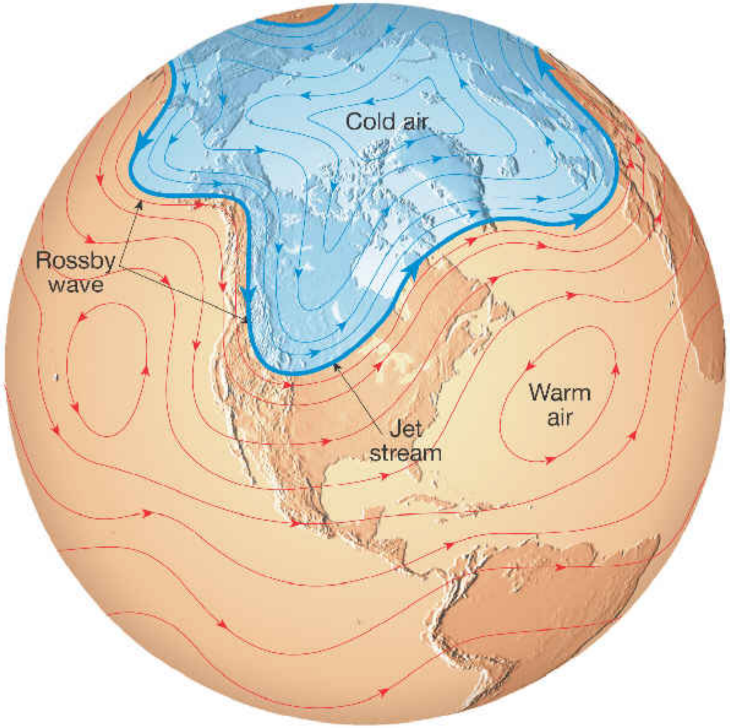
Introducing the Rossby Wave Packet Tool



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Acknowledgements

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Training Outline

- **Overview of Wave Packets**
- **How to View Wave Packets**
- **Methods of Computing Wave Packet Envelopes**
- **Wave Packet Climatology**
- **Utilization of Wave Packets**

Why Wave Packets?

- High impact weather has been found to be associated with wave packets (Archambault et al. 2010)
- 500 hPa geopotential heights move with phase velocity, while wave packets propagate with group velocity which can be an indicator of downstream development
- Potential indicator of uncertainty – forecast errors can develop and propagate like wave packets (Hakim 2005)

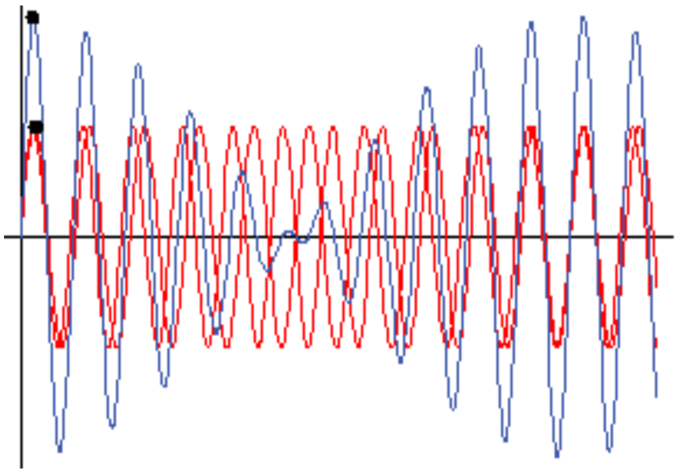
What are Wave Packets ?

- Baroclinic waves propogate chaotically and are driven primarily by phase speed

- A wave packet encompasses several waves and will propagate with the group velocity which is much faster than the phase speed of individual troughs

▪ Red curves are two sine curves which can represent troughs and ridges

▪ Blue curve is the wave packet which encompasses the toughs/ridges

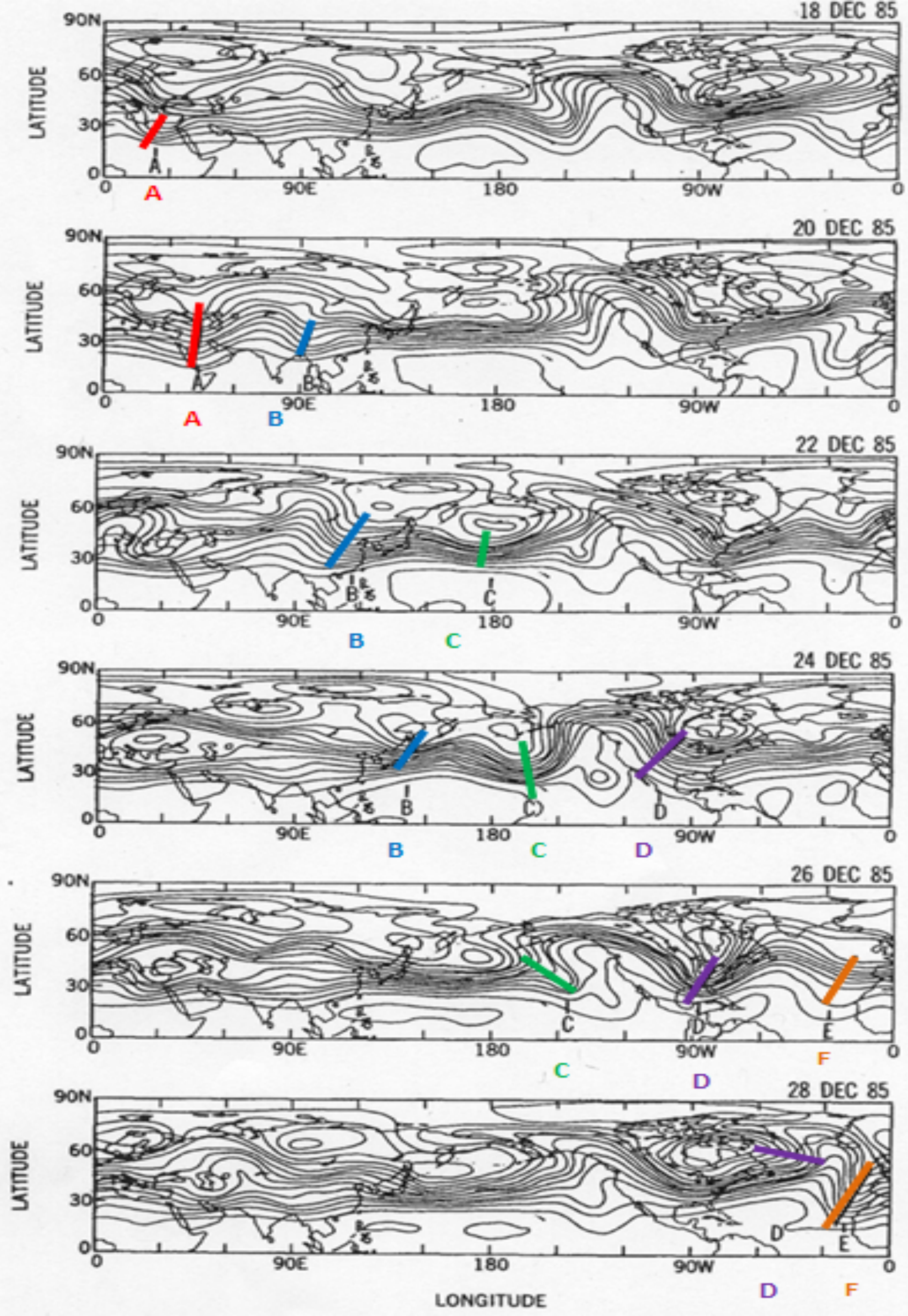


The figure on the right shows 300 hPa geopotenital heights for the period 18-28 December, 1985 (Chang 1993).

- **Wave packets are useful in forecasting because since they propagate with this much faster group velocity, the packets will often result in downstream development.**

- **Since the flow in the mid-latitudes is typically from west to east, trough (or even ridge) development can be found on the eastern or leading edge of these wave packets.**

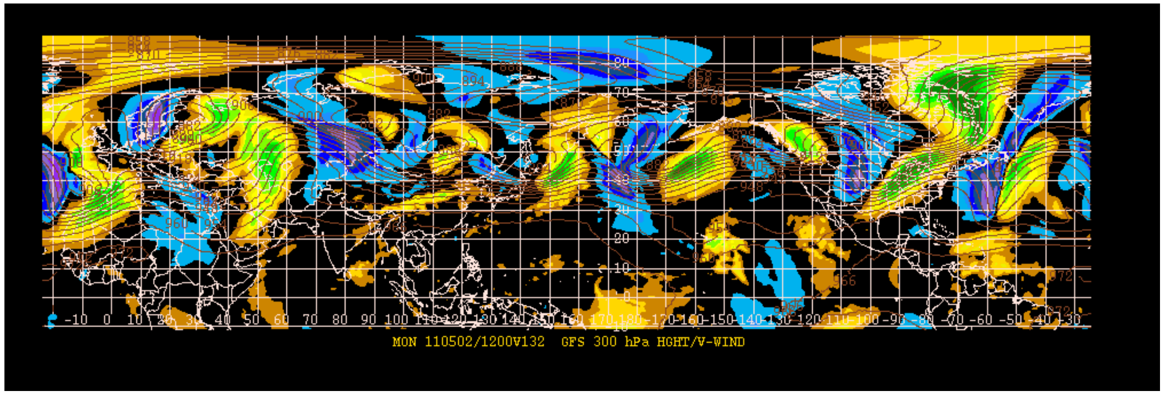
- **On the western or back edge of the packet, trough and ridge decay often occurs.**



Visualizing Wave Packets

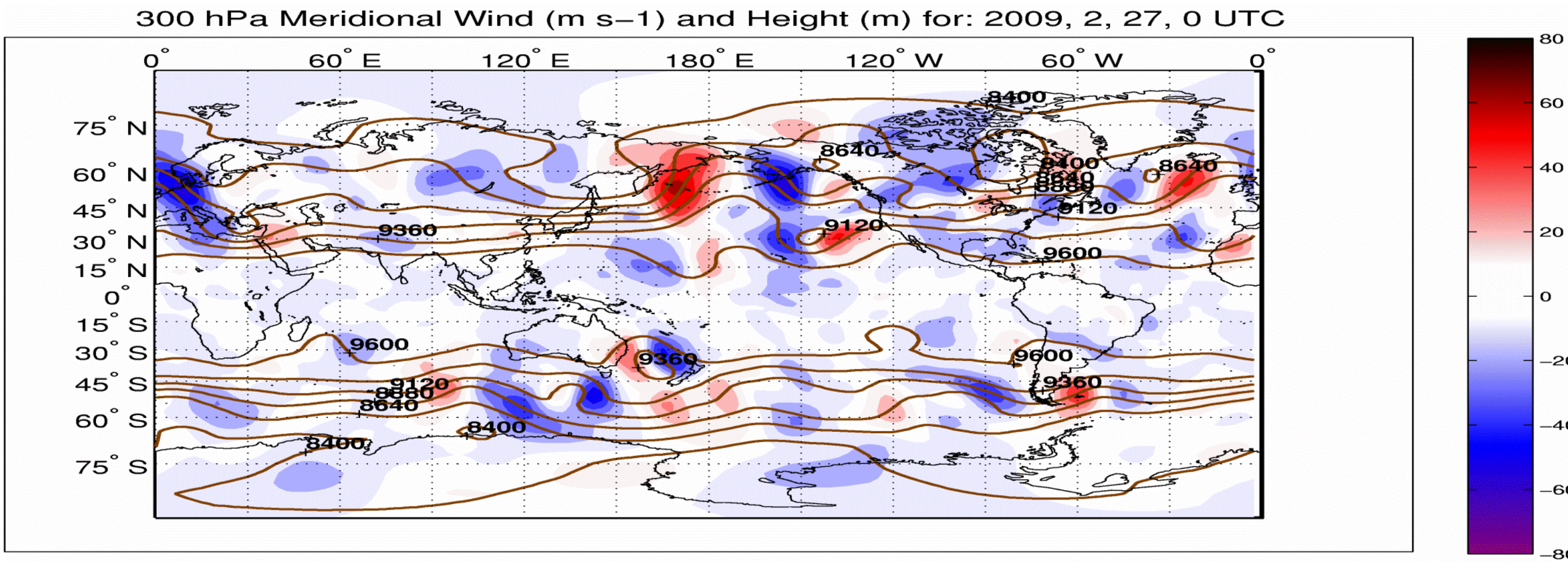
Wave progression can be followed on a plan view display by overlaying the 300 hPa geopotential heights with 300 hPa meridional (v) winds.

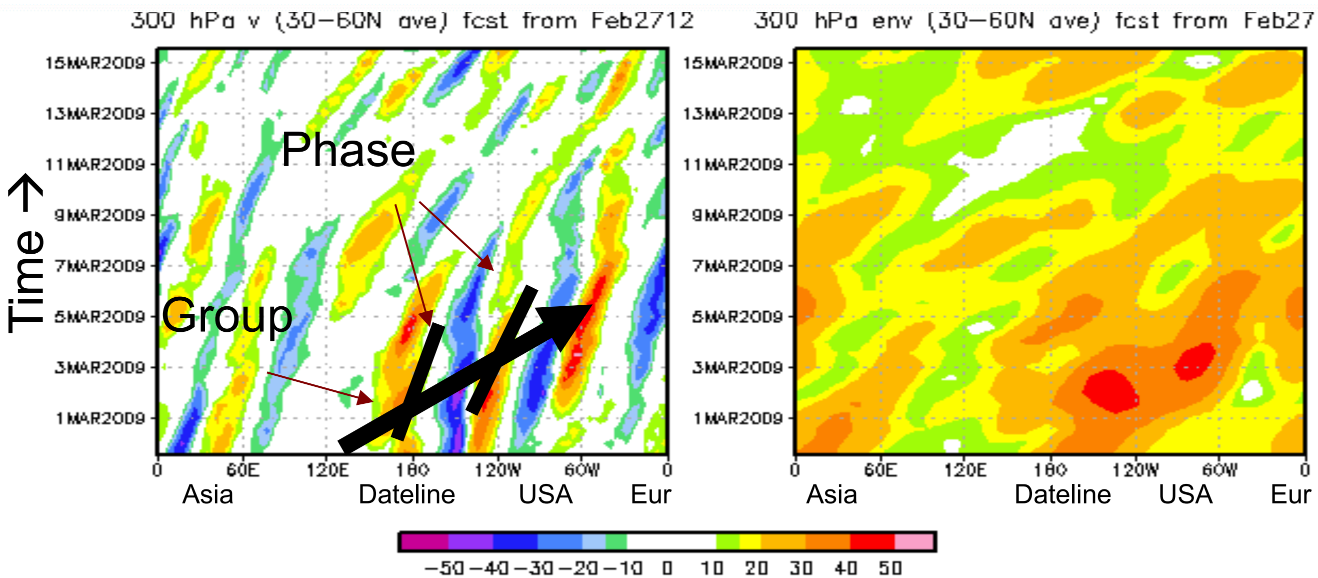
*The meridional (v) wind is used because it is dominated by the higher zonal wave numbers (5-8) which are typically associated with the higher frequency disturbance that effect mid latitude weather.



As illustrated in the previous slide, the v-winds can also be tracked on a Hovmoller plot.

Identifying Rossby Wave Packets





Hovmoller Diagram: 300 hPa Meridional Wind (left) and Wave Packet Envelope Amplitude (right) for March 2, 2009 NYC Snow Event

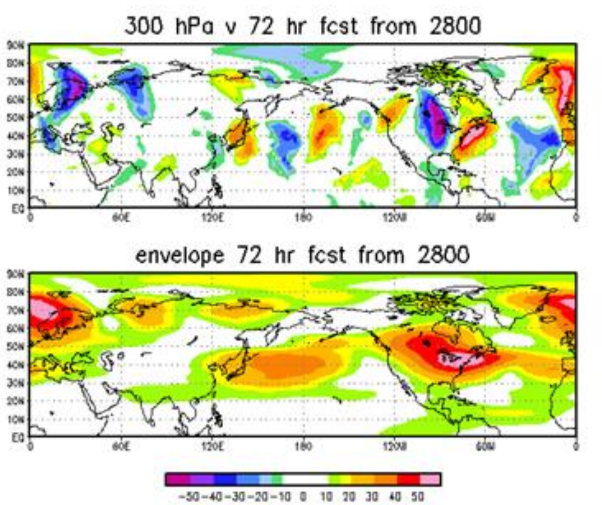
Wave Packet Envelopes

In the early 1990s, Isaac Held from Princeton and GFDL developed a procedure called *complex demodulation*. This procedure models in 2 dimensions, the structure of the baroclinic waves in the packet as a function of longitude and varying meridional velocity (v) over a sinusoidal wave function

$$A(x)\cos(kx + c(x))$$

where k = wavenumber (5-8 in mid-latitudes), c(x) = slow varying phase of wave packet, and A(x) = slowly varying envelope.

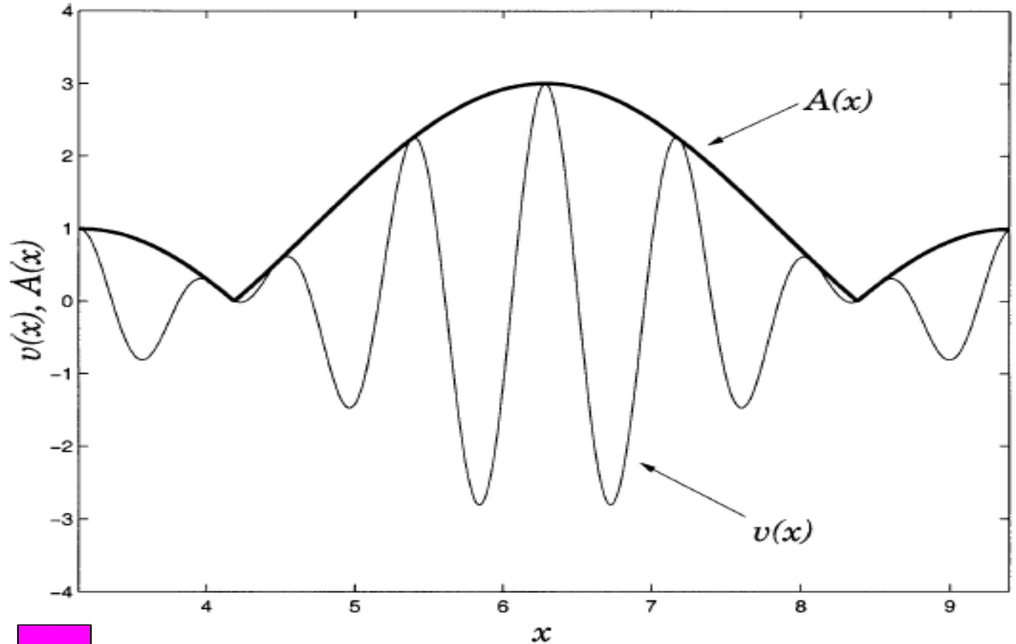
So solving for A(x) will give you an envelope solution to the wave packet.

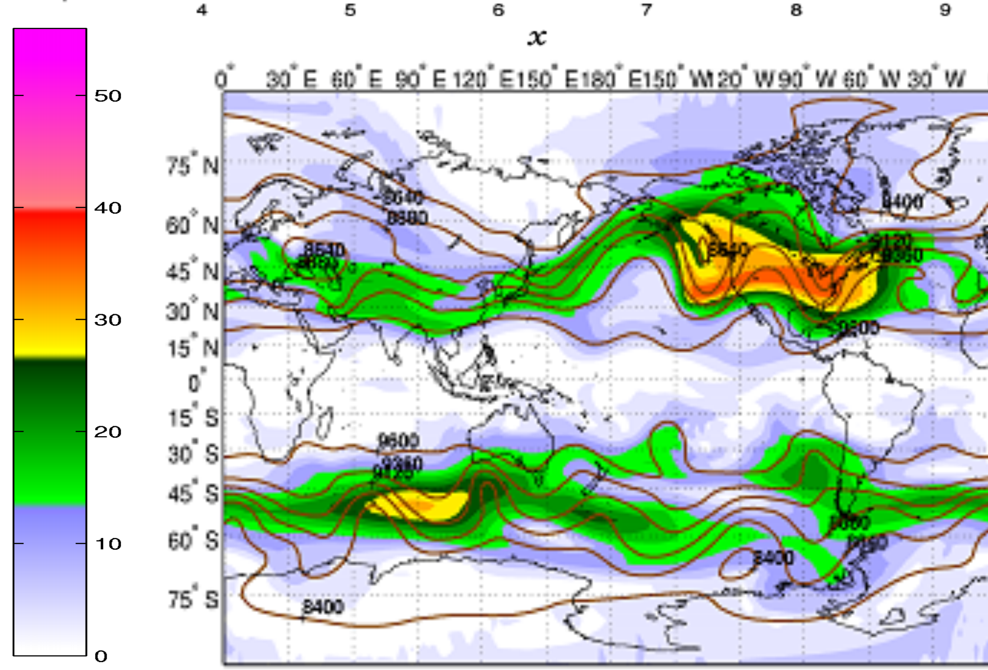


a) The top figure depicts the 300 hPa wave packets based on the model forecast.
b) The bottom figures shows the complex demodulation applied to the forecast wave packet (A(x)).

Further Development of Wave Packet Envelopes

- Implemented the Hilbert transform stream flow technique described by Zimin et al. (2006) using 300 hPa meridional wind to extract wave packet envelope amplitude (WPA)
- NCEP/NCAR global 2.5 degree reanalysis (1948-2009)
- 14-day running mean 300 hPa wind used to establish the stream flow along which packets propagate

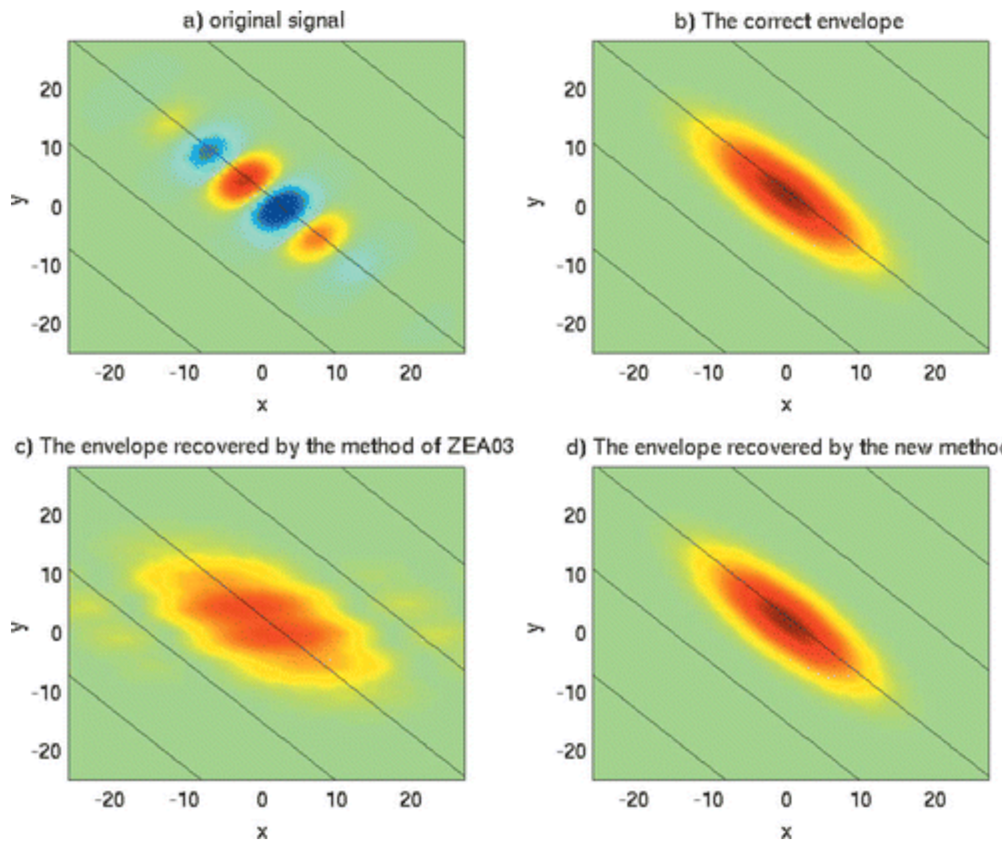




Idealized graph plots of methods

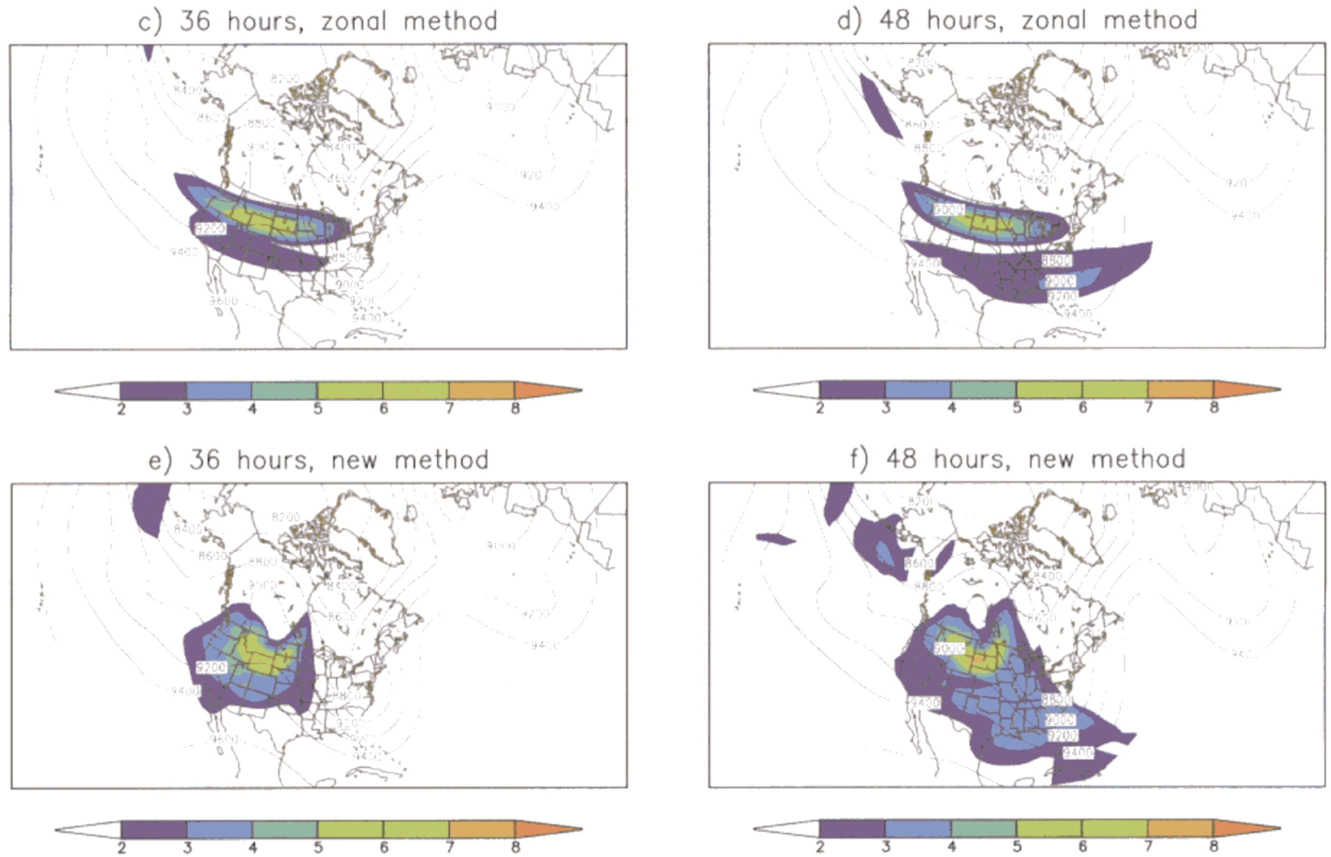
- Figure a) shows the actual wave packet plots at $\Phi(x, y)$
- Figure b) shows the wave packet envelope $A(x,y)$
- Figure c) depicts the packet envelope computed using the latitude circle method
- Figure d) depicts the streamline method of computing the packet envelop

Stony Brook uses this method



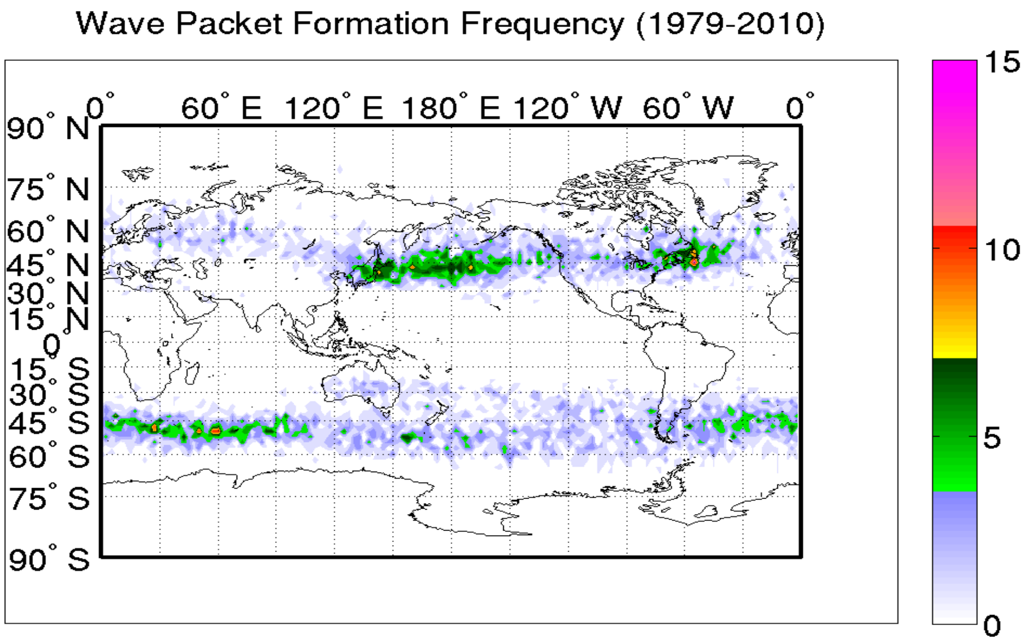
Method used at HPC

Zimin computation both with and without zonal averaging



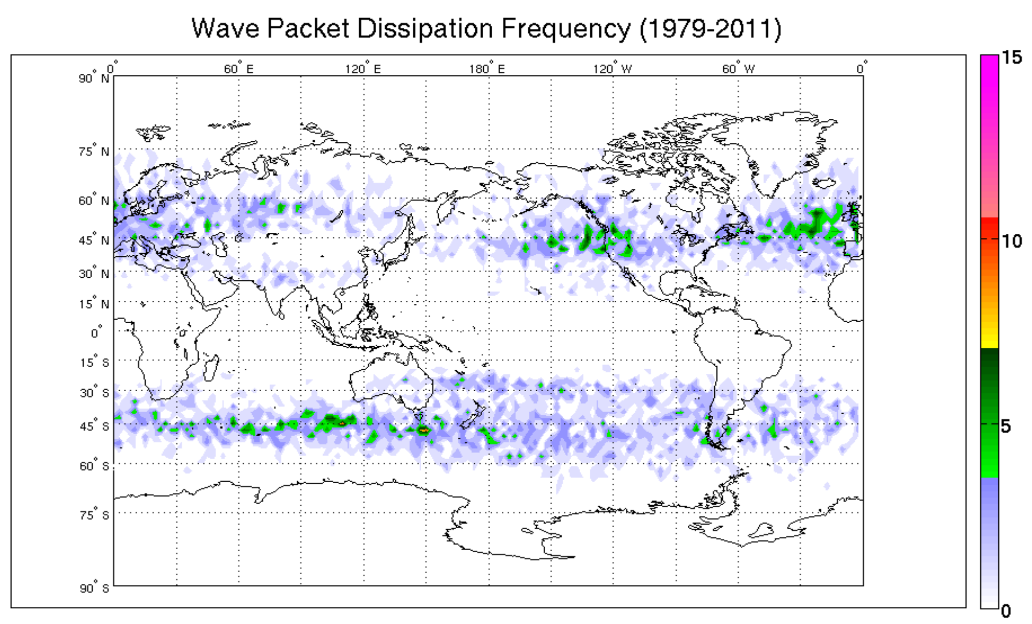
HPC uses new method

Track Formation and Dissipation



- **Formation (LEFT) controlled by initial impulses (cyclones) and thus most common where PV gradient is large (western ends of storm track belts)**

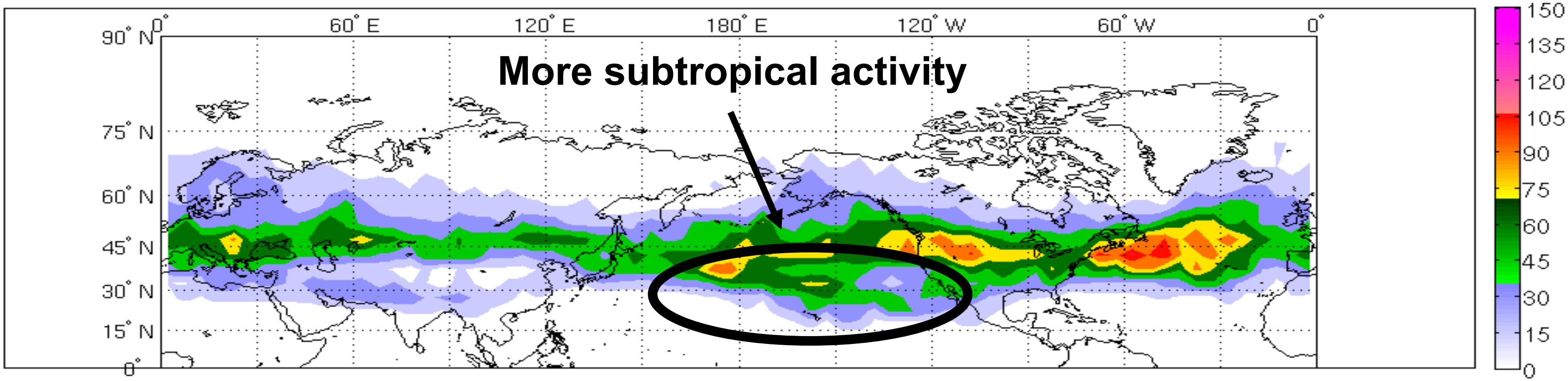
- **Dissipation (RIGHT) forced by many factors (split flows, wave breaks, loss of baroclinicity, topographic barriers, e.g.) and favored at the eastern edges of storm track belts and NW of Tibet**



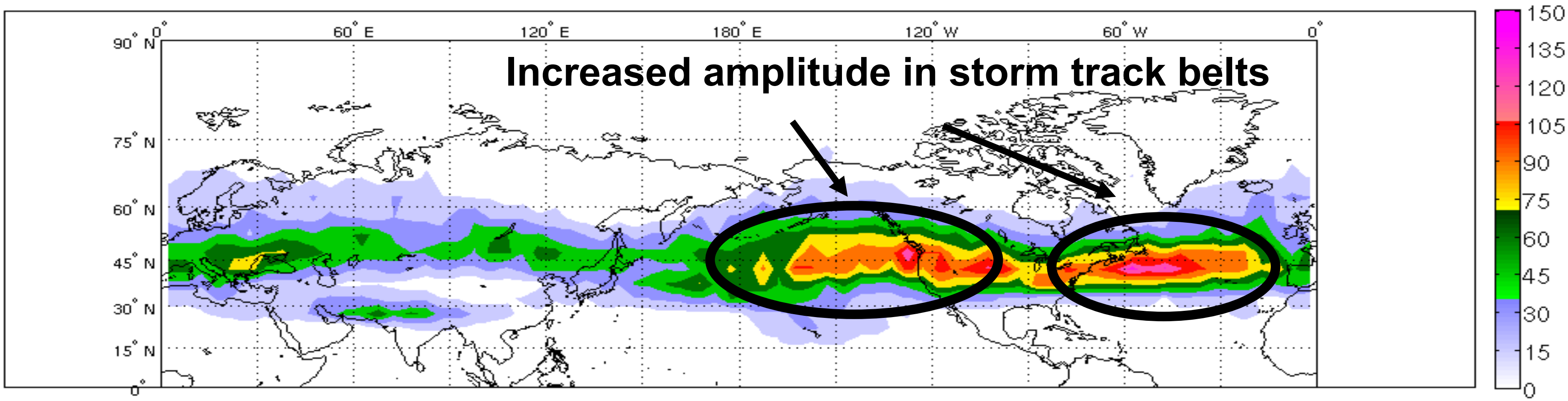
Northern Hemisphere Winter ENSO Signals

Multivariate ENSO Index (Wolter, 1987) > 0.5 (El Nino) and < -0.5 (La Nina)

Average Intensity Volume during winter (DJF) in five-degree bins for El Nino Seasons
NCEP/NCAR Reanalysis - 1948-2009



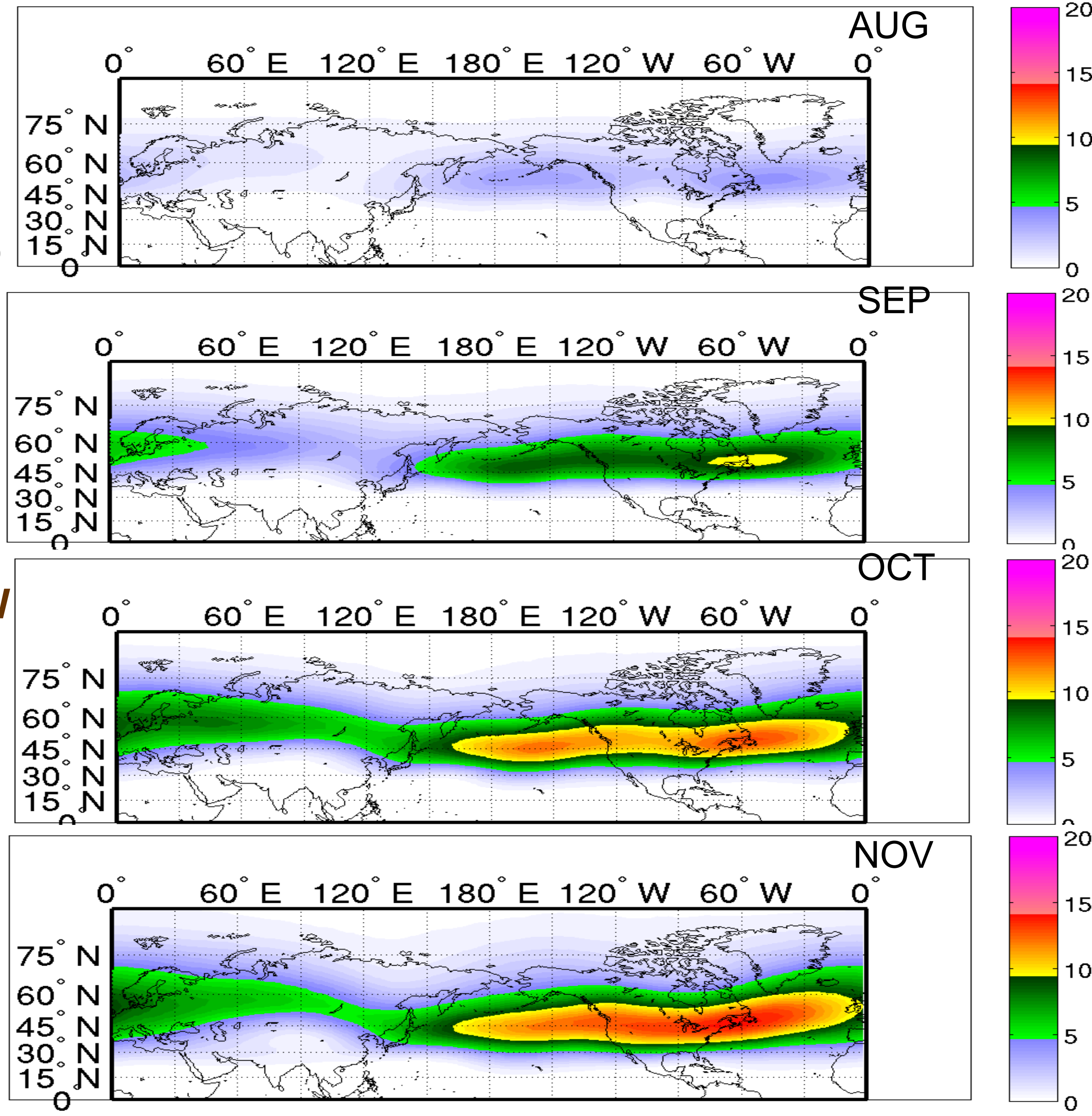
Average Winter (DJF) WPA Intensity Volume in five-degree bins during La Nina Seasons
NCEP/NCAR Reanalysis - 1948-2009



Average WPA in Significant Wave Packets by Month (ms-1) Summer to Fall Transition:

- Rapid Increase from Aug to Sept over C. Pac and NW Atlantic

- Maxima shift SE toward PacNW and SW toward Eastern North America

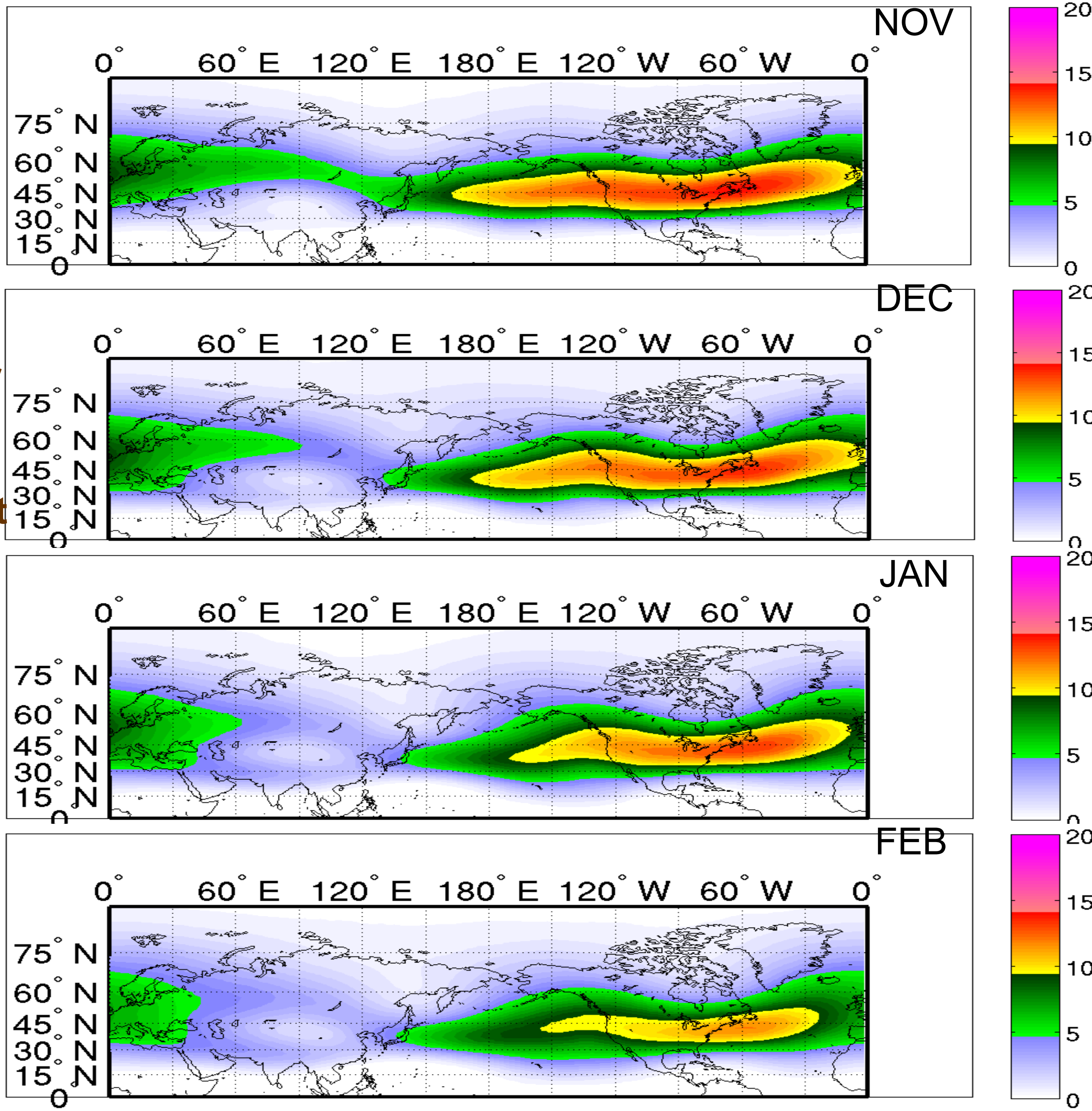


Average WPA in Significant Wave Packets by Month (ms-1) Fall to Midwinter Transition:

- Activity weakens throughout the winter months in the E PAC. Atlantic weakens less. Both tracks drift S.

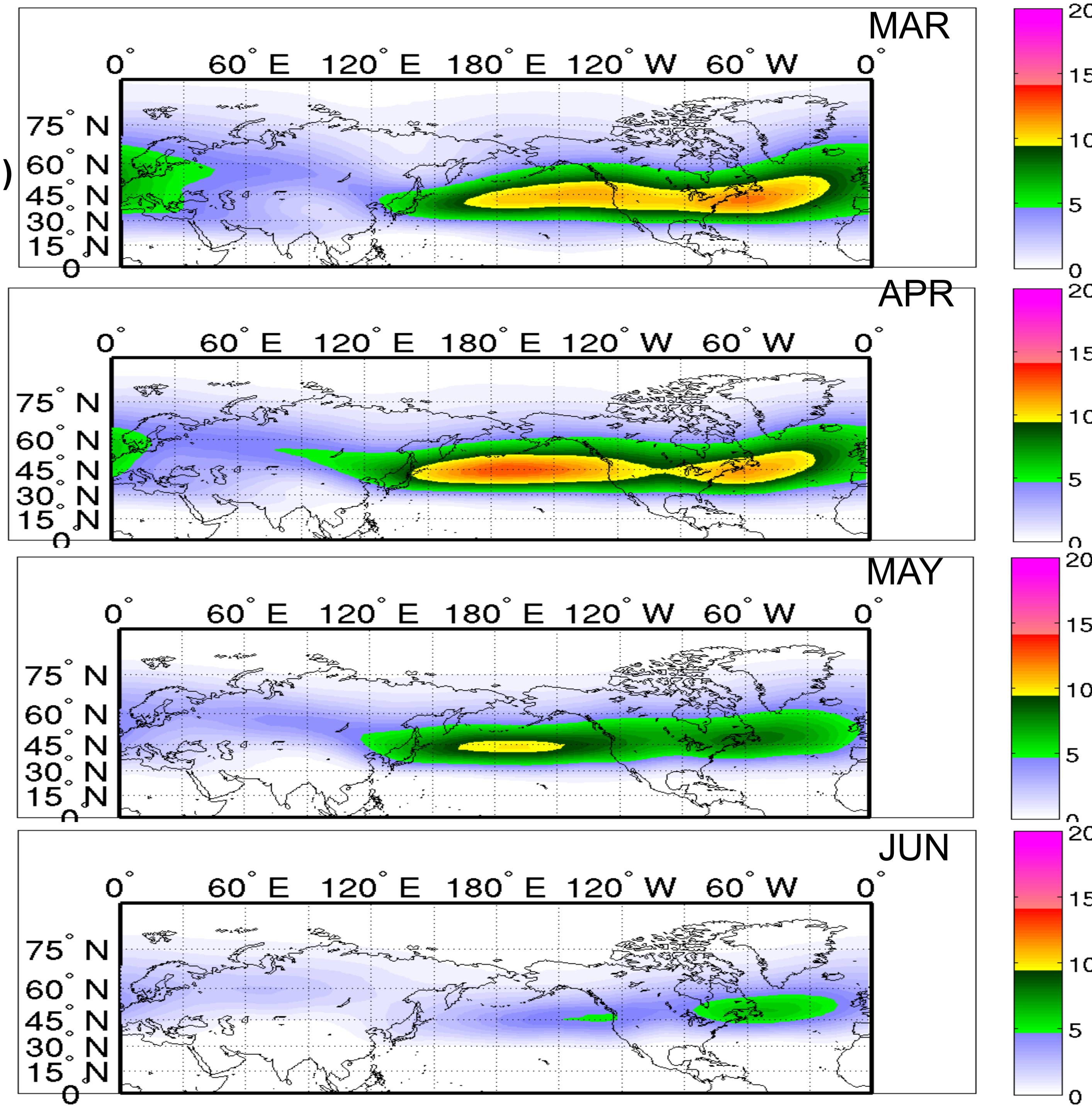
- Midwinter minimum consistent with storm track climatologies.

- More activity S of Tibet and near Hawaii in JAN/FEB



Average WPA in Significant Wave Packets by Month (ms-1) Winter/Summer Transition:

- Spring maxima in March in W ATL and April in C PAC
- Maxima shift away from land toward the C oceans again
- Both tracks shift north and weaken
- Activity in summer months limited to near Aleutian Low, Icelandic Wheel and N Europe



Utilization of Wave Packets

- **Wave packets are important to help identify high impact or extreme weather events.**

- **Wave packets can be used in model diagnostics. The rapid speed of the packets can help account for errors in initial conditions. These errors can be propagated with the wave packet.**

- **Cyclogenesis can be evaluated in the medium range by noting the eastern edge of the packet envelope.**

- **The new NTRANS tool is another method to contrast the forecast and initialization of the GFS and ECMWF by displaying the envelope forecast for both models.**

How to Use Wave Packets to Assess Confidence in a Medium Range Forecast

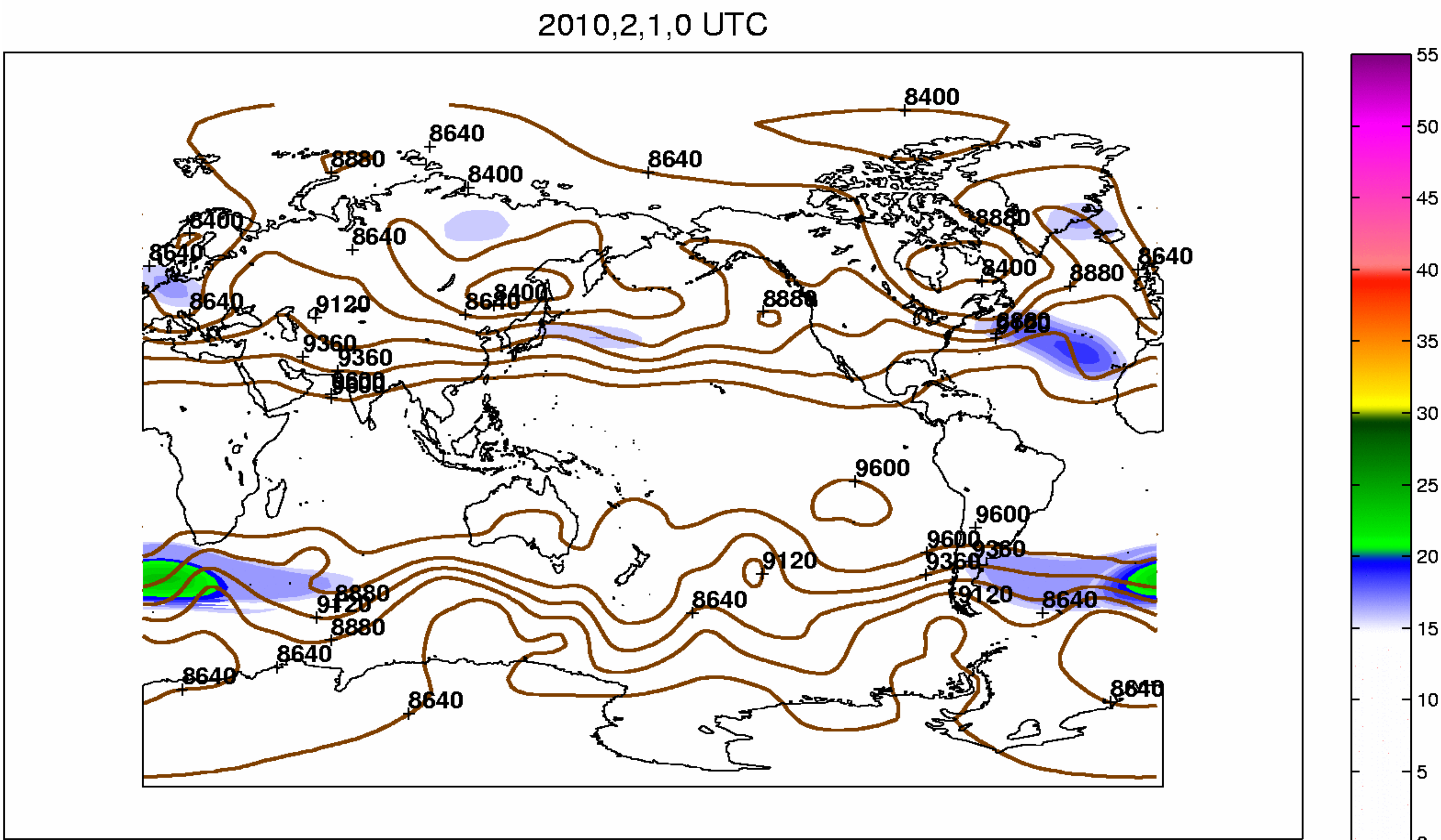
All of the following need to be analyzed and considered when checking for potential errors, and run to run/model to model consistencies.

- **Packets jumping from storm track to storm track**
  - Models can have difficulty handling the transfer of energy from the Pacific to Atlantic storm track or the Atlantic/trans European track to the Pacific.

- **At periods of formation**
  - Timing and intensity at the initialization point of the packet
  - Strong turbulent diffusion in presence of a strong jet
  - No strong jet- be skeptical of wave packet

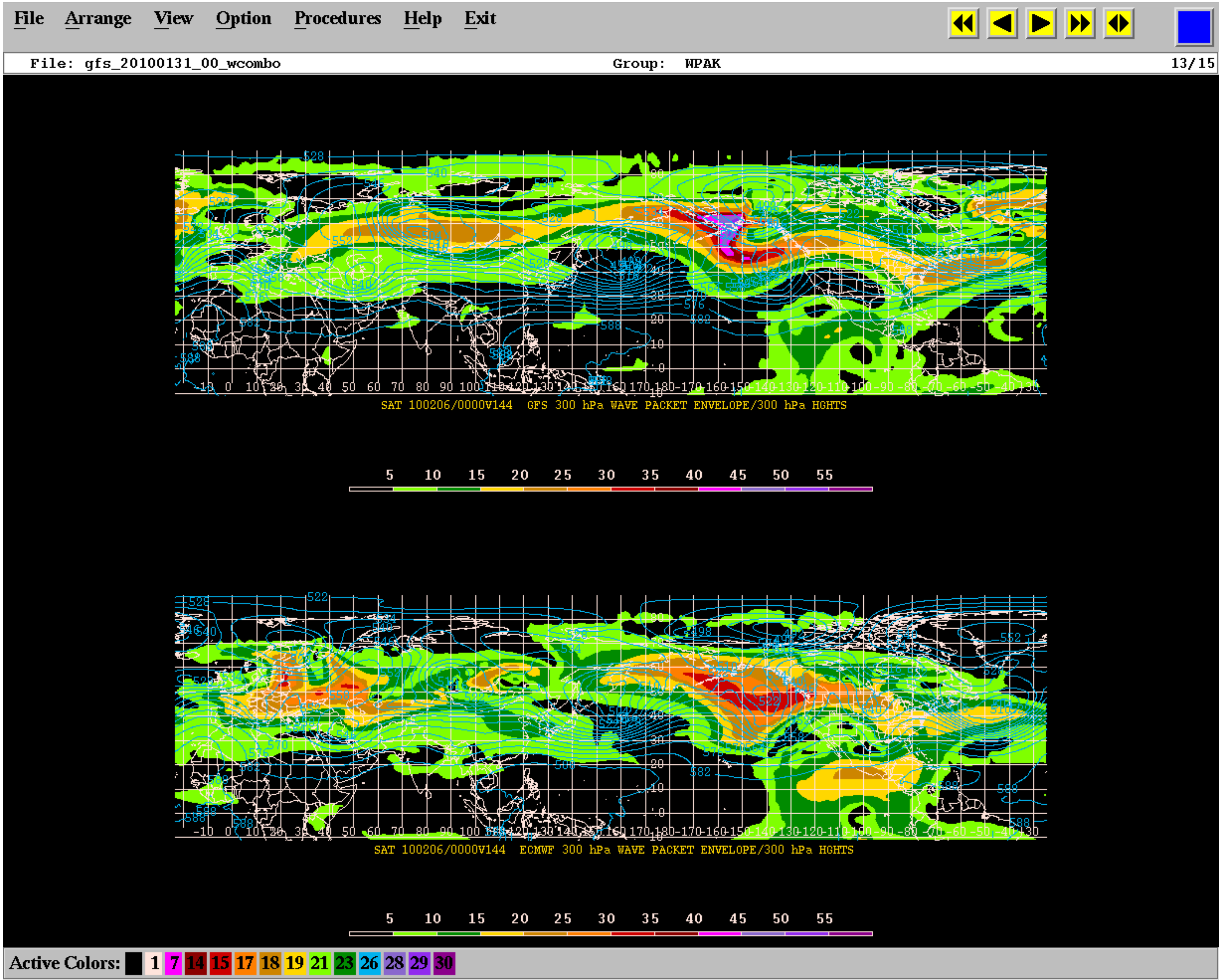
- **At time of decay**
  - Post wave breaking
  - Trough becomes negatively tilted
  - Energy transfers from zonal to meridional thus weakening the packet

High Predictability Case Study: 02/05/10



WPA (shaded, ms-1) and 300 hPa height (contours, m) – NCAR Reanlaysis

GFS and EC Forecast in NTRANS



GFS/EC Comparison

6-Day Forecast

- GFS too amplified with northern stream wave packet (and too fast)

- EC performed better in southern stream

5-Day Forecast

- EC performed better with southern stream forecast

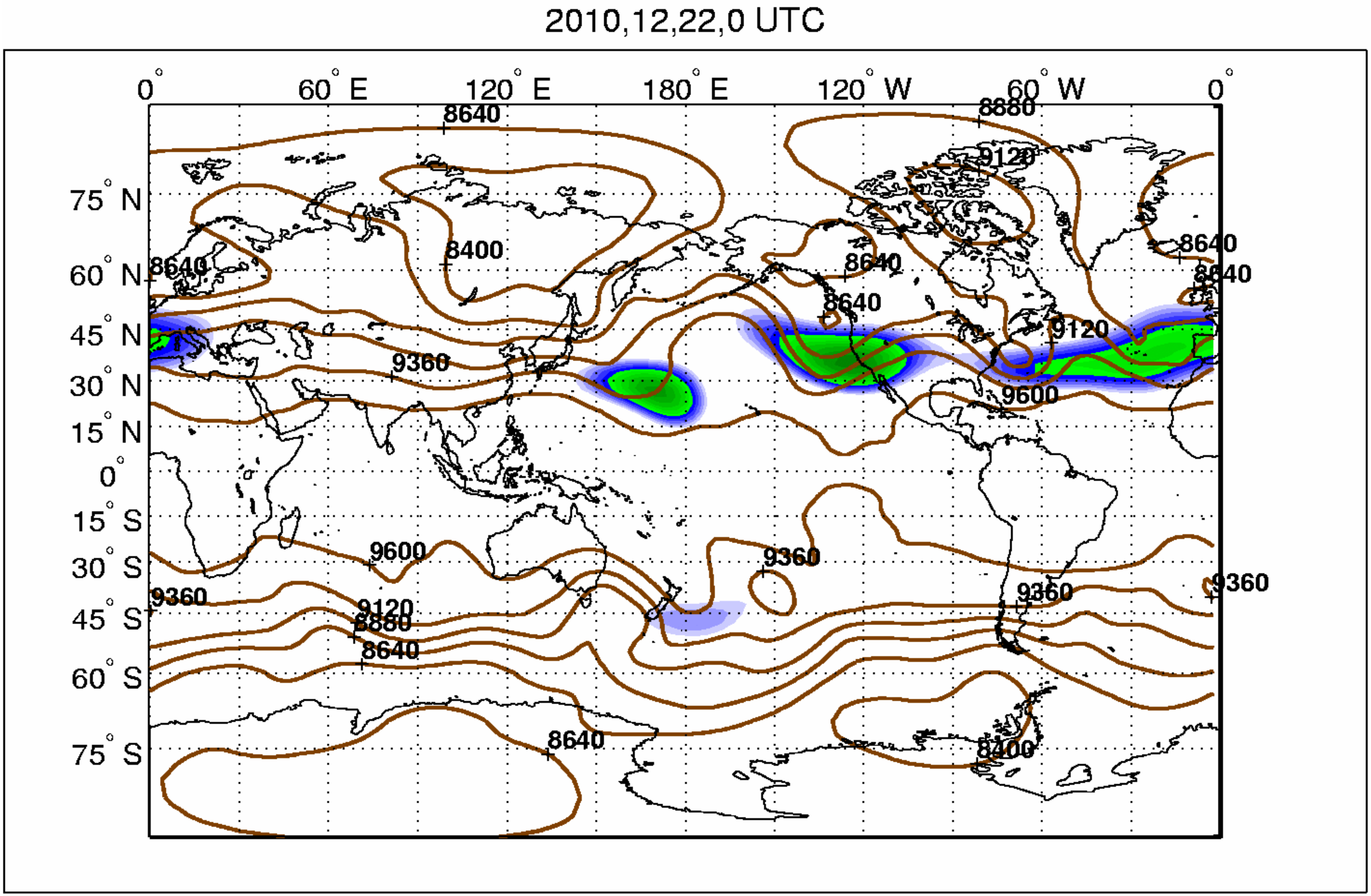
- GFS too much amplification over N. Pacific therefore no energy can leak into southern stream

4-Day Forecast

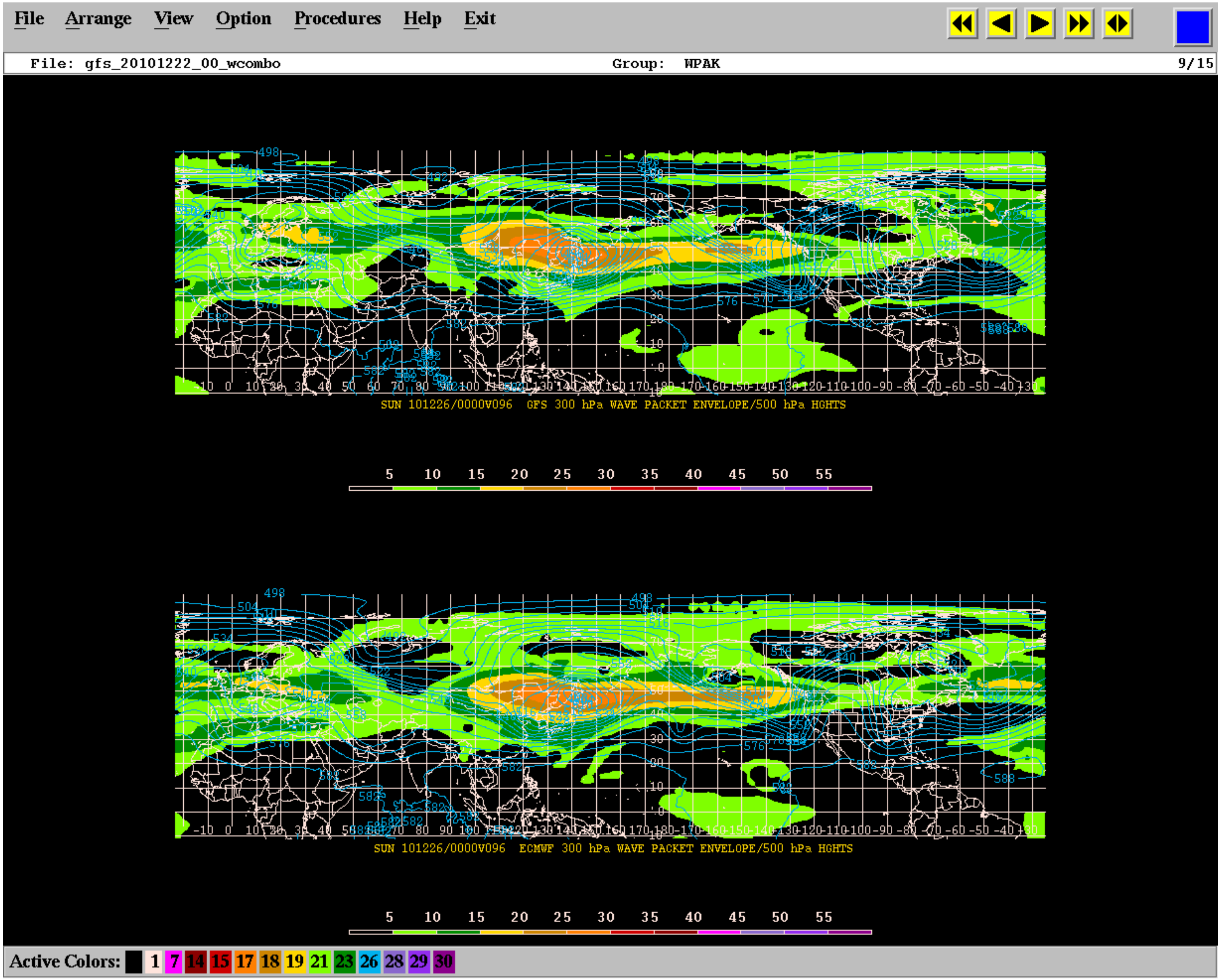
- GFS catches up with EC by transferring some energy into the southern stream

- GFS still too aggressive in northern stream, therefore not enough backing of heights along east coast

Low Predictability Case Study: 12/26/10



GFS and EC Forecast in NTRANS



GFS/EC Comparison

Both models has difficulty transferring energy from the wave packet to the storm

6 and 7-Day Forecast

- **Both GFS and EC amplify North American ridge at eastern end of packet**
- **GFS ridge too broad which resulted in NE cutoff being too far east**

5-Day Forecast

- **Key feature is digging short wave into Great Lakes and Ohio Valley**
- **EC better handles this feature due to better amplification of the western North American ridge**
- **GFS holds energy back in Pacific**
- **EC suggests successful transfer of wave packet across NA in non-zonal flow environment**
- **GFS somewhat flatter with the ridge therefore eastern U.S. storm more progressive**

Summary

- Real time wave packet forecast are available in NTRANS to compare the GFS and EC
- High impact weather has been found to be associated with wave packets
- Wave packets are another way to evaluate model consistency and confidence
- The stronger and more concentrated the envelope, with storms developing at the leading edge or too far downstream of the wave packet, the greater the forecast uncertainty
- The weaker and more elongated the envelope, with storms developing within the domain of wave packet, closer to the center, the lower the forecast uncertainty
- When examining wave packets for errors and run to run consistencies, focus on periods of formation and decay, and packets jumping storm tracks

References

Archambault, H.M., D. Keyser, and L.F. Bosart, 2010: Relationships between large-scale regime transitions and major cool-season precipitation events in the northeastern United States. Mon Wea. Rev., 138, 3454-3473.

Chang, E.K.M., 1993: Downstream development of baroclinic waves as inferred from regression analysis. J. Atmos. Sci., 50, 2038-2053.

Hakim, G.J., 2005: Vertical structure of midlatitude analysis and forecast errors. Mon. Wea Review., 133, 567-575.

James, Ian N., Introduction to Circulating Atmospheres, 1994, Cambridge University Press.

Lee, S., and I.M. Held, 1993: Baroclinic wave packets in models and observations. J Atmos. Sci., 50, 1413-1428.

Zimin, A.V., I. Szunyogh, B.R. Hung, and E. Orr, 2006: Extracting envelopes of nonzonally propagating Rossby wave packets. Mon. Wea. Review, 134, 1329-1333.