Nonlinear interactions in practical wind wave models

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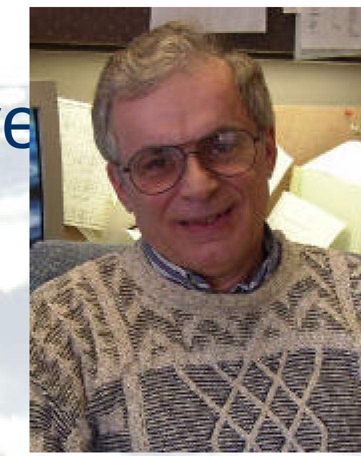

he DIA

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Background 1

- Nonlinear four-wave interactions have been in the center of interest for wave modeling since the 1960's with pioneering work of Hasselmann and Zakharov.
- Most other processes in a wind wave model are inherently linear. These high order interactions are nevertheless relevant and essential, because they provide the lowest order processes to shift wave energy to lower frequencies, and they stabilize the spectral shape during wave growth.

Background 2

- First economically viable approach for practical wave models is the DIA, introduced by Hasselmann et al. (1985, JPO).
- The DIA made third-generation wave models possible, but it's limitations are now considered to hamper further development of physics of wave growth and decay in such models.
- Three approaches followed in recent research :
  - Speed up "exact" interactions.
  - Make DIA more accurate by expanding.
  - Develop alternative "cheap" approximations.

Background 3

- Speed up the exact interactions:
  - Improving general methodology.
    - Many authors over last three decades (Webb, Masuda, Hasselmann, Herterich, Tracy, Resio, Perrie, Komatsu, Van Vledder etc.).
  - Filtering and other simplifications = trading accuracy for speed.
    - Snyder et al (1998).
    - Van Vledder (2001).
    - Hashimoto and Kawaguchi (2001).
    - ….

not now

Background

- Expand the DIA = trading speed for accuracy. Present ratio of computing cost / power makes this feasible:
  - Add more representative quadruplets.
  - Increase flexibility of representative quadruplet.
  - Add tuning parameters to interaction strength
    - Ueno and Ishizaki (1997).
    - Hashimoto and Kawaguchi (2001).
    - Van Vledder (2001, 2002).
    - Polnikov and Farina (2002), Polnikov (2003).
    - ....

More to follow

Background

- Alternative approaches :
  - Full parametric approaches generally not viable as discussed in DIA paper.
  - Diffusion approach is cheap, but accuracy not fully addressed yet.
    - Zakharov and Pushkarev (1999).
    - Jenkins and Phillips (2001).

  Not here

  - Neural Network approach. Can be cheap and accurate, robustness is main issue.
    - Has some links with the original DIA paper.
    - Ongoing research at NCEP.

  More to follow

NCEP strategy

Originally, we envisioned a DIA based NN, or a DIA with dynamically adjusted parameters (NN or other approaches)

- Strategy A: Build upon the success of the DIA. Present level of computing power allows for more expensive approach.
  - Comprehensive comparison of DIAs from litterature.
  - New approaches ?
- Strategy B: Use our in-house expertise in Neural Network technology to develop a new approach (NNIA).
  - Start with 100% NN approach.
  - Incrementally bring in physics.

Track A :

The Discrete Interaction Approximation

DIA work at NCEP

- First study:

Tolman, (2004)

  - Inventory of previously suggested modifications to the DIA.
  - Suggest some logical extensions.
  - Test by comparing/optimizing with WRT approach for a small number of spectra.
- Second study:

In progress

  - Focus on behavior of several DIA approaches when used in a wave model.
  - Holistic optimization approach.

First Study 1

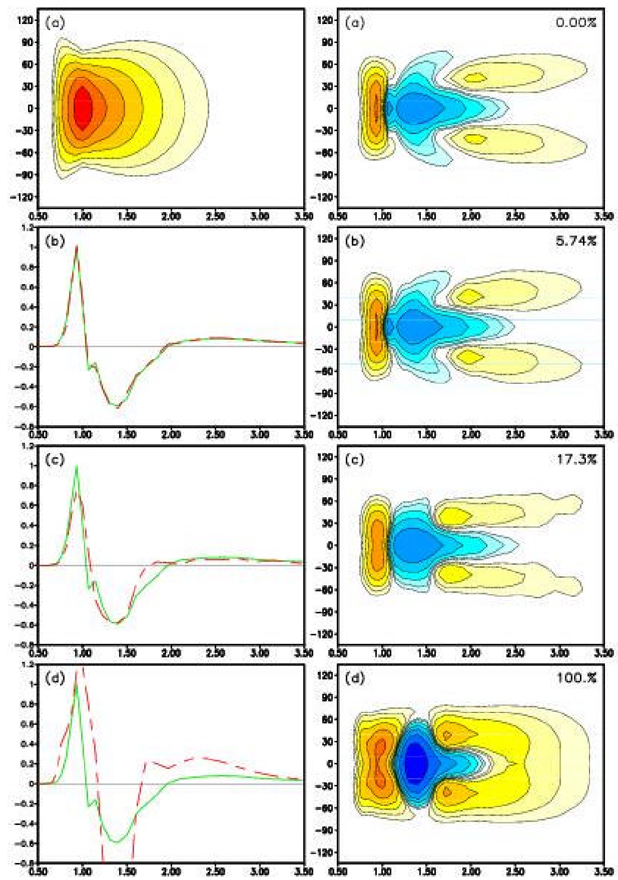
- Test previously suggested modifications, with conventional testing for test spectra:
  - Alternative quadruplet layout.
  - Multiple representative quadruplets.
  - Multiple proportionality constants.
- New modifications suggested:
  - Additional symmetrical quadruplet layouts.
  - “Variable” DIA approach with quadruplet layout as a function of spectral frequency.

First Study 2

- Main conclusions:
  - One parameter quadruplet layout of original DIA restricts its accuracy.
  - A four component DIA with extended quadruplet definition can be extremely accurate.
  - A vari… …improvements.

Not worth the complication

- Surprise: Not all accurate DIAs result in stable model integration.



Exact (WRT)

MDIA N = 4

VDIA N = 1

DIA

Second Study 1

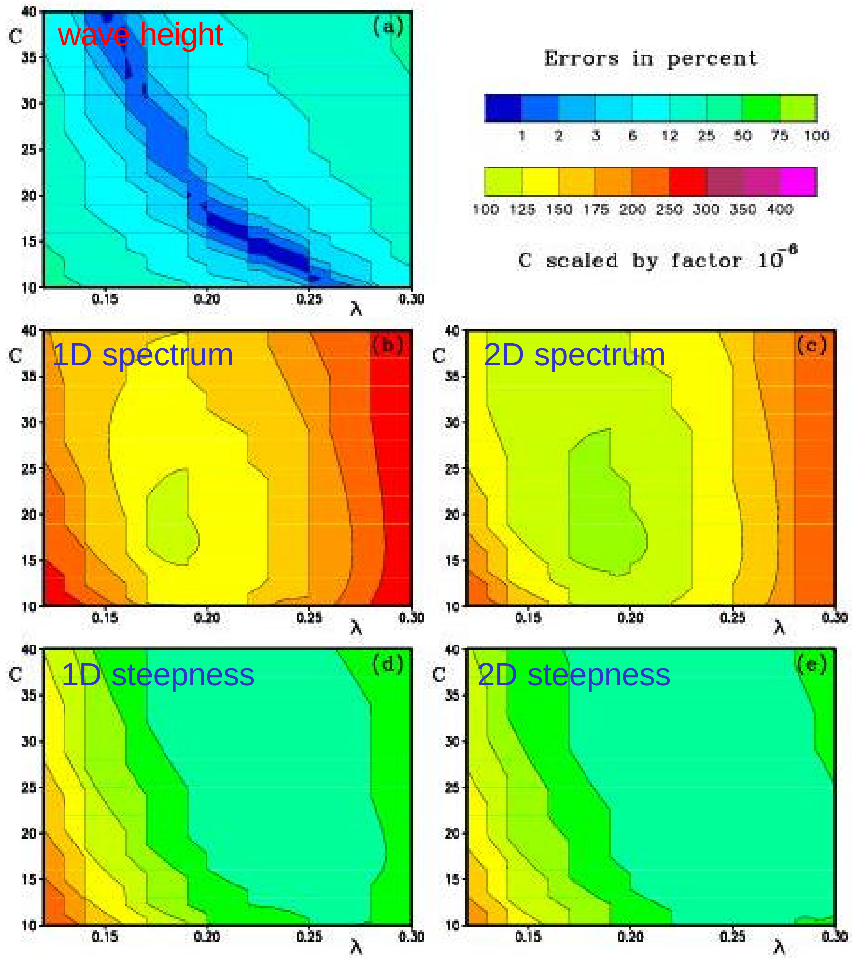
- Concentrate on model integration:
  - Why do not all DIAs result in stable model integration?
  - Which DIAs do, and which don't?
  - Holistic optimization of the DIA: Do not optimize individual interactions, but the wave conditions from the model.
    - → Traditional time limited growth test.
    - → Traditional fetch limited growth test.

Second Study 2

- The traditional, single component DIA.
  - Single parameter λ defines layout of quadruplet.
  - Single constant *C* determines strength of interactions.
- Simplicity of approach allows for full mapping of errors in parameter space.
  - Wave height errors.
  - 1D and 2D spectrum and steepness spectrum errors.
  - Errors locally normalized.

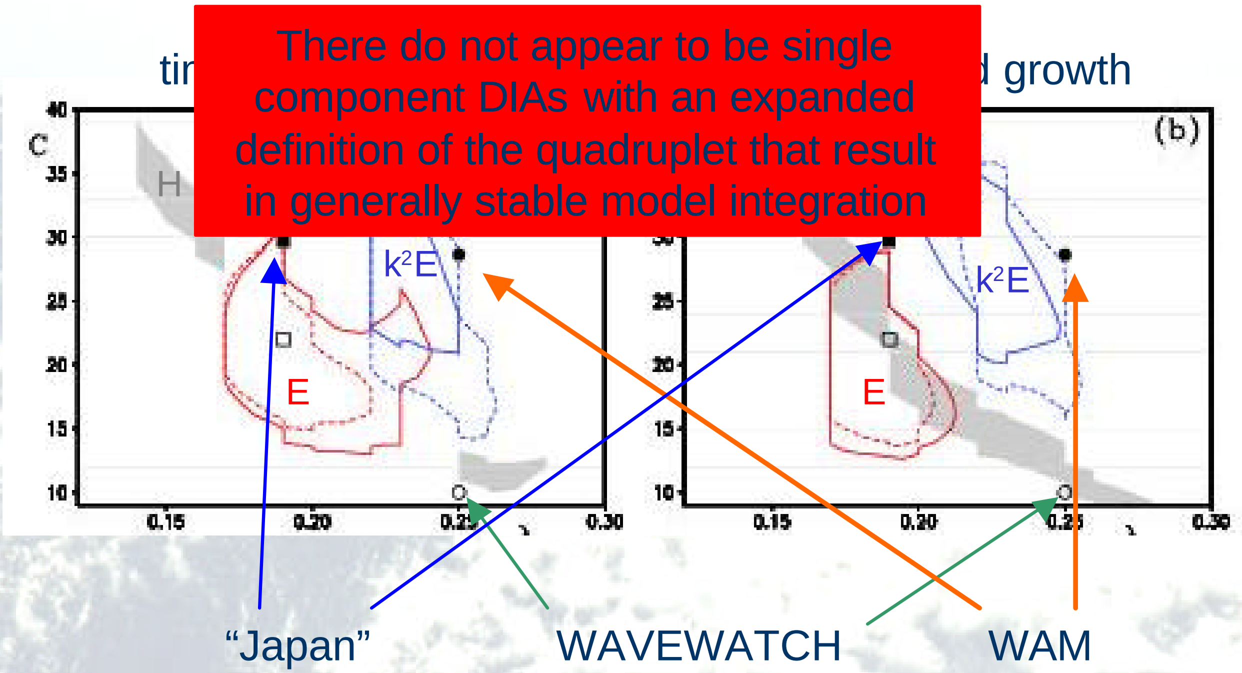
Second Study 3

- Wave heights can be represented accurately by traditional DIA. (error < 5%)
- Spectral errors are much larger, order of 75% for 1D spectra and order of 30% for 2D spectra.
- For each error measure, there is a fairly large area in parameter space with near optimal behavior (particularly for the wave height error).



Second Study 4

- The figures below shows areas of near-ideal model behavior. Not all parameters can be optimized simultaneously !



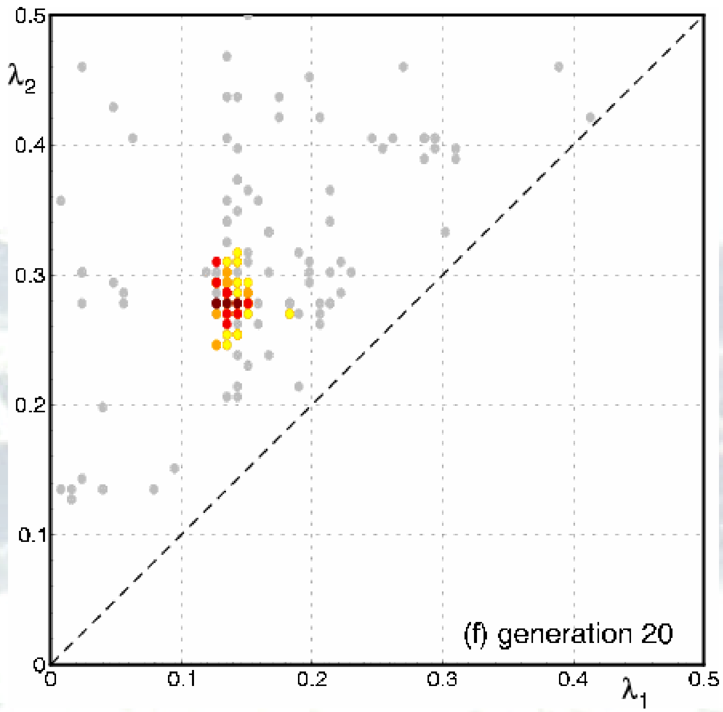
Second Study 5

- Optimizing MDIAs holistically, considering number of components and 1, 2 or 3 parameter quadruplet definition.
- Genetic search algorithms employed.
- Using single cost function made up of previous 5 error measures.
- Results obtained so far are promising, final cost function (%) presented in the table.

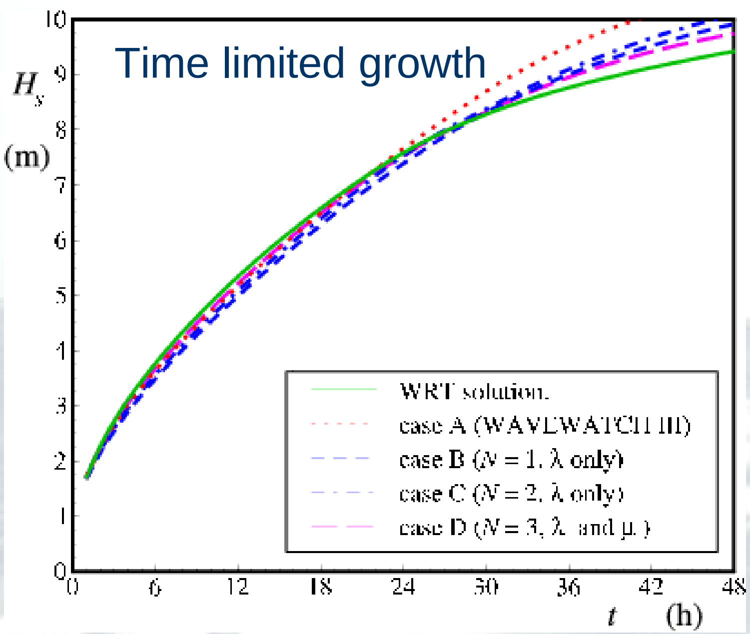
N	Quadruplet definition		
	1	2	3
1	26.0		
2	16.3		
3	16.1	11.6	?
4	16.1	12.0	???
5			???

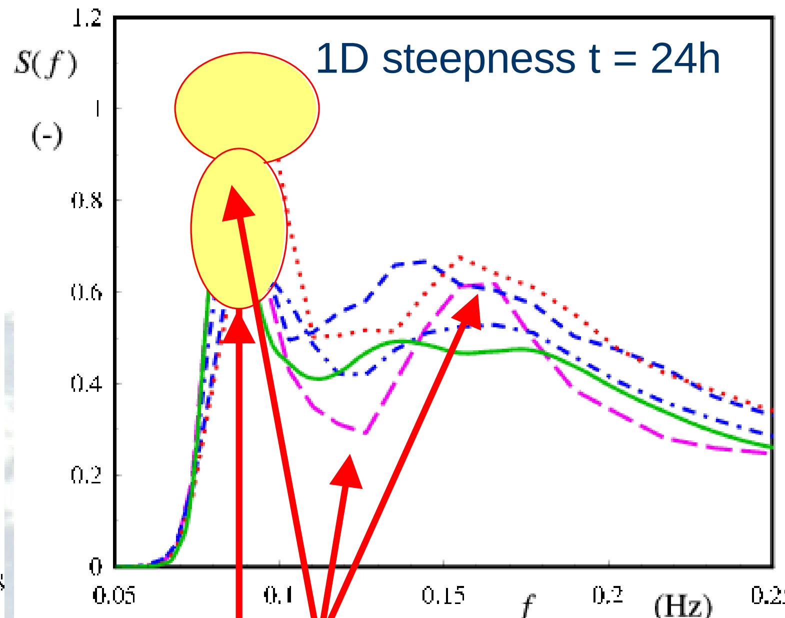
Second Study [6]

- Genetic search algorithms:
  - Parameters -> bit string = “genome”.
  - Generate population.
  - Biologically inspired reproduction rules.
  - Survival of the fittest.
- Can be interpreted as “targeted random search”.
- Combined with descent methods.



Second Study





Massive improvements D… using
a more complex DIA, b… sys… dered
so far, deficiencies rem…

Peak better, but intermediate frequencies not for more complex quadruplet

Summary

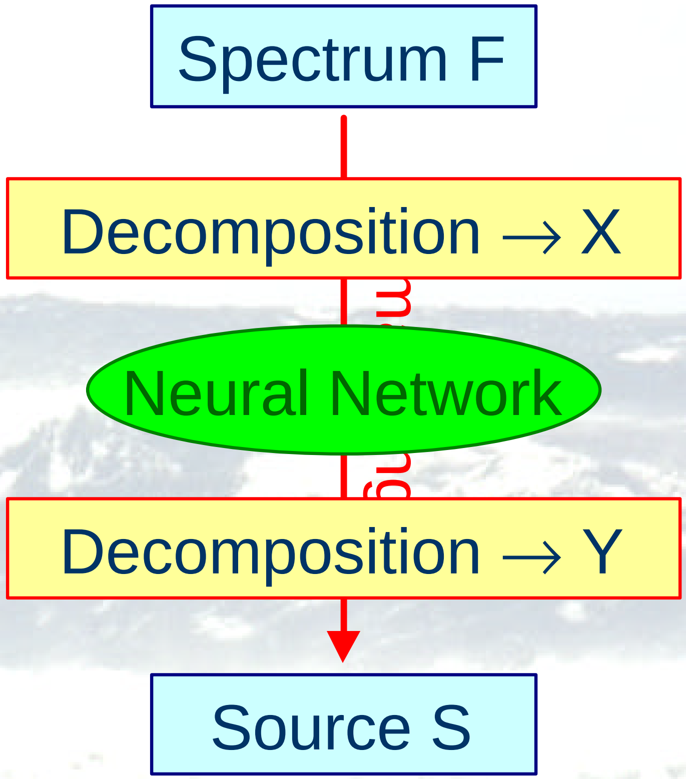
- The original DIA is very stable when applied to a wave model, but cannot "do it all". Good representation of wave heights goes hand in hand with significant errors in spectral shape.
- Expanding the quadruplet layout in single component DIAs seems to generate DIAs that are not generally stable when applied in a full wave model.
- The DIA with several components and with an expanded definition of the quadruplet can give much better results in a holistic optimization.

Track B :

A Neural Network Interaction Approximation

The Basics [1]

- We have a spectrum F and a source term S defined in the same spectral space.
- Consider this as a mapping problem from F to S, where a NN can be used to economically approximate the mapping.
- To reduce number of degrees of freedom in NN, NN is applied to F and S decomposed using basis functions.



The Basics 2

- Main issues for developing a NN:
  - A NN is developed in a process called training, where spectra F and source terms S are given, and the NN is trained to reproduce S from F.
    - → The training data set needs to be an envelope of possible conditions. In such a case the NN with "interpolate" and give good results
    - → Training is expensive, but the resulting NN is cheap …..

The Basics 3

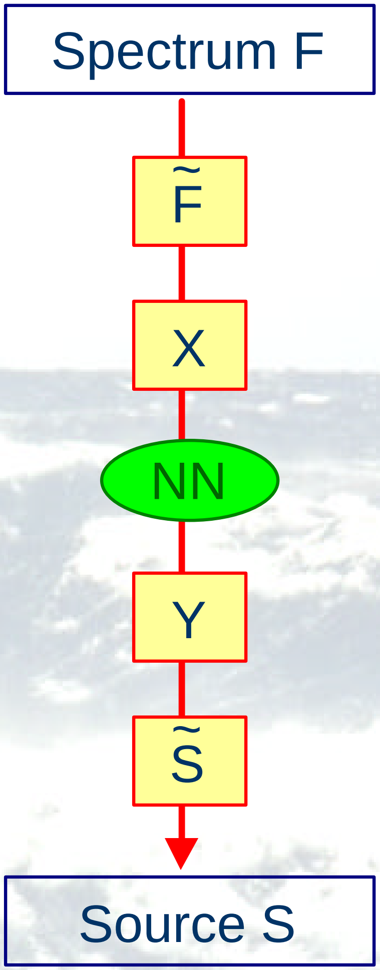
- Main issues cont'd:
  - A decomposition technique needs to be selected.
  - Accuracy of the NNIA depends on:
    - → Accuracy of decompositions X and Y and the corresponding error in representing F and S.
    - → Accuracy of the NN in estimating Y (S) from X (F).
  - In principle, unlimited accuracy can be reached, but at what cost ?

NNIA Evolution

- Feasibility study. Krasnopolsky *et al*. (2002)
  - Simple training data set with four-peaked spectra to establish base economy of NNIA.
- First attempt. Tolman *et al*. (2005)
  - Rich set of parametric wind sea spectra to establish decomposition techniques in context of accuracy for individual spectra and it's economy.
- Establish techniques that allow for stable and robust growth curve computations. In progress
  - "The real test of the feasibility of an NNIA."

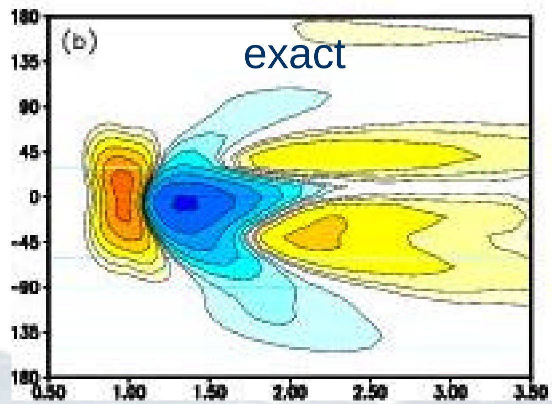
First Study [1]

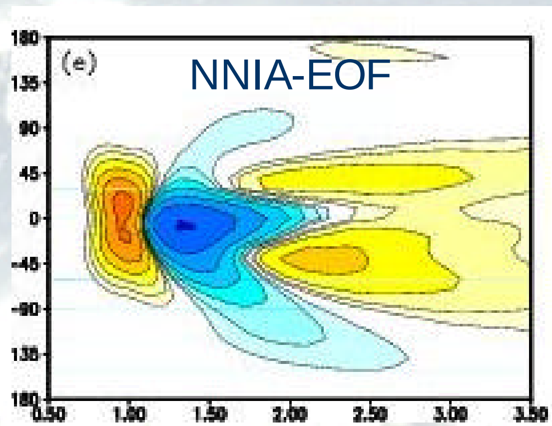
- Starting with basic NNIA design from feasibility study.
- Applying decompositions and NN to non-dimensional F and S to automatically build in scaling.
- Experiment with decom-position of feasibility study and Emperical Orthogonal Functions (EOFs).
- Generate a rich training data set based on parametric spectra.



First Study [2]

- EOF decomposition superior to Legendre / Fourier approach.
- Excellent interactions for spectra within family of parametric training spectra. (example on right).
- Reasonable results for modeled spectra (not shown here).
- Peculiarities of modeled spectra not in training set, therefore this NNIA is not yet applicable to models.



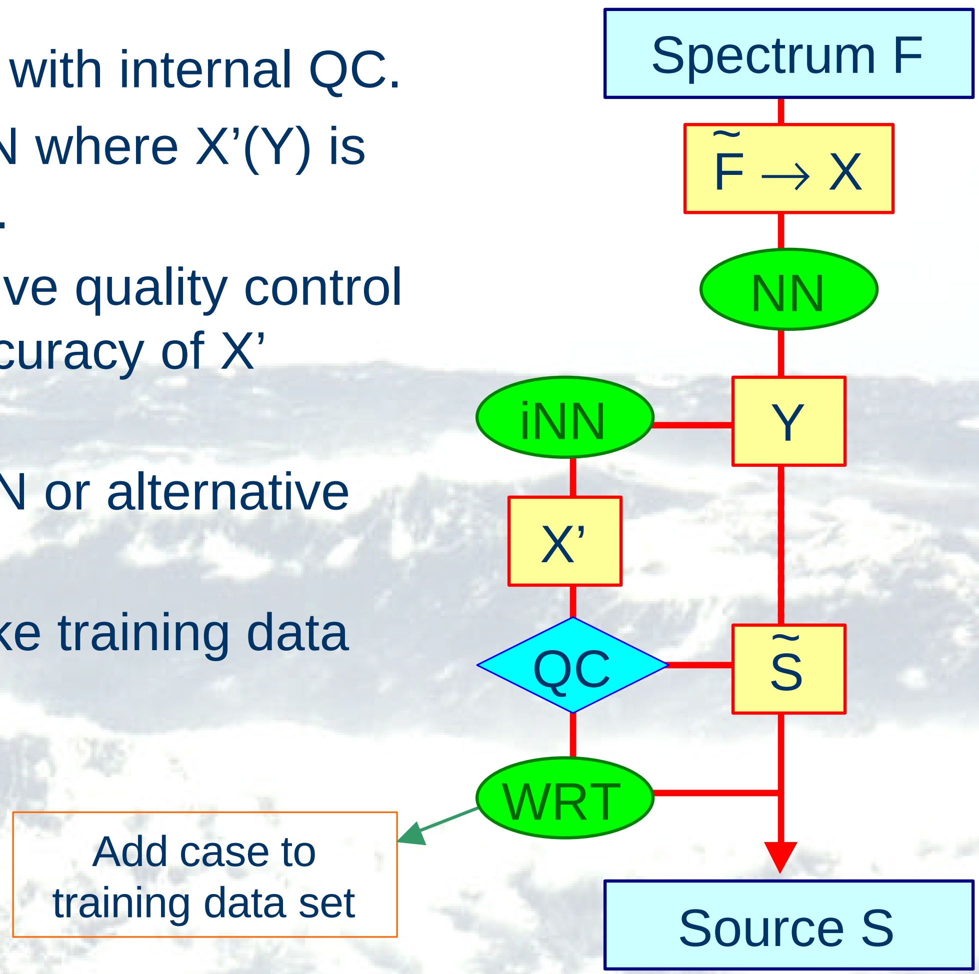


Second Study [1]

- In order to get a NNIA that is applicable to wave models, it needs to be trained with wave model data. The second study therefore uses spectra and source terms from time limited growth cases based on exact (WRT) interactions, with wind speeds and directions varying in time.
- Recognizing that it may be impossible to train a NNIA for completely arbitrary spectra, it is imperative to introduce objective quality control (QC), identifying when the NNIA should NOT be used.

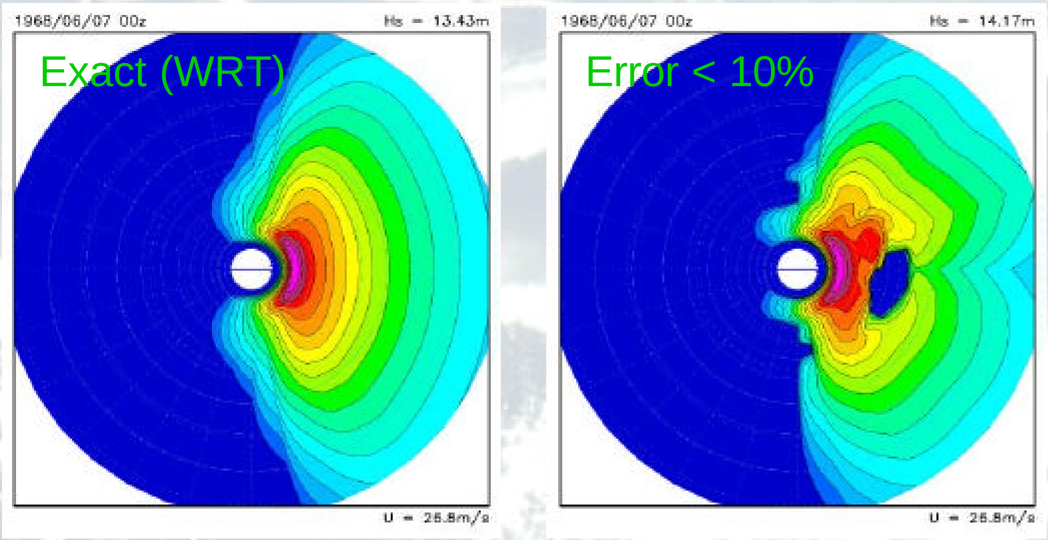
Second Study [2]

- Hybrid NNIA design with internal QC.
  - Add “inverse” NN where X’(Y) is an estimate of X.
  - Introduce objective quality control by assessing accuracy of X’ relative to X.
  - Decide to use NN or alternative scheme (WRT)
  - Dynamically make training data set broader.



Second Study [3]

- We are presently developing this Hybrid NNIA. The first issue is to see if adding QC can result in reasonable growth behavior in the model.



IT WORKS !

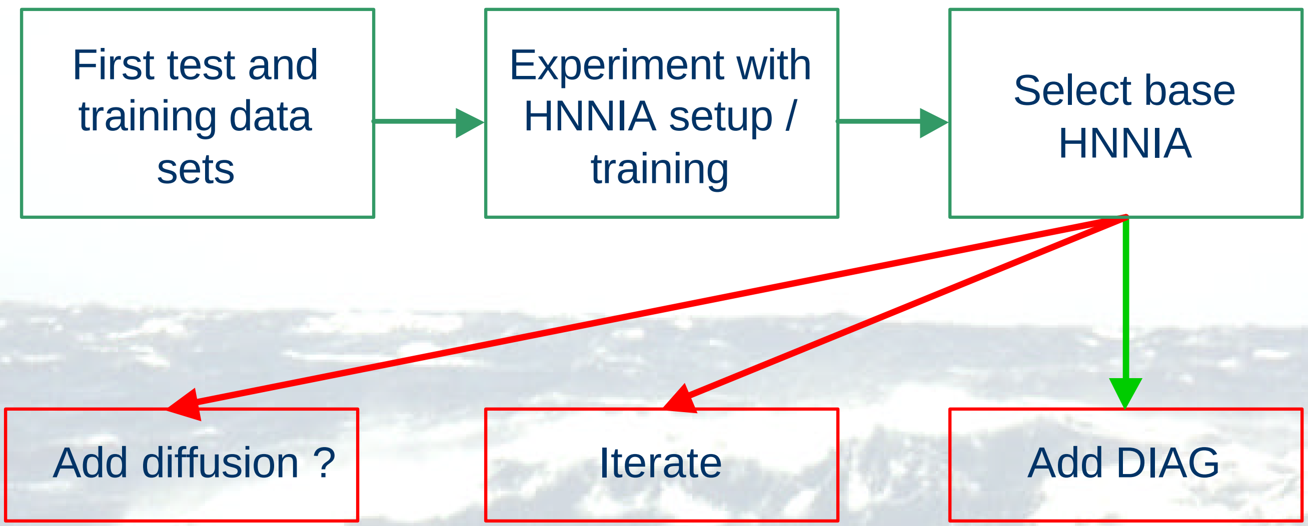
Problems occur mostly at higher frequencies.

High frequency problems can be reduced with alternative training (not shown here).

High frequency noise negatively impacts time steps (not shown here).

Second Study

4



he final step will be to put it all together, and iterate up to “convergence” with a proper size training data set.

Summary

- Recent results indicate that a hybrid NNIA with internal QC and a reversion to other methods if needed is feasible.
- Much work is needed to show robustness accuracy and economy in the limited growth conditions that are presently considered.
- If this hybrid NNIA approach proves feasible for the present idealized conditions, it will need to be expanded to more realistic conditions :
  - Arbitrary swells added.
  - Shallow water.

Concluding Remarks

- All of this is a work in progress. Two main conclusions, however, already stand out.
  - By having made a reasonably stable model integration with a hybrid NNIA, it appears to have potential for application in practical wave models.
  - Holistically optimized expanded DIAs can greatly increase model accuracy.
  - For Snl, a simple “mapping” approach to optimization is grossly inadequate, and a holistic optimization inside a full wave model appears necessary.