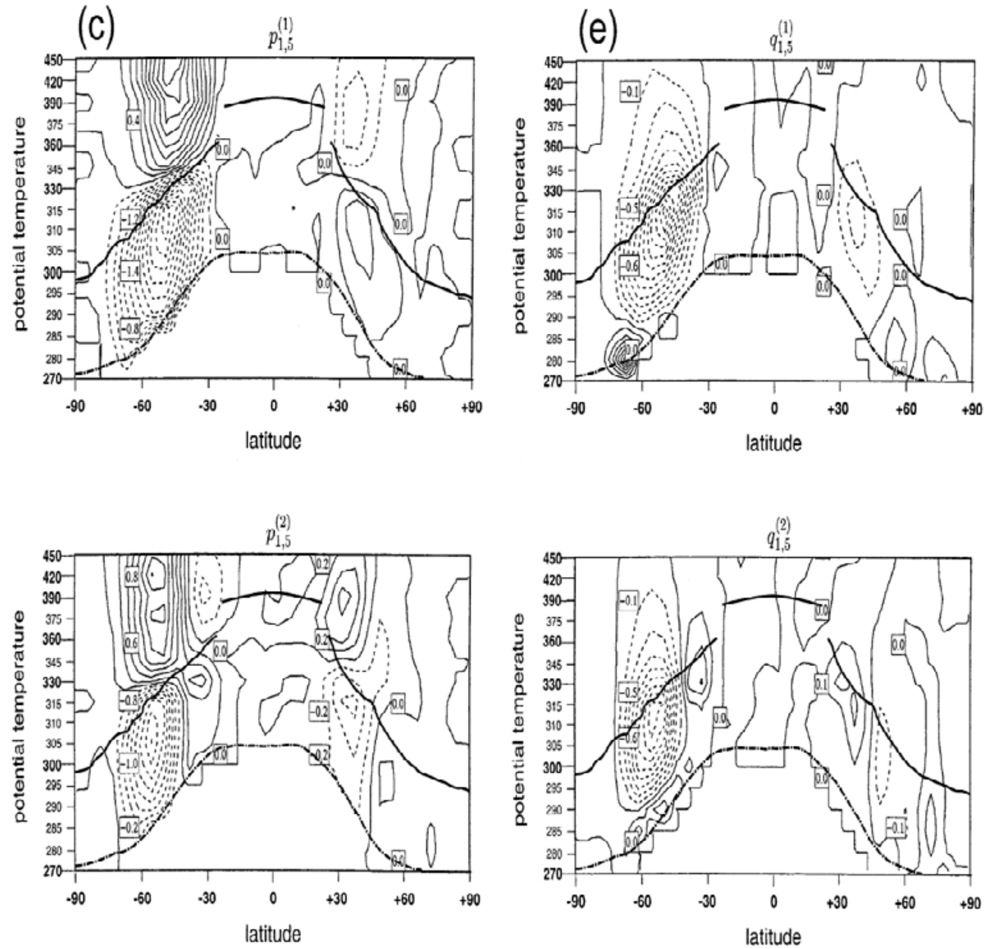
- Lin and Chan (1989)
- Rivest and Farell (1992)

Tropopause quasi-mode theory

  - Quasi monochromatic and damped mode;
  - Dipole pressure anomaly at the tropopause;
  - Observed and theoretical damping rate of 3 days.

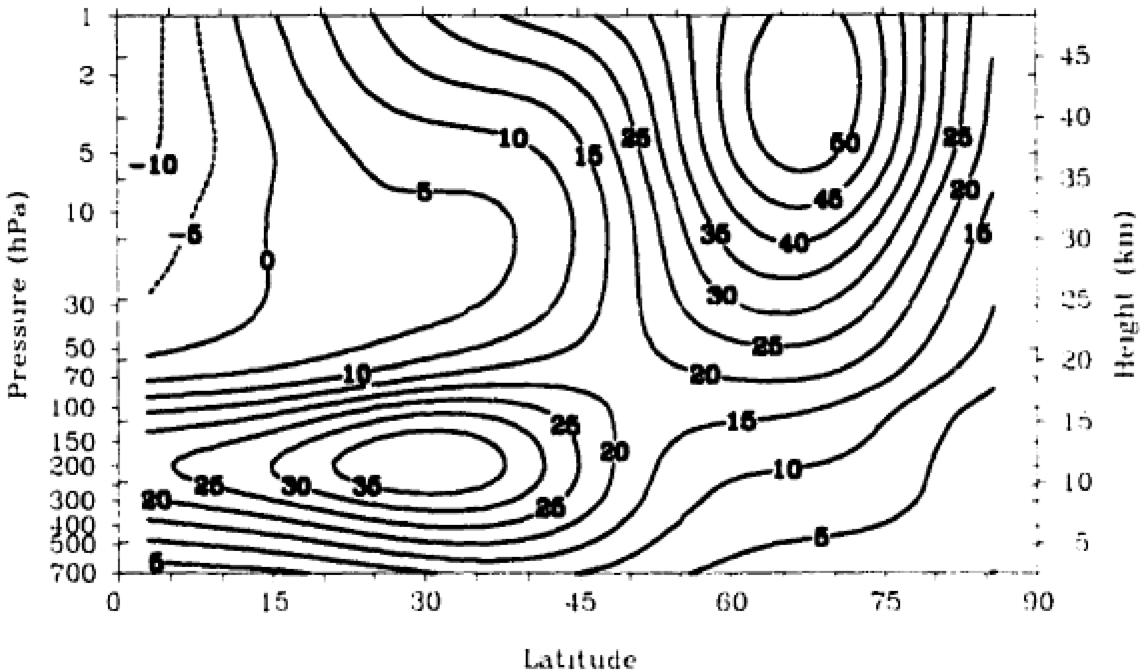
- A framework to look at troposphere-stratosphere exchange?

ENM Pressure ENM PV



Zadra et al., 2002

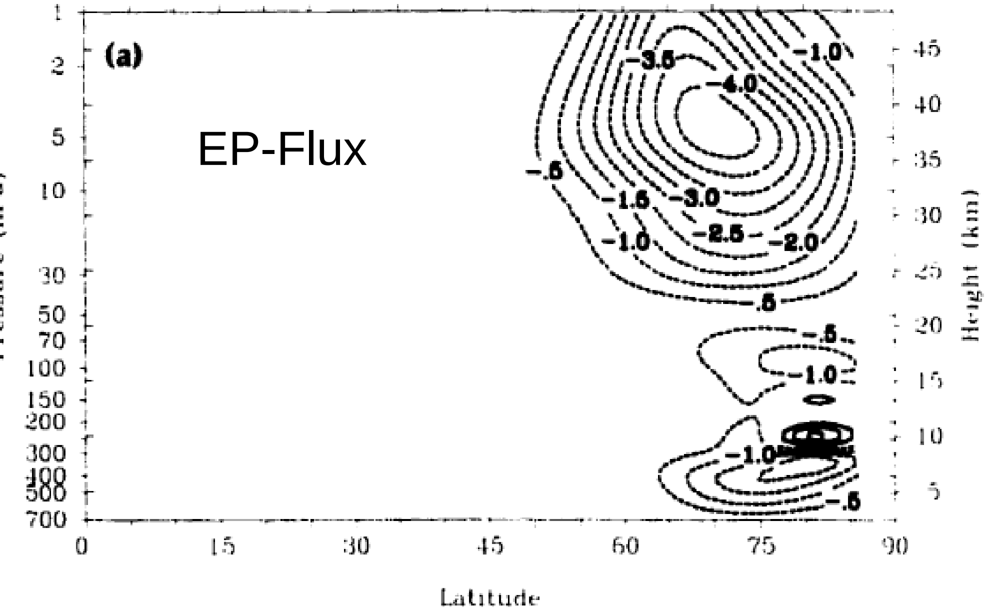
ENM in Application:
Sudden Stratospheric Warming (SSW)
D. Tran, PhD thesis, McGill University, 1998

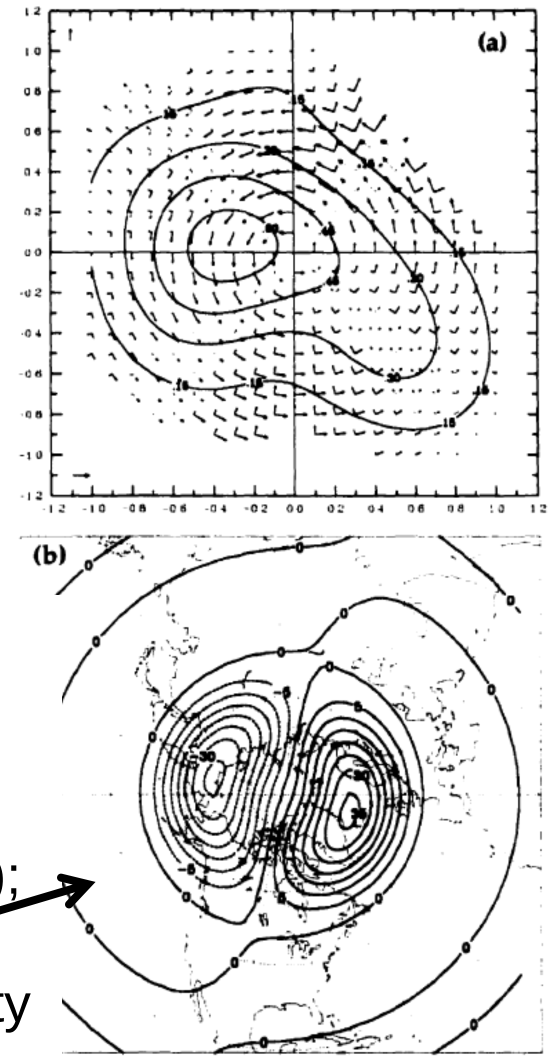


Average of pre-warmings (onsets of minor and major SSW) zonal mean wind (m/s) from 1980-1990 data set.

- Warming periods: Over 95% of the wave activity is explained by 4 “zonal wave number” 1 and 2 zonal “wave number 2” ENMs.

ENM in Application: SSW

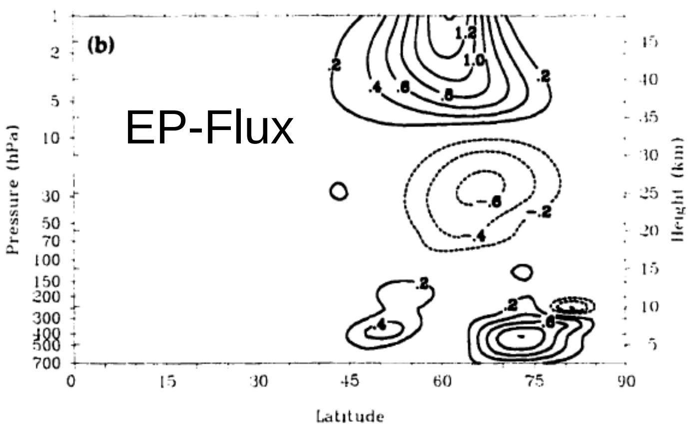




Wave activity flux divergence of the first 4 ENMs with wave number 1 for the growing periods

- Phase space diagram of ENM1 wave number 1 (probability distribution function and time tendency);
- Resonant period (20-30 days);
- Geographical composite of the highest probability where we see the Aleutian High push northward.

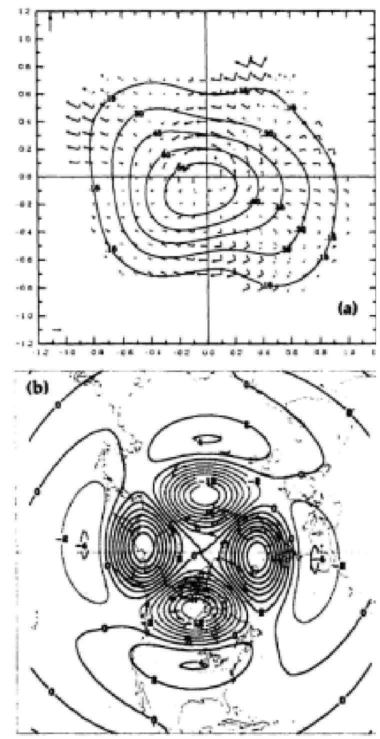
3D ENM in Application: SSW



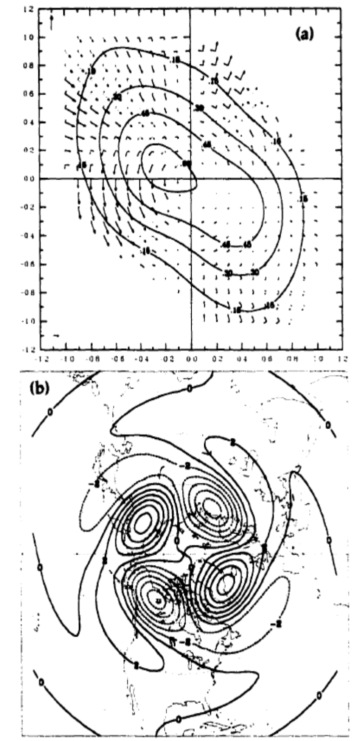
Wave activity flux divergence of the first 2 ENMs for wave number 2 for the growing periods

- Overall wave number 2 ENM1 and ENM 2 tend to split the polar vortex in two parts.

ENM 1



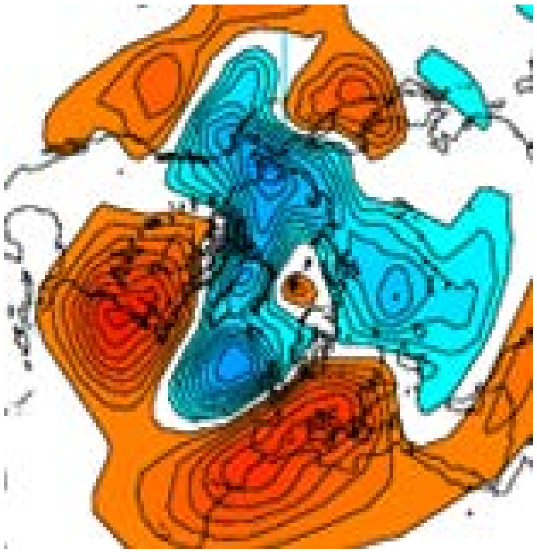
ENM 2

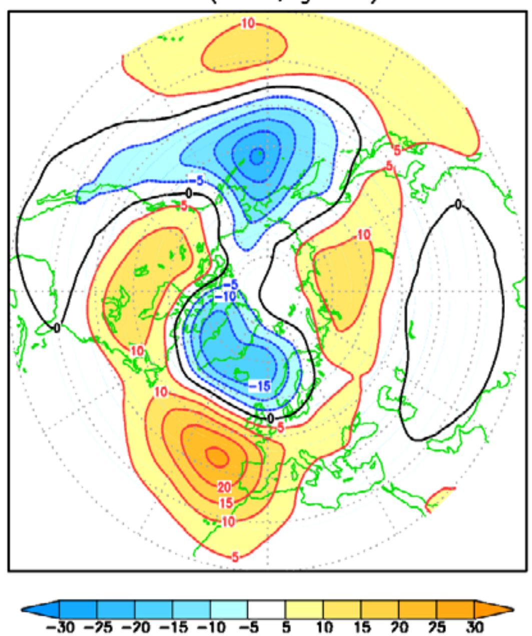


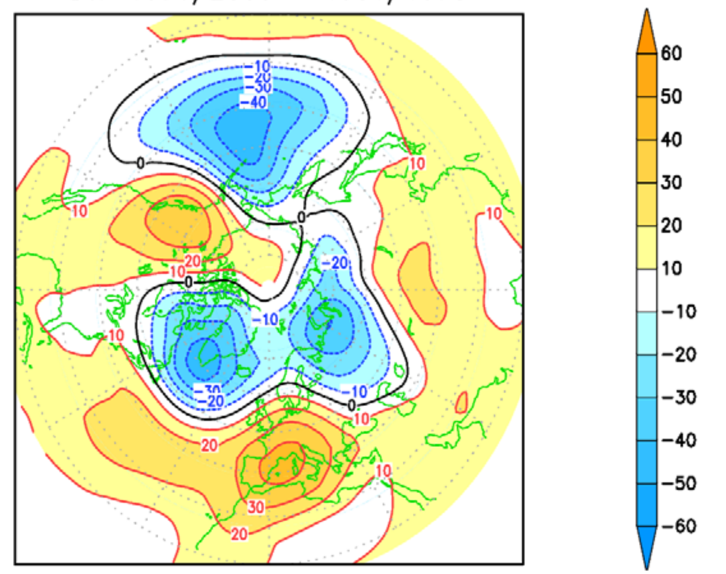
- Phase space diagrams of ENM1 and ENM2 wave number 2 (probability distribution function and time tendency);

- Geographical composite of the highest probability.

A planetary-wave signal common to different time scales? Resonance?







Z 500hPa anomaly

MJO phase3 + 10d   DJF W. Indian Oc. Rain   20th C. decadal variability

Acknowledgement: Franco Molteni

- Coumou, D., V. Petoukhov and S. Rahmstorf, 2014 Quasi-resonant circulation regimes and hemispheric synchronization of extreme weather in boreal summer. PNAS, 111, 12331–12336.
- Petoukhov, V., S. Rahmstorf, S. Petri and H.J. Schellnhuber 2013. Quasi-resonant amplification of planetary waves and recent Northern Hemisphere weather extremes. PNAS, 110, 5336–5341.

Conclusion

“A major weakness in dynamical meteorology is that there is currently no comprehensive theory capturing the different processes acting at all stages of the blocking life cycle: onset, maintenance and decay”
Blocking and its response to Climate Change, Woollings et al., 2018.

We propose here a dynamical framework that could be a first step to alleviate this issue

- We can diagnose the S2S atmospheric variability by splitting the diabatic and adiabatic flow components using fundamental principles from geophysical fluid dynamics;

- We believe that empirical normal mode (ENM) analysis, with its built-in characteristics based on conservation laws, EOF analyses and normal mode theory, provides an appropriate theoretical framework to suitably frame S2S scientific studies and bring new perspectives (e.g. partitioning the S2S variability in fast and slow modes based on the ENM intrinsic phase speed);

Conclusion

S2S variability (NAO, PNA, Atlantic blockings, MJO, SSW …) controls significantly the distribution of high-impact weather.

Hence there is a need to:

- Characterize dynamical processes and predictability of S2S variability, including weather and socio-economic impacts, in re-analyses and reforecasting experiments;

- This has direct relevance for the emerging field of attribution where weather events are linked to external (anthropogenic) and internal (natural variability) climate forcing (e.g. Stott et al., 2015), including weather regime responses to climate change (structure and occurrence, Palmer 1999).