Using precipitation and latent heating measurements of the GPM constellation to improve the 1-3 day prediction of tropical – extratropical potential energy surges and their impact on significant extratropical weather.

I. Scientific Problem and Hypothesis

As a key component of NASA's strategic goal 2 to "Advance Earth System Science to meet the challenges of climate and environmental change" the Global Precipitation Mission (GPM) has built instrumentation to directly observe atmospheric precipitation and attendant atmospheric forcing mechanisms including latent heating across the globe. Our recent work has revealed important direct atmospheric structural implications of latent heating that can be quantified directly from the latent heating algorithms and used to improve atmospheric thermodynamic and dynamic analyses. This new information can potentially improve short and medium range numerical prediction of significant weather, both precipitating and non precipitating over the continental United States (CONUS). Below, we propose a study to *develop methodologies employing TRMM and GPM observations to improve the analysis and forecast of the subtropical jet stream and its critical interactions with the extratropical wave stream affecting significant weather over CONUS*. **This proposal is in response to research category 2.3 (3rd bullet) of Appendix 2.3 of the NASA ROSES NRA .**

In this study, we propose to combine observations and theory to translate observed precipitation to model-state perturbations to a model analysis, and compute the impact of those model-state perturbations on the evolution of the subtropical and polar jets most responsible for atmospheric rivers. Latent heat profiles derived from the GPM precipitation algorithm will be employed to develop model analysis-perturbations that are consistent with the observed latent heating. Model adjoints will be used to compute the sensitivity of various aspects of the midlatitude forecast to these theoretical analysis-perturbations. This study will help conceptualize the translation of precipitation information to analysis-increment through the latent heat forcing, and provide both quantitative and qualitative analysis of the importance of those analysis-perturbations to forecasts of atmospheric rivers and the global atmospheric environment from which atmospheric rivers develop.

a. JAPE surges

Atmospheric rivers are responsible for a majority of moisture transport outside of the tropics (Zhu and Newell 1998), and are responsible for the formation of extreme weather events such as intense flooding (e.g. Moore et al. 2012). These phenomena are associated with Sawyer-Eliassen circulations associated with the ageostrophic response to jet stream propagation in the upper atmosphere. Ageostrophic circulations occur in response to both polar jet (PJ) streams and subtropical jet (STJ) streams. However, the ageostrophic circulations associated with the STJ are the circulations that tap directly into deep tropics forming atmospheric rivers of moisture (also called tropical plumes) into the extratropics. Heavy extratropical precipitation associated with these circulations, however, is most often associated with the interaction of the STJ with the PJ.

The underlying energetics and dynamics driving these interactions results from a transfer of available potential energy (Lorenz, 1955, Krishnamurti, 1961ab, Paului et al., 2010) placed in the tropical upper troposphere Lower Stratosphere (UTLS). This energy is derived from tropical latent heating that expands the atmosphere upward elevating the thickness of isentropic layers of the UTLS. Once there, this potential energy becomes inertially and radiatively (above level of zero net radiation tendency) trapped until it eventually becomes injected into the extratropical wave stream. Interactions between the STJ and PJ in the extratropics represent the most important mechanism of this energy transfer.

We can quantify the amount of this potential energy that would be "available" for release by this transfer by comparing the potential energy at any particular location to a globally defined and constant reference profile. We take that reference to be a standard extratropical sounding. The potential energy difference between a sounding in the tropics compared to a standard sounding will then represent how much energy would be released if the tropical sounding relaxed to the standard sounding, and so can be viewed as "available" to be released if a tropical plume merged into an extratropical atmosphere. We call this energy, the "Jet Available Potential Energy", or JAPE, because it is a good indication of the potential energy available for conversion to the kinetic energy of a jet stream. The formulation is:

$$JAPE = \frac{\rho - \rho_s}{\rho} gz$$

where atmospheric density is ρ , ρ_s is the density of a standard sounding, g is gravity and z is the MSL height. Defining JAPE relative to a standard sounding produces a constant reference both in space and time. As a result, the horizontal variability of JAPE is identical to that of the total potential energy, but while suggesting the degree of its anomaly relative to extratropics by virtue of the reference comparison. JAPE is found to be concentrated in the tropical UTLS, as seen in figure 1:

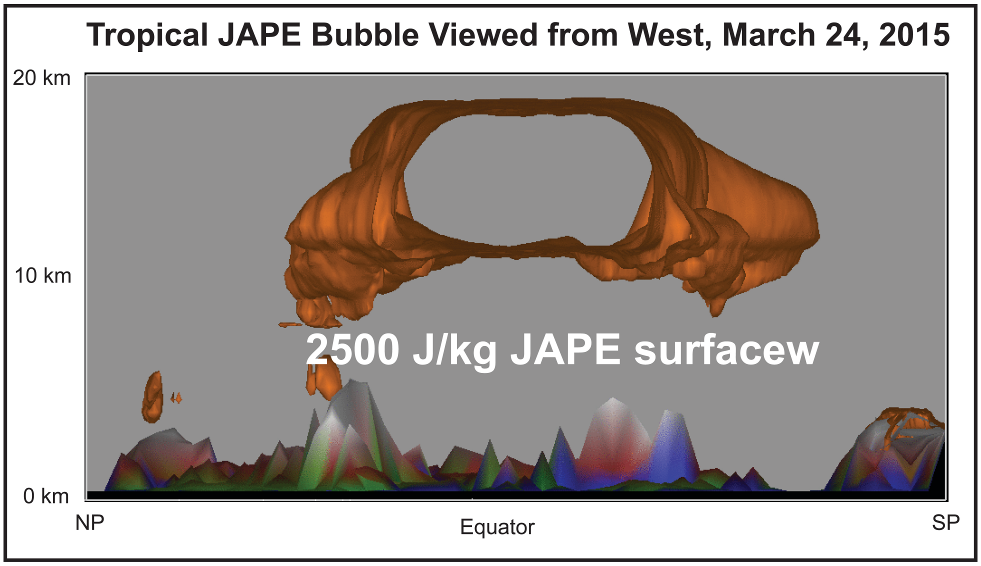

Figure 1: View of global tropical JAPE bubble from the west. Note that the Positive JAPE is confined to the UTLS, such that its upper surface defines the elevated tropical tropopause.

Analysis of such JAPE surges over the past 3 decades, suggests that the interaction is deliberate (Mecikalski and Tripoli, 1998). As the STJ interacts with the lowered inertial stability on the equatorward side of the PJ, the inertial trapping of the UTLS potential energy is weakened, causing the STJ, which bounds the poleward edge of the tropical UTLS, to arch poleward and draw closer to the polar jet trough, which bounds the low level polar air mass on its equatorward side. The two jets are drawn together, usually on the eastern side of a PJ trough, where the energy exchange commences.

As a result of the energy transfer, tropical JAPE is converted into the kinetic energy of the PJ, by way of the STJ. The transfer results in the substantial speed (or kinetic energy) increase in the PJ and Rossby wave train amplitude and the weakening of the STJ as its supporting energy cache is depleted. Importantly, the transfer accelerates a deepened Sawyer Eliassen circulation of the combined jets, creating a strong flow of tropical moisture into the Rossby wave train out of the extratropics, which is commonly recognized as a tropical plume (Mecikalski and Tripoli, 1998) or atmospheric river (Winters and Martin, 2014, Christenson and Martin, 2012).

The transfer of energy can be termed a poleward JAPE "surge" of the tropical UTLS into the extratropical Rossby wave train, and represents a key component of the general circulation of the planet (McGuirk, 1993; McGuirk, and Ush, 1990; McGuirk and Schafer, 1988; Paului et al., 2010; Johnson, 1989. Our analysis, reveals JAPE surges are most frequent in the winter hemisphere, but can occur in the supper hemisphere less often. Quasi-geostrophic (QG) dynamics dictates that the surges will grow two (vertical) direct circulation cells in the entrance of an amplifying polar jet streak see figure 2.

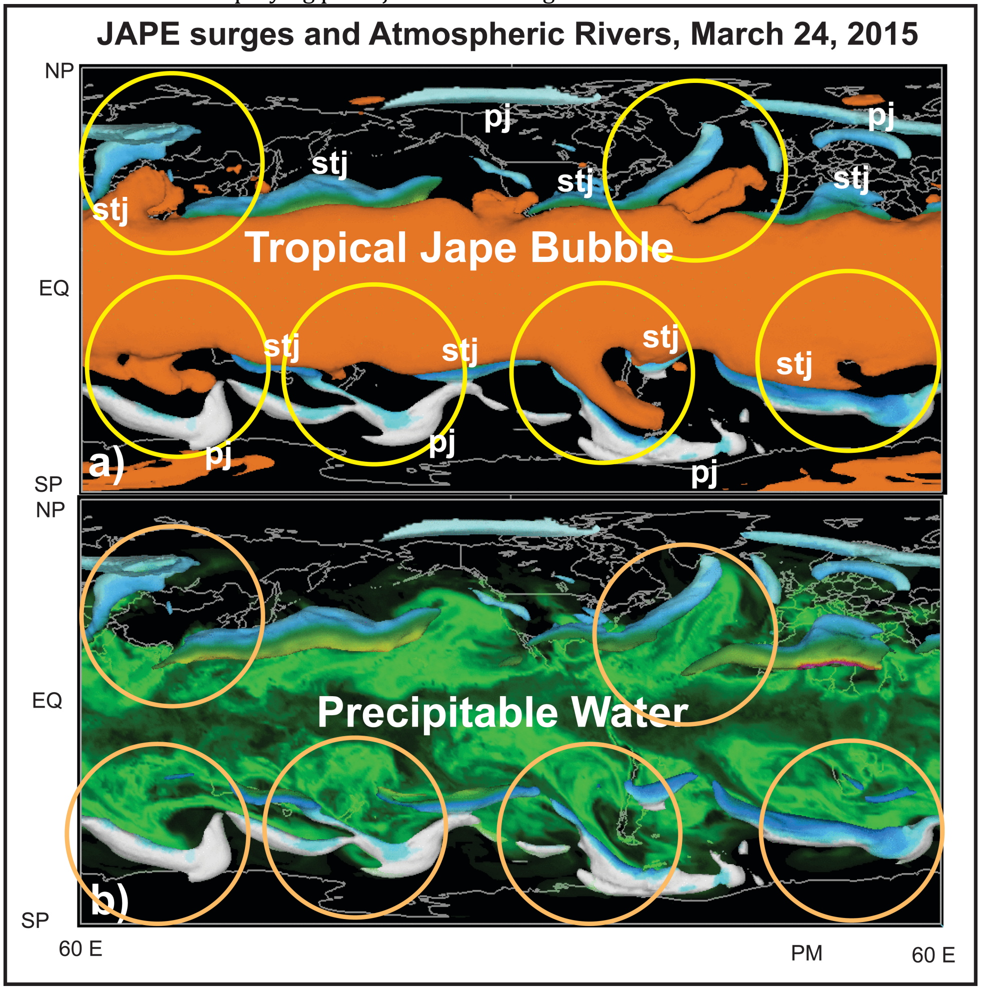

Figure 2: Depiction of global tropical JAPE bubble shown in figure 1 but viewed from above. Part a depicts the JAPE bubble 2500 J/kg surface in conjunction with STJs and PJS, while part b depicts the precipitable water and atmospheric rivers also in conjunction with the jets. The jets are the 42 m/s westerly wind surface, colored by potential vorticity. Subtropical jets are more green and blue depicting very low tropical potential vorticity while the polar jets are white colors indicating their much higher potential vorticity. In (a) the yellow circles depict regions of JAPE surges and in (b) the orange circles depict corresponding regions of atmospheric rivers associated with JAPE surges. Explicit STJ-PJ JAPE transfers are most notable in the southern hemisphere, which is exhibiting more baroclinicity or winter-like behavior on this date.

The upper cell will transport the cold JAPE bubble downward while the lower cell will transport the low troposphere warm anomaly (compared to high latitudes) upward. The return circulation of the lower circulation transports cold air poleward of the polar jet down and the upper level return circulation poleward of the jet lifts relatively warm stratosphere upward. The baroclinicity of the upper cell, between the polar stratosphere and tropical JAPE bubble, is sometimes the dominant baroclinic energy source.

These circulations will spawn a strong veering vertical wind profile in the lower troposphere that can be conducive to severe storms when CAPE conditions are supportive, typically in the spring. At other times, the associated atmospheric rivers will supply copious moisture to enhanced baroclinic storms, or even convective events (Lang, etc). The energized Rossby wave train itself increases the intensity of baroclinic storms, and together with associated moisture fluxes can lead to severe blizzards in winter months. The exit region of the PJ is also amplified, causing an enhanced indirect circulation, strengthening baroclinicity downstream beyond that existing upstream prior to the JAPE surge. Interestingly, there is good evidence that upstream tropical JAPE surges are the source of enhanced cold air systems such as the so-called "polar vortex". In fact, our analysis of these exchanges over the past 3 decades suggests that it is these tropical UTLS surges that drive the most significant weather of the extratropics in virtually all seasons of the year.

Global numerical models are capable of representing impending JAPE surges, but only to the extent that they define the STJ structure (i.e. the tropical UTLS JAPE bubble) competently so an impending surge can be predicted. Atmospheric river systems affecting CONUS are affected by poleward arching STJs, initially over the Pacific. Except for limited sounding locations, in situ observations of the JAPE anomalies over much of the Pacific do not exist. Hence satellite AMVs and soundings, combined with model based attempts to predict JAPE production using cumulus parameterization over long periods, results in the STJ definition as the STJ approaches the west coast of the US. More often than not, our observation of the GFS analysis reveals that the GFS detects the incoming STJ, but often underestimates its strength and misrepresents its vertical structure. As a consequence the 1-3 day forecast of significant precipitation and significant weather of all types over the central CONUS suddenly "improves" as the STJ crosses into CONUS sounding network. Often this is too late for timely warning of approaching severe weather, resulting in significant losses during high-risk events.

This problem is critical because the large energy infusions of the JAPE plume can produce significant weather, e.g. the April, 2011 tornado outbreak, where a more advanced warning capability of several days would be important. On the west coast of CONUS, there is even more need to improve the definition of the JAPE plume over the Pacific. The so-called "pineapple express" is an atmospheric river created by a JAPE surge that leads to major rain and snow events in the West. Precise prediction of these events has important societal and economic implications.

b. Origins of JAPE

A detailed energy analysis of tropical cyclone genesis (Tripoli, 2015, in preparation) shows that JAPE is produced as a by-product of deep moist adiabatic overturning. Simply stated, it results from the conversion of latent heating to Gibbs energy in excess of that consumed by expansion and other local dynamic accelerations (Tripoli, 2015, in preparation). It is available for further work. Figure 1 compares the difference between average

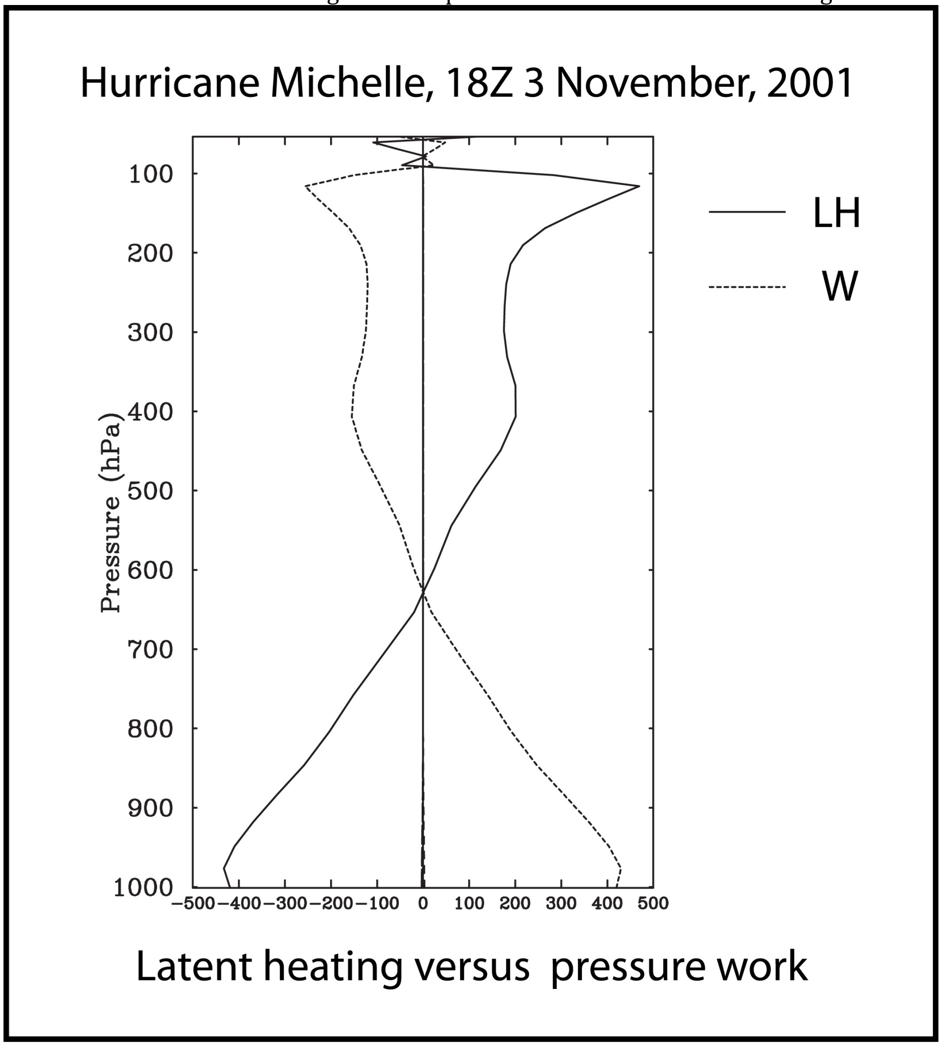

Figure 3: Graph of total domain scale (inner grid nest) latent Heating and work performed against expansion (109 GW) over 6 hours during the growth phase of Hurricane Michelle while over the Caribbean. The inner grid-averaging domain is 360 km across. Note that heating produces slightly greater heating than the consumption by parcel expansion in the upper atmosphere.**

therefore represents potential energy left over in the UTLS from a moist overturning, that expansion to the diabatic heating of a cloud resolving, fully compressible simulated storm to the diagnosed JAPE change over a 6 hour period, showing that this energy excess is efficiently sequestered as a JAPE change, confined to the UTLS. This is shown in figure 2, where JAPE production matches the residual energy of expansion versus heating.

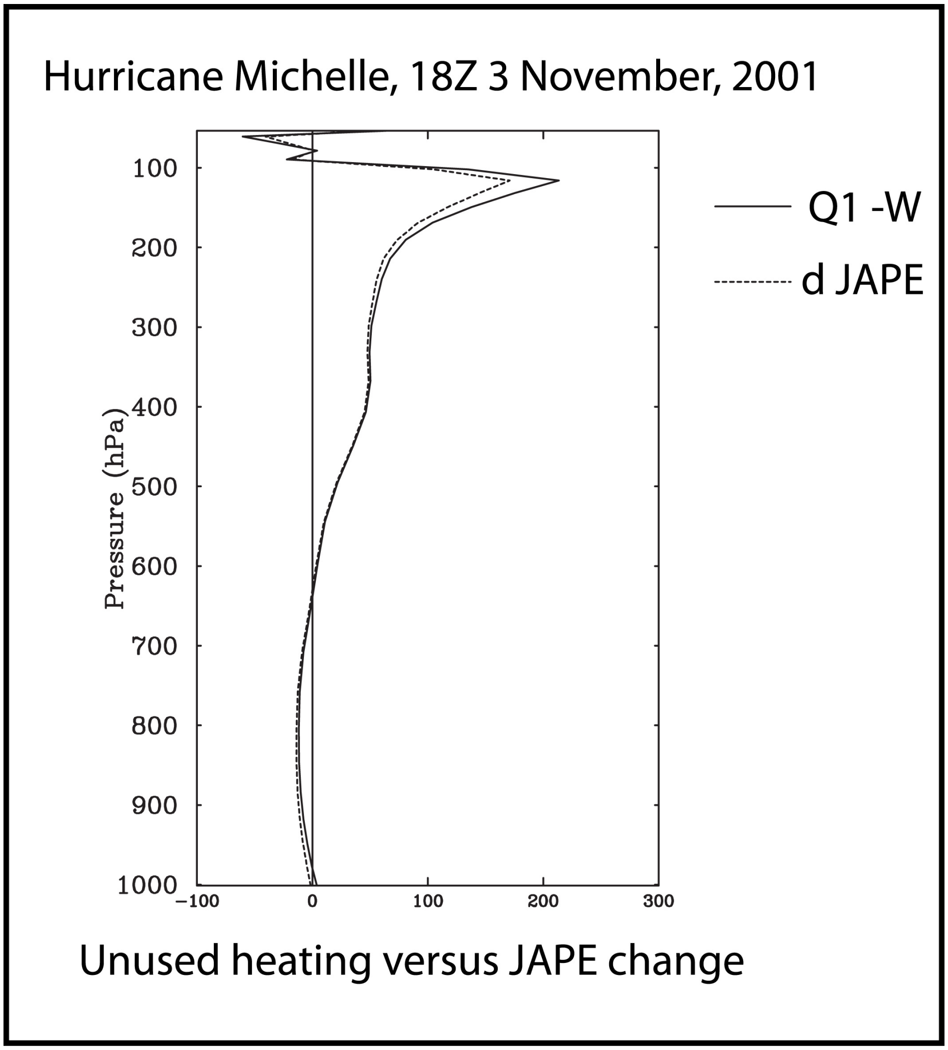

Figure 4: Same as figure 1 except for JAPE production compared to the residual energy left over after work of expansion consumes much of the latent heating.

JAPE can be viewed as positive isentropic thickness anomaly in the tropical UTLS that is responsible for the elevated tropical tropopause. We can expect that all deep convection or any circulation involving latent heat release, tropics or extratropics, may also be capable of depositing JAPE into the tropical UTLS "JAPE bubble" or at least an isentropic layer consistent with the moist entropy of the convective plume outside the tropics.

c. Hypotheses

Real time observation of numerous prediction failures of the GFS and its dependence on the early analysis of a developing JAPE plume, suggests that there is an opportunity to improve the prediction of major weather events associated with the STJ and JAPE surges by a better depiction of the tropical JAPE bubble while it is over the in situ data void of the Pacific. This leads to three hypotheses:

i. *Hypothesis 1: The poleward surge of potential energy anomalies built up in tropical UTLS causes a direct infusion of tropical energy into the extratropical wave stream, inducing a lower tropospheric Sawyer Eliassen Circulation resulting in the formation of a lower tropospheric Atmospheric River*
ii. *Hypothesis 2: Estimates of latent heating by the GPM Constellation can be assimilated into numerical prediction systems to detect isentropic mass tendencies in the tropical UTLS, and so improve the prediction of the JAPE bubble, and STJ formation .*
iii. *Hypothesis 3: The improvements of Hypothesis 2, will lead to important improvements to the 1-5 day forecast of JAPE surges, associated atmospheric rivers, and significant extratropical weather associated with these events.*

II. Approach to Verifying Hypotheses

The goals of this study are to verify the above hypotheses by (a) improving the GPM latent heating algorithms if necessary, (b) testing GPM latent heating algorithm for the sensitivity of predicted JAPE production to latent heating data from GPK+M latent heating algorithm or improvements thereof using adjoint-based numerical sensitivity testing, (3) use further adjoint-based numerical data impact tests to determine the influence of these latent heating products on the quality of the STJ simulation and the impact on significant extratropical weather events.

a) Latent Heating Algorithm Analysis

The GPM latent heating algorithms are designed as "heating" algorithms, but may not effectively capture isentropic mass movements accurately. If they do not, unrealistic production of entropy may result in model applications that cause overall entropy loss or gain. This then may degrade the model's ability to capture entropy mass interactions along isentropic layer, one of which is the process of JAPE surging.

Recognizing entropy injection, as opposed to "heating" depends on identifying the moist entropy produced by the latent heating and requiring that it be placed in the appropriate isentropic layer. The current GPM latent heating functions are representing this process as a heating tendency and so may not produce the correct entropy exchanges that latent heating implies, and so may not enable the model to place the resultant vertical mass fluxes into the correct isentropic layers. Our goal will be to refine the GPM latent heating algorithm to produce the correct isentropic mass fluxes when added to a sigma model, and to develop an alternate form to the GPM latent heating algorithm recast into the form of a profile of entropy fluxes that can be used in a model to appropriately add mass to specific isentropic layers, within the sigma coordinate.

More accurately representing the vertical distribution of JAPE production according to its entropy would enable the latent heating algorithm to improve a model's ability to assimilate and then predict JAPE buildup and response. Because the vertical distribution of JAPE results from the isentropic distribution of vertical mass flux, these improvements will improve the model forecasted definition of the JAPE bubble and the model's ability to capture the timing and structures of JAPE surges and attendant extratropical weather.

b. Adjoint analysis of sensitivities

The adjoint of a numerical weather prediction (NWP) model is a tool used to evaluate the sensitivity of a differentiable function of the model forecast state (the response function) to changes in the forecast trajectory and boundary conditions at earlier times (Errico, 1994). The (adjoint-derived) sensitivity is defined as the gradient of the response function, defined at the final time, with respect to the model state at some earlier time including the boundary conditions. The adjoint of NWP models are developed from the tangent linear model (TLM) of the corresponding nonlinear NWP model, linearized about a forecast trajectory. At the coding level, the adjoint model represents the line-by-line transpose of the coded TLM.

Adjoint-derived forecast sensitivity gradients have been used in a variety of meteorological applications. For four-dimensional variational data assimilation (4DVAR), the adjoint model is used along with minimization algorithms to determine an optimal analysis of a model initial state by combining knowledge of the misfit between a model forecast trajectory and observations, as well as the error covariances associated with each (e.g., Talagrand and Courtier 1987). Adjoint models have also been applied to problems concerning parameter estimation and stability analysis (e.g., Hall et al. 1982). The computation of optimal perturbations, and in particular "singular vectors" (Farrell 1989; Buizza et al. 1993), also requires an adjoint model. Assuming a perfect model and some measure of actual forecast error, an adjoint model can also be used to evaluate possible initial condition errors (Rabier et al. 1996; Klinker et al. 1998; Hello et al. 2000; Langland et al. 2002). Adjoints of NWP models are also used in case studies of weather systems. In these studies, physical interpretations of the sensitivity fields, their evolution, and their relation to the basic state model fields are used to understand the impacts of perturbations to the important dynamical processes associated with the weather systems (Errico and Vuckicekic, 1992; Vukicevic and Raeder, 1995; Lewis et al, 2001; Kleist and Morgan, 2005; Hoover and Morgan, 2011; Hoover 2015).

c. Impact of Observations on NWP Forecast

Traditionally, the impacts of observations on numerical weather forecasts have been measured mainly through observing system experiments (OSEs), in which observations are removed from (or added to) a data assimilation system and the resulting forecasts compared against ones produced using a control set. In contrast to these OSEs, the adjoint-based forecast sensitivity to observation (FSO) method is an efficient approach to assess the relative observation impact of each individual observation on some aspect of a forecast (Langland and Baker, 2004). Unlike OSEs, which measure effects of a single observation on all forecast metrics, FSO quantifies *simultaneously* the response of a single forecast metric to all perturbations of the observing systems (e.g., Langland and Baker, 2004; Cardinali, 2009). The FSO method can be used to assess directly the impact of any or all observations used by a forecasting system during data assimilation on a selected measure of a short-range forecast (often this is a measure of forecast error), as opposed to adding or withholding observations during assimilation (Zhang et al., 2015). Adjoint-derived observation-impact has been found to produce information that is complementary to but not necessarily overlapping with information produced from OSEs (Gelaro and Zhu 2009).

III. Proposed work

a. Latent Heating Algorithm

We will closely examine the latent heating algorithm by applying it to a cloud-resolving model to determine if the algorithm physically leads to the entropy exchanges that are associated with the formation of JAPE anomalies. If this is not the case, we will determine how the algorithm can be adjusted to provide the appropriate isentropic forcing and develop a method to translate latent heating derived from the GPM product to an analysis-perturbation. Our goal with the adjoint model is to define the sensitivity of various relevant aspects of the midlatitude forecast (e.g. JAPE injection into the midlatitudes, development of atmospheric rivers, etc.) to perturbations of the model initial (analysis) state, and then to compute the estimated impact of latent-heating-based analysis-perturbations on the forecast. These perturbations can then be evolved through the non-linear model to observe the impact on the forecast directly.

b. Adjoint studies

We propose a modeling study of JAPE surges and atmospheric river events utilizing the nonlinear, tangent-linear, and adjoint formulations of NWP models to gain insight into the evolution of these features as well as the sensitivity of NWP forecasts to their depiction in the initial state. Likewise, we wish to investigate the impact of routinely assimilated observations on the forecast of atmospheric rivers to perform an assessment of the value of various observation platforms to the forecasting of these events. Adjoint-derived sensitivity gradients provide information on the dynamical features driving the evolution of the atmospheric rivers, and provide information on where in the atmosphere new observations may have the potential for modifying the forecast of the atmospheric rivers specifically.

This project directly addresses section A.23-2.2 of the PMM program: Methodology Development for Improved Applications of Satellite Products. Adjoint-tools can be employed for the "development of metrics and methodologies for assessing satellite precipitation products in hydrological applications" (point-2). This will take the form of developing specific metrics for the midlatitude forecast (JAPE production, moisture transport, precipitation, etc.) and defining both the sensitivity of these forecast features to initial conditions, as well as estimating the observation-impact from currently assimilated observations. Estimated observation-impact allows for a comparison of the value of observations from different platforms/variables/vertical levels/etc. to the forecast of atmospheric rivers. Sensitivity gradients provide information on where analysis-perturbations, such as those derived from the GPM latent heating product, may have the most impact on the forecast.

i) Sensitivity analysis of atmospheric river forecasts

We propose to consider response functions that are related to measures of the strength of atmospheric rivers and JAPE and seek adjoint-derived sensitivities to these response functions to model control variables and derived functions of those control variables (like vorticity, e.g. Kleist and Morgan 2005). The proposed response functions include the horizontal water vapor transport (flux), $\boldsymbol{vq}$ through a vertical cross section at the time when the moisture surge associated with the AR is a maximum, JAPE, and a combined dynamic and thermodynamic response function that measure the "total energy". Sensitivities to vorticity could be used to determine the sensitivity of the model state inertial stability.

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The location of large sensitivity of atmospheric-river response functions to the initial (analysis) state can provide a wealth of information on the dynamics involved in the evolution of the atmospheric river, and the interaction of various features of the atmosphere that may be important to the formation of an atmospheric river. Theories pertaining to the creation of an atmospheric river can be tested against the observed sensitivity, and analysis of the sensitivity gradients can lead to new theories about atmospheric river formation. We have particular interest in discerning the role of the subtropical jet, and its interaction with the polar jet, on the formation of atmospheric rivers.

ii) Perturbation tests based on adjoint-derived sensitivity

Given a constraint about which to minimize (e.g. total energy), one can use adjoint-derived sensitivity gradients to derive optimal perturbations for influencing a chosen response function of the forecast state (Errico 1997). We plan to produce sensitivity gradients for multiple aspects of the formation of an atmospheric river; from these gradients, we can produce perturbations to the model initial state and allow the perturbed state to evolve in both the tangent-linear and nonlinear model to observe the precise relationship between regions highlighted by adjoint-derived sensitivity and the formation of the atmospheric river. This also provides an opportunity to check the impact of the linearity and simplified moisture physics of the adjoint on the accuracy of the derived sensitivity gradients.

Similarly, we can produce perturbations to the analysis-state based on the GPM latent heating product, and perform a similar analysis. The estimated impact on various aspects of the forecast can be estimated using the adjoint-derived sensitivity gradient, and the perturbations can be evolved through the nonlinear model to directly observe their impact on the forecast.

iii) Observation-impact

Utilizing the adjoint of both the NWP model and the data assimilation system, sensitivity of aspects of the atmospheric river can be computed with respect to the assimilation of individual observations assimilated into the initial (analysis) state. The inner-product of the observation-space sensitivity and the innovation provided by the observation determines the observation's impact on the atmospheric river forecast. This information can be collected to compare different observing systems in regard to their importance to the atmospheric river forecast, using specialized response functions defined for the atmospheric river forecast specifically; this information is distinctly different from the more traditional observation-impact metric routinely used to monitor the short-range forecast, which typically relies on a global energy norm. Here, we can address questions about the value of latent heating algorithms, to the JAPE and STJ and JAPE surge forecasts, and compare their value to other satellite as well as their value at different times. Since the formation and evolution of the JAPE bubbles typically takes place over the ocean, it is expected that latent heating observations will have a significant impact on the JAPE evolution and surge points in the NWP forecast. However, the surge is also dependent on the meridional wind structure associated with the movements of the PJ as well as the STJ. Simulating these interactions will also require the assimilation of AMVs . Through these adjoint studies, the relative importance of the current and possibly improved GPM latent heating estimations will be learned.

iv) Modeling systems used

At present there are few modeling systems with corresponding adjoints available for non-operational research applications. Two to be used in the proposed study include the NASA Goddard Earth Observing System Model, Version 5 (GEOS-5) and the Advanced Research Weather Research and Forecast Model (WRF-ARW). The GEOS-5 Data Assimilation System (GEOS-5 DAS) integrates the GEOS-5 Atmospheric Global Climate Model (GEOS-5 AGCM) with the Gridpoint Statistical Interpolation (GSI) atmospheric analysis developed jointly with NOAA/NCEP/EMC and includes the adjoint of both systems (Zhu and Gelaro, 2008). The GEOS-5 adjoint contains a state-of-the-art adjoint of the relaxed Arakawa-Schubert convective parameterization scheme used in the nonlinear model (Holdaway and Errico 2013), allowing the adjoint model to take into account both model-resolved and parameterized convection (Holdaway et al. 2014), This makes the GEOS-5 system particularly attractive for sensitivity studies where accurate representation of moist physics are a priority.

WRFPLUS includes a linearization and its adjoint of the dry dynamics of the WRF model, a simplified vertical diffusion scheme, and a large-scale condensation scheme (Xiao et al. 2008, Zhang et al. 2013). There are no other moist processes represented in WRFPLUS. The WRF model and its adjoint are capable of producing high-resolution regional simulations of atmospheric river events, providing complementary information to the lower-resolution, global GEOS-5 simulations.

c. Summary (tasks)

   a. Physically study the implications of the GPM latent heating estimates on the formation of JAPE. If the estimates fail to properly place the vertical mass fluxes from latent heating in the appropriate isentropic layers, engineer some simple improvements to ensure these characteristics.

b. Use adjoints applied to numerical simulations to study the relative sensitivities of the JAPE bubble and STJ forecast on the assimilation of upstream latent heating, AMVs and possibly other satellite data products.
c. Again use adjoints applied to numerical simulations to study the relative sensitivities of the forecast of downstream surge events on the assimilation of upstream latent heating, AMVs and possibly other satellite data products
d. Deliverable will be a series of papers describing the relationship between precursor tropical events and the surge, the important satellite data products that toward improving the ability of models to detect critical structures of the JAPE anomaly and STJs and the downstream STJ PJ interactions that drive the formation of JAPE surges, atmospheric rivers, and significant extratropical weather.
e. Timeline
   i. Task a completed by 6 months, year1
   ii. Task b completed by 1.5 years into project
   iii. Task c completed by 3 years
   iv. Task d, ie papers will be completed at the conclusions of tasks a-c

IV. Relationship of proposed work to NRA

a. The proposed work is in response NRA ROSES PMM, A23.2.2: Utilization of Satellite/GV products for Process Studies and Model Development; Analysis of TRMM and other current satellite-based precipitation information from observations and models to produce improved analysis of rainfall,….and improved application of satellite products in numerical weather prediction and data assimilation.
b. The proposed work also addresses NRA ROSES PMM A23.2.3: Methodology Development for improved applications of Satellite Products; Development and implementation of data assimilation techniques for improved forecasts of significant weather (e.g.tropical cyclones and floods)….using satellite-based precipitation measurements.

V. Broader Impacts

a. This study is addressing a specific process by which tropical rainfall influences extratropical weather via the STJ. The proposed approach and supporting theory will help open a new paradigm relating to how tropical weather impacts extratropical weather which goes beyond the simple Hadley/Ferrel/ Polar cell models and instead views the circulation as comprised of catastrophic surges, the precursors of which are hypothesized to be predictable by satellite, and in particular observations of the GPM constellation.

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