Observational Study of Subtropical Highs

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Organization of Talk

- There are 5 subtropical highs

- Question: What season (or month) is each high strongest?
- Question: What are other climatological aspects of the highs?
- Question: What are some simple conceptual models?
- Question: What remote processes seem linked to each high, and which leads?

- Simple statistical analyses: means, variation, 1-pt correlations, composites will be shown

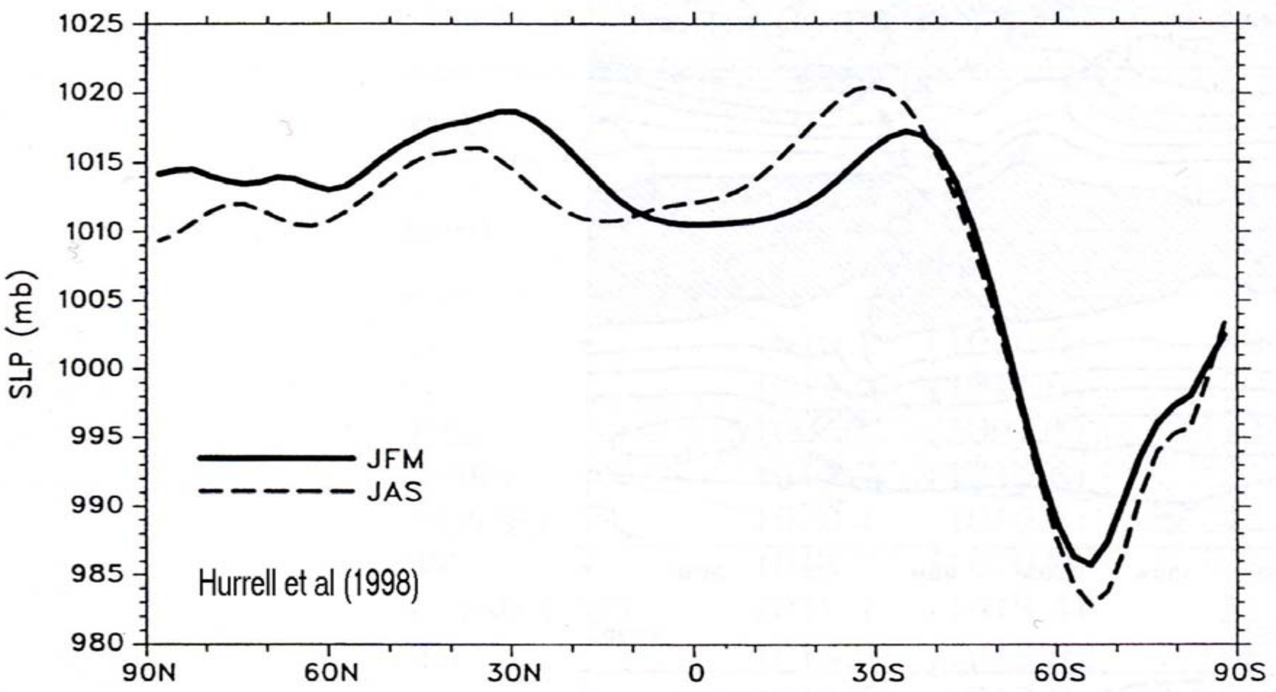
- Apology: This is **NOT** a comprehensive survey of observational work by others.

- Note: I will **NOT** discuss theories except to list them and state how they provide rationales for choosing certain remote variables.

A Simple Fact about the Subtropical Highs

On a ZONAL MEAN, they are strongest in winter.

- NH SH

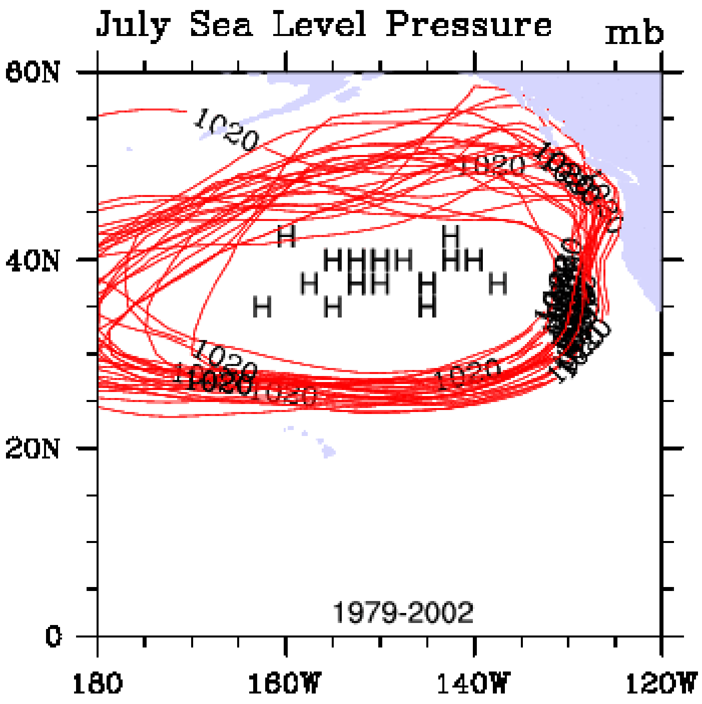


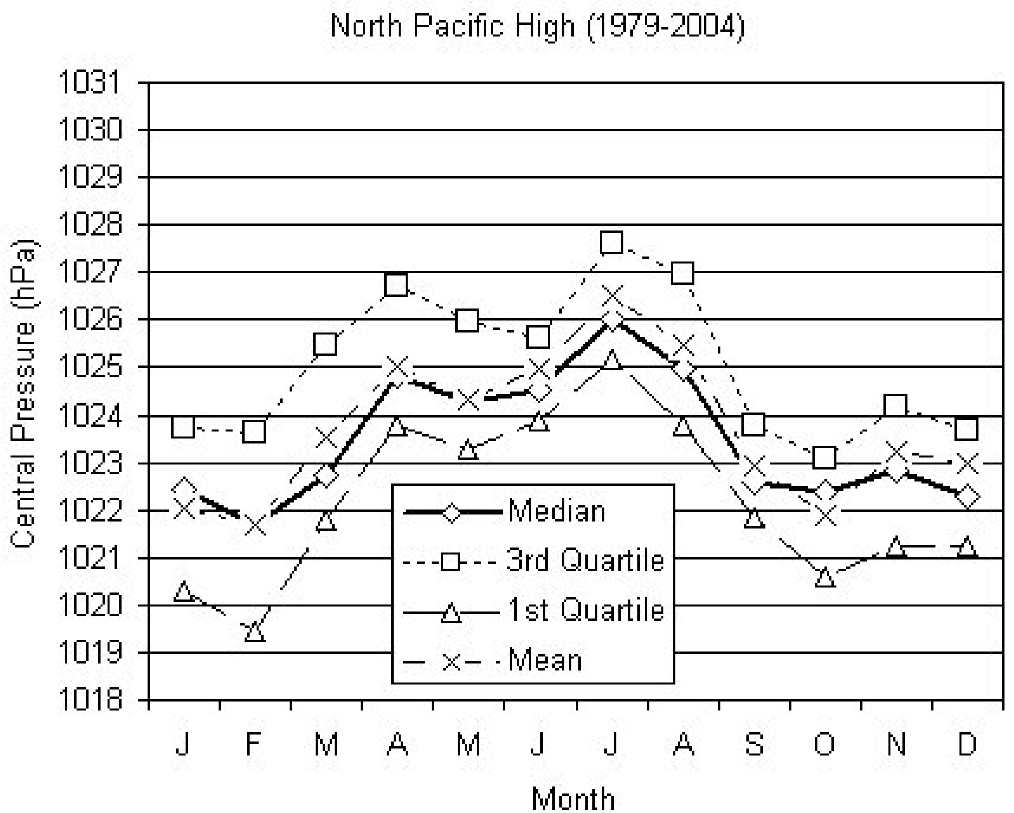
Do individual subtropical highs have the same seasonal max?

Not necessarily!

Climatology: North Pacific High

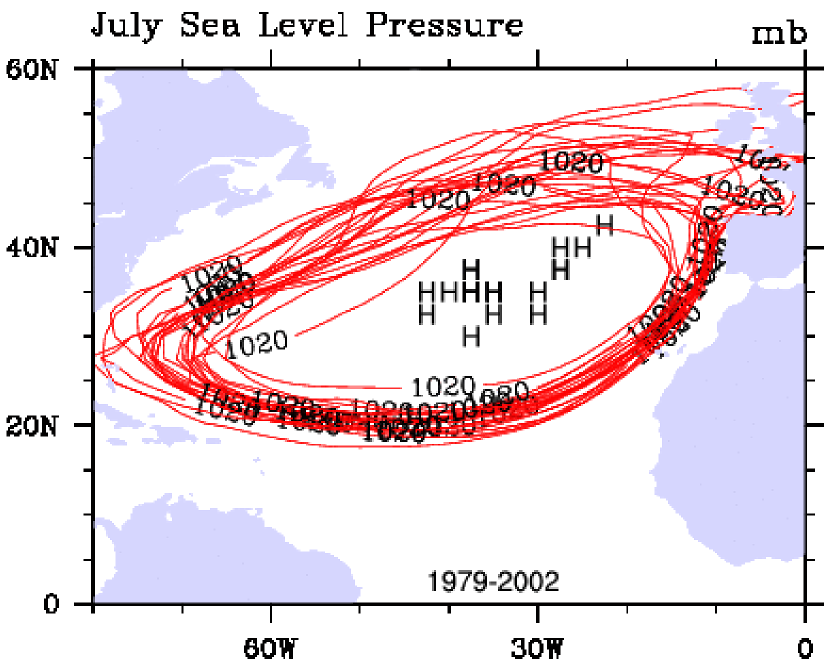
- On a long term monthly mean, the central pressure is greatest in SUMMER not winter.
  - Summer (July)
- Shape is fairly consistent from year to year
- location of the max SLP varies

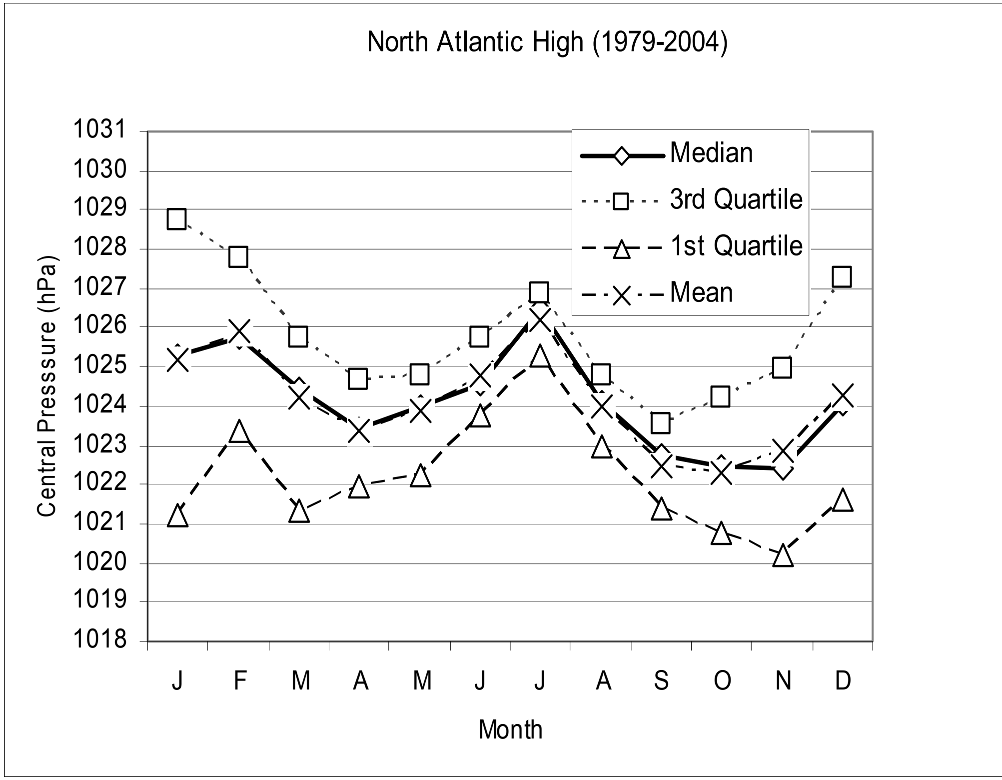




Climatology: North Atlantic High

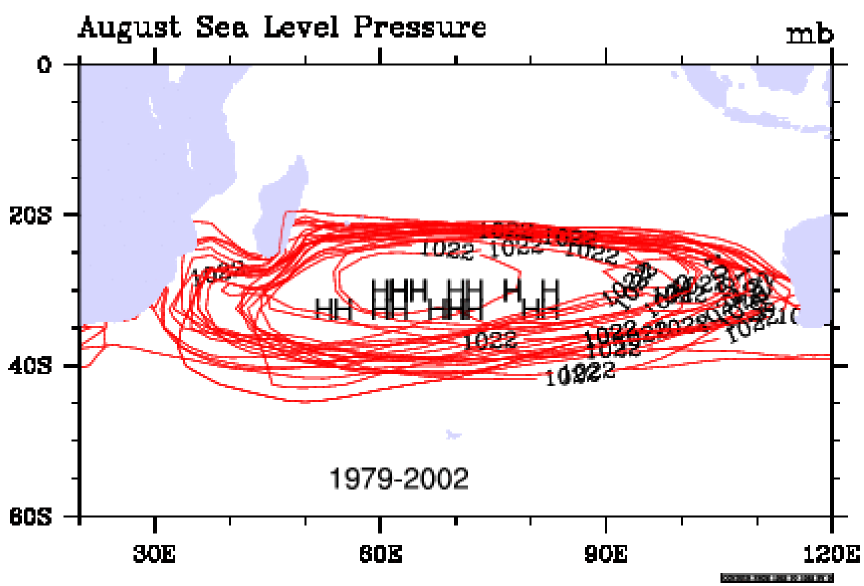
- On a long term monthly mean, the central pressure is greatest in SUMMER not winter.
  - Summer (July)
  - Secondary max in winter due to spill over from N. African cold high
- Shape quite consistent from year to year
- location of max SLP largest latitude variation

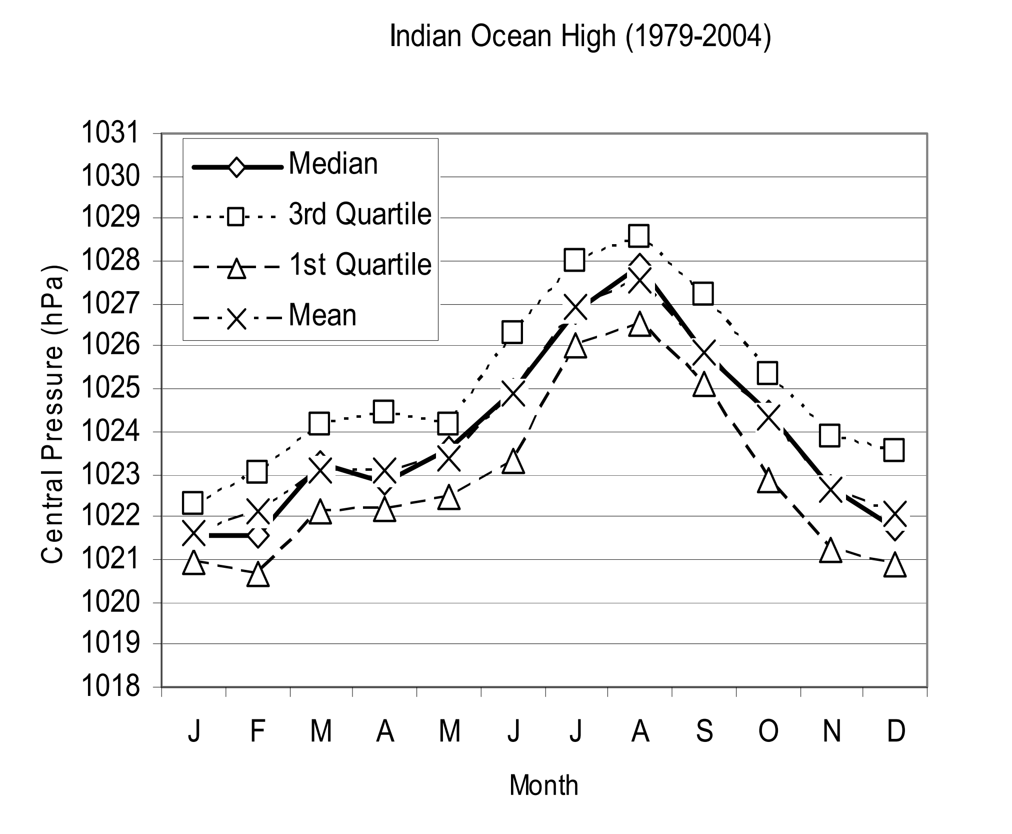




Climatology: South Indian Ocean High

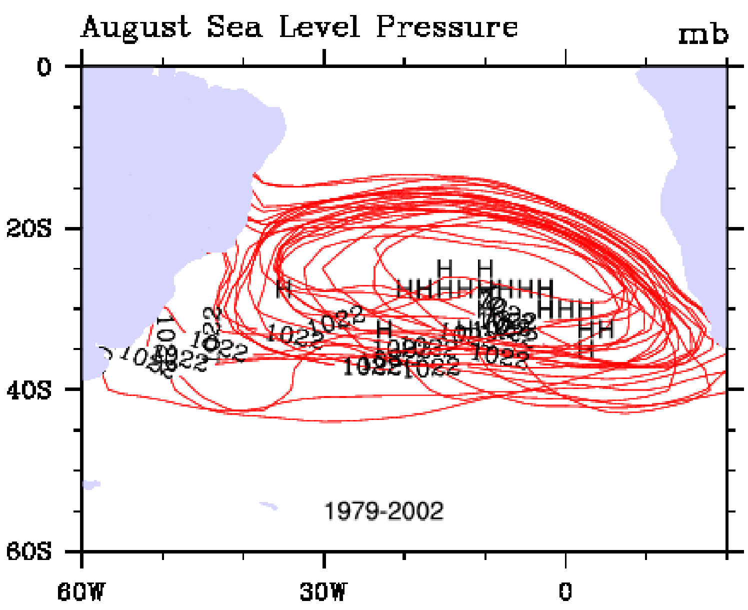
- On a long term monthly mean, the central pressure is greatest in winter.
  - Winter (August)
  - Has the highest average SLP
- Shape somewhat consistent from year to year,
- Is the largest and most elongated of the highs.
- Max location has largest variation

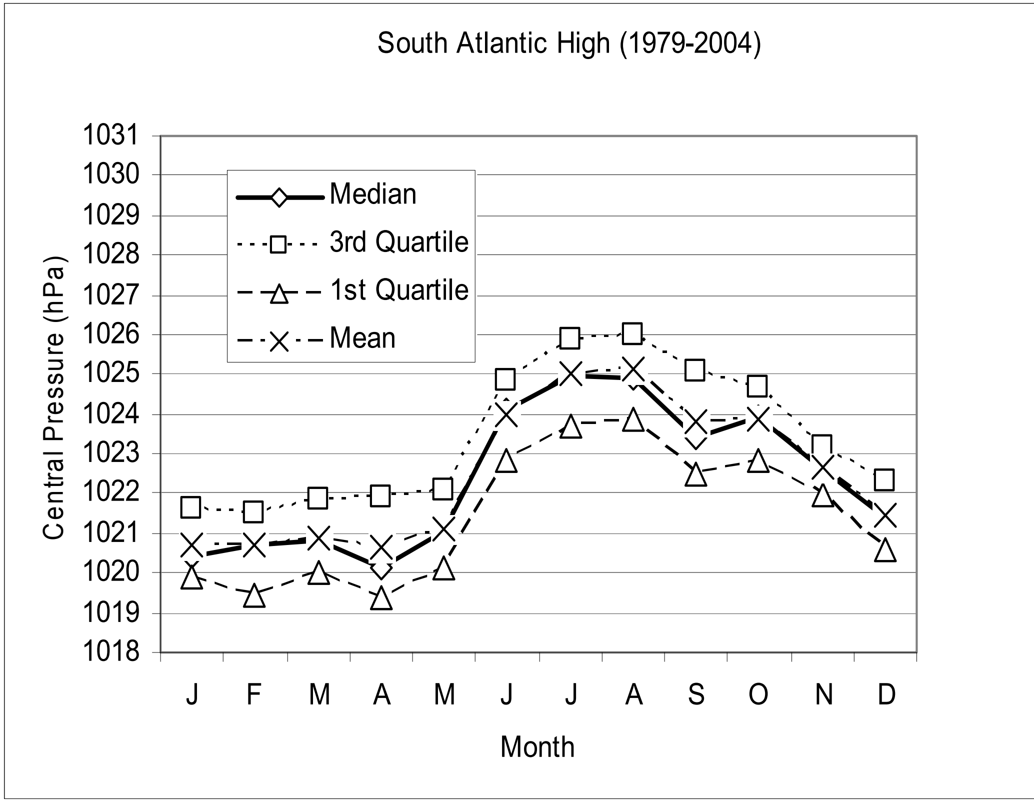




Climatology: South Atlantic High

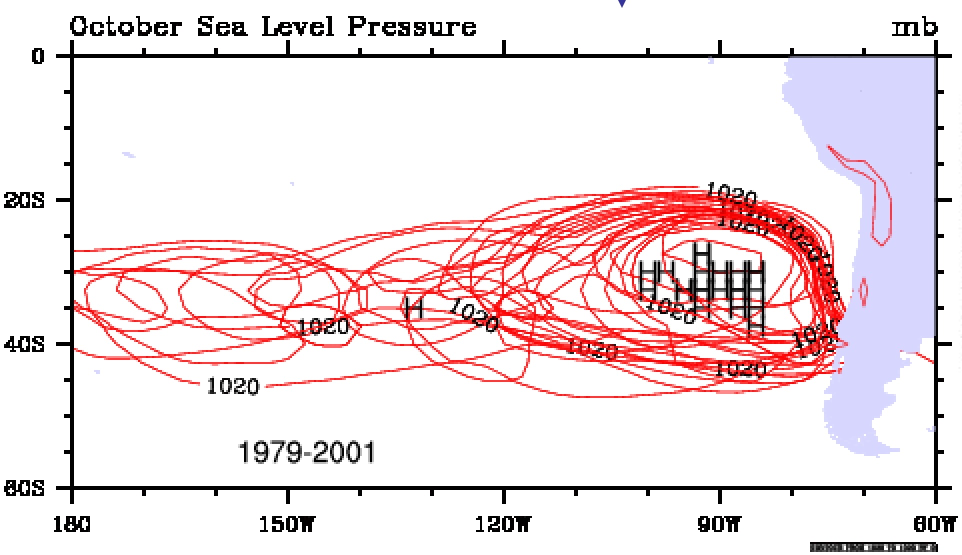
- On a long term monthly mean, the central pressure is greatest in winter.
  - Winter (August)
- Smallest of the highs
- Central max moves around a lot (still less than South Indian max)
- Shape varies a lot

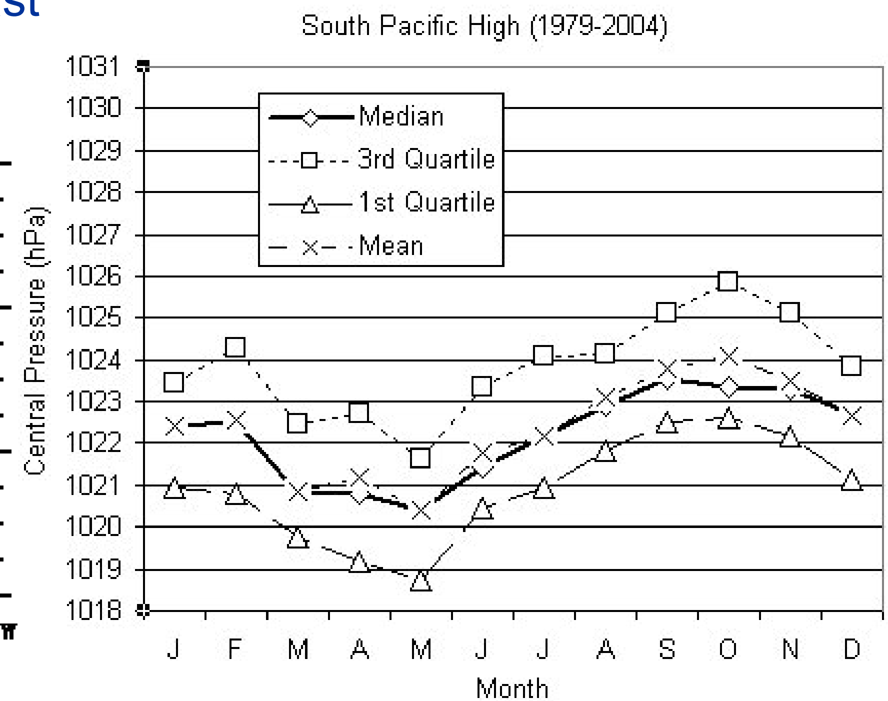




Climatology: South Pacific High

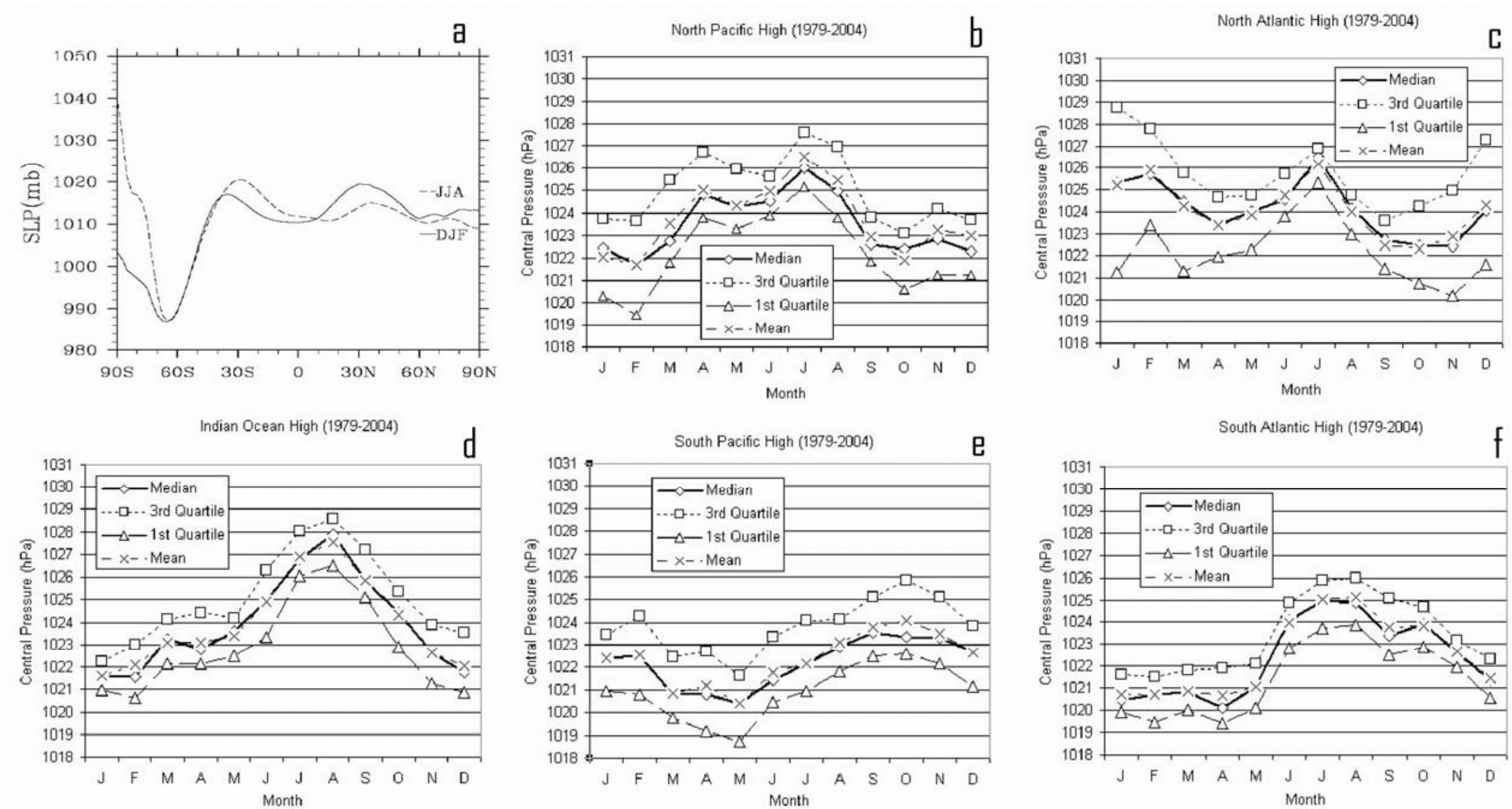
- Somewhat confounding, the climatology differs for this high from the others
  - On a long term monthly mean, the central pressure is greatest in **Spring** (October)
  - Only high to have clear tropical connections without the need to filter out midlatitude frontal systems.
  - Lowest average SLP
- Pattern has some variation over time, but mainly on the west side
- The central max location varies least





Review: Subtropical Highs Seasonal Variation

- In N. Hemisphere:
  - N. Atlantic & N. Pacific highs have peak values in summer (but low SLP over land compensates)
  - In winter SLP pattern is more uniform with longitude, making zonal mean greater
- In S. Hemisphere:
  - S. Atlantic and S. Indian highs stronger in winter than summer.
  - S. Pacific high similar strength in winter and summer. Strongest in spring.
- **So, don't say they are all stronger in summer!**



Grotjahn and Osman, 2005

Test: In what month did this day occur?

- July?
- August?
- June?

The actual date is:
24 December 2006

•The point?
•This "summer" pattern reflects an absence of frontal cyclone activity.
•Frontal cyclones obscure our perception of the subtropical high strength.
•Perhaps they contribute to the high.

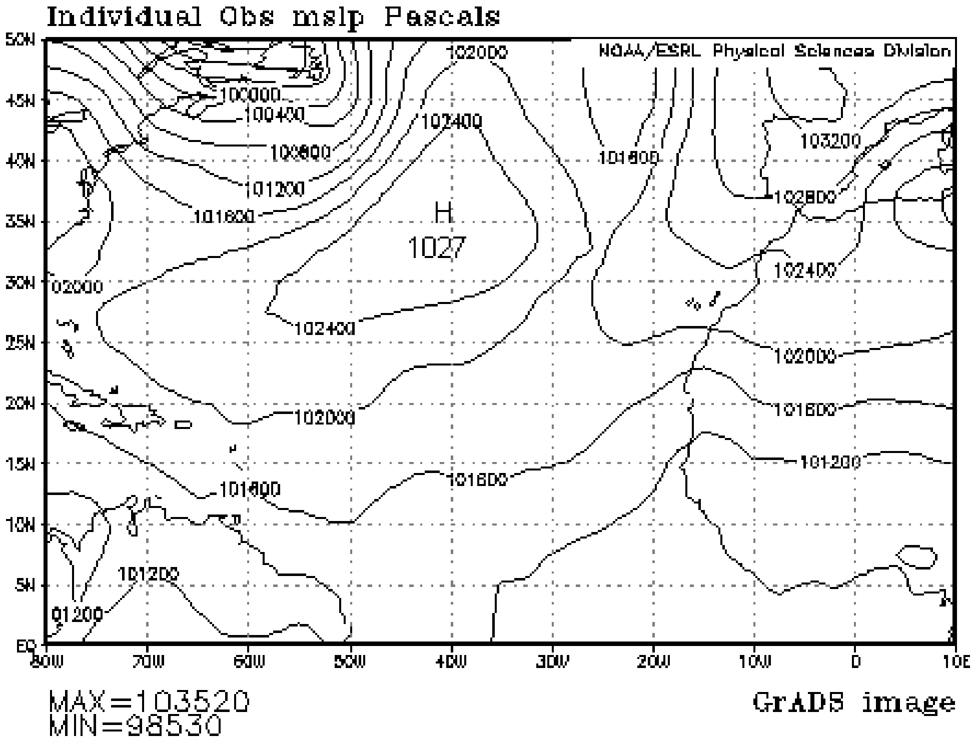


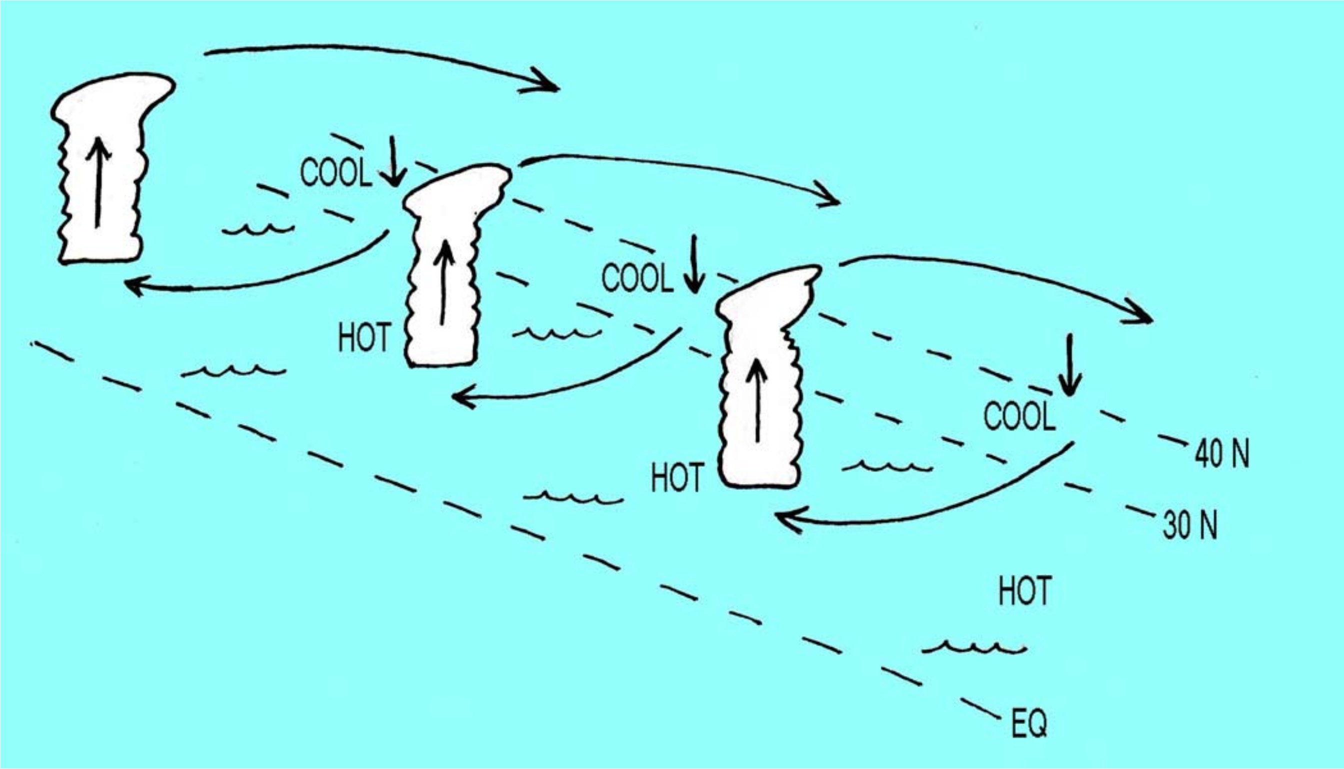
Image of North Atlantic Sea Level Pressure provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, from their Web site at http://www.cdc.noaa.gov/.

Simple Conceptual Models

- What can these tell us to look for in observations?

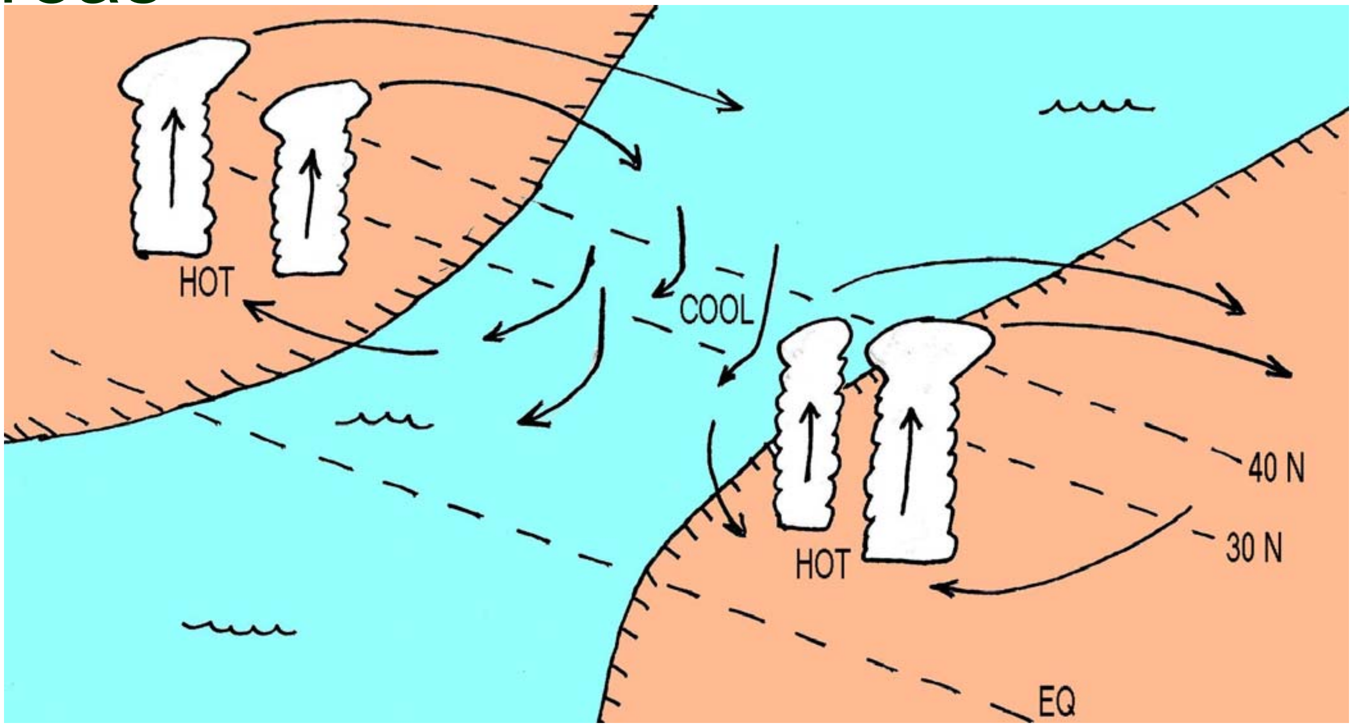
Planet: Aqua

- Uniform surface, uniform “Hadley” cell.
- N. Hemisphere summer



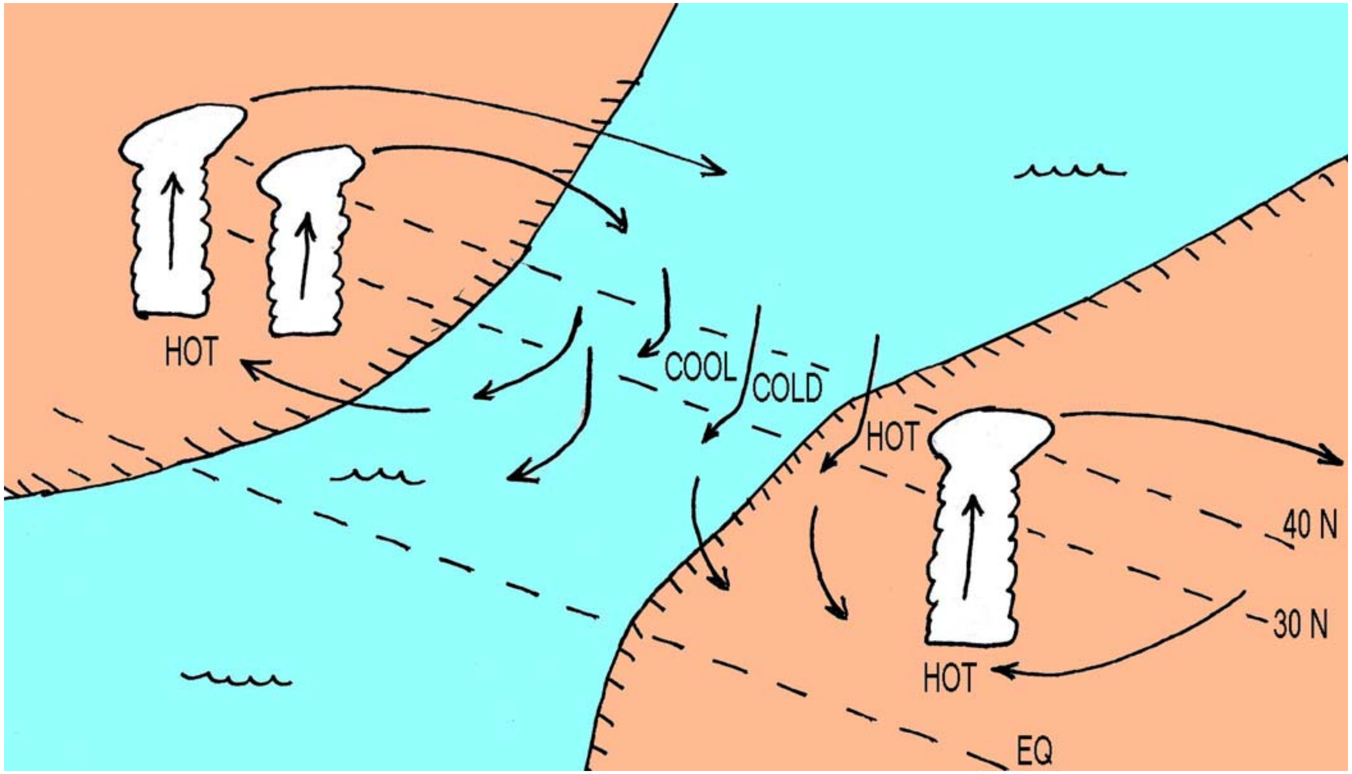
Planet: Aqua-terra

- Now include land areas (summer)
- Land areas hotter than cooler ocean areas



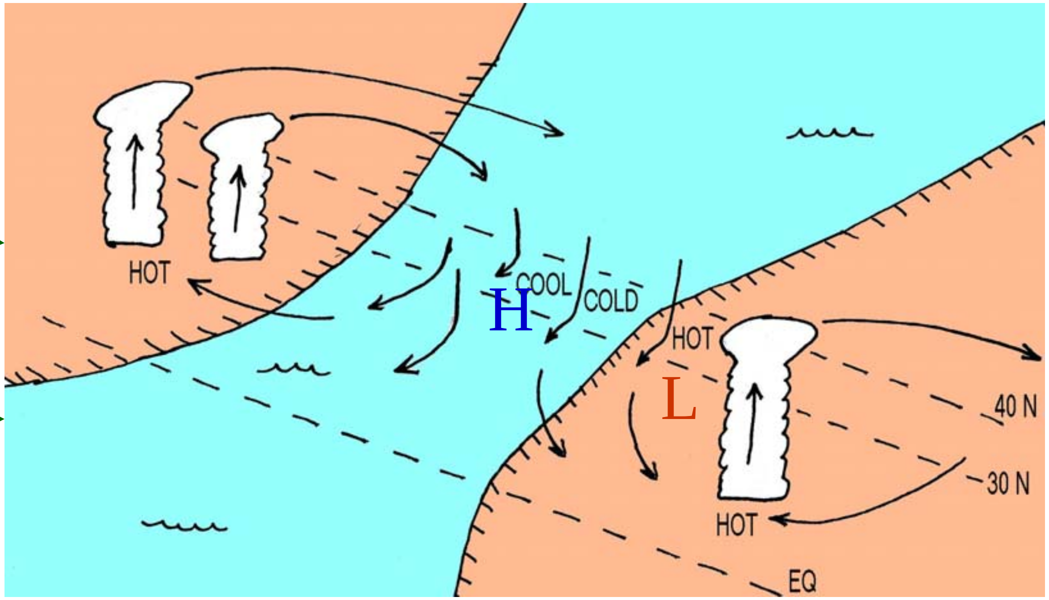
Planet: Aqua-terra 2

- Now allow subsidence over W land areas: extra solar heating & adiabatic compression
- Equatorward motion ($\partial w/\partial z \sim \beta v < 0$) causes ocean upwelling => cooling.
- Strong horizontal T gradient.



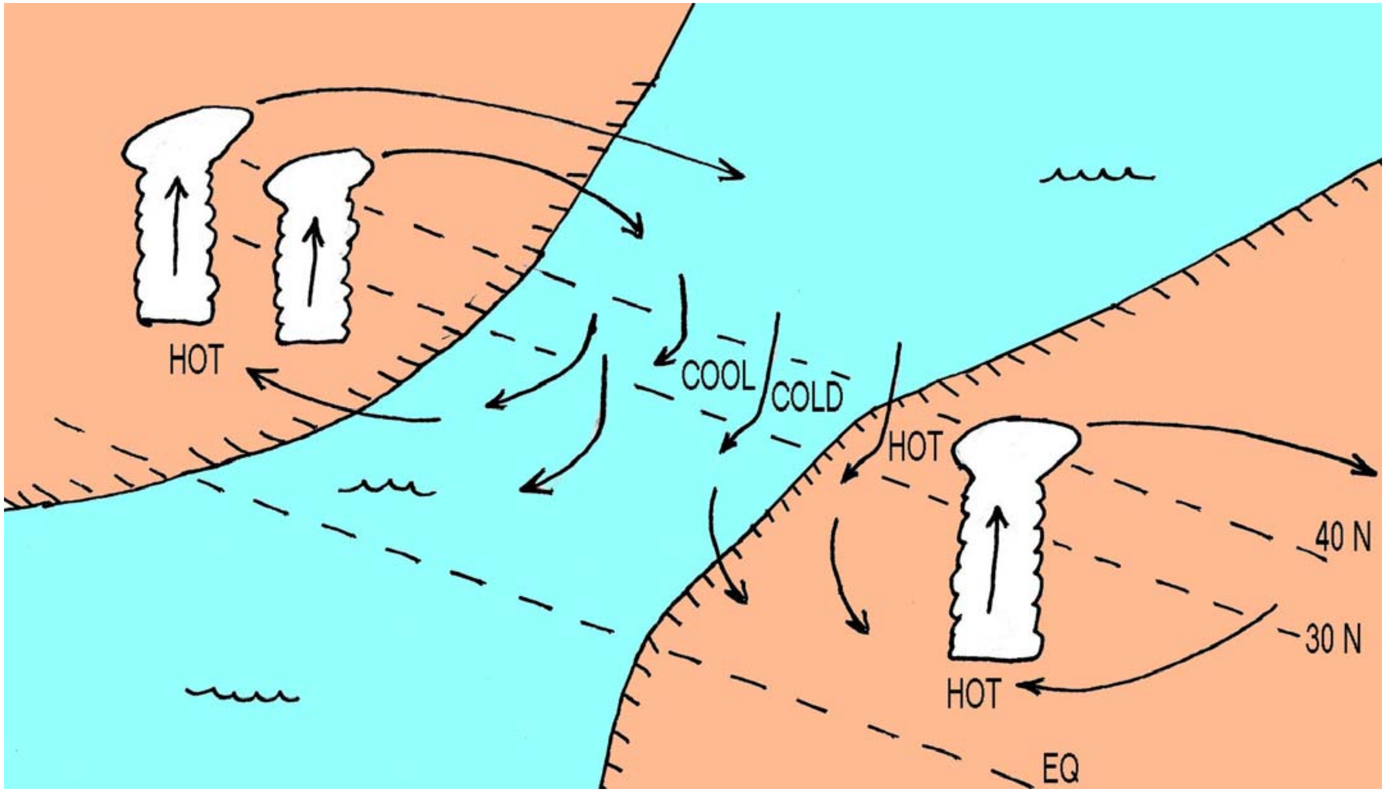
Simplified "PV" analysis

- Surface cold area: anticyclonic PV. So, subtropical high (H) over ocean.
- Surface warm area: cyclonic PV. So, thermal low over land
- Equatorward motion enhances the upwelling, etc.



What's Missing?

- interaction with mid-latitudes
- connecting the circulation pieces
- other forcing mechanisms



The mid-latitude connection

- Consider upper level divergent motions.(July)
- $V_a \sim V_{div}$
- Simplified time mean balance: $u \, \delta u / \delta x = f \, v_a$
- *(Namas & Clapp, 1949; Blackmon et al, 1977)*
- Upper level convergence (schematic diagram)
- "Hadley" cell extension (red arrows)
- Observed pattern less clear.
  - Atlantic perhaps most like the schematic
  - Pacific less so

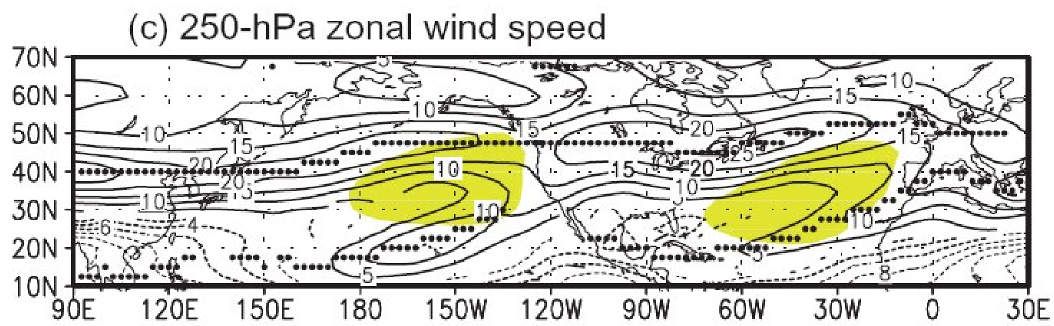
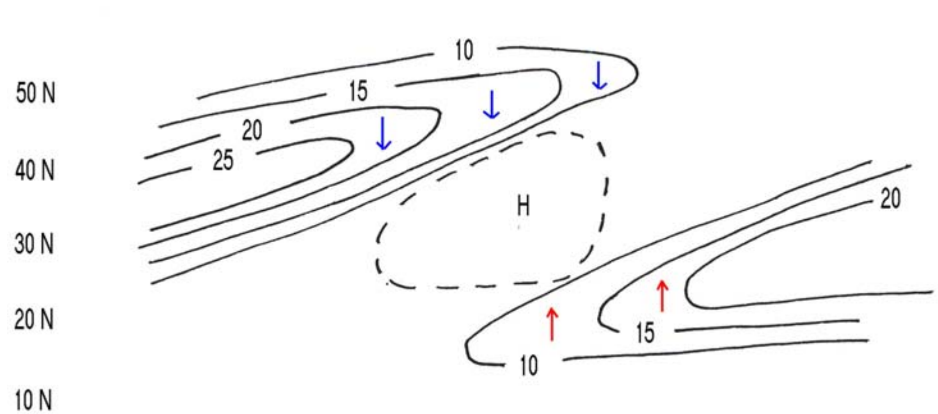


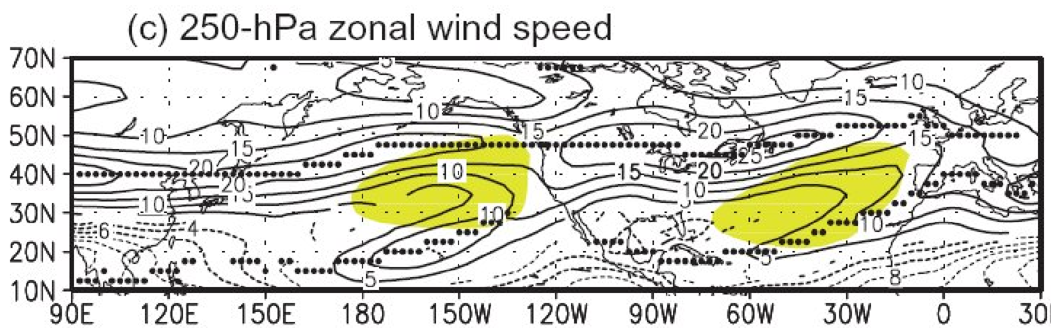
Figure from Nakamura and Miyasaka (2004) – July conditions



200 mb isotachs (solid);
SLP (dashed);
meridional ageostrophic wind (arrows)

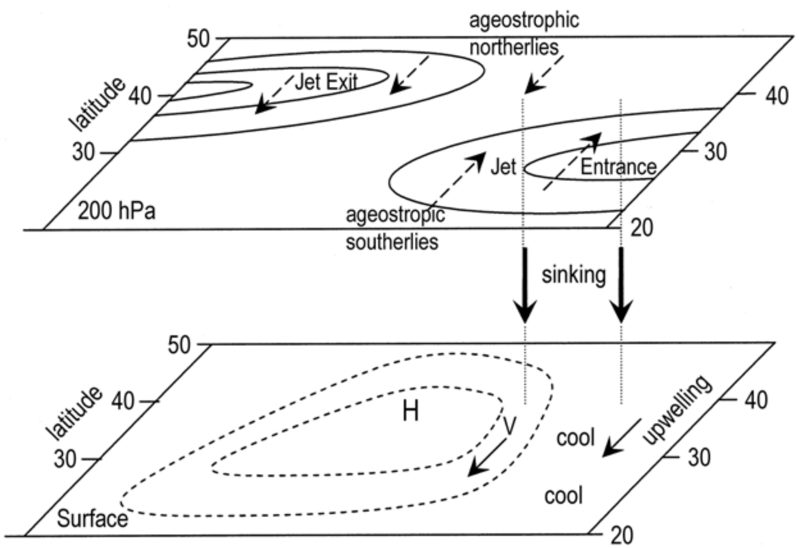
The mid-latitude connection part 2

- Simplified time mean balance: $u\, \delta u / \delta x = f\, v_a$
- *(Namias & Clapp, 1949; Blackmon et al, 1977)*



Nakamura and Miyasaka (2004)

- Upper level convergence (schematic diagram) from equatorward flow:
- Northerlies like "local Ferrel cell" with presumably similar forcing: frontal cyclones.



200 mb isotachs (solid);
SLP (dashed);
meridional ageostrophic wind (arrows)

Various proposed forcing mechanisms

Examine these proxy variables

Remote:

1. subtropical high is element of "Hadley" circulation driven by ICZ
2. monsoonal circulations to the west (e.g. "Walker" cell; *Ting, Chen etal*)

P, OLR, V_{div}

3. monsoonal circulations to the east ("Gill" model anal.; *Hoskins etal*)
4. convection spreads to west subtropical ocean from destabilization by poleward advection atmosphere & ocean (*Seager etal*)
5. topographic forcing (planetary wave problem)

T_{sfc}, θ_{sfc}

6. non-latent diabatic heating to the east (Tibet, large W-E T gradient at W coast, etc; *Liu etal, Nakamura & Miyasaka, Wu etal, etc*)

Midlats.

7. midlatitude frontal cyclones (K-E eqn, jet dyn, CAA, merging, etc.; *Grotjahn*)

Local:

OLR

1. net radiative cooling (top of stratus deck)

V_{div}

2. subsidence to east creates equatorward wind ($dw/dz \sim \beta v$; *Hoskins*)

T_{sfc}, θ_{sfc}

3. ocean upwelling of cold water (& transport away)
4. Other air-sea interaction cooling eastern subtrop. SST (*Seager etal*)

Data Handling Issues

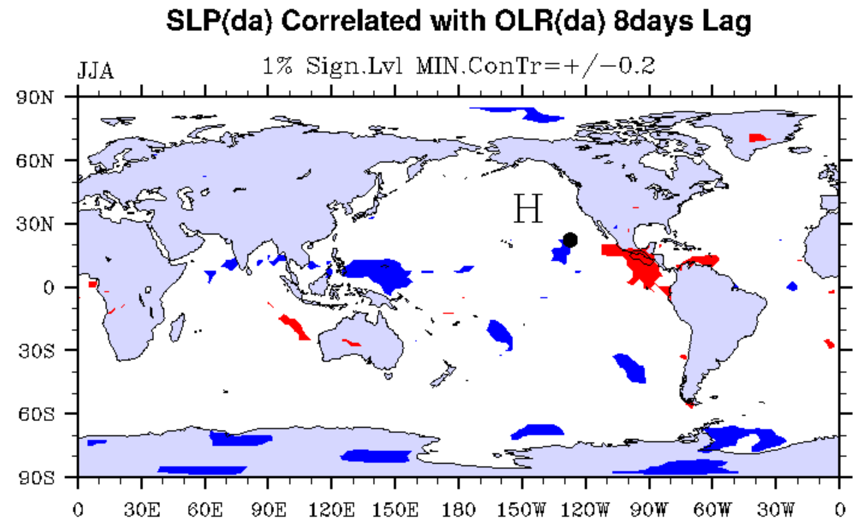
For most highs…

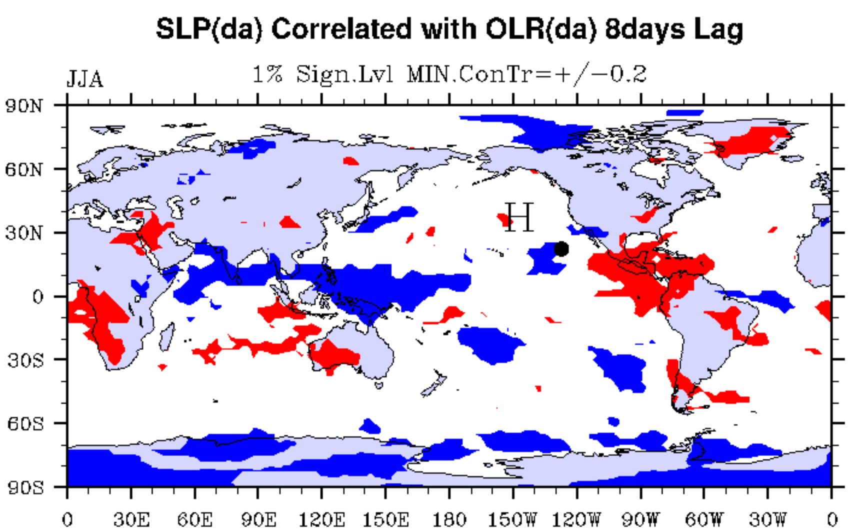
- Without time filtering, there is no discernable tropical signal; every property dominated by midlatitude storm track
- Main exception: South Pacific high
- Filtering and subsampling
  - Provide more useful results
  - Power spectrum is blue, so monthly mean has a lot of variance removed

Signal improves with time filtering and subsampling

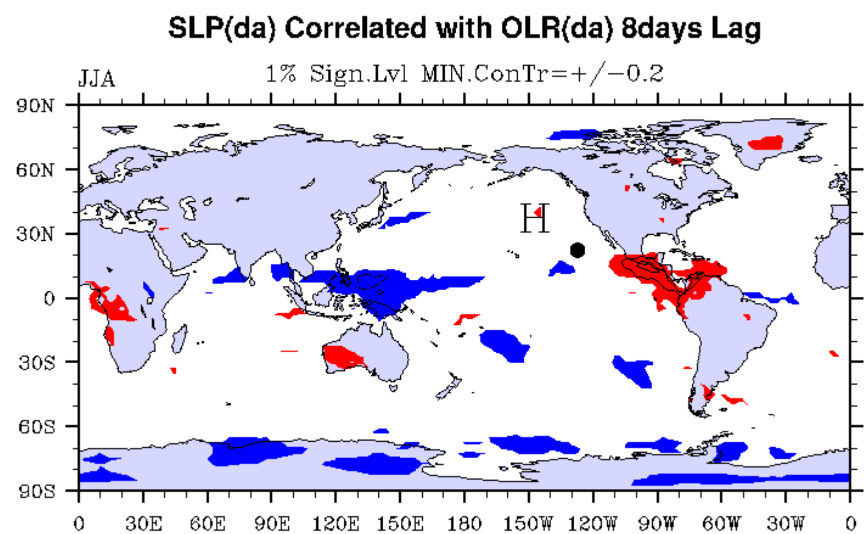
Shown:
Anomalous OLR (2-D field) 8 days before anomalous SLP at black dot.

Sub-sampled every 4th day SLPda-OLRda





Raw SLPda-OLRda



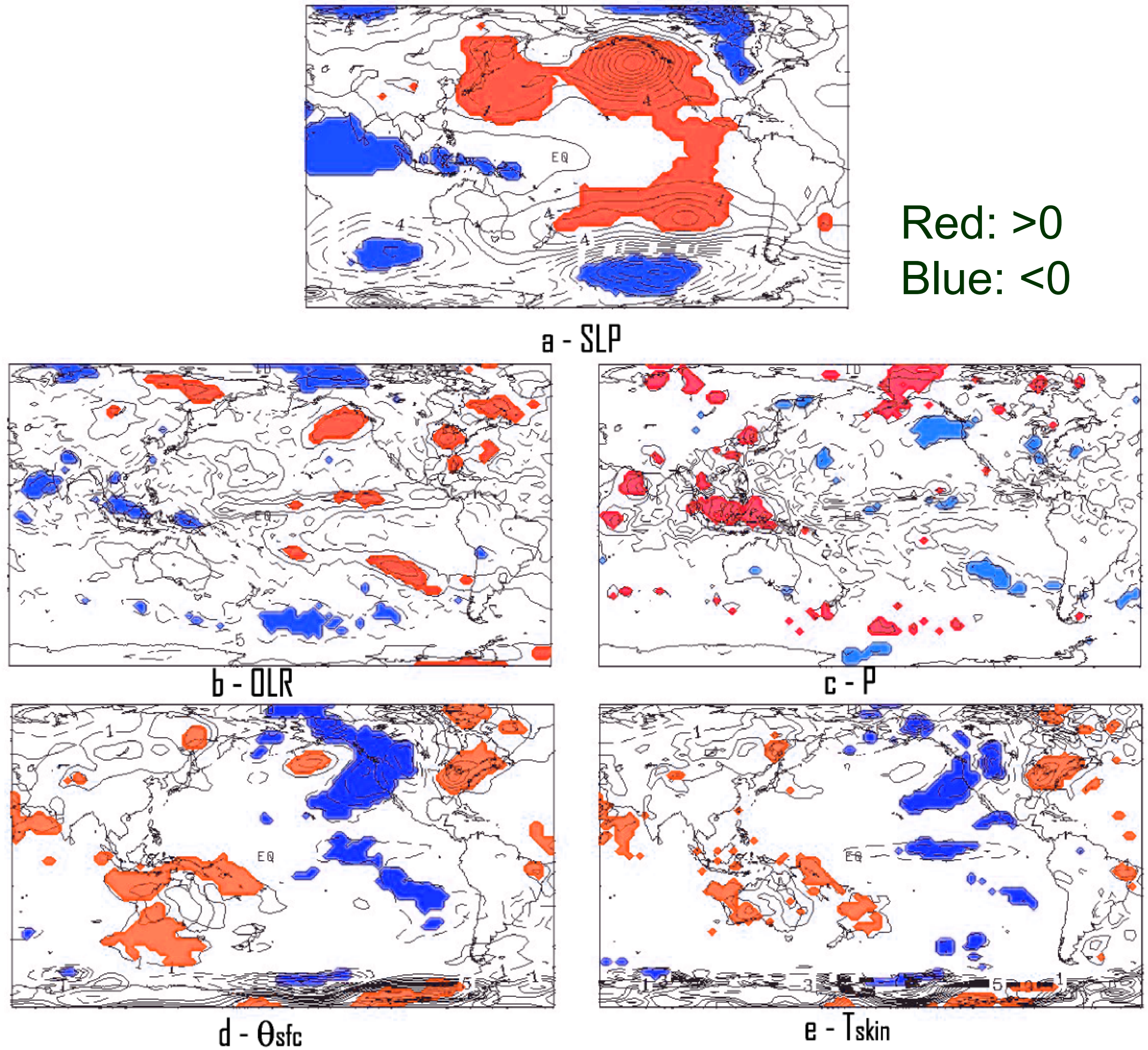
Filtered and sub-sampled every 4th day SLPda-OLRda

Selected Results by Subtropical High

- North Pacific
- North Atlantic
- South Indian
- South Atlantic
- South Pacific

North Pacific: Composites difference

- JJA monthly mean anomalies
- 8 strongest months minus 8 weakest months over 23 yrs.
- SLP has strong local connection but also lowered SLP over N. America.
- N. Pac. High also associated with S. Pac. High (common connection?)
- OLR and P consistent,
  - hint of higher P (lower OLR) over Indonesia
  - suppressed P (higher OLR) over N. America
  - SPCZ shift west
- T_{skin} and θ_{sfc}
  - lowered to east and S of N. Pac. High. Consistent with cold T advection on that side, perhaps upwelling.
  - Warming over eastern half of N. America
- Composites generally consistent with 1-pt correlation.
- Use 1-pt to assess timing

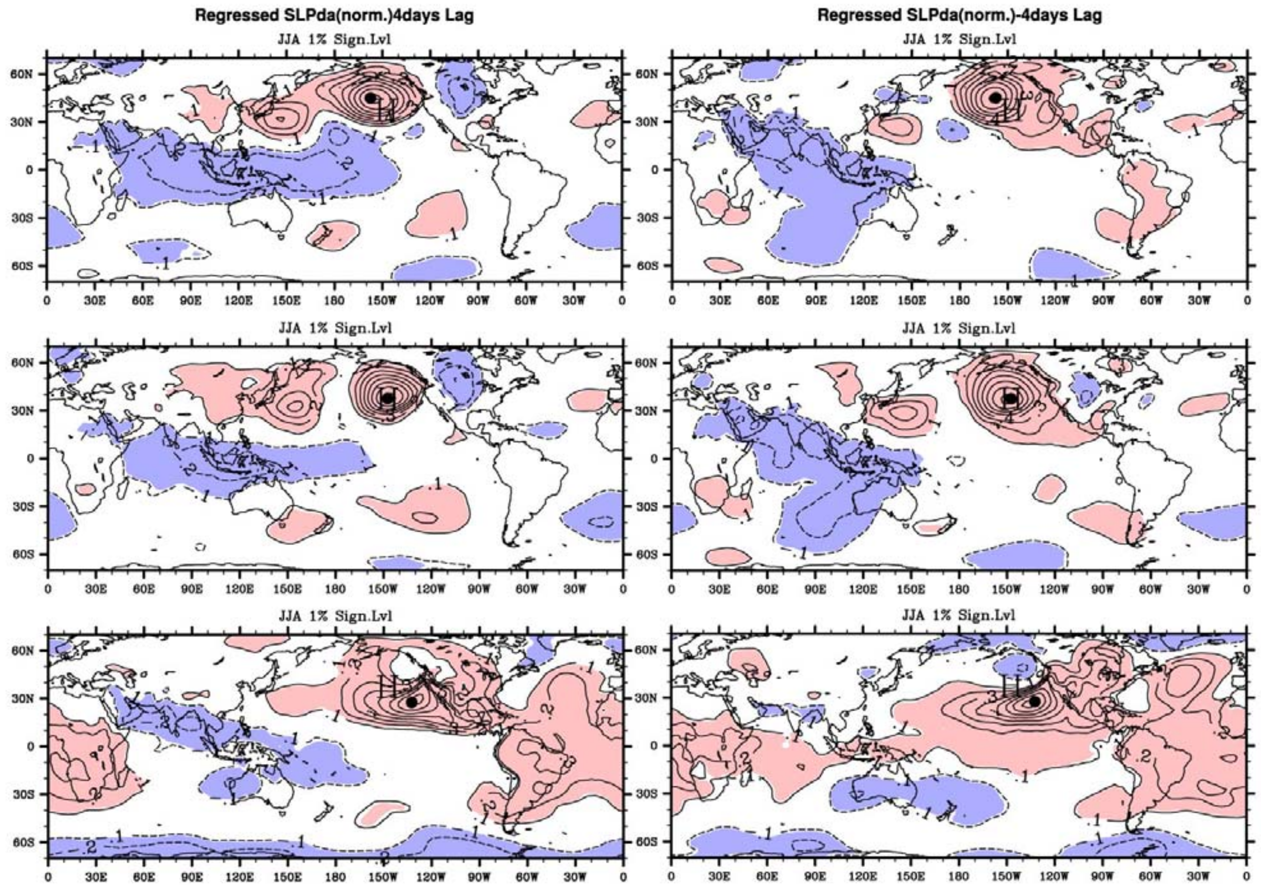


Red: >0
Blue: <0

North Pacific: SLP autocorrelation

- Daily anomaly data
- 20d cut-off can find lowered SLP in tropical Indian and Indonesia area that precedes higher N. Pac. High.
- Oddity: SE side of NP high has large regions of significant correlation well into the southern hemisphere.

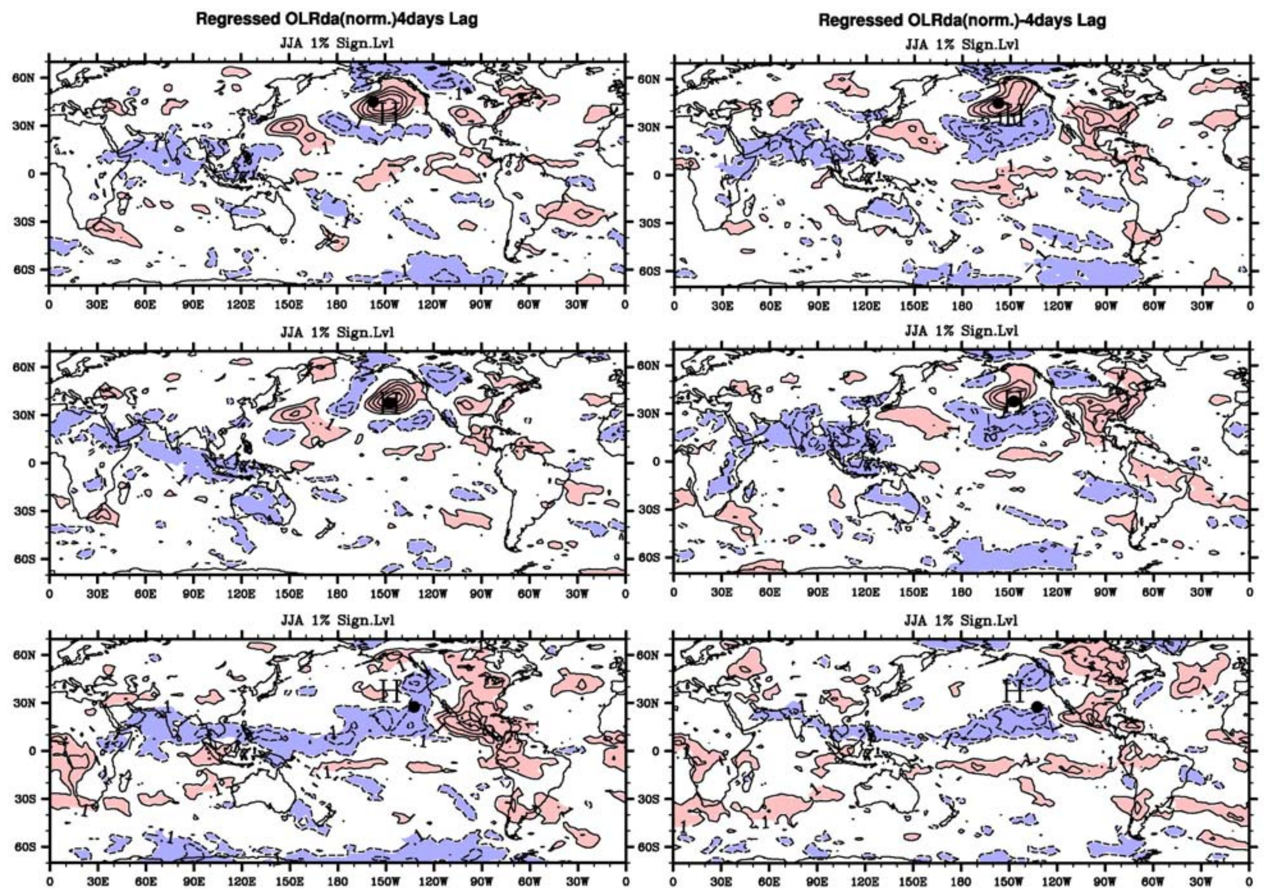
+4 days Time → - 4 days



North Pacific: SLP vs OLR

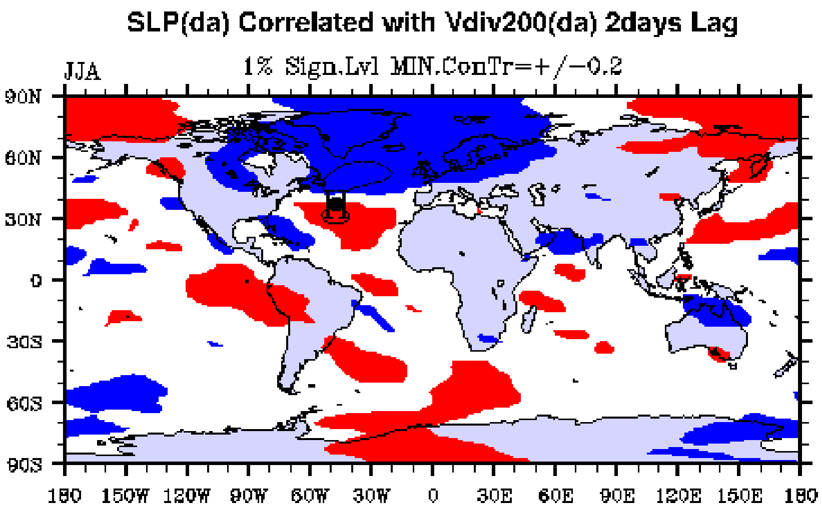
- 3 representative points & 20d filter cut-off shown
- Theories get mixed support
- Surface T theory:
  - SE pt consistent
  - Cooler T on S & E side of high ***follows*** SLP change (high enhances upwelling and T advection)
  - Warmer temperatures further east ***follow*** the stronger NP high.
  - OLR (shown) consistent with T_{skin} , θ_{sfc} (surface potential temperature)
- Walker circ. theory
  - Indonesian **lowered** OLR seems to *follow* the SLP change more than lead it.
- Gill model theory:
  - SE side pt follows ***elevated*** OLR over Central America
- Midlatitudes
  - Pattern shifts eastward
  - Storm track wavetrain

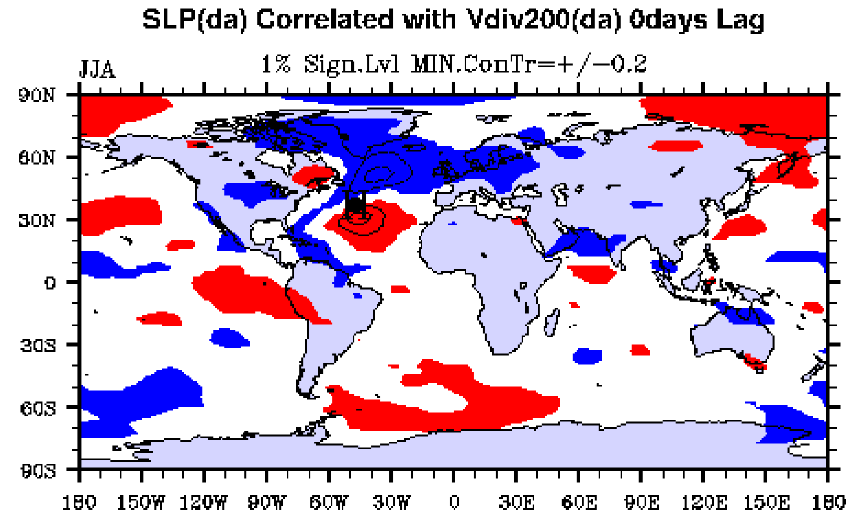
+4 days Time → - 4 days



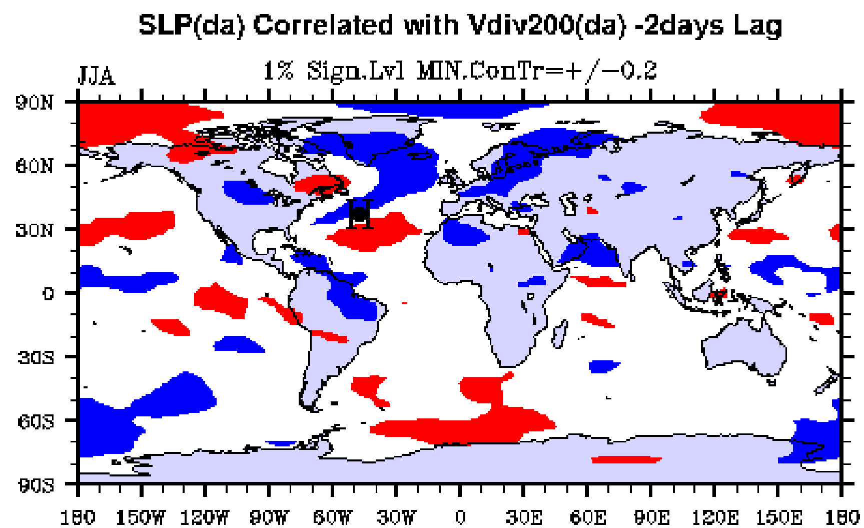
North Atlantic

North Atlantic: SLP vs 200 hpa v_{div}



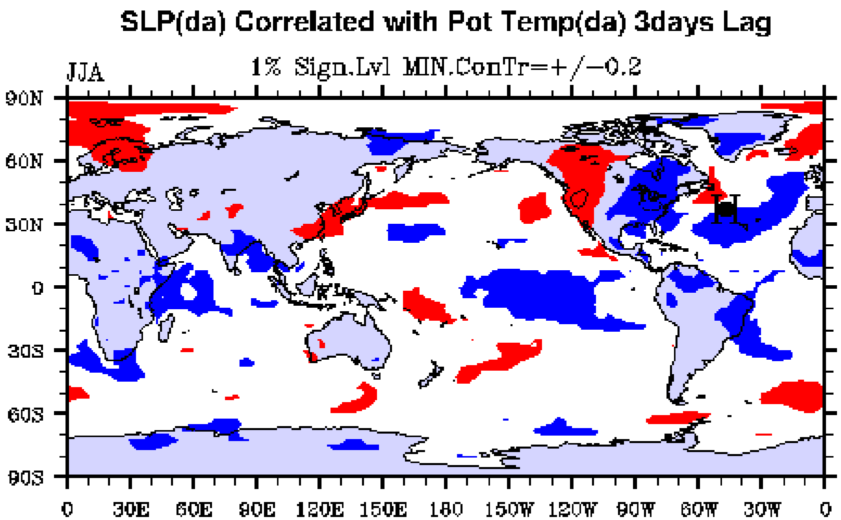


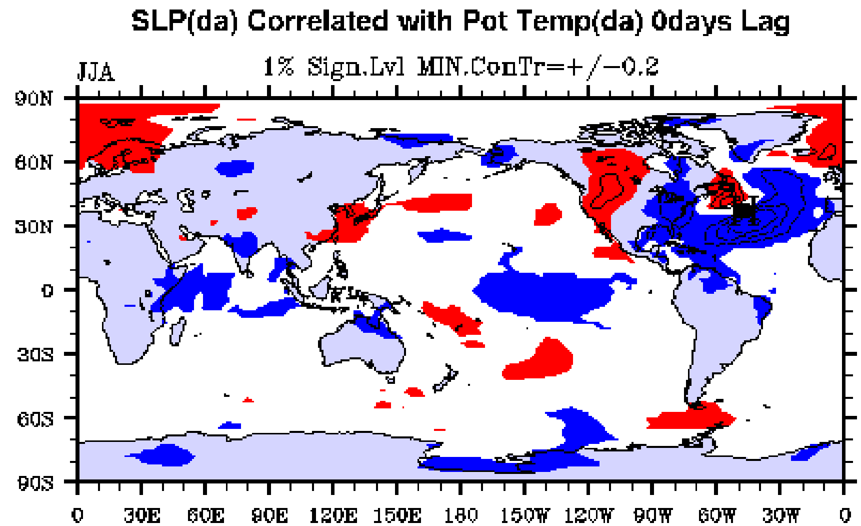
- Unfiltered, 10d cutoff, 20d cutoff data all show strong midlatitude connection.
- Midlatitude wavelength increases as cut-off increases
- Other results:
  - Upper V_{div} shows more upper convergence over correl pt before higher SLP than after.
  - At 0 lag upper convergence is east of pt.
  - For longer cut offs can see signal for larger lead/lag times
  - Almost no tropical V_{div} correl. for unfiltered data. Except on tropical side of the high.



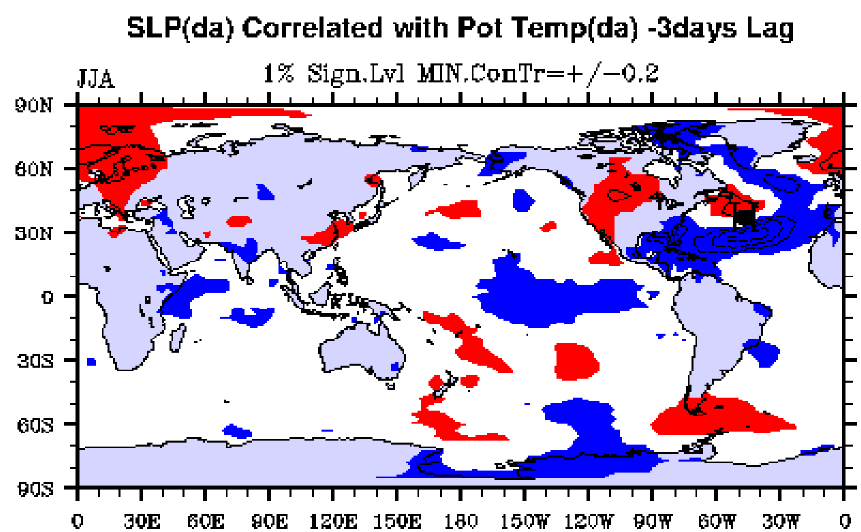
Time goes ‘clockwise’ from top left

North Atlantic: SLP vs θ_{sfc}



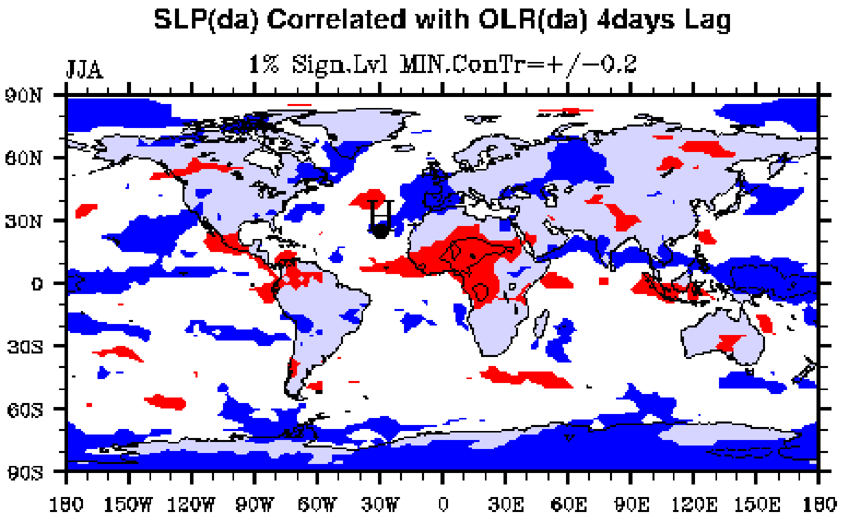


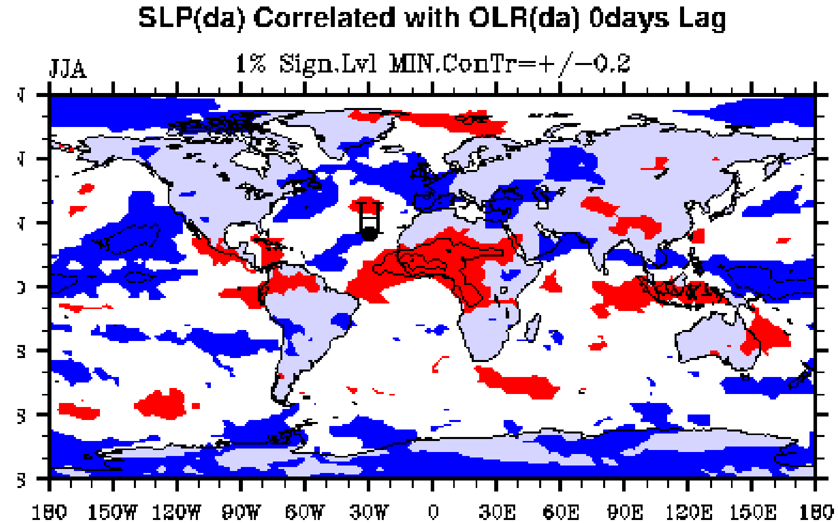
- For no cutoff and 6 day cut off one sees
  - θ_{sfc} on south and east side of high **follows** the SLP change,
  - possibly consistent with T advection around the high.
  - Warmth downstream (North Sea) **follows** the SLP change too.



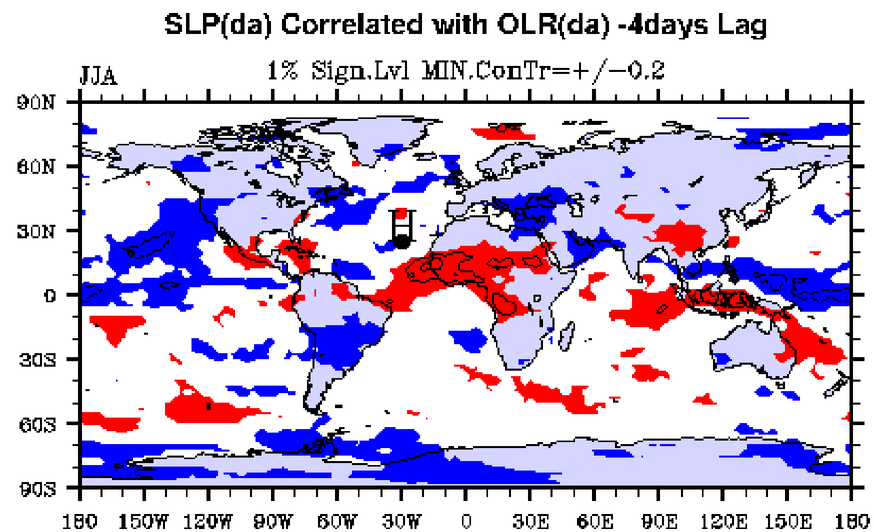
Time goes ‘clockwise’ from top left

North Atlantic: SLP vs OLR





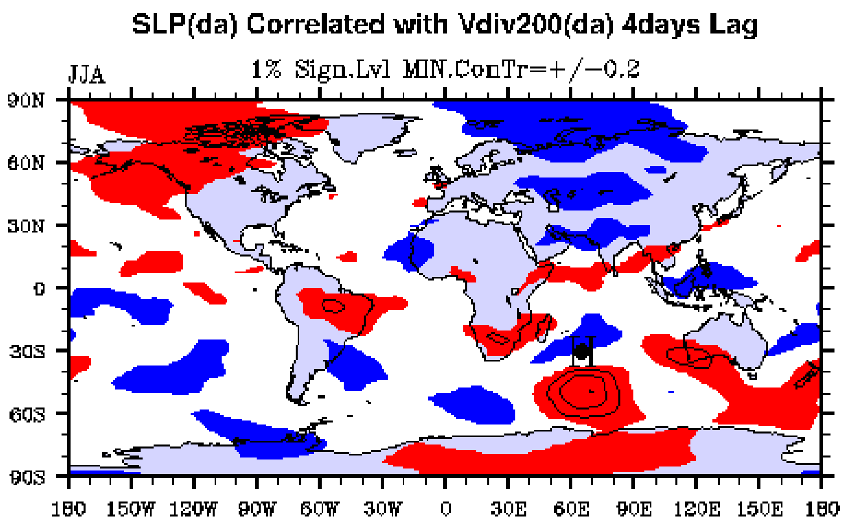
- Stronger SLP at climatological center (not shown) associated with:
  - elevated OLR NNW of high center preceding stronger SLP.
  - Consistent with upper level convergence there
  - midlatitude connection
- Tropical side of the high (25N shown):
  - Stronger connection to west Africa, but timing is after the stronger SLP & the convection is reduced.
  - Other tropical connections: OLR generally lags, but TOGA-COARE region leads SLP weakly.

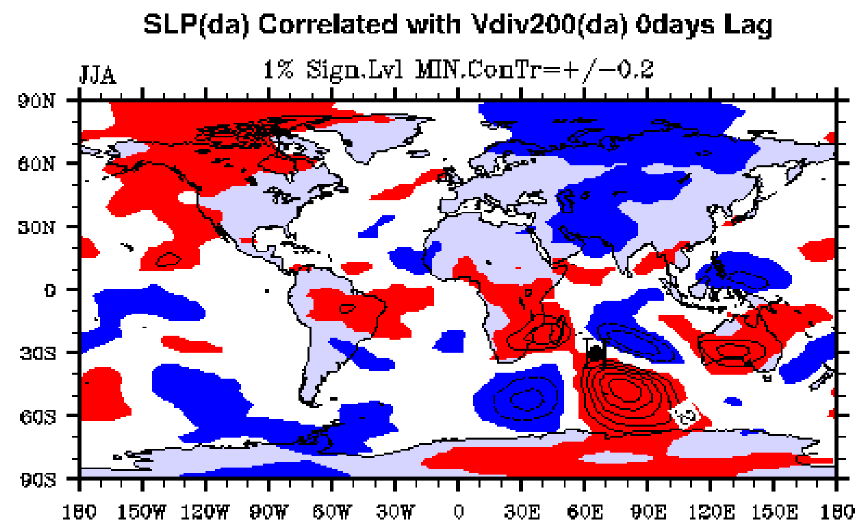


Time goes ‘clockwise’ from top left

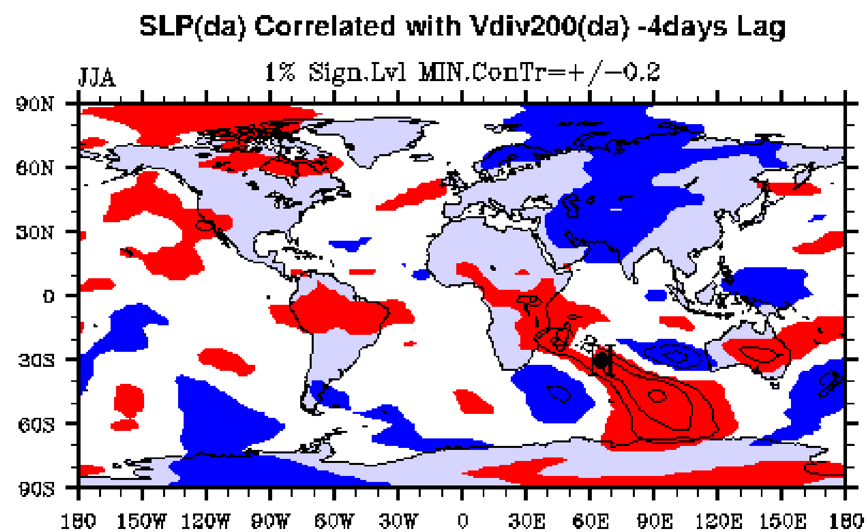
South Indian Ocean

South Indian: SLP vs 200 hPa v_{div}





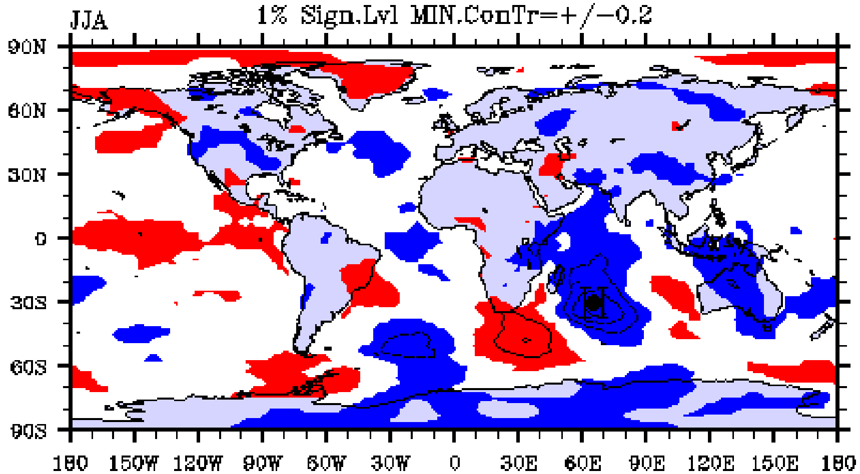
- Data all show strong midlatitude connection.
  - Upper convergence that leads the increased SLP
  - Occurs on all sides and center of high
  - Part of long wave pattern



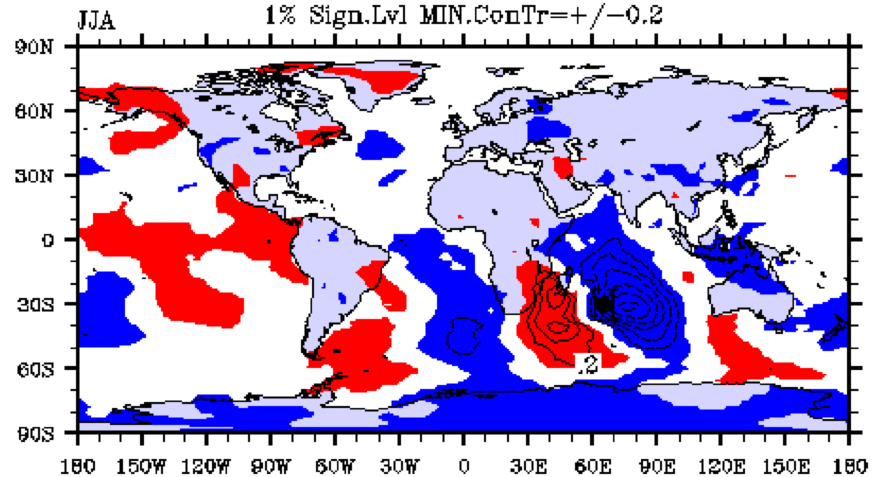
Time goes ‘clockwise’

South Indian: SLP vs θ_{sfc}

SLP(da) Correlated with Pot Temp(da) 4days Lag

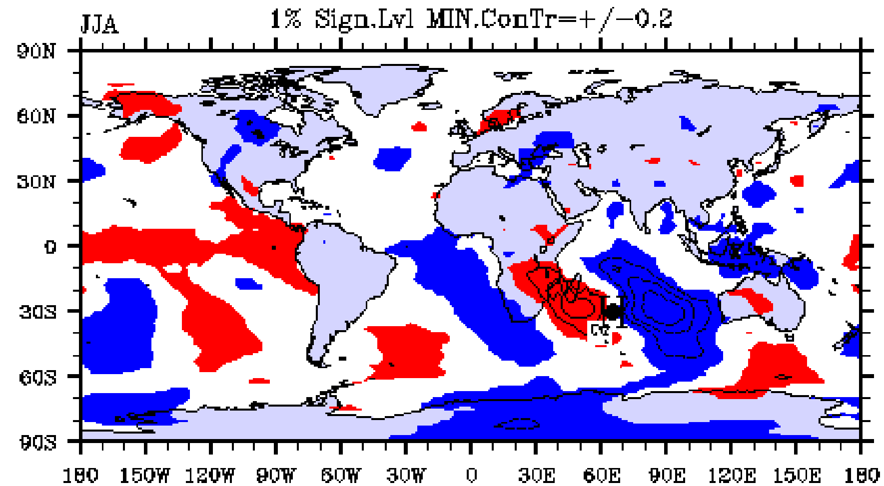


SLP(da) Correlated with Pot Temp(da) 0days Lag



- For 10-d filtering, see strong connection to middle latitude long wave pattern:
  - Eastward phase speed: 1kkm/day ~ 11 – 12 m/s
  - Wavelength: #4 - #5, ~8kkm
  - θ_{sfc} results consistent with SLP autocorrelation (not shown)
  - consistent with T advection around the high.

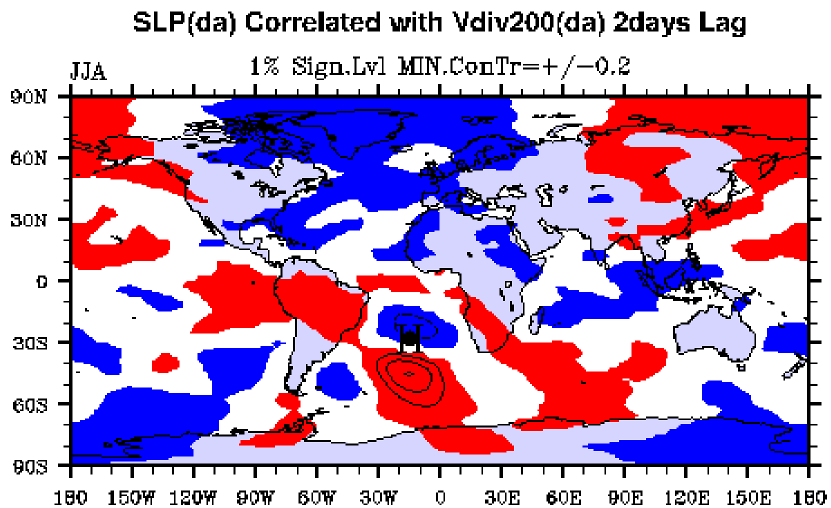
SLP(da) Correlated with Pot Temp(da) -4days Lag

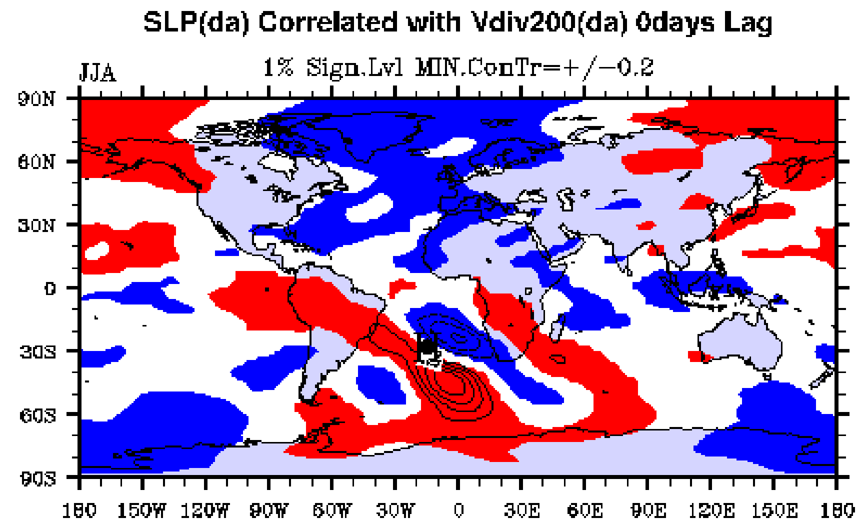


Time goes 'clockwise'

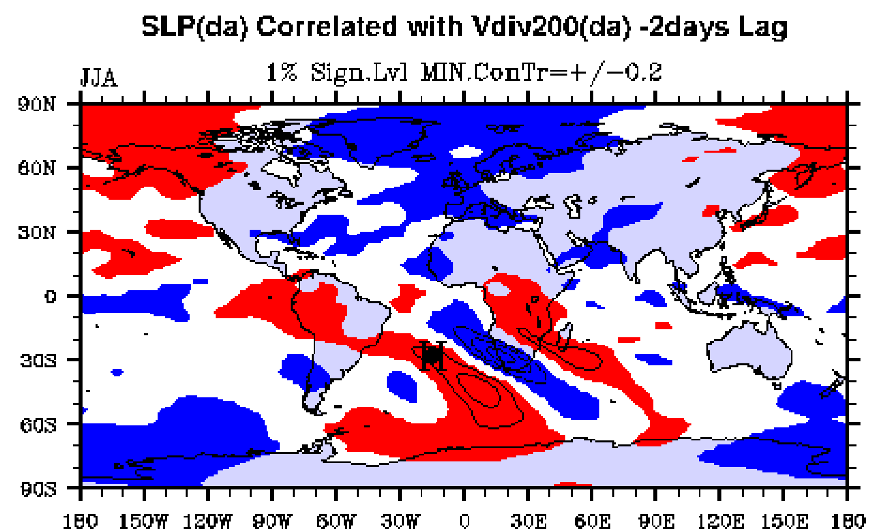
South Atlantic

South Atlantic: SLP vs 200 hPa v_{div}



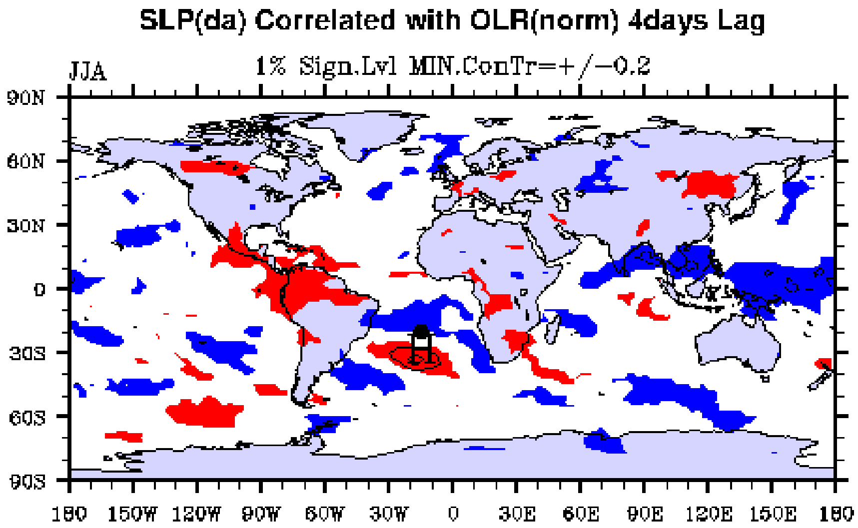


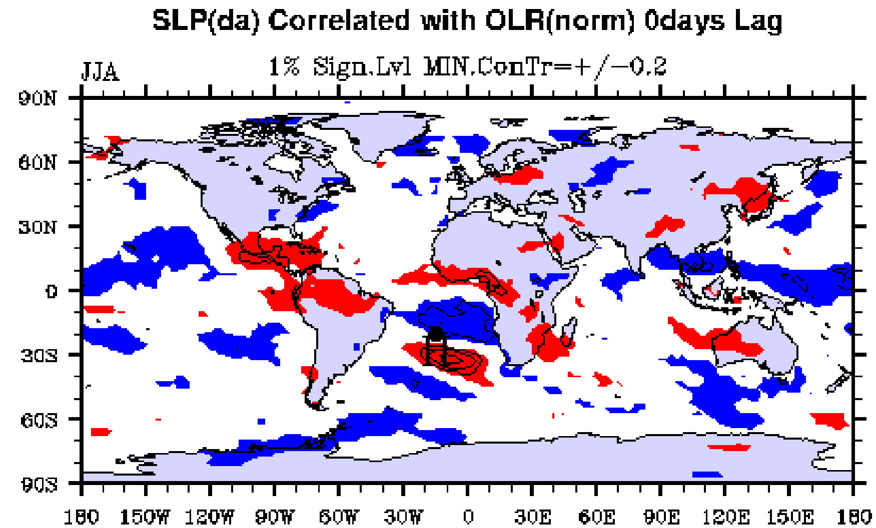
- Data all show strong midlatitude connection.
  - Similar to South Indian result
  - Unfiltered data (shown) has upper convergence that leads the increased SLPover correl pt. 1-2 days.
  - At 0 lag the convergence is east of the pt.
  - Occurs on all sides and center of high
  - Part of long wave pattern, almost not tropical upper v_{div} association with SLP
- For longer cut offs:
  - signal seen for larger leads/lags
  - wavelength increases



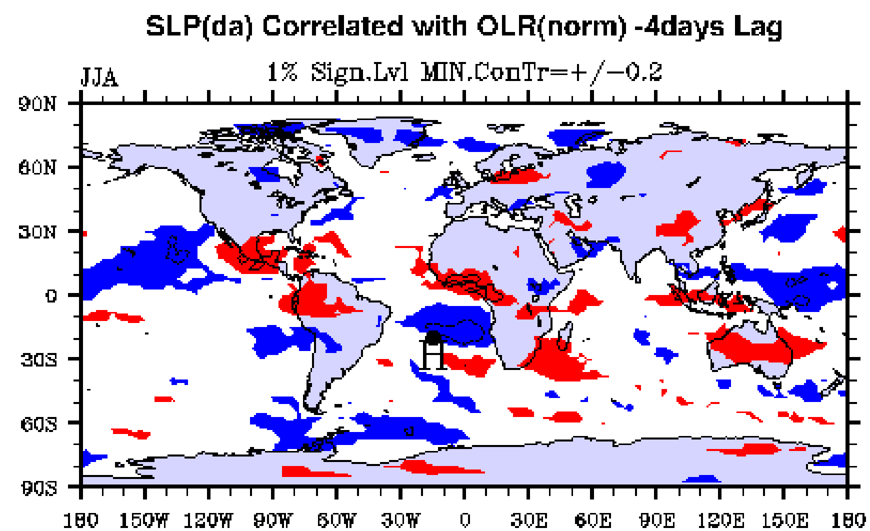
Time goes ‘clockwise’

South Atlantic: N side SLP vs OLR





- Data on **tropical side** show tropical and higher latitude connections.
- OLR association is mainly **after** the SLP change
  - W African OLR increase (ICZ suppressed) after SLP increase.
  - OLR: Subtropical decrease and SW side of high increase consistent with T advection around the high.
  - Association of OLR with SLP consistent with θ_{sfc} results (not shown)
- For longer cut offs can see signal for larger leads/lags



Time goes ‘clockwise’

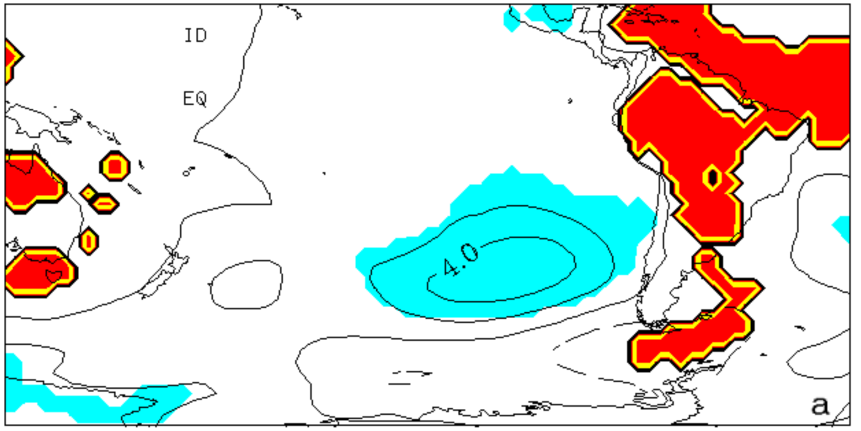
South Pacific

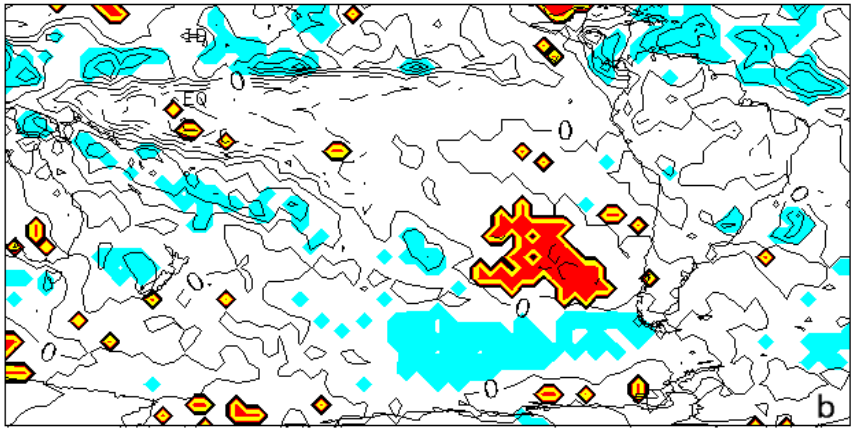
South Pacific: Composites difference

- DJF monthly mean anomalies
- 6 strongest months minus 6 weakest months over 19 yrs.
- SLP:
  - Locally higher (by definition)
  - Lower over Amazonia and tropical Atlantic
  - Lower over N. Australia/Indonesia.
- P:
  - Dipole pattern on South side of high: midlatitude storm track displaced
  - Higher P tropical Atlantic
  - Possible SPCZ shift west
  - hint of higher P over Indonesia

Red: >0 Blue: <0

SLP

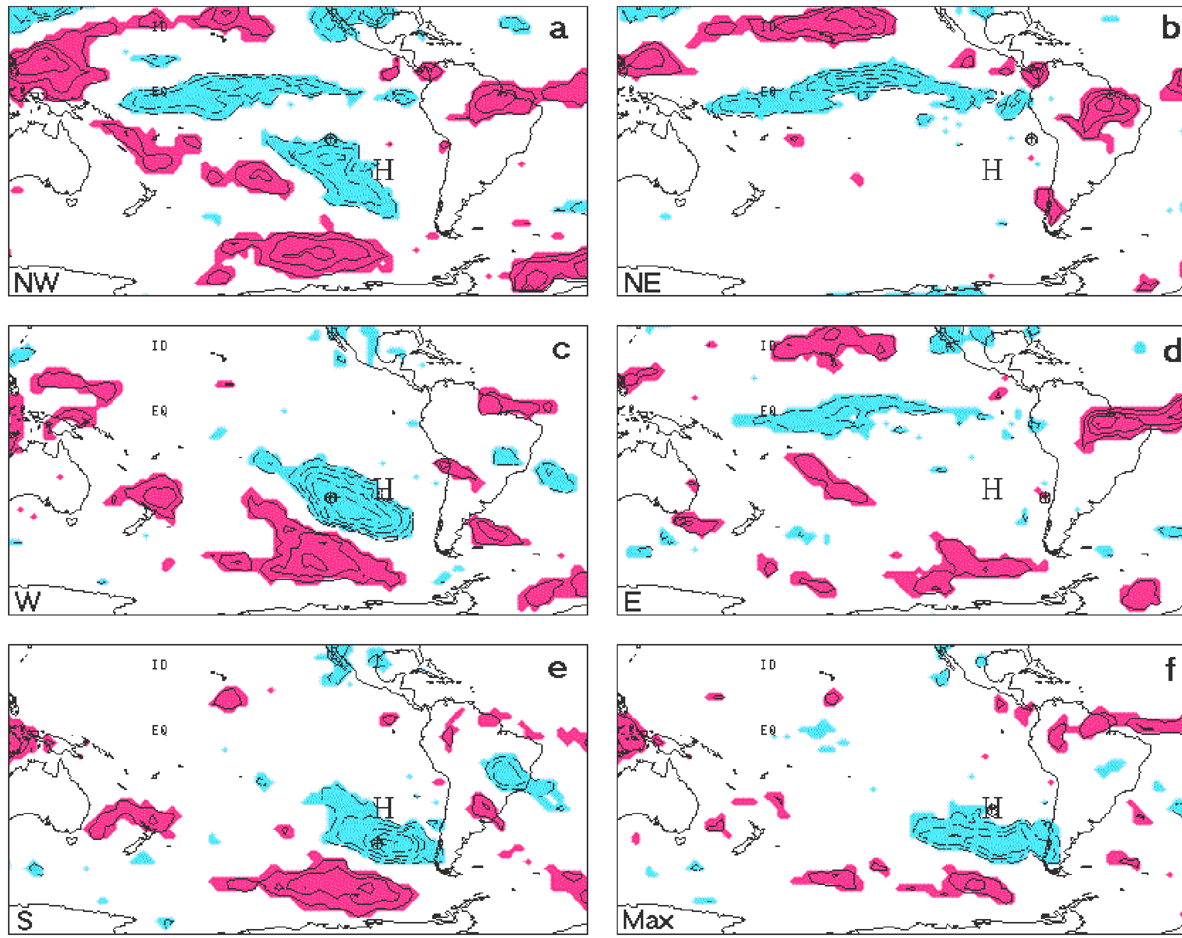




P = precipitation

South Pacific: SLP vs P

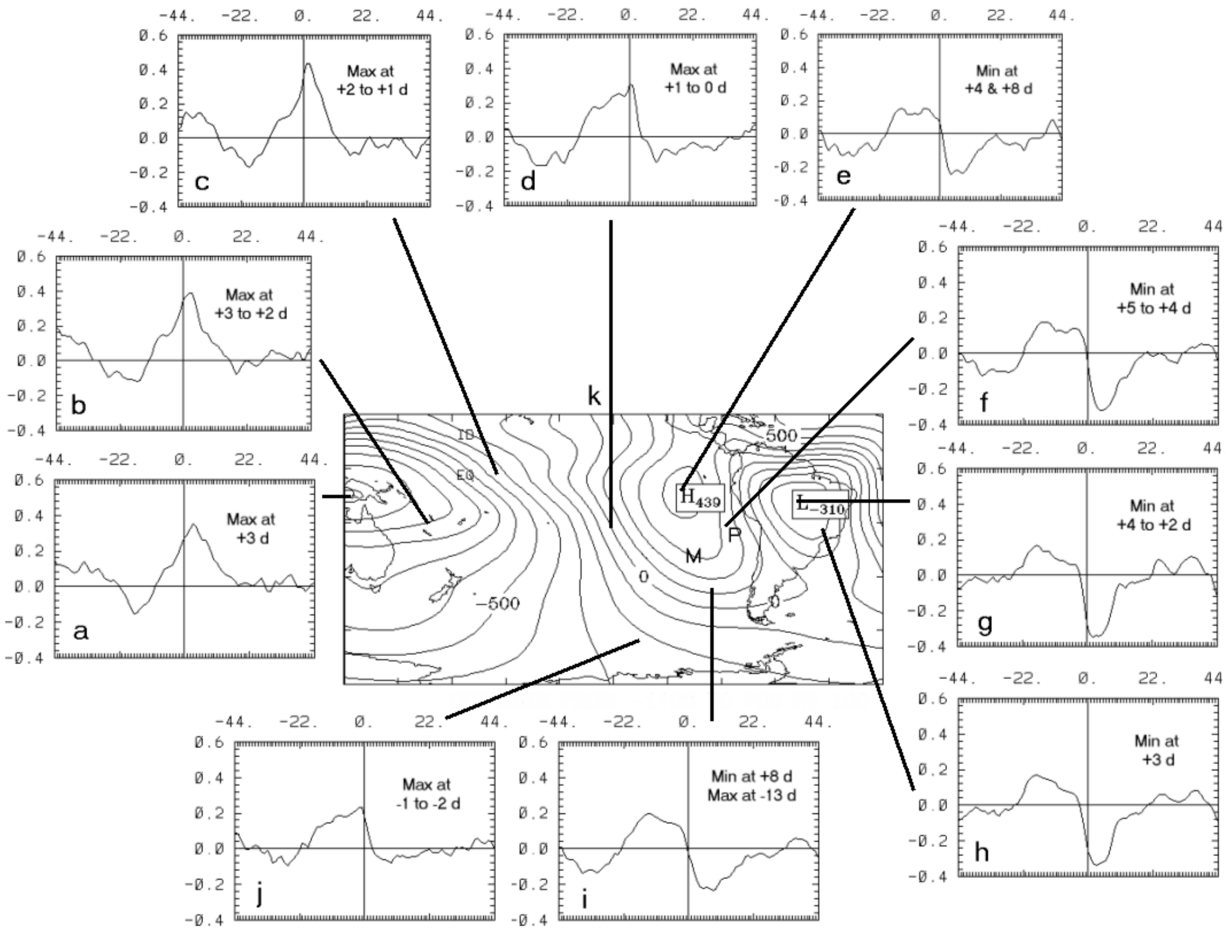
- 1-pt correlations of monthly mean anomalies
- Points on different sides of high:
  - generally respond to events on that side.
  - Midlatitude connection for most sides except NE side
- P is:
  - Inc. over Amazonia
  - ICZ central & E Pacific shift north
  - Inc. over W. tropical Pacific
  - SPCZ shift west
  - Midlatitude storm track shift south



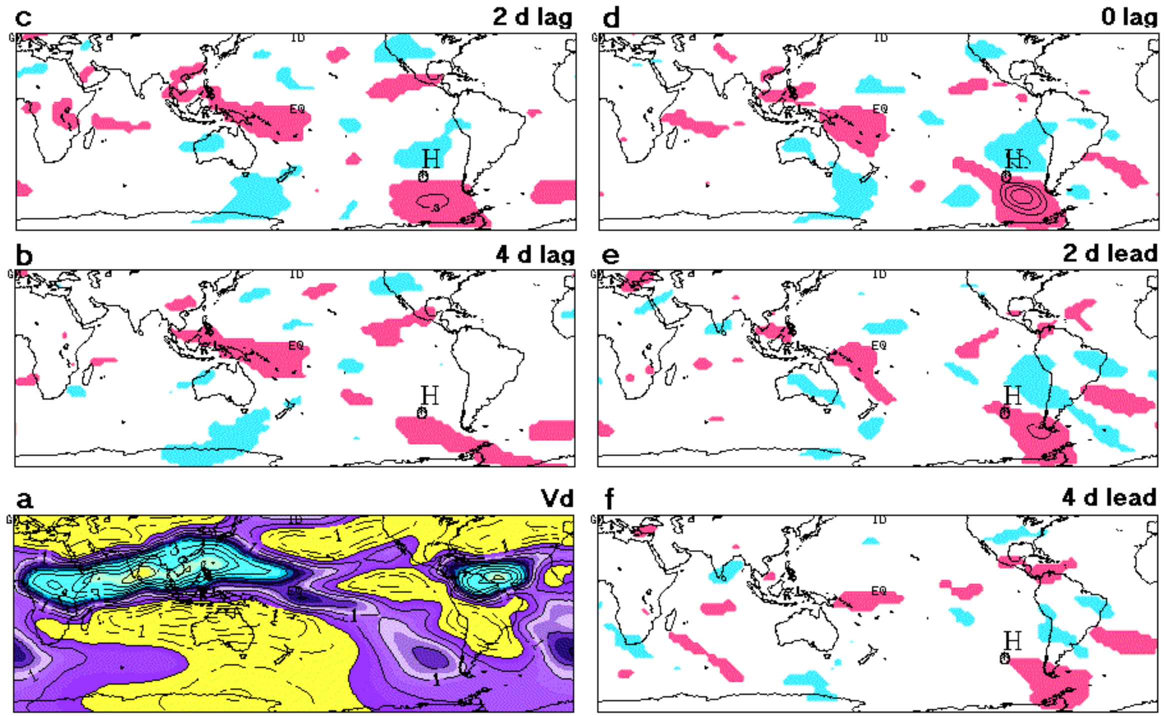
South Pacific: SLP vs VP crosscorrelation

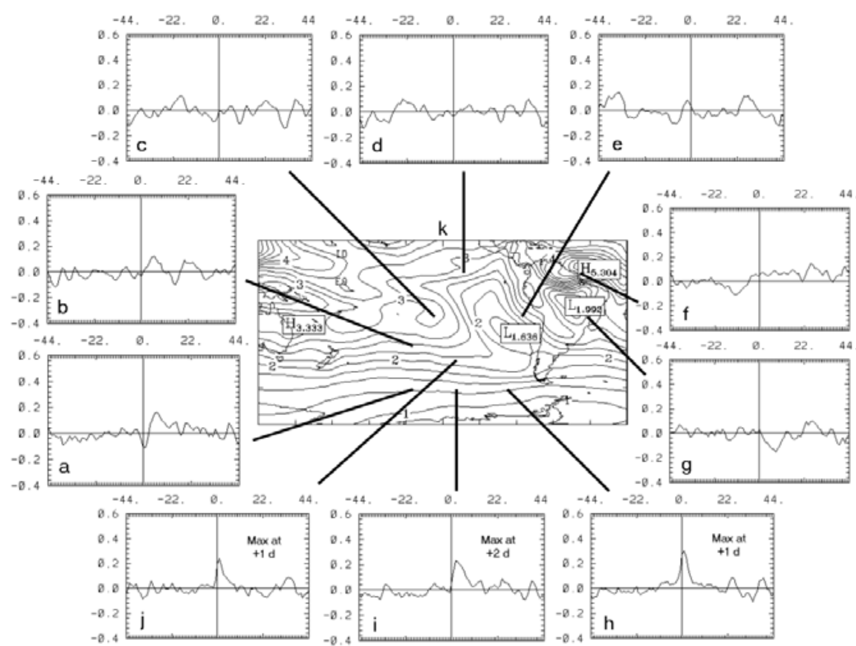
- Cross correlations
  - Of SLP and VP (velocity potential)
  - at different lag and lead times
  - for point "P" on NE side of high (the point most strongly influenced by the tropics.
- Cross correlations show:
  - MJO like period for tropical pts a-e
  - Amazonia VP reduced (convection enhanced) 2-3 days prior
  - E. Pacific VP reduced 4-8 days prior
  - Central Pacific VP increased (convection suppressed) 0-2 days prior
  - New Guinea convection suppressed 3 days prior

In each thumbnail x-correlation function:
Time goes right to left such that
SLP occurs first ← time, P occurs first



South Pacific: SLP vs 200 hPa v_{div}

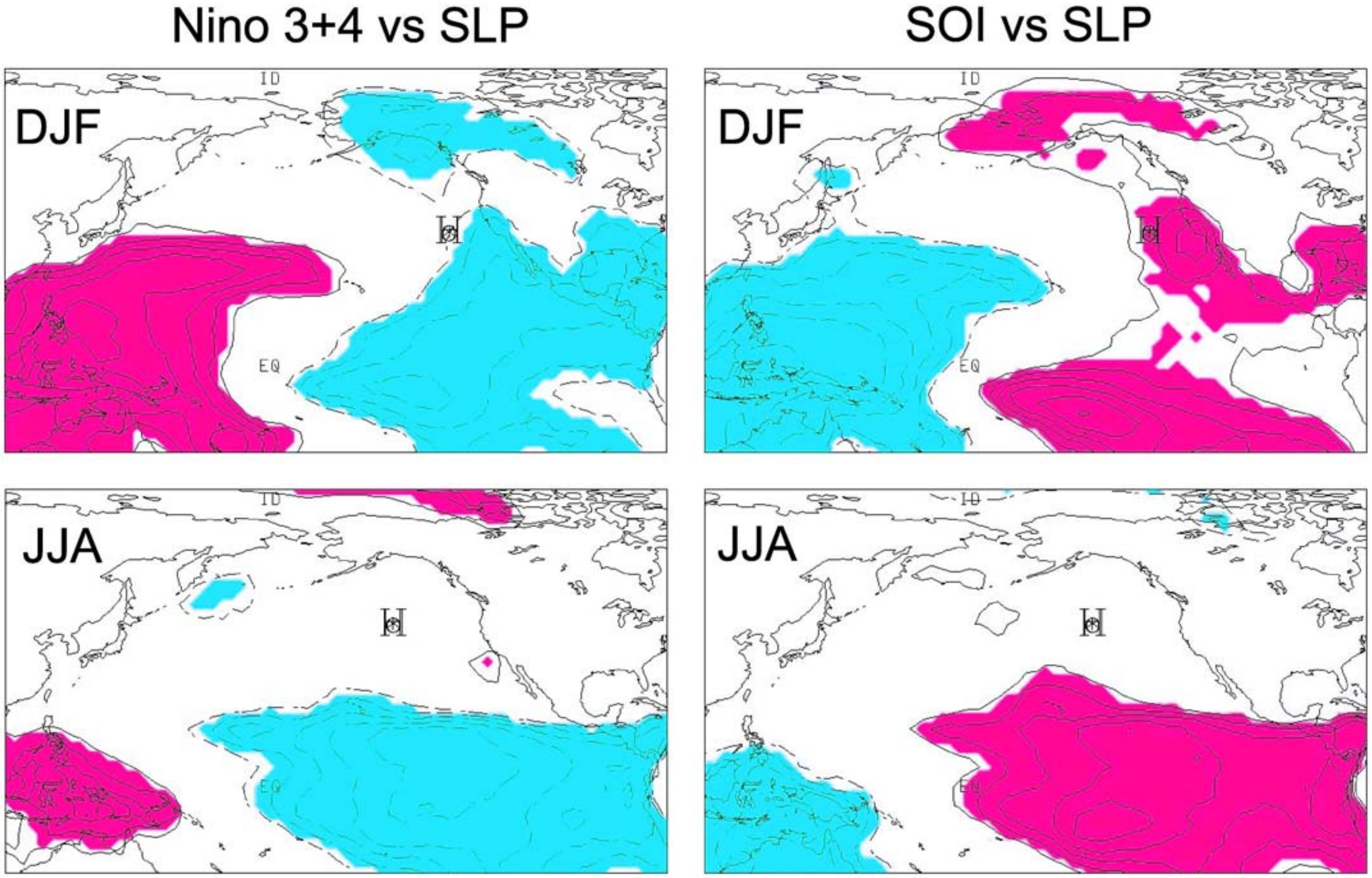




- lag/lead daily correlations for pt just SW of high center
- Meridional divergent wind component 1-pt maps:
  - Time mean (fig. a) has convergence over southern S. America
  - Upper convergence enhanced over E side of high 2 days prior to SLP increase
  - Part of eastward propagating pattern
- Cross correlations:
  - No tropical links,
  - Only midlatitude seen in this unfiltered data
- W, SW, S & SE pts similar

North & South Pacific SLP vs MJO & ENSO

- MJO has notable connection only to points on the tropical edge of either subtropical high (not shown)
- ENSO:
  - Connection in northern subtropics only during winter (DJF)
  - Connection to southern subtropics both seasons



Conclusions (1 of 2)

- The highs have different seasonal cycles.
  - The Northern Hemisphere highs have a summer max, while the South Indian and South Atlantic highs have a winter max.
  - The shape and location of the high varies most for the South Indian and South Atlantic highs.
  - The south Pacific high has different behavior
- The highs have somewhat different shapes
- The subtropical highs sit at a ‘crossroads’ between tropical and midlatitude weather, responding to both.
  - The higher latitude side responds primarily to middle latitude phenomena
  - The lower latitude side responds to tropical and subtropical phenomena and may respond to midlatitudes as well.
  - Any attempt to understand the highs properties must include both midlatitude and tropical phenomena, which have different time and length scales.

Conclusions (2 of 2)

- Some general results:
  - Subtropical high variability strongly influenced by midlatitude traveling weather systems.
  - Upper level convergence precedes the higher SLP and tends to be east of the high center
  - Low level cooling on the east and equatorial side of the high tends to occur shortly after the SLP increase and is consistent with: T advection, additional upwelling
  - Warming further to the east tends to follow the stronger SLP by a few days and is accompanied by lower SLP
- Observational indicators of proposed remote forcing do not seem to support theories well
  - West-East T gradient develops after high strengthens
  - Enhanced convection east and equatorward of the high is often suppressed after the high strengthens, though S. Pacific high is a partial exception
  - Enhanced convection to the west and equatorward of the high has mixed evidence (follows S Pacific high by weeks, weak evidence for the N Pacific)
- Now that I've disappointed the theoreticians, perhaps this is not a great time to finish and open the discussion to your questions!