WCRP Workshop on Seasonal to Multi-Decadal Predictability of Polar Climate
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Numerical studies on internal and external variations of the winter polar vortex with a mechanistic circulation model

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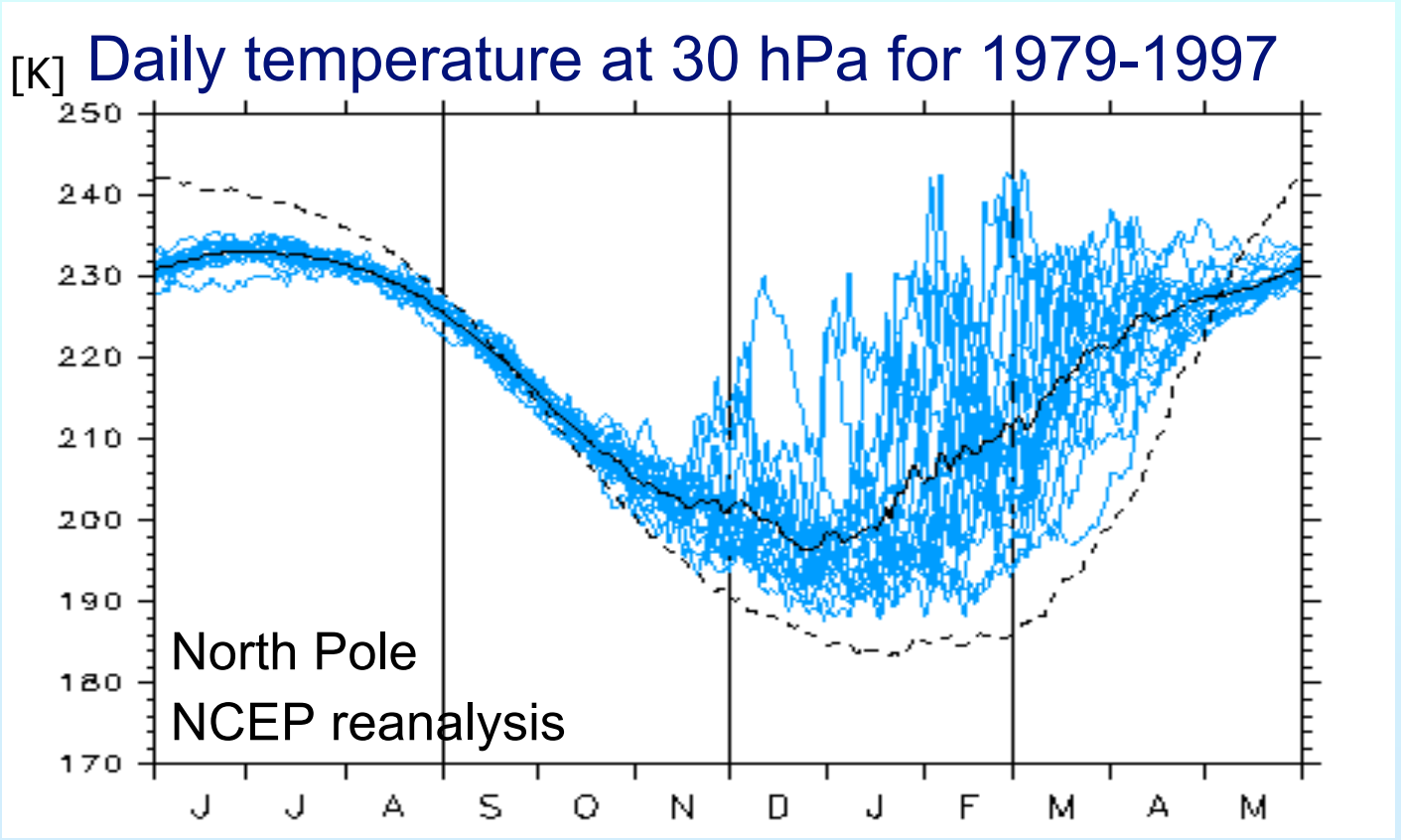
1. General introduction
2. Internal variations of the polar vortex
3. Response to external variations
4. Associated predictability variations
5. Concluding remarks

1. General introduction

❖ stratospheric sudden warming (SSW)

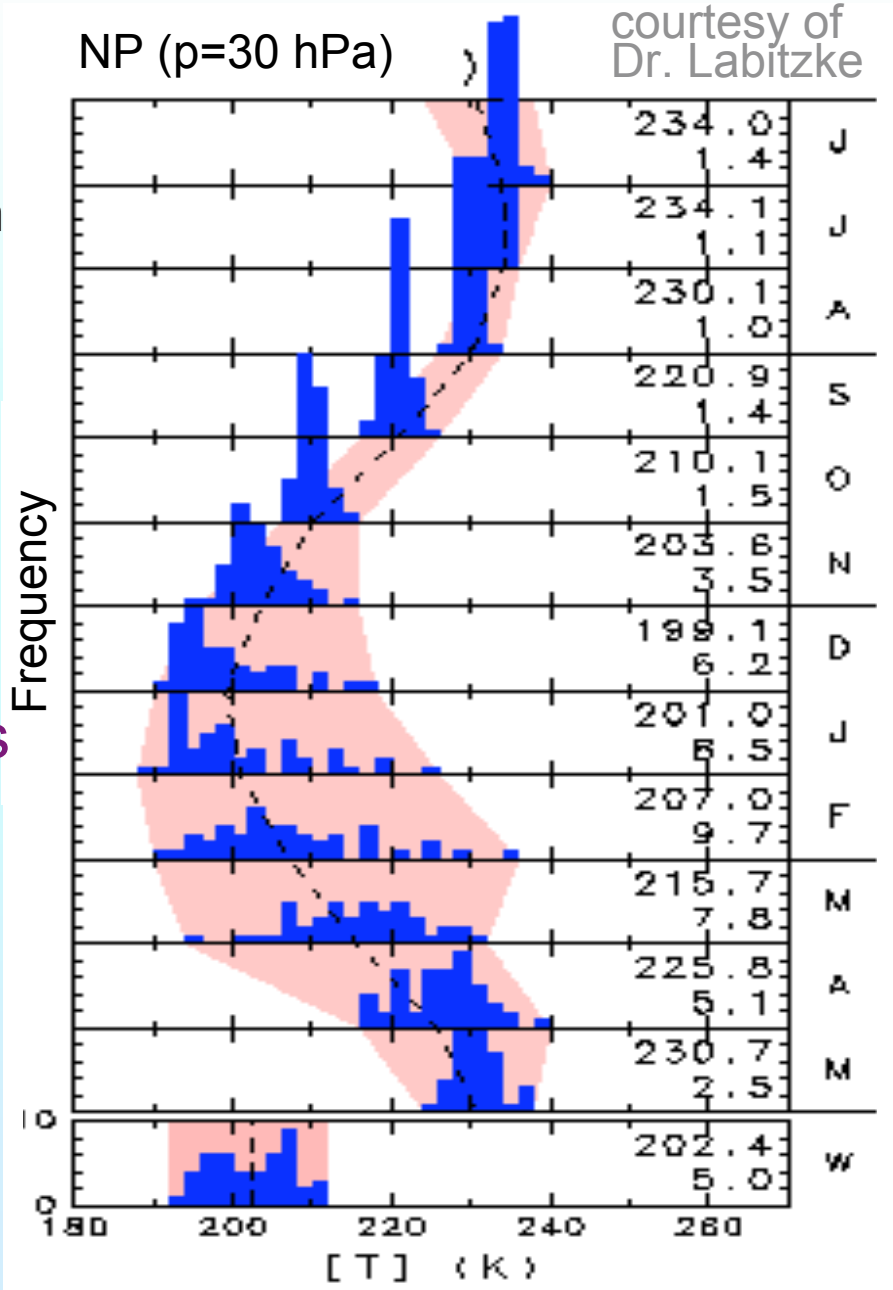
- breakdown of the polar vortex in the winter stratosphere
  - ➢ a rise of temperature by several tens K in a few days
  - ➢ several minor warming events in a year, while a major warming event occurring roughly every two years



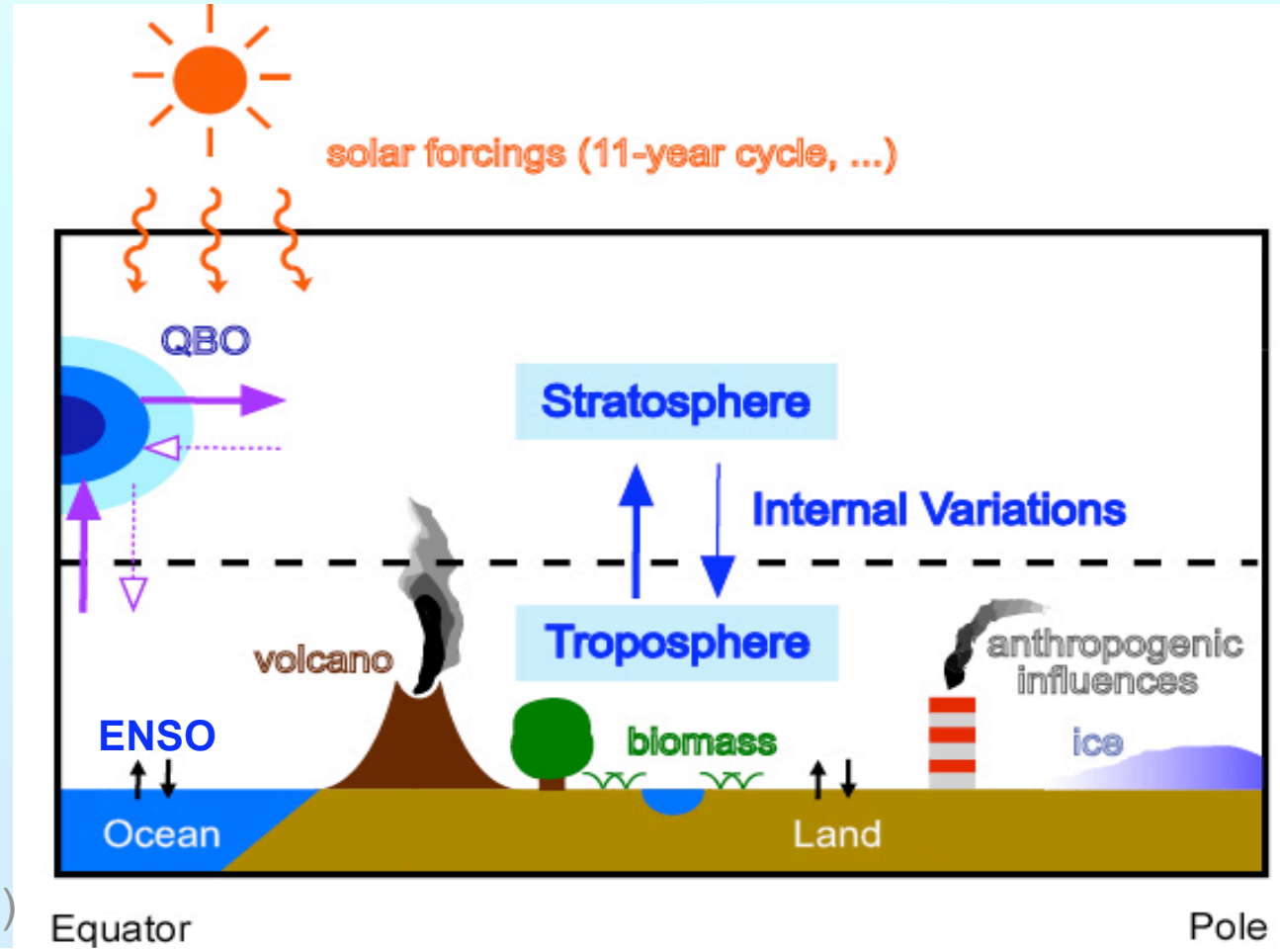
Yoden et al. (2002, *JMSJ*)

❖ intraseasonal and interannual variability in the stratosphere

- Labitzke diagram
  - ➢ histograms of the monthly mean temperature at the North Pole
- large variability in winter
  - ➢ mostly due to the occurrence or non-occirrence of an SSW
- internal variations
  vs
  responses to external forcings

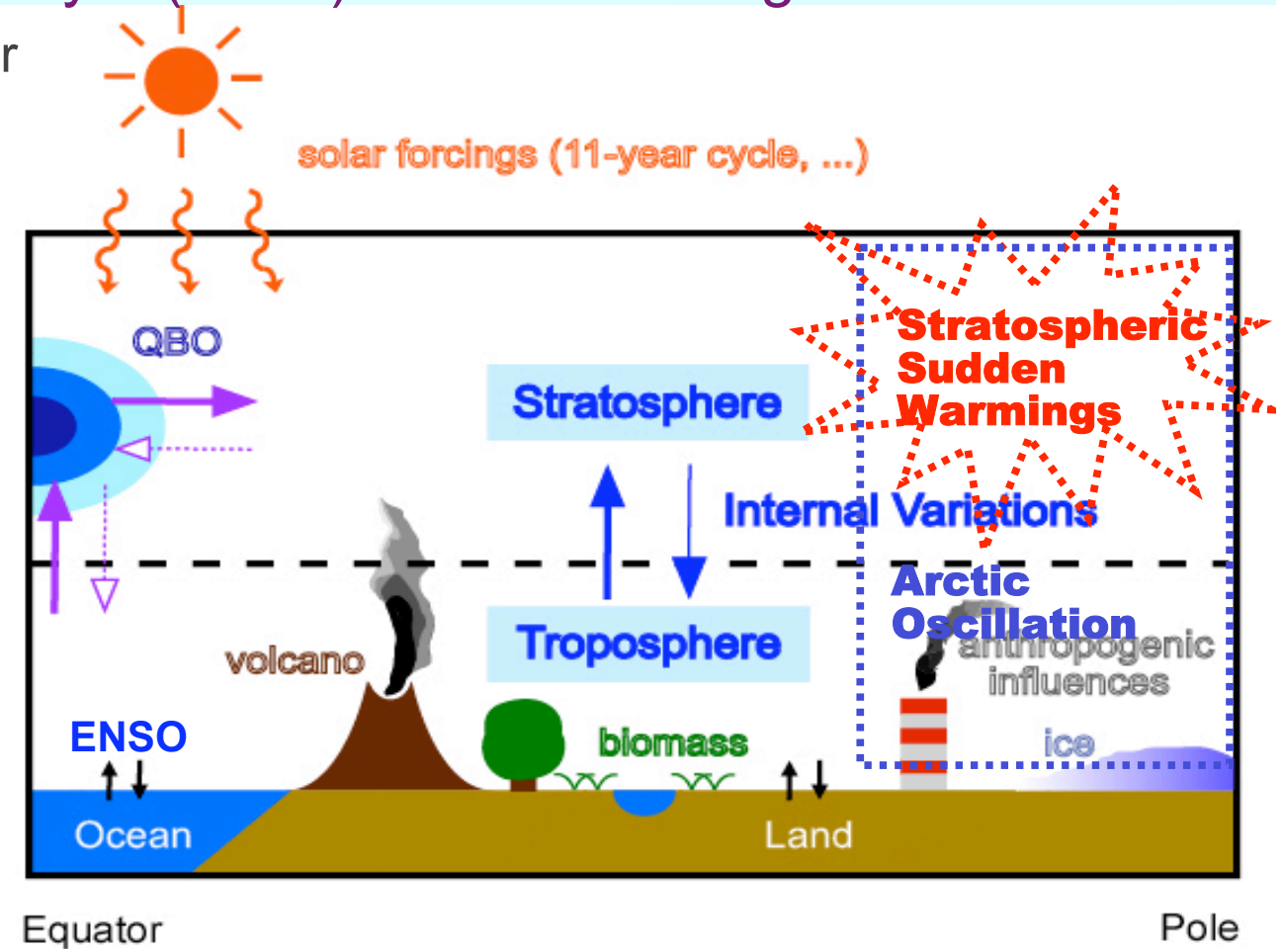


- possible “external” forcings
  - out of the atmosphere: solar forcings, volcanic eruption, biomass, anthropogenic influences (~trend)
  - in the atmosphere but far from the poles: equatorial QBO, ENSO



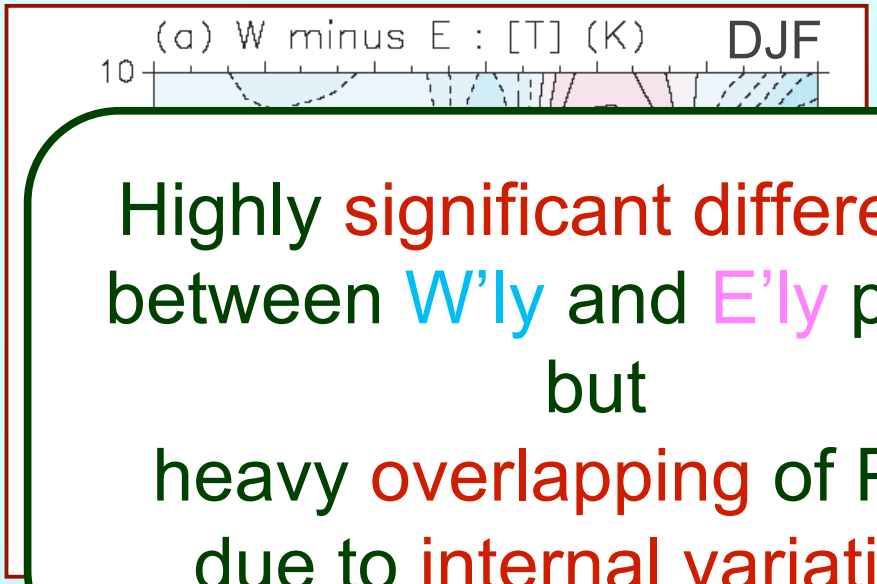
Yoden et al. (2002, *JMSJ*)

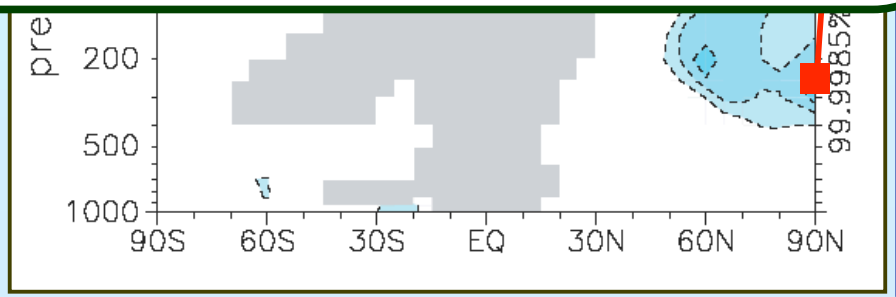
- possible “external” forcings
  - out of the atmosphere: solar forcings, volcanic eruption, biomass, anthropogenic influences (~trend)
  - in the atmosphere but far from the poles: equatorial QBO, ENSO
- SSW and associated variations could be a key process which may amplify a (small) external forcing
  - highly nonlinear
  - c.f. stochastic resonance
- An example: QBO influence

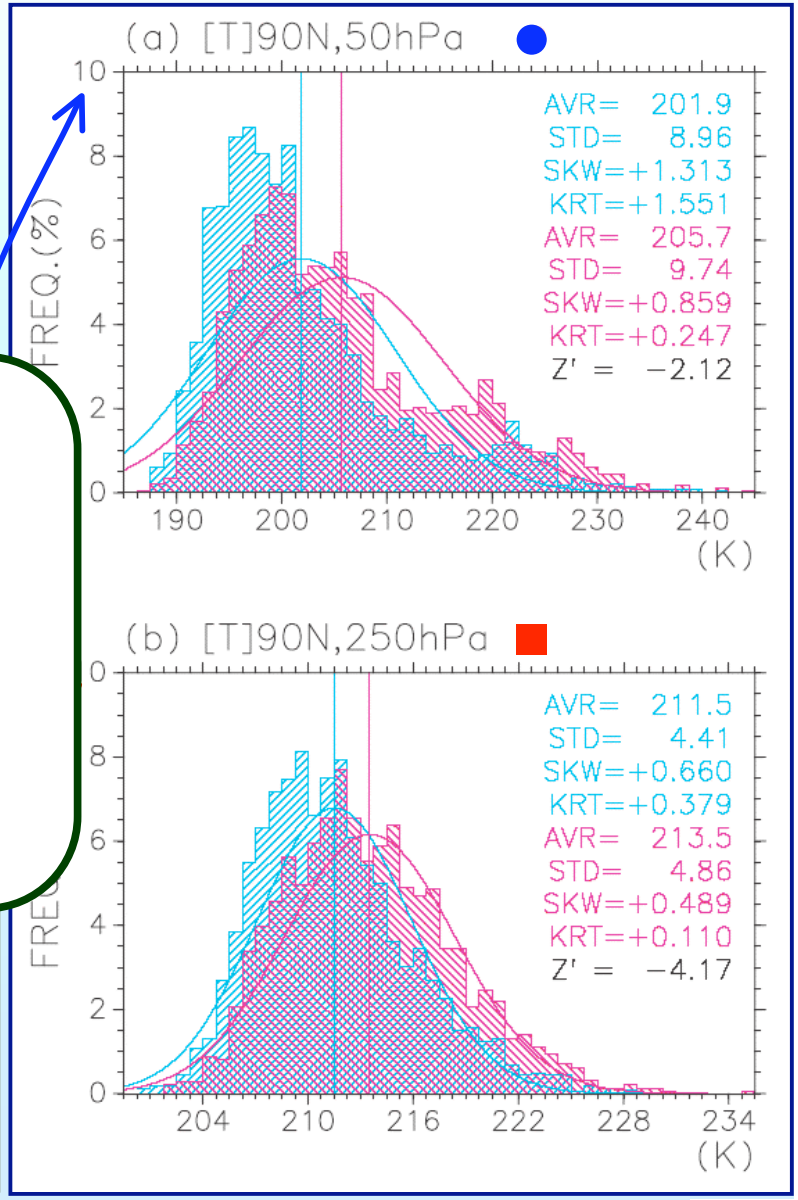


Yoden et al. (2002, *JMSJ*)

- Naito and Yoden (2005, *SOLA*)
  "Statistical analysis of the QBO effects on the extratropical stratosphere and troposphere"
  - NCEP/NCAR reanalysis data:
    ~2,000 days for each of
    Westerly or Easterly phase



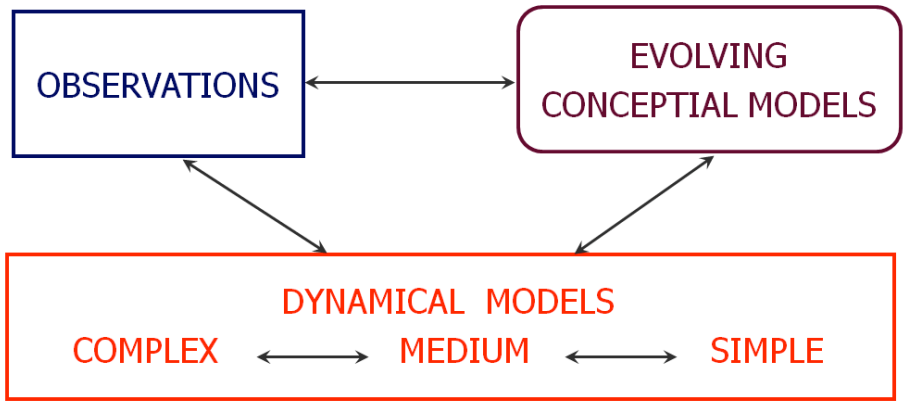




Highly significant differences between W'ly and E'ly phases but heavy overlapping of PDFs due to internal variations

- some difficulty in observational studies
  - data length is limited
    - at most 50 years (e.g., Berlin data since 1950s)
  - essential difficulty (nearly impossible) in separation of each response of the polar stratosphere variations
    - highly nonlinear processes with interactions among dynamics, radiation and/or chemistry with multiple time scales
- Only numerical experiments overcome this difficulty
  - can supply much longer data to obtain statistical significance
  - can do the experiments that control the external forcings
- hierarchy of numerical models
  - Hoskins (1983, *Q.J.R.M.S.*) "Dynamical processes in the atmosphere and the use of models"

the optimum situation for meteorological research



- Over a decade in Kyoto, we have made numerical studies on internal and external variations of the winter polar vortex with a mechanistic circulation model
  - 3-D global MCM
    - GFD Dennou Club AGCM5 (1998)
    - Resolution: T21L42 (surface to the mesopause)
    - Simplified physical processes:
      - Newtonian heating/cooling (in some cases, under perpetual-winter condition)
      - Rayleigh friction at the surface and at the top sponge layer
      - dry atmosphere
      - idealized surface topography
        only in NH, *s* =1, *amp* =1000m
  - experiments on
    some parameter dependence
    with long enough data
    for statistical significance tests

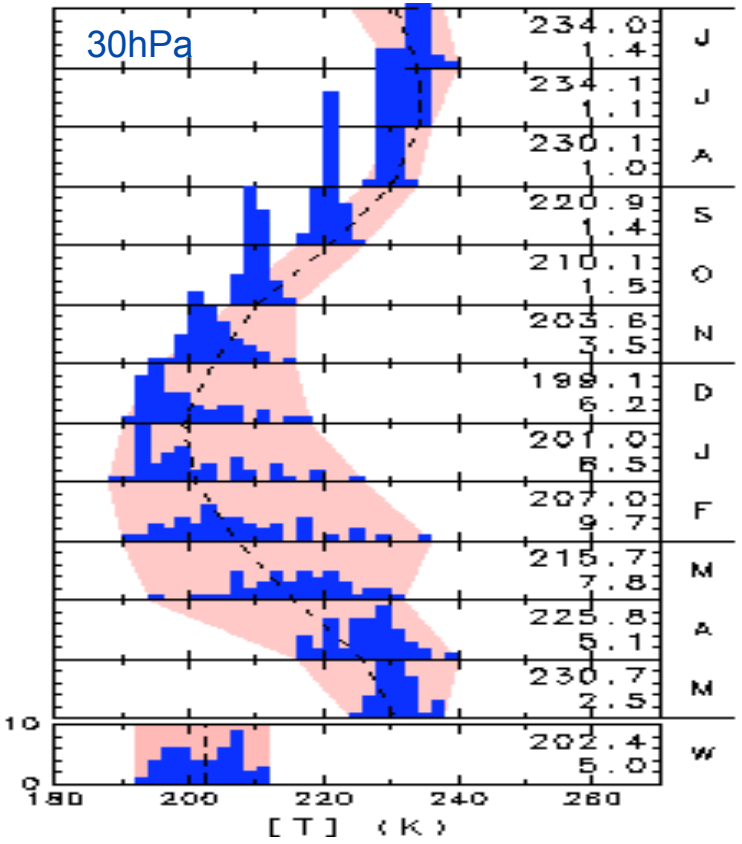
- experiments on some parameter dependence with long enough data (max ~ 15,000 years) for statistical significance
  - Taguchi, Yamaga and Yoden (2001)
    SSWs in a stratosphere-troposphere (S-T) coupled system
  - Taguchi and Yoden (2002a,b,c)
    internal variations associated with SSWs
  - Naito, Taguchi and Yoden (2003)
    QBO effects
  - Nishizawa and Yoden (2004)
    annular-mode variability
  - Nishizawa and Yoden (2005)
    spurious trends due to short dataset
  - Naito and Yoden (2006)
    QBO effects on SSWs
  - Ito, Naito and Yoden (2009)
    QBO and 11-year solar cycle
  - Kohma, Nishizawa and Yoden (2010)
    PJO and fast variations (SSW, VI)

2. Internal variations of the polar vortex

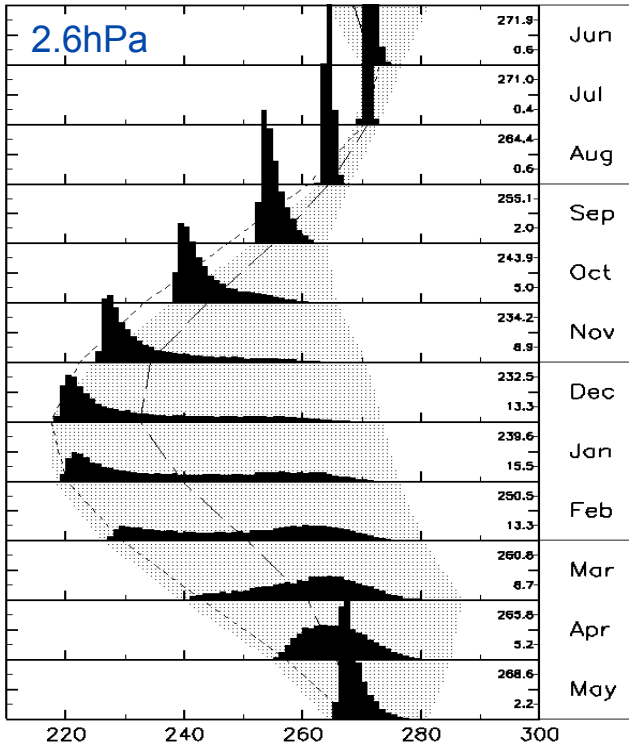
❖ seasonal dependence of internal interannual variability

- due to the occurrence of SSWs in winter stratosphere
- breakdown of the polar vortex is a highly nonlinear process under a purely periodic annual forcing

Real atmosphere (Berlin data)

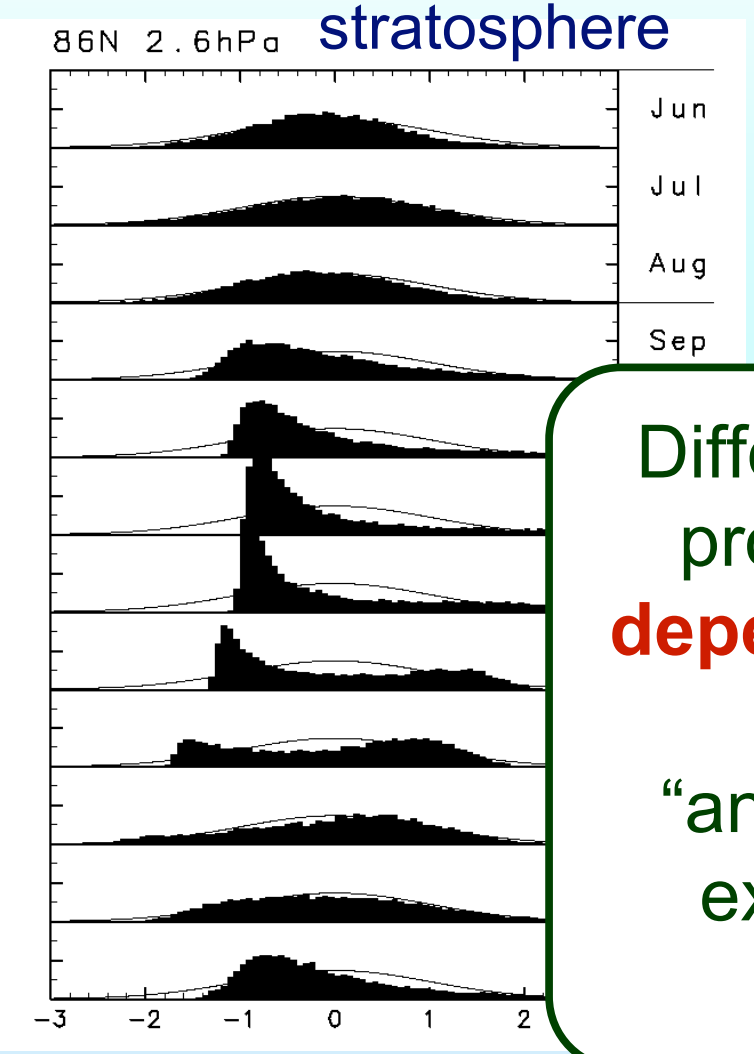


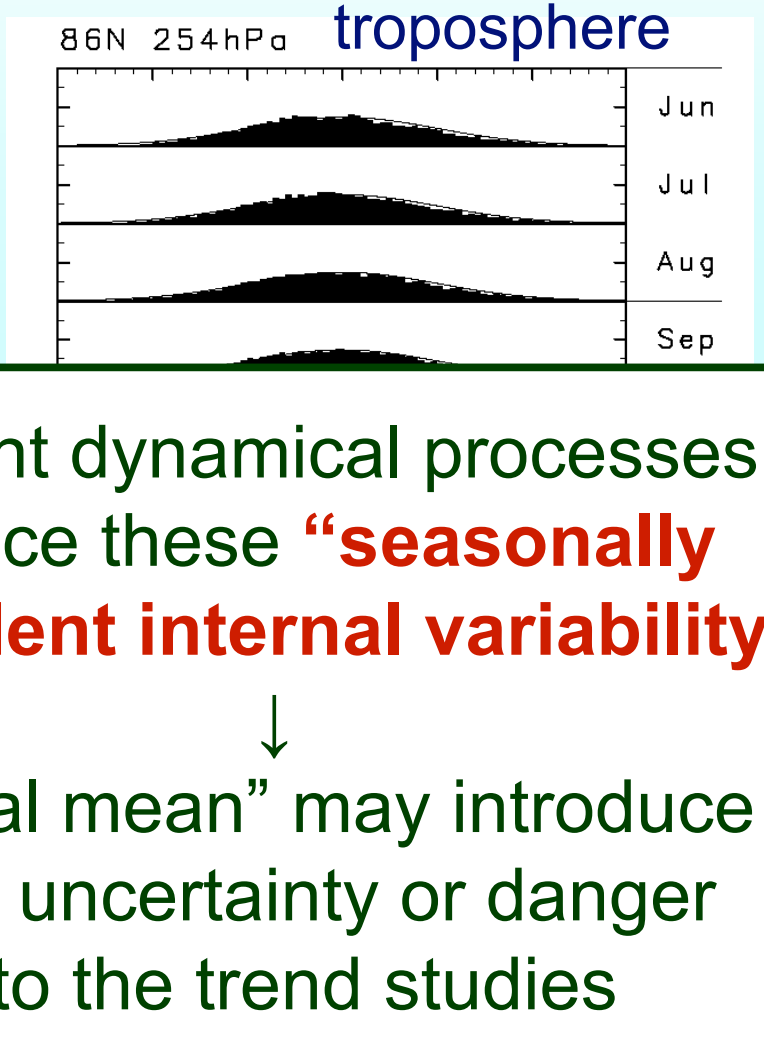
MCM(15,200years)



Labitzke diagram of the polar stratospheric [T]
(Nishizawa and Yoden, 2005, *JGR*)

- Nishizawa and Yoden (2005, JGR)
  non-Gaussian nature of internal interannual variability
  - normalized pdfs of monthly [T] at the north pole





Different dynamical processes produce these **"seasonally dependent internal variability"**

↓

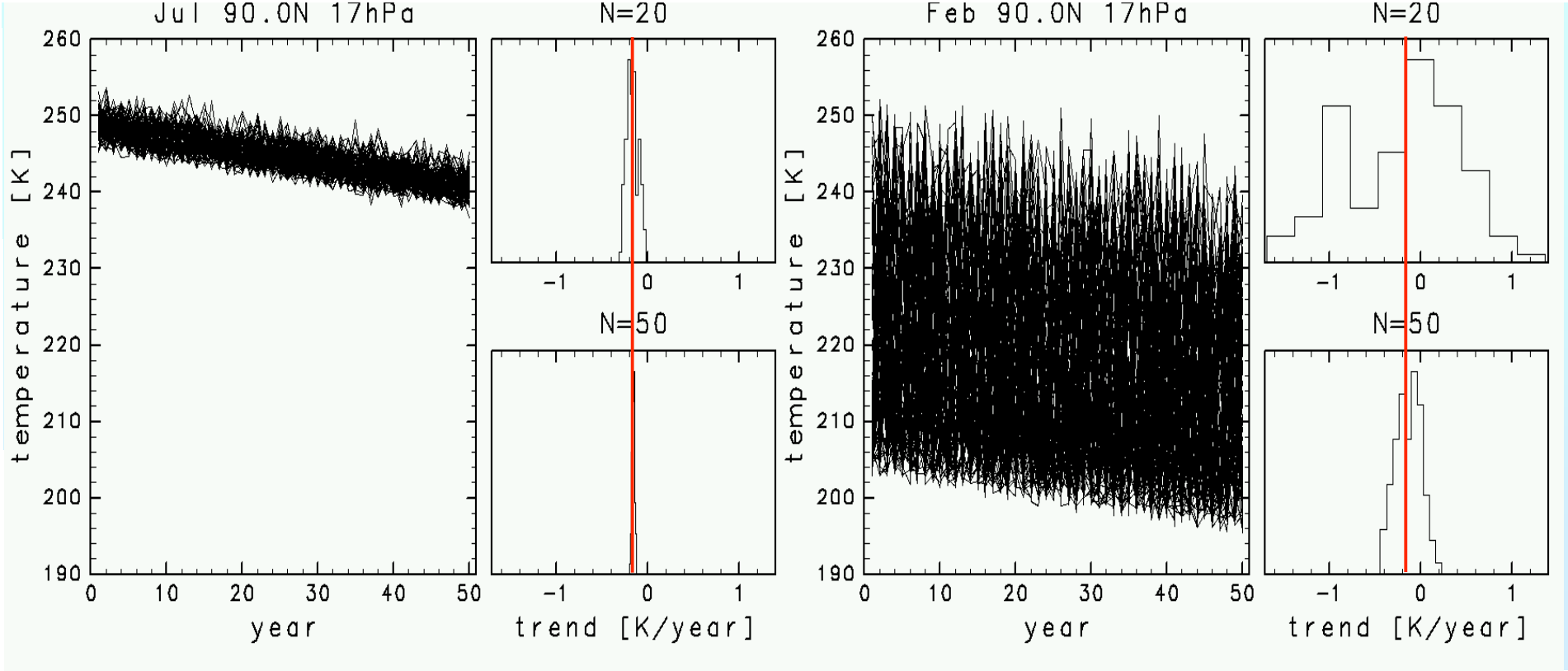
"annual mean" may introduce extra uncertainty or danger into the trend studies

❖ an application: seasonally dependent detectability of a linear trend

- a cooling trend experiment
  - ➢ 96 ensembles of 50-year integration with an external linear trend
    -0.25K/year around 1hPa

Natural variability:

small in summer (July) large in winter (Feb.)

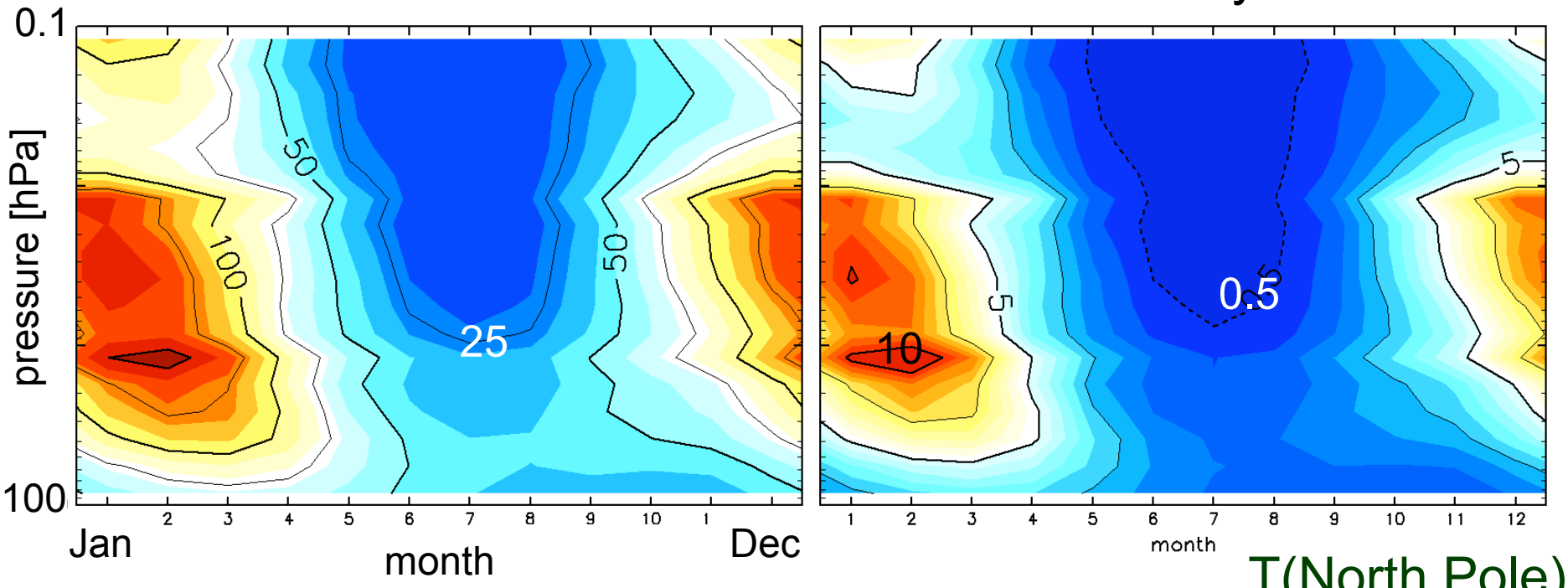


❖ seasonally dependent detectability

- How many years do we need to get a statistically significant trend ?
- How small trend can we detect in finite length data with a statistical significance ?

necessary data length [years] to detect a linear trend of - 0.5K/decade with 90% conf.

necessary magnitude of the trend [K/decade] to detect with a 20-year dataset



T(North Pole)

3. Response to external variations

❖ QBO effects on the occurrence of SSWs

- Naito, Taguchi and Yoden (2003, *JAS*)
- Naito and Yoden (2006, *JAS*)
  - "QBO forcing" in the zonal momentum eq.:

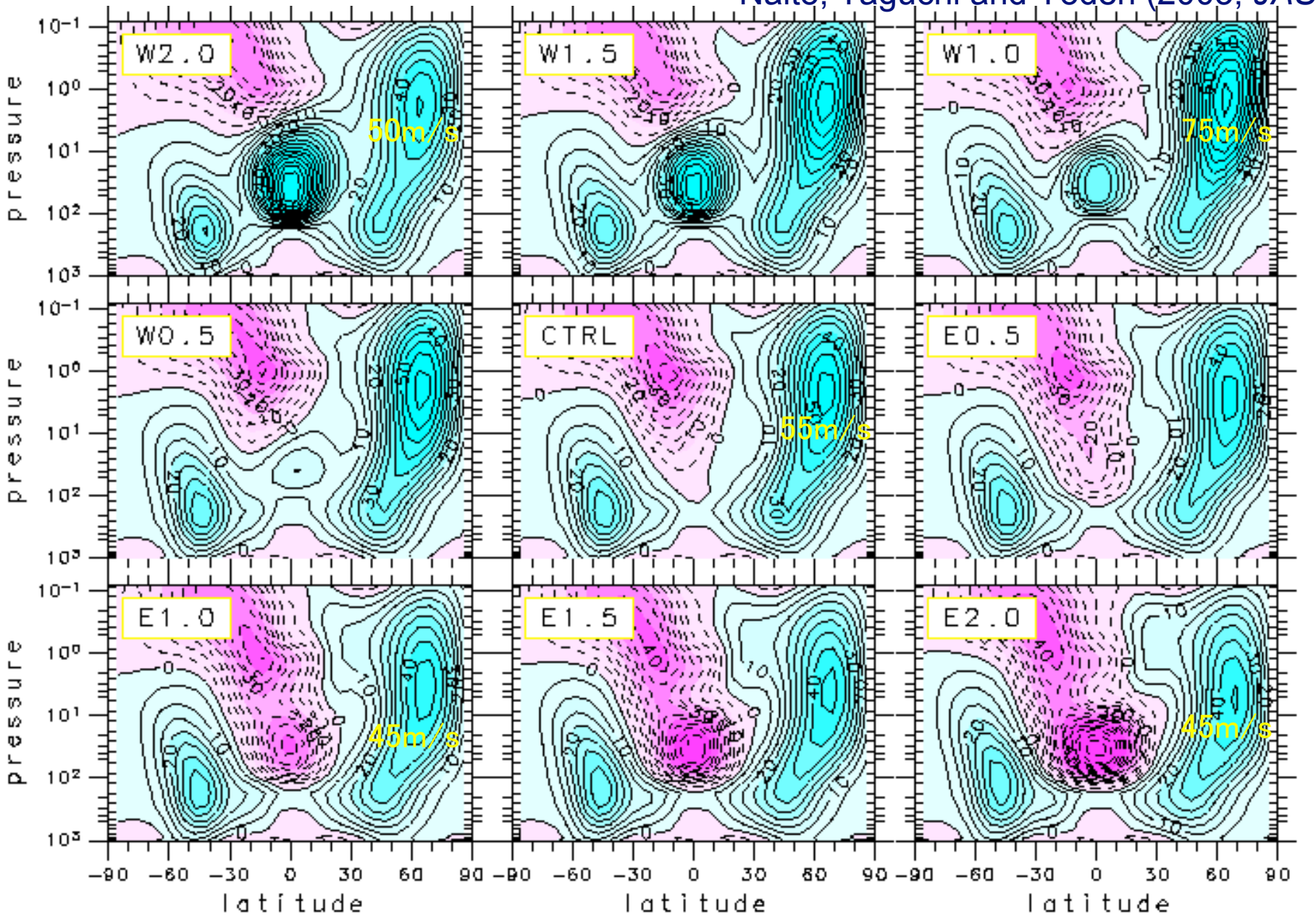
$$\partial u / \partial t = \cdots - \alpha_{QBO} \left(u - U_{QBO} \right)$$

U_{QBO} : prescribed zonal mean zonal wind of a particular phase of the QBO

  - Under a perpetual winter condition (10,800-day statistics)
  - Assess the atmospheric response to a small (or finite) change in the external parameter by a statistical method

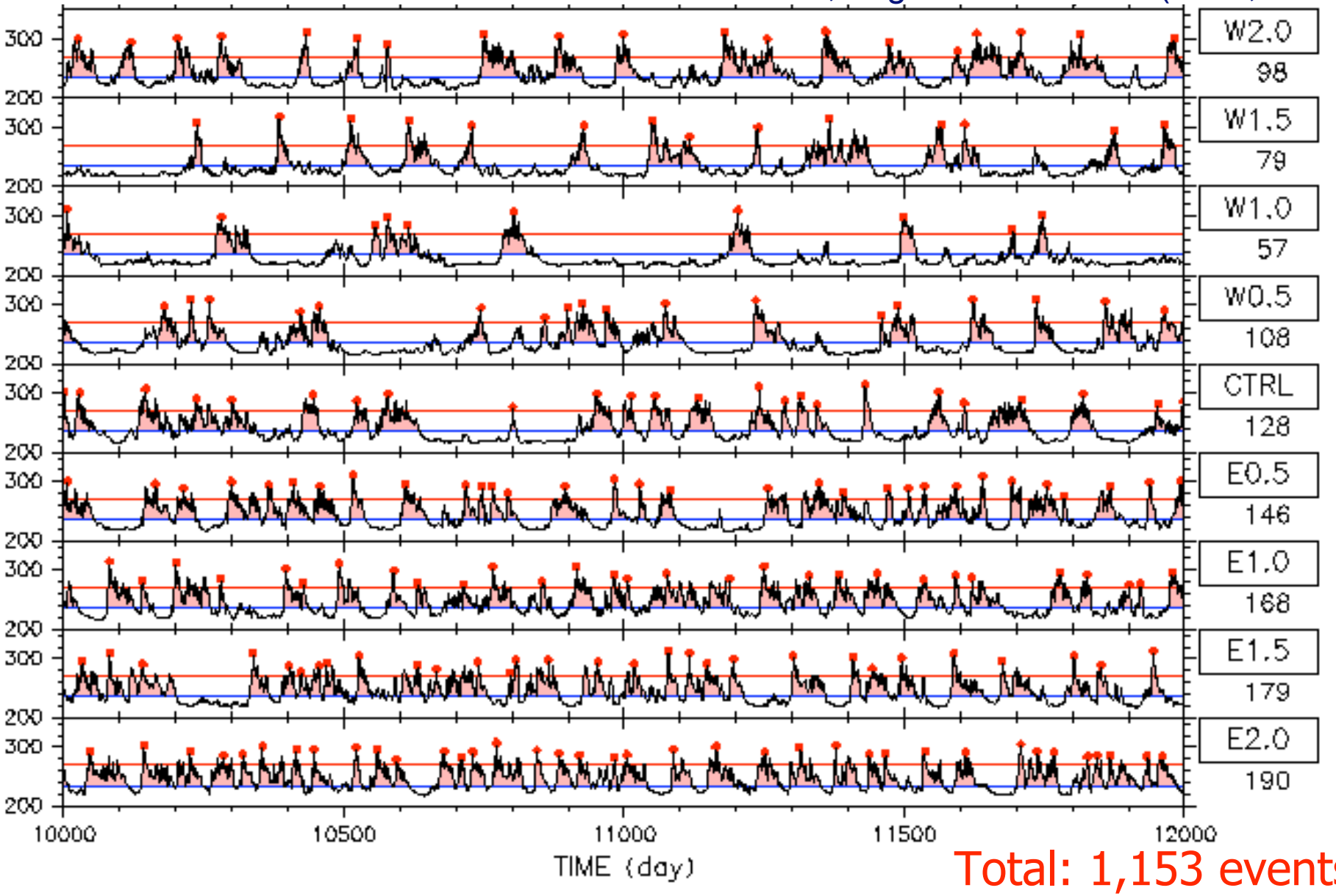
10,800-day mean fields of zonal-mean zonal wind [m/s]

Naito, Taguchi and Yoden (2003, *JAS*)



Time series of zonal-mean temperature [K] at φ=86N, *p* =2.6hPa for 2,000 days

Naito, Taguchi and Yoden (2003, *JAS*)



Total: 1,153 events

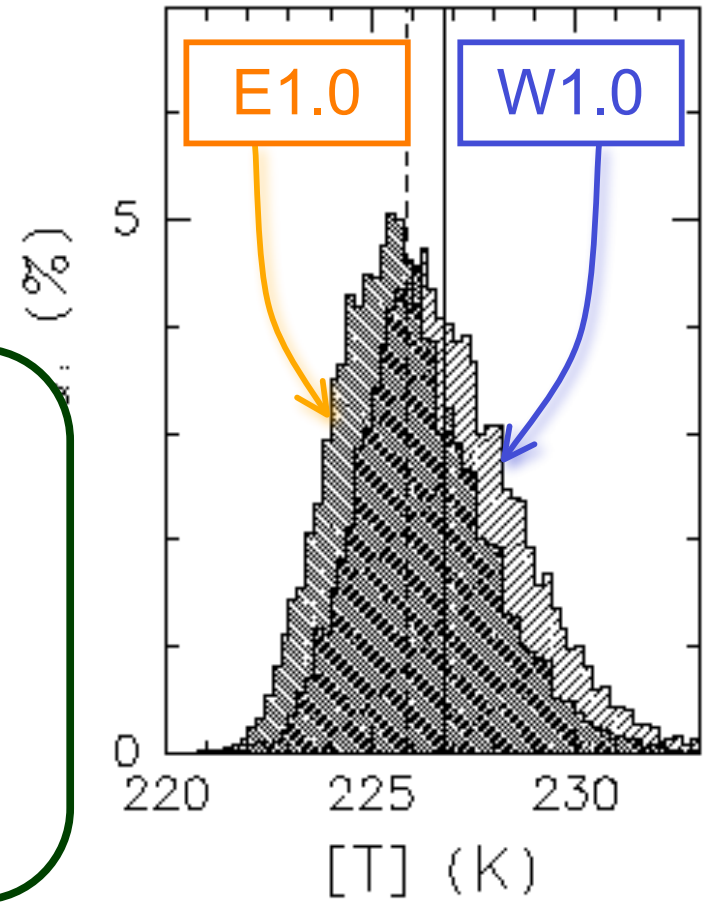
- statistical assessment of difference:
  QBO effects on the polar troposphere
- a large sample method
  - A standard normal variable:

$$Z = \frac{[T_W] - [T_E]}{\sqrt{\frac{\sigma_W^2}{N_W} + \frac{\sigma_E^2}{N_E}}}$$

$$= \frac{226.8 - 225.8}{\sqrt{\frac{1.87^2}{} \quad \frac{1.75^2}{}}} = 40.6$$

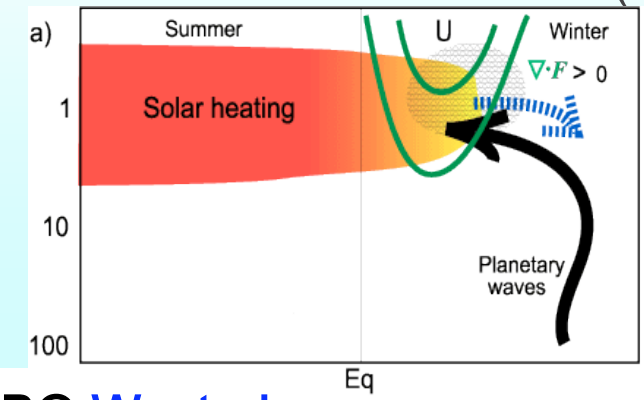
Highly significant differences between W'ly and E'ly phases but heavy overlapping of PDFs due to internal variations

Frequency distributions of zonal-mean temperature [K]
(86N, 449hPa, 10800 days)



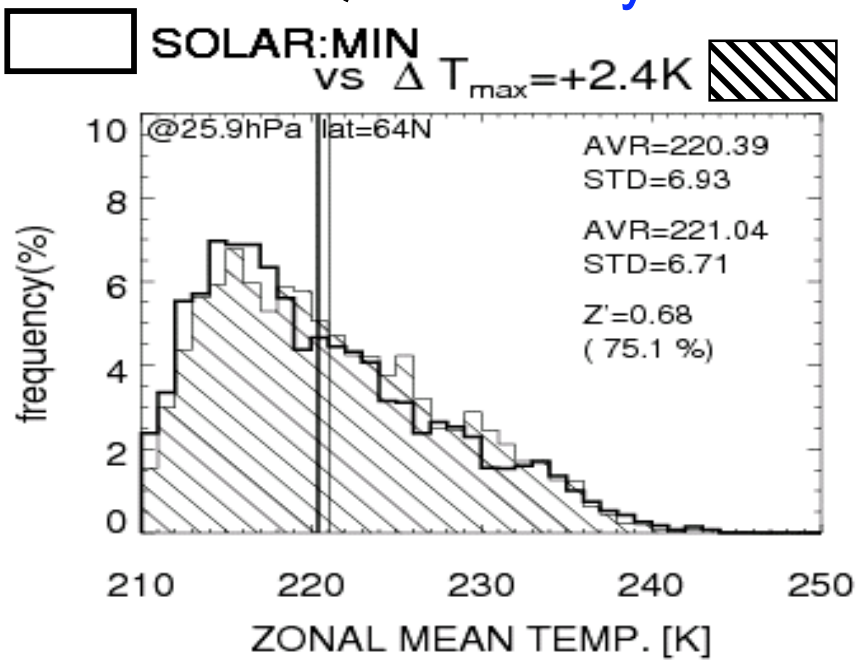
❖ solar effect in the presence of QBO

- Ito, Naito and Yoden (2009, *GRL*)
  - ➢ Examination of Labitzke's relationship (1987, 2006) and Kodera and Kuroda's idea (2002)

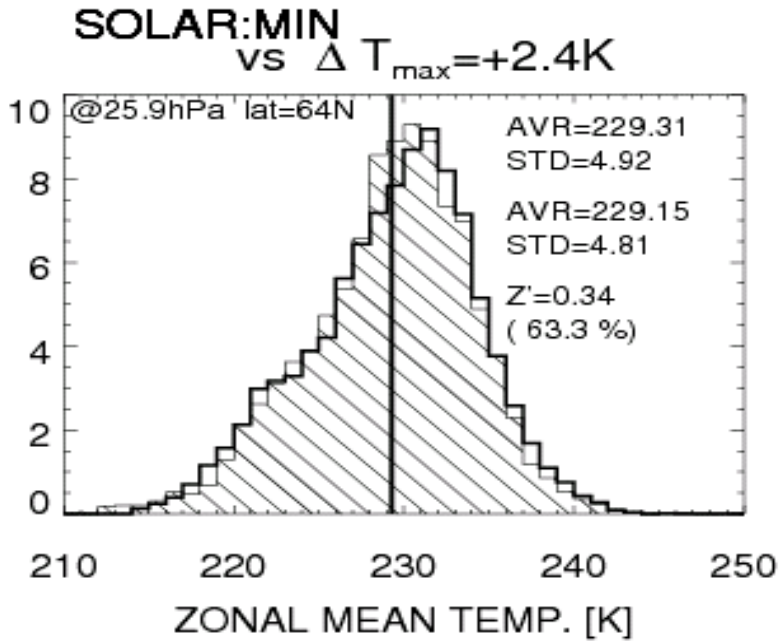


Labitzke (1987)	W	E
Max	W	C
Min	C	W

QBO Westerly



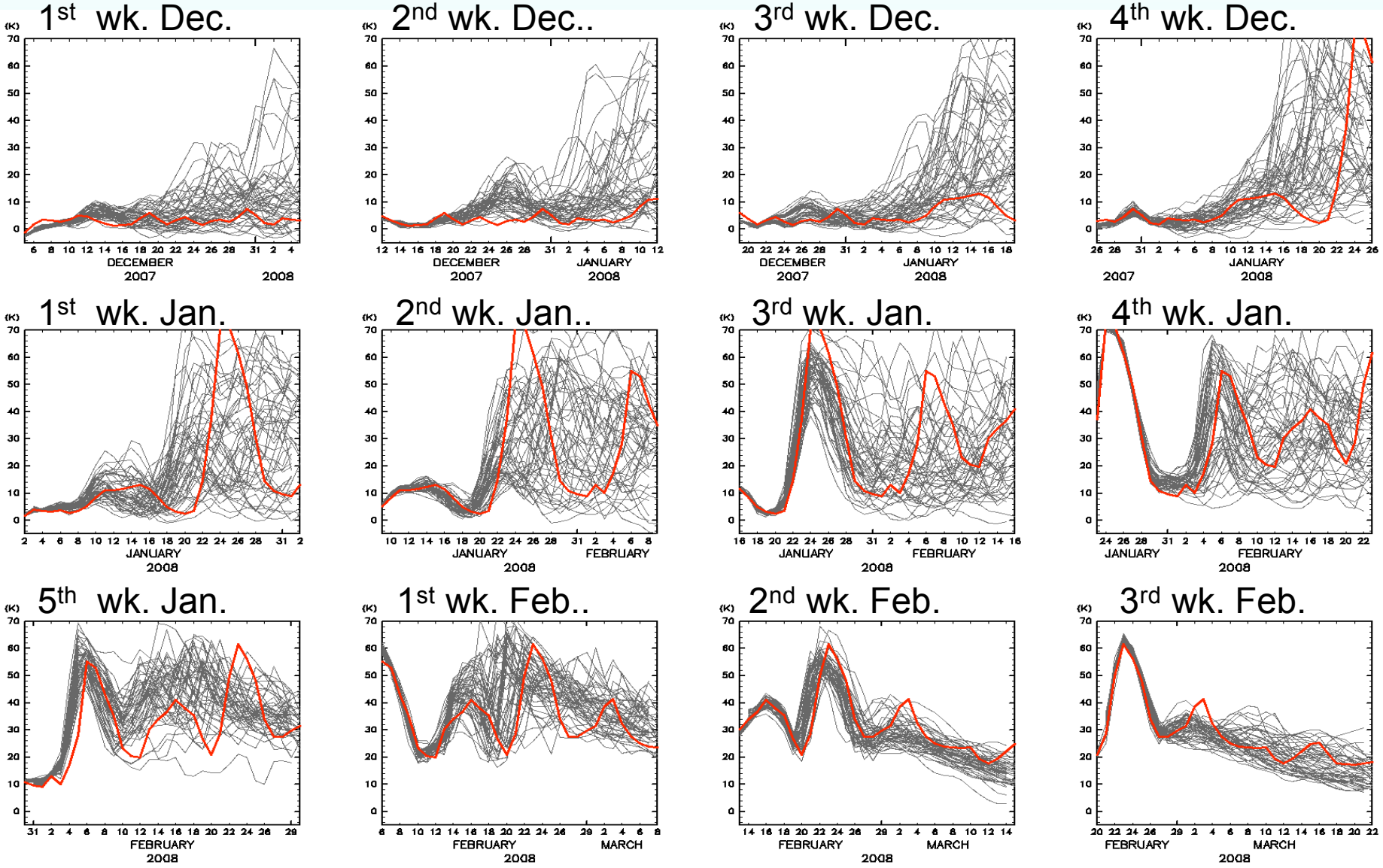
QBO Easterly



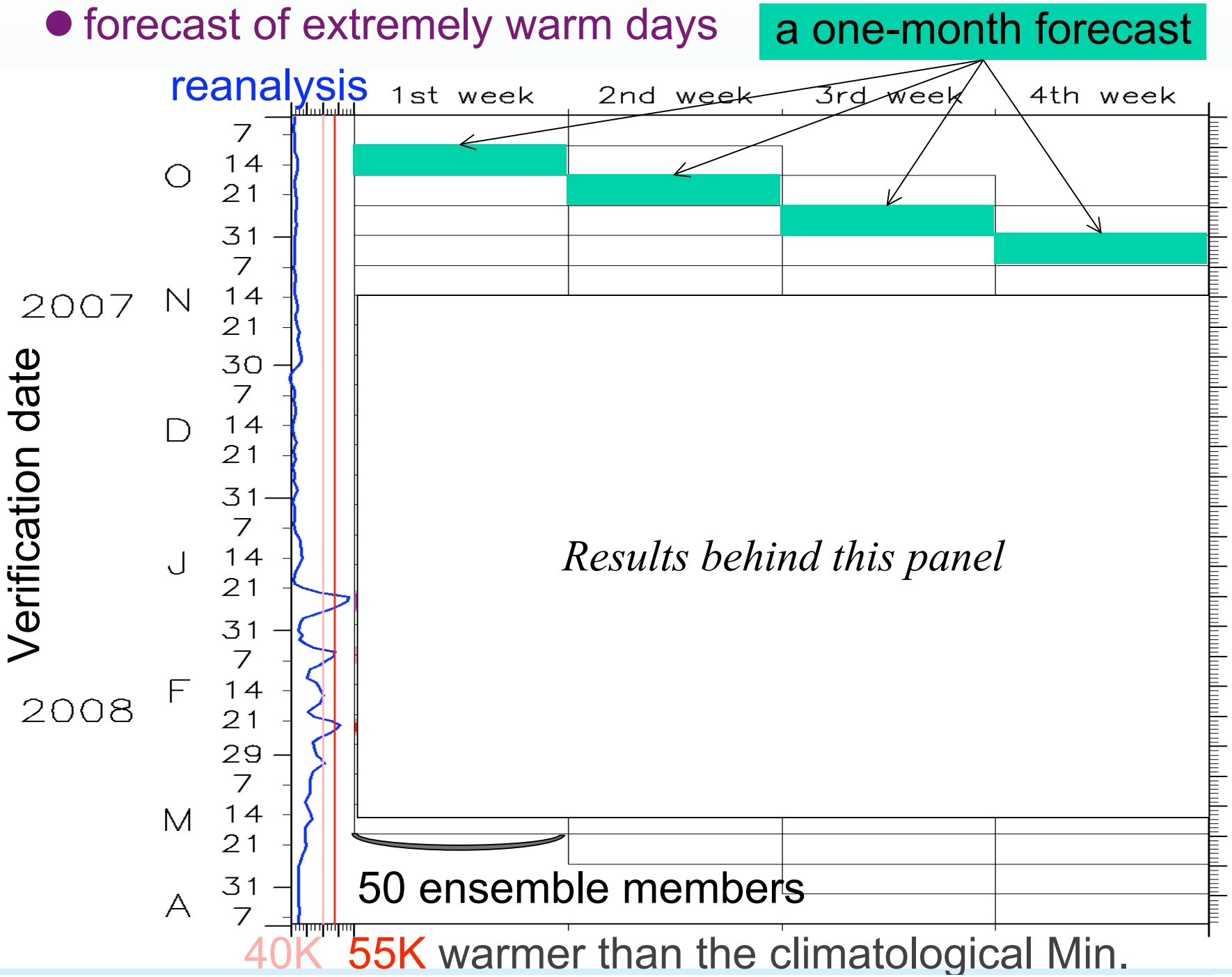
4. Associated predictability variations

- a preliminary result on predictability variations in JMA operational one-month numerical weather predictions (NWPs)
  - global atmospheric model
    - with observed SST anomalies at $t = 0$
  - full stratosphere
    - p_top = 0.1 hPa, 60 layer
  - breeding + time-lagged ensemble forecasts
    - once a week: every Wednesday and Thursday (25+25 = 50 members)

- temperature deviation from the climatological Min. for each calendar day at the North Pole, p=10 hPa in 2007-8 winter
  - cf. Kohma, Nishizawa and Yoden (2010, *J. Climate*)



- forecast of extremely warm days



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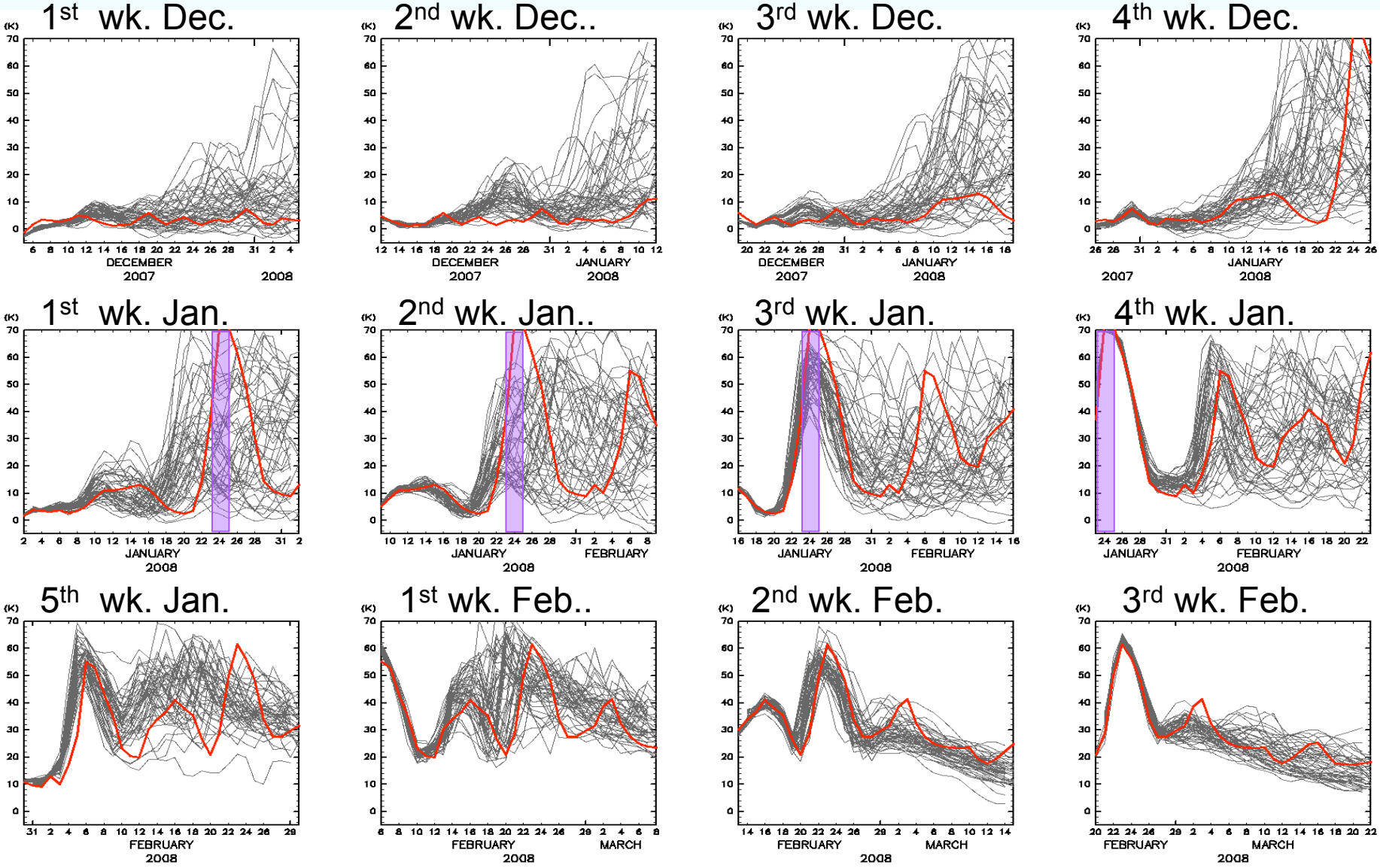
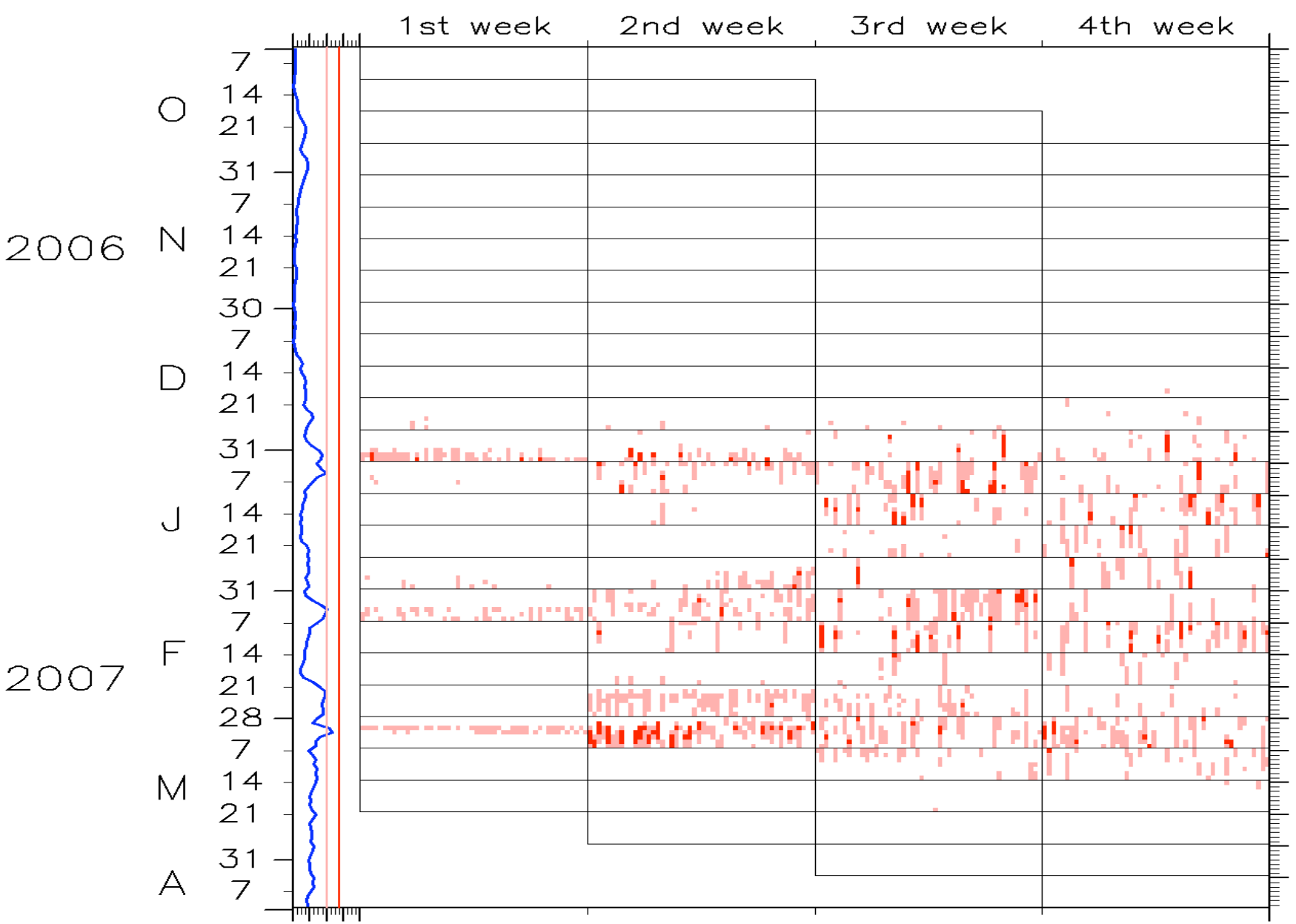


- another year: 2006-7 winter

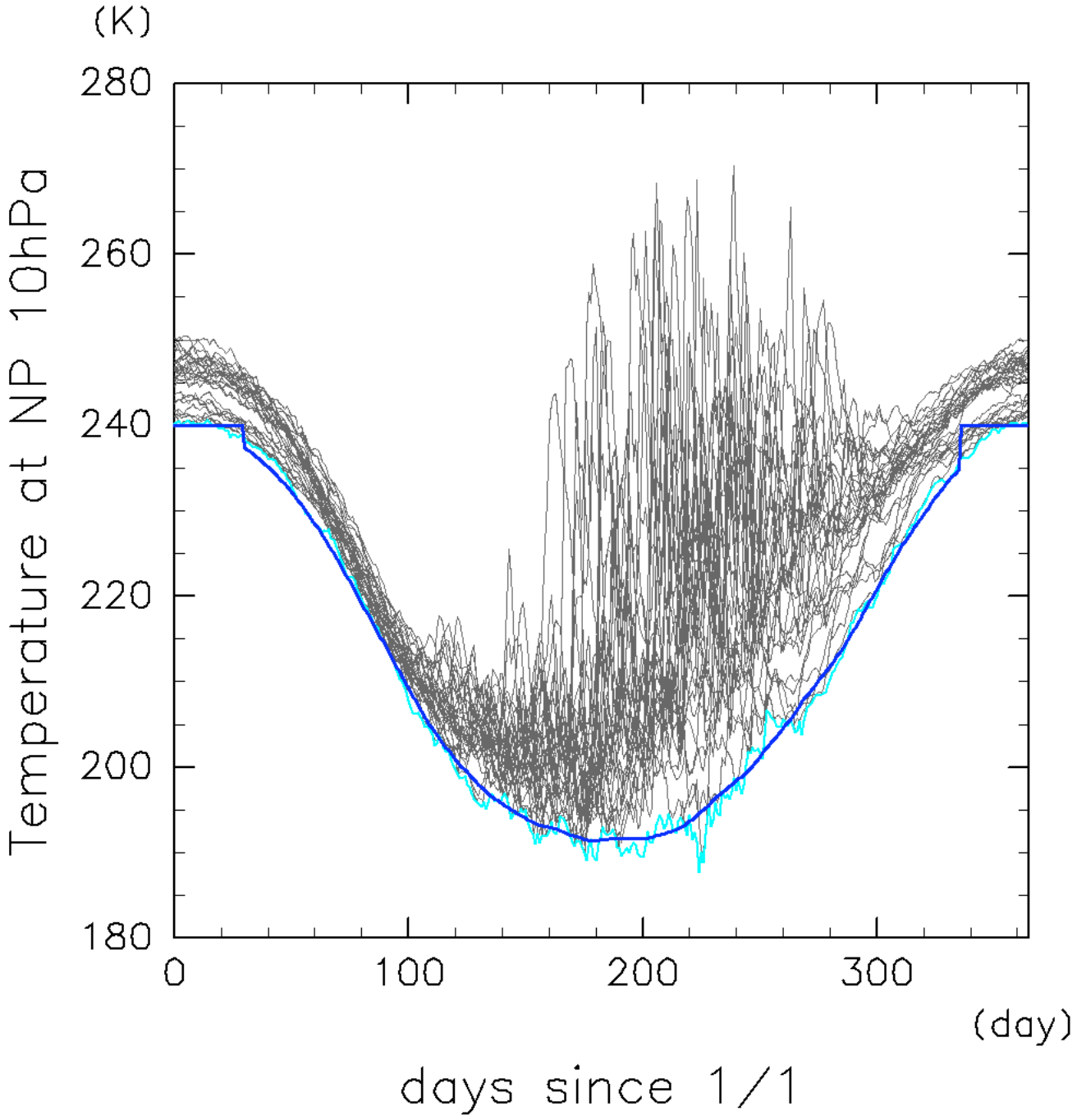


5. Concluding remarks

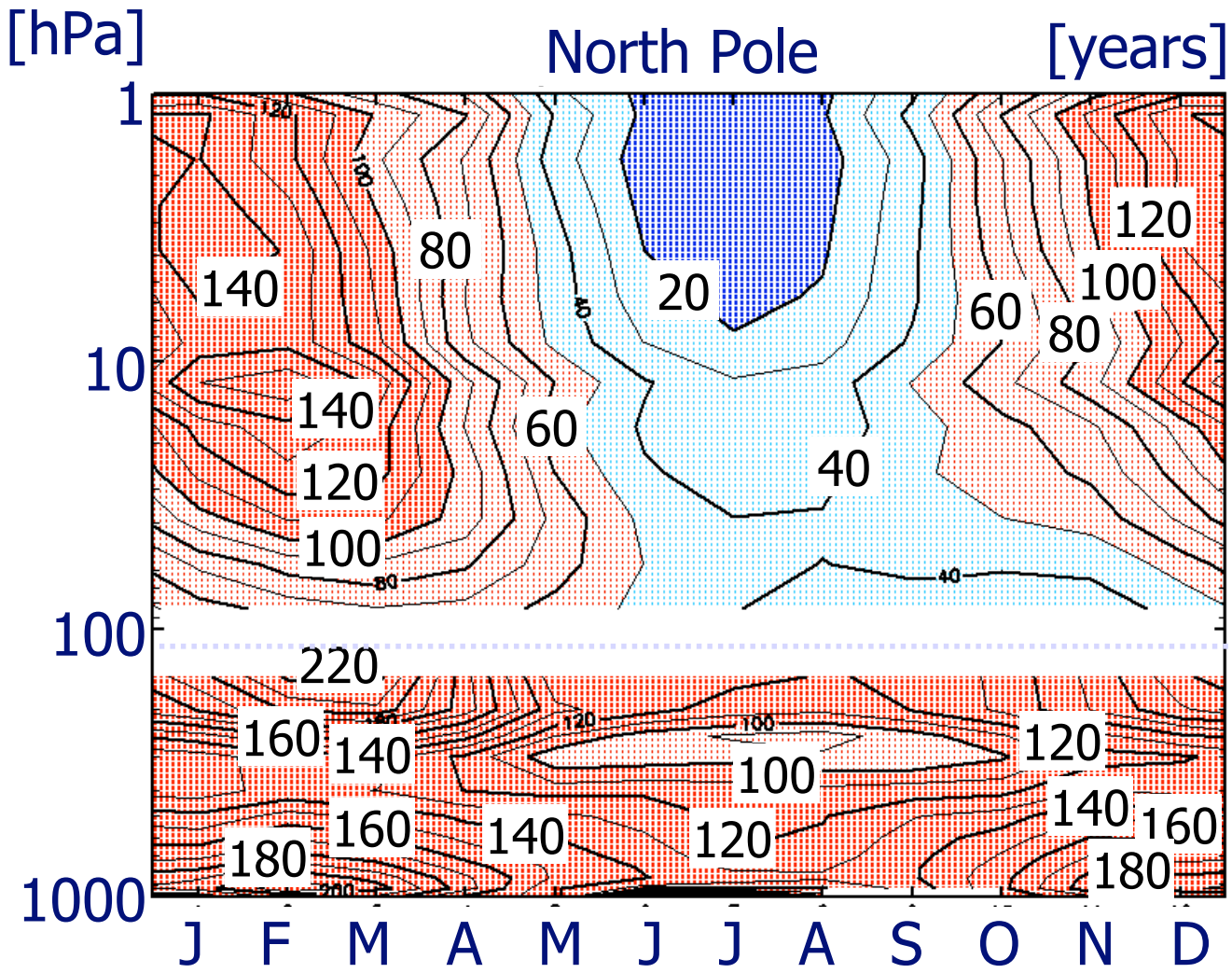
- Stratospheric sudden warming is the most important process to cause intraseasonal and interannual variability in the stratosphere
  - a highly nonlinear process: breakdown of the polar vortex
  - mostly (largely) due to internal dynamics in planetary scales
  - could be a key process which may amplify a (small) external forcing, such as solar influence, QBO, or else
- There are some difficulties in observational studies
  - data length is at most 50 years
  - difficulty in the separation of the stratospheric responses to external forcings (solar cycle, QBO, …) from large internal variations
  - limitation of a cause-result argument for highly nonlinear processes with interactions among dynamics, radiation and/or chemistry with multiple time scales

- Only numerical experiments overcome the difficulties
  - can supply much longer data to obtain statistical significance
  - can do the experiments that control the external forcings
  - can provide dynamically consistent and complete data
- Advancement in computing powers has enabled us to perform numerical experiments with 3-D MCMs
  - very long-time integrations to obtain reliable PDFs
    - non-Gaussian, bimodal, ...
      - ➔ nonlinear perspectives on climatic variations and trend
    - large sample method is useful for statistical assessment
  - parameter sweep experiments to investigate for highly nonlinear processes with combination of external forcings
- Predictability variations in operational one-month numerical weather predictions look interesting
  - long (3~4 weeks?) lead time for extremely warm days (SSWs)


Thank you !
June 14, 2010 Mt. Rainier


(K)
280
260
240
220
200
180
Temperature at NP 10hPa
0
100
200
300
(day)
days since 1/1

- ❖ seasonally dependent detectability in the troposphere
- a natural variability run of AOGCM for 1,000 years
- necessary data length [years] to detect a linear trend of +0.05K/decade with 90% statistical significance



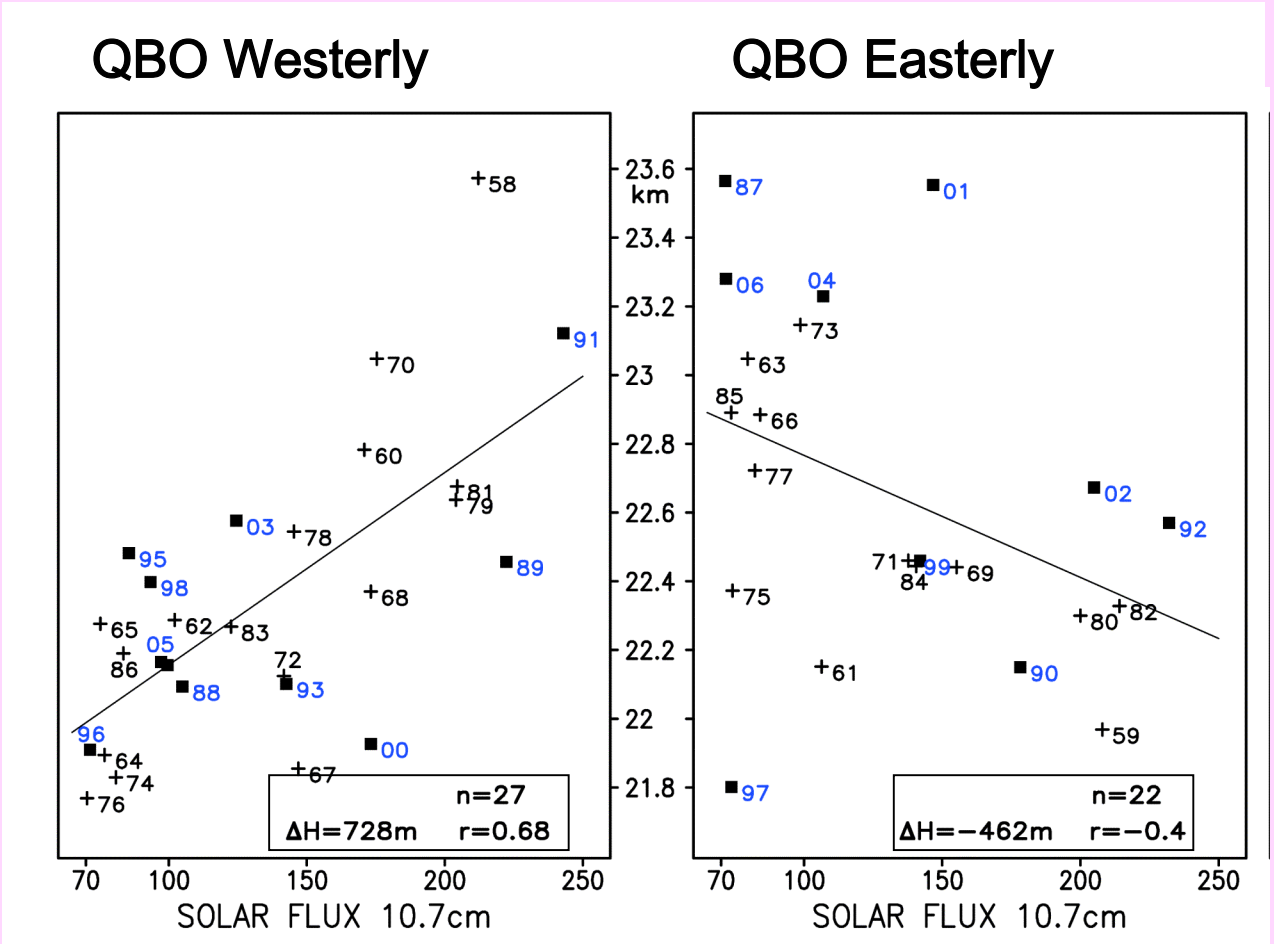
Nishizawa, Yoden & Nozawa (unpublished)

stratosphere
- 0.5K/decade
(MCM;
15,200years)

troposphere
+0.05K/decade
(AOGCM;
1,000years)

3. Solar effect in the presence of QBO

- Motivations
  - Labitzke (1987, 2006)
    - Correlations between 30-hPa heights and the solar flux of 10.7cm
    - 1958-2006 (49 years; NCEP/NCAR RA), (20 more years, in blue)

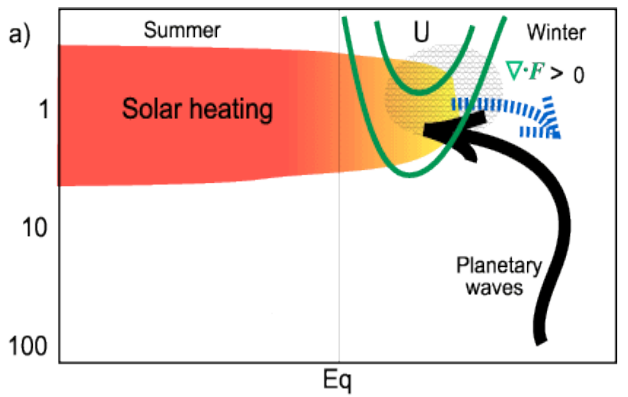


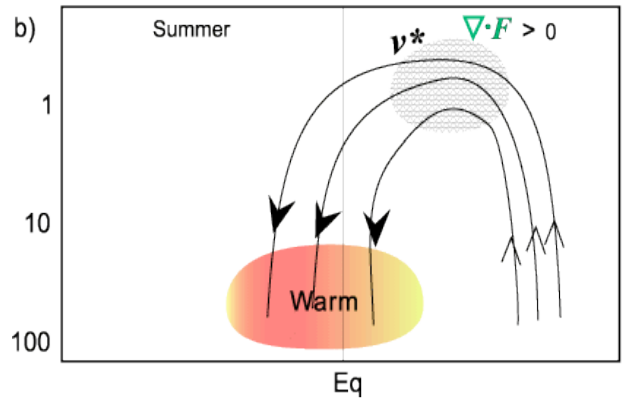
	W	E
MA	W	C
MI	C	W

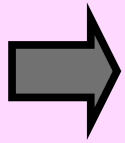
❖ Experimental design

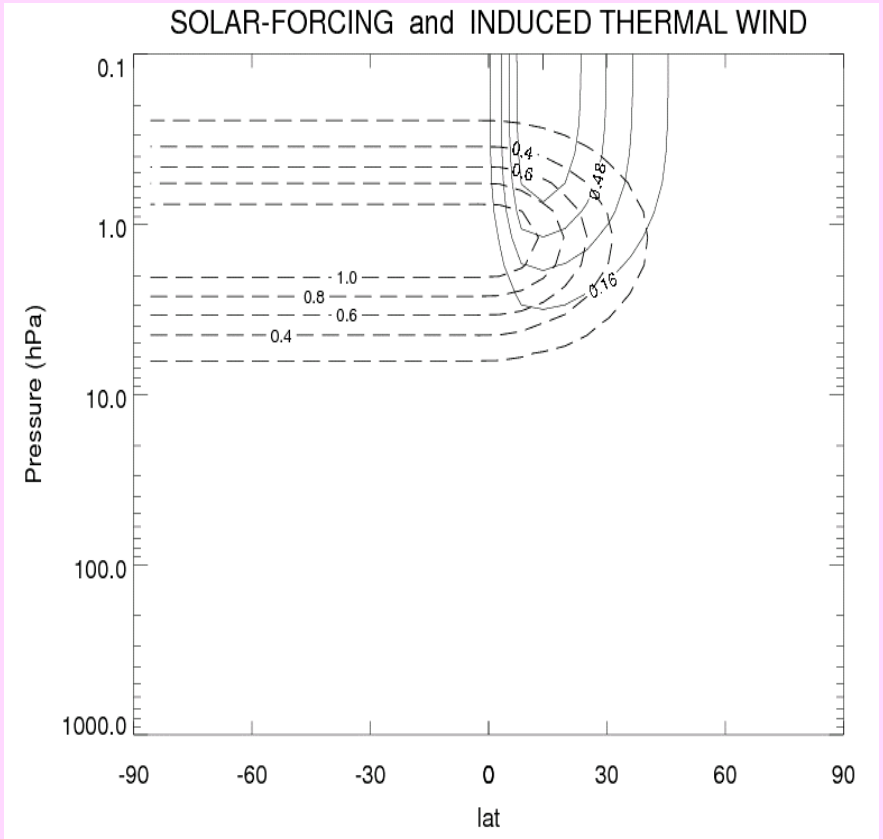
- equatorial QBO
  - ➢ identical to Naito and Yoden(2006)
  - ➢ WWWW and EEEE

- solar heating
  - ➢ Kodera and Kuroda(2002)



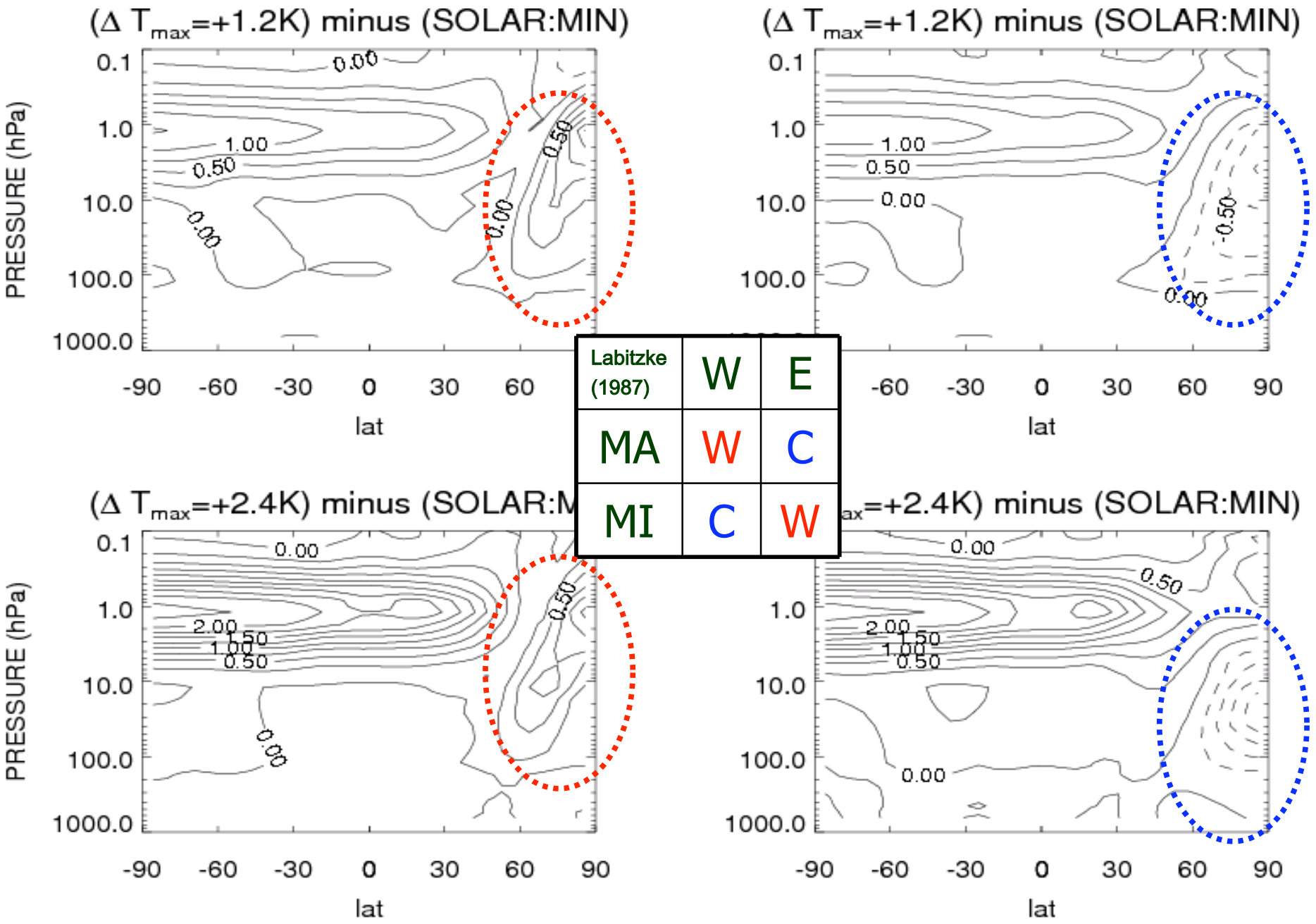






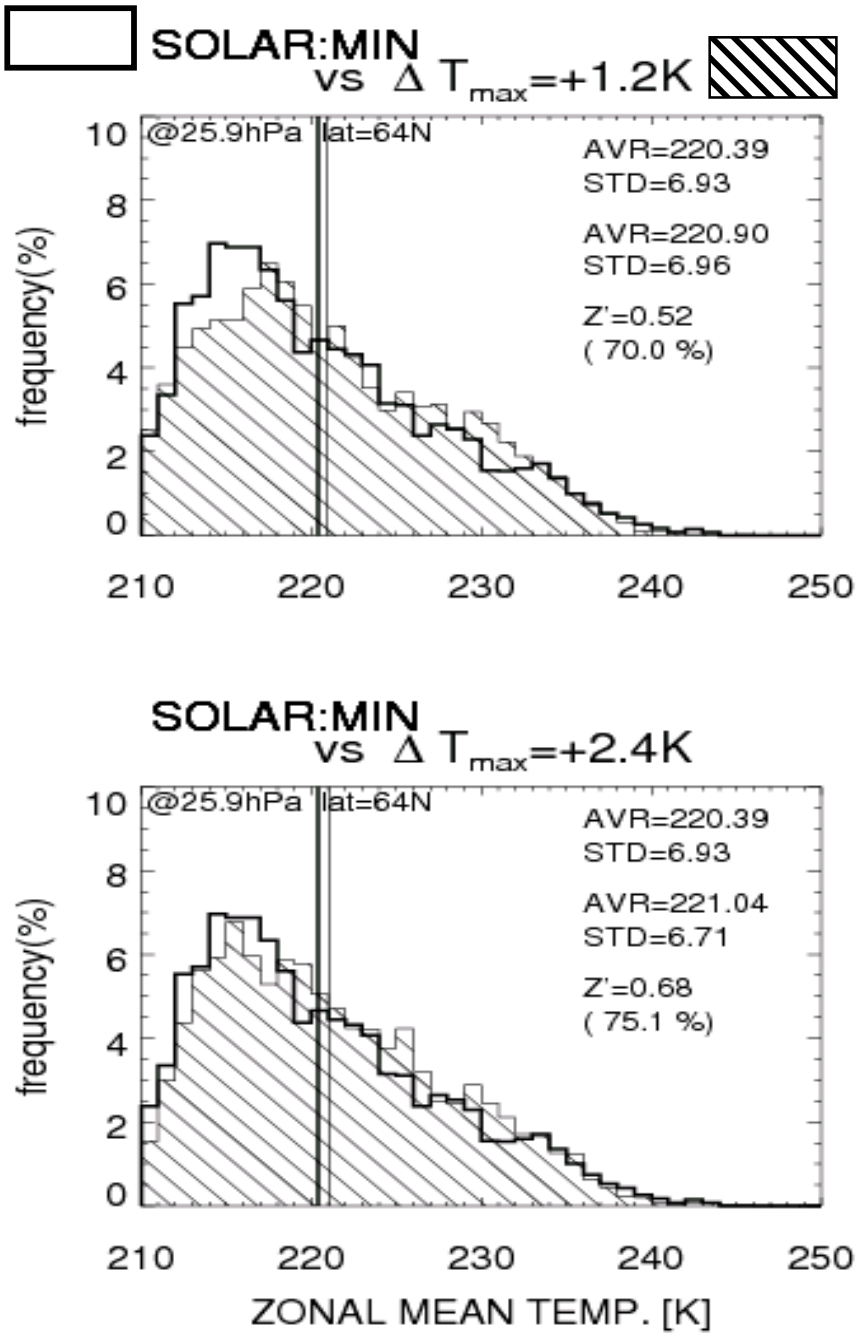
QBO Westerly

QBO Easterly

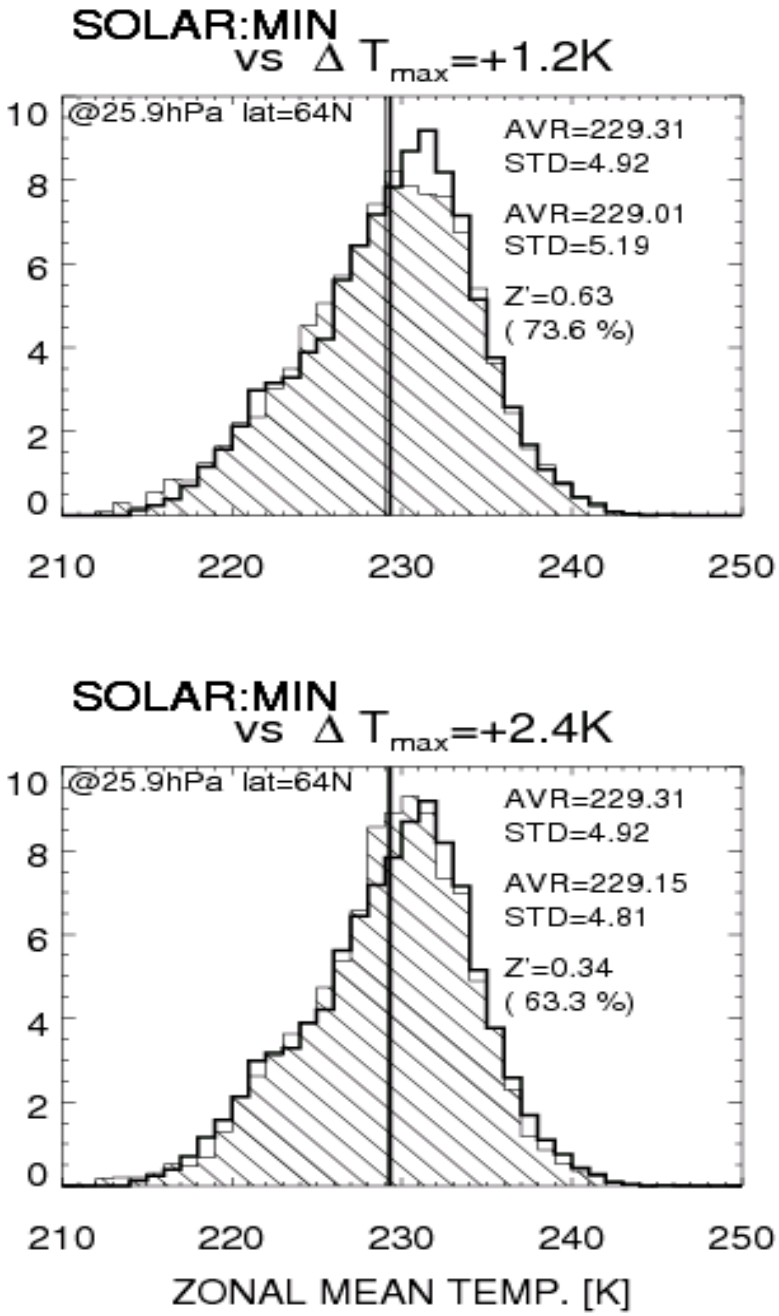


Labitzke (1987)	W	E
MA	W	C
MI	C	W

QBO Westerly

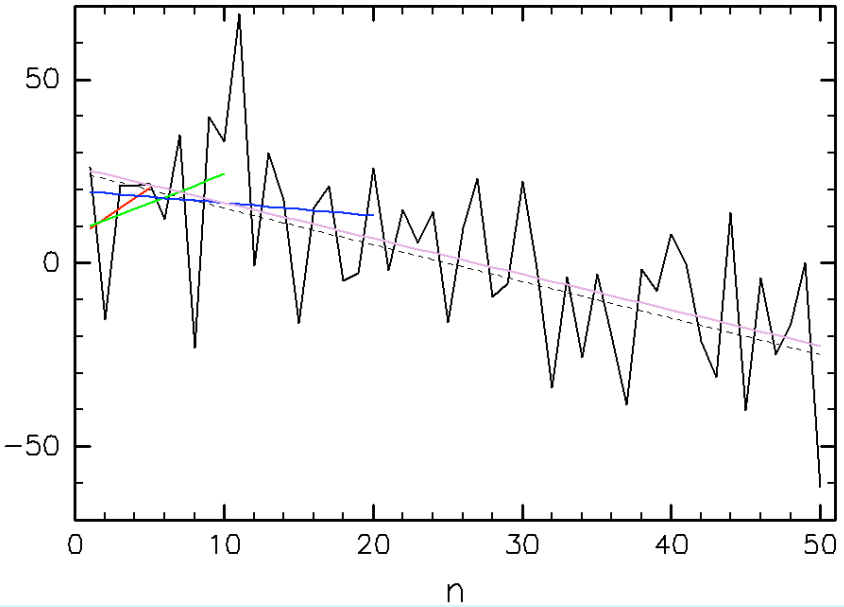


QBO Easterly



❖ Spurious trend may exist in a finite-length dataset

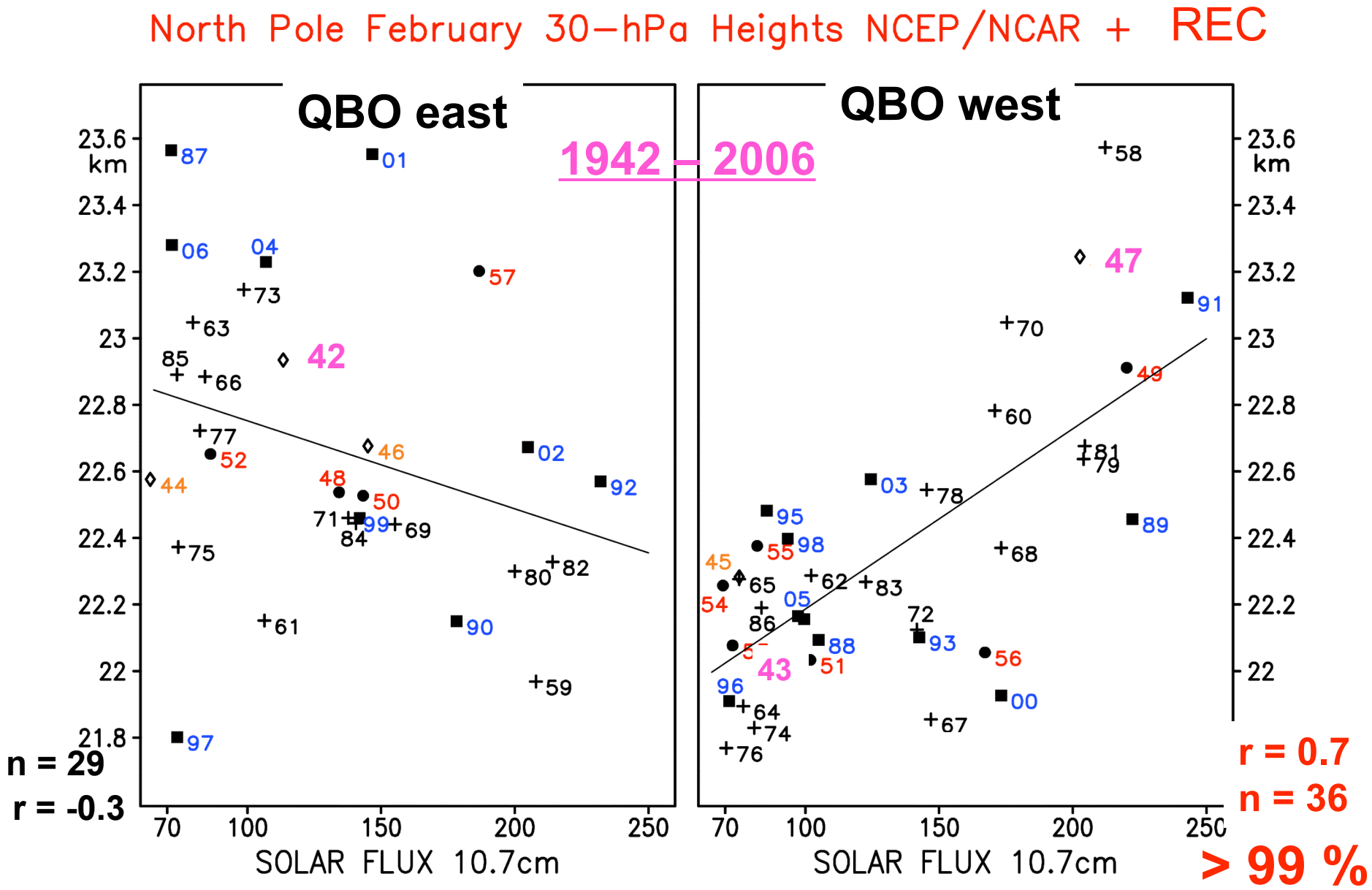
- natural variability



- long period variations of external forcing
  - ➢ periodic forcing: solar 11-year cycle
  - ➢ intermittent forcing: volcanic eruptions
- gap in quality of data
  - ➢ change in observation method: Start of satellite obs., ...

- Previous studies
  - Standard deviation of the spurious trend
    - Tiao et al. (1990)
    - Weatherhead et al. (1998)
  - Student's *t* -test for statistical significance of estimated trend
    - assumption: the spurious trend has a normal distribution

- The PDF of the spurious trend depends on the PDF of natural variability
  - Some atmospheric natural variations have a non-normal distribution



Correlations between 30-hPa Heights and the Solar Flux

3) 16 years back: 1948 – 1957 (10 y, red); 1942 –1947 (6 y, orange, REC)

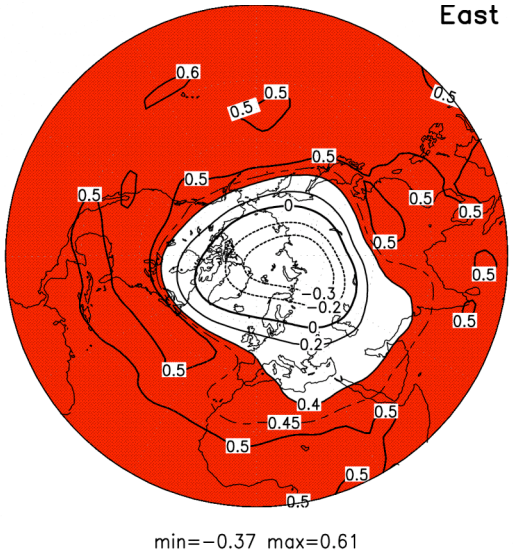
30-hPa Heights
February
(~ 22 – 24 km)

East
r max = 0.61
n = 26
95%

West
r max = 0.68
n = 33
99%

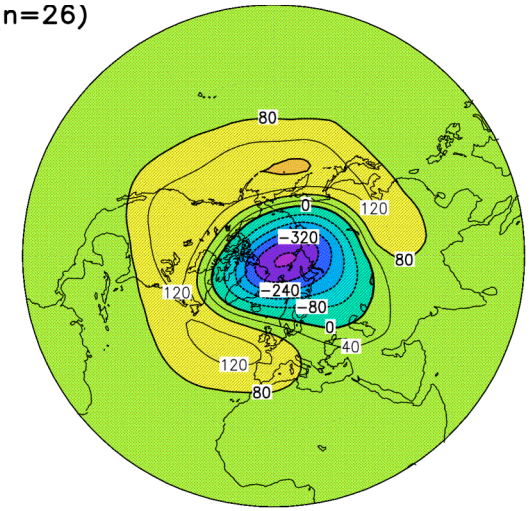
(Labitzke et al., 2006)

Correlations

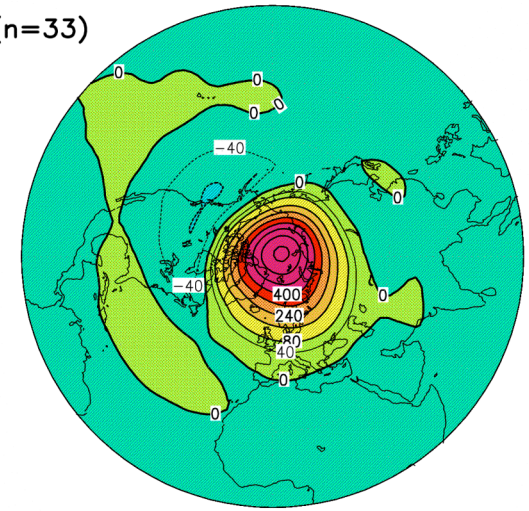


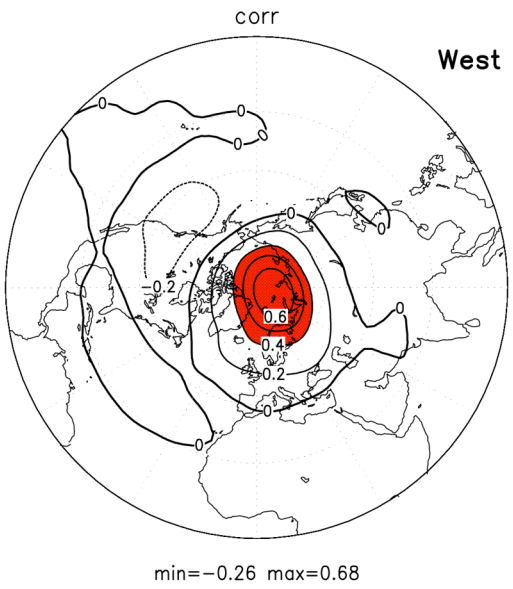
Height Differences (gpm)
solar max – solar min

- 400m



+640m





February 1948 – 2006, NCEP/NCAR, n = 59 years