POLAR SCIENCE
FOR PLANET EARTH

The interplanetary magnetic field (IMF) influence on mid-latitude surface atmospheric pressure

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NATURAL ENVIRONMENT RESEARCH COUNCIL

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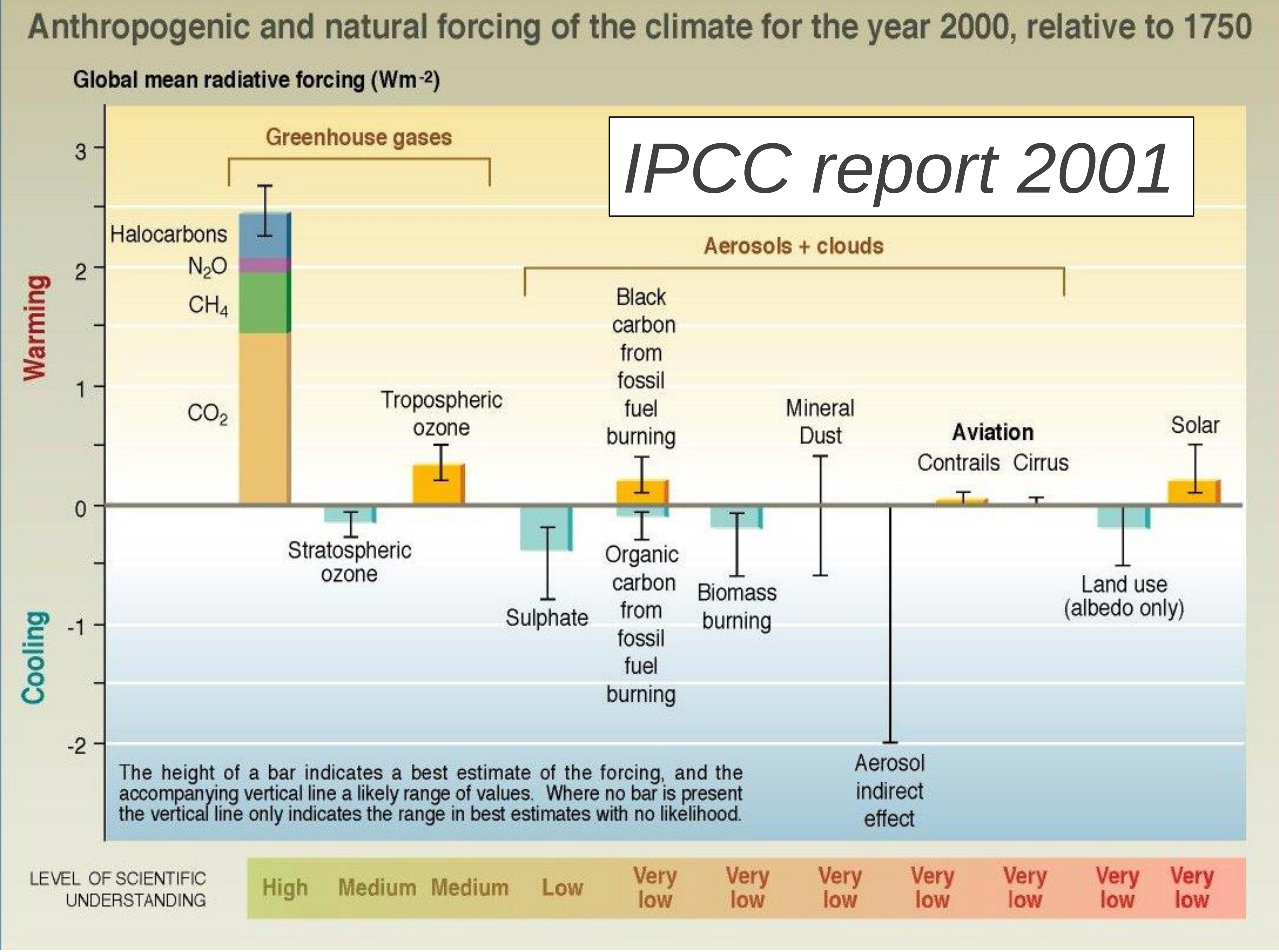
Outline

- Background
  - Why are we interested?
  - Global atmospheric electric circuit (**GEC**)
  - Vertical fair-weather current in GEC can affect cloud dynamics
  - *Burns et al, 2008*: polar meteorological response to **IMF B_y**

- Our project
  - Extend to global study
  - Confirm polar results
  - Previously unrecognised mid-latitude correlation – Rossby waves
  - Two stage mechanism (i) polar, (ii) mid-latitude

- Implications and summary
  - Global connection via non-linearity



Anthropogenic and natural forcing of the climate for the year 2000, relative to 1750
IPCC report 2001
Global mean radiative forcing (Wm-2)
Warming
Cooling
3
2
1
0
-1
-2
Greenhouse gases
Halocarbons
N2O
CH4
CO2
Stratospheric ozone
Tropospheric ozone
Aerosols + clouds
Sulphate
Black carbon from fossil fuel burning
Organic carbon from fossil fuel burning
Biomass burning
Mineral Dust
Aerosol indirect effect
Aviation
Contrails
Cirrus
Land use (albedo only)
Solar
The height of a bar indicates a best estimate of the forcing, and the accompanying vertical line a likely range of values. Where no bar is present the vertical line only indicates the range in best estimates with no likelihood.
LEVEL OF SCIENTIFIC UNDERSTANDING
High
Medium
Medium
Low
Very low
Very low
Very low
Very low
Very low
Very low
Very low

Anthropogenic and natural forcing of the climate for the year 2000, relative to 1750

Global mean radiative forcing (Wm-2)

Warming 3 2 1 0 -1 -2 Cooling

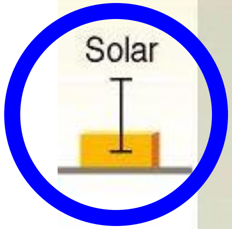
Solar forcing

IPCC, 2007
"*more research on climate is needed before the magnitude of solar effects on climate can be started with certainty*"

Gray et al, 2010

"*The most mature Sun-climate mechanism ... variation in solar UV radiation affecting stratospheric ozone*"...

"...the *solar modulation of global electric circuit...has only just begun to be tested in physical models*"



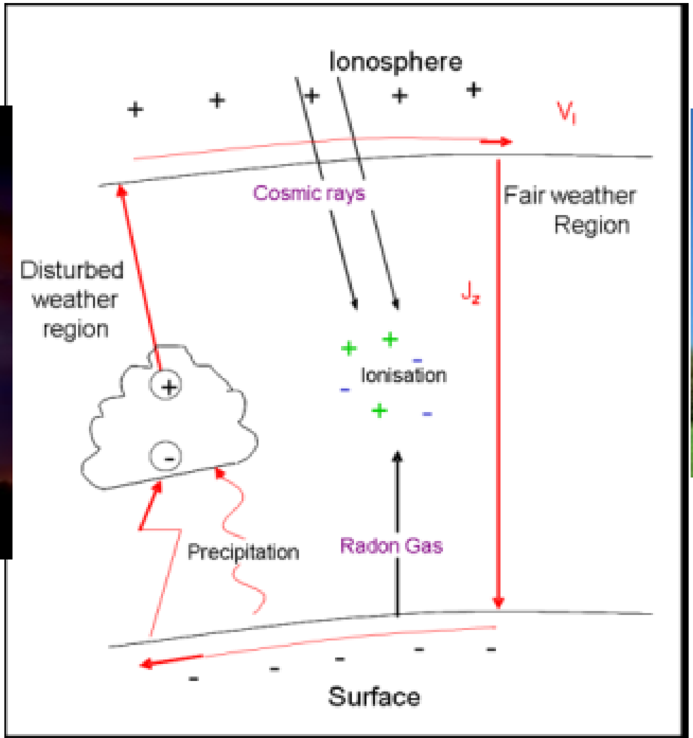
LEVEL OF SCIENTIFIC UNDERSTANDING | High | Medium | Medium | Low | Very low | Very low | Very low | Very low | Very low | Very low | Very low

Global electric circuit in Earth's atmosphere

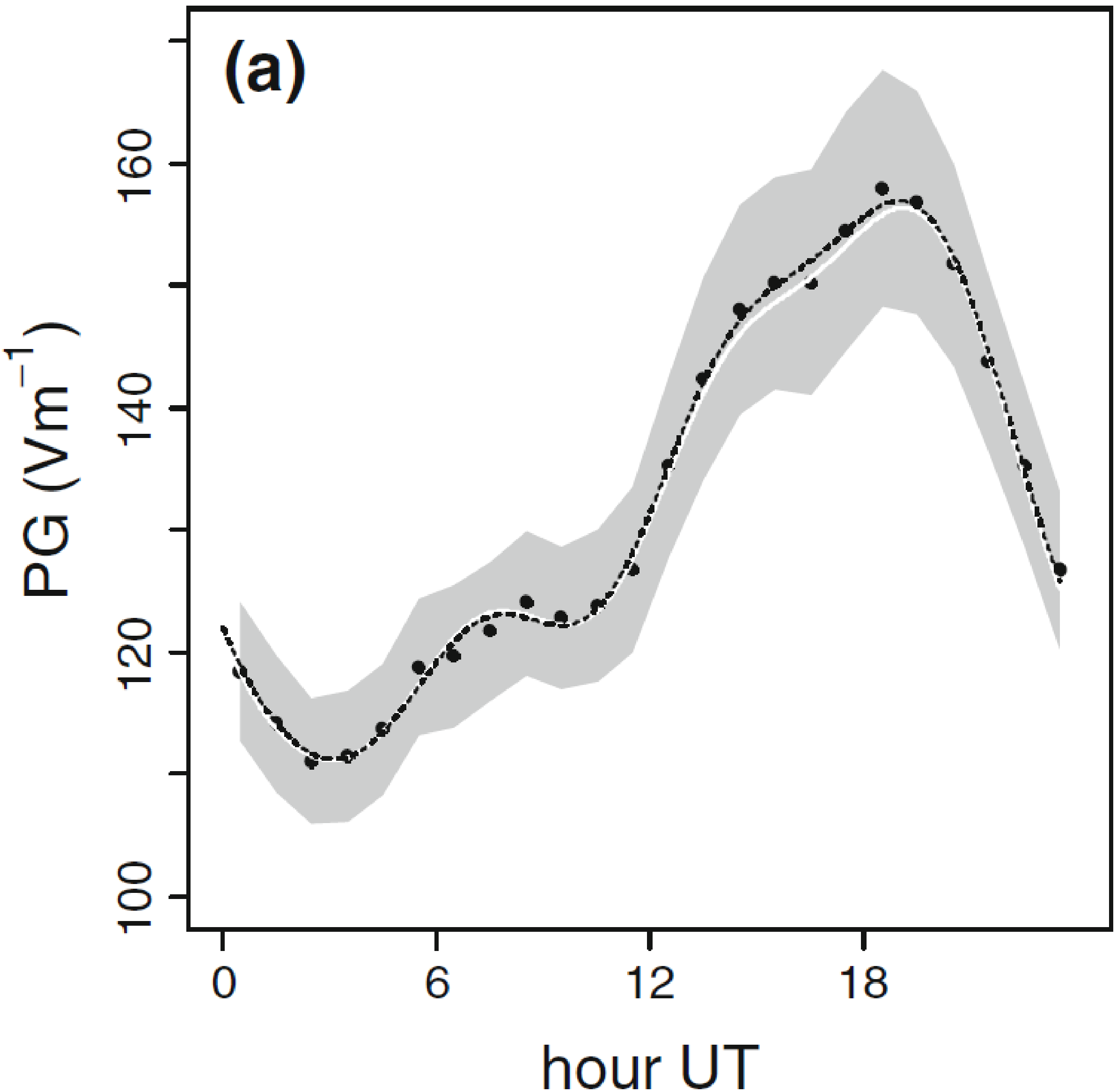
- Global thunderstorms (~1000 at any one time) maintain vertical potential difference of V_i ~ 250 kV between ground and ionosphere

- V_i drives horizontal currents along highly-conducting regions: surface of Earth and ionosphere.

- Closed by ground-thunderstorm, thunderstorm-ionosphere currents, and by ionosphere-ground global fair-weather currents J_z



Global electric circuit in Earth's atmosphere

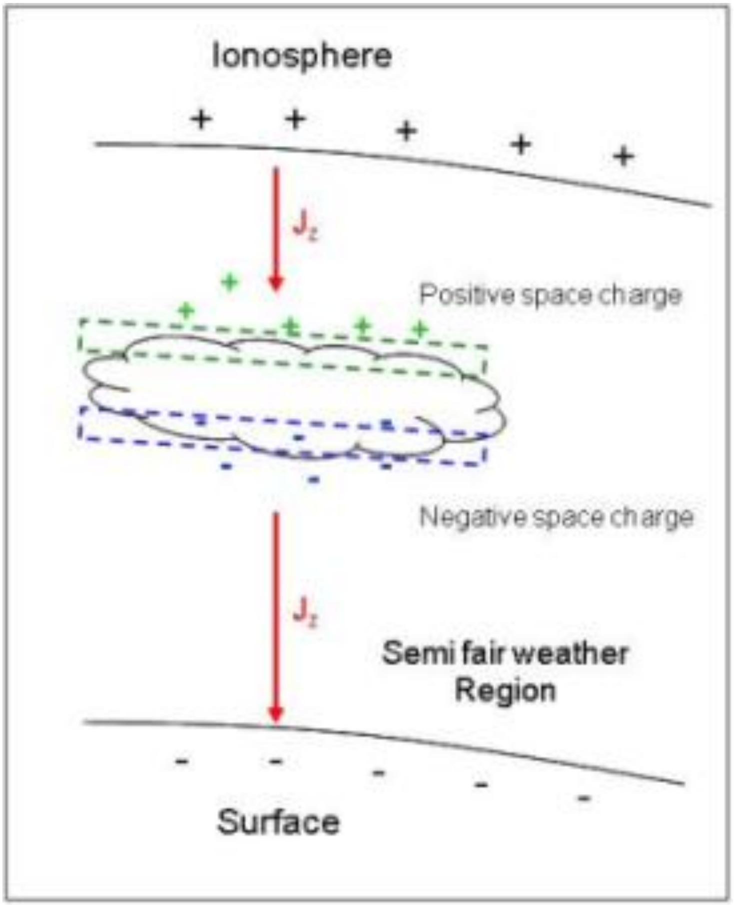


Carnegie curve for any fair-weather location on Earth

Harrison, 2013

J_z can affect layer cloud microphysics

- Low level clouds form when rising moist air condenses on submicron atmospheric particles
- Droplet growth occurs by water vapour diffusion and collisions with other droplets
- Current J_z causes droplet electrification at lower edge of cloud
- Can affect droplet formation, droplet-particle and droplet-droplet collisions and coalescence
- Affects cloud lifetime, precipitation, radiative balance, dynamics of atmosphere
- Any processes that modulates Vi or σ, varies $J_z = \sigma\ E(Vi)$

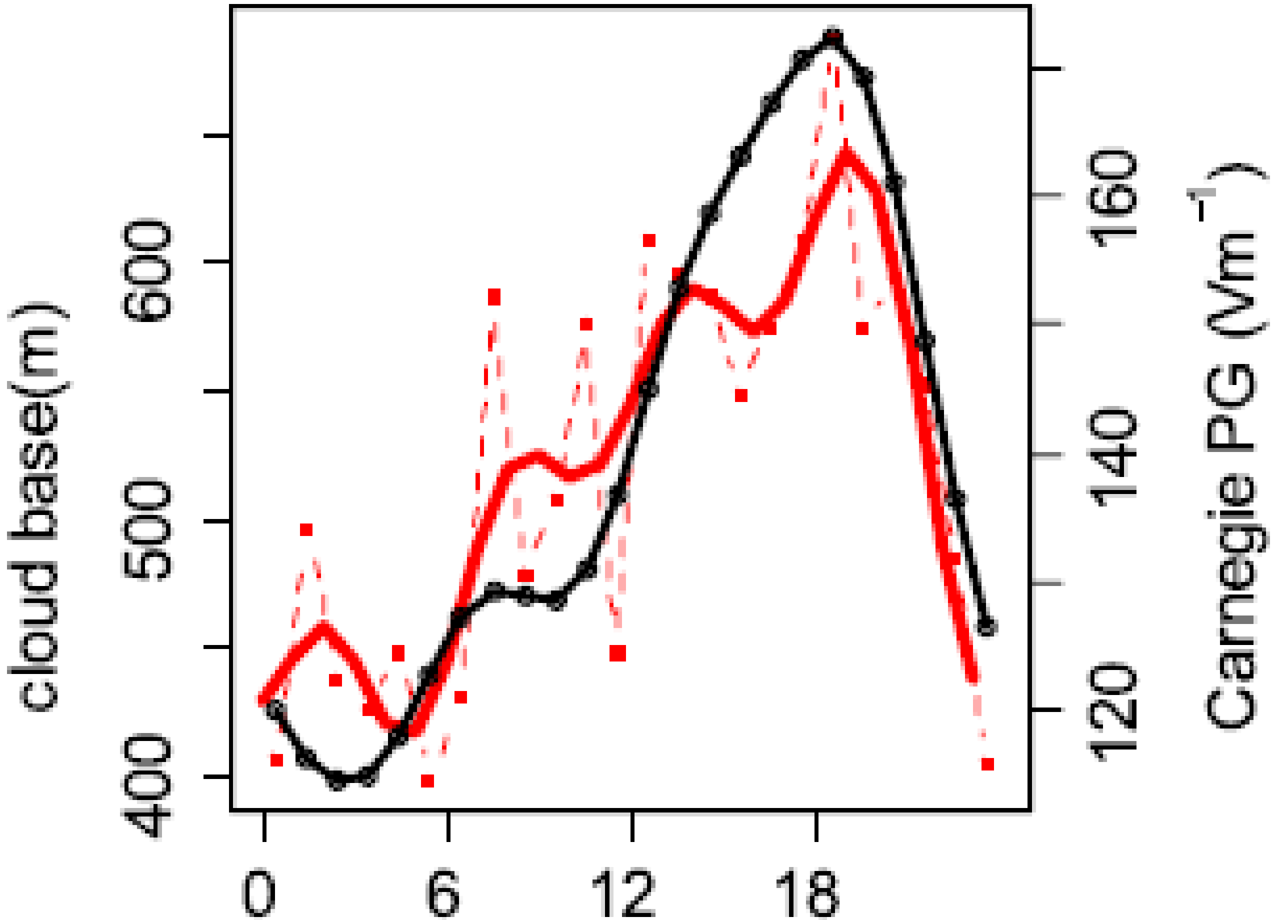


Layer cloud measurements by Harrison & Ambaum

- Layer (stratus/stratified) clouds found globally (29%)

Cloud base height (Sodankylä)

Carnegie curve



hour (UT)

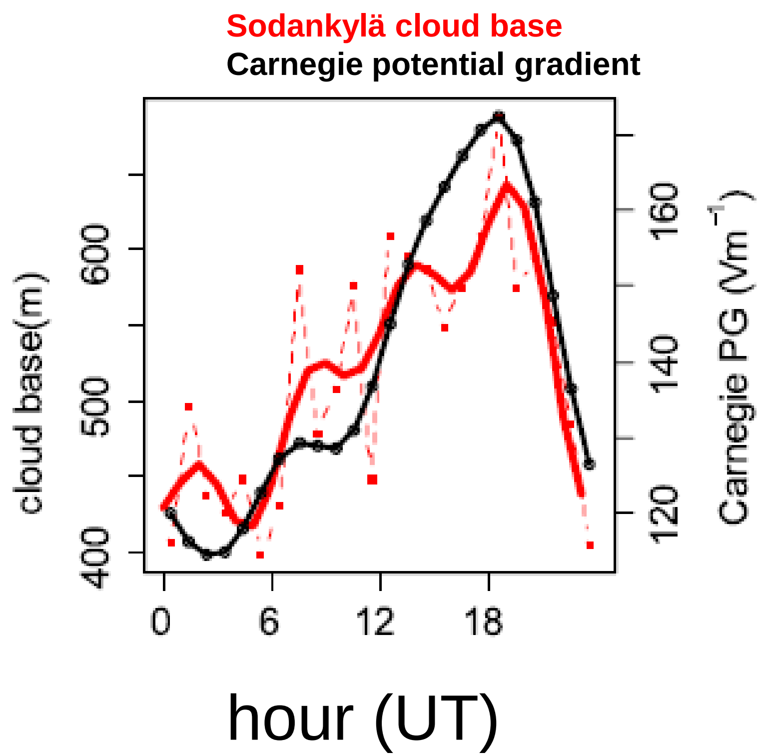
Using laser cloud base recorder
Vaisala CT25K ceilometer
2006-2011 polar winter

Harrison and Ambaum, 2013

Cloud base height variation similar to Carnegie curve

- Layer clouds found globally (29%)

- Polar-winter: cloud base height correlates with fair-weather potential gradient (Carnegie curve) r = 0.8

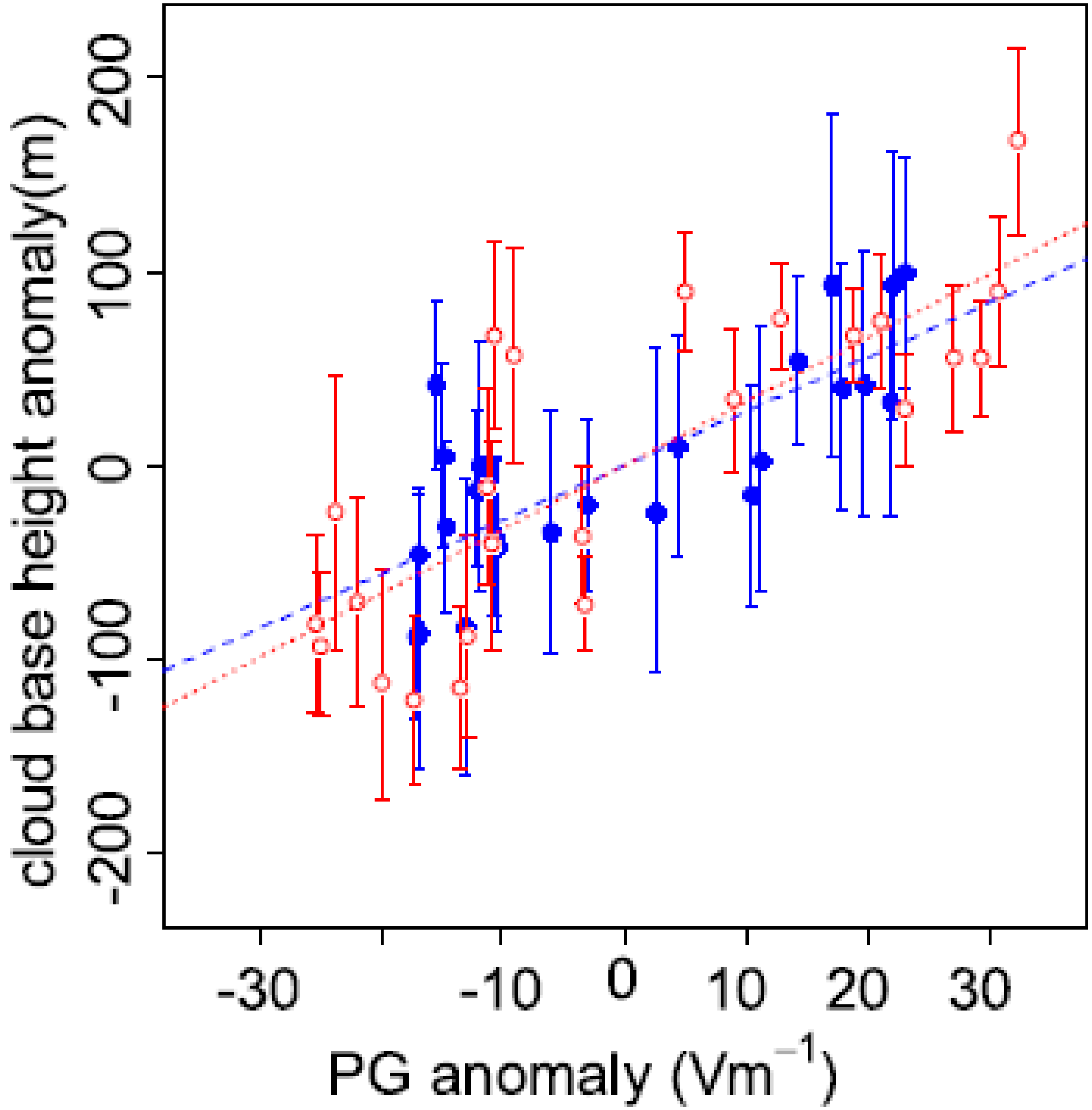


Harrison and Ambaum, 2013

Dependence of cloud base height on PG similar at poles

Sodankylä

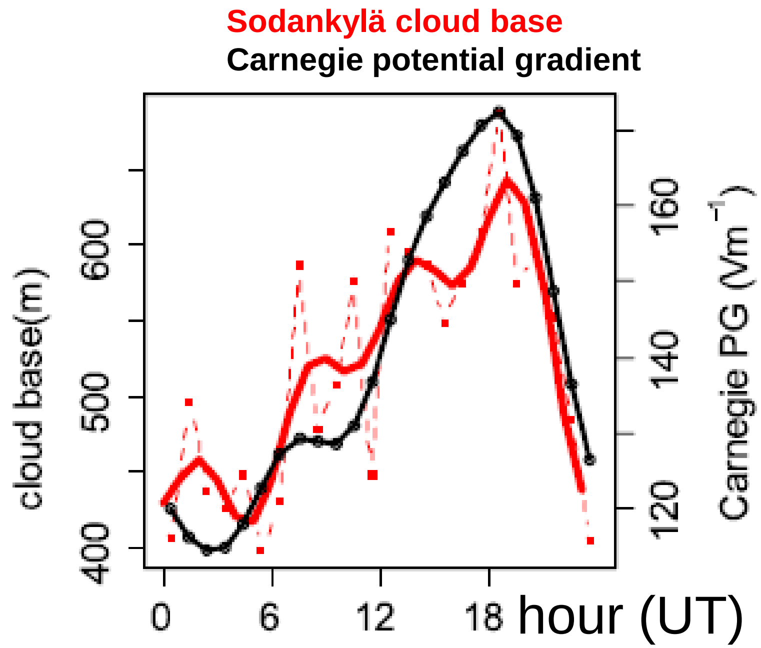
Halley

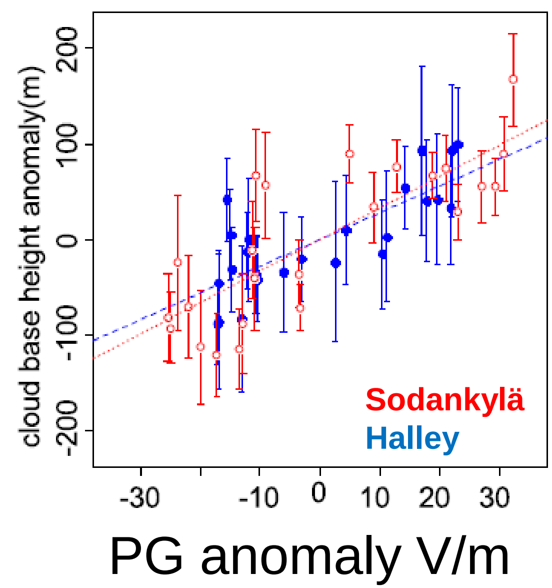


Harrison and Ambaum, 2013

Direct coupling between GEC and layer cloud base height

- Layer (stratus) clouds found globally (29%)
- Polar-winter: cloud base height correlates with fair-weather potential gradient (Carnegie curve) r = 0.8
- Carnegie curve ⇒ $\Delta h_{CB} = 100$ m; $\Delta t_{CB} = 1$ K
- Direct coupling (τ < 1h) between global electric circuit current J_Z and layer cloud properties





Harrison and Ambaum, 2013

What can change J_z?

- Global ionospheric potential
- Polar cap ionospheric potential

Changes in potential

- Relativistic electron flux changes
- Solar proton events
- Cosmic ray Forbush decreases

Changes in conductivity

Day-to-day meteorological correlations with J_z - papers

- Global ionospheric potential

  Burns et al. 2007; 2008;

- Polar cap ionospheric potential

  Mansurov et al. 1974; Burns et al. 2007; 2008

  } IMF B_y

- Relativistic electron flux changes

  Wilcox et al. 1973; Hines and Halevy 1977; Larsen and Kelly 1977; Tinsley et al. 1994; Kirkland et al. 1996; Kniveton and Tinsley 2004; Roldugin and Tinsley 2004; Misumi 1983

- Solar proton events

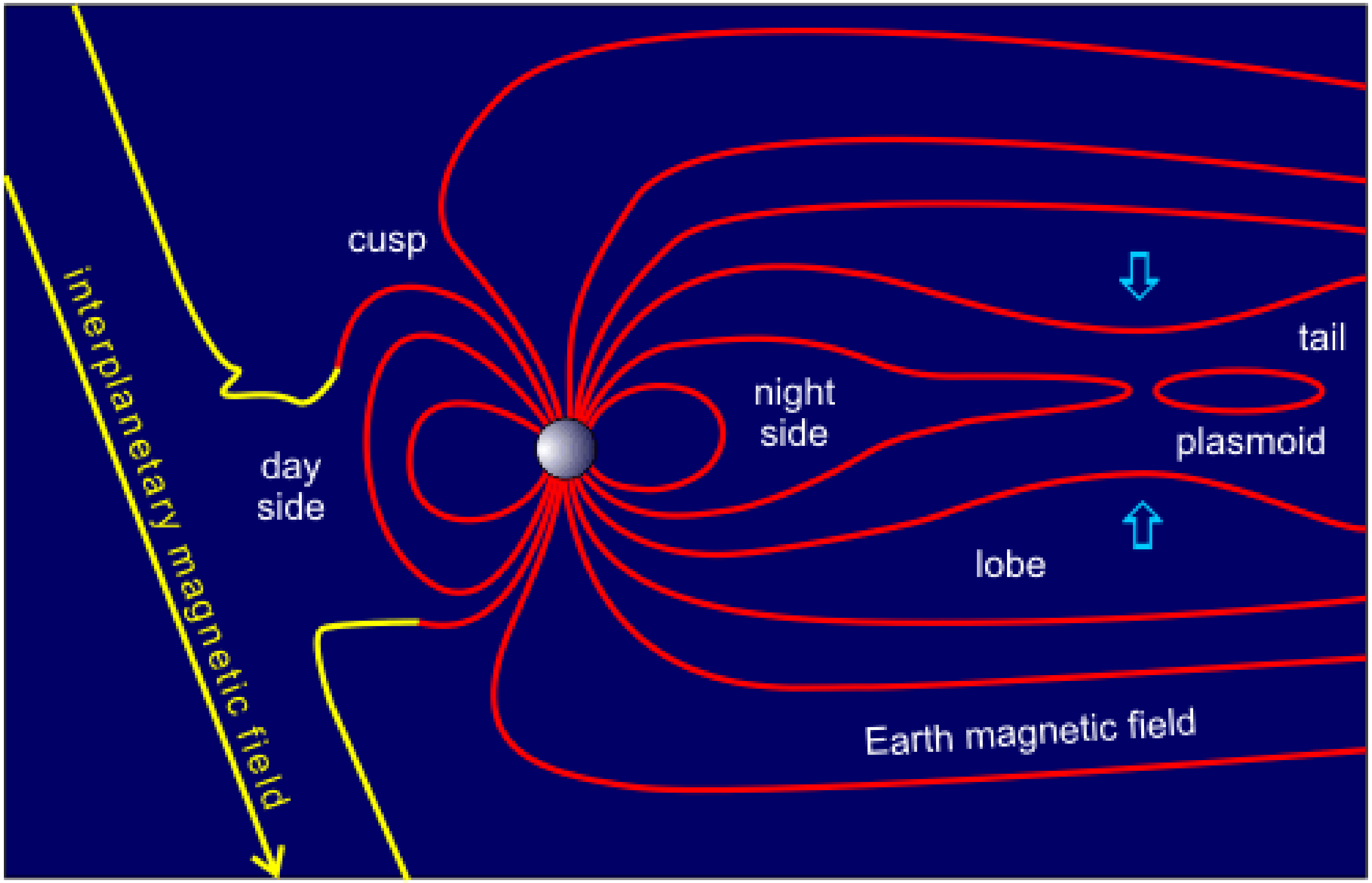
  Schuurmans et al. 1965; 1969; Veretenenko et al. 1999; 2000; 2004; 2005

- Cosmic ray Forbush decreases

  Roberts and Olsen 1973, Padgoankar and Arora 1981; Tinsley et al. 1989; Tinsley and Deen 1991; Pudovkin and Veretenenko 1995; Todd and Kniveton 2001; Egorova et al. 2000

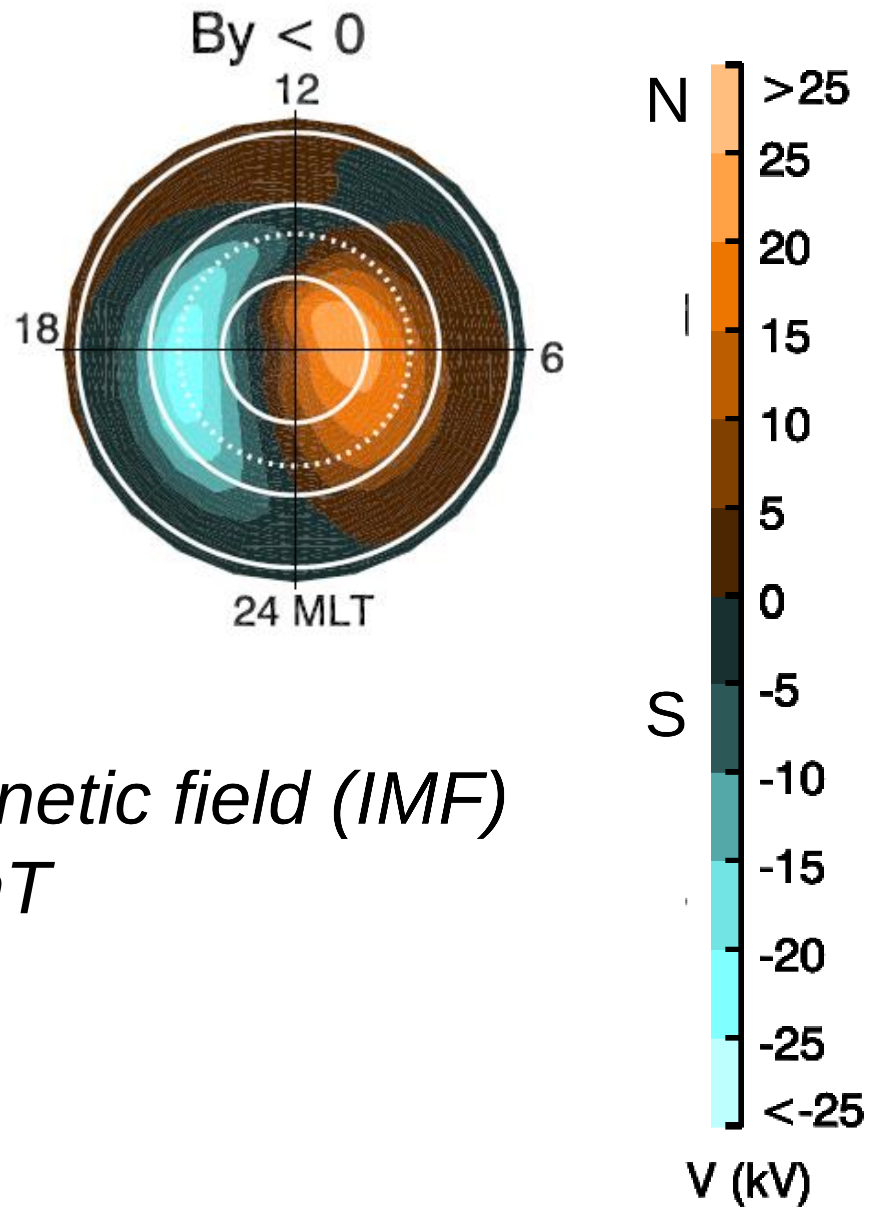
Solar-wind variations in V_i (and hence J_z)

- Magnetic reconnection ⇒ dawn-dusk potential in magnetosphere, V_{sw} ~ 30 - 150 kV: maps to high-latitude ionosphere
- $V_{\mathrm{sw}} = -\boldsymbol{u}_{\mathbf{sw}} \times \boldsymbol{B}$ depends on IMF $\boldsymbol{B} = (B_x, B_y, B_z)$



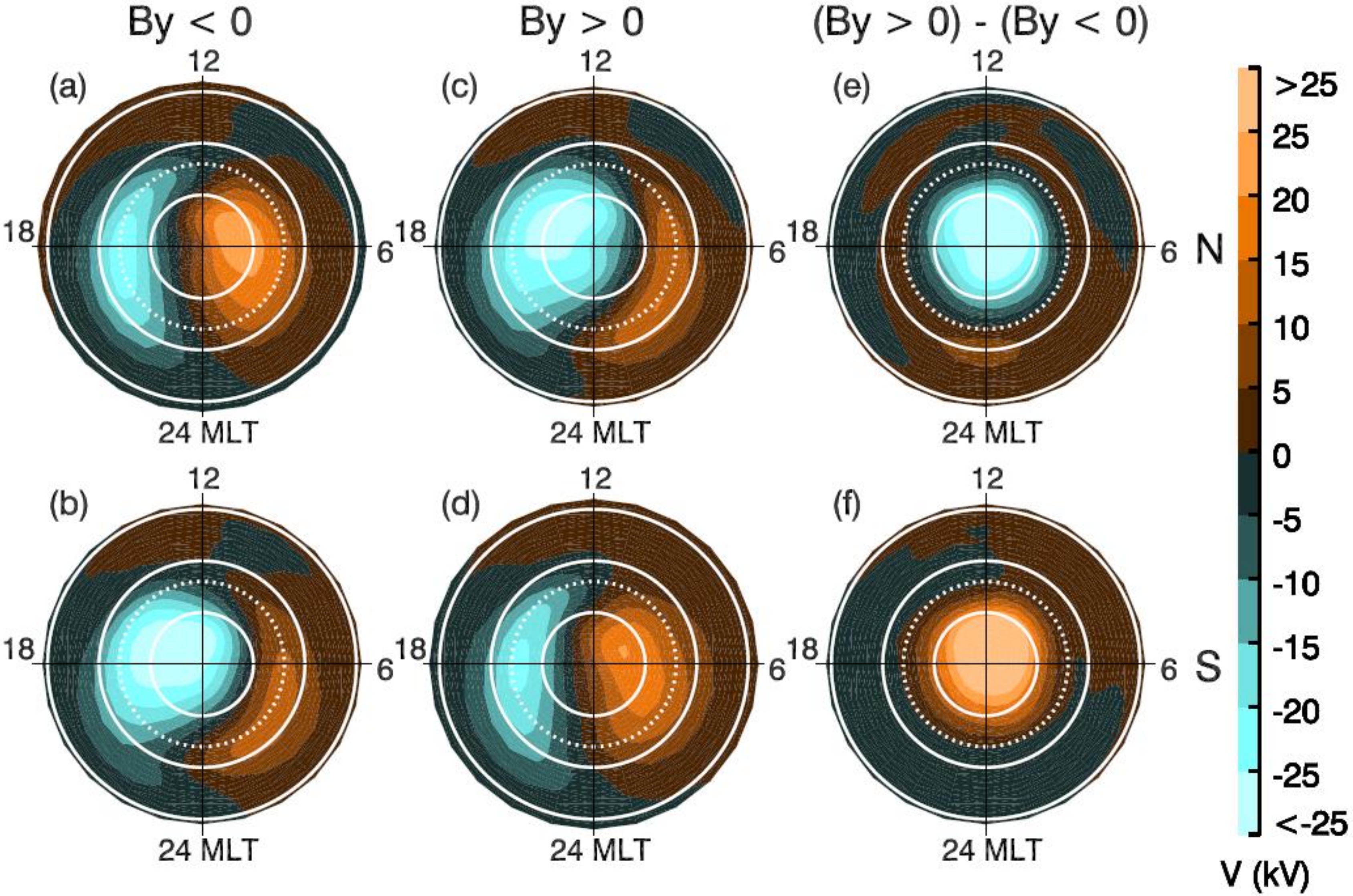
2D ionospheric electric potential

Using model from 1998 – 2002 SuperDARN radar data



Large interplanetary magnetic field (IMF)
*5 < |**B**| < 10 nT*

The ionospheric electric potential ordered by IMF B_y



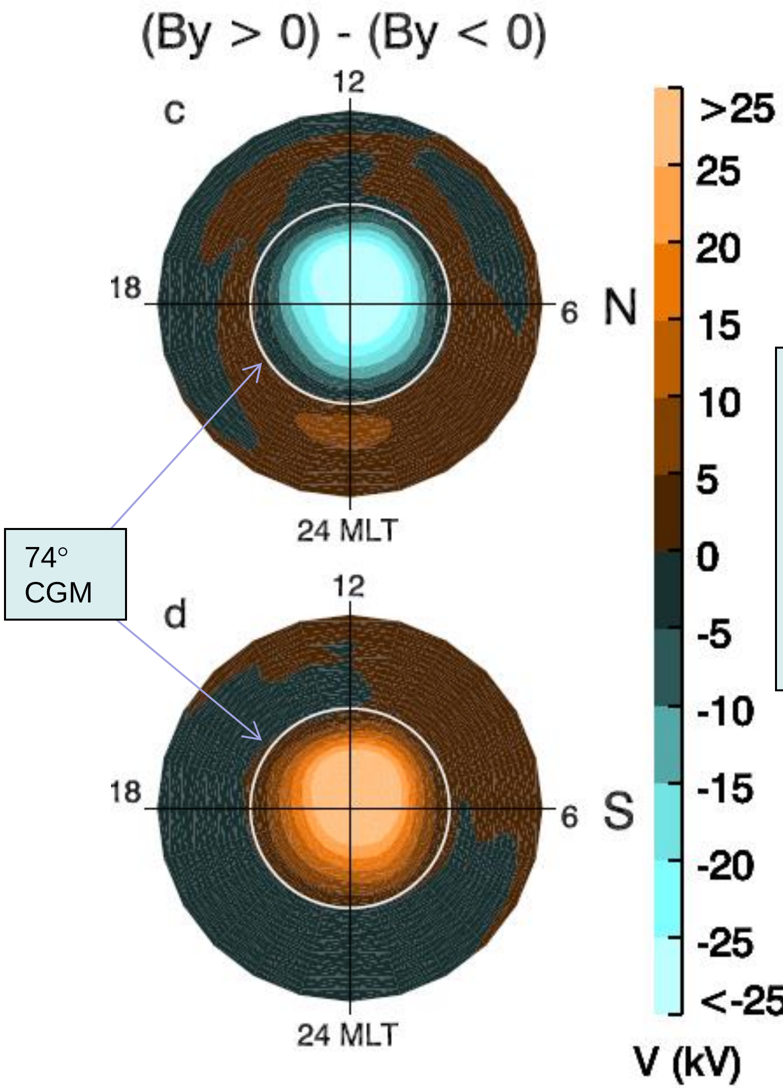
5 < |**B**| < 10 nT

Lam et al. 2013

ΔV : difference between By > 0 and By < 0 potential

Might expect any direct effect on atmosphere via J_Z to:

- maximise at high latitudes
- vary with hemisphere
- vary with B_y



$$\Delta V = V_i(B_y^+) - V_i(B_y^-)$$

$\Delta V < 0$ for >74° N CGM

$\Delta V > 0$ for >74° S CGM

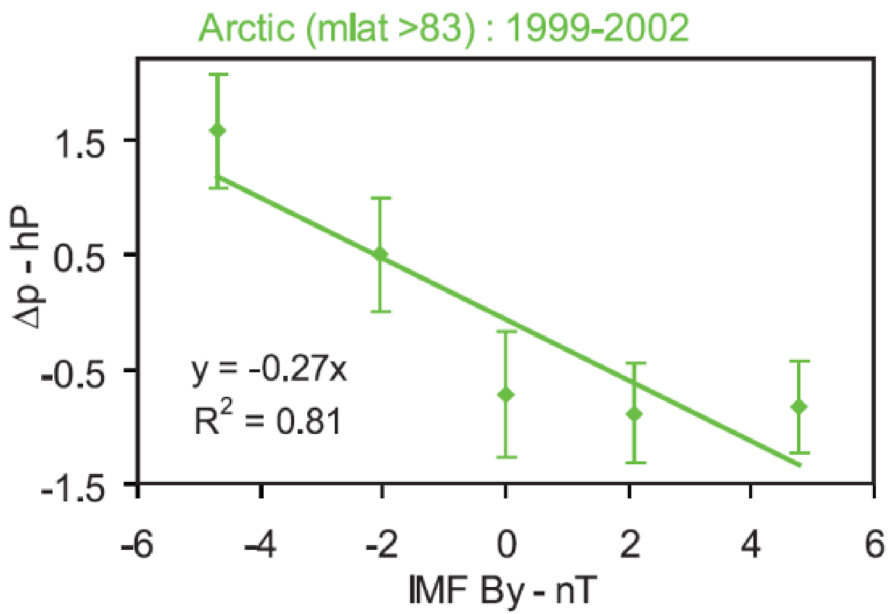
Geomagnetic co-ordinates

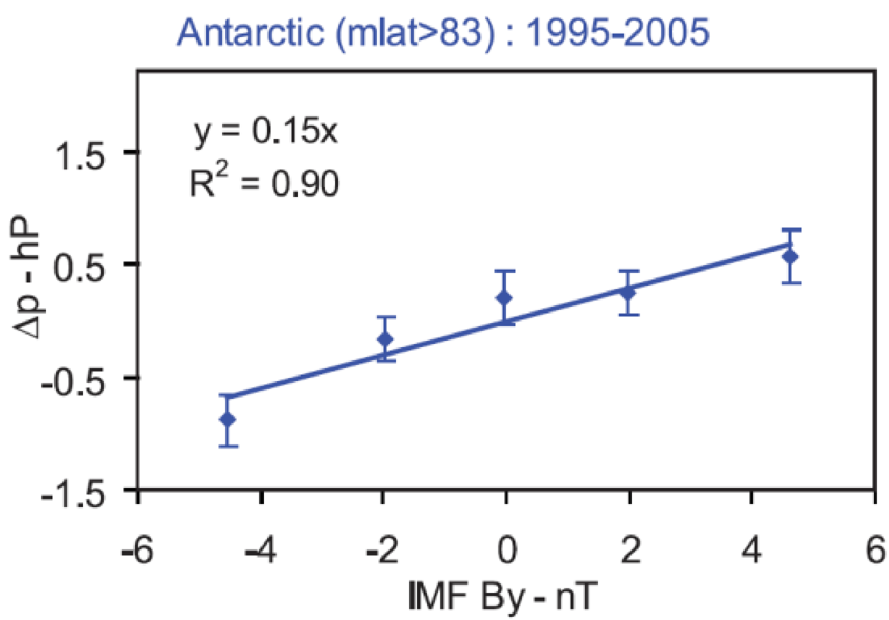
5 < |**B**| < 10 nT

Lam et al. 2013

Surface pressure vs IMF B_y

- Polar meteorological response to IMF By well established (Mansurov et al, 1974)
- Burns et al, 2008
- Fluctuations in surface pressure Δp vary with IMF B_y (1 - 2 hPa per 8 nT)
- Sign of $\Delta p{:}B_y$ opposite in N and S



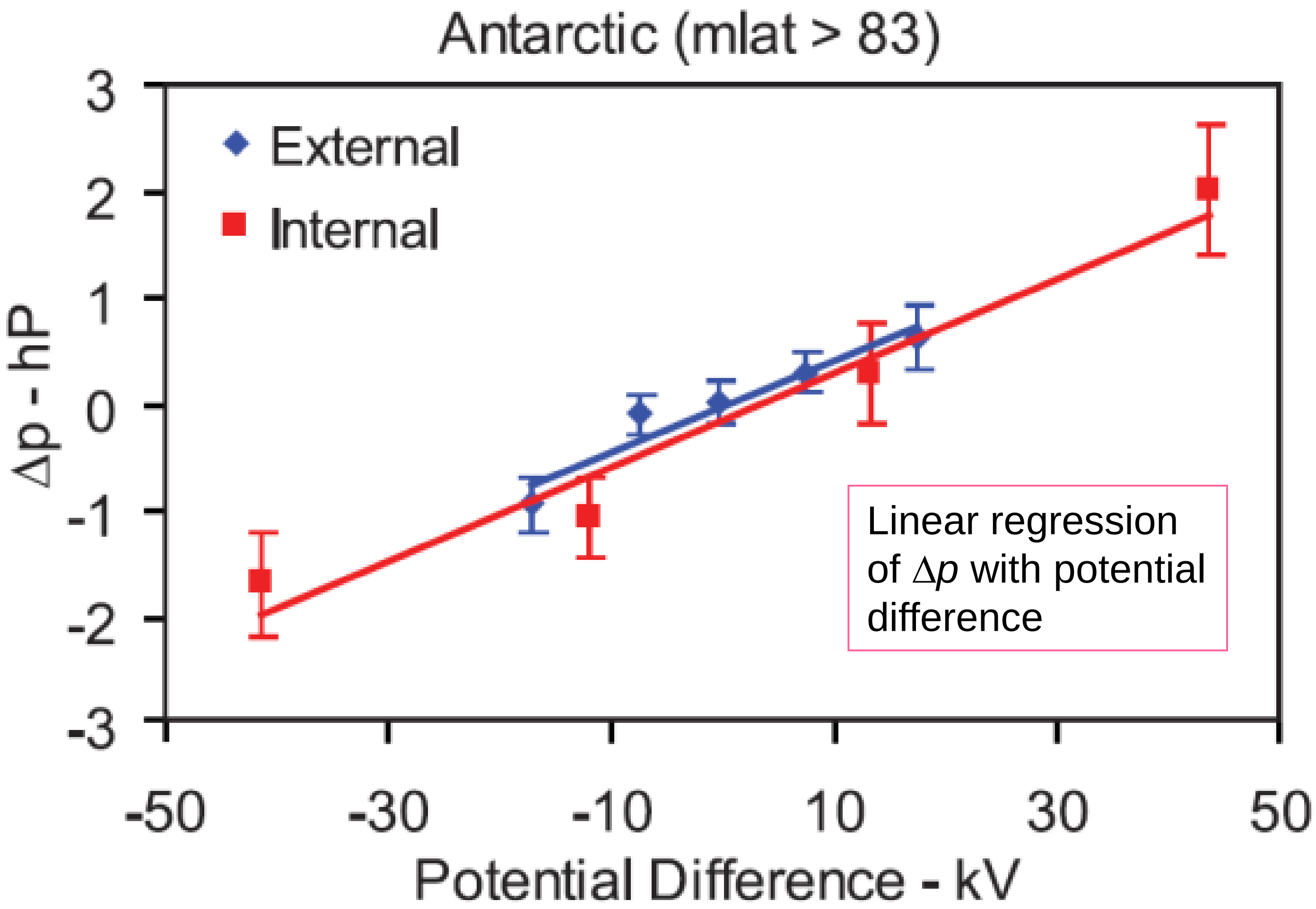


Δp - difference between daily value of surface pressure and 30-day running mean

Linear regression of Δp with IMF B_y

Burns et al. 2008

Same change in pressure with internal and external p.d.



External: Weimer 2001 to estimate ionosphere-earth p.d. from solar wind data
Internal: vertical electric field measurements at Vostok

Burns et al. 2008

Evidence for direct action of Vi on surface pressure (i)

- Sign of $\Delta p{:}B_y$ depends on hemisphere

- Slopes of $\Delta p{:}V$ same for external and internal p.d

- t~0 time lags not inconsistent with mechanism involving global atmospheric electric circuit

- Evidence of direct action of ionospheric potential on cloud base height

Quantifying the effect of the upper atmospheric electric potential on lower atmospheric temperature and pressure

- Correlate surface pressure with ionospheric electric potential itself
  - 15 years SuperDARN data, 20 radars

- Use reanalysis data for *p* and *T* *1948 → 6h*
  - high resolution in latitude, longitude, altitude

- Correlation does not prove causal link
  - test specific mechanisms using **spatial** and time lag information

- Investigate role of B_z
  - Burns et al. 2007 used Vostok; low variation with V_{sw}

Global study of surface pressure - method

- Extend polar study of Burns et al. (2008) to global, zero-lag study
- Use 12 UT NCEP NCAR reanalysis surface pressure $p(\lambda, \phi, t)$ with seasonal cycle removed [λ latitude; ϕ longitude]
- Daily averages of IMF B_y calculated from hourly NSSDC OMNIWeb data 1999 – 2002

$\bar{p}_+(\lambda, \phi)$: **mean** p **for all days when** $B_y \geq$ **3 nT**
$\bar{p}_-(\lambda, \phi)$: **mean** p **for all days when** $B_y \leq -$ **3 nT**
$\bar{p}_{all}(\lambda, \phi)$: **mean** p **for all days**

$\bar{p}_{z+}(\lambda)$: **zonal mean of** $p_+(\lambda, \phi)$
$\bar{p}_{z-}(\lambda)$: **zonal mean of** $p_-(\lambda, \phi)$
$\bar{p}_z(\lambda)$: **zonal mean of** $p_{all}(\lambda, \phi)$

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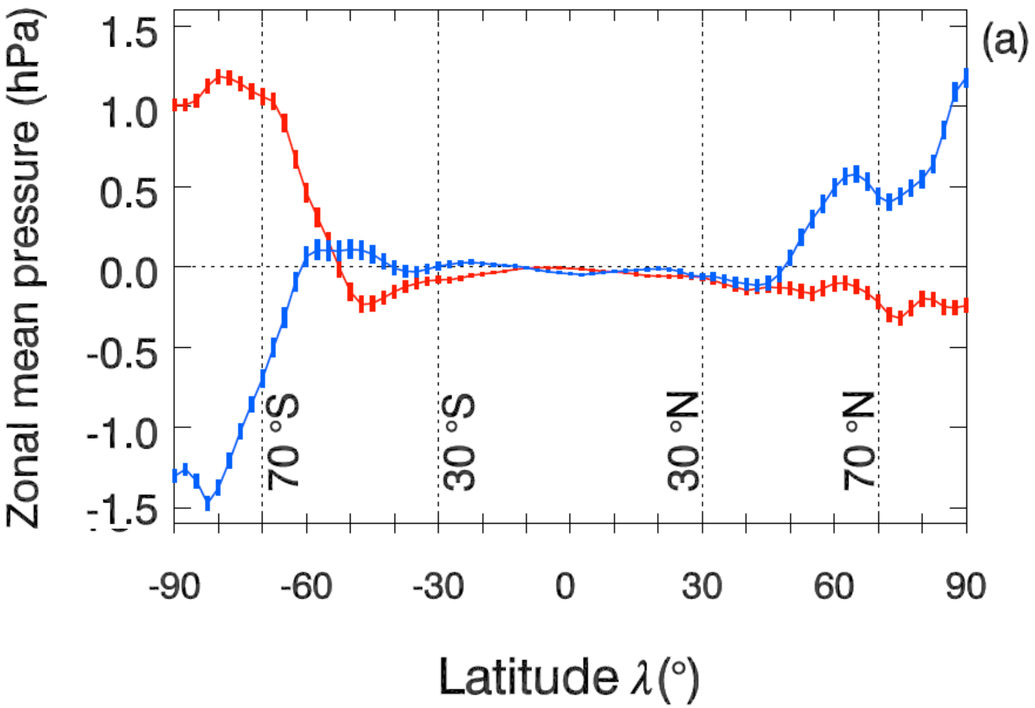
Mean zonal surface pressure oppositely ordered by IMF B_y in polar north and polar south



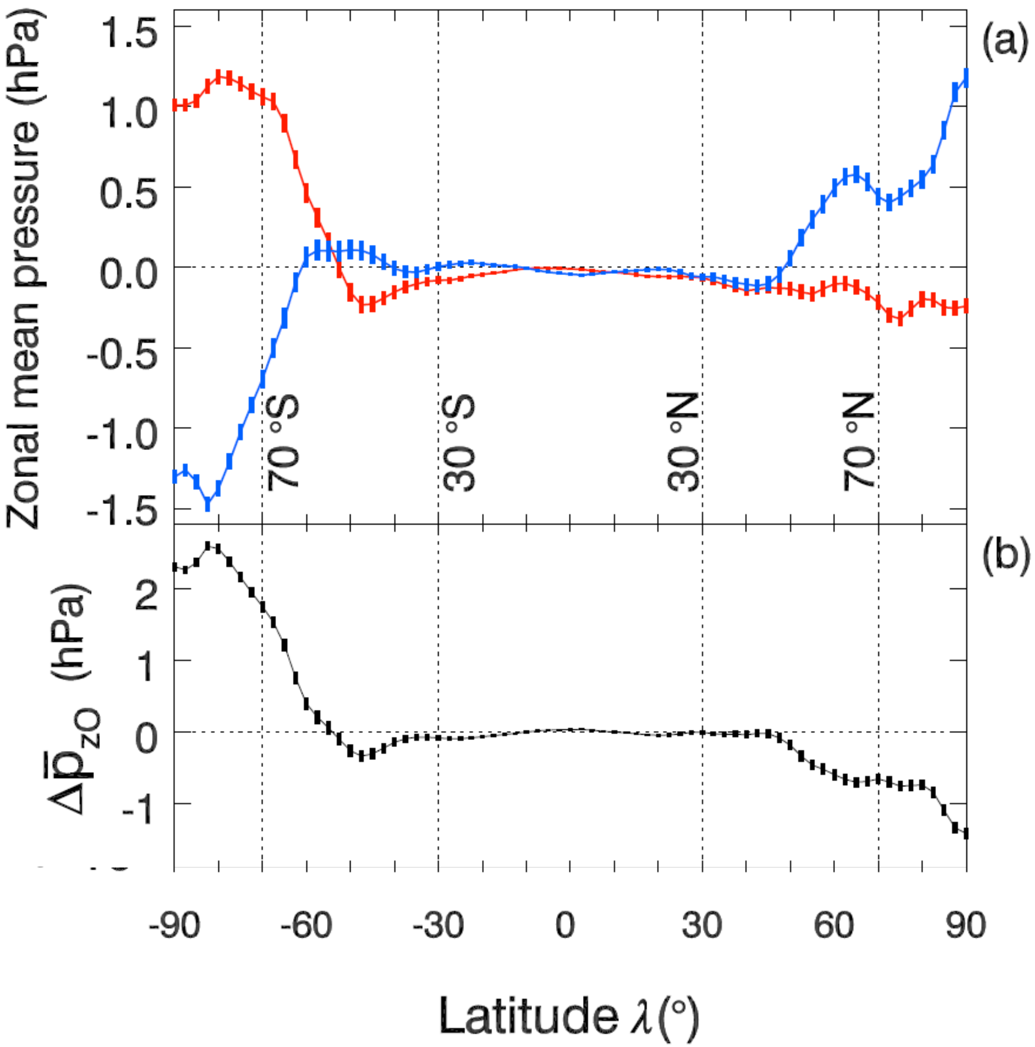
(a) Zonal mean pressure for IMF By ≥ 3 nT

Zonal mean pressure for IMF By ≤ - 3 nT

Error bars are 'error in the mean'

Lam et al. 2013

Mean zonal surface pressure oppositely ordered by IMF B_y in polar north and polar south



(a) Zonal mean pressure for IMF By ≥ 3 nT

Zonal mean pressure for IMF By ≤ - 3 nT

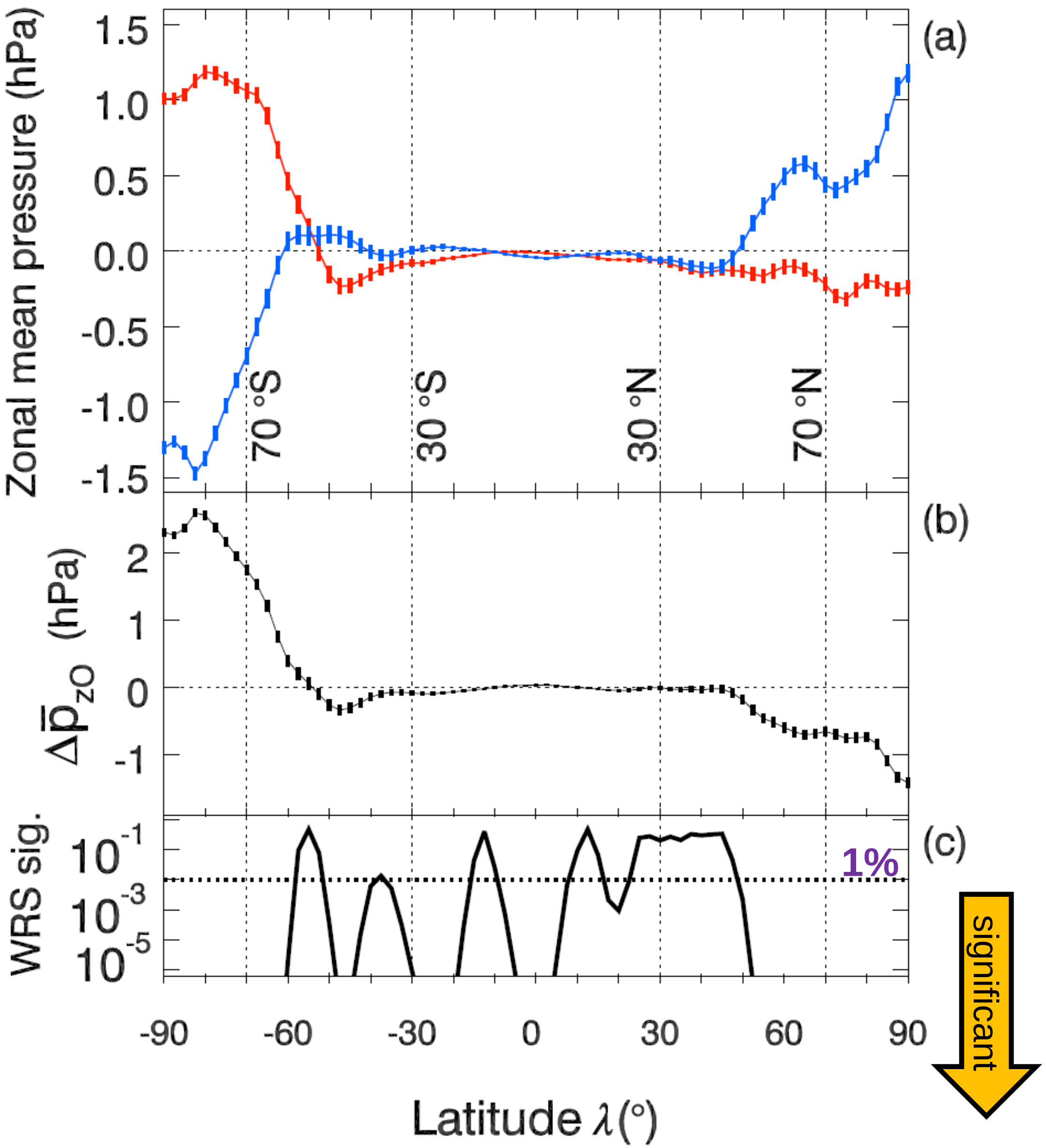
Error bars are 'error in the mean'

(b) The difference between the blue and red curves

$$\Delta\bar{p}_{zO}(\lambda) = \bar{p}_{z+}(\lambda) - \bar{p}_{z-}(\lambda)$$

Lam et al. 2013

Mean zonal surface pressure oppositely ordered by IMF B_y in polar north and polar south



(a) Zonal mean pressure for IMF By ≥ 3 nT

Zonal mean pressure for IMF By ≤ - 3 nT

Error bars are 'error in the mean'

(b) The difference between the blue and red curves

$$\Delta\bar{p}_{zO}(\lambda) = \bar{p}_{z+}(\lambda) - \bar{p}_{z-}(\lambda)$$

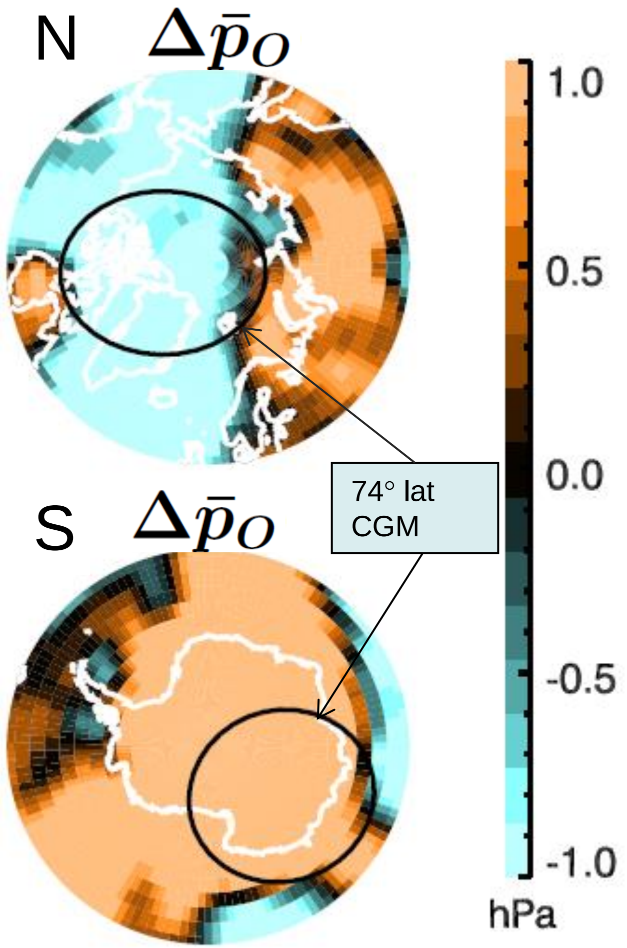
(c) Significance of difference between data that make up blue and red curves in panel (a) using Wilcoxon Rank-Sum test

Surface pressure ordered by IMF B_y: Arctic and Antarctica

$$\Delta \bar{p}_O(\boldsymbol{\lambda}, \phi) = \bar{p}_+(\boldsymbol{\lambda}, \phi) - \bar{p}_-(\boldsymbol{\lambda}, \phi)$$

Surface pressure ordered by IMF B_y: Arctic and Antarctica

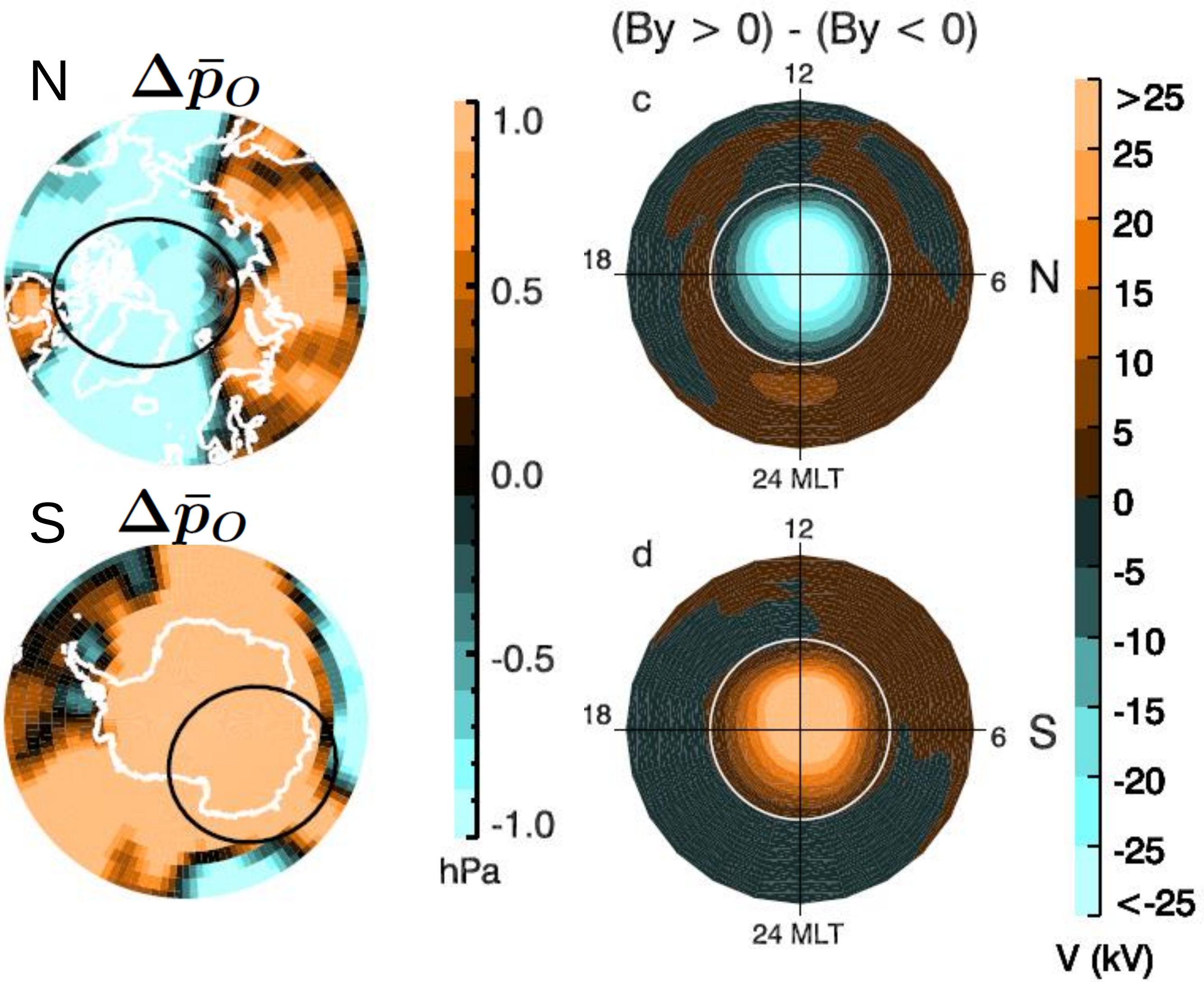
$$\Delta\bar{p}_O(\lambda,\phi) = \bar{p}_+(\lambda,\phi) - \bar{p}_-(\lambda,\phi)$$



- Size and sign of $\Delta\bar{p}_O(\lambda,\phi)$ at poles similar to Burns et al. study

Lam et al. 2013

Polar $\Delta\bar{p}_O$ resembles ΔV - supports GEC mechanism (i)

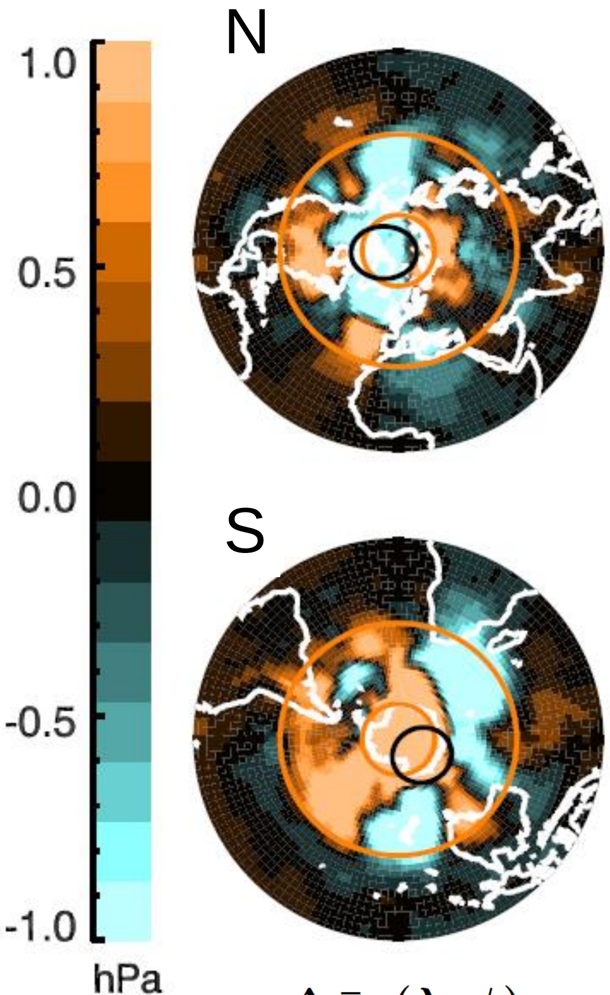


$$\Delta V = V_i(B_y^+) - V_i(B_y^-)$$

Lam et al. 2013

2D surface pressure is ordered by IMF B_y at high latitudes

$$\Delta\bar{p}_O(\boldsymbol{\lambda}, \phi) = \bar{p}_+(\boldsymbol{\lambda}, \phi) - \bar{p}_-(\boldsymbol{\lambda}, \phi)$$



$\Delta\bar{p}_O(\boldsymbol{\lambda}, \phi)$

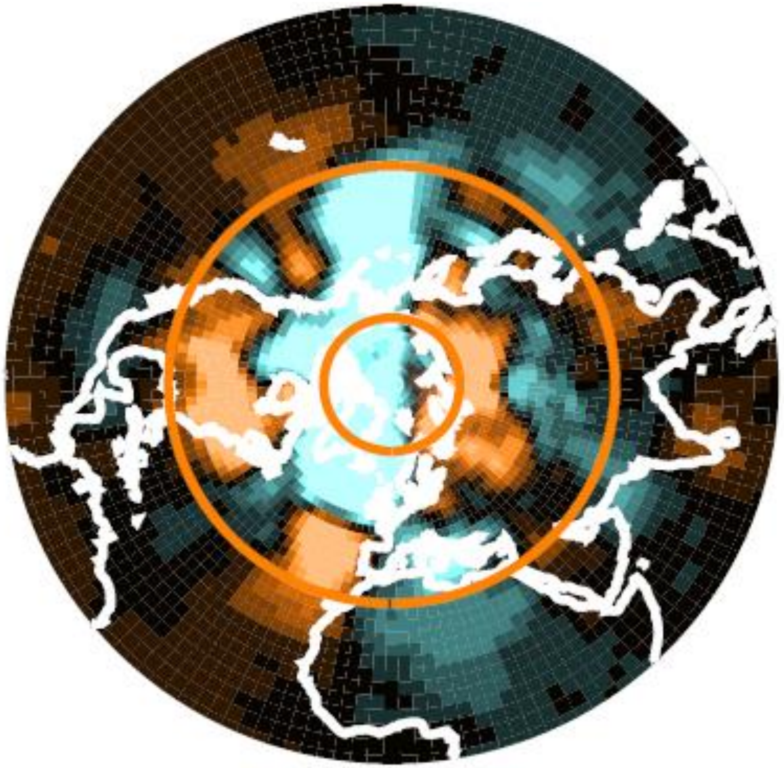
- Size and sign of $\Delta\bar{p}_O(\boldsymbol{\lambda}, \phi)$ at poles similar to Burns et al. study

Orange circles at 30° and 70 °

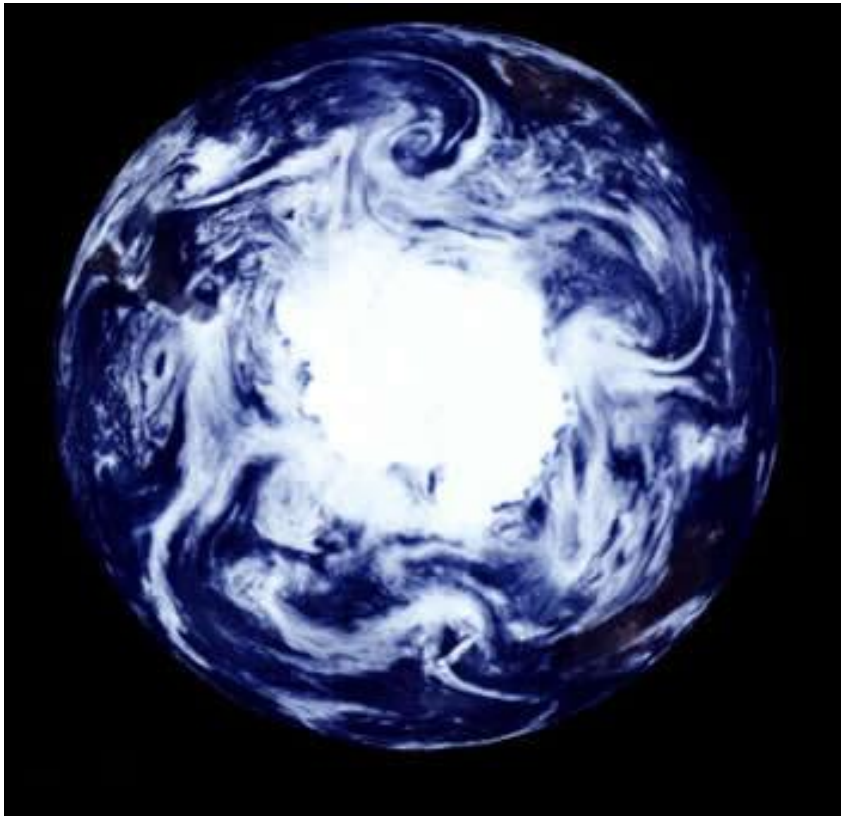
Lam et al. 2013

2D surface pressure ordered by IMF B_y resembles Rossby wavefield at mid latitudes

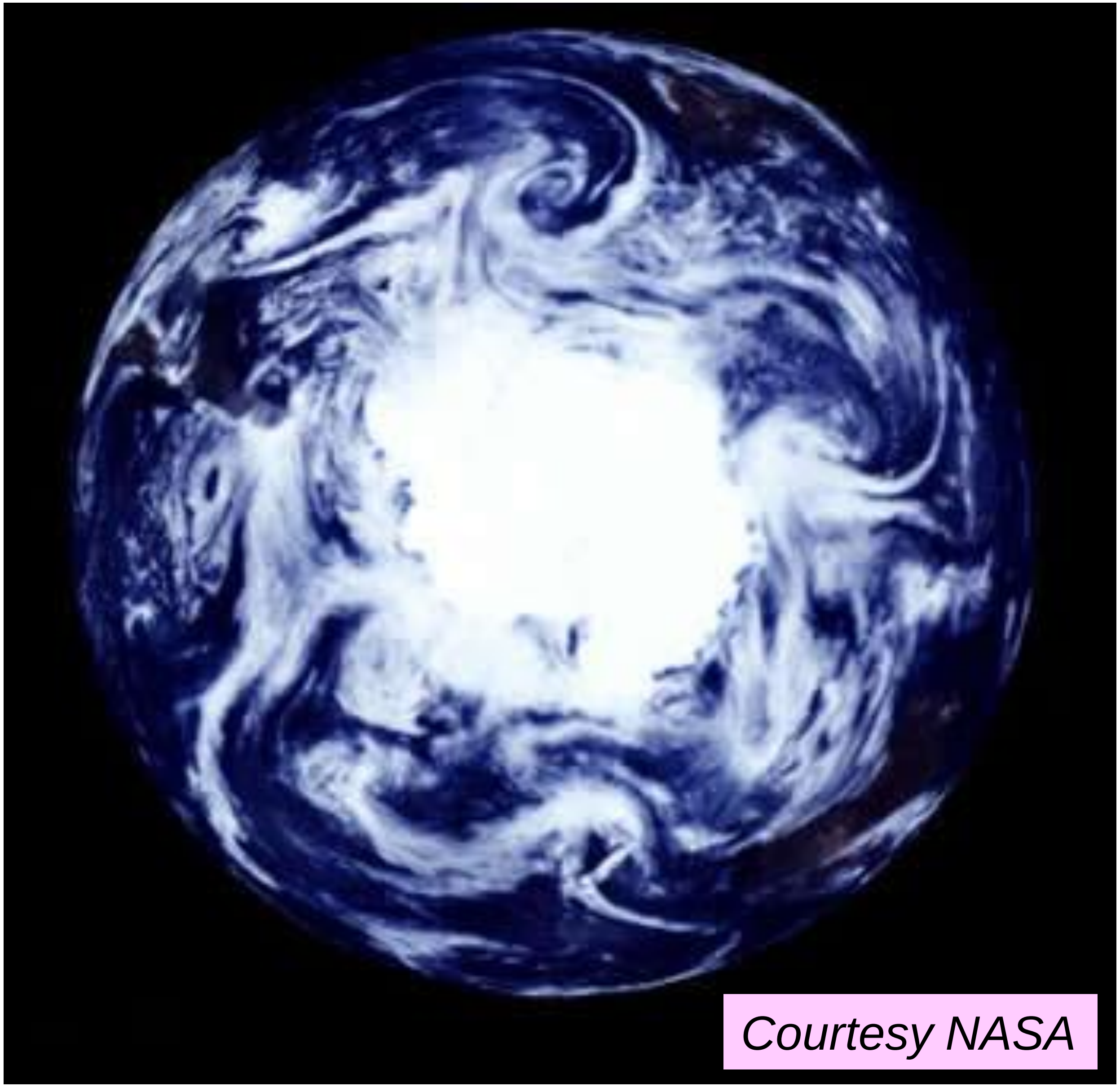
$$\Delta\bar{p}_O(\lambda, \phi)$$



Rossby waves



Atmospheric Rossby waves



- Satellite view of atmospheric circulation centred at the South Pole
- Shows characteristic Rossby (or planetary) quasi-stationary waves; Usually 4 - 6 waves at mid-latitudes
- The 2D surface pressure ordered by IMF By (previous slide) resembles this Rossby wave field

Significance (Wilcoxon + field testing) high, except equatorial region

$$\Delta\bar{p}_O(\boldsymbol{\lambda},\phi) = \bar{p}_+(\boldsymbol{\lambda},\phi) - \bar{p}_-(\boldsymbol{\lambda},\phi)$$

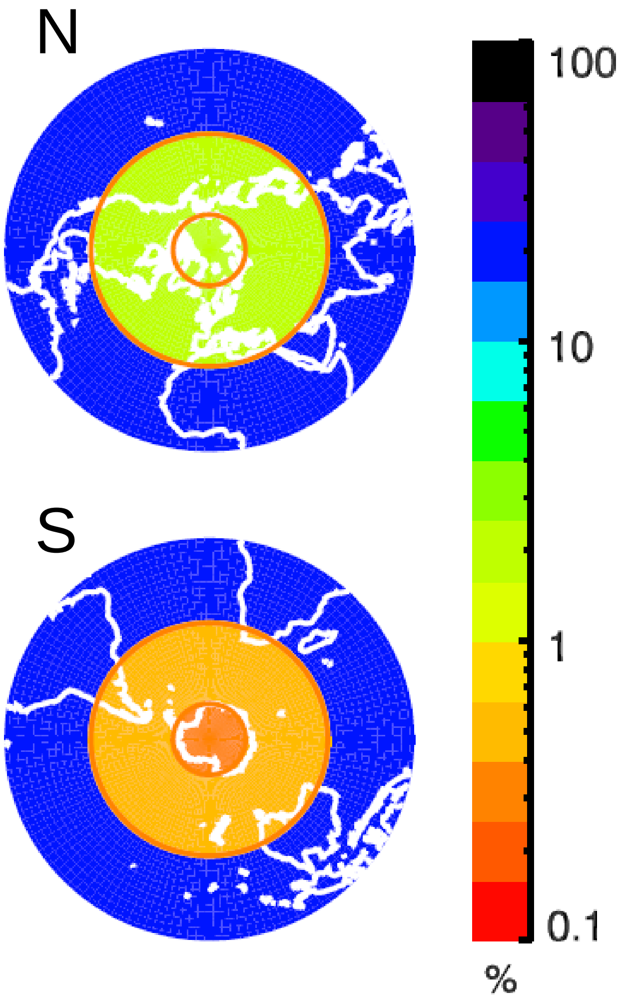


Table 1. Field significances for WRS test between $\bar{p}_+$ and $\bar{p}_-$

Region	Latitude range (°)	Field significance (%, 2 s.f.)
Arctic	70.0 N–90.0 N	1.9
Mid latitude (north)	30.0 N–67.5 N	2.1
Equatorial	27.5 S–27.5 N	23 ←
Mid latitude (south)	30.0 S–67.5 S	0.4
Antarctica	70.0 S–90.0 S	0.3
Globe	90.0 S–90.0 N	2.0

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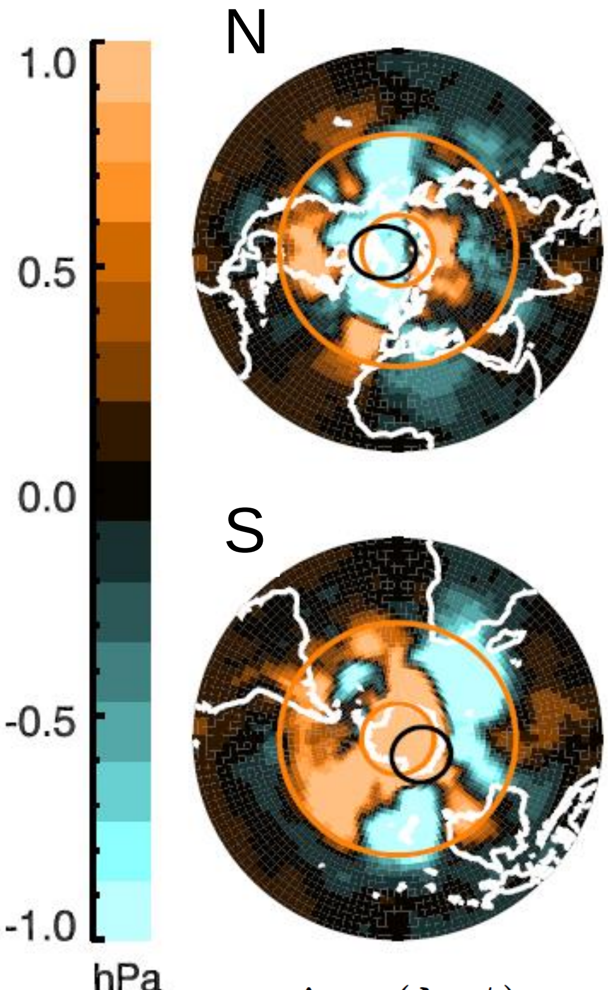
2D surface pressure is ordered by IMF B_y at mid latitudes

$$\Delta\bar{p}_O(\lambda,\phi) = \bar{p}_+(\lambda,\phi) - \bar{p}_-(\lambda,\phi)$$



$\Delta\bar{p}_O(\lambda,\phi)$

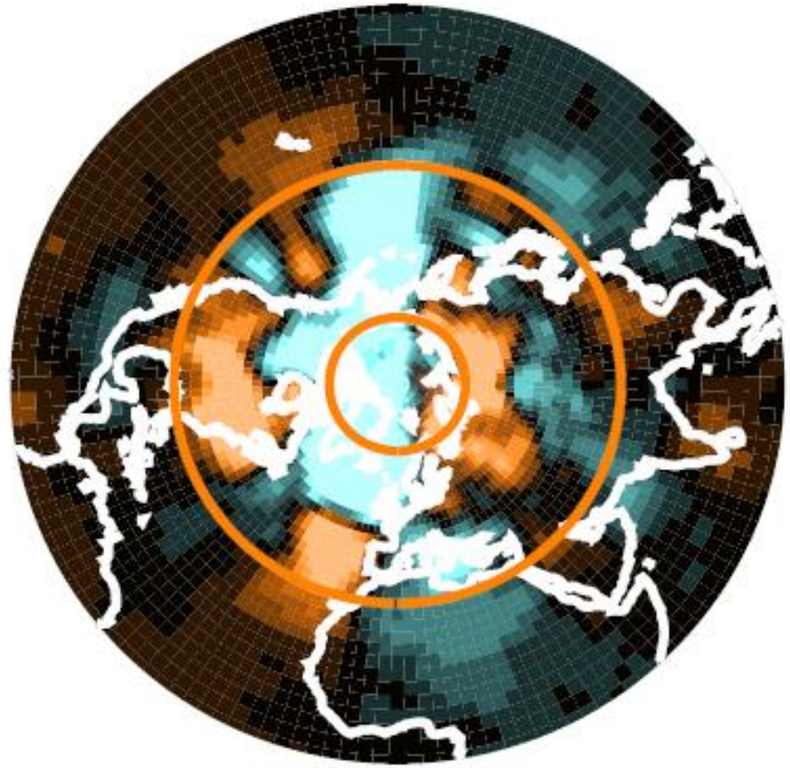
- Size and sign of $\Delta\bar{p}_O(\lambda,\phi)$ at poles similar to Burns et al. study
- Size of $\Delta\bar{p}_O(\lambda,\phi)$ at mid latitudes similar to:
  - that at poles
  - effect comparable to initial uncertainties in zonal wind in ensemble numerical weather predictions
  - appearance of quasi-stationary Rossby waves

Orange circles at 30° and 70°

Lam et al. 2013

2-stage mechanism

$$\Delta\bar{p}_O(\boldsymbol{\lambda}, \phi)$$



i. Change in polar surface pressure involving global atmospheric electric circuit

ii. Resulting change in mid-latitude surface pressure via conventional meteorology

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Mechanism stage (ii): 2D quasi-stationary Rossby waves

- Coriolis force varies linearly in co-latitude θ
- Stationary solutions for wind in longitudinal and latitudinal directions
- Integer number of azimuthal planetary waves, *m*
- Geostrophic approximation – horizontal motion balanced by pressure force

Wavelength in latitudinal direction:

$$L_\theta = \frac{2\pi R \sin\theta}{[(4\omega^2 R^2 \rho \cos\theta \sin^3\theta)/(\mathrm{d}\bar{p}/\mathrm{d}\theta) - m^2]^{1/2}}$$

depends on meridional gradient of zonally-averaged pressure, which changes with IMF B_y

Accounts for Rossby-wave-like form of $\Delta\bar{\mathbf{p}}_O(\boldsymbol{\lambda}, \phi)$

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Implications

- Rossby wave field key in determining trajectories of storm tracks
- Configuration of North Atlantic jet stream particularly susceptible to changes in forcing...
- ... & location/timing of blocking events? ($\Rightarrow$ periods low/high pressure)
- Upper-level Rossby wavebreaking $\Rightarrow$ low-frequency variability of NAO
- NAO key to climate variability over Atlantic-European sector
- Eurasian winter T $\Leftrightarrow$ solar variabilty, and for 'Wilcox' effect.
- Importance of nonlinear dynamics

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Summary

• Changes in IMF B_y correlate to changes in surface pressure above 30°; For zonal average, largest effect near poles

• Mid-latitude effect: difference in surface pressure for high positive and negative IMF B_y resembles Rossby wave field

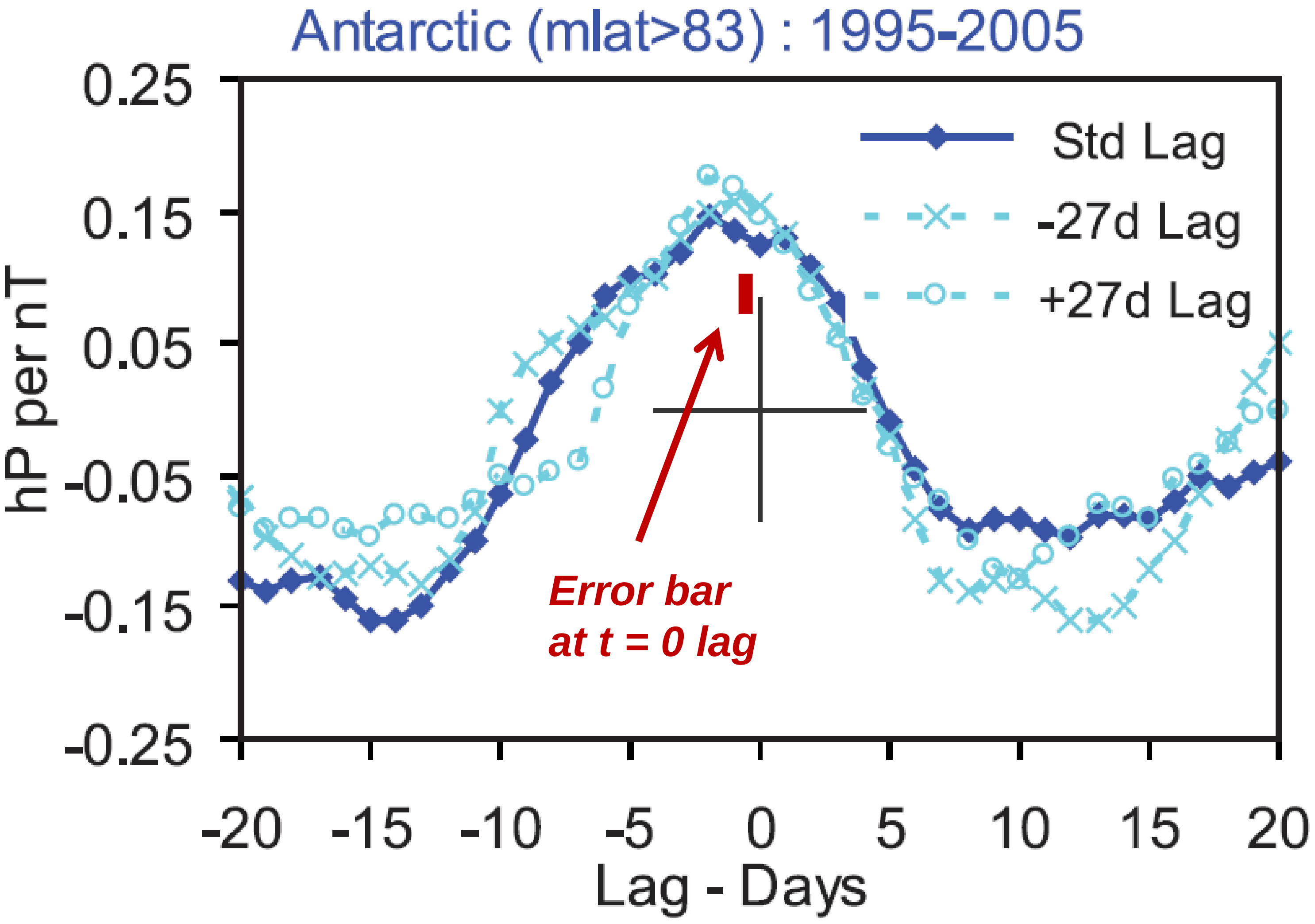
• 2 stage mechanism (i) polar, (ii) mid-latitude
  (i) Direct action of ionospheric potential on cloud dynamics via GEC
  (ii) associated changes to atmospheric pressure modify
    2D quasi-stationary Rossby waves via zonal wind

• Small, localised solar influence on upper atmosphere may influence populated regions (European climate, breakup Arctic sea ice...)

Global connection via non-linearity

Acknowledgments:
• *NCEP Reanalysis data provided by NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from http://www.esrl.noaa.gov/psd/*
• *OMNI data obtained from GSFC/SPDF OMNIWeb interface http://omniweb.gsfc.nasa.gov*
• *Software to produce plots of ionospheric potential written by Ellen Pettigrew*

Regression coefficient between pressure and IMF B_y as function of time lag



Burns et al. 2008