# *Relationships between the 5-Day External Rossby Mode and Extratropical Storm Tracks*

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# *Motivation*

Free Rossby Modes have been observed for over 50 years

A spectacular example of linear theory verified by observations!

Hundreds of papers have been written on these modes

Usually studied by projection of data onto pre-determined theoretical structures (i.e. the MODES approach)

Storm track and convective activity will be shown to be related to the 5 day wave

We will outline a modification of the past methodology to study these waves…of interest will be a comparison with other approaches

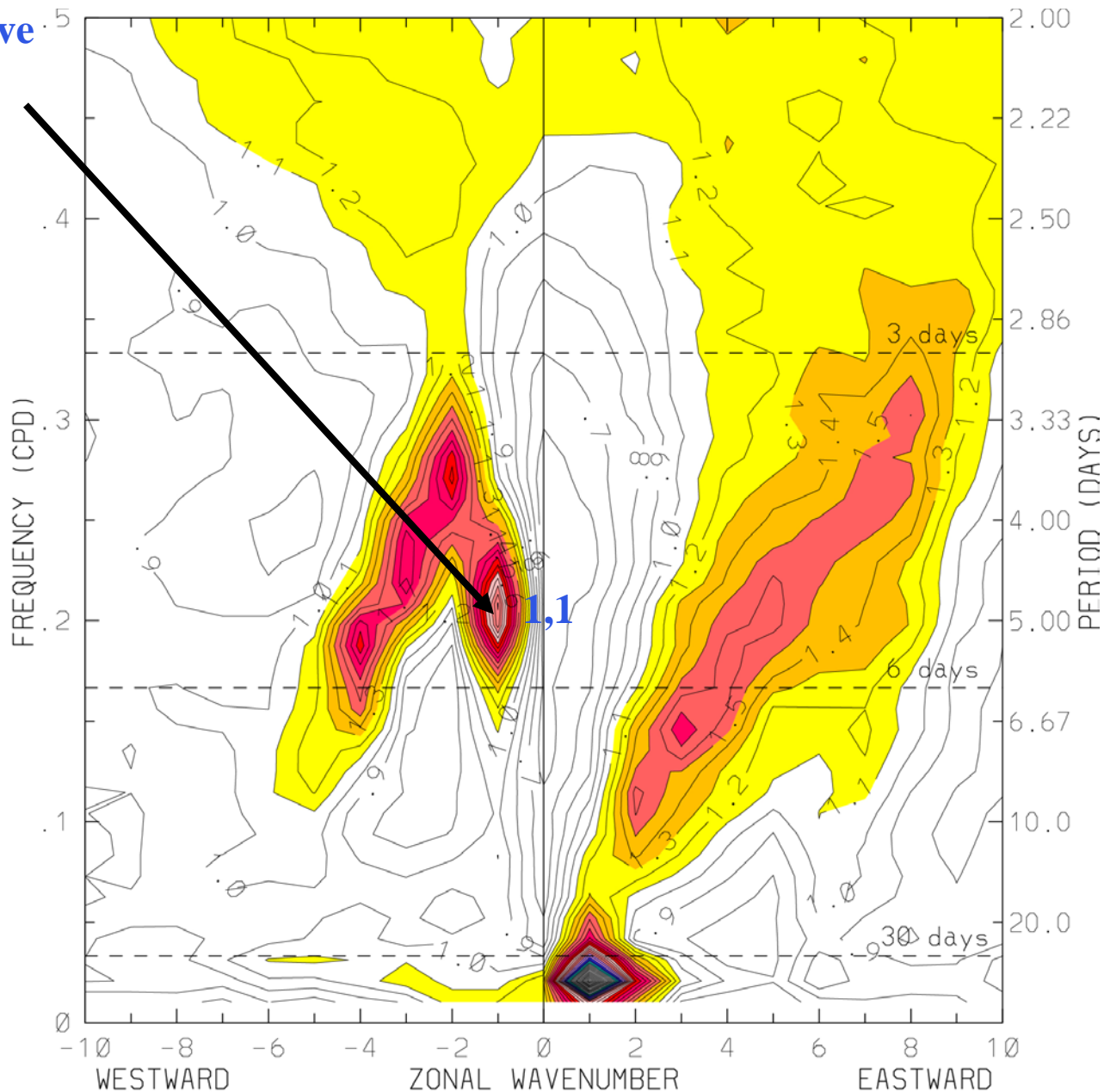# ERAI U850 Power spectrum/Background, 15ºS-15ºN, 1979-2012 (Symmetric)
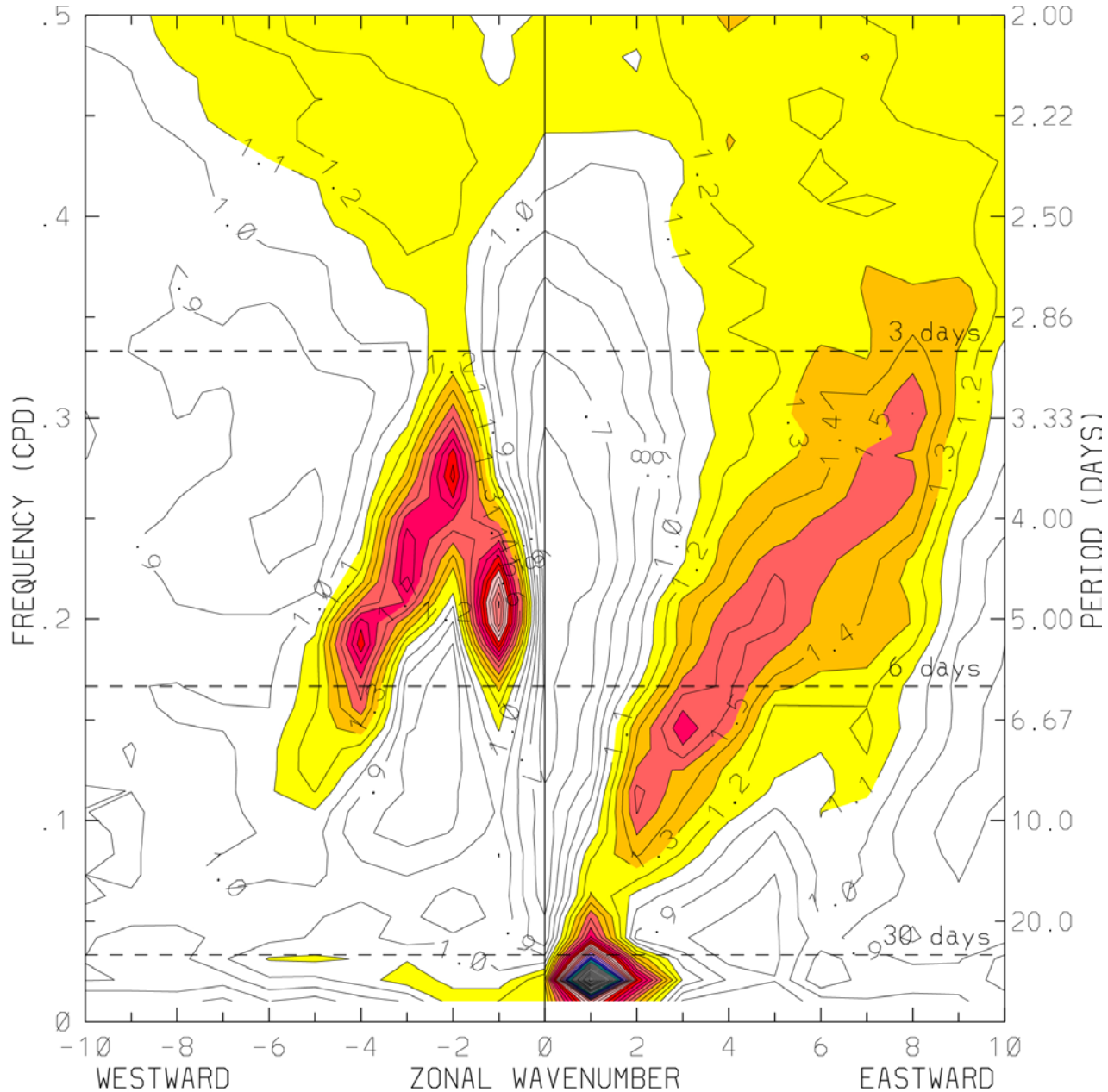


see Hendon and Wheeler 2008; Gehne and Kleeman 2012

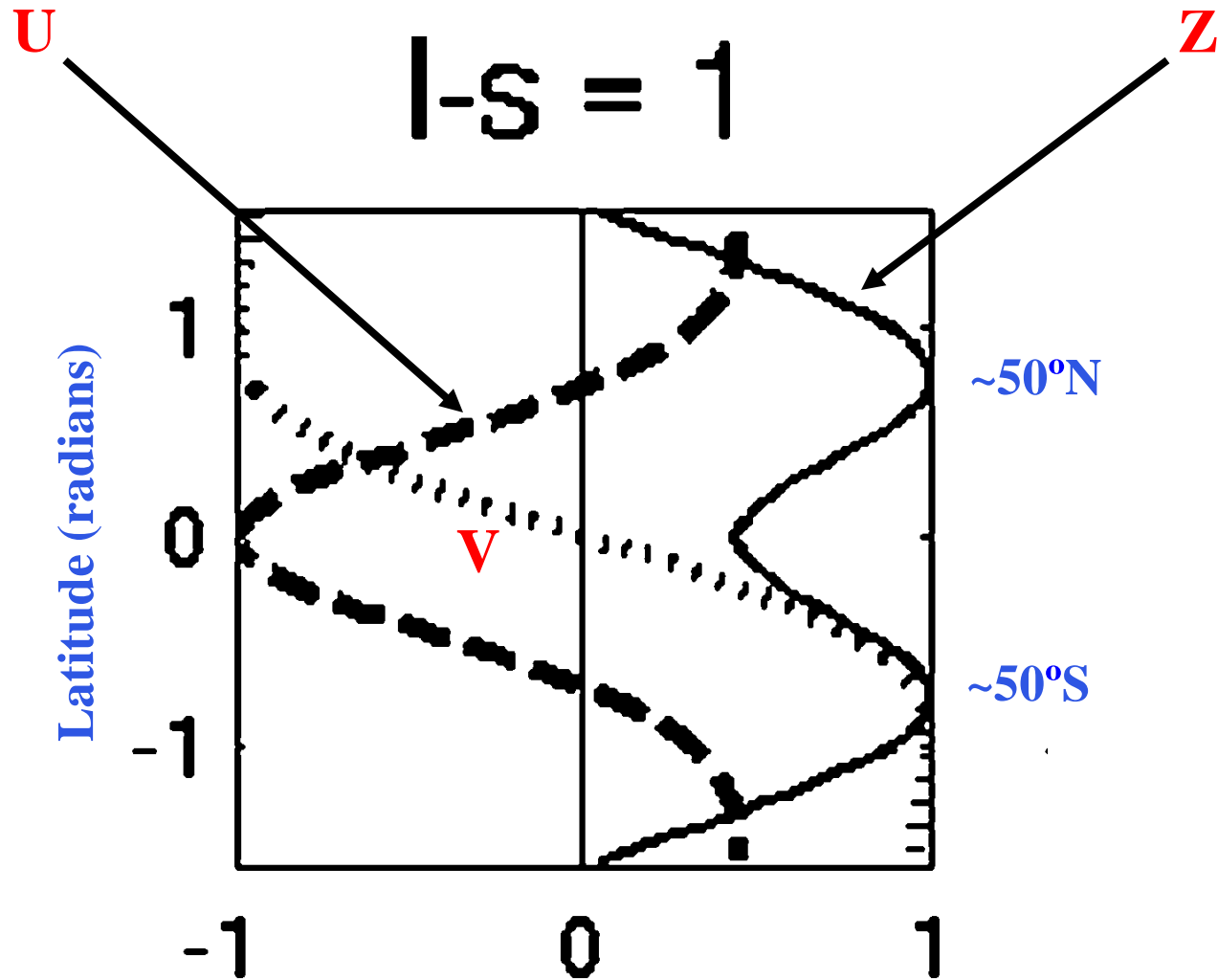# ERAI U850 Power spectrum/Background, 15ºS-15ºN, 1979-2012 (Symmetric)



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# ERAI U850 Power spectrum/Background, 15ºS-15ºN, 1979-2012 (Symmetric)



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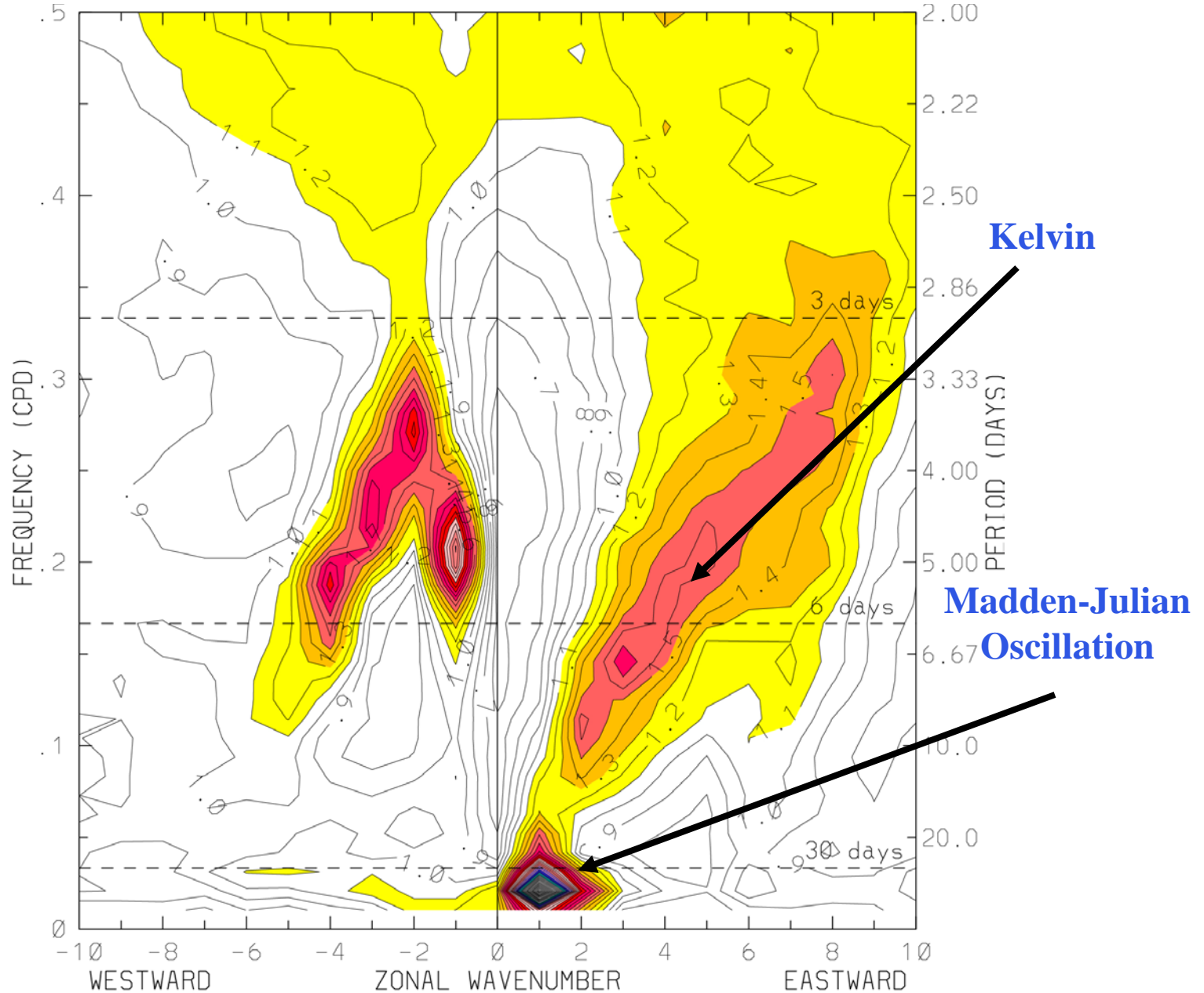
# ERAI U850 Power spectrum/Background, 15ºS-15ºN, 1979-2012 (Symmetric)



5 Day Wave

1,1

see Hendon and Wheeler 2008; Gehne and Kleeman 2012

# Hough Functions Corresponding to the Latitudinal Structure of the Wave 1 n=1 (1,1) Mode or "5 Day Wave"



Z (solid), U (dash) and V (dots)

Madden 2007

# *Isolating the 5 Day Wave*

*Traditionally, free Rossby modes have been identified by projecting data onto their expected theoretical structures, usually the meridional structure from the associated Hough functions*

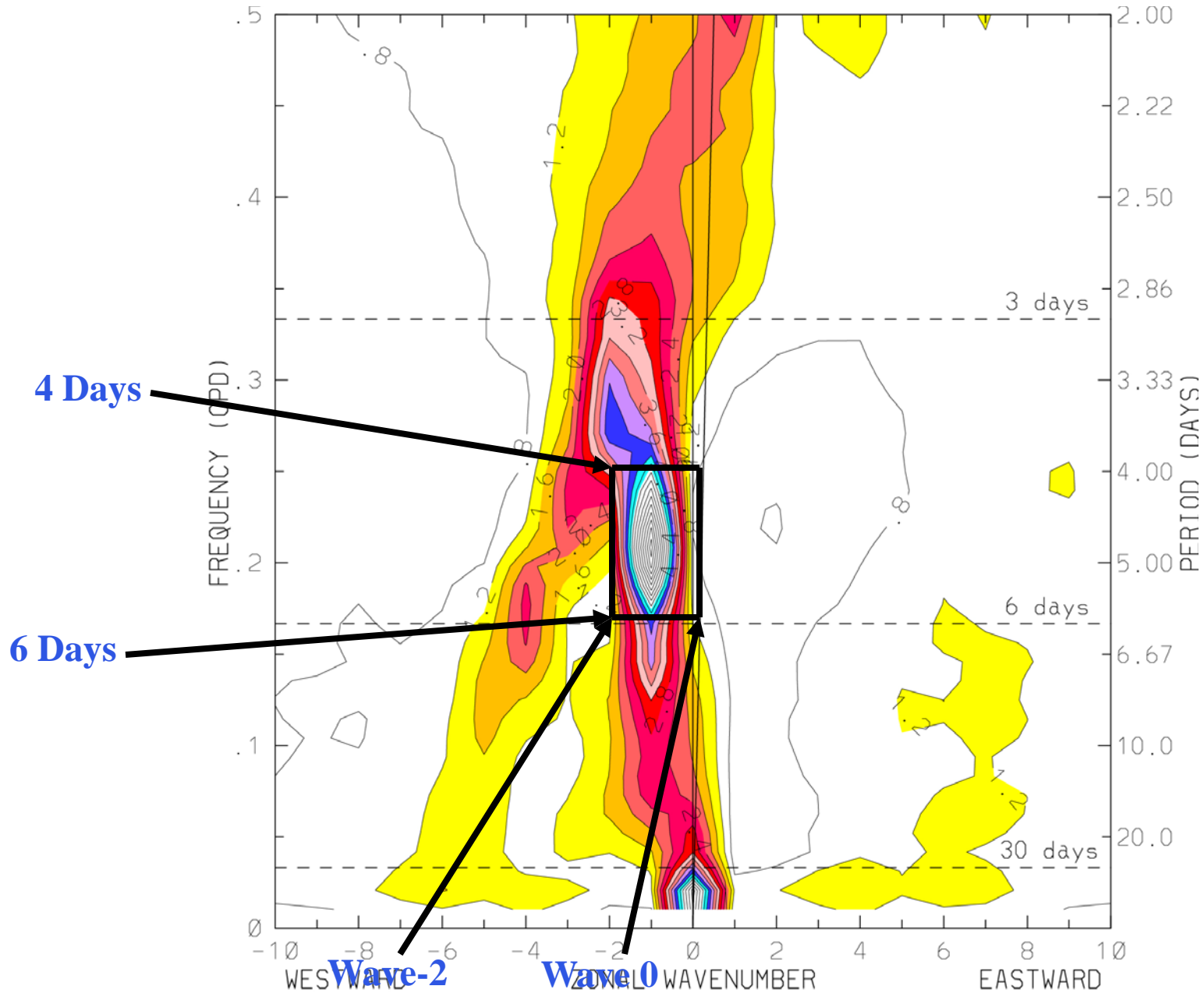*Here we use "5 Day Wave filtered" data to isolate the free (1,1) Rossby mode*

**ERAI U850 Power spectrum/Background, 15ºS-15ºN, 1979-2012 (Symmetric)**
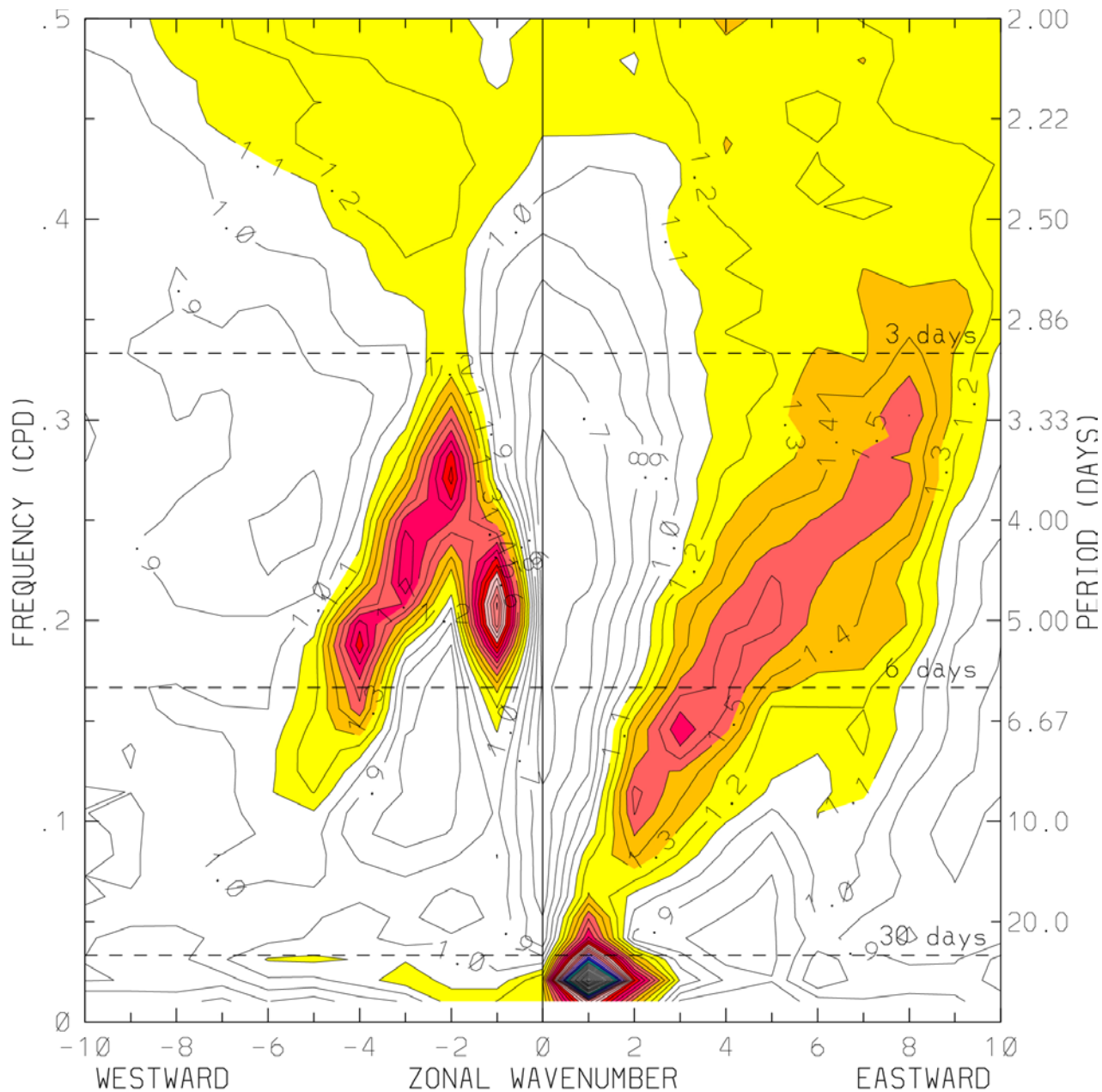
# ERAI G300 Power spectrum/Background, 15ºS-15ºN, 1979-2012 (Symmetric)
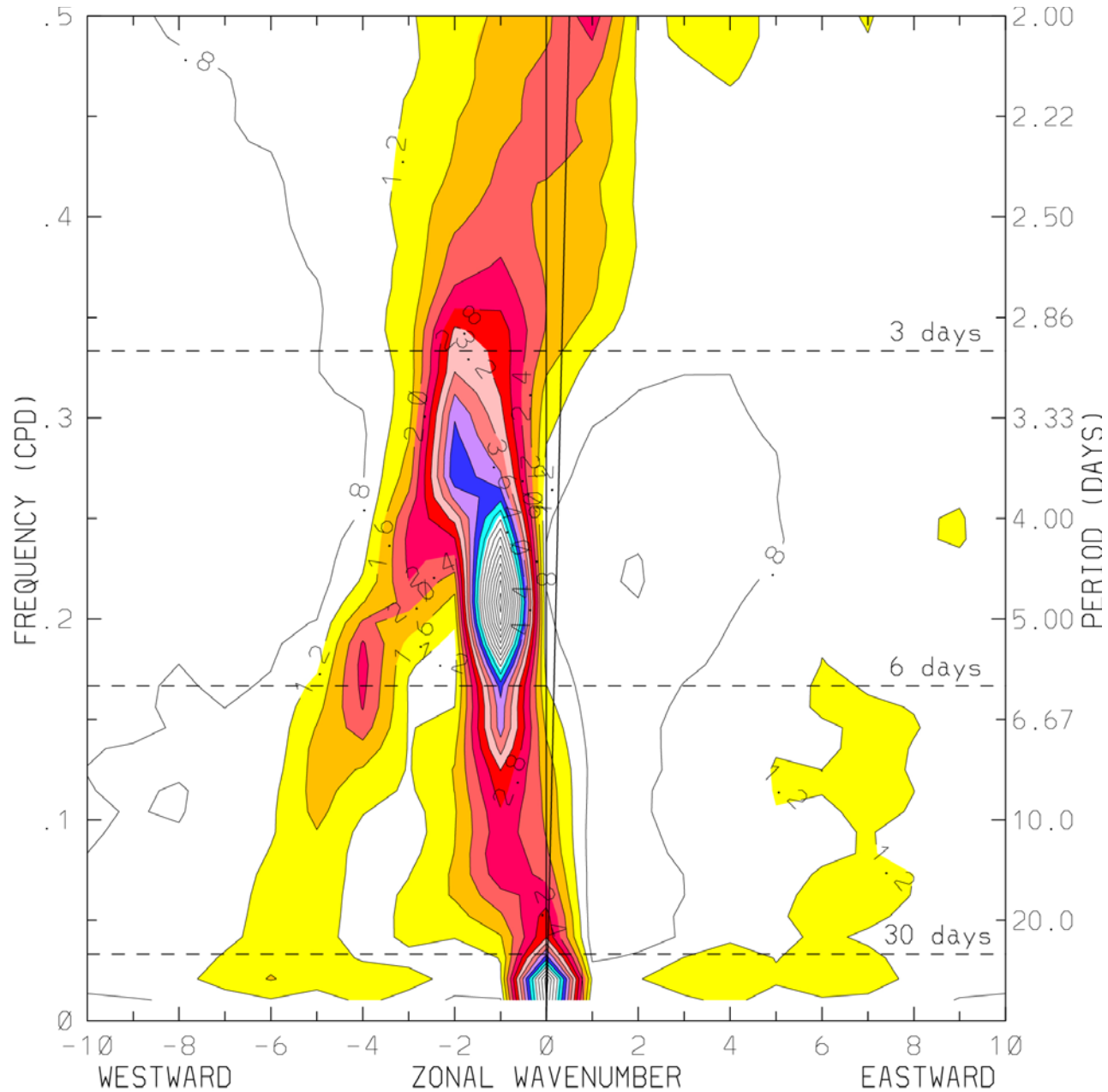
# ERAI G300 Power spectrum/Background, 15ºS-15ºN, 1979-2012 (Symmetric)

# *EOF Analysis*

*EOFs calculated from a combined covariance matrix of global 5-Day filtered zonal wind at 850, 550, and 250 hPa, 1979-2013*

*Results are very insensitive to the levels used…*

*EOFs are also calculated by individual seasons (DJF, MAM, etc.)*

*In all cases two leading modes in quadrature, representing a propagating signal, are obtained*

*Dynamical structures are obtained by projection of raw (unfiltered) ERA data onto the associated Principal Components (PCs)*

*Statistical significance calculated at the 95% level*

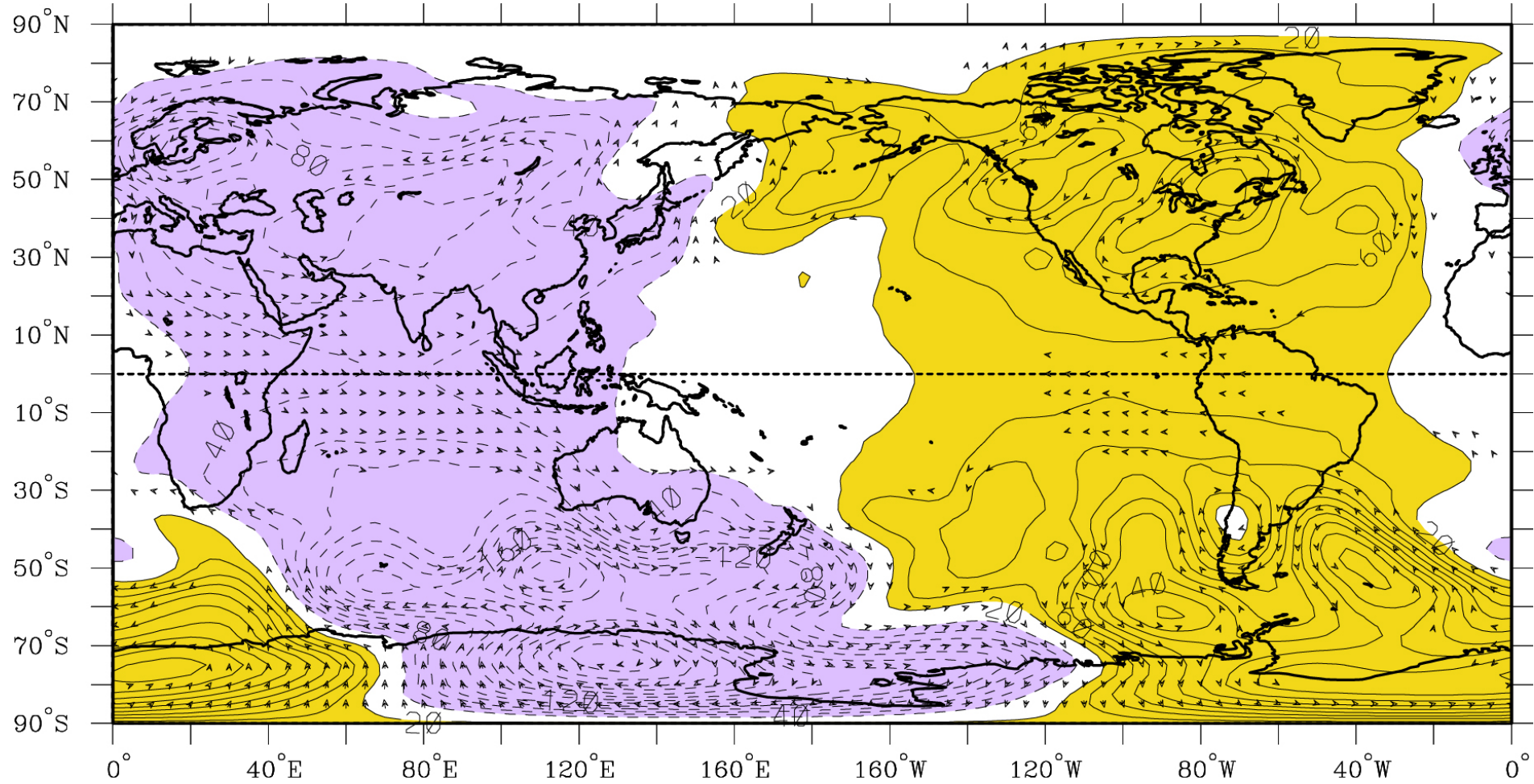# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa
## Annual
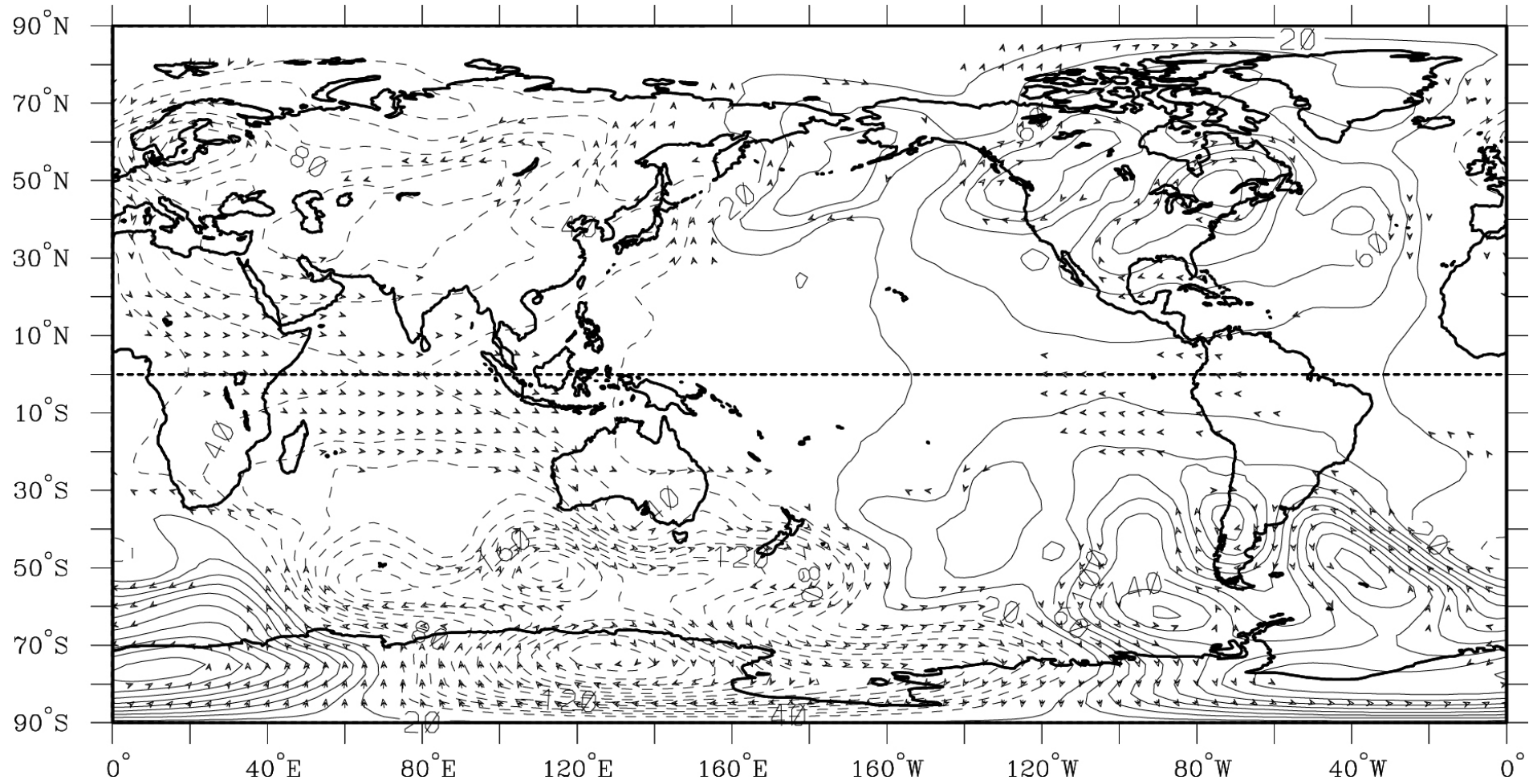


Geopotential (contours 20 X 10$^5$ m$^2$ s$^{-2}$)
Wind (vectors, largest around 2 m s$^{-1}$)

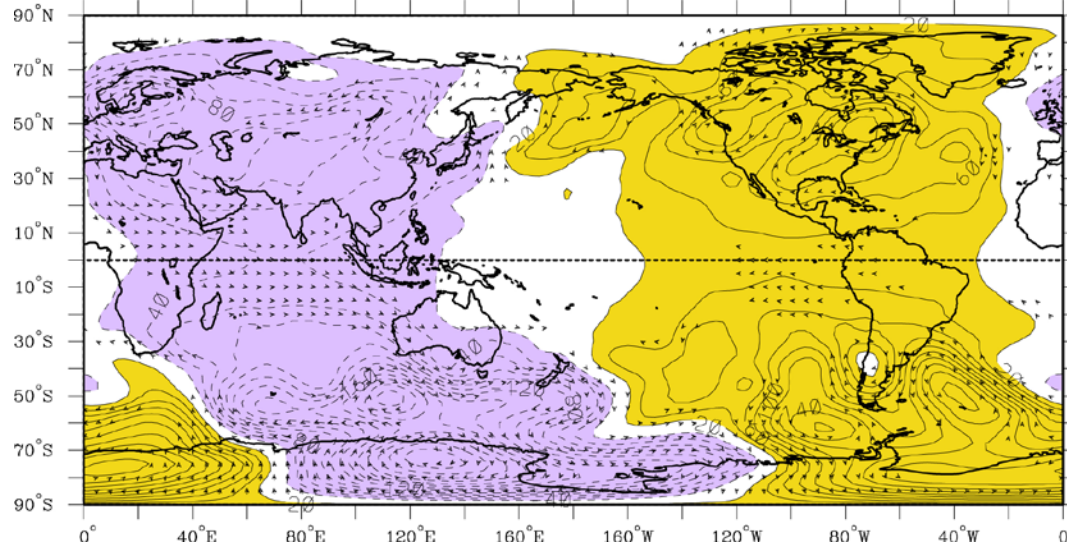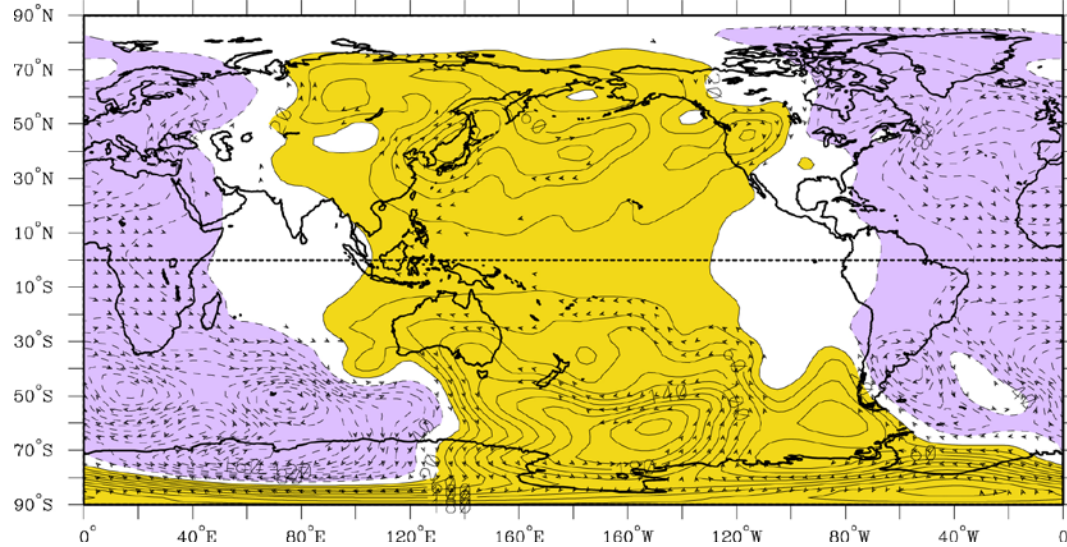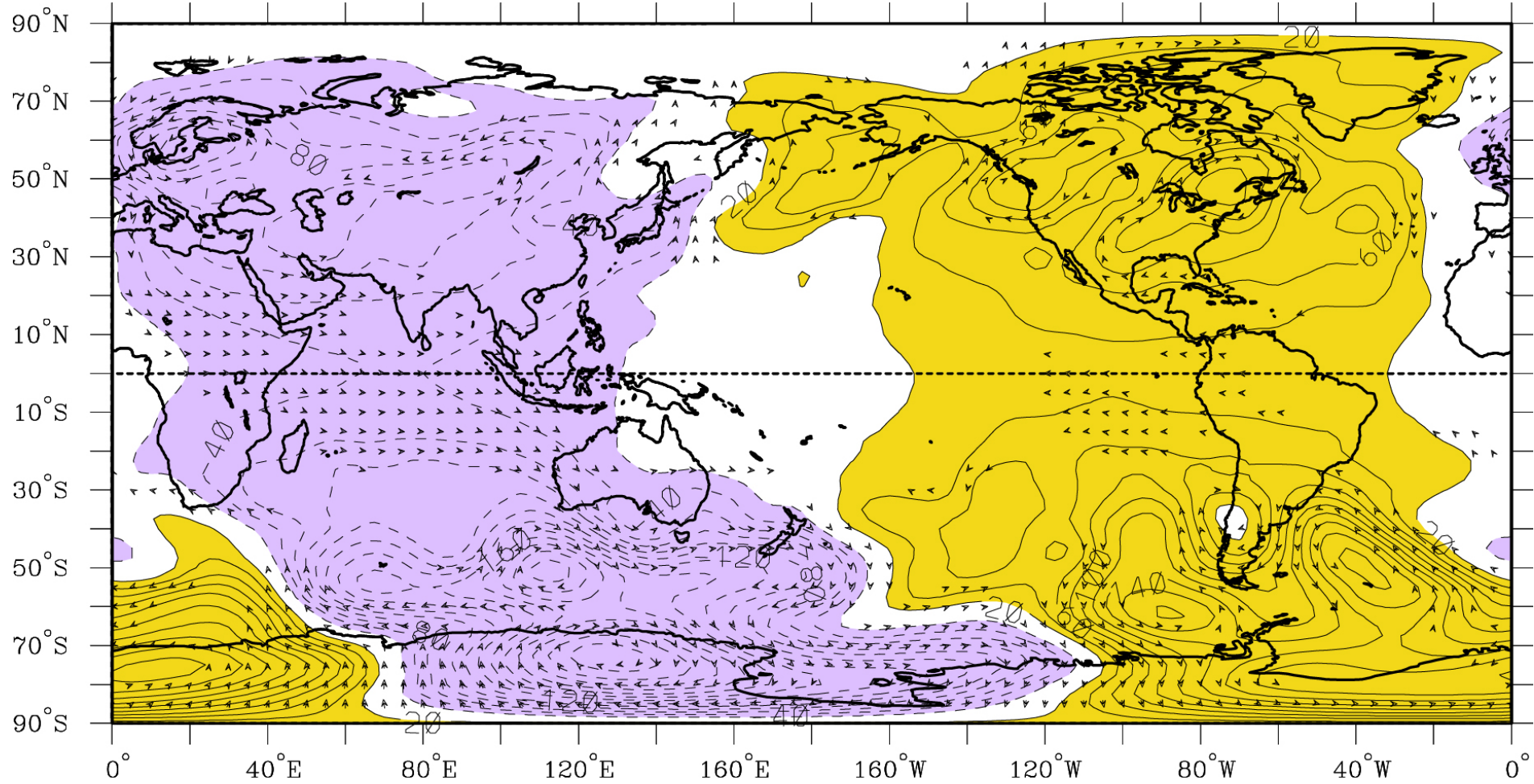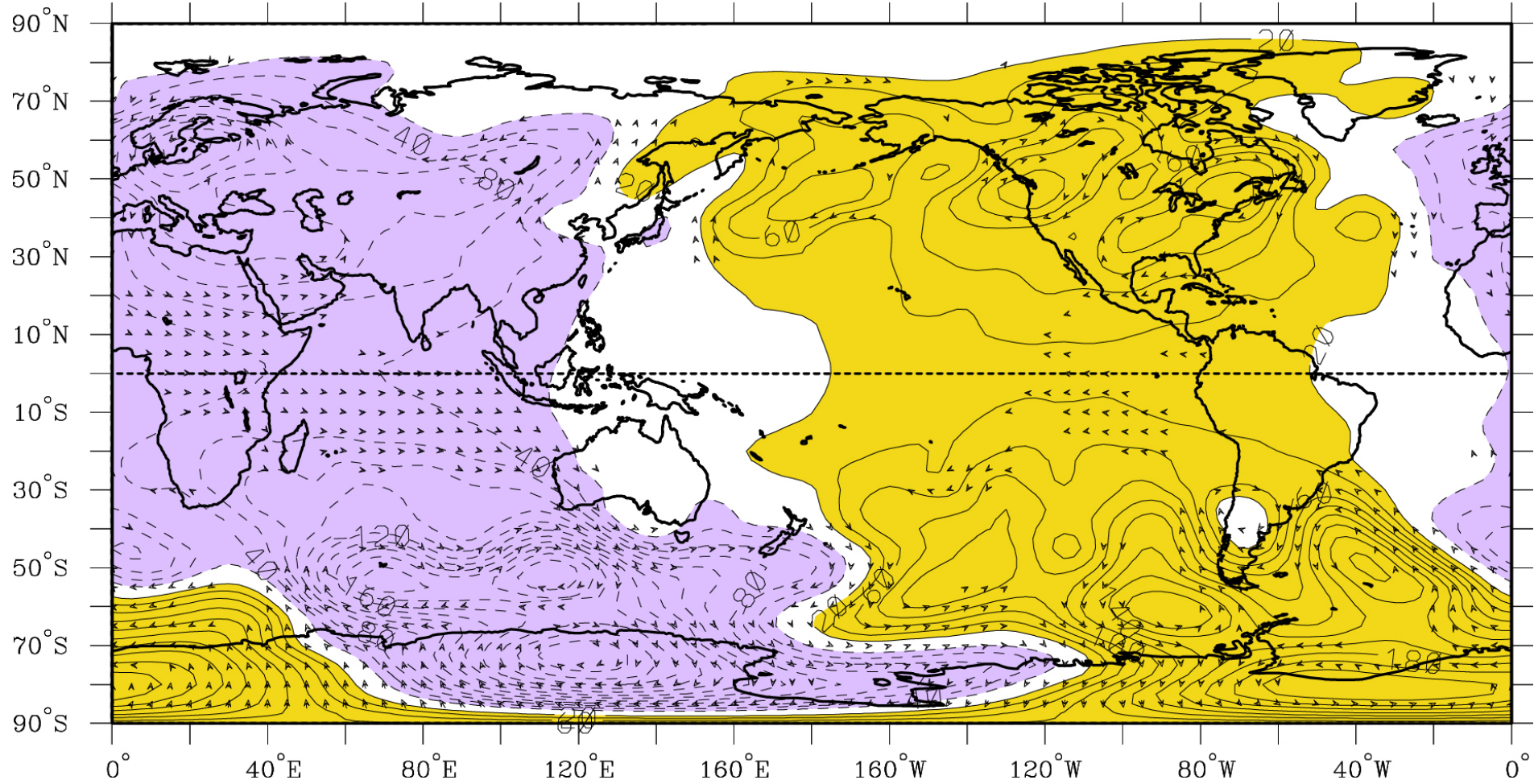# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa

## Annual



Geopotential (contours 20 X 10⁵ m² s⁻²)
Wind (vectors, largest around 2 m s⁻¹)

# First 2 EOFs of 5 Day Filtered 850+550+250 hPa Geopotential at 300

**EOF1**

**EOF2**



Geopotential (contours 20 X $10^5$ m$^2$ s$^{-2}$)
Wind (vectors, largest around 2 m s$^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa
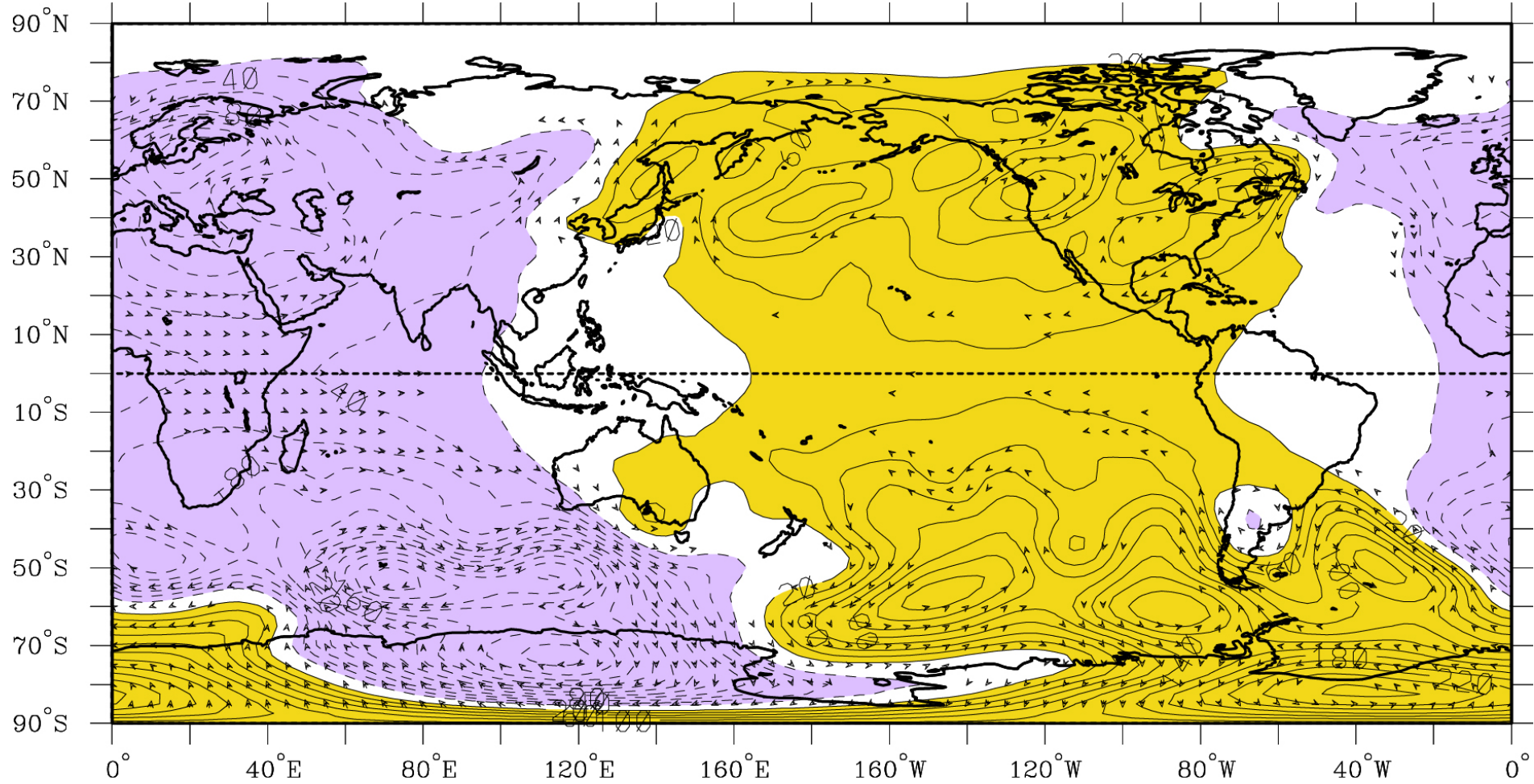
**Annual**                    Day 0



Geopotential (contours 20 X $10^5$ $m^2$ $s^{-2}$)
Wind (vectors, largest around 2 m $s^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa
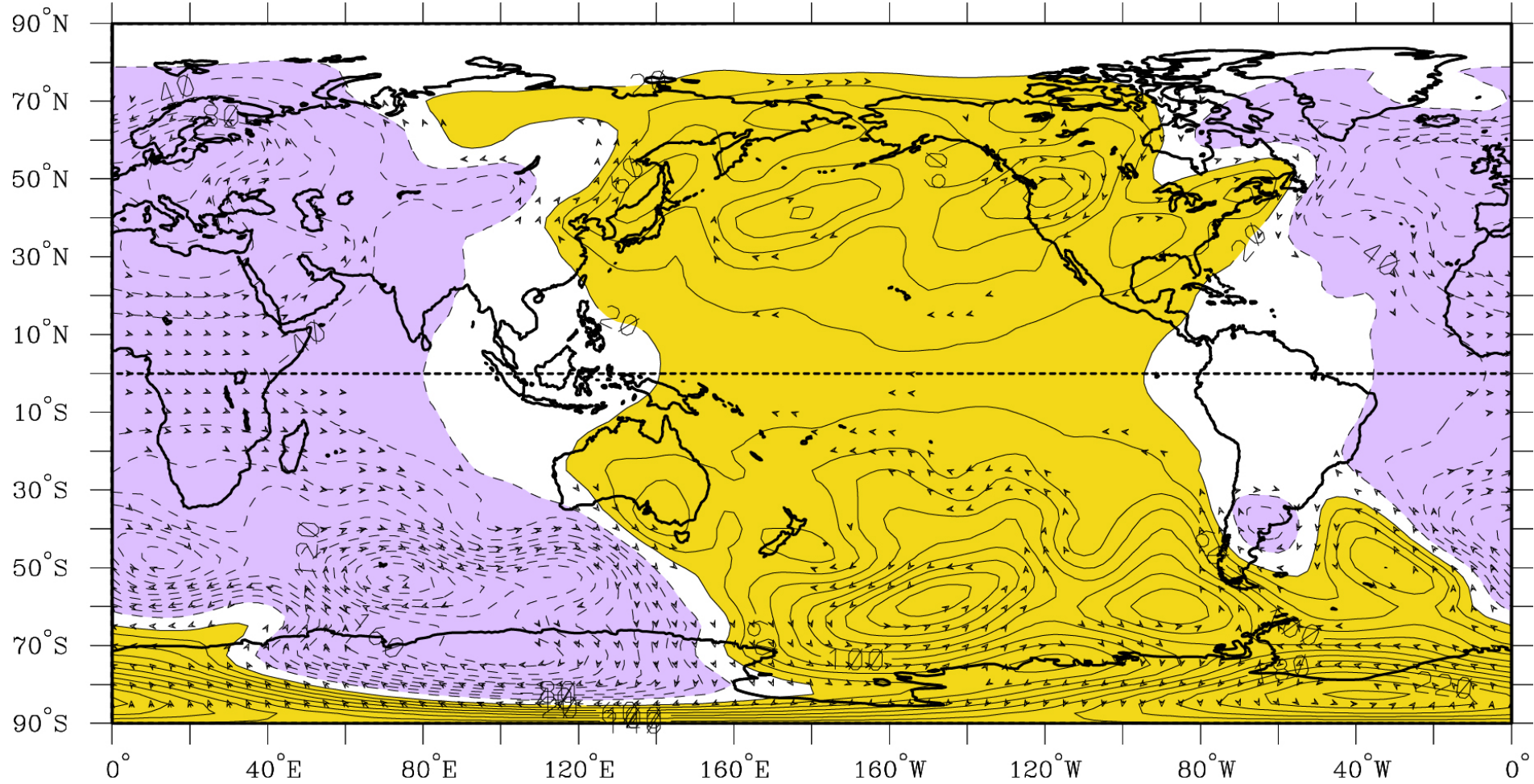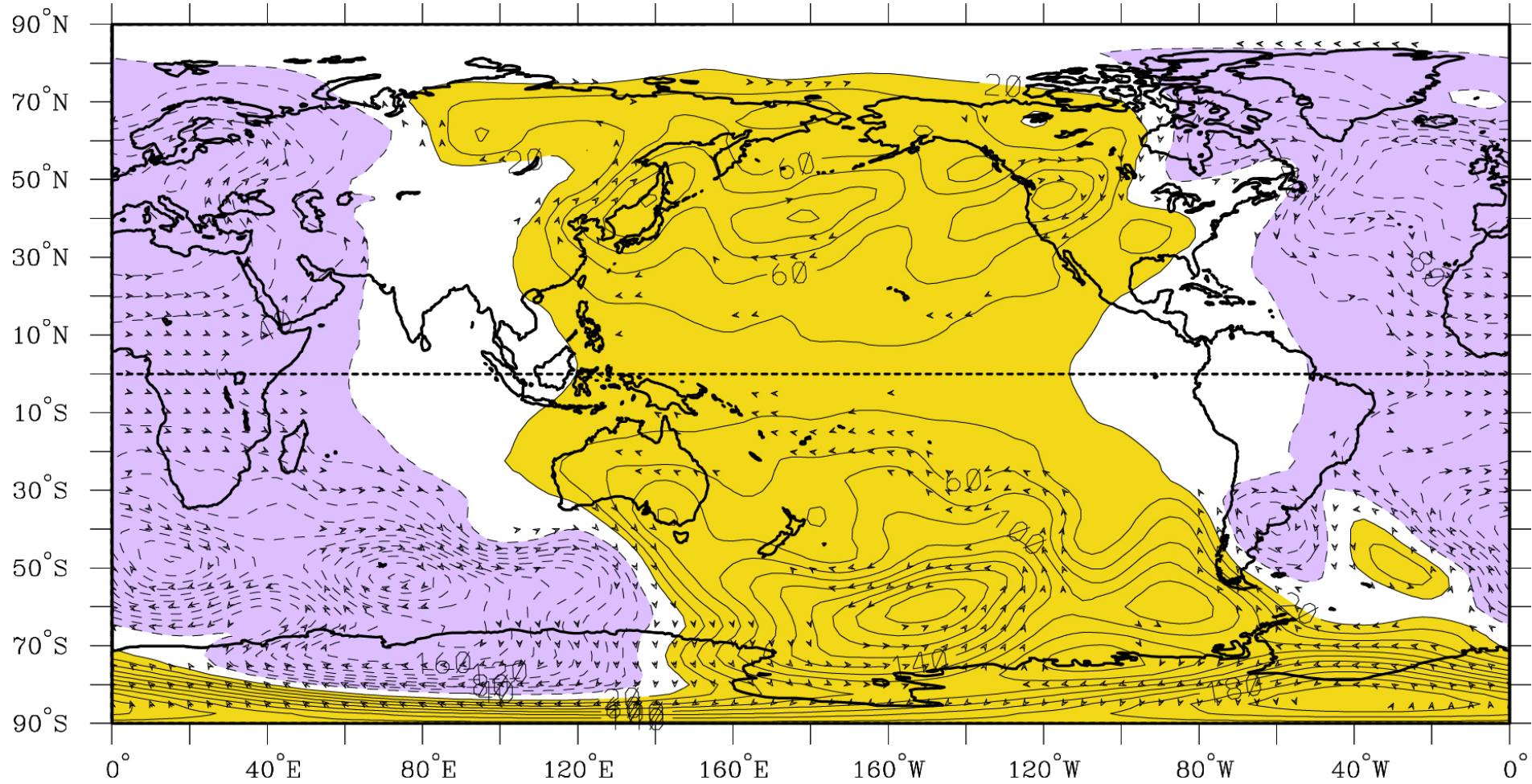
**Annual**          Day+.25



Geopotential (contours 20 X $10^5$ $m^2 s^{-2}$)
Wind (vectors, largest around 2 m $s^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa
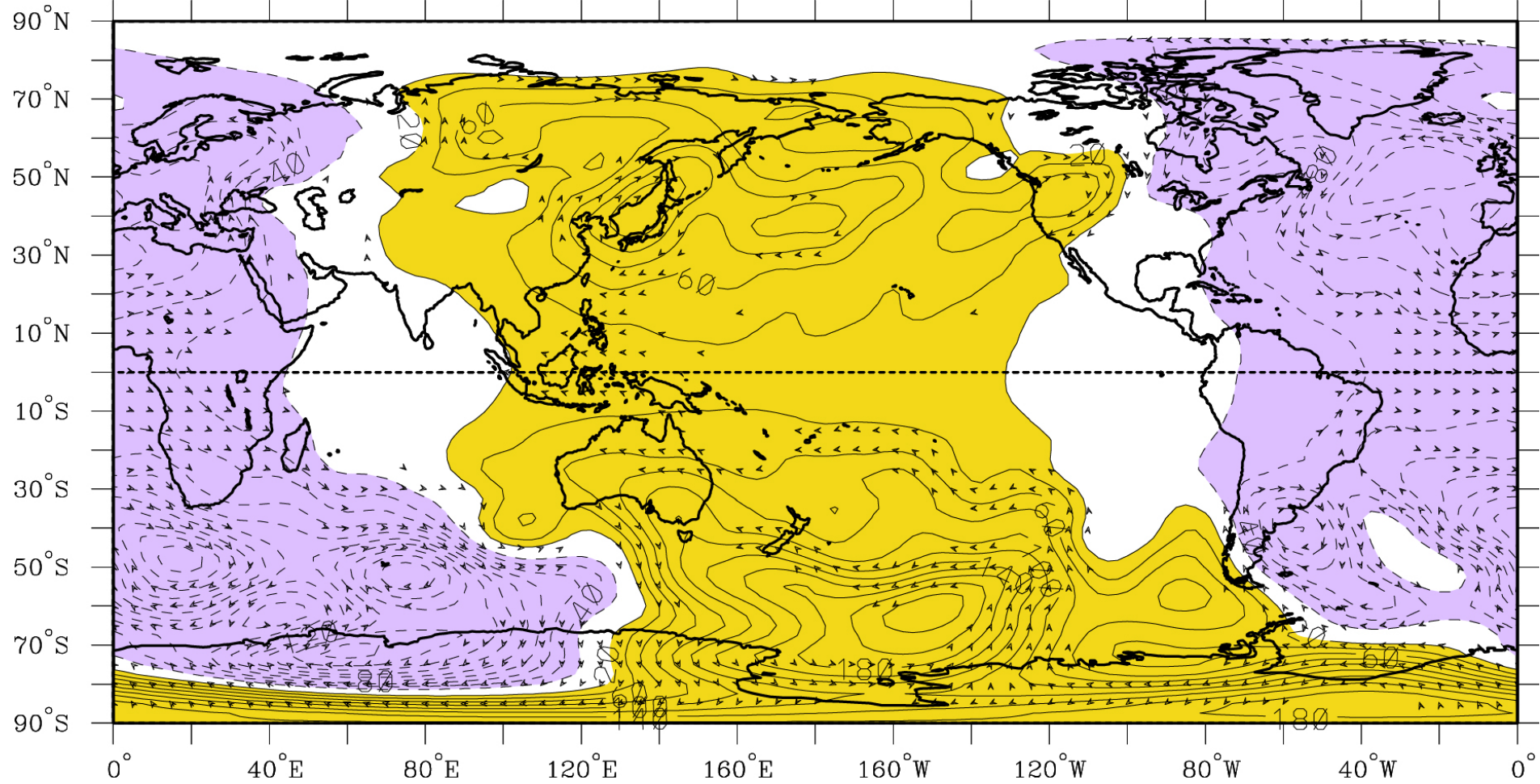
**Annual**                              Day+.50



Geopotential (contours 20 X 10$^5$ m$^2$ s$^{-2}$)
Wind (vectors, largest around 2 m s$^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa

## Annual Day+.75



Geopotential (contours 20 X $10^5$ m$^2$ s$^{-2}$)
Wind (vectors, largest around 2 m s$^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa
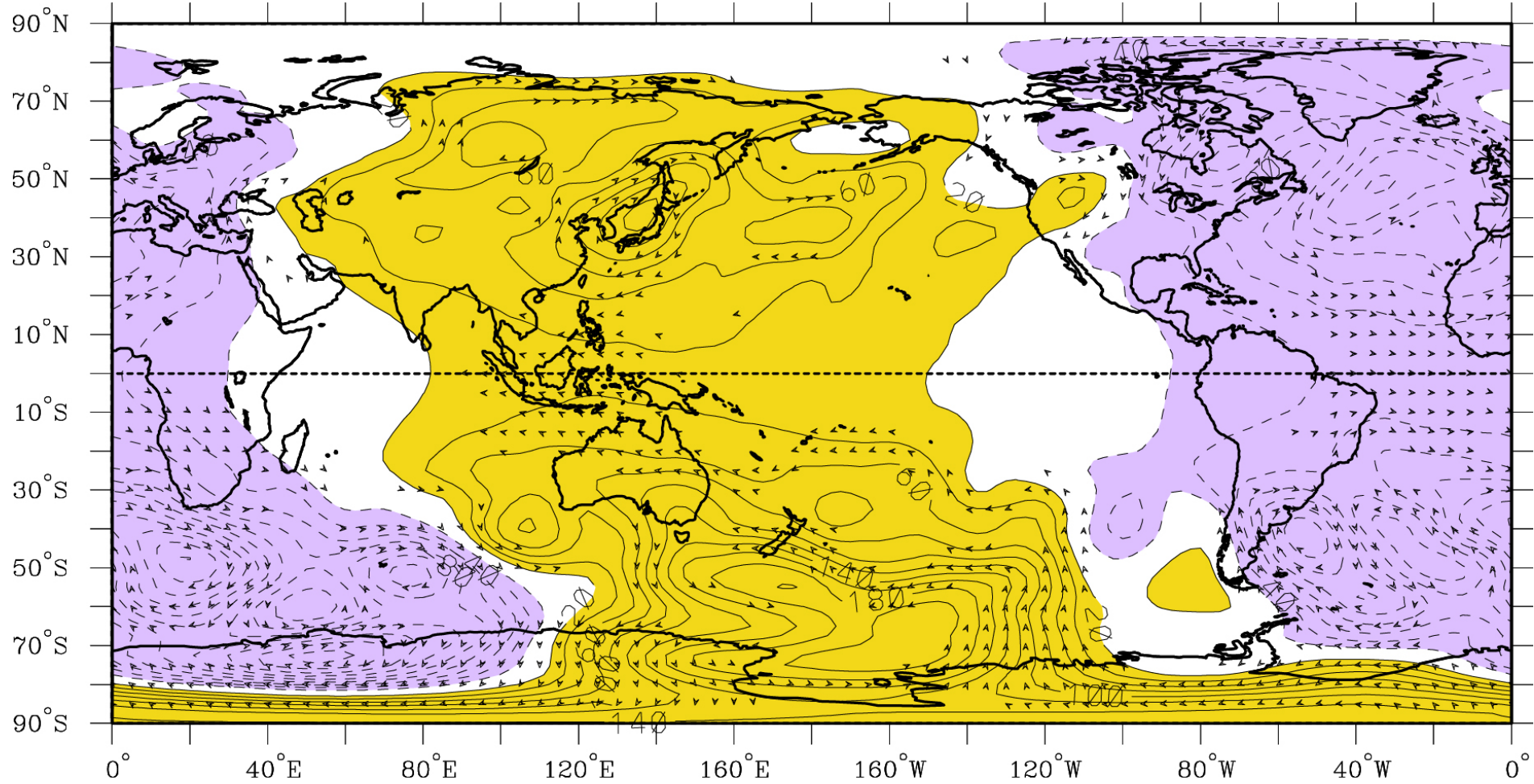
**Annual**                          Day+1



Geopotential (contours 20 X 10⁵ m² s⁻²)
Wind (vectors, largest around 2 m s⁻¹)

First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa

Annual          Day+1.25

Geopotential (contours 20 X $10^5$ $m^2$ $s^{-2}$)
Wind (vectors, largest around 2 m $s^{-1}$)

First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa

**Annual**          Day+1.50
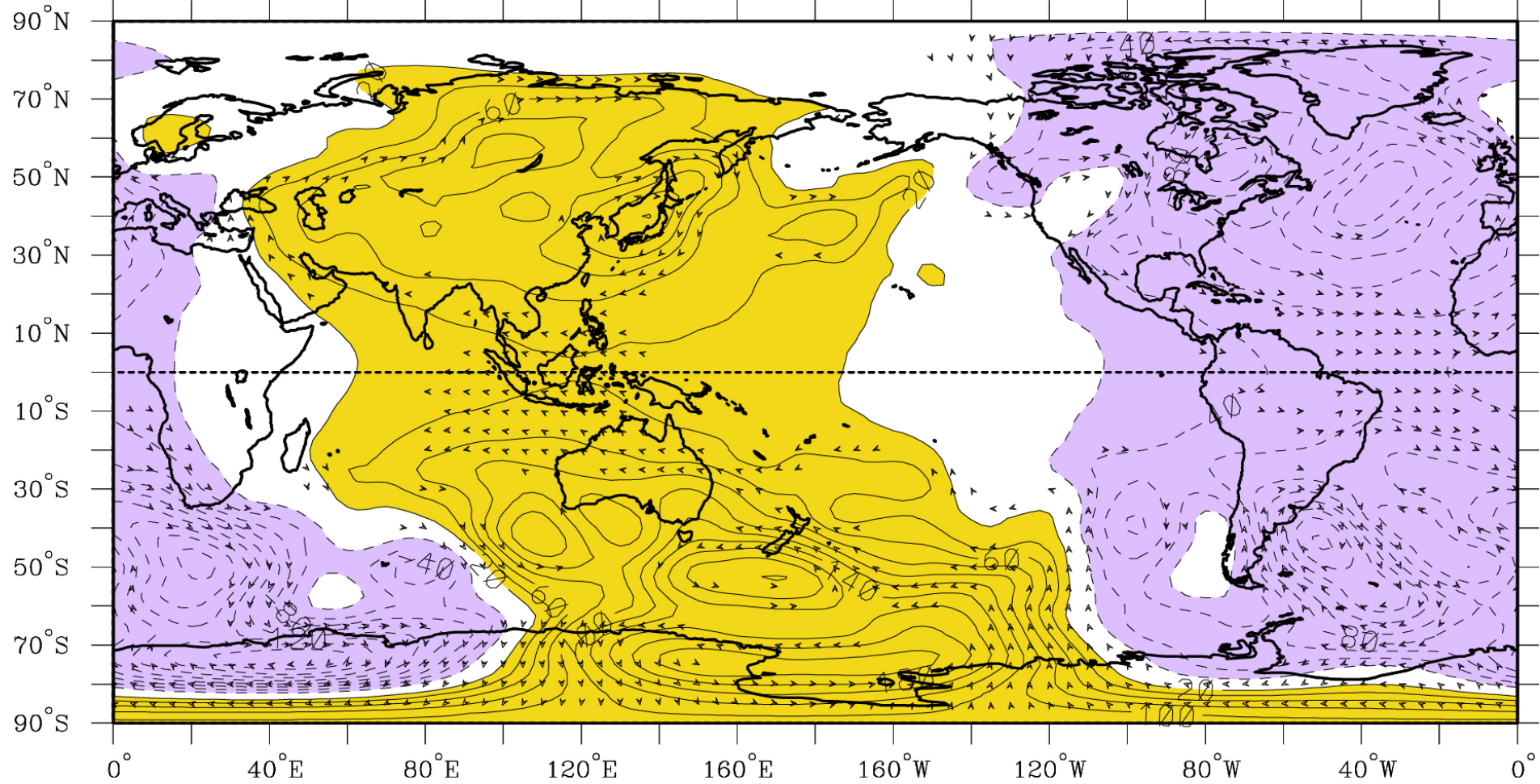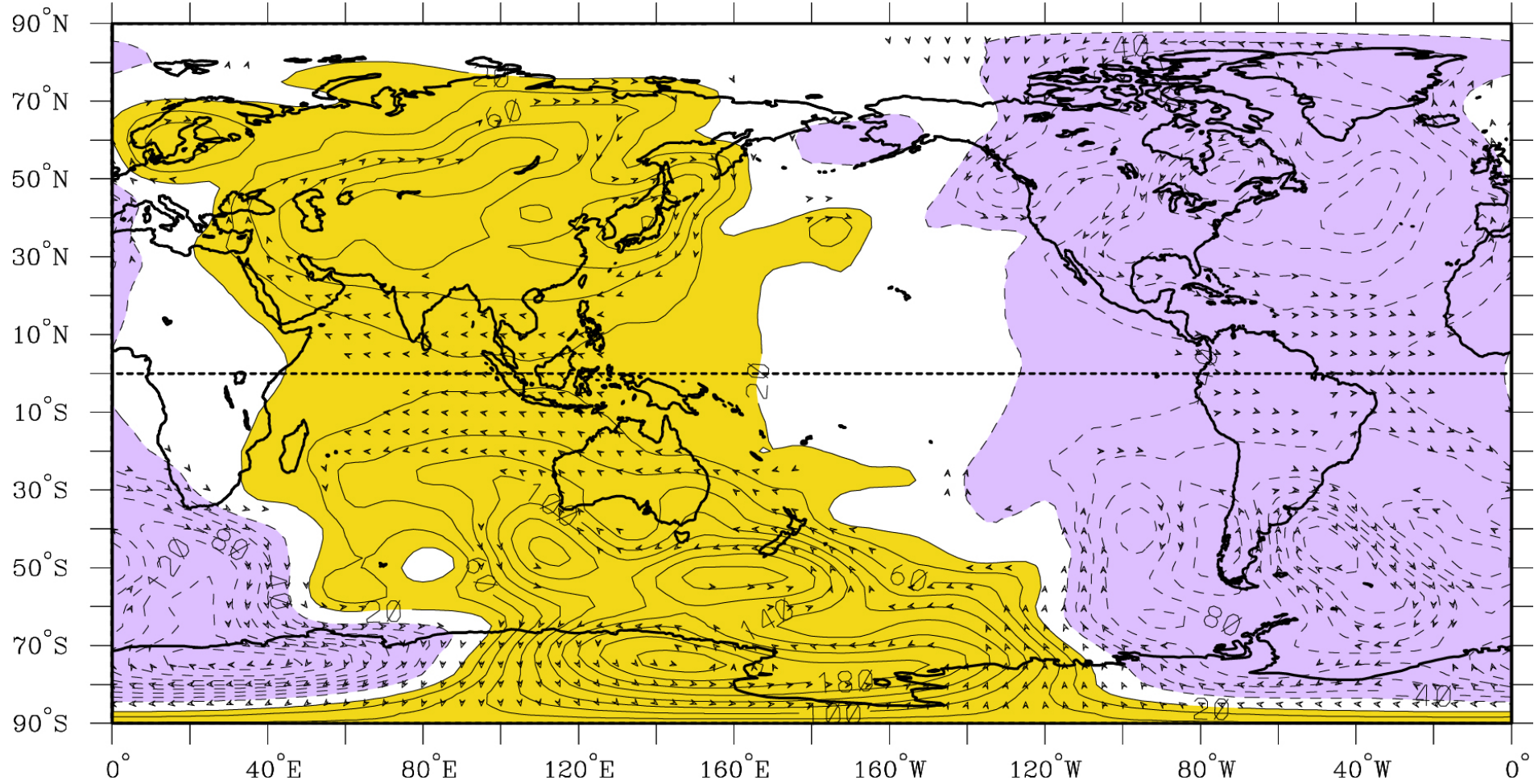
Geopotential (contours 20 X $10^5$ $m^2$ $s^{-2}$)
Wind (vectors, largest around 2 m $s^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa
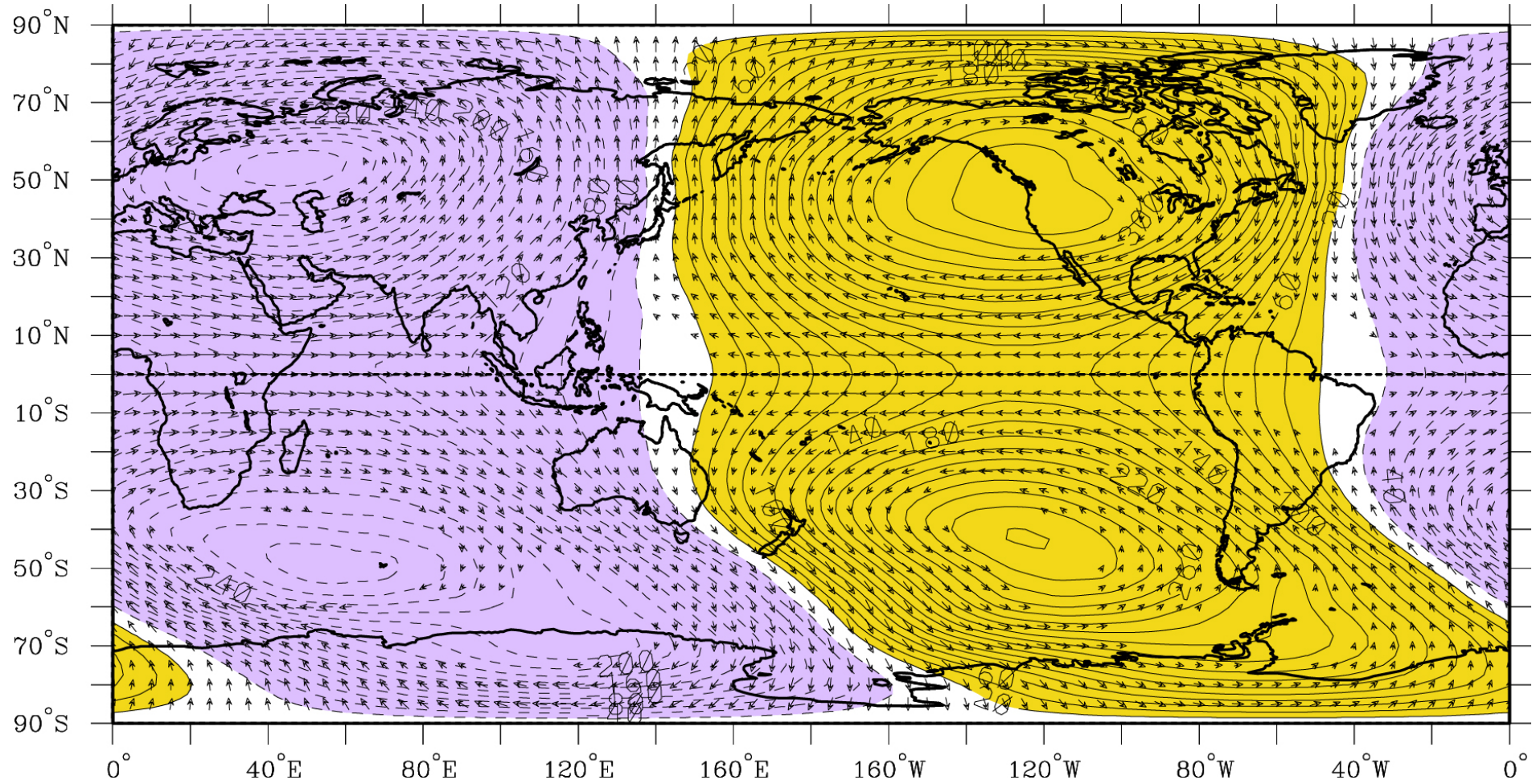
**Annual**                     Day+1.75



Geopotential (contours $20 \times 10^5$ m$^2$ s$^{-2}$)
Wind (vectors, largest around 2 m s$^{-1}$)

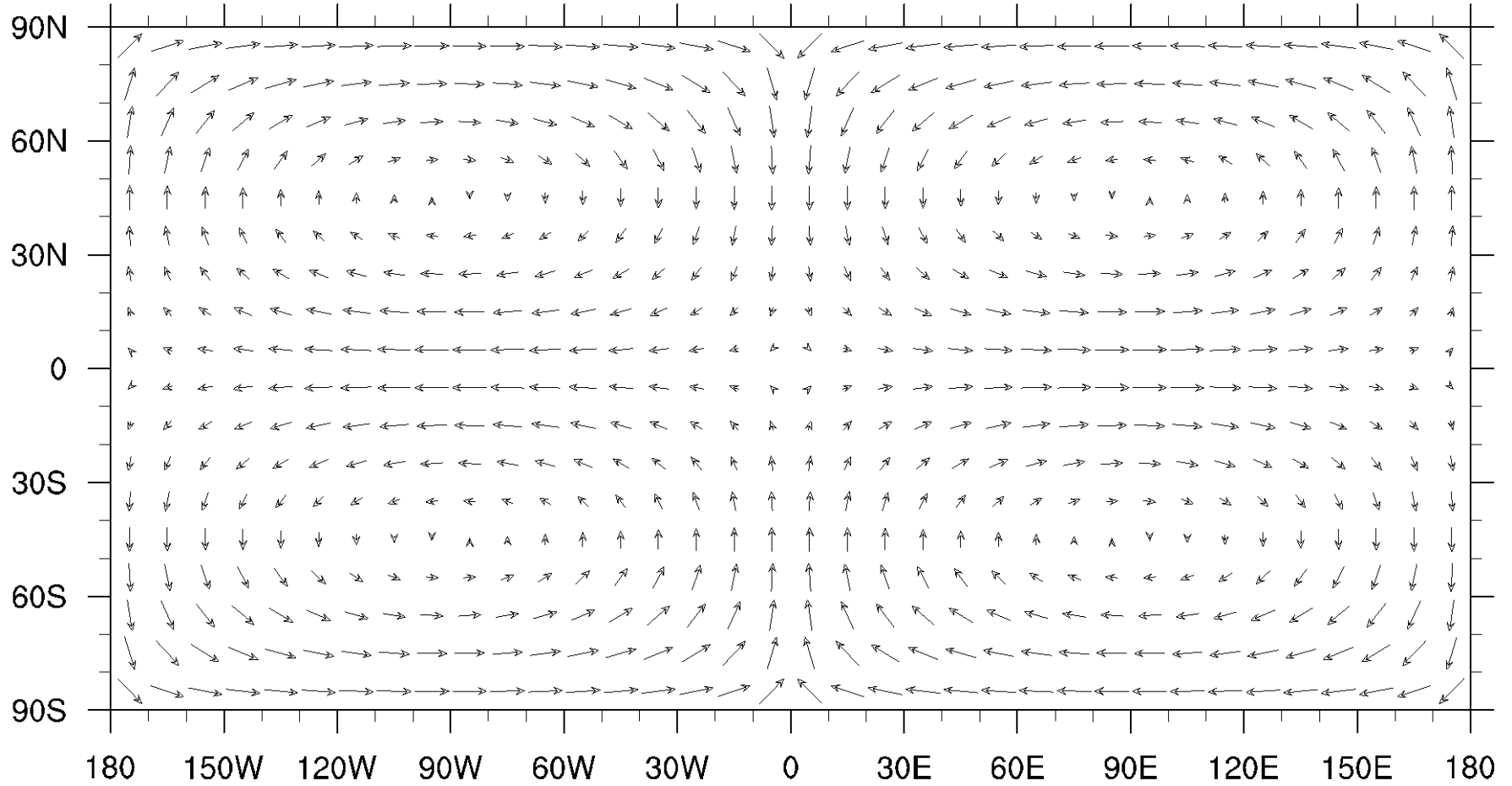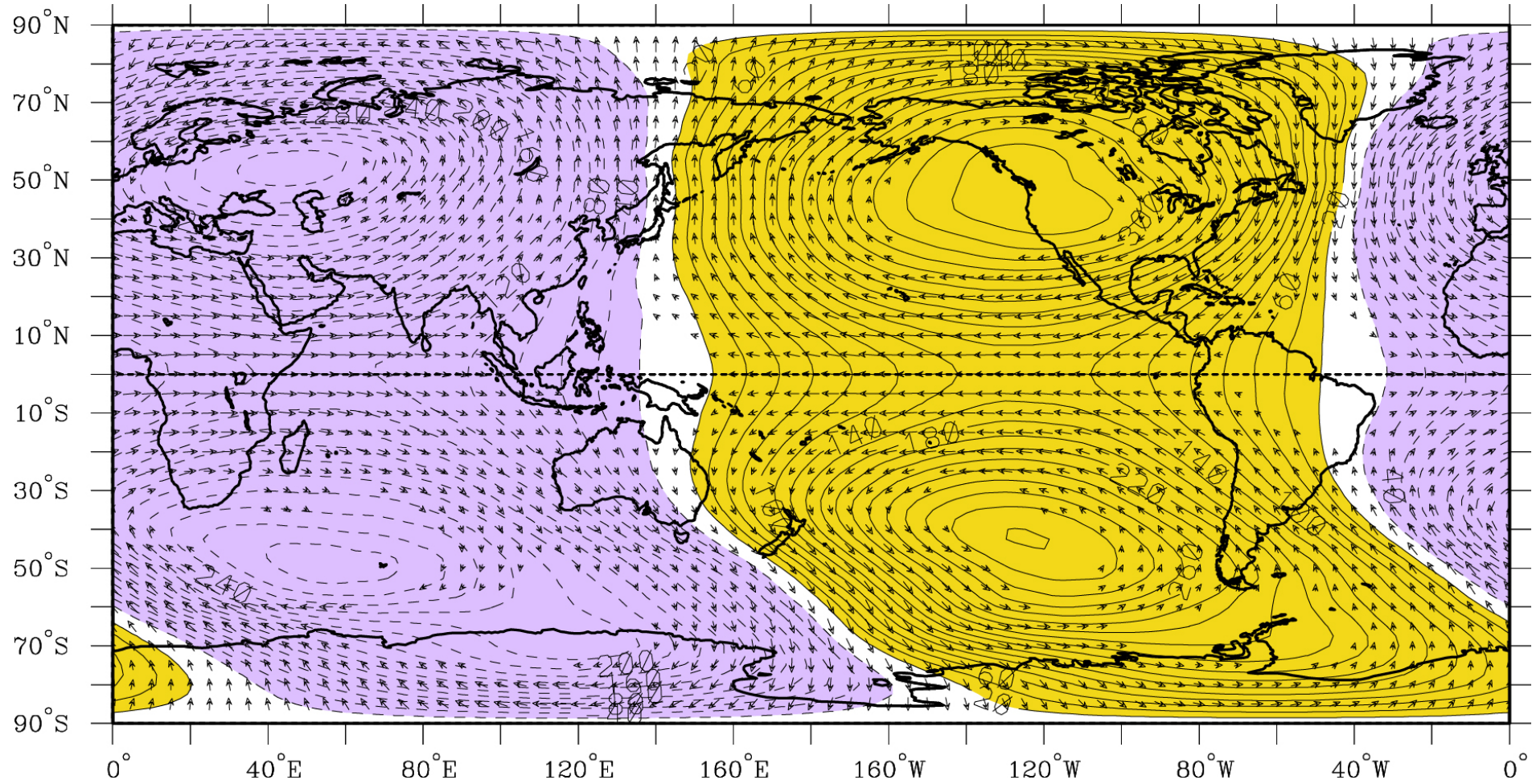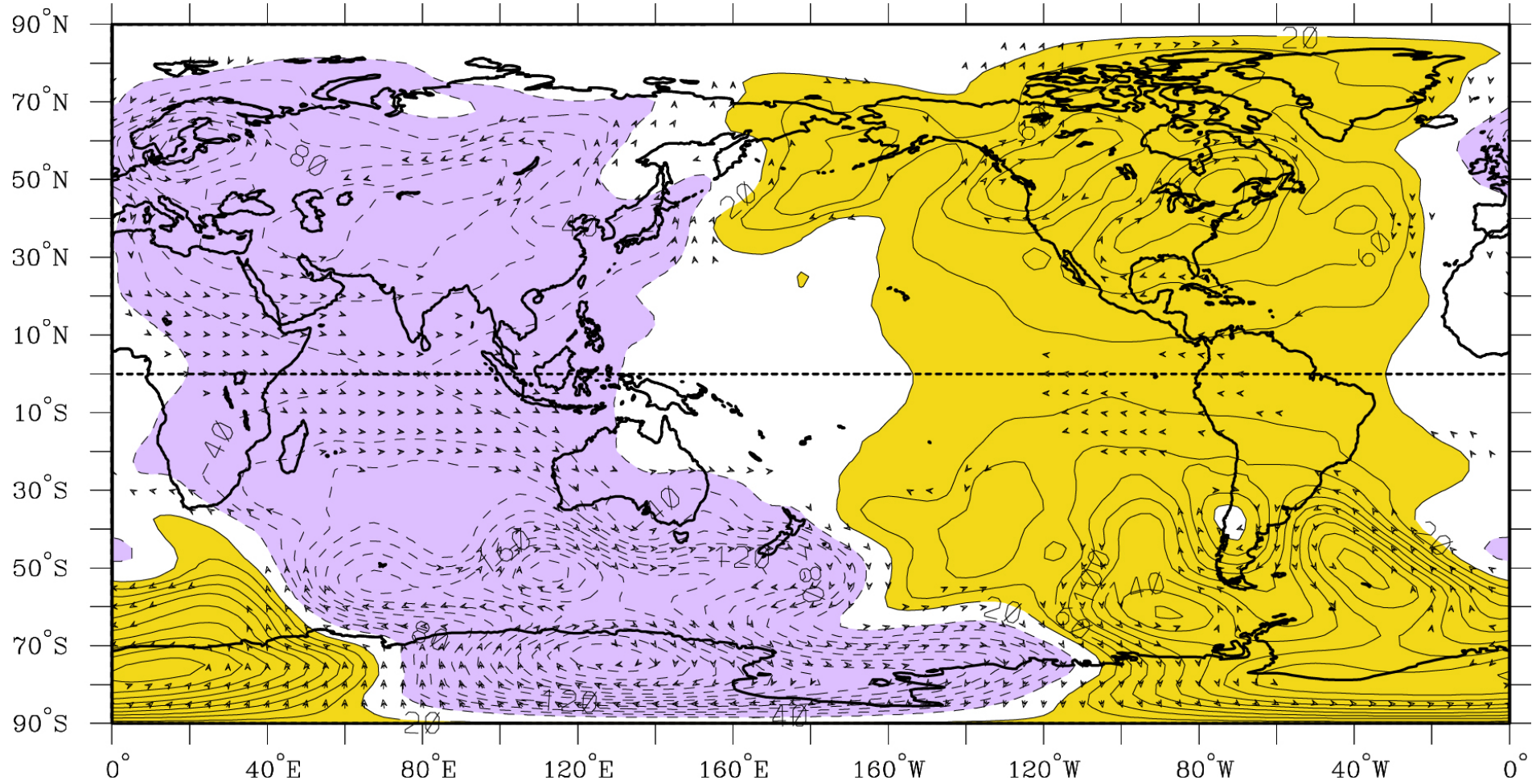# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa

**Annual**                           Day+2



Geopotential (contours 20 X 10$^5$ m$^2$ s$^{-2}$)
Wind (vectors, largest around 2 m s$^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 1 hPa
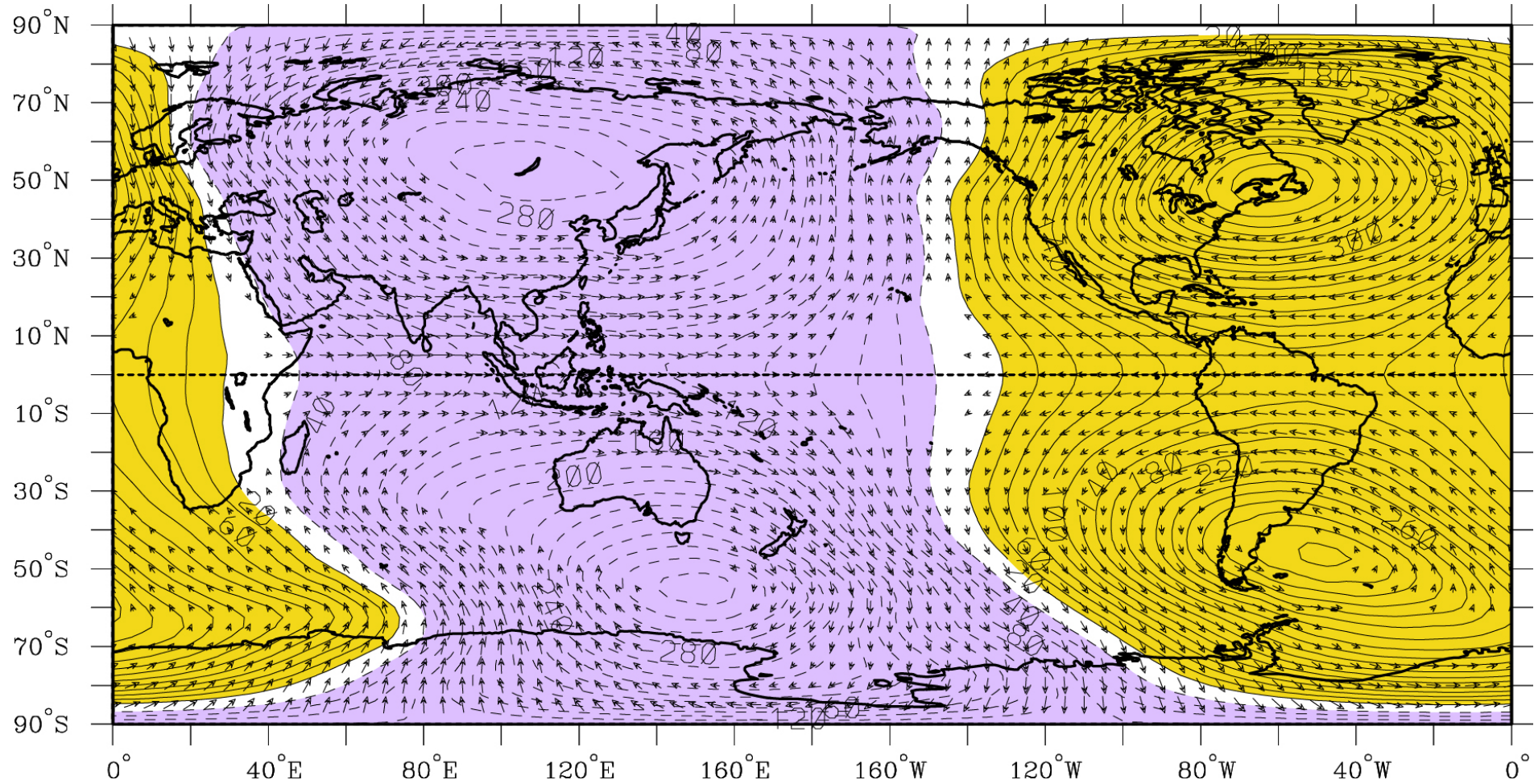
**Annual**                                    Day 0



Geopotential (contours 20 X $10^5$ m$^2$ s$^{-2}$)
Wind (vectors, largest around 2 m s$^{-1}$)

# Theoretical Wind Structure of the n=1 (1,1) Mode or "5 Day Wave"



King, Wheeler and Lane, 2015

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 1 hPa

**Annual**                                    Day 0



Geopotential (contours 20 X $10^5$ $m^2$ $s^{-2}$)
Wind (vectors, largest around 2 $m\,s^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa

**Annual**                                Day 0



Geopotential (contours 20 X 10$^5$ m$^2$ s$^{-2}$)
Wind (vectors, largest around 2 m s$^{-1}$)

First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 1 hPa

**Annual**                    Day-1
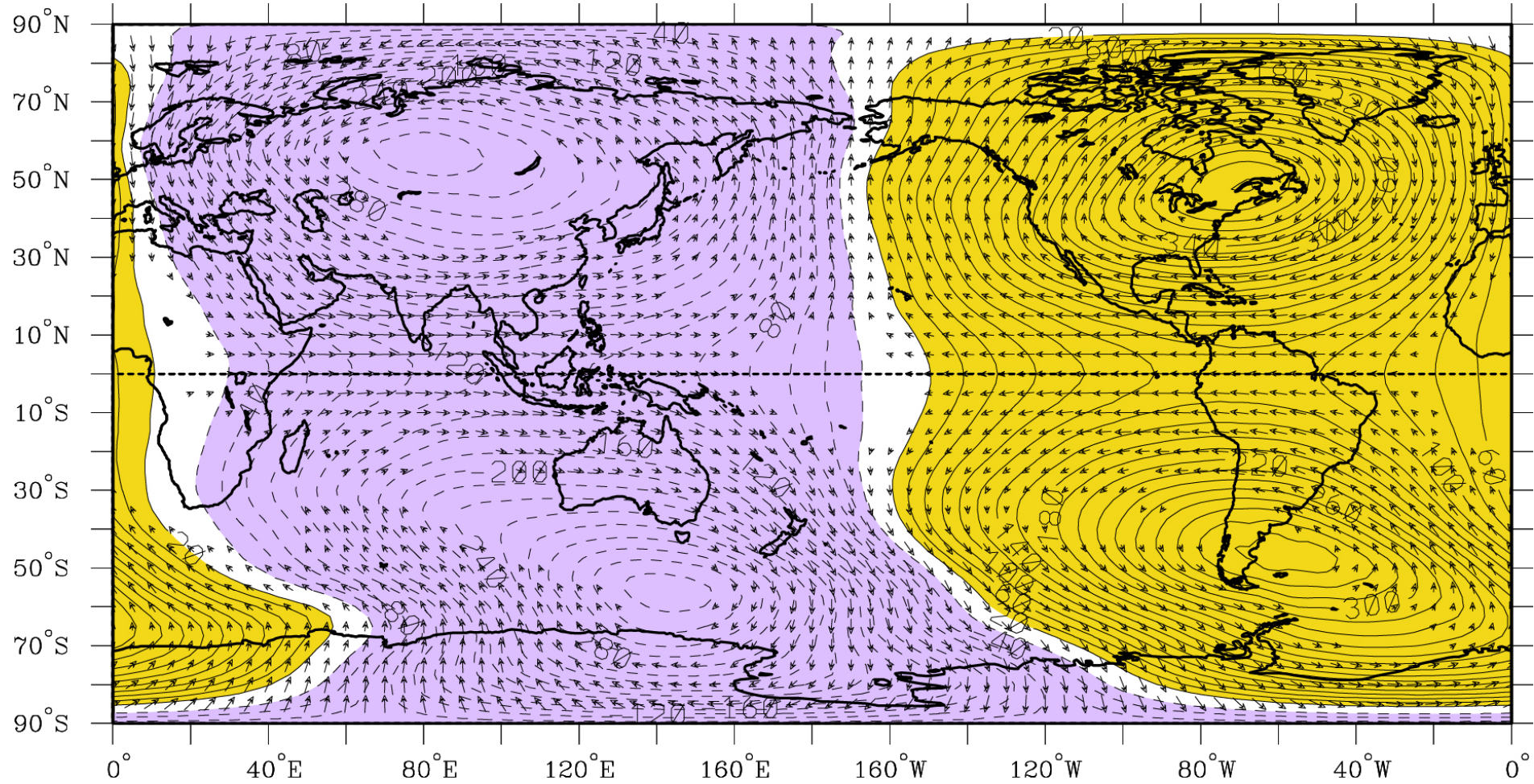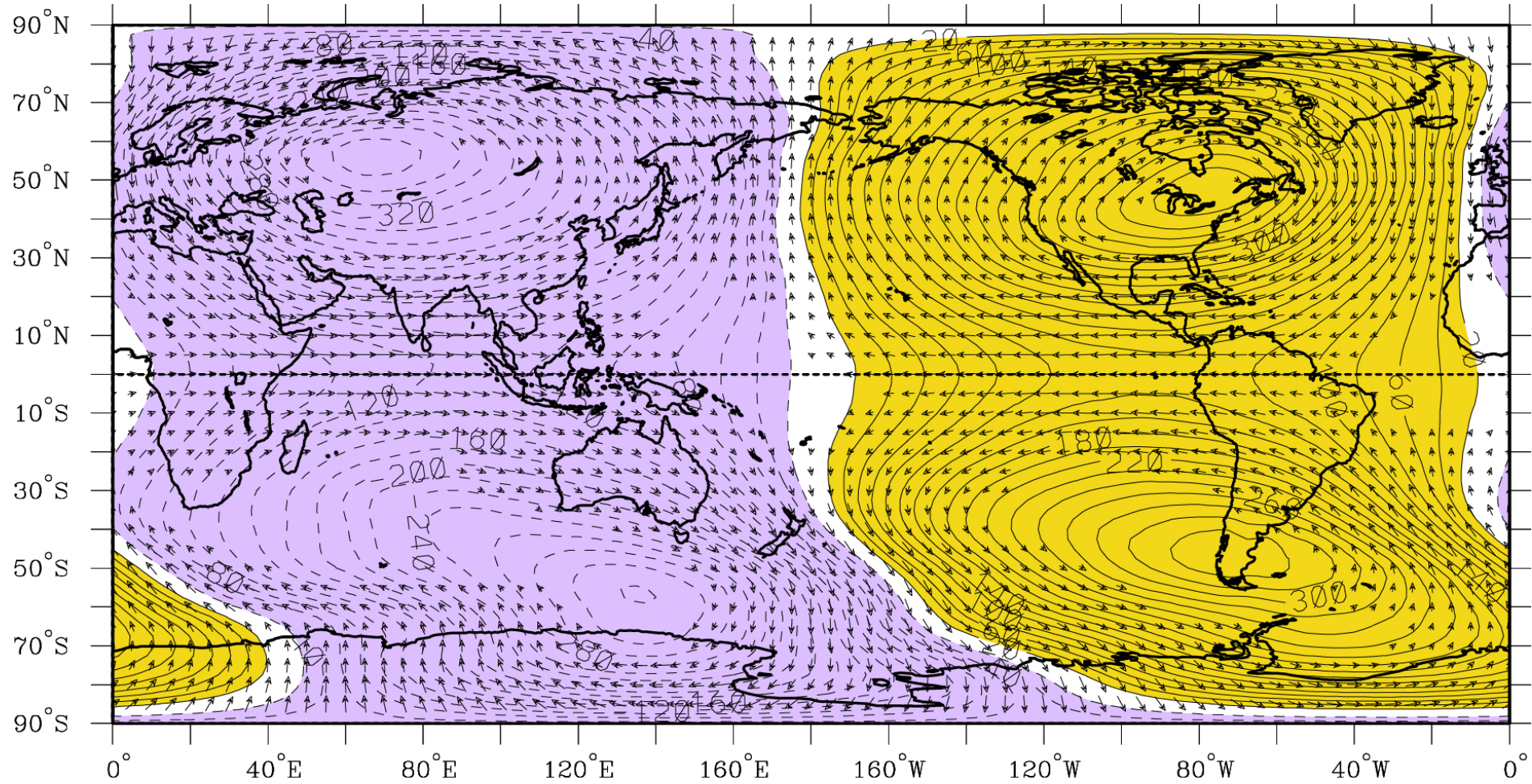


Geopotential (contours 20 X 10$^5$ m$^2$ s$^{-2}$)
Wind (vectors, largest around 2 m s$^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 1 hPa

**Annual**          Day-.75
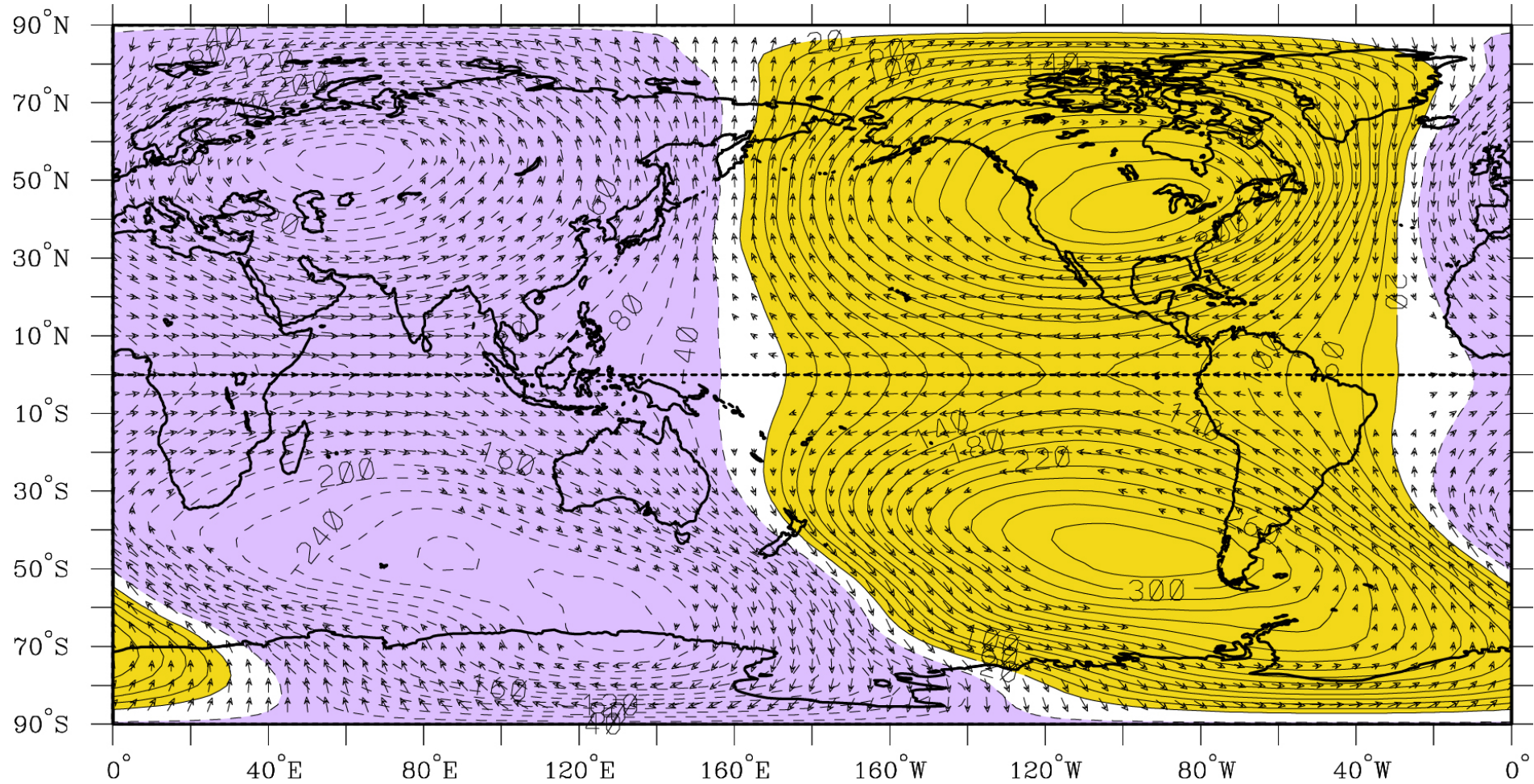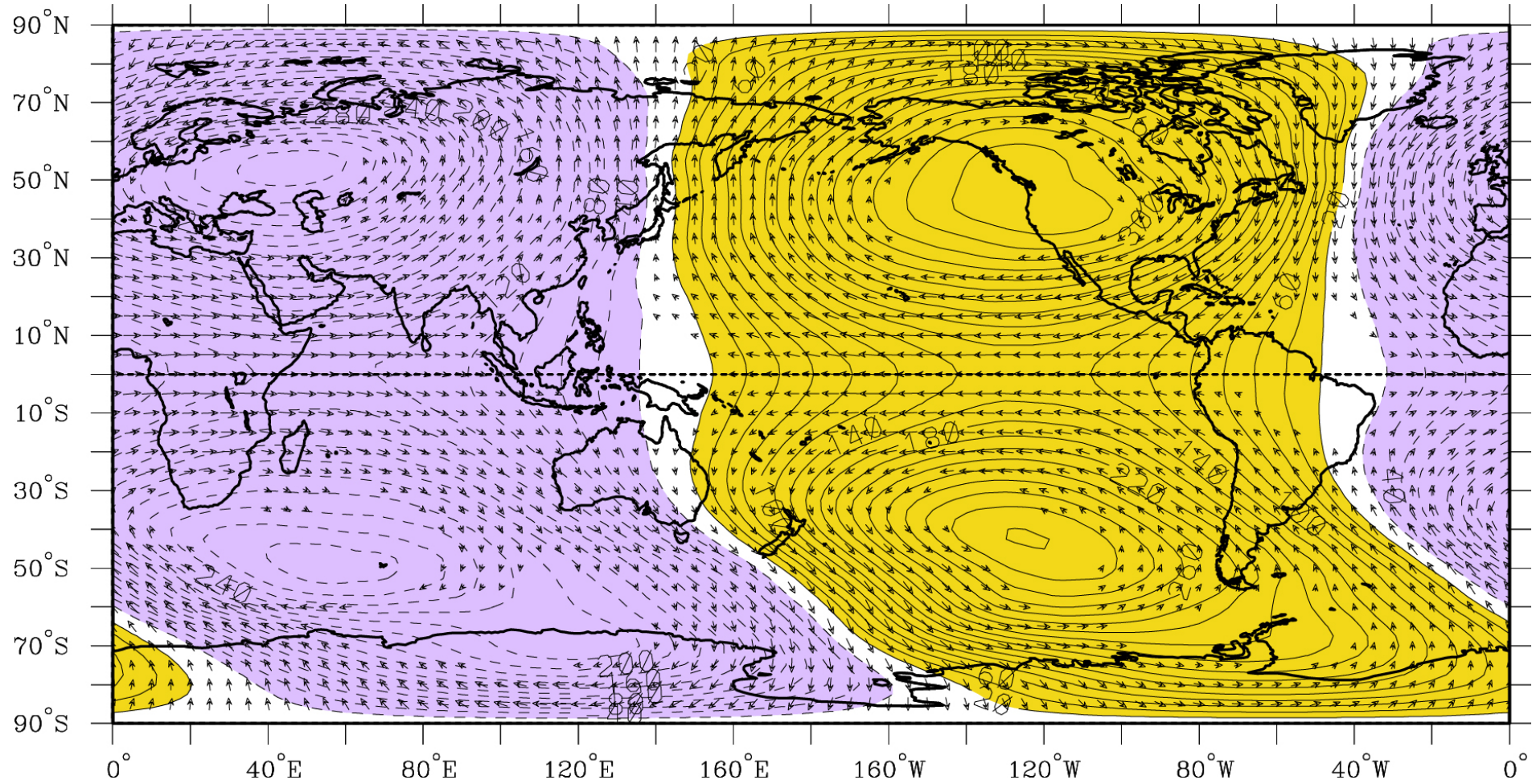


Geopotential (contours 20 X $10^5$ $m^2\,s^{-2}$)
Wind (vectors, largest around 2 $m\,s^{-1}$)

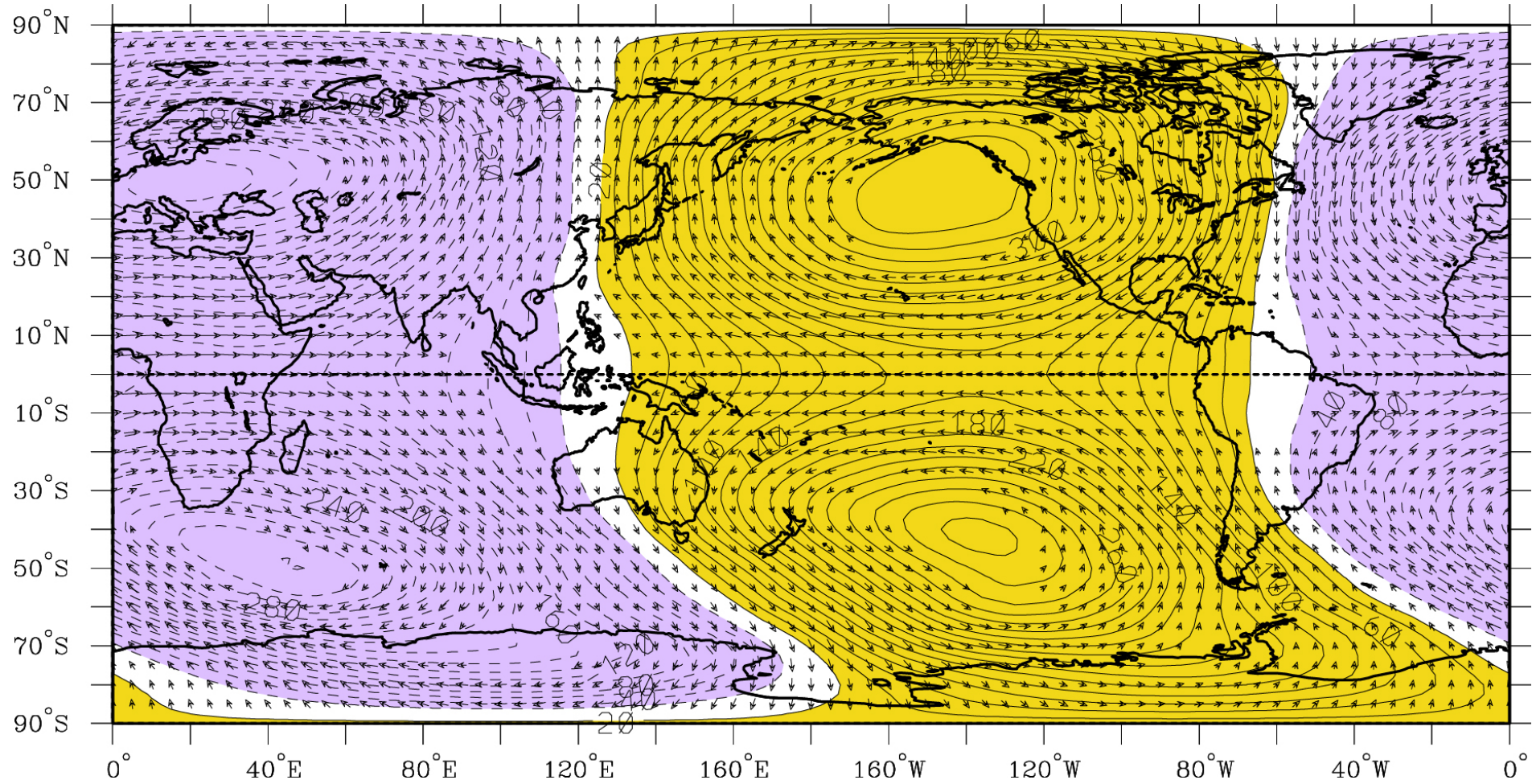First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 1 hPa

**Annual**  Day-.50

Geopotential (contours $20 \times 10^5 \ m^2 \ s^{-2}$)
Wind (vectors, largest around $2 \ m \ s^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 1 hPa
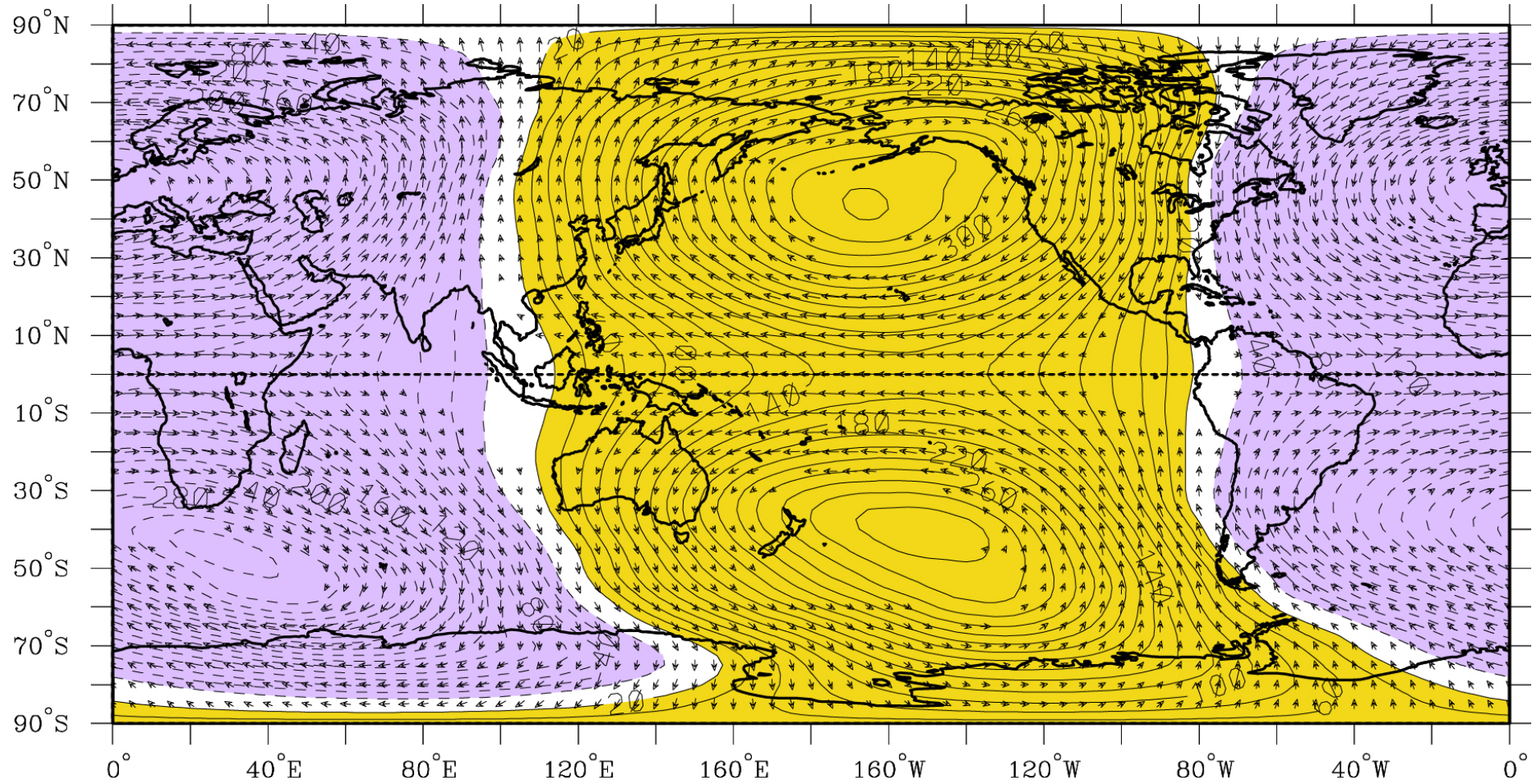
**Annual**           Day-.25



Geopotential (contours 20 X $10^5$ $m^2$ $s^{-2}$)
Wind (vectors, largest around 2 m $s^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 1 hPa

**Annual**                    Day 0



Geopotential (contours 20 X $10^5$ m$^2$ s$^{-2}$)
Wind (vectors, largest around 2 m s$^{-1}$)

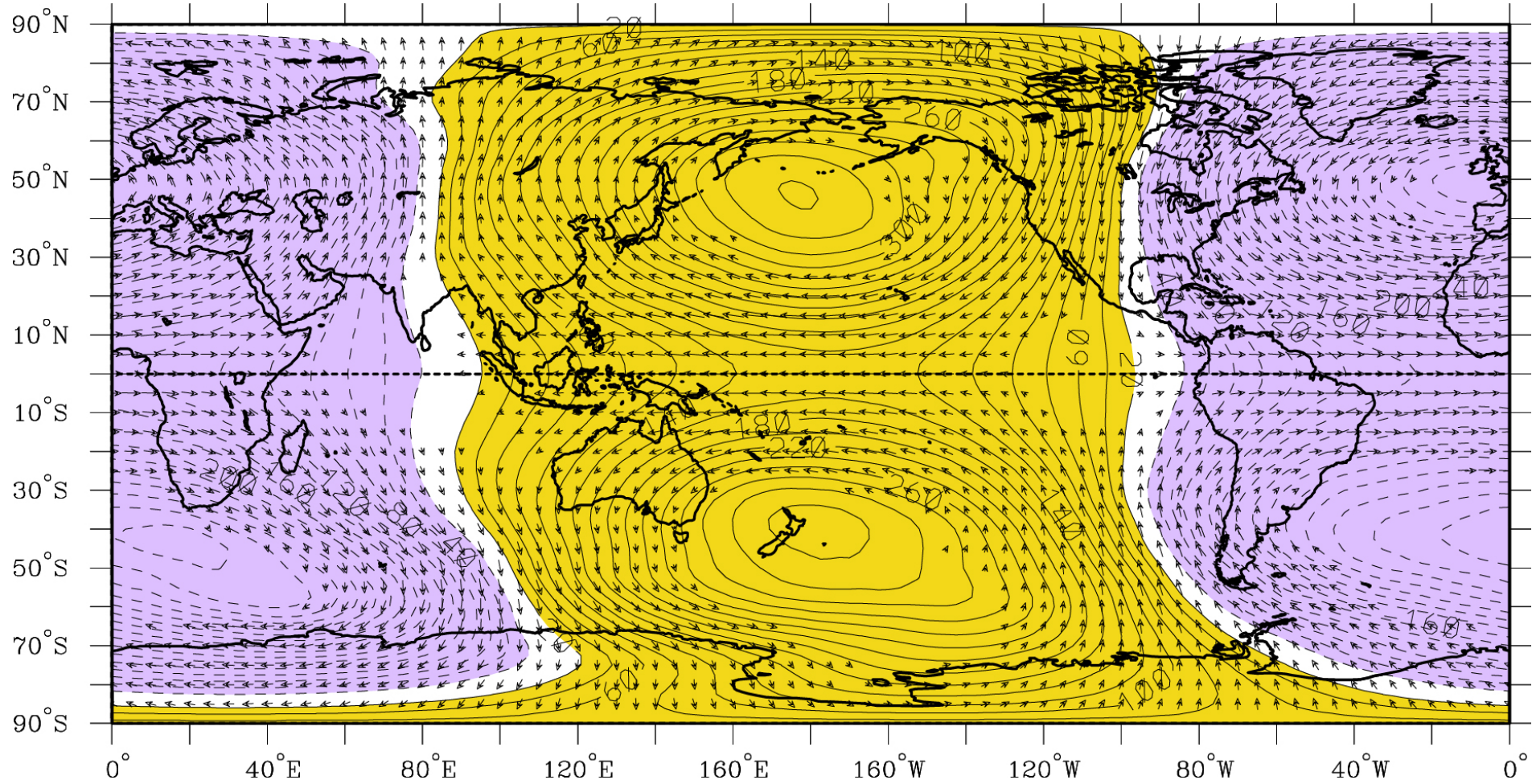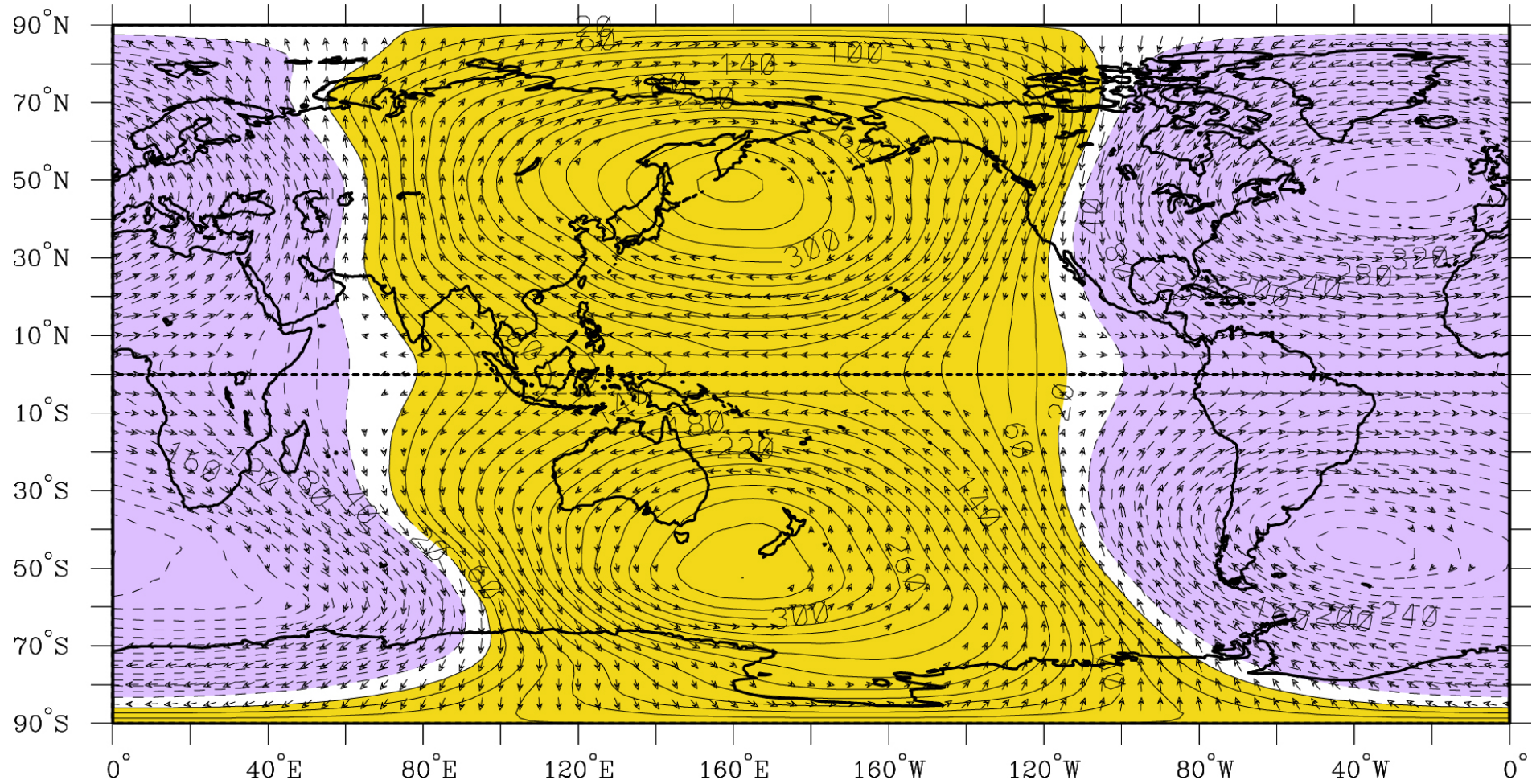First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 1 hPa

**Annual**    Day+.25

Geopotential (contours 20 X $10^5$ $m^2$ $s^{-2}$)
Wind (vectors, largest around 2 m $s^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 1 hPa
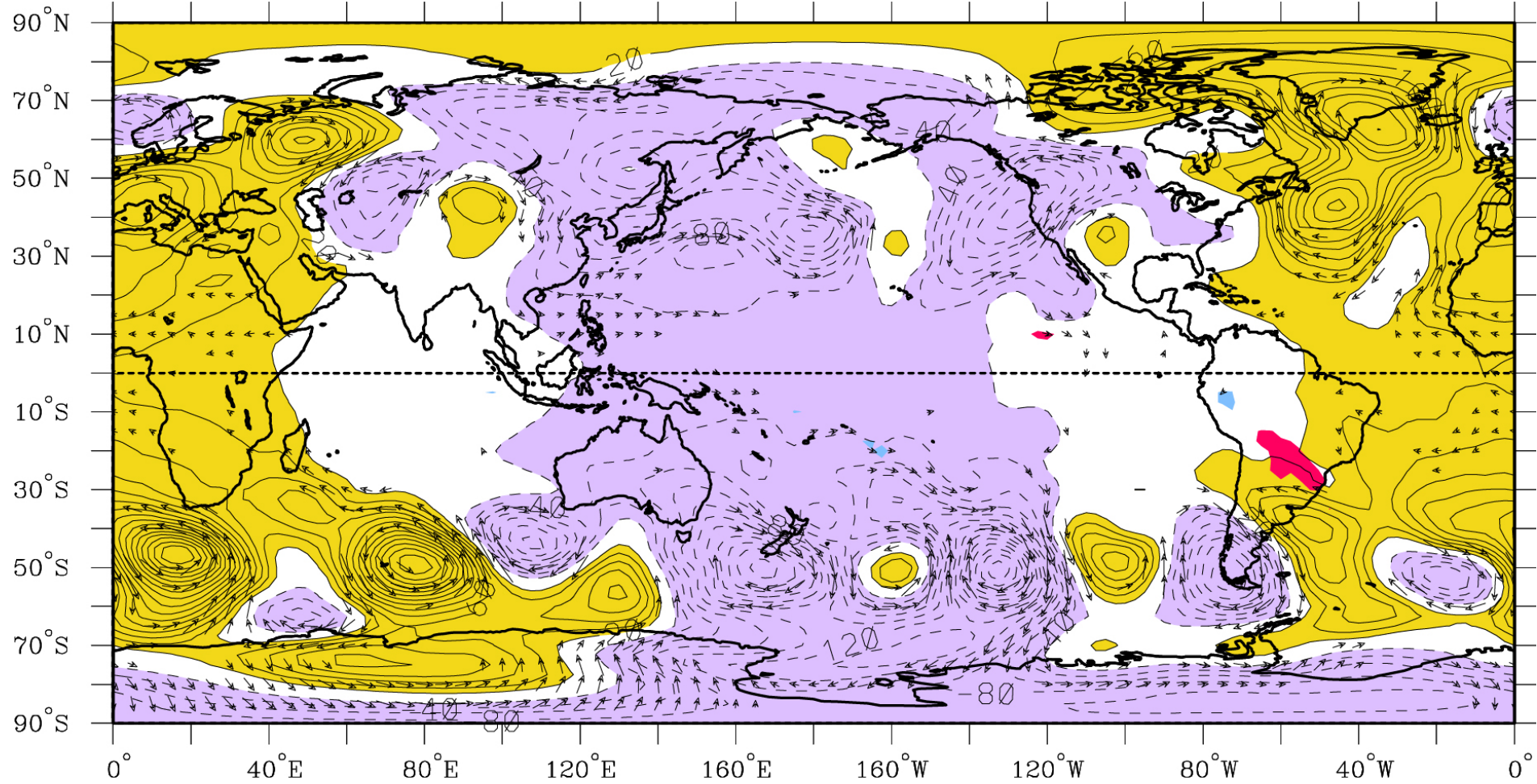
## Annual                            Day+.50



Geopotential (contours 20 X $10^5$ m$^2$ s$^{-2}$)
Wind (vectors, largest around 2 m s$^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 1 hPa

**Annual**  Day+.75



Geopotential (contours 20 X 10$^5$ m$^2$ s$^{-2}$)
Wind (vectors, largest around 2 m s$^{-1}$)

First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 1 hPa

**Annual**                    Day+1

Geopotential (contours 20 X $10^5$ $m^2$ $s^{-2}$)
Wind (vectors, largest around 2 m $s^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa
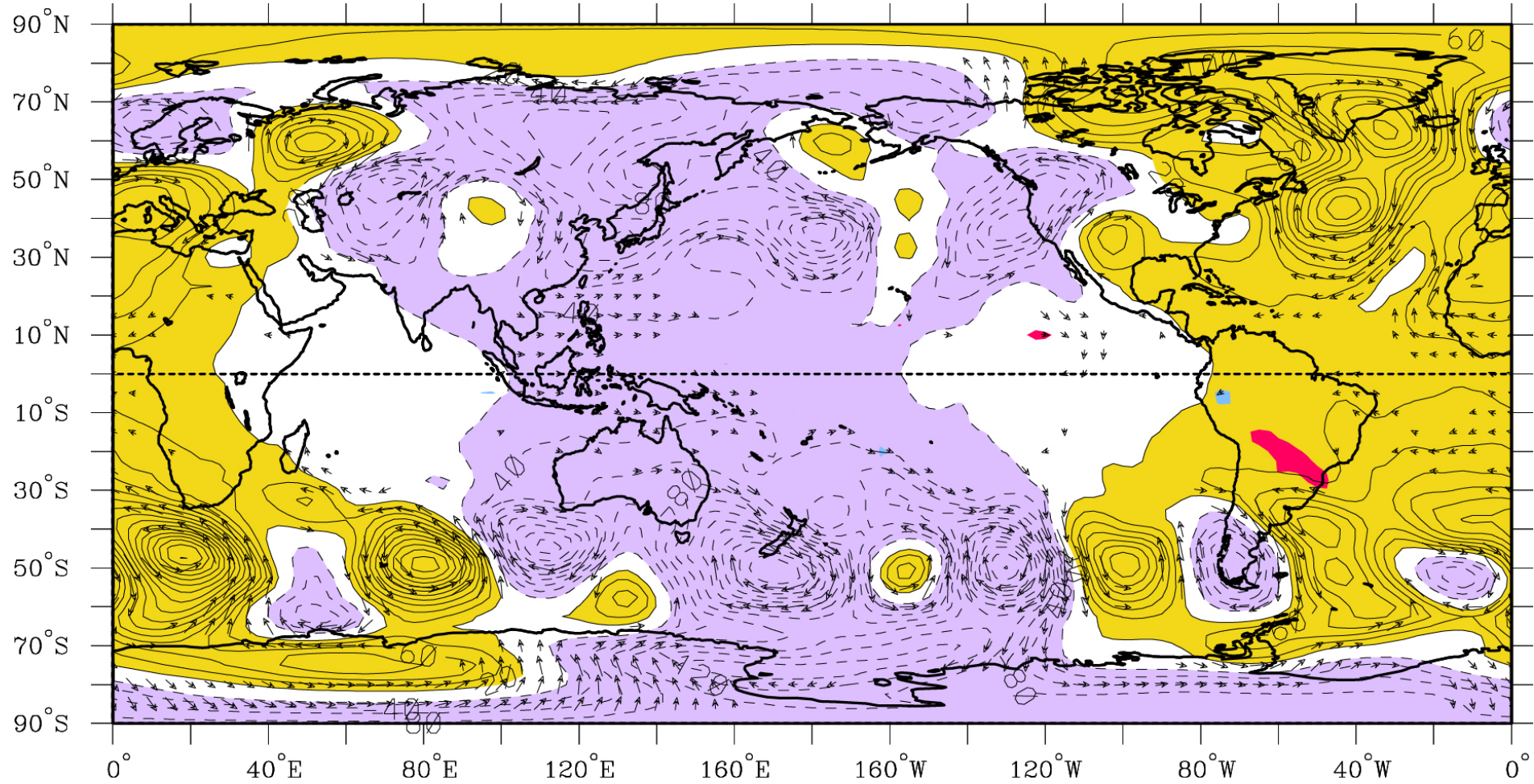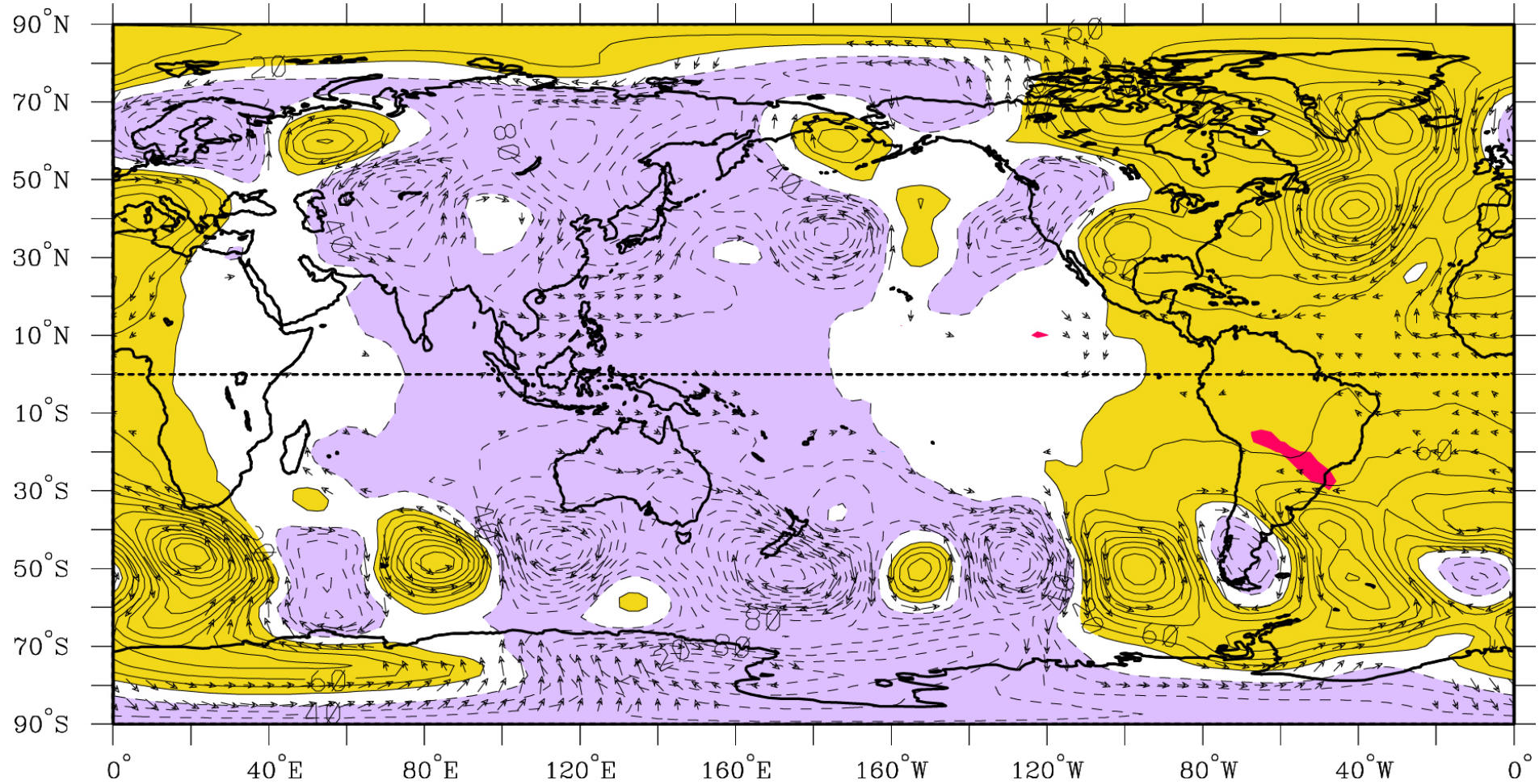
## December-February          Day-2



Geopotential (contours 20 X $10^5$ $m^2$ $s^{-2}$)
Wind (vectors, largest around 2 m $s^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa
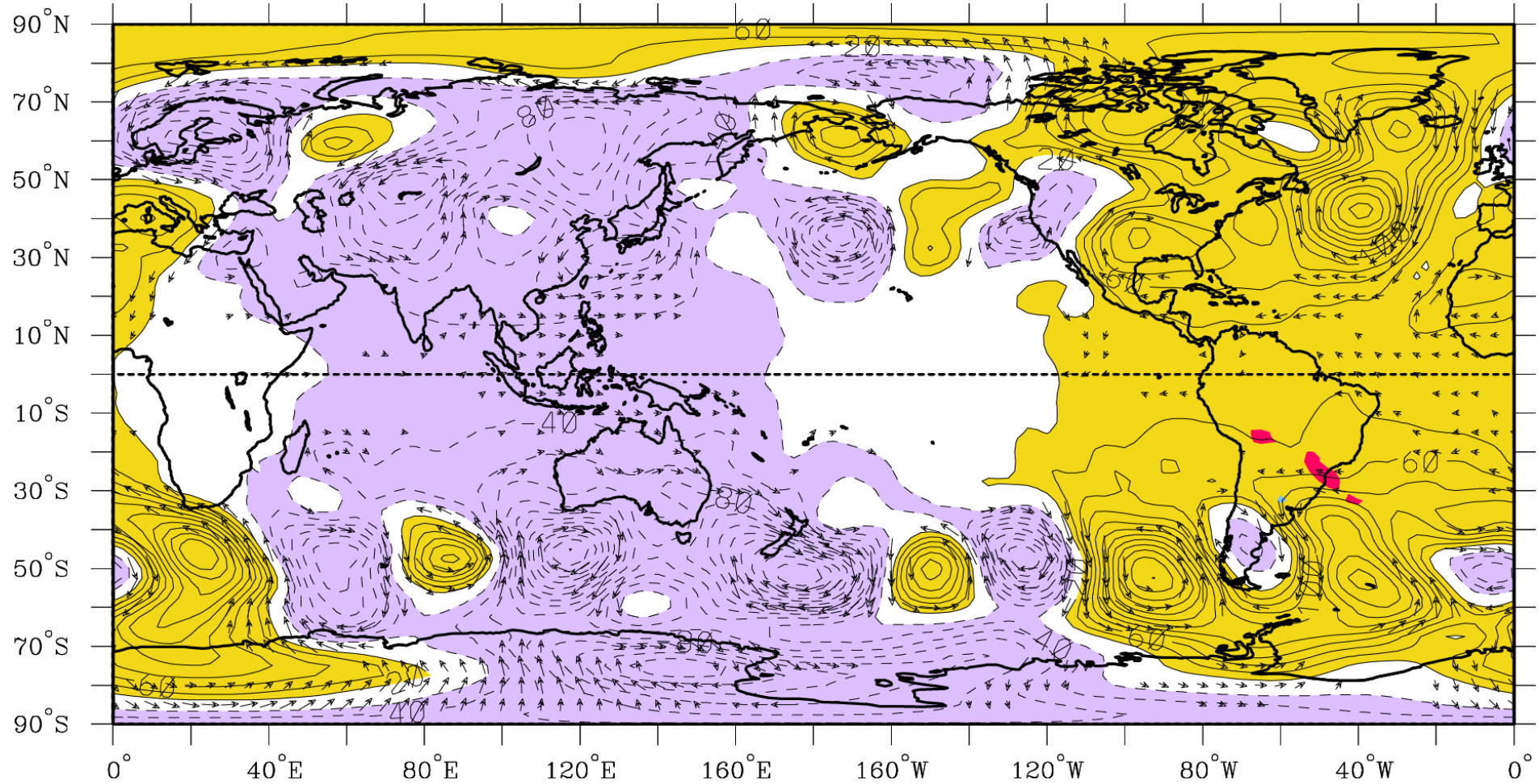
**December-February**     Day-1.75



Geopotential (contours 20 X 10$^5$ m$^2$ s$^{-2}$)
Wind (vectors, largest around 2 m s$^{-1}$)

First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa
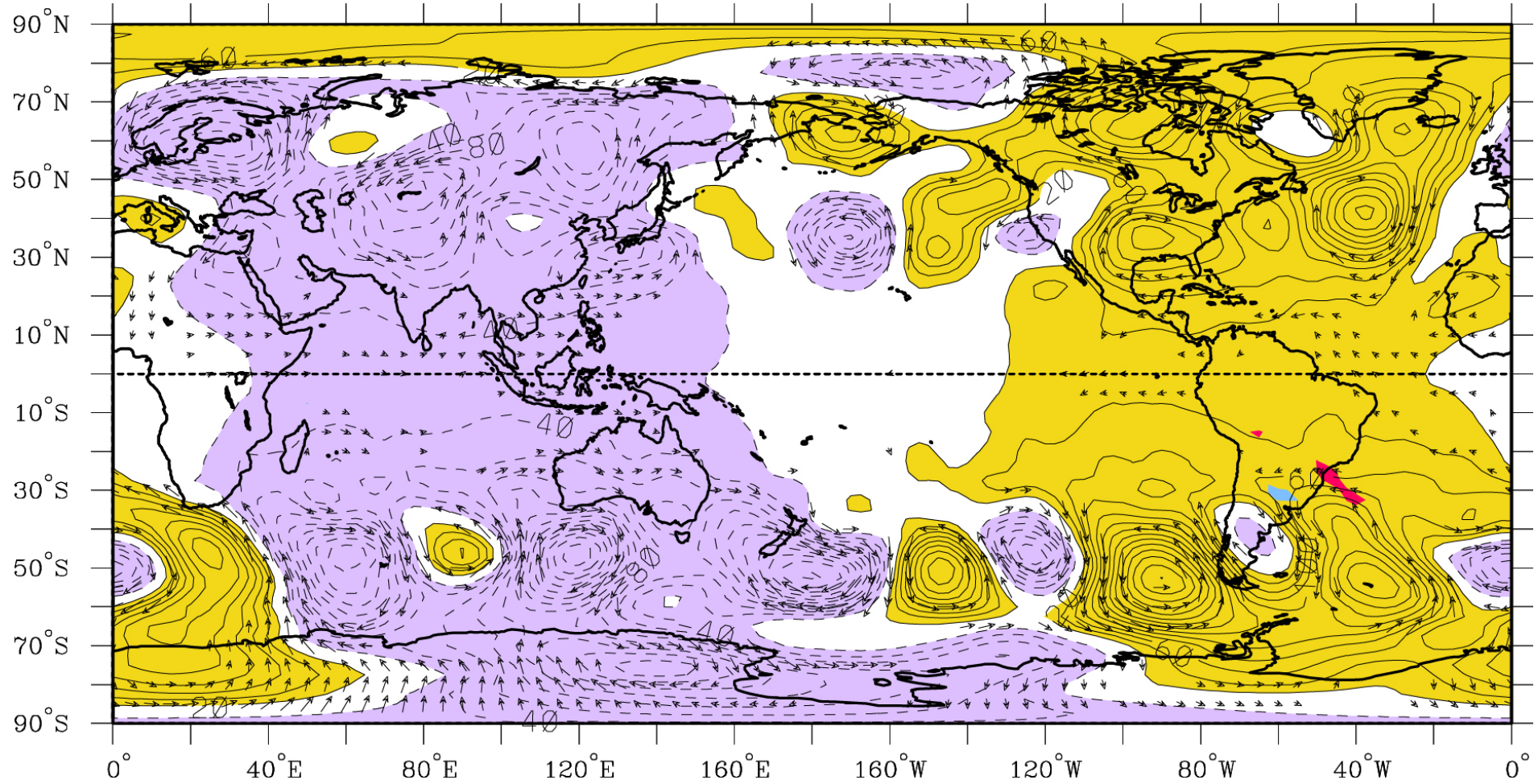
**December-February**      Day-1.50

Geopotential (contours 20 X 10$^5$ m$^2$ s$^{-2}$)
Wind (vectors, largest around 2 m s$^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa
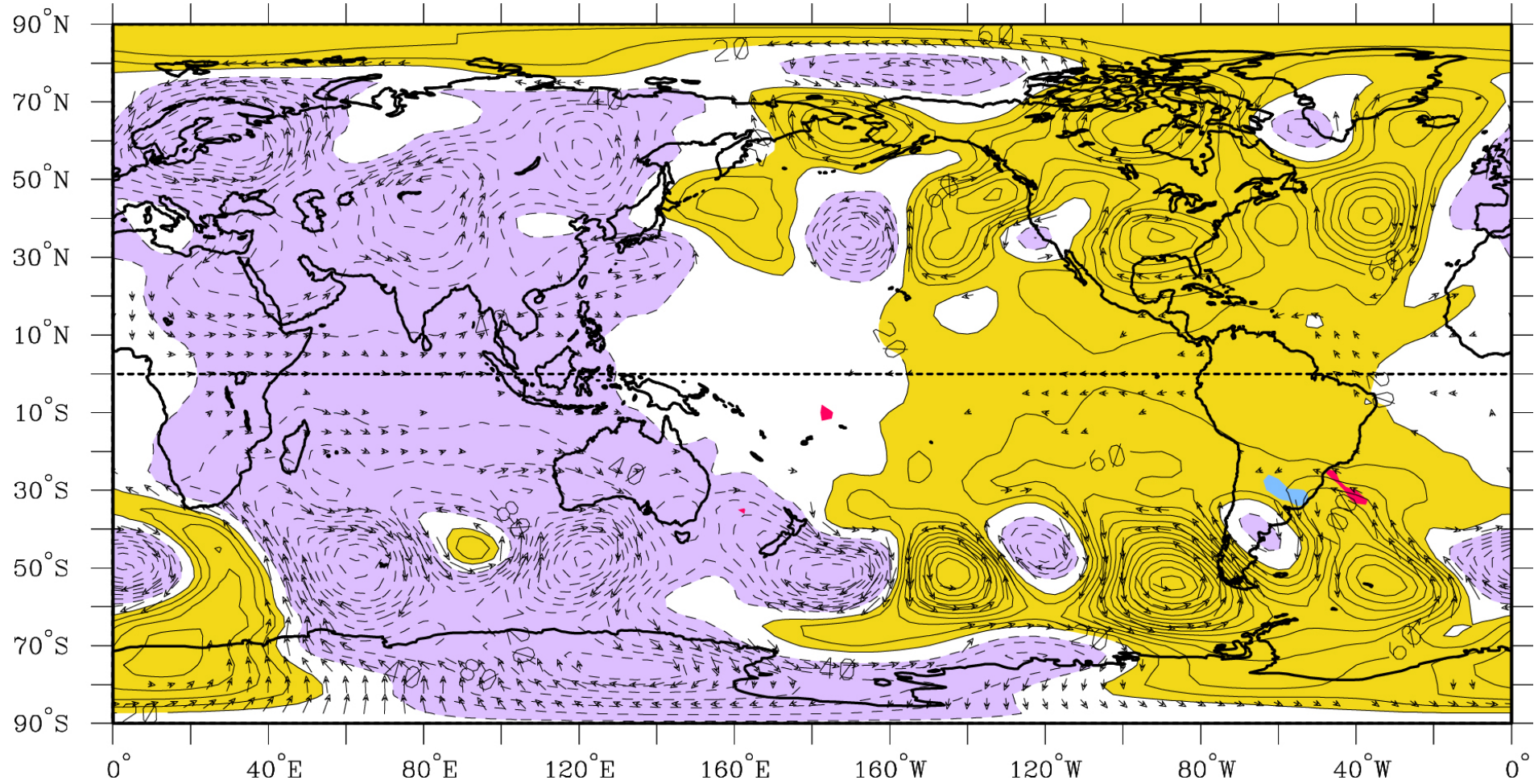
## December-February        Day-1.25



Geopotential (contours 20 X $10^5$ m$^2$ s$^{-2}$)
Wind (vectors, largest around 2 m s$^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa
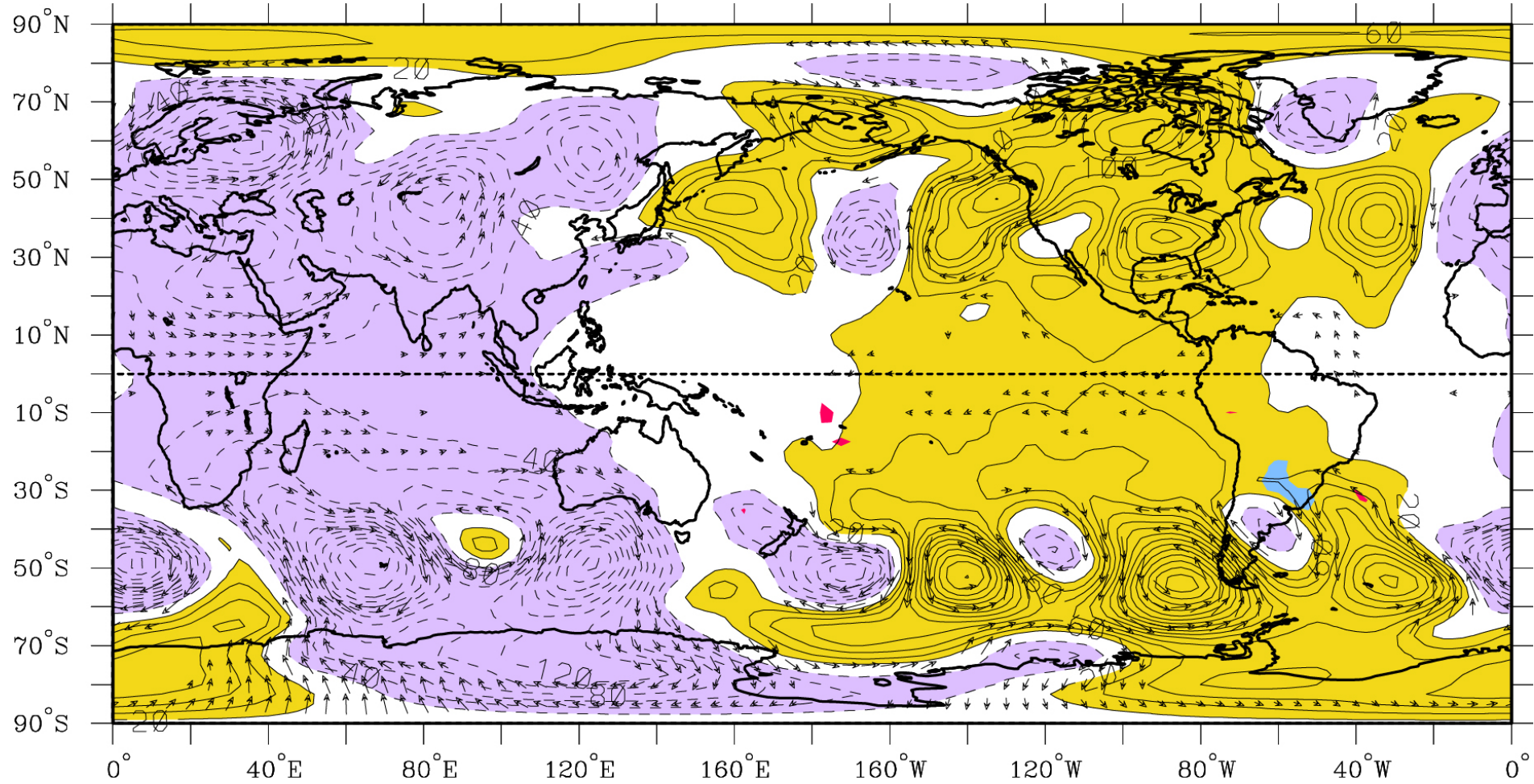
## December-February          Day-1



Geopotential (contours 20 X $10^5$ m$^2$ s$^{-2}$)
Wind (vectors, largest around 2 m s$^{-1}$)

First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa
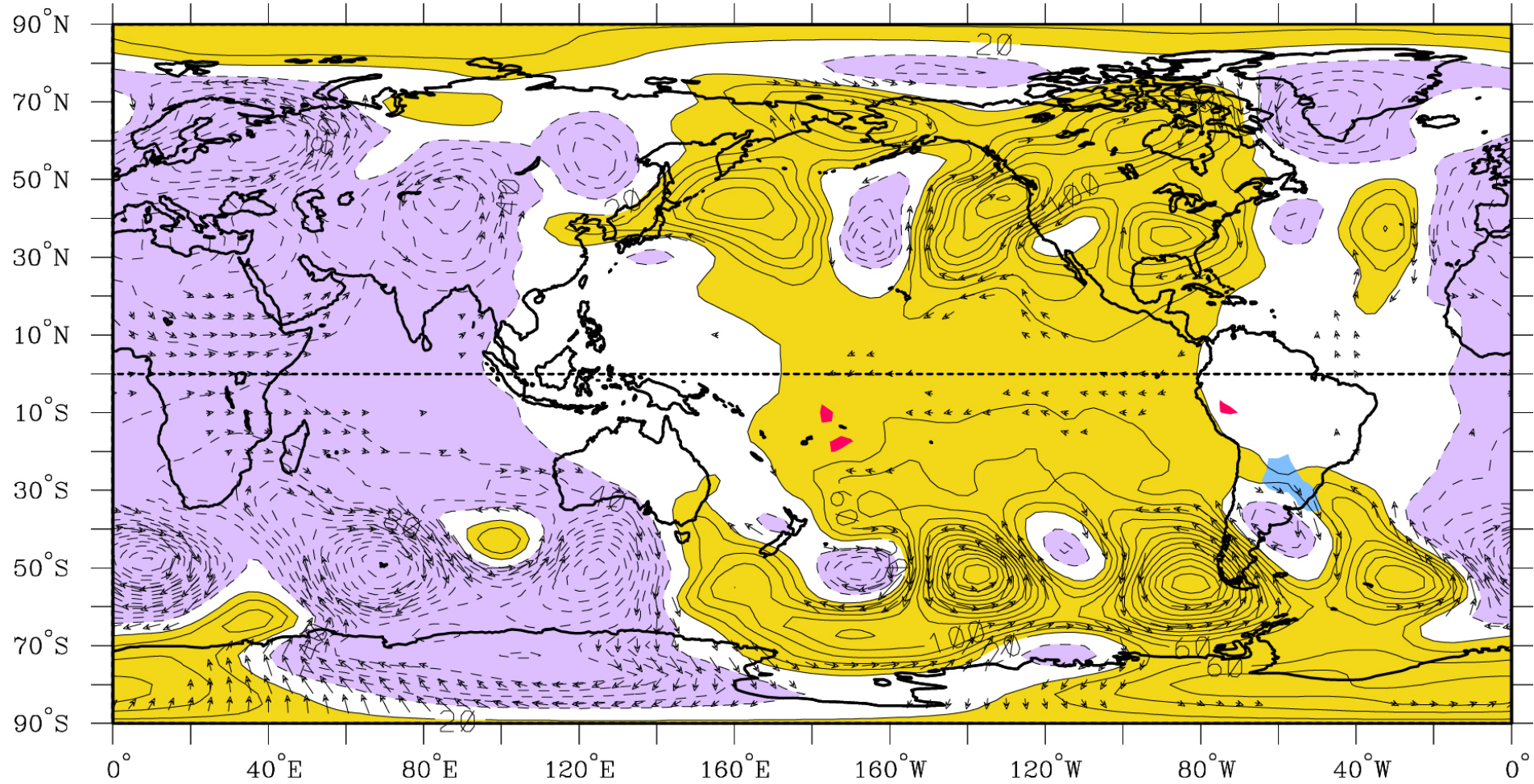
**December-February**    Day-.75



Geopotential (contours 20 X 10$^5$ m$^2$ s$^{-2}$)
Wind (vectors, largest around 2 m s$^{-1}$)

First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa
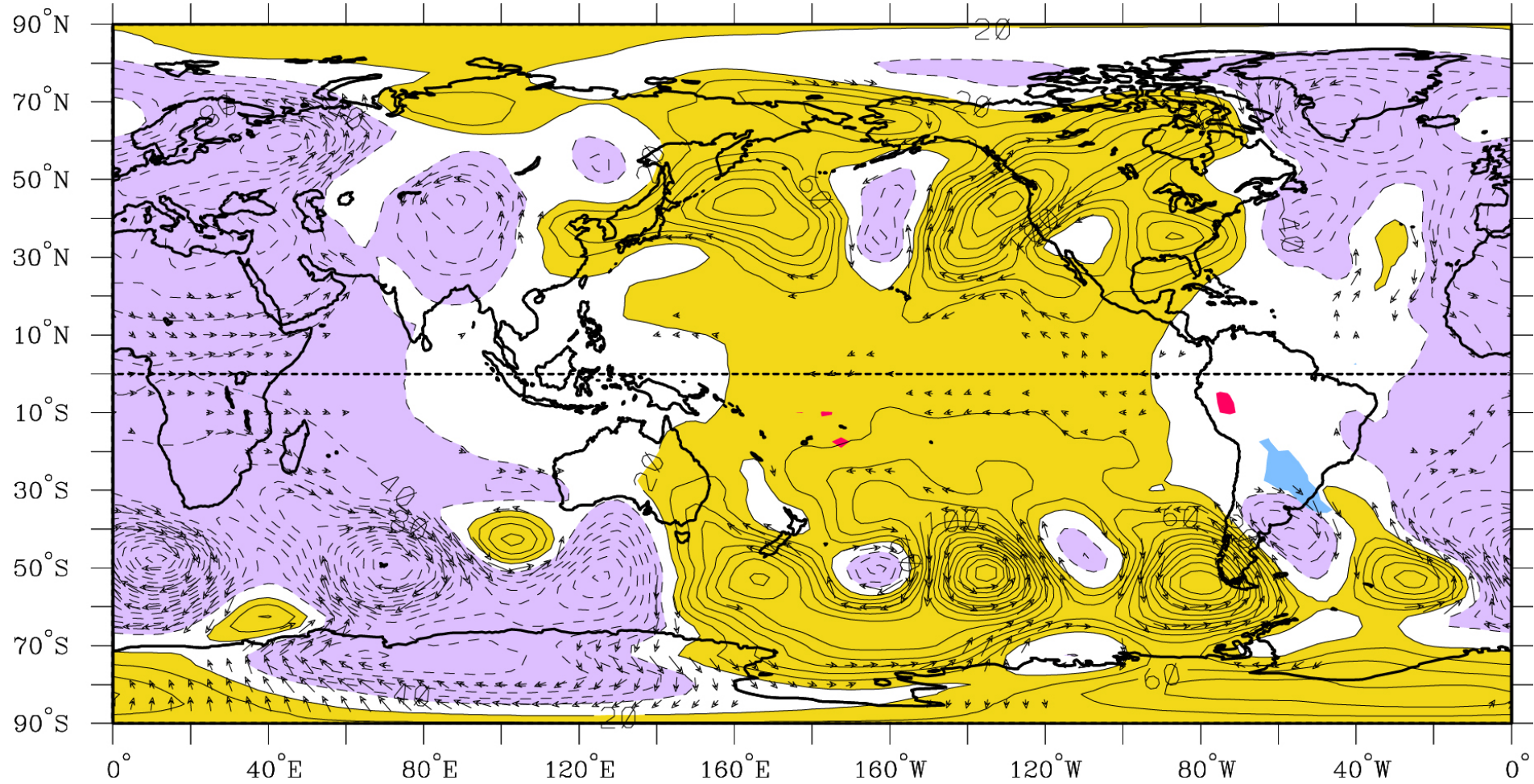
**December-February**        Day-.50

Geopotential (contours 20 X 10$^5$ m$^2$ s$^{-2}$)
Wind (vectors, largest around 2 m s$^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa
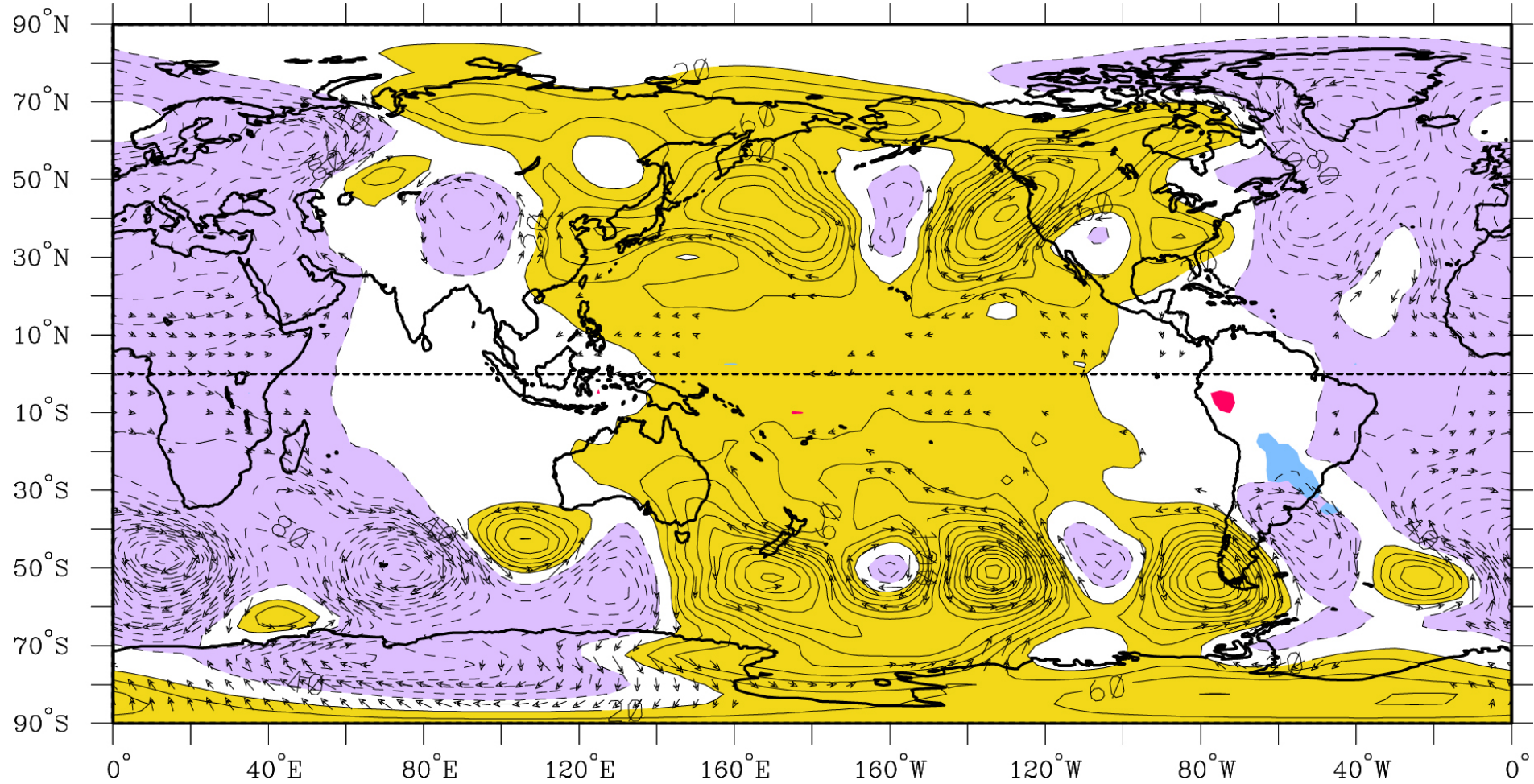
## December-February          Day-.25



Geopotential (contours 20 X $10^5$ $m^2 s^{-2}$)
Wind (vectors, largest around 2 m $s^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa
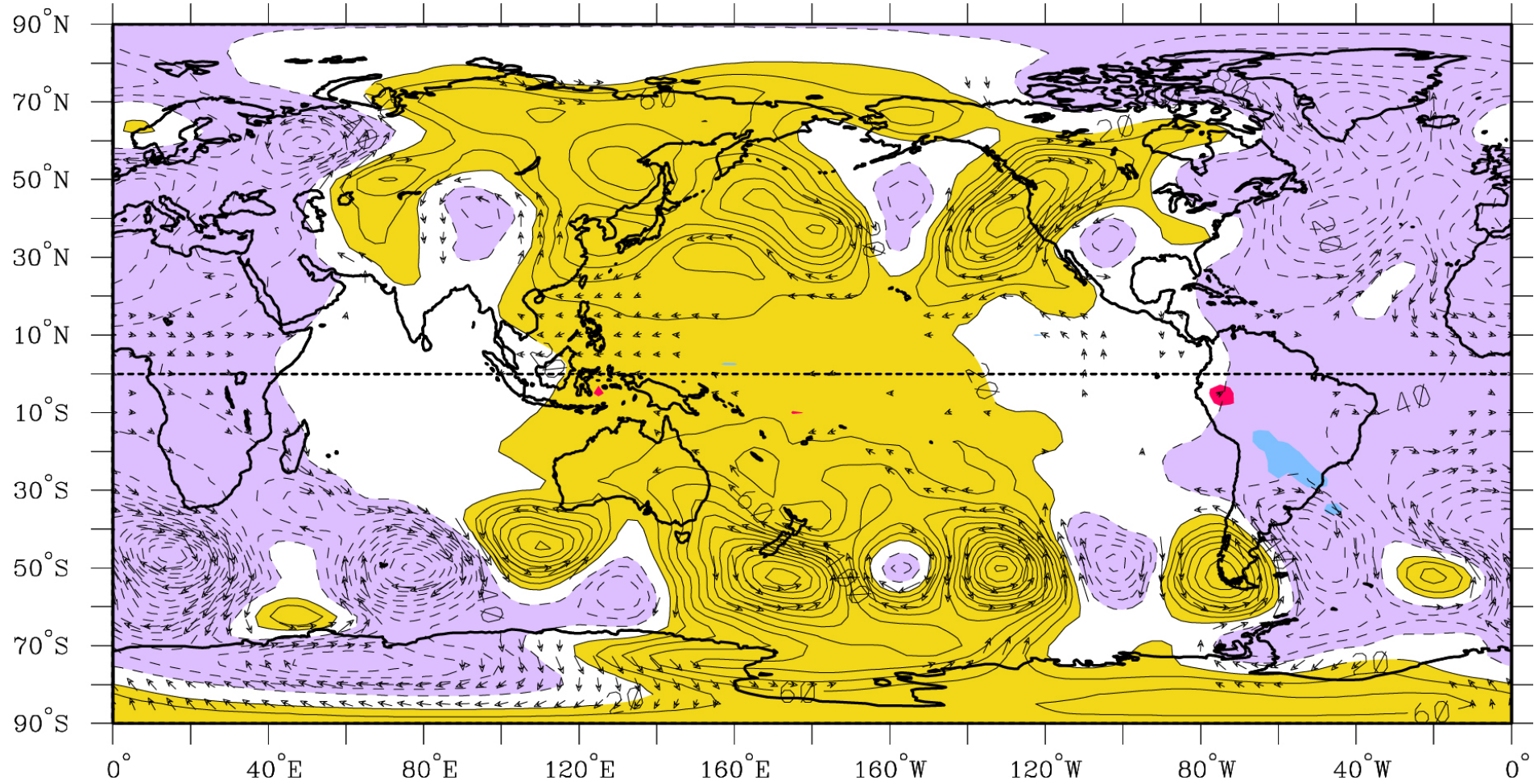
## December-February          Day 0



Geopotential (contours 20 X 10$^5$ m$^2$ s$^{-2}$)
Wind (vectors, largest around 2 m s$^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa
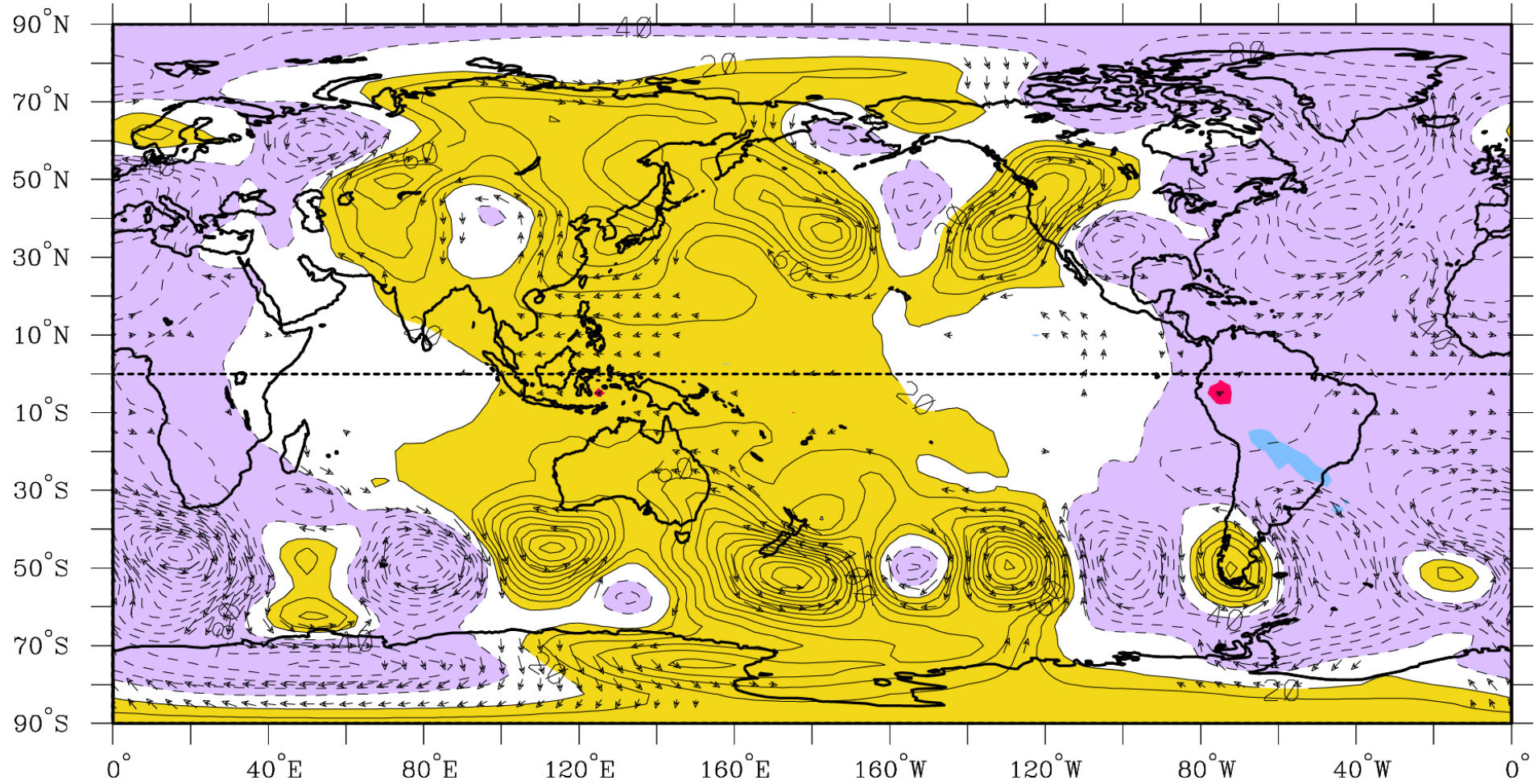
## December-February     Day+.25



Geopotential (contours 20 X 10$^5$ m$^2$ s$^{-2}$)
Wind (vectors, largest around 2 m s$^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa
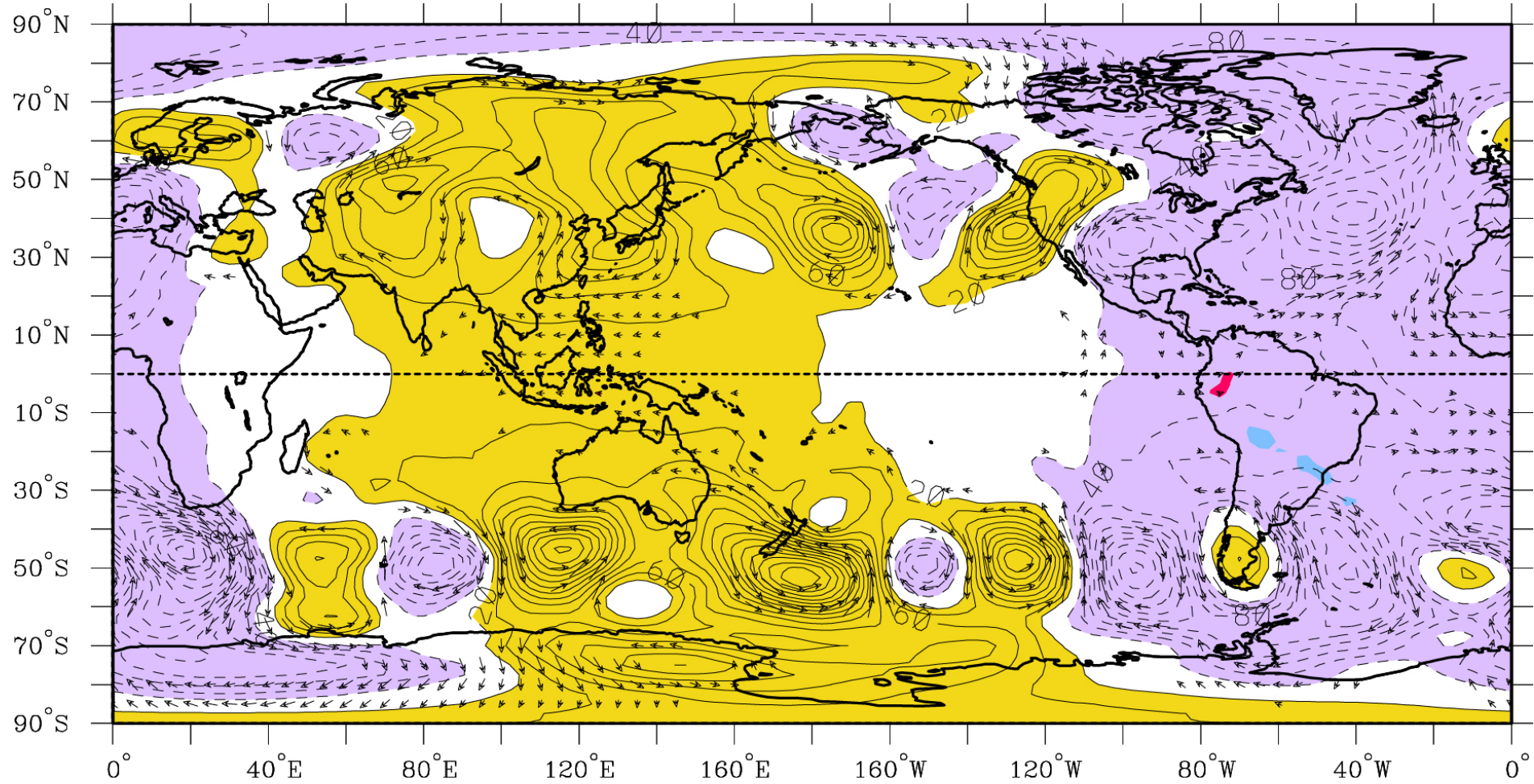
## December-February        Day+.50



Geopotential (contours 20 X $10^5$ $m^2$ $s^{-2}$)
Wind (vectors, largest around 2 m $s^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa
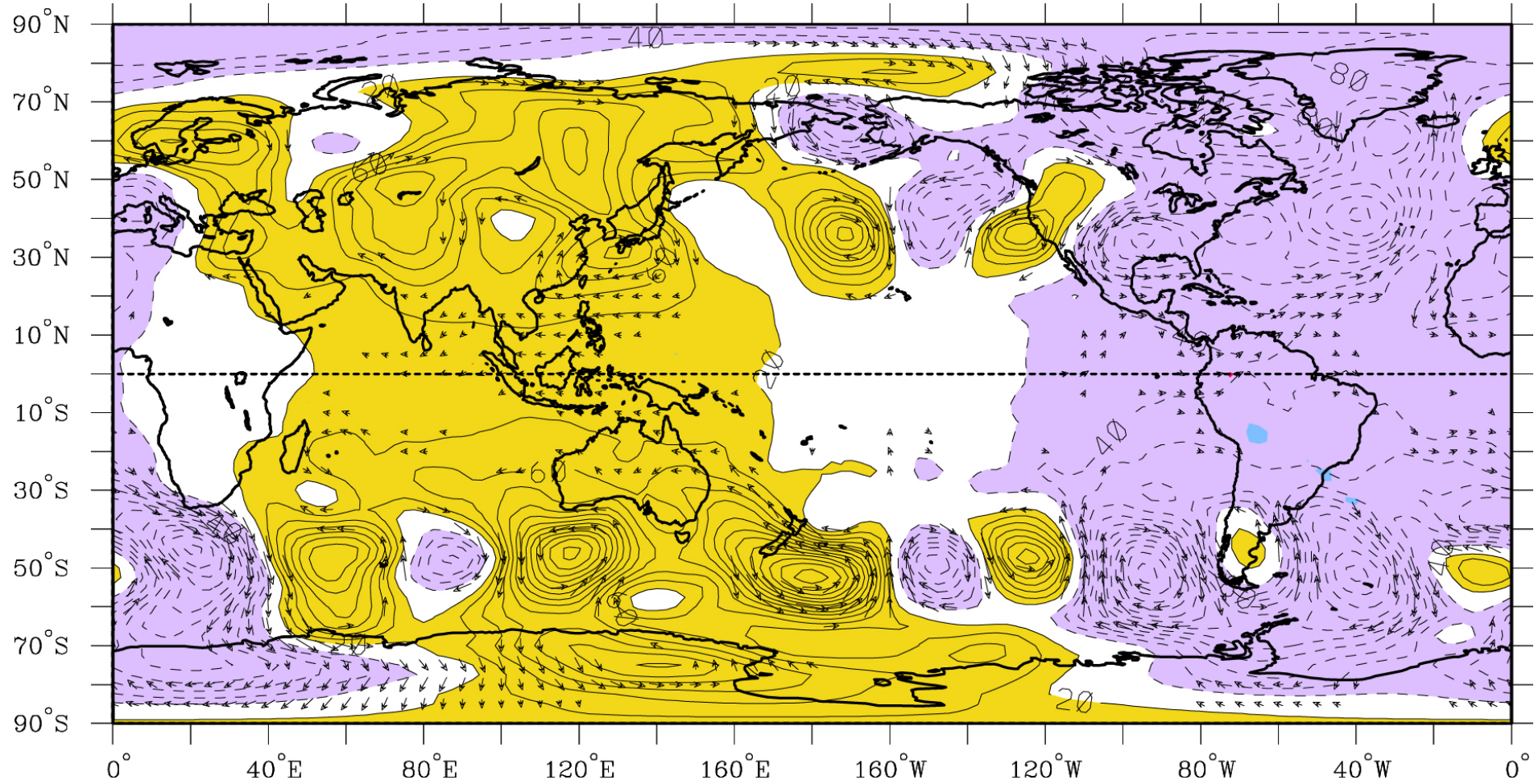
## December-February          Day+.75



Geopotential (contours 20 X 10$^5$ m$^2$ s$^{-2}$)
Wind (vectors, largest around 2 m s$^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa
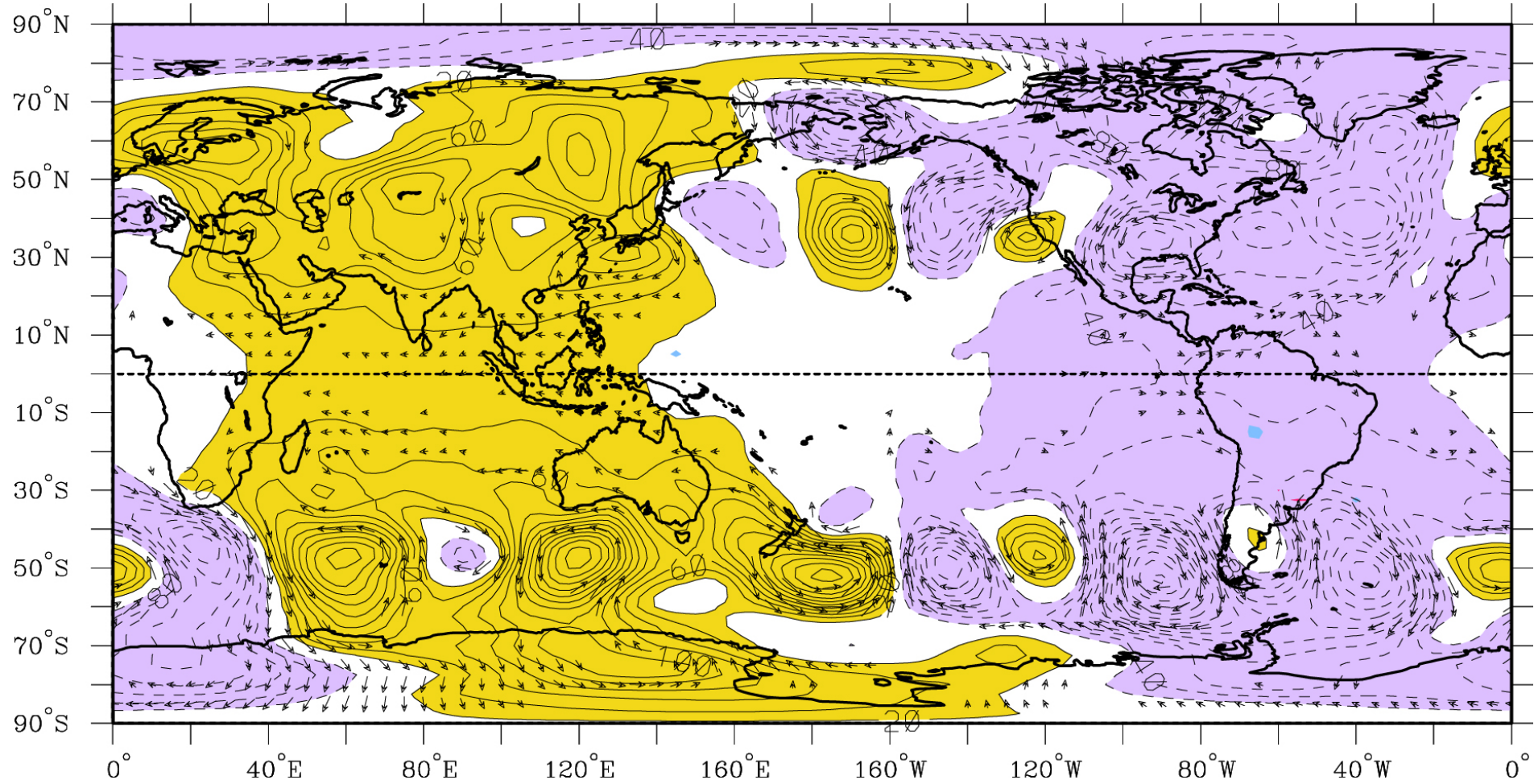
## December-February        Day+1



Geopotential (contours 20 X 10$^5$ m$^2$ s$^{-2}$)
Wind (vectors, largest around 2 m s$^{-1}$)

First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa
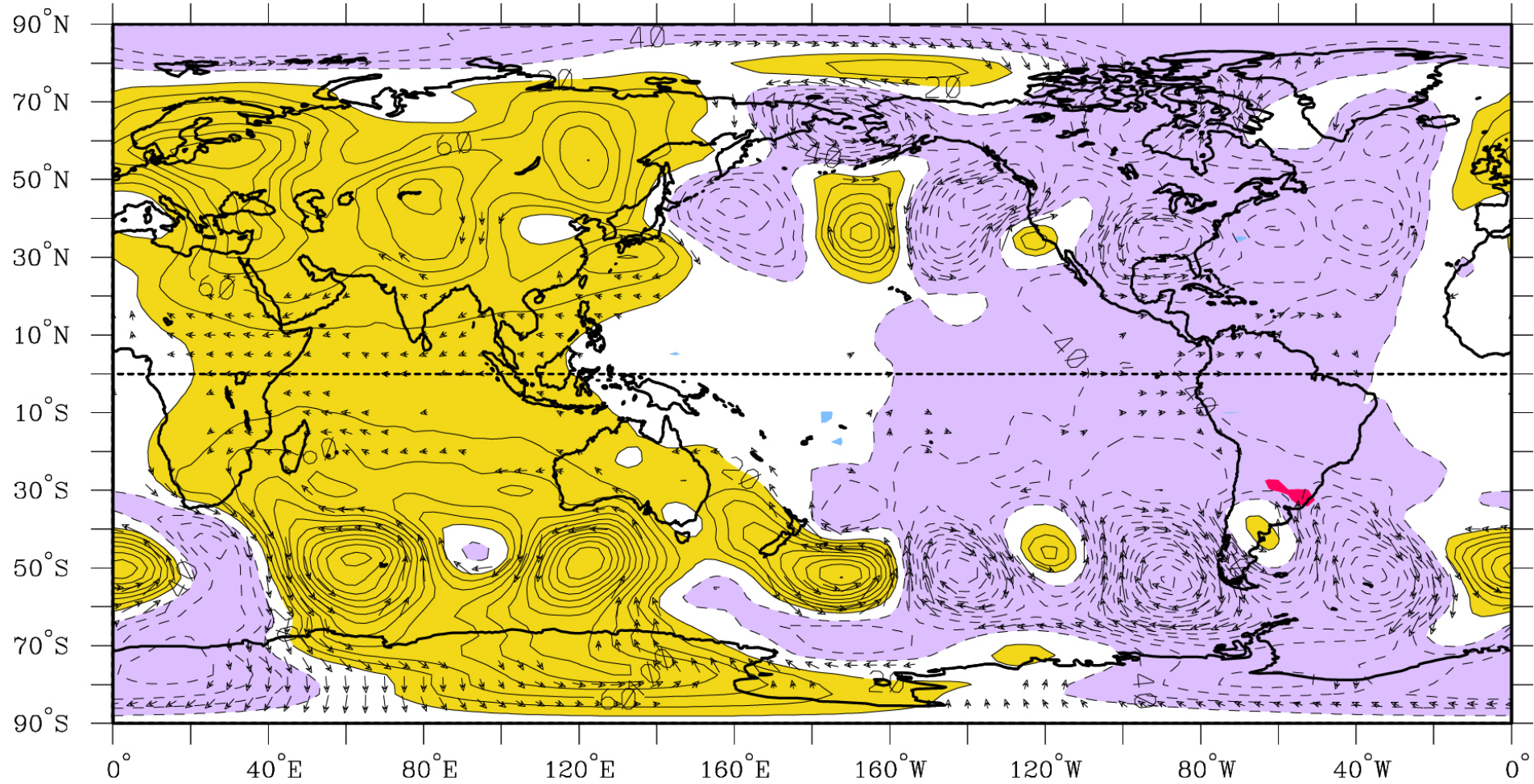
**December-February**     Day+1.25

Geopotential (contours 20 X $10^5$ $m^2$ $s^{-2}$)
Wind (vectors, largest around 2 $m$ $s^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa
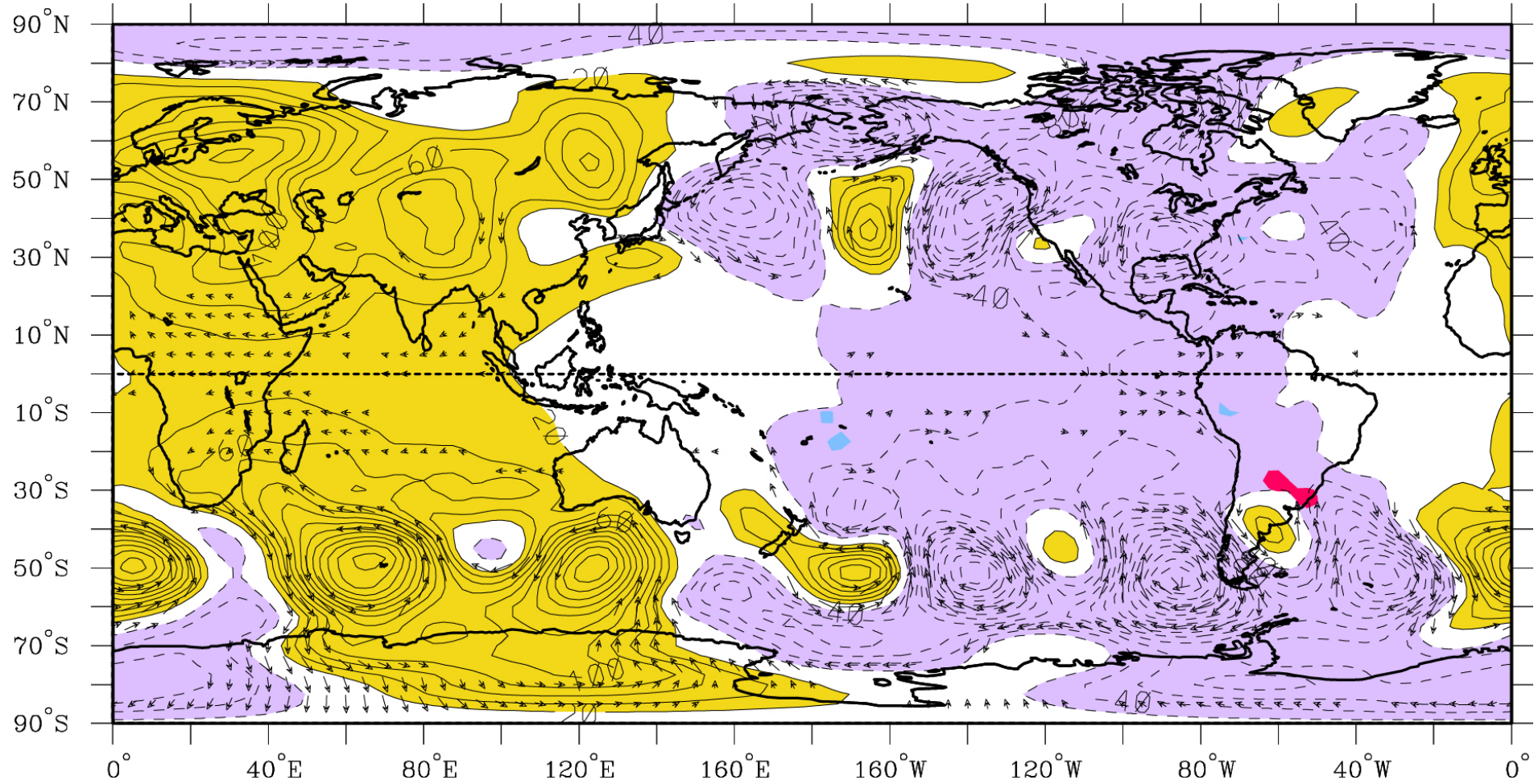
## December-February       Day+1.50



Geopotential (contours 20 X $10^5$ $m^2$ $s^{-2}$)
Wind (vectors, largest around 2 m $s^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa
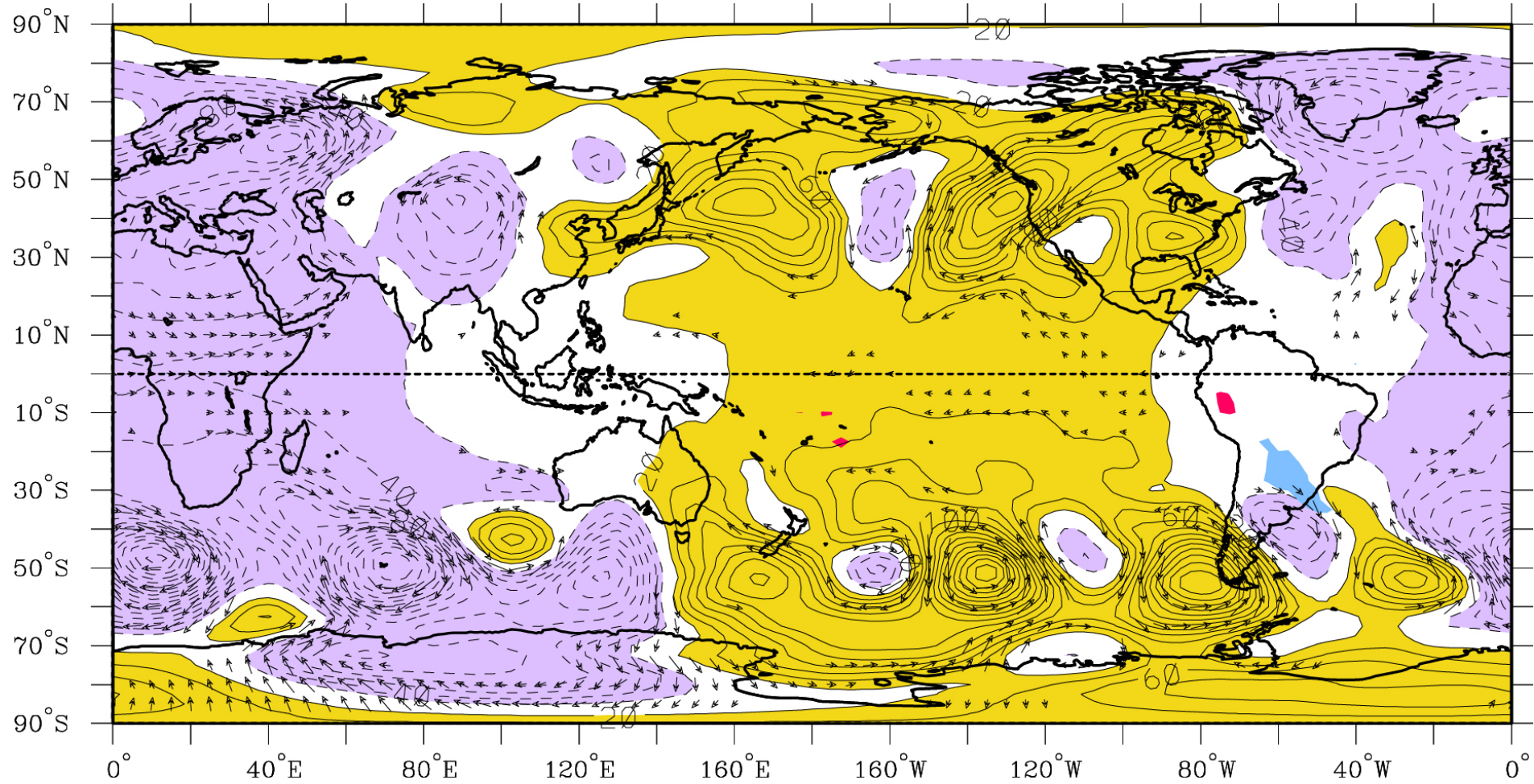
## December-February          Day+1.75



Geopotential (contours 20 X $10^5$ $m^2$ $s^{-2}$)
Wind (vectors, largest around 2 $m$ $s^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa

## December-February    Day+2.00



Geopotential (contours 20 X $10^5$ $m^2$ $s^{-2}$)
Wind (vectors, largest around 2 m $s^{-1}$)

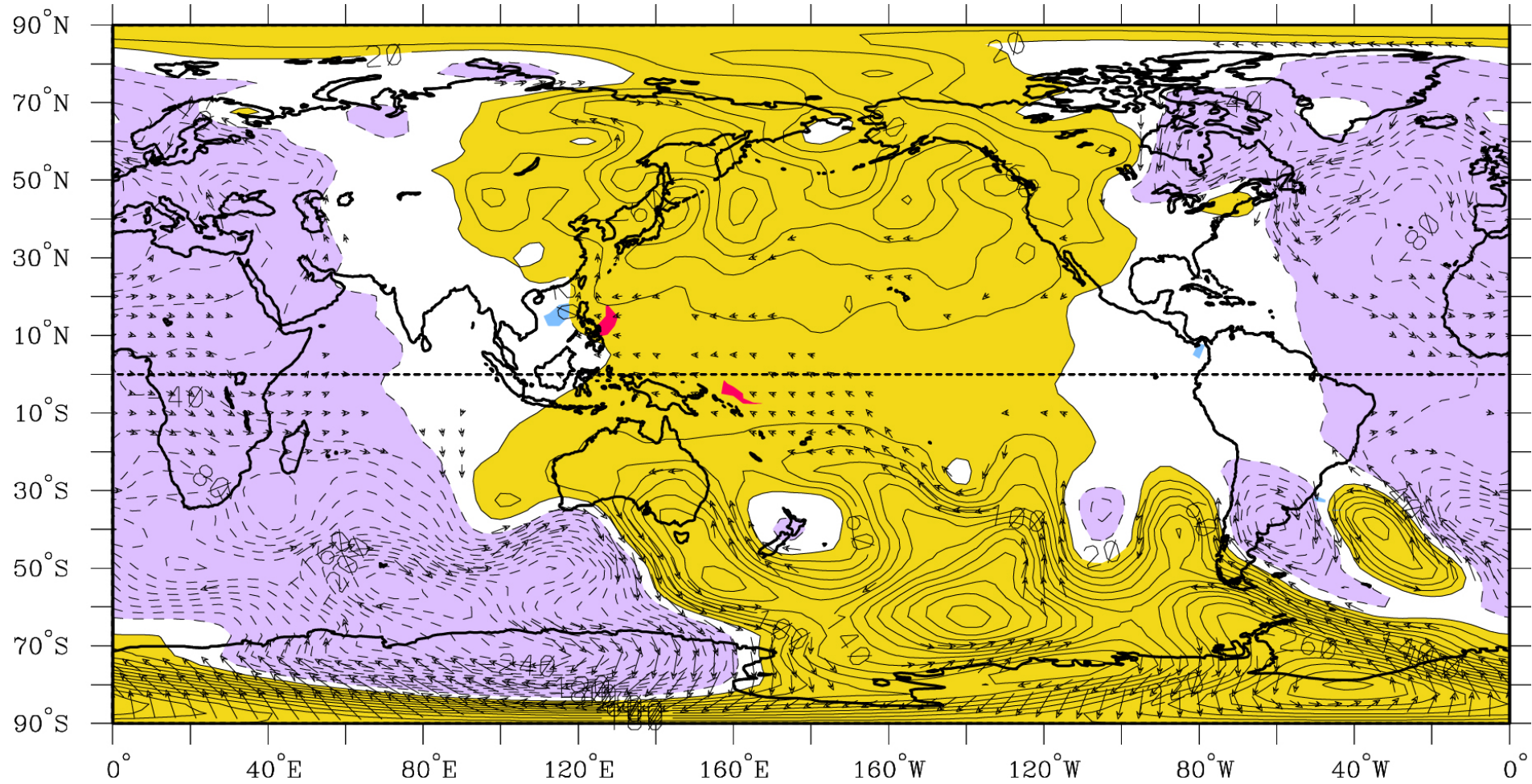First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa

December-February

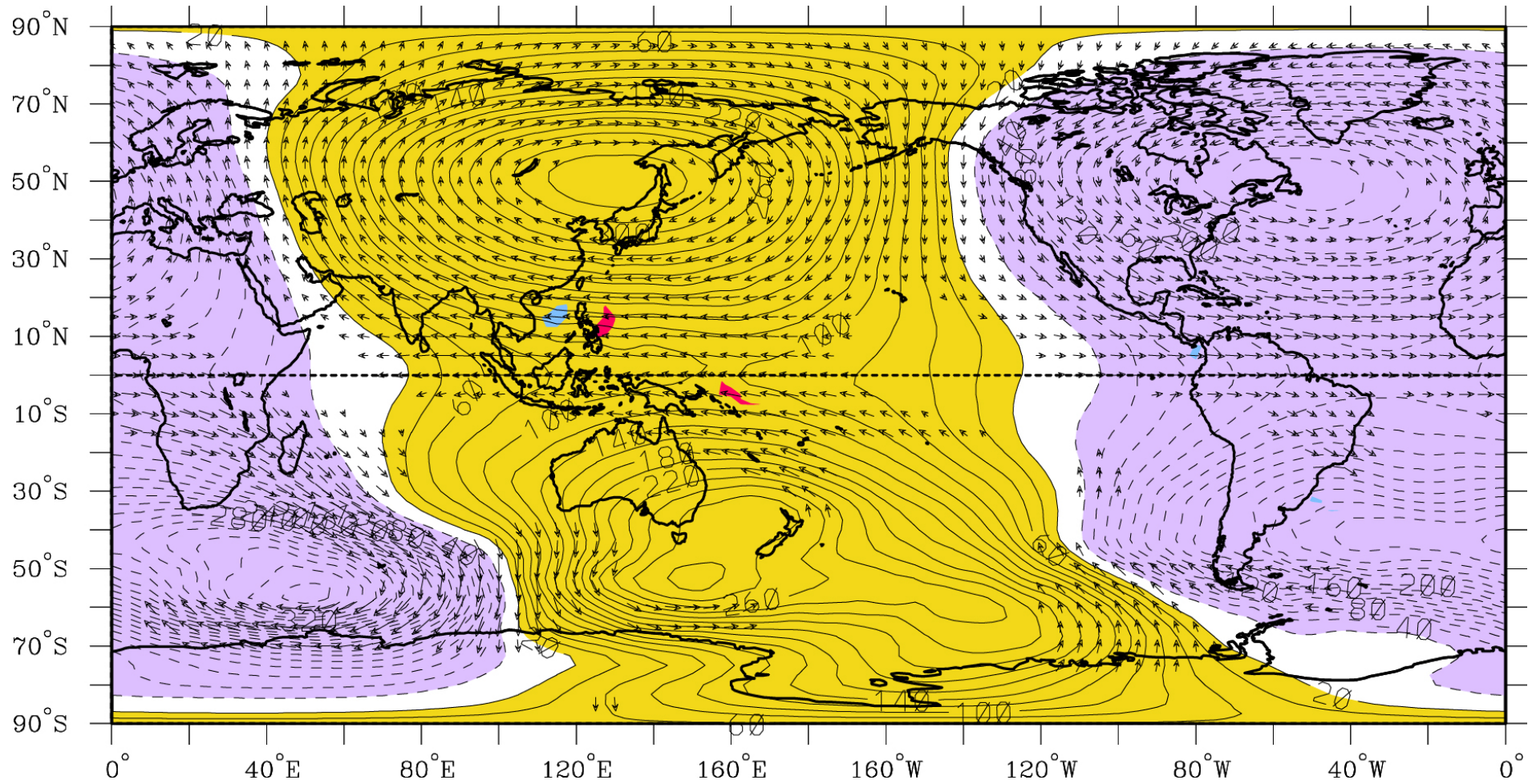Geopotential (contours $20 \times 10^5$ m$^2$ s$^{-2}$)
Wind (vectors, largest around 2 m s$^{-1}$)

# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 300 hPa
## June-August



Geopotential (contours 20 X 10$^5$ m$^2$ s$^{-2}$)
Wind (vectors, largest around 2 m s$^{-1}$)

First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 1 hPa

June-August

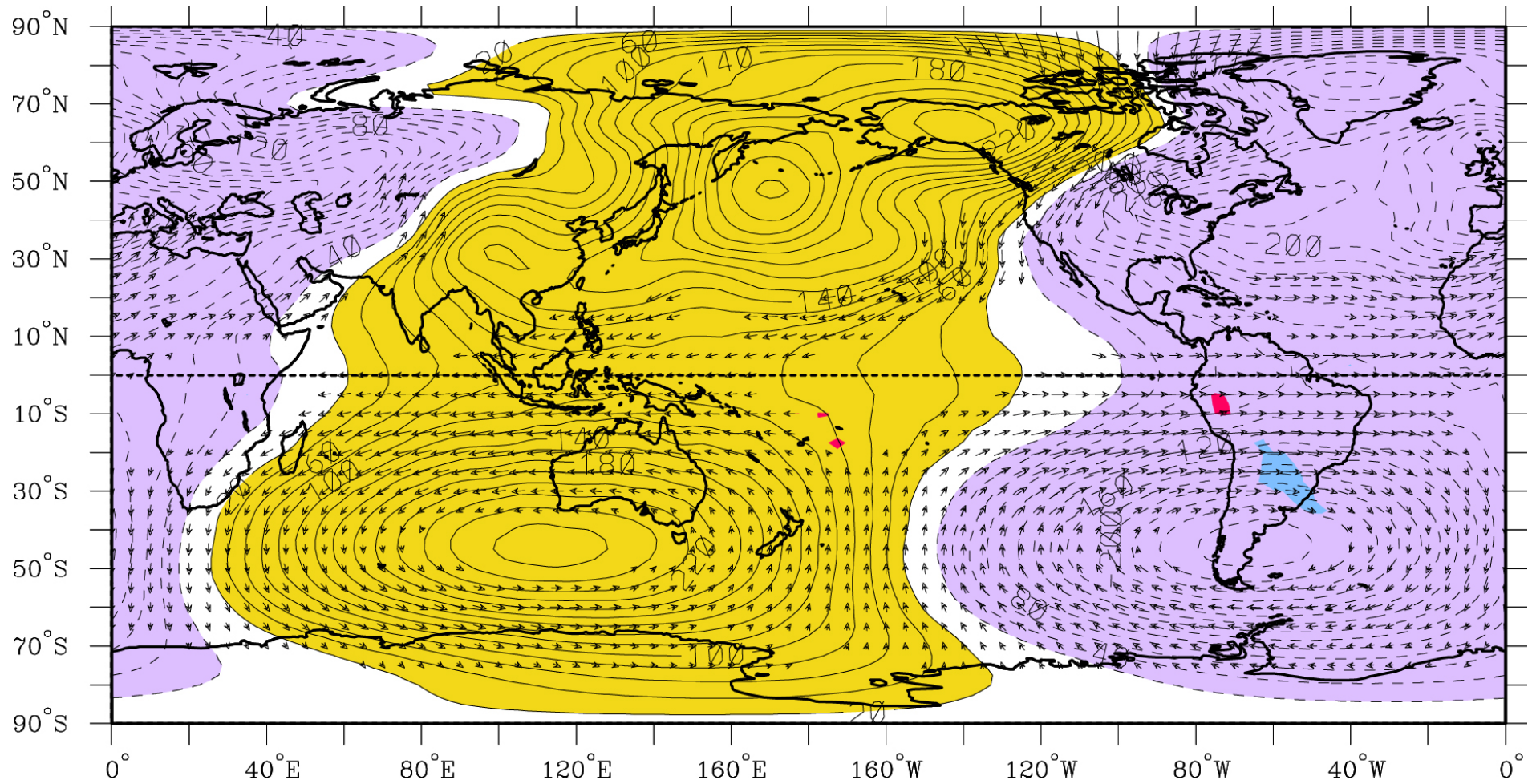Geopotential (contours 20 X $10^5$ $m^2$ $s^{-2}$)
Wind (vectors, largest around 2 m $s^{-1}$)

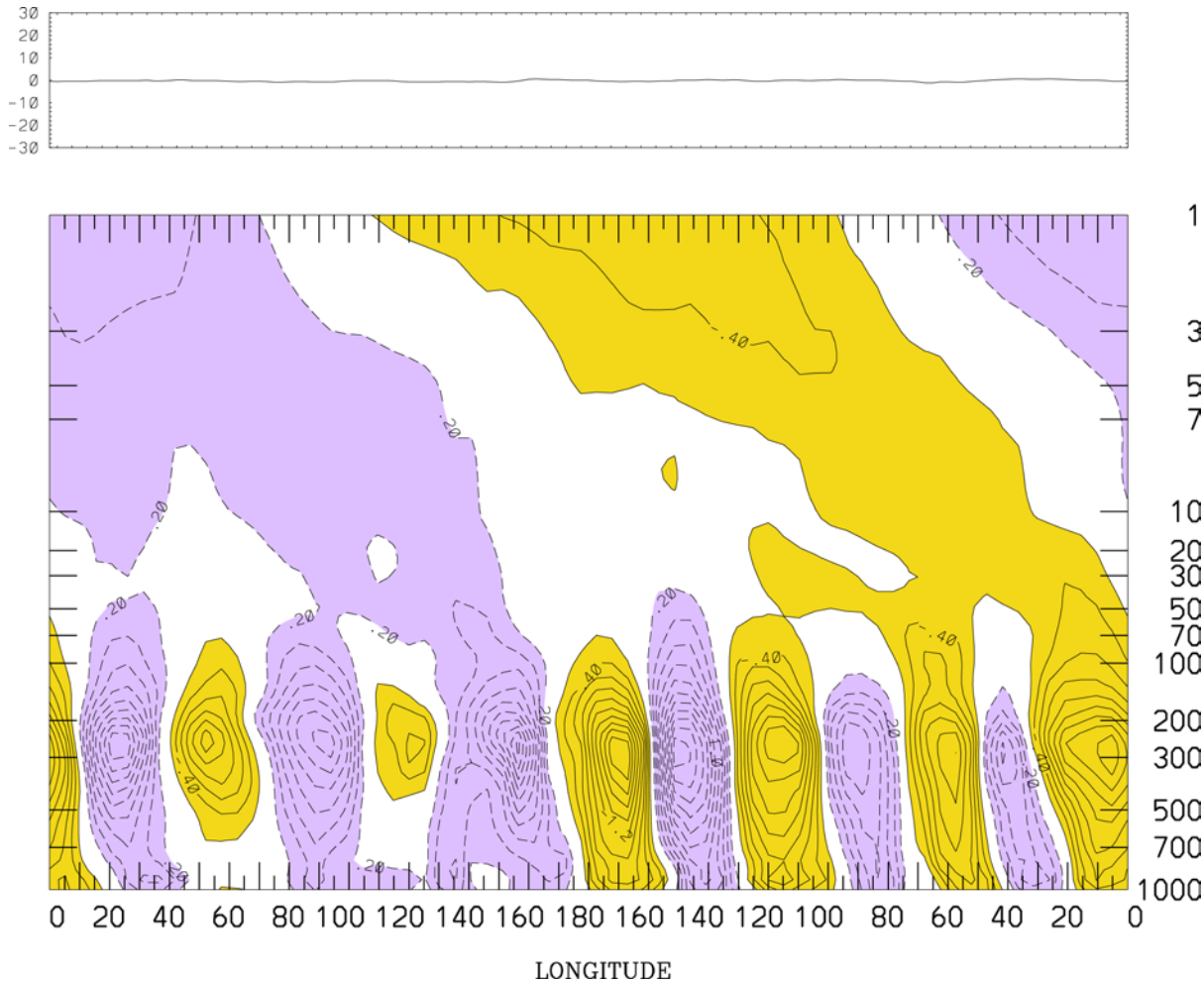# First EOF of 5 Day Filtered 850+550+250 hPa Geopotential at 1 hPa

## December-February



Geopotential (contours 20 X $10^5$ m$^2$ s$^{-2}$)
Wind (vectors, largest around 2 m s$^{-1}$)

# Vertical Section of Meridional Wind, EOF1 at 50S    1996-2012
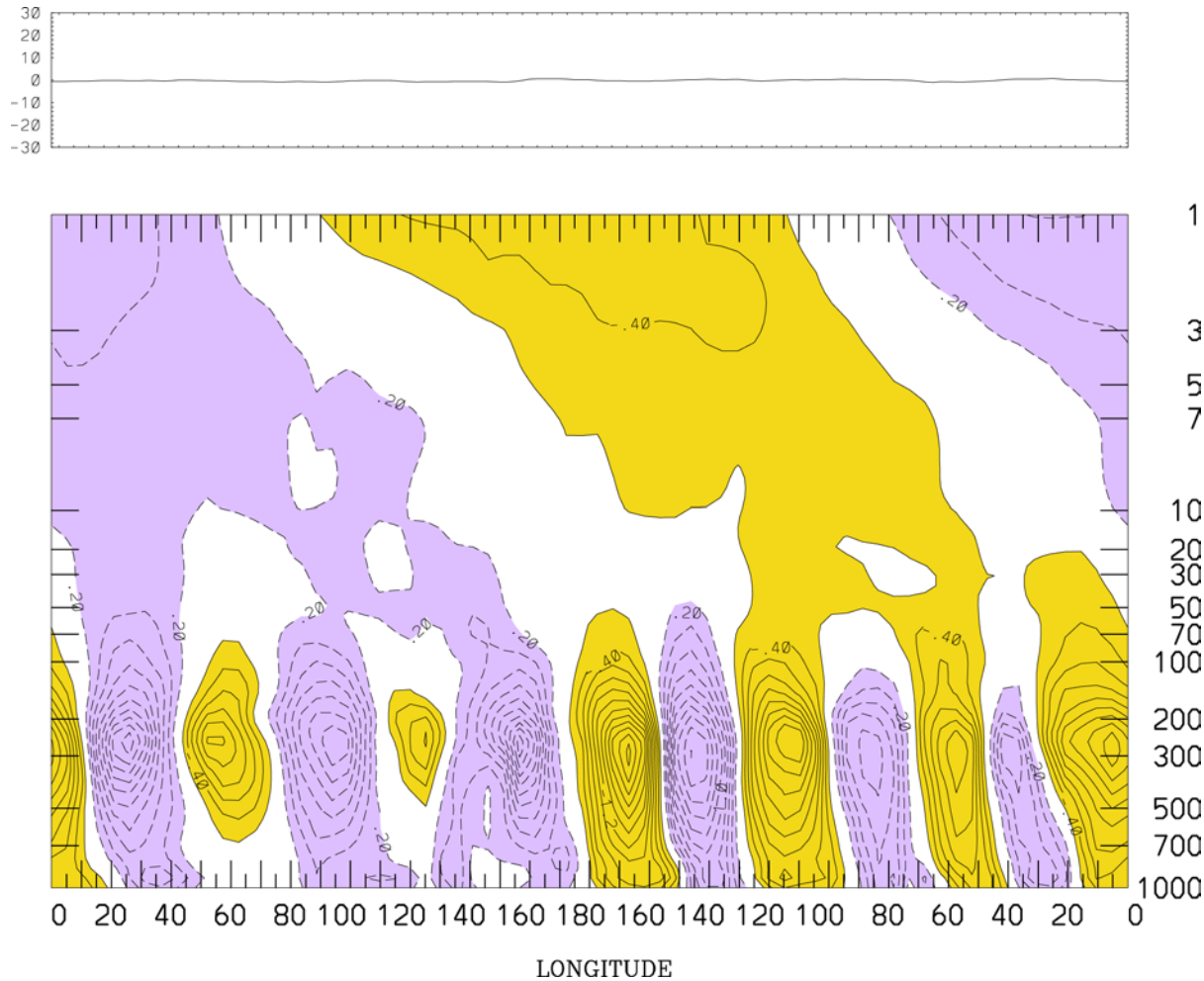
## December-February        Day-2.00



Meridional Wind (contours at .2 m s⁻¹ purple negative)

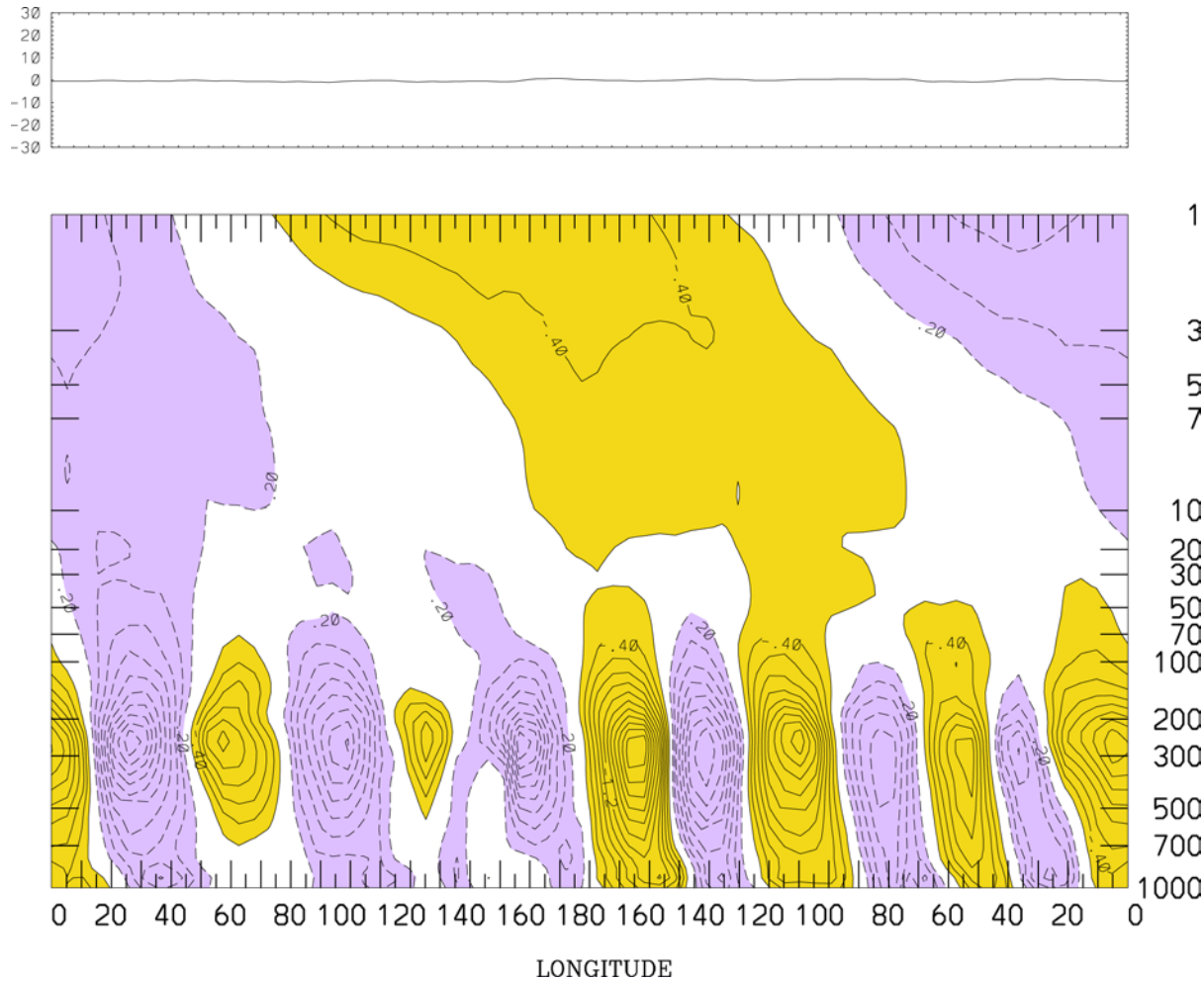# Vertical Section of Meridional Wind, EOF1 at 50S   1996-2012

## December-February        Day-1.75



Meridional Wind (contours at .2 m s$^{-1}$ purple negative)

Vertical Section of Meridional Wind, EOF1 at 50S 1996-2012
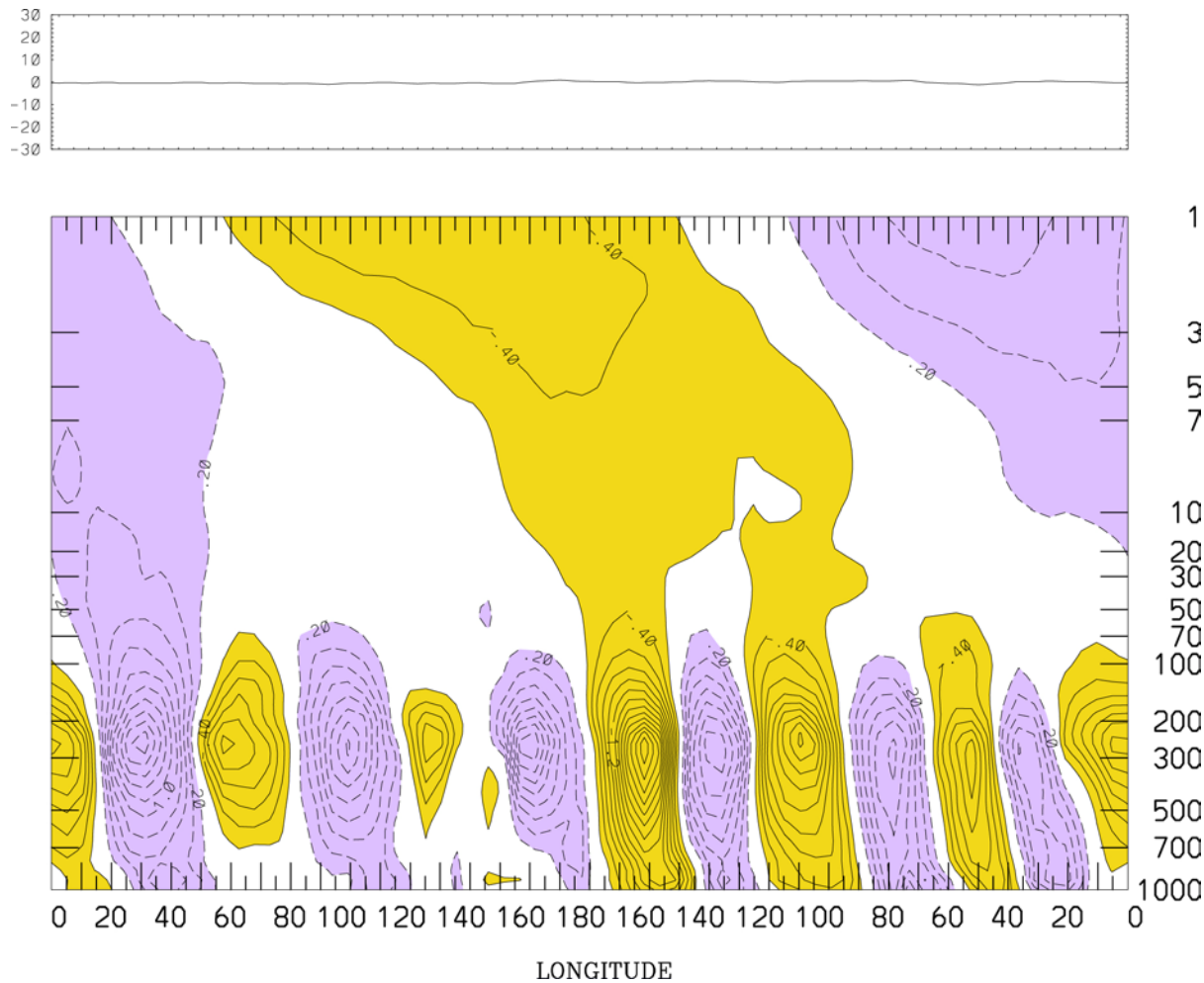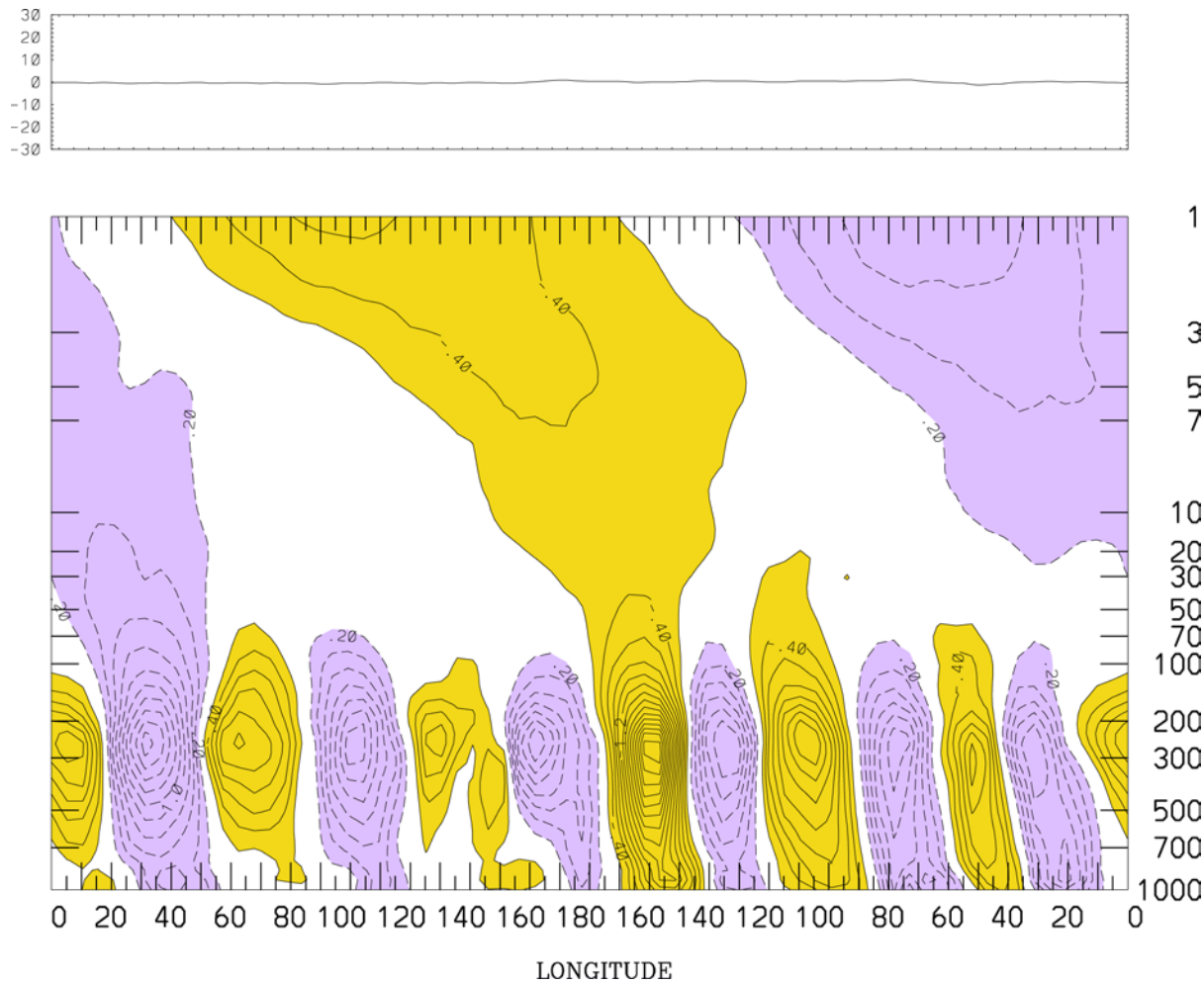December-February    Day-1.50

Meridional Wind (contours at .2 m s⁻¹ purple negative)

# Vertical Section of Meridional Wind, EOF1 at 50S   1996-2012

## December-February        Day-1.25



Meridional Wind (contours at .2 m s⁻¹ purple negative)

# Vertical Section of Meridional Wind, EOF1 at 50S   1996-2012
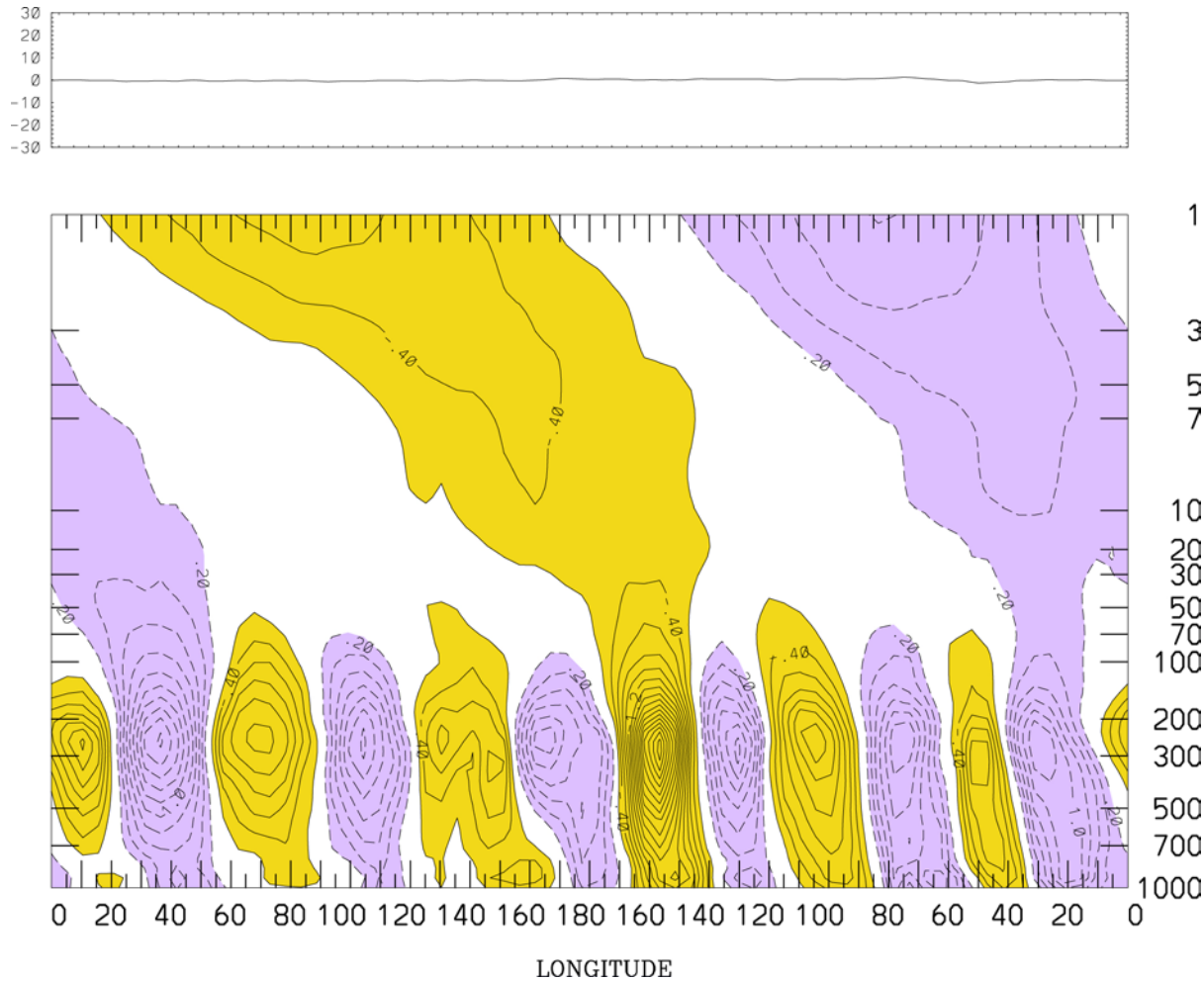
## December-February        Day-1



Meridional Wind (contours at .2 m s⁻¹ purple negative)

# Vertical Section of Meridional Wind, EOF1 at 50S   1996-2012
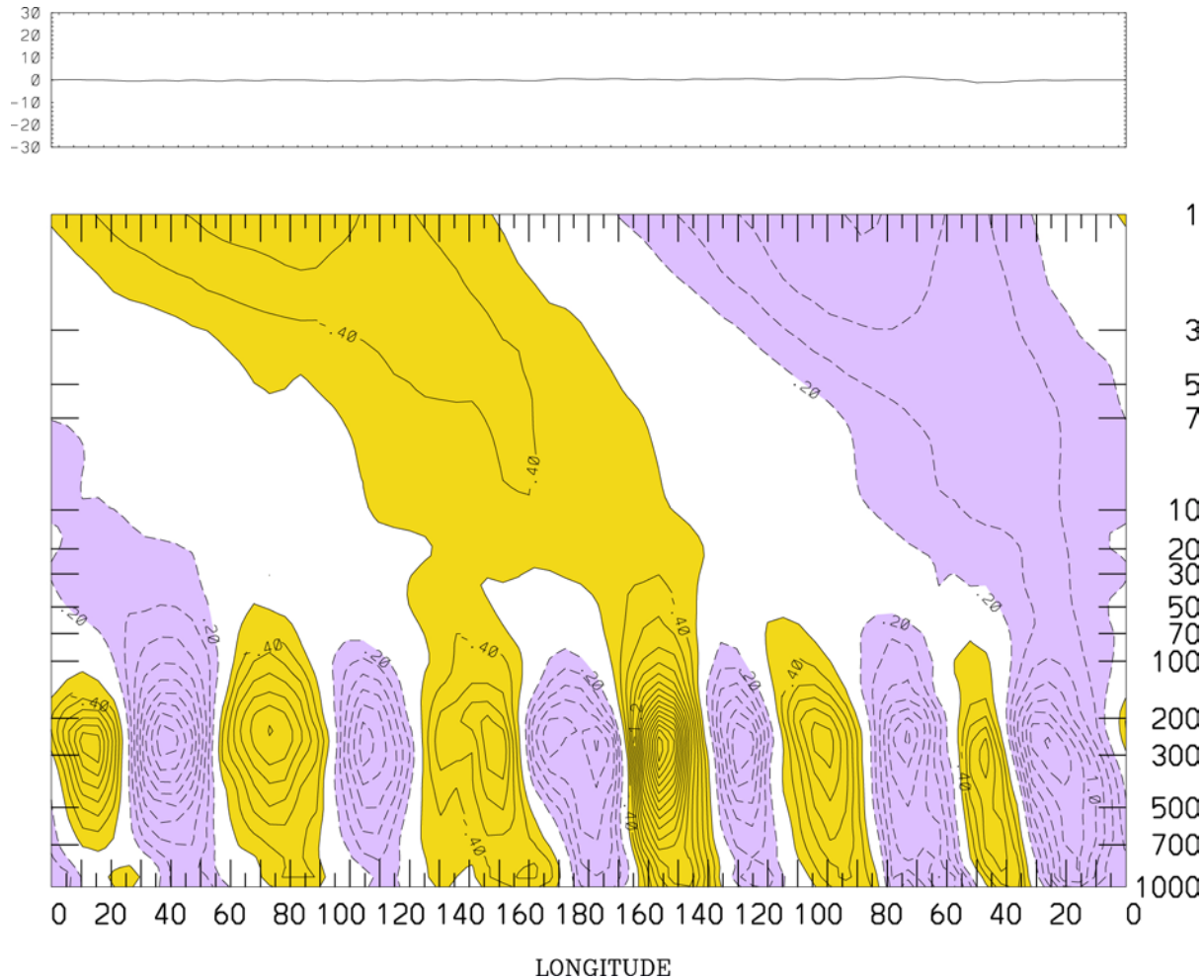
## December-February        Day-.75



Meridional Wind (contours at .2 m s$^{-1}$ purple negative)

# Vertical Section of Meridional Wind, EOF1 at 50S   1996-2012

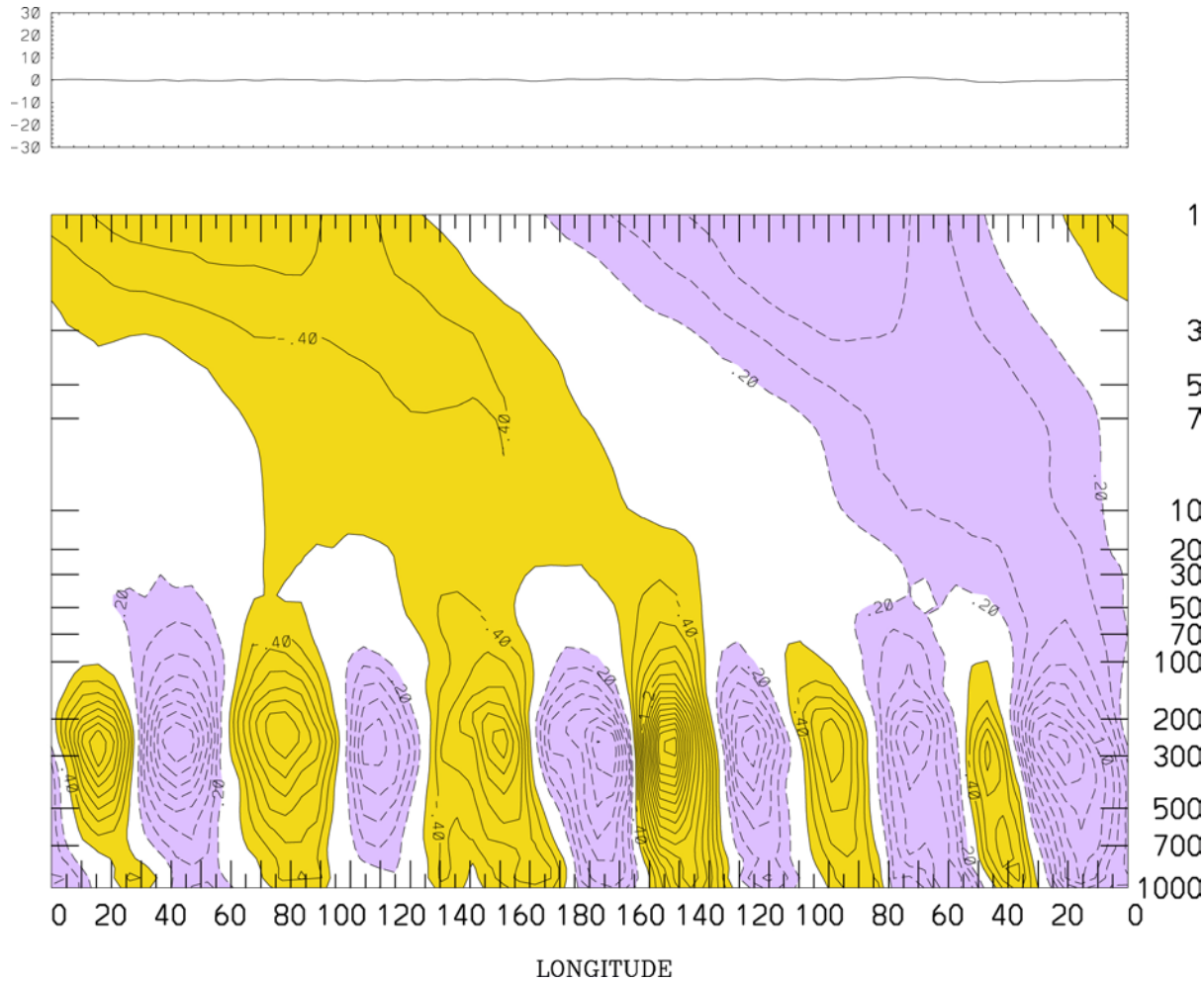## December-February        Day-.50



Meridional Wind (contours at .2 m s$^{-1}$ purple negative)

# Vertical Section of Meridional Wind, EOF1 at 50S   1996-2012
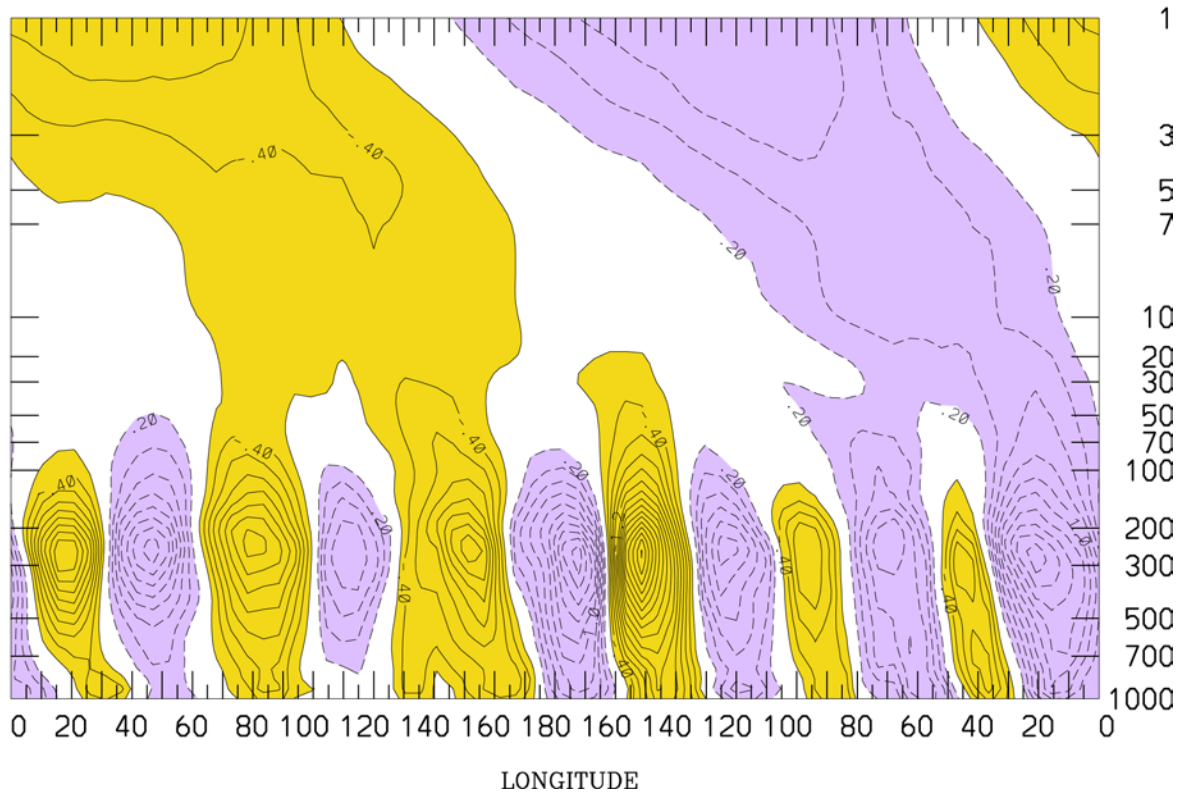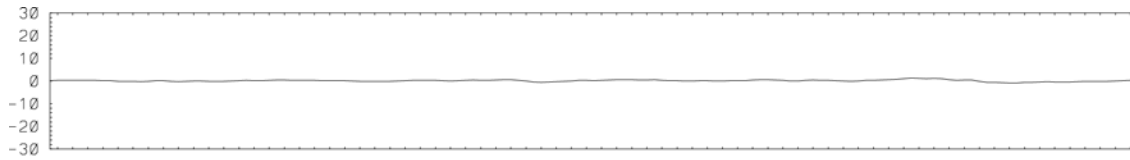
## December-February        Day-.25



Meridional Wind (contours at .2 m s⁻¹ purple negative)

# Vertical Section of Meridional Wind, EOF1 at 50S   1996-2012
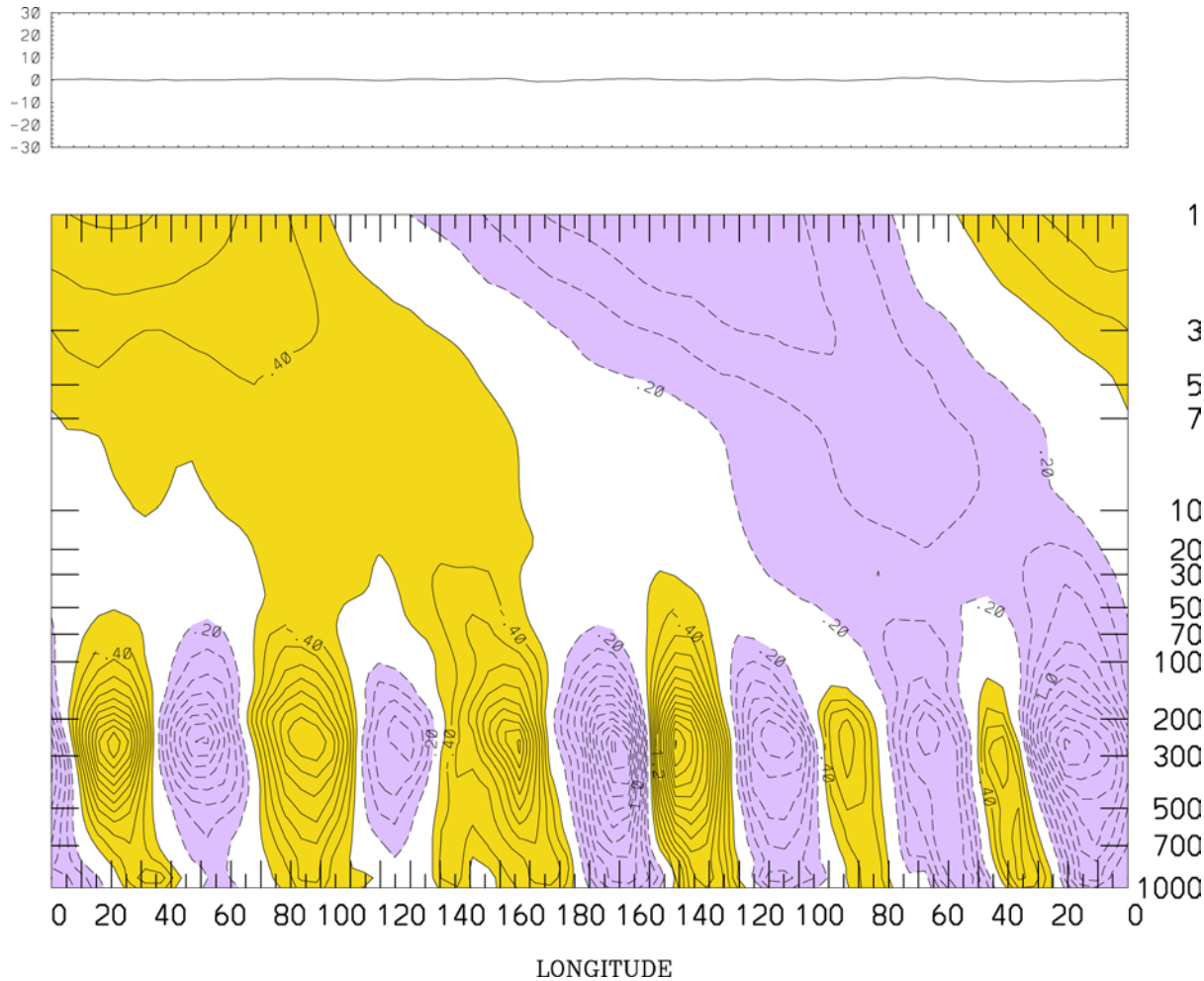
## December-February        Day 0



Meridional Wind (contours at .2 m s$^{-1}$ purple negative)

# Vertical Section of Meridional Wind, EOF1 at 50S   1996-2012

## December-February        Day .25



Meridional Wind (contours at .2 m s⁻¹ purple negative)

# Vertical Section of Meridional Wind, EOF1 at 50S   1996-2012

## December-February        Day .50



Meridional Wind (contours at .2 m s$^{-1}$ purple negative)

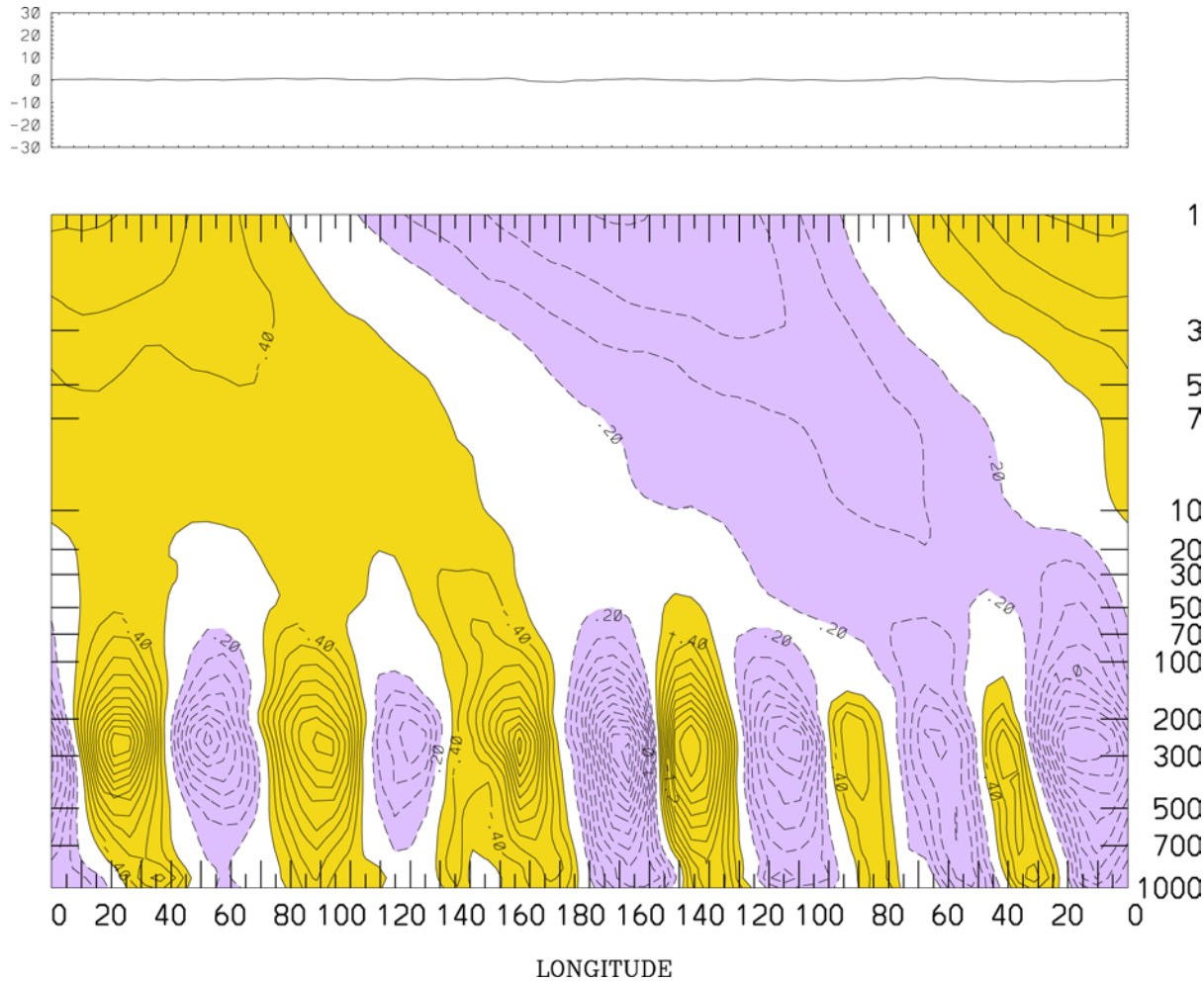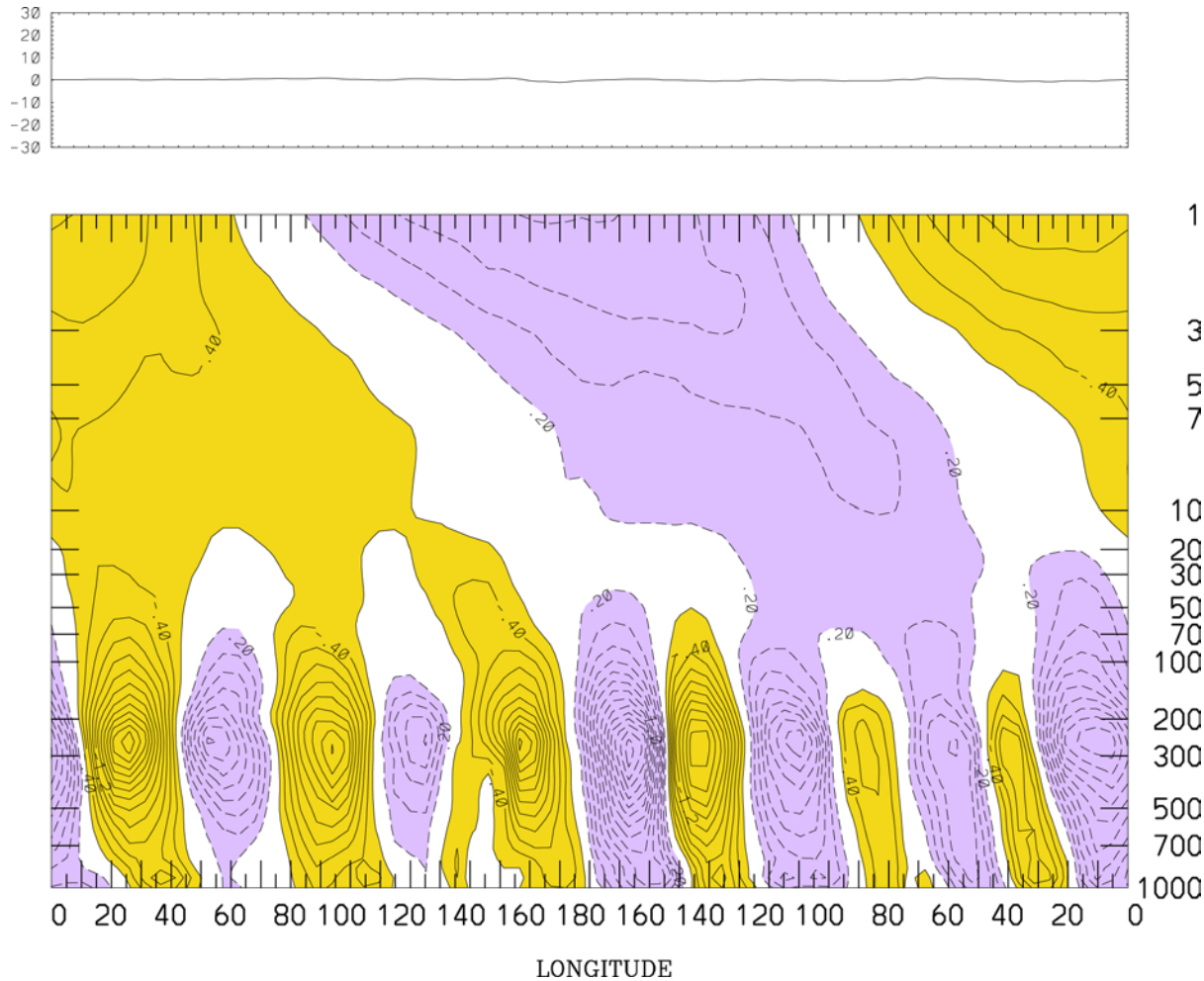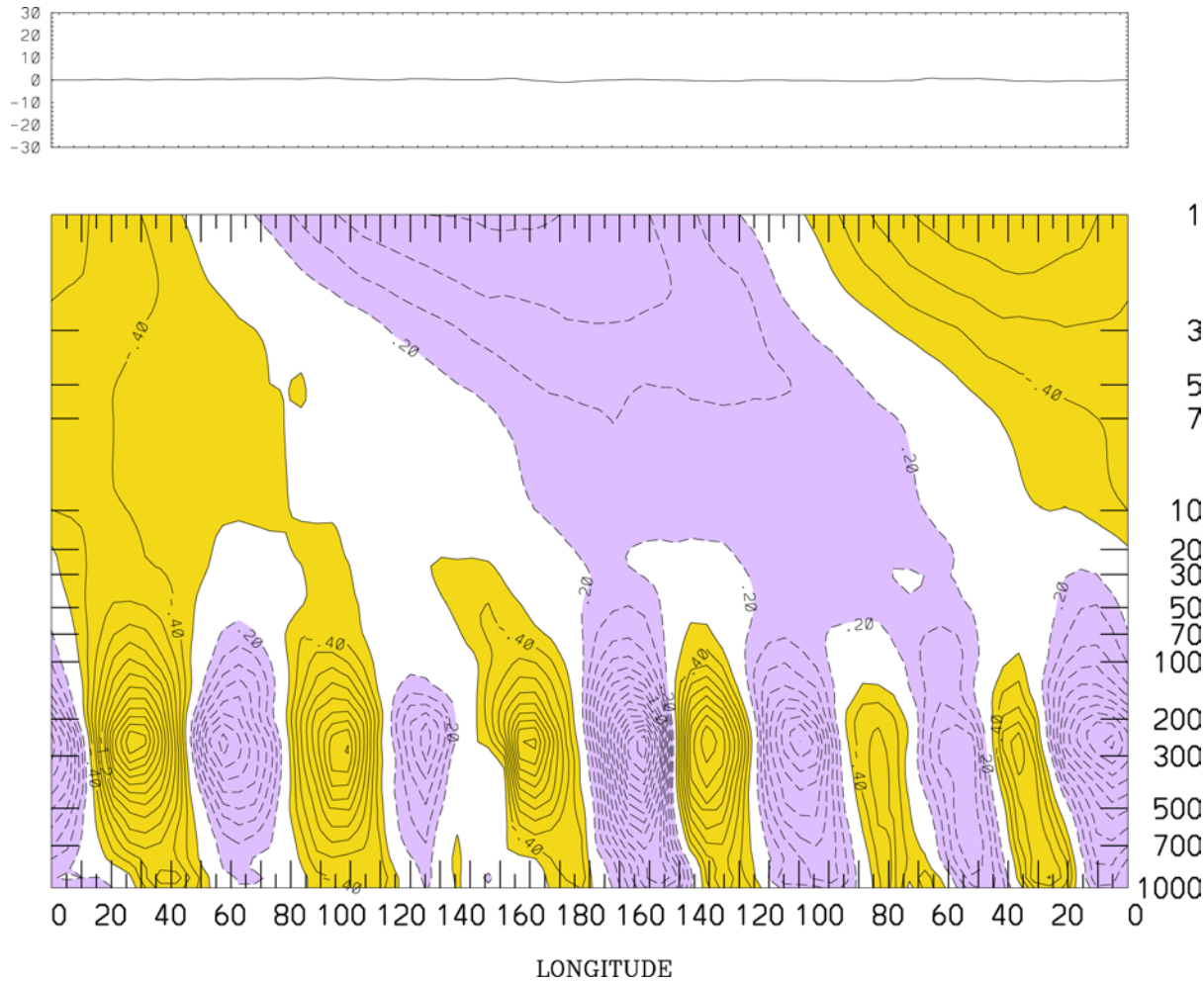# Vertical Section of Meridional Wind, EOF1 at 50S   1996-2012

## December-February        Day .75



Meridional Wind (contours at .2 m s$^{-1}$ purple negative)

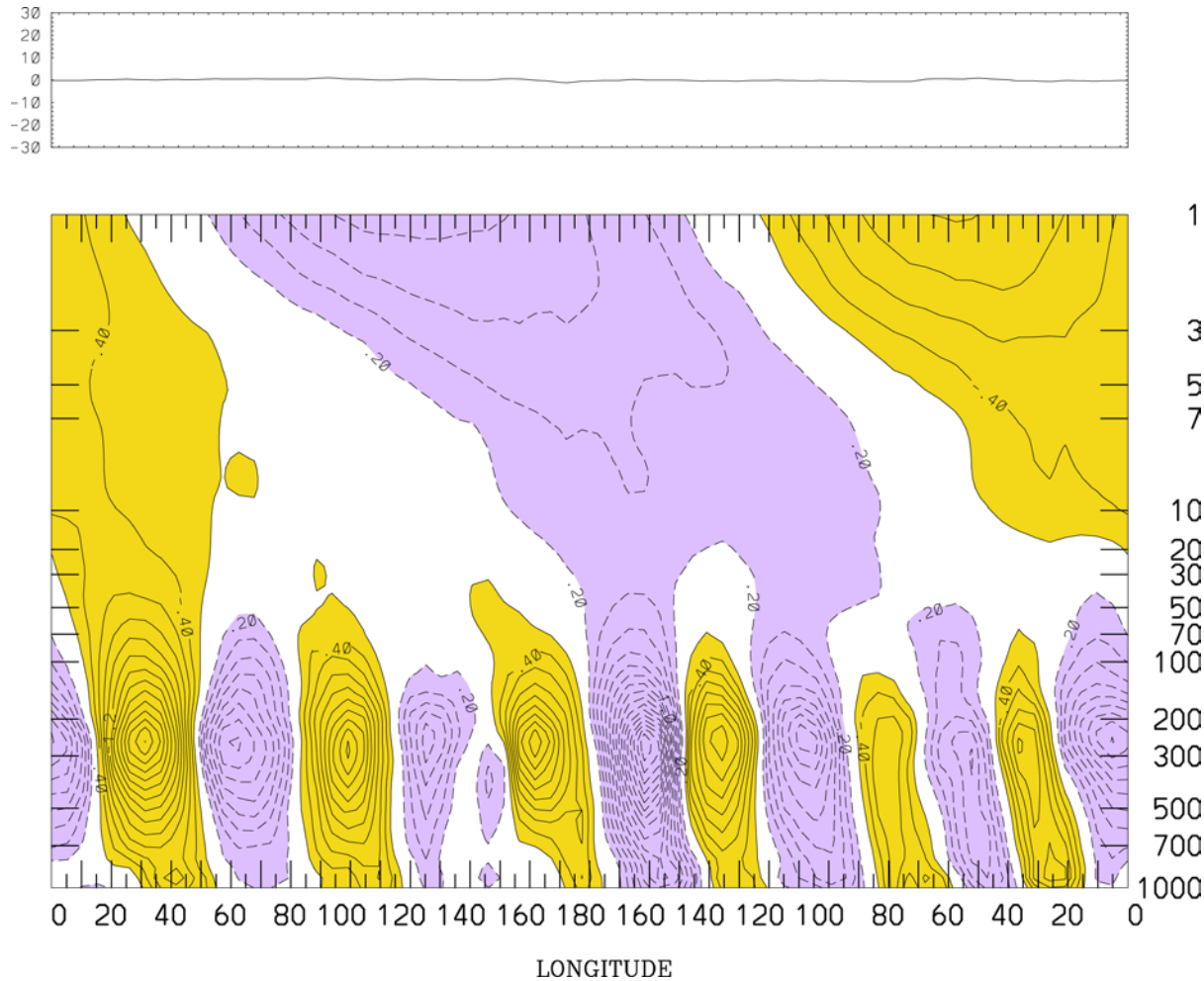# Vertical Section of Meridional Wind, EOF1 at 50S   1996-2012

## December-February        Day 1.00



Meridional Wind (contours at .2 m s$^{-1}$ purple negative)

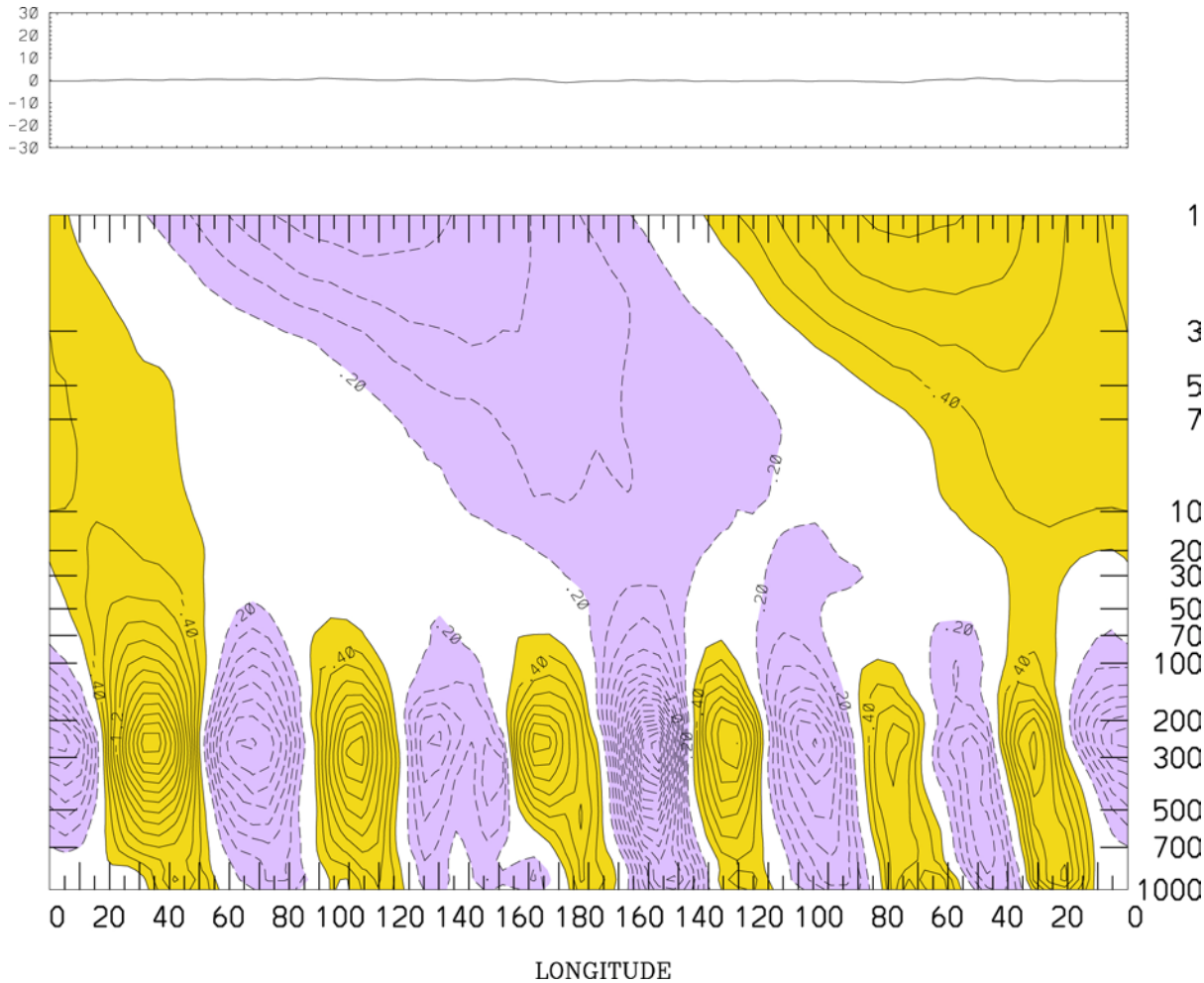# Vertical Section of Meridional Wind, EOF1 at 50S   1996-2012

## December-February        Day 1.25



Meridional Wind (contours at .2 m s$^{-1}$ purple negative)

# Vertical Section of Meridional Wind, EOF1 at 50S   1996-2012

## December-February        Day 1.50



Meridional Wind (contours at .2 m s⁻¹ purple negative)

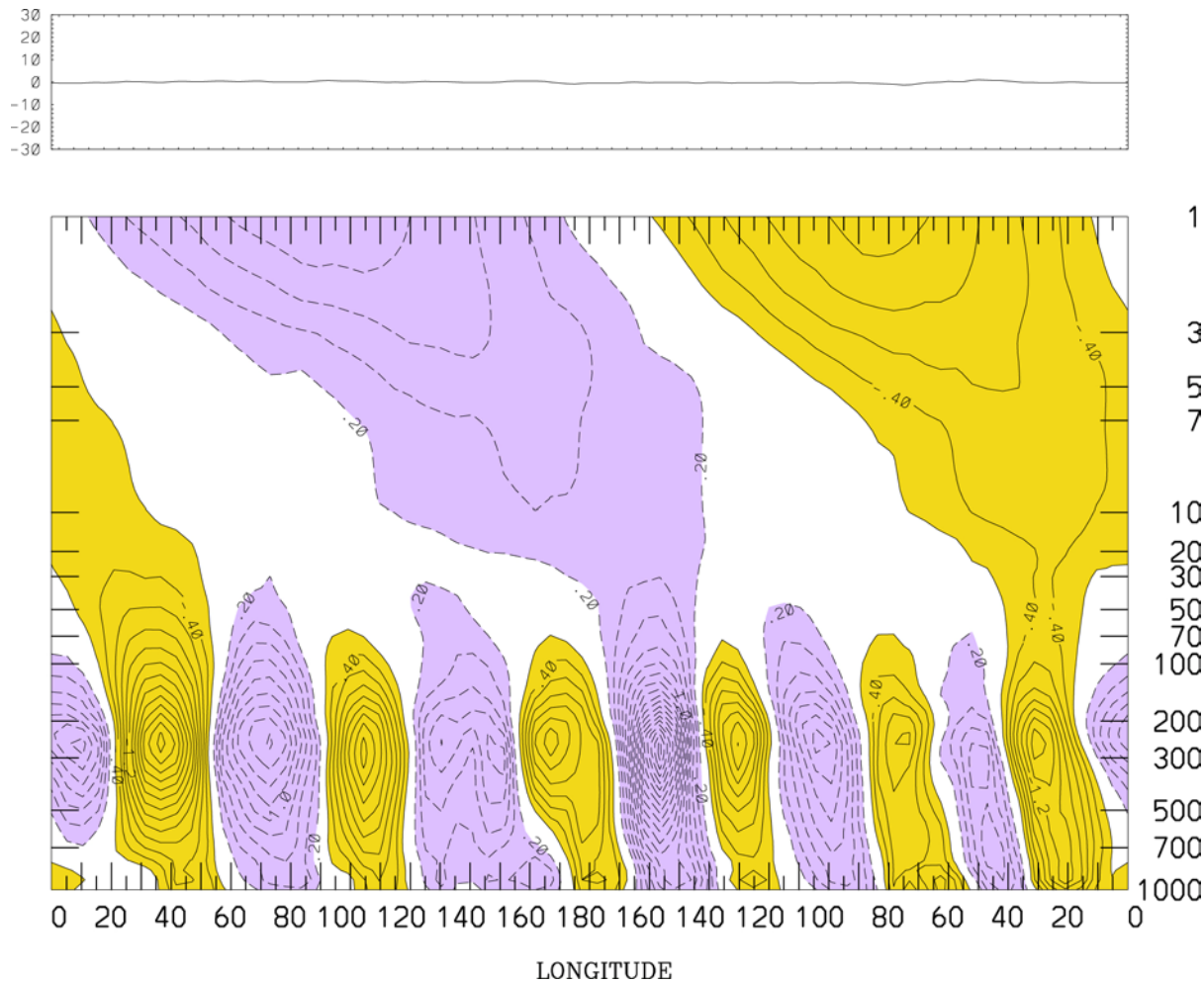# Vertical Section of Meridional Wind, EOF1 at 50S   1996-2012

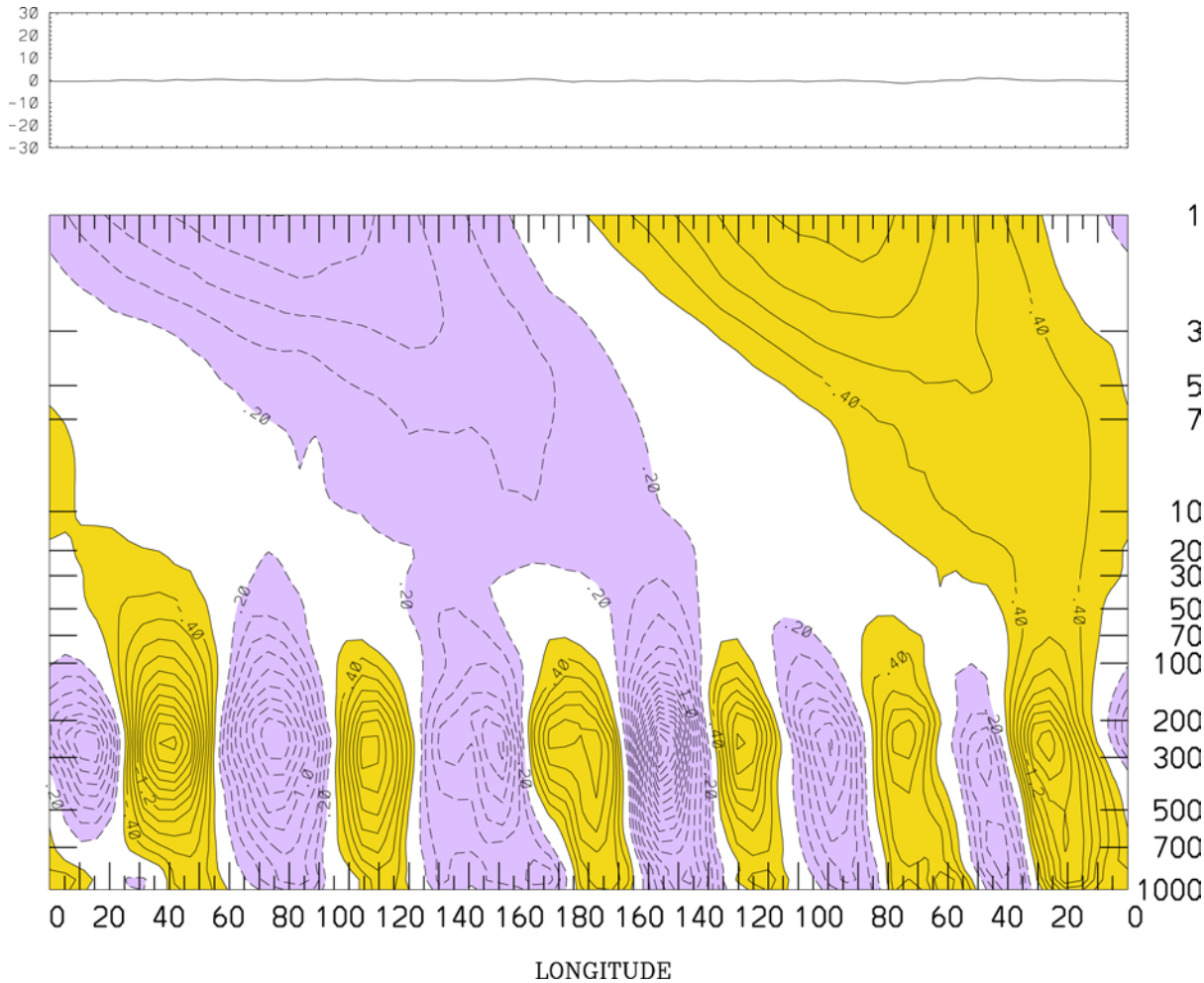## December-February        Day 1.75



Meridional Wind (contours at .2 m s$^{-1}$ purple negative)

# Vertical Section of Meridional Wind, EOF1 at 50S 1996-2012

## December-February        Day 2.00



Meridional Wind (contours at .2 m s⁻¹ purple negative)

# Vertical Section of Meridional Wind, EOF1 at 50S  1979-1995

## December-February        Day 0
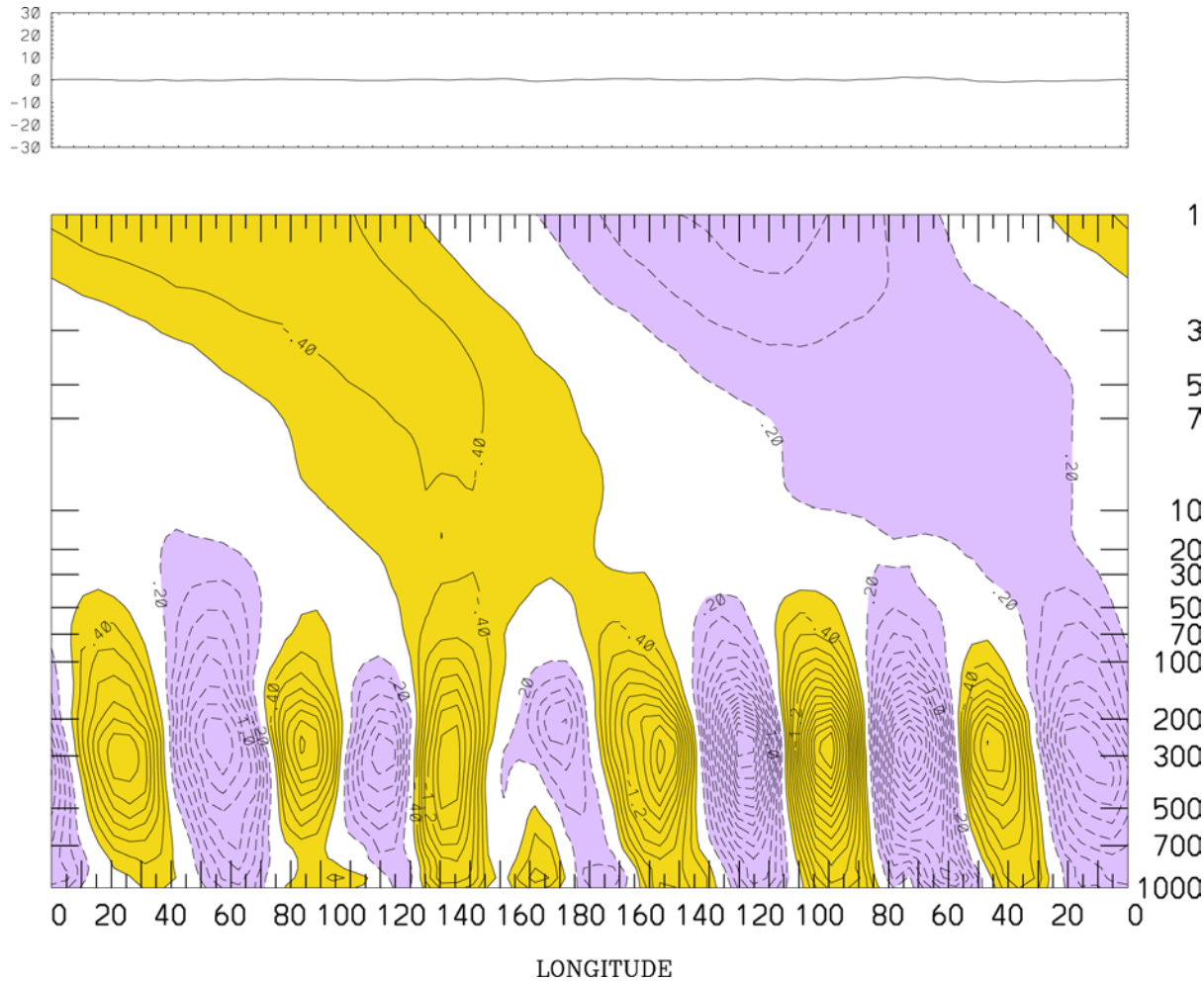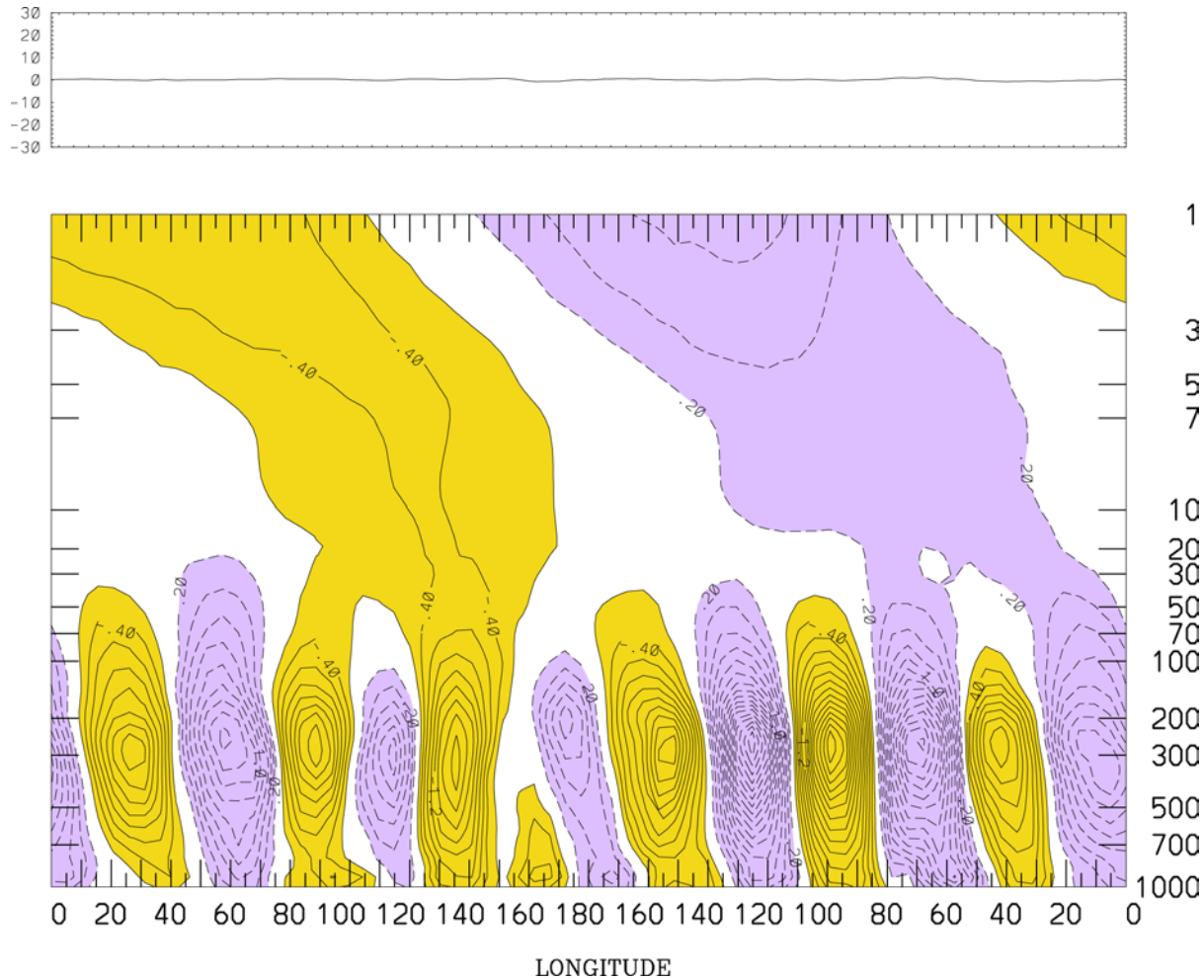


Meridional Wind (contours at .2 m s$^{-1}$ purple negative)

# Vertical Section of Meridional Wind, EOF1 at 50S   1979-1995

## December-February        Day+.25



Meridional Wind (contours at .2 m s$^{-1}$ purple negative)

# Vertical Section of Meridional Wind, EOF1 at 50S  1996-2012

## December-February        Day 0



Meridional Wind (contours at .2 m s$^{-1}$ purple negative)

# Vertical Section of Meridional Wind, EOF1 at 50S   1979-1995

## December-February        Day .50
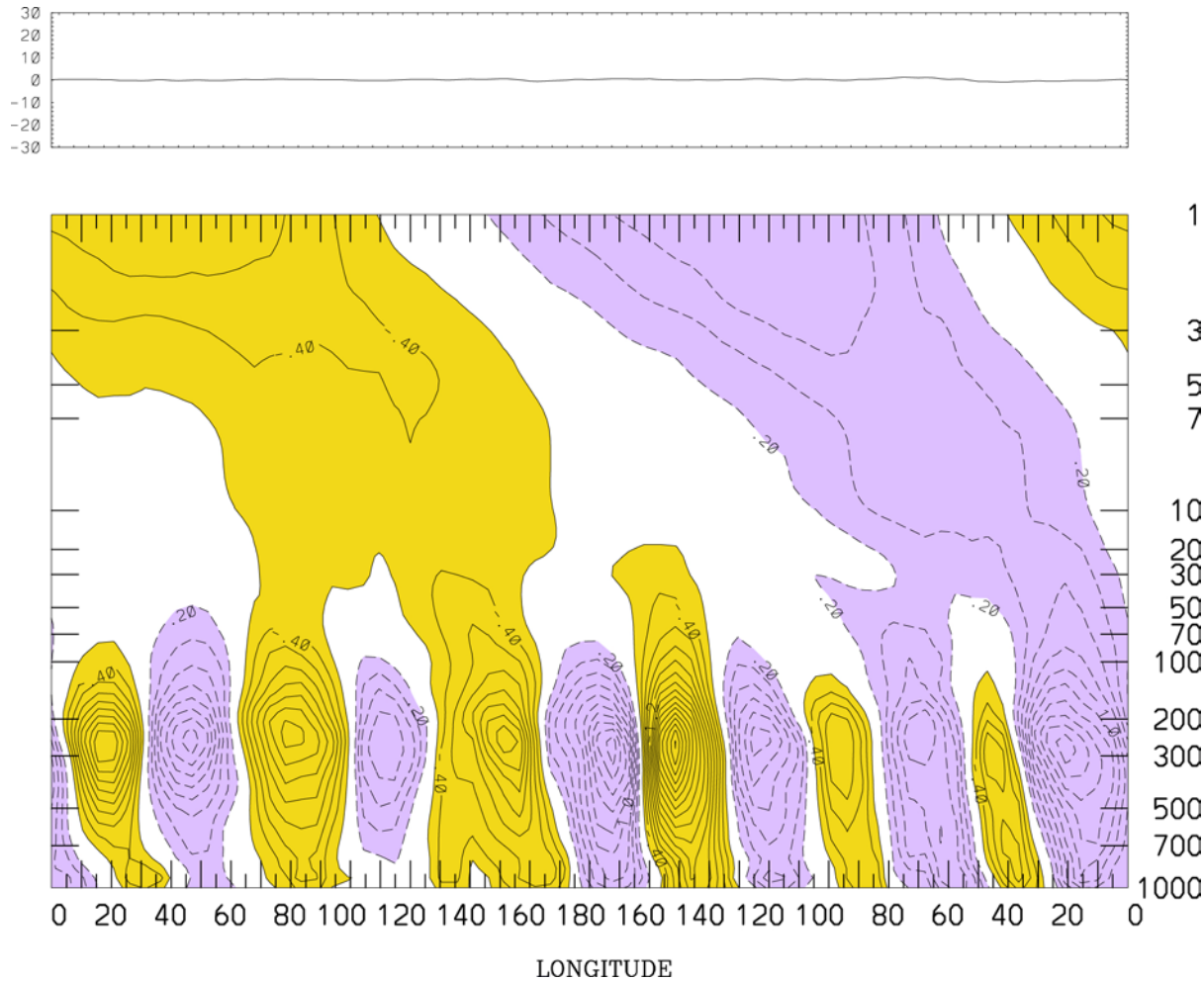


Meridional Wind (contours at .2 m s$^{-1}$ purple negative)

# Vertical Section of Meridional Wind, EOF1 at 50S   1996-2012
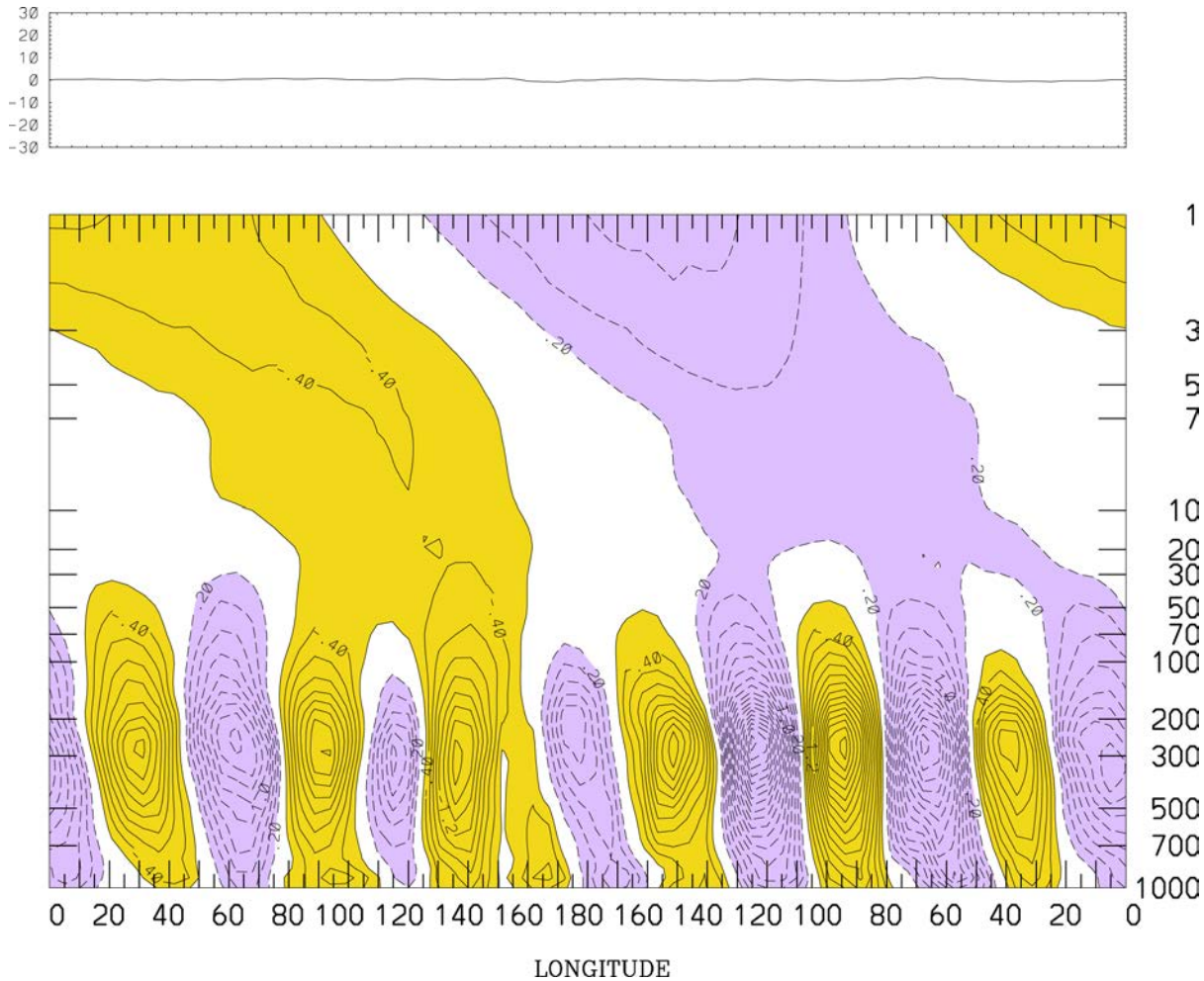
## December-February        Day .25



Meridional Wind (contours at .2 m s$^{-1}$ purple negative)

# Vertical Section of Meridional Wind, EOF1 at 50S  1979-1995

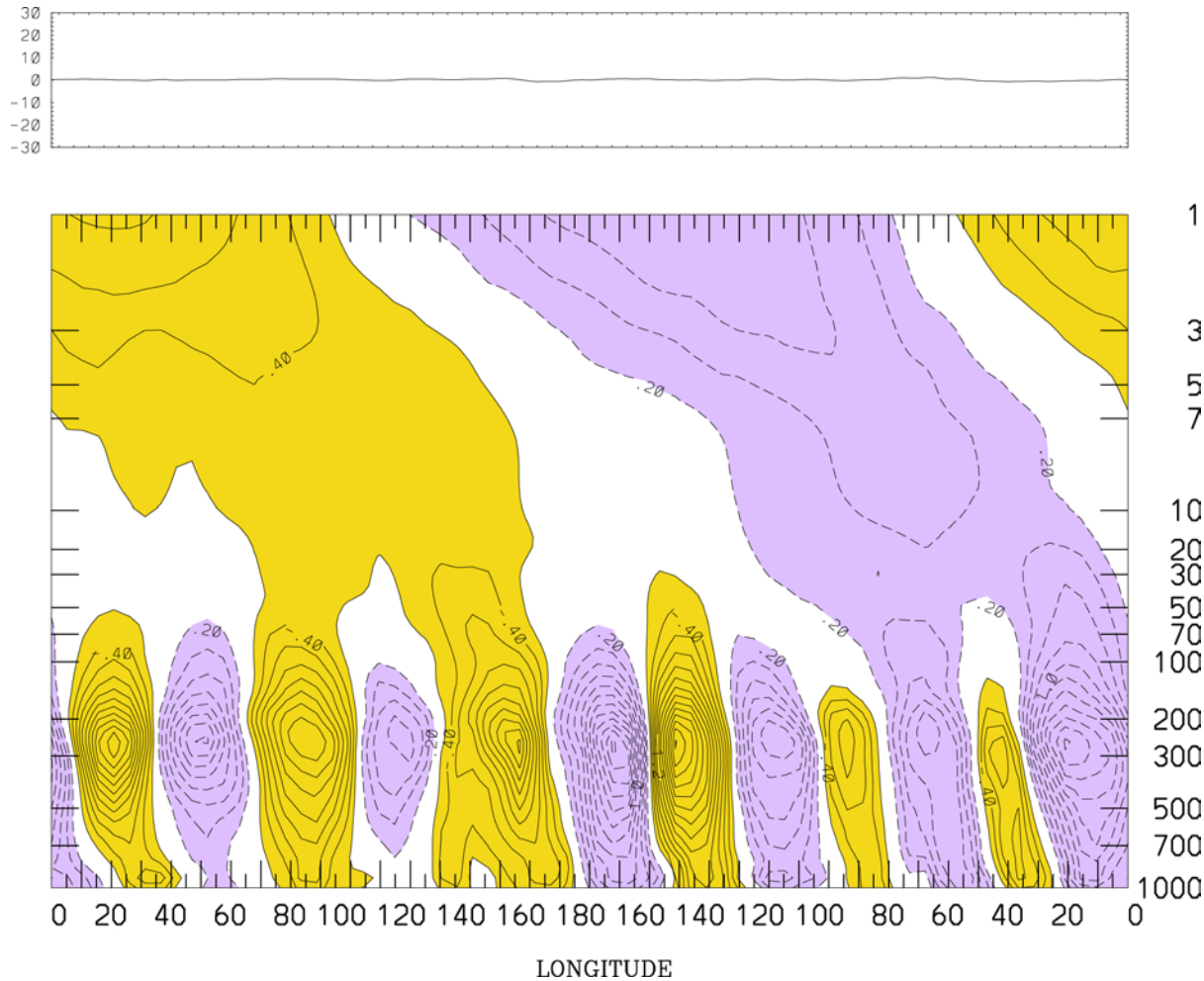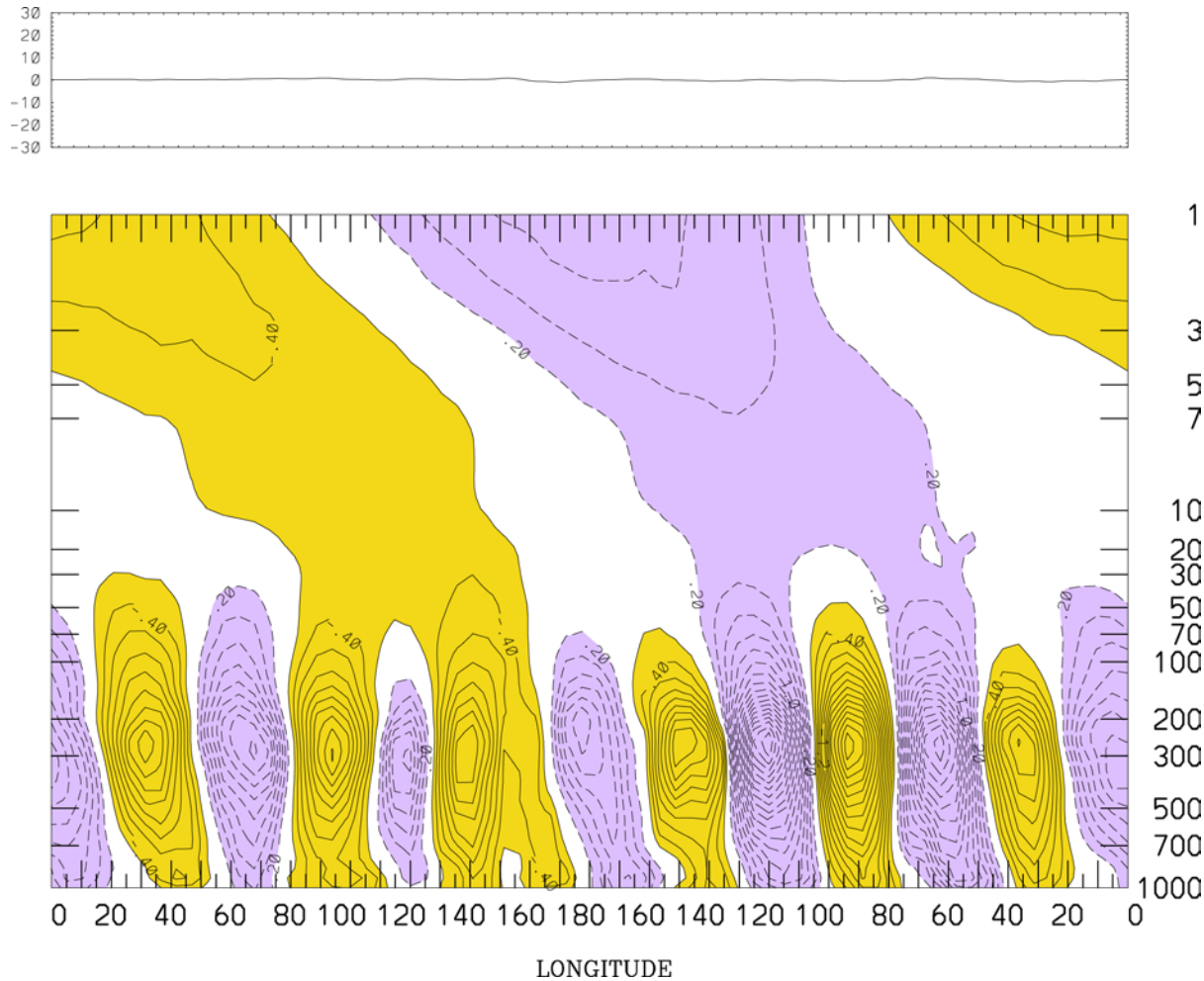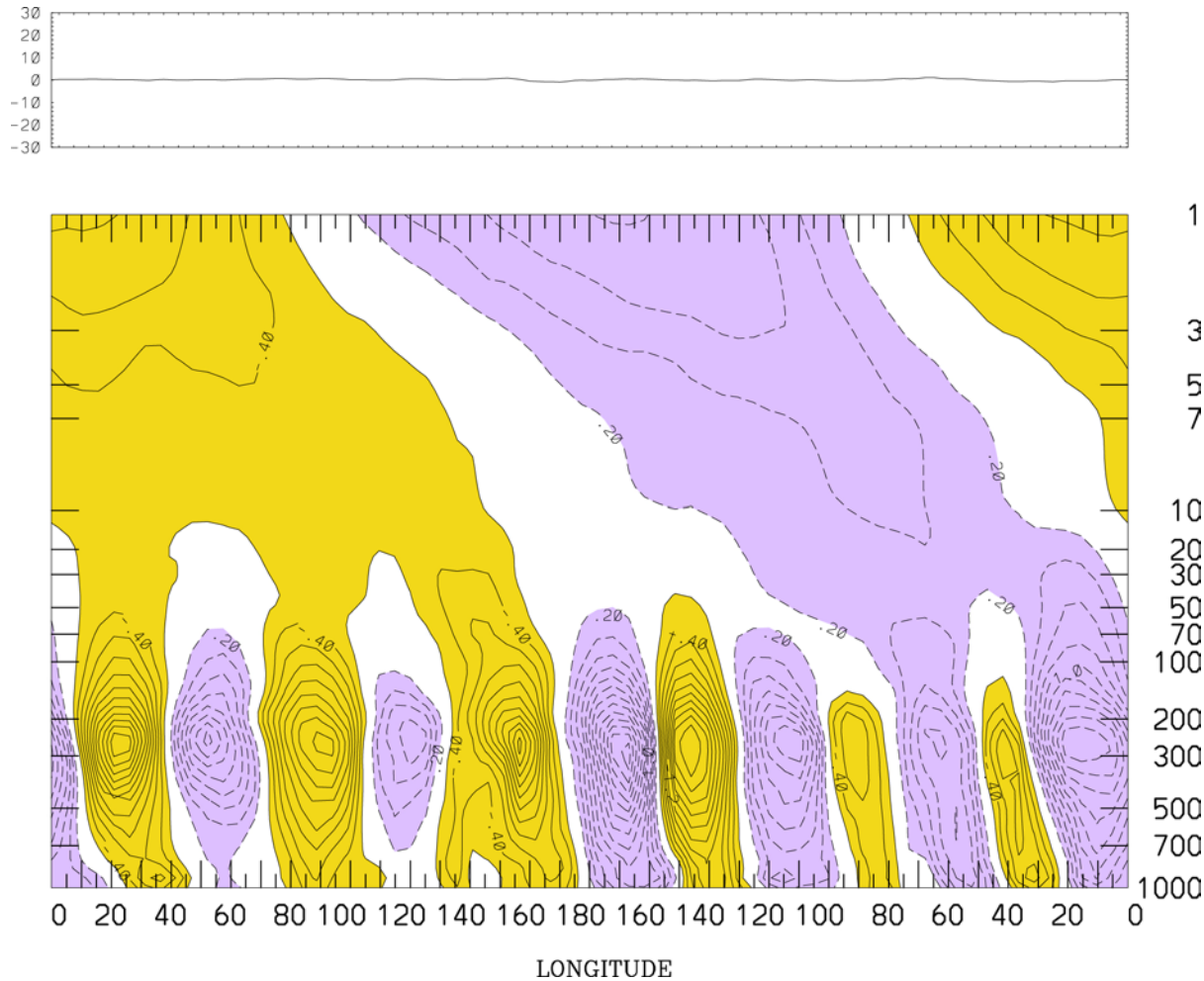## December-February  Day .75



Meridional Wind (contours at .2 m s$^{-1}$ purple negative)

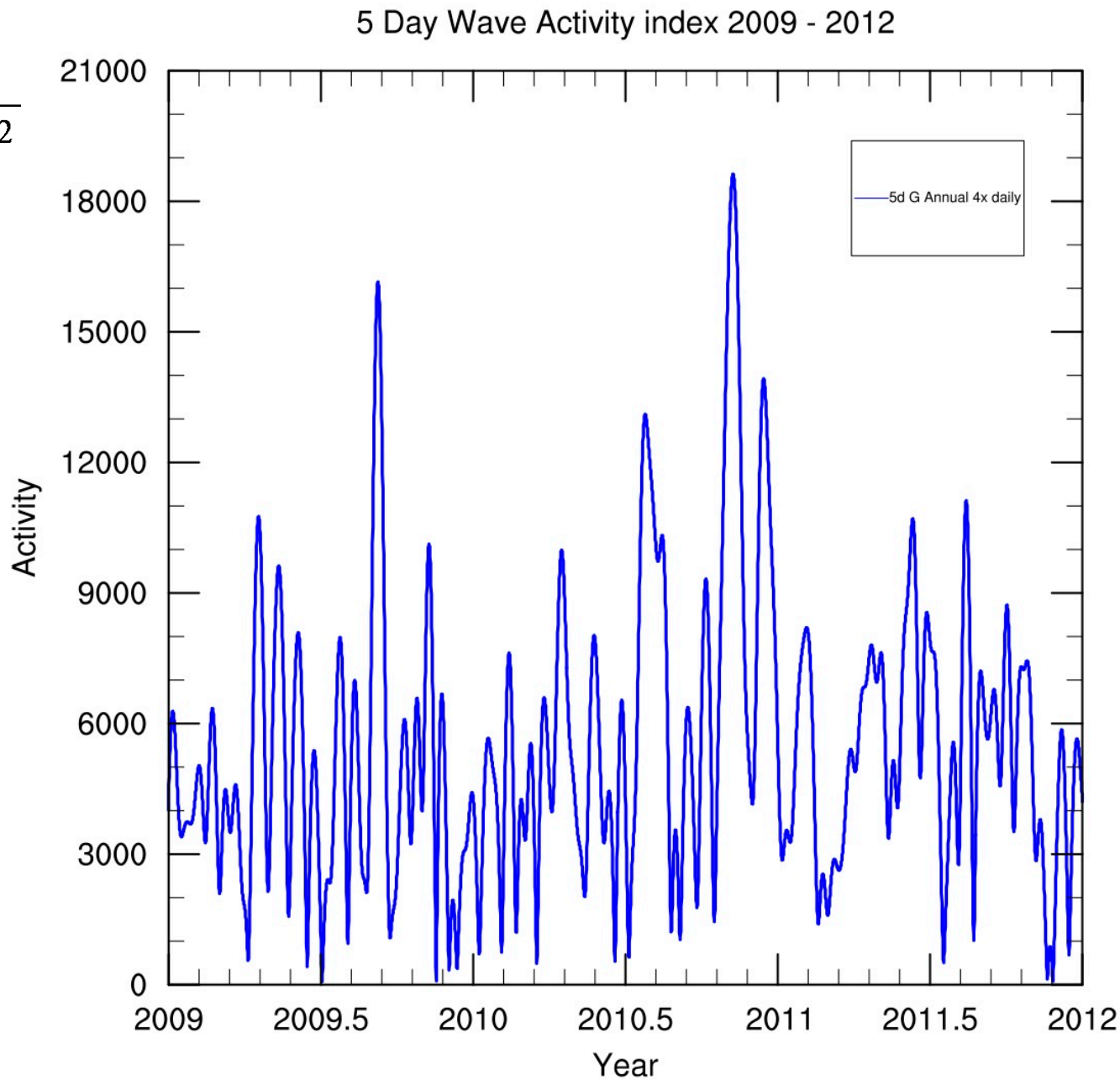# Vertical Section of Meridional Wind, EOF1 at 50S 1996-2012

## December-February     Day .50



Meridional Wind (contours at .2 m s$^{-1}$ purple negative)

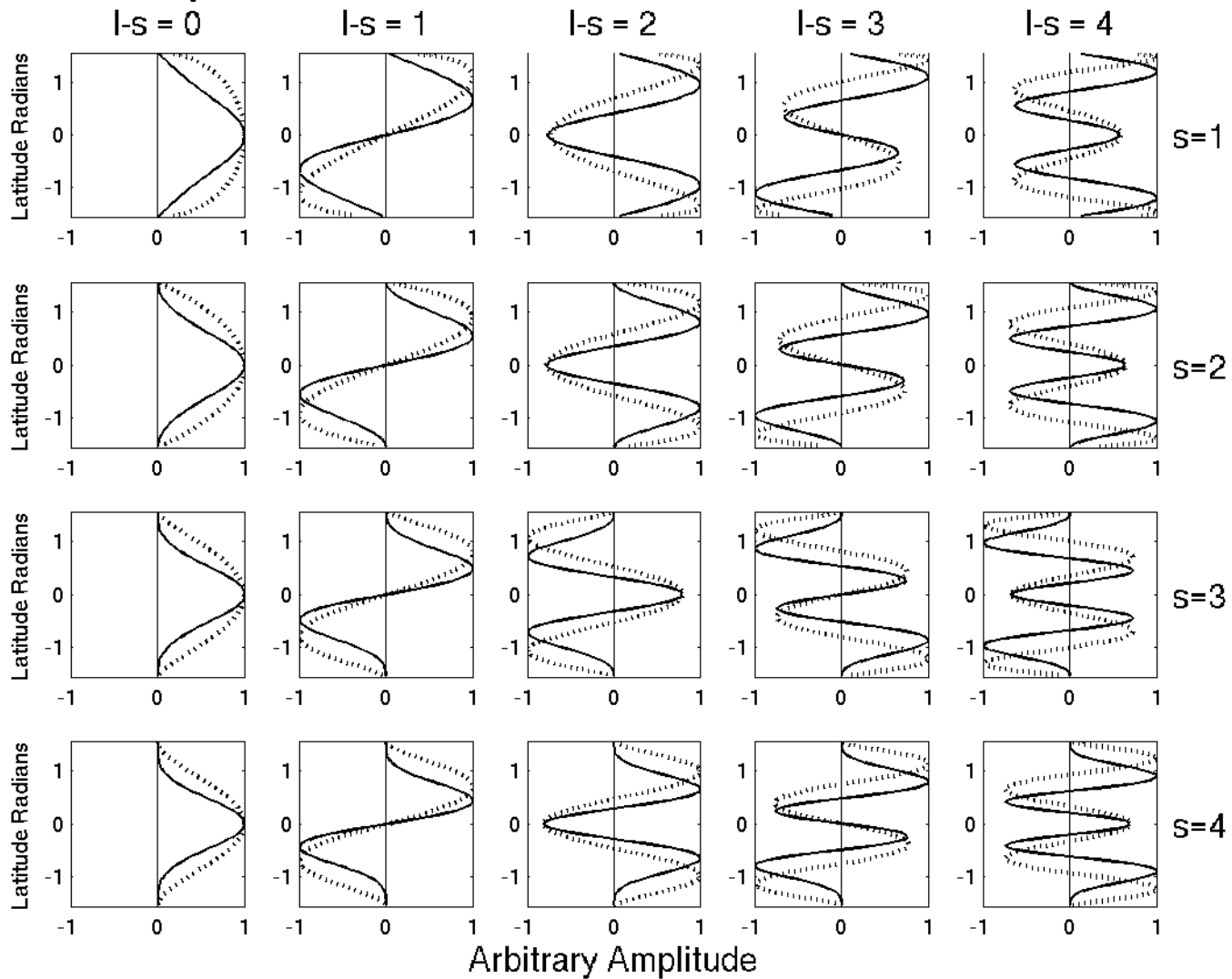# Time Series of 5 Day Wave Activity from the First Two Principal Components

$$\sqrt{PC1^2 + PC2^2}$$



5 Day Wave Activity index 2009 - 2012

# Comparison with Rol's Results for 2010-2012

# Latitudinal Profiles
## Depictions of the Stream Function for Various Modes



Associated Legendre Functions ($P^s_l$) - dotted;

Hough Functions (ex. 5-Day Wave $0.993P^1_2 + 0.110P^1_{4+...}$) - solid

# Comparison with Rol's Results for 2010-2012

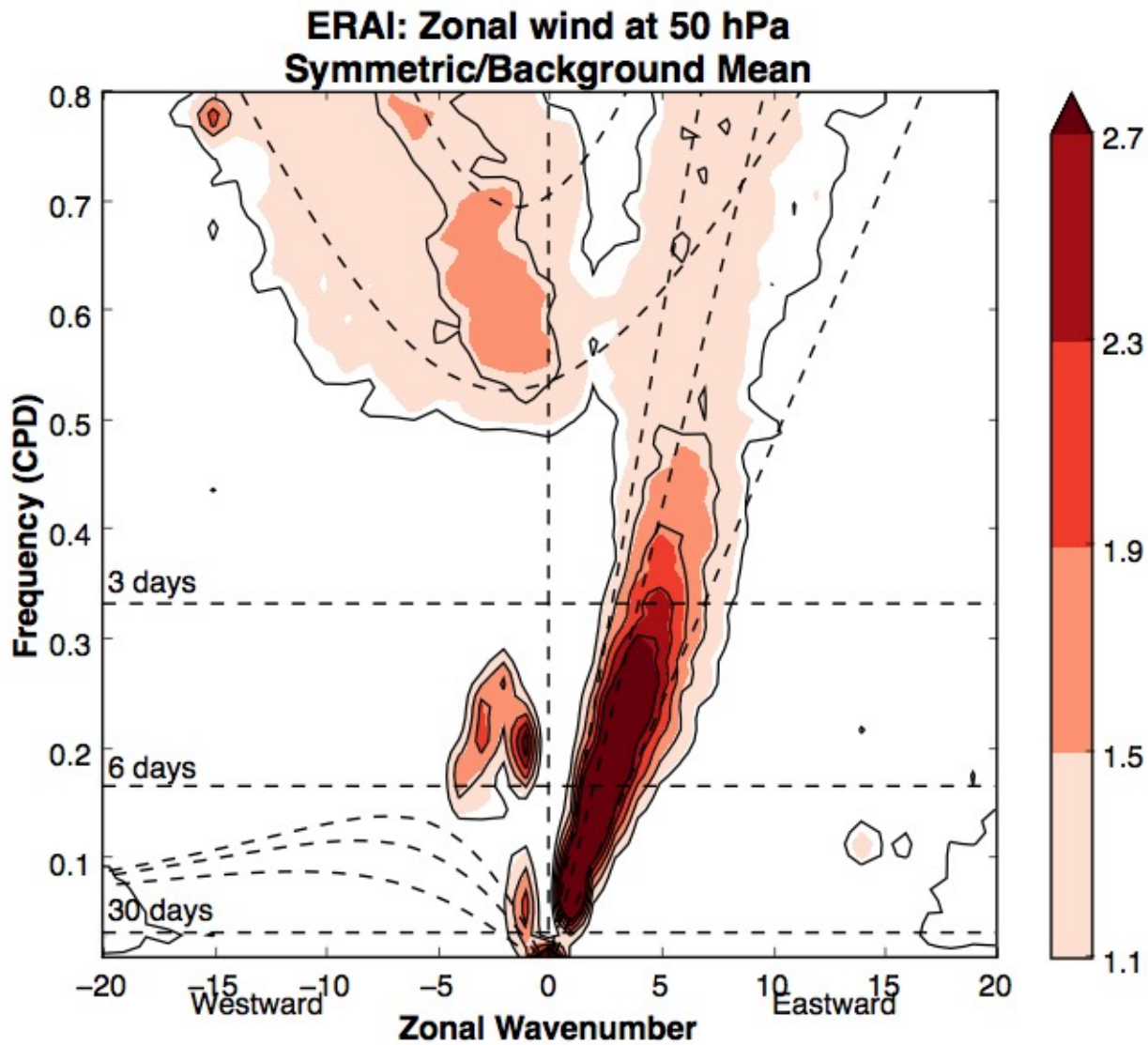Correlation between EOF1 and Rol's cos Component: -.60 (+1.25 days)

Correlation between EOF1 and Rol's sin Component: -.56

Correlation between our AMP and Rol's AMP Component: .44

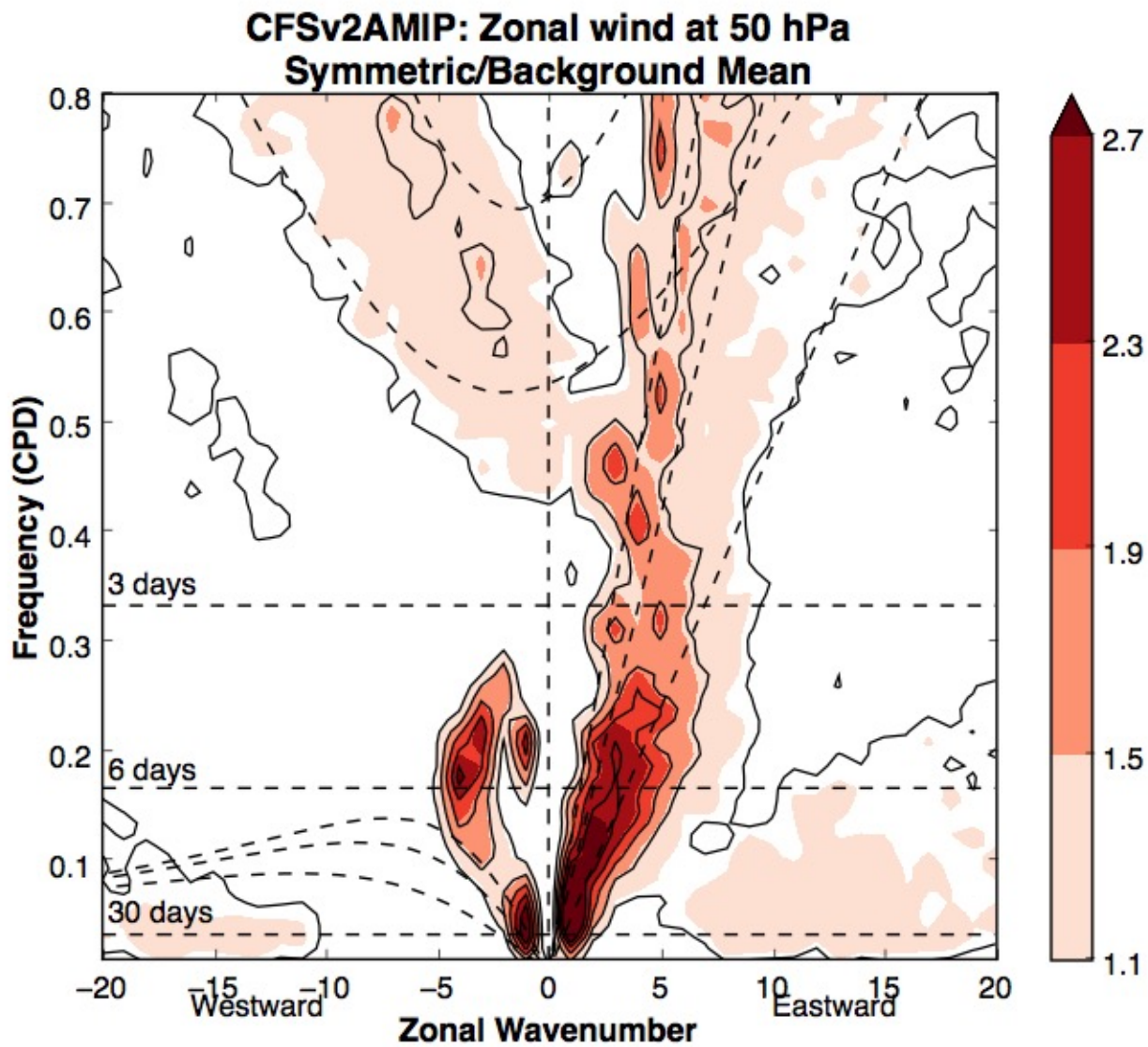# *Free Rossby Modes in GCMs*

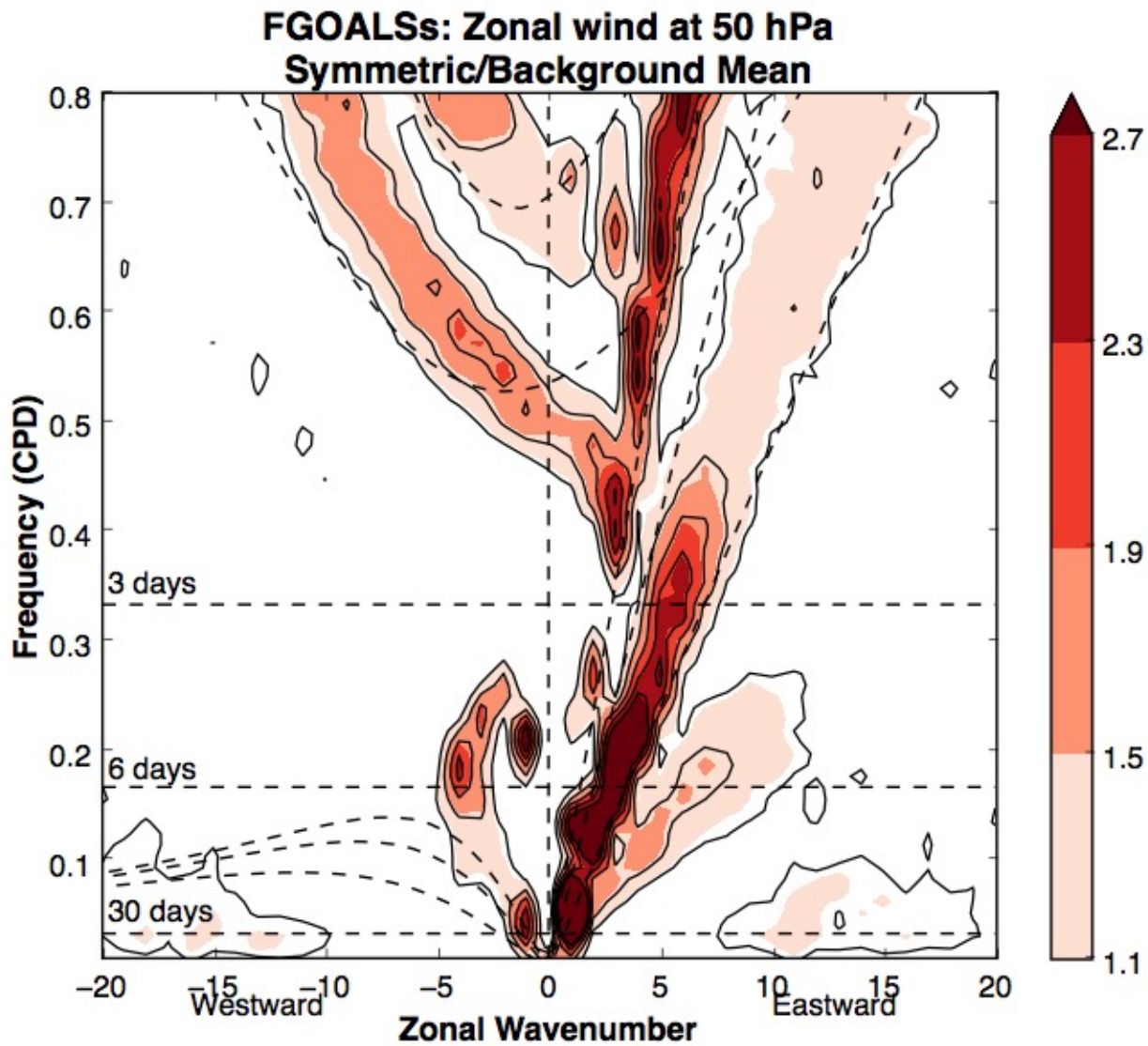Comparison of CMIP5 Models with reanalysis in the stratosphere…

# CMIP5 50 hPa Symmetric Zonal Wind 15S-15N



ERAI: Zonal wind at 50 hPa
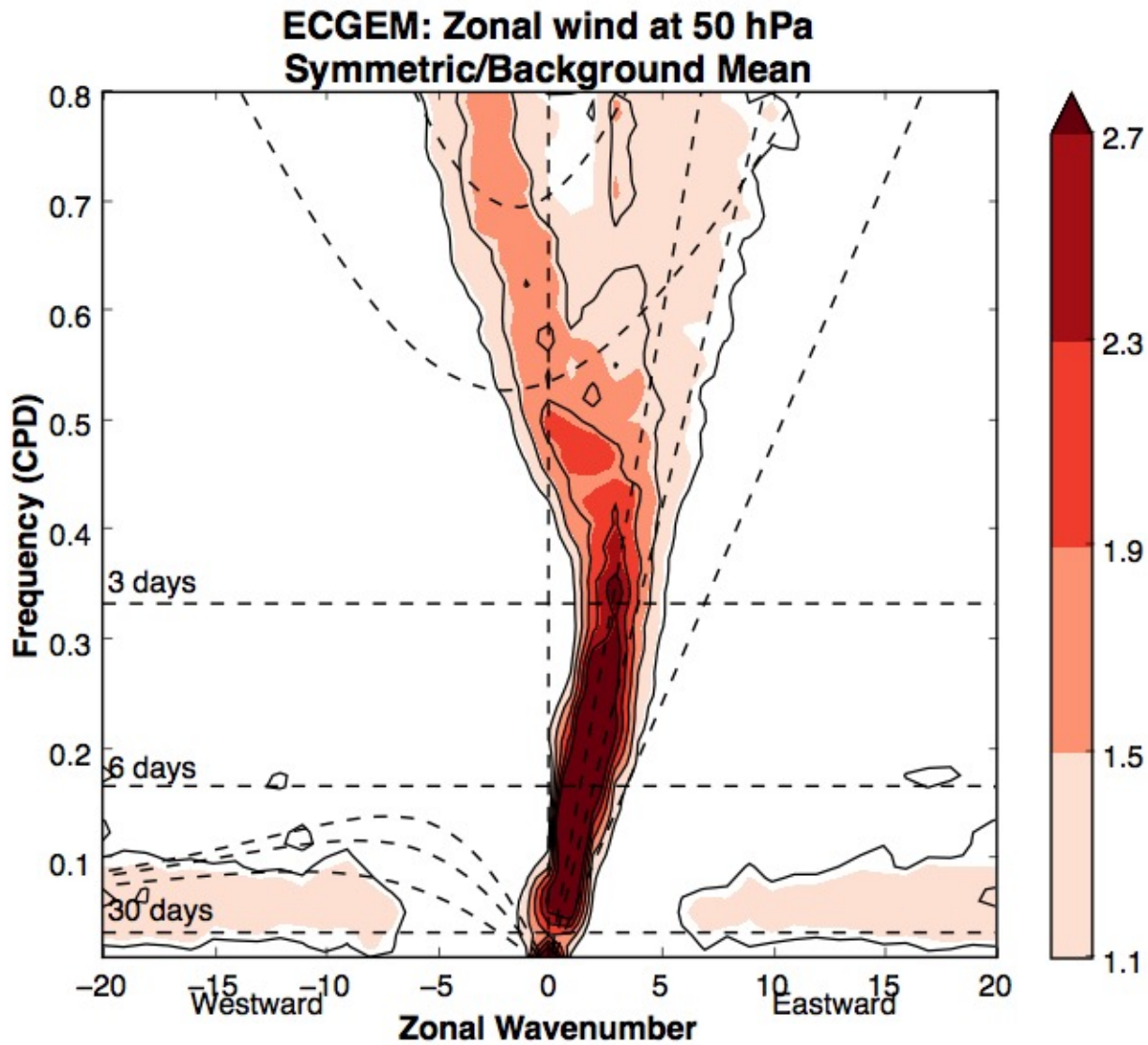Symmetric/Background Mean

# CMIP5 50 hPa Symmetric Zonal Wind 15S-15N



CFSv2AMIP: Zonal wind at 50 hPa
Symmetric/Background Mean

# CMIP5 50 hPa Symmetric Zonal Wind 15S-15N



FGOALSs: Zonal wind at 50 hPa
Symmetric/Background Mean

# CMIP5 50 hPa Symmetric Zonal Wind 15S-15N



ECGEM: Zonal wind at 50 hPa
Symmetric/Background Mean

# CMIP5 50 hPa Symmetric Zonal Wind 15S-15N



GISS_ModelE: Zonal wind at 50 hPa
Symmetric/Background Mean

# CMIP5 50 hPa Symmetric Zonal Wind 15S-15N



MPI-ESM: Zonal wind at 50 hPa
Symmetric/Background Mean

SPCCSM: Zonal wind at 50 hPa
Symmetric/Background Mean
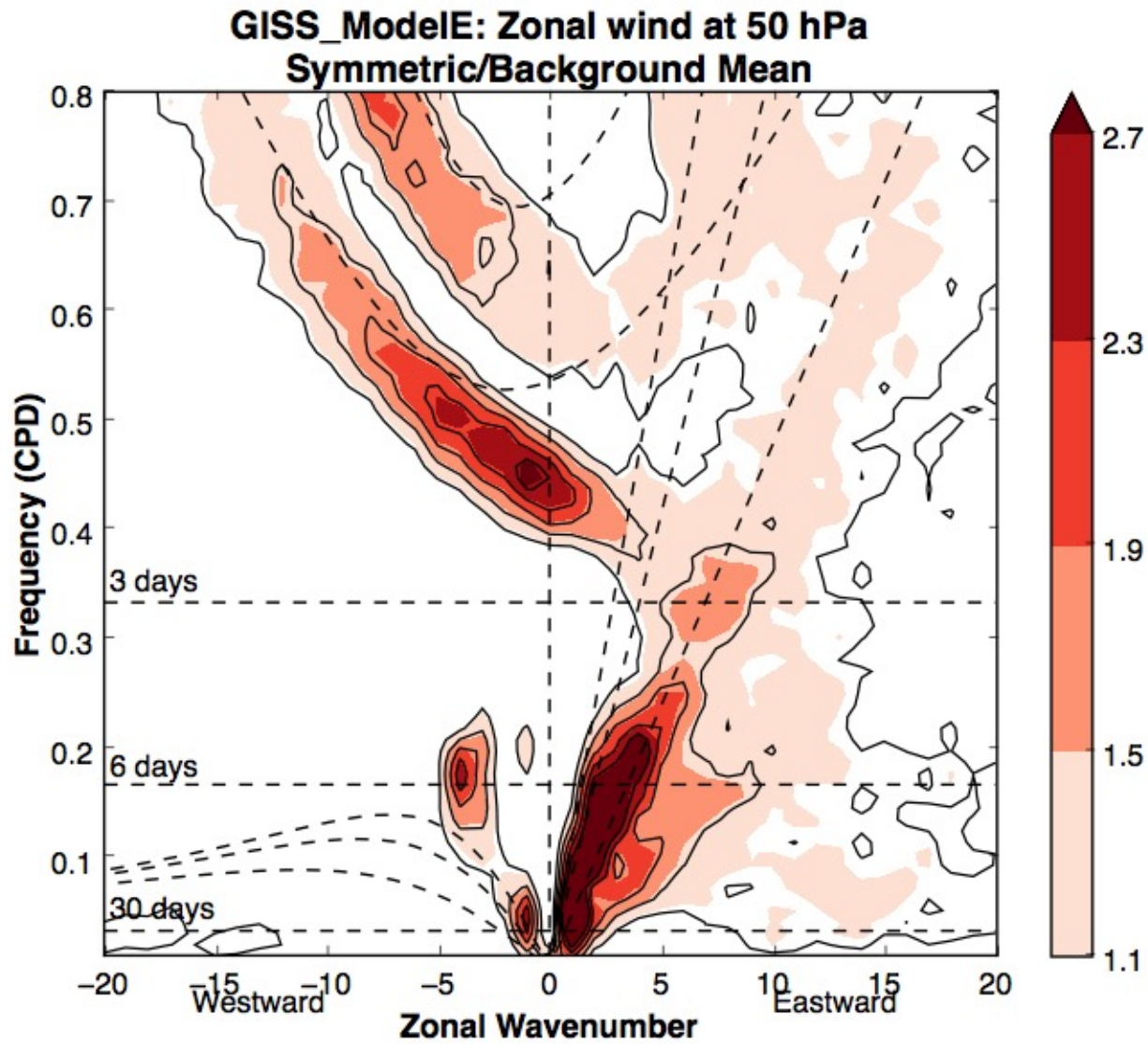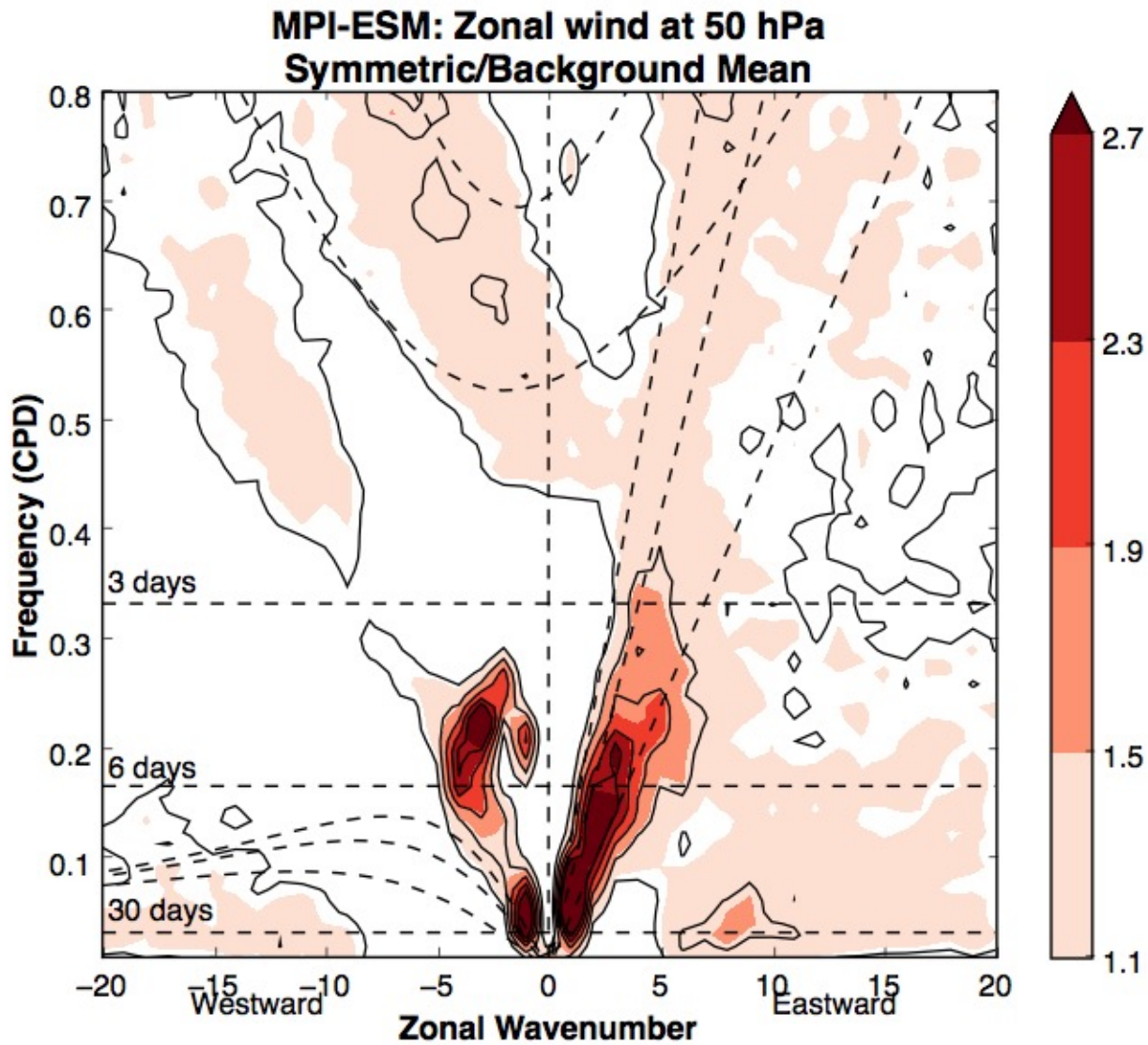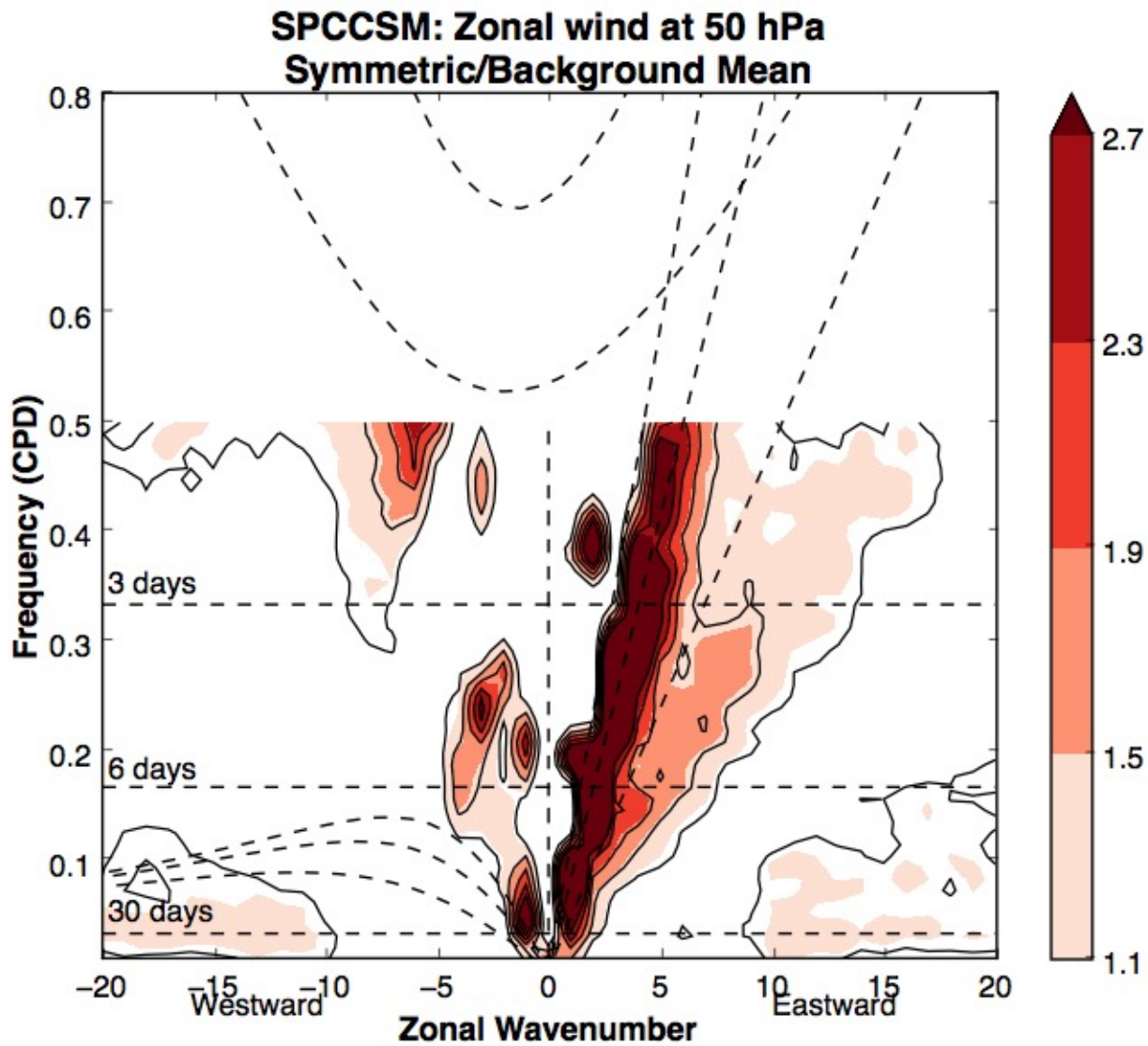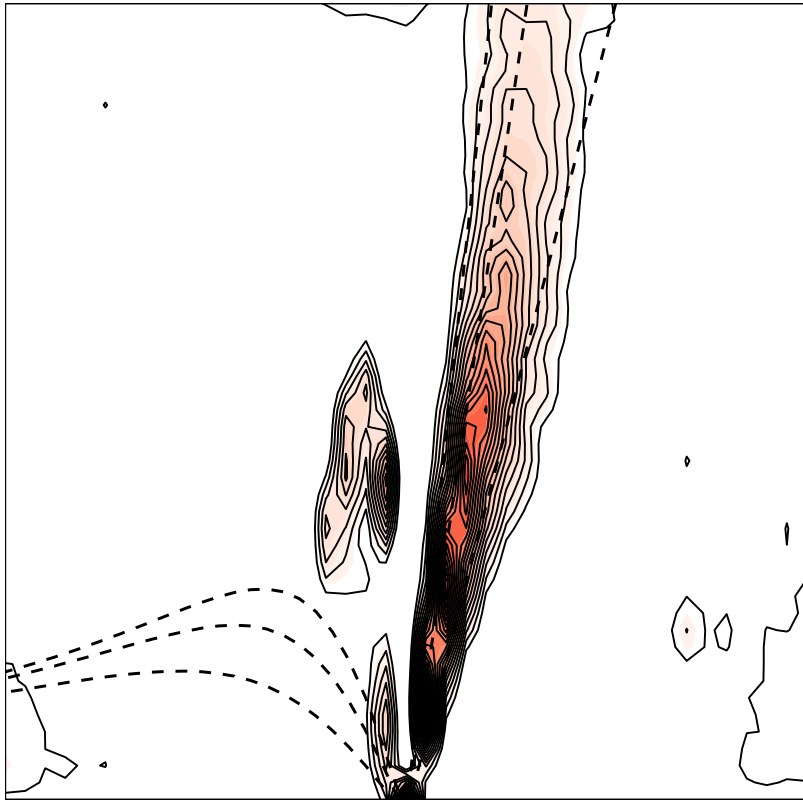
9      3.5      4.1      4.7      5.3      5.9

# *Conclusions*

**EOF analysis of 5 Day Wave filtered ERAI data is effective at isolating the statistical dynamical structure of that wave**

**There is systematic storm track activity associated with the 5 Day Wave in both hemispheres (direction??)**

**The 5 Day wave has substantial variability on intraseasonal time scales, some of which may be related to the Madden-Julian Oscillation**

**GCMs vary greatly as to their ability to simulate external Rossby modes**

**MODES analyses will be interesting to compare to EOF results**

**Relationships with satellite data in the upper stratosphere and mesosphere will also be investigated…**